

# SYMPOSIUM PM02

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Conductive Materials Reliability in Flexible Electronics  
November 27 - November 29, 2018

## Symposium Organizers

Aram Amassian, King Abdullah University of Science and Technology  
Alon Gorodetsky, University of California, Irvine  
Jesse Jur, North Carolina State University  
Jennifer Lewis, Harvard University

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\* Invited Paper

SESSION PM02.01: Flexible Transparent Conductive Materials  
Session Chairs: Aram Amassian and Alon Gorodetsky  
Tuesday Afternoon, November 27, 2018  
Hynes, Level 1, Room 109

### 1:30 PM \*PM02.01.01

**Recent Progress on Flexible, Intrinsically Stretchable and Healable Organic Electronics** Qibing Pei; University of California, Los Angeles, Los Angeles, California, United States.

The emergence of devices that combine elasticity with electronic or optoelectronic properties offers exciting new opportunities for applications, but brings significant materials challenges. This presentation will describe our latest results in the materials efforts in developing intrinsically stretchable conductors, semiconductors, dielectric polymers, and demonstrating integrated stretchable electronic devices. Specific examples include a polymer composite comprising surface-embedded silver nanowires with high transparency, high surface conductivity, and low surface roughness. The mechanical properties of the transparent composite electrode are determined by the polymer matrix employed, and demonstrated properties include flexibility, shape memory, self-healing, and rubbery deformation. Results on the healing efficiency of the healable composite with failure induced by both mechanical and electrical loading will also be presented. Touch panels were fabricated to demonstrate the applicability of the AgNW healable composite material.

### 2:00 PM PM02.01.02

**Enhancing Flexibility of Highly Conductive and Transparent Platform with Buffered Conducting Polymer Layer** Devendra Singh and Gilles Lubineau; King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

The design of new electronic system featuring flexibility and stretchability requires using advanced materials and microstructure. Classical inorganic materials are conductive but brittle in nature. On another side, organic materials are flexible but comparatively less conductive and are sensitive to environmental conditions. Here, we propose a novel approach to integrate the advantages of both inorganic (Indium tin oxide) as well as organic materials, here PEDOT:PSS (poly-(3,4 ethylenedioxythiophene): poly (styrene sulfonic acid)) as conducting polymer, for their conductive and flexible intrinsic properties, respectively. In this work, a PEDOT:PSS buffer layer is used between ITO layer and PET [polyethylene terephthalate] substrate such that during the deformation of the film, the stacked system retains its high conductivity with strong stability. The reason for using a PEDOT:PSS buffer layer is to substantially reduce the detrimental effects of cracks in the ITO layer in terms of an overall conductivity of the system. The highly conductive and transparent ITO films were sputter deposited on PET substrates at room temperature, and different configurations (with and without annealing and/or an intermediate layer of PEDOT:PSS) has been studied extensively. Structural, optical, mechanical and morphological studies have been carried out to understand the behavior of involved layers qualitatively and quantitatively. We find that integration of an ITO thin film with PEDOT:PSS buffer layer results in robust synergetic behavior, showing a relatively low initial electrical sheet resistance that is very stable even under strong bending (value of bending radii down to 2.5 mm, repeated cycles up to 1000 cycles). This high stability can be attributed to an improvement of the electrical transfer at the delaminated interfaces due to supporting buffer layer. Results show that this highly conductive, flexible and transparent platforms can be used for advanced flexible devices.

### 2:15 PM OPEN DISCUSSION

### 2:30 PM PM02.01.04

**Transparent Heteroepitaxy (Ba, La)SnO<sub>3</sub>/Muscovite for Flexible Optoelectronics** Chih-Yu Yang<sup>1</sup>, Min Yen<sup>1</sup>, Kee Hoon Kim<sup>2</sup> and Ying-Hao Chu<sup>1,3,4</sup>; <sup>1</sup>Materials Science and Engineering, National Chiao Tung University, Hsinchu City, Taiwan; <sup>2</sup>Physics and Astronomy, Seoul National University, Seoul, Korea (the Republic of); <sup>3</sup>Electrophysics, National Chiao Tung University, Hsinchu City, Taiwan; <sup>4</sup>Materials and Chemical Research Laboratories, Industrial Technology Research Institute, Hsinchu City, Taiwan.

Lanthanum-doped barium stannate (Ba,La)SnO<sub>3</sub> (BLSO), as a new TCO with high electron mobility which is higher than 100 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>, has captivated the interest of researchers over the last few years. To achieve a high mobility BLSO thin film, high crystallinity is essential and can be obtained under high temperature processes. In view of this, instead of commercial flexible substrates such as polymers, muscovite is used as the substrate to introduce TCO into flexible devices due to its crystalline structure, high thermal stability, high flexibility and high transparency. In this study, we fabricate BLSO thin film on muscovite via pulsed laser deposition (PLD) and this heteroepitaxial BSLO thin film shows transmittance up to 90 % in visible range with mobility reaching 16 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>. Furthermore, BLSO thin film can stand less than 5 mm bending radius with the change of resistance no more than 4 %. The transport properties still remain outstanding after 1000 times bending cycles. The combination of BLSO and muscovite exhibits not only excellent electrical properties but also remarkable flexibility and transparency that can have a significant impact on flexible next-generation optoelectronic devices.

#### 2:45 PM PM02.01.05

**High-Performance Robust and Flexible Transparent Film Heater by Room-Temperature Transfer Printing Method** [Yoonkap Kim](#)<sup>1</sup>, Han-Jung Kim<sup>2</sup>, Sam-Soo Kim<sup>1</sup>, Sung-Eun Park<sup>1</sup> and Gyuseok Choi<sup>1</sup>; <sup>1</sup>Advanced Materials Component Research Center, Innovation & Technology Research Division, Gumi Electronics & Information Technology Research Institute, Gumi, Korea (the Republic of); <sup>2</sup>Korea Research Institute of Bioscience & Biotechnology (KRIBB), Daejeon, Korea (the Republic of).

High-performance flexible transparent heaters are very useful for the anti-fogging, anti-icing and de-icing of optics and optoelectronic devices such as outdoor displays, light emitting diode (LED) automobile headlamps, windows, mirrors and camera lenses. Here, we report the uniformly interconnected metal (CuNi, CuMg, AgNi, Ni etc.) micromesh/nanomesh structures on various polymer substrates (Polyethersulfone (PES), Polyimide (PI), Polyethylene terephthalate (PET) etc.) which have been fabricated using room-temperature transfer printing method. These metal micromesh/nanomesh structures on diverse substrates showed effective and rapid heating performance at low input voltage (below DC 9V), and high long-term stability to oxidation, heat, and chemicals. Furthermore, the metal micromesh/nanomesh film heater exhibited high reliability for outer bending and electrical switching cycle test. These results demonstrate that the high-performance is attributed to the creation of a high quality network over the whole surface area and strong adhesion to its substrate. The heating performance of the flexible transparent film heater improved with Pt-decoration, and oxygen (O<sub>2</sub>) plasma and self-assembled monolayer (SAM) treatment. In addition, the convection phenomenon by our flexible film heater was investigated for the consistent and sensitive detection of target materials (particulate matter (PM) or gases). Therefore, the flexible transparent heater based on the metal micromesh/nanomesh is considered suitable operations as defogging/deicing systems for an automobile side-view mirror and camera lens, transparent heating block systems for polymerase chain reaction (PCR) devices, and particulate matter (PM) detecting systems for PM<sub>2.5</sub> sensors.

#### 3:00 PM BREAK

#### 3:30 PM OPEN DISCUSSION

#### 3:45 PM PM02.01.07

**High Dielectric Constants of Transparent and Flexible Cellulose Hybrid Films Using Multidimensional Metal Nanostructures for Flexible Touchscreen Panels** [Sangyoon Ji](#), Jiuk Jang and Jang-Ung Park; UNIST, Ulsan, Korea (the Republic of).

Various forms of wearable electronics have been developed, including wrist bands, smart glasses, and watches, which are exposed extensively to outdoor activities. The key metrics for these rapidly-emerging, wearable electronics are high touch sensitivity and good mechanical and thermal stability of the flexible touchscreen panels (TSPs). The dielectric constants (k) of their protective cover layers are very important because they can determine touch sensitivities. Thus, studies on cover layers that are flexible and transparent and that have high-k dielectric films with outstanding mechanical and thermal reliabilities are essential for the success of future wearable electronics. Herein, we report an unconventional approach for forming flexible and transparent cellulose nanofiber (CNF) films. These films are used to embed random networks of ultra-long metal nanofibers that serve as nanofillers to increase the value of k significantly (above 9.2 with the high transmittance of 90%). Also, by controlling the dimensions and aspect ratios of these metallic fillers, we studied the effects of the fillers' nanostructures and contents on the optical and dielectric properties of the resulting films. The length of the metal nanofibers can be controlled precisely using a stretching method locally to break the highly-aligned, ultra-long nanofibers. These nanofiber-embedded, high-k films are mechanically and thermally stable, and they have a better Young's modulus and better tensile strength with lower thermal expansion than commercial transparent plastics. Our demonstration of highly-sensitive, flexible TSPs using high-k CNF film for smartphones suggested that this film has significant potential for use in next-generation, portable electronic devices.

#### 4:00 PM PM02.01.08

**High Performance Flexible Transparent Electrodes and Thin Film Heaters via Simple Solvent Treatment of Ag Nanowire Networks** [Insu Jin](#) and Jaewoong Jung; KyungHee University, Yongin-si, Korea (the Republic of).

Silver nanowires (Ag NWs) have been extensively studied as the material of the transparent conductive electrode (TCE), as a promising replacement of conventional indium tin oxide (ITO). However, a typical polyol synthesis of Ag NWs employs insulating polymers as surfactants for the growth, stability and dispersion of silver, which limits efficient electron transport between each nanowire. Although the conventional post-treatments such as thermal welding process could improve transmittance and sheet resistance of Ag NWs networks, they usually require high temperature or complicated process that may limit the choice of substrate. In this presentation, we demonstrate the simple solvent treatment to enhance the optoelectronic properties of Ag NW networks. The solvent treatment effectively washes out the surrounding insulating polymer, which results in significantly improvement of transmittance and sheet resistance of Ag NW networks. By the optimization of the solvent treatment, we successfully fabricated a high performance TCE with a sheet resistance of 12.95  $\Omega$ /sq and a transmittance of 81.25% at 550 nm. The solvent treatment was also suitable for flexible substrate, leading to 16.29  $\Omega$ /sq and a transmittance of 78.76% at 550 nm. For the practical applications, transparent thin film heaters (TFHs) made of Ag NW networks followed by the solvent treatment was also fabricated. The TFHs exhibited a good performance of 155 °C at a bias of 5 V. In addition, the flexible TFHs based on Noland Optical Adhesive 63 as a substrate afforded a high performance flexible TFHs with a quick response time (15 s). This TFH exhibits good optoelectronic properties and outstanding mechanical robustness against deformation, such as flexibility and deformability. Therefore, this substrate can be used as a flexible and deformable heater and the temperature can exceed 110 °C at a bias of 4 V. This work clearly demonstrates the efficacy of simple solvent treatment for practical use of Ag NWs and to be formed into various shapes for TCE and TFHs.

#### 4:15 PM PM02.01.09

**Highly Conducting Transparent and Stretchable PEDOT:PSS Electrodes—Investigation of the Role of Additives** [Emilie Dauzon](#)<sup>1,2</sup>, Ahmed E. Mansour<sup>1</sup>, Fabrice Goubard<sup>2</sup> and Aram Amassian<sup>1</sup>; <sup>1</sup>King Abdullah University of Science and Technology, Thuwal, Saudi Arabia; <sup>2</sup>Laboratoire de Physicochimie des Polymères et des Interfaces, Cergy, France.

Poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT:PSS) is a potential candidate as a transparent soft conducting electrode for electronic and bio-electronic devices. It has also recently emerged as a potentially stretchable electrode when prepared under certain conditions. Despite a significant growth of the interest in this material, there is still significant debate about the causes and mechanisms involved in significant conductivity improvements in PEDOT:PSS films when processed in presence of certain additives, such as dimethylsulfoxide (DMSO) and Zonyl-FS300. Understanding the effects of these additives is crucial to further progress in the field, as it pertains to the design of even better electrode materials with finely tuned functionalities. The addition of DMSO co-solvent significantly improved the conductivity and the carrier concentration by several orders of magnitude, as confirmed by Hall effect transport measurements. Addition of the Zonyl elastomer also improved the electrical properties, but to a slightly lesser extent. Importantly, it softens PEDOT:PSS significantly by reducing its Young's modulus by more than an order of magnitude, making it increasingly stretchable and mechanically compliant. We show that these benefits can be combined to achieve excellent electrical, optical and mechanical properties. To understand the effect of these additives in isolation and in combination with each other, we have investigated the relationship between the transport properties of

PEDOT:PSS and the morphology and microstructure of these films by performing atomic force microscopy (AFM) and grazing incidence wide-angle X-ray scattering (GIWAXS). Our analysis reveals distinctive impact of the two additives on the PEDOT and PSS components in the solid-state PEDOT:PSS films. The DMSO enhances the aggregation of PEDOT, while Zonyl introduces order into PSS domains. Both additives induce fibrillar formation in the film and the combination of the two additives only enhances the fibrillary nature and the aggregations of both PEDOT and PSS components of the film. In-situ GIWAXS investigation performed during the spin-coating and annealing steps showed that the presence of the additives influenced the aggregation behaviors of the PEDOT and PSS components directly during the transition from wet to dry film, i.e., during solvent removal, and do not evolve further during subsequent annealing. These results indicate that the additives directly influence the self-assembly behaviors of PEDOT and PSS during the ink-to-solid phase transformation.

#### 4:30 PM PM02.01.10

**Modification of PEDOT:PSS with Triblock Copolymer and Sulfuric Acid for Stretchable Transparent Electrode** Jinho Lee and Jeong Sook Ha; Korea University, Seoul, Korea (the Republic of).

In this study, we report on the fabrication of a highly conductive, stretchable, transparent electrode based on modified poly(3,4 ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) with triblock copolymer (PEO<sub>20</sub>-PPO<sub>70</sub>-PEO<sub>20</sub>, Pluronic<sup>®</sup> P123) and post-treatment via sulfuric acid. Sulfuric acid post treatment is well known to increase the electrical conductivity of PEDOT:PSS via crystallization of PEDOT, conductive part of PEDOT:PSS. Since the sulfuric acid treated PEDOT:PSS film is not stretchable, however, we introduce P123 as a secondary dopant and plasticizer to enhance the stretchability via crosslinking as well as the electrical conductivity of PEDOT:PSS. The fabricated electrode shows high transparency of 89%, high electrical conductivity of ~1,700 S/cm, and minimal change in resistance of ~4% during repetitive stretch-release cycles by 40% tensile strain. By utilizing the high transparency and low resistance change with stretching of the electrode, a stretchable transparent touch sensor array with light emitting diodes is fabricated and it exhibits mechanical stability upon stretching by 30%. This work demonstrates the facile chemical modification to develop PEDOT:PSS based stretchable electrode with high transparency and high electrical conductivity.

#### 4:45 PM PM02.01.11

**Mechanically-Durable Printed Transparent Electrodes for Ultra-Flexible Organic Photovoltaics** Zhi Jiang<sup>1,2</sup>, Kenjiro Fukuda<sup>1,3,4</sup>, Sungjun Park<sup>3</sup> and Takao Someya<sup>1,2,3</sup>; <sup>1</sup>Thin-Film Device Laboratory, RIKEN, Hirosawa, Wako, Saitama, Japan; <sup>2</sup>Electrical and Electronic Engineering and Information Systems, The University of Tokyo, Tokyo, Japan; <sup>3</sup>Center for Emergent Matter Science, RIKEN, Saitama, Japan; <sup>4</sup>Japan Science and Technology Agency, Saitama, Japan.

Conformable large-area optoelectronic devices are necessary for self-powered ultra-flexible applications to realize multi-functional systems, such as sensing, imaging, and healthcare-monitoring [1, 2]. Since conventional transparent electrodes, such as ITO, are brittle, novel transparent conductors owing good mechanical robustness are indispensable to these ultra-flexible photonic devices. Printing technology will make these novel ultra-flexible transparent electrodes closer to the step of their real application [3]; however, it remains challenging to obtain feasible printed transparent electrodes with ultra-thinness, good uniformity over a large area, and high conductance simultaneously [4]. There exists a trade-off between thickness and conductance. Highly conductive Ag mesh electrodes usually have a thickness in the range of 2-20  $\mu\text{m}$ , which can limit the flexibility and inhibit utilization in ultrathin photonic devices. Reducing the thickness and keeping a high conductivity simultaneously is needed for ultra-flexible photonic devices.

Here, we present ultra-flexible and mechanically durable Ag mesh transparent electrodes fabricated by a reverse offset printing technique, which simultaneously achieved high conductance, high transparency, and good mechanical properties. Reverse-offset printing technology enabled high resolution (100 nm and 5  $\mu\text{m}$  in thickness and width, respectively) and high uniformity of Ag mesh over a large area. The high uniformity comes from the good quality of Ag nanoparticle ink (good dispersion, ultrafine diameter, and uniformity of Ag nanoparticles), and small roughness of both glass cliché and PDMS transfer blanket. Consequently, the printed transparent electrodes exhibited a 17  $\Omega/\text{sq}$  sheet resistance at 93.2% transmittance. Furthermore, they showed an insignificant resistance increase (10.6%) after 500 cycles of 100% stretch/release deformation. The key mechanism for the mechanical robustness is the ultrathin thickness and buckling structure. Due to the total thickness of our printed ultrathin Ag mesh transparent electrodes is less than 1.5  $\mu\text{m}$ , they can be easily used in ultra-flexible photonic devices. As a demonstration, organic photovoltaics (OPVs) are fabricated using our printed Ag mesh transparent electrodes, which showed a comparable power conversion efficiency (8.3%) to those using traditional ITO electrodes (8.6%).

The insight gained from the ultra-flexible printed Ag mesh transparent electrodes and their application in ultrathin organic photovoltaics will help to apply such novel transparent electrode into other ultrathin photonic devices, and even ultra-flexible systems.

#### Reference:

- [1] T. Yokota, et al., *Sci. Adv.* 2, e1501856 (2016).
- [2] M. S. White, et al., *Nat. Photo.* 7, 811 (2013).
- [3] Fukuda K, et al., *Adv. Mater.*, 25, 29 (2017).
- [4] Z. Jiang, et al., *Adv. Mater.* 1707526 (2018).

SESSION PM02.02: Flexible Electronics Processing I  
Session Chairs: Aram Amassian and Inhwan Kim  
Wednesday Morning, November 28, 2018  
Hynes, Level 1, Room 109

#### 8:30 AM \*PM02.02.01

**E-Textiles Fabricated via Inkjet Printing of Particle-Free Conductive Inks** William Babe<sup>1</sup>, Hasan Shaharior<sup>2,3</sup>, Jesse Jur<sup>2</sup> and Chengto Gwengo<sup>1</sup>; <sup>1</sup>Liquid X Printed Metals, Pittsburgh, Pennsylvania, United States; <sup>2</sup>North Carolina State University, Raleigh, North Carolina, United States; <sup>3</sup>Funxion Wear, Raleigh, North Carolina, United States.

This paper describes a conformal inkjet printing process of particle-free silver ink on uncoated polyester-based textile surfaces. In-situ heat curing of the textiles during the printing process is used to significantly improve the conductivity and line resolution of the printed traces. A minimum sheet resistance of 0.1 ohms per square has been achieved on polyester-based knit, woven and nonwoven fabrics. Durability testing results suggest the conductive fabrics can withstand bend, stretch, abrasion and wash testing. These findings create the possibility of integrating inkjet printing in the scalable & automated manufacturing process for e-textile products.

#### 9:00 AM PM02.02.02

**Interaction of an Inkjet Printed Conductive Ink with Textile Substrates** Zixin Wang, Teruo Hashimoto, Tristan Lowe and Brian Derby; University of Manchester, Manchester, United Kingdom.

Textile substrates present considerable challenges for the printing of functional devices, because of their considerable roughness and intrinsic porosity, not present on conventional polymer film flexible substrates. Initial ink behaviour after printing is governed by two processes, the spreading of ink across and the infiltration of ink into the fibrous substrate. The presence of ink deposits on the substrate enables better electrical conductivity and finer feature resolution, however, infiltration within the textile promotes durability and resistance to degradation through wash cycles. Most existing studies of fluid infiltration into textile substrates have investigated large scale fluid infiltration, e.g. water wicking in garments or polymer infiltration during composite fabrication. Consequently, most modelling approaches are based on homogenised approximations to the real pore structure in textiles, typically using Darcy's law or the Washburn equation, which cannot capture the complex fibre architecture in a typical textile. This is of particular concern with inkjet printing where a typical drop has a length scale comparable with the warp and weft of a fabric.

The behaviour of drops of a nanoparticle silver ink deposited by inkjet printing on woven textile has been observed using 2- 3-dimensional imaging techniques. Computed X-ray microtomography has been used to characterise ink transport through the fabric fibre architecture illustrating the influence of the warp and weft. Detailed surface structure of the fabric and the distribution of nanoparticles on the textile surface after printing and heat treatment has been studied by SEM including 3-D reconstructions from sequential sliced images. The porosity within a tow of fibres (yarn) plays an important role in controlling ink spreading and penetration. This is shown to be more important than the larger scale inter-tow porosity governed by the weave. The importance of the fibre surface properties in controlling ink behaviour is further demonstrated through a comparative study of the interaction of a nanoparticle silver ink with cotton and polyester textile surfaces. The more hydrophilic cotton fabric shows greater spreading and infiltration of the ink than is observed with the polyester materials. Further hydrophobic chemical treatment of the fabrics using commercial water repellent finishes reduces the fabric surface tension, leading to reduced ink spreading and smoother ink deposition on the surface with higher areal ink concentration and improved electrical conductivity. Fibre architecture is shown to influence ink penetration and spreading in the longitudinal and transverse directions of a fibre tow with tighter fibre structures inducing lower levels of spreading.

#### 9:15 AM PM02.02.03

**Inkjet Printing of Conductive Gold Traces on Multiple Surfaces with Rapid Low-Power Plasma Sintering** Wenyi Li<sup>1</sup>, Elijah Shirman<sup>2</sup>, Yu Wang<sup>1</sup>, Benedetto Marelli<sup>3</sup>, Beom Joon Kim<sup>1</sup> and Fiorenzo G. Omenetto<sup>1</sup>; <sup>1</sup>Tufts University, Medford, Massachusetts, United States; <sup>2</sup>Harvard University, Cambridge, Massachusetts, United States; <sup>3</sup>Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Printed electronics has attracted considerable interest as an alternative manufacturing process to realize circuits or devices on paper or plastic considering its low material consumption and fast accessibility. Using metallic nanoparticles to create conductive traces for lower cost and faster process has been extensively investigated, but often limited by the sintering process. Plasma sintering is widely employed given its lower processing temperature and lower extent of damage caused to the substrate by avoiding the high temperatures of sintering. In spite of its advantages, the process suffers from skin effect due to the top-down treatment process which can hinder sufficient curing throughout the entirety of the printed patterns imposing either long-last processing times or the use of high-power plasma with potential for damage to the substrate.

Gold nanorods (AuNRs) are compelling as printable metals compared with other counterparts not only because of their chemically inert nature, but also because their anisotropic structure suppresses the coffee-ring effect and lowers the electrical percolation threshold, giving the potential to generate a conductive trace with low deposition amounts and the ability to be sintered with low power and short exposures to plasma.

We show here the generation of conductive traces by inkjet printing AuNRs when combined with low temperature and low power oxygen plasma sintering. Traces composed of 10-layer AuNRs with resistivity  $5e-7 \Omega m$  were generated after 300-second plasma sintering. Compared with spherical gold nanoparticles at equal volume size and weight concentration, AuNRs traces show higher conductivity under the same sintering condition.

Topographical, electrical and elemental analyses are performed to assess the quality of the conductive traces and to confirm the chemical composition of the printed traces and assess the residual presence of surfactant or any residual contamination.

This approach offers a convenient way to print conductive, inert traces that can be interfaced with a variety of flexible surfaces ordinarily not accessible to these methods because of processing limitations.

#### 9:30 AM PM02.02.04

**Reliability of Ink-Jet Printed Silver Nanoparticle Interconnects on Deformable Substrates Tested Through an Electromechanical *In Situ* Technique** Martina A. Costa Angeli<sup>1</sup>, Tobias Cramer<sup>2</sup>, Beatrice Fraboni<sup>2</sup>, Luca Magagnoli<sup>1</sup>, Dario Gastaldi<sup>1</sup> and Pasquale Vena<sup>1</sup>; <sup>1</sup>Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano, Milano, Italy; <sup>2</sup>Department of Physics and Astronomy, University of Bologna, Bologna, Italy.

Inkjet printing is a relatively new and promising technology for fabrication; its major advantages, compared with traditional photolithography, rely on fabrication costs reduction, reduced material waste output, and simpler manufacturing steps. This technology has gained increasing interest in the fabrication of thin films for flexible and stretchable electronics using new functional nanomaterial inks. Despite the established advantages of this technology, the electromechanical reliability of the fabricated material systems is still a key point to achieve competitive devices. In particular, bendable and stretchable electronics require electromechanical reliable interconnects as they are subject to mechanical loading which jeopardize the integrity of the material itself (the electrical interconnects) or that of the interfaces.

This work is focused on the electromechanical reliability of bendable and stretchable interconnects obtained through ink-jet printing by using a Dimatix Fujifilm printer. PET and PDMS were chosen as substrates in order to realize flexible and stretchable interconnections, respectively. Conductive ink, containing Silver Nanoparticles (AgNPs), was printed directly on PET. Since the direct printing on PDMS is a challenging task due to its elastomeric, hydrophobic, and inert nature, a different fabrication procedure was assessed for the PDMS substrate, combining the inkjet printing of AgNPs ink with transfer printing technique. For each substrate the experimental protocol was defined: (i) pre-treatment of the surface, if needed; (ii) optimization of the printing parameters; (iii) definition of the sintering temperature to optimize the conductivity, while maintaining compatibility with the glass transition temperature of the substrate. The selection of the above parameters was optimized as to maximize the capability to withstand mechanical strain without significant loss of electrical resistivity. Furthermore, an investigation on the role of the geometrical features of printed silver interconnections was also performed. Printed rectilinear and serpentine shapes interconnections of various geometries were characterized in-situ electromechanical tensile tests with Confocal Laser Scanning microscope. The microscopy analyses were aimed at estimating the integrity of the AgNPs sintered material. The experiments confirmed that electromechanical reliability is strongly affected by the geometrical layout: serpentine interconnections exhibited higher electromechanical reliability than the linear ones; although the directionality of the printing process should be taken into account when planning the geometrical features. As for the interconnects on PDMS, the curing process introduces a residual stress field in the AgNPs layers which may fracture. A suitable selection of curing temperature, components ratio and silicone thickness are key factors for a flowless and electro-mechanically reliable stretchable silver interconnects.

9:45 AM PM02.02.05

**“Drop-on-Textile” Direct-Writing Patternable Aqueous PEDOT Composite Ink Providing Highly Stretchable and Wash-Resistant Electrodes for Electronic Textiles** Jung Ah Lim<sup>1</sup>, Min Jung Kye<sup>1</sup>, Ho Sun Lim<sup>2</sup> and Eunji Lee<sup>3</sup>; <sup>1</sup>Korea Institute of Science and Technology, Seoul, Korea (the Republic of); <sup>2</sup>Sookmyung Women's University, Seoul, Korea (the Republic of); <sup>3</sup>Gwangju Institute of Science and Technology, Gwangju, Korea (the Republic of).

With increasing interest in textile-based wearable electronic devices, there is a considerable need to develop stretchable and elastic conductors that can be directly patterned on a fabric. One of the most promising classes of conducting materials for e-textiles is a poly (3,4-ethylenedioxythiophene) complex with a water-dispersible polyelectrolyte dopant of poly (styrene sulfonate) (PEDOT:PSS). Due to its high conductivity, good compatibility with various electronic materials, biocompatibility, and easy processability using solution coating. However, for practical e-textile applications of PEDOT:PSS, development of a highly stretchable PEDOT:PSS materials and their highly efficient, direct patterning process are still required. Moreover, for daily use of textile devices, improvement in the long-term environmental stability and wash-resistance of PEDOT:PSS is also necessary.

Here, we demonstrate a direct-write patternable water-based poly (3,4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT:PSS) composite ink which is capable of providing highly stretchable and washing-resistant electrodes on a fabric substrate for electronic textile applications. An aqueous composite ink consisting of PEDOT:PSS, graphene oxide nanosheets and anionic polyurethane does readily not permeate into hygroscopic fabric, which facilitate direct drawing of fine PEDOT electrode on the fabric without undesired blur effect. The PEDOT composite film shows unique structure of the PEDOT nanofibril network embedded by the polyurethane matrix, which resulted in an enough electrical pathway for charge carriers even though only 2.9 wt% of PEDOT:PSS existed in the composite film. The PEDOT composite film exhibited electrical conductivity of 4.6 S/cm, extremely high stretchability of 375% rupture strain, and high durability for repeated washing process with strong bleaching agent. Light emitting diode incorporated on the stretchable spandex with interconnects of the PEDOT composite pattern showed that LED light intensity was almost maintained even with stretching of PEDOT interconnects to 290%.

10:00 AM BREAK

10:30 AM PM02.02.06

**Direct Photochemical Deposition of Metallic Patterns on Polyimides for Development of Flexible Transparent Conductive Films** Kensuke Akamatsu, Yuma Yoshikawa, Yohei Takashima and Takaaki Tsuruoka; Konan University, Kobe, Japan.

Demand for the development of novel strategies for polymer metallization has been rapidly growing in the field of various flexible electronics applications, such as the liquid crystal displays, electronic paper, and solar cells. Polyimide film has been widely used to date for such applications as a low-k substrate, due to its chemical and thermal stability, and outstanding dielectric properties. Therefore, various processes for the metallization of polyimide films have been investigated for the development of flexible circuit elements in microelectronics applications. Additionally, adhesion strength between metal films and underlying polymer substrates becomes much more important when the device dimensions are in a sub-micrometer scale. The conventional approach to the fabrication of metal patterns on polyimide substrates utilizes a subtractive-based strategy, i.e., lamination metal films on polyimide films followed by patterning through lithographic methods, but this approach requires stringent environmental control, costly equipment, and complex, multistep processes such as resist-coating, lithography, and etching.

In order to sustain the demand for generating multichip packaging systems for future flexible electronic devices, it would be exceedingly useful to develop an additive-based strategy with high-throughput capability that would allow site-selective, direct metallization of flexible low-k substrates. In this contribution, we present surface modification-based strategy for the direct fabrication of microscopic silver circuit patterns on polyimide surface. Deposition of silver patterns has been achieved by using ion-doped precursor films, through the process of chemical hydrolysis of polyimide by alkali treatment, doping of silver ions into the modified films followed by UV irradiation using photomasks. The high sensitivity of silver ions to UV light allows for direct area-selective photochemical reactions without the use of photocatalysts, providing granular nanostructures consisting of silver nanoparticles at metal/polymer interface. This granular structures ensure high adhesion between deposited metals and underlying polymer substrates. Subsequent electroless copper deposition provides copper circuit patterns on polyimide substrate, providing effective methodology for direct fabrication of circuit patterns on flexible polyimide substrate in fully additive based strategy. Specifically, the use of photomasks with square patterns (negative photomasks) provided flexible, transparent conductive films, which can be used in applications such as flexible displays and electronic papers.

10:45 AM PM02.02.07

**Flexible, Foldable, and Wearable Carbon-Based Electronic/Electrochemical Devices on Paper** Murilo Santhiago, Mariane P. Pereira, Cátia C. Corrêa and Carlos C. Bufon; Brazilian Nanotechnology National Laboratory, Campinas, Brazil.

In this work we will describe the fabrication of flexible, foldable, and wearable electronic/electrochemical devices using carbon-based materials. The first fabrication route is based on a direct, simple, and dry transfer method of graphite onto paper with unprecedented electrochemical features on paper. We have selected soft pencils to transfer graphite onto paper and achieved comparatively low sheet resistances. The sluggish electron transfer observed on bare pencil drawn surfaces was enhanced by two steps. The surface was first electrochemically oxidized and reduced. The origin of such unprecedented performance was characterized by atomic force microscopy, laser scanning confocal microscopy, X-ray photoelectron spectroscopy, Raman spectroscopy, and contact angle measurements. We observed that the oxidation process causes the formation of a few microcracks on the electrode surface. Also, different chemical groups are formed and reduced due to the electrochemical treatment. Some of the weakly attached graphite particles and carbon nanodebris are detached from the electrode surface after the electrochemical treatment. Our results suggest that oxidation process leads to chemical and structural transformations on the electrode surface, and these transformations are responsible for the electrode response improvements. The second route to fabricate carbon-based devices on paper is based on the use of sacrificial adhesive layers. It is extremely challenging to fabricate carbon-based nanostructures on paper that has the potential to meet some of the recent demands of paper-based devices, namely: (i) low sheet resistance, (ii) high folding stability, (iii) flexible electrochemical cells with high performance and (iv) tunable electric properties to fabricate motion and wearable sensors. With this method it is possible to print different compositions of binder/carbon black with no extra care related to viscosity, particle size and solvent composition. The carbon black tracks have low sheet resistance and a high-record folding stability. I will also demonstrate the fabrication of a 3D paper-based electrochemical cell made from a single carbon-black track. Moreover, the ink was tailored in order to electrochemically detect biologically relevant molecules at low potentials. Flexible circuits can be fully crumpled and operated again with no significant response loss. Finally, we have created bioinspired motion and wearable devices by locally tuning the electrical properties of the conductive tracks.

11:00 AM OPEN SLOT

11:30 AM PM02.02.09

**Three-Dimensional Organic Conductive Networks Embedded in Paper for Flexible and Foldable Devices** Murilo Santhiago and Carlos Cesar Bof Bufon; Brazilian Nanotech National Laboratory, Campinas, Brazil.

Flexible and foldable devices have gained much attention in the field of low-cost electronics and wearable devices. Among the flexible materials used as substrates, paper is an exciting candidate with several attractive advantages. For instance, paper is a natural polymer broadly available worldwide, lightweight, disposable, portable and foldable. Also, paper has the unique porous structure formed by cellulose fibers, which can drive solutions by capillary action. Here, we described the fabrication of three-dimensional (3D) conductive tracks through the porous structure of paper [1]. We combined paper microfluidics and gas-phase pyrrole monomers to synthesize polypyrrole-conducting channels embedded in-between the cellulose fibers chemically. By using the proposed method, foldable conductive structures can be created across the whole paper structure, allowing the electrical connection between both sides of the substrate. Our approach is a step forward towards the development of 3D-electronic devices on paper. As a proof of concept, Top-Channel-Top (TCT) and Top-Channel-Bottom (TCB) conductive interconnections, as well as all-organic paper-based touch buttons are demonstrated. By functionalizing the conducting tracks, we also created paper-based sensors to assess the local humidity changes in fully-enclosed paper microfluidic elements. The sensors exhibit excellent mechanical stability, with more than 600 bending cycles achieved. Additionally, we observed that the electrical resistance increases with relative humidity (RH) increase. Most importantly, the humidity sensor response is reversible. Our work essentially paves the way toward 3D fabrication of electrochemical devices [2], including sensors, capacitors, and energy harvesting systems. Several devices can be manufactured in parallel, and the fabrication process allows high-volume production.

Acknowledgments:

We would like to thank National Center for Research in Energy and Materials (CNPEM), Brazilian Nanotechnology National Laboratory (LNNano), CNPq and FAPESP

References:

[1] Murilo Santhiago, Jefferson Bettini, Sidnei R. Araújo, Carlos C. B. Bufon, ACS Appl. Mater. Interfaces 8, 10661(2016).

[2] Murilo Santhiago, John B. Widallys, Lauro T. Kubota, Charles S. Henry, Anal. Chem. 85, 5233 (2013).

#### 11:45 AM PM02.02.10

**Printing of Poly(P-Phenylene Vinylene) (PPV) on Bacterial Cellulose-Based Paper by Direct Laser Writing for Flexible Devices** Cleber Mendonca<sup>1</sup>, Oriana Avila<sup>1</sup>, Moliria Santos<sup>1</sup>, Flavio Shimizu<sup>1</sup>, Gustavo Almeida<sup>1</sup>, Jonathas Siqueira<sup>1</sup>, Marcelo Andrade<sup>1</sup>, Debora Balogh<sup>1</sup> and Sidney Ribeiro<sup>2</sup>; <sup>1</sup>University of Sao Paulo, Sao Carlos, Brazil; <sup>2</sup>University of São Paulo State–UNESP, Araraquara, Brazil.

Cellulose-based flexible electronics has prompted as an interesting approach for the development of novel technologies, given its unique properties. Printed paper-based electronics have been usually accomplished by using standard printing methods, such as screen and inkjet printing. Some materials of interest for this field, however, are insoluble, hindering its use with solution-based direct printing techniques. This is the case, for example, of poly(p-phenylene vinylene) (PPV), a material that presents outstanding electrical, photo-luminescent and electro-luminescent properties, with great potential for applications. In this work we demonstrate the use of femtosecond laser induced forward transfer for creating high-resolution patterns of the conductive polymer PPV onto bacterial cellulose (BC) substrate, advancing the use of cellulose-based materials for printed flexible electronics, by offering a new approach for solid materials patterning. Such approach successfully allowed transferring PPV with resolution on the order of 10 µm and without materials degradation, which was subsequently doped to increase the electrical conductivity and exploited in the fabrication of functional devices. Our results open new avenues in the fabrication of paper-based devices, by combining high resolution and new classes of patterning materials.

SESSION PM02.03: Wearables and Flexible Device Applications

Session Chairs: Alon Gorodetsky and Martin Kaltenbrunner

Wednesday Afternoon, November 28, 2018

Hynes, Level 1, Room 109

#### 1:30 PM \*PM02.03.01

**Electrical and Mechanical Properties of Screen Printed Inks for Flexible and Wearable Applications** Jeffrey Meth<sup>1</sup>, David S. Rosenfeld<sup>1</sup>, John Crumpton<sup>1</sup>, Mark Lamontia<sup>1</sup>, Hoang Vi Tran<sup>1</sup>, Michael Wolfe<sup>1</sup>, Mark D. Poliks<sup>2</sup>, Peter Borgeson<sup>2</sup>, Suresh Sitaraman<sup>3</sup>, Justin Chow<sup>3</sup>, Olivier Pierron<sup>3</sup> and Gabriel Cahn<sup>3</sup>; <sup>1</sup>DuPont, Wilmington, Delaware, United States; <sup>2</sup>Chemistry and Materials Science and Engineering, SUNY Binghamton, Binghamton, New York, United States; <sup>3</sup>George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, United States.

Producing flexible, wearable circuitry relies on having robust electrical connectivity between components. The electrical traces must provide low resistance and predictable properties, especially over time, where a garment will see washing cycles and repeated mechanical stresses. Screen printing is a widely-used technique for making the conductive traces. Designing optimal inks in combination with various substrates for these applications requires control over several aspects of composites: 1) maintaining percolative conductivity; 2) control of the viscoelastic properties of the polymer binder and the substrate; 3) control over the adhesive interaction between the ink and the substrate; and 4) understanding the fracture behavior of this complex system. Industrial-academic partnerships, combined with internal research, provides a full context for working on and solving these problems. This presentation will show how the mechanical properties of the substrate and inks are interrelated and how that relationship affects electrical conductivity. We will also show the evolution of materials to more reliable, conductive compositions by applying lessons learned from extensive testing. Finally, we will discuss the current issues and where future work needs to be done.

#### 2:00 PM \*PM02.03.02

**Wearable and Flexible Biosensor for Continuous Sweat Analysis** Wei Gao; Engineering and Applied Science, California Institute of Technology, Pasadena, California, United States.

The rising clinical and basic research interest in personalized and precision medicine promises to revolutionize traditional medical practices. This presents a tremendous opportunity for developing wearable devices toward predictive analytics and treatment. In this talk, I will introduce fully-integrated flexible biosensors for multiplexed in-situ perspiration analysis, which can selectively measure a wide spectrum of sweat analytes (e.g. metabolites, electrolytes, heavy metals, drugs and other small molecules) and allow us to gain real-time insight into the sweat-secretion and gland physiology. I will also demonstrate an integrated wearable sweat extraction and sensing system which can be programmed to induce sweat on demand with various secretion profiles. To demonstrate the clinical value of our platform, human subject studies were performed in the context of the cystic fibrosis diagnosis. These wearable and flexible devices open the door to a wide range of personalized diagnostic and therapeutic applications.

#### 2:30 PM BREAK

#### 3:30 PM PM02.03.03

**System Designs and Considerations Toward Self-Powered and Adaptive Low Power Textile Integrated Wearable Devices** [Amanda Myers](#), Braden M. Li, Raj Bhakta and Jesse Jur; North Carolina State University, Raleigh, North Carolina, United States.

Cardiovascular disease is the leading cause of death in the United States. As a result, wearable health monitoring devices have become a heavily researched area. In order to provide long term monitoring of patients with heart-related diseases, electrocardiogram (ECG) studies employing textile-based wearable technologies. Concerns exist in these wearables in terms of data quality, power consumption, human design and manufacturing design. This work presents a systems-level approach towards the design of a self-powered ECG textile garment that seeks to resolve these issues. These garments are battery-less, open architecture sensor platforms that utilize continuous energy harvesting to ensure vigilant cardiac monitoring. Key stakeholder needs such as comfort, passive user-experience, accuracy, and data streaming were discovered during the NSF I-Corps program after interviewing patients, doctors, hospitals, and dentists. Component level integration and testing strategies are presented in the use of flexible interconnects, durable connectors, printed ECG electrodes, and energy harvesting integration. Finally, the garment design is considered based on understanding the use-cases in real-time cardiac monitoring health monitoring.

**3:45 PM PM02.03.04**

**Influences of the Human-Apparel System on Energy Harvesting toward Self-Powered Textile-Integrated Wearable Devices** [Braden M. Li](#), Amanda Myers and Jesse Jur; North Carolina State University, Raleigh, North Carolina, United States.

With the rise of wearable technologies there has been an unprecedented demand in finding suitable power supplies. As an alternative to conventional battery supplies, on-body energy harvesting is a promising avenue due to the limitless energy supply that is the human body. The majority of current studies of on-body energy harvesting focus on improving and optimizing the materials performance of the energy harvesting device. However, the interactions between the human and the energy harvester platform play a critical role in the energy harvesting ability of the wearable device. In this talk, we explore the key variables affecting energy harvesting output at varying on-body locations for commercial thermoelectric generators (TEGs) integrated within a textile-based wearable platform. TEGs are integrated into custom whole garment knitted shirts in the following locations: wrist, shoulder, front torso, back torso, and side torso. Employing human trial studies, these platforms enable direct comparison of the amount of energy harvested from the aforementioned on-body areas to the various movement profiles and ambient environment, e.g. walking, running, and stationary for periods of up to 60 minutes. During testing, environmental conditions such as ambient temperature and humidity, as well as acceleration and instantaneous power from the TEGs are recorded during the various activities and correlated to the harvested energy. Our analysis shows that higher intensity movements result in larger instantaneous power outputs. We also demonstrate how location of TEGs and fitness levels affect instantaneous power output. This method is demonstrated to provide the location specific energy harvesting that is possible during long term (full day to multi-day) use, a key necessity to self-powered wearable systems.

**4:00 PM PM02.03.05**

**Flexible and Transparent Fingerprint Sensor with Multiplexed Detection of Touching Pressure and Finger Skin Temperature** [Hyeon Seok An](#)<sup>1</sup>, Sanghyun Heo<sup>2</sup>, Sangyoon Ji<sup>1</sup>, Franklin Bien<sup>2</sup> and Jang-Ung Park<sup>1</sup>; <sup>1</sup>Materials Science and Engineering, Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of); <sup>2</sup>Electrical Engineering, Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Biometrics are an effective way for technology to use signature indicators of a user's body, such as the iris, facial features, or fingerprint, to create secure access methods. Especially, the recognition of fingerprints is one of the most popular techniques for mobile security applications. Capacitive fingerprint sensors have been widely used for contemporary portable electronic devices, including smartphones, with opaque sensor structures implemented in activation buttons or behind the phone. In the design of a device, the display occupies a relatively larger area of the total device size for improved usability. Except for the display, it would be optimal to reduce or completely remove other components (e.g., bezels, buttons, and sensors), from the front side of a product. As such, there has been a strong push for the development of invisible fingerprint sensors that are embedded in the display. However, the sheet resistance of conventional transparent electrode materials, such as indium tin oxide (ITO), carbon nanotubes, graphene, metal nanowires, or fine metal mesh patterns, are too high to allow high-frequency signals to drive the capacitive fingerprint sensors against noise from mobile devices. Here, we developed a transparent and flexible, capacitive fingerprint sensor array with multiplexed, simultaneous detection of tactile pressure and finger skin temperature for mobile smart devices. In our approach, random networks of hybrid nanostructures using ultra-long metal nanofibers and finer metal nanowires were formed as transparent and flexible electrodes of a multifunctional sensor array. The sensor array exhibited excellent optoelectronic properties (~ 1.03 Ohm/sq with an optical transmittance of 91 % in the visible light region) and outstanding reliability against mechanical bending. This resulting fingerprint sensor array has a high resolution (318 capacitors per inch) with good transparency (89%). This sensor offers a capacitance variation (between a ridge and valley) ~ 17 times better than the variation for the same sensor pattern using ITO electrodes, instead of the transparent hybrid electrode. This sensor with the hybrid electrode also operates at a high frequency (1 MHz) with negligible degradation in its performance against various noise signals from mobile devices. Furthermore, this fingerprint sensor array can be integrated with all transparent forms of tactile pressure sensors (sensing range from 10 kPa to 1.6 MPa) and skin temperature sensors (from 30 °C to 45 °C), to enable the detection of a finger pressing on the display. This will allow for the complete removal of any activation buttons on smart devices. Additionally, the capability to recognize artificial fingerprints further improves security. These results suggest the future promise of transparent and flexible devices for next-generation, interactive electronics.

**4:15 PM PM02.03.06**

**Printable Strain Gauge of High Sensitivity and Wide Range for Simple Structural Health Monitoring Implemented with Wireless Measurement System** [Tepei Araki](#)<sup>1,2</sup>, Shusuke Yoshimoto<sup>1</sup>, Noda Yuki<sup>1</sup>, Takafumi Uemura<sup>1,2</sup>, Yuko Kasai<sup>1,2</sup>, Shintaro Izumi<sup>1</sup> and Tsuyoshi Sekitani<sup>1,2</sup>; <sup>1</sup>The Institute of Scientific and Industrial Research, Osaka University, Ibaraki, Japan; <sup>2</sup>Advanced Photonics and Biosensing Open Innovation Laboratory, AIST-Osaka University, Suita, Japan.

This work proposes a printable strain gauge that exhibits high sensitivity (gauge factor < 100), a wide range (0.001% to 20% strain), and high durability (< a million strain cycles). The printable strain gauge is capable of detecting microcracks and microstrains simultaneously for long-term while conventional gauges lack the characteristic. A wireless system is installed, which further simplifies structural health monitoring for maintenance, inspection, triage, and infrastructure remediation via the Internet of Things (IoT).

Currently, strain gauges are utilized to monitor microdeformation in concrete structures and to detect the risk of structural failures. Conventional reinforced concrete has a material breakdown limit of -10%–20% strain [1]. However, it deforms by -0.2%–0.2% strain per day. Conventional gauges do not provide a sufficiently wide measurement range [2]. The optimal gauge is selected as a function of strain range.

In this paper, a high-sensitivity wide-range wireless strain gauge system is presented for simple structural health monitoring. The strain gauge contains 83wt% of graphite. It was fabricated through screen printing on a polyimide substrate with a width of 0.5–2 mm and a scalability of < 1 m. A printed track was composed of highly conductive graphite fillers and a blended binder of poly-N-vinylacetamide (PNVA) and cellulose; this resulted in an electrical resistivity of 0.3 ohm cm. The printed track acts as a resistance-type strain sensor with the same sensitivity as that of a conventional gauge (correlative factor: over 0.99). Experimental results showed that PNVA, whose molecular structure consists of a strong network of hydrogen bonds, acted to improve performance under cyclic strain. As a consequence, the printable strain gauge exhibited high durability and retained its high sensitivity and wide

measurement range even after < 1,000,000 strain cycles. It achieved long-term wireless monitoring in actual structural objects for over a month. Our printable strain gauge, which is operated using a wireless system, can contribute to the inspection of deterioration rates in large-area infrastructure at low cost.

[1] J. K. Wight, and J. G. McGregor, Reinforced Concrete: Mechanics and Design, Prentice Hall, 2000.

[2] J. Park., et al., ChemPhysChem, 16, 1155–1163, 2015.

#### 4:30 PM PM02.03.07

**All-Climate Aqueous Fiber-Shaped Supercapacitors with Record Areal Energy Density and High Safety** Bin Wang and Jianli Cheng; China Academy of Engineering Physics, Chengdu, China.

Flexible fiber-shaped supercapacitors (FSSs) are promising energy storage candidates for wearable electronics. However, most of reported FSSs are operated at room temperature and used the toxic flammable organic electrolyte or corrosive strong acid or base which may have safety hazards especially for wearable textiles directly sticking on the human skin at harsh environmental temperatures. Here we reported a new kind of aqueous symmetric FSSs with high safety and record high areal energy density at wide operating temperature ranging from -60 (14.2  $\mu\text{W h cm}^{-2}$ ) to 75 degree (22.9  $\mu\text{W h cm}^{-2}$ ) based on aqueous LiCl-PVA based gel electrolyte and core-shell nanocrystalline polymer fiber electrode. The fabricated aqueous FSSs demonstrate high flexibility, high areal/volumetric energy density and stable cycle life at different operating temperatures, showing the potential application in all-climate wearable electronics.

#### 4:45 PM PM02.03.08

**Reduced Graphene Oxide Based Field-Effect Transistors in a Four-Terminal Nano-Crossbar Array Switch Structure** Serzat Safaltin<sup>1</sup>, Ceylan Morgul<sup>2</sup>, Sebahattin Gurmen<sup>1</sup>, Csaba A. Moritz<sup>3</sup> and Mustafa Altun<sup>2</sup>; <sup>1</sup>Department of Metallurgical and Materials Engineering, Istanbul Technical University, Istanbul, Turkey; <sup>2</sup>Department of Electronics and Telecommunications Engineering, Istanbul Technical University, Istanbul, Turkey; <sup>3</sup>Department of Electrical and Computer Engineering, University of Massachusetts Amherst, Amherst, Massachusetts, United States.

Graphene and derived structures are promising electronic materials based on two dimensional hybrid sp<sup>2</sup> honeycomb structure that provide unique electrical, thermal and optical properties. Structure shows zero-band-gap properties with very high mobility rates which provide potential applications for flexible electronics and device miniaturization, but requires treatment with dopants or defects to work in a desired bandgap like n or p type semiconductors because of low on/off ratio. Treatment ensures that desired physical and electrical properties can be obtained and suitable reduced graphene oxide (rGO) structure can be applied for various switch designs. Nano-crossbar arrays are emerging structures as an area efficient state-of-art alternative to conventional CMOS devices. These array structure uses crosspoints as four-terminal switch and enables high complexity for logic synthesis compared to two-terminal switches. Besides that, fabrication of these switches require careful design features to perform symmetrically and accordingly.

In this study, nanostructured flakes of rGO were produced from graphene oxide (GO). GO was prepared with modified Hummers' method by chemically exfoliation and oxidation reactions. GO was washed, filtrated, centrifuged and vacuum-dried to obtain solid GO residue. Dry GO then powdered and sifted for further steps. Thermal treatment is applied for reduction of organic groups and expansion of GO into rGO, which took place in pure nitrogen flow (1 l/min.) with high heating rate and kept at high temperature (800°C) to form C:O structure with reduced oxygen content and high defects to be used in four-terminal switch device. The changes in structure and particle properties were investigated with scanning electron microscopy (SEM) for morphology, energy dispersive spectroscopy (EDS) for composition, X-ray diffraction (XRD) for crystal structure and stack layer quantifications, Brunauer-Emmett-Teller (BET) surface area analysis for effective surface area, Raman spectra for lattice distortions and defect structures and FTIR to identify functional groups. Products are then used in inkjet suitable ink for device fabrication. rGO-inks printed on PET and PI substrates as transistor channel between metal electrodes. I-V characteristics are measured to obtain the saturation region and channel effects between terminal switch options. Results show promising applications of graphene and derived structures for flexible electronics.

### SESSION PM02.04: Flexible Electronics Processing II

Session Chairs: Jesse Jur and Chengyi Xu

Thursday Morning, November 29, 2018

Hynes, Level 1, Room 109

#### 8:30 AM PM02.04.01

**Formation of Printable Granular and Colloidal Chains through Capillary Effects and Dielectrophoresis** Zbigniew Rozynek<sup>1,2</sup>, Ming Han<sup>3</sup>, Filip Dutka<sup>1,4</sup>, Piotr Garstecki<sup>1</sup>, Arkadiusz Jozefczak<sup>2</sup> and Erik Luijten<sup>5</sup>; <sup>1</sup>Institute of Physical Chemistry, Polish Academy of Sciences, Warsaw, Poland; <sup>2</sup>Faculty of Physics, Adam Mickiewicz University, Poznan, Poland; <sup>3</sup>Applied Physics Graduate Program, Northwestern University, Evanston, Illinois, United States; <sup>4</sup>Faculty of Physics, University of Warsaw, Warsaw, Poland; <sup>5</sup>Departments of Materials Science & Engineering, Engineering Sciences & Applied Mathematics, Physics & Astronomy, Northwestern University, Evanston, Illinois, United States.

One-dimensional conductive particle assembly holds promise for a variety of practical applications, in particular for a new generation of electronic devices. However, synthesis of such chains with programmable shapes outside a liquid environment has proven difficult. Here we report a route to simply 'pull' flexible granular and colloidal chains out of a dispersion by combining field-directed assembly and capillary effects. These chains are automatically stabilized by liquid bridges formed between adjacent particles, without the need for continuous energy input or special particle functionalization. They can further be deposited onto any surface and form desired conductive patterns, potentially applicable to the manufacturing of simple electronic circuits. Various aspects of our route, including the role of particle size and the voltages needed, are studied in detail. Looking towards practical applications, we also present the possibility of two-dimensional writing, rapid solidification of chains and methods to scale up chain production.

#### 8:45 AM PM02.04.02

**From 2D to 3D—A Mechanical Deterministic Approach for Stretchable Printed Electronics** Lu Yin and Joseph Wang; Nanoengineering, University of California, San Diego, La Jolla, California, United States.

The world of electronics is shifting away from rigid, bulky and fragile to flexible, miniaturized and sturdy, underlining the need for stretchability in the design form factors. Screen printing, as the most widely used manufacturing technique for circuit boards, is low cost, high throughput and versatile. This work demonstrates the photoresist-etching-inspired new screen-printing technique that combines flexible conductive composite ink, water-soluble sacrificial material and mechanical buckling, allowing printed circuits to be stretchable and high-strain-enduring. Furthermore, utilizing selective bonding

to substrate and guided buckling by thickness control, complex 3D structures buckled from 2D planar design can be easily fabricated in few simple steps. This novel fabrication technique brings technological advantages of the inclusion of wide selection of materials in composite inks. Hence, a one-step integration of various printed devices such as batteries, supercapacitors, biofuel cells and sensors into stretchable and mechanical durable device can be realized. Several fabrication examples including the reversible buckling of several 3D structures and the free-standing serpentine interconnected battery group is demonstrated, which exhibited minimal performance change even under 100% stretching deformation. The successful implementation of such fabrication technique offers a promising route for the wide adaption of stretchable device.

#### 9:00 AM \*PM02.04.03

**Direct Fabrication of Flexible and Stretchable Conductor by Electrohydrodynamic (EHD) Printing** [Jingyan Dong](#); North Carolina State University, Raleigh, North Carolina, United States.

Direct printing of flexible and stretchable conductors provides a low-cost mask-less approach for the fabrication of next generation electronics. In this work, an electrohydrodynamic (EHD) printing technology was studied for a number of functional materials (e.g. low-melting-point metal alloys, 1D silver nanowires) that are hard to be printed with traditional print methods. We successfully achieved high-resolution printing of these materials, which enables low-cost direct fabrication of metallic conductors with sub-50 $\mu$ m resolution. The EHD printed microscale metallic conductors represent a promising way to create conductive paths with metallic conductivity and excellent flexibility and stretchability. A stable electrical response was achieved after hundreds of bending cycles and during stretching/releasing cycles in a large range of tensile strain (0-70%) for the printed conductors with properly designed 2D patterns. When using low-melting-point metal alloys as functional inks, due to their low melting point, the printed conductor demonstrated excellent self-healing capability, which recovered from failure simply by heating the device above the eutectic temperature of the metal ink and applying slight pressure. A few device demonstrations, including a high-density touch sensor array and AgNW heaters and electrocardiogram (ECG) electrodes, were fabricated to demonstrate the high-resolution capability of the EHD printing for the direction fabrication of flexible and stretchable devices.

#### 9:30 AM \*PM02.04.04

**Accelerating Design Through Flexible Hybrid Electronics Materials Data Collaboration** [Scott M. Miller](#); NextFlex, San Jose, California, United States.

Flexible Hybrid Electronics encompasses a rapidly growing set of technology and manufacturing capabilities that enable the creation of electronics with previously impossible form factors. The field combines printed electronic materials, additive processing, traditional semiconductor integrated circuits, and substrates that can bend, flex, and stretch. NextFlex, established in 2015 as America's Flexible Hybrid Electronics (FHE) Manufacturing Innovation Institute, is a Public Private Partnership between the US Department of Defense and the private sector. The Institute brings together more than 85 companies and universities and 17 government organizations to shape the future of FHE, accelerate its development and commercialization, catalyze the manufacturing workforce of tomorrow, and ensure American manufacturing competitiveness in FHE. The Institute does this through a variety of mechanisms – jointly developing technology roadmaps; funding projects to advance the technology; performing technical projects to develop components, devices, and manufacturing processes; operating a low-volume production and prototyping fab; convening members of the ecosystem to collaborate; and developing education and training programs for both the next generation of talent and the current workforce.

One key challenge in FHE arises from one of its strengths – the abundance of materials that are available to use in designing and fabricating FHE devices. The material properties of common FHE materials are often dependent on the fabrication processes employed and the specific operating parameters used in those processes. The consequence is that a designer cannot look to a single data source for properties needed to conduct design, modeling, and simulation, and often requires an intimate knowledge of the fabrication process. In practice, design and fabrication often become linked by an iterative loop to arrive at the final design. This slows the design cycle for FHE devices. Furthermore, test methods are not standardized for FHE devices that undergo high strain, and these devices therefore require customized qualification testing.

This talk will present work that NextFlex has undertaken to address the data and design challenge by creating means for researchers, developers, and designers to collaborate. Tools like the NextFlex Material & Process Database provide a searchable repository for property data linked to specific labs or manufacturers, and specific processes. Examples of the use of this tool will be included. NextFlex funded projects that are developing design tools, test methods, and reliability testing will also be discussed.

#### 10:00 AM BREAK

#### 10:30 AM \*PM02.04.05

**Polymer-Assisted Metal Deposition for Soft Electronics** [Zijian Zheng](#); Hong Kong Polytechnic University, Hong Kong, Hong Kong.

Metal electrodes are indispensable element for most future soft electronic devices. One critical challenge in this field is how to fabricate highly conductive, adhesive, smooth, and soft metal conductors at low temperature under ambient conditions, and preferably in a roll-to-roll manner. Our laboratory recently develops Polymer-Assisted Metal Deposition (PAMD) to address this issue. PAMD allows ambient fabrication of flexible, foldable, stretchable, compressible, and wearable metal (especially Cu) conductors with very high conductivity. Importantly, PAMD is compatible with versatile substrates and different printing technologies at ambient conditions. This seminar will discuss the materials chemistry of PAMD and demonstrate their applications in several important soft electronic devices including circuits, solar cells, supercapacitors, and transistors.

#### 11:00 AM PM02.04.06

**Undercooled Liquid Metal Particle Inks for Flexible Conductive Traces Using Direct Writing** [Andrew Martin](#)<sup>1</sup>, [Christophe Frankiewicz](#)<sup>3</sup>, [Zach Martin](#)<sup>2</sup>, [Dipak Paramanik](#)<sup>2</sup>, [Ian Tevis](#)<sup>2</sup> and [Martin Thuo](#)<sup>1,4,5</sup>; <sup>1</sup>Material Science and Engineering, Iowa State University, Ames, Iowa, United States; <sup>2</sup>SAFI-Tech LLC, Ames, Iowa, United States; <sup>3</sup>Sep-All LLC, Ames, Iowa, United States; <sup>4</sup>Microelectronics Research Center, Iowa State University, Ames, Iowa, United States; <sup>5</sup>Center for Bioplastics and Biocomposites, Ames, Iowa, United States.

Flexible electronics offer the promise of comfortable and less-intrusive bio-interfacing devices and affordable and rugged displays in packaging. Thermal sensitivity of the typical substrates used, however, makes it challenging to mount components or create conductive lines on these devices. Silver nanoinks have emerged as a lower-temperature processing alternative; although curing temperatures significantly above ambient eliminates use of a significant number of heat sensitive substrates. Advances in synthesis of core-shell undercooled metal, and associated heat-free lead-free solders, offers a new approach to ambient fabrication of conductive lines and component soldering. Herein, we demonstrate the adoption of undercooled liquid metal particles in fabrication of flexible electronic devices via direct write or screen printing. Devices ranging from MEM sensors, Wheatstone bridge, conductive traces and LED arrays are used to demonstrate versatility of this heat-free fabrication technique.

11:15 AM PM02.04.07

**Hierarchical Self-Assembly in 3D Printable Carbon Nanotube (CNT) Based Inks** [Shayandev Sinha](#), Yanbin Wang and Siddhartha Das; University of Maryland, College Park, Maryland, United States.

Compared to the traditional metallic materials CNT is known to have superior thermal and electronic conductivity. Printability of such CNT based inks thus can change the way we make electronic devices, composite materials etc. For any large-scale manufacturing, a chemical binder free CNT based ink will be useful but the bottleneck is the solubility of CNT in water - which is very low. Here we include graphene oxide (GO) which increases the dispersion of CNT inside the water. This ink is then printed using a syringe 3D printer with optimized pressure on a 3D printed soft surface made of an UV curable adhesive material (NEA 121) and sintered at 150 °C for 8 hours. The water evaporation during sintering causes the CNT and GO particles to assemble on the soft solid. A detailed electron microscopy study reveals a very interesting feature- hierarchical self-assembly of CNT and GO where CNTs self-assembled over nanoscale is sandwiched between layers of GO self-assembled over microscale. GO covers the whole printed line and exhibits flake-like behavior covering the internal CNT layers. Thus, the composition of CNT: GO ratio changes the whole procedure of self-assembly and reveals various highly intriguing internal structures. This also affects the electrical conductivity and the overall printability of the ink. We believe that such kind of inks will be key for fabricating embedded electronics inside the conformable composites.

11:30 AM PM02.04.08

**Junction-Modulated Silver Nanowire-Elastomer Composite Films for Stretchable Transparent Conductors** [Jae-Chan Lee](#), Soyeon Lee, Phillip Won, Jung-Jae Park, Seung Hwan Ko and Young-chang Joo; Seoul National University, Seoul, Korea (the Republic of).

Recent demand of reducing physical distance between devices and human have attracted considerable interests in flexible and stretchable devices for wearable electronics. Nanostructured metals, especially silver nanowires (AgNWs) have emerged as most promising transparent electrodes for stretchable and wearable devices owing to their high mechanical endurance. Many research groups have examined fracture strain of freestanding single nanowire. To develop commercially available AgNW films in stretchable and wearable electronics, it is necessary to investigate on the factors such as junctions and interaction between nanowires and elastomeric substrates on stretchability of entire AgNW films. However, there have been few researches on the factors affect to reliability of entire AgNW films in stretching conditions instead of single nanowire for transparent electrodes. Here, we investigate the effect of post treatment on tensile reliability by in situ tensile testing within scanning electron microscope (SEM).

AgNWs were synthesized by polyol process and assembled to network on polydimethylsiloxane (PDMS) and Solaris by vacuum filtration method. Two types of post treatment, laser-welding and thermal treatment, was conducted at the air ambient. Resistance of AgNW film was measured with varying uniaxial tensile strain and stretching cycling by tensile test system at constant strain rate (0.01mm/s). In addition, in situ tensile tests was performed on the holder designed to apply tensile strain inside SEM instrument.

During being stretched to 50% of tensile strain, both thermal annealed and laser-welded AgNWs showed more stable resistance behavior than as deposited AgNWs, especially laser-welded samples showed lowest resistance ( $R = 71 \Omega$ ) even after 50% stretching. Interestingly, at the low level of strain (~ 10%), thermally treated AgNWs exhibited lower resistance than laser-welded AgNWs in contrast to the case of high strain. These tensile behavior of post treated AgNWs would originate from the integration of junctions and interactions between nanowires and substrates. Thermal treatment affect to adhesion property between nanowires and substrate, which makes each nanowires attach to the elastomeric substrate more strongly, inducing strain localization when the low level of strain applied to the AgNW networks. However, laser-welding selectively produces heat on junction of each nanowires and induces strong junction on networks without affecting adhesion between nanowires and substrate. When the higher strain is applied to the AgNW films, thermally treated AgNW highly combined to substrate is exposed to additional compressive strain due to poisson's ratio mismatch. The morphological change of AgNW networks with respect to tensile strain through SEM also will be discussed.

11:45 AM PM02.04.09

**Flexible Supercapacitor Electrodes with Silver Nanowire Networks** Recep Yuksel, Sahin Coskun and [Husnu E. Unalan](#); Middle East Technical University, Ankara, Turkey.

Silver nanowires (Ag NWs) are appealing candidates for supercapacitor electrodes due to their high conductivity in addition to their allowance for all active materials to be in close contact to facilitate charge transport. All are very important to attain maximum charge accumulation provided that Ag NWs are electrochemically stable within the utilized potential window. In this work, high aspect ratio Ag NWs are used within a coaxial and/or network-like flexible nanocomposite structure in supercapacitor electrodes. Utilization of Ag NWs as conductive templates also results in rapid deposition of electrode active materials. We have fabricated supercapacitors using Ag NWs and their nanocomposites with molybdenum oxide ( $\text{MoO}_3$ ) ( $500.7 \text{ F g}^{-1}$ ) [1], nickel hydroxide ( $\text{Ni(OH)}_2$ ) ( $1165.2 \text{ F g}^{-1}$ ) [2], polypyrrole (PPy) ( $509 \text{ F g}^{-1}$ ) and some PEDOT derivatives ( $61.5 \text{ F g}^{-1}$ ). Highly conductive Ag NWs were utilized as the only current collectors and templates for these electrode active materials. Electrochemical properties of the fabricated Ag NW based flexible nanocomposite supercapacitor electrodes were investigated through galvanostatic charge-discharge, cyclic voltammetry, and electrochemical impedance spectroscopy. We will present a detailed analysis of utilization of Ag NWs in the fabricated supercapacitors to underline their charge transport behavior. Our results showed the potential of the use of Ag NWs in energy storage devices and the structures presented in this work is highly plausible and can be easily extended to other metal nanowire, metal oxide and conducting polymer systems.

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[4] R. Yuksel, S. Coskun, G. Gunbas, A. Cirpan, L. Toppare, H. E. Unalan, Silver Nanowire / Conducting Polymer Nanocomposite Electrochromic Supercapacitor Electrodes, *J. Electrochem. Soc.* 164 (2017) A721.

SESSION PM02.05: Soft Electronics and Reliability

Session Chairs: Jesse Jur and Amanda Myers

Thursday Afternoon, November 29, 2018

Hynes, Level 1, Room 109

1:30 PM \*PM02.05.01

**Imperceptible Electronics—Design, Reliability, Applications and Future Trends** [Martin Kaltenbrunner](#); Soft Electronics Laboratory, Johannes Kepler University, Linz, Austria.

Electronics of tomorrow will be imperceptible and will form a seamless link between soft, living beings and the digital world. Exploring the fundamental physics, mechanical form factors, and materials required to meet the needs of this new generation of *soft* electronics is driving multidisciplinary research worldwide. Weight, flexibility and conformability are pivotal for future wearable, soft and stretchable electronics to proliferate. The abilities to be imperceptible, epidermal, transient and self-healing are fueling the vision of autonomous smart appliances to be embedded everywhere, on textiles, on our skin, and even in our body.

This talk introduces a technology platform for the development of large-area, ultrathin and lightweight electronic and photonic devices, including solar cells, light emitting diodes and photodetectors, active-matrix touch panels, implantable organic electronics, imperceptible electronic wraps and “sixth-sense” magnetoception in electronic skins. Air stable perovskite solar cells, only 3  $\mu\text{m}$  thick, endure extreme mechanical deformation and have an unprecedented power output per weight of 23 W/g. Highly flexible, stretchable organic light emitting diodes are combined with photodetectors for on-skin photonics and pulse oximetry, providing electrical functionality in yet unexplored ways. Tactile sensor arrays based on active-matrix organic thin film transistors can be operated at elevated temperatures and in aqueous environments as an imperceptible sensing system that ensures the smallest possible discomfort for patients requiring medical care and monitoring. Combined with organic amplifiers and biocompatible conductive gels, we demonstrate *in vivo* recording of vital signals. E-skins with GMR-based magnetic field sensors equip the wearer with an unfamiliar sense that enables perceiving of and navigating in magnetic fields. These large area sensor networks build the framework for electronic foils and artificial sensor skins that are not only highly flexible but become highly stretchable and deployable when combined with engineered soft substrates such as elastomers, shape memory polymers or hydrogels. We show mobile health monitoring systems, smart, tissue-like electronics and soft robots that utilize tough hydrogels as soft transducers, generators and adaptive lenses.

In addition, we will demonstrate concepts that allow tuning the band gap of perovskite semiconductors via quantum size effects. Without manipulation of halide stoichiometry, we achieve fine-tuning of color emission from near infrared to ultraviolet through solid-state confinement in nanoporous alumina or silicon scaffolds. Our perovskite nanocrystal emitters may be employed in next generation flexible, solution-derived photonic sources.

#### 2:00 PM PM02.05.02

**Toward Rubber Solar Cells—Increasing the Deformability of Semiconducting and Conducting Polymers** [Darren J. Lipomi](#); University of California, San Diego, La Jolla, California, United States.

Mechanical deformability underpins many of the advantages of organic semiconductors in applications from flexible solar cells to wearable devices for healthcare and virtual touch. The mechanical properties of these materials are, however, diverse, and the molecular characteristics that permit charge transport can render the materials stiff and brittle. In this talk, I describe the ways in which molecular structure and solid-state packing structure govern the mechanical properties of organic semiconductors, especially of  $\pi$ -conjugated polymers. In particular, I describe how low modulus, good adhesion, and absolute extensibility prior to fracture enable robust performance, along with mechanical “imperceptibility” if worn on the skin. The discussion focuses on the mechanisms by which mechanical energy is either stored (i.e., elastically) or dissipated (i.e., by plastic deformation or fracture). Mechanical energy is mediated at the level of both the molecular structure (determined by synthesis) and solid-state packing structure (determined by processing techniques). Development of metrological methods are critical for the accurate determination of the mechanical properties of thin films of materials for which only small quantities are available from laboratory-scale synthesis. We often find that the interplay between the semiconducting polymer and the substrate influence the mechanical properties and the fracture behavior. Computational molecular dynamics simulations have been particularly helpful in predicting the molecular mechanisms responsible for deformation. The talk concludes with applications of organic semiconductor devices in which every component is intrinsically stretchable or highly flexible.

#### 2:15 PM PM02.05.03

**Soft Organic Electronics Using Strengthened Graphene Electrodes** [Kilwon Cho](#) and Boseok Kang; Pohang University of Science and Technology, Pohang, Korea (the Republic of).

Recent research in organic electronics has focused on developing next-generation practical soft devices that use graphene materials, which are a single-atom-thick sheet of  $sp^2$ -hybridized carbon atoms. However, currently-available graphene materials are too fragile to meet industrial requirements for mass production, but also for use of electrodes in soft organic devices. Therefore, a main challenge in this field is to increase the strength and chemical stability of such material without degrading its electronic properties. In this talk I will present our recent study about nanoscale organic layers to strengthen monolayer graphene sheets. We found that alkylsilane molecules can self-assemble on flaws in the surface of graphene and form nanometer-thick patches on them, in a phenomenon that resembles suturing of wounds. This process dramatically improves graphene’s mechanical durability while preserving its other attractive characteristics. The nano-patched graphene was exploited to demonstrate soft electronic skin sensors and organic field-effect transistors that have superior electrical properties. We believe that this nanopatch method would have a wide range of applications and contribute to development of graphene-electrode-based soft organic devices that are robust and practical.

#### 2:30 PM PM02.05.04

**Sintered Silver Nanoparticles and EGAIn for Stretchable Printed Electronics** Mahmoud Tavakoli<sup>2</sup>, [Mohammad H. Malakooti](#)<sup>1</sup>, Hugo Paisana<sup>2</sup>, Yun Sik Ohm<sup>1</sup>, Daniel Green Marques<sup>2</sup>, Pedro Alhais Lopes<sup>2</sup>, Ana P. Piedade<sup>2</sup>, Anibal T. de Almeida<sup>2</sup> and Carmel Majidi<sup>1</sup>; <sup>1</sup>Carnegie Mellon University, Pittsburgh, Pennsylvania, United States; <sup>2</sup>University of Coimbra, Coimbra, Portugal.

Robust flexible conductors are essential for the development of wearable electronics and soft robotics. While there are various types of compliant polymers such as elastomers that are highly flexible and moderately stretchable, the number of flexible functional materials is very limited. To address this challenge, we have developed stretchable thin-film conductors suitable for wearable electronics. The newly synthesized metallic conductors are composed of silver nanoparticles (AgNP) and eutectic gallium indium (EGAIn) alloy. This talk covers design, fabrication, and characterization of stretchable thin-film metallic conductors with applications in integrated soft electronic devices. The rapid manufacturing method developed for these flexible electronics is based on printing silver ink on a temporary tattoo paper (with a thickness of 5 microns) followed by deposition of EGAIn to the printed circuits. With a thin layer of EGAIn, the electrical conductivity and mechanical failure strain of the printed silver traces significantly improved. A volume conductivity of  $4.8 \times 10^6 \text{ Sm}^{-1}$  was achieved while the stretchability of circuits was enhanced as much as 20 times when compared to traces with pure silver ink. Extensive electromechanical characterization on the printed traces will be presented to demonstrate the practical potential of sintered AgNP-EGAIn traces. Furthermore, functioning circuits with surface mounted microelectronic chips will be presented to show the performance of AgNP-EGAIn traces as soft, stretchable, skin-like electronics.

#### 2:45 PM PM02.05.05

**Rapid Healing of Metal Thin Films on Flexible Substrates** [Stefano Danzi](#), Volker Schnabel, Giulia Biffi, Johannes Gabl, Alla Sologubenko, Henning Galinski and Ralph Spolenak; Department of Materials, ETH Zurich, Laboratory for NanoMetallurgy, Zurich, Switzerland.

In the past two decades, the use of metallic thin films as principal conductive material has been extended from Silicon-based microelectronics to electronic circuitry on flexible substrates. This spans from bendable sub-micron sensors to meter-long displays. For commercial applications and wearable or implantable healthcare devices, however, one key point that is yet to be thoroughly addressed is their long-term reliability. Indeed, the lifetime of flexible devices is limited by performance degradation often due to fatigue failure of metallic conductors. In our work, we introduce a new concept for healing of metal films on flexible substrates while in operation. Integrating Ni/Al multilayers as latent heat sources, we demonstrate that the self-sustained solitary heat wave generated by the intermetallic-forming reaction can be harvested to locally heal cracks. Damage repair is activated on-demand at room temperature by a low energy current pulse that is compatible with standard current-voltage operation conditions of electronic circuitry. After healing, which is completed in a single microsecond, in-situ electrical probing shows a conductance recovery as high as 90% for crack opening up to 500 nm in different metals, such as copper and gold. Intrinsic heat source healing represents a unique concept for rapid repair of metallic thin films, which can be applied to flexible electronics or even integrated in temperature-sensitive components in Si-based microelectronics.

### 3:00 PM BREAK

#### 3:30 PM PM02.05.06

**In Situ Test Method for Identifying Cracks in Conductive Printed Materials Used in Textile Electronics** Raj Bhakta and Jesse Jur; North Carolina State University, Raleigh, North Carolina, United States.

Reliability of printed devices within the field of textile electronics is a significant roadblock to their widespread market adoption. This problem is further exacerbated by the lack of test methods for evaluating the failure modes of printed devices such as interconnects under mechanical strain. A simple but effective thermo-electro-mechanical method for identifying cracks within printed conductive pathways on textiles and on planar films laminated on textiles is presented. This method utilizes resistive joule heating to isolate conductive areas where cracks can form in-situ. It requires only a DC power source, thermal imaging device, tensile testing setup, and printed conductive samples. It has been shown that along a printed interconnect, cracks can form along print directions that endure high localized strain such as at curved junctions or at connection points for many sinusoidal based interconnect geometries. Compared to post visual inspection utilizing optical microscopy<sup>1</sup>, SEM microscopy<sup>1</sup>, or atomic force microscopy<sup>2</sup> which can be time-consuming and expensive, our method is simple and cost-effective as a first pass for identifying the localized area wherein a crack has formed in-situ. In this talk we will show results for printed devices on films and conductive pathways 'embedded' into a textile by direct-write printing.

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2. Cramer, T. et al. Direct imaging of Defect Formation in Strained Organic Flexible Electronics by Scanning Kelvin Probe Microscopy. *Sci. Rep.* 6, 38203; doi: 10.1038/srep38203 (2016).

#### 3:45 PM PM02.05.07

**Tensile and Fatigue Ductility Testing of Free Standing Cu Films and of Cu Films on Polyimide Substrates** Ulrich R. Memmert and Roland Herold; Atotech Deutschland GmbH, Berlin, Germany.

Mechanical properties like the ductility of Cu structures are often discussed in the context of reliability considerations. Often experimental data for free standing films of around 50  $\mu\text{m}$  thickness are used. The influence of the layer thickness or of the interactions with the substrate or the surrounding materials is often not known.

Thin Cu films were investigated as free standing films (Cu thickness 10  $\mu\text{m}$  – 60  $\mu\text{m}$ ) and deposited on polyimide (PI) substrates (Cu thickness 2  $\mu\text{m}$  – 60  $\mu\text{m}$ ) by tensile testing. The ductility and the yield strength were determined. Both sample types were also investigated for Cu thicknesses between 10  $\mu\text{m}$  and 50  $\mu\text{m}$  by a cyclic bending test. From these data the fatigue ductility was determined. For some of the samples the grain structure was investigated before and after tensile testing by secondary electron microscopy (SEM).

The measured tensile ductility varies significantly with layer thickness and is, at least for low layer thickness, also significantly affected by the presence of the PI substrate. For low layer thickness it decreases in the case of free standing films while it is significantly enhanced when in being contact to a PI substrate. The fatigue ductility decreases with decreasing layer thickness and shows no strong sensitivity to the presence of the PI substrate. SEM imaging shows the grain structure for the original layers to be rather independent of the layer thickness. After tensile testing a clear refinement of the grains is found.

#### 4:00 PM PM02.05.08

**Fatigue-Free and Self-Healing Stretchable Transparent Electrodes** Chuanfei Guo<sup>1</sup> and Zhifeng Ren<sup>2</sup>; <sup>1</sup>Materials Science and Engineering, Southern University of Science and Technology, Shenzhen, China; <sup>2</sup>University of Houston, Houston, Texas, United States.

Flexible transparent electrodes are key elements in flexible electronics and soft robotics. Stretchability is one of the most demanding mechanical modes of flexibility. A material that is optically transparent and electrically conducting is often not stretchable. However, a transparent conducting film can become stretchable if it is tailored to a network. In addition, one-dimensional materials that are intrinsically stiff can become stretchable when tailored to serpentine structures. We used a method that we call grain boundary lithography and successfully fabricated Au nanomeshes with curved ligaments, exhibiting indium tin oxide (ITO) level sheet resistance and transparency, together with exceptionally large stretchability.[1,2] The Au nanomesh with an optimized topology and interfacial strength can be one-time stretched to 300%, or cyclically stretched/released to 150% for 50,000 cycles without showing significant change in resistance or in microstructure. Fatigue is a deadly disease for metals and it is often believed that only liquid does not show fatigue, but here our Au nanomesh is totally free of fatigue. We show that the adhesion between the Au nanomesh and the underlying substrate plays an important role to the stretchability and strain fatigue of the electrode. The scratch resistance of the Au nanomesh can be improved by introducing a chemical bonding between the metal and the underlying substrate.[3] We have also found that capillary force on nanoscale is effective for cold-welding of flexible transparent electrodes, or for the self-healing of damaged electrodes.[4] The fatigue-free and self-healing nature of the electrode will provide high durability of the electrode in real-world applications including soft and intelligent robotics, highly stretchable photoelectronics, implantable electronics, and flexible medical devices.

#### References

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3. Chuan Fei Guo, Yan Chen, Lu Tang, Fang Wang, Zhifeng Ren. Enhancing scratch-resistance by introducing chemical bonding in highly stretchable and transparent electrodes. *Nano Lett.* 2016, 16, 594–600.
4. Yuan Liu, Jianming Zhang, Heng Gao, Yan Wang, Qingxian Liu, Siya Huang, Chuan Fei Guo, Zhifeng Ren, Capillary-Force-Induced Cold Welding in

Silver-Nanowire-Based Flexible Transparent Electrodes. *Nano Lett.* 2017, 17, 1090-1096.

#### 4:15 PM PM02.05.09

**Tough Bonding of Conductive Hydrogel to Diverse Substrates** [Akihisa Inoue](#)<sup>1,2</sup>, Hyunwoo Yuk<sup>1</sup>, Baoyang Lu<sup>1</sup> and Xuanhe Zhao<sup>1</sup>; <sup>1</sup>Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; <sup>2</sup>JSR Corporation, Tokyo, Japan.

Conductive polymer, such as poly(3,4-ethylene dioxathiophene)(PEDOT) have been attracting great attention because of their biocompatibility, relatively softness and highly conductivity. In addition, conductive polymer hydrogel which have properties both conductivity and hydrogel, based on PEDOT or another conjugated polymer are highly attractive materials in biomedical application, soft robotics and sensors. However, there is limitation to fabricate them into such applications with reliability to use due to poor adhesion to another materials. There are a few known approaches to achieve better adhesion of PEDOT on substrate, but those methods require special EDOT monomer for adhesion improvement. Therefore, to provide useful and general method for tough bonding of conductive hydrogel to diverse substrates has remained as grand challenge in this field.

Here, we report a useful and remarkable promising tough bonding method of conductive hydrogel to diverse substrates, such as glass, PDMS, polyimide and metal. We also demonstrate quantitative characterization of adhesion performance of conductive hydrogel on diverse substrates. This method will provide a simple yet truly useful and powerful tools for the fabrication of unprecedented devices in diverse fields.

#### 4:30 PM PM02.05.10

**Reliability Assessment of Conductive Interfaces for Flexible Electronics** [Kyungjin Kim](#), Gabriel Cahn, Suresh Sitaraman, Olivier Pierron and Samuel Graham; Georgia Institute of Technology, Atlanta, Georgia, United States.

Flexible electronics are next generation devices due to thin and light features that results in low manufacturing, installation and maintenance costs. These can be applied to wearable technology by allowing devices to conform to bodies while offering great utility. Additionally, silver ink applications have been developed recently as potential flexible circuits for consumer electronics, medical devices and alternative-energy solutions. In each case, reliability assessment is important at every stage of development to ensure reliable functioning for an adequate period of service. In this study, we focused on conductive materials that are (1) used in wearable flexible electronics or (2) fabricated on polymer substrates for flexible circuits. We first demonstrated the wearable conductive interfaces' degradation over time in various environmental and mechanical conditions and analyzed the data. A Garmin conductive pad, Zephyr conductive fabric, Polar T-shirt conductive pad were kept in deionized (DI) water, 3.5% NaCl solution and simulated perspiration, and conductance measurement were recorded until they completely degraded. Simulated perspiration was found to be the harshest condition for the Zephyr fabric, while the pad types were not affected by any of the solutions. Scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) were performed on the Zephyr fabric to image the surface degradation and predict the chemical reaction in NaCl and simulated perspiration conditions as compared to DI water. In addition to the above, the degradation of conductive inks on polymer substrates and the effect of barrier coatings on their degradation were studied further. A comparative in-situ microscopy tensile test and resistance measurement of a flake and a sintered-silver electric circuit pad on polymer substrate were conducted. The development of cracks in various types of polymer substrates was compared and analyzed using a depth-profiling technique in laser scanning confocal microscopy. The effect of atomic layer deposition (ALD) encapsulation layer on the development of cracks in the silver inks' surface was also examined.

#### 4:45 PM PM02.05.11

**Fatigue Damage in Ag Nanowire Networks** [Chongguang Liu](#), William Sampson and Brian Derby; University of Manchester, Manchester, United Kingdom.

Transparent conductive thin films (TCF) are widely used in electrical devices, especially for organic light-emitting diodes (OLED), screens & displays, solar cells and touch panels. TCFs must have low sheet resistance and high light transmittance. Generally, the materials used to make TCFs should behave low sheet resistance and high light transparency, typically the sheet resistance,  $R_s$ , should be  $\leq 100 \Omega/m^2$  with optical transmittance,  $T \geq 90\%$ . The current industry standard material that is used to define these standards is indium tin oxide (ITO). For applications in flexible and stretchable electronics, such films must be resistant to damage after significant strain, a requirement that cannot be satisfied using ITO TCFs. Potential replacement materials include conductive polymers, carbon nanotubes, metallic grids, graphene, and metallic nanowires. Silver nanowire networks (AgNW) can show lower sheet resistance with higher light transmittance than ITO thin films; they also display a much greater strain to failure and greater resistance to mechanical damage. This study investigates the optoelectric properties and flexibility of AgNW networks with the objective of developing a fuller understanding of their behaviour, damage mechanisms and how these can be developed into predictive models for their properties and lifetime. Silver nanowires have been deposited onto flexible polymer substrates by spray coating to form a continuous stochastic network. Post-spraying treatment of either a low temperature anneal or a normal pressure is used to improve wire-wire electrical contact and reduce the network sheet resistance while maintaining optical transparency. The structural integrity of the film under flexible electronics service conditions has been assessed through repeated bending tests in a high cycle fatigue environment. Film electrical properties degrade with increasing cycle number, leading to a 40% increase in sheet resistivity after  $5 \times 10^6$  cycles through a strain of  $\pm 1.7\%$ . This change in film electrical properties is correlated with observations of distributed local fracture events observed after testing by SEM studies of the fatigued networks. The fibre fracture events visible on SEM images can be quantified using an image analysis routine to count the number of fibres fractured during the bending process. These data can be used in conjunction with a model for the sheet resistance of stochastic conducting networks to predict the increase in resistance as a function of mean fibre length and hence correlated with the number of fractured fibres.

SESSION PM02.06: Poster Session  
Session Chairs: Jesse Jur and Braden Li  
Thursday Afternoon, November 29, 2018  
8:00 PM - 10:00 PM  
Hynes, Level 1, Hall B

#### PM02.06.01

**Changes in the Conductivity of FDM Printed Commercial Graphene-Infused PLA Under Short and Long-Term Electrical Stresses** [Adam Krajewski](#); Materials Science and Engineering, Case Western Reserve University, Cleveland, Ohio, United States.

The Graphene-Infused PLA is a material made by melt blending commonly used Polylactic acid (PLA) with a few weight percent reduced graphene oxide

(r-GO) to create an electrically conductive filament for polymer additive manufacturing. Among the other possible uses, it allows printing conductive circuits inside 3D printed PLA models using dual-extrusion with no change in mechanical properties of the model and printing flexible conductive circuits on fabrics using a standard FDM printer. In the recent years there were multiple successful studies on adjusting its composition and processing methods to achieve high conductivity. However, none of the studies have investigated how this property change over time when the material is used in a working device, what can be crucial to reliability of such device.

In the course of this study, we have investigated changes in the conductivity of as-printed Graphene-Infused PLA under electrical stress conditions that could be found in the target applications. Over 60 samples of additively manufactured tracks with 1.26mm x 4mm cross-section and 90±5µm layer height were prepared on non-conductive PLA substrate using popular Ultimaker 2+ FDM printer. Samples were studied in two separate experimental setups. In the first one, 36 samples underwent long-term study in which they were placed in groups, with different constant potentials applied and monitored for multiple weeks. The goal was to investigate reliability, variability and performance changes that would happen over lifetime of low-power devices like wearable electronics. In the second experiment, samples underwent short-term 6 hour long tests in which conductivity was measured with higher frequency and electrical stress characteristics were varied over broader spectrum, in order to well investigate the process of conductivity change and help formulate a theory explaining it.

#### PM02.06.02

**Nanoparticle Indium Tin Oxide Films Deposited by Mist Deposition System** Yasutaka Nishi<sup>1,2</sup>, Ryoko Suzuki<sup>1,2</sup>, Makoto Nakazumi<sup>1</sup>, Koichiro Iwahori<sup>1</sup>, Yoshiaki Kito<sup>1</sup>, Masaki Kato<sup>1</sup>, Kiyoshi Kanie<sup>2</sup> and Atsushi Muramatsu<sup>2</sup>; <sup>1</sup>Nikon Corp, Sagami-hara, Japan; <sup>2</sup>Tohoku University, Sendai, Miyagi, Japan.

Indium Tin Oxide (ITO) is a widely used transparent conducting oxide (TCO). TCO films have been deposited by solution deposition process using ITO nanoparticle. However, it is difficult to obtain high quality ITO film at less than 200°C because of high contact resistivity. The electrical properties of nanoparticle TCO films deposited by solution process should be strongly affected by the residual surface acting agent. Therefore, in order to obtain the high-quality nanoparticle TCO films by solution process with low resistivity, the after annealing temperature should be higher than 300°C. In this study, ITO films were deposited on substrates by mist deposition process. The deposition rate was almost equal to the one deposited by conventional sputtering depositions. The mist disposition process using a nanoparticle should be one of the most possible techniques for atmospheric pressure deposition, because these ITO films were consisted by high crystalline crystal grain.

ITO nanoparticles were dispersed in H<sub>2</sub>O solution with surface acting agent by ultrasonic dispersion (20kHz). H<sub>2</sub>O solution which include the ITO nanoparticle was atomized by ultrasonic transducer (2.4MHz). The solution mist were transported to substrate by carrier gas such as Ar or N<sub>2</sub>. The sheet resistivity was around 100 Ω/sq, where the post annealing temperature was 150°C. All the films showed more than 80% transmittance in the visible region. The transmittance decreased in the near-infrared region where reflectance increased. This behavior can be explained in terms of the variation in plasma oscillation in the near-infrared region, which is well known in highly degenerate TCO films. Capacitive touch-sensing device was fabricated by Nanoparticle ITO. Lozenge-patterned ITO films were created by FPD Lithography Systems.

#### PM02.06.03

**Highly Sensitive Crack-Based Strain Sensor on Elastomer Fabricated by Laser Transfer of Silver Nanoparticles** Wooseop Shin<sup>1</sup>, Younggeun Lee<sup>1</sup>, Saewoong Park<sup>1</sup>, Seongje Park<sup>1</sup>, Jaemook Lim<sup>1</sup>, Junyeob Yeo<sup>2</sup> and Sukjoon Hong<sup>1</sup>; <sup>1</sup>Optical Nanoprocessing Lab, Department of Mechanical Engineering, Hanyang University, Ansan, Korea (the Republic of); <sup>2</sup>Novel Applied Nano Optics Lab, Department of Physics, Kyungpook National University, Daegu, Korea (the Republic of).

Precise detection and control of strain at micro-nano scale is important for upcoming technologies such as robotics, automation factory and wearable medical applications. Fabrication of sensitive strain sensor on elastomer is key to monitor physiological information like human voice. Among various elastomers, polydimethylsiloxane (PDMS) has been studied for wearable devices since PDMS has a number of advantages such as biocompatibility, cost-effectiveness, transparency in visible region and conformal adhesion to versatile geometries given that the PDMS is sufficiently thin. However, preparation of a sensing unit on the PDMS has been remained as a difficult task to date because of its low surface energy and poor wettability.

In order to fabricate a sensitive strain sensor on the PDMS, we suggest a facile method to fabricate unstable metal micro lines on a PDMS by selective laser transfer of silver (Ag) nanoparticle (NP) ink. This instability enables controllable generation of cracks on the metal micro lines whose gap, or its overall electrical resistance, is easily changed by small external disturbance such as external pressure/strain or vibration. The detailed experimental methods are summarized in the following section.

Firstly, prepare sufficiently thin PDMS with ~500 µm thickness to be adhered to substrate conformally. Secondly, coat Ag NPs ink on a separate glass by spin coater at 1000 rpm for 600 seconds. Thirdly, attach the PDMS on the top of Ag NP ink coated glass and irradiate 532 nm continuous wave (CW) Nd:YAG Gaussian laser at 0.21W power and 130mm/s scanning speed through 5X objective lens. Finally, detach the PDMS film from the glass. Sintered Ag patterns are transferred to the PDMS along the scanned path as a resultant.

Given that the laser power is sufficient, it is observed that the transfer of the sintered Ag NP to the PDMS film only happens when the scanning speed exceeds certain threshold, and we presume this result is stemmed from rapid thermal expansion and contraction of PDMS film. Thermal expansion coefficient of PDMS (907X10<sup>-6</sup>/K) is known to be much larger than that of Ag (19X10<sup>-6</sup>/K) or glass substrate. (4X10<sup>-6</sup>/K) Consequently, large temperature gradient induced by rapid scanning is expected to cause a shear stress between these layers to promote the transfer of Ag NP towards the PDMS film.

The performance of the resultant sensor is related to the configurations of cracks which are derived from the detaching process. Among various factors, it is known from the previously reported that the crack spacing can affect the performance of the sensor in a controllable manner. In this study, the crack density is altered by exploiting the cylinders with different diameter to attain various bending curvature radii for the detaching process. The resultant crack-based strain sensor on elastomer at its optimum crack density has proven to be compatible to highly sensitive applications such as sound wave recognition.

#### PM02.06.04

**Highly Stretchable/Bendable Skin-Mimic Organic Transistors** Hwasung Lee; Hanbat National University, Daejeon, Korea (the Republic of).

Stretchable electronics have recently been extensively investigated for development of highly advanced human-interactive devices, by using elastomeric templates. However, mechanical properties of transistor components cannot keep up with the high stretchability of the elastomeric substrate, resulting in a problem that the device electrical performances are drastically decreased. Herein, a hard parylene-C layer was deposited on the pre-strained Ecoflex surface to fabricate a corrugated substrate which is a structure that can prevent damage against the external force. The metal electrode, the dielectric (parylene-C), the organic semiconductor (DNNT) layers were formed thereon. As the results, a maximum and average field-effect mobilities of 0.83 and 0.65 cm<sup>2</sup>/Vs, respectively, was measured, and these device performances were maintained up to 30% strain. In particular, the results remained stable even when 20% tensile was repeatedly applied 1000 times.

#### PM02.06.05

**Investigation of Charge Transfer Ability of Nanocomposites Based on Cellulose Nanowhiskers, Silver Nanoparticles and Electrospun Nanofibers** Kelcilene B. Teodoro<sup>1,3</sup>, Flavio Shimizu<sup>2</sup>, Vanessa P. Scagion<sup>1,3</sup> and Daniel S. Correa<sup>1,3</sup>; <sup>1</sup>Nanotechnology National Laboratory for Agriculture (LNNA), Embrapa Instrumentacao, Sao Carlos, Brazil; <sup>2</sup>São Carlos Institute of Physics, University of Sao Paulo, Sao Carlos, Brazil; <sup>3</sup>PPGQ - Department of Chemistry, Federal University of Sao Carlos, Sao Carlos, Brazil.

Novel sensors and biosensors have been fabricated with nanostructured materials in order to provide specific chemical functionalization and enhance their sensing properties. For instance, cellulose nanowhiskers (CNW) has been combined with functional materials as silver nanoparticles (AgNP) to application in sensor devices [1]. Combining these nanostructures with polymeric nanofibers becomes interesting once CNW can work as scaffolds for nanoparticles deposition. In this work, polyamide 6 electrospun nanofibers were combined with CNW and AgNP employing distinct strategies and were deposited onto fluorine doped tin oxide electrodes (FTO) surface. A hybrid material composed of CNW and AgNP resultant of previous study was also employed as strategy (CNW:Ag) [2]. The distinct nanocomposites were produced as follows: i) neat polyamide 6 fibers - (PA6), ii) PA6 fibers containing CNW in the bulk - (PA6/CNW)<sub>bulk</sub>, iii) PA6 fibers containing CNW:AgNP in the bulk - (PA6/CNW:Ag)<sub>bulk</sub>, iv) PA6 fibers coated with CNW:Ag - (PA6)<sub>mod\_CNWAg</sub> and v) fiber coated with AgNP (PA6/CNW)<sub>mod\_Ag</sub>. Samples (i – iii) were produced by electrospinning from PA6 solution (10% w/v) and a mixture of PA6 solution and CNW or CNW:Ag (1 %w/v), using formic acid as solvent. Experimental parameters used for electrospinning were: feed rate of 0.02 mL h<sup>-1</sup>, electrical field of 20 kV, working distance of 5 cm, interval deposition of 7 minutes. Otherwise, samples (iv – v) were resultant of 2 hours-immersion of electrospun fibers in a CNW:Ag or AgNP aqueous solutions. Nanocomposites were then characterized in terms of morphology by scanning electron microscopy (SEM) and the ability of charge transfer was evaluated by electrochemical impedance spectroscopy (EIS) and cycle voltammetry (CV). For nanocomposites (PA6)<sub>mod\_CNWAg</sub> no clusters were observed in SEM images, in contrast to (PA6/CNW)<sub>mod\_Ag</sub>, which displayed AgNP clusters at the surface, suggesting that CNW:Ag hybrid helps silver nanoparticles dispersion. Nyquist plots associated to EIS experiments showed a decrease on the charge transfer resistance, as consequence of the AgNPs and CNW:Ag conducting characteristics. Moreover, cyclic voltammograms revealed an evident electrocatalytic activity with the increase of current peak as consequence of CNW and CNW:Ag presence. Lower values of resistance and current peak were attributed to sample (iv), formed by PA6 fibers coated with CNW:Ag, revealing that the distribution of AgNPs led to an enhancement of charge transference. These results suggest the feasibility of applying these nanocomposites as sensitive layer of sensors and biosensors. Authors thank the financial support from CNPq, FAPESP (2014/21184-5), MCTI-SisNano, FINEP and Embrapa AgroNano research network.

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#### PM02.06.06

**Air-Liquid Interfacial Polymerization of Lacey Polypyrrole Thin Films** Luciano Santino<sup>1</sup> and Julio M. D'Arcy<sup>1,2</sup>; <sup>1</sup>Department of Chemistry, Washington University in St. Louis, St. Louis, Missouri, United States; <sup>2</sup>Institute of Materials Science and Engineering, Washington University in St. Louis, St. Louis, Missouri, United States.

Conducting polymers are commonly thought of as rigid materials with high glass transition temperatures, making them less attractive for flexible electronics. We report on developments in the vapor-liquid interfacial synthesis large area lacey (macroporous) polypyrrole films with submicron thickness. These lacey films are translucent, conductive, and continuous. Their porosity keeps them flexible under extreme conditions like immersion in liquid nitrogen, bypassing the limitations imposed by the high glass transition temperature of polypyrrole. The polypyrrole lace floats on water due to the surface tension created by the wetting of their segregated pores, allowing for easy deposition onto substrates from solution. The freestanding films can be manually twisted into micron-diameter strings of highly porous and conductive polypyrrole, which exhibit exemplary tensile strength. A detailed mechanistic investigation shows the initial nucleation and polymerization of pyrrole vapor on aqueous oxidant forms an interconnected polymer skeleton. As the reaction progresses, the skeleton grows laterally, confined by Langmuir-Blodgett forces at the air-liquid interface. Lacey polypyrrole is shown to have impressive electrochemical energy storage abilities without the use of any conductive substrate backing.

#### PM02.06.07

**Fabrication of Flexible Transparent Electrode with High Durability Based on Au Grid and Doped PEDOT:PSS for Perovskite Optoelectronic Devices** Yonghui Lee, Sang Woo Jin and Jeong Sook Ha; Korea University, Seoul, Korea (the Republic of).

Along with the development of various flexible optoelectronic devices, there has been increased demand for high performance flexible transparent electrodes. Even though there has been extensive efforts to fulfill the requirements of ultra-flexibility, high transparency, high electrical conductivity, and high resistance to high temperature and chemically harsh processes, there still remains much room for improvement.

In this work, we report on the fabrication of ultra-flexible, highly transparent and highly durable electrode via combined application of Au grid with ethylene glycol doped PEDOT:PSS onto a colorless polyimide coated NOA63 substrate. The fabricated transparent electrode shows a transparency of 90.7 % at 550 nm, sheet resistance of 30.3 Ω/sq, and high durability during the processes involving the thermal annealing at 180 °C and the treatment with acidic solution of pH 0.3 at 70 °C. The electrode also exhibits a high mechanical stability under 10,000 repetitive bending at a bending radius of 0.7 mm. By fully utilizing such a high performance of the electrode, we demonstrate the ultra-flexible perovskite solar cell and light emitting diode. The perovskite solar cell exhibits a steady state power conversion efficiency of 12.7% and the performance remains stable under 2000 repetitive bending deformation at a bending radius of 1 mm. Furthermore, the flexible perovskite LED is stably operated while attached onto a curved surface.

This work suggests the high potential application of our ultra-flexible transparent electrode with a high durability in various high performance flexible optoelectronic devices.

#### PM02.06.08

**Printed Biocompatible and Bioinspired Electrode Grids for Flexible Light-Emitting Electrochemical Cells** Martin Held<sup>1,2</sup>, Daniel Ehjeij<sup>3</sup>, Johannes Zimmermann<sup>1,2</sup>, Stefan Schliske<sup>1,2</sup>, Tobias Rödlmeier<sup>1,2</sup> and Gerardo Hernandez-Sosa<sup>1,2</sup>; <sup>1</sup>Light Technology Institute, Karlsruhe Institute of Technology, Karlsruhe, Germany; <sup>2</sup>Innovation Lab, Heidelberg, Germany; <sup>3</sup>Heidelberg University, Heidelberg, Germany.

Electrodes in light-emitting electrochemical cells (LEC) do not only supply the necessary drive current, but need to provide sufficient transparency for the emission. Designing the entire device to be fully printed, biodegradable and compatible with the human body presents an additional challenge. While PEDOT:PSS electrodes are transparent and considered biocompatible, their relatively high sheet resistance produces high turn-on voltages in fully biodegradable printed LECs. To overcome this limit, inkjet printed gold grids are imprinted into the substrate below the PEDOT:PSS electrodes in various symmetric, deterministic and nature-inspired patterns. Inkjet printing supports full freedom of pattern design and scalability to industrial processes. Their contribution to the conductivity and reduction in transmittance is estimated with a simple model and experimentally confirmed. Different stretchable substrates with increasing ultimate strain from thermoplastic cellulose acetate to parylene to biodegradable elastomers are utilized to test the benefits and

limits of these printed grid patterns. Owing to the choice of gold ink, the resulting LECs are completely biodegradable/ biocompatible and emphasize the potential of biomaterial based light-emitting devices. The use of flexible biomaterials in electronics in combination with scalable manufacturing of electrodes will enable the fabrication of transient and disposable technologies ranging from smart packaging and advertisement to degradable healthcare applications.

#### PM02.06.09

**Low Temperature, High Stability of Conductive Copper Electrode for Flexible Applications by Acid-Assisted Laser Sintering Process** Jinhyeong Kwon<sup>1</sup>, Hyunmin Cho<sup>1</sup>, Jinwook Jung<sup>1</sup>, Sukjoon Hong<sup>2</sup>, Junyeob Yeo<sup>3</sup> and Seung Hwan Ko<sup>1</sup>; <sup>1</sup>Seoul National University, Seoul, Korea (the Republic of); <sup>2</sup>Hanyang University, Ansan, Korea (the Republic of); <sup>3</sup>Kyungpook National University, Daegu, Korea (the Republic of).

Copper is good electrical and thermal conductivity, which compatible with noble metals such as gold and silver. However, the oxidation of copper under an ambient condition is a crucial issue for practical applications. The copper electrode is fabricated on the flexible substrate by acetic acid treatment (AAT), laser sintering process (LSP) and acid-assisted laser sintering process (ALSP). Various analytic measurements such as surface morphology, mechanical bending test, adhesion strength, chemical binding energy and humidity-temperature test are verified to examine the stability of the copper electrode with different post-treatment. In the case of ALSP, the change of the sheet resistance is 1.5% up to 4,000 cycles by mechanical bending test and its adhesion strength to the substrate is better than that of electrodes by AAT and LSP. After a humidity-temperature test, the copper electrode fabricated by the ALSP shows most stable chemical and electrical performances. Finally, the ALSP-processed copper electrode is employed to the flexible applications such as Joule-heater and touch screen panel.

#### PM02.06.10

**Influence of Semiconductor Deposition Pattern in the Fabrication of Organic Field-Effect Transistors by Inkjet Printing Technique** Josiani Cristina Stefanelo, João Henrique Rocha Matos, José Alberto Giacometti and Roberto M. Faria; São Carlos Institute of Physics, University of São Paulo, São Carlos, Brazil.

In the last years, the organic electronics has attracted great efforts at fundamental and technological researches. The organic electronics enables large-area fabrication, the use of flexible substrates, solution processing at low temperatures, and deposition by printing techniques. Moreover, several technological devices, such as, flexible displays, disposable sensors, RFID tags and wearable electronics can be produced using organic materials. To make possible these applications, is needed the production of field-effect transistor, an essential circuit component, which is used to amplify and switch digital and analog signals. Due to its importance, there is great interest at fabrication of organic field-effect transistors (OFETs). Among the developed printing technologies, inkjet is one of the most appropriate for microelectronics. It is a noncontact technique which uses low amount of material to print defined patterns, avoiding waste; furthermore it enables to change the printed pattern with easiness. Here, we present OFETs fabricated at the bottom gate-top contact architecture with the semiconductor deposited by inkjet printing technique. The semiconductor used was the *6,13-bis(triisopropylsilyl)ethynyl-pentacene* (TIPS-pentacene), a promising material as p-type semiconductor, due to its high mobility, air stability and solution processability. In this work, the transistor performance was evaluated changing the distance between drops and printing patterns. The semiconductor was deposited on the organic dielectric layer. Different printing patterns of parallel lines were deposited with respect to direction of electronic conduction. Transistors presented higher performance for the pattern with same dispensing direction, achieving mobilities on the order of  $10^{-2}$  cm<sup>2</sup>/V.s and on/off ratio of  $10^4$ . Similar features were obtained for the distance between drops of 250 μm. The better OFETs performance is associated with the printed film morphology, due to homogeneous semiconductor layer and oriented crystallization on the direction electronic conduction.

#### PM02.06.11

**Strain Effects on Electrical Performance of Polymer Supported Dupont 5025 Conductive Ag Ink** Gabriel Cahn, Samuel Graham and Olivier Pierron; Georgia Institute of Technology, Atlanta, Georgia, United States.

Improvements in materials science and precision printing technologies have given rise to flexible hybrid electronics, allowing for the creation of components that are lightweight, and able to conform to non-planar and amorphous surfaces. Unlike conventional rigid printed circuit boards, the application space of flexible electronics includes high strain use cases. Polymer supported conductive inks have become principle building blocks of flexible electronic assemblies, and ongoing academic research endeavors to optimize electrical performance of such inks against induced strain. This work investigates DuPont's 5025 ink, comprised of 80% by volume silver flakes in a polymer matrix. The ink is separately screen printed onto Kapton Polyimide (PI), Thermoplastic Polyurethane (TPU), and Polyethylene Terephthalate (PET), and subjected to strains in tension while measuring resistance of a circuit trace pattern. As strain increases, resistance rises at a rate dependent upon the stiffness of the supporting substrate. For example when supported by PI and PET, which have elastic moduli of 2.5GPa and 3.5 GPa, respectively, at 5% strain the measured resistance approximately doubles from a preloaded condition. When supported by TPU, with a modulus of 100MPa, the trace resistance was measured to triple. This disparity only increases with strain. In-situ optical microscopy revealed channel cracking of the ink as the primary cause of the increase in resistance, over that of length and cross-sectional area changes in the conductor due to the Poisson Effect. Of particular note is that cracking did not occur within the Ag flakes themselves, but rather at the flake/matrix interface. Post-mortem SEM imaging confirmed these findings. Furthermore, these channel cracks were observed to nucleate and grow more rapidly in inks supported by the softer TPU substrate. After loading, specimens were unloaded to assess the potential of electrical performance recovery after strain-induced damage. PI supported inks showed decreasing recovery, from approximately 100% after 1% strain, to 50% after 15% strain. PET samples decreased in a similar manner from 100%, but stabilized at approximately 65% recovery beyond 10% strain. TPU, having proved the most susceptible to strain damage, was shown to only recover 80% of its original performance after 1% strain, decreasing rapidly to a 25% recovery rate beyond 10% strain. Strain cycling conducted on PET supported inks indicates that strain amplitude has the greatest impact on electrical performance, above that of mean strain or strain rate. Given these findings, there is a strong link between electrical performance of 5025 and its supporting substrate. Designers must be aware of these relationships when selecting supporting materials for specific applications.

#### PM02.06.13

**Preparation of Cu Nanoparticle Colloid from a Cu Ion Solution by Using Protein Surfactant** Masatoshi Sekiguchi, Kei Oikawa, Mizuki Nakahara, Yuusuke Inaba, Taiyo Maeda, Akinori Matsui and Hiroki Ishizaki; Saitama Institute of Technology, Fukaya, Japan.

Recently, metal nanoparticles colloid had many problems such as the aggregation of nanoparticles, oxidation resistance and non-uniformity of nanoparticles. In order to dissolve many problems mentioned above, we support that oxidation and aggregation will be improved by using casein contained in milk as a polymeric surfactant. In this investigation Cu nanoparticle colloid will be grown from the aqueous solution containing Cu ion and casein. Also, high purity water by liquid phase reduction method was used. As a preparation method, copper sulfate, citric acid, and urea were dissolved in ultrapure water, and an aqueous copper ion solution was made strong alkali with an aqueous sodium hydroxide solution. Next, the copper ion aqueous solution, the surfactant solution and the reducing agent were stirred to prepare a copper nanoparticle precursor solution. The copper nanoparticle precursor solution was kept at 80 °C. for 20 minutes to prepare an aqueous copper nanoparticle colloid solution. For the actual results, the concentration of the nanoparticle colloid will be controlled by the surfactant concentration. Since the wavelength of the absorption spectrum shifts to the shorter wavelength side, the size of

the nanoparticle colloid is considered to be smaller.

#### **PM02.06.14**

**Improved Stability and Adhesion of Printed Graphene and Silver-Copper Composites for Circuits on the Foldable Substrates** Hui Jae Choi, Gyeong Seok Hwang, Ohyoung Kim, Dong Hyun Lee and Byung Doo Chin; Dankook University, Yongin, Korea (the Republic of).

Soft conductive materials, such as graphene and silver-based composites, are ideal for the electronic components of circuits and electrodes on the flexible, foldable, and even stretchable devices. Recently, stability against significantly smaller curvature and larger mechanical stress for repeated operation became a key factor to obtain a successful manufacturing of the commercial application of foldable electronic devices. Here, we have demonstrated the printed circuits on the foldable substrate with graphene ink and silver-copper nanocomposites. Few layer graphene powder nano-platelet, Angstrom materials graphene N002-PDR, was dispersed in solvents with appropriate binders to formulate a screen-printable paste. The paste was also modified for an electro-hydrodynamic jet printing toward a fabrication of fine line patterns on the foldable paper substrates and flexible polyimide films. In order to modify the surface toward smoothness at foldable operation, poly(4-vinylphenol) coating on the commercial paper substrate was employed. In case of graphene/silver composites printed, circuit showed superior performance as well as folding stability; decrease of relative conductance for  $-90^\circ$  and  $-180^\circ$  folding (toward inside direction) was only 5% and 12%. Moreover, the conductance was maintained about 80% of initial value after 1000 cycle of continuous folding. For higher conductance circuit, silver-copper composite inks were printed and compared with graphene-based composites. In order to further improve the stability against continuous folding and unfolding deformation, paper and plastic substrates were treated with primer containing the flexible additive, poly (ethyleneglycol) diacrylate (PEGDA). The folding stability of circuit conductance, employed as auxiliary electrode of green organic light emitting diode, was significantly improved by the enhancement of adhesion between PEGDA primer layer, foldable paper, and printed circuits.

#### **PM02.06.15**

**Fabrication of Ultra-Light Porous Boron Nitride/Polyimide (BN/PI) Composite Films with High Thermal Diffusivity and Low Dielectric Properties** Yang Kwansoo<sup>1,2</sup>, Dong Gyun Kim<sup>1</sup>, No Kyun Park<sup>1</sup>, Jong Chan Won<sup>1,2</sup> and Yun Ho Kim<sup>1,2</sup>; <sup>1</sup>Korean Research Institute of Chemical Technology, Daejeon, Korea (the Republic of); <sup>2</sup>University of Science and Technology, Daejeon, Korea (the Republic of).

As modern electronic devices become functionalized, miniaturized, more integrated, and exhibit higher performances, one of the most important issues is to efficiently remove heat generated by high-power integrated circuits. In addition to the high thermal conductivity, the low values of dielectric properties such as the dielectric constant ( $\epsilon$ ) and dielectric loss ( $\tan \delta$ ), are another important factors for future electronic devices using a high-frequency band, particularly for the 5G communications using frequencies above 2.8 GHz.

Here, we report a simple fabrication of ultra-light porous boron-nitride-(BN)/polyimide-(PI) composite films with high thermal diffusivities and low dielectric constants by combining high-internal-phase Pickering emulsification (HIPPE) and subsequent hot-pressing. BN nanoparticles in composite foams were well dispersed and three-dimensionally connected following the surface of the PI skeleton used as the polymer matrix. The BN contents in the BN/PI composite foams were adjusted in the range of 20–80 wt%. The porosities of the composite films were controlled according to the hot-pressing conditions such as the temperature. The internal porous morphologies of the BN/PI composite foams and films were characterized by scanning electron microscopy. The 400-°C-hot-pressed BN/PI composite films had higher thermal diffusivities than those of BN/PI composite films prepared by the conventional solution blending method, despite the presence of internal air pores reducing the thermal conductivity. In addition, the internal pores provided lower dielectric constants of the BN/PI composite films. The porous BN/PI composite films exhibited high thermal diffusivities of 0.059–1.033 mm<sup>2</sup>/s and low dielectric constants of 2.08–3.48 at 1 GHz for BN contents of 20–80 wt%. In particular, our porous BN/PI composite films had extremely low dielectric loss values, close to zero ( $< 0.002$ ) at high frequencies regardless of the BN content and pressing conditions, which is essential for the 5G communication technology. Therefore, our porous BN/PI composite films with high thermal diffusivities and weak dielectric properties are promising for applications as packaging materials for integrated and miniaturized microelectronic devices.