Deposition of Thin Films of CuFeS₂ by Method of Flash and Their Properties

The calculation of the electrostatic screening length has been an open issue in electron scattering problems in semiconductors since pointed out by Nevill Mott, more than eighty years ago. Over that time, Thomas-Fermi screening has been the dominant approach for calculating the screening constant in degenerate materials. In its formulation, parabolic energy bands are assumed. In the case of degenerate semiconductors, the assumption of parabolic bands can become a serious source of error. The Thomas-Fermi formula predicts screening that is too weak relative to self-consistent field methods in highly degenerate systems, including metal alloys. We have found an analytical solution for the calculation of the Fermi level and the electrostatic screening length for semiconductors and metal alloys in the degenerate limit using non-parabolic energy bands and Fermi statistics. This solution yields a more accurate determination of Fermi levels than methods that assume parabolic energy bands and presents a more accurate determination of screening length than the Thomas-Fermi formula. It is hoped that these equations will be useful to researchers investigating highly degenerate material systems, including metal alloys, from theoretical and numerical viewpoints.

Non-Destructive X-Ray Metrology of GST Phase Change Material Deposition

Process control of multi-element thin films is crucial for many applications in the semiconductor industry. More specifically, control of the thickness as well as composition of such thin films leads to improved yield of products and devices. X-Ray fluorescence (XRF) spectrometry is a method which can be used to determine thickness and composition of thin films simultaneously, provided that it has been calibrated with suitable standards. Accurate knowledge of calibration standard properties such as the thickness is crucial and cannot be reliably estimated from XRF measurements. GST (GeSbTe) is a phase change material which is used for applications in phase change memory and rewritable optical discs. The composition of GST influences the crystallization speed and the material stability, and therefore needs to be controlled. Similarly, the thickness of a layer is an important process parameter. Here, we show a method of measurement. In the present study a wavelength-dispersive X-Ray fluorescence spectrometer (PANalytical 2830 ZT Wafer Analyzer) is used to determine the thickness and composition of different GST films. GST films have an expected composition of Ge₅₀Sb₂₀Te₃₀, a nominal thickness of 10nm, and were manufactured under different Ar gas flux conditions (200ccm, 500ccm, and 800ccm). Prior to the analysis of these unknown samples, the XRF spectrometer was calibrated with a set of standards. Pure metal thin films (Ge on Si, Sb on Si, and Te on Si) were used, as well as a blank Si wafer. Thickness and density of these thin film standards was determined by X-ray reflectometry and used as an input for the calibration of the wafer analyzer. This procedure could be externalized as it is only necessary to establish the standard values once. Measurements on the GST layer were performed using two different spot sizes (diameter of 10 or 40mm), and a measurement time of 60s. First the precision of the technique was established, measuring one center spot repeatedly (n=10). After that, the thickness and composition of a number of layers were investigated by measuring at 21 different locations across the wafer surface with the 10mm spot size. The thickness of the films decreases from approx. 9.9nm for the 200ccm film, to approx. 7.5nm for the 800ccm film. Also, a variation of composition can be observed, as a trend Ge and Sb content decreases, whereas Te content increases as the deposition conditions change from 200ccm to 800ccm. Using the 40mm spot size, generally a relative standard deviation of <0.5% can be achieved. Smaller spot sizes increased the relative standard deviation. This paper describes how XRF can be used for composition and thickness determination following a one-time calibration of thickness by XRR for process control in semiconductor manufacturing.

Non-Destructive X-Ray Metrology of GST Phase Change Material Deposition

Sensors Directorate, Air Force Research Laboratory, WPAFB, Ohio, United States.

Deposition (Student) Using First-Principles to Explore Pathways to Enhance p-Type Conductivity in SrTiO₃

In this study, the effects of other common impurities such as Cu, K, Na, and Zn were explored using defect formation energies derived from density functional theory calculations performed with screened hybrid exchange correlation functionals. Cu and Zn were found to substitute on the Sr and Ti sites respectively depending on the processing conditions present for the Ti site overall. Na and K substitute primarily on the Sr site. All four were found to be acceptors in STO with defect levels within 0.3 eV of the valence band. With the possibility to form acceptor defects on both the A and B orbitals, these impurities can be used for tailoring the electrical properties of SrTiO₃ for applications in solid-state devices.
and B sites of the perovskite lattice, co-doping STO with these lesser known impurities in addition to Al, Mg, and Ni may enhance p-type conduction in certain processing conditions. The authors acknowledge financial support from AFOSR BRI grants FA9550-14-1-0264 and FA9550-17-1-0138 and a DoD NDSEG fellowship.

**PS07**

**Plasmonic Terahertz Response of P-Diamond** Michael Shurí, Sergey Rudin, Greg Rupper and Tony Ivanov; 'Army Research Laboratory, Adelphi, Maryland, United States; 2Rensselaer Polytechnic Institute, Troy, New York, United States.

The wide bandgap of 5.46 eV, the high breakdown field of over 10 MV/cm, and a high thermal conductivity over 20 W/cmK make diamond to be a promising semiconductor material for high-power and high-temperature operation. The diamond transistors operated to at least 350°C with a very low leakage currents and steep slopes in the subthreshold regime (down to ~10⁻¹⁰ A and close to 60 mV/decade, respectively). The highest reported values of the diamond electron and hole mobilities are 7.3 cm²/Vs and 5.300 cm²/Vs, respectively. The reported values of the hole effective mass range from 0.74 to 2.12. For the highest reported values of these parameters, the room temperature momentum relaxation time could be as high as 6 ps. At such high values of the momentum relaxation time, the plasmon frequency is in the THz regime and can be enhanced up to 50 THz if the carrier density of carriers can be increased to ~ 10²⁰ cm⁻³.

**PS09**

**Phono Transport in n-Al₂O₃-ZnO Superlattice Thin Films and Their In-Plane Thermoelectric Energy Generating Performance** Sang-Kwon Lee, No-Won Park, Won-Yong Lee and Gil-Sung Kim; Physics, Chung-Ang University, Seoul, Korea (the Republic of).

Recently, significant progress has been made in increasing the figure-of-merit of various nanostructured materials, including thin-film and quantum dot superlattice structures. Studies have focused on the size reduction and control of the surface or interface of nanostructured materials since these approaches enhance the thermopower and phonon scattering in quantum and superlattice structures. However, new and promising thermoelectric (TE) materials with enhanced TE performance, including doped oxide semiconductor, including zinc oxide (ZnO) multilayer or superlattice thin films, are also required for designing solid-state TE power generating devices with a maximum output power density and for investigating the physics of using zinc TE-doped and silver oxide micro-powders. SA₅O₅/ZnO (AO/ZnO) superlattice thin films, which were prepared by atomic layer deposition, and the evaluation of their in-plane electrical and TE properties. All the in-plane TE properties, including Seebeck coefficient, electrical conductivity, and thermal conductivity of the AO/ZnO superlattice and AO/ZnO film were evaluated in the temperature range from 40 to 300 K. Furthermore, the electrical power generation efficiency of the TE energy generator, consisting of four couples of n-AO/ZnO superlattice films and p-Bi₅₃Sb₆₆Te₇₆ (p-BST) thin-film legs on the substrate, was demonstrated.

**PS10**

**Tunable Giant Magnetocapacitance in Single Layer Capacitative Device on Epitaxial Nickel Zinc Ferrite Thin Film** Rajeev S. Joshi1, Debangsu Roy3, Sidharth Dash1, Sukhjit Singh1, S Bhat3 and P S Anil Kumar1; 1Department of Physics, Central University of Karnataka, Kalaburagi, India; 2Physics, Nano-magnetism Research Center, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan, Israel; 3Department of Physics, Indian Institute of Science, Bengaluru, India.

Spintronics is one of the most important and emerging areas of electronics. It uses spin of the electron and its transport in solids for development of new devices [1]. Development of tunable high frequency spin based devices is one of the major challenges for the field. In the present work, we demonstrate large magneto-capacitance in interdigital capacitor based device formed on to Ni₅Zn₃Fe₂O₇ epitaxial thin films. Ni₅Zn₃Fe₂O₇ thin films were grown on isostructural single crystalline MgAl₂O₄ (004) using pulsed laser deposition. The structural and magnetic properties of the films deposited were analyzed using X-ray diffraction, Raman scattering and vibrating sample magnetometry. It was found that these films are well-ordered and exhibit a high magnetic moment. This could be due to the epitaxial growth of these films on the MgAl₂O₄ substrate. The properties of these films have been investigated using polar and rectangular waveguide spectroscopy and transport measurements. The measured values of the capacitance and the magnetic response are compared to those reported in literature. The results show that the films exhibit a significant increase in capacitance under magnetic field, and this effect is tunable by varying the thickness of the film. The measured capacitance values are comparable to those reported for other magnetic materials. The results are consistent with the theory of magneto-capacitance and suggest that these films could be used in future devices for their potential applications in spintronics.
PS11 Optical and Electrical Characterization of Ultrathin Tellurium Nanowires Synthesized by Vapor Phase Deposition Keshab R. Sarkota, Ting Shan Luk, Douglas L. Medlin and George T. Wang; Sandia National Laboratories, Albuquerque, New Mexico, United States.

Tellurium (Te) is a semiconductor with a slightly indirect bulk bandgap of 0.35 eV. The trigonal crystal structure of Te consists of 1D helical chains of Te atoms stacked together by van der Waals type bonds arranged on 2D hexagonal lattice. Each Te atom is covalently bonded with its two nearest neighbors on the same chain. Because of its unique crystal structure, nanostructures of Te can be synthesized as one dimensional Te nanowires as well as two dimensional hexagonal Te nanoplates. Recent calculations have also showed that monolayer and multilayers of Te can potentially exist in a stable 1T-MoS$_2$-like (α-Te) structure, as well as the metastable tetragonal (β-Te) and 2H-MoS$_2$-like (γ-Te) structures. The α- and β-Te can thus be considered as transition metal dichalcogenides of general formula MX$_2$ in which transition metal (M) has been replaced by Te. These α- and γ-Te phases 2D structures are expected to have nearly direct band gap with significantly higher carrier mobilities compared to MoS$_2$, suggesting that 2D structures of Te are potentially applicable for novel electronic and optical devices. Here we discuss the vapor phase synthesis and characterizations of ultrathin Te nanostructures. While most 1D and 2D Te-nanostructures have been prepared through top-down methods, here we report the synthesis of ultrathin Te-nanostructures on sapphire substrates by a high temperature vapor phase method which can yield high quality Te-nanostructures. These ultrathin Te nanowires were morphologically and structurally characterized by scanning electron microscopy (SEM), atomic force microscopy (AFM) and cross-sectional transmission electron microscopy (TEM), and have thickness as low as ~4 nm. The optical properties of these nanowires were studied by room-temperature micro-photoluminescence (micro-PL) measurements which show a strong violet-blue luminescence at ~ 445 nm that lies at a significantly higher energy level than the expected bandgap level. Finally we present the Optical transport properties of ultrathin Te nanowire devices fabricated by electron-beam lithography. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by NTESS Corporation, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

PS12 Local Photovoltage Imaging of ZnTe/CdTe Heterojunction Yohan Yoon¹, David Maggipinto², Erfan Pourshaban³, Vasilios Palexis⁴, Chih-An Tsai⁵, Chris Ferekides³, Michael Scarpulla¹, ² and Heayoung P. Yoon¹; ¹Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah, United States; ²Materials Science and Engineering, University of Utah, Salt Lake City, Utah, United States; ⁴Electrical Engineering, University of South Florida, Tampa, Florida, United States.

Polycrystalline thin-film solar cells (e.g., Cu(In, Ga)Se$_2$, CdTe) represent the most successful photovoltaic (PV) technology in the market today, owing to the stability, the ability to achieve high-throughput processing, and the flexibility of integrating them to various substrates. At the best cell efficiency of 22%, however, the efficiencies remain well below theoretically predicted limits (~ 32%). Among the key PV parameters, recent advances have made significant enhancements in the short-circuit current (I_sc) and the fill-factor (FF), whereas the open-circuit voltage (V_oc) of standard CdTe devices remains pinned at about 850 mV. One of the requirements for high I_sc is to create an ohmic contact on the CdTe absorber, which can decrease the loss of photogenerated carriers at the back contact. ZnTe (E_g ~ 2.26 eV) is one such interfacial material that acts as a back surface field (BSF) layer (1) to repel the carriers from the CdTe/ZnTe heterojunction. With the presence of electrically-active grain boundaries in CdTe, the heterojunction interface properties of CdTe/ZnTe are not presently well understood. In this work, we present a characterization technique that can visualize the local interface photovoltage of individual grains and grain boundaries at the nanoscale. Prior to the measurements, we fabricated a n-CdTe/p-ZnTe heterojunction on a MgZnO/OITF glass substrate. A thin layer of ZnTe was sputtered on p-CdTe. High-resolution SEM/EDS (Scanning Electron Microscopy / Energy Dispersive X-ray Spectroscopy) images showed a conformal deposition of the ZnTe layer. The nominal size of the CdTe grains was 4 μm. A conventional setup of Kelvin Probe Force Microscopy (KPFM) was used to measure the contact potential difference (CPD) in the near-field regime. The red shift was due to the flatband voltage condition, which allows us to separate the contribution of interfacial dopants and bulk carriers within the NW.

PS14 Wafer Mapping with Scanning Projected-Frame Reciprocal Space Maps Scott Speckman¹, Mike Hawkridge and Lars Greigere; Malvern Panalytical, Westboro, Massachusetts, United States.

Wafer mapping with X-ray diffraction is used to monitor uniformity or to quantify spatial gradients for combinatorial processing. Wafer maps are usually produced from a series of triple-axis rocking curves. Rocking curves provide limited information, but are the only traditional X-ray diffraction technique that are fast enough to produce a wafer map with adequate throughput. Recent innovations in hybrid pixel detector technology have allowed the collection of “ultrafast” double-axis reciprocal space maps using a scanning frame-based method. This method reduces the data collection time for reciprocal space mapping from hours to minutes. This speed, combined with automated data analysis in new software, makes it possible to map wafers using information-rich reciprocal space maps. This poster will explain the methodology and advantages of wafer mapping with scanning projected-frame reciprocal space maps.

PS16 Effect of the Magnetic Order on the Energy Gap of Mn-Doped ZnO Thin Films Antonio Ruotolo¹,², Xiaolei Wang¹ and Qi Shao¹; ¹City University of Hong Kong, Kowloon, Hong Kong; ²City University of Shenzhen Institute, Shenzhen, China.

The wide-bandgap semiconductor zinc oxide (ZnO) is commonly used in optoelectronics. Doping with transition metals can be used to tune its optical behavior. In particular, doping with Mn is expected to widen the bandgap and produce a blue-shift in the near band edge emission peak. Interestingly, a red-shift has been reported in weakly doped Mn-ZnO nanorods [2,3] and crystallites [4] showing ferromagnetic behavior at room temperature. It has been suggested that, similarly to the case of II-VI binary diluted magnetic semiconductors [5], the red-shift is due to the same long-range exchange interaction which is in the origin of the magnetic ordering, i.e. a correlation exists in these systems between optical and magnetic properties. Here we show that a strong correlation between the magnetic and optical behavior of Mn-doped ZnO exists in these films with enhanced exchange interaction. We observe a red-shift in films with low concentration of Mn. The expected blue-shift is recovered upon increasing the concentration of the dopant. Increasing the magnetic moment by increasing the concentration of oxygen vacancies results in an
increase of both blue- and red-shift. Films with different concentration of dopant and different concentration of oxygen vacancies were grown by using a pulsed KrF excimer laser. The structural, electrical, magnetic and optical properties of the films were studied. Photoluminescence spectra (PL) of the films were recorded. A magnetometer was used to measure their magnetic moment. Films grown at higher temperature have a larger concentration of oxygen vacancies, and therefore a larger magnetic moment. We observe a blue-shift in 4% Mn-doped ZnO that is in agreement with theory. Interestingly we observe a shift to longer wavelengths (red-shift) in 2% Mn-doped ZnO. This behavior is similar to that reported at low temperature for other dilute magnetic semiconductors, such as Zn$_x$Mn$_{1-x}$Se and Cd$_x$Zn$_{1-x}$Te [5]. The decrease of the band-gap is attributed to the sp-d interaction between free charge carriers in the band of the semiconductor and the localized magnetic moments. The effect has been theoretically modeled by using a second order perturbation theory [5]. On the other hand, ferromagnetism in Mn-ZnO is commonly believed to be due to interaction between the localized magnetic moments mediated by the free charge carriers. It is therefore reasonable to expect that an increase of the charge carriers should lead to an increase to magnetic moment and, consequently, an increase of the red-shift in the near band edge emission peak. In films grown at room temperature and 600 °C the red-shift is, respectively, $\Delta\lambda_{600} = 7.6 \text{ nm}$ and $\Delta\lambda_{300} = 9.2 \text{ nm}$ with a peak position for the ZnO at $\lambda_{600} = 275.9 \text{ nm}$, independent on the growth temperature for OTFTs. This owning largely to lower stage of carrier concentration and magnetic moment in 2% Mn-doped ZnO when increasing the growth temperature [6,7]. Similar results were obtained on films deposited by sol-gel method [8].

References


PS17

(Student) Benchmarking Digital Logic Styles for High-Performance OTFT Circuits Zhuozhi Yao, Ting-Jung Chang, Ryoto Sekine, David Wentzloff and Barry P. Rand 1, 2; Electrical Engineering, Princeton University, Princeton, New Jersey, United States; 2Andlinger Center for Energy and the Environment, Princeton University, Princeton, New Jersey, United States.

Organic thin-film transistors (OTFTs) are a promising technology for large area electronics, but choosing an appropriate circuit style is key to OTFT circuit functionality and reliability. Typically, p-type logic is implemented for OTFT circuits, with the advantage to lower static and dynamic power consumption. However, complementary logic is required to provide the required output swing for OTFT circuits. This disparity incurs higher cost and complicate fabrication processes. In this work, we compare Pseudo-CMOS logic (pseudo-D, pseudo-E), and complementary logic (CMOS) to investigate the efficiency and reliability of OTFT circuits.

Organic Thin-Film Transistors with Liquid Crystalline Semiconducting Polymers on Photo-Aligned Polymeric Insulator Kigook Song and Jinboo Bae; Advanced Materials Engineering, Kyung Hee University, Yongin, Korea (the Republic of).

Organic thin-film transistors (OTFTs) have been extensively investigated because of their potential applications in ultrathin, large-area, low-cost and stretchable electronics. Numerous efforts have been made to improve the OTFT performance of organic semiconductors and organic gate insulators. In particular, it has been proven that control of the molecular ordering and crystalline orientation of organic thin film semiconductors in OTFTs is essential for achieving high carrier mobility because the movement of charge relies on intermolecular interactions. The crystalline orientation of organic semiconductor films or to induce better molecular chain ordering of liquid crystal (LC) polymeric semiconductors, several methods such as mechanical stretching, liquid-crystalline self-organization, rubbing, and interface treatments between the semiconductor and gate dielectric insulator have been developed for the application of LC-based devices with anisotropic charge carrier mobility. Among them, orientation-controlled pentacene semiconductor films have been recently investigated due to their superior potential for enhancing mobilities and providing more unusual properties such as optical and electrical anisotropic characteristics. In this study, we fabricated OTFTs onto a photo-aligned polyvinylideneamide (PVCN) gate insulator to facilitate a highly oriented microstructure of liquid crystalline poly(2,5-bis-(3-tetracyclithiophen-2-yl)phenylene[3,2-b]thiophene) (PBTTT) as an active layer. The photoinduced PVCN layer, which is a mechanically unrubbed alignment surface, was introduced as an alignment layer to induce favorable molecular orientation of the liquid crystalline polymeric semiconductor. Also, this photo-alignment technique avoids the undesirable rubbing technique in un-runnable LC devices. Therefore, it is expected that the photo-aligned PVCN film which effectively induces the alignment of the liquid crystalline semiconductor material can be simultaneously used as a gate insulating layer of OTFT. Unlike inorganic gate dielectrics, PVCN polymer gate dielectrics can be deposited by solution processing such as spin-coating, spray-coating, and printing. The PVCN layer plays an important role in the fabrication of OTFTs with solution processable liquid crystalline semiconductor polymers, such as PBTTT, because it provides orientation of liquid crystalline polymer chains as well as gate insulating characteristics. PBTTT-OTFT was fabricated with the LPUV irradiated PVCN film as underneath gate dielectric layer and LC-like PBTTT as semiconducting layer. The PVCN layer provides orientation of the liquid crystalline polymer chains as well as gate insulating characteristics. The orientation of LC-like PBTTT chains induced on the LPUV irradiated PVCN film was investigated using a polarized UV/Vis spectroscopy. The PBTTT layer shows the UV/Vis dichroism which indicates that PBTTT chains preferentially orient along the perpendicular direction against the LPUV. In the perpendicular PBTTT-OTFT, more PBTTT chains orient along the channel direction whereas more chains are oriented perpendicular to the channel direction in the parallel PBTTT-OTFT. Therefore, it is understandable that the perpendicular PBTTT-OTFT (0.025 cm2/V) has larger carrier mobility than the parallel PBTTT-OTFT (0.008 cm2/V). These results suggest that use of the photo-aligned PVCN film as a dielectric layer and power is feasible for fabrication of OTFTs with solution processable LC-like semiconductor polymers.
For decades, nonlinear optical (NLO) polymers have been studied extensively because of their multimodal applications in ultrafast optical switching, high-speed optical modulator, optical fiber communications and high-density optical data storage. NLO polymers have many advantages superior to conventional inorganic ones such as light weight, low cost, ultrafast response, wide response wave band, high optical damage threshold, and good processability to form optical devices. A potential NLO polymer must contain highly polarizable conjugated electronic systems and has to be mechanically very strong. NLO polymers for electro-optic device applications, stabilization of electrically induced dipole alignment is one of important considerations. In this work reported here, we prepared new polyester 4 containing dinitroadoxazobenzene group as NLO chromophores, which are components of the polymer backbone. We selected the latter as NLO chromophore because it was expected to have high optical nonlinearities and thermal stability. Furthermore, this dinitroadoxazobenzene group constitutes a novel X-type NLO polyester, and this X-type NLO polyester is expected to exceed high temperature and good processability to form optical devices. This colloidal solution was made in different solvents and compared with the performance of the evaporated EIL layer. References: [1] D. Sun, M. Wong, L. Sun, Y. Li, N. Miyatake, H. Jue, Journal of Sol-Gel Science and Technology 43(2) (2007) 237–43.

Printable organic light emitting diodes (OLED) are being developed for applications such as aesthetic lighting and signage. Major challenge is to develop materials that can be printed, in other words a functional ink needs to be formulated. Specifically, development of ink for electron injection layer (EIL) which is typically a low work function metal like Ca in inorganic OLEDs. Calcium carbonate, CaS is not stable in air due to moisture absorption and synthesis and purification process of Caesium stearate is quite complicated. We have decided to develop Zno as it is air stable and can be easily incorporated in low cost printing processes. We are investigating Zno nanoparticle film as a solution processed EIL, in our standard OLED stack (ITO/PEDOT/PSS/ MEH-PPV/Zno NPs/AI). In this normal OLED structure (EIL is deposited on the emissive layer), processing temperature should be less than 200°C, otherwise high temperature will damage the emissive layers. In order to reduce the annealing temperature, we have adopted the approach to first synthesizing the nanoparticles of Zno which can be annealed at low temperatures around 100°C. The process described by Sun et al is used to synthesize Zno nanoparticles[1]. We varied temperature during synthesis from 25, 40 and 65°C, TEM image analysis shows nanoparticle size changes from 12, 6 and 4nm, respectively. Dynamic light scattering measurements show size in 100s of nm indicating aggregation and poor film formation. To suppress aggregation, repeated purification (up to three times) process lead to narrow particle size distribution and reduced particle size. This colloidal solution was made in different solvents and used to make thin films on glass using spin coating. Film morphology and structure is studied using AFM, XRD and thickness is measured using profilometer. Film compatibility with the MEH-PPV emissive layer was also evaluated. Finally, solution processed OLED were fabricated using this EIL, and compared with the performance of the evaporated EIL layer. References: [1] D. Sun, M. Wong, L. Sun, Y. Li, N. Miyatake, H-J. Sue Journal of Sol-Gel Science and Technology 43(2) (2007) 237–43.
PS23 Terahertz Radiation Characteristics of Si-Based Catalyst-Free InAs Nanowires with Different Structural Properties Dong Woo Park1, Ilguy Choi1, Cheul-Ro Lee1 and Jin Soo Kim1; 1Department of Electronic and Information Materials Engineering, and Division of Advanced Materials Engineering, Kyungpook National University, Daegu, Republic of Korea; 2Electronics and Telecommunication Research Institute (ETRI), Daejeon-si, Korea (the Republic of).

Recently, terahertz (THz) sources based on InAs nanowires (NWs) are expected to be applied to biomedical fields due to larger effective interface between chemical and biological features compared to that of epilayer structures. That is, the contact area of NWs with biomedical specimens can be enhanced because of the additional side-wall contact compared to commercial InAs wafers, resulting in an increase in the reliability level of information. In this paper, we report structural and THz radiation characteristics of catalyst-free InAs NWs formed on Si(111) substrates, grown by a metal-organic chemical vapor deposition epitaxy. Field-emission scanning-electron microscope images of InAs NWs revealed that height and spatial density were systematically manipulated by varying flux ratio of indium to arsenic, substrate temperature, and deposition time. For example, the average heights of InAs NWs were measured to be 0.6, 1.2, 2.1, 4.6, and 5.8 μm for the V/III ratio of 50, 100, 200, 300, and 400, respectively. Also, the spatial density of InAs NWs was increased from 8 × 10^6 to 1.5 × 10^7 cm⁻² with increasing V/III ratio. Both zincblende (ZB) and wurzite (WZ) structures including stacking faults were observed in transmission-electron microscope images measured along the vertical direction of InAs NWs. The structural ratio of ZB to WZ was also controlled by changing growth parameter conditions including doping. The THz radiations of InAs NWs were successfully obtained without a direct-current bias due to the large difference of mobility between electrons and holes generated from an external excitation source. The peak-to-peak current signal (PPCS) of undoped InAs NWs with the average height of 10 μm, obtained from THz time-domain (TD) spectroscopy, was measured to be 4.95 nA, which is 40% of an undoped InAs wafer. Considering the factor of 0.005 for the InAs NWs, defined as the ratio of the total area of the top surfaces for InAs NWs to the flat surface, it is noteworthy that the amplitude of the PPCS is comparable to that of the InAs wafer. The THz spectra of the InAs NWs, obtained by applying a fast Fourier transformation to the TD current signals, show the frequency of ~0.5 THz. The amplitude of the THz spectra of InAs NWs linearly increased with increasing excitation intensity at ~0.5 THz. Even though the bandwidth for InAs NWs is smaller than those of the InAs wafers (~ up to 2.0 THz), the NWs can be applied to biomedical specimens such as basal cell carcinoma and normal human skin tissue sensitive to the frequency range of ~0.5 THz. By using catalyst-free InAs NWs, we successfully obtained a clear THz image from a small piece of pork belly.


It can be argued that science is not the pursuit of what we know with certainty, but rather that pursuit in which we evaluate how well we know what we assert is true. Uncertainty analysis thus becomes a key component in the evaluation of scientific “truth.” This poster will describe resources made available by the National Institute of Standards and Technology (NIST) and other world-wide national metrology institutes to aid technologists in the evaluation of uncertainty in their data. These resources include the NIST Uncertainty Machine, a free on-line Monte Carlo simulatoruncertainty.nist.gov/nist Technical Note 1297, https://www.nist.gov/pml/nist-technical-note-1297, and the more comprehensive Guide to the Expression of Uncertainty in Measurement, the “GUM”, https://www.bipm.org/en/publications/guides/gum.html. We will illustrate uncertainty analyses conducted on catalyst-free InAs nanowires with structural and electronic properties, random error and statistical independence. Student attendees of the Electronic Materials Conference are encouraged to use this information in applications for the NIST-sponsored Student Uncertainty Analysis award.

PS25 A New Directly Placement Method for Individual Carbon Nanotube Devices and Its Applications to the Nanoelectromechanical Systems (NEMS) Xinhe Wang1, Xiaoyang Lin1, Guangwei Deng1, Guoping Guo1, Kaili Jiang2 and Weisheng Zhao2; 1Beihang University, Beijing, China; 2Tsinghua University, Beijing, China; University of Science and Technology of China, Beijing, China.

Though carbon nanotube (CNT) is acknowledged as an ideal system for one-dimensional physics, making ultraclean nanotubes with electrical circuits of arbitrary complexity is still a challenge. We develop a new directly deterministic placement technique that allows us to operate each CNT under an optical microscope and ambient conditions. For an individual ultralong few walled CNT, after deposit nanoparticles on the suspended part of it for visualization, we draw the inner shell of the CNT, and transfer it between the two homemade tips, then place it to the target position on the device chip. The CNTs transferred by this method are perfect clean since they are inner shell of the CNTs and not suffer from any wet process. The way to transfer and placement is so flexible and steerable that the construction of complex multi-nanotube devices can be allowed. Using this technique, we fabricate the CNT electromechanical resonators and study the different types of coupling effects, including the Rabi oscillation of the coherent phonon between the coupling modes and the nonlocal coupling of phonon. Further, we realized the stressed CNT devices for high tunability, high quality factor, single mode GHz resonators. Our CNT resonator is promising for ground-state cooling and quantum manipulation, as well as the RF applications. It also enables the integration of homogeneous devices, and will play a key role in the emerging applications of NEMS.

PS26 Nanostructures Based on Self-Organized Growth of Aluminum Nanowires in Silicon Ingridv J. Jensen1, Annett Thøgersen1, Marit Stange1, Torunn Kjeldstad1, Ole M. Levik1, Alexander G. Ulyashin2 and Spyros Diplas3; 1SINTEF Materials Physics, Oslo, Norway; 2SINTEF Thin Films & Membrane Technology, Oslo, Norway; 3SINTEF Metal Production & Processing, Oslo, Norway.

Nanostructured materials offer unique electronic and optical properties compared to their bulk counterparts, such as tunable band gaps and indirect-to-direct band gap transitions. In the case of nanowire synthesis either “top-down” or “bottom-up” approaches are typically used, and the balance between control of design, size limitations, up-scalability and contamination is what generally makes the nanowire fabrication process difficult. In this work we show that self-assembled Al nanowires in an amorphous Si can be produced by magnetron co-sputtering using two targets at room temperature. The Al nanowires can be removed by HCl etching, to produce an inverted nanowire silicon structure. These inverted Si nanowires may offer similar optical and electronic properties as Si nanowires, while also providing structural integrity. The samples were characterized by transmission electron microscopy and high-resolution transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS) and UV-Vis-Spectrometry. Density functional theory (DFT) calculations were performed on crystalline inverted Si nanowire models of realistic size. A direct bandgap was found, confirming the resemblance to conventional Si nanowires.

PS27 Large-Area MoTe2 Layer Growth Using High-Vacuum Ampoule Process David J. Maggipinto1, Xueling Cheng1, Prashanth Gopalak1, Berardi Sensale Rodriguez2 and Heayoung P. Yoon3; 1Materials Science and Engineering, University of Utah, Salt Lake City, Utah, United States; 2Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah, United States.

Two-dimensional transition metal dichalcogenides (TMDs) have shown interesting electronic properties, amenable to spintronics, valleytronics, and optoelectronic applications. Molybdenum ditelluride (MoTe2) is one such material, with the energy band-gap of about 1 eV, and a band structure that is relatively insensitive to the number of monolayers. Recent work has demonstrated the growth of high-quality MoTe2 using chemical vapor deposition (CVD) techniques. However, the size of the grains is still on the order of a couple of μm, limiting its application in practice. In this work, we present a large-area MoTe2 growth approach using a high-vacuum ampoule process. Prior to ampoule sealing, a thin layer of Mo film (~5 nm) was sputtered on quartz and sapphire substrates. Each substrate was sealed in a quartz ampoule along with high-purity Te powder, and placed in a tube furnace. The quartz ampoule was heated at 600°C for two hours. The samples were then slowly cooled to room temperature (~0.5°C/min). For a comparison, we also performed a CVD process on the same Mo substrate. The collected Raman spectra confirm that the typical 2H-MoTe2 phase is present in the CVD-grown samples. A nominal grain size of the CVD-grown samples is about 30 nm. In contrast, the grain size of the ampoule-processed MoTe2 is as large as 10 μm. Interestingly, most ampoule-grown MoTe2 layers contain a thick piece of Mo near the center of the grains, as confirmed by energy dispersive X-ray spectroscopy (EDS) elemental maps. It is likely that the conformal Mo layer (~5 nm thick) became aggregates (~ a few μm x 1 μm), acting as a seed for the growth of a large-area film. Further studies on the role of the Mo seed layer and the underlying mechanism of grain growth are in progress.
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compared to either n-type or p-type ZnO NWs in terms of piezoelectric grow p-n junction type ZnO NWs as they show better performance ZnO NWs on metal substrate. We used a two-step hydrothermal method to (e.g. Cr, Al) which requires first to grow the patterned vertically aligned used to supply energy for sensors. Piezoelectric nanogenerator (PENG) environmental energies from sources such as solar, wind, vibration, temperature differences, electromagnetic, and acoustic can potentially be used to supply energy for sensors. Piezoelectric nanogenerator (PENG) based on ZnO nanowire arrays is quite mature technology for harvesting ambient tiny mechanical energies and converting them into electrical energy. Our goal is to make PENGs directly fabricated on metal substrate (e.g. Cr, Al) which requires first to grow the patterned vertically aligned ZnO NWs on metal substrate. We used a two-step hydrothermal method to grow p-n junction type ZnO NWs as they show better performance compared to either n-type or p-type ZnO NWs in terms of piezoelectric response. After cleaning a 1.2 x 1.2 cm² thin substrate using standard cleaning process, a thick layer of Cr (200nm) is deposited using magnetron sputtering which serves as the bottom electrode. After that a seed layer of aluminum doped zinc oxide (AZO) is deposited on top of the Cr layer using plasma enhanced chemical vapor deposition (PECVD) for the purpose of improving the thermal growth of ZnO nanowires. To grow p-n junction type NWs two-step hydrothermal method is used. In the first step to grow n-type ZnO NWs a mixture of zinc nitrate hexahydrate (25 mM), hexamethylenetetramine (HMTA) (25 mM) and aluminum nitrate nonahydrate (25 mM) is used. In the second step, to obtain p-type ZnO NWs (Li-doped), a doping reagent, lithium nitrate (75 mM) along with the above solutions is added. In both steps, the solutions is kept at a constant 88°C during reaction which is optimum for the growth of nanowires instead of growing nanoballs (below 75°C) and nanorods (above 95°C), and the ZnO NW length is simply controlled by growth time. All samples are cleaned using a standard process. After the growth and characterization of ZnO NWs, they are encapsulated with PMMA which protects the NWs from damage and prevents the electrical shortage between top and bottom electrode thus increasing the robustness of the PENG. After that a 100 nm thick Al layer is deposited as the top electrode. Finally two Cu wires are connected to the top and bottom electrode for characterization. NG piezoelectric response is measured using a system that includes a close loop controller and a linear shaker that is capable of providing mechanical strain to the device with a particular frequency, known acceleration and particular amount of force. For this device, the output open circuit voltage has an average peak of 5.1V and output short circuit current has an average peak of 175nA with 5Hz frequency and 5nm peak-to-peak displacement of the shaker hammer. Output voltage and current signals are measured using Stanford low-voltage/current preamplifiers (Model SR560/570) when 100 Ω (SR560) and 10 kΩ (SR570) resistors are used as the input resistances of the preamplifiers, respectively.

PS31

Development and Thermoelectric Properties of Vanadate Oxide System Amorphous Thin Films: Akifumi Matsuda1, Yuki Fujimoto1, Satoru Kaneko2, Yoshito Kimura3 and Mamoru Yoshimoto4, 1Department of Materials Science and Engineering, Tokyo Institute of Technology, Yokohama, Japan; 2Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada; 3Department of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada; 4Shinco, Cambridge, Ontario, Canada.

One-dimensional (1D) nanostructures demonstrate enthralling properties due to their quantum confinement effects which results from their low dimensionality. Piezoelectric properties intertwined with the semiconducting properties of several 1D nanostructures (e.g. ZnO and GaN) offers noble way of manipulating charge-carrier transport, generation, recombination or separation through the application of external mechanical strain that leads to unprecedented device characteristics. Not only ZnO nanowires are non-centrosymmetric which comes from their wurtzite structure, but also their large electromechanical coupling make them ideal candidate for use in a variety of electronic devices mostly as piezoelectric material. Structural health monitoring (SHM) system is a damage detection and characterization technique for engineering structures which is based on three so-called effects as mentioned from an array of sensors. To make the SHM system self-powered, environmental energies from sources such as solar, wind, vibration, thermal conductivity, electromagnetic, and acoustic can potentially be used to supply energy for sensors. Piezoelectric nanogenerator (PENG) as typified by Bi–Te and semiconductors such as Si–Ge system and Mg–In—Ga2O3. Epitaxial –Ga2O3. Epitaxy by Excimer Laser Annealing Akifumi Matsuda1, Kisho Nakamura1, Hiroyuki Morita1, Nobuo Tsuchimine1, Osami Sakata1, Satoru Kaneko2 and Mamoru Yoshimoto4, 1Department of Materials Science and Engineering, Tokyo Institute of Technology, Yokohama, Japan; 2Tokyo Institute of Technology, Yokohama, Japan; 3Toshiba Manufacturing Co., Ltd., Higashi-Matsuyama, Japan; 4Synchrotron X-ray Station at SPring-8, National Institute for Materials Science, Sayo, Japan; 5Kanagawa Institute of Industrial Science and Technology, Ebina, Japan.

Low-temperature epitaxy technique for β-GaO3 thin films should contribute to development of multilayered devices avoiding desorption of components and compositional deviation and interfacial interdiffusion as well as excessive grain growth and roughness. The following three approaches should be effective for reducing the epitaxy temperature: (1) utilization of atomic-steps on substrates for modification of nucleation sites and growth orientation, (2) introduction of buffer layer to reduce planar lattice mismatch, and (3) application of room-temperature laser processes, especially excimer laser annealing (ELA) that allows solid-phase crystallization via ultra-rapid treatment. In this study, effect of structural symmetry, lattice parameter and chemical species of buffer layers on oriented crystallization of β-GaO3 thin films by ELA at room-temperature was investigated. Precursor amorphous Ga2O3 thin films were grown on ultra-thin (~2 nm) epitaxial buffer layers of rock-salt and wurtzite type crystals such as NiO and ZnO, respectively, as well as corundum α-Al2O3 (0001) substrates by PLD equipped with KrF excimer laser. Subsequent ELA was carried out at room-temperature using the same excimer laser which has λ=248 nm correspondent to the bandgap of β-Ga2O3. Epitaxial β-Ga2O3 (~201) thin films were obtained as results of irradiation of 500 pulses to precursor layer grown on (111) planes of rock-salt type buffer materials [1]. Meanwhile, ELA also led to crystallization of β-Ga2O3 on α-Al2O3 (0001) and ZnO (0001), though the films were mono-axially oriented with lack of planar anisotropy. The epitaxial β-Ga2O3 (~201) thin film obtained by present ELA technique at room-temperature revealed excellent β-bandgap of ~4.9 eV at high-temperature grown films and relatively flat surface of R_{q,min}~0.2 nm in contrast to high-temperature grown films. Application of other substrate crystals and planes as well as the structural details will be discussed.[1] D. Shojiri et al., Appl. Phys. Exp. 9 (2016) 105502.
We present the Ga$_2$O$_3$ epitaxial growth on c-plane sapphire substrates under different growth temperatures, ranging from 600 to 1100 °C in a MOVPE reactor, as shown in Fig. 1. The MOVPE reactor is made of quartz tube, and the reactor has two gas inlets, the tri-ethyl-gallium (TEG) and O$_2$ as the carrier gas, the gallium source, and the oxygen source, respectively. During 30-minute epitaxial growth, the TEG/O$_2$ partial pressure ratio was kept at 0.0104 (0.03 Torr:2.874 Torr) and the temperature ranged from 600 to 1100 °C with the step of 100 °C at 100 Torr. The samples, grown from 600 to 1100 °C, are defined as S1 to S6. The surface roughness and morphology, crystal structure and quality, growth rate, and transmission spectrum of the epilayers have been characterized in this study. The surface roughness and morphology were characterized by an atom force microscope (AFM). The roughness of S1 to S6 are 5.46, 14.14, 34.70, 24.94, 18.92, and 28.39 nm, respectively, as shown in Fig. 1. The roughness increases from S1 to S3, then the roughness decreases from S3 to S5 but is dominant for S6. The surface morphology shows: there are circular grains on the surface at S1, and then the circular grains turn into rectangular plates at S2 and the size of plates is increased to the maximum at S3. At S4, the rectangular plates turn into square plates with round corner, and the size of plates is decreased at S5. Finally, the plates become irregular shape at S6. It is noted that the surface roughness is correlated to the size of plates, which have been illustrated by the circular grains or smaller plates have smoother surface. The crystal structure and quality were characterized by X-ray diffraction (XRD), as shown in Fig. 2. For S1, the XRD result shows the epilayer film has a mixed phase of β- and ε-Ga$_2$O$_3$, and the peaks intensity of ε-Ga$_2$O$_3$ is stronger compared to the peaks of β-Ga$_2$O$_3$, indicating that ε-Ga$_2$O$_3$ might be dominant. Among the rest of the samples, ε-Ga$_2$O$_3$ was not observed and the epilayer films are pure β-Ga$_2$O$_3$. However, except the most common (-201) oriented peaks, minor peaks such as (601), (20-4) show up when the temperature raises from S2 to S6. For S3, there are eight minor peaks appear which might be correlated to large rectangular plates on the rough surface. Rectangular plates have many facets with different orientations and thus contributed to the minor peaks. For S6, all the minor peaks disappear except for the (401) and (620) peaks. The full width at half maximum (FWHM) of (201) peaks by the rocking curves for S1 to S6 are 0.93°, 1.63°, 1.52°, 1.39°, 1.59°, and 2.36°, respectively. This means the higher temperature did not improve the crystal quality of β-Ga$_2$O$_3$ amide. The thickness was measured by XRD interference thin-film analyzer. The growth rates, at the precursor concentrations used, of S1 to S6 are 1.2, 1.13, 1.07, 1.01, 0.9, and 0.75 μm/hr, respectively. The growth rate linearly decreased versus the temperature and the decreasing rate is higher after 900 °C. The transmission was measured by UV-Vis spectrometer. All the samples show a sharp absorption edge and visible-transparent, which means there is no deep level absorption and low impurity concentration in the film. Except S3 has lower absorption edge at 4.75 eV, the rest of samples have absorption edge at 4.82 eV, as shown in Fig. 3.

**PS34**

(Student) MOCVD-Grown β-Phase Ga$_2$O$_3$ Thin Films on Al$_2$O$_3$ with Different Temperature Huang-Hui Li$^1$, Haiding Sun$^1$, Carlos Torres-Castanedo$^1$, Che-Hao Liao$^1$, Hsin-Hung Yao$^1$, Serdal Okur$^2$, Tom Salagaj$^2$, Aaron Feldman$^1$, Gary Tompa$^1$ and Xiaohang Li$^1$; $^1$CEMSE, KAUST, Thuwal, Saudi Arabia; $^2$Structured Materials Industries, Piscataway, New Jersey, United States.

We present the Ga$_2$O$_3$ epitaxial growth on c-plane sapphire substrates under different growth temperatures, ranging from 600 to 1100 °C in a MOVPE reactor, as shown in Fig. 1. The MOVPE reactor is made of quartz tube, and the reactor has two gas inlets, the tri-ethyl-gallium (TEG) and O$_2$ as the carrier gas, the gallium source, and the oxygen source, respectively. During 30-minute epitaxial growth, the TEG/O$_2$ partial pressure ratio was kept at 0.0104 (0.03 Torr:2.874 Torr) and the temperature ranged from 600 to 1100 °C with the step of 100 °C at 100 Torr. The samples, grown from 600 to 1100 °C, are defined as S1 to S6. The surface roughness and morphology, crystal structure and quality, growth rate, and transmission spectrum of the epilayers have been characterized in this study. The surface roughness and morphology were characterized by an atom force microscope (AFM). The roughness of S1 to S6 are 5.46, 14.14, 34.70, 24.94, 18.92, and 28.39 nm, respectively, as shown in Fig. 1. The roughness increases from S1 to S3, then the roughness decreases from S3 to S5 but is dominant for S6. The surface morphology shows: there are circular grains on the surface at S1, and then the circular grains turn into rectangular plates at S2 and the size of plates is increased to the maximum at S3. At S4, the rectangular plates turn into square plates with round corner, and the size of plates is decreased at S5. Finally, the plates become irregular shape at S6. It is noted that the surface roughness is correlated to the size of plates, which have been illustrated by the circular grains or smaller plates have smoother surface. The crystal structure and quality were characterized by X-ray diffraction (XRD), as shown in Fig. 2. For S1, the XRD result shows the epilayer film has a mixed phase of β- and ε-Ga$_2$O$_3$, and the peaks intensity of ε-Ga$_2$O$_3$ is stronger compared to the peaks of β-Ga$_2$O$_3$, indicating that ε-Ga$_2$O$_3$ might be dominant. Among the rest of the samples, ε-Ga$_2$O$_3$ was not observed and the epilayer films are pure β-Ga$_2$O$_3$. However, except the most common (-201) oriented peaks, minor peaks such as (601), (20-4) show up when the temperature raises from S2 to S6. For S3, there are eight minor peaks appear which might be correlated to large rectangular plates on the rough surface. Rectangular plates have many facets with different orientations and thus contributed to the minor peaks. For S6, all the minor peaks disappear except for the (401) and (620) peaks. The full width at half maximum (FWHM) of (201) peaks by the rocking curves for S1 to S6 are 0.93°, 1.63°, 1.52°, 1.39°, 1.59°, and 2.36°, respectively. This means the higher temperature did not improve the crystal quality of β-Ga$_2$O$_3$ amide. The thickness was measured by XRD interference thin-film analyzer. The growth rates, at the precursor concentrations used, of S1 to S6 are 1.2, 1.13, 1.07, 1.01, 0.9, and 0.75 μm/hr, respectively. The growth rate linearly decreased versus the temperature and the decreasing rate is higher after 900 °C. The transmission was measured by UV-Vis spectrometer. All the samples show a sharp absorption edge and visible-transparent, which means there is no deep level absorption and low impurity concentration in the film. Except S3 has lower absorption edge at 4.75 eV, the rest of samples have absorption edge at 4.82 eV, as shown in Fig. 3.

**PS38**


We report on self-powered Schottky deep-UV detector on homoepitaxial β-Ga$_2$O$_3$ grown by plasma-assisted MBE on Fe-doped semi-insulating (010)-oriented β-Ga$_2$O$_3$ substrate. The Schottky detectors with vertical device geometry exhibited more than 7 orders of rectification at 2 V with an external quantum efficiency of 3% and 11% at zero bias and a reverse bias of 8 V respectively. The detectors also exhibited ~3 orders of UV-to-visible rejection ratio in conjunction with ~2 orders of photo-to-dark current ratio at zero bias with no persistent photoconductivity in transient response. Solar-blind UV detectors sensitive to wavelengths below ~290 nm are of great interest for a plethora of applications. There are several reports of metal-semiconductor-metal (MSM) deep-UV detectors based on epitaxial β-Ga$_2$O$_3$ and on bulk β-Ga$_2$O$_3$; however, a few reports of vertical Schottky detector on epitaxial or bulk β-Ga$_2$O$_3$ substrate exist [1-5]. In this work, devices were realized on plasma-assisted MBE-grown β-Ga$_2$O$_3$ unintentionally doped layer (UID) (Thickness ~100 nm) on top of heavily Si-doped (Doping concentration ~2 × 10$^{18}$ cm$^{-3}$) substrate (~1.5 X 10$^{19}$ cm$^{-3}$). The thickness of the reference sample was 8 × 10$^{10}$ Torr, which was used during β-Ga$_2$O$_3$ growth. The substrate temperature was 700 °C. The root mean square (RMS) roughness was ~ 1.0 nm for a scan area of 5 X 5 μm$^2$ (from AFM). Ni/Au (30/100 nm) metal stack was e-beam evaporated on the top undoped layer to form Schottky contact and Indium dot was used to form the bottom Ohmic contact to the n+ doped substrate. The peak responsivity values of 4 mA/W (corresponding EQE ~ 3%) and 21 mA/W (EQE ~ 11%) were measured at zero bias and -8 V respectively, indicating the self-powered nature. The cut-off was observed at 253-255 nm (4.9 eV). The UV-to-visible rejection ratio was found to be
~ 3 orders at zero bias, indicating true solar blind nature. The detectors exhibited an asymmetric dark-current-voltage (I-V) characteristic with > 10^6 rectification at a bias of 2 V. The ideality factor was extracted from the linear fitting of dark I-V characteristics, which comes out to be 1.31. The extracted Schottky barrier height at Ni: β-Ga2O3 junction was found to be 1.4 eV, which is close to reports in the literature [6]. A photo-to-dark current ratio of ~ 2 orders at zero bias and in reverse bias regions was measured. Photocurrent remained almost the same as dark current in forward bias region, which is typical of Schottky detectors. The detectors showed gain at biases higher than -10 V. The transient response showed no persistent photoconductivity in transient response measurements. The rise and fall times (10% to 90% s) were found to be 120 and 500 s (at zero bias) respectively. [Funding: This work was funded by Space Technology Cell (STC) and Joint Advanced Technology Program (JATP), Department of the Defense, Defense Threat Reduction Agency (Grant HDTRA11710034), ONR EXEDE MURI program, and the OSU Institute for Materials Research Seed Program. [References: [1] Oshino et al, APL, 1, 11202 (2008); [2] Guo et al, Opt. Mat. Exp. 4, 1067 (2014); [3] Pratvish et al, APL, 110, 221107 (2017); [4] Alema et al, Proc. Of SPIE, 10105 (2017) [5] Chen et al, R, 8, 4185 (2016) [6] Farzana et al, APL, 110, 202102 (2017)]

PS40
(Studenant) Demonstration of High Responsivity Epitaxial β-Ga2O3/GaN Metal-Heterojunction-Metal (MHM) Broadband UV-A/UV-C Detector Anisha Kalra, Sandeep Vura, Shashwat Rathikanhiar, Rangarajan Murائدharan, Sriivasnan Raghavan and Digbijoy N. Nath; Centre for Nanoscience and Engineering, Indian Institute of Science, Bangalore, India.

We report on the first demonstration of a β-Ga2O3/GaN-based vertical metal-heterojunction-metal (MHM) broadband UV detector on a silicon (111) platform. This is also the first report of a device with both β-Ga2O3 and GaN as active layers, on a silicon platform. The device design utilises the small conduction-band offset (ΔEc) of 0.1 eV between Ga2O3 and GaN to realise detectors with an asymmetric spectral response with respect to applied bias. Two peaks at 256 nm and 365 nm are observed corresponding to the band gaps of β-Ga2O3 and GaN. When Ga2O3 was biased positive at 5 V, a high SR of 3.7 A/W was measured for both 256 and 365 nm, giving a broadband UV-A/UV-C response for the reverse bias configuration. At 365 nm the device showed a 256 nm, responsivity of 0.6 A/W and 0.75 A/W at 256 nm and 365 nm, respectively at 40 V. The UV-to-Visible rejection ratio was > 10^4 for the devices with a photo-to-dark current ratio ~ 10^6. This new vertical MHM detector realised on silicon is fully scalable and is promising for enabling focal plane arrays (FPA) for broadband UV sensing. The possibility of growing monolcnic β-Ga2O3 epitaxially on wurtzite GaN and the small conduction-band offset (CBO) between the two allows for exciting band engineering towards novel device designs. Although a fast-expanding β-Ga2O3 device community has widely reported UV detectors based on bulk wafer or epitaxial β-Ga2O3 on sapphire, yet there are few reports on epitaxial β-Ga2O3/GaN-based vertical detectors. The β-Ga2O3/GaN vertical photodetector was demonstrated on a silicon (111) substrate. The threshold lasing power intensity and lasing spectra was measured by optically pumping the GaN NW arrays with a 266 nm laser using a photoluminescence (PL) setup (fig. 2). The minimum pump intensity threshold for lasing was found to be 3.31 MW/cm2. As a precursor to manufacturing, finite-difference time-domain (FDTD) modeling was used to optimize the geometry at the device level. Vertical grating coupler, waveguide, and optical resonators are evaluated as a means to optically pump a single GaN NW probe at the device level (fig. 3). Different waveguide materials and boundary conditions were assessed for an efficient, low loss method of energy transmission to the GaN NW probe: Si02, AlN, GaN, Si3N4, and Air. Preliminary results showed that an air-AIN-NW-AIN-air configuration compared to a purely GaN-AlN waveguide has the highest coupling efficiency and transmission through the waveguide. Manufacturing progress and preliminary characterization of the gratings coupled and waveguide is reported. We also present preliminary work towards an electrically pumped GaN NW on Si based AFM probes. Traditionally, n-type GaN and p-type GaN are grown sequentially to form a p-n junction. Here, we report on how Mg diffusion on an existing Si doped n-type GaN NW to form a p-type shell. This design of electrically or optically pumped AFM lasing probes has the potential to reduce the fabrication costs of NSOM probes as it is possible to use the probe as light emitter, collector and nanometerolgy tool.

PS42
Effects of Annealing Capped HVPE GaN Films Grown at High Temperatures Michael A. Derenge and Ken Jones; RDRL-SED-E, Army Research Lab, Adelphi, Maryland, United States.

Ion implantation used to locally dope semiconductor device structures requires removing induced damage by annealing the sample at prescribed temperatures and times. The temperatures are usually ones where at least one of the the constituents is significant and will evaporate. For compound semiconductors this causes the surface to roughen and the preferential evaporation of one of the constituents will create vacancies that are almost always electrically active. This is a particularly difficult problem for the III-Nitrides. In this talk we show that other processes occur that can affect the electrical properties of the material when it is heated to annealing temperatures as high as 1300C for times as long as 8 min even when there is no physical evidence that N has escaped from the GaN surface. We do this by showing that the electrical properties of Schottky diodes fabricated on samples annealed in this way can have quite different electrical properties than those that have not been annealed. A 2” x 2” x 0.15” GaN wafer was cut into 12 11.5 x 10 cm and 4 triangular pieces. All but 1 triangular piece that was used as a standard were capped with 80 nm AlGaN/GaN film grown at 900C and 1 μm sputtered AlGaN film and annealed at 1150, 1200, 1250, or 1300C for 1, 2, 4 or 8 min. The cap was removed and then examined for electron-beam damage using an AFM and an SEM was used to search for hexagonal thermal etch pits. Lateral Ni-Schottky diodes with diameters of 70, 170, or 270 μm were fabricated with Ti/Al/Ag ohmic contacts that were annealed at 750C
for 30 sec. CV and J/V measurements were made on diodes with each diameter. We focus on the 170 μm diodes. Few thermal etch pits were observed and the 5-5 μm rms roughness of the as-grown and etched samples ranged from 0.52 to 1.2 with only one value > 1. The carrier concentration, Np of the as-deposited diode was 1.1×10^{20} cm^{-3}, the median offset voltage 11 V, and the spread in the values is 0.29 V with the larger values being closer to the center. We see that in most of our other sets of samples and attribute it to the piezoelectric effect in this relatively thick film and the strain being larger in the center. The median conductance, Gm, was 274 A/cm^2 and the median J = 1 × 10^4 A/cm^2 suggesting that the diode operates by thermionic emission. All samples annealed from 1150 to 1300°C had Gm, shifted to higher voltages by ~ 0.3 V. This could be explained by an increase in the doping concentration, Np, (4.6×10^{19} cm^{-3}), but this is a relatively small increase. It could also be explained by electron traps being created near the interface creating a min structure. This can also explain why J = smaller with the median values being 4×10^3, 2×10^3, 2×10^2 A/cm^2 for the 2, 4 and 8 min anneals at 1150°C. The median conductance, Gm, is larger showing that annealing initially improves the material. Np, remains constant, Gm, continues to increase, as does J = for the 1200, and 1250°C anneals. The properties only begin to degrade for the 1300°C anneals for the longer times suggesting that N is beginning to escape. This is particularly true for devices in the center where the stress is higher. All 1150, 1200 and 1250°C 1&2 minute anneals had the same mean Nd. 1250°C 4 and 8 minute anneals had the same Nd values, but Nd progressively increased with distance from the edge with 8 minute more pronounced than 4 minute. All of the 1300°C annealed samples had the same progression of Nd increasing from center to edge. That the cap is beginning suggesting that the cap of the 1300°C annealed samples had the same progression of Nd increasing distance from the edge with 8 minute more pronounced than 4 minute. All anneals had the same mean Nd. 1250°C 4 and 8 annealed diodes near the center where the stress is higher. All 1150, 1200 and 1250°C 1&2 minute anneals that N is beginning to escape. This is particularly true for devices in the center where the stress is higher. All 1150, 1200 and 1250°C 1&2 minute anneals had the same mean Nd. 1250°C 4 and 8 annealed diodes near the edge had the same Nd values, but Nd progressively increased with distance from the edge with 8 minute more pronounced than 4 minute. All of the 1300°C annealed samples had the same progression of Nd increasing from center to edge. That the cap is beginning suggesting that the cap would be effective if the film wasn’t stressed, which would be the case a GaN single crystal substrate was used.

PS43
Cavity Engineering of Photon-Phonon Interactions in Silicon Nanowire Cavities
Daksh Agarwal and Ritesh Agarwal; University of Pennsylvania, Sunnyvale, California, United States.

Nanowires show interesting properties which are different from bulk materials and have applications in various fields such as photocatalysis, medicine and nanoscale devices. These exceptional properties are enabled because of tight confinement of light in resonant nanowires which is difficult to obtain in bulk materials. The current work aims at tuning the phonon-photon interactions in Si nanowire cavities using Raman spectroscopy. In bulk materials a phonon is equally likely to interact with a phonon in ground state (corresponding to Stokes Raman scattering) and in excited state (corresponding to Anti Stokes Raman scattering). But in Si nanowires, the nanowire cavity mode can be tuned to make a photon more likely to interact with a phonon in excited state than in the ground state (higher Anti Stokes scattering) and vice versa. Experiments reveal that the room temperature Anti Stokes to Stokes Raman scattering ratio which is ~0.1 in bulk Si can be varied in the range 0.035 - 0.45 demonstrating tunability of phonon photon interactions by over an order of magnitude. Numerical calculations done to explain these results reveal that the tunability is almost directly proportional to the relative strength of cavity modes at Anti Stokes and Stokes wavelength and holds true for a wide range of nanowire diameters, cavity structure as well as excitation wavelength. Nanowire cavity modes can be easily changed by changing the nanowire diameter, cavity structure or wavelength which provides efficient ways of tuning these interactions. This is a new approach of tuning phonon-photon interactions at the nanoscale and opens up new avenues of research and applications in the fields of Silicon photonics, telecommunication and optical cooling of semiconductors.

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(Student) Improvement in Heat Dissipation Performance of InGaN-Based Green LEDs via Introduction of Hexagonal Boron Nitride by Ilgyu Choi1, Kwanjae Lee1, Cheul-Ro Lee1, Jin Soo Kim1, Joon-Sung Lee1, Min Hyung Park1, and Chael-Jong Choi and Han-Soo Jang; School of Semiconductor and Chemical Engineering, Chonbuk National University, Jeonju, Korea (the Republic of).

We have investigated the effect of sulfur passivation using aqueous and alcoholic ammonium sulfide solutions on the specific contact resistivity of Ni contact to InAs layer epitaxially grown on In0.56Ga0.47As epilayer. Prior measurements revealed that the work function of alcoholic ammonium sulfide treatment was much lower than that of aqueous sulfuric acid at room temperature. Moreover, many defects/dislocations at the GaN-based epitaxial layers are generated mainly due to large difference in lattice constants and thermal expansion coefficients between the epilayer and the substrate. These intrinsic properties typically result in serious degradation in heat-escaping properties of LED chips. It is revealed that hexagonal boron nitride (hBN) has very high TC (~2.800 WmK^{-1}) in addition to its unique mechanical and electrical properties. Many studies have largely focused on obtaining the hBN-based composites with high TC. That is, there has been no study on the use of hBN as heat-escaping channels for optoelectronic devices. In this paper, we report on the improvement in heat dissipation performance of green LEDs with InGaN/GaN quantum wells (QWs) via the introduction of additional hBN heat-escaping medium. To reduce the defects/dislocations and strain at the QWs, Si-doped graded short-period InGaN/GaN superlattice, formed by indium-conversion technique, were inserted above an n-type cladding layer. The strong and stable electroluminescence spectrum was observed at the wavelength of 531 nm. The fluorescent microscope image difference of a LED with and without the inserted hBN superlattice demonstrated that the hBN-LED showed more uniform heat distribution than the Ref-LED. The maximum temperatures of the LED chips were measured as 136.9 °C, obtained at the bright metal electrodes. From the temperature-time curve of the hBN-LED chip, the time required to reach maximum temperature was 6 s, which is faster than that of the Ref-LED (12 s). After switching off the Ref-LED, it took 265 s to cool down to 35 °C. On the other hand, the time required for the hBN-LED to cool down to 35 °C was 35 s, which is considerably faster than that of the Ref-LED. To compare heat-transfer ability between two LEDs, heat-flow difference, defined as the temperature difference between the reference Al2O3 substrate and the LED chips, was measured by varying ambient temperature ranging from 25 to 150 °C. The heat-flow difference for the hBN-LED was measured as ~6.73 °C at the ambient temperature of 120 °C, which is higher than that of the Ref-LED (6.51 °C). While the heat-flow difference for hBN-LED continuously increases with increasing temperature, the heat-flow difference of the Ref-LED decreases with increasing temperatures above 133 °C. Based on this consideration, hBN can be used as a good heat-escaping medium for optical devices including LEDs.
Epitaxial layer exfoliation of III-V materials from their respective substrates provides a cost-effective route for fabricating multi-junction solar cells. Porous indium phosphide (InP) electrochemically etched onto a InP substrate facilitates this layer transfer through weakened mechanical properties at the porous layer-substrate interface. We previously demonstrated high quality homoepitaxial overgrowth and layer transfer from such porous structures [1], but longer timescales (hours) at elevated (> 550 C) temperatures typical of epitaxy of multi-junction solar cells were not considered. Therefore, porous layer stability during device growth and whether layer exfoliation occurs during the growth remains unknown. This work studies the variation in porous InP morphology with annealing temperatures (550 C to 650 C) and times (2 hr) comparable to that of double-junction solar cell fabrication. Silicon nitride layers were deposited onto the porous layers prior to annealing to prevent phosphorous depletion at elevated temperatures. Our earlier work showed that the porous layer evolution during epitaxial growth was the same as annealing at the epitaxial growth temperature [1] so here, we only studied capped porous layers. Plan-view and cross-section secondary electron microscope (SEM) images show that the InP layer deposition does not induce any pore coalescence in the layer. Increasing the annealing temperature from 550 C to 650 C showed an overall increase in pore coalescence both in the plan-view and at the porous-substrate interface. Plan-view SEM images show that the surface porosity does not change for the 550 C annealed layer, while the surface porosity decreases from 11% to 8% for the 650 C layer. The void fraction at the interface, on the other hand, increased from ~28% to ~49% as the annealing temperature increased. Combining the plan-view and cross-section images, we observe that diffusion-induced coalescence of the pores is more significant after the 650 C process (resulting in voids at the InP interface and reduction in porosity at the surface). The porous InP layers remained single crystalline (as verified by triple axis x-ray diffraction omega scans and TEM cross section images). The peaks simultaneously show high crystalline contributions (i.e. narrow peak width) and tail broadening due to diffuse scattering from inhomogeneous materials (i.e. porous layer). Moreover, changes in the tail broadening with SiN deposition and porous InP are observed. Pore coalescence during annealing/epitaxial growth can facilitate layer transfer after the device has been grown, and we show that no premature exfoliation occurs for time scales and temperatures comparable to that of double-heterojunction solar cell epitaxy. References: [1] Chen, D., Kou, X., Saremianaeini, S. and Goorsky, M.S. ECS Transactions, 64, pp.49-55 (2014).


From Submission to Publication: The Inside Workings of a Peer Reviewed Journal (JEM) Fatemeh (Staeli) Shafieipour-Sandvik; SUNY Polytechnic Institute, Albany, New York, United States.

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