NIR-to-memory capability. We also demonstrate color differentiation between NIR and visible incidents with preferred NIR selectivity. Due to circuit
filter-free near-infrared (NIR) imaging and memory purposes. The device transforms NIR signals into grey scale nonvolatile resistance states, enabling a

* Invited Paper

copolymers with D−A structures exhibiting p-tpye, n-type and ambipolar behavior as well.[3-6]

with a dynamic range of 62 dB and 86 dB photoswitch under green light (550 nm). On the other hand, we report the design and synthesis of some
design, our retinal system accommodates a bi-modal operation with respect to incident wavelengths. It functions as nonvolatile memory under NIR (850 nm)

Semiconductor Microstructures


4. Jie Yang, Hanlin Wang, Jinyang Chen, Jianyao Huang, Yingying Jiang, Jianqi Zhang, Longxian Shi, Yunlong Sun, Zhixiang Wei, Gui Yu, Yunlong

5. Chunguang Zhu, Zhiyuan Zhao, Huajie Chen, Liping Zheng, Xiaolin Li, Jinyang Chen, Yanming Sun, Feng Liu, Yunlong Guo, and Yunqi Liu, J. Am.

8:30 AM *BM08.01.02
Highly Sensitive Flexible Pressure Sensors Based on Printed Organic Transistors with Three-Dimensionally Self-Organized Organic
Semiconductor Microstructures Jung Ah Lim; Korea Institute of Science and Technology, Seoul, Korea (the Republic of).

Highly sensitive flexible pressure sensors are at the forefront of the development of future mobile applications, such as rollable touch displays, health
monitoring, and electronic skin. Recently, monolithic organic field-effect transistors (OFETs) combined directly with pressure-sensitive components have
been demonstrated as actively workable pressure sensors due to cost-effectiveness, good flexibility, and large-area solution processing, which effectively
enables conformal large-area contact with a surface. Despite many pioneering efforts, the low cost and easy fabrication of OFET devices cannot be fully
exploited without the development of OFET-based pressure sensor printing processes. In this presentation, we will introduce a highly sensitive pressure
sensor based on a printed OFET with centro-apically self-organized organic semiconductor microstructures. Unlike previously reported OFET-based
pressure sensors prepared with a top microstructured dielectric layer, we designed a unique OFET bottom layer consisting of semiconductor channels
positioned at the highest summit of printed cylindrical microstructures, referred as “3D OSC”. This unique microstructure was achieved simply by printing
an organic semiconductor and a polymer blend, which self-organized after deposition without additional process. The proposed 3D OSC OFET pressure
sensors demonstrated a high pressure sensitivity of 1.07 kPa⁻¹ and a rapid response time of <20 ms with a high reliability over 1000 cycles. We
demonstrated that our sensors are applicable to the real-time monitoring of radial artery pulse waves and as touch sensors for use in realistic prosthetic
hands.
Intuitive monitoring of physical and chemical patient data is changing the health industry. Real-time monitoring devices, such as implantable and wearable tools for diagnostics, need truly flexible transistors for advanced electronics and elegant sensors. Previous reports have realized flexibility through geometric patterning[1] or intrinsically stretchable semiconductors[2]. For gate dielectric insulators, researchers have utilized elastomeric matrices and polymer electrolyte systems to achieve flexibility. Ionic liquid-based gel electrolytes offer high capacitance, a large electrochemical stability window, and are nonvolatile. Typical demonstrations of these ion gels use block copolymers[3] or chemically crosslinked in situ polymerization to add support, though some have demonstrated that colloidal particles dispersed in ionic liquids can result in gels[4].

In this work, we differ from previous reports of ionic liquid-based transistors (IL-OFETs) by using a colloidal dispersion of silica nanoparticles to support the ionic liquid. This scaffold is advantageous over existing triblock copolymers or chemically crosslinked gels because of its facile fabrication for conformal gel coating. Specifically, triblock copolymers have complex chemistry and in situ methods require additional crosslinking steps, such as UV treatment to form a gel, which could be difficult to apply to certain substrate types and geometries. Contrastingly, these silica dispersion gels are easily applied after gelation for a conformal coating.

We employ 1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide as the ionic liquid and poly(3-hexylthiophene) as the organic semiconductor, both well studied materials in regards to IL-OFETs[5]. We achieve OFET performance assessed by output and transfer characteristics. Use of this ion gel results in an on-off ratio of $10^{5}$, threshold voltage of -1.65V, an operating window of 0 to -2.7V, and allows for transistor development on softer, more flexible substrates than typical silicon or glass. For demonstration, we employ our transistor on a linen thread, which could offer a route to 3D monitoring of health in the form of smart sutures and transdermal implementations. This resulted in an off-on ratio of $10^{3}$, threshold voltage of -2.8V, and an operating window of 0 to -4V. These preliminary results validate this proposed material selection and design as ideal for electronics and sensors on both 2D and 3D flexible substrates.


9:00 AM **BM08.01.04**

High ON-Current Vertical Dot Transistors as a Novel Platform for Flexible and Wearable Electronics

Jeongkyun Roh, Hyeong Jin Yun and Victor I. Klimov; Los Alamos National Laboratory, Los Alamos, New Mexico, United States.

Colloidal quantum dots (QDs) have gained tremendous attention as a new class of nanomaterials that can potentially enable the next-generation solution-processable electronic and optoelectronic devices (Science 353, aaq5523, 2016). Owing to their superior optical properties, intense studies on QD-based color converters, light-emitting diodes (Nature 515, 96, 2014, Nat. Photon. 12, 159, 2018) and solar cells (Nat. Nanotechnol. 13, 456, 2018) have been underway leading to successful commercialization of the QD-display technology. The next frontier is exploration of electronically coupled QD solids in the context of prospective applications in solution-processable flexible electronics toward wearable electronic and sensing systems. One existing challenge in this area is low mobility of QD films, which limits performance characteristics of QD-based field-effect transistors (FETs) that represent basic building blocks of electronic circuits. Low mobilities lead to low ON-currents of typical QD-FETs. Increase in the current is possible by reducing the FET channel length, however, this would require the use of expensive and nonscalable patterning methods such as e-beam lithography.

Here, we demonstrate high ON-current QD p-type FETs by employing a vertical architecture, which is a vertical stack of a gate electrode, a gate insulator, a source electrode, semiconducting transport layer, and a drain electrode. Using this approach, we reduce a channel length down to submicron-meter scale, which allows for the gate-controlled electric field to penetrate into a vertical channel and modulate a charge carrier density. The pattern of the source electrode, however, this would require the use of expensive and nonscalable patterning methods such as e-beam lithography.

We employ a porous structure of a source electrode which can be used as a new platform to enable a variety of QD-based sensing, electronic and optoelectronic applications such as photodetector, light-emitting transistor, and infrared-to-visible up-converters.

9:15 AM **BM08.01.05**

Towards Low-Cost Electronics on Three-Dimensional Substrates

Tong Yang1, Jeremy S. Mehta2; Alexander M. Haruk2,3, Xiangyi Wu1, Shan Yan3, Jin Lou1; Chuan-Jian Zhong1 and Jeffrey M. Mativetsky1,2; 1Materials Science and Engineering, Binghamton University, Binghamton, New York, United States; 2Department of Physics, Applied Physics and Astronomy, Binghamton University, The State University of New York, Binghamton, New York, United States; 3Department of Chemistry, Binghamton University, The State University of New York, Binghamton, New York, United States.

Solution-based electronic material deposition holds promise to enable the low-cost fabrication of wearable electronics, soft robotics, and energy harvesting technologies. Conventional deposition and patterning methods for electrically-active materials, however, are only compatible with flat substrates, while future technologies will integrate circuitry into three-dimensional platforms, such as prosthetics, car windshields, or contact lenses. In this presentation, we will introduce methodologies for depositing and patterning functional materials on three-dimensional substrates. The processes are simple, scalable, and use minimal quantities of starting material, opening new possibilities for device integration.

Decanethiolate-capped gold nanoparticles were deposited and laser-sintered to pattern micron-resolution electrodes on cylindrical substrates with diameters as small as a human hair. We will show how this platform enables new approaches to local pressure and chemical sensing, while balancing the need for simple processing and high performance. In addition, stripes of high-performance organic semiconductor crystallites (6,13-Bis(trispropylsilyl)pentacene,TIPS-pentacene) were deposited at targeted locations on folded flexible substrates and complex three-dimensional objects. Preferential crystallite alignment led to anisotropic charge transport, with a hole mobility of up to 0.83 cm²V⁻¹s⁻¹ along the crystalline axis. These experiments lay the groundwork for the low-cost integration of electronic function into arbitrary non-planar substrates for sensing, energy harvesting, and display applications.

9:30 AM **BM08.01.06**

Flexible Organic Sensors for Biomechanical Measurements

Zhenghui Wu, Moran Amat and Tse Nga Ng; University of California, San Diego, La Jolla, United States.
Photosensors responsive to the short wavelength infrared (SWIR) spectra are used in a variety of applications including environmental monitoring and medical diagnosis. However, conventional SWIR sensors are limited by complex die transfer and bonding processing. Here we are advancing SWIR photodiodes by using a new generation of narrow bandgap conjugated polymers that are processed by solution processing techniques and allow simple direct deposition. The polymers are processed into bulk heterojunction photodiodes with photoreponse up to wavelength of 1.8 micron. The performances of devices with different polymer structures were compared through metrics including detectivity, quantum efficiency, response time and rectification ratio.

Example applications including blood pulse measurements and spectroscopic identification will be demonstrated.

In addition to optoelectronics, I will also show an example of an instrumented glove for augmenting movement disorder assessments. The system is based on capacitive pressure sensing, and the validation allows an objective, repeatable metric that improve resolution over the current best practices. The glove measures the power required to move a patient’s arm and shows reduced inter- and intra-rater variability. Our approach using wearable sensors offers an objective approach for the characterization of movement patterns, which would permit the effective evaluation of intervention outcomes, as well as provide a platform for novel motor interventions in the future.

10:30 AM BM08.01.07 Enhancing the Sensitivity in Capacitive-Type Strain Sensors Using Thin Au Film Electrodes Kodai Nur, Naoki Matsuhashi, Zhi Jiang, Md Osman Goni Nayeem, Tomoyuki Yokota and Takao Someya; The University of Tokyo, Tokyo, Japan.

Wearable sensors are a vital component in wearable electronics, since they are responsible for transducing external stimuli into electronic signals. In particular, strain sensors are needed for applications involving motion detection and the monitoring of vital bio-signals. Capacitive-type strain sensors are excellent candidates for practical applications due to their excellent linearity, high stretchability, and low hysteresis. However, a huge limitation of this sensor is its low sensitivity due to the constraints of the parallel-plate capacitor structure under applied strain operations. At best due to theoretical limitations, this structure can achieve a gauge factor (sensitivity) of 1. Here, we present a design technique to enhance the sensitivity in capacitive-type strain sensors through using thin Au film electrodes. We achieved a best gauge factor (GF) slightly above 3 over a high stretchability of 140% strain with great linearity and negligible hysteresis. We further found that the gauge factor of this strain sensor is tunable through varying the film thickness of the electrode. The enhanced sensitivity in capacitive-type strain sensors allows for the opportunity to distinguish subtle motions more sensitively for reliable and practical wearable applications.

10:45 AM BM08.01.08 Flexography Printing of Liquid Alloy-Based Stretchable Electronics Shuo Zhang, Bei Wang, Jiajun Jiang, Kang Wu and Zhigang Wu; Huazhong University of Science & Technology, Wuhan, China.

This work presents a rapid method to selectively print liquid alloy circuits on soft substrate at ambient environment using a laser-treated stamp, by tuning the liquid alloy wettability on different surfaces. This technology has the advantage of efficient as it only need inking and imprinting in just two steps. It can compatibility with existed industrial line equipment for complex and volume automation production easily.

Room temperature liquid alloy has been widely used in stretchable and flexible electronics because of high adaptability, fluidity and high conductivity. Numerous approaches were developed for pattern, such as injection, masked deposition, directly writing, and so on. However, these processing techniques are lack of compatibility to fit existing production lines directly. A simple way with more excellent portability is still being sought. In this work, a stamp was fabricated by selectively laser treatment on the surface of carbon filled PDMS (cPDMS). The laser processed cPDMS demonstrated an alloy-phobic behavior which could attach and then transfer liquid alloy to target substrate easily, while the left parts show an alloy-philic behavior. The difference of adhesion can be characterized quantitatively by measuring the bias of advancing and receding contact angles and calculating theoretically. After inked on electrode. The enhanced sensitivity in capacitive-type strain sensors allows for the opportunity to distinguish subtle motions more sensitively for reliable and practical wearable applications.

11:00 AM BM08.01.09 Controlling Thermoplastic Elastomer Optical Properties by Mechanical Processing—Materials for Stretchable Fiber Optic Sensors Margaret Campbell, Paramjit Singh, Kunal Kate and Cindy K. Harrett; University of Louisville, Louisville, Kentucky, United States.

We demonstrate that changing the extrusion speed of thermoplastic elastomer (TPE) fiber can modify its optical transmission by a factor of more than 100. Recently, we created stretchable fiber optic sensors from commercial urethane elastomer fibers that could detect muscle activity when sewn into textiles [1]. By extruding fiber from pellets at slow speeds, optical transmission increased beyond that of the commercial material, potentially leading to sensors that measure deformation on the meter scale instead of cm scale.

Thermoplastic elastomer pellets (Versaflex CL40, PolyOne Corp.) were dehydrated overnight at 60 °C, then extruded at 190 °C at rates between 0.005 and 0.3 mm/s. The 0.005 mm/s specimen appeared clear upon extrusion while successively faster speeds appeared hazier. Optical transmission was measured with a photodiode and light source. Stress-strain testing showed that the fastest-extruded filaments had a greater ultimate tensile strength than filaments extruded at slower speeds.

Waveguiding in a stretchable optical fiber requires a stretchable cladding with lower refractive index than the core. Our previous silicone coating approach worked with the new extruded cores. However, the silicone claddings peeled under extreme strain (>100%). Therefore, we investigated whether solvents could improve cladding adhesion, waveguiding and light-coupling properties of the fibers. Soaking the fibers in NMP (n-methyl-2-pyrrolidinone), then stretching the fibers while the solvent dried, turned out to modify the fibers in a way that solvents alone did not. The clearest, slowest-extruded cores were relatively unchanged by the NMP “soak-and-stretch” treatment, while the faster-extruded, hazier cores developed a porous, textured cladding with a uniform thickness.

The differing optical properties, mechanical properties, and response to solvents are likely caused by a transition from amorphous polymer at low extrusion speeds, to crystalline at high extrusion speeds. The microstructural properties of urethane based TPEs are known to involve pseudo-crosslinks, which are not chemical bonds but rather physical connections between the monomers of the block co-polymer [2], and which may be disrupted by the soak-and-
A Novel, Low Cost, Rapid, Disposable, Enzyme-Free and Colorimetric Paper-Based Platform for Point-of-Care Testing on Glucose Sensing in the Physiological Range Elvira Fortunato1, 2 and Rodrigo Martins1, 2; 1FCT-UNL, Caparica, Portugal; 2CEMOP-UNINOVA, Caparica, Portugal.

Diabetes mellitus is currently one of the most serious and prevalent diseases in the world, affecting millions of people worldwide and the rate of new cases is expected to continue increasing. Therefore, the development of cheap and simple methodologies for point-of-care glucose sensing is of paramount relevance for an effective diagnosis and management of patients, mostly in underdeveloped and developing countries where the access to medical infrastructures is limited and cost-effect and simplicity are of major concerns. Due to its properties, paper represents an alternative in the performance of point-of-care tests for colorimetric determination of glucose levels, providing simple, rapid and inexpensive means of diagnosis. In this work, we report the development of a novel, rapid, disposable, inexpensive, enzyme-free and colorimetric paper-based platform for point-of-care glucose detection. This method is based on the synthesis of gold nanoparticles (AuNPs) by reducing of a gold salt precursor in which glucose is the reducing agent. Different concentrations of glucose present during the reduction process result in the formation of AuNPs of different size, to which color changes of the sensor are associated. The developed platform was tested and calibrated using different physiological concentrations of glucose from 1.25 to 50 mM and the obtained results were visually examined and digitally analysed through an image analysis software. It was also compared the colorimetric results obtained with a commercial scanner and with a smartphone camera, concluding that both methods are viable alternatives in the digital analysis of the sensor. The colorimetric sensor revealed sensitivity to determination of glucose levels in samples, in a simple, rapid, inexpensive and eco-friendly way.
Therefore, we propose smart contact lenses which can detect the glucose concentrations in tear fluid. For the superior stretchability and transparency, the signals from the smart contact lens could restrict the user’s activities. These limitations reduce the convenience and features of the smart contact lenses. Smart contact lenses are fabricated using silver nanowire (AgNW) networks and graphene which have stretchable and transparent properties. Therefore, the resulting smart contact lens can provide a clear vision. In addition, the antenna composed of AgNWs enables the wireless communication, so the results of glucose sensor in smart contact lens could be wirelessly monitored. These sensor platforms based on AgNWs and graphene can be exploited as not only smart contact lenses but also internet of things (IoTs) for the environment monitoring. Furthermore, the smart contact lens integrated with wireless display can exhibit the sensing results through the display pixel and exclude the use of bulky measurement equipment which reduces user convenience. Therefore, we believe that the smart contact lenses suggest a promising strategy towards wearable electronics for the diagnosis of diseases.

2:30 PM BM08.02.04
Towards a Flexible and Biocompatible Implantable Sensor for Wireless Monitoring of Human Bladder Volume Filippo Melloni, Giorgio Ernesto Bonacchini, Mario Caironi and Guglielmo Lanzani; Istituto Italiano di Tecnologia, Milan, Italy.

The incidence of pathologies related to bladder dysfunction is clinically relevant, these including spinal injuries and neurological disorders. A considerable part of these illnesses is associated to urinary incontinence, which is not only cause of severe discomfort for patients, but in cases of poor or erroneous treatment it could lead to infections and tissue lacerations, with serious threats for health. A number of therapies are currently available for micrurition control, however a definitive solution for real-time and adequate monitoring of bladder volume is still not available. Such a solution would allow the continuous probing of the filling state of the organ, thus avoiding the incidence of two complications, i.e. excessive expansion of the bladder and its incomplete evacuation. This aid could work in cooperation with a wearable unit or also as feedback for already existing systems apt to urinary stimulation.

We herein propose an innovative design for a capacitive strain gauge, fabricated with a hybrid process that exploits organic and flexible materials as scaffold, metallic conductive layer as electrodes and an electrical insulator coating as protective and dielectric layer. The main challenge for this application is to design a strain gauge able to match the high elasticity of the organ under study by ensuring the sensor integrity in time, as these features hardly can be found in elastomers nowadays used in biomedical implants. The original prototype introduced in this work ensures a variation of capacitance that is proportional to the bladder tissue elongation, and it is able to accommodate the wide and repeated volume changes to which the organ is subject, without exposing the device components to continuous and recurrent mechanical deformations. The proposed design allows for a discrete strain analysis exploiting a principle similar to a linear encoder, and embeds contactless communication through an integrated RF antenna. In our work, we operate the system on an artificial bladder model, demonstrating contactless data read-out via a passive communication system, and thus paving the way towards testing on more realistic ex vivo and in vivo models.

The sensing system proposed in this work thus aims at providing a novel approach to the long-standing issue of bladder volume measurements, by advancing a design that could in principle allow for easy and reliable monitoring, not achievable with current technologies. Further developments of this approach could lead to the coupling of such device to implantable stimulating ones, hence helping to restore the original bladder functionality in patients, as well as enable direct data communication and control though smartphones or other handheld devices.

2:45 PM BM08.02.05
Bioinspired Multifunctional Nanostructures Integrated in Micro-Optical Sensor for Translational Implants Radwanul H. Siddique1, Vinayak Narasimhan1, Jeong-Ok Lee1, Shalabh Kumar1, David Sletzav2 and Hyuck Choo1, 2; 1California Institute of Technology, Pasadena, California, United States; 2University of California, San Francisco, San Francisco, California, United States;

While numerous multifunctional anti fouling nanostructures on insect wings have been previously studied and replicated, their potential incorporation into implantable medical devices remains unexplored. We have demonstrated the use of multifunctional bioinspired nanostructured membrane inspired by transparent butterfly wings for intraocular pressure (IOP) sensing in vivo. [1].

We investigated the multifunctional properties of the biophotonic nanostructures found on the wings of the longtail glasswing (C. faunus) butterfly. The AFM, SEM, optical, and biological characterizations have revealed that two groups of dome-shaped nanostructures with different periodicity co-exist on the transparent wings of the C. faunus: (1) angle-independent anti-reflective nanostructures with periods of 140-180 nm in the postdiscal areas; (2) angle-independent transmissive light-scattering nanostructures with periods of 200-300 nm in the basal areas. In vitro testing has revealed both regions displayed anti-fouling properties based on physically-induced cell lysis. We have (1) adapted the coherence-preserving angle-independent transmissive light-scattering property of the basal nanostructures that could make optical sensors such as Fabry Perot (FP) resonators more angle-independent; and (2) by further engineering the basal nanostructures, created bioinspired nanostructures (BINS) that would prevent biofouling without inducing cell lysis and suppress inflammation. To produce BINS with periods of 385-505 nm on a Si3N4-membrane, we used a polymer-phase-separation process following the nature’s way of forming nanostructures [2,3]. Angle-resolved transmission spectroscopy showed that the light transmission of the BINS-integrated membrane was twice more angle-independent than a flat Si3N4-membrane. In a series of in vitro studies, the BINS-integrated Si3N4 surface displayed remarkable anti-biofouling properties against proteins (albumin and streptavidin, ***P ≤ 0.001), prokaryotes (E. coli, **P ≤ 0.01), and eukaryotes (HeLa cells, **P ≤ 0.001) when compared to flat Si3N4 and control (glass) surfaces.

Finally, we integrated BINS onto the FP-resonator-based IOP sensor that was recently developed in our lab [4]. However, its practical applications were limited by its narrow readout angle inherent to FP-resonators and infrequent but severe biofouling observed after long-term implantation. The BINS integration onto the IOP sensor led to a 2.5-fold improvement in readout angle allowing easy handheld monitoring and in a one-month in vivo study conducted in rabbits, showed a 3-fold reduction in IOP error and 12-fold reduction in tissue encapsulation and inflammation, compared to an IOP sensor without BINS.

References
Epidermal electrophysiological devices, including biosensors and biofuel cells, have received considerable attention in the fields of wearable devices and mobile health. A challenge unique for realizing such wearable electrophysiological devices is mechanical resiliency. Mechanical damage-induced device failure is a common occurrence that can limit the operational lifespan of wearable bioelectronic devices. Recognizing these issues and challenges, this presentation will describe the use of advanced materials for imparting remarkable stretchability and self-healing abilities that enable epidermal bioelectronic devices to endure extreme deformations experienced by the human skin without compromising their bioelectronic characteristics. Particular attention will be given to specially-engineered inks for creating printable electrochemical biosensors and biofuel cells that can endure strains as high as 500% and offer autonomous healing ability without impacting their sensing or energy-harvesting ability.

**4:00 PM BM08.02.07**

**Highly Adhesive, Stretchable and Transparent Electrodes for Epidermal Electronics**

Jin-Hoon Kim, Seung-Rok Kim and Jin-Woo Park; Yonsei University, Seoul, Korea (the Republic of).

Wearable or implantable biosensors for the monitoring of biosignals, such as body motion, body temperature, electrocardiogram (ECG), and electroencephalography (EEG) have become one of the most important elements of wearable electronic devices for healthcare application. These devices are attached to the skin or organs to detect various biosignals. Hence, the maintenance of good conformal contact between the sensor and skin is essential for obtaining precise biosignals because the human skin and organs are highly rough and dynamically moving. Various materials such as hydrogels, polyacrylate, polyurethane and silicone have been used to improve conformability by increasing the adhesion force between the biosensors. Among them, silicone-based polymers are one of the most suitable materials for biosensors due to its good biocompatibility, stretchability, transparency, and tunable adhesion forces. Since most biosignals are interpreted as electrical signals, solid conductive fillers such as conducting polymers, metal nanoparticles, metal nanowires, carbon nanotubes (CNT) have been integrated into silicone elastomers to make elastomers electrically conductive. In this study, we present a highly conformable, stretchable, and transparent electrode for application in epidermal electronics based on polydimethylsiloxane (PDMS) and Ag nanowire networks (AgNWs). With the addition of a small amount of a commercially available non-ionic surfactant, Triton X, PDMS became highly adhesive and mechanically compliant, which are key factors for the development of conformable and stretchable substrates. The Young’s modulus and elongation at break of a-PDMS were 40 kPa and over 400% respectively. Also, the adhesion force of the a-PDMS was seven times higher than the unmodified PDMS. The polar functional groups present in Triton X interacted with the Pt catalyst present in the PDMS curing agent, thereby hindering the crosslinking reaction of PDMS and modulating the mechanical properties of the polymer. Due to the strong interactions that occur between the polar functional groups of Triton X and AgNWs, AgNWs were effectively embedded in the adhesive PDMS (a-PDMS) matrix, and the highly enhanced conformability, mechanical stretchability, and transparency of the a-PDMS matrix were maintained in the resulting AgNW-embedded a-PDMS matrix. The AgNW-embedded a-PDMS showed stable stretchability compared with the AgNW-embedded unmodified PDMS electrodes. Finally, wearable strain and ECG sensors were fabricated from the AgNW-embedded a-PDMS. The a-PDMS-based strain and ECG sensors exhibited significantly improved sensing performances compared with those of the bare PDMS-based sensors because of the better stretchability and conformability to skin of the former sensors.

**4:15 PM BM08.02.08**

**Ultra-Swellable Fast-Swelling Anti-Fatigue Hydrogel Machine Inspired by Pufferfish**

Xinyue Liu, Shaoing Lin, Christoph Steiger and Xuanhe Zhao; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Whereas the major components of human body are hydrogels, polymer networks infiltrated with water; machines that interact with living organisms are mostly made of metals, silicon, glass and rigid polymers. Owning to hydrogels’ superior biocompatibility and bioactivity, hydrogel machines that can quickly swell up in human body, perform long-term functions and degrade on demand will enable new possibilities in pharmacetics, medical devices and human enhancement. However, properties of high swelling ratio and speed, long-term robustness, and degradability do not co-exist in conventional hydrogels, severely limiting their innovations and applications. In nature, pufferfish can rapidly inflate its body into a large balloon by imbibing water, while maintaining the body’s strength. Here we introduce a pufferfish-inspired hydrogel machine capable of rapid swelling (e.g., 10,000 vol. % in 10 min) into a large soft balloon (e.g., diameter 7 cm, modulus 3 kPa), which maintains robustness under repeated mechanical loads over long time (e.g., 26880 cycles of 20 N force over two weeks). The hydrogel machine also de-swells and disintegrates quickly in response to biocompatible triggers. In vitro and large-animal tests further demonstrate superior performances of the hydrogel machine as soft gastric-retentive devices for monitoring and diagnosis, nutritional modulation, and prolonged drug delivery.

**4:30 PM BM08.02.09**

**Portable Respiration Sensor Using Nanoparticle Film for Monitoring Respiratory Condition**

Shinya Kano and Minoru Fujii; Kobe University, Kobe, Japan.

Respiration is one of the important vital signs of human in daily life. Respiratory signals including the information of rates, patterns, and phase are highly related to condition of respiratory organs and activity of exercise. Monitoring respiration rates helps us to find a risk of respiratory disorders such as sleep apnea, asthma, and chronic obstructive pulmonary disease. Conventional respiratory monitoring system, such as transthoracic impedance plethysmography, mainly records respiration of subjects at rest because motion of a target person can affect the observation of respiration. Therefore, wearable respiration sensors using various sensing mechanisms have been intensively studied. In this study, for monitoring human respiratory condition during exercise, we develop a portable respiration sensor with a humidity-sensitive nanoparticle film. We adopt surface-oxidized silicon-based nanoparticle (silicon nanocrystal, silica nanoparticle) thin films as a humidity-sensitive film. The thin films are solution-processed on flexible polyimide films by using the colloidal nanoparticle solution. Interdigitated electrodes on the polyimide films have 100 μm spacing. Fabricated devices work as a respiration sensor which detects water vapor in exhaled air. Response of the respiration sensor is fast enough to fully monitor human respiratory condition up to 1.7 Hz. Patterns and phase of respiration can be analyzed by using the signal of the sensor. We also demonstrate a portable sensor using a portable data logger and a humidity-sensitive film for monitoring human respiration during running. This sensor can track and assess respiratory information during exercise easily.
A wearable thread based sensor patch for continuous multiplexed analysis of sweat is reported. This sensor performs real-time, simultaneous, on-body measurements of important sweat markers such as electrolytes (sodium and ammonium ions), metabolites (glucose and lactate), sweat pH and body temperature. Low cost and flexible polyester threads coated with conductive inks were used as sensing electrodes. Selective potentiometric detection of electrolytes and pH was achieved by an ion-selective membrane and pH-sensitive polyaniline coating on threads respectively. Whereas threads functionalized with enzymes were used in the amperometric detection of glucose and lactate. The selectivity and sensitivity of these sensors in detecting the known concentration of target analyte were studied. The array of these selective thread sensors were further integrated on a patch that can be worn on the skin with readout electronics for real-time sensing. The real-time data was recorded by placing the sensor on the human volunteer during strenuous exercise condition. This sensor device can also be integrated with wireless data communication and storage for real-time data analytics. Proposed thread based sensing platform truly offers a great avenue for simple, low cost, flexible and stretchable wearable sensor development which can be sewn, woven or sutured on any substrate including body tissues.

SESSION BM08.03: Poster Session I: Materials-to-Devices for Integrated Wearable Systems—Energy Harvesting and Storage, Sensors/Actuators and Integration
Session Chairs: Jinhye Bae and Choongho Yu
Monday Afternoon, November 26, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

BM08.03.01 Self-Healable, Transparent and Stretchable Pressure-Sensitive Capacitor Using Light-Induced Curable Polymer Based on Dynamic Reversible Urea Bonds
Sun Ok Kim1, Cheul-Ro Lee2, Youngmin Kim2 and Jong-Woong Kim2; 1Korea Electronics Technology Institute, Seongnam Gyeonggi, Korea (the Republic of); 2School of Advanced Materials Engineering, Chonbuk National University, Jeonju, Korea (the Republic of).

Since the functionalization of the pressure sensor is basically based on contact with external objects and mechanical deformation of the sensor, efforts to render the pressure-sensitive devices robust and durable to withstand mechanical damages have led to development of various self-healable polymers. Considering that polymers are susceptible to be damaged which would severely weaken the mechanical properties and lifetime of materials, the integration of the pressure sensing functionalities with the ability to self-heal would be highly beneficial to all the domains of their application. One of the most prominent self-healing approaches is Diels-Alder (DA) reaction, which utilize reversible covalent bond formation. Previous studies have revealed that in polymeric materials based on multi-furan and multi-maleimide synthesized via the DA reaction, the inter-monomer linkages disconnect at temperatures above 120 °C (corresponding to the retro-DA reaction) and subsequently reconnect upon cooling. It was revealed that the DA adducts can be used in fabrication of self-healable and stretchable substrate due to their impressive healing performance and mechanical softness. However, DA-based elastomeric polymers are not considered to be suitable as a material for fabricating a pressure sensor because of their insufficient toughness and strength. Recently, the urea bonds with bulky substituents have drawn much attention as the linkages for the self-healing polymers because they were reversibly transformed to their starting materials of isocyanate and amine groups in the mild condition. Furthermore, the Young’s moduli of the polymers with the dynamic urea bonds can be enhanced when they were produced through the UV curing process due to the high density in crosslinking. Inspired by this, we have synthesized the UV-curable urethane acrylate and monomer featuring the dynamic urea bonds. The mechanical properties and the self-healing capabilities were adjusted by mixing the urethane acrylate and the monomer. Based on this, we fabricated a self-healable, stretchable and transparent pressure-sensitive capacitor by embedding Ag nanowire (AgNW) patterns just underneath the surface of the polymer. A simple tandem compound electrode was patterned on AgNW electrodes, allowing a capacitance to be formed between the parallel electrodes, which varies with the gap. The resulting sensor was mechanically stable even under severe bending or stretching, and was highly sensitive to the direct contact pressure or its deformations. Most interestingly, many artificially formed scratches by steel brushes on AgNW electrodes were instantaneously removed by irradiations of intense-pulsed-light (IPL). The scratches formed at the surface of the electrode were healed and electrical conductivity was efficiently recovered by the photo-thermal effect. The scratching and healing were repeatedly demonstrated at the same location for several times.
Due to the simple fabrication process and remarkable temperature sensing ability, the cascaded thermocouples could be integrated easily into the flexible thermocouple, 39.60 μV/K. Furthermore, we have fabricated this cascaded array on flexible substrates - parylene-C, making it potentially useful in We have got a 64-cascaded thermocouple achieved a Seebeck coefficient of up to 55.69 μV/K, which is much higher than that of a commercial type-K metal thin film thermocouples, which consist of a 5 μm narrow stripe and a 100 μm wide stripe.

Here we will introduce a kind of cascaded devices with a single layer of metal thin-film thermocouple (TFTC) [3]. A single layer metal thermocouple is similar to a conventional bimetallic thermocouple, but the two beams of the sensor are of different widths and composed of the same metal thin film, which leads to that the sensitivities of the single-metal TFTCs were all around 1 μV/K or less. In view of this situation, we developed the cascaded array of single metal thin film thermocouples, which consist of a 5 μm narrow stripe and a 100 μm wide stripe. We have got a 64-cascaded thermocouple achieved a Seebeck coefficient of up to 55.69 μV/K, which is much higher than that of a commercial type-K thermocouple, 39.60 μV/K. Furthermore, we have fabricated this cascaded array on flexible substrates - parylene-C, making it potentially useful in practical applications such as measuring arm surface temperature, as seen in Figure 1. Due to the simple fabrication process and remarkable temperature sensing ability, the cascaded thermocouples could be integrated easily into the flexible electronics and wearable devices, as well as find potential applications in monitoring temperature of body surface and interior in real time under various conditions, which would be beneficial to public health and care.

controlled by customizing the physicochemical properties of the gels by varying the amount of either polymer or MNPs concentrations.

The macro-structure of the magnetic gels can be tailored to optimise their mechanical properties. We have used a nature-inspired approach, by utilizing the structural and functional features of mollusc nacre (i.e., the inner shell layer) to improve the compressibility and strength of the gels. 3D printed templates were employed to develop hexagonal moulds that were used to assemble the gel into various layer-by-layer structures. This technique allowed the Young’s modulus of the layered gels to be increased up to 5 times, compared to the non-layered material.

The biocompatibility, customizable properties and robustness allows for these materials to be used as wearable drug release devices for both external and sub-epidermal applications. The magnetic component allows for remote control actuation, as well as the possibility to be activated via hyperthermia. Such a platform can potentially lead to significant improvements in targeted drug delivery, with minimal invasive procedures.

BM08.03.06
Low Voltage, Core-Shell Electrospinning Patterning of Submicron Silver Fibres  Wenyu Wang, Xia Li and Yan Yan Shery Huang; Engineering Department, University of Cambridge, Cambridge, United Kingdom.

Ultrathin, meso-scaled metallic fibres possess unique mechanical, electrical and optical properties, such as high aspect ratio, transparency, and lightweight. These properties enable a wide range of novel applications such as fibre-based circuitry, and flexible and transparent electrodes. Due to their low bending stiffness, meso-scaled metallic fibres produced by existing fabrication techniques are restricted to applications where the fibres were bound to a supporting substrate. Such a configuration inevitably compromises the unique attributes of the meso-scaled fibre structure, as the mechanical and optical properties of substrate can dominate the performance of final products. Herein, we introduce a novel one-step printing technique to synthesis and pattern conductive silver meso-fibres under mild temperatures and atmospheric conditions. We demonstrate spanning silver core-shell fibre arrays with an average diameter of ~1μm and best conductivity of 1.8×106 S/m. A rapid line writing speed of 600 mm/s is achieved, where fibres can span across a distance of up to 10mm with both ends making direct electrical contact with external circuits. No post-processing such as annealing is required in this process. Based on this technique, 'floating' electronic structures are demonstrated with LEDs and photodiodes. Unlike traditional transparent or flexible electrodes confined to a substrate, in our work, electronics can be mechanically suspended and electrically connected by the meso-fibre array alone. Tensile test shows that the mechanical property of the fibres is similar to human skin, indicating potentials for artificial skin and wearable sensors. Overall, we demonstrate an efficient and rapid silver meso-fibre patterning technique, and its applications in facilitating facile circuitry connection for unconventional, floating electronic structures.

BM08.03.07
A Novel and Rapid Single Step Approach Toward Fabrication of Piezoelectric Sensors  Chithira Parameswaran and Dipti Gupta; Indian Institute of Technology Bombay, Powai, India.

Sensors for biomedical applications have become indispensable for their signal detection and simplicity. Various fabrication techniques are being explored for fabrication of cost effective and high sensitive piezoelectric sensors, both capacitive and resistive in nature. For this purpose elastomers sponges have been targeted due to their skin conformity and bio-friendly nature. Here we introduce a novel one-step mediated process for obtaining PDMS sponges over large area. These are then realized in capacitive sensors over a large pressure range from finger touch to pulse sensing with better sensitivity (0.756 kPa-1 < 5kPa) to the best of our knowledge. This approach is further extended in obtaining resistive pressure sensor by bringing a variant in the synthesis. The hydrophilic sponge is made resistive using a dip-and-dry method in a commercially available ink. A compression induced in the sponge decreases the resistance providing an electrical equivalent of the applied mechanical stimulus providing an efficient resistive sensor with good cyclic response and sensitivity. The approach presented here paves way for huge feasibility in obtaining desired sensitivity and porosity during the in-situ fabrication process which is a first report in literature.

References:

BM08.03.08
Broadband LED and Piezo-Phototronics Enhanced Photodetector on CMOS Compatible Flexible Si Platforms  Arjit Sarkar1, Ajit K. Katiyar1, Amal K. Das2 and Samit K. Ray1,1; 1.S.N. Bose National Centre for Basic Sciences, Kolkata, India; 2Advanced Technology Development Centre, Indian Institute of Technology Kharagpur, Kharagpur, India; 3Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur, India.

Development in mechanically flexible optoelectronic devices on Si platforms, compatible with conventional CMOS technology are encouraging for future integration of wearable and flexible optical sources, detectors, displays and solar cells. Typical flexible devices based on organic semiconductors are fabricated on plastic substrates. These devices have the disadvantages of thermal and chemical degradation as well as low mobility of carriers and low efficiency compared to Si based devices. Therefore, optoelectronic devices fabricated on mechanically flexible Si substrates are very promising in this regard. Here we report the fabrication of flexible Si membranes (3-5 μm thick) acting as a substrate to develop a low power consuming broadband visible light emitting diode (LED) and a high responsive photodetector, sensitive to both UV and visible photons. The p-Si membranes are fabricated by simple and cost effective chemical etching method followed by n-ZnO thin film (~180 nm) deposition by RF sputtering method forming a p-n heterojunction. The n-ZnO/p-Si membrane heterojunction exhibits very good rectification behaviour and broad band electroluminescence (EL) in the 400-850 nm wavelength range at room temperature under forward bias condition. The minimum operating voltage of the fabricated flexible LED is 3.19 V which is lowest on comparing with other reported results on similar device structure. The EL from the device appears to be yellowish white to naked eye in a dark room. The flexibility of the device was tested by recording EL spectra at different bending conditions, from relaxed to bend to a semi-circle. In all the cases the EL spectra exhibited no significant change in intensity or emission feature. This confirms that the fabricated flexible LED performed brilliantly under different mechanical bending conditions.

Similar n-ZnO/p-Si membrane heterojunction was also developed into a flexible and high responsive photodetector which demonstrated enhanced photoresponse in UV and visible wavelength range utilizing piezo-phototronic effect. A peak responsivity of 0.20 AW-1 with detectivity of 4.8 × 1011 cm Hz1/2W-1 has been obtained without applying any external bias. The high mechanical flexibility of the Si membranes and the inherent piezoelectric property of ZnO thin film have been utilized to enhance the performance of the device via piezo-phototronic effect. On application of external tensile strain, piezo-potential developed in piezoelectric ZnO thin film has been exploited to modulate the transport property of the photo generated carriers thereby enhancing the device performance. Photoresponse has increased by 22% with gradual increase in the applied external tensile strain. Thus the fabricated mechanically flexible n-ZnO/p-Si membrane heterojunction based low power consuming broad band visible LED and piezo-photodetector is very promising for future wearable optoelectronic applications such as flexible displays and CCD devices.
Stretchable and electrically conductive onedimensional fibers are important for diverse applications. Here we report the DNA supercoil structure inspired composite fibers which are highly stretchable, and electrically conductive. Carbon nanotube wrapped sheath on commercially available spandex core fibers were fabricated and giant twist was inserted for supercoiling. The resulting supercoiled composite fibers show highly ordered and compact structures along fiber direction, which enable superelasticity (up to 1300%). The supercoiled fiber exhibited stretch-invariant electrical property that very low resistance increase is observed for a fully stretch, when especially overcoated by passivation layer. Moreover, by incorporating pseudocapactive MnO2 active materials on the supercoiled fibers, we demonstrated the superelastic supercapacitors with high linear and areal capacitances, which are highly retained when reversibly deformed in the fiber direction.

BM08.03.10
Graphene Oxide Modification for Machine Learning-Based Multisensor Systems
Fedor S. Fedorov, Alena Alekseeva, Stanislav Evlashin, Vladislav Kondrashov, Maxim Panov, Alexander Shapiev and Albert Nasibulin; Skolkovo Institute of Science and Technology, Moscow, Russian Federation.

Monitoring of temperature, air humidity, concentration of CO2 and CO, air pollutants (NOx, SOx), and volatile organic compounds requires new sensor systems which would combine enhanced selectivity and low detection limit. Among criteria to be fulfilled, we could outline low power consumption what requires room temperature operation, simple manufacturing protocols and long-term performance that generally determines the cost of the final product [1]. Thus, the key element of the sensor is a sensing material whose properties should be properly tuned to enable good performance. Here we propose a single material sensor platform based on graphene oxide (GO)/reduced graphene oxide (rGO) which is a unique material sensitive to humidity, pollutants and other gases [2]. The material also responds well to temperature changes. GO/rGO shows good response, stability, reversibility at ambient conditions, though, lacks the selectivity. To approach the selectivity, we combine several sensors based on GO/rGO material in an array whose vector signal is processed by pattern recognition algorithms to get a “fingerprint” of the gas mixture at defined temperature, following known multisensory concept. Sufficient variation of the sensor properties enables successful discrimination of the environment changes. Such variation we create by partial reduction GO by laser under developed treatment protocols [3].

Particularly, we will discuss the results on sensor arrays fabricated by irradiation of GO by laser to transform it to rGO tuning the ratio between GO/rGO areas what allows us to get different response for each sensor element in the array. The reconstruction of the environment changes from property variations is realized by modern machine-learning algorithms what we illustrate by successful determination of both the humidity (from 5% to 95% RH) and the temperature (up to 60 °C).

The authors acknowledge MIT Skoltech Next Generation Project.

The method involves three stages. The first stage requires a calibration step in which the strain of the sensor material is measured using a webcam while requiring bespoke manufacture. We present a general method for calibrating highly hysteretic resistive stretch sensors. We show results for 1D and 2D textile and elastomeric stretch sensors however we believe the method is directly applicable to any physical choice of sensor material and fabrication, and easily adaptable to other applications.

There is a growing need for flexible stretch sensors to monitor real-time stress and strain in wearable technology. However, developing stretch sensors with improved properties is challenging. We developed a rapid desktop method that requires less than one hour of data collection followed by a fully automated calibration routine based on LSTM. Highly accurate stretch topology mapping (within 5-15% errors) is achieved for the sensor skins tested including three different commercially available flexible sensor materials (Medtex P130, Techniktex P130B, and Adafruit conductive rubber) as well as a bespoke printed composite silicone stretch sensor.

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We discuss the application of our approach to various real-world use scenarios in emerging wearable technology sectors including prosthetics and assistive technology.
BM08.03.16
Integrating MXene Electrochemical Microsupercapacitor with Triboelectric Nanogenerator as a Wearable Self-Charging Power Unit Qiu Jiang1, Changsheng Wu2, Zhengjun Wang2, Aurelia C. Wang3, Jr-Hau He1, Zhong Lin Wang2 and Husam N. Alshareef1; 1King Abdullah University of Science & Technology, Thuwal, Saudi Arabia; 2Georgia Institute of Technology, Atlanta, Georgia, United States.

One aspect that has been poorly studied in the field of wearable electronics is the integration of energy harvesting and storage devices. By using silicone to encapsulate TENG device and solid-state microsupercapacitor into a single monolithic device, a power unit made of a single-electrode-mode TENG and 2D MXene-based solid-state microsupercapacitor can sufficiently convert and store mechanical energy of human biomechanical motions into electrochemical energy, while maintaining long life time and high mechanical flexibility. The device can utilize and store the random energy from human activities in a standby mode and provide power to electronics when active. As a result, our microsupercapacitor delivers a capacitance of 23 mF/cm² with 95% capacitance retention after 10,000 charge-discharge cycles, while the triboelectric nanogenerator exhibits a maximum output power of 7.8 µW/cm². Given the simplicity and integrated nature, our device can be integrated with a variety of electronic devices and sensors.

BM08.03.17
Facilely Prepared Layer-by-Layer Graphene Membrane-Based Pressure Sensor with High Sensitivity and Stability to Detect Human Motions Liu Tao. City University of Hong Kong, Hong Kong, Hong Kong.

With the prosperous development of artificial intelligence, medical diagnostic and electronic skins, wearable electronic devices have drawn much attention in our daily life. Flexible pressure sensors with high sensitivity, especially in a large pressure range regime are highly required in the past decades. In this work, graphene membrane with a layer-by-layer structure has been successfully prepared via a facile self-assembly & air-drying (SAAD) method. Air-drying the graphene hydrogel contributes to the uniform and compact layer structure in the obtained membrane. Owing to the excellent electrical and mechanical properties of the prepared graphene membrane, the pressure sensor based on several layers of membranes has high sensitivity and repetitability in the pressure range of 0-20 kPa. What’s more, the pressure sensor shows desired results in wearable applications to detect human motions. We demonstrate it can be used for pulse monitoring, breathing detection as well as various intense motion recording such as walk, run and squat et al. We hope the facilely prepared layer-by-layer graphene membrane-based pressure sensor will have great potentials in the fields of smart electronics for medical health, human motions and even artificial intelligence and robot technology development.

BM08.03.18
Flexible InO/Al2O3 Hetero-Interface Diode Using PEAld for Active-Matrix Tactile Sensor Array Platform Hye-In Yoon, Guk-Jin Jeon, Steve Park and Sang-Hee K. Park; Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

With a rapid development in Internet of Things (IoT), intelligent terminals including smart wearable devices, humanoid robotics, and artificial electronic skins (E-skin) have attracted huge attention. For those advanced applications, it is necessary to develop a proper tactile sensor array system. Especially for our targeted application (E-skin), we have to consider the low-pressure regime (1-10 kPa), a common but crucial range, covering a pressure on a daily activities. Resistive type sensors are often used due to their simple structure and easy read-out system. So, they offer significant advantages over other types of pressure sensor in terms of integration with other circuit system. Also, backplane can be one of the key component for the tactile sensor array, enabling precise sensing contrast with low noise level and low power consumption. As a switching device in each pixel, organic thin-film transistor (OTFT) has usually been adopted in resistive sensor array, however, they often suffered from environmental degradation and poor electrical performance. Herein, we demonstrate highly stable and sensitive tactile sensor array platform using flexible InO/Al2O3 hetero-interface diode using plasma-enhanced atomic layer deposition (PEALD). As a starting step, we had to carefully consider proper diode structures according to their environmental stabilities, on-to-off ratio, and on-current level. Then, the metal/oxide semiconductor (OS)/insulator/metal (MSIM) structure was adopted and was successfully developed with the ultra-thin indium oxide layer(<3nm) and alumina layer(<20nm) using PEALD, showing outstanding rectifying performance as a switching device. The on-to-off ratio is over 107 and off-current density is lower than 100 nA/cm². There could be several reasons for the fairly stable current flowing phenomenon through the interface between OS and insulator. One plausible cause is enhancement of electron injection from cathode to insulator through thin OS layer, thereby electron can easily flow to anode under forward bias. Thus, on the basis of our active-matrix sensor array platform, any kind of resistive sensor can be integrated with it. The 8x8 matrix arrays were fabricated by photolithography process and top anode was patterned as interdigitated electrode. Then, a microstructured PDMS sheets coated with MWCNT would be integrated on them. We will further discuss about electrical properties and sensing performance.

BM08.03.19
Development of Highly Stretchable Printed Circuit Board Towards Reliable Integration of Electric Components Minsoo Kim2, Kyuyoung Kim1, Hyunae Lim1 and Inkyu Park1; 1Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of); 2Korea Institute of Machinery and Materials, Daejeon, Korea (the Republic of).

We developed stretchable printed circuit board (PCB) which can easily integrate electric components with high electrical and mechanical reliability. To surely apply techniques of stretchable electronics to wearable devices, it is necessary to realize totally stretchable device including complex interconnections between electric components. Stretchable PCB is the one of the most promising solution to achieve the all-stretchable electronics. We chose most suitable elastomeric polymer as a substrate of the PCB by conducting electromechanical tests. Also metal film and highly conductive nanomaterials were used as conductor line buried in the substrate. Under the stretched state, metal film which is strongly adhered to the substrate and metallic nanowire act as electrical anchor and bridge respectively. Not only this hybridization effect but serpentine patterns of conductive materials contribute to improvement of the performances of stretchable PCB in terms of stretchability and strain-insensitivity. Additionally, other electric components can be easily integrated onto the opening of substrate occurring electrical/mechanical contact with buried conductor line, which is similar with surface mount technology of conventional PCB. The integration region includes tiny parts of rigid film to minimize stress applied to the mounted components, leading reliable integration. Finally, we show electromechanical characteristics of the fabricated stretchable PCB, and demonstrate the integration performance of which additional components are negligibly affected by the strain of the PCB.

BM08.03.20
Epidermal Multiple-Stimulus Electroluminescence Sensor for Human Activity Monitoring Fuhyuk Kim, Hyowon Han and Cheolmin Park; Yonsei University, Seoul, Korea (the Republic of).

Wearable human-interactive electronics require the stimuli-responsive sensor that can detect stimuli in human body with vital signals of health-monitoring in epidermal skin through several sensing mechanisms. Here, we describe an epidermal electronic electroluminescence based multiple-stimuli sensor that allows for both monitoring and visualization of human-readable response. This “epidermal multiple-stimulus electroluminescence sensor” (EMES) is
capable of human activity monitoring including internal body information and external stimuli. Our device consists of stacked bilayers of sensing layer on two separated electrodes separated by an in-plane air gap on single side and the epidermal skin itself. The pressure and conductance sensing architecture is achieved to field induced between two separated electrode and skin is controlled by the capacitance change or impedance change of the sensing layer on epidermal skin. The utility of the EMES for human activity signal has been successfully demonstrated by touch, blood pressure, respiration, motion behaviour, fingerprint recognition, heat/cold, and humidity. Our multiple-stimuli sensor devices provide potential advantages in terms of simplicity, functionality, and broad applicability compared to previous wearable sensor based highly flexible and ultrathin substrate that involve conformal attachment of active elements onto skin.

BM08.03.21
The Effect of Interfacial Interaction on the Conformational Variation of poly(vinylidene fluoride) (PVDF) Chains in PVDF/Graphene Oxide (GO) Nanocomposite Fibers Jeong-Fun Lee, Sojeong Heo, Youngho Eom, Sang-Ha Hwang and Han Gi Chae; Ulsan National Institute of Science and Technology (UNIST) U PnC Lab, Ulsan, Korea (the Republic of).

Polymers such as poly(vinylidene fluoride) (PVDF), and its copolymers with hexafluoropropylene (HFP), trifluoroethylene (TrFE) and chlorotrifluoroethylene (CTFE) are known to possess electroactive properties and have been studied for decades, enabling them one of the most promising candidates for wearable and smart textile applications. Nonetheless, the practical applications are still limited and are in the early stage of development because of poor mechanical integrity. In the current study, we have prepared PVDF/graphene oxide (GO) nanocomposite fibers by dry-jet wet spinning method at the GO concentrations of 0, 1, and 2 wt% with respect to the polymer weight. The as-spun fibers were drawn in the draw ratio (DR) range of 2 to 6.5, and the correlation between the PVDF chain conformation and the mechanical properties of the fibers upon drawing has been studied by 2D correlation spectroscopy (COS) of Fourier-transformed infrared (FTIR), wide-angle X-ray diffraction (WAXD), differential scanning calorimetry (DSC), and tensile testing. The PVDF/GO nanocomposite fibers exhibited that the mobile PVDF crystals were nucleated because it was based on the conformational defects and kinks due to the polar interaction between PVDF chains and functional groups of GO, whereas the control PVDF fiber showed the conventional transition of crystal polymorphs (α and γ phases to β phase). As a result, the nanocomposite fiber showed dramatically improved toughness (enhanced by 1123% at a DR of 2 and 120% at a DR of 6.5) as compared to that of the control fiber. Furthermore, the tensile strength and modulus of the PVDF/GO (2 wt%) fiber were 394 MPa and 4.6 GPa, respectively, while those of the control PVDF fiber were 295 MPa and 3.9 GPa.

BM08.03.22
Stretchable Ultrasonic Transducer Arrays for Three-Dimensional Imaging on Complex Surfaces Hongjie Hu, Xuan Zhu, Chonghe Wang, Lin Zhang, Francesco Lanza di Scalea and Sheng Xu; University of California, San Diego, San Diego, California, United States.

Ultrasonic imaging has been implemented as a powerful tool for noninvasive subsurface inspections of both structural and biological media. Current ultrasound probes are rigid and bulky and cannot readily image through nonplanar three-dimensional surfaces. However, imaging through these complicated surfaces is vital because stress concentrations at geometrical discontinuities render these surfaces highly prone to defects. This study reports a stretchable ultrasound probe that can conform to and detect nonplanar complex surfaces. The probe consists of a 10 × 10 array of piezoelectric transducers that exploit an “island-bridge” layout with multilayer electrodes, encapsulated by thin and compliant silicone elastomers. The stretchable probe shows excellent electromechanical coupling, minimal cross-talk, and more than 50% stretchability. Its performance is demonstrated by reconstructing defects in 3D space with high spatial resolution through flat, concave, and convex surfaces. The results hold great implications for applications of ultrasound that require imaging through complex surfaces.

BM08.03.23
Strongly Correlated Oxides as Electric Field Sensors for Haptics Zhen Zhang, Derek Schwanz and Shriram Ramanathan; Purdue University, West Lafayette, Indiana, United States.

Advancing sensing modalities to monitor bio-matter and chemical signatures in water-containing environment is of great importance in emerging fields of haptics and robotics. However, sensing multiple properties with the same material is often impossible due to instability when exposed to water. On the other hand, elasmobranch marine organisms such as sharks have evolved to naturally detect their environment through various electrosensory organs, positioning them as apex predators. In this work, we will discuss how perovskite nickelates such as SmNiO, can directly mimic the functionality of the gel-like Ampullae of Lorenzini electrosensory organs in sharks. Such sensing behavior of nickelates is enabled by an electric-field-driven Mott phase transition in aqueous environment which is accompanied by large nonlinear electrical resistivity increase and visible color change. These unprecedented properties of metastable oxide materials introduce a new sensing modality for environmental sensing that may be adapted to wearables and autonomous systems that operate in unstructured environments.

BM08.03.24
A Novel Straightforward Wet Pulling Technique to Fabricate Carbon Nanotube Fibers Mariia Gonecharova1, Eugene Shulga1, Sergey Shandakov2, Ivan Sergeichev3, Evgenia Gilishlent1, Anton Anisimov1 and Albert Nasibulin1; Skolkovo Institute of Science and Technology, Moscow, Russian Federation; Kemerovo State University, Kemerovo, Russian Federation; Canatu Ltd, Helsinki, Finland.

The growing demand for wearable electronics requires flexible and stretchable conductive materials. Among them, carbon nanotubes are recognized for their outstanding mechanical, electrical, optical properties and chemical stability. Although CNTs possess remarkable properties, the devices made of individual CNTs are quite challenging in fabrication. CNTs are usually used in the form of fibers, arrays, or films. In this work, we introduce a novel technique of carbon nanotube fiber fabrication, which we named Wet Pulling. The method allows straightforward fiber production out of carbon nanotube thin films, collected on a filter after the synthesis or deposited onto any substrate. It relies on a combination of film properties and self-assembly due to surface tension. The wet pulling technique has prominent advantages that make it a promising candidate for both small and large-scale production of CNT fibers with desired properties. By varying parameters of the CNT films, we demonstrated the possibility to control the strength of the SWCNT fibers from 300 to 700 MPa and their resistance from 60 to 300 Ohm (for 1 cm long fiber). The method is also easily adaptive to different kinds of carbon nanotubes and allows rapid fabrication of both active and passive flexible electronic components. A tactile sensor, a pulsometer and an electrical circuit are fabricated for the demonstration of their applicability. We expect this new approach to simplify the production of functional carbon nanotube fibers and to enlarge their usage in diverse applications.

This work was supported by MIT Skoltech NGP Program (Skoltech-MIT joint project).

BM08.03.25
A Bandage-Type, Wearable and Luminescent Sensor for Monitoring Transcutaneous Oxygen Pressure Changjin Lim, Soyeon Lee and Jin-Woo Park; Yonsei University, Seoul, Korea (the Republic of).
We present a new concept for a wearable oxygen (O₂) sensor for transcutaneous O₂ pressure (tcpO₂) monitoring by combining the technologies of luminescence gas sensing and wearable devices. tcpO₂ monitoring has been extensively studied given its central role in diagnosing various diseases. The ability to quantify the physiological distribution and real-time dynamics of O₂ from subcellular to the macroscopic level is required to fully understand mechanisms associated with both normal physiological and pathological conditions. Despite its profound biological and clinical importance, few effective methods exist for noninvasively quantifying O₂ in a physiological setting. The wearable sensor developed here consists of three components: a luminescent sensing film attached onto skin, an organic light-emitting diode (OLED) as a light source, and an organic photodiode (OPD) as a light detector. The green OLED was fabricated to excite the sensing film in accordance with absorption spectrum of oxygen sensitive material, 2,3,7,9,12,13,17,18-octaehtyl-2H,23H-porphyrin, platinum(II), (PtOEP) changing the ratio of PL intensity (sensitivity, L/I₈₅₀) in relation to O₂ concentration. After energy excitation of luminophores by light absorption from OLED, the PL emission intensity decreases by energy transfer from PtOEP molecules to surrounding O₂ molecules which is called quenching effect. P3HT:PCBM bulk heterojunction based OPD precisely detects the red PL intensity change from the O₂ sensing film. All the components are solution-processable and integrated on a plane in a bandage-like configuration. To verify the performance, tcpO₂ variations by pressure-induced occlusion were measured in the lower arm and a thumb by the wearable sensor, and the results were comparable to those measured by a commercial instrument. Due to its noninvasive and flexible features, the wearable bandage-like O₂ sensor proposed in this study can monitor the tcpO₂ in any part of the body, even when a person is exercising or working, which is currently beyond the restrictions of existing commercially available monitoring systems. Our wearable, bandage-like O₂ sensor opens new possibilities for the continuous monitoring of not only patients during surgery and recuperation but also out-patients suffering from Raynaud disease, diabetic ulcers and similar ailments.

BM08.03.36
Electroactive Polymer-Electrolyte-Composite Artificial Muscles of Greatly Enhanced Strength Zachary A. Goodwin¹, Michael Eikerling², Hartmut Lowen³ and Alexei Kornyshev⁴; ¹Imperial College London, Cambridge, United Kingdom; ²Chemistry, Simon Fraser University, Vancouver, British Columbia, Canada; ³Theoretical Physics, Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany.

There is great interest in developing artificial muscles for soft robotics. ¹ Such electroactuators, composed of polymer-electrolyte films with bulky mobile cations, confined between two electrodes, curve in response to an applied voltage between the electrodes (forward actuation). On the other hand, upon bending an output voltage or current can be generated (reverse actuation). Both of which, forward and reverse actuation, involve the redistribution of the mobile cations and solvent. To further understand and develop these much-desired devices, we present a unified theory that describes both forward and reverse actuation with flat and porous electrodes.

Forward actuation with flat electrodes has a limited response from an applied voltage because stressful regions only develop in a minor part of the hydrated ionomer, within the electrical double layers near the electrodes. ² To overcome this limitation, one can use volume- or porous electrodes, with pores filled with the ion conductor membrane. To give a foundation for engineering improved devices, we developed a theory of an electroactuator with such electrodes. ³ We found that the electroactive response is dramatically enhanced (potentially orders of magnitude) as compared to those with flat electrodes. However the actuator response time, which should be no longer than 1 s for most applications, was found to impose constraints on the pore length. Results suggest that complex devices consisting of bundled elementary electroactuators could perform significant work in myriad applications.

It is well known that reverse actuation produces significantly smaller voltages than the applied voltage for forward actuation with the same curvature; thus practically limiting reverse actuation to sensing applications. ⁴ We develop a theory, the underlying basis of which is similar to that of forward actuation, in which ions are treated as volumetric defects. ⁵ The signal generated by bending the actuator depends on the volume of mobile ions, as in agreement with experiments. Cases of open and short-circuit operation modes were investigated separately, which suggested several options for self-sensing artificial muscles: for open-circuit sensing, bundles of microstructured actuators, for forward actuation, should include flat electrode actuators which are substantially thicker; whereas for short-circuit sensing, the design can be based only on microstructured electrodes.

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⁵Z Goodwin, A Kornyshev, Theory of sensing for polymer-electrolyte-composite artificial muscles with flat or volume filling electrodes, submitted to Soft Matter

BM08.03.27
Printed Integration of High-Performance Intrinsically Stretchable TFTs with Soft Sensors for Mass Customization of Wearable Electronics Byeongmoon Lee, Jiseok Seo, Hyeon Cho, Taehoon Kim and Yongtaek Hong; Department of Electrical and Computer Engineering, Inter-University Semiconductor Research Center, Seoul National University, Seoul, Korea (the Republic of).

Soft electronics has become the driving force of innovation in the way that the electronic systems maintain their performance under harsh deformation and are conformably attached on arbitrary-shaped surfaces, thus realizing stretchable display, skin-patch devices, and implantable biomedical electronics. As core components in electronic systems, thin film transistors (TFTs) also need to be soft, in order to give the soft electronic system sophisticated functions without hindering its softness. For this reason, intrinsically stretchable TFTs have attracted great research attention in recent years. Several leading groups have realized this soft basis by exploiting 1-dimensional materials such as single-walled carbon nanotube (SWCNT) as semiconductors and electrodes. Another novel idea has been reported to make polymer semiconductors stretchable by forming nanonconfined morphology. In spite of these remarkable achievements, there are still many challenges in integrating stretchable TFTs with active components such as soft sensors into various forms of wearable electronics. Most of the previous works have fabrication complexity and low design freedom, including repeated photo- patterning and laminations. In this work, we report a facile and low-cost fabrication strategy based on ink-jet-printing for high-performance intrinsically stretchable TFTs. The materials are carefully selected in order to achieve both high electrical performance and stretchability. We exploit high-K elastomeric dielectrics for gate insulators, SWCNT for active layers, and highly conductive silver nanowire (AgNW)-based stretchable conductors for gate/source/drain electrodes. The components including the gate/source/drain electrodes and the active layers are ink-jet-printed so that all layers of the device are fully customizable. The fabricated devices show mobility of 5–10 cm²V⁻¹s⁻¹, on/off ratio over 10⁵, low operation-voltage under 5V, and stretchability over 50%, which imply the feasibility of our devices for applications in wearable integrated circuits. Furthermore, our ink-jet-printing-based fabrication strategy enables not only facile integration of stretchable soft TFTs with printing-based soft sensors, but also other soft wearable systems. For proof of concept, we demonstrate a series of ink-jet-printed active matrix sensor arrays with various layouts. We believe that this work contributes to the effective integration of soft components into functional wearable systems. The detailed methods and results will be discussed later.

This work was partly supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No.2017-0-00048, Development of Core Technologies for Tactile Input/Output Panels in Skintronics (Skin Electronics)) and the Center for Advanced Soft-Electronics grant funded by the Ministry of Science, ICT and Future Planning as Global Frontier Project (CASE-2015M3A6A5065309).
Principles of Multi-Layer Encapsulation Design for Wearable and Implantable Systems

Xi Jin1, Enming Song2, John A. Rogers1 and M. Ashraf Alam1; 1Purdue University, West Lafayette, Indiana, United States; 2University of Illinois at Urbana-Champaign, Champaign, Illinois, United States; 3Northwestern University, Evanston, Illinois, United States.

Wearable and implantable electronic devices are enabling in a new generation customized healthcare real-time monitoring system [1]. Some of the most sophisticated systems involve silicid MOSFETs as the basis for active sensors as well as digital and analog circuits, in a thin, flexible form [2][3]. Protecting these transistors in a harsh fluidic environment is relatively difficult because the requirement of wearability demands biocompatible encapsulation with low flexural rigidity. The charged ions (such as Na+) from the biofluids are capable of diffusing rapidly through the thin encapsulation layer and destabilize the entire system. Moisture is another problem since the water molecules could either penetrate through or dissolve the encapsulation layer in a temperature-dependent rate. The optimization of the encapsulation layer is, therefore, a critical challenge for the development of wearable/implantable system design.

In this work, we describe the design principles of stacks of encapsulation layers as biofluid barrier for flexible electronic implants. The multi-layer encapsulation can be conformally coated on both sides of a flexible electronic platform with an array of NMOS transistors. The threshold voltage shift of the NMOS ($\Delta V_{th}$) transistor indicates the level of performance degradation. Accelerated soaking experiments show that (1) thermally grown SiO2/SiN, bilayer block the passenger of ions [4][5]. (2) HfO2 coated thermal SiO2 slows down both moisture diffusion and dissolution of the encapsulation layer by orders of magnitude [6]. Systematic theoretical investigations reveal the details associated with encapsulant material property [7]. In this context, both numerical and analytical models describe the ion penetration as well as the moisture assisted dissolution process. Coupled with the device physics of MOSFET, our model predicts that $\Delta V_{th}$ follows accelerate growth over time due to the coupled effect of ion transport and encapsulant dissolution. The predictions are well validated by results of the accelerated soaking experiment. Our physics-based model serves as the basis for lifetime projection for MOSFET-based wearable/implantable electronics under different operating conditions in a harsh biological environment. Ion and moisture penetration through encapsulant is a generic problem, therefore our results are also relevant for encapsulation of electronic, mechanical, and chemical systems.

References:

Compositional Dependence of Electromechanical Response in Lead-Free Piezoelectric Thin Films for Wearable Electronics

Rajinder S. Deol, Soumen Saha, Bhaskar Mitra and Madhusudan Singh; Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, India.

Wearable sensors and other electronic devices require reliable autonomous power generators that are compact and can scavenge mechanical vibration energy sourced from various movements of the human body. While lead zirconium titanate (PZT) and its derivatives are usable in compact piezoelectric devices, the presence of lead limits their use due to health and environmental concerns. Thus, lead-free high-performance piezoelectric materials are uniquely needed for wearable sensor applications. Further, piezoelectric materials can be used to sense human movement itself through time variation of stress. The highest piezoelectric response in one such material, potassium sodium niobate (KNN), is expected at the morphotropic phase boundary (MPB) separating rhombohedral and tetragonal symmetry in the phase diagram. Given the complexity of the phase diagram, and the difficulty of achieving uniform composition throughout the solid, it has been challenging to achieve precise process control over the final phase and composition. This picture is further complicated by the tendency of potassium to migrate out of the solid solution upon annealing, which is considered desirable for high electromechanical coefficients, as well as non-uniformities arising from the polycrystalline nature of the solid. In this work, we have investigated sol-gel synthesis pathways to amorphous unannealed uniform thick films for three different compositions, and the impact of processing conditions and composition on the electromechanical coefficient using piezo-response force microscopy (PFM). Sols for each composition were deposited on substrates using spin-coating and dried at low temperature (~60°C) to remove excess solvent. Thin films (~70nm thickness) with low surface roughness were achieved (~20nm RMS), confirmed with atomic force microscopy (AFM). Thin film X-ray diffraction (XRD) scans of the as-deposited thin films with a Cu Kα source revealed amorphous nature of the films, consistent with mixed orthorhombic, monoclinic, and cubic phases, the precise composition dictating the relative abundances. The composition and stoichiometric ratios of the deposited thin films were verified using energy dispersive X-ray spectroscopy (EDX). PFM displacement amplitudes were maximized for equimolar KNN, falling away significantly for K and Na-rich thin film. The derived d33 of equimolar KNN was found to be ~95 pC/N, which compares favorably with published data for annealed films of undoped KNN deposited using a variety of non-solution-based techniques. This improved low-temperature process is compatible with polyimide and other plastic substrates suitable for wearable electronics.

Upconversion Nanoparticles/Graphene—Opening New Windows for Highly Sensitive Photodetection

Monika Katarz1,2,3, Wei-Hua Wang1,2,3 and Yang-Fang Chen4; (1) Molecular Science and Technology (MST) Program, Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan; (2) Institute of Atomic and Molecular Science, Academia Sinica, Taipei, Taiwan; (3) Department of Physics, National Central University, Chung-Li, Taiwan; (4) Department of Physics, National Taiwan University, Taipei, Taiwan.

With recent technological advancements engulfing the world and making it a better place to live, wearable transparent electronics definitely have a crucial role to play. Plentiful studies on upconversion mechanism observed in lanthanide doped core-shell upconversion nanoparticles (UCNPs) have successfully marked their presence in the ongoing research fields of displays, solar cells, etc. The lanthanides doped core-shell UCNPs are capable of sequentially absorbing two or more photons of higher wavelength leading to an emission of photons of lower wavelengths. Graphene is a 2D material which is famous for its high carrier mobility, short carrier life time, flexibility and its optical transparency. Since graphene has a low density of states around the Dirac point therefore its conductance is influenced by external perturbations from allied materials. Therefore placing core-shell UCNPs in close vicinity of graphene opens a new window for highly sensitive photodetection. In this work we demonstrate a very novel approach towards lanthanide doped core-shell UCNPs and graphene hybrid rippled structure photodetector. The 4F electronic configuration of lanthanides contributes for a multi-energy sublevels which eventually results in longer excited state lifetime for photogenerated charge carriers due to the presence of metastable states when subjected to laser illumination. This unlocks a new regime for ultrahigh sensitivity in lanthanide doped core-shell UCNPs (NaYF4:Yb:Er:Nd@NaYF4:Nd) and graphene hybrid rippled structure photodetector. The device fabrication process includes the usage of core-shell structured UCNPs and monolayer graphene on pre-strained poly(dimethylsiloxane) (PDMS) substrate which was later released to get a core-shell UCNPs/rippled graphene structure hybrid wearable photodetector. Under 808nm laser illumination, core-shell UCNPs/rippled graphene structure hybrid photodetector exhibits the highest responsivity of the order of ~31 AW-1 among core-shell UCNPs based hybrid photodetectors based on the upconversion transitions of the several energy sublevels of core-shell UCNPs. Also, the rippled graphene structure helps to increase the optical absorption of photons for core-shell UCNPs. The graphene ripples...
Triboelectric Nanogenerators for Powering Portable, Wearable and Body-Implantable Devices

Robert Ccorahua, Alexandra Cordero, Juan Huaroto, Maria Quintana and Emir Vela; Universidad Peruana Cayetano Heredia, Lima, Peru.

Triboelectric nanogenerators (TENGs) have become one of the most sustainable ways to scavenge blue energy from mechanical movements. However, fabrication of TENGs often requires use of expensive instruments. Some attempts to reduce costs, using biomaterials of cellulose and chitosan, were reported. Nevertheless, to date only few low-cost bio-based materials have been reported to be useful as TENGs but they still keep employing costly nano-fabrication techniques. Herein, a new bio-based starch-cellulose TENG fabricated without using complex equipment is reported for the first time. Chopped samples of peruvian potato (Solana num tuberosum: yellow variety) were homogenized in a blender, sieved and left for decantation. After 4 h, supernatant was discarded and the precipitate was degreased by resuspension in a solution of 1:1 methanol:water. The obtained starch was dried at 60°C for 24 h. Starch films were prepared by casting. Dried starch was diluted in distilled water to form a 5% (w/w) starch solution. This solution was partially hydrolyzed in dilute hydrochloric acid (0.1 N) adjusting pH to 2.0. Glycerol was added at ratio of 2.5 (glycerol:starch (dry basis)). The starch solution was homogenized by stirring for 15 min at 95°C. Then, the solution was neutralized in dilute sodium hydroxide (0.1 N) adjusting the pH to 10 to stop hydrolysis. Finally, the starch solution (7% (w/w)) was poured on Petri dishes containing substrates of sand paper (grit #400) and placed in an oven at 40°C. After 48 h of drying, films of about 50 to 200 µm in thickness were obtained. For the complementary dielectric film, a microfiltration membrane of 47 µm of pore size was used. The surfaces open to the air (upper part) of the films were covered with a thin layer of commercial aluminum foil by using double sided adhesive tape. The resulted TENG was electrically characterized by using a linear motor as a vibrating external source at forces up to 6 N. Surprisingly, despite both dielectric films inside the TENG were made of biomaterials, the electrical output was considerably higher than other biomaterial-based TENGs reported to date. Our results showed that, depending on the film thickness, electric outputs varied from 60 mV to 300 mV per 4 cm² area. The thicker the film, the lower the electrical outputs, and vice versa. Moreover, FTIR-ATR analysis also showed that no chemical modification was made on the surface of starch after casting. Therefore, starch remained unmodified at the time of characterization, being this performance proper of a pristine starch. In addition, though organic starch isolation, fabrication of the proposed TENG was entirely handmade, thus avoiding use of complex equipment of nano- and micro-fabrication which resulted in the development of an eco-friendly TENG with very good performance according to the state-of-the-art.

Development of a Sheet-Like pH Imaging Sensor with Polyelectrolyte Multilayered Thin Films

Shinji Takeoka, Daichi Someya, Satoshi Arai and Toshinori Fujie; Waseda University, Tokyo, Japan.

We developed flexible and physically adhesive polymer thin films (nanosheets) for biomedical or bioelectronic applications. Recently, we reported a temperature sensor nanosheet with a two-layered structure of temperature-sensitive and insensitive fluorescent molecules. In this talk, we present a sheet-like pH imaging sensor based on polymeric ultra-thin film (referred to as “pH sensor nanosheets”). It is composed of two layers: a pH-sensitive polyelectrolyte multilayer with fluorescein-conjugated poly(acrylic acid) and poly(sallylamine hydrochloride) and a pH-insensitive poly(D,L-lactic acid) layer containing Nile red. It responds to pH changes within 20 sec and demonstrates a ratiometric phosphorescent imaging of pH gradients in a leaf apoplastic ion milieu responding to the external NaCl stress. The pH sensor nanosheet will be useful for biology or medicine if it is combined with the temperature sensor nanosheet.
Then the different improvement parameters will be discussed. As main topics, I will present a couple of recent achievements transparent flexible graphene triboelectric generators, textile-based wearable triboelectric power generators, etc. The recent research and design efforts to enhancing power generation performance of generators to realize self powering of portable and wearable sensors and electronics will also be discussed in this talk. In addition, I will address a high performance inertia driven triboelectric nanogenerator based on body motion and gravity. The packaged device has successfully harvested around 144 mW during day time in preclinical test, and real-time output voltage data is monitored via Bluetooth low energy information transmit system.

9:00 AM BM08.04.04
Soft, Stretchable, Conductive Metal-Polymer Composites as Nonlinear Springs for Broadband Vibration Energy Harvesting Zining Yang and Seek Kim; University of Illinois at Urbana-Champaign, Urbana, Illinois, United States.

Energy harvesting from ambient vibrations is widely considered as a solution for the most prominent obstacle towards the commercialization of internet of things (IoT), which is the expenses and human efforts invested in battery replacement for millions of wireless sensor nodes. Unfortunately, ambient vibrations are generally distributed over a low-frequency domain with wide bandwidth, which renders most microscale vibration energy harvesters unpractical for real-world applications. Here, a vibration energy harvester with both low operation frequency and a broadband response is achieved by using a resonator with soft and nonlinear springs. A soft, deformable, and electrically conductive metal-polymer composite is employed as the spring material, not only to obtain a low spring constant using a compact clamped-clamped beam design but also to trigger the broadband behavior by harnessing the geometric nonlinearity of the doubly clamped beam at large deflection. A highly miniaturized (footprint < 1 cm2) capacitive vibration energy harvester with low operation frequency (resonant frequency 73Hz), broad bandwidth (28% of the resonant frequency), and high power density (171 μW/cm3 at resonant frequency) is realized using the soft spring resonator. The energy harvesting device is also used as a wearable, self-powered acceleration sensor with a voltage sensitivity of around 0.78 V/g.

9:15 AM BM08.04.05
Textile Based Triboelectric Nanogenerator with Fully Stretchable Knitted Fabrics Sung Soo Kwak1, Jihye Kim and Sang-Woo Kim; Sungkyunkwan Univ, Suwon-si, Korea (the Republic of).

Harvesting human-motion energy for power-integrated wearable electronics could be a promising way to extend the battery-operation time of small low-power-consumption electronics such as various sensors. For this purpose, a fully stretchable triboelectric nanogenerator (S-TENG) that has been fabricated with knitted fabrics and has been integrated with the directly available materials and techniques of the textile industry is introduced. This device has been adapted to cloth movement and can generate electricity under compression and stretching. We investigated plain-, double-, and rib-fabric structures and analyzed their potentials for textile-based energy harvesting. The superior stretchable property of the rib-knitted fabric contributed to a dramatic enhancement of the triboelectric power-generation performance owing to the increased contact surface. The present study shows that, under stretching motions of up to 30 %, the S-TENG generates a maximum voltage and a current of 23.50 V and 1.05 μA, respectively, depending on the fabric structures. Under compressions at 3.3 Hz, the S-TENG generated a constant average root-mean square power of up to 60 μW. The results of this work show the feasibility of a cloth-integrated and industrial-ready TENG for the harvesting of energy from human biomechanical movements in cloth and garments.

9:30 AM BM08.04.06
Super-Stretchable and Mechanically-Durable Triboelectric Nanogenerator for Wearable Energy Harvesting and Self-Powered Tactile Sensing Ying-Chih Lai1 and Zhong Lin Wang2; 1Materials Science and Engineering, National Chung Hsing University, Taichung City, Taiwan; 2Georgia Institute of Technology, Atlanta, Georgia, United States.

In this present, we demonstrate a mechanically durable and resilient triboelectric nanogenerator (MDTENG) with unprecedented features of ultrahigh omnidirectional stretchability and capability to produce energy in different extreme mechanical deformations. The innovative nanogenerator can be adaptive on various desired non-planar and irregular objects, including human bodies, spheres, and tubes, etc., and act as power sources for other electronic components. The MDTENG was realized through composed of intrinsic stretchable and durable components that enable the device to generate electricity from tapping or skin touching despite under various deformations. Based on the durable materials, the triboelectric nanogenerator is omnidirectionally stretchable over 500% strain. Even experiencing severe tearing damages, the device can still function as an effective power source for the load. Moreover, the energy produced has been demonstrated to be able to sustainably power a commercial smart watch. Based on the stretchable and durable nanogenerators, we further demonstrated the first fully autonomous and self-powered adaptive e-skin system that can map touch by responding to visual light-emitting diode (LED) signals without the need of external power supply. The work presented here are timely and beneficial for the development of wearable, deformable electronics and self-powered electronic and sensing systems. [Ref]


9:45 AM BREAK

10:15 AM BM08.04.07
Triboelectric Nanogenerator as a Power Source and Self-Powered Sensor Zhong Lin Wang1, 2; 1Georgia Institute of Technology, Atlanta, Georgia, United States; 2Beijing Institute of Nanoenergy and Nanosystems, Beijing, China.

Triboelectrification is an effect that is known to each and every one probably ever since the ancient Greek time, but it is usually taken as a negative effect and is avoided in many technologies. We have recently invented a triboelectric nanogenerator (TENG) that is used to convert mechanical energy into electricity by a conjunction of triboelectrification and electrostatic induction. As for this power generation unit, in the inner circuit, a potential is created by the triboelectric effect due to the charge transfer between two thin organic/inorganic films that exhibit opposite tribo-polarity; in the outer circuit, electrons are driven to flow between two electrodes attached on the back sides of the films in order to balance the potential. Ever since the first report of the TENG in January 2012, the output power density of TENG has been improved for five orders of magnitude within 12 months. The area power density reaches 500 W/m², volume density reaches 490 kW/m³, and a conversion efficiency of ~50% has been demonstrated. The TENG can be applied to harvest all kind mechanical energy that is available but wasted in our daily life, such as human motion, walking, vibration, mechanical triggering, rotating tire, wind, flowing water and more. Alternatively, TENG can also be used as a self-powered sensor for actively detecting the static and dynamic processes arising from mechanical agitation using the voltage and current output signals of the TENG, respectively, with potential applications for touch pad and smart skin technologies. This presentation will focus on TENG for wearable electronics.


[Ref]
Body-implantable bioelectronics devices that monitor and modulate abnormalities in patients are highly sophisticated technologies, and long-term operation of such in vivo devices has faced a major technological challenge. Currently, medical implant devices require high-risk repeat surgery to replace used devices; permanent operation of body-implantable bioelectronics devices will reduce the patient’s risk of surgery, including device removal and replacement. Notwithstanding that a variety of in vivo energy harvesters using near-field or mid-field electromagnetics, thermal gradient, and mechanical movements of organ have been proposed, in vivo power generators are still limited, which are lack of power to charge storage device as energy sources for bioelectronics devices. Especially, the metal package of in vivo devices interferes with energy transfer, resulting in low energy conversion. In addition, in vivo energy transfer systems require external energy transmitters that can be inconvenient for the user. Thus, while the only possible and promised energy source for implantable medical devices is batteries, batteries with limited dimensions, capacity, or stability have a finite lifespan.

We demonstrate a high-performance inertia-driven triboelectric nanogenerator (I-TENG) based on body motion and gravity. We also successfully operated the I-TENG in a preclinical test and collected real-time output-voltage data via a Bluetooth low-energy (BLE) information-transmitting system. A synchronous stack structure, which achieves current waveform superposition, can step the peak current value up without additional components, so that, the I-TENG generated 7.3 mW Peak and 90 μW RMS in laboratory experiment, and harvested around 144 mW during the daytime in the preclinical testing in a dog is asleep. In other words, securing the minimum normal direction displacement in multidirectional body motion ensures natural operation of the I-TENG.

Body Implantable Triboelectric Nanogenerator Driven by Inertia for Powering Implantable Medical Device Hanjun Ryu and Sang-Woo Kim; Sungkyunkwan University, Suwon, Korea (the Republic of).

By considering these merits of simple fabrication, outstanding performance, robust characteristic and low-cost technology, we believe that TENGs can provide insight to material design for achieving high-performance stretchable self-powered electronic systems.

A synchronous stack structure, which achieves current waveform superposition, can step the peak current value up without additional components, so that, the I-TENG generated 7.3 mW Peak and 90 μW RMS in laboratory experiment, and harvested around 144 mW during the daytime in the preclinical testing in a dog is asleep. In other words, securing the minimum normal direction displacement in multidirectional body motion ensures natural operation of the I-TENG.

11:15 AM BM08.04.10
Increasing Surface Charge Density by Intrinsic Charge Layer Inclusion for High-Performance Triboelectric Nanogenerator Devices Aravind Ravichandran and Marc Ramuz; EMSE-CMP, Gardanne, France.

With the rapid development of wearable electronics and sensor networks, batteries cannot meet the sustainable energy requirement due to their limited lifetime, size and degradation. With miniaturization leading to high-power and robustness, triboelectric nanogenerators(TENGs) have been conceived as a promising technology by harvesting mechanical energy to power small electronics and wearables. The main issues associated with TENGs are their very low output power leading to lower output charge density and high impedance matching.

In this work, a state of the art multilayer flexible structure is devised which not only increases the charge density but also provides a high average(RMS) power output. Thin-film organic flexible materials are deposited to trap the charges from the triboelectrification process, allowing the acceptance of more charges from an electrode and thereby increasing the power output. Material work function provides better understanding towards charge transfer process.

A concept wearable device is conceptualized for use in a highly efficient self-powered sensor network system, converting ambient mechanical energy to electricity with a 1.2kV peak amplitude and a charge density of 1000 μC/m2. This device structure makes the TENGs attractive to charging applications for wearables and large-scale harvesting without massive volume. By this technique, we have overcome numerous friction-based operation challenges including lack of uniform contact, material loss through wear, high sensitivity to humidity, and output power storage.

By considering these merits of simple fabrication, outstanding performance, robust characteristic and low-cost technology, we believe that TENGs can open up great opportunities not only for powering small electronics but can contribute to large-scale energy harvesting through engineering design being complementary to existing energy sources.

Thermoplastic Elastomer-Based Stretchable Devices Unyong Jeong; Pohang University of Science and Technology, Pohang, Korea (the Republic of).

The Folding and stretching will be the key characteristics in the next-generation electronic devices. The stretchable electronics have motivated scientists to...
develop deformable materials for use in electrodes, semiconductors, bio-interfaces, and sensors. To realize fully stretchable electronic devices, each component of the devices must maintain its performance up to critical strain. This talk will present recent developments of stretchable polymeric conductors and semiconductors, and stretchable devices that are based on thermoplastic elastomers. Special focus will be put on the thermoplastic block copolymer composites for their uses as substrates, electrodes, interfacial adhesives, and circuits. This talk presents a generalized platform that can be used for a variety of stretchable devices and several stretchable devices will be demonstrated including real-time a long-term use heart sensor, haptic device, display, energy harvesting, and stretchable transistors.

2:00 PM BM08.05.02
High-Performance Flexible Carbon Nanotube Complementary Electronics for Integrated Sensor Systems

Li Xiang, Heng Zhang, Jian-Mao Peng and Youfan Hu;
Peking University, Beijing, China.

The longterm vacancy of high-performance complementary metal-oxide-semiconductor (CMOS) technology on plastics is a nonnegligible obstacle to the applications of flexible electronics with advanced functions, such as continuous health monitoring with in situ signal processing and wireless communication capabilities, in which high speed, low power consumption, and complex functionality are desired for integrated circuits (ICs). Here, we report the implementation of carbon nanotube (CNT)-based high-performance CMOS technology and its application for signal processing in an integrated sensor system for human body monitoring on ultrathin plastic foil with a thickness of 2.5μm. The performances of both the p- and n-type CNT field-effect transistors (FETs) are excellent and symmetric on plastic foil with a low operation voltage of 2 V. width-normalized transconductances (gm/W) as high as 4.69 μS/μm and 5.45 μS/μm, width-normalized on-state currents reaching 5.85 μA/μm and 6.05 μA/μm, and mobilities up to 80.2 cm2V−1s−1 and 97.1 cm2V−1s−1, respectively, together with a current on/off ratio of approximately 105. The devices were mechanically robust, withstanding a curvature radius down to 124 μm. Utilizing these transistors, various high-performance CMOS digital ICs with rail-to-rail output and a ring oscillator on plastics with an oscillation frequency of 5 MHz were demonstrated. Furthermore, an ultrathin skin-mounted humidity sensor system with in situ frequency modulation signal processing capability was realized to monitor human body sweating.

2:15 PM BM08.05.03
Super-Elastic Electronic and Photonic Fiber Devices via Thermal Drawing

Fabien Sorin1, Yunpeng Qu1, Dang Tung Nguyen1, Alexis Page1, Wei Yan1, Tapajyoti Dasgupta1, Rene M. Rossii2 and Nicola Bartolomei1; 1Ecole Polytechnique Federale de Lausanne, Switzerland, Lausanne, Switzerland; 2Empa-Swiss Federal Laboratories for Materials Science and Technology, Saint-Gallen, Switzerland.

Stretchable optical and electronic fibers constitute increasingly important building blocks for a myriad of emerging applications, such as in robotics or medical implants. They are particularly suitable for wearable and smart textiles as seamlessly integrated devices that can bring high added values in monitoring and energy harvesting. Fibers can indeed integrate complex sensing and actuating functionalities such as light, heat, chemicals or pressure sensing, as well as piezoelectric actuation. They can also be used for energy harvesting from heat, light or mechanical movement. Yet, it remains challenging to fabricate efficient and advanced soft fiber-base devices that can undergo significant mechanical deformation in a simple and scalable way. Conventional fiber manufacturing methods, such as wet and dry spinning, or extrusion, are not well adapted to fabricate multi-material functional fibers. The preform-to-fiber thermal drawing technique on the other hand is an emerging powerful platform to fabricate multi-material fibers with complex architectures and functionalities. Thus far however, this fabrication approach has been restricted to rigid thermoplastic or glass fibers, preventing their use for mechanical sensing or actuation, and rendering difficult their use in wearable approaches or within textiles.

In this contribution we will show how we could revisit the selection criteria for cladding materials compatible with the thermal drawing process, and fabricate super-elastic fibers with advanced optical and electronic functionalities. We will demonstrate how, thanks to a deeper rheological characterization, we could identify thermoplastic elastomers that could be drawn from a solid preform at high viscosity. Subsequently, we will demonstrate that thermoplastics, liquids metals, and conductive polymer composites could be co-drawn with prescribed architectures within thermoplastic elastomer cladding. This allowed us to successfully fabricate stretchable optical and electronic fibers that are used as precise and robust pressure, strain or more generally deformation sensors, as well as soft and stretchable waveguides. This work was just published (Advanced Materials, 2018, 201707251) and highlighted in several news media (here is a video highlighting this recent breakthrough: https://actu.epfl.ch/news/an-elastic-fiber-set-to-revolutionize-smart-clothes/). As we will show via concrete examples, the ability to thermally draw soft multi-material fibers open new opportunities in robotics as well as fiber integrated devices and wearable technologies. These results open opportunities not only for exploring new academic research directions, but also in industrializing fiber-based flexible and stretchable devices for applications in sensing, health care, robotics, wearable devices and smart textiles.

2:30 PM BM08.05.04
Integrated Wearable Electronic System with Stretchability, Modularity and Self-Healability

Jiheong Kang and Zhenan Bao; Stanford University, Stanford, California, United States.

Electronic skin devices capable of monitoring physiological signals and displaying feedback information through closed-loop communication between user and electronics are being considered for next-generation wearables and Internet-of-Things. Such devices need to be ultrathin to achieve seamless and conformal contact with our human body, to accommodate strains from repeated movement such as bending, and, more importantly, be comfortable to wear. However, ultrathin materials are inevitably more susceptible to our daily wear and tear processes. Recently, self-healing chemistry has driven important advances in deformable and reconfigurable electronics, particularly with self-healable electrodes as the key enabler. Although polymer substrates are self-healable due to its dynamic nature, the disrupted conducting network is unable to recover its stretchability after damage. In addition, commonly used self-healing polymeric materials have poor mechanical properties, which have limited their applications in simple self-healable conductive wire applications. Herein, we present my efforts to develop new self-healing polymeric material and its impact on the development of which enable to observe the self-reconstruction of conducting nanostructures. This finding, combined with the self-bonding property of self-healing polymer, allowed subsequent heterogeneous multi-component device integration, including interconnects, sensors, and light emitting devices, into a single multi-functional system. We will also introduce new wearable electronic systems with modularity. In my presentation, more details for the material developments and its integration technology will be discussed.

2:45 PM BM08.05.05
Organic Haptics—Soft Materials for Artificial Touch

Darren J. Lipomi; University of California, San Diego, La Jolla, California, United States.

Human culture is replete with artifacts that interact with the senses of sight, hearing, taste, and smell. Material objects whose purpose is to produce a thoughtful or emotional response through the sense of touch, however, are rare. In this talk, I present my group’s recent work on the intersection between the science of soft materials and the science of touch. This field, which we have named “organic haptics,” combines active polymers, contact mechanics, and psychophysics. We are beginning to understand the ways in which stick slip friction, adhesion, and capillary forces between planar surfaces and human skin affect the ways materials produce tactile objects in consciousness as mediated by the sense of touch. This work, which combines human subject experiments, laboratory mockups of human skin, and analytical models accounting for friction, has led to several important observations. In particular, we
Flexible/stretchable conductive composites and fibers have received considerable attention for wearable electronics. They are typically composed of conductive fillers and flexible/stretchable polymer matrix. This talk presents the filler percolation network design strategies investigated in our laboratory. Firstly, filler designs for electrically conductive composites will be discussed. Carbon nanotubes have been actively investigated for conductive fillers due to the excellent electrical properties. However, the high electrical conductivity of bulk composites could not be realized by carbon nanotubes alone. We constructed filler percolation networks by combining one-dimensional carbon nanotubes, 0-dimensional silver nanoparticles pre-functionalized on the surface of nanotubes, and 2/3-dimensional micro-scale silver particles [1-4]. This architecture significantly increased electrical conductivity of flexible/stretchable nanocomposites [1-3] and fibers [4]. More recently, we developed flower-shaped silver nanoparticles (Ag nanoflowers) to further enhance electrical conductivity of wet-spun fibers and inks [5, 6]. An extraordinary high electrical conductivity was obtained by Ag nanoflowers, and the wet knitted fabric provided negligible resistance change up to ~200% strain with excellent cycleability [5]. Ag nanoflower-graphene sponge with variable stiffness will also be introduced [7]. Secondly, the filler design strategy to achieve high thermal conductivity of nanocomposites will be discussed in applications for soft thermal interface materials [8]. Recent advances in enhancing electrical/thermal conductivity and mechanical strength of fibers will also be introduced. References: [1] Advanced Materials, 24, 3344 (2012) [2] Nature Nanotechnology, 5, 853 (2010) [3] Advanced Materials, 25, 2548 (2013) [4] Nano Letters, 14, 1944 (2014) [5] ACS Nano, 9, 10876 (2015) [6] Scientific Reports, 6:34894-1-9 (2016). [7] Small, 1800549 (2018). [8] Advanced Materials, 28, 7220 (2016)

4:00 PM BM08.05.07
Cold-Blooded Circuits—Transient Electronics that Require Constant Heat Input to Prevent Dissolution Xin Zhang and Leon Bellan; Vanderbilt University, Nashville, Tennessee, United States.

Implantable medical devices containing electronic components are becoming more widespread due to improved sensing and communications capabilities, as well as enhanced biocompatibility of the materials used to for the devices. While implantable medical devices to treat or monitor chronic conditions ought to be long-lasting, devices to treat or monitor transient conditions should be eliminated when the condition has been resolved. To avoid the need for surgical extraction, many implantable devices now employ bioresorbable materials that degrade after a period of time. This lifetime, however, is preprogrammed upon device fabrication; on-demand disintegration is not possible. To develop a materials platform that would enable on-demand, non-invasive disintegration of an implanted circuit, we have produced thermoresponsive transient circuitry that demonstrates stable conductivity in warm aqueous environments but rapidly dissolves and loses function in cold aqueous environments. In other words, a constant source of heat (provided by a water bath, host tissue surrounding an implant, etc.) is required to prevent disintegration.

To form thermoresponsive transient circuitry, we combined thermoresponsive polymers that exhibit a lower critical solution temperature (LCST) with patterned conductive nanowire networks. In solution above the LCST, the polymer serves as a “binder” that holds the nanowire network in place, assuring a percolating network that supports an electrically conductive path. Once the solution temperature has dropped below the LCST, however, the polymer quickly dissipates and the conductive network falls apart, causing the device to lose function and macroscopically disappear. To form patterned conductive traces, we used a parylene mask as a stencil to pattern networks of silver nanowires at densities above the percolation threshold. We then spun the LCST polymer (e.g. PNIPAM, methylcellulose) over the nanowire networks. Upon drying, the polymer film (with embedded nanowires) can be peeled off and serves as the circuit’s substrate. Multi-layer devices can be formed using solvent welding, and this approach can be used to form parallel plate capacitors employing electrodes on both sides of the film. Thus, by forming a composite of conductive nanowires and thermoresponsive polymer binder, we are able to achieve a unique transient circuit that requires heat input to prevent irreversible disintegration. Such systems have potential for use in applications such implantable circuitry that dissolves upon loss of life, removal from host tissue, or local application of ice to cool the skin.

4:15 PM BM08.05.08
Constructing p-n Junctions in a Single Planar Polymer Film Hong Wang; Frontier Institute of Science and Technology, Xi'an, China.

Constructing p-n junctions with a single planar polymer film will not only largely reduce the fabrication cost but also largely increase the integration density of organic electronics. However, it is very challenging to build Schottky barriers or p-n junctions in only one organic material because diffusion of the counter-ion dopants renders such structures very unstable. Here we show a rectifying curve obtained from a single planar polymer film with a high current density of 2-3 orders higher than conventional organic rectifiers. The structure was built by convert half of the film from p type into n type using a chemical reaction other than a doping method. This approach is expected to be extended into other polymers. We hope our work could open the door for designing flexible and portable organic devices with high integration level.

References:

4:30 PM BM08.05.09
Printed Light-Emitting Devices Comprising Biocompatible Materials Johannes Zimmermann1,2, Luca Porcarelli1, Nils Juergensen1,2, Tobias Rödlmeier1,2,Ana Sanchez-Sanchez1, David Mecerreyes1 and Gerardo Hernandez-Sosa1,2; 1Karlsruhe Institute of Technology, Karlsruhe, Germany; 2InnovationLab, Heidelberg, Germany; 3POLYMAT, University of the Basque Country, Donostia-San Sebastian, Spain.

Organic light-emitting devices have become a big topic in modern research and are often discussed as a future leading technology because of their light weight, flexibility and solution-processability. Here we refer to a further advantage of this technology, namely the possibility of producing biodegradable/biocompatible devices, which will open the pathway to a whole new field of future applications ranging from healthcare and medicine to smart packaging, disposable and wearable electronics.

In this work we present the fabrication of light-emitting electroluminescent cells (LECs) comprising a non-halogenated bio-friendly solid-polymer electrolyte (poly (c-caprolactone-co-trimethylene carbonate) plus tetрабutylammonium bis-oxalato borate) on biodegradable cellulose di-acetate substrates by
industrially relevant printing techniques. [1] By using a biocompatible electrode system consisting of PEDOT:PSS and ZnO we could produce functional devices comprising up to 90 vol% of biocompatible materials. The devices are semi-transparent and flexible even under operation. A maximum luminance of over 200 cd m⁻² is achieved significant for display and lighting applications. The relatively short lifetime on the timescale of some minutes can be compensated by a fully-printed production process utilizing inkjet printing and blade coating, relevant for an industrially cost-efficient production of disposable/transient electronics.


4:45 PM BM08.05.10
Tissue-Adhesive Optoelectronics for Wirelessly-Operated Photodynamic Therapy

Toshibori Fujie1, 2, Kento Yamagishi1, Izumi Kirino1, Isao Takahashi1, Hizuru Amano1, Shintar Akeoka2 and Yuji Morimoto3; 1Waseda Institute for Advanced Study, Waseda University, Tokyo, Japan; 2PRESTO, Japan Science and Technology Agency, Saitama, Japan; 3Graduate School of Advanced Science and Engineering, Waseda University, Tokyo, Japan; 4Graduate School of Medicine, Kyoto University, Kyoto, Japan; 5Graduate School of Medicine, The University of Tokyo, Tokyo, Japan; 6Department of Physiology, National Defense Medical College, Saitama, Japan.

Implantable medical device is expected for revolutionizing clinical interventions, those were not achieved by conventional therapy. In this regard, we focused on low-dose yet long-term photodynamic therapy (PDT), referred to as metronomic PDT (mPDT). The mPDT is expected for minimally-invasive cancer treatment, while requiring a stable fixation of optical devices inside the body to allow the continuous delivery of light to the lesions for tens to hundreds of hours. In addition, surgical suturing, considered as the first choice for device fixation, however, is unsuitable in the presence of surrounding major nerves and blood vessels in organs or tissues that are fragile, change their shape or actively move. Here, we report a local antitumor effect of implantable, wirelessly-powered mPDT based on a tissue-adhesive optoelectronic device stably fixed onto the surface of the internal animal tissue without surgical suturing. We developed a bio-adhesive and stretchable nanosheet composed of polydopamine (PDA) and poly(dimethylsiloxane) (PDMS) (~600 nm thick). By sandwiching a near field communication-based light emitting diode (LED) chip with a pair of PDA-PDMS nanosheets, we subcutaneously implanted the optical device in a cancer tumor model mouse. The implanted device was stably fixed in the body and locally irradiated the target tumor for 10 days. Of note, green LEDs showed significant antitumor effects with about 1000 times lower intensity (< 100 μW/cm²) of conventional laser-based PDT method (> 100 mW/cm²). The implantable and wirelessly-powered mPDT system utilizing tissue-adhesive optoelectronics will open a new avenue for the treatment of undetectable micrometastases or deeply located lesions where light does not reach.

BM08.06.01
Binder Jetting Fabrication of Graphene Composite Structures for Printed 3D Electronic Devices

Xuechen Shen and Hani E. Naguib; University of Toronto, Toronto, Ontario, Canada.

Carbon-based nanomaterials see ubiquitous usage in research and industry as structural reinforcement in composites. Aside from excellent mechanical properties, carbon-based nanomaterials also demonstrate desirable electrical properties. Graphene has current carrying capacity several magnitudes higher than copper, able to achieve a current density on the scale of 10⁷Acm⁻², compared to the current density of copper at 10⁶Acm⁻². The improved current density of graphene over traditional conductive materials is significant for reducing the size of electronic devices to meet demands for higher device density. Furthermore, graphene has high affinity for compositing with polymer materials, enabling the fabrication of flexible and conductive composites. Such graphene-polymer composites are highly suitable for wearable electronics and soft robotics applications. Developing additive manufacturing techniques for 3D carbon nanomaterial structures could lead to manufacturing processes that facilitate rapid prototyping and promote more ubiquitous usage of nanomaterials in flexible sensors, actuators, and energy devices.

Graphene oxide (GO) is a popular material choice in 2D circuit printing due to its ease of processability. As GO, the material disperses well in water, and aligns readily when extruded from thin micronozzles, which enhances mechanical and electrical properties over bulk material. GO inks need to be reduced to graphene after printing to recover conductive properties.

In an ongoing study, we Investigate the use of principles from 2D inkjet printing of GO in a binder jetting process to additively manufacture 3D electronics including actuators, sensors, energy storage, and integrated electronic systems. In this system, a GO/water dispersion is used as binder. The dispersion is jetted onto a polymer or metal powder to temporarily bind adjacent particles. Dropping binder to define 2D patterns over stacked layers of powder builds a 3D object. Following post-processing procedures, the final product is a 3D printed composite material of graphene and the polymer or metal powder.

Our first study investigates Polyvinyl alcohol (PVA) as powder because it dissolves in water and forms a flexible plastic when dried. This property gives PVA powder high affinity with a graphene oxide/water binder, which is a well-studied material. The effect of adding Intrinsically Conductive Polymers (ICP) such as poly(pyrrole) or polyanilines mixed with PVA is investigated to increase conductivity of the graphene composite without significant increase in cost.

Our second study investigates Copper as powder to fabricate a high conductivity composite. The resulting structure is significantly less flexible compared to a polymer composite, but it exhibits high electrical conductivity and density, forming a metal-graphene composite with exceptional electrical properties.

BM08.06.02
Integrated Energy Devices for Smart Textiles and Electronic Skins

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Rapid advancements in wearable smart textiles and stretchable/multifunctional electronics impose the challenge on corresponding power devices that they should possess comparable flexibility, stretchability and functionalities. Here, we briefly summarize our recent progresses on wearable energy storage and
harvesting devices, especially energy devices aiming to power smart textiles and artificial electronic skins. Both yarn or textile-based electrochemical energy storage devices and textile-based triboelectric nanogenerators (TENGs) have been developed, meantime, self-charging systems have been achieved by integrating them so that energies harvested from daily human motions can be stored simultaneously. It is even more challenging to provide power sources for electronic skins or soft electronics/robotics. We report a soft skin-like triboelectric nanogenerator that enables both biomechanical energy harvesting and tactile sensing by hybridizing elastomer and ionic hydrogel as the electrification layer and electrode, respectively. Ultra-high stretchability and transparency are achieved simultaneously for an energy-harvesting device. Our work provides new opportunities for soft power sources and potential applications in soft/wearyears electronics.

**BM08.06.03**

Flexible Drug Delivery Device for Controlled Administration Sang Hyun Sung and Keon Jae Lee; KAIST, Daejeon, Korea (the Republic of).

We report flexible drug delivery microdevices (f-DDM) that are capable of controlled administration. The unique structure of the f-DDM consisting of freestanding gold membranes over the microreservoirs was enabled by reversing the fabrication order of the reservoir and sealing membrane. We optimized the design of the f-DDM by a finite element analysis (FEA) to prevent thermal damage during the laser transfer process. The required current density for reliable drug release operation was determined through an electrochemical analysis. The f-DDM was conformally implanted on the curved cerebral cortex, and localized drug delivery was confirmed by the diffusion of two different types of fluorescent neurotracers. Finally, in vivo therapeutic treatment using the f-DDM was demonstrated by the controlled release of an anti-epileptic drug into the mice.

**BM08.06.04**

Study of Long-Term Biocompatibility and Bio-Safety of Implantable Nanogenerators Jun Li, Lei Kang, Yanhao Yu, Yin Long, Justin Jeffery, Weibo Cai and Xudong Wang; University of Wisconsin-Madison, Madison, Wisconsin, United States.

Since the first demonstration of ZnO nanowire-based implantable nanogenerator (i-NG) in 2010,[1] i-NGs have been consistently investigated and developed as self-sustainable implantable power sources and real-time healthcare monitoring sensors.[2,3] One of the most essential requirements for i-NG development is the long-term bio-compatibility and bio-safety considering years-long lifespan of most implantable medical devices (IMDs). Although earlier work on NG development has demonstrated extensively long working cycles of the piezoelectric functional components which is sufficient for in vivo operation of NG over 5-10 years in theory,[4,5], long-term assessment of i-NG in biological systems has not been investigated. Meanwhile, considering the potential risks of immune reactions and infections over a long period of time, biological influence of i-NG also needs to be fully evaluated to justify their implantation feasibility. To fill the gap and address this critical issue, herein we present a systematic study of polydimethylsiloxane (PDMS) and PDMS/Parylene-C packaged polyvinylidene fluoride (PVDF) NGs implanted inside female ICR (Institute of Cancer Research) mice for up to six months.

The packaged PVDF NG had a stable in vitro output of 0.3 V when bended for 7200 cycles. After i-NGs were implanted between the skin and muscle of mice at lower right back, multiple advanced imaging techniques, including computed tomography (CT), ultrasound, and photoacoustic were used to characterize the embedded i-NGs in vivo. These techniques not only demonstrated that the i-NGs kept excellent adhesion to the adjacent muscle surface and exhibited intactness without damage but also observed the real-time motion of packaged i-NGs in response to muscle movements. While no signs of toxicity or incompatibility were found from the surrounding tissues based on complete pathological analyses, the whole body functions of mice kept normal evidenced by the blood and serum test. Moreover, all devices exhibited stable electrical output during the entire examine period and packages were also able to effectively insulate the i-NG in biological environment with negligible stray currents at a pA scale.

These series of in-vivo and in-vitro studies confirmed the high biological feasibility of using i-NG in vivo for biomechanical energy harvesting, and thereby further enables self-powered capability of practical IMDs bypassing the requirement of batteries. This research provided the first cornerstone for the future intelligent self-powered IMD system implantation.

References:


**BM08.06.05**

Sensitivity Controllable, Printed Flexible Vibration Sensor Daisuke Yamamoto1, Takayuki Arie1, Seiji Akita1 and Kuni Takei1,2; 1Osaka Prefecture University, Sakai, Japan; 2JST PRESTO, Chiyoda, Japan.

Trillion sensor concept requires many sensors on everywhere including humans and infrastructures to monitor a lot of information. One of the important information is to monitor infrastructures such as strain and vibration. Vibration can be often monitored by inflexible acceleration sensor. Although few demonstrations about flexible acceleration sensor have been reported, the detail study of the printed flexible acceleration sensor has yet to be conducted. This studies printed flexible acceleration sensors to control the sensitivity and demonstrates a vibration monitoring. By optimizing the device size and materials, we successfully monitored small vibrations. This technique can be monitored infrastructure vibration mapping by attaching the sensor sheet on the objects.

The flexible acceleration sensor consists of 4 beam structure with various beam length (L) and width (W). Strain sensors formed by Ag nanoparticles and carbon nanotube inks were printed on three beams, and Ag ground electrode was printed on another beam on PET film. The strain sensor is resistive-change sensor.

First, real-time resistive change of a sensor was monitored by applying different acceleration directions. The results explain that resistance change is different depending on the acceleration directions, which are in good agreement with simulation results. To observe the size dependence, acceleration dependences of different beam length and width were characterized. The results show that the sensor with longer length and narrower width has lower threshold acceleration. Based on the results, threshold acceleration is proportional to $-L^{2.77}$ and $-W^{2}$. To support these experimental results, finite element method simulation to extract the force for 1 mm displacement with three different beam lengths and widths was conducted. These suggest that the trends of length and width dependences were well matched between them. Based on the results, it can be concluded that mechanism of strain distribution for flexible acceleration sensor is explained by the standard spring mechanism. For mechanical flexibility of the acceleration sensor, the normalized sensitivity change as a function of bending radius is studied. At smaller bending radius, the sensitivity increases (decreases) when the bending direction is along
Control of Mouse Behavior via Flexible Vertical Light-Emitting Diodes on the Cortical Surface

Jung Ho Shin, Seung Hyun Lee, Han Eol Lee and Keon Jae Lee; Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

The stimulation of targeted neural regions in the brain is one of the attractive technology in neuroscience for controlling physical movement, and long-range interactions. Recently biomedical implants now employ flexible light emitting-diodes combined with optogenetic mouse models to generate the neural signals in high resolution. However, most conventional devices are fabricated to stimulate functional regions through blue-light driven channelrhodopsin.

In this report, we introduce flexible AlGaNP vertical light-emitting diodes (VLEDs) for the stimulation of functional cortical regions in the mouse brain. Micro-sized LED chips effectively captured the conductive particles in anisotropic conductive film (ACF) inducing red light emissions with high optical power density, which are high enough to modulate motor neurons deep below layer III from the cortical surface. Stable operation of pulsed red light from f-VLEDs causes mouse body movements and electromyogram (EMG) signal changes. The expression of chimson, red-shifted channelrhodopsin, enables red-light excitation of targeted functional cortical regions. This demonstration opens new opportunities for sophisticated cortical mapping, analyzing the interactions between different motor regions in the mouse brain.

Thermally Invisible Optoelectronic Patch for the Skin

Han Hee Jung and Kyung In Jung; DGIST (Daegu Gyeongbuk Institute of Science and Technology), Daegue, Korea (the Republic of).

Nowadays, as wearable sensor technologies have surpassed the limits of technologies such as electronics, healthcare system and medical devices, which have been in the past, the interest of necessity measuring the physiological signal actively and accurately is critical for prophylaxis and prediagnosis. There are many devices that can easily check the conditions of the body, and pulse oximetry is the most commonly used in daily life and clinics for monitoring the vital signal. Because of pulse oximetry, it is convenient to check and readily predict health condition by observing cardiac and cerebral activities by monitoring heartrate and dynamics of blood flow. Although the applications of modern optoelectronic devices have been extended and provided practical tools for seamless real-time monitoring of blood flow dynamics, there are still prominent challenges in thermal management for optoelectronic devices due to undesired thermal energy originated from light source. The optoelectronic device exhibits very high surface temperature compared to that of neighboring
biological epidermis layer, which resulting skin integrity issues and deterioration of the light-emitting diode functionality. In this study, we propose heterogeneity evaporation of the light-emitting diode photodetector and thin metallic heatsink element embedded in the optoelectronic module which can provide an attractive architecture for sustainable in-situ spatiotemporal measurement of blood flow dynamics with excellent thermal management. Experimental and computational analysis clearly explain that the proposed optoelectronic device with heatsink element has excellent heat dissipation and long-term usability with thermally safe operating condition to the skin in virtue of high thermal conductivity and thin film geometrical design of the embedded heatsink. The biomimetic demonstration envisions that the proposed optoelectronic device with metallic heatsink is an ideal blood flow monitoring system, which is mechanically and thermally compliant to the skin and offer opportunities for long-term clinical applications, such as sleep study for insomnia patients.

BM08.06.10
Structural Design and Optimization of Wearable Thermoelectric Generator System Jeong Hun Kim1, Junsoo Kim2, Jong-Pil Im1, Jaewoo Lee1, Solyee Im1 and Seungseon Moos1; 1Electronics and Telecommunications Research Institute, Daejeon, Korea (the Republic of); 2Harvard University, Boston, Massachusetts, United States.

A thermoelectric generator (TEG) is promising energy harvesting device that can convert heat generated from power plant, furnace and combustion engine to electric energy. A TEG can use various heat sources not affected by weather, interests are growing by its stable energy generation property. In this paper, we not only have measured heat resistance of human body also optimized the structure of the thermoelectric element (TE) and TEG. From this result, we fabricated wearable TEG system and show the application using electrical energy converted from body heat.

As a TE for fabrication of TEG, we used BiTe-based material which is most widely used for TEG system. The surface area and height were fixed as 1 mm² and 3 mm respectively from our previous research and the module size was 22 mm x 36 mm. Then the numerical simulation about the temperature difference of hot and cold side, open circuit voltage (OCV) and output power of the module have been conducted as the number of TE pairs are increased. For the TEG module fabrication, we assembled 31 pair of TE on the PCB substrate using metal jig. Because the general PCB substrates for fabrication of TEG are rigid, though metal PCB is facile material to make high performance TEG, but it cannot suitable for the wearable energy harvesting system. To solve this problem, we adopted two kinds of flexible PCBs which are made from polyimide and epoxy/silica composite. The polyimide PCB (PI-PCB) is very promising platform because of its flexibility, thin structure and thermal resistance. But in the TEG system, the temperature difference between hot and cold side that concludes the output power decreases from its low thermal conductivity, therefore, other materials have to be considered. The composite PCB consists of epoxy/silica shows higher thermal conductivity, and we could make up for the weakness of the PI-PCB. As over time, the temperature difference would decrease if heat dissipation at the cold side is not sufficient. Though metal fin is most widely used structure for the heat sink, it is not suitable for wearable system because of the rigidity and bulky structure. We proposed novel bio-inspired heat sink system composed of polymer micro structures. Our heat sink is not only flexible also able to change structures by temperature modulation by the characteristic of Poly(N-isopropylacrylamide) (PNIPAAm) that can shrink under 32 °C and expands over 32 °C. Likewise sweat gland of human body, this bio-inspired heat sink can prevent evaporation of water in low temperature via structural expansion, but in the high temperature, heat sink releases the heat of the TEG through water evaporation opened region by shrinkage of the active polymer. The TEG module using our heat sink show two times higher output power than using the metal fin. The optimized TEG module components were integrated for wearable energy harvesting system and we could demonstrate turning on a light emitting diode via body heat.

BM08.06.11
Functionalised Nanoporous Gold as a New Biosensor for Quantitative Detection in Ultra-Low Concentrations Paola Rizzi, Federico Scaglione, Eugenio Alladio, Francesco Turci, Cristina Giovannoli, Silvia Bordiga and Livio Battezzati; Università di Torino, Torino, Italy.

The development of a new generation of ultra-sensitive sensors for analytical and bio-diagnostic devices requires a strong signal in front of a very small quantities of material. Taking advantage of peculiar plasmonic properties of nanoporous gold (NPG), a promising sensor for selective detection of Human Serum Albumin (HSA), as a proof of concept, has been prepared by a proper functionalization of the substrate. NPG has been synthesized by chemical de-alloying an amorphous precursor, Au₃₅Cu₃₅Pd₃₀Si₂₀, starting from melt spun ribbons. A fully de-alloyed ribbon with ligaments of around 60 nm was obtained after 4 h of de-alloying in proper conditions of temperature and concentration of the electrolyte. This material is self-standing and mechanical resistant and then well-versed for applications. At this stage, NPG is SERS active toward probe molecules (i.e. pyridine, bi-pyridine, rhodamine) even in very low concentration, but not specific for other complex molecule of interest such as HSA. Ad hoc functionalization is then required for this purpose. Bare NPG has been bound with a selective ligand i.e. a target-directed antibody (anti-Human Serum Albumin, Ab anti-HSA) covalently grafted onto the gold surface and then tested by Surface Enhanced Raman Spectroscopy (SERS) measurements as a function of HSA concentration. Data analyses in junction with a chemometric approach have successfully demonstrated that the NPG sensor is able to perform HSA quantitative detection in ultra-low concentrations.

BM08.06.13
Non-Invasive Monitoring of Ketosis for Improved Therapy of Epilepsy with Breath Acetone Sensors Julia F. Kornapilla, Andreas T. Günther and Sotiris E. Pratsinis; ETH Zurich, Zurich, Switzerland.

By implementing healthcare sensors into portable or even wearable devices, continuous monitoring of the patient’s physiological state is possible. Chemo-resistive gas sensors based on semiconductor metal-oxides could give such continuous feedback by analyzing exhaled breath. This could enable routine and personalized dietary monitoring needed1 for the treatment of drug-resistant epilepsy affecting 15 million people worldwide2. More specifically breath acetone detection could be a non-invasive and cost-effective way to monitor ketogenic diets (KD; high fat at low carbohydrate and protein intake). Here, a portable breath acetone sensor based on flame-made Si-doped WO₃1 was used for non-invasive ketosis monitoring of 20 volunteers following a 36-hour KD. This sensor could accurately follow the ketosis level over a wide acetone concentration range (0.4 – 30 ppm) relevant for this application. Furthermore, the individual metabolic responses of the volunteers could be easily distinguished by this sensor as validated by parallel capillary blood BOHB. As a result, this portable acetone sensor embodies a reliable device for non-invasive monitoring of enhanced ketosis during KDs enabling routine and personalized dietary monitoring and epilepsy treatment. With the potential for compact size and low power consumption of this sensor fabrication technology, this sensor could be readily incorporated into integrated health monitors.

Wearable health devices enable cost-effective, user-friendly and continuous personalized healthcare at any time and place. For this, biological fluids such as sweat or breath are attractive as they are readily accessible providing a non-invasive insight into human metabolism. For instance, tracing exhaled acetone, a volatile by-product of ketosis, could enable close monitoring of the interplay between fat and glucose metabolism thus enabling individual customization of physical activity and dietary regimes towards optimal performance and fat loss. Chemo-resistive gas sensors are appealing for breath acetone sensing as they feature high miniaturization potential, low power consumption. When based on Si-doped WO3 nanoparticles, acetone can be detected down to 20 ppb with high selectivity to interfering analytes. Such sensors have been applied already successfully on 20 volunteers to measure their individual fat burn rates during and post exercise. As current technologies to monitor the interplay between fat and glucose metabolism are either invasive (e.g. blood assay) or too expensive for widespread application (e.g. indirect calorimetry) such sensors might be ideal for personalized metabolic monitoring.

Here, a portable breath acetone sensor consisting flame-made Si-doped WO3 films is presented that can follow individual changes between fat and glucose metabolism in real-time. We applied this sensor on 11 healthy volunteers in a test course first stimulating ketogenic by exercise (i.e. 3 × 30 min of cycling) and thereafter rapidly inhibiting fat metabolism by an oral glucose tolerance test (i.e. intake of 75 g glucose). The sensor clearly followed breath acetone concentrations during the test course in good agreement to bench-top mass spectrometry. Thereby, the sensor correctly identifying a shift from fat to glucose metabolism for all volunteers even recognizing individual dynamics between the subjects, as validated by parallel capillary blood β-hydroxybutyrate (BOHB) and glucose measurements. In the long run, this sensor is highly promising for integration into wearable devices to guide daily diet and exercise routines towards optimal performance or fat loss.


A Bio-Inspired Mineral Hydrogel as a Mechanically Adaptable Ionic Skin for Highly Sensitive Pressure Sensing

BM08.06.14 Metabolic Monitoring from Breath with Portable Acetone Sensors Stéphanie Schon, Andreas T. Güntner and Sotiris E. Pratsinis; ETH Zurich, Zurich, Switzerland.

BM08.06.15 A Bio-Inspired Mineral Hydrogel as a Mechanically Adaptable Ionic Skin for Highly Sensitive Pressure Sensing

Human skin is soft, robust, self-healable and able to sense subtle environmental differences like a gentle breeze, which has stimulated numerous studies of artificial skin-like materials, especially electronic skins or soft wearable sensors. However, profound challenges remain in terms of imitating natural skins because of their unique combination of mechanical and sensory properties. Currently, there are three major approaches to stretchable electronic skins: (1) buckling flexible electronic devices, (2) patterning discontinuous stiff components, and (3) developing intrinsically stretchable materials. While for the purpose of biomimetic and medical uses, materials that are flexible and/or stretchable are not sufficient. A soft artificial skin needs to be mechanically compliant and durable for practical applications, i.e., plastically deformable to fully match curved and dynamic surfaces and autonomously self-healable to “sense” a wound and quickly repair itself.

Inspired by the concept of “ionic skin” that relies on ionic transduction through hydrogels or ionic gels, a bio-inspired mineral hydrogel is developed to fabricate a novel type of mechanically adaptable intelligent skin. The hydrogel is composed of very small amorphous calcium carbonate (ACC) nanoparticles (about 5 nm) physically crosslinked by polyacrylic acid (PAA) and alginate chains. Due to the dynamic crosslinks, the hydrogel is autonomously self-healable, mechanically deformable to curved and dynamic surfaces, and exhibit relatively high sensitivity. The hydrogel-based ionic skin can sense subtle pressure changes, such as a gentle finger touch, human motion or even small water droplets. This work may not only not show the great potential of physically-crosslinked hydrogels as novel intelligent skins, but also enrich the design of artificial skins for future large-scale Internet of Things applications.

BM08.06.16 Highly Stretchable, Transparent and Biocompatible Gelatin-Supported Deep Eutectic Solvent Gels for Strain and Pressure Sensors

Huan Qin and Matthew J. Panzer; Tufts Univ, Medford, Massachusetts, United States.

There is a growing demand for flexible and soft electronic devices in the past two decades because of their broad applications in personal healthcare, human motion detection, and soft robotics. Hydrogels have been intensively investigated and utilized for multiple sensing applications due to their high ionic conductivity, good biocompatibility and tunable stretchability and toughness. However, the long-term use of hydrogel-based devices is limited by the dehydration of most hydrogels in ambient conditions. Ionogels based on ionic liquids with relatively lower ionic conductivity and nonvolatility have attracted considerable attention in sensing applications, but their high cost and toxicity make them unlikely to replace hydrogels. Deep eutectic solvents (DESs) with similar physical properties (e.g. moderate ionic conductivity and low volatility) are generally low cost and environmentally-friendly, which endows them with a great potential for sensor applications. Herein, we present the first example of DES gels as ionic conductors for multiple capacitive-type sensor prototypes. A DES based on choline chloride and ethylene glycol has been prepared and transparent DES gels have been synthesized in a facile manner using the coil-helix transition process of gelatin. AC impedance spectroscopy and tensile tests are used to characterize the ionic conductivity and stretchability of DES gels containing different amount of gelatin. A DES gel containing 22 wt.% gelatin could be stretched up to 400% without breaking while retaining a decent room temperature ionic conductivity of 2.5 mS/cm. Further stress-strain and strain cycling tests have been performed on the 22 wt.% gelatin gel. There is no obvious hysteresis response up to a strain of ~130% and the elastic modulus decreased slightly (27 kPa to 23 kPa) over 10 cycles at a strain of ~130%, indicating its excellent durability. Therefore, the DES gel with 22 wt.% gelatin was selected to be incorporated into capacitive-type sensor prototypes, where a stretchable tape was inserted as an insulator between two layers of DES gel. A relative capacitance change of 35% was obtained when bending a finger attached to a sensor. Tensile testing has also been carried out for the device and a good linearity between capacitance vs. strain was obtained over ~130% strain with a gauge factor close to 1, which is the theoretical limit of capacitive-type strain sensors. A pressure sensor prototype has also been fabricated and could measure pressures as low as 1 kPa. These promising device results and the low volatility of the DES gel prove that these materials could be an ideal alternative to hydrogels in multiple sensing applications and offer a novel solution to the development of soft electronics.

BM08.06.17
Gold Nanoparticles Decorated on Single Layer Graphene Applied for Electrochemical Ultrasensitive Glucose Biosensor Shifeng Hou; Shandong University, Jinan, China.

A glucose biosensor was fabricated by glucose oxidase (GOD) immobilized on gold nanoparticles decorated on single layer graphene (Au/SLG) modified glassy carbon electrode, with 6-(ferroceny1)hexanethiol (Fc-C6H12-SH) as electron transfer medium (Fc/GOD/Au/SLG/GCE). The free-standing Au/SLG was obtained by sputtered gold nanoparticles on CVD-generated monolayer graphene. The good dispersion and clean surface of gold nanoparticles on graphene promote immobilization of GOD. The synergistic effect of graphene and electron mediator facilitates electron transfer process, which was account for the enhanced electrochemical performance with the detection limit of 0.1 nM (S/N = 3). The CVD-generated monolayer graphene has lower background current and good ductility, with free polymer transfer process bring clean surface, which is suit as platform for ultrasensitive detection of glucose. The biosensor was further studied for real perspiration test with attractive feasibility, which has potential application in large-scale production and perspiration-based wearable glucose detection.

BM08.06.18
Development of Biocompatible Microbatteries Aimed at Ingestible Sensors Using MEMS-Fabrication Processes Sven Stauss1, Shinya Yoshida2,3, Tsutomu Nakamura2 and Itaru Honma2; 1Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai, Japan; 2Graduate School of Engineering, Tohoku University, Sendai, Japan; 3Innovation Center for Creation of a Resilient Society, Tohoku University, Sendai, Japan.

Biocompatible microbatteries hold promise for a wide range of applications, especially for health care devices and environmental sensors. One specific example where biocompatible batteries can be employed is in ingestible devices, which can be used for regular monitoring of vital body functions, drug release, or for controlling medication adherence. Currently, ingestible sensor devices are often powered by large batteries that contain electrode materials that are toxic, requiring special encapsulation to ensure their safe use. This leads to bulky systems that are difficult to swallow and also expensive. Moreover, fabrication processes of the batteries are based on conventional methods and therefore possess only limited potential for miniaturization and eventually mass production, to lower the cost of the devices. We have developed biocompatible microbatteries that use gastric fluid as an electrolyte and which can be realized using existing microfabrication processes.

The microbatteries consisted of essentially two main parts: An Si substrate, that contained microstructures acting as passive, biomimetic capillary pumps, and electrodes of the microbatteries which were deposited on glass wafers containing W- vias for connecting front and backside electrodes. Microfluidic reservoirs containing the capillary pumps were realized in Si by standard photolithography and deep reactive ion etching, to depths ranging between 100-200 μm. The capillary pumps enabled more controlled filling of the microreservoir with electrolyte, reducing the risk of trapping gas bubbles which could prevent operation of the microbatteries.

For the microbatteries, electrodes with nominal footprints of 0.7 x 3.2 mm2 and consisting of about 3 μm thick AgCl cathodes and Zn anodes were fabricated by sputtering using shadow masks. The AgCl cathodes were then formed by electrochemical oxidation of the sputtered Ag films in 0.1 M KCl solutions.

Finally, the Si and glass wafers were bonded together and diced to chips of 5 x 5 mm2. The microbatteries were characterized by galvanostatic testing in simulated gastric fluid at current levels ranging from 1 to 100 μA. The cell output reached values of the order of 0.9 V, close to the theoretical value 0.984 V of the AgCl/Zn redox couple. The operation time of the microbatteries was limited to about 5-8 minutes, but it is expected that by using thick film techniques, that the operation time can be increased.

It is also anticipated that the use of Si-compatible MEMS fabrication will enable further size reduction of the microbatteries and therby facilitate their integration in future sensor devices aimed at medical and environmental applications.

BM08.06.19
Interfacial Adhesion Improvement Between Stretchable PDMS and Ecoflex Layers with Nanoparticles for Electroadhesion Robot Gripper Application Lim Hanhuy2,3 and Baekjin Kim2; 1Yonsei University, Seoul, Korea (the Republic of); 2Green Chemistry and Materials Group, Korea Institute of Industrial Technology, Cheonan, Korea (the Republic of).

The polymer layers could be easily deformed by external force because of its intrinsic elasticity. In the case of multi-layered polymer thin films, however, it could bring a certain problem. If the adhesion between the interfaces isn't sufficient, slip may be occurred. Particularly, the nanoparticles such as TiO2, SiO2, Al2O3, and BaTiO3 dispersed polymers are further modified and affects to the adhesive force. Therefore, it is necessary to predict the relationship among deformation, composites and interfacial adhesion. In this study, the modulus and interfacial strength of whole layers were measured by Universal Test Machine (UTM) in the ASTM-638. Based on this result, the maximized interfacial adhesion value was confirmed less than 10 N with 200 μm thickness. For the test, the pristine polymer and NP embedded polymer were spin coated to form bilayer shape with single layer tail. As a result, the NP contained polymer showed similar mechanical strength with double error range 1 N compared to the pristine polymer’s modulus. Furthermore, we also introduced an adhesive layer such as primer and polyethylene imine (PEI) added PDMS to improve the interfacial adhesion. With NP/PDMS composites, we applied to electroadhesion (EA) robot gripper. NPs have higher dielectric constant than polymer so that it can increase EA force in the same potentials. Furthermore, the critical parts of robot gripper are skin layer and EA layer. Both of skin and EA layers are composed of stretchable polymers so that our achievement could be used for it. As a result, highly adhesive EA gripper was investigated by solving interfacial adhesive problem.

BM08.06.20
High-Performance Energy Devices Based on Amphiphilic Core-Sheath Structured Fibers Xuemei Fu, Hao Sun, Songlin Xie, Limin Xu, Zuoer Li and Huisheng Peng; State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science and Laboratory of Advanced Materials, Fudan University, Shanghai, China.

Owing to the lightweight, flexibility and adaptation to various curved surfaces like our bodies, fibrous energy devices are widely studied to revolutionize electronic fields. Numerous efforts have been made to develop high-performance fibrous electrodes which demonstrate high mechanical strength, electrical conductivity and electrochemical activity. As a candidate, carbon nanotube (CNT) fibers have attracted extensive attention but the poor electrochemical activities need addressed. Plasma treatment has been thus adopted to obtain hydrophilic oxygenated CNT (OCNT) followed by introducing active materials. However, the defects formed during treatment largely decrease the mechanical strength and electrical conductivity. The balance between these two aspects requires to be struck for realizing high-performance fibrous energy devices.

Herein, a novel family of amphiphilic core-sheath structured fiber is developed as high-performance fibrous electrode. The hydrophobic CNT core provides high mechanical strength and electrical conductivity while the hydrophilic OCNT sheath acts as platform depositing electrochemically active materials. When the core-sheath fiber used as counter electrode for fibrous dye-sensitized solar cell, a power conversion efficiency of 10% has been achieved, representing the highest power conversion efficiency among all kinds of fibrous solar cells. Further, upgraded core-sheath fibers are applied to fibrous supercapacitors which show excellent capacitance of 324 F/cm3 retained at 79% as current density up to 50 A/cm2. The structure design can be generalized
to other high-performance energy devices.

Reference
2 Sun, H.; Fu, X.; et al. Adv. Mater. 2016, 28, 6429-6435. († co-first authors)

BM08.06.22
Highly Sensitive Crack Based Strain Sensor Using Microsphere Expansion Young Jana1,2 and Hanchul Cho1; 1Korea Institute of Industrial Technology, Seoul, Korea (the Republic of); 2Mechanical Engineering, Pusan National University, Buan, Korea (the Republic of).

In recent years, the needs for flexible and wearable electronics have rapidly increased. Among them, strain sensors based on polymer such as PDMS, Ecolflex, Dragon Skin play an important role in the human motion monitoring, electronic skin, etc. Most of these strain sensors with high sensitivity have cracks on the conductive layer, which maximizes the sensitivity of the sensors. However, there is a limitation that the process of making such micro/nano cracks is difficult to manufacture in a large area and the productivity is low. In this work, we suggest new crack fabrication method on the conductive layer using thermal expandable microsphere (T EM). The microsphere consists of thermoplastic resin and hydrocarbon like a balloon. TEM expands 5–7 times at operating temperature. The cracks are formed by expanding of microsphere in the PDMS/Microsphere composite. Owing to its unique structure and mechanism, strain sensors can have high sensitivity in the 10 percent strain range, good mechanical property, fast response time and high durability in the cyclic tests. We verified the crack propagation using in-situ scanning electron microscope (SEM) when microsphere was expanded and the sensors were strained. We compared with experimental results and theoretical models. Furthermore, we controlled the expansion rate of microsphere by adjusting the temperature, which affected the size and total length of cracks. Sensitivity of the fabricated sensor could be tuned by controlling the temperature for the various strain range. The sensors showed significant performance to detect very tiny human body motion like a finger, wrist and neck.

BM08.06.23
Development of a GaN Based Liquid Sensor Using FIB Milling Technique Inas Taha1,2, Nitul Rajput1, Tomas Palacios2, Mustapha Jouid1 and Daniel Choi1; 1Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates; 2Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Gallium nitride (GaN) has the advantage over many other semiconductor materials in sensor applications at high temperature environment because of its high thermal stability. Moreover, it has potential capability in sensing polar liquids due to its high internal piezoelectric polarization and chemical stability. Water adsorbs dissociatively on the GaN surface with a sticking coefficient ≥ 0.45 [1]. Dissociation of the water molecules is an exothermic reaction (-44 kcal/mol); therefore, it is thermodynamically favored. Through a reaction chain, oxygen can eventually bound to Ga, and hydrogen desorbs from GaN. Hydrogen desorption is an endothermic process. Moreover, it has potential capability in sensing polar liquids due to its high internal piezoelectric polarization and chemical stability. Water adsorbs dissociatively on the GaN surface with a sticking coefficient ≥ 0.45 [1]. Dissociation of the water molecules is an exothermic reaction (-44 kcal/mol); therefore, it is thermodynamically favored. Through a reaction chain, oxygen can eventually bound to Ga, and hydrogen desorbs.

Interconnection of Flexible NAND Flash Memory via Roll-to-Plate Transfer Method Taekyoung Kim, Do Hyun Kim and Keon Jae Lee; Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

Roll-based fabrication has received large attention for the mass production of unconventional soft electronics. Recently, a number of research groups have shown innovative methods in roll-to-roll (R2R) processing such as graphene fabrication, nanotexturing, nanoimprint lithography, and transfer of oxide thin-film transistors (TFTs). However, fully packaged flexible large-scale integrated circuits (LSI) for the computational application should be accomplished in roll-based technology to utilize fully operational roll-based flexible electronic systems. In this work, our group demonstrated the ultrathin silicon-based flexible NAND flash memory (f-NAND) fabricated by highly-productive roll-based flip-chip packaging technology. The roll-to-roll thermo-compression bonding enables the interconnection of the f-NAND on a flexible printed circuit board (FPCB), realized by non-linear elastic deformation of the anisotropic conductive film (ACF). The ACF packaging materials exhibits high compatibility with the continuous roll-transfer process and excellent flexibility even after the interconnection. To confirm non-linear deformation during the roll-based ACF transfer bonding, finite element analysis (FEA) was carried out. The reliable circuitry operation of the 16×16 f-NAND is observed through addressing and bending tests, enabled by the high flexibility of ACF interconnections. This work suggests a significant breakthrough toward the mass commercialization of roll-based advanced LSI integration technology.

BM08.06.25
All-Soft and Liquid-Phase Supercapacitors Based on CNT-Integrated Liquid Metal Electrodes Min-koo Kim1,2, Byeongyong Lee1, Seung Woo Lee1 and Oliver Brand1,2; 1School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, United States; 2Institute for Electronics and Nanotechnology, Georgia Institute of Technology, Atlanta, Georgia, United States; 3George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, United States.

Soft energy storage systems are a core technology for powering wearable and skin-mountable electronics. Supercapacitors are considered promising energy storage components for these applications because of their ultralow power supply and long cycle life; however, their relatively low energy density compared to Li-ion batteries is the major limitation. Moreover, conventional supercapacitors are manufactured from hard and brittle materials, which fail at less than 2% strain. Thus, interfacial failure between soft skin and rigid electronics is the major limiting factor for wearable and skin-mountable electronics. As a result, a key consideration for realizing all-soft supercapacitors is that each electrode component must be soft and conductive without sacrificing electrochemical performance. The use of liquid-phase conductors, such as eutectic Ga-In alloy (EGaIn), can open a new path for all-soft, deformable, and self-healing electronics because of its low melting temperature (T <15 °C), non-toxicity, favorable electrical conductivity (~3.4×10⁹ S/m), and unlimited mechanical stretchability. In addition, nanocarbon materials, such as carbon nanotubes (CNT), have been actively investigated for improving the energy density even after the interconnection. The ACF packaging materials exhibits high compatibility with the continuous roll-transfer process and excellent flexibility even after the interconnection. To confirm non-linear deformation during the roll-based ACF transfer bonding, finite element analysis (FEA) was carried out. The reliable circuitry operation of the 16×16 f-NAND is observed through addressing and bending tests, enabled by the high flexibility of ACF interconnections. This work suggests a significant breakthrough toward the mass commercialization of roll-based advanced LSI integration technology.
This paper presents all-soft and liquid-phase supercapacitors based on CNT integrated with EGaIn electrodes. Soft and stretchable CNT-integrated liquid metal electrodes are enabled by i) large area EGaIn thin-film patterning on polydimethylsiloxane (PDMS) substrates using an additive stamping process and ii) functionalization of EGaIn with CNT via a layer-by-layer (LbL) adsorption technique. The additive stamping approach provides large area (~cm²) and uniform EGaIn patterning with a lateral resolution of 500 μm at film thicknesses of ~1.5 μm. The EGaIn patterns will serve as the electron transport channel and support for CNT adsorption. The oxygen functional groups on the CNT enhance the energy density of the electrodes as well as interaction with native oxide (Ga2O3) on the surface of EGaIn, resulting in a 3D network on the EGaIn surface with strong adhesion even at 50% applied strain. To demonstrate supercapacitors with a parallel-plate configuration, CNT-integrated EGaIn electrodes were vertically integrated with a soft separator, comprising a porous PDMS structure filled with ionic liquid. The ionic-liquid-filled soft separator enables physical separation between the two electrodes for all-soft and liquid-phase supercapacitors. Our preliminary data show that the areal capacitance increases almost linearly with the number of LbL adsorption steps with a measured areal capacitance ~15 mF/cm² with 30 LbL steps. Moreover, the specific capacitances remain nearly unchanged for >2000 cycles, which indicates excellent electrochemical stability. The demonstrated all-soft and liquid-phase supercapacitors overcome the limitation of rigid supercapacitor configuration and could enable fully-integrated wearable and skin-mountable electronics.

BM08.06.26
Advanced MEMS Vibrating Ring Gyroscope for Miniaturized Space Attitude Control System
Daniel Choi1, 2, Boo Hyun An1, Mariam S. Mansouri1, Wajih Syed1, Zakriya Mohammed1 and Ibrahim Elfaied1; Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates; 2UAE Space Agency, Abu Dhabi, United Arab Emirates.

Extremely miniaturized, very low power, navigation-grade attitude control systems are an enabling technology for a number of civilian and defense systems, including miniature, autonomous sensors, navigation systems for satellites and unmanned air vehicles (UAVs), ground and underwater robotic systems, and defense and law-enforcement systems for widely dispersed surveillance and precision targets. Space systems employing an attitude control system should include the control and processing appropriate electronics to provide the most direct method for sensing inertial angular velocity. While micro-electromechanical systems (MEMS) are playing a growing role on earth in safety critical applications, in the harsh and remote environment of space, reliability is still the crucial issue, and the absence of an accepted qualification methodology is holding back MEMS from wider use.

In this study, we develop an innovative, affordable, miniature, low-power, navigation-grade integrated gyroscope for the attitude control system that applies MEMS technology to achieve the performance, size, power, sensitivity, and cost objectives of space and other commercial applications.

We have designed physical model of MEMS gyroscope investigated using Finite Elements Method (FEM) simulation by improving previous developed vibrating ring gyroscope (VRG) designs. Design parameters and elements are modified to narrow down bandwidth and improve shock resistance. To meet the requirements of MEMS gyroscopes for space application, the proposed model of MEMS VRG is designed with shock resistive dual spring structure and multiple ring structure for increasing shock resistance and Q factor. The MEMS VRG is designed in 5 x 5 mm device with 3 mm diameter of the vibrating structure.

BM08.06.27
MEMS Accelerometer Based on GaN for Harsh Environment
Daniel Choi1, 2, Boo Hyun An1, Mengyang Yuan2, Tomas Palacios2, Inas Taha3, Nitul Rajput1, Hamad Al Yassi1, Mihai Sanduleanu1, Tawaddod Alkindi1, Mariam S. Mansouri1 and Maryam Alnahyan1; Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates; 2Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Inertial sensing technologies in high temperature environments over 500°C are in great demand in aerospace, power plants and material processing applications. However, conventional micro-electromechanical systems (MEMS) sensors still cannot be operated at such high temperature and need to be isolated in controlled environment.

Gallium nitride (GaN) is very promising for high power devices, high temperature electronics and microsystems due to their wide energy bandgap with low intrinsic carrier density at high temperature over 500°C.

Capacitive inertial sensors have lower thermal drift, high resolution and good noise performance compared to piezoresistive sensors.

In this study, we develop MEMS accelerometer as part of the smart sensor system that will be utilized for monitoring the catalysts inside of the high temperature furnace for the oil refining process. We will discuss a design of MEMS accelerometer using GaN as structure layer, grown epitaxially on aluminum nitride/silicon substrate. The resonance frequency of the designed accelerometer is found to be 2.235 kHz and bandwidth is around 1.2 kHz.

Modeling and simulation results of the GaN accelerometer will be discussed and characterization of the fabricated devices would be presented.

nanowires and poly(styrene-butadiene-styrene) elastomer. We synthesized ultralong Ag nanowires encapsulated with a smooth and uniform Au sheath and then mixed them with the polymer. Phase separation of Ag-Au NWs and SBS occurs, which forms microstructures in the composite, reduces Young’s modulus, and increase softness and conductivity of the composite, allowing it to be stretched up to ~260% whilst maintaining a conductivity of 41,850 S/cm. By increasing the content of Ag-Au nanowires, the nanocomposite can achieve conductivity up to ~72,600 S/cm. Using the heat rolling-press, stretchability of the nanocomposite can be further increased up to 840%. We used the Ag-Au nanocomposite to develop a wearable device for recording electrophysiological signals through the skin and delivering electrical and thermal stimulations that respond to sensor signals. We also designed and fabricated a customized multi-channel soft cardiac mesh for the swine heart. The mesh monitors cardiac activation signals from ventricles and stimulates at any sites in the ventricles without being hindered by anatomical obstacles.

8:30 AM BM08.07.02
4D Printing of Magnetically Functionalised Chainmail for Exoskeletal Biomedical Applications Anna Ploszajski; Richard Jackson, Mark Ransley and Mark A. Miodownik; University College London, London, United Kingdom.

At some point in our lives, many of us, either through injury, chronic disease or old age, will have to rely on technologies to mechanically assist and support our bodies. Current solutions tend to rely on robotics which often involve cumbersome electronics and heavy power packs. One new approach is the use of soft robotics using pneumatic actuators, which is proving fruitful but usually requires the provision of compressed air through a tether. Actuating smart materials are a potential lightweight and low-power alternative but until recently, their reliable integration into wearable technology has proved difficult. However, recent advances in the field of 3D printing of smart materials (so-called 4D printing), has led to growth of both the hardware and software available for successful integration of these materials into biomedical devices. Here we report on our progress using 4D printing to create active chainmail fabrics for use as wearable exoskeleton supports.

This paper describes the characterisation and processing parameters of magnetically functionalised chainmail fabric that can be used as a biomedical device with controllable stiffness. The use of 3D printing techniques to fabricate the device allows it to be digitally designed by clinicians to exactly fit a patient’s needs. The magnetic actuation results in an on/off state for each controllable link in the chainmail making stiffness a tailored metaproperty of the device, which can be controlled by the clinician.

The chainmail fabric is made by selective laser sintering (SLS) nylon. These 3D prints have high inherent porosity, and easily take up a fluid containing magnetic nanoparticles through capillary action in post-processing. When dried, the magnetic nanoparticles coat the interior of the porous material, such that it becomes uniformly magnetically functionalised. We show that the location and strength of magnetic actuation can be controlled at the scale of individual links in the chainmail.

SLS printing is well-suited to making the complex geometries required for wearable fabrics. The functional chainmail reported can be regarded as a mechanical metamaterial, since its design at the macroscale directly influences its mechanical properties. The smallest elements of mechanical metamaterials have become known as mexels (mechanical pixels). In this case, our mexels are individual links in the chainmail. Through our 4D fabrication process they can be designed to be in one of two states – locked or unlocked – and a magnet can be used to flip between them. We show that when all mexels are in the locked state this corresponds to an overall rigid fabric, whereas mexels in the unlocked states renders the material flexible. By design, there are a large number of states in-between fully rigid and fully flexible which is what gives this approach so much potential for wearable exoskeleton support garments.

8:45 AM BM08.07.03
Central Blood Pressure Waveform Monitoring by Conformal Ultrasonic Devices Chonghe Wang, Xiaoshi Li, Hongjie Hu, Lin Zhang, Zhenlong Huang, Muyang Lin, Zhouzi Zhang and Sheng Xu; University of California, San Diego, La Jolla, California, United States.

Monitoring of central blood pressure (CBP) waveform from deeply embedded vessels, such as the carotid artery and jugular vein, has significant clinical values due to their proximity to the heart. The CBP waveform has a direct relationship with the cardiovascular status such as the atrial, ventricular, and valvar activities on both left and right sides. The most accurate method for measuring CBP, namely cannulation, is too invasive to allow frequent measurements, even though it is crucial for many conditions related to all-cause cardiovascular mortality prediction. Existing non-invasive solutions, including photoplethysmography (PPG) and tonometry, have significant challenges to provide accurate and reliable measurements on blood vessels that are deep underneath the skin. Here, we demonstrate a skin-integrated conformal ultrasonic device that overcomes all these limitations by combined strategies of material design and advanced microfabrication. This conformal probe has an ultrathin profile (240 μm in thickness), a high reversible stretchability (60%), and a comparable axial resolution (400 μm) with commercial transducers. This study demonstrates the first conformal electronics capable of launching ultrasonic waves that penetrate into deep biological tissues (~4 cm) in a gel-free manner, and acquiring accurate CBP waveforms at deeply embedded arterial and venous sites to monitor cardiovascular events. Also, this is the first conformal device that enables observing the prominent pressure amplification caused by progressive increase in vessel stiffness along the arterial tree, by comparing the captured peripheral blood pressure (PPB) with the CBP waveforms. Additionally, this device allows correlating the blood pressure (BP) waveforms at different locations of the body with a simultaneous electrocardiogram (ECG) to evaluate arterial stiffness along conduit arteries. Collectively, this opens up extensive opportunities for continuous and accurate deep tissue diagnosis and prognosis using non-invasive wearable electronics.

9:00 AM BM08.07.04

This talk describes materials and device designs for soft, skin-compatible, battery-free platforms that offer unique capabilities in quantitative capture, storage and in situ chemical analysis of microliter volumes of sweat. These systems have options in integration of enzymatic biofuel cells, microfluidic networks, colorimetric chemical reagents and near-field communication (NFC) electronics for readout. A demonstrator includes a reusable NFC electronic module with reversible magnetic connection to a single-use soft, flexible microfluidic component for simultaneous tracking of sweat rate, total sweat loss and pH and of concentrations of lactate, glucose and chloride using biofuel cell and colorimetric approaches. Detailed benchtop studies and field tests on human subjects establish quantitative correlation of data collected using these devices with those obtained by nuclear magnetic resonance spectroscopy, chloridometry and pH measurements.

9:30 AM BM08.07.05
Highly Sensitive and Robust Soft Pressure Sensor Using 3D-structured Microchannel and Liquid Metal for Wearable Applications Kyuyoung Kim1, Yongrok Jeong1, Jacho Park1, Minseong Kim1, Yong Suk Oh1 and Inkyu Park1; 1Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of); 2Northwestern University, Chicago, Illinois, United States.
In this study, we have developed a highly sensitive and robust soft pressure sensor for wearable applications using 3D-structured microchannel and liquid metal. Liquid metal is used as a stretchable conductor because of its high conductivity and high adaptability to the mechanical deformation. First, the 3D-structured microchannel was fabricated using 3D-printed dissolvable molds. Using fused deposition modeling (FDM) 3D printing, 3D-printed molds with micro-bumps were fabricated and removed after casting into an elastomer. Then, the liquid metal was inserted into the prepared microchannel using vacuum filling method. It is a competitive fabrication method for its simplicity and cost-effectiveness for not using conventional photolithography.

When the pressure is applied, the cross-sectional area of the microchannel decreases, which increases the resistance of the sensor. The high sensitivity of the pressure sensor is achieved by two strategies. First, conventional microchannels fabricated with photolithography were not able to have different thickness of the channel in Z-direction. Using 3D printing technology, we fabricated the 3D-structured microchannel. It is more advantageous for them to close the channel against the small pressure compared with those with uniform thickness. Second, liquid metal reservoirs fabricated at the ends of the sensor acted as a buffer zone for liquid metal flow. Since there was enough room for liquid metal flow, the sectional area of the microchannel could change in respect to the given pressure.

In our study, the pressure sensors with different styles were tested with corresponding finite element method (FEM) simulation results. The geometry and the stiffness of the bumps were controlled. On the other hand, it is desirable for the pressure sensor to be robust and reliable. The proposed pressure sensor has a high sensitivity and robustness having a long life cycle and a simple and cost-effective fabrication process. It is expected to be applied to various applications such as wearable devices, electronic skins, and soft robotics.

9:45 AM BREAK

SESSION BM08.08: Flexible and Wearable Thermal Energy Harvesting/Storage Materials/Devices
Session Chairs: Woohul Kim and Choongho Yu
Wednesday Morning, November 28, 2018
Sheraton, 2nd Floor, Grand Ballroom

10:15 AM **BM08.08.01**
Large Low Temperature ThermoElectric Power Factor from Completely Organic NanoCoatings on Textiles Jaime C. Grunlan1, Chungyeon Cho1,2 and Choongho Yu1; 1Texas A&M University, College Station, Texas, United States; 2Wonkwang University, Jeonbuk, Korea (the Republic of).

In an effort to create a paintable/printable thermoelectric material, comprised exclusively of organic components, polyaniline (PANI), graphene, and double-walled carbon nanotubes (DWNT) were alternately deposited from aqueous solutions using the layer-by-layer assembly technique. Graphene and DWNT are stabilized with an intrinsically conductive polymer, poly[3,4-ethylenedioxythiophene]:poly(styrenesulfonate) (PEDOT:PSS). A 1 µm thick film, composed of 80 PANI/graphene-PEDOT:PSS/PANI/DWNT-PEDOT:PSS quads (QL) exhibits electrical conductivity (σ) of 1.88 X 104 S/m and a Seebeck coefficient (S) of 120 µV/K, producing a thermoelectric power factor (σS) of 2710 µW/(mK)2. This is the highest value ever reported for a completely organic material measured at room temperature. Furthermore, this performance matches or exceeds that of commercial bismuth telluride. These outstanding properties are attributed to the highly ordered structure in the multilayer assembly. The thermoelectric power output increased with the number of cycles deposited, yielding 8.5 mW at 80 QL for ΔT = 5.6 K. A simple thermoelectric generator was prepared with selectively-patterned, fabric-based system. The electric voltage generated by each TE device increased in a linear relationship with both ΔT and the number of TE legs, producing ~ 5 mV with just five legs and a ΔT of 9.5 K. This unique TE coating system is water-based and uses only organic components. For the first time, there is a real opportunity to harness waste heat from unconventional sources, such as body heat to power devices in an environmentally-benign way.

10:45 AM **BM08.08.02**
Large Volume Change in a Conjugated Polymer with Polar Side Chains During Electrochemical Doping Eleni Stavrinidou1, Johannes Gladisch1,2, Alexander Giovanitti3,4, Daniel Simon1, Iain McCulloch4,5 and Magnus Berggren1; 1Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, Norrköping, Sweden; 2Printed and Organic Electronics, RISE ICT/Acreo, Research Institutes of Sweden, Norrköping, Sweden; 3Department of Physics, Imperial College London, London, United Kingdom; 4Department of Chemistry, Imperial College London, London, United Kingdom; 5Physical Sciences and Engineering Division, KAUST Solar Center (KSC), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia.

Conjugated polymers can be doped or de-doped electrochemically by exchange of ions with an electrolyte under the influence of an electric field. Their ability to conduct both electronic and ionic carriers in a tightly coupled fashion makes them attractive materials for bioelectronic and energy applications. During electrochemical doping dimensional changes occur in the polymer film due to ion and solvent movement but also changes in the polymer chain conformation. Volume change has been reported for various conjugated polymers with polypyrrole being the most widely explored in particular for soft actuators and artificial muscles. Here we report a record volume change of a recently synthesized conjugated polymer. The homo-alkoxybithiophene polymer p(tG2) consists of an electron rich alkoxybithiophene backbone and methyl end-capped triethylene glycol side chains (TEG) https://arxiv.org/ftp/arxiv/papers/1711/1711.10457.pdf). The polymer shows good solubility in organic solvents such as chloroform or DMF and thus can be processed from solution. In addition it has low oxidation potential 0.3V vs Ag/AgCl and great stability during electrochemical switching with less than 20% degradation over 1000 cycles. In order to characterize the volume change we coated carbon monofilaments coaxially and electrochemically switch the polymer in an aqueous electrolyte. The polymer upon oxidation expands in the direction perpendicular to the fiber while the areal strain. Also, the initial signal level has to be maintained after the deformation. To demonstrate the robustness of the proposed sensor, we performed various complex deformation modes including stretching, folding, twisting, stretching + folding, stretching + twisting, and so on and observed the change of the signal. As wearable applications, we implemented five pressure sensors into the textile and monitored the pressure distribution during sitting and lying. For the real-life wearable applications, it is important for the sensor to be robust and reliable. The proposed pressure sensor has a high sensitivity and robustness having a long life cycle and a simple and cost-effective fabrication process. It is expected to be applied to various applications such as wearable devices, electronic skins, and soft robotics.

11:00 AM **BM08.08.03**
Thermoelectrics for Harvesting Body Heat in Wearable Devices—Optimizing the System-Level Problem Kedar Hippalgaonkar1,2; 1Institute of Materials Research and Engineering, Singapore, Singapore; 2Materials Science and Engineering, Nanyang Technological University, Singapore, Singapore.

Thermoelectrics (TE) materials are able to transform heat into electrical power. Design and manufacturing of new materials for energy harvesting of low grade waste heat have different design principles than traditional high temperature, high power applications. For example, low power wearable and
Thermoelectric materials for energy generation have several advantages over conventional power cycles including lack of moving parts, silent operation, miniaturizability, and CO₂-free conversion of heat to electricity. Molecular materials and hybrid organic-inorganics bring the promise of inexpensive, solution processable, mechanically durable devices potentially suitable for wearable applications. While highly conductive polymers are now commonplace, they generally demonstrate lower thermopower at a given conductivity than inorganic counterparts. Ion conducting materials have previously been demonstrated to have very large Seebeck coefficients, and a major advantage of polymers over inorganics is the high room temperature ionic conductivity. Notably, PEDOT:PSS demonstrates a significant but short-term increase in Seebeck coefficient which is attributed to a large ionic Seebeck contribution. We have recently shown that doping with protonic ionic liquids and other proton conductors can be used to control the thermoelectric behavior of polymers. In this talk, I will discuss how chemical and electrical transistor geometries can be used to control the thermal to electric conversion efficiency of these ion conducting materials.

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Thermoelectric generators (TEGs) are promising for harvesting waste heat from the environment to power wireless sensor nodes in smart buildings. In this talk, I will share our recent research effort on developing non-flexible micro-TEGs by integrating pulsed electroplating with microfabrication processes. We systematically studied the effects of the pulse electroplating conditions on the composition, microstructure, and thermoelectric properties of the electroplated Bi2Te3 thin films. Our results show that the thermoelectric figure of merit of the electroplated Bi2Te3 films can be enhanced by increasing the pulse off-to-on ratio, which is mainly due to the reduced thermal conductivity and the increased Seebeck coefficient. A maximum ZT of 0.16 is obtained at the pulse off-to-on ratio of 50 at room temperature. Based on the fundamental materials research, we further developed cross-plane micro-TEGs on a SiO2/Si substrate. The device consists of a total of 127 pairs of n-type Bi2Te3 and p-type Sb2Te3 thermoelectric pillars embedded in a SU-8 matrix. Both thermoelectric pillars and interconnectors are formed by electroplating, which is advantageous because of low parasitic electrical resistances. The micro-TEG we developed demonstrates a maximum power of 3 mW at a temperature difference of 52.5°C, corresponding to a power density as high as 9.2 mW cm⁻². The power density of our TEG is more than two times the highest value reported for the electroplated TEGs in the literature, which can be attributed to the low internal resistance and high packing density of thermoelectric pillars.

With expediting trends in electronic device miniaturization, thermoelectric energy harvesting becomes increasingly valuable, especially in wearable technologies and sensors for the internet-of-things. However, it has been impossible to match the device thermal impedance with the natural heat gradient using the thin-film thermoelectric materials much needed for device miniaturization. This limitation has prevented thermoelectrics from competing as a harvesting technology at small scale. Here, we propose and demonstrate an architectural solution to this dilemma, whereby thin-film thermoelectric materials are mechanically assembled into three-dimensional (3D) coil architectures. This approach not only allows thermal impedance matching but also multiplies the heat flow through the harvester, thus increasing the efficiency for energy conversion. We design and fabricate thermoelectric coils with silicon as the active material that achieve flexibility, scalability, and durability. An array of such coils produces a power of 2 nW, with calculated projections showing the orders-of-magnitude improvement up to a few μW by replacing silicon with state-of-the-art thermoelectric materials. Demonstrations of the idea open up long-awaited paths to utilize thermoelectric thin films and provides strategies to interface hard thermoelectric materials with soft harvesting environments, such as those of the human body.

In our living environment, in addition to the direct heat source, light source (such as the infrared light) can also provide thermal energy through the photothermal effect. Based on the photothermal effect and Seebeck effect, photo-thermoelectric generator has been rapidly developed for converting photon energy into electricity without a spatial temperature gradient in the environment. To generate a necessary ΔT, the conventional approach is utilizing various bulky components such as a vacuum enclosure, condenser lens, and heat sink. Nevertheless, these extra modules will not only increase the weight and size of thermoelectric generators but also are unfavorable for the flexibility of the whole devices which is of great importance for wearable electronics. Therefore, developing novel photothermal materials and device structure is essential for the photo-thermoelectric nanogenerator (PTENG). In this work, we report on a flexible photo-thermoelectric nanogenerator (PTENG) by hybridizing MoS2/PU photothermal layer with tellurium (Te) nanowire based thermoelectric device. The MoS2/PU film, which is flexible and transferable, exhibits excellent photothermal characteristics due to its exceptional surface-area-to-mass ratio of MoS2 nanoclusters. Te nanowire is chosen for the thermoelectric nanogenerator because of its excellent thermoelectric properties, such as low thermal conductivity and a wide temperature range. By integrating the photothermal layer with thermoelectric device, the PTENG can absorb infrared light to form a temperature difference across the device. With this, a potential difference between two electrodes can be established and used for electrical energy generation. Therefore, the PTENG can generate electricity without a spatial temperature gradient. Furthermore, the PTENG is flexible and shape-adaptive can demonstrate great practical application of photo-thermoelectric energy harvesting for wearable electronics and implantable electronics.

Considerable thermal energy is available for energy harvesting from diverse sources in our environment like industrial machines, heat engines and human bodies. This heat, otherwise wasted, can be converted to electrical energy by a thermoelectric energy generator, but in order to make use of it, the heat needs to be efficiently converted to electricity charging, powering smart wearable devices or even enabling the Internet of Things. State of the art thermoelectric generators (TEGs) make use of the Bi2Te3 (bismuth telluride) thermoelectric alloys, which are inorganic, brittle, non-flexible, and require expensive processing. The TEGs are typically based on a longitudinal pi structure, which is complex, both in terms of electrical connections and manufacturing. Moreover, such TEGs often feature a bulky heat sink to maintain high temperature differences between the hot and cold sides. These reasons limit their large scale use in ambient energy harvesting. In this work we report a low cost, flexible TEG based on transverse thermoelectric effects. A transverse TEG consists of tilted multi-layers made of...
alternating metal and semiconductor materials. In such a device, a thermoelectric voltage can be generated in the direction perpendicular to the vertical temperature gradients, which makes the transverse structure suitable for planar devices. For our transverse TEG we use aluminum or nickel as the metal layers and carbon-nanotube (CNT)-polydimethylsiloxane (PDMS) composites as the semiconductor layers. Both materials are inexpensive with the TE composites being solution processable. For device fabrication the polymer composite solution is cast in between 3D-printed metal layers followed by air drying to obtain the transverse device. By filling the metal layer gaps partially with the polymer composite solution the upper portions of the metal layers are directly exposed to air at the cold side, thus acting as a fin type heat exchanger for lowering the cold side temperature by air convection. The use of flexible composites as the semiconductor material imparts flexibility to the TEG in one direction. It can therefore make good thermal contact with curved surfaces like hot water pipes, solar reflectors and even human skin, thus enabling TE energy harvesting from such surfaces. Transverse TEG architecture provides a number of degrees of freedom like the layer thickness, tilt angle, fin length, which can be varied to study the power generated. We present detailed thermoelectric properties of the CNT-PDMS polymer composites as well as its performance under bending tests. We also present a full range of experimental results of the fabricated transverse TEGs augmented with finite element simulations to optimize the device design for maximum power output.

4:45 PM BM08.09.08/TP03.09.08
Development of N-Type Single-Walled Carbon Nanotube Sheet with Excellent Air Stability
Tsuynohiko Fujigaya1,2; Kyushu University, Fukuoka, Japan; 1JST, Saitama, Japan.

Thermoelectric (TE) conversion is one of the most promising methods for the generation of cost-effective electricity. TE devices have applications in many fields especially microelectronics devices due to their simple device structures. TE generation using Seebeck effect requires both n-type and p-type TE materials for the efficient conversion; however, deterioration of n-type nature due to air oxidation has been the critical issue. Recently, we reported single-walled carbon nanotubes (SWCNT) sheet doped by 2-(2-methoxyphenyl)-1,3-dimethyl-2,3-dihydro-1H-benzimidazole (o-MeO-DMBI) showed n-type property and remarkable air-stability.[1] We chose o-MeO-DMBI because of the following reasons: i) o-MeO-DMBI is stable under atmospheric conditions, ii) the cationic form of o-MeO-DMBI is also stable and, iii) n-doping of the other carbon materials such as fullerene and graphene has already been reported.[2,3] Here, we study the mechanism of the air stability of o-MeO-DMBI-doped SWCNT films by changing the doping level. eDIPS (Meijo Nano Carbon, EC1.5) was used as SWCNT. SWCNT films were dipped in the 0.01, 0.1, 1.0, 10 and 50 mM ethanol solutions of o-MeO-DMBI for 10 min and dried in vacuum at room temperature for 12 h. The time course of Seebeck coefficient of the SWCNT films doped with various concentration of o-MeO-DMBI solution was studied. It is noted that the films were kept under air condition at room temperature to evaluate the air stability of the o-MeO-DMBI-doped SWCNT films. Positive value of Seebeck coefficient for 0.01 and 0.1 mM doped films indicated p-type, and negative value for 1.0, 10 and 50 mM doped films showed n-type nature of the films. Interestingly, we found that Seebeck coefficient of 1.0 mM doped film changed to positive, while 10 mM doped film showed stable negative value. From above results, we conclude that the mechanism of the air-stabilization of n-doping is the passivation effect by the formation of o-MeO-DMBI layer onto the surface of SWCNT films.


SESSION BM08.10: Poster Session III: Materials-to-Devices for Integrated Wearable Systems—Energy Harvesting and Storage, Sensors/Actuators and Integration
Session Chairs: Renkun Chen and Woocul Kim
Wednesday Afternoon, November 28, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

BM08.10.01
A Fully Inkjet Printed Disposable Metabolite Sensor on Paper
Eloise Bihar1, Shofarul Wustoni1, Anna-Maria Pappa2, Khaled Salama1, Derya Baran1 and Sahika Inal1; 1King Abdullah University of Science and Technology, Thuwal, Saudi Arabia; 2University of Cambridge, Cambridge, United Kingdom.

Inexpensive and easy-to-use diagnostic tools for fast health screening are imperative, especially in the developing world, where portability and affordability are a necessity. Continuous monitoring of metabolite levels can provide crucial information regarding key metabolic activities of the body and thus detect associated irregularities such as in the case of diabetes, a worldwide chronic disease.

In this work, we develop an electrochemical sensor where all the components are inkjet printed on a paper substrate. We employ the conducting polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate as the electroactive component and enzymes as the biorecognition unit. The sensor can measure metabolite concentrations in alternative bodily fluids such as sweat and saliva, exhibiting high performance characteristics one month after fabrication and storage at room temperature. This all-polymer “smart multisensor” fully printed on paper advances on the next generation low cost, disposable, noninvasive, multianalyte sensing wearable biomedical devices.

BM08.10.02
Porous Polymer Microneedles for the Sensing of Subcutaneous Interstitial Fluid
Hiroyuki Kai, Kumata Hiroki and Matsuhiko Nishizawa; Tohoku University, Sendai, Japan.

The microneedle array, a two-dimensional array of needles of a few hundred micrometers, penetrates skin in a minimally invasive manner, and they have been applied to transdermal drug delivery and sampling and analysis of subcutaneous interstitial fluid. Microneedles with different materials have been developed such as hollow silicon microneedles, hydrogel microneedles, and dissolvable microneedles. We have previously developed a porous polymer microneedle array using a polymer monolith of polyglycidyl methacrylate). It combines continuous internal micropores to absorb water quickly and sufficient mechanical strength and tip sharpness to penetrate skin.

In this work, we fabricated proof-of-concept microneedle sensors using the porous polymer microneedles. We adopted two different strategies to integrate sensors into the micropores of the microneedles. (1) Electroless gold plating was applied to the surface of the micropores to obtain a porous microneedle electrode, and redox enzymes were immobilized on the electrode surface to conduct amperometric sensing. (2) Hydrogel that contains a boronic acid-based...
fluorescent glucose sensor was filled into the micropores to optically quantify glucose concentration of an analyte. These designs enable the sensors to quickly interact with analytes absorbed into the micropores. In addition, they do not require an extra step of measurement following the removal from skin, which potentially makes the continuous readout from the outside of the skin feasible.

BM08.10.03
High-Performance Triboelectric Nanogenerators Using Visco-Poroelastic Ion Pump Joo Sung Kim1, Heejae Hwang2, Han Wool Park3, Eunsong Jee1, Dukhyun Choi1 and Do Hwan Kim1; 1Hanyang Univ., Seoul, Korea (the Republic of); 2Kyung Hee University, Yongin, Korea (the Republic of).

Recently, many attempts have been made to implement stretchable triboelectric nanogenerators (TENGs) that can be energy harvesting systems and self-powered electronic devices. There are several kinds of soft materials to enhance the power efficiency and power density of TENGs. Especially, ionic materials such as ionic hydrogels, which are capable of achieving electrical double layer (EDL) phenomena and polarization of ions, are regarded as a new platform to achieve high-performance and stretchable TENGs. A similar concept has been reported by using ionic materials as conductor and electrification layer. However, since free ions contained in the ion materials are able to carry electric charges, unlike conventional tribomaterials having dielectric characteristics, it is required to consider electrical characteristics and electrochemical properties of ionic materials.

In this talk, we describe a highly deformable and visco-poroelastic ion pump as a potential triboelectric channel with high power density and its impact on self-powered mechanotransducers. Upon applying mechanical stimuli such as pressure and strain to the ionic TENG devices, effective pumping of the ions that are confined into ionic channel could support the electrode charging derived from contact electrification. This could lead to produce an unprecedented high output power compared to non-ionic and even other ionic systems. A systematical study related to the electrochemical properties of ion pump provides an in-depth understanding of its working mechanism. In addition, based on visco-poroelastic ion pumps suggested by us, flexible and self-powered mechanotransducer arrays could be demonstrated for being applicable to interactive touch devices as a promising candidate among electronic skin (e-skin) platforms.

BM08.10.04
Novel Electrode Architectures for Achieving Thickness-Independent Capacitance in 2D Transition Metal Carbides (MXenes) Tyler Mathis1, Yu Xia2, Mengqiang Zhao1, Babak Anasori1, Alei Dam1, Zehang Zhou2, Hyesung Cho2, Shu Yang2 and Yury Gogotsi1; 1Drexel Nanomaterials Institute, Philadelphia, Pennsylvania, United States; 2Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, United States.

The family of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides known as MXenes have received considerable attention for energy storage applications due to their favorable and tunable electronic and physical properties. MXenes have high specific capacitances1 due to their redox-active transition metal surfaces and when MXenes are fabricated into binder-free, free-standing films they have high electronic conductivity (>8000 S/cm). In addition to the intrinsic electrochemical properties of MXenes, their hydrophilicity allows formulation of functional inks that can readily be printed, spray-coated, or spin cast in any desired pattern, enabling the creation of MXene thin-film coatings that are ideal for applications that require microscale energy storage devices.

However, the traditional methods used to create electrodes from 2D materials for energy storage applications, namely vacuum assisted filtration, result in densely restacked films. This electrode architecture impedes electrode infiltration and transport in thick films (>10 μm), which has put a limit on the practical implementation of not only MXene electrodes, but other 2D materials like graphene and transitional-metal dichalcogenides. For this reason, developing new methods for fabricating thick films using 2D materials is desirable, and in a recent study we have developed a technique for vertically aligning the 2D flakes of MXenes to create rapid, directional ion transport.2 By mechanically shearing a discotic lamellar liquid crystal phase of titanium carbide MXene (Ti3C2) we can produce electrode films that are hundreds of microns in thickness that show thickness-independent specific capacitance. Our approach for aligning 2D materials is not limited to MXenes and energy storage applications, this method can be modified to suit any 2D material and can be extended to any application where directional transport is desirable, e.g. catalysis and filtration systems.


BM08.10.05
A Finite Element Design of a Kirigami-Based Wearable Device for Human Joints Antonio Avila; Mechanical Engineering, Univ Federal-Minas Gerais, Belo Horizonte, Brazil.

Human skin of elbows, ankles and knees undergo considerable deformations during the body motion. Therefore, wearable devices (WD) for such regions shall be capable of sustaining these deformations while remaining into the elastic regime. Silicone rubber, e.g. polydimethylsiloxane (PDMS), is a natural candidate to be used as subtract for such wearable devices. Unfortunately, most of PDMS have a limitation regarding the total elastic strain, which is in the 200-300% range. Moreover, due to these body part’s morphologies, these wearable devices not only have to undergo extreme large strains but they are also inhomogeneous. To be able to design a stretchable wearable devices for human joints, the ancient Japanese art of paper cutting, often known as Kirigami is applied to PDMS thin films doped with carbon nanotubes. The multi-walled carbon nanotubes were placed into the PDMS surface’s to create a conductive network. The Kirigami configuration is analyzed by a finite element method, where the hyper-elastic second order Ogden model is employed. The wearable device design two main constraints must be fulfilled, i.e. the large stretchability and the MWNT network continuity. Based on these conditions a finite element analysis was performed, where boundary conditions, such as number of cuts, its length and spatial distributions were varied. The main objective was to obtain a near optimum design. The numerical simulations indicate that elastic strains up to 900% can be achieved with effective elastic strain around 75% of the ultimate stress. From the Fracture Mechanics perspective, the Kirigami configuration introduces an increase on local stress field near the cut/crack tip. The MWNT surface distribution not only induces a local inhomogeneity but it also changes the stress intensity factors around the cut/crack tips. Experimental data and the ones obtained from the numerical simulations are in good agreement.

BM08.10.06
Flexible Ferroelectric Electronic Skins with Ultrahigh Pressure Sensitivity and Linear Response over Exceptionally Broad Pressure Range Youngcheol Lee; Jongwha Park, Soowon Cho, Young-Eun Shin, Chunggi Baik and Hyunhyub Ko; Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Flexible ferroelectric electronic skins were fabricated by printing, spray-coating, or spin-casting dense restacked MXene films of Ti3C2. This electrode architecture impedes electrolyte infiltration and transport in thick films (>10 μm), which has put a limit on the practical implementation of MXene electrodes, but other 2D materials like graphene and transitional-metal dichalcogenides. For this reason, developing new methods for fabricating thick films using 2D materials is desirable, and in a recent study we have developed a technique for vertically aligning the 2D flakes of MXenes to create rapid, directional ion transport.1 By mechanically shearing a discotic lamellar liquid crystal phase of titanium carbide MXene (Ti3C2) we can produce electrode films that are hundreds of microns in thickness that show thickness-independent specific capacitance. Our approach for aligning 2D materials is not limited to MXenes and energy storage applications, this method can be modified to suit any 2D material and can be extended to any application where directional transport is desirable, e.g. catalysis and filtration systems.

Flexible pressure sensors with a high sensitivity and linear response over a broad pressure range can simplify the wearable sensing systems without additional signal processing for the linear output, enabling device miniaturization and low power consumption. Here, we demonstrate a flexible ferroelectric sensor with ultrahigh pressure sensitivity and linear response over an exceptionally broad pressure range based on the material and structural design of ferroelectric composites with a multilayer interlocked microdome geometry. Due to the stress concentration between interlocked microdome arrays and increased contact area in multilayer design, the flexible ferroelectric sensors could perceive static/dynamic pressure with high sensitivity (47.7 kPa⁻¹, 1.3 Pa minimum detection). In addition, efficient stress distribution between stacked multilayers enables linear sensing over exceptionally broad pressure range (0.0013 – 353 kPa) with fast response time (20 ms) and high reliability over 5,000 repetitive cycles even at extremely high pressure of 272 kPa. Our sensor can be used to monitor diverse stimuli from low to high pressure range including weak gas flow, acoustic sound, wrist pulse pressure, respiration, and foot pressure with a single device.

BM08.10.07

Triboelectric Energy Generator for Powering Implanteble Electronics Hong Joon Yoon and Sang-Woo Kim; Sungkyunkwan Univ, Suwon, Korea (the Republic of).

A great challenge in research for powering or being self-powered implantable electronics, scavenging very limited biomechanical energy such as pulse by heart, respiration, circulation, is to generate extremely low electrical energy. Without technological breakthrough, energy harvester would not supply sufficient power to operate not only in vivo medical gadget, but charging rechargeable battery. Here, we demonstrate the use of external mechanical energy as non-invasive kinetic energy to transmit through human skin and trigger oscillation. We first show external mechanical energy driven very tiny oscillation inside the body is enough to induce micrometer scaled displacement of a biocompatible membrane and to generate electrical energy by contact electrification. Generated voltage and current values are 10 V and 300 μA which is almost 100 times higher than previously reported triboelectric generators. In addition, we use this approach to charge commercial Li-ion battery, resulting in charging rate of about 50 μC/s. Our results establish external kinetic triggers as powerful energy harvesting method in biomedical electronics research.

BM08.10.08

Calculation of Polarization and Bound Charge Density Inside a Dielectric Material in Triboelectric Nanogenerators—Analytical and Numerical Study SeongMin Kim1, Yohan Jeong2 and Sang-Woo Kim1; 1Sungkyunkwan University, Suwon, Korea (the Republic of).

We analytically calculated polarization and bound charge density inside the dielectric material in metal-to-dielectric–mode triboelectric nanogenerators (TENG) where the transferred charges are collected on the bottom metal via electrostatic induction from the triboelectric charges that are generated by frictional contact. This bound charge density is associated with the surface density of states (DOS), Ns(E). Two cases are considered here: i) for Ns(E) >> 1, it is calculated that the bound charge density is proportional to the dielectric constant and the work function difference between the two materials, but inversely proportional to the thickness of the dielectric material, the bound charge density is mostly proportional to the work function difference between the materials, and inversely proportional to the thickness of the dielectric material.

BM08.10.09

Highly Sensitive Transparent and Flexible Pressure Sensors Based on ZnO Nanocrystals by All Solution-Process Ho Kun Woo, Bang JunSung, Junhyuk Ahn and Soongju Oh; Materials Science and Engineering, Korea University, Seoul, Korea (the Republic of).

Applications of pressure sensors have increased in popularity as they are used to measure human motion and monitor the industry. However, complicated and expensive processes and/or low sensitivity remained challenging issues. Herein, a simple and inexpensive process using Silver Nanowire (NW) and ZnO Nanocrystals (NCs) without lithography is developed to fabricate a transparent pressure sensor. ZnO NCs guarantee the transparency of the device and improve the sensitivity of the device while it is rugged on the surface. Device performance analysis with structural, chemical, and electronic characterization and conductive atomic force microscopy study reveal that hybrid nanostructure-based pressure sensor shows a sensitivity of higher than 90 kPa⁻¹, reliability and stability. Finally, we demonstrate that all solution sensors can be easily applicable to many fields such as wearable or attachable sensors by sensing a wide range of pressures.

BM08.10.10

Flexible, Fiber-Shaped Supercapacitors with Roll-Type Assembly Seongil Yu and Heejoon Ahn; Hanyang University, Seoul, Korea (the Republic of).

A fiber-shaped supercapacitor with a unique roll-type configuration is developed by simply rolling polyaniline-coated carbon fiber bundle electrodes and using an H2SO4/polyvinyl alcohol gel electrolyte. The electrochemical performances of this device are characterized and compared with those of a twist-type fiber-shaped supercapacitor. The roll-type polyaniline-coated carbon fibers fiber-shaped supercapacitor exhibits four times higher capacitance retention than the twist-type fiber-shaped supercapacitor at a high scan rate of 100 mV s⁻¹ and shows a gravimetric energy density of 2.97 Wh kg⁻¹ at a power density of 4 kW kg⁻¹, which is almost three orders of magnitude higher than that of the twist-type fiber-shaped supercapacitor (0.004 Wh kg⁻¹). The enhanced performance of the roll-type fiber-shaped supercapacitor is attributable to its unique roll-type configuration, which creates a short and consistent distance between the electrodes. The capacitance and voltage are tripled by simply connecting three roll-type fiber-shaped supercapacitors in parallel or series, respectively. In addition, the roll-type fiber-shaped supercapacitor shows excellent mechanical stability. The excellent performance of the roll-type fiber-shaped supercapacitor suggests its potential as a flexible energy storage device in portable and wearable electronics.

BM08.10.11

Textile-Permeable Conductive Inks for Electrophysiological Sensors on Garments Hanbit Jin, Tomoyuki Yokota and Takao Someya; Electrical and Electronic Engineering and Information Systems, Univ of Tokyo, Tokyo, Japan.

It is important to make soft and stretchable circuits for wearable biometric sensors, since human body has a curvilinear surface which dynamically moves and deforms. Textile is one of the ultimate wearable platform because of their mechanical flexibility, thermal properties and breathability originated from their porous structure. A seamless integration of electronics into the textile has been researched and it became a field of technology, so-called E-textile. Recently, researchers have achieved highly conductive and stretchable wiring on the textile by using metal plating2 and weaving3, although those methods have challenges in patterning which are crucial for electronic circuits. Printing is an alternative method for fabricating conductive wirings on textile. However, it is difficult to achieve high stretchability more than 30% strain since the textile has porous and significant contours on the surface which make printed film susceptible to the cracking. In this work, we propose textile-permeable stretchable conductor which resulted in significant improvement of stretchability and cyclic durability of printed wiring. Specifically, a new type of ink that easily permeates textile substrate was developed, initial sheet resistance of printed wiring on textile was 0.06 Ω/sq, and increased only 70 times after stretching 450%. And resistance change after 100 cycles at 30% strain was less than 10 times while the resistance of printed trace on elastomer film increases 10⁵ times. The ink is comprised of silver flakes, fluoroc stapler, and slow evaporating solvent (2-2-butyl ether ethyl acetate). The key idea to realize stretchable wirings in textile is building conductive
pathways inside of the fiber bundles by permeating ink deeply, instead of forming a thick film on the surface of the textile. We systematically investigated penetration of ink by changing evaporation speed and viscosity of ink, also optimized the composition of the ink. Finally, we demonstrate 8-channel EMG monitoring garment which can monitor muscle activity of upper body during the pitching motion of baseball pitcher and transmit the data wirelessly.


**BM08.10.12**

**Microstructural Engineering of the Multidirectional Electronic Skins for Customizable Force Sensitivity and Selectivity**

Jonghwa Park, Jinyoung Kim, Jaehyung Hong, Hochan Lee, Youngoh Lee, Seungse Cho, Sung-Woo Kim, Jae Joon Kim, Sung Youb Kim and Hyunhyub Ko; Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Electronic skins (e-skins) with high sensitivity to multidirectional mechanical stimuli are crucial for healthcare monitoring devices, robotics, and wearable sensors. Previously, numerous e-skins have been successfully demonstrated to improve the tactile sensing performance using various microstructure arrays. However, there have been no systematic studies of the effects of the microstructure geometry on force-induced microstructure deformation and the resulting force sensitivity and selectivity in response to multidirectional mechanical stimuli. To investigate the geometrical effects of microstructure arrays on force-sensing capabilities, we here present three kinds of piezoresistive e-skins based on carbon nanotube/elastomer composites with different surface microstructures (i.e., dome, pyramid, and pillar). In addition, we compared the experimental piezoresistive properties and finite-element simulations of changes in the contact area and localized stress distributions in the microstructures. Depending on the microstructure geometry, distinct variations in contact area and localized stress distribution are observed under different mechanical forces (i.e., normal, shear, stretching, and bending), which critically affect the force sensitivity, selectivity, response/relaxation time, and mechanical stability of e-skins. As proof-of-concept demonstration in healthcare monitoring applications, our e-skins are used for detecting various bio-signals including acoustic waves, breathing, and human artery/carotid pulse pressures. Unveiling the relationship between the microstructure geometry of e-skins and their sensing capability provides a platform for the future development of high-performance microstructured e-skins.

**BM08.10.13**

**Smartphone Based Phage-ColorSensor to Detect Ovarian Cancer**

Dong-Guk Shin1, Seung-Wuk Lee2 and Hyo-Eon Jin1; 1College of Pharmacy, Ajou University, Suwon-si, Gyeonggi-do, Korea (the Republic of); 2University of California, Berkeley, Berkeley, California, United States.

We developed phage-based colorimetric sensors to diagnose ovarian cancer. Ovarian cancer is known as a “silent killer” because its symptoms are minimal or very rare. The 5-year relative survival rate of ovarian cancer is higher than 90% if detected early, whereas drastically lowered to 40% when detected after stage III. Therefore, early diagnosis is critical for treatment and survival of the ovarian cancer. It has been known that serum and salivary CA125 and HE4 biomarkers were correlated in ovarian cancer patients. Therefore, we developed phage-biosensor to detect the CA125 and HE4 ovarian cancer biomarkers in saliva. We identified highly specific phages to CA125 or HE4 through high-throughput phage display technique. We then genetically engineered the phages to express CA125 and HE4 receptors on the major coat protein. Using the resulting engineered phages, we fabricated self-assembled matrices composed of quasi-ordered fiber bundle structures to exhibit tunable colors by self-templating assembly approach. Upon exposure of different concentrations of biomarkers, the multi-color phase matrices exhibited distinct color changes that can be correlated to colorimetric measurement. Furthermore, we used home-designed smart phone app to detect the biomarkers selectively and sensitively from the human saliva. We believe that our phage-based ovarian cancer biomarker detection approach will be useful for early detection of ovarian cancer and increase of the survival rate.

**BM08.10.14**

**All Transparent-Stretchable Electrochromic-Supercapacitor Wearable Patch Device**

Tae Gwang Yun, Dong-Ha Kim, Jin Gook Bae and Il Doo Kim; Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

Electrochemical devices, that control transmittance of ultraviolet and visible light by electrochromism due to charge transfer, have been applied to low emission mirrors and energy saving systems by suppressing the internal temperature rise of the smart building system. Furthermore, electrochemical device can be used as a wearable healthcare device that detect harmful substances in human body as electric signals. For example, wearable electrochromic chemical sensor technology have been developed by integrating a chemical sensor that detects resistance change by a target chemical component and an electrochemical device that generates a color change by electron movement. Wearable electrochemical devices have attractive functions and development possibilities that can be applied in everyday life, however, the limitations of conventional electrochemical devices based on ITO-glass, which is brittle and required external electrical input did not overcome. All transparent-stretchable electrochromic-supercapacitor wearable patch devices with high electrochemical and electrochemical performance was fabricated to overcome the limitations of conventional electrochemical devices. All transparent-stretchable wearable patch device was consisted of transparent-stretchable low density silver nanowire embedded PDMS substrate, electrospun nanotube-PEDOT:PSS thin layer composite and transparent-stretchable Li ion-poly acryamide based hydrogel electrolyte. Especially, the contact efficiency of WO3 nanotube-PEDOT:PSS thin overlay was introduced to prevent the delamination of WO3 nanotube and offer enhanced coloration efficiency by dual electrochromic coloration. As a result, electrochemical energy capacity, electrochemical cycle reliability and electrochromic coloration efficiency were enhanced 20.6%, 7.0%, 12.0% by using WO3 nanotube-PEDOT:PSS active materials. The electrochromic-supercapacitor wearable patch device capable of stretching-bending deformation and simultaneously electrochromic coloration-electrochemical energy storage with enhanced electrochemical-electrochromic properties was operated by integrated hydrogel electrolyte with high ionic conductivity, transparency and more than 80% elongation. Therefore, the fabricated all transparent-stretchable electrochromic-supercapacitor wearable patch device is highly suitable for wearable electronic applications.

**BM08.10.15**

**Polymer-Based Wearable Throat Microphone with High Sensitivity and Flat Frequency Response**

Siyounge Lee, Hyungsuk Lim, Woong Sung, SungSik Park and Kilwon Cho; Pohang University of Science and Technology, Pohang, Korea (the Republic of).

Flexible and skin-attachable vibration sensors have been researched for wearable mechanosensors to recognize human voice, the most important bio-signal for communication. However, the reported sensors so far have shown low sensitivity and non-flat response. In this work, we present polymer-based wearable throat microphone that detects the neck skin acceleration, which has high and linear correlation with the voice pressure. Our device exhibits a
uniformity in the spin coating of the electrodes remained a critical issue. Moreover, poor adhesion of the carbon material to the metal contact pads leads to the risk of low electrode retention in subsequent fabrication steps – resulting in low output power and energy performance.

In this work, we present a CMOS compatible electrode deposition process for reduced graphene oxide (rGO) using spin coating. Additionally, we report improvements in adhesion and surface uniformity by employing surface roughening through Fe nanoparticle formation. A 4 nm thick Fe layer was evaporated on the bare Si/SiO₂ surface and then annealed at 500°C for 2 min, which magnifies the average mean surface roughness from 0.175 nm to 1.45 nm. This roughening leads to better interaction of the nanofillers with the substrate, enhancing the adhesion and uniformity of the deposited layers.

Electrodes revealed a 62% GO mass retention on the roughened sample in comparison to only 18% retention on the non-roughened device. We believe that these improvements are critical for the efficient operation of microsupercapacitors, where high surface area and dense packing of nano-fillers are essential for high energy density.

Polymer Functionalized Carbon Nanomaterials for Flexible Tactile Sensors

In biomedical applications, sensors play a critical role in detecting and monitoring the human activities. In particular, tactile sensors are useful in detecting the external stimulus which is highly required in designing the biofunctional prosthetic system. In real-time, prosthetic system may undergo different kinds of motion like bending, twisting and rotating. Functioning of tactile sensor in all these circumstances, demands high flexibility along with robustness. To design such system, fabrication of polymer nanocomposite is one of the ideal solutions. In this regard, researchers have started exploring novel nano materials like carbon nanotubes (CNT), graphene, nanowires and nanoparticles. Due to the exceptional electrical, mechanical and thermal properties, CNT and graphene can be used as nano-fillers in the polymer matrix substrate to enhance the electrical characteristics of the polymer nano-composites. Due to the high surface energy of the nano-fillers, it gets easily agglomerated in the polymer matrix and reduces the electrical conductivity of the film. Hence, it is essential to functionalize the nano-fillers to enhance the dispersion in the matrix and hence the electrical conductivity. In the present work, we analyzed the effect of two selective polymer functionalisation of multiwall CNT and hydrogen exfoliated graphene (HEG) fillers in a suitable polymer matrix and investigated the electrical conductivity of the polymer composites. The polymer functionalisation enhances the dispersion of the nano-fillers without introducing the defects in the structure and enhances the electrical conductivity. When force/strain is applied on the polymer nanocomposite, the established conducting networks is affected which leads to change in resistance, which is used as an electrical readout signal for actuating the prosthetic system. This sensor can be extended to the different applications like wearable electronics, robotics and structural health monitoring.

In order to be able to use autonomous (wireless) miniaturized sensor nodes as part of the Internet of Things, integrating CMOS compatible sensor manufacturing technology with energy harvesting and energy storage devices would be a significant advantage. Supercapacitors are devices which store energy by charge accumulation (and/or transfer) at an electrode-electrolyte interface. Previous attempts at manufacturing microsupercapacitor electrodes for microsystem integration have required techniques such as laser scribing, doctor blade coating, or reactive chemical growth for their deposition. Replacement of these techniques with a simple CMOS compatible spin coating technique is therefore highly desirable. Although previous investigations establish fabrication of microsupercapacitors through spin coated graphene oxide (GO) layers, the non-uniformity in the spin coating of the electrodes remains a critical issue. Moreover, poor adhesion of the carbon material to the metal contact pads leads to the risk of low electrode retention in subsequent fabrication steps – resulting in low output power and energy performance.

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A Solution Processable Conjugated Polymer for Direct Metabolite Sensing and Energy Powering Device

In biomedical applications, sensors play a critical role in detecting and monitoring the human activities. In particular, tactile sensors are useful in detecting the external stimulus which is highly required in designing the biofunctional prosthetic system. In real-time, prosthetic system may undergo different kinds of motion like bending, twisting and rotating. Functioning of tactile sensor in all these circumstances, demands high flexibility along with robustness. To design such system, fabrication of polymer nanocomposite is one of the ideal solutions. In this regard, researchers have started exploring novel nano materials like carbon nanotubes (CNT), graphene, nanowires and nanoparticles. Due to the exceptional electrical, mechanical and thermal properties, CNT and graphene can be used as nano-fillers in the polymer matrix substrate to enhance the electrical characteristics of the polymer nano-composites. Due to the high surface energy of the nano-fillers, it gets easily agglomerated in the polymer matrix and reduces the electrical conductivity of the film. Hence, it is essential to functionalize the nano-fillers to enhance the dispersion in the matrix and hence the electrical conductivity. In the present work, we analyzed the effect of two selective polymer functionalisation of multiwall CNT and hydrogen exfoliated graphene (HEG) fillers in a suitable polymer matrix and investigated the electrical conductivity of the polymer composites. The polymer functionalisation enhances the dispersion of the nano-fillers without introducing the defects in the structure and enhances the electrical conductivity. When force/strain is applied on the polymer nanocomposite, the established conducting networks is affected which leads to change in resistance, which is used as an electrical readout signal for actuating the prosthetic system. This sensor can be extended to the different applications like wearable electronics, robotics and structural health monitoring.

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Biosensors and biosensing protocols can detect a wide range of compounds, sensitively and selectively, with their application range extending from security and health care for point-of-care analyses of diseases to environmental safety. Since the first implantation of a pacemaker in 1960, tremendous efforts have been made to develop small power-supply medical devices for environmental safety, healthcare monitoring, neural disorders and hearing loss. Amongst them, biofuel cells have attracted significant attention due to their ability to convert the energy of metabolism into electricity. Unlike other conventional fuel cells, biofuel cells find their substrate directly in biofluids, where the metabolite of choice is abundant, cost efficient and offers a clean source of energy. Herein, we present a novel enzymatic biofuel cell design, based on an n-type semi-conducting polymer where the anode creates current in the presence of the metabolite in the solution. Due to the specific design of the polymer structure, enzymes are able to adsorb on the surface of the polymer film, avoiding the tedious processes of enzyme immobilization and leading to a mediator-free system. Moreover, since the power output of the cell is directly dependent on the metabolite concentration, the enzymatic biofuel cell acts itself as a biosensor. The polymer based (i.e biocompatible) membrane-less biofuel is simple and scalable. The power output of this novel n-type polymer-based biofuel cell (626 mWcm⁻²) outperforms other systems reported. Finally, the power delivered from the proposed biofuel cell can be collectively implemented to measure multiple analytes. This design paves the route of self-powered multi-analyte sensors for continuous healthcare monitoring.

Aloe Vera-Based Conducting Polymer Electrodes for Transcranial Electrical Stimulation

Transcranial electrical stimulation (TES) is an emerging neurostimulation technique. It is minimally invasive and utilizes electrodes on the surface of the skin or skull, avoiding damage to brain tissue. However, the poor mechanical contact combined with high electrochemical impedance of the metal-body interface mandates high power stimulation protocols for effective interventions. As a result, TES has poor spatial resolution and anatomical specificity. The
hypothesize that improving the interface between the stimulating electrode and body would result in lower stimulating power and better localization of electric stimulation. We developed TES electrodes that consist of a standalone composite film based on aloe vera hydrogel and poly(3,4-ethylendioxythiophene) doped with polystyrene sulfonate (PEDOT:PSS). The aloe vera hydrogel matrix provides unique properties to the film including conformability, softness when in a hydrated state, and strong adhesion with the surface of the skull after dehydration. In parallel, PEDOT:PSS ensures high conductivity and a low skull-electrode interface impedance, enabling efficient ion-to-electron conversion. The hydrogel-based electrodes were implanted in vivo on the surface of the rat skull, where SEM images of the skull-electrode interface demonstrated a conformable contact, highlighting its efficient mechanical interface. The effect of film composition and surface area on the electrochemical impedance were characterized and compared to a conventional TES electrode, and a significant reduction in impedance and increase in charge capacity was observed. The hydrogel-based electrodes did not require any additional adhesive to attach to the surface of the rat skull, forming an in vivo TES-based, closed-loop system for detection and stimulation of interictal epileptiform discharges (IED). Efficacy and stimulation thresholds were determined by in vivo electrochemical impedance spectroscopy and power titration, and comparison was made to conventional metallic electrodes. Overall, such films demonstrated high stability, biocompatibility, and spatial resolution for transcranial stimulation and hold a great promise in improving the efficacy of TES as a non-invasive intervention for neuropsychiatric disorders.

**BM08.10.20**

Patternable Nano-Cracked Strain Sensor Based on One-Step Laser Heat Encapsulation **Chan Park**, Hyunsuk Jung, Hyunwoo Lee, Hong Sung Uk, Hyonguk Kim, Seong Kyung Hong and Seong Jin Cho; Department of Mechanical Engineering, Chungnam National University, Chungnam, Korea (the Republic of).

Skin mountable or wearable electronic devices have recently grown in popularity due to their numerous advantages in the context of human-machine interactions. Despite the improved performance of recently developed flexible and stretchable strain sensors, performance degradation caused by a change in external environmental conditions such as humidity and dust is a critical barrier to practical use. Here, we report a benefit of highly stretchable crack-based strain sensors using a novel laser heating encapsulation method optimized for thin a film structure, first, unlike other encapsulation methods such as liquid polymer, multilayer, resin, bar sealing, and laser sealing, it is possible to fabricate the patternable, cutting, and bonding of sensors without complicating one-step. Second, the novel encapsulation process is an economical process because it does not require additional materials such as PDMS(Polydimethylsiloxane), resin, frit. Third, it does not adhere directly to the metal thin film, so the performance does not deteriorate. Since the part to be bonded is the edge to which the laser is irradiated, there is no influence on the metal. Finally, we evaluated the performance of the sensor after inserting sensor in water, and confirmed the possibility of encapsulation by comparing the performance of the sensor encapsulated in dust state and detergent state and the bare sensor. We believe that our sensor and encapsulation process will be useful in environments that need to be controlled by shape, and in environments such as underwater conditions motion monitoring where there are many foreign substances.

**BM08.10.21**

MXene Enables Wearable Energy Storage **Shayan Seyedin**1, 2; Si (Alex) Qin1, Jihzen Zhang1, Zhiyu Wang1, Raquel Ovalle-Robles1, Ray H. Baughman2, Yury Gogotsi2 and Joselito Razal1; 1Institute for Frontier Materials, Deakin University, Geelong, Victoria, Australia; 2A.J. Drexel Nanomaterials Institute, Drexel University, Philadelphia, Pennsylvania, United States; 3Nano-Science & Technology Center, Lintec of America, Richardson, Texas, United States; 4Alan G. MacDiarmid NanoTech Institute, The University of Texas at Dallas, Richardson, Texas, United States.

A recently discovered family of 2-D early transition metal carbides or carbonitrides called “MXene” has presented a distinct combination of metallic conductivity, outstanding electrochemical properties, and hydrophilic behavior. MXenes have been used to prepare films, papers, and composites with electrical conductivity of up to ~10,000 S cm⁻¹ and volumetric capacitance of up to ~1,500 F cm⁻³, rivalling existing materials for energy storage applications. To date, however, approaches for preparing MXene-based fibers or yarns for wearable applications have been relatively unexplored. Small sheet size (~2 mm), weak inter-sheet interactions, and lack of efficient processing have made it challenging to fabricate MXene-based fibers or yarns. Here, we present strategies to achieve fibers or yarns from the most prominent member of MXene family (Ti,C₂). We first demonstrate MXene’s potential in fabricating high-performance yarn supercapacitors by coating MXene on conductive carbon fiber bundles. The MXene-coated yarn supercapacitor device (at mass loading of 2 mg cm⁻²) showed a high length capacitance of ~132 mF cm⁻² which is higher than the literature reports (typically lower than 100 mF cm⁻²). We then produce MXene-based fibers using a wet-spinning technique by taking advantage of the templating role of liquid crystalline (LC) graphene oxide (GO). We show that the favorable interactions of GO and MXene flakes result in the preservation of the LC property of the GO dispersion at an extremely high MXene content of ~88 wt. %, a key to its fiber processing. The MXene-based fiber demonstrates excellent flexibility and a high volumetric capacitance of ~341 F cm⁻³. By employing a bisscrolling technique that traps MXene nanosheets within carbon nanotube yarn scrolls, we achieve yarns that are predominantly composed of MXene (containing up to ~98 wt. % MXene). This MXene-based yarn provides an areal capacitance of as high as ~3,188 mF cm⁻² (volumetric capacitance ~1,083 mF cm⁻³), which exceeds the previously recorded performance for any fiber or yarn supercapacitor electrode. When fabricated into a yarn supercapacitor device, the asymmetric electrode configuration reach a maximum energy and power densities of ~61.6 mWh cm⁻³ and ~5,428 mW cm⁻³ respectively. We show that the MXene-based fibers and yarns are useful for powering small electronic devices when knitted or woven into a textile. The MXene fibers and yarns developed in this work, introduce new classes of fibers and yarns from an emerging family of 2-D nanomaterials, and are excellent candidates for integration with textile-based electronics to meet the energy demands of future wearable devices.

**BM08.10.22**

Chemically/Biochemically Enhanced Nanoelectronic Gas Sensor for Airmen Performance and Protection **Yen Ngo1, 2; Taneha Littlejohn1, Michael Brothers1, 2, Ahmad E. Islam1, 2, Benji Maruyama1, Calude Grigsby1, Jennifer Martin1, Mitchell Rubenstein1, Rajesh Naik1 and Steve S. Kim1; 1711th Human Performance Wing, Air Force Research Laboratory, Wpafb, Ohio, United States; 2UES, Inc., Dayton, Ohio, United States; 3Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB, Ohio, United States.

Air Force interest in wearable sensors for continuous force protection and human performance monitoring require airborne chemical/biochemical sensors with high sensitivity, selectivity and specificity. Additionally, these sensors must be both portable and energy-efficient for continuous deployment. Sensors with all of these attributes are currently unavailable in commercial off the shelf sensors. Of these challenges, specificity is particularly challenging, especially in the presence of the large number of non-specific analytes found in human/environmental field samples. Increasing the affinity and/or specificity of the Chemical Recognition Elements (CREs) will benefit the sensor response to the target, leading to a corresponding enhancement of not only the signal to noise ratio, but also a significant reduction in sensor response time and non-specific interferences. Based on nature’s olfactory receptor-like concept, we demonstrated how a bio-inspired CRE acts as the “sensing material” which can selectively bind to the target chemical. The CRE’s influence on enhancing the sensitivity and selectivity of a nanoelectronic/electrochemical sensor is discussed in this talk. In addition, we will discuss other, future detection strategies we are pursuing for an airborne simulated chemical warfare agent.

**BM08.10.23**

Highly Sensitive Pressure Sensor Based on Baking-Like Foaming Process for Wearable Human Activity Monitoring Device **Guk-Jin Jeon, Hye-In...**
Flexible physical sensors that can replace human skin or interface human to robots have been attracting many interests over last several decades, as revealed by the outstanding developments in various applications, such as artificial electronic textile/skin, motion monitoring, and personal healthcare. Such physical sensors are classified mainly by the signal to be measured, such as pressure, strain, temperature and humidity. Among the various physical sensors, the pressure sensor can detect the pressure generated by human-body activity, which is distributed in low-pressure regimes (<10 kPa) and medium-pressure regimes (10-100 kPa). The pressure can be detected typically by three types of transduction mechanisms, such as piezoeffects, piezocapacitance and piezoelectricity, converting pressure stimuli into electrical signals. The piezoelectric pressure sensors are normally composed of an elastomeric insulating polymer, such as polyurethane, polydimethylsiloxane (PDMS) and Ecoflex, sandwiched between the two conducting plates, and preferred to detect wide pressure range up to about 100 kPa. When the pressure is applied to the surface of sensors, the thickness of insulator is reduced, causing the increase in capacitance. Therefore, it is necessary for the elastomeric insulator to be deformed sensitively according to the external pressure. For that intention, microstructured, porous, or air-gap embedded form have been typically suggested for high sensitivity at the low-pressure regime. However, although those sensors have excellent sensitivity, they have a relatively narrow pressure sensing range. Porous structures were conventionally fabricated by hard-template/etching and phase separation, which are highly time-consuming processes.

In this study, we present highly sensitive pressure sensor fabricated by simple and fast baking-like foaming process. The mixture of PDMS and Ecoflex is used to form an elastomeric insulator of pressure sensor. In order to introduce microporous structure in the insulator, NaHCO3 and CH3COOH are blended as pore precursors in PDMS/Ecoflex. Since NaHCO3 and CH3COOH are used even for food, they are biocompatible and easy to use. While curing the elastic mixture, NaHCO3 and CH3COOH chemically react and produce CO2 gas. All the process to fabricate the insulator are completed within 1 hour. Flexible electrodes are made of PDMS coated with Ag NW, and two electrodes are separated by the insulator. The pressure sensors will be electrically characterized by a capacitance versus pressure measurement system.
X-rays are a critical tool which finds applications in a number of different sectors including medical diagnostics and treatment, homeland security and non-destructive evaluation among many others. The modern genre of detectors or imagers used in this regard are based on a flat panel architecture whose geometric restrictions necessitates either complicated arrays of X-ray sources or a significant level of post-computational activities. For example, cadmium zinc telluride or even single crystal perovskites often requires high quality single crystals that are several millimetres thick.

Organic semiconductors have emerged as a route towards enabling system that have the potential to address factors such as cost and geometric restrictions placed by conventional semiconducting systems. However for X-ray detecting applications, the X-ray attenuation or stopping power enabled by organics is significantly low for satisfactory X-ray detection.

Herein, we introduce a direct conversion X-ray sensing architecture [1] based on the incorporation of high Z bismuth oxide nanoparticles within a ~20-30 µm thick organic bulk heterojunction system consisting of hole transporting polymer [mainly, poly(3-hexylthiophene) or P3HT] and electron transporting small molecule [mainly, [6,6]-Phenyl-C71-butyric acid methyl ester or PC70BM]. These hybrid detectors demonstrate high sensitivities of ~1.7 mC mGy⁻¹ cm⁻² when irradiated under a 50 kV X-ray source which are ~1-2 orders of magnitude higher in terms of sensitivity obtained using other emerging and enabling X-ray sensing materials such as perovskites. We also expand the application of these hybrid X-ray sensors to the Hard X-ray energy range by carrying our measurements under a medical Linear Accelerator (LINAC). Noticeably, this hybrid detector architecture enables a sensitivity of ~60 µC mGy⁻¹ cm⁻² which exceeds previous reports on direct and scintillator based X-ray detectors [2,3]. Notably, such high sensitivities are enabled at low bias voltages of ~10V which indicates the potential of this new detector architecture for real time radiation monitoring in a real world environment.

References

SESSION BM08.11: Flexible/Wearable Energy Storage I
Session Chair: Renkun Chen
Thursday Morning, November 29, 2018
Sheraton, 2nd Floor, Grand Ballroom

8:00 AM-#BM08.11.01
Reduced Graphene Oxide—Aramid Nanofiber Capacitors for Structural Energy and Power Jodie Lutkenhaus1, James Boyd1, Dimitris Lagoudas1, Micah Green1 and Haleh Ardebili1; 1Texas A&M University, College Station, Texas, United States; 2University of Houston, Houston, Texas, United States.

Structural energy and power systems both mechanical and electrochemical performance in a single multifunctional platform. These are of growing interest because they potentially offer reduction in mass and/or volume for aircraft, satellites, and ground transportation. The long-term vision is to combine the mechanical properties of structural composites with the energy storage properties of batteries or capacitors. However, there is a natural tradeoff between mechanical and energy storage properties, such that it remains difficult to synergistically optimize both. To this end, flexible graphene-based supercapacitors have attracted much attention due to their extraordinary mechanical and electrical properties, yet they suffer from poor strength. This problem may be exacerbated with the inclusion of functional guest materials, often yielding strengths of less than 15 MPa. Here, we show that reduced graphene oxide paper supercapacitor electrodes containing aramid nanofibers as guest materials exhibit extraordinarily high tensile strength (100.6 MPa) and excellent electrochemical stability (Kwon, S. et al. ACS Nano 11 (7), 6682-6690 (2017)). This is achieved by extensive hydrogen-bonding and π-π interactions between the reduced graphene oxide sheets and aramid nanofibers. Aramid nanofibers are the nanoscale version of Kevlar, which is known for its exceptional mechanical properties and use in bullet-proof vests. The tradeoff between capacitance and mechanical properties is evaluated as a function of aramid nanofiber loading, where it is shown that these electrodes exhibit multifunctionality superior to that of other reduced graphene oxide-based supercapacitors. We anticipate these composite electrodes to be a starting point for structural energy and power systems that harness the mechanical
properties of aramid nanofibers. Our future work, which includes an informatics-driven assessment of the system as well as functionalization effects of the reduced graphene oxide sheets will also be discussed.

8:30 AM BM08.11.02
Flexible All Organic Batteries Based on Conducting Redox Polymers Christian Strietzel, Rikard Emanuelsson, Maria Stromme and Martin Sjödin; Nanotechnology and Functional Materials, Department of Engineering Sciences The Ångström Laboratory, Uppsala University, Uppsala, Sweden.

Batteries consisting of naturally occurring organic materials can be envisioned as sustainable alternatives to conventional metal-based batteries, thus avoiding the negative environmental impact associated with the production and recycling of the latter. In this way the negative environmental impact of the constantly increasing demand for secondary batteries can be decreased. Apart from being fully organic, such batteries also open up for flexible battery designs as they can be produced in a roll-to-roll process and they are anticipated to be viable in a broad range of applications as energy supplies in innovative flexible electronics designs. In the current work, fully organic batteries are realized utilizing conducting redox polymers (CRPs) as electrode materials. CRPs combine the high charge storage capacity of a redox active pendant group (PG) with the conduction properties of a conducting polymer (CP) backbone, both to reduce the need for addition of conductive carbon black and increasing the stability of the PG redox conversion in a battery setup. The first results from a fully organic, aqueous battery based on CRP electrode material are presented. Challenges and possibilities of this type of battery in flexible battery designs are discussed.

8:45 AM +BM08.11.03
Fiber-Shaped Energy Harvesting and Storage Devices Huisheng Peng; Fudan University, Shanghai, China.

It is critically important to develop miniature energy storage and conversion devices in modern electronics, e.g., for portable and wearable electronic facilities. Here a novel family of energy storage and conversion devices as well as their integrated devices in 1D configuration are carefully discussed with unique and promising advantages such as lightweight and wearable compared with the conventional planar architecture. For the energy conversion devices in 1D configuration, fiber-shaped dye-sensitized solar cells, polymer solar cells and perovskite solar cells are covered. For the energy storage devices, fiber-shaped electrochemical capacitors, lithium ion batteries, lithium sulfur batteries, lithium air batteries and zinc air batteries are carefully investigated. The main efforts will be made to highlight the recent advancement in the electrode material, device structure and property extension.

9:15 AM BM08.11.04
Thermally Chargeable Supercapacitors with Charging and Discharging Cycles for Wearable and IoT Electronics Angel Mohammed Abdul Mageeth, Myunghwan Jeong and Choongho Yu; Texas A&M University, College Station, Texas, United States.

Thermally chargeable planar supercapacitors are good candidates for energy harvesting and storage in wearable and internet-of-things (IoT) electronic devices. We report a graphene oxide based supercapacitor which can be thermally chargeable and has good areal capacitance and charge storage capability in conjunction with a shape memory polymer (SMP) to create a device operating in a cyclic manner having thermal charging and discharging cycles. The supercapacitor has reduced sulfate graphene oxide electrodes fabricated by laser irradiation on a film of graphene oxide over PET substrate using a 3D printer with laser diode assembly. Graphene oxide with H2SO4 acts as separator/electrolyte for the super capacitor. The fabricated supercapacitor employs the Soret effect as the transport mechanism, which results in high thermoelectric voltage. The shape memory polymer was prepared from EPON 826 resin with neopentyl glycol diglycidyl ether (NGDE) added at 1:1 molar ratio to have a glass transition temperature just above room temperature. The SMP after preparation was casted onto a rubber mold of desired shape made by 3D printing and cured to impart the final shape. An array of supercapacitor specimen modules were placed over the SMP film connected in series or parallel depending on the voltage and current requirements of the device application. Temperature gradients applied across the two ends of the SMP film were used for thermal charging, and a shape change was utilized for discharging when the applied temperature gradient raised the temperature of the SMP. The mechanism developed here can be easily integrated into various devices operating intermittently with low power consumption.

9:30 AM BM08.11.05
Design of A Flexible and Stretchable Full-Cell Lithium-Ion-Battery Based on Hydrogel Electrolyte and Polymer Composite Current Collector Xi Chen, Long Pan, Haijian Huang and Markus Niederberger; Laboratory for Multifunctional Materials, Department of Materials, ETH Zurich, Zurich, Switzerland.

We designed a flexible and stretchable thin film battery with potential application in wearable devices and flexible electronics. A polymer electrolyte is prepared by utilizing the swelling behavior of a cross-linked hydrogel, which allows the water contained in the network structure of the polymer chains to be replaced by the concentrated aqueous solution of the lithium salt. A high ionic conductivity of 10^-3 S/cm is achieved at room temperature, which is comparable to the typical liquid electrolyte and about 10-100 times higher than the conventional polymer gel electrolytes. The outstanding flexibility and stretchability of the hydrogel are also preserved after the salt incorporation. The ultra-high lithium salt concentration successfully broadens the stability voltage window of the hydrogel electrolyte to about 3.0 V, ensuring a good energy density of the battery. Being limited by this window, a rational material screening process is performed and LiMn2O4-TiO2 is selected as a proper electrode pair which can reach the optimized performance.

Huisheng Peng; Fudan University, Shanghai, China.

Aqeel Mohammed Abdul Mageeth, Myunghwan Jeong and Choongho Yu; Texas A&M University, College Station, Texas, United States.

Angel Mohammed Abdul Mageeth, Myunghwan Jeong and Choongho Yu; Texas A&M University, College Station, Texas, United States.

Huisheng Peng; Fudan University, Shanghai, China.

Angel Mohammed Abdul Mageeth, Myunghwan Jeong and Choongho Yu; Texas A&M University, College Station, Texas, United States.

8:45 AM BREAK
MXene Coated Cellulose Based Yarns for Wearable Supercapacitor Applications

Simge Uzun1, Ariana S. Levitt1, Mohamed Alhabeb1, Genevieve Dion2 and Yury Gogotsi3; 1Materials Science and Engineering, Drexel University, Philadelphia, Pennsylvania, United States; 2Department of Design, Drexel University, Philadelphia, Pennsylvania, United States.

Two-dimensional (2D) metal carbides, known as MXenes, have recently attracted much attention due to their unique combination of properties, including high metallic conductivity (up to 10,000 S/cm as a free-standing film), excellent mechanical properties, electrochemical activity, and chemical stability. As such, MXenes are promising for a diverse range of wearable applications, including energy storage, harvesting, sensing, and electromagnetic interference (EMI) shielding. These applications require the development of highly conductive fibers that are well-suited for dynamic environments, meaning that the fibers are lightweight, flexible, and durable.

Ti3C2 MXene, the most widely studied MXene in the family to date, has been incorporated into yarns via a variety of methods, including dip-coating, drop-casting, and biocasting, and processed into fibers via wet-spinning and electrospinning. Using these fiber-processing methods, MXene fibers can be produced with tunable properties, such as fiber diameter, which can range from the nano-scale via electrospinning to the micro-scale, via wet-spinning. Not only have MXenes demonstrated unique properties on their own, but they have also been incorporated into a variety of polymer matrices and mixed with other nanomaterials, such as carbon nanotubes (CNTs) and graphene oxide (GO) and processed into composite fibers. These MXene composite fibers have shown enhanced mechanical, thermal, and electrochemical properties. In this talk, an overview of the methods developed to process MXenes into fibers will be presented, in addition to their electrochemical, electronic, and mechanical properties. The potential applications of these fibers in wearable applications, such as energy storage, will be discussed.

Colloidal Synthesis of Colloidal Synthesis of Nanomaterials as Building Blocks for Functional Fibers

Vida Jamali1, Farnaz Nirou1, Matteo Pasquali2 and A. P. Alivisatos2; 1University of California, Berkeley, Berkeley, California, United States; 2University of California, Berkeley, Berkeley, California, United States.

Smart fabrics that combine traditional clothing with functional devices are a topic of a growing field of research with a broad range of applications in areas including healthcare, sports and internet of things development. Two common approaches for producing smart fabrics are 1) to adhere fabricated devices on top of a pre-woven fabric, and 2) to develop devices in form of fibers that can be then integrated into large area textile. The latter approach allows us to combine fibers with different functionalities into a large area fabric showing a collective complex functionality. Functionality of the fibers can be tuned using a large library of nanomaterials as building blocks. Here, we propose a layer by layer assembly process to fabricate functional fibers using colloidally synthesized nanomaterials. As an example, we will discuss fabrication of solution-processable, flexible, and wearable light emitting fibers with a potential to be incorporated into light-emitting fabrics.

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Significant efforts have been made in recent years for the development of wearable technologies. Many of these devices necessitate robust energy storage solutions to operate at a cost-effective level. Flexible and electrochemically active yarns can be knitted into full fabrics and function as energy storage devices such as supercapacitors, enabling integration into a variety of garments with specified power and energy densities with a limited footprint [1]. Two-dimensional metal carbides, known as MXenes, are considered for energy storage applications due to their metallic conductivity, high electrochemical activity (reversible redox processes), and chemical stability [2].

In this work, we demonstrate a scalable dip-coating approach for fabricating high-performing supercapacitor yarns using low-cost, commercial cellulose-based yarns. Since MXenes are processible in various solvents [3], it can be incorporated into conventional yarns using a simple dipping and drying procedure. Concentration and flake size distribution of MXene solutions were tailored to ensure effective penetration of MXene flakes into the individual fibers and under the yarn surface without sacrificing adhesion to the fiber substrate. The high porosity of cellulose-based yarns offers a large surface area for MXene uptake and electrolyte exposure to facilitate charge transport. Finally, the knittability of the electrode yarns into full fabrics on industrially used machines will be discussed. This study provides insight into the processing requirements for coating cellulose-based yarns. Furthermore, the effect of MXene flake size on coating uniformity, yarn conductivity, and supercapacitor performance was investigated. Our findings suggest the potential use of MXene for achieving large-scale and cost-effective production of high-performance supercapacitors as energy storage devices for powering wearable electronics.


10:15 AM BM08.12.01

11:00 AM BM08.12.03

11:15 AM BM08.12.04
and/or vigorous motion and preventing evaporation of collected sweat. This talk introduces materials and device architectures for waterproof, skin-like, microfluidic and electronic systems that adhere to the skin to enable capture, storage and analysis of sweat, even while fully underwater. A method of forming ultra thin, low modulus epidermal microfluidic systems and a scheme for using physically patterned, skin-safe adhesives enable reliable operation during swimming for two hours, or more, with minimal influence of the surrounding water or of biological effects such as compensatory sweating. The combination of an elastomeric polymer with excellent barrier properties and computationally guided design of microfluidic channel geometries prevents contamination from environmental water and minimizes evaporative loss of collected sweat during dryland studies. Field trials demonstrate the functionality of these devices during cycling and swimming in controlled, indoor conditions and in open water swimming in the ocean. Wireless, digital measurements of skin temperature via integration of systems that operate via near field communication protocols not only elucidates differences in the thermal response of the skin during exercise in aquatic and dry environments but also, more generally, illustrates the ability to co-integrate electronics into these platforms. A demonstrator device leveraging all of the key materials and design strategies introduced here enables quantitative in situ measurements of chloride concentration, total sweat loss (and sweat rate), and skin temperature during vigorous physical activity in aquatic environments.

SESSION BM08.13: Functional Materials and Devices with Energy Harvesting and Storage II

1:30 PM *BM08.13.01
Energy Harvesting, Energy Storing and Comfort Adjusting Yarns and Textiles Ray H. Baughman: The University of Texas at Dallas, Richardson, Texas, United States.

The design, fabrication, and performance of multifunctional yarns and fibers for energy harvesting, energy storage, and actuation in textiles, as well as for other applications, will be discussed. Our bicomponent technology can be used to trap up to 95 wt % of a functional guest in the helical corridors of nanofiber yarns that are wearable, washable, and knot-able without sacrificing guest functionality. One application area is in comfort adjusting clothing that automatically opens and closes porosity depending upon the temperature or the presence of perspiration. When used as large-stroke artificial muscles, these yarns are twisted until they fully coil, and in this coiled state they can deliver tensile strokes exceeding 40% and generate contractile stresses, gravimetric work densities, and gravimetric power densities that are 230, 65, and 95 times that of natural muscle, respectively. Depending upon the relative chirality of yarn and coil, homochiral and heterochiral muscles are obtained, which respectively contract and expand when yarn volume increases. Related electrochemical twistron mechanical energy harvesters will also be described, which are electrochemical muscles operated in reverse. Without requiring an external power source to provide a bias voltage, these twistrons can generate 250 watts per kilogram of peak electrical power when cycled up to 30 hertz, as well as over 41 joules per kilogram of electrical energy per mechanical cycle, when normalized to harvester yarn weight. All solid-state twistrons will be described that are woven into textiles to generate electricity from body movement.

2:00 PM BM08.13.02
Ultraflexible Organic Photovoltaic Modules Combined with Organic Light-Emitting Diodes for Self-Powered Wearable Indicators Hiroaki Jinno1,2, Kenjiro Fukuda2, Xiaomin Xu2, Sungjun Park2, Tomoyuki Yokota1, Itaru Osaka1 and Takao Someya1,2: 1The University of Tokyo, Tokyo, Japan; 2Riken, Wako, Japan; 3Hiroshima University, Higashi-Hiroshima, Japan.

For continuous operation of wearable sensors for the Internet of Things (IoT), ultraflexible organic photovoltaics (OPV) are the most promising among all existing energy harvesting power sources because of their exceptional flexibility, environmental stability, and high efficiency [Ref 1, 2]. Since sufficiently high output power (typically ranging from 1-10 mW) is necessary to operate external circuitry, sensors, and displays, making OPVs as module devices with series and/or parallel connection between each individual cell is important. Though much progress has been made with ultraflexible OPVs as a single device, there is little research focusing on making modules with OPVs to increase output power necessary for practical applications [Ref. 3]. Moreover, to our knowledge, there are no examples of ultraflexible self-powered devices integrated with ultraflexible light-emitting diodes (LEDs). Here, we show ultraflexible and efficient OPV modules with various series and/or parallel connections to achieve high current and/or voltage output. The OPV modules are based on an inverted structure with an active layer of a D–A polymer with quaterthiophene and naphth[1,2;5,6-c]bis[1,2,5]thiadiazole (NTz) (PNTz4T) and [6,6]-phenyl C71-butyric acid methyl ester (PC71BM). The module with 10 series connections features high open circuit voltage up to 6.8 V and short circuit current of 0.61 mA on 1-µm-thick foil. At the maximum power point of the OPV module, the module shows an output power of 2.78 mW. We achieved large-area OPV modules with 5 parallel connections, each containing 3 single cells in connected in series. The module exhibited an output voltage of 2.01 V and a short-current of 4.81 mA, resulting in a maximum power of 5.54 mW. Additionally, inverted structure ultraflexible OLEDs with yellow-color emission were fabricated. The ultraflexible OLED shows an external quantum efficiency of 1.3%, which is sufficiently high enough to be detected by the human eye. Finally, we demonstrated a self-powered indicator for imperceptible wearable devices consisting of an ultraflexible OPV module with 8 series connections connected to an OLED. These results highlighted the potential advantage of ultraflexible OPVs for IoT device applications.

**SESSION BM08.14: Flexible/Wearable Energy Storage II**

**Session Chair:** Hong Wang

**Thursday Afternoon, November 29, 2018**

**Sheraton, 2nd Floor, Grand Ballroom**

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### 2:30 PM BM08.13.04

**Self-Powered Graphite-Polymer Flexible Strain Sensors with Ultrasensitivity and Durability for Real-Time Human Vital Signal Monitoring and Posture Correction of Musical Instrument Learners**  
Weigua Li and Donglei (Emma) Fan; The University of Texas at Austin, Austin, Texas, United States.

Flexible electronics have emerged as one of the most potential technologies that could revolutionize the modern society. However, the state-of-the-art flexible electronics still largely rely on rigid and bulky power sources, which has greatly compromised the advantages offered by flexible technology in convenience, comfort, and wearability. In this work, the authors present 3-D graphite foam as the key sensing element of polymer composite strain sensors that offer ultrahigh sensitivity and durability in the detection of fine motions. The graphite-polymer sensor in this work provides high bending sensitivities that are reproducible within 3% signal shift after 11,000 bending cycles and exhibit gauge factors of 100 at tensile strains of 90%. The sensing mechanism is modeled and correlated with experimental studies. The high strain sensitivity compared to graphene-based devices is analyzed and understood with respect to levels of defects in materials. Moreover, a new type of flexible all-solid-state supercapacitors is integrated with the strain sensor into self-powered devices for detection of both coarse and fine motions on human skins in real time, i.e., those from finger bending and heart beating. Such graphite-polymer sensors are also applied in the detection of posture correctness of musical instrument learners for the first time.

### 2:45 PM BM08.13.05

**Sonochemically Synthesized ZnO Nanostructured Piezoelectric Layers for Self-Powered Sensor Applications**  
Fahmida Alam, Sadegh Mehdi Aghaei, Ahmed H. Jalal, Naznin Akter and Nezih Pala; Electrical and Computer Engineering, Florida International University, Miami, Florida, United States.

Energy harvesting from ambient environments is enticing and has received increasing deal of attention for building the self-powered systems recently. Nanogenerators have shown the capability to harvest the mechanical energies in different forms. A piezoelectric-based nanogenerator is particularly interesting for portable smart nanoelectronics because it can scavenge biomechanical energy from human body motions and activities, such as heartbeat, blood flow, muscle stretching, or eye blinking, and turns it into electricity. Thin film based piezoelectric nanogenerators have proven to be suitable for scavenging irregular mechanical sources from bending or rolling motions. It is shown that the output of a piezoelectric nanogenerator is associated with the coupling of the piezoelectric and the semiconducting properties of the piezoelectric nanomaterial. ZnO-based piezoelectric nanogenerators are the subject of extensive research due to the advantages of ZnO over other materials. ZnO shows both semiconducting and piezoelectric properties that can form the basis for electromechanically coupled sensors and nanogenerators. ZnO is also relatively safe and biocompatible, and it can be used for biomedical applications. Moreover, ZnO thin films exhibit high elasticity and resistance to mechanical degradation. Finally, ZnO based nanogenerators have a great potential for applications in self-powered and sustainable self-sufficient micro- and nano-systems owing to their demonstrated high power density.

In this paper, we report on the flexible thin film piezoelectric nanogenerators based on two-dimensional ZnO nanoflakes (NFs) directly deposited onto flexible polyethylene terephthalate (PET) and graphene substrates using a simple sonochemical reaction in aqueous solution at room temperature. Our sonochemical synthesis method is a rapid, highly stable, low-cost, and reproducible method, which can be performed at ambient conditions. These advantages of the sonochemical method allow the synthesis of many different ZnO nanostructures including 1D nanowires, 2D nanoflakes, nanowalls and nanobelts virtually on any substrate. The structural investigations using scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray diffraction (XRD) indicated that the ZnO NFs grew with high level of crystallinity and without any thermal damage on the substrates. We compare the size, thickness, distribution and average piezoelectric power output of the ZnO-NF based nanogenerators fabricated under different conditions and with different designs. The fabrication of these devices provides a promising solution for developing flexible and self-powered electronic devices particularly wearable and implantable sensors.

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**SESSION BM08.14: Flexible/Wearable Energy Storage II**

**Session Chair:** Hong Wang

**Thursday Afternoon, November 29, 2018**

**Sheraton, 2nd Floor, Grand Ballroom**

### 3:30 PM *BM08.14.01*

**Fiber-Enabled Wearable Electrochemical Energy Storage**  
Zrijian Zheng; Hong Kong Polytechnic University, Hong Kong, Hong Kong.

Wearable electronics is foreseen to be the next major technology after smart phone in the near future. However, most conventional energy supplying devices are rigid, bulky, and heavy, making them not suitable for wearable applications. On the other hand, fibres are materials that have been worn by human beings for more than a thousand years. Fibres are flexible, lightweight, conformal, and highly manufacture-able. This talk will introduce how our research group makes use of fibre for wearable electrochemical energy storage devices including supercapacitors and lithium batteries. These fibre-based devices can maintain the flexibility, lightweight, permeability, processibility, and even washing ability like textiles. In addition, we also show that fibrous materials can significant improve the electrochemical properties of the devices.

### 4:00 PM BM08.14.02

**Ultra-Tough Ion Conducting Elastomers for Stretchable Lithium-Ion Batteries**  
David Mackanie1, Yi Cui2 and Zhenan Bao1; 1Chemical Engineering, Stanford University, Stanford, California, United States; 2Materials Science and Engineering, Stanford University, Stanford, California, United States.

Batteries for wearable electronics should be safe, flexible, and robust. Solid-state batteries based on either solid or gelled polymer electrolytes have the potential to fulfill these criteria. However, many current electrolyte architectures in solid-state batteries utilize polymers that are either weak or easily deformable. Herein, we employ rational polymer design and synthesis to create a series of extremely tough elastomers with remarkably high lithium-ion conductivity. The catalogue of ion conducting elastomers (ICEs) are created by varying the strength of polymer-polymer interactions within the electrolyte. In their optimal configuration, the gelled ICEs can be stretched elastically to over 30x their original length and have an ionic conductivity of 2E-4 at 25 °C. By tuning the strength of polymer-polymer interactions, we develop insights into the effect of mechanical strength on the chemical, electrochemical, and ion transport properties of a series of ICEs. It is observed that controlling polymer-polymer interactions allows for de-coupling of ion transport from the...
mechanical robustness of the films. We also demonstrate the application of ICEs in a quasi-solid-state battery configuration. In this setup, ICE is used as both a solid electrolyte and a binder for the electrodes. Intermolecular interactions help adhere the battery layers, leading to an integrated all-stretchable battery stack. The interfacial interactions also minimize interfacial impedance, leading to improved cycling. Successful operation of such a battery is demonstrated at conditions that mimic those of wearable electronics.

4:15 PM BM08.14.03
A Novel Strategy of One Device Achieves Two Functions—Energy Storage and Temperature Sense Multi-Functions Device Based on Graphene Planar-Structure Supercapacitor Ziyu Yue and Chunyang Jia; University of Electronic Science and Technology of China, Chengdu, China.

Multi-functions devices attract much attention due to their great potential and large demands in wearable electronics. Besides some practical applications of integrated different functional devices as one, there is a novel strategy to fabricate multi-functions devices, that using one device to achieve two or more functions. Herein, we report the energy storage and temperature sense dual function device based on graphene planar-structure supercapacitor. Combining the supercapacitor and electronic components on one flexible printed circuit board, the obtained device could detect environmental temperature by measuring the change of leakage current of supercapacitor. The temperature sense function exhibits a high resolution of 0.0588 °C due to the 0.0407 μA precision of leakage current measurement, and the high accuracy of 1 °C comparing with temperature sensor chip. Meanwhile, as an energy storage device, the supercapacitor presents excellent electrochemical performance with the areal capacitance of 118 μF cm–2 at scan rate of 0.1 V s–1. This work demonstrates the feasibility of using one supercapacitor to achieve energy storage and temperature sensing dual function simultaneously.

4:30 PM BM08.14.04
2D Auxetic Reentrant Graphene Nanostructures for Stretchable Energy Storage Electrodes Jeong Gon Son; Korea Institute of Science and Technology, Seoul, Korea (the Republic of).

Stretchable electronics, which require the flexibility and stretchability necessary to endure complex motions from humans, have recently attracted considerable attention because of the increasing demand for bio-implantable and wearable devices. To accommodate large applied strains without fracturing the materials, structure-assisted stretchability, which provides brittle materials with the stretchability, can be an ideal approach. In this talk, we suggest self-assembly based approaches for structure-assisted stretchable energy storage electrodes. Additionally, vertically aligned graphene/CNT networks provided a plentiful of surface area and induced sufficient ion transport pathways on 2D auxetic structures. Radial compression process up to 1/10th densified the electrode, significantly increasing the areal and volumetric capacitances of graphene/CNT networks and maintained excellent electrical conductivities under biaxial stretching conditions and showed a slightly negative or near-zero Poisson’s ratio over a wide strain range because of their structural uniqueness. For practical applications, we fabricated all-solid-state supercapacitors based on 2D auxetic structures. Radial compression process up to 1/10th densified the electrode, significantly increasing the areal and volumetric capacitances of the electrodes. Additionally, vertically aligned graphene/CNT networks provided a plentiful of surface area and induced sufficient ion transport pathways of the electrodes. Therefore, these exhibited high gravimetric and areal capacitance values of 152.4 F g–1 and 2.9 F cm–2, respectively, and had an excellent retention ratio of 88% under a biaxial strain of 100%. The auxetic cellular and vertically aligned structures provide a new strategy for preparation of robust supercapacitor electrodes.

4:45 PM BM08.14.05
Dual-Crosslinking Design for Resilient Lithium-Ion Conductor Jeffrey F. Lopez1,2, Yongming Sun2, Yi Cui2 and Zhenan Bao1; 1Chemical Engineering, Stanford University, Stanford, California, United States; 2Materials Science and Engineering, Stanford University, Stanford, California, United States.

Solid-state electrolyte materials are attractive options for meeting the safety and performance needs of advanced lithium based rechargeable battery technologies because of their improved mechanical and thermal stability compared to liquid electrolytes. However, there is typically a tradeoff between mechanical and electrochemical performance. Here we describe an elastic Li-ion conductor with dual covalent and dynamic hydrogen bonding crosslinks to provide high mechanical resilience while maintaining high room temperature ionic conductivity. A solid-state lithium metal/LiFePO4 full cell with this resilient electrolyte can operate at room temperature with a high cathode capacity of 152 mAh g–1 for 300 cycles and can maintain operation even after being subjected to intense mechanical impact testing. Our new dual crosslinking design provides robust mechanical properties without decreasing the ionic conductivity and opens a route toward stable, high-performance operation of solid-state batteries even under extreme abuse.

SESSION BM08.15: Poster Session IV: Materials-to-Devices for Integrated Wearable Systems—Energy Harvesting and Storage, Sensors/Actuators and Integration

BM08.15.01
Diagnostic Redox Biosensors Based on Immobilized Aptamer Scaffolds Nancy Nguyen, Jessica Anderson, Amira Gee and Mehnaaz F. Ali; Chemistry, Xavier University of Louisiana, New Orleans, Louisiana, United States.

Applications of detection systems at the nanomedicine regime require highly sensitive, quantitative and selective analysis platforms for the real-time multiplexed monitoring of target analytes. Developing biosensors with an electrochemical output allows for the sensitive detection of analytes with an inherent amplification system that can be easily amenable to bioelectronic devices. Our work focuses on sensing relevant small-molecules and biomarkers through the design of aptamer scaffolds that are bound to a redox trigger. The aptamer scaffolds allow for allosteric binding of both the redox signaling trigger and the clinical target. We use a redox trigger within a double-surface electrochemical approach where target recognition is performed at a different surface from that enabling signal transduction. This strategy allows for independent optimization of the target recognition and electrochemical detection steps. We have demonstrated the utility of such systems for clinically relevant molecules such as miRNA’s and small molecules such as ATP. Current studies demonstrate the design of an adaptable aptamer scaffold, which is utilized for the detection of biomarkers for prolonged concussion symptoms. Isothermal
Here we report on utilising Ti3C2 MXene to design an accommodating intraocular lens with the ability to mimic controlled changes in refractive power. A technique where by the irradiation of polyimide (PI) films with a pulsed CO2 infrared laser a photothermal reaction occurs, which leads to the formation of nanocoatings.


Lenses Limited, Worthing, United Kingdom; 3A. J. Drexel Nanomaterials Institute, Philadelphia, Pennsylvania, United States.


7. Intraocular lenses (IOLs) have been under development to treat cataracts since the late 1940s(1). Whilst significant changes in materials and design have enhanced IOLs, there still remain several deficiencies linked to poor biocompatibility and failure to mimic the refractive properties of the natural lens. One approach is to incorporate transparent, electrically conductive, biocompatible materials. A new class of two-dimensional metal carbides, known as MXenes, have shown outstanding capabilities in electrical conductivity and biocompatibility(2–4). Since their discovery in 2011, investigations involving MXenes have increased considerably. With approximately 20 variations of MXenes being synthesised, the most studied being titanium carbide (Ti3C2Sn)(6). Here we report on utilising Ti3C2Sn MXene to design an accommodating intraocular lens with the ability to mimic controlled changes in refractive power. Whilst there has been a rise in research involving MXenes, the biological evaluation of toxicity remains largely under investigated(5). Optoelectronic properties of Ti3C2Sn were optimised and fully characterised. In vitro cell models were used to measure the suppression of oxidative stress, cell adhesion and inflammatory response of Ti3C2Sn thin films.


stacked graphene structures. LIG emerges thus as a rising substitute to produce graphene-based devices. This work consists in the development and optimization of flexible UV sensors with zinc oxide nanostructures as the active layer for the UV detection. PI as the substrate and its respective LIG as electrodes. The nanostructures with higher area-volume ratio, synthesized through a microwave assisted hydrothermal method, were selected and deposited by drop casting onto the electrodes that in turn were optimized to enhance electrical properties by varying the laser parameters. The assembled sensors were able to successfully detect the UV radiation with a responsivity of 92 and 2 nA/W for 1 V bias for the PI substrate. In addition, the PI sensor has shown to be capable of working under strain and to be stable after several hours of constant cyclic operation.

**BM08.15.05**

_Vapor-Printed Polymers for Flexible Electronics_  
Wen Jun Jia, Vladimir Bulović, Karen Gleason, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Oxidative Chemical Vapor Deposition (oCVD) is able to achieve polymer synthesis, thickness-defined patterned deposition, and anion doping in a single step at low temperatures (below 150 °C) for a variety of technological applications. During the process, the monomer and oxidant precursors diffuse to the target surface via the vapor phase, and then lead to polymerization, dopant insertion, and thin film formation at the same time. Consequently, oCVD fabrication independent of material solubility and substrate properties to enable insoluble polymers to be coated in a conformal manner without any solvent damage to the substrate. This key differentiator from solution-based approaches makes oCVD a substrate-independent scalable platform technology for surface modification and device fabrication. Based on the commercialization-critical benefits, semiconductor and conducting polymer thin films with suitable properties, patterns, and size can be directly integrated into flexible electronics such as organic photovoltaics on unmodified papers, thereby enhancing its functionality significantly.

**BM08.15.06**

_Smart Coloration Electrochromic-Supercapacitor for Wearable and Portable Electronics_  
Tae Gwang Yun, Donghyuk Kim, Chang-Soo Woo, Seunghoon Nam and Seunimin Hyun, Korea Institute of Machinery and Metals, Deajeon, Korea (the Republic of).

Electrochromic devices have been widely applied in energy saving applications by taking advantage of the electrode coloration. Electrochromic system capable of autonomous transmittance tuning in response to incident sunlight will be useful in architecture, automotive industry and especially the emerging field of wearable electronics, where otherwise transparent electrochromic device that can reversibly change color while also allowing for reliable energy storage. For electrochromic system to be applied in wearable and portable electronics, the system should be able to demonstrate efficient and reversible electrochromic coloration while retaining its performance levels even throughout the repeated mechanical straining. In this study, we demonstrate photo-responsive electrochromic-supercapacitor based on cellulose nanofiber/silver nanowire/reduced graphene oxide/WO3 composite electrode capable of undergoing “smart” reversible coloration and simultaneously function as a reliable energy storage device. The fabricated electrode demonstrates good optical properties, exceptionally high transmittance of 99.1%, owing to the use of ultra-thin cellulose nanofiber (CNF) paper as a substrate. CNF, Silver nanowire coated CNF, WO3 nanoparticle/reduced graphene oxide coated on silver nanowire/CNF were shown to exhibit transmittances of 89.9% and 83.4% respectively at a wavelength of 600nm. The composition of electrochromic-supercapacitor device is composed of electrode with cathodic electrochromic material and transparent Li based gel-electrolyte. The fabricated device exhibited a high coloration efficiency of 64.8cm2/g, specific capacitance of 406.0F/g, and electrochemical performance of 40.6Wh/kg-47.8Wh/kg, 6.8kW/kg-16.9kW/kg. In addition, the electrochromic-supercapacitor exhibited a long cycle life with 75.0% and 94.1% retention of its coloration efficiency and electrochemical performance over 10,000 charge-discharge cycles. Photo-responsive coloration and energy storage were demonstrated to show applicability as a smart color tunable electrochromic-supercapacitor device. Integration with a solar cell as a smart coloration in response to incident sunlight thereby supplying energy and inducing photo-responsive coloration in the fabricated smart color tunable electrochromic-supercapacitor device.

**BM08.15.07**

_Printed Conducting Polymers on Flexible and Stretchable Substrates for Wearable Electronics_  
Sneh Sinha, Yeonisk Noh, Gregory Treich, Ki Chon and Gregory Soetzing, University of Connecticut, Storrs, Connecticut, United States.

Poly (3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) is one of the most successful conducting polymers capable of carrying both ionic and electric current. Printed electronics combines the materials chemistry with the conventional printing technology resulting in high throughput fabrication of cheap and light-weight electronic devices. The work described here demonstrates printing of PEDOT:PSS onto flexible nonwoven polyester (PET) textiles as well as stretchable spandex fabric. Firstly, an optimization study was carried out to determine the relationship between number of printing layers and resistance of printed PEDOT:PSS. PEDOT:PSS based organic wires on PET was shown to have current carrying capacities approaching that of copper. To demonstrate the practical applicability of the printed wires, PEDOT:PSS wires connected to Ag/AgCl electrodes was shown to recording electrocardiogram (ECG) signal. Secondly, PEDOT:PSS wires were then combined with PEDOT:PSS electrodes on PET and ECG signal were recorded at rest in both dry skin conditions and with a moisturizing lotion on skin. Lastly, a prototype shirt was also developed with PEDOT:PSS electrodes for measuring ECG signal under exercise avoiding the need of hydrogel and adhesive around the electrode. The signal was recorded in dry skin conditions which showed an increase in amplitude because of transpiration of water vapor from the skin. The prototype was shown to be record signal even after 1 month of fabrication and also after three wash cycles. The above work focuses on designing prototype device for health monitoring from commercially available sources using a conventional screen printing process rendering it industrially scalable. The applications of this prototype could be extended beyond healthcare into military and gaming industry.

**BM08.15.09**

_High-Gain Low-Power Active-Load Monolithic Amplifier Based on Depletion-Mode Organic Field Effect Transistor (OFET) for Health Monitoring Applications_  
Chenxi Xu and Ni Zhao, The Chinese University of Hong Kong, Hong Kong, Hong Kong.

Wearable technologies have been developed rapidly recently, from tracking of personal sweat chemicals during exercise to daily cardiovascular monitoring for prevention of chronic diseases. Wearable electronics are designed to achieve high fidelity and ease of use. However, the poor signal-to-noise ratio of the measurement circuitry often limits the devices from picking up small physiological signal variations at the device-skin interface. In-situ amplification of sensor signals could be an effective way to minimize the wiring-induced noise and greatly reduce the stringent requirement of rear-end amplification circuit, and it calls for a device technology that can be easily integrated with the sensor fabrication.

Organic transistors are a suitable candidate for this application owing to their fabrication versatility, mechanical flexibility and tunable amplification gain via material engineering. In this work, we introduce a novel monolithic active-load amplifier (MALA) based on threshold-voltage-tunable depletion mode OFET, which can achieve a gain up to 34dB@17Hz with a battery voltage source. This MALA also holds a great potential to be optimized towards a fully flexible in-situ pre-amplifier utilized in biomedical signal sensing such as ECG/EMG, which will highly enhance the simplification of data acquisition circuit for wearable electronics. In this presentation I will mainly focus on the design principles of the device structure, the achievement of tunable gain via composition tuning of the active material and the implementation of MALA-assisted ECG measurement.
Ultra-Sensitive, Highly-Selective, Real-Time Chemical Wearable Sensors Based on Hydrogel Interferometer

Ximin He1, Mo Sun1, Ruobing Bai2 and Zhgang Sao2
1University of California, Los Angeles, Los Angeles, California, United States; 2Harvard University, Cambridge, Massachusetts, United States.

The fast development of wearable sensors has been promoted by the broad needs for real-time monitoring the bodily functions and air quality. Interests in many wearable sensors however have seen a decrease over time, due to the needs of frequent charging of batteries in practical usage. Wearable colorimetric sensors, using optical read-out signals under ambient light without any electronic components, become highly advantageous. Here we report an adaptive colorimetric sensing platform based on a bulk structure of covalently bonded hydrogel thin film-substrate system. External stimuli from the analytes can rapidly change the thickness of the hydrogel film, resulting in an instant color change. The soft and highly stretchable robust synthetic hydrogel materials can form a highly compliant contact human epidermis and has good self-recovery capability, as an ideal candidate for soft matrices of wearable devices. Also, this colorimetric sensing platform allows for in situ quantitative analysis by naked eye or camera via analysis app, as a wireless wearable sensing component for the next-generation textile. We have shown this customizable adaptive platform can detect a large variety of analytes including cations for hydration and other physiologic metabolic state monitoring, Cu²⁺ for Wilson's disease prescreening, glucose for diabetes monitoring, and sulfur dioxide and nitrogen dioxide for air quality detecting. This sensing platform showed a high performance on the sensitivity and response time. The limit of detection for Cu²⁺ could reach as low as 10.0 pM with only 1-2 second. Such high performance is attributed by this unique chemo-mechano-optical signal transduction mechanism, which effectively amplifies the nm-scale hydrogel thickness change to a greater and more detectable optical spectrum change. This will lead to a broad platform of a new class of wearable sensors with superior performance at low cost.

ZnO Nanostructures Based Flexible FET for Immuno-Sensing Applications

Syed K. Pasha, Fahmida Alam, Mubarak Mujawar, Nezih Pala and Shekhar Bhansali; Florida International University, Miami, Florida, United States.

Zinc oxide (ZnO) nanostructures serve as an ideal substrate for binding bio-recognition molecules viz., antibodies, aptamers, enzymes, microorganisms etc. Biocompatibility, ease of deposition and low cost makes it an ideal material for application to biosensing. The binding of biomolecules to ZnO is facilitated by the difference in the isoelectric points of the bioreceptor molecules (~5) and ZnO (~9). Using this strategy, construction of bio-functionalized field effect
transistors (FETs) is proposed here for linker-free and label-free detection of biomarkers. ZnO thin film/nanostructure-based FETs with channel length 2, 1, 0.5 mm and width as 4mm were fabricated on both rigid (Si/glass) and flexible (PET) substrates. The ZnO films were deposited using sputtering and sonochemical method. The thin film thickness varied between 30 - 100nm after deposition, the films were characterized using SEM, XRD and Raman spectroscopy. Electrical properties of the FET devices were measured using semiconductor parameter analyzer. The surface of the ZnO nanostructures was functionalized with cortisol-specific antibodies without any linker molecules for label-free detection of cortisol. Cortisol, the stress hormone is chosen as a model biomarker because of its importance in health-related disorders.

BM08.15.16 Assessment of the Chemical Properties of the Supported Monolayer CVD Grown Graphene Using a Hybrid Substrate Towards Biosensing Applications Ayaz Hassan and Frank N. Crespihllo; USP, Institute of Chemistry of Sao Carlos, Sao Carlos, Brazil.

Graphene, a 2D material exhibits exceptional electronic, thermal and mechanical properties and due to these unique properties, graphene-based materials have gained a widespread attention in various applications, including electronics, optoelectronics, semiconductors, energy storage and many others. However, to properly exploit the use of graphene in these devices, a chemical functionalization is usually required, because this approach allows the proper understanding of the electron transfer properties of these electrodes, exploitation of their physical and chemical properties and finally their use in various applications. The main approach to functionalize monolayer graphene on substrate is the covalent functionalization through diazonium chemistry. Nevertheless, due to single atomic layer, the chemical properties and hence the reactivity of supported graphene depends on various factors, including the number of layers of graphene, shape of graphene and nature of the substrate, the last one of fundamental importance in diazonium chemistry. Though several substrates have been used to evaluate the electronic properties of the graphene, in all the previous studies the graphene is mostly supported on one substrate or other. Here in this work, we proposed a hybrid substrate, based on the modification of the surface of SiO2/Si substrate with some metallic film, such as Au, Pt, Cu etc, which is lithographically decorated on SiO2/Si and then supported with monolayer chemical vapor deposition (CVD) grown graphene. The metallic substrate beneath the graphene is expected to further enhance the electronic properties of the graphene as compared to the graphene supported on SiO2/Si. This was initially observed in the diazonium chemistry, where a surface coverage of 4.3 x 10^-9 mol.cm^-2 was achieved for the graphene, supported partially on the metal and partially on the SiO2/Si, as compared to the surface coverage of 2.3 x 10^-10 mol.cm^-2 obtained for the graphene supported only on SiO2/Si; almost 20 times enhancement was achieved for the attachment of the molecules to the surface. The chemical functionalization of the graphene was confirmed through micro-FTIR spectroscopy and FTIR chemical imaging, as well as through micro-Raman spectroscopy on both kinds of substrate. The charge transfer properties of the fabricated graphene device were further evaluated through various electrochemical techniques, where a 2-3 fold enhancement in the electron transfer kinetics was achieved for the graphene supported on M-SiO2/Si (M= Au, Pt, Cu) substrate as compared to the substrate without the presence of metal i.e SiO2/Si. Our developed device may thus find potential applications in the ultra-fast and sensitive sensing of biomolecules in the biosensors and biodevices.

BM08.15.17 Multifunctional Electrospun Multilayered Separator for Flexible Battery Applications Wisawat Keaswejareansuk and Jianyu Liang; Worcester Polytechnic Institute, Worcester, Massachusetts, United States.

Lithium-ion battery (LIB) is highly demanded in rapidly developing smart and connected livings, sensorization, and wearable electronics. While the battery safety is a visible challenge beside the numerous efforts to increase electrochemical performance, the flexibility in shape and size is an important factor for moving toward those applications. A separator is an electrochemically inactive component and essential for providing safety to the battery. It is known as the weakest component because of an anisotropic characteristic of the primary commercial separator, polyolefin. Electrospinning is a simple and efficient process to create the continuous fibers at nanoscale and fabricate the high porous membranes with high surface area to volume ratio. The electrospun, non-woven mats are lightweight with spaces between the mesh for electrolyte uptake and surface functionalization. The membrane’s characteristics and properties are customized by simultaneously adjusting material parameters and regulating process parameters. In this work, the electrospun separators with multilayers of different types of polymer are created with good physical affinity. The multilayered separators offer multifunction owing to the material properties of different polymers. In this presentation, we will discuss the material selections, material and process parameters of the electrospinning, the electrospinning routines, and the characterizations of the fabricated electrospun multilayered separator, which has enhanced battery safety, increased ionic conductivity, and provided shape flexibility.

BM08.15.18 Intrinsically Stretchable Organic Electrochemical Transistors Yang Li1, Shiming Zhang2 and Fabio Cicoira1; 1Department of Chemical Engineering, Polytechnique Montreal, Montreal, Quebec, Canada; 2California NanoSystems Institute, University of California, Los Angeles, Los Angeles, California, United States.

Stretchable electronics show great significance for emerging biomedical sensing and wearable healthcare application, since it can allow intimate contact with soft objects. Recently, organic electrochemical transistors (OECTs) become suitable candidates for biological interfacing and logic circuitry applications due to the synthetic tunability, facile fabrication and bio-compatibility. However, intrinsic stretchable OECTs, which enable simple fabrication process and low cost, haven’t achieved intrinsic stretchability, due to the brittleness of conducting polymer and metal electrodes1. This talk focuses on intrinsically stretchable OECTs, which can be stretched up to 30% strain while maintaining identical transistor characteristics. The intrinsic stretchability is obtained by synergistically optimizing the processing conditions during device fabrication through which we can control the formation of microcracks in the device with a pre-set strain. These microcracks maintain the current stable while being stretched. This work paves the way for OECTs applications as conformable biosensors and its integration with wearable electronics.

BM08.15.19 Low-Cost, Mass-Manufacturable Microfluidic Systems for Wearable Diagnostic Devices Amber Routiie1, Matthew Talbot, Bailey Corless, Chris Toothaker and Caitlin Howell; Department of Chemical and Biological Engineering, University of Maine, Orono, Maine, United States.

The use of microfluidics in wearable diagnostics presents multiple opportunities for sophisticated, continuous monitoring. However, many of the most popular microfluidic components used today are typically made of materials that are expensive and difficult to manufacture on a large scale. In this work, we use an existing roll-to-roll release paper manufacturing process to create precisely patterned sheets of flexible acylated channels on a paper backing. The channels are used to direct capillary or pressurized fluid flow, mix in reagents, and direct the final sample to a detection zone. Proof-of-concept tests and theoretical modeling examined the efficacy of these systems toward applications in “smart” bandages and diapers are presented.

BM08.15.20 Transferring Microelectromechanical Devices to Breathable Fabric Carriers with Strain-Engineered Grippers Canisha Ternival, Mohammad S. Islam, Jasmin Beharic and Cindy K. Harnett; University of Louisville, Louisville, Kentucky, United States.
We demonstrate a path to transfer microelectromechanical systems (MEMS) from silicon wafers to soft, porous, fiber-based materials using strain engineering to wrap microfabricated grippers around fibers in a target mesh. Applications include sensor integration into breathable, high conduction flow-through structures like tissue engineering scaffolds, bandages, and air filters.

Grippers were made from thin-film bilayers on a silicon substrate, typically a metal on a thermal oxide, using a self-aligned lift-off and etch process to define bilayer beams with lengths in the 0.2 - 1 mm range. The patterned silicon substrate was loosely covered with a fiber mesh by taping it down at the edges. A xenon difluoride (Xactix Inc) dry silicon etcher exposed the substrate to 3 Torr XeF₂ for 20 cycles, undercutting the grippers through holes in the mesh. The compressively-stressed oxide layer caused the MEMS grippers to curl from the surface and interact with the mesh fibers. The grippers' radius of curvature was set by the thickness and elastic modulus of the layers [1].

We were able to release bilayer structures underneath 100% nylon mesh with 0.5mm to 1mm diameter openings and fiber diameters of ~50 microns. We investigated which planar layouts and curvatures worked well as grippers in this range of fiber diameter and mesh hole spacing. Because the goal is to transfer large-area integrated circuits to porous carriers, we also investigated serpentine structures to connect multiple grippers into a continuous circuit that could survive the transfer process.

Stretchable electronics fabrication generally relies on fine-tuning adhesion forces, putting some restrictions on what the carrier layer can be. In contrast to adhesion, mechanical taping makes more kinds of carrier materials available. Antibacterial, conductive, heat-responsive and other functions can be brought in by fiber networks as long as they are compatible with the highly selective silicon etch process. The grippers can also bring electronic contacts from one side of a mesh to the other, which is difficult to do on continuous thin films of other soft materials like silicone or polyimide. Our solution produces large arrays of redundant contacts that could potentially be used for connecting soft circuits without alignment [2]. When used with a stretchable mesh, this surface micromachining method provides a route for MEMS and integrated circuits to move from a small-diameter wafer to a larger surface area.


**BM08.15.21**

Conductive Silk Material Produced from Silk Fibroin and Waste Biomass Diego López Barreiro1, Zaira Martín-Moldes1, Francisco J. Martín-Martínez1, David Kaplan2 and Markus Buehler1; 1Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; 2Tufts University, Medford, Massachusetts, United States.

Silk fibrein (SF), a protein obtained from Bombyx mori cocoons, can be used to manufacture biocompatible and biodegradable materials with outstanding flexibility and mechanical properties. Activated carbons (ACs) derived from biomass are nanostructured porous materials with highly aromatic structures populated with doping elements (mainly nitrogen), and with good electron conductivity. The polar nature of the ACs facilitate their interaction with SF. Thus, combining ACs and SF to manufacture conductive silk-based materials is a promising approach to develop environmentally matched and biocompatible biomaterials where silk provides flexibility and strength, and ACs provide conductivity and mechanical reinforcement. These materials can be of interest for the biomedical field, to develop wearable sensors or conductive coatings, among other biomaterials. In this work, we present the mechanical properties, cyto compatibility and nanostructures of SF-AC biomaterials, such as membranes or hydrogels, using a synergetic approach of experimental synthesis and computational modeling.

**BM08.15.22**

Ultrathin, Stretchable, and Flexible Structural Color Filters Based on a Metal-Dielectric-Metal Structure David D. Ordinario, Hiroaki Jinno, Md Osman Goni Nayeem, Yutaro Tachibana, Tomoyuki Yokota and Takao Someya; University of Tokyo, Tokyo, Japan.

Color filters are a simple yet highly relevant device in today’s increasingly technology-driven world and can be found in a large number of applications such as displays, sensors, and photovoltaics. For flexible electronics, a flexible color filter would be suitable for a wide range of potential uses where an unusual form factor is required, or even integration with wearable devices. One important factor to consider is conformal adhesion to a complex surface while preserving filter effectiveness. Increased adhesion while preserving filter effectiveness would be highly conductive for any future applications. Here, we demonstrate ultrathin, stretchable, and flexible structural color filters based on a simple MDM (metal-dielectric-metal) structure on a 1.3 μm-thick ultrathin substrate. We first characterize the basic optical and mechanical characteristics of the flexible color filters. We next investigate how effective they are at both passing the desired wavelengths and blocking the undesired wavelengths both before and after mechanical deformation. We also describe their angular sensitivity and assess its overall impact on filter performance. Remarkably, we find that the performance of the filters is not greatly impacted by repeated mechanical deformation. Overall, our findings represent a potential strategy for making adhesive color filters with compatible mechanical properties to current flexible and/or wearable technologies without sacrificing functionality.

**BM08.15.23**

Patternable Ionic Gels for Tactile Sensors Yoon Ji Seo, Heeeun Lee, Hyemin Lee and Hyunsik Yoon; Seoul National University of Science and Technology, Seoul, Korea (the Republic of).

Wearable electronics and robotics have received attention because of potential applications such as health monitoring and rehabilitation. For the devices, there are many components which should be developed, for example, power sources, actuators, and sensors. Ionic gels have been studied to be harnessed as wearable sensors due to their high stretchability, biocompatibility and conductivity. However, when we synthesize the ionic gel in water environment, the modulus is too small to be constructed in microscale. Moreover, it is almost impossible to deposit metal films onto the gel in a vacuum condition. In this work, we present a method to prepare ionic gels without water environment to construct microscale structures, such as pillars, lines, prisms and pyramids. We fabricate tactile sensors with ionic gels with various structures and conditions and compare the electrical characteristics. Furthermore, we use a model to explain the difference and find an optimum condition.
In this work, we present the fabrication of small molecule-based intrinsic (flat-form) SOLED capable of performing under various bend and strain values (stretch). This makes it difficult to achieve the luminance in an identical CIE (wavelength) region for the same device under different strain conditions. Our approach is based on the development of a novel class of organic light-emitting diodes (SOLEDs) that can be fabricated with high efficiency and stability, even under mechanical stress.

The use of custom sensing platforms, such as electrodes, allows for the selection of optimum characteristics for the system such as: size, robustness, flexibility and biocompatibility, among others. Colibactin is a genotoxin produced by the polyketide synthase multienzyme (pks genomic island) encountered in the human gut microbiota. Many studies link colibactin production to different kinds of cancers, therefore making it a molecule of interest in the biomedical research field. More specifically, certain strains of *Escherichia coli* have been found to harbor pks genomic island that induced DNA damage. Here, we developed a PCR mediated-electrochemical protocol to successfully identify the presence of the pks genomic island in DNA samples utilizing a custom gold electrode platform. For this, pks and non-pks containing *E. coli* DNA were imidopedically analyzed before and after amplification using polymerase chain reaction (PCR) protocol. Custom DNA primers were synthesized in order to selectively amplify a specific 400 base pair sequence from the cibN gene from the pks island. Impedance data showed a 97% increase in charge transfer resistance after the protocol was applied for the pks containing samples as opposed to the 15% increase for the non-pks containing DNA samples. Overall, effective identification of the pks genomic island was achieved.

**BM08.15.24**

**Electrochemical, PCR-Mediated Biosensor for the Detection of pks Genomic Island in *E. coli* Samples Utilizing Custom Gold Flexible Electrodes**

Nadia E. Solis Marcano1, Marjorie Lopez-Nieves1, Ramon Gomez-Moreno2, Dina Bracho-Rincón1 and Carlos R. Cabrera1; 1University of Puerto Rico, Rio Piedras Campus, Carolina, Puerto Rico, United States; 2University of Puerto Rico Medical Science Campus, San Juan, Puerto Rico, United States.

The detection of heavy metal ions is of great significance in healthcare, environmental monitoring and drinking water safety. The current states of strategies for heavy metal detection in water are mainly focusing on electrochemical and optical techniques, which are restricted to laboratory testing due to the bulky and expensive instrument involved. The emergence of the microfluidics technology coupled with flow-induced electrochemical has boosted the development of innovative self-powered micro-sensors. We here demonstrate a soft self-powered microfluidic sensor mainly constructed by PDMS. The working mechanism of the sensor is based on liquid-solid contact electrification between the testing liquid sample and the sensing channel and its modification with metal ions coordinating. When flowing samples into the sensor, their electrochemical potentials can be determined by measuring the static induction current over an electrode patterned on the channel's outer surface. Once metal ions from the sample are captured onto the channel surface, the flowing electrification effects would be alerted due to the changes of surface potentials, which are highly sensitive to ions concentration. Only a small amount of liquid samples (~30 μL) is needed in this method. By measuring the potential generated from Pb²⁺ solution is more than 2.5 times larger than that from Cu²⁺, Zn²⁺ and Al³⁺, indicating selectively sensing capability of the sensor. Moreover, the polyurethane (PU) encapsulation was performed on the SOLED devices, which enabled it to be water-resistant and the device's operation with a small decrease in efficiency. AgNW-PU electrode was utilized as anode, which maintained a high conductivity (low sheet resistance of 20 Ω/sqr) up to a strain of 50%.

**BM08.15.25**

**Dispersion Methods of Nanoparticles in Stretchable PDMS and Their Dielectric Constant to Fabricate Electroadhesion Gripper**

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Polymer/nanoparticle (NP) composite is well known methodology to improve physical and chemical properties depending on its polymerization conditions and kind of NPs such as TiO₂, SiO₂, Al₂O₃ and BaTiO₃. However, when we applied high amount of NPs, the aggregation was occurred due to its dispersion. To overcome this problem, we optimized the dispersion by choosing the suitable dispersion method according to the viscosity of composites. In less than 10,000 CPS, homogenizer and Ultrasonicator were used to mix NPs into polymers. Higher than 10,000 CPS, however, it is almost impossible to mix NPs into polymer so we changed mixer to plenary machine in the high viscous condition. As a result, a well dispersed polymer/NP composite was fabricated with higher than dielectric constant of 4 via its equipment and observed by HR-SEM and TEM. Furthermore, the high dielectric constant layers were applied to an electrical adhesion robot gripper comprised of robot arm, skin layer and EA layer based on stretchable polymer. The gripper was controlled with voltage ON/OFF to attach and detach target materials.

**BM08.15.26**

**A Soft Self-Powered Microfluidic Sensor for Heavy Metal Ions Detection**

PeiXi Song1,2, Guang Yang2 and Ken-Tye Yong2; 1School of Physics, Huazhong University of Science and Technology, Wuhan, China; 2School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

The use of custom sensing platforms, such as electrodes, allows for the selection of optimum characteristics for the system such as: size, robustness, flexibility and biocompatibility, among others. Colibactin is a genotoxin produced by the polyketide synthase multienzyme (pks genomic island) encountered in the human gut microbiota. Many studies link colibactin production to different kinds of cancers, therefore making it a molecule of interest in the biomedical research field. More specifically, certain strains of *Escherichia coli* have been found to harbor pks genomic island that induced DNA damage. Here, we developed a PCR mediated-electrochemical protocol to successfully identify the presence of the pks genomic island in DNA samples utilizing a custom gold electrode platform. For this, pks and non-pks containing *E. coli* DNA were imidopedically analyzed before and after amplification using polymerase chain reaction (PCR) protocol. Custom DNA primers were synthesized in order to selectively amplify a specific 400 base pair sequence from the cibN gene from the pks island. Impedance data showed a 97% increase in charge transfer resistance after the protocol was applied for the pks containing samples as opposed to the 15% increase for the non-pks containing DNA samples. Overall, effective identification of the pks genomic island was achieved.
The approach mentioned in this work has high potential to realize small molecule-based intrinsic water-resistant SOLEDs, which can provide high performance under strain without any shift in the CIE.

BM08.15.28
Soft Knee-Exoskeleton System Using Variable-Stiffness Magnetorheological(MR) Gel to Reduce the Energy Cost of Human Walking Jung Hwan Youn1, Yun Soo Back2 and Kil Kuk Kyung3; 1Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of); 2Department of Mechanical Engineering, Yonsei University, Seoul, Korea (the Republic of); 3Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

Robotic exoskeletons have been investigated for assisting or enhancing human activities and rehabilitation. Although direct-driven actuators such as motors or hydraulic actuators are widely used in wearable robot applications, due to small torque to weight ratio making the system bulky and heavy, previous systems often deliver discomfort or even pain to users as well as insufficiency of use.[1,2] One recent approach for better efficiency is a Variable Stiffness Actuator(VSA) based wearable mechanism which modulates stiffness at joint in accordance with monitoring user requirement in real time. It is reported that VSA approach significantly reduces in energy expenditure and transmitted force of user and improve human-robot interaction.[3] However, as previously suggested VSAs are designed to have high stiffness and heavy structure, in addition to have the function of lightening the burden of the wearers during walking, the VSAs have challenges in low impedence and high flexibility for enhancing usability. [4]

In this research, a new type of VSA with light weight, compact size and simple structure using variable stiffness material, MR(Magnetorheological) Gels, is proposed. MR Gels are composite gels containing magnetic particles suspended in soft polymer gel. MR Gels have advantage of being able to control initial viscosity, storage modulus and resistance by tuning external magnetic field. In the research, MR gels are fabricated by mixing carrageenan mixture and micron size carbonyl iron particles(CIPs) with 60wt% in room temperature. Various properties tests have been conducted and results showed under 180mT of applied magnetic field, Young’s modulus of carrageenan MR Gel changed from 16.7kPa to 33.3kPa(99.4% change) and resistance of MR Gel changed 4.52MΩ to 3.15 MΩ(30.3% change). By modulating the Young’s modulus of MR Gel with external magnetic field, MR Gel is used as VSAs. Moreover, MR Gel can be used as a type of magnetic sensor by measuring the resistance. In the future, knee-exoskeleton system is developed using self-sensing MR Gel VSA, and performance will be evaluated.


BM08.15.29
Fabrication of Capacitive Pressure Sensor Using Single Crystal Diamond for Micro-Electromechanical Systems Jiao Fu, Tianfei Zha, Hong-Xing Wang, Zhangcheng Liu, Zongchen Liu, Dan Zhao, Yan-Feng Wang, Xiaohui Chang and Gaoqing Shao; Xi’an Jiaotong University, Institute of Wide Bandgap Semiconductors, Xi’an, China.

Diamond is the ideal material for high-performance MEMS devices due to its outstanding properties, such as extremely high Young’s modulus, low mass density, the highest thermal conductivity, high corrosion resistance and biocompatibility. However, the micro-machining of three-dimensional structures in bulk diamond is technologically difficult. In this paper, single crystal diamond (SCD) capacitive pressure sensor has been successfully carried out. Firstly, the SCD cantilever has been fabricated on HPHT diamond substrate by using selective high-energy ion implantation, metal patterning, ICP etching and electrochemical etching techniques. Secondly, the diamond cantilever was treated with photolithography and metal evaporation techniques to pattern the desired electrode patterns for electrical measurements of capacitive pressure sensor. Furthermore, the displacement of cantilever under different pressure conditions were investigated by atomic force microscopy. The capacitance variations of SCD cantilever as a function of electrodes space were measured by using Agilent B1505A parameter analyzer. The results show that sensitivity increases with electrode area of cantilever increasing and decreases with measurement frequency increasing.

BM08.15.30
Wearable and Luminescent Oxygen-Sensing Films with Improved Sensitivity Based on Light Scattering by TiO2 Particles Changjin Lim and Jin-Woo Park; Yonsei University, Seoul, Korea (the Republic of).

Oxygen (O2) is an essential element for energy production and cellular respiration in a human body. Insufficient O2 delivery can cause peripheral artery diseases (PAD) such as cancers, diabetic foot ulcer, and Raynaud’s disease. Based on the fact that transcutaneous oxygen pressure (tcpO2) is proportional to O2 concentration of tissues, research for measuring tcpO2 in real time and in a large area have been done to diagnosis and monitor PAD. As a golden standard for sensing tcpO2, Clark electrode has been extensively used, which operates based on electrochemical reaction. However, this method is an invasive technique accompanying pain and consumes O2 during the measurement. Recently, luminescence-based O2 sensing mechanism has been studied as non-invasive method and for a large-area mapping of O2 distribution. The new concept of luminescent tcpO2 sensor consists of an O2 sensing mechanism has been studied and a photodiode as the photoluminescence (PL) detector. The luminescent oxygen sensors can be based on either the photoluminescence intensity or light-quenching lifetime of the sensing films. The ratiometric method based on the intensity analysis approach has been introduced to provide a low-cost technique capable of quantitatively and accurately measuring the oxygen distribution over large areas. However, to utilize the ratiometric method, the sensitivity of intensity-based methods to ambient light, photobleaching, and self-quenching of dye molecules should be minimized for accurate analysis. To improve the signal-to-noise ratio and sensitivity (\(I_0/I\)) of the oxygen sensor, in this study, we investigated the effects of embedded titanium dioxide (\(TiO_2\)) nanoparticles on the photocurrent and sensitivity of luminescent oxygen-sensing films based on platinum octaethylporphyrin (PtOEP), which is an indicator dye. The effects of the particle size and n on the photocurrent and \(I_0/I\) of the oxygen sensor were investigated based on Mie light-scattering theory.\(^{25}\) The diameter and n of the \(TiO_2\) nanoparticles were varied by the simple processes of laser irradiation and thermal annealing. Finally, an integrated sensing platform (luminescent sensor) was made with the sensing film with \(TiO_2\), and it was confirmed that the photocurrent and sensitivity of the oxygen-sensing films were greatly improved with increases in the size and refractive index (n) of the embedded \(TiO_2\) nanoparticles. Furthermore, the improvements in the photocurrent and sensitivity of the oxygen-sensing films allowed the fabrication of a high-resolution oxygen-sensing film that can detect the oxygen distribution over large areas.

BM08.15.31
Fabrication of Flexible and Wearable Thermoelectric Fibers with Micro- and Nanoscale Structures Based on Laser-Induced In-Fiber Capillary Instability Jing Zhang, Ting Zhang and Lei Wei; School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore.

High-performance flexible and wearable thermoelectric (TE) devices are increasingly needed in many applications for thermal energy conversion. Well-designed thermoelectric devices open a path to recycle waste heat energy owing to its intrinsic capacity. Unfortunately, existing TE devices with high
energy conversion efficiency are mainly constituted by inorganic TE materials, making those devices inflexible and bulky. Thus they are unsuitable for using on heat sources with irregular or curved surfaces. To bridge the gap, we develop a flexible and ultralong TE fiber with precisely patterned micro- and nanoscale in-fiber structures. The fabrication process that takes advantages in thermal drawing process and laser-induced in-fiber capillary instability phenomenon is designed and realized in this study.

Our process begins with the fabrication of a macroscopic preform, next we scale down the preform into micro- or nanoscopic fibers by thermal drawing. The prior issues in multi-materials fiber thermal drawing process are to match the melting/softening temperatures and the linear thermal expansion coefficients of the fiber core and cladding materials. Herein, we choose p-type Bi$_2$Sb$_3$Te$_6$ and n-type Bi$_2$Se$_3$ as the TE fiber core and the borosilicate glass as the fiber cladding. To achieve mechanical protection, a polymer layer is also coated onto the fiber outer surface. We calculate the thermal conductivities of 0.839 W/m K for the n-type fiber and 0.844 W/m K for the p-type fiber and obtain the ZT values of 0.23 for the n-type fiber and 1.25 for the p-type fiber at room temperature.

Furthermore, TE fibers with multiple functionalities and energy-storage capabilities could be achieved by patterning designed structures in fibers with functional materials such as metals and semiconductors. To avoid mixing and disrupting the device structures during the fiber thermal drawing process, we introduce a method that utilizes the in-fiber capillary instability phenomenon to define the inner structures of multi-functional TE fibers. A CO$_2$ laser serves as heating source induces the capillary instability occurring at certain positions of fiber. The instability transforms continuous fiber core into designed and periodic micro- and nanoscale structures, such as spheres, rods, and spindles by carefully determining the laser treatment parameters. This step brings TE functional materials to interact with other materials (such as metal and semiconductors) in a precisely controlled procedure, forming a ladder-like structure in fiber. This structure makes energy conversion much feasible and efficient in the TE fiber. More importantly, the combination of fiber thermal drawing process and utilizing in-fiber capillary instability phenomenon could offer more design spaces and finally lead to high-performance, micro- and nanoscale, flexible and wearable TE devices to be available in the near future.

**BM08.15.32**
Highly Sensitive Flexible Capacitive E-Skins with Biomimetic Ionic Gel Jingyi Yang and Chuanfei Guo; Southern University of Science & Technology, Shenzhen, China.

Flexible electronic skins (e-skins) with high sensitivity and low-cost fabrication have been intensively desired in human motion detection, health monitoring, soft robotics, etc. Capacitive type flexible e-skins usually improve sensitivity though introducing surface microstructures, but the change of the dimensions in dielectric layer is quite limited thus the improvement is also limited. Herein, we demonstrated a low-cost and highly sensitive flexible capacitive e-skin with biomimetic ionic gel (BIG). The BIG film with uniform cone-like microstructures, is templated from a Calathea zebrine leaf through soft lithography. Both the top and bottom electrodes are fabricated via spraying AgNWs onto a colorless polyimide (CPI). The device is in framework of CPI/AgNWs/BIG/AgNWs/CPI. Owing to the electrical double layer contributed by BIG film, this device exhibits a ultralow limit of detection around 0.1 Pa, and a ultrahigh sensitivity of 54.31 kPa$^{-1}$ in low pressure regime (<0.5 Pa), and a strong response of larger than 1 kPa$^{-1}$ over a wide range of pressure from 0.1 Pa to 15 kPa. Such high performance e-skins have great potential in motion monitoring, health monitoring and human-machine interaction, etc.

**BM08.15.33**
Implanted Battery-Free Direct-Current Micro-Power Supply from In Vivo Breath Energy Harvesting Jun Li, Lei Kang, Yin Long, Hao Wei, Weibo Cai and Xudong Wang; University of Wisconsin-Madison, Madison, Wisconsin, United States.

Majority of current IMDs are powered by conventional primary or secondary batteries that contribute up to 90% weight and volume of the entire device. [1,2] While replacement of or recharging the batteries requires substantial surgical or technical efforts, introducing additional suffering and complexity to the patients, other batteries potential issues such as overheat and leakage of toxic electrolyte further prohibit the advancement and miniaturization of IMDs. Therefore, increasing efforts are now being focused on the innovation of designated IMD power sources. Implantable nanogenerators (i-NGs) have been designed to convert biomechanical energy into electricity. [3,4] In spite of their numerous merits, the outputs of state-of-the-art i-NGs are always in a form of largely discrete pulses. Although their theoretical output power could be sufficient for IMDs, battery component is still needed in the i-NG design to produce a steady and useable direct current (DC) output. Moreover, most i-NGs are non-stretchable with incompatible mechanical properties compared to soft biological tissues, which further challenges their practical applications.

In this work, we reported an ultra-soft stretchable i-NG system that could function as a battery-free DC micro-power supply. The i-NG consisted of ultrafine micro-scale interdigital electrodes (IDEs) and multi tribo-active layers with a small working area (approximately 2 cm$^2$), packaged by biocompatible silicone elastomer. While the micro IDEs support the output of high frequency electricity (1 μA at 70 Hz) driven by slow mechanical stimulation, the silicone elastomer and an embedded cavity design enable i-NGs with extremely low Young’s Modulus (46 kPa), exactly matching the mechanical property range of most soft biological tissues. By implanted inside the abdominal cavity of Sprague Dawley (SD) adult rats, the i-NG could convert slow diaphragm movement during normal breath into stable high-frequency electrical spikes, which were readily transmitted into a continuous ~2.2 V DC output on a LED load after being integrated with a basic electrical circuit (rectifier and capacitor) for a relatively long period of time.

This electric output could continuously power the LED without any observable power decay, successfully demonstrating a constant operation of small electronics DC power free of the battery component. This solely biomechanical-energy driven DC micro power supply offers a very promising solution for the development of self-powered IMDs in the near future.

References:

**BM08.15.34**
Bio-Inspired Structural Designs for Bendable, Foldable and Stretchable Lithium-Ion Battery with High Energy Density Xiangbiao Li, Guoyu Qian, Yuan Yang and Xi Chen; Columbia University, New York, New York, United States; ‘Earth and Environmental Engineering, Columbia University, New York, New York, United States.

Flexible batteries are attractive for wearable devices for various applications, such as health care. It is challenging to achieve high energy density and high mechanical flexibility simultaneously. In this work, we propose feasible and scalable strategies to fabricate flexible lithium-ion batteries, which can concurrently obtain high energy density and mechanical flexibility, including bendability, foldability, twistability and stretchability. Inspired by the structure of animal spine, the vertebrae-like hard segments with multiple layers of conventional anode/separator/cathode stack to offer energy storage are...
interconnected by the soft components as narrow with the monolayer stack to provide flexibility. Its nonoptimized energy density of 242 Wh/L can be over
85% of a standard prismatic cell. It should be emphasized that the improved design allows the battery to sustain stable elecetrochemical performance even
upon continuous dynamic mechanical deformation including twisting and bending (Guoyu Qian, Bin Zhu, Xiangbiao Liao, et al. Advanced Materials 30.12
(2018): 1704947). Additionally, a wrinkling structure replacing the flat interconnector in between two hard segments is introduced to realize stretchability
up to 50%. To further improve energy density and mechanical stability, we minimize the width of soft components by asymmetrically folding one long
strip of electrode stack, where complex fabrication process of winding and cutting is not needed. Thanks to this improved design, the battery exhibits
excellent mechanical and electrochemical stability upon up to 180 degree folding. Our facile and scalable designs of flexible lithium ion battery potentially
play an important role in wearable electronics.

BM08.15.35
Applicable Phase Transition Capsule to Smart Fabric for Thermal Energy Storage Youngkyun Jung1, Taegu Do1, Youngsang Chun2 and Young Gun
Ko2, 1Korea Institute of Science and Technology, Seoul, Korea (the Republic of); 2KAERI, Daejeon, Korea (the Republic of).

The need for the manufacturing of innovative fabric product has been required for using the waste heat. Fiber and fibril which have automatic
acclimatising properties have recently attracted more attention. The phase transition capsules (PTCs), which can storage the thermal energy using the latent
heat from solar heat and body temperature, have been highlighted. In order to apply the PTCs to industrial fields, the metallic, inorganic, or polymeric shell
coated PTCs had been studied. However, metallic and inorganic shell is corrodirable in aqueous liquid such as water and perspiration, and polymeric shell
has low thermal conductivity. Furthermore, because the previously studied capsules have low core content, the capsules have low thermal energy capacity.
In this work, we used Pickering emulsion based encapsulation method to enhance the core content for high thermal energy capacity, and encapsulated the
phase transition material (PTM) with water-absorbable polymeric shell to enhance the thermal conductivity. Paraffin wax was used as core thanks to its
high heat storage capacity and nontoxic properties. And the poly(2-hydroxyethyl methacrylate) (pHEMA), a water-absorbable polymer, was used as a shell
because the pHEMA can show high thermal conductivity after absorbing a water. The thermal conductivity of pHEMA was measured according to the
water content by LFA, and the thermal conductivity of fully hydrous pHEMA was measured to be 0.45 W/m K which is far higher than the other polymers.
The manufactured PTC showed good durability owing to the flexibility and elasticity of hydrous pHEMA. The thermal storage properties of the PTC were
measured by DSC, and the thermal storage capability of the PTC was calculated to be 99.7%, which is higher than previously researched other PTCs
thanks to its high core content.

Our study demonstrates that the PTCs with water-absorbable polymer are an attractive material for effective thermal storage and delivery. In addition to the
use of the PTCs as thermal energy carrier, the PTCs can become an attractive material for various heat sensitive industrial fields, such as wall materials of
buildings or houses, refrigerator vehicles, and outdoor wear by storage and release thermal energy.

BM08.15.36
Mapping Strain/Pressure with ZnO Nanowire Arrays by Piezotronic and Piezo-Phototronic Effect Chunfeng Pan1, Xiaojia Zhang1 and Zhong Lin
Wang1, 1University of Chinese Academy of Sciences, Beijing, China; 2Georgia Institute of Technology, Atlanta, Georgia, United States.

Emulation of human senses via electronic means has long been a grand challenge in research of artificial intelligence as well as prosthetics, and is of
pivotal importance for developing intelligently accessible and natural interfaces between human/environment and machine. In this talk, we present a novel
design of ZnO nanowire arrays, which can be used to directly record the strain distribution by piezotronic and piezo-phototronic effect.

First, we have reported large-array three-dimensional (3D) circuitry integration of piezotronic transistors based on vertical zinc oxide nanowires as active
taxel-addressable pressure/force-sensor matrix for tactile imaging with a high resolution of 100 μm3. The device matrix has been demonstrated for
achieving shape-adaptive high-resolution tactile imaging and self-powered, multi-dimensional active sensing. However, the signal of the piezotronic
transistors array is the change of the resistance of each NWs, which can only be measured in a series way. That means such piezotronic transistors array can
only mapping a static strain.

Different with the electrical signal, the optical signal can be measured in a parallel way. In our previous work, we have demonstrated how the piezo-
phototronic effect can be effectively utilized to enhance the emission intensity of an n-ZnO/p-GaN NW LED. Here, we extend the single NW device to
NW LEDs array, for pressure/force sensor arrays for mapping strain with a resolution as high as 2.7 μm. Such sensors are capable of recording spatial profiles of pressure distribution, and the tactile pixel area density of our device array is 6250000/cm2

When the device is under pressure, the images unambiguously show that the change in LED intensity occurred apparently at the pixels that were being
compressed by the molded pattern, while those were off the molded characters showed almost no change in LED intensity. Instead of using the cross-bar
electrodes for sequential data output, the pressure image is read out in parallel for all of the pixels at a response and recovery time-resolution of 90 ms. This
may be a major step toward digital imaging of mechanical signals by optical means, with potential applications in touch pad technology, personalized
signatures, bio-imaging and optical MEMS.

Furthermore, our recent studies achieve such piezo-phototronic effect induced strain mapping in a flexible n-ZnO NWs/p-polymer LEDs array system
composed of PEDOT:PSS and patterned ZnO NWs with a spatial resolution of 7 μm for mapping of spatial pressure distributions. The emission intensity
of the LED array sensor matrix is dominated by locally applied strains as indicated by piezo-phototronic effect. Therefore, spatial pressure distributions are
immediately obtained by parallel-reading the illumination intensities of LED arrays based on electroluminescence working mechanism. A wide range of
pressure measurements from 40 MPa to 100 MPa was achieved through controlling the growth conditions of ZnO nanowire array

BM08.15.37
Free-Standing Graphene Films Prepared via Foam Film Method for Impressive Performance Flexible Supercapacitors Zhu Yucan, Xingke Ye,
Hedong Jiang and Chuyang Jia; University of Electronic Science and Technology of China, Chengdu, China.

Supercapacitor is regarded as the ideal power source in wearable electronic device, the electrode materials of which are always research focus due to it is a
key component in the supercapacitor. Among numerous electrode materials, graphene has attracted significant attention for its outstanding electrochemical
performance and mechanical properties, which endows graphene films with great potential of applications in future flexible electronics. Therefore,
effective preparing methods of graphene films were researched and reported extensively in recent years. Herein, we fabricate a novel graphene oxide (GO)
film with excellent mechanical properties via foam film method. Its thickness can be simply regulated by changing the concentration of the surfactant.
After chemical reduction, the reduced GO (rGO) films exhibit impressive electrical conductivity of ~172 S cm⁻¹. The supercapacitors based on the
fabricated rGO films exhibit satisfied capacitive performance of ~56 mF cm⁻² at 0.2 mA cm⁻² with 6 M KOH solution. Furthermore, the flexible all-solid-
state supercapacitors (FSSCs) based on the rGO films also show great volumetric capacitance of ~2810 mF cm⁻³ at 12 mA cm⁻² (~1607 mF cm⁻³ at 613 mA
cm⁻²) with polyvinyl alcohol-KOH gel electrolyte, which indicates great rate performance of solid-state devices. Besides, the supercapacitor also show
great cycling stability and flexibility: after 10000 cycles and continuously bent to 180° for 300 times, the volumetric capacitance of the FSSC remains at
81.4% and 90.4% of its initial capacitance value, respectively. All the results demonstrate the free-standing rGO films prepared via foam film method in
this study could be considered as promising electrode materials for high performance flexible supercapacitors.

BM08.15.38
Flexible all-solid-state supercapacitor is highly desired for integration with flexible electronic products. However, most current flexible supercapacitor electrodes show mediocre performance, especially for high mass loading electrodes. Herein, we report high performance chlorine-doped (Cl-doped) graphene films with either low or high mass loading prepared by a facile hydrothermal method. Benefiting from the enhanced electroconductivity and electrochemical activity resulted from Cl-doped effect, the film electrode with 1.06 mg cm\(^{-2}\) shows a high gravimetric capacitance of 210 F g\(^{-1}\) at 1 A g\(^{-1}\) and the capacitance of the electrode still remains 71.2% (149.5 F g\(^{-1}\)) at 100 A g\(^{-1}\). Moreover, when the mass loading of the film increases to 10.1 mg cm\(^{-2}\), the gravimetric capacitance can retain 92% (193.2 F g\(^{-1}\)) at 1 A g\(^{-1}\), showing little decrease compared with that of low mass loading film. Besides, the film shows a high areal capacitance of 2110 mF cm\(^{-2}\) and 1487 mF cm\(^{-2}\) at 1 mA cm\(^{-2}\) and 50 mA cm\(^{-2}\), respectively. Furthermore, a symmetric flexible all-solid-state supercapacitor is assembled by two films with 11.0 mg cm\(^{-2}\) mass loading. The flexible all-solid-state supercapacitor shows almost the same capacitance under different bending angles and can retain 98% capacitance after bending 500-time. The flexible all-solid-state supercapacitor also shows a high areal energy density of 160.7 µWh cm\(^{-2}\). All the above results demonstrate Cl-doped graphene electrode is a promising material for flexible all-solid-state supercapacitor.

**BM08.15.39**

Bioresorbable Silicon Nanomembranes and Iron Catalyst Nanoparticles for Neurotransmitter Sensors

Seung Min Yang, Hyun-Seung Kim, Tae-Min Jang and Suk-won Hwang; KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul, Korea (the Republic of).

We introduce a strategy of materials synthesis, characteristic evaluations and manufacturing process for a mechanically elastic, biologically safe silicon-based dopamine detector that is designed to be completely transient, i.e. dissolved in the brain and/or other body organs after a desired period of operation. Dopamine is an electroactive neurotransmitter released by the brain, playing critical roles in the mammalian central nervous system. Abnormal lack of dopamine levels in the brain has been implicated in chronic neurological disorders such as Parkinson’s disease, Attention deficit hyperactivity disorder (ADHD), schizophrenia. Therefore, rapid and sensitive detection of dopamine has been required for accurate diagnosis and monitoring of such diseases. A fundamental mechanism responsible for dopamine detection is that dopamine molecules are adsorbed onto the CPPy surface of the hybrid NPs (Fe\(^{III}\)_CPPy NPs) via pi-pi interactions and oxidized to form dopamine-derivative quinone, i.e. dopamine-o-quinone, catalyzed by a number of transition metal (Fe) NPs. As a result, generated electrons from the reactions transferred to highly p-doped Si NMs-based electrodes contributed to modulations in electrical characteristics. Use of inexpensive, bioresorbable iron (Fe) nanoparticles (NPs) is one of attractive choices for efficient catalytic oxidation of dopamine as an alternative for noble, non-transient platinum (Pt) nanoparticles, based on extensive studies of synthesized materials and catalytic reactions. Arrays of transient dopamine sensors validate electrochemical functionality to determine physiological levels of dopamine and to selectively sense dopamine in a variety of neurotransmitters, illuminating feasibilities for a higher level of soft, transient electronic implants integrated with other components of overall system.

**BM08.15.40**

Flexible Ferroelectric Nanocomposite Film for Enhanced Triboelectric Effect

Huidrom Hemojit Singh and Neeraj Khare; Department of Physics, Indian Institute of Technology Delhi, New Delhi, India.

Triboelectric nanogenerators (TENGs) are the devices which can convert low-frequency mechanical vibrations into electrical energy. These devices can be used for sustainable energy source as there are abundant mechanical vibrations like muscle contraction, body movement, vehicular movements, ocean waves, etc.[1-2] Moreover, these devices are easy to fabricate, robust and not costly. However, there is a need to enhance their output power so that it can be used effectively for driving the electronic devices.[3-5]

In the present work, we have prepared a flexible nanocomposite film of polyvinylidene fluoride (PVDF) with hydrothermally synthesized ZnO nanorods embedded inside it. The flexible nanocomposite film shows an enhanced triboelectric effect. The triboelectric nanogenerator fabricated by coupling ZnO-PVDF flexible nanocomposite film with polytetrafluoroethylene (PTFE) shows a much enhanced triboelectric output of voltage of ~119 V and short circuit current of ~1.6 µA. The device gives an instantaneous output power of ~10.6 µW cm\(^{-2}\). The instantaneous power is 65.6% more as compared to PVDF/PTFE based TENG. Upon analysing the possible factors contributing the enhanced triboelectric effect of PVDF with the incorporation of ZnO into it, it is found that the enhancement in the triboelectric effect is due to (1) the increase in β-phase content of PVDF, which increases the polarizability of PVDF/PTFE based TENG. Upon analysing the possible factors contributing the enhanced triboelectric effect of PVDF with the incorporation of ZnO into it, it is found that the enhancement in the triboelectric effect is due to (1) the increase in β-phase content of PVDF, which increases the polarizability of

**BM08.15.41**

Highly Conductive and Flexible Composite Integrated with Personal Earphone for Simple, Wireless, Real-Time Monitoring of Electrophysiological Signs

Joong Hoon Lee1, Ji-Young Hwang2, Jia Zhu3, Ha Ryeon Hwang1, Seung Min Lee4, Huanyu Cheng3, Sang-Hoon Lee1, 5 and Zhongquan Wan; University of Electronic Science and Technology of China, Chengdu, China.

Institute of Carbon Convergence Technology, JEONJU, Korea (the Republic of); 3The Pennsylvania State University, University Park, Pennsylvania, United States; 4Kookmin University, SEOUL, Korea (the Republic of); 5Biomedical Engineering, Korea University, SEOUL, Korea (the Republic of).

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**References**

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**BM08.15.41**

Highly Conductive and Flexible Composite Integrated with Personal Earphone for Simple, Wireless, Real-Time Monitoring of Electrophysiological Signs

Joong Hoon Lee1, Ji-Young Hwang2, Jia Zhu3, Ha Ryeon Hwang1, Seung Min Lee4, Huanyu Cheng3, Sang-Hoon Lee1, 5 and Suk-won Hwang1; KU-KIST Graduate School of Converging Science and Technology, Korea University, SEOUL, Korea (the Republic of); 1Korea Institute of Carbon Convergence Technology, JEONJU, Korea (the Republic of); 2The Pennsylvania State University, University Park, Pennsylvania, United States; 3Kookmin University, SEOUL, Korea (the Republic of); 4Biomedical Engineering, Korea University, SEOUL, Korea (the Republic of).

Electroencephalogram (EEG) is one of most important noninvasive brain signal measurement method to diagnose various brain diseases on the scalp. With the advance of science and technologies, diverse EEG applications have been developed in various areas such as ubiquitous (U)-healthcare and brain computer interface (BCI). In addition, simple and insensible recording of EEG is highly required for EEG applications. Therefore, many different wearable EEG sensors have been developed for simple and comfortable EEG recording. However, conventional EEG sensors still have limitations such as ugly wearing, reliability and inconvenience.

We introduce optimized elastomeric conductive electrodes using a mixture of silver nanowires (AgNWs) with carbon nanotubes/polydimethylsiloxane (CNTs/PDMS), to build a portable earphone type of wearable system that is designed to enable recording brain activities as well as listening to music at the same time. A custom-built, plastic frame integrated with soft, deformable fabric-based memory foam of earmuffs facilitates essential electronic components, such as conductive elastomers, metal strips, signal transducers and a speaker. Such platform incorporates with accessory cables to attain wireless, real-time monitoring of electrical potentials whose information can be displayed on a cell phone during outdoor activities and music appreciation. Careful evaluations on experimental results reveal that the performance of fabricated dry electrodes are
comparable to that of commercial wet electrodes, and position-dependent signal behaviors provide a route toward accomplishing maximized signal quality. This research offers a facile approach for a wearable healthcare monitor via integration of soft electronic constituents with personal belongings.

**BM08.15.43**

**Flexible PVDF Based Nanocomposite Piezoelectric Nanogenerators for Enhanced Performance** Neeraj Khare and Huidrom Hemojit Singh; Department of Physics, Indian Institute of Technology Delhi, New Delhi, India.

The number of electronic devices used in our daily life has been increasing tremendously since the last decades. Several devices require only few milli-watt power. Piezoelectric nanogenerators based on the flexible piezoelectric polymers mainly Polyvinylidene fluoride (PVDF) is a path-breaking device that can power these small-scale electronic devices directly [1-2]. Although the intrinsic piezoelectric property of PVDF is low, many methods have been employed to enhance the piezoelectric property like thermal treatment, mechanical stretching and electrical poling [3]. In the present work, we will compare the performance of piezoelectric nanogenerator fabricated using various PVDF nanocomposite films. We have achieved enhanced piezoelectric property of PVDF just by adding nanostructures such as ZnO, NaNO3, BaTiO3 without any further heat, electrical or mechanical treatment. XRD, polarization-electric field (P-E) measurement, Fourier transform infrared spectroscopy (FTIR) measurements have been performed, and the reason behind this enhancement in the piezoelectric property has been analyzed and discussed. We have compared the enhancement by adding a different amount of nanofillers of different shapes, and this gives a brief idea of choosing the appropriate nanofillers for enhancing the piezoelectric property of PVDF. Comparison of the performance of these nanogenerators fabricated from PVDF nanocomposites will be presented.

**References**


**BM08.15.44**

**Stiffness Tunable (ST3R) Composite by Mechanical Actuation** Boyce S. Chang, Ravi Tutika, Michael D. Bartlett and Martin Thuo; Materials Science and Engineering, Iowa State University, Ames, Iowa, United States.

Smart responsive composites can be realized using various stimuli including heat, light, swelling, electricity, and magnetic fields to induce a change in material properties. Synthetic challenges, however, impede the fabrication of mechanically responsive materials. We report a thermodynamically driven mechanically responsive composite, exploiting irreversible phase-transformation (relaxation) of metastable undercooled liquid metal core shell particle fillers. As the composite is deformed, the core shell architecture is broken, leading to solidification of the undercooled liquid metal. This results in a 300% increase in Young’s modulus. In contrast to previous phase change materials, this dramatic change in stiffness occurs autonomously under deformation, is insensitive to environmental conditions, and does not require external energy sources such as heat, light, or electricity. We demonstrate the utility of this approach by transforming a flat, flexible composite strip into a rigid, 3D structure that is capable of supporting 50x its own weight. The ability for shape change and reconfiguration are further highlighted, indicating potential for multiple pathways to trigger or tune composite stiffness.

**BM08.15.45**

**Flexible Organic/Inorganic Hybrids for High-Performance Wearable Thermoelectrics** Zimeng Zhang and Shiren Wang; Texas A&M University, College Station, Texas, United States.

Flexible organic-inorganic hybrids are promising for high-performance wearable thermoelectric materials. However, current organic/inorganic hybrids suffer from inferior thermoelectric properties due to aggregate nanostructures. In this paper, we fabricate flexible organic-inorganic hybrids by incorporating monodispersed Bi2Te3 nanoparticles into the continuous conductive polymer phase at different loading fraction while no nanoparticle percolation is observed. Monodispersed and non-percolated nanoparticles significantly scatter phonons while continuous polymer phase facilitate the electronic transport, resulting in ultrahigh power factor of \(-1350 \mu W m^{-1} K^{-2}\) and ultralow in-plane thermal conductivity of \(-0.7 W m^{-1} K^{-1}\). Consequently, figure-of-merit (ZT) of 0.58 is obtained at room temperature, outperforming all reported flexible thermoelectric materials. Thermoelectric properties of as-fabricated hybrids show negligible change for bending 100 cycles, indicating superior mechanical flexibility. These findings provide significant scientific foundation for shaping flexible thermoelectric functionality via synergistic integration of organic and inorganic components.

**BM08.15.46**

**3D Printing of Kirigami-Inspired Structures for Flexible Electronics** Derrick Bamerige, Muthirthi-David Kern, Xochitl C. Hernandez and Konstantinos Sierros; Mechanical and Aerospace Engineering, West Virginia University, Morgantown, West Virginia, United States.

Direct ink writing allows for the low-temperature processing of soft 3D functional materials with a wide range of applications from flexible batteries to soft actuators. Direct ink writing in conjunction with kirigami (a variation of origami that includes cutting) and embedded conductive nanoparticles provides a means of low thermal budget processing of electronic devices. Additively manufactured elastomers such as polydimethylsiloxane (PDMS) can be used as platforms to provide flexibility and stretchability to such devices. The direct writing of kirigami-inspired functional PDMS structures is completed in net shape without the use of physical cuts. Instead, the “cuts” are included in the printed pattern design. The effects of composition of the printed inks and printing parameters are studied to control the functionality of the final structures. Electromechanical properties of the printed structures are also investigated to elucidate the applicability to soft robotics applications.

**BM08.15.47**

**Solvent-Assisted Direct Writing of Polydimethylsiloxane (PDMS)** Rahul Karyappa1 and Michinao Hashimoto2; 1Digital Manufacturing and Design Centre, Singapore University of Technology and Design, Singapore, Singapore; 2Pillar of Engineering Product Development, Singapore University of Technology and Design, Singapore, Singapore.

Polydimethylsiloxane (PDMS) is the material of the choice for various kinds of micro/nano-fluidic, lab-on-chip and microelectromechanical (MEMS) devices. PDMS offers many advantages due to inherent properties such as flexibility, biocompatibility and optical transparency. It can be easily and quickly molded at low cost by soft lithography, a technique based on the fabrication and/or replication of predefined structure using stamps, molds or photomasks. Direct fabrication of microchannels have been demonstrated such as direct patterning through wet and dry etching, but these techniques require long processing time in the cleanroom.
In this work, we proposed to apply direct ink writing for the fabrication of microfluidic devices using PDMS and various substrates. We developed a unique method of direct writing of PDMS by dispensing it in a bath of a solvent. Direct writing involved extrusion of PDMS through nozzles of different diameters, which was driven by the applied pressure. The proposed method has the capability of writing PDMS (addition curing, heat curing as well as UV curing) with a broad range of viscosity. We evaluated the effect of dispensing head velocity (v) and curing time (t) (in case of addition curing) on the diameter of filament extruded through the nozzle. Different types of substrates—including rigid, soft and wearable substrates—were evaluated for adhesion of fabricated PDMS filaments. PDMS can be easily made functional and writing can be achieved. By extending the concept of the proposed method, in situ fabrication of different types of microchannels was demonstrated. The proposed method is simple and offers a great potential in fabricating microchannels that avoids the need of mold fabrication. The flexibility of the proposed method also offers a simple method of fabrication of flexible wearables and soft actuators.

BM08.15.48
Design and Synthesis of PS-b-PSS Block Copolymer for Ionic Electroactive Artificial Muscles

Van Hieu Nguyen1, Jaehwan Kim1, Rassoul Tabassian1, Mounita Kotal1, Kiwoo Jun1, Jung-Hwan Oh1, Ji-Myeong Son1, Muhammad Taha Manzoor2, Kwang Jin Kim2 and Il-Kwon Oh1

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea (the Republic of); 2Mechanical Engineering, University of Nevada, Las Vegas, Las Vegas, Nevada, United States.

Ionic electroactive artificial muscles containing a polymer electrolyte membrane sandwiched between two electrodes have received intensive attention for converting electrical energy into mechanical motion, which benefits many applications like wearable electronics. Realizing such applications requires these actuators to display large deformation without back relaxation and long-term durability, which demand advances in electrodes and polymer electrolytes. However, while electrodes have been intensively researched, polymer electrolytes have progressed slowly due to the antagonistic relationship between ionic conductivity and mechanical stability. Furthermore, polymer electrolytes having continuous ionic channels are desirable but difficult to develop [1-5]. For example, poly[1-(4-butyl-styrene)-b-(ethylene-r-propylene)-b-(styrene-r-styrene sulfonate)-b-(ethylene-r-propylene)-b-(1-butyl-styrene)] (SSPB) has closed-end ionic channels, inducing slow response with back relaxation. Despite adding sulfonated montmorillonite, SSPB actuator responded slowly (600 seconds) [4]. Simplifying SSPB to poly(styrene-r-styrene sulfonate)-b-(ethylene-r-propylene) (PSS-b-PMB) formed continuous conducting domains, hence reduced the rise time to 60 seconds [5]. However, PSS-b-PMB has some drawbacks like the non-conducting styrene units in its conducting block. Hence, designing and synthesizing new polymers are required.

Herein, we describe an unprecedented block copolymer, polystyrene-b-polystyrene (PSS-b-PMB), which was designed according to the application requirements. PS-b-PSS-EMfm has two distinct blocks enabling to handle the antagonistic properties somewhat independently. While conducting block containing full PSS-EMfm enhances ionic conductivity, structural block with cross-linked PS provides mechanical stability. This polymer was synthesized by RAFT polymerization, and characterized by 1H NMR spectroscopy, gel permeation chromatography, double aberration-corrected transmission electron microscopy, field emission scanning electron microscopy, differential scanning calorimetry, and electrochemical impedance spectroscopy [6].

The as-produced actuator was investigated over wide-range conditions. At ultra-low voltage of 0.5 V, the actuator exhibited high displacement of 8.2 mm (0.37 % strain), no back relaxation, excellent durability over 14,000 cycles, and fast response of five seconds. Such short rise time is 12 and 120 times smaller than those of PSS-b-PMB and SSPB, respectively [4,5]. These excellent performances demonstrate the proper design and successful synthesis of PS-b-PSS-EMfm, together with the potential of the actuator for applications. We also expect the use of our approach in preparing novel polymers for related fields like fuel cells and solid-state lithium battery.

SESSION BM08.16: Wearable/Flexible Actuators/Sensors

Session Chairs: Kyu-Jin Cho and Woochul Kim

Friday Morning, November 30, 2018

Hynes, Level 2, Room 209

8:15 AM BM08.16.01
Low Power Flexible Electrostatic Transducers for Haptic Communication

Ian Trase1, Zhe Xu1, Xiaomin Han1, Yin Liu1, Frances Lau2, Ali Israr2, Zi Chen2 and John X. Zhang1

1Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, United States; 2Facebook Inc., Menlo Park, California, United States.

Introduction: Long-range communication has occurred exclusively through visual and auditory means, which disadvantages those for whom these modes of communication are inconvenient or impossible. Current social networking infrastructure does not adequately reproduce normal communication, which can involve touch when face-to-face. No current integrated wearable technology enables touch-at-a-distance, where the transducer would allow a user’s touch to be recorded, digitized, and reproduced on a remote device. We design a matrix of low-power flexible electrostatic transducers (FETs) with air-gap coupling to the skin for both actuation and sensing functionalities. We then demonstrate the usage of these wearable transducers, which can detect simple sensations from and transmit forces to the skin.

Materials and Methods: We use curved electrodes, flexible substrates, and mechanical buckling to create low-voltage electrostatic actuators that generate large forces over macroscopic distances. The actuators are composed of a pair of Kapton film insulators coated with gold electrodes. One film is buckled and affixed to the other, generating motion when voltage is applied as the films move together and apart. The force sensors are made of porous polyvinylidene fluoride (PVDF), a biocompatible piezoelectric polymer. The device was mounted to a group of subject’s forearms to determine comfort and perceptibility.

Results and Discussion: We determined that for optimum perceptibility and comfort, the device should operate at voltages under 500V and frequencies under 100Hz. The electrostatic airgap transducers were found to deliver perceivable forces to the skin when operated with a 500V 1-100Hz signal. The actuator reached its maximum displacement at around 500V, and further increases in voltage did not lead to significant changes in perceptibility. The sensor had a minimum detection threshold of 0.5N, and the voltage output rose linearly with force until 1.5N. We also conducted a pilot user study in which force and comfort were measured at 1, 5, 10, 20, 50, and 100Hz. Users were able to feel the device and qualitatively characterize the frequencies at frequencies above 5Hz. Low frequencies were more comfortable than high frequencies, and maximum comfort was achieved at 5Hz. Conversely,
frequencies above 100Hz were found to be less comfortable.

**Conclusions:** We demonstrated a wearable electrostatic transducer with significant potential to provide a new mode of communication using human touch. The displacement and force results indicated that perceptibility is achievable in low-power situations. The actuator was able to generate displacements of up to 4mm at 500V, and 2mm at 100V. This technology will both allow for communication in situations where auditory or visual communication is difficult, as well as greatly enhance the quality of remote communication for social networking.

8:30 AM BM08.16.02
**Exo-Glove Poly II—Soft Wearable Robot that Enables People with Hand Disabilities to Grasp** Kyu-Jin Cho; Soft Robotics Research Center, Biorobotics Lab, Dept. of Mechanical Engineering, Seoul National University, Seoul, Korea (the Republic of).

Recently, owing to the rapidly increasing number of individuals suffering from spinal cord injury (SCI) and stroke, many wearable devices have been developed to assist with activities of daily living (ADLs) or to help rehabilitation. But there is still a big gap between the users and the technologies that are available, to cope with the wide variety of needs for the people with disability to live an independent life. Seoul National University Biorobotics Lab has been developing soft wearable robots that can meet the unmet needs of the people with disability. Examples include a device that can be used to pressure the belly of people who lost the ability to use their abdominal muscles to help them breath, speak and even sing, and a simple glove that can be worn by people who cannot move their fingers to enable them to hold various objects.

In this presentation, we will present Exo-Glove Poly II, a polymer based soft wearable robot for the hand that enables people who lost their hand function to grasp various objects with their hand. Exo-Glove Poly is built using polymer for comfort of the user and easy sanitization. Exo-Glove Poly II is composed of wearable body, a glove, and actuation system. Design features to allow adjustment to different hand sizes and to protect users from injury were implemented. To verify the grasping performance of the robot, various experiments were conducted with two SCI patients with lost hand mobility. By restoring the hand function with this assistive technology, we hope that more people with disability will be able to live a better independent life.

9:00 AM BM08.16.03
**Mechanics-Guided Design of Active Material—Hard-Magnetic Soft Actuator** Ruike Zhao1,2, Yoohoo Kim1, Shawn A. Chester3 and Xuanhe Zhao1; 1Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; 2The Ohio State University, Columbus, Ohio, United States; 3New Jersey Institute of Technology, Newark, New Jersey, United States.

Composed of polymeric matrices embedded with magnetic responsive soft particles, magnetoeactive soft materials can rapidly and dramatically deform under magnetic fields. Since existing magnetoeactive soft materials mostly rely on paramagnetic or low-coercivity ferromagnetic particles, they usually give simple deformations such as elongation and compression under applied magnetic fields. Recently, high-coercivity ferromagnetic particles have been embedded in magnetoeactive soft materials, in which complex patterns of hard-magnetic domains can be programmed by three-dimensional printing. As the applied magnetic fields generate stresses and torques on hard-magnetic domains, the hard-magnetic soft materials with patterned domains can give rapid, untethered and complex modes of deformations, leading to new applications in soft robotics, flexible electronics and biomedical devices. This paper is aimed to develop a framework of theory, constitutive law and computational model for hard-magnetic soft materials, in order to facilitate rational design of new materials, structures and devices. We adopt a nonlinear field theory that accounts for finite deformation coupled with magnetic fields in soft materials. We propose a new constitutive law named ideal hard-magnetic soft materials and implement it into numerical models with finite-element simulation. The theory, constitutive law and numerical model are validated with a set of experiments on various modes of deformations of hard-magnetic soft materials. In addition, the mechanics-guided complex structures of the 3D-printed hard-magnetic soft materials with programmed magnetic domains are demonstrated.

9:15 AM BM08.16.04
**Supramolecular Biomimetic Skins Combining a Wide Spectrum of Mechanical Properties and Multiple Sensory Capabilities** PeiYi Wu1, 2; 1Department of Macromolecular Science, Fudan University, Shanghai, China; 2Chemistry, Chemical Engineering and Biotechnology, Donghua University, Shanghai, China.

Biomimetic skin-like materials, capable of adapting shapes to variable environments and sensing different external stimuli, are of great significance in a wide range of applications including artificial intelligence, soft robots and smart wearable devices. However, such highly sophistiacted intelligence has been mainly found in natural creatures while rarely realized in artificial materials. Herein, I will introduce several types of supramolecular polyelectrolytes with different molecular interactions to fabricate biomimetic iontronics and imitate natural skins. Their dynamic viscoelastic networks provide the biomimetic skins with a wide spectrum of mechanical properties, including flexible reconfiguration ability, robust elasticity, extremely large stretchability, autonomous self-healability and recyclability. Meanwhile, polyelectrolytes’ ionic conductivity allows multiple sensory capabilities towards humidity, temperature, strain and stress. Furthermore, in this presentation, I will share insights on the soft material design from the perspective of molecule-level dynamic interactions and hope they are inspiring for facile preparation of artificial neurosensory and neuromuscular systems.

9:30 AM BM08.16.05
**Flexible Metasurfaces for Versatile Haptic Interfaces** Osama Bilal1, Vincenzo Costanza2, Antonio Palermo1, Paolo Celli1, Ali Israr2, Frances Lau2 and Chiara Daraio1; 1California Institute of Technology, Pasadena, California, United States; 2Facebook, Palo Alto, California, United States.

Haptic feedback is the most significant sensory interface after visual cues. Developing thin, flexible skins that function as haptic interfaces is important for augmenting virtual reality, wearable devices, robotics and prosthesis. For example, adding a haptic feedback interface to prosthesis could improve their acceptance among amputees. State of the art haptic technology is still limited by inadequate sensory feedback or complicated actuation mechanisms. Here, we present flexible metasurfaces designed for generic haptic interfaces. When actuated, the metasurfaces can produce complex tactile patterns on the human skin. The metasurfaces are composed of multiple resonant “pixels” that can locally amplify both input displacements and forces. Each of these pixels encodes various deformation patterns capable of producing different sensations on contact. The metasurfaces transform a harmonic signal containing multiple frequencies into a complex preprogrammed tactile pattern.

9:45 AM BM08.16.06
**Three-Dimensional Microporous Pressure Sensor Fabricated Using Droplet-Based Microfluidic Assisted Emulsion Self-Assembly** Jin-Oh Kim and Steve Park; Korea Advanced Institute of Science and Technology (KAIST), Deajeon, Korea (the Republic of).

Pressure sensors have been a subject of great interest over the past decade, with a wide-variety of exciting applications such as interactive wearable electronics, health monitoring systems, touch screens, and soft robotics with human-like functionalities. Large area processability, flexibility, high sensitivity, ability to sense both low pressure and high pressure range, and high spatial resolution and uniformity are some of the key features necessary for various pressure sensing applications. A variety of methods to detect pressure have been reported such as piezo-resistance, capacitance, piezoelectric, optics, and inductance.
Polydimethylsiloxane (PDMS) is often chosen as the dielectric material due to its ease of processability, compliance with human body, and biocompatibility. However, PDMS has a relatively high compressive modulus, yielding devices with low sensitivity. To overcome this issue, PDMS has been microstructured using silicon mold. However, these devices generally lose their sensitivity when pressure exceeds tens of kPa. This restricts their applicability to devices that require large pressure sensing range (e.g. devices that mimic human skin require pressure sensing range of ~0.1—100 kPa).

To expand the pressure sensing range, we present a novel droplet-based microfluidic assisted emulsion technique to generate 3-dimensional microporous structure for high performance capacitive pressure sensors. Our technique can generate uniformly sized pores assembled in an orderly close-packed manner over a large area without the use of any sacrificial template. The size of the pores can easily be tuned from 100 µm to 500 µm by adjusting the relative flow rates of the oil and aqueous solutions. The sensitivity of the sensors increased with increasing pore size to as high as 0.83 kPa⁻¹, which can be attributed to the relatively low pressure needed to induce buckling of the columns between the larger pores. Our sensor also exhibited high pressure sensing range up to 100 kPa and high spatial uniformity. Furthermore, we have combined this technique with standard replica molding to generate 3-dimensionally shaped microporous pressure sensors, through which sensitivity was further enhanced to 2.45 kPa⁻¹. Lastly, we have adhered our sensors to human body to detect subtle human motions. These demonstrations of facile and large-area processability, high sensitivity, large pressure sensing range, and high spatial uniformity make our device unique and promising for many future pressure sensing applications.

10:00 AM BREAK

10:30 AM BM08.16.07

Highly Flexible Multi-Modal Capacitive Pressure Sensor Responsive to Tactile and Wide Pressure Range  
Haehang Lee, Hanul Moon, Hyukyun Kwon and Seunghyup Yoo; School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of).

Flexible pressure sensors have been attracting great amount of attention as they are key elements in realizing artificial skin, friendly human-machine interface, and wearable healthcare products. To apply pressure sensors to the aforementioned applications, they should not only be highly sensitive in low pressure region to detect tiny stimuli such as tactile or blood pulse but be operable over a wide pressure range as well to catch up with the performance of human skin. In addition, they need to be thin enough as it can be applied to high flexible products. For this reason, film-type pressure sensors using a variety of materials and structures have been studied. However, it has been challenging to realize a wide pressure sensing range and high flexibility at the same time, because there is a trade-off relation between dynamic range and thickness of the pressure sensors. Furthermore, the problem becomes more difficult considering a multi-modal sensor having high sensitivity in low pressure region as well.

In this study, we propose a flexible capacitive pressure sensor using a structured ionic gel film as a dielectric layer whose capacitance is responsive to applied pressure. The ionic gel film is largely beneficial for high sensitivity attributed to ultra-high capacitance based on electric double layers, and it has suitable mechanical properties as a pressure sensing material because it has low Young’s modulus similar to that of rubber. By structuring the surface of the ionic gel film in several micro-meter scale to utilize confined air between the ionic gel and an electrode, linear response to large pressure range of over 100 kPa was secured. In addition, the complete pressure sensor can be highly flexible because the thickness of the ionic gel film can be reduced near or even below 10 µm. By using an appropriate surface structure of ionic gel film, the sensor shows distinguished response to low and high pressure regions, and although recent studies have focused on ionic materials or elastomers that can be actuated by heat or electricity, none have yet surpassed the performance of the mechanical systems. Furthermore, fabricating such artificial muscles with high yield and at low cost remains to be demonstrated. Here, we report thermally actuated “artificial muscle” devices produced via a cost-effective iterative thermal fiber drawing technique, which mimics the strength and responsiveness of biological muscle. These fiber-based artificial muscles can be manufactured across size ranges from macro to micro.

To achieve actuation in fibers, we sought out to create bimorph structures by combining two materials with high and low expansion coefficients, respectively: for example, an elastomer and a high-performance engineering polymer. To prototype this approach, we have demonstrated several "muscle" types using cyclic olefin copolymer elastomer (COCe) and polyethylene (PE). The bimorph fibers were thermally drawn from macroscale preforms and then subjected to elongation stress (cold drawing). Cold drawing created an excessive strain on PE and COCe components, and upon release, the strained fibers assumed a helical shape due to the high resilience of COCe and high plastic deformation in PE. The strained fibers could then be actuated thermally and were outfitted with silver nanowire mesh electrodes to provide feedback akin to the biological muscle. By controlling the fiber dimensions and the built-in strain, the strength and the temporal dynamics of the artificial muscles were engineered.

The observed actuation and feedback of the reported fiber-based artificial muscles indicate their potential utility in robotics, haptics, and prosthetics, at a significantly lower cost and higher throughput than existing actuator technologies.

11:00 AM BM08.16.09

Bioinspired, SWCNT-Coated, Micro-Hexagonal Array Based Electronic Skin for Mechanical Sensing  
Changyeon Jeong, Seonghwan Lee and Young-Bin Park; Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Highly sensitive, flexible electronic skins (e-skins) with multi-modal, vibration sensing ability is of great interest for various applications, such as tactile sensing in robots, earthquake monitoring, human healthcare and wearable electronics. Here, we present an e-skin based on bioinspired, micro-hexagonal pillar arrays coated with single-walled carbon nanotubes (SWCNTs). The interlocking configuration between the meshed arrays allows stable sensing performance under both static and dynamic mechanical stimuli, including pressure, shear, and bending through the piezoresistive principle. Furthermore, the optimized interlocking geometries based on micro-hexagonal pillar arrays show enhanced sensitivity and ability to differentiate various modes of
mechanical loading owing to the surface contacts between the microstructures, whose contact-separation behavior depends on the type of loading. We also showed that our e-skin can detect internal and external vibrations for various applications, including earthquake monitoring, smart phone detection and voice recognition, and demonstrated that they can measure different types and intensities of vibration.

11:15 AM BM08.16.10
Flexible Optomechanical Actuators Based on Light-Induced Demagnetization of Low Curie Temperature Composites Meng Li1, Yu Wang1, Aiping Chen2, Bradley Napier1, Wenyi Li1, Scott Crooker1 and Fiorenzo G. Omenetto1; 1Tufts University, Medford, Massachusetts, United States; 2Center for Integrated Nanotechnologies, Los Alamos National Laboratory, Los Alamos, New Mexico, United States; 3National High Magnetic Field Laboratory, Los Alamos National Laboratory, Los Alamos, New Mexico, United States.

Actuators are components that are used to move a mechanical system or perform shape morphing under certain stimulus. Among various stimuli, light has distinguishing advantages of non-contact control, and being capable of localized actuation with high resolution. Most optomechanical devices can perform simple movement such as bending, twisting, or expansion with simple light modulation. However, it is only with complicated light patterning or structured design that they can achieve complex movement like rotating, folding, walking or waving. There are many situations where complex modulations cannot be enacted, and the versatility is limited by the specific design.

In this work, we introduce an approach of wireless actuation based on optically-induced demagnetization which provides multiple opportunities for shape-morphing and deformation in response to light in easy-to-use formats. We fabricate light-responsive magnetic composites by incorporating CrO2 in multiple flexible, elastomeric, and mechanically robust, durable materials. Because of their polymorphic nature along with their flexibility and high failure strain, biopolymers (silk fibroin) and elastomers (PDMS) are used as magnetically inert host material matrices for ferromagnetic dopants. When illuminated, the composite are capable of macroscale motion, through the interplay of optically-absorptive elements and low-Curie temperature magnetic materials (CrO2). These composites can be formed into films, sponges, monoliths and hydrogels, and can be actuated with light at desired locations. With no need for specific pattern design and complicated light modulation, we have successfully demonstrated a gripper that is activated by stationary light and is able to grab and release objects. The gripper experiences cyclic tightening and loosening, which has the potential for continuous object gripping and relocation. The combination of magnetic force and localized laser illumination can achieve more complex actuation patterns, other than bending and twisting. A Curie rotary engine powered by light is demonstrated at a rotation speed of 2 rpm. The concepts presented here represent a comprehensive baseline of a composite platform that merges optomechanical and magnetic functions. We believe that this approach offers an interesting platform to achieve delicate and desired light-induced motion with easily accessible equipment and facile manufacturing processes, opening opportunities for manufacturing flexible, simple, and cheap actuators at multiple forms from the micro- to the macro-scale.

11:30 AM BM08.16.11
Multifunctional Smart Electronic Glove for Robotic Prosthesis Controls Min Ku Kim1 and Chi Hwan Lee1, 2, 3; 1Biomedical Engineering, Purdue University, West Lafayette, Indiana, United States; 2Mechanical Engineering, Purdue University, West Lafayette, Indiana, United States; 3Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana, United States.

The human hand is one of the foremost part of the body in a physical interaction serving as an indispensable instrument to our daily lives. Therefore, any form of disfigurement or loss of the limb can negatively affect quality of life. Current evidence-based interventions demonstrates using robotic prosthetic hands as a supplementary movement aid to restore vital mobility. Recent developments of artificial electronic skin embedded with thin-film based flexible sensors can provide valuable functionality to sense external stimuli, thereby imitating humanlike sensory perception. Despite these technological advances, the devices suffer from difficulties in seamless integration of electronic skin with pre-existing robotic prosthetics, leading to poor physical bonding and degradation of sensor performance. Moreover, the price of these instrumented prosthetics remains consistently high due to the expensive materials used and limited production numbers due to advanced fabrication methods involved in electronic skin with pre-existing robotic prosthetics, leading to poor physical bonding and degradation of sensor performance. This talk outlines materials, mechanistic design features and rapid prototyping fabrication methods employed for an innovative multifunctional smart electronic glove (or simply e-glove) that can be easily worn onto arbitrary robotic hands to simultaneously replicate the humanlike sensory perception, appearance, selectivity to ammonia, acetone and ethanol. An orthogonal array consisting of the individual materials was assembled and tested in 60 different 3-gas mixtures containing random but realistic concentrations of ammonia (250-2000 ppb), acetone (250-1800 ppb) and ethanol (50-600 ppb), simulating human breath. The here presented array quantified all analytes in the realistic gas mixtures with high accuracy, precision, and high coefficients of determination ($R^2 > 0.88$) needed for real-life applications. As a result, this sensor array shows high potential as compact module for portable or wearable devices for the monitoring of specific disease- or metabolic-related markers by nanostructured metal oxide gas sensors is promising, as they respond in real-time and feature sizes smaller than the tip of a match. Therefore, they could easily be incorporated into portable or wearable devices. Particularly interesting markers are ammonia, ethanol and acetone, being related to an impaired urea cycle due to kidney or liver disease,2 gut bacteria3 and fat metabolism,4, respectively. Here flame aerosol made nanostructured gas sensors were produced and systematically tailored (e.g. particle size, shape and film morphology) for distinct selectivity to ammonia, acetone and ethanol. An orthogonal array consisting of the individual materials was assembled and tested in 60 different 3-gas mixtures containing random but realistic concentrations of ammonia (250-2000 ppb), acetone (250-1800 ppb) and ethanol (50-600 ppb), simulating human breath. The here presented array quantified all analytes in the realistic gas mixtures with high accuracy, precision, and high coefficients of determination ($R^2 > 0.88$) needed for real-life applications. As a result, this sensor array shows high potential as compact module for portable or wearable devices for the noninvasive monitoring of metabolic related ammonia, acetone and ethanol in real-time, or could be used to detect entrapped humans after an earthquake.5

Convection, conduction and thermal radiation play an important role in the personal thermal management. However, clothes have been typically engineered for comfort in cold environment by e.g., reducing their thermal conduction via pockets in feathers, furs and woolen fabrics. This makes warm clothes bulky and reduces persons mobility. Cooling effect is even harder to achieve without the use of active devices such as fans, air conditioners or water-cooled electric coolers. As such, lightweight fabrics and textiles that can provide fully passive temperature control without external power sources can truly revolutionize wearable technologies.

Recent advances in fabrics wicking technology help to enhance cooling via convection, but this technology is mostly suitable for athletic apparel as it only gets activated once perspiration occurs. To enable both passive cooling without breaking a sweat and heating without adding metal layers to the wearables, we design, develop, and investigate polymer fabrics that control thermal radiation from the skin. Fabrics can achieve cooling effect by letting thermal radiation from the body pass through without being absorbed or reflected. The caveat is that the material has to be transparent in the infrared, and most polymers strongly absorb in this spectral range. The polymer that has ideal optical properties – i.e., high IR transmittance and low absorbance – is polyethylene (PE). PE is a very common lightweight and cheap plastic, which, however, is not typically considered a good material candidates for wearable technologies.

We will show that passively cooling fabrics made of PE microfibers can be made visibly opaque, yet infrared-transparent, and as a result can reduce the skin temperature by several degrees. Owing to their microfiber structure, PE fabrics can also provide high level of comfort, and excellent water wicking functionalities. We will also discuss the optimum sizes of the microfibers for indoor and outdoor applications of the passively cooling fabrics. Finally, we will show that by a judicious choice of the fiber size, PE fabrics can be engineered to reflect IR radiation back to the skin, thus providing a heating functionality for the cold-weather lightweight garments development.

Finally, we will discuss ways to enhance PE fabrics by adding visible color effects, invisible communications features, self-cleaning and microbial treatment by sunlight.

This work was supported by the NSRDEC ‘Thermal Management of Fibers and Films’ program, through ARO sponsored ISN.

2:00 PM BM08.17.02

All-Solid-State Glucose Fuel Cell for Energy Harvesting in the Human Body

Philipp Simons,1,2 Marco A. Gysel1 and Jennifer L. Rupp1,2; 1Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; 2Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Efficiently powering sensors, pacemakers and bio-electronic devices for the human body defines a new era of medicine to track, support and operate body functions. Here, glucose fuel cells have seen a renaissance in recent years as an implantable power source harvesting energy from readily available fuels in the human blood stream. Compared to existing implantable batteries, glucose fuel cells do not require frequent replacement surgery. However, state-of-the-art glucose fuel cells are primarily based on polymer electrolytes being relatively bulky, suffer from long-term stability issues and exhibit low power densities. Here, we innovate a miniaturized glucose fuel cell, which is fully composed of solid state materials based on thin film processing. This all-solid-state glucose fuel cell can be scaled down to the sub-micrometer range for unprecedented miniaturization and is built on a Si-chip using standard semiconductor fabrication methods suitable for integrated and direct powering of bioelectronic devices and implants. Through the use of abiotic catalysts instead of conventional biological catalysts such as enzymes and microbes, long term stability and increased power density are in perspective. Free-standing fuel cell membranes based on a proton conducting oxide on Si-chips were assembled using a microfabrication route with standard semiconductor processing techniques. Oxide thin films were prepared via pulsed laser deposition. The anode is in contact with glucose in phosphate buffered saline solution to mimic blood, whereas the cathode is in contact with oxygen. Performance characterizations were carried out via electrochemical impedance spectroscopy and galvanostatic polarization curve measurements. During this presentation we will present that the proposed cell is electrochemically active and shows promise in functioning as the first all-solid-state glucose fuel cell with a roughly 100-fold lowered thickness of the device (only 250 nm) compared to polymer-based glucose fuel cells.


2:15 PM BM08.17.03

Smart Polymer for Autonomous Tracking and Harvesting of Energetic Emission

Ximin He, Xiaoshi Qian, Yusen Zhao and Yousif Alsaid; University of California, Los Angeles, Los Angeles, California, United States.

Enhancement and optimization of the receiving input power density is a key to many applications that requires maximizing the energy input, such as energy harvesting, small signal sensing, etc. Normal incidental illumination is the most direct way to maximize the input power density when the input energy is in a form of parallel electromagnetic wave. In nature, many plants have developed phototropism to spontaneously sense and track the light source and maintain their disk to be illuminated normally to the photonic input. By tracking the sun, the sunflowers are able to efficiently raise the temperature of their disk in the morning in time to attract more visits of the pollinators. Tree leaves could also track the sunlight to obtain the highest temperature they can to extract water from the root. Currently there is no synthetic material system can omnidirectionally sense, track and harvest the input emissive energy. In this work, we report a soft material system that can self-adaptively track the energy source whichever the direction of the source goes. We proposed a physically symmetric system based on photo-sensitive polymers. Input photonic energy shines on the geometrically symmetric hydrogel system and induce non-symmetric temperature gradient. The polymer will automatically bend toward the light source. The bending will be terminated when the top of the material points direct to the light source. We studied the tracking system with a simple mechanical model and FEA simulation. The hydrogel system has been optimized to achieve fast and omni-directional real-time tracking in all direction. The light tracking is as fast as 30 degrees per second and the tracking performance covers 360 degrees of azimuthal plane. The error of tracking accuracy is better than 1%. A demonstration of an omni-directional solar vapor generator that maintain >90% solar energy harvesting even under large incident angles has been achieved. The enhancement of energy harvesting reaches as high as 425% over non-tropistic surfaces, indicating a significant compensation of energy harvesting in the case of the angular incidence attributed to the tracking functionality. We believe that the proposed material system can be applied in many applications that require...
maximizing their energy input.

2:30 PM BM08.17.04
3D Printed Flexible and Transparent Polymer Piezoelectric Generators for Powering Electronic Devices
Nick Adamson1, Alexey Glushenkov1, Mitchell Sess2, Vanessa Lussini2, Phillip Fox3, Greg Dicinoski1 and Amanda V. Ellis4; 1Department of Chemical Engineering, The University of Melbourne, Parkville, Victoria, Australia; 2Department of Engineering, La Trobe University, Bundoora, Victoria, Australia; 3Note Issue Department, Reserve Bank of Australia, Craigieburn, Victoria, Australia.

The global need for sustainable and green power generation methods has resulted in renewable energy harvesting technologies such as photovoltaics. This method has low energy conversion efficiencies <15% and only operates at maximum efficiency in direct sunlight. For the purposes of always-on, self-powered sensors and portable/wearable electronics, novel reliable energy scavenging techniques are required. Piezoelectric generators convert mechanical energy from external sources to electricity, with energy conversion efficiencies >35%. Furthermore, recent advances in piezoelectric fluoropolymers suggest prospects for flexible polymer-based piezoelectric generators with high visible-wavelength transparency.

Despite the promising nature of piezoelectric polymers, they are difficult to process into the polar (all-trans) β phase, with high energy methods commonly utilized as an additional step to orient dipoles after deposition as thin films. The β phase of fluoropolymers is desired as it exhibits the highest electromechanical coupling properties. Shear stresses have previously been found to reorient fluoropolymers into the polar β phase. Our computational fluid dynamics models show high shear stresses at the exit of pressure-based 3D printing nozzles, showing the potential for 3D printing techniques to induce the β phase. Increases in aspect ratio of the polymers are linked to an improved electrical output, further enhancing the potential of 3D printing as a deposition method for polymer piezoelectric generators. Recent literature investigating effects of ionic additives to fluoropolymers suggests increased re-orientation from non-polar to polar phase due to ion-dipole interactions, with further enhancement upon doping with low (<1 wt%) concentrations of graphitic carbon nanomaterials (such as carbon nanotubes).

This study presents the prospects of 3D printing of fluoropolymers for their use as piezoelectric generators, removing the requirement of post-processing to align dipoles. The scope for the use of 3D printed piezoelectric polymer microstructures as a method of enhancing voltage output up to 4.5x over that of thin films is discussed. Diffusion kinetics of solvent evaporation-assisted 3D printing is investigated and linked to nucleation into β phase and hence additional increases in voltage of 2x at optimised conditions. Further self-orientation of 3D printed fluoropolymers at room temperature is shown through the utilization of polar-ionic liquid additive matrices, previously only used in high temperature processing such as melt mixing and extrusion.


2:45 PM BM08.17.05
Printable Fabrication of Fully Integrated and Self-Powered Sensor System on Plastic Substrates
Yuanjing Lin1, Jiaqi Chen1, Mohammad Mahdi Tavakoli2,3, Yuan Gao2,3 and Zhiyong Fan1; 1The Hong Kong University of Science and Technology, Hong Kong, Hong Kong; 2Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; 3The Hong Kong Polytechnic University, Hong Kong, Hong Kong.

Wearable and portable devices with desirable flexibility, operational safety and long cruising time, are in great demand for applications in wireless communications, multifunctional electronics, personal health monitoring, etc. Herein, a monolithically integrated self-powered smart sensor system with printed interconnects, fully printable gas sensor for ethanol and acetone detection, printable supercapacitors and embedded solar cells as energy sources, was successfully demonstrated in a wearable wristband fashion by utilizing inkjet printing technique as a proof-of-concept. In such a“wearable wristband”, the harvested solar energy can either directly drive the sensors and power up light emitting diode (LED) as a warning signal, or can be stored in the planar supercapacitors in a standby mode, and the energy released from supercapacitors can compensate the intermittency of light illumination. To the best of our knowledge, demonstration of such a printable and wearable self-powered sensor system integrated onto a single piece of flexible substrate has rarely been reported. Particularly, the printable micro-supercapacitors delivered an areal capacitance of 12.9 mF cm⁻² and the fully printed tin (IV) oxides (SnO₂) gas sensor showed decent sensitivity for ethanol and acetone detection at room temperature. The printable strategies for device fabrication and system integration developed in this work show great potency for scalable and facile fabrication of a variety of wearable devices.

3:00 PM BREAK

3:30 PM *BM08.17.06
Stretchable Organic Photovoltaic Cells and Wireless Power Transmission for Smart Apparel and Wearables
Takasuke Someya1, Kenjiro Fukuda2, Sungjun Park2, Xiaomin Xu1, Hiroaki Jinno1 and Tomoyuki Yokota1; 1Electrical and Electronic Engineering and Information Systems, The University of Tokyo, Tokyo, Japan; 2RIKEN Center for Emergent Matter Science, Saitama, Japan.

Wearable electronics and smart textiles have attractive much attention, because they are expected to monitor biometric information with high precision. One of their major bottlenecks is a power solution to continuously supply electricity to health-monitoring sensors. In particular, it is important to solve this issue when long-term monitoring is required. In this presentation, we will report on recent progresses of ultraflexible organic photovoltaic cells and wireless power transmission for applications to smart apparel and wearables. First, we design two mechanical and environment stability of ultrathin organic photovoltaic cells. Then, we will explain remaining issues and future prospects of power solutions for wearables.

4:00 PM BM08.17.07
Graphene-Based Nanocellulose Composites for 3D Printed Electrodes
Taylor J. Morrison1 and Hani E. Naguib1,2,3; 1Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario, Canada; 2Materials Science and Engineering, University of Toronto, Toronto, Ontario, Canada; 3Institute of Biomaterials & Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada.

Academic interest in additive manufacturing (AM) is rapidly growing as researchers work to find new ways this innovative technology can be applied to revolutionize product prototyping and production in various industries. One of the fields in which there is excellent opportunity for advancement is energy storage. There is a growing demand for specialized energy storage devices due to the increased prevalence of integrated electronics across a wide range of applications. Rising technologies such as wearable electronics, internet-of-things products, and advanced biomedical devices could see significant benefit from mobile power supplies that are more physically versatile and energy dense than what is currently available. The performance and functionality of
4:30 PM BM08.17.08
The Role of Responsive Polymers and Hydrogels in ‘Smart’ Material Systems
Raymond Oliver1 and Lynn Tandler2; 1Northumbria University, Newcastle upon Tyne, United Kingdom; 2Fashion and Textiles, Royal college of Art, London, United Kingdom.

We are living in an age of technological convergence. Early 21st century materials science and fabrication, when coupled with creative design fundamentals, provide a new and compelling view that can drive innovative applications and manufacturing solutions that also meet human centred needs. This paper demystifies the idea of smart fabrics and discuss current and future developments in woven textiles, their formation and potential use in new product formation scenarios.

Woven textiles are material systems governed by the principles of structural hierarchy. It is this inherent structural complexity that attributes woven textiles with a unique set of properties and, which gives them a performance advantage over other textile forms. Today, so-called ‘smart’ textiles are beginning to take centre stage due to the majority of accounts still holding to the belief that any piece of textile that presents properties over and above those of conventional textiles is worthy of the description smart. However, the problem here is that smartness in textiles is viewed as a synonym for responsive behaviour: something that is susceptible to changes in the environment such as moisture, temperature, light, electrical current, pH, chemical or pathogen driven external stimuli. This assumption is very misleading since we find from our own work that nearly all textile components are susceptible to changes in the environment to some extent and when we deal with worn apparel, the ‘around body’ stimuli become real and often spasmodic. Therefore, we set out to investigate the claim that a textile as a smart object is to over claim and presume that the relationship between the inherent properties of materials and the technology on which material systems are produced are in sync. We will present evidence based data that highlights the responsiveness of different fibres and yarns to support the argument that there are no smart textile materials, only smart textile material systems.

The study indicates revisiting the principles of woven textile constructions as an inspiration for the creation of new material fabrications. We will also show that genuinely smart textiles will not be textiles at all as we currently know them to be but rather micro or nano scalar material systems that although created by textile methodologies present an entirely different set of physical, mechanical, electrical and aesthetic performance characteristics. Finally, we also show that the use of 3D printing cannot create the flexibility and topography associated with a woven construct.

4:45 PM BM08.17.10
Self-Powered Wireless Optical Transmission of Mechanical Agitation Signals
Wenbo Ding and Zhong Lin Wang; Georgia Institute of Technology, Atlanta, Georgia, United States.

The ubiquitous sensors have accelerated the realization of Internet of Things (IoT) but also raised challenges to the current overcrowding radio frequency (RF) based communications. The optical wireless communications (OWC) that utilize the wide optic bandwidth can well solve the spectrum crisis and is an appealing complementary solution to the IoT applications. However, the additional direct current (DC) power supply and complicated modulating and power management circuits may limit the large-scale deployment of OWC systems. In this paper, by integrating with triboelectric nanogenerators (TENGs), the light-emitting diode (LED) could be directly transformed into a wireless transmitter that conveys the information associated with mechanical stimuli without additional power supply. With the customized TENG devices and the help of advanced image processing and machine learning techniques, three demonstrations with functions of optical remote control, pressure sensing, and security authentication, were demonstrated. The concept and results in this paper may greatly broaden the application of IoT through the integration of OWC and TENG.