SYMPOSIUM EP08

TUTORIAL: Ultra-Wide-Bandgap Semiconductors—From Materials to Devices
November 25 - November 25, 2018

* Invited Paper

TUTORIAL
Ultra-Wide-Bandgap Semiconductors—From Materials to Devices

Sunday Afternoon, November 25, 2018
Hynes, Level 2, Room 209

The Ultra-Wide-Bandgap (UWBG) materials represent the next chapter in the history of semiconductor physics, with potential applications to optoelectronics, radio-frequency electronics, power switching electronics, electronics and sensors for harsh environments, platforms for quantum information processing, and possibly as-yet-unforeseen areas. Such applications are enabled by the properties of the materials and the novel device structures enabled by those properties. The first part of this tutorial will focus on the unique physical properties of the key UWBG semiconductors (AlN, BN, Ga2O3, diamond, etc.) as well as the challenges in their growth and manipulation (substrates, doping, defects, etc.) The second part will focus on potential applications and the device structures appropriate for those applications (LEDs, vertical and lateral transistors, etc.) as well as the challenges associated with the design and processing of such devices (metal-semiconductor contacts, surface passivation, etc.) The goal is to provide a comprehensive overview of the key aspects of this new and exciting field.

1:30 PM
Ultra-Wide-Bandgap Semiconductors: Materials Robert J. Nemanich; Arizona State University

The first part of the tutorial will focus on the unique physical properties of the key UWBG semiconductors (AlN, BN, Ga2O3, diamond, etc.) as well as the challenges in their growth and manipulation (substrates, doping, defects, etc.)

3:00 PM BREAK

3:30 PM
Ultra-Wide-Bandgap Semiconductors: Devices Robert J. Kaplar; Sandia National Laboratory

The second part of the tutorial will focus on potential applications of UWBG semiconductors, and the device structures appropriate for those applications (LEDs, vertical and lateral transistors, etc.) as well as the challenges associated with the design and processing of such devices (metal-semiconductor contacts, surface passivation, etc.)

SYMPOSIUM EP08

Ultra-Wide-Bandgap Materials and Devices
November 26 - November 29, 2018

Symposium Organizers
Mark Hollis, Massachusetts Institute of Technology - Lincoln Laboratory
Robert Kaplar, Sandia National Laboratories
David Moran, University of Glasgow
Rachael Myers-Ward, U.S. Naval Research Laboratory

Symposium Support
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* Invited Paper

SESSION EP08.01: Oxide Devices I
Session Chair: Mark Hollis
Monday Morning, November 26, 2018
Hynes, Level 2, Room 209

8:30 AM *EP08.01.01
Investigation of Process Techniques for Ga_2O_3 Based Diodes Fan Ren[1], Jiancheng Yang[1], Stephen J. Pearton[1], Marko Tadjer[2] and Akito Kuramata[3]; [1]University of Florida, Gainesville, Florida, United States; [2]U.S. Naval Research Laboratory, Washington DC, District of Columbia, United States; [3]Tamura Corporation and Novel Crystal Technology, Inc, Sayama Saitama, Japan.

Monoclinic β-phase Ga_2O_3 has outstanding potential for power electronics, and high quality, large diameter bulk crystals and epitaxial layers of Ga_2O_3 are already available with a range of controllable n-type doping levels by edge-defined film-fed (EFG) growth using iridium crucibles, by Czochralski or by float zone. The direct energy bandgap of Ga_2O_3, ~4.9 eV, yields a very high theoretical breakdown electric field (~8 MV/cm). For power electronics, the Baliga figure-of-merit proportional carrier mobility, critical electric field and breakdown voltage, is almost four times higher for Ga_2O_3 than for GaN. Currently, the major limitation for Ga_2O_3 based device fabrication is the lack of low resistance Ohmic contacts, low damage dry etching process, and thermally stable Schottky contacts. In this work, we report a technique by employing Aluminum Zinc Oxide (AZO) to improve Ohmic contacts on Ga_2O_3, studies of etch rates and etching induced damages with Cl_2/Ar and BCl_3/Ar based discharge, surface treatment prior to Schottky metal deposition as well as Ni/Au and Pt/Au Schottky contacts, and demonstration of 2300 V breakdown voltage Ga_2O_3 Schottly diode.

9:00 AM *EP08.01.02
Advances in Ga_2O_3 MOSFETs for Power Switching and Beyond Masataka Higashiwaki[1], Man Hoi Wong[1], Takafumi Kamimura[1], Yoshiaki Nakata[1], Chia-Hung Lin[1], Akinori Takeyama[2], Takahiro Makino[2], Takeshi Ohshima[2], Manikant Singh[3], James W. Pomeroy[3], Michael J. Uren[3], Michael A. Casbon[4], Paul J. Tasker[4], Ken Goto[5], Kohei Sasaki[5], Akito Kuramata[5], Shigenobu Yamakoshi[5], Martin Kuball[3], Hisashi Murakami[6] and Yoshinao Kumagai[6]; [1]National Institute of Information and Communications Technology, Koganei, Japan; [2]National Institutes for Quantum and Radiological Science and Technology, Takasaki, Japan; [3]University of Bristol, Bristol, United Kingdom; [4]Cardiff University, Cardiff, United Kingdom; [5]Tamura Corporation, Sayama, Japan; [6]Tokyo University of Agriculture and Technology, Koganei, Japan.

Ga_2O_3 has emerged as a noteworthy ultrawide bandgap semiconductor in the past five years. Owing to excellent material properties based on an extremely large bandgap of over 4.5 eV and the commercial availability of native wafers produced from melt-grown bulk single crystals, Ga_2O_3-based electronic devices are promising candidates for various applications in power switching, RF, and harsh-environment electronics.
First, this presentation will give an overview of our state-of-the-art lateral depletion-mode (D-mode) Ga_2O_3 metal-oxide-semiconductor field-effect transistors (MOSFETs) [1]. The devices demonstrated an off-state breakdown voltage of over 750 V, a drain current on/off ratio of more than nine orders of magnitude, stable device operation at temperatures up to 300°C, and negligibly small DC–RF dispersion. Furthermore, the bulk Ga_2O_3 channel exhibited strong gamma-ray tolerance by virtue of showing very little on-resistance degradation and threshold voltage shift, thereby demonstrating the strong potential of Ga_2O_3 devices for radiation-hard electronics [2]. We will also present RF and thermal characteristics of the lateral MOSFETs [3-5].
In the second part, we will discuss our recent developments of vertical D-mode Ga_2O_3 MOSFETs [6, 7]. The devices had a current blocking layer formed by Mg- or N-ion implantation and successfully demonstrated drain current modulation by an applied gate bias. However, the devices were still at a primitive development stage and had some severe issues to be resolved.
This work was partially supported by Council for Science, Technology, and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Next-generation power electronics” (funding agency: NEDO).

[1] M. H. Wong, M. Higashiwaki *et al.*, IEEE Electron Device Lett. 37, 212 (2016).
[2] M. H. Wong, M. Higashiwaki *et al.*, Appl. Phys. Lett. 112, 023503 (2018).
[3] M. H. Wong, M. Higashiwaki *et al*., Appl. Phys. Lett. 109, 193503 (2016).
[4] Manikant, M. Higashiwaki, M. Kuball *et al.*, *Compound Semiconductor Week 2018, May 2018.*
[5] J. W. Pomeroy, M. Higashiwaki, M. Kuball *et al.*, *60th Electronic Materials Conference, June 2018.*
[6] M. H. Wong, M. Higashiwaki *et al.*, Appl. Phys. Express 11, 064102 (2018).
[7] M. H. Wong, M. Higashiwaki *et al.*, *Compound Semiconductor Week 2018, May 2018.*

9:30 AM EP08.01.03
Gate Dielectrics for Gallium Oxide MISFETs Sarit Dhar[1], Asanka Jayawardena[1], Ayayi Ahyi[1], Rahul P. Ramamurthy[2], Dallas Morisette[2] and Jacob H. Leach[3]; [1]Physics, Auburn University, Auburn, Alabama, United States; [2]Electrical Eng., Purdue University, West Lafayette, Indiana, United States; [3]Kyma Technologies Inc., Raleigh, North Carolina, United States.

In this paper, we report performance comparisons between Silicon Dioxide (SiO_2) and Aluminum Oxide (Al_2O_3) as gate dielectrics for beta-Gallium Oxide (**β**-Ga_2O_3) metal insulator semiconductor transistors (MISFETs). To this end, we will present charge trapping results in MIS capacitors fabricated on commercial (-201) oriented **β**-Ga_2O_3 substrates using atomic layer deposition (low temperature process, for Al_2O_3 and SiO_2) and low-pressure chemical vapor deposition (high temperature process for SiO_2). Our findings indicate that the both interface trap density and ‘slow’ border trap density at ALD Al_2O_3/Ga_2O_3 interfaces are about 2x lower than that of LPCVD SiO_2/Ga_2O_3 interfaces. Despite this shortcoming, LPCVD SiO_2 gated devices have significantly lower leakage current and higher breakdown strength compared to different ALD Al_2O_3 processes, consistent with the higher conduction band offset in SiO_2/**β**-Ga_2O_3. For future **β**-Ga_2O_3 based high voltage power electronics, this factor makes SiO_2 more attractive. In addition, the significantly higher fixed/stable negative charge at SiO_2interfaces, is conducive for normally-off MISFET channel design, which is highly desirable for power switching. To demonstrate this proof-of-concept, LPCVD SiO_2 was used as gate dielectric to fabricate lateral long channel MISFETs on a (010) oriented **β**-Ga_2O_3 homoepitaxial thin film grown using HVPE at Kyma Technologies (USA). While the devices were not optimized, the threshold voltages were ~10 V which indeed indicate normally-off operation. In this paper, these initial results will be complimented with results from ongoing experiments and the factors to be considered when choosing the gate dielectric in Ga_2O_3 MISFETs, will be discussed in detail.

9:45 AM EP08.01.04
Nitrogen Ion Implantation for the Effective Inter-Device Isolation of β-Ga_2O_3 Power Transistors Kornelius Tetzner[1], Eldad Bahat-Treidel[1], Andreas Thies[1], Frank Brunner[1], Günter Wagner[2] and Joachim Würfl[1]; [1]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin,

Germany; [2]Leibniz-Institut für Kristallzüchtung, Berlin, Germany.

The ultra-wide bandgap semiconductor β-Ga_2O_3 has received great attention in recent years due to its potential to become an attractive alternative to conventionally used materials for future power electronic applications. The estimated dielectric strength of 8 MV/cm in combination with the expected Baliga's figure of merit are promising indicators to pave the way for the realization of power devices with even higher breakdown voltages and efficiencies than their SiC and GaN counterparts. Up to now several studies have demonstrated the successful realization of Schottky barrier diodes and field-effect transistors based on β-Ga_2O_3 with promising results for the development of high efficiency power converters. In order to electrically isolate such electronic devices from each other dry etching of mesa structures into the β-Ga_2O_3 is commonly carried out. On the other hand device isolation by ion implantation was shown in several reports on GaN-based devices to be an attractive alternative as it allows maintaining the planarity of the wafer surface and thus significantly improves the yield in fine-pitch lithography. However, the inter-device isolation by ion implantation of Ga_2O_3 has not yet been investigated and the applicability of this technology in terms of processing boundary conditions on β-Ga_2O_3 is still unknown to date. In this study we report on the application of multiple energy nitrogen ion implantation for the electrical isolation of electronic devices on monoclinic β-Ga_2O_3. By the introduction of uniformly distributed midgap damage-related levels in the β-Ga_2O_3 crystal lattice we are able to increase the sheet resistances by more than 9 orders of magnitude to $\geq 10^{13}$ Ω/sq which remains electrically stable up to annealing temperatures of 600 °C carried out for 60 seconds under nitrogen atmosphere. At higher annealing temperatures the damage-related trap levels are being removed causing a significant drop of the sheet resistance down to 4 x 10^5 Ω/sq after annealing at 800 °C. This effect is preceded by a structural recovery of the implantation damages via the recrystallization of the crystal lattice at already 400 °C as verified by x-ray diffraction measurements. The extracted activation energies of the deep states responsible for the high resistive β-Ga_2O_3 layer after implantation is in the range of 0.7 eV. It shows a strong correlation with the annealing temperature dependence of the sheet resistance and thus supports the theory of a damage-induced isolation mechanism. The outcome of this work is an important step towards a more robust fabrication method of electronic devices based on β-Ga_2O_3 for high efficiency power electronics of the next generation.

10:00 AM BREAK

SESSION EP08.02: Late News—Gallium Oxide and III-Nitride Materials
Session Chair: Robert Kaplar
Monday Morning, November 26, 2018
Hynes, Level 2, Room 209

10:30 AM EP08.02.01
High Performance β-Ga_2O_3 Based Vertical Solar Blind Schottky Photodiode Fikadu Alema[1], Brain Hertog[1], Andrei Osinsky[1], Yuewei Zhang[2], Akhil Mauze[2], James S. Speck[2], Partha Mukhopadhyay[3] and Winston V. Schoenfeld[3]; [1]Agnitron Technology Incorporated, Eden Prairie, Minnesota, United States; [2]Materials Department, University of California, Santa Barbara, Santa Barbara, California, United States; [3]CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida, United States.

We report on high performance solar blind vertical Schottky photodiode which utilizes high quality n β-Ga_2O_3 epitaxial film with an electron mobility of up to 176 cm^2/Vs in the active area of the device. The growth of the β-Ga_2O_3 epitaxial layer was conducted by MOCVD on an n^+β-Ga_2O_3(010) substrate. The layer was fabricated into a vertical Schottky photodiode with a Pt/n(-)Ga_2O_3/$n^{(+)}Ga_2O_3$(010) structure. A 30Å semitransparent Pt metal was used on the active part of the photodiode to form good Schottky contact. The photovoltaic response of the devices showed a maximum responsivity of 0.16 A/W at 222 nm at zero bias with the corresponding external quantum efficiency (EQE) of ~87 %. The cutoff wavelength and the out of band rejection ratio were ~260 nm and ~10^4, respectively, showing a true solar blind operation with an excellent selectivity of the device. The time response of the photodiode is in the millisecond range and has no long-time decay component which is common in the photoconductive wide bandgap devices. In this work, we will also discuss the rectifying characteristics, reverse bias leakage currents up to critical breakdown fields, and the temperature dependence of the Schottky photodiode showing its potential use for applications where high optical gains are required.

10:45 AM EP08.02.02
Device Quality β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ Heterostructures—Control of Doping and Impurity incorporation in MOCVD Process Fikadu Alema[1], Andrei Osinsky[1], Yuewei Zhang[2], Akhil Mauze[2] and James S. Speck[2]; [1]Agnitron Technology Incorporated, Eden Prairie, Minnesota, United States; [2]Materials Department, University of California, Santa Barbara, Santa Barbara, California, United States.

We report on the MOCVD growth of controllably doped device quality β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ epitaxial layers with carrier concentration between 1E15 and 1E20 1/cm^3. For the realization of β-Ga_2O_3 based high performance power electronics with high breakdown voltages and low on-resistance, the low background impurity concentration and high electron mobility are critical. However, one of the challenges in the MOCVD growth of β-Ga_2O_3 is the presence of unintentional background concentration which is mainly attributed to carbon and hydrogen impurities that incorporate into the epilayers primarily from the metalorganic precursors. Here, we present an in-situ and ex-situ methods used to reduce the incorporation of these impurities. Optimization of the MOCVD growth condition, including O_2 flow rate, chamber pressure, and temperature were found to be critical to control the incorporation of these impurities, hence the background concentration and electron mobility in the film. With optimal growth conditions, films with record electron mobility of up to 176 cm^2/Vs and ~3500 cm^2/Vs were measured at room temperature and 54 K, respectively [1]. Low background concentration of ~1.5E15 1/cm^3 was obtained. A short post growth annealing of the β-Ga_2O_3 in an oxygen atmosphere was also found to reduce the background concentration in the films with no influence on the electron mobility. Si doping of β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ alloys using silane and tetraethoxysilane (TEOS) was systematically investigated with the carrier concentration ranging between 1E15 and 1E20 1/cm^3. The effect of using silane and TEOS on the incorporation of carbon and hydrogen impurities in the doped layers will be discussed. The growth of high-quality strained β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures and superlattices on (010) β-Ga_2O_3 substrates will be presented. The structural quality, abruptness of hetero-interfaces, surface morphology and electrical properties of the heterostructures will be discussed.

[1]. Yuewei Zhang, Fikadu Alema, Akhil Mauze, James Speck, Andrei Osinsky, and Ross Miller, "MOCVD grown epitaxial β-Ga2O3 thin film with an electron mobility of 176 cm2/Vs" submitted for publication to APL materials.

11:00 AM EP08.02.03
Polarization Engineering of ε-$(AlGa)_2O_3$/ε-Ga_2O_3 Heterostructures Praneeth Ranga[1], Sung Beom Cho[2], Rohan Mishra[2] and Sriram Krishnamoorthy[1]; [1]University of Utah, Salt Lake City, Utah, United States; [2]Washington University in St. Louis, St. Louis, Missouri, United States.

In this work, we predict the formation of two-dimensional electron gas (2DEG) at ε-$AlGaO_3$/ε-Ga_2O_3- based heterostructures. β-Ga_2O_3 is an ultra-wide band gap semiconductor, with favorable material properties for high power applications. Being the most stable phase of Ga_2O_3 and its ease of bulk crystal growth β-Ga_2O_3 is the most studied phase of Ga_2O_3. Recently, ε-Ga_2O_3, a metastable phase, has been predicted to be polar with a large spontaneous polarization and a wide band gap. It has also been predicted that ε-Ga_2O_3 can be stabilized by epitaxial strain. Theoretical modeling of ε-Ga_2O_3 material properties is important to gauge the potential of this material. There is little information on the properties of ε-Ga_2O_3 and its alloys in literature. Ab-initio modeling of ε-Ga_2O_3 and alloys was done using density functional theory. Parameters such as spontaneous polarization, elastic constants, band offsets etc. were calculated for both disordered and ordered alloys of ε-Ga_2O_3. Calculations show that spontaneous polarization of ε-Ga_2O_3 to be 0.23 C/cm^2, which is much higher than other wurtzite semiconductors such as GaN and AlN[1]. ε-Ga_2O_3 is also predicted to be a ferroelectric semiconductor with a switching barrier of 0.93 eV to switch the polarization field[1]. Calculated band parameters indicate a large band offset at the interface, ideal for confining electrons. Band diagram calculations using Schrödinger -Poisson solver between ε-$(AlGa)_2O_3$(0001) /ε-Ga_2O_3(0001) show the formation of 2DEG at the heterojunction. The 2DEG carrier concentration was in the range of 1-5e13 cm^{-2} at the interface. Spontaneous polarization was found to be the dominant contribution to the 2DEG formation. A 2DEG can also be formed by reversing the polarization between ε-$(AlGa)_2O_3$(000-1) /ε-Ga_2O_3(000-1) interface in this case, a graded back barrier with n-type doping to account for an electron source for 2DEG. The 2DEG density was found close to the ε-$(AlGa)_2O_3$(0001) /ε-Ga_2O_3(0001) interface. The polarization of the selective barrier layers can be flipped by applying a bias to the Schottky gate metal-2deg electrodes. The 2DEG density modulation using gate bias can be potentially used as a ferroelectric memory switch. This is first theoretical study which predicts 2DEG formation at ε-$(AlGa)_2O_3$(0001) /ε-Ga_2O_3(0001) interface. These results show that polar ε-Ga_2O_3 is a promising semiconductor for high frequency and high power and memory applications.

[1] SB Cho, R Mishra Applied Physics Letters 112 (16), 162101, 2018

11:15 AM EP08.02.04
Development of Selective Trench Refilling Epitaxy Process to Form p-n Junction on GaN-on-Sapphire Substrate Sizhen Wang[1], Andrew Klump[1], Felix Kaess[2, 1], Ramon Collazo[1], Zlatko Sitar[1] and Alex Huang[3]; [1]North Carolina State University, Raleigh, North Carolina, United States; [2]IQE, Inc., Boston, Massachusetts, United States; [3]The University of Texas at Austin, Austin, Texas, United States.

GaN-based power devices are under intensive study in academy and industry because of superior physical properties of GaN materials, such as high critical electrical field, high electron saturation velocity. And lateral GaN HEMT or MOS-HEMT structures are favorable as the high mobility of 2DEG in AlGaN/GaN heterojunction can be transferred to low on-state resistance, many technology innovations such as p-Gate, multiple field plate, in-situ passivation have been implemented to enhance GaN power transistor performance. But till now, there is relatively large gap comparing to ideal device figure-of-merit in 1D junction case. The root cause can be traced to lack of selective area doping technology, which was used in conventional Si, and SiC power device fabrication to modulate electrical field in surface and bulk semiconductor materials. The lack of selective doping technique also makes the development of vertical GaN power devices is challenging. Since applying Magnesium ion implantation and annealing to form p-GaN is not very successful, we proposed selective trench refilling epitaxy to form p-n junction on GaN-on-Sapphire or free-standing GaN substrate, this technology involved deep GaN trench etch, and p-GaN refilling epitaxy with MOCVD. We have developed this process integration technology, and made significant progresses. Those highlighted results are listed here: 1) anisotropic trench refilling epitaxy characteristic was studied, and it was found lateral growth in (11-20) plane is much faster than the growth in (1-100) plane. 2) hexagonal device layout, instead of conventional circular shape layout, was modified to mitigate the anisotropic growth characteristic. 3) process optimizations, such as trench surface wet KOH etch, and pre-growth in-situ cleaning, were studied and high forward current density (100A/cm^2 at 5V forward bias) of p-n diode was achieved. 4) p-n junction diode Ion/Ioff ratio of $1x10^6$ (±5V bias) was achieved by separating regrowth interface and junction interface.

11:30 AM EP08.02.05
AlGaN/GaN HEMT Operation with Body-Diode Back-Gate Control—Enabling Dynamic Control of Device Behavior Isra Mahaboob, Michael Yakimov, Kasey Hogan, Emma Rocco, Sean Tozier and F.Shadi Shahedipour-Sandvik; Nanoscale Science and Engineering, SUNY Polytechnic Institute, Albany, New York, United States.

AlGaN/GaN based High Electron Mobility Transistors (HEMTs) have emerged as promising candidates in high-power/high-frequency and sensing applications due to their excellent material properties. The tremendous success of this device technology is due to the presence of high density and high mobility two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface. In the power switching domain, AlGaN/GaN based HEMTs are believed to make an impact similar to what Si MOSFETs did in 1970s in switching power supply applications by replacing BJTs. However, a major challenge with this device technology is the normally-ON nature which reduces their efficiency in power systems. There have been multiple instances of overcoming this issue by various (post growth) processing methods [1][2]. Here we show, for the first time, the integration of a body-diode based back-gate control in AlGaN/GaN HEMTs to shift the threshold voltage to normally-OFF regime and dynamically control the device performance with a fourth back-gate terminal. This approach is similar to the body-bias technique of threshold voltage control in CMOS [3].

We experimentally demonstrate the role of the back-gate voltage in controlling the performance of HEMTs in both ON and OFF states of the device. The HEMT structure used in this study has been epitaxially grown using metal organic chemical vapor deposition technique. To incorporate body-diode, conventional HEMT structure was epitaxially grown on p-type GaN. The role of Mg activation in the p-GaN layer on the electrical properties of the device has been studied and will be discussed. With the integration of body-diode, the 2DEG current shows modulation with the change in magnitude and polarity of the back-gate voltage. An increase in 2DEG current is measured with the application of a positive back-gate voltage and a decrease is measured under a negative back-gate bias. Moreover, a positive/negative shift in the threshold voltage is observed with the application of negative/positive back-gate voltage. The modulation of 2DEG density is attributed to the modulation of the body-diode depletion width. Along with extensive results of such modulation, a comprehensive study demonstrating 3-terminal and 4-terminal output/transfer characteristics and capacitance-voltage characteristic of this novel device structure will be presented.

References:
[1] W.-T. Lin, W.-C. Liao, Y.-N. Zhong, and Y. Hsin, “AlGaN/GaN HEMTs with 2DHG Back Gate Control,” *MRS Adv.*, vol. 3, no. 3, pp. 137–141, Dec. 2017.
[2] M. Meneghini, O. Hilt, J. Wuerfl, and G. Meneghesso, “Technology and Reliability of Normally-Off GaN HEMTs with p-Type Gate,” *Energies*, vol. 10, no. 2, p. 153, Jan. 2017.
[3] V. Kursun and E. G. Friedman, “Multi-voltage CMOS circuit design, ch. 3, sec. 3.3.1, pp. 58-74,” Aug. 2006.

11:45 AM EP08.02.06
InGaN Nanowire Light Emitting Diode Integrated with Field Effect Transistor Matthew Hartensveld and Jing Zhang; Microsystems, Rochester Institute of Technology, Rochester, New York, United States.

Current display technology is reaching its practical limitations as the Thin-Film-Transistors (TFTs) that make up displays are struggling to be reduced further in size. Emerging technologies such as Augmented and Virtual Reality are also challenged to find transparent and high-resolution displays. Nanowire (NW) Light Emitting Diodes (LEDs) are appearing as the solution due to higher efficiencies (70% vs. 5%), high reliability, and the ability to be manufactured at nanoscale. Though NW LEDs are being pursued, there are key issues in monolithically integrating Field Effect Transistors (FETs) with those LEDs. Common solutions include growth on Silicon to incorporate Complementary Metal Oxide Semiconductor (CMOS) technology, layer regrowth for High Electron Mobility Transistors (HEMTs), and deposition of classical TFTs on top of the LEDs. Nevertheless, all these approaches would sacrifice display area and device performance to introduce FETs to LEDs.

Presented here is a novel monolithic integration scheme to vertically combine GaN NW FETs with InGaN NW LEDs. Novel to this work, the layer of unintentionally doped GaN (u-GaN), serving as a template to LED growth, is used for FET channel. This makes the FET in series with an NW LED for switching. Our approach allows for straightforward fabrication, no loss of display area, and eliminates device degradation. Many different types of FETs can be realized, and here a Static Induction Transistor (SIT) is selected due to the ease of fabrication.

To start, a conventional LED structure is used consisting of sapphire, u-GaN, n-type GaN, InGaN quantum wells, and p-type GaN. The NWs are fabricated through a top-down method utilizing Reactive Ion Etching (RIE) to etch down into the u-GaN layer. The etched NWs are then immersed in a KOH solution to crystallographically wet etch the wires, shrinking the diameters along with removing etch damage. Titanium is next evaporated at the base of the wires and annealed. Annealing creates nitrogen vacancies which construct the n-i-n structure common to modern transistors. Following the anneal, Polydimethylsiloxane (PDMS) is deposited and etched back to provide an insulating layer. Nickel is then evaporated creating a 30 nm schottky gate on the u-GaN. A second layer of PDMS is then coated and etched back to reveal the NW tips, followed by a deposition of Indium Tin Oxide (ITO) for top contact. These preliminary devices show good gate control with the ability to switch on/off the NW LEDs. As the gate becomes reverse bias the depletion region of the gate pinches off the current flow through the u-GaN layer, switching off the LED. Silvaco simulations are additionally performed to investigate and model device operation. This monolithically integration of NW LED and SIT can open the door to the next generation of display technology with the ability to be fabricated at diameters smaller than 100 nm, along with the inherent ability to be fully transparent.

SESSION EP08.03: Oxide Devices II
Session Chair: David Moran
Monday Afternoon, November 26, 2018
Hynes, Level 2, Room 209

1:30 PM *EP08.03.01
Electrical and Thermal Studies of β-Ga_2O_3 Nano-Membrane Field-Effect Transistors on Different Substrates Peide P. Ye; Purdue University, West Lafayette, Indiana, United States.

β-Ga_2O_3 is an emerging wide bandgap semiconductor for the next generation power devices to replace GaN and SiC. It has an ultra-wide bandgap of 4.8 eV and a corresponding high breakdown field of 8 MV/cm. However, the β-Ga_2O_3 bulk substrate has a low thermal conductivity (k) of 10-25 W/mK and thus severe self-heating effects (SHE) can be observed. In high-power electronic devices, the output power density and the maximum drain current can be significantly limited by the elevated channel temperature caused by SHE and it has become a key challenges in β-Ga_2O_3 research. To suppress severe self-heating at high powers, we herein demonstrate top-gate nano-membrane β-Ga_2O_3 field effect transistors on a high thermal conductivity diamond substrate. The devices exhibit enhanced performance, with a record high maximum drain current of 980 mA/mm for top-gate β-Ga_2O_3 field effect transistors and 60% less temperature increase from reduced self-heating, compared to the device on sapphire substrate operating at the same power. With Improved heat dissipation, β-Ga_2O_3 field effect transistors on a diamond substrate are validated using a newly developed ultrafast high-resolution thermoreflectance imaging technique, Raman themography, and thermal simulations. The work is in close collaborations with Dr. Marko Tadjer's team at NRL and Prof. Ali Shakouri's team at Purdue University.

2:00 PM EP08.03.02
Developing New High Thermal Conductivity Materials for Thermal Management of High-Power Electronics Joon Sang Kang, Man Li, Huuduy Nguyen, Huan Wu and Yongjie Hu; University of California, Los Angeles, Los Angeles, California, United States.

Heat dissipation has become an increasingly critical technological challenge in modern electronics and photonics. To address this challenge, discovering new high thermal conductivity materials that can efficiently dissipate heat from hot spots and improve the device performance of gallium nitride based electronics are urgently needed. Recent theoretical work including ab initio has predicted a new class of thermal materials, however, experimental demonstration has been challenged by materials synthesis and thermal characterization. Here, we describe our current progress in developing and characterizing these emerging high thermal conductivity materials [1-3].

We have chemically synthesized high-quality boron phosphide single crystals and measured their thermal conductivity as a record-high 460 W/mK at room temperature[1]. We have, for the first time, experimentally measured the phonon mean free path spectra of boron phosphide and analyzed experimental results by solving three-dimensional and spectral-dependent phonon Boltzmann transport equation using the variance-reduced Monte Carlo method. The experimental results are in good agreement with that predicted by multiscale simulations and density functional theory, which together quantify the heat conduction through the phonon mode dependent scattering process.

Our finding underscores the promise of the emerging high thermal conductivity material for advanced thermal management and provides a microscopic-level understanding of the phonon spectra and thermal transport mechanisms. The study aims to enable a rational design of thermal materials and nano- to multiscale devices, including the heat management of wide-bandgap electronics.

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2:15 PM EP08.03.03
Etchpits with a Core Related to the Leakage Current of HVPE (001) β-Ga_2O_3 Schottky Barrier Diodes Makoto Kasu[1], Eitesu Katagiri[1], Kohei Sasaki[2, 4], Katsumi Kawasaki[3], Jun Hirabayashi[3] and Akito Kuramata[2, 4]; [1]Saga University, Saga, Japan; [2]Novel Crystal Technologies, Sayama, Japan; [3]TDK Corporation, Tokyo, Japan; [4]Tamura Corporation, Sayama, Japan.

β-Ga_2O_3, with a bandgap of 4.8 eV, is expected to be power semiconductor whose performance exceeds that of SiC and GaN. Recently, halide vapor-phase epitaxy (HVPE) has progressed rapidly and has led to the epitaxial growth of high-quality films at high growth rates. Previously, we reported the relationship between etch pits and leakage current in β-Ga_2O_3 crystals grown by edge-defined film-fed growth (EFG) Schottky barrier diodes (SBDs) on (010), (-201), and (001) and identified etch pits responsible for leakage current.[1] In this talk, we identify etch pits responsible for leakage current in HVPE-grown β-Ga_2O_3 SBDs.

The sample was a HVPE-grown 6- to 11-μm-thick epitaxial layer grown on an EFG-grown β-Ga_2O_3 (001) substrate. On the entire back face, Ti/ Au ohmic contacts were formed; on the surface side, a pixel array of Pt/ Ti/ Au Schottky contacts with a 400-μm diameter were formed. After current–voltage and capacitance–voltage measurements of the SBDs, we observed light emission inside the SBDs with a high reverse bias operation. After the measurements, the SBD contacts were etched and the etch pits were observed by differential interference contrast microscopy and atomic force microscopy.

On the HVPE-grown surface after etching, bullet-shaped etch pits were observed. They are similar to those on the EFG-grown (001) surface. [2] However, among the bullet-shaped etch pits, we found that some have a deep core near their point. In parallel, inside the SBD with a high leakage current, we observed emission spots under a high reverse bias condition. Further we have found that at the position of some emission spots, the bullet-shaped etch pits with a core at their point exist. This suggests that a bullet-shaped etch pit with a core at the point is one of leakage-current paths of the SBD.

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2:30 PM EP08.03.04
Band Engineering of Ga_2O_3 and In_2O_3 by Adding Post Transition Metals Fernando P. Sabino and Anderson Janotti; University of Delaware, Newark, Delaware, United States.

Wide-band-gap semiconductors such as Ga_2O_3 and In_2O_3 are used in a wide range of technological application which include solar cells, OLEDs, high-power transistors, etc. Most of the oxides, including Ga_2O_3 and In_2O_3, show an unintentional n-type conductivity. This can be explained by their typical high electronic affinity, i.e., their conduction band are quite low with respect to the vacuum level, such that many impurities tend to act as shallow donors. On the other hand, their localized valence band is composed by O *p*-orbitals and lie very low in absolute energy, leading to high ionization potential. Thus, impurities with one less valence electrons than the host atoms tend to act as deep acceptors. In addition, holes tend to self-trap, forming small polarons, making it impossible to achieve p-type doping conductivity. To overcome this problem, we propose to rise the valence band by alloying Ga_2O_3 and In_2O_3 with post transition metals. Using the density functional theory with the Heyd-Scuseria-Ernzerhof hybrid functional (HSE) we calculate the alloy stability, formation enthalpies, and the band gap variation as a function of alloy concentration. We also address the band alignment between the different alloy compositions and the parent compounds and discuss the effects of alloying on the optical properties.

2:45 PM EP08.03.05
Stability, Band Gap and Band Edge Positions of $(Al_xGa_{1-x})_2O_3$ Alloys Tianshi Wang, Wei Li, Chaoying Ni and Anderson Janotti; University of Delaware, Newark, Delaware, United States.

Ga_2O_3 is an important material for solar-blind UV photodetectors and high-power transistors. Alloying with Al, as in $(Al_xGa_{1-x})_2O_3$, adds great flexibility to the design of Ga_2O_3-based devices through band engineering. Basic key parameters in the device design, such as band gap variation with alloy composition and band offset between Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$, are yet to be established. Using density functional theory with the HSE hybrid functional, we find that the formation enthalpies of $(Al_xGa_{1-x})_2O_3$ alloys are significantly lower than that of $(In_xGa_{1-x})_2O_3$, and the $(Al_xGa_{1-x})_2O_3$ with x=0.5 can be considered as an ordered compound $AlGaO_3$ in the monoclinic phase, with Al occupying the octahedral sites and Ga occupying the tetrahedral sites. By adjusting Al composition, the direct band gaps of the alloys can be tuned from 4.69 to 7.03 eV for the monoclinic phase and from 5.25 to 8.56 eV for the corundum phase. The band offset of the $(Al_xGa_{1-x})_2O_3$ alloy mainly arises from the discontinuity in the conduction band. Consequences for designing modulation-doped field effect transistors (MODFETs) based on $(Al_xGa_{1-x})_2O_3$ /Ga_2O_3 are also discussed.

3:00 PM BREAK

3:30 PM *EP08.03.06
β-Ga_2O_3 Nano-Electronic Devices Jihyun Kim; Korea University, Seoul, Korea (the Republic of).

The preparation of nano-layer β-Ga_2O_3 flake by a mechanical exfoliation method and its fabrication into various types of electron and optoelectronic devices will be presented. Firstly, we will show a heterostructure n-channel depletion-mode β-Ga_2O_3 junction field-effect transistor through a van der Walls bonding with an exfoliated p-WSe_2 flake. β-Ga_2O_3 and hexagonal boron nitride heterostructure-based metal-insulator-semiconductor field-effect transistors (MISFETs) are achieved by integrating mechanical exfoliation of quasi-two-dimensional materials with dry transfer process, where nano-thin flakes of β-Ga_2O_3 and h-BN were utilized as the channel and gate dielectric, respectively, of the MISFET. We will present a β-Ga_2O_3 metal-semiconductor field-effect transistor with a high off-state breakdown voltage (344 V), based on a exfoliated β-Ga_2O_3 field-plated with hexagonal boron nitride. This heterostructured ultra-wide bandgap nanodevice shows a new route toward high power nano-electronic devices.

4:00 PM EP08.03.07
Anisotropic Optical Properties in Zn_2GeO_4 and Ga_2O_3 Nanowires Jaime Dolado[1], Manuel Alonso-Orts[1], Iñaki Lopez[2, 1], Pedro Hidalgo[1], Emilio Nogales[1] and Bianchi Mendez[1]; [1]University of Complutense, Madrid, Spain; [2]Istituto Nazionale di Ottica, Florence, Italy.

Zinc germanate (Zn_2GeO_4) and gallium oxide (Ga_2O_3) are wide band gap semiconductors (E_g = 4.5 and 4.9 eV, respectively) with promising applications due to their matching with UV radiation in UV photodetectors, phosphors in flat panel displays or photo catalysis. In addition, Ga_2O_3, in particular, is becoming an emergent material for high power devices while Zn_2GeO_4 is a good candidate to be used in Li-ion batteries. In both oxides, the electronic and optical properties have been investigated recently, and an active research is going on. For example, there is still controversy about the origin of the visible luminescence of these oxides, usually attributed to oxygen vacancies, which are mainstream defects in oxide materials. Furthermore, doping oxides to modify electronic conductivity or luminescence properties is also a challenge because of the interplay of impurities with native defects, which add more complexity to the physical properties. On the other hand, nanowire morphologies of a number of compounds have been recently studied on the view of

particular applications, such as optical microcavities or vertical devices designs. Since optoelectronic properties are intrinsically related to the electronic levels in the band gap, high-energy electron and UV light are suitable probes to test these properties. In this work, we explore the optical properties of undoped Zn_2GeO_4 and Zn doped Ga_2O_3 and nanostructures synthetized by a thermal evaporation method. We will carry out polarization dependent luminescence and Raman measurements to get some insight into their luminescence features and their correlation with their chemical and structural configuration at atomic scale level.

4:15 PM EP08.03.08
Gallium Oxide Nanowires for Gas Sensing Applications—Growth, Device Fabrication and Gas Response Guillem Domenech-Gil[1, 2], Irmina Peiró[1], Jordi Sama[1, 2], Paolo Pellegrino[1, 2], Sergi Hernández[1, 2], Mauricio Moreno[1, 2], J.D. Prades[1, 2], Isabel Gràcia[3], Carles Cané[3], Sven Barth[4] and Albert Romano-Rodriguez[1, 2]; [1]Department of Electronic and Biomedical Engineering, Universitat de Barcelona (UB), Barcelona, Spain; [2]Institute of Nanoscience and Nanotechnology (IN2UB), Universitat de Barcelona (UB), Barcelona, Spain; [3]CNM, Bellaterra, Spain; [4]TUW, Wien, Austria.

Gallium oxide (Ga_2O_3) is a wide band gap semiconductor material that has been widely studied during the last three decades in the form of thin films for its high-temperature sensing properties towards oxygen and reducing gases. Its optical and sensing properties have been largely studied and several improvements for its use as gas sensor have been achieved introducing different modifications. These changes, that include surface functionalization, material doping or nanowire (NW) morphology, allow working at low temperatures where the sensing mechanisms are supposed to be deactivated. The high surface-to-volume ratio attributed to nanowire morphology decreases the power consumption of the devices, while allowing to sense at lower temperatures than thin films. In our study, devices containing a single Ga_2O_3 NW are studied as humidity sensors, working at room temperature. β-Ga_2O_3 nanowires were fabricated via a metal-assisted vapor-liquid-solid process using a carbothermal reduction and the synthetized nanowires were structurally and optically characterized using X-ray diffraction, scanning and transmission electron microscopy and related techniques as well as photoluminescence and X-ray photoelectron spectroscopy. Measurements revealed a crystalline material, different photoluminescence emission peaks in the visible range, and a transition band gap of 4.2 eV that suggests the presence of a high density of intraband states.
Using Focused Electron Beam Induced Deposition techniques, nanowires were individually contacted for their use as gas sensors. The fabricated devices have been tested, from room temperature up to 200 C, in environments with different concentrations of relevant gases for air quality monitoring, such as nitrogen dioxide and carbon monoxide, as well as oxygen and water vapor,. Fast, stable and reproducible response was measured towards water vapor at room temperature (25 C) using power consumptions between 0.25 and 250 nW. Tests under nitrogen ambient revealed that, at room temperature, the pre-adsorbtion of oxygen ions at the NW surface is mandatory for the water vapor sensing and that oxygen, even at low concentrations, is rapidly re-adsorbed at the surface of the material in a lapse of one minute. Furthermore, the presence of carbon at the surface of the nanowires, result of the growth process, plays an important role in sensing capabilities and will be discussed.

4:30 PM EP08.03.09
New Perspective of Room-Temperature Gas Sensor Using Ionic Conduction Based SnO_2 Nanorods Young Geun Song[1, 2], Young-Seok Shim[3], Jun Min Suh[4], Ho Won Jang[4], Byeong-Kwon Ju[2] and Chong-Yun Kang[1, 5]; [1]Center for Electronic Materials, Korea Institute of Science and Technology, Seoul, Korea (the Republic of); [2]College of Engineering, Korea University, Seoul, Korea (the Republic of); [3]Korea Advanced Institute of Science and Technology, Daejeon, Korea (the Republic of); [4]Seoul National University, Seoul, Korea (the Republic of); [5]KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul, Korea (the Republic of).

Gas sensors with intelligent systems have become a core part of the complete Internet of Things (IoT) since they offer continuous information on the presence of specific gases in the ambient atmosphere. As a representative gas sensor, semiconducting type has attracted much attention due to their cost effectiveness, simplicity in fabrication, high response and easy integration with electronic circuits. Generally, the semiconducting gas sensors require a high operating temperature of 150–400°C for adsorption and desorption of target molecules. However, high temperature reduces sensor stability and life time due to thermally induced growth of grains, and can lead to risks of ignition when detecting flammable or explosive analytes. Furthermore, it can also affect interconnected electronics and requires high power consumption that is an important parameter for the new generation of battery-loaded wireless sensors, resulting in reluctant practical application. Hence, one of the most important challenge and issue in gas sensor society is to make a high-performance gas sensor that operates at room temperature for high stability and low-power consumption. Over the past decade, there are various approaches to enhance the sensing performance at room-temperature using metal additives or heterojunctions and two-dimensional materials. Despite these extensive efforts, there remain challenging including poor response and incomplete recovery because electronic conduction based sensing mechanism is limited by insufficient reaction energy between the analytical molecule and sensing material at room-temperature. Herein, we suggest a new strategy for a room temperature gas sensor using the ionic conduction based gas sensing mechanism. Glancing angle deposition (GLAD) method was used to fabricate highly porous SnO_2nanorods. The ionic conduction induced by humidity was confirmed using impedance spectroscopy, I-V characteristic and XPS analysis. The relation between the sensing properties and relative humidity was systematically investigated. Our experimental results show that the response of SnO_2 nanorods to 5 ppm NO_2 has a maximum response over 1400 at RH 20%. Also, it is observed that the response rate and recovery rate are accelerated as relative humidity increases. The gas sensing mechanism can be demonstrated based on the principle of the ionic conduction, humidity sensor, and water splitting. We believe that the ionic conduction based SnO_2 nanorods open a new direction for developing the room temperature gas sensor.

4:45 PM EP08.03.10
Doping Dependence of Electrical Characteristics of Zn-O-N Thin-Film Transistors Hiroshi Tsuji, Tatsuya Takei, Mitsuru Nakata, Masashi Miyakawa and Yoshihide Fujisaki; NHK Science & Technology Research Labs, Tokyo, Japan.

Thin-film transistors (TFTs) that utilize oxide semiconductors as channel materials have become a key technology for various applications such as displays, sensors, and memory devices due to their superior characteristics, which include high mobility, low off-current, low processing temperature, and applicability to large-area production. Zn-O-N (ZnON) [1] has recently received attention as a channel material for high-mobility TFTs, especially those employed in demanding applications such as large ultra-high definition organic light-emitting diode displays. ZnON-TFTs exhibit much higher field-effect mobilities (>50 cm^2/Vs) [2] than conventional oxide TFTs. However, ZnON-TFTs have some drawbacks that must be addressed, including a negatively shifted threshold voltage (V_{th}), a large subthreshold swing (SS), and V_{th} instability when stored in air. We have recently reported that Si doping of ZnON is effective for improving the switching characteristics and long-term stability of ZnON-TFTs [3].
In the present work, the effects of impurity doping on the electrical characteristics of ZnON-TFTs are further investigated by co-sputtering of Zn and other elements (Ta, Zr, or In). The results indicate that doping with Ta or Zr, both of which have a high bond-dissociation energy with nitrogen, is effective for overcoming the drawbacks of ZnON-TFTs, as in the case of Si doping [3]. In particular, Ta-doped ZnON-TFTs with an optimal doping level exhibited a high field-effect mobility of 49 cm^2/Vs, improved switching behavior (less negative V_{th} and smaller SS), and better V_{th} stability than non-doped ZnON-TFTs. On the other hand, the use of In doping enhanced the mobility of ZnON-TFTs, and this could be attributed to the electron pathways formed by the broad 5s orbitals of In. In-doped ZnON-TFTs exhibited a high field-effect mobility of up to 59 cm^2/Vs, although a more negative V_{th} was also observed. These results indicate that impurity doping is an effective approach to improving and enhancing the performance of ZnON-TFTs.

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SESSION EP08.04: Oxide Growth
Session Chair: Robert Kaplar
Tuesday Morning, November 27, 2018
Hynes, Level 2, Room 209

8:30 AM *EP08.04.01
Bulk Crystal Growth and Devices Fabrication of β-Ga_2O_3 Xutang Tao; Shandong University, Jinan Shandong, China.

At present, silicon based devices have gradually reached their theoretical limits. Wide-bandgap semiconductors have been considered as the candidates for high-performance electronic devices and deep UV optoelectronic devices.[1] The bandgap of β-Ga_2O_3 is as large as 4.7 eV, as a new type of ultra-wide bandgap semiconductor, it is attracting more and more attention in recent years. β-Ga_2O_3 has the advantages of higher breakdown field, bigger Baliga FOM and shorter UV cutoff edge compared to the traditional wide-bandgap semiconductors including ZnO, SiC and GaN. Furthermore, large size and high quality β-Ga_2O_3 crystals could be grown by Czochralski method or edge-defined film-fed growth (EFG) method such as Si and GaAs.[2] Therefore, β-Ga_2O_3 is a desirable material for high voltage, high power, low loss power devices and deep UV optoelectronic devices, such as: deep UV photodetectors, transparent thin film transistors, light-emitting diodes (LEDs), Schottky diodes, high voltage transistors and high temperature gas sensors.
In recent years, the basic research and commercialization of β-Ga_2O_3 develop quickly. The size of bulk crystals is enlarging, the quality of epitaxial films is improving and the performance of semiconductor devices keep breaking records. However, as a novel semiconductor material, the research of β-Ga_2O_3 is still in the early stage. The crystal quality, basic physical properties, physical properties optimization and devices performance optimization are still need be systematically studied.
In this work, we focus on the crystal growth of high quality β-Ga_2O_3 to meet the requirements of different devices. The crystal growth methods and equipment modification, crystal growth process optimization, electrical properties optimization and crystal wafer processing are systematically studied. Furthermore, high-performance UV detector and Schottky diodes have been obtained based on high quality single crystal wafers.

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9:00 AM EP08.04.02
Epitaxial Lateral Overgrowth of α-Ga_2O_3 on Sapphire Substrates Riena Jinno, Nobuhiro Yoshimura, Kentaro Kaneko and Shizuo Fujita; Kyoto University, Kyoto, Japan.

Ga_2O_3, which is one of the ultra wide-bandgap (UWBG) semiconductors, has attracted attentions as a next-generation material of power devices [1]. Among their six different phases (α, β, γ, δ, ε, and κ), the α-phase is the most suitable for bandgap engineering due to its crystal structure of corundum, although it is the metastable phase. Alloys with α-Al_2O_3 and α-In_2O_3enabled the bandgap engineering from 3.7 to 8.7 eV[2]. However, we must consider dislocations in α-Ga_2O_3 formed due to large lattice mismatch to sapphire substrates. In this study, epitaxial lateral overgrowth (ELO) of α-Ga_2O_3 was conducted on sapphire substrates, aiming at reducing the dislocation density in α-Ga_2O_3.
Stripe-patterned dielectric masks of SiO_2 were formed on sapphire substrates. The both widths of openings and masks were 5 μm. The various orientations of substrates (c-, a-, m- and r-planes) and openings were used. All the growth of α-Ga_2O_3 was conducted on the patterned substrates by using the mist-CVD method. $GaCl_3$ was adopted as a Ga source, which enables the growth rate of α-Ga_2O_3 as high as 7 μm/hour. The growth temperature was changed between 500 and 700 ºC.
α-Ga_2O_3 was selectively grown on the openings at the temperatures higher than 550 ºC, while the deposition on masks was observed at 500 ºC irrespective of the orientation of sapphire substrates and openings.
When α-Ga_2O_3 was grown on c-plane sapphire substrates, the triangular stripes with {10-11} and {10-12} facets were formed for <11-20> openings, while the rectangular cross section with a (0001) top facet and {11-20} sidewalls was observed for <10-10> stripes. Although the shapes of the features depended on the orientations of substrates and openings, all the facets were formed by {10-11}, {10-12}, {11-20} and (0001), which are consistent with stacking of oxygen and gallium layers. These planes were considered to be stable under the oxygen rich growth condition by the mist-CVD method. The growth of α-Ga_2O_3 on a-plane sapphires with <10-10> stripes showed the largest ratio of the lateral and vertical growth rates, that is, 0.87. Under this condition, the coalescence of two adjacent wings was achieved. TEM observations were conducted to discuss dislocation structure in the α-Ga_2O_3. The cross sectional TEM images revealed that the dislocation density in the α-Ga_2O_3 was successfully reduced, while the dislocations on the openings were propagated without bending.
From these results, the ELO technique is useful to reduce the dislocation density in α-Ga_2O_3. We need to investigate the growth conditions with bending dislocations on openings to decrease the dislocations on openings effectively.
Part of this work was supported by the New Energy and Industrial Technology Development Organization (NEDO).
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9:15 AM EP08.04.03
Low Pressure CVD Growth of N-Type Ga_2O_3 Thin Films Using Solid Ge Source Praneeth Ranga, Berardi Sensale-Rodriguez, Michael Scarpulla and Sriram Krishnamoorthy; Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah, United States.

We report on growth studies and germanium doping of heteroepitaxial and homoepitaxial beta- Gallium Oxide using low pressure chemical vapor deposition technique. Gallium oxide has attracted a lot of attention because of its potential applications in high power devices. The main advantage of Ga_2O_3 over other wide band gap materials is the availability of a high quality commercial substrates and shallow n-type dopants. A variety of growth techniques exist for growth of Ga_2O_3 thin films including MBE, MOCVD, HVPE etc. Low pressure CVD [1] is a simple, low-cost technique to grow high-quality Gallium Oxide with sufficiently high growth rates and low impurity concentration, as the precursors are ultrapure Gallium, oxygen gas and Argon carrier gas.
To calibrate the growth rates and understand the growth regimes, we characterized gallium oxide thin films grown on sapphire substrates as a function of

growth temperature, oxygen flow rate and Argon flow rate. The nominal growth rate (characterized using cross sectional SEM) varies from 2.5µm/hr to 3.5 µm/hr for temperature between 850 C – 950 C, for chamber pressure of 1.5 Torr. At low oxygen concentrations, the growth rate doesn't show significant variation with oxygen flow rate indicating a mass transport limited growth, at the substrate temperature of 935 C. With flow rates higher than 6 sccm (Ar flow rate of 140 sccm), gallium oxide power formation was observed which resulted in much thinner films. Ga_2O_3 films were grown on both c-plane and vicinal sapphire substrates, thin films on vicinal sapphire were much smoother than c-plane wafers. Also, the roughness of these films dropped with increasing oxygen flow rate. Using a two-step growth technique, surface roughness was reduced to as low as 10 nm for a 10 micron thick LPCVD grown film. Using CV characterization on undoped films grown on Sn-doped n-type bulk substrates, background carrier concentration as low as 1e15 cm^{-3} was obtained. Solid Ge source was used to explore n-type doping. Using transfer length method (TLM) structures fabricated using annealed Ti (50 nm)/ Au(100 nm)/ Ni(100 nm) metal stack, resistivity ranging from 0.1 to 7.5 ohm-cm was obtained. Temperature dependent hall mobility and carrier concentration, activation energy for Ge dopants in Ga2O3 will be presented. These results indicate the promise for controlled high quality growth of Ga2O3 with high growth rates for high performance power electronics.
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9:30 AM EP08.04.04
High-Bias-Stability in Atomic-Layer-Deposition Al_2O_3 by Post-Deposition-Anneal on Wide- and Ultra-Wide-Bandgap Semiconductors Kiyotaka Horikawa[1], Atsushi Hiraiwa[2], Satoshi Okubo[1], Taisuke Kageura[1] and Hiroshi Kawarada[1]; [1]Waseda University, Tokyo, Japan; [2]Nagoya University, Nagoya, Japan.

The metal-insulator- Wide- and ultra-wide-bandgap semiconductor field-effect transistors (MISFETs) are expected to realize good characteristic in terms of high breakdown voltage and low-loss features. However,it was difficult to form a thermally SiO_2 film as a gate insulating or passivation film on Wide- and ultra-wide-bandgap semiconductors. Various insulators have been investigated using atomic layer deposition (ALD), which forms films with unparalleled uniformity and reproducibility. Among those films, ALD-Al_2O_3 is an attractive candidate, having a wide bandgap of 7eV [1], a high dielectric constant of 9 [2], etc. A major challenge for the Al_2O_3 in practical applications is Al_2O_3-related bias instability (BI) needs to be reduced. The purpose of this study is to achieve this by performing high-temperature annealing after ALD-Al_2O_3.
Measurement of the bias stability is observed by shifting the flat band voltage before and after the constant-voltage. The flat-band voltage shift was estimated by alternately repeating capacitance−voltage (*C-V*) measurement and constant-voltage stressing of the MIS capacitors. The flat-band voltage shift of stressed Al_2O_3 MIS capacitors is approximately a Kohlrausch-type complementary extended exponential function of stress time [3], thereby enabling to estimate the maximum flat-band voltage shift ($\Delta V_{fb,max}$) based on a finite-time data set. In this way, we compared the$\Delta V_{fb,max}$ of post-deposition-anneal (PDA) temperature at 973K. This comparison was made for different substrates: Si, GaN and Ga_2O_3.
The Al_2O_3 films on Si and GaN can suppress the $\Delta V_{fb,max}$ by PDA at 973K better than the $\Delta V_{fb,max}$ of as-deposited Al_2O_3 on Si and GaN. These observations indicate that PDA at 973K caused a decrease the defects in the Al_2O_3 film and at the Al_2O_3/substrate-interface.Therefore, this Al_2O_3 is the most promising insulator for high-reliability gate insulation and passivation. In the Ga_2O_3 substrate, however, the $\Delta V_{fb,max}$ increases by PDA at 973K. We will investigate the optimum PDA condition and announce it on the day.
This research is supported by the "Program for research and development of next-generation semiconductor to realize energy-saving society" of the Ministry of Education, Culture, Sports, Science and Technology, Japan.
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9:45 AM BREAK

10:15 AM *EP08.04.05
Molecular Beam Epitaxy of β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$ Elaheh Ahmadi[2], Onur Koksaldi[1], Feng Wu[1], Umesh Mishra[1] and James S. Speck[1]; [1]University of California, Santa Barbara, Santa Barbara, California, United States; [2]EECS, University of Michigan, Ann Arbor, Michigan, United States.

β-Ga_2O_3 has attracted a lot of interest for high power electronic applications [1]. Although the calculated electron mobility in Ga_2O_3 is much lower than that in GaN (300 cm^2/vs vs 1200 cm^2/vs), it has a four times larger Baliga figure of merit (FOM) (3400)[1] compared to GaN, due to its very large bandgap (4.8 eV). Moreover, high quality single crystal β-Ga_2O_3 can be grown economically using melt growth techniques such as edge-defined film-fed growth[2], the floating zone techniques[3] or Czochralski (Cz).[4]
Using plasma-assisted molecular beam epitaxy (PAMBE), we have demonstrated successful growth of β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures with β-$(Al_xGa_{1-x})_2O_3$ films having Al content up to 18% [5], [6]. We also studied Schottky diodes fabricated on these structures using Ni as the Schottky contact metal, and measured the barrier height, and the dependence of ideality factor on temperature and Al content [7].
We have also successfully achieved a wide range of electron concentration in β-Ga_2O_3 films using Sn [8] as the dopant. In addition, we have investigated Ge as n-type dopant in β-Ga_2O_3 (010) films, and obtained a wide range of electron concentration(1×10^{17} cm^{-3} - 1×10^{20} cm^{-3})[8]. Mobility of 97 cm^2/Vs was achieved for a charge density of 1.6×10^{18} cm^{-3} using Ge as dopant. This mobility is two times higher than the mobility achieved for a similar charge density using Sn.
Using Ge as the intentional donor, we recently demonstrated modulation doping in β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructures. The formation of 2DEG was confirmed by capacitance-voltage measurements. Modulation doping field effect transistors were fabricated. A maximum current density of 20 mA/mm, with a pinch of voltage of -6V was achieved on the sample with a 2DEG sheet charge density of 1.2×10^{13} cm^{-2}.[9]
In this talk, I will discuss the above-mentioned progress in detail.

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10:45 AM EP08.04.06

High-Quality β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ (010) and Si-Doped β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ (010) Heterostructures Grown by Pulsed Laser Epitaxy Shanee Pacley, Shin Mou, Adam Neal, Kurt Eyink, Krishnamurthy Mahalingam, Lawrence Grazulius, Eric Heller, Brandon M. Howe, Kelson Chabak and Gregg Jessen; Air Force Research Laboratory, Wright-Patterson AFB, Ohio, United States.

Here, we present the results of a fundamental growth investigation into the effects of Al-alloying and delta doping using Si on the structural and electronic properties of β-$(Al_xGa_{1-x})_2O_3$ heterostructures grown on semi-insulating Fe-doped β-Ga_2O_3 (010) single crystals. High quality β-$(Al_xGa_{1-x})_2O_3$ and Si-doped β-$(Al_xGa_{1-x})_2O_3$ epitaxial layers were grown using ultra-high vacuum pulsed laser epitaxy at 500 °C, using a KrF excimer laser (λ=248nm) operating at 4 Hz and a fluence of ~3 J/cm^2. Targets with an Al content ranging from x = 0.175 - 0.5 were used for undoped layers of β-$(Al_xGa_{1-x})_2O_3$, while targets with an Al content of x = .175, .225 and a Si content of 0.1% were used for the doped heterostructures. The Al content was varied to increase the bandgap, and Si was used in the heterobarrier of β-$(Al_xGa_{1-x})_2O_3$ for modulation doped field-effect transistors. High-resolution X-ray diffraction (HRXRD) and high-resolution transmission electron microscopy (HRTEM) confirm both β-$(Al_xGa_{1-x})_2O_3$ and Si doped β-$(Al_xGa_{1-x})_2O_3$ films. Both HRXRD and HRTEM showed we were able to obtain high quality epitaxial films of β-$(Al_xGa_{1-x})_2O_3$ up to x = .225, which was confirmed by X-ray photoelectron spectroscopy (XPS). However, HRTEM suggests we were able to obtain β-$(Al_xGa_{1-x})_2O_3$ up to 50%, but the stability of this phase is still under investigation. As a result of this research, we demonstrate that pulsed laser deposition can be used to grow both β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ and Si-doped β-$(Al_xGa_{1-x})_2O_3/Ga_2O_3$ heterostructures for wide bandgap electronic devices and specifically, modulation doped transistors. Finally, Hall transport and capacitance-voltage will be used to characterize the heterojunction electrical properties, and XPS will be used to correlate Al content with band offset.

11:00 AM EP08.04.07
TEM-EELS Analysis of Ga_2O_3 /SiO_2 and Ga_2O_3 /Al_2O_3 Interface Structures with Electron Beam Induced Crystallization of Al_2O_3 Gate Layer Christopher Klingshirn[1], Asanka Jayawardena[2], Sarit Dhar[2], Tsvetanka Zheleva[3], Aivars Lelis[3] and Lourdes G. Salamanca-Riba[1]; [1]Materials Science and Engineering, University of Maryland, College Park, Maryland, United States; [2]Physics, Auburn University, Auburn, Alabama, United States; [3]U.S. Army Research Laboratory, Adelphi, Maryland, United States.

The intrinsic structural and electronic properties of Ga_2O_3 suggest that it may ultimately outperform existing wide-gap semiconductors such as SiC for certain metal oxide semiconductor (MOS) device applications, especially at very high power. However, as with SiC, interfacial defects at the Ga_2O_3 / gate oxide interface adversely affects the performance of Ga_2O_3-based MOS devices. The various choices of gate oxide material for Ga_2O_3 -based devices, such as SiO_2 and Al_2O_3, present their own trade-offs in terms of electrical properties (bandgap and breakdown strength) and interface abruptness and stability. Previous work on SiC has shown that a narrower transition layer at the SiC/ SiO_2 interface correlates to decreased interface trap density and enhanced channel mobility.

In this work, we discuss chemical and structural features of interfaces between Ga_2O_3 and SiO_2 and Al_2O_3 investigated using high resolution transmission electron microscopy (HRTEM) and high angle annular dark field scanning TEM (HAADF-STEM) combined with electron energy loss spectroscopy spectrum imaging (EELS SI). STEM and EELS measurements allow identification of the width, composition, and bonding characteristics of the interfacial region. Hyperspectral decomposition of EELS signals using machine learning techniques reveal components corresponding to Ga, O, and Si or Al. Gate dielectric deposition and post-deposition annealing (PDA) conditions are found to affect interface quality, with higher temperature processing correlated with interfacial roughness. The Ga_2O_3 / Al_2O_3 interface is not fully abrupt and contains an interfacial region likely corresponding to interdiffusion between Ga and Al. Additionally, rapid crystallization of the Al_2O_3 gate oxide layers, outward from the interface, was observed during TEM imaging despite remaining at a lower temperature than during the gate deposition or PDA processes. Contributions of thermal gradient, strain and radiolysis to this beam-induced crystallization effect will be presented.

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11:15 AM EP08.04.08
Scanning Transmission Electron Microscopy of Gallium Oxide Materials and Interfaces Jared M. Johnson, Yuewei Zhang, Md Rezaul Karim, Hongping Zhao, Siddharth Rajan and Jinwoo Hwang; Ohio State University, Columbus, Ohio, United States.

We perform a microscopic investigation of ultra-wide bandgap (UWBG) *β*-Ga_2O_3 materials and interfaces using atomic resolution scanning transmission electron microscopy (STEM). Our goal is to establish fundamental understanding on the atomic to nanoscale structure and defects that directly affect the basic materials properties and device performance of *β*-Ga_2O_3, which is essential to advance *β*-Ga_2O_3 to many technologically important UWBG applications. Here, we present the details of our STEM investigation and the experimental results from various *β*-Ga_2O_3 materials and heterostructures. First, we will present the unique technical challenges in the STEM characterization of *β*-Ga_2O_3 due to its high structural anisotropy and TEM sample preparation. Second, we will show the detailed structure, formation, and dynamics of extended defects that can directly influence the properties of various homo- and hetero- *β*-Ga_2O_3 interfaces. Finally, we will present our ongoing development of the new STEM imaging mode that uses the electron channeling effect to image individual point defects (both intrinsic and extrinsic) in *β*-Ga_2O_3. The imaging mode can utilize the new-generation pixelated fast STEM detector, which can capture the channeling signals at a narrowly confined scattering angle and determine the position and structure of point defects with high precision.

SESSION EP08.05: Oxide Physics
Session Chair: Rachael Myers-Ward
Tuesday Afternoon, November 27, 2018
Hynes, Level 2, Room 209

1:45 PM *EP08.05.01
Topics in the *Ab Initio* Theory of Ga_2O_3, Mainly the ε Phase Barbara Maccioni[1], Roberta Farris[1], Paola Alippi[2] and Vincenzo Fiorentini[1]; [1]University di Cagliari, Monserrato, Italy; [2]CNR-ISM, Rome, Italy.

This presentation is about ab initio calculations in the area of Ga_2O_3 and thereabouts. I will first discuss the anisotropy of absorption in the β phase of Ga_2O_3, and a revised mixing phase diagram of InGaO phases including strain. I will then concentrate on the newly-synthesised ε (epsilon) phase of Ga_2O_3, in particular in relation to its polarization properties (is this a pyro- or a ferro-electric ?), electronic structure (first ARPES spectra, Seebeck and Peltier cofficients), and phonons (dispersion, thermal conductivity, thermoelectric ZT, and core lineshapes).

2:15 PM EP08.05.02
Characterizing the Influence of Impurities and Dopants on the Electrical Properties of Ga_2O_3 Through Hybrid Functional Calculations Joel B. Varley; Lawrence Livermore National Laboratory, Livermore, California, United States.

Gallium oxide has emerged as a promising candidate for next-generation power electronics due to a number of favorable properties such as its large band gap, controllable conductivity and the availability of large single-crystal substrates grown from the melt. Despite the rapid surge of interest in this material, there are still a number of outstanding questions as to how various defects, i.e. native point defects and extrinsic impurities, influence the properties of this material. In this talk we use hybrid functional calculations to elucidate the role of common impurities that have been identified in Ga_2O_3 single crystals and epitaxial films. Particularly we discuss the role of Fe and Ir impurities, which we find to be highly soluble in Ga_2O_3 and both electrically and optically active defects depending on the conditions. Our results identify that Fe impurities act as a highly soluble deep acceptors that are commonly observed in Ga_2O_3 bulk samples, while Ir is a deep donor that can degrade optical performance in insulating samples. We discuss our results in the context of recent experimental evidence of properties correlated with the presence of these impurities.

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2:30 PM EP08.05.03
Dynamically Modeled Current Conduction in Atomic-Layer-Deposited Al_2O_3 on Wide- and Ultra-Wide-Bandgap Semiconductors Atsushi Hiraiwa[2, 1], Kiyotaka Horikawa[2], Satoshi Okubo[2] and Hiroshi Kawarada[2]; [1]Tokyo Branch, Nagoya University, Tokyo, Japan; [2]Waseda University, Tokyo, Japan.

Wide- and ultra-wide-bandgap semiconductors are promising power-device materials due to high blocking capability. The wide bandgap, however, poses a serious challenge of gate insulation and surface passivation, because the insulator barrier against carrier emission from the semiconductors is inevitably small requiring wide-bandgap insulators. Although having the widest bandgap and well established in Si industry, thermal SiO_2 is not amenable here. Therefore, atomic-layer-deposited (ALD) Al_2O_3 is the most promising insulator owing to wide bandgap (7 eV), relatively high dielectric constant (9), and good uniformity/reproducibility specific to ALD [1]. To promote the practical application of this Al_2O_3, Al_2O_3-related bias instability (BI) needs to be reduced. This study aims to achieve this through investigating the current conduction process in ALD Al_2O_3.
The current conduction in Al_2O_3 follows the space-charge-controlled field emission (SCC-FE) process [2], which, however, is hitherto only suitable for low-field analysis, imposing a limitation on its BI analysis. To solve this problem, the charged state of Al_2O_3 is assumed to dynamically change with bias voltage and is investigated by alternately measuring current-voltage (*I*-*V*) and capacitance-voltage (*C*-*V*) characteristics of Al_2O_3 metal-insulator-semiconductor capacitors, with the stop voltage of the *I*–*V* measurements increasing successively. The Al_2O_3 charged states in the *I*-*V* measurements, except for the first one, remain unchanged until the stop voltage and, therefore, the barrier height is accurately extracted based on the static SCC-FE process. Then, the sheet of Al_2O_3 charge is estimated as a function of bias voltage and, using the flat-band voltages obtained from the *C*-*V* characteristics, the sheet of charge at the Al_2O_3/substrate interface is given as a function of bias voltage. In this way, we compared the charged states of four kinds of Al_2O_3 deposited by varying the oxidant (H_2O or O_3) and the temperature (200 or 450 °C). This comparison was made for different substrates: Si, GaN and Ga_2O_3.
The Al_2O_3 films on GaN and Ga_2O_3 have smaller barrier heights than those on Si but allow smaller leakage currents because of less Al_2O_3 positive charge. Despite a large leakage current, high-temperature H_2O-grown Al_2O_3 is found to exhibit the highest bias stability, irrespective of the substrates, due to the excellent Al_2O_3/substrate-interface stability against biasing. Therefore, together with the longest dielectric-breakdown lifetime [3], this Al_2O_3 is the most promising insulator for high-reliability gate insulation and passivation.
This research is supported by the “Program for research and development of next-generation semiconductor to realize energy-saving society” of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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2:45 PM EP08.05.04
How the Competition Between Compact and Diffuse States Can Determine Luminescence Properties in Wide Gap Nitrides and Oxides John Buckeridge[1], Zijuan Xie[2], Richard Catlow[1], Aron Walsh[2], David O. Scanlon[1] and Alexey Sokol[1]; [1]University College London, London, United Kingdom; [2]Materials, Imperial College London, London, United Kingdom.

The recombination of photoexcited carriers with electrons or holes bound to point defects results in many experimentally observed optical phenomena in wide gap systems, such as ultra-violet, yellow, green, and red luminescence in GaN. Such processes are usually explained with reference to a particular defect state and often such states are studied systematically via computational techniques. The balance between different defect states, however, which may be metastable but relevant in the time-scale of optical processes, is frequently omitted from such analysis. Here we study how different configurations of electrons and holes, whether bound to defects in well-localised 'compact' states, or in extended 'diffuse' states, can alter the observed luminescence in GaN. For our calculations we employ the hybrid quantum mechanical/molecular mechanical embedded cluster method, which offers advantages over more commonly-applied supercell-based techniques when modelling defects in wide gap materials. The analysis regarding the balance between compact and diffuse states, however, is not dependent on the computational technique we employ. Our results allow us to account for various photoluminescence peaks observed routinely in doped and nominally undoped GaN samples. In particular, we attribute the 3.46 eV and 3.26 eV ultraviolet emission peaks to nitrogen vacancies binding compact and diffuse holes respectively, and describe processes related to gallium vacancy complexes that result in yellow, green and red luminescence. We demonstrate that the competition between these differently bound carrier states is key to understanding the luminescence properties of GaN, a point that also has implications for wide gap oxides. Indeed, we show that taking into account the diffuse states associated with oxygen vacancies in In_2O_3, ZnO and SnO_2 helps explain the different intrinsic conductivity properties of these transparent conductors.

3:00 PM BREAK

3:30 PM *EP08.05.05
Doping and Defects in β-Ga_2O_3 Klaus Irmscher, Andreas Fiedler, Zbigniew Galazka, Günter Wagner, Andreas Popp, Robert Schewski and Martin Albrecht; Leibniz Institute for Crystal Growth, Berlin, Germany.

Monoclinic gallium sesquioxide (β-Ga_2O_3) belongs to the transparent semiconducting oxides. It is distinguished by its large band gap of about 4.7 eV, which is the reason for an optical transparency range extending deep into the ultraviolet and for a high electrical break down field estimated at 8 MV/cm.

Combined with the feasibility of *n*-type doping by Sn, Si, or Ge, β-Ga_2O_3 has great potential as a material for solar-blind photodetection and for power electronics where it might outperform GaN and SiC. To fully exploit the favorable properties of β-Ga_2O_3, single-crystalline material of high structural perfection and controlled electrical characteristics is a prerequisite. In particular, it is necessary to find out how the material can be doped in a controlled manner. Not only the selection of suitable dopants plays a role, but also the formation of compensating defects, including the introduction of unwanted impurities, must be understood.
Here we present a critical review of these doping issues. While *p*-type conduction might be impossible to be achieved due to intrinsic obstacles such as self-trapping of holes and large effective hole mass, intentional *n*-type doping has to cover wider ranges, must be reproducible and thermally stable. In this context, we discuss own and recently reported results of temperature dependent Hall effect measurements, deep level transient spectroscopy, local vibrational mode spectroscopy, electron paramagnetic resonance spectroscopy, and electronic Raman scattering investigations. Silicon, germanium, and tin are revealed to be effective-mass like shallow donors without any peculiarity such as *DX* behaviour. Compensation of shallow donors by gallium vacancies interacting with hydrogen is proposed as an alternative to other compensation mechanisms. In bulk crystals grown from the melt additionally transition metal impurities must be taken into account as compensating acceptors. Furthermore, we show that the deterioration of *n*-type doping in epitaxially grown layers may be due to extended defects rather than due to point defects and can be overcome under proper growth conditions. In cases of point defects, latest theoretical predictions of charge state transition levels and formation energies are compared with experimental values of energy levels and defect concentrations.

4:00 PM EP08.05.06
Impact of Neutron Irradiation on Deep Levels in Ge-Doped (010) β-Ga_2O_3 Layers Grown by Plasma-Assisted Molecular Beam Epitaxy Esmat Farzana[1], Akhil Mauze[2], James S. Speck[2], Aaron R. Arehart[1] and Steven A. Ringel[1]; [1]The Ohio State University, Columbus, Ohio, United States; [2]Materials Department, University of California, Santa Barbara, California, United States.

Beta-phase gallium oxide (β-Ga_2O_3) is attracting great interest for high power devices due to its ~4.8eV bandgap, projected ~8 MV/cm breakdown field, and the availability of native substrates. [1] Moreover, its predicted high radiation hardness makes it a prospective candidate for space applications. [2] However, due to the early stage of development, knowledge about its response in harsh radiation environment is very limited. Here, we investigate the presence and properties of defects introduced by high energy neutron irradiation throughout the bandgap of plasma-assisted molecular beam epitaxy (PAMBE)-grown Ge-doped (010) β-Ga_2O_3 homoepitaxy using deep level transient/optical spectroscopy (DLTS/DLOS). The introduction rates of individual defect states and their possible role in carrier compensation are explored as a function of neutron irradiation fluence.

The epitaxy structure consisted of a ~200 nm of n+ β-Ga_2O_3:Ge layer on Sn-doped substrate to support an Ohmic contact, followed by a lightly-doped, ~600 nm layer of β-Ga_2O_3:Ge (measured doping ~8×10^{16} cm^{-3}) to serve as the test layer, patterned with 8 nm Ni Schottky. The samples were irradiated with fast neutrons (> 0.5 eV) in the Ohio State Nuclear Reactor Laboratory with 2×10^{15} cm^{-2} and 4×10^{15} cm^{-2} fluences. The same diodes were characterized by current-voltage, capacitance-voltage, DLTS and DLOS measurements, before and after irradiation to allow convincing comparisons. The discussion below is focused on the 2×10^{15} cm^{-2} fluence results.

The Schottky diodes showed similar leakage (on order of 10 $\mu A/cm^2$) before and after irradiation. However, a significant carrier reduction of ~1.7×10^{16} cm^{-3} was observed in the irradiated sample, indicating formation of compensating defects by irradiation which were explored by DLTS and DLOS. The pre-irradiation defect spectra consisted of states at E_C - 0.21-0.25 eV, 0.42 eV, 0.60 eV, 0.96 eV, 1.29 eV, 2.00 eV and 4.40 eV. After irradiation, DLTS detected a previously unobserved state at E_C-0.78 eV with ~10^{15} cm^{-3} concentration. Earlier worked reported introduction of a similar state by proton irradiation in β-Ga_2O_3 materials [3]. There was also a noticeable increase of the pre-existing $E_C - 1.29$ eV and $E_C - 2.00$ eV states after irradiation. This implies that they are native, and likely responsible for carrier compensation. Theoretical studies predicted oxygen and gallium vacancies or hydrogenated-gallium complexes near these levels [4, 5]. We are currently investigating irradiation effects at the other fluence to create a comprehensive picture with respect to individual defects, which will be reported at the conference.

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4:15 PM EP08.05.07
Interface Chemistry and Electrical Characteristics of 4H-SiC/SiO_2 After Nitridation in Varying Atmospheres Anna Regoutz[1], Gregor Pobegen[2] and Thomas Aichinger[3]; [1]Imperial College London, London, United Kingdom; [2]Kompetenzzentrum für Automobil- und Industrieelektronik GmbH, Villach, Austria; [3]Infineon Technologies Austria AG, Villach, Austria.

Interfaces govern the behaviour of all electronic devices. Herbert Kroemer coined the famous phrase "*the interface is the device*" in his 2000 Nobel Prize lecture, and we are still applying tremendous effort to understand interfaces in new material generations, with wide-bandgap materials being no exception. If anything, wide bandgap materials are more vulnerable to defect states purely due to their larger bandgap. Understanding gained for the bulk behaviour of semiconductors can often not be extended to the behaviour of materials in structured film stacks were interfaces play a vital role. SiC/SiO_2 is a prototypical wide-bandgap semiconductor/dielectric interface, which represents the challenges faced by many such material systems. A multitude of different defects leads to unacceptably large defect densities exceeding 10^{13} cm^{-2} eV^{-1} in the vicinity of the conduction band of 4H-SiC. The management of interfacial defects still remains a topic of lively discussion and current interest.
The main reasons for the ongoing struggle in understanding and controlling such defects lies in the lack of direct probes for chemical states at interfaces. Interfaces present a special challenge for physical characterisation techniques due to the spatial confinement of defects in a narrow region, the fact that by their nature interfaces are buried beneath a variety of overlayers, and the starkly different behaviour of chemical species at interfaces compared to surfaces and bulk. Advanced X-ray spectroscopy methods can tackle some of these issues, and X-ray Photoelectron Spectroscopy (XPS) in particular can deliver great insight into interfaces as it combines both qualitative and quantitative information on elemental distributions, chemical environments, and valence states.
Here, we present a systematic study of the 4H-SiC/SiO_2 interface in industrially manufactured samples with a particular focus on the effects of nitridation in a variety of atmospheres, to reduce interface defect states. Clear differences are found in both spectroscopy and electrical behaviour after high temperature treatments in N_2, NO, NH_3 and NO+NH_3 atmospheres. Si 2*p*, C 1*s*, O 1*s*, and N 1*s* core level spectra are analysed to give a complete picture of chemical environments present in the oxide and carbide layers as well as at the interface. Several species are found only at the interface providing insight into defect states and how they are compensated by nitridation. Mixed silicon oxycarbides (SiO_xC_y) and oxynitrides (SiO_xN_y) as well as Si-C-N species from reaction of N with dangling C defects on the SiC side of the interface are identified. The findings from XPS are used to explain changes in the electrical behaviour of these device stacks.
Ultimately, the detailed understanding of advanced spectroscopy results in combination with electrical characterisation can be applied to a wide range of

materials, particularly to wide- and ultra-wide-bandgap materials.

4:30 PM EP08.05.08
High-Resolution Observation of Defects at SiO_2/SiC Interfaces by Local Deep Level Transient Spectroscopy Based on Time-Resolved Scanning Nonlinear Dielectric Microscopy Yuji Yamagishi and Yasuo Cho; Tohoku University, Sendai, Japan.

Characterization of SiC/SiO_2 interface is important for the improvement of device performance of silicon carbide metal–oxide–semiconductor field-effect transistors (SiC-MOSFETs).[1] While it is well known that conventional dry oxidation of SiC usually results in a high density of interface states and that post-oxidation annealing in a nitrogen-containing gas can improve the properties of SiC/SiO_2 interface, the mechanism of the nitridation is still poorly understood.
To investigate the density and energy depth of the interface states, deep level transient spectroscopy (DLTS) is a powerful technique.[2] While typical DLTS measurement usually employs a MOS capacitor and consequently is not capable of analyzing the spatial distribution of the interface states, the additional function to visualize the spatial distribution is hopeful to allow obtaining information on the properties of the interface states from another point of view. Based on this idea, we recently developed the measurement system to perform the DLTS measurement locally using a cantilever and visualized the distribution of interface states at nanoscales.[3] The current measurement system is based on time-resolved scanning nonlinear dielectric microscopy (tr-SNDM), which is a capacitance microscopy with a high capacitive sensitivity and an excellent time resolution. In the recent study, we reported that non-uniform contrasts with the scale of several hundreds of nanometres were observed in the map of the density of interface states (D_{it}) of SiO_2/SiC samples.[4] However, the spatial resolution reported in the study was not sufficiently-high compared to the expected sizes of the clusters of the excess atoms at the SiO_2/SiC interfaces.[1] Because the spatial resolution of tr-SNDM is influenced by factors such as the tip radius of the capacitance probe or the oxide thickness of the sample, refining these parameters are essential for visualizing finer structures in the distribution of interface states. In this work, we perform mapping of D_{it} with a higher spatial resolution using a cantilever with a tip radius of 25 nm and employing a SiO_2/SiC sample with an oxide thickness of 10 nm. The spatial resolution of tr-SNDM is also discussed based on the results obtained by TCAD simulation.
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4:45 PM EP08.05.09
Quantum Sensing in 4H-SiC Power Devices Tuan M. Hoang[1], Takeshi Ohshima[2], Makoto Nakajima[1], Kosuke Mizuno[1], Yuta Masuyama[1], Takayuki Iwasaki[1], Digh Hisamoto[1] and Mutsuko Hatano[1]; [1]Tokyo Institute of Technology, Tokyo, Japan; [2]National Institutes for Quantum and Radiological Science and Technology, Chiba, Japan.

The information inside Silicon carbide (SiC) power devices such as temperature or leak current is required for reliable power electronic operations. Sensing using defects in wide bandgap materials has been intensively studied because of its potential for room-temperature quantum technologies [1]. The silicon vacancy (V_{Si}) in SiC has the possibility of detecting the magnetic field and temperature through the optically detected magnetic resonance (ODMR) method [2].
As a first step, we improved the sensitivity of the V_{Si}-based sensors due to the insignificant contrast of the observed ODMR signals in temperature sensing experiments. We exploited V_{Si} in 4H-SiC for measuring the magnetic field at room temperature and evaluated the spin coherence time dependence on the annealing temperature as a first step of improving the sensitivity.
We used a home-built microscope to perform measurements on 4H-SiC samples irradiated with 2 MeV electrons at a fluence of 10^{18} cm^{-2} at room temperature. The 532 nm laser expanded by a beam expander was defocused onto the 4H-SiC sample by an oil objective. The fluorescence was collected through the same oil objective before transmitted through a beam splitter and a 900 nm long pass filter to a detector. In ODMR experiments the radio-frequency signal was generated by a signal generator and subsequently amplified by an amplifier. In annealing experiments, the 4H-SiC samples were thermally annealed in several steps from 200°C to 800°C.
In the magnetic sensing experiments, without applying the magnetic field, we observed the maximum intensity of the ODMR line around 70 MHz, corresponding to the zero-field splitting of V_{Si} in the ground state [1]. When an external magnetic field is applied parallel to the c-axis of 4H-SiC crystal, the ODMR line is split by the Zeeman effect. Additionally, the ODMR linewidth and contrast are strongly dependent on the RF power. We also observed that the revivals resulted from the spin-spin interactions between the vacancy and nearby nuclei appear in the echo modulation of V_{Si} by using the Hahn-echo sequence. In annealing experiments, increasing the annealing temperature resulted in the diminishing of the revivals and an increase of more than 2 times (from 1.6 µs to 3.5 µs) in the spin coherence time T_2 of V_{Si} corresponding to non-annealing and the annealing temperature of 800°C. We confirmed that the ODMR of V_{Si} can be improved by an appropriate annealing process.
In conclusion, we proved that the magnetic field dependent ODMR of V_{Si} under 532 nm excitation agrees well with theoretical calculations. Associating with the temperature sensitive property of V_{Si} in 4H-SiC, the results presented in this report will open up an opportunity to realize highly sensitive temperature sensors.
Acknowledgments: This study was partially supported by JSP CREST Grant (No. JPMJCR1333).
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SESSION EP08.06/EP09.08: Joint Session I: Diamond Devices
Session Chairs: Etienne Gheeraert and Mark Hollis
Wednesday Morning, November 28, 2018
Hynes, Level 2, Room 207

8:30 AM *EP08.06.01/EP09.08.01
Recent Progresses in Deep Depletion Diamond MOSFET Cedric Masante[1], Toan Thanh Pham[1, 2], Nicolas Rouger[4], Gauthier Chicot[1, 2], Florin Udrea[3], David Eon[1], Etienne Gheeraert[1], Daniel Araujo[5] and Julien Pernot[1]; [1]University Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France; [2]Univ. Grenoble Alpes, CNRS, Grenoble INP G2Elab, Grenoble, France, Grenoble, France; [3]Department of Engineering, The University of Cambridge, Cambridge, United Kingdom; [4]Université de Toulouse; LAPLACE; CNRS; INPT; UPS, Toulouse, France; [5]Dpto. Ciencia de los Materiales, Universidad de Cadiz, Cadiz, Spain.

Diamond is a fascinating semiconductor with exceptional physical properties such as a wide band gap, a high breakdown electric field (10 MV/cm), an

outstanding thermal conductivity (20 W/cm/K) and high carrier mobilities. These exceptional properties, or more precisely, the combination of some of these properties makes diamond an ideal semiconductor for high power and/or high frequency electronics which should surpass other materials like silicon, silicon carbide or gallium nitride. Numerous diamond field effect transistors are under investigation: H-terminated accumulation FET, O-terminated inversion channel FET, metal-semiconductor FET and junction FET.
In this work, we propose a new transistor concept in order to exploit the full potentialities of diamond material[1]. The deep depletion concept will be described and proposed for MOSFET devices. A proof of concept of deep depletion diamond MOSFETs will be presented[1-3]. Finally, the recent progresses achieved in terms of device performances will be discussed.

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9:00 AM *EP08.06.02/EP09.08.02

High Frequency, High Voltage and Vertical Diamond MOSFETs Using Two-Dimensional Hole Gas Hiroshi Kawarada[1], Nobutaka Oi[1], Shoichiro Imanishi[1], Masayuki Iwataki[1] and Atsushi Hiraiwa[2]; [1]Waseda University, Tokyo, Japan.

Low SBH for 2DHG:
Diamond has superior properties as p-type conducting compared with other wide bandgap semiconductors. Among them P-type Schottky barrier height (SBH) is very low (< 0.1eV) on the hydrogen terminated (C-H) diamond surface in high work-function metal such as Au [1]. This property enables hole injection smoothly from metal to diamond subsurface when surface electron potential is high (surface band bends upward). It is realized by negatively charged surface or negative surface voltage bias. Then, 2 dimensional hole gas (2DHG) is produced by hole injection from metal. It is desirable for high speed FET operation [1].
High Frequency FET:
The first GHz operation in diamond [2] has been realized by metal semiconductor (MES) FET, where Au is used for source and drain contacts and Al for Schottky gate on the same C-H diamond surface. Al shows the SBH of 0.6 eV, because Al work function is lower than Au by 0.7 eV. The work function dependence of SBH indicates that C-H diamond surface has low surface states density, necessary for MOSFET. In addition to MESFET [3], MOSFETs [4,5] exhibited GHz operation up to 70 GHz [6] in f_T (cutoff frequency) and >100GHz [3] in f_{max}. The power density is now 3.8 Wmm^{-1} [7] at 1GHz obtained by high bias voltage (~50V). Its electric field is above $2x10^5$ Vcm^{-1}, where the hole velocity is nearly saturated in an entire FET. The power density is lower than AlGaN/GaN HEMT, but higher voltage operation can enhance it much further.
High Voltage FET:
C-H diamond MOSFETs are uniquely designed for high-voltage (~1000V) and high-temperature (up to 400°C) operation using the high temperature (450°C) ALD Al_2O_3 as gate oxide and passivation of gate-drain (drift) region. The maximum breakdown voltages (V_B) are above 1500 V [8] obtained at long drift region (L_{GD} > 15 um). V_B/L_{GD} is ~1.0 MV/cm, which is equivalent to those of SiC MOSFET and AlGan/GaN HEMT. The drain current density is comparable to SiC, but 3-4 times lower than AlGaN/GaN at similar V_B. Conductivity in drift region must be improved by mobility enhancement.
Vertical FET:
The first vertical diamond MOSFETs have been developed using 2DHG layer on trench structure [9]. Hole conduction at the trench side wall (3-4 um depth) acts as drift region and is electrically connected to p+ substrate (drain). The drain current density of active planar area has reached to 5000 Acm^{-2} [10], which is comparable to those of SiC or GaN MOSFET. Specific on resistance is 5 $m\Omega cm^2$ at present.

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9:30 AM EP08.06.03/EP09.08.03

Integration of V2O5 into H-Diamond MOSFETs for Enhanced Device Performance David Macdonald[1], Kevin Crawford[1], Alexandre Tallaire[2], Riadh Issaoui[2] and David A. Moran[1]; [1]University of Glasgow, Glasgow, United Kingdom; [2]LSPM-CNRS, Université Paris, Paris, France.

As a semiconductor, diamond possesses many unique properties that make it attractive for the production of high performance devices such as robust, high power RF FETs. Such properties include a large bandgap of 5.5 eV, high thermal conductivity of up to 20 Wcm^-1K^-1 and high carrier saturation velocity of 2 × 10^7 cm^-1 for electrons and 0.8 × 10^7 cm^-1 for holes. Development of electronic diamond devices has been largely limited however by the immaturity of existing doping processes used to introduce mobile charge into its naturally insulating crystal structure. ‘Transfer doping’ of hydrogen-terminated diamond (H-diamond) presents a potential solution to this challenge which has allowed for the production of high performance FETs. Stability issues associated with traditional transfer doping, which relies on the presence of atmospheric species on the diamond surface, has limited the maturity of device technologies that exploit these doping techniques. More recently, various work has demonstrated the potential to improve the stability and efficiency of transfer doping in diamond utilising electron acceptor oxide materials on the diamond surface.
In this work, we apply the electron oxide acceptor material V2O5 into H-diamond FET technology and demonstrate substantial performance improvement in comparison with traditional atmosphere-exposed devices. These performance figures include the highest reported drain current and transconductance for a H-diamond FET to incorporate an electron acceptor oxide such as V2O5. Furthermore, a 400C anneal stage utilised in the process flow for devices (as required to ensure stability of the V2O5 layer) is also found to reduce the ohmic contact resistance and increase the carrier concentration beneath the gate of the devices, further improving device performance.
The potential mechanisms for this performance enhancement and future implementation of these techniques to enhance the performance and robust operation of H-diamond FET technology will be discussed.

9:45 AM EP08.06.04/EP09.08.04

Diamond Surface Conduction FET RF Performance Correlated to Internal Charge Carrier Characteristics Pankaj Shah, James Weil, Khamsouk Kingkeo, Kevin Crawford, Mahesh R. Neupane, Anthony G. Birdwell, Edward Viveiros and Tony Ivanov; Army Research Laboratory, Adelphi, Maryland, United States.

Higher power, higher frequency RF transistors than those possible using the III-nitride semiconductors are desired for large data (high bandwidth) information transmission, highly advanced radar detection, and more efficient communication. We are developing hydrogenated diamond surface conduction field effect transistors (FETs) for use in these next generation RF systems accessing diamond's wide bandgap (5.47 eV) extremely high thermal conductivity (> 20 W/cm) and impressive breakdown field (10 MV/cm). Our latest unpassivated, atmospheric transfer doped FETs have maintained high current density performance (up to 700 mA/mm at 10 V) with occasional testing over an 8 month period indicating very limited degradation in an indoor environment and the ability to maintain DC operation powers of ≈ 7 W/mm.

Optimizing RF surface channel FETs is most effectively done using device physics information obtained directly from the same device that the RF measurements are made on. This best connects the influence of material, fabrication steps and structure on performance. In this regard, we obtained the hole velocity in the FET channel using a delay time measurement and this is we believe the first ever discussion of velocity obtained in this way applied directly on a diamond RF FET. This will be related to carrier density and effective mobility obtained from RF FETs. RF small signal characteristics (current and power gain cutoff frequencies (Ft, Fmax)) and large signal characteristics (power, gain and efficiency) from load pull measurements will also be discussed for the same devices.

Transit time values obtained from a delay time measurement indicates these FETs have a hole velocity in the channel ≈ 5×10^6 cm/s and drain depletion region delay ≈ 2.5 ps. On wafer RF measurements for intrinsic current gain cutoff frequency indicate an opposite trend with gate length of Ft = 70 GHz (Lg = 50 nm), 49 GHz, (100 nm), and 10 GHz, (500 nm) when Vds = 10V. With improved contact and access region resistances we expect the frequency bandwidth to increase. Load pull measurements indicate RF output power densities increased 30% as the drain and gate bias voltage pulse spacing increased (a duty cycle reduction from 5% to 0.5%) suggesting that RF output power is affected by heating of the transfer dopant in unpassivated FETs. These measurements also demonstrate a peak RF output power density of 0.66 W/mm at 2 GHz.

We have also observed that the Schottky barrier heights for the atmospheric transfer doped devices with good gate control are over 0.38 eV and range up to 0.63 eV, however, the ideality factor is quite high (between 1.5 and 7.3). This may be an indication of the roughness of the surface and challenge contacting a hydrogenated region that the gate finger metal sits on. As the gate length reduced from 3 micron down to 50 nm the FET current density increased six fold, and knee voltage reduced uniformly by 50%.

10:00 AM BREAK

10:30 AM *EP08.06.05/EP09.08.05
Diamond Power Electronic Devices—Schottky Diodes Timothy A. Grotjohn[1, 2], John Albrecht[1], Michael Becker[2], Ayan Bhattacharya[1], Ramon Diaz[1], Aaron Hardy[2], Timothy Hogan[1], Matthias Muehle[2], Robert Rechenberg[2], Thomas Schuelke[1, 2] and Steven Zajac[1]; [1]Michigan State University, East Lansing, Michigan, United States; [2]Fraunhofer USA Center for Coatings and Diamond Technologies, East Lansing, Michigan, United States.

This paper will overview the status and prospects of diamond for power electronics applications. Both the potential and the current/future challenges will be discussed. The particular example of diamond Schottky diodes for power electronics will be explored in more detail. The authors have worked on diamond diodes by developing high quality substrates, low-defect doped epitaxial layers and diamond microfabrication processes. Two diode structures studied are the vertical Schottky diode and the pseudo-vertical diode. The vertical diode requires a thick (>250 µm) p^+ doped substrate and the pseudo-vertical diode requires an undoped substrate with low dislocation defect density. Part of this effort is directed at providing substrates of p^+ diamond to thicknesses >250 µm and providing p^+ epi-layers for the pseudo-vertical devices. Improvement of the p^+ epi-layer deposition was studied by reducing the particles landing on the surface during deposition and increasing the time the diamond CVD reactor can run before soot formed that required the run be terminated. The soot formation is a known problem for diamond deposition using microwave plasma-assisted CVD due to the high boron level added to the deposition process. The boron doped p^- layer is the region that provides the breakdown voltage of the Schottky diode. The p^- region needs to be deposited/grown with low dislocation defect density, controlled doping, controlled thickness and low compensation from impurities like nitrogen. The p^- layer was grown at 800C with a feedgas of hydrogen, methane (4%), oxygen and a small amount of diborane as needed for the desired p-type doping concentration. The addition of the oxygen helps to improve the quality of the epi-layer and reduce passivation of the boron doping by hydrogen. Schottky diodes fabricated showed breakdown voltages exceeding 1800 V. The 1800 V diodes showed forward current densities of up to 300 A/cm^2. Other diamond diode work will also be overviewed.

11:00 AM *EP08.06.06/EP09.08.06
Recent Progress in Diamond Field-Effect Transistor Technologies Makoto Kasu; Saga University, Saga, Japan.

A diamond semiconductor with a bandgap of 5.47 eV is expected to be the ultimate power device because of its exceptional physical properties, such as a high breakdown field (>10 MV/cm), high mobility, and highest thermal conductivity [20 W/(cm K)]. We previously reported high radio-frequency (RF) power performance of diamond field-effect transistors with a power-gain cutoff frequency, $f_{MAX,}$ of 120 GHz and an RF output power of 2.1 W/mm at 1 GHz. In this talk, we focus on very recent progress in two basic technologies related to diamond electronics: wafer technology and carrier doping technology.

To overcome the size limitation of diamond crystals, diamond heteroepitaxy technology has progressed rapidly. A 1-inch heteroepitaxial diamond has been demonstrated. In heteroepitaxy, epitaxial overgrowth technology is used to drastically decrease the dislocation density. Furthermore, microneedle technology has been proposed and demonstrated as a method to delaminate heteroepitaxial diamond from its substrate without cracking. [1] In the final process of heteroepitaxy technology, chemical mechanical planarization of the heteroepitaxial diamond surface is important for obtaining a damage-free and smooth surface. The full-width at half-maximum of the (004) plane was as low as 0.03°, and the curvature was 0.29 m, indicating the world's highest quality heteroepitaxial diamond. The size and quality of diamond crystals is improving. We have fabricated diamond field-effect transistors on heteroepitaxial diamond, and the resultant device shows the same drain-current level as conventional homoepitaxial diamond on a HPHT substrate.

Concerning carrier doping technology in diamond, Kubovic and Kasu previously reported NO_2 p-type doping, which they used to fabricate FETs; that is, NO_2, O_3, NO, and SO_2 molecules adsorbed onto H-diamond generated hole carriers and the hole sheet concentration was as high as $\sim1\times10^{14}$ cm^{-2} at room temperature. [2] Shiraishi and Kasu explained this phenomenon as the LUMO/SOMO orbital energies in the inorganic molecules adsorbed onto H-diamond being below the valence-band top of H-diamond, resulting in electron transfer from H-diamond to these molecules. Recently, Geis and Wade at the Massachusetts Institute of Technology investigated the NO_2–H-diamond surface further by surface chemical techniques such as Fourier transform infrared spectroscopy and elucidated the surface reaction and states. Their reports surprisingly agree with our previous findings. Recently, we used synchrotron X-ray photoelectron spectroscopy/X-ray absorption near-edge spectroscopy and capacitance and conductance measurements to determine the energy band diagram and found oxygen-related states and boundary states in the metal-oxide-semiconductor interface.

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11:30 AM EP08.06.07/EP09.08.07
Diamond:H/Transition Metal Oxides Transfer-Doping Efficiency and Transistors Performance Moshe Tordjman[2, 1], Zongyou Yin[3, 2], youngtack Lee[2], Alon Vardi[2], Rafi Kalish[1] and Jesus A. del Alamo[2]; [1]Technion–Israel Institute of Technology, Haifa, Israel; [2]Microsystems Technology Laboratories, Massachusetts Institute of Technology, Boston, Massachusetts, United States; [3]Research School of Chemistry, The Australian National University, Canberra, Australian Capital Territory, Australia.

Transfer doping of hydrogen terminated diamond (Diamond:H) with various molecular-like surface acceptors suffers from low efficiency and temperature instability. In contrast, high electron affinity transition-metal oxides (TMOs) (i.e. MoO_3, WO_3, V_2O_5 and ReO_3), when employed as surface acceptors for transfer doping on Diamond:H, have recently yielded improved p-type sheet conductivity and remarkable thermal stability even with only a few monolayers of coverage[1-4].
Despite these properties, the realization of Diamond:H electronic devices using TMOs remains very challenging[5,6]. This is due to undesirable changes in the physical and electronic characteristics of the TMO caused by the device fabrication process. In particular, stoichiometry reduction, crystalline phase transitions and structural morphology aggregations take place.
In this work, we will discuss how different TMOs' physical parameters affect the electrical properties of the resulting diamond:H/TMO-based transistors, and how these undesirable effects can be minimized. Electrical and surface characterization monitored before and after transistor fabrication reveal TMO oxygen reduction and a change in its oxidation state leading to electrical conductivity degradation. Based on these findings, we propose and demonstrate a way to improve diamond:H/TMO transistor performance and stability.
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11:45 AM EP08.06.08/EP09.08.08
3.8 W/mm Power Density at 1GHz for ALD-Al_2O_3 2DHG Diamond High Frequency MOSFETs Shoichiro Imanishi[1], Nobutaka Oi[1], Satoshi Okubo[1], Kiyotaka Horikawa[1], Taisuke Kageura[1], Atsushi Hiraiwa[1] and Hiroshi Kawarada[1, 2]; [1]Waseda University, Tokyo, Japan; [2]The Kagami Memorial Laboratory for Materials Science and Technology, Waseda University, Tokyo, Japan.

H-terminated diamond with 2 dimensional hole gas (2DHG) provides a promising surface channel for high-power and high-frequency applications due to its excellent properties for FETs. From 2001, mile stones of RF performance of diamond FETs are first GHz operation in MESFETs [1], MISFETs with cutoff frequency (f_T) > 20 GHz [2], high power density > 2.0 W/mm [3], maximum oscillating frequency (f_{max}) > 100 GHz [4] and f_T > 50GHz [5]. Particularly, the power density of diamond FETs (up to 2.2 W/mm) [3, 6] is higher than those of GaAs and LDMOS. However, the operating voltage was as low as 15 ~ 20 V because of low breakdown voltage. Power density would be much more improved by realizing high voltage operation. Recently, we reported high average electric field [7] in MOSFETs with Al_2O_3 deposited as gate insulator [6, 8] and passivation layer [9] by high temperature atomic layer deposition (ALD) [10]. In this work, we fabricated ALD-Al_2O_3 2DHG diamond MOSFETs, whose structure is capable of withstanding high voltage, and evaluated small signal and large signal performance at high voltage operation ($|V_{DS}| \leqq 60$ V). As a result, the highest power density of 3.8 W/mm was obtained in diamond.
We fabricated ALD-Al_2O_3 2DHG diamond MOSFETs with 100 nm Al_2O_3 film on IIa-type polycrystalline diamond substrate with a <110> preferential growth surface. The source-gate length, gate length (L_G) and gate width were fixed to 0.5, 0.5 and 100 μm, respectively and gate-drain length (L_{GD}) was ranged from 1 to 3 μm.
The drain current density (I_{DS}) was −730 mA/mm at V_{GS} = −20 V and V_{DS} = −40 V and the transconductance was 15 mS/mm at V_{GS} = 12 V and V_{DS} = −40 V for L_{GD} = 1 μm. Extrinsic f_T and f_{max}, including parasitic pad capacitances and inductances, were 30 GHz and 27 GHz at V_{GS} = 16 V and V_{DS} = −60 V for L_{GD} = 3 μm. f_T = 30 GHz @ L_G = 0.5 μm corresponds the saturation velocity of $1x10^7$ cm/s. It is the first report that diamond FET reaches its saturation velocity. The large signal performance was evaluated using load pull system. The bias point for A-class operation were V_{GS} = 12 V, V_{DS} = −50 V and I_{DS} = −405 mA/mm, respectively. The power density reached 3.8 W/mm at 1 GHz with associated gain of 11.6 dB and power added efficiently of 23.1 % for L_{GD} = 2 μm. The power density is the highest ever reported for diamond FETs.
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SESSION EP08.07/EP09.09: Joint Session II: Diamond Growth
Session Chairs: Philippe Bergonzo and Travis Wade
Wednesday Afternoon, November 28, 2018
Hynes, Level 2, Room 207

1:30 PM *EP08.07.01/EP09.09.01
Heteroepitaxial Diamond—Scaling of an Ultra-Wide-Bandgap Material to Wafer Dimensions Matthias Schreck[1], Stefan Gsell[2], Martin Fischer[2], Michael Mayr[1] and Björn-Christoph Gallheber[1]; [1]University of Augsburg, Augsburg, Germany; [2]Augsburg Diamond Technology GmbH, Augsburg,

Germany.

In the field of power devices, diamond's intrinsic physical properties suggest that they can facilitate ultimate device performance. Just as for other wide-bandgap materials, the availability of wafer-size diamond substrates with high single crystal quality is an indispensable prerequisite. There are two approaches which start from opposite points: First, homoepitaxial growth on carefully selected rather small single crystals with minimum dislocation densities can be performed in such a way that the available area is increased step by step while the dislocation density is kept low. By a similar approach, 4H-SiC has progressively been scaled over 20 years starting from small Acheson platelets to 6" wafer size [1]. The second alternative is based on heteroepitaxy which starts on large areas but with high dislocation densities (DDs). The challenge here consists in a controlled decrease of the DD by several orders of magnitude while preserving the initial size.
This presentation is focused on heteroepitaxy of diamond on Ir/YSZ/Si(001) which has recently provided the first single-crystal diamond wafer with a diameter > 3.5" and a total weight of 155 carat [2]. All relevant steps for the wafer preparation will be described. First applications of the material will be presented and the potential for further applications will be discussed.
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2:00 PM *EP08.07.02/EP09.09.02
Engineering Doped Single Crystal Diamond Films for Electronic and Quantum Applications Jocelyn Achard[1], Riadh Issaoui[1], Alexandre Tallaire[1, 2], Ovidiu Brinza[1], Vianney Mille[1], Audrey Valentin[1], André Tardieu[1] and Fabien Bénédic[1]; [1]LSPM-CNRS, Villetaneuse, France; [2]IRCP - Ecole Nationale Supérieure de Chimie de Paris, Paris, France.

Diamond is a transparent wide band gap material with outstanding optical and electronic properties that are attracting a lot of attention for the development of the next generation of devices. Indeed single crystal diamond provides an ideal host material to incorporate different types of impurities that can drastically modify its properties. The use of dopants such as boron can for example allow tuning the electrical conductivity of the film up to the metallic conduction which could allow to produce highly boron doped substrates and develop vertical components whose design and architecture for the realization of more complex function is simpler. In addition nitrogen or silicon are some of the elements that can be introduced in the crystal in order to create optically active centres such as the well-known NV (nitrogen-vacancy) and SiV (silicon-vacancy). Both defects exist in different charge states that can be stabilized depending on the doping level of the diamond.
In this presentation, we will focus more specifically on the production aspects of doped monocrystalline diamond films by chemical vapour deposition assisted by microwave plasma with either boron or nitrogen, highlighting all the constraints inherent to the targeted field of application. In the case of boron doping, particular attention will be paid to showing the plasma conditions which it is essential to maintain in order to obtain a sufficiently thick and doped film leading to on state resistances compatible with their use in vertical components. It will be shown in particular the importance of the gas composition to inject high microwave power allowing coupling high material quality with high growth rate. With regard to nitrogen doping, the conditions for optimizing the formation and orientation of NV colour centres will be discussed and the role of temperature, substrate orientation and gas composition will be highlighted.

2:30 PM BREAK

3:30 PM *EP08.07.03/EP09.09.03
Heteroepitaxial Growth of Diamond on 3C-SiC/Si Substrates for Diamond Electronics Mutsuko Hatano and Takayuki Iwasaki; Tokyo Institute of Technology, Tokyo, Japan.

To realize next-generation power devices and highly sensitive quantum sensors, heteroepitaxy of diamond on Si substrates is a key technology from the viewpoint of scalability and Si CMOS hybrid system [1-3]. We utilize 3C-SiC as an intermediate layer between Si substrates and diamond films because it can be directly grown on the Si and the lattice constant and the surface energy of the SiC are close to the diamond.
We would like to introduce the heteroepitaxial growth of diamond on both Si (001) and (111) substrates by original antenna-edge type microwave plasma CVD with in-situ bias current monitoring during bias enhanced nucleation(BEN). We show the properties of the diamond films, and then the potentials for both power devices (Schottky barrier diodes) and quantum sensors.
Concerning the schottky barrier diodes (SBDs) on heteroepitaxial diamond (001) films, the specific on-resistance of 0.2 Ω−cm^2 and high rectification of 10^8 (±5 V) were obtained which are comparable for SBDs on homoepitaxial diamond films.
The sensor devices using nitrogen-vacancy (NV) centers were formed in the heteroepitaxial diamond (111) films. The NV centers could be preferentially aligned of the NV axis to the one direction and be leading to improving the sensitivity was confirmed.
This work was supported in part by JST-CREST Grant No. JPMJCR1333, KAKENHI (17H01262 and 18H01472), and JSPS Bilateral Open Partnership Joint Research Projects.

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4:00 PM *EP08.07.04/EP09.09.04
Thin CVD Diamond Films on AlGaN/GaN HEMT Structures Ken Haenen[1, 2]; [1]Institute for Materials Research (IMO), Hasselt University, Diepenbeek, Belgium; [2]IMOMEC, IMEC vzw, Diepenbeek, Belgium.

Diamond's extreme properties make it a prime candidate for next-gen electronic devices, including high frequency and high power operation. While monolithic diamond devices based on doped monocyrstalline layers, enabling both unipolor as well as well as bipolar design schemes, have great potential, the currenly obtainable substrate size and quality leave several years of scientific and technological development. The fact that diamond has an extremely high thermal conductivity and can be deposited on non-diamond substrates, opens up an intermediate pathway for hybrid power devices that integrate diamond with other wide bandgap materials such as SiC or GaN. The main goal in such cases is to achieve an enhanced reliability of the latter active materials by providing superior cooling minimizing thermal hotspots and withstanding large break down electric fields.

Here, the case of diamond on GaN-based HEMT structures is considered. First, the deposition of thin CVD diamond layers will be discussed, including the surface chemistry governing the nanodiamond particle seeding, the deposition conditions, and the use of different microwave-based CVD techniques, including resonant cavity and linear antenna technology. Cross-sectional TEM and EELS mapping of the stacks are employed to discuss the structural and

morphological properties and to extract possible changes in composition in the underlying Si_3N_4/AlGaN/GaN interfacial layers induced by the substrate temperture during diamond deposition. Finally, the evaluation of the effective thermal conductivity of the thin diamond layers is discussed. The contactless transient thermoreflectance technique, used to study the heat spreading capabilities, shed light on the thermal conductivity and interfacial thermal boundary resistance.

4:30 PM EP08.07.05/EP09.09.05
Gate Oxide Stability in Diamond Power Transistors Loto Oluwasayo[1], Matthieu Florentin[1], Cedric Masante[1], Nazareno Donato[3], Marie-Laure Hicks[4], Alex C. Pakpour-Tabrizi[4], Richard B. Jackman[4], Verena Zuerbig[5], Philippe Godignon[6], David Eon[1], Julien Pernot[1], Florin Udrea[3], Daniel Araujo[7] and Etienne Gheeraert[1, 2]; [1]University of Grenoble-Alpes, Grenoble, France; [2]University of Tsukuba, Tsukuba, Japan; [3]University of Cambridge, Cambridge, United Kingdom; [4]University College London, London, United Kingdom; [5]Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany; [6]Centro National de Microelectronica, Barcelona, Spain; [7]University of Cadix, Cadix, Spain.

Semiconducting diamond is an attractive candidate for the next generation of high voltage and high frequency power devices, thanks to his exceptional properties in terms of wide bandgap, high breakdown field and thermal conductivity. In the literature, several diamond-based field-effect-transistors (FETs) have already revealed good on state performance and high blocking voltage capability (~2kV) in a wide range of operating temperatures. The possibility of generating an inversion regime in diamond metal-oxide-semiconductor FET (MOSFET), and the new Deep Depletion regime (D2MOSFET) specific to wide bandgap semiconductors pave the way for a new generation of power devices. The critical part of the transistor is the gate oxide, with electrical charge traps located within the oxide or at its interface with the semiconductor. These traps can screen the gate potential and shift the threshold voltage, making the devices unusable. The reduction of the trap density is a major concern in all MOS technologies, as well as its stability with time under bias stress.
The latest results about diamond MOS transistors prepared in the framework of the European GreenDiamond project will be presented, and the evolution of the diamond MOS properties with time will be reported for the first time.

4:45 PM EP08.07.06/EP09.09.06
Diamond Power Electronics—Drift Layer Doping vs Injection Mode Transport Robert J. Nemanich[1], Raghuraj Hathwar[1], Manpuneet Benipal[2], Franz A. Koeck[1], Mohamadali Malakoutian[3], Srabanti Chowdhury[3] and Stephen M. Goodnick[1]; [1]Arizona State University, Tempe, Arizona, United States; [2]Advent Diamond, Tempe, Arizona, United States; [3]University of California - Davis, Davis, California, United States.

The properties of diamond (high mobilities and ultra-gap) suggest different current transport modes that can support high current operation which is sustained and actually improved at high temperatures. This study presents experimental results of forward current density vs voltage which shows a V^2 dependence indicative of injection mode transport. The Schottky-PIN devices show high values of forward current density (> 500A/cm^2 at 3 V) that is stable and actually improves at elevated temperature. Perhaps the most stunning aspect of these results is that the diode specific on-resistance (R_{onS}) decreases as the voltage increases. The results indicate a new mode of operation of high mobility diamond power devices where the high carrier mobilities and low phonon scattering will support current injection and drift with a reducing resistance as the current is increased. We present a comparison between diodes that operate in injection mode and the more conventional doped drift layer. We discuss modifications of the standard power electrons figure of merit for projecting the operation of diamond devices that operate in the injection transport mode.
This research is supported through the NASA HOTTECH program.

SESSION EP08.08: III-Nitrides I
Session Chair: Robert Kaplar
Thursday Morning, November 29, 2018
Hynes, Level 2, Room 209

8:15 AM *EP08.08.01
High-Al $Al_xGa_{1-x}N$ Channel Transistors Over Thick AlN/Sapphire Templates Asif Khan, Xuhong Hu, Richard Floyd, Abu Shahab, Kamal Hussein, Seongmo Hwang, Fatema Asif, Grigory Simin and MVS Chandrashekhar; University of South Carolina, Columbia, South Carolina, United States.

$Al_xGa_{1-x}N$ channel high electron mobility transistors (HEMTs) are ideal for high-temperature/voltage/power applications. Their increased breakdown field and thermal conductivity with Al-alloy composition, leads to a much higher Baliga Figure of Merit [1]. We have recently reported on $Al_xGa_{1-x}N$ channel MESFETs [2],[3], Polarization Doped FETs (PDFETs) [4] and high electron mobility transistors (HEMTs) [5] grown on low-defect AlN/sapphire templates. For these devices the channel electron mobility was a strong function of the Al-composition and decreased with higher doping. Thus, for the lowest channel sheet resistance, an undoped heterojunction FET (HFET) is the preferred device design. However, this design, makes the ohmic-contact formation very challenging leading to a contact resistivity well over 20 Ω-mm. Doping the barrier to reduce the contact resistivity leads to excessive gate-leakage currents. These limitations, till recently, the limited the highest demonstrated currents in undoped $Al_xGa_{1-x}N$ HFETs to 0.1-0.3 A/mm.
Now, our group has explored a new doped barrier high-Al channel HFET design with PECVD SiO_2 and ALD TiO_2/ZrO_2 as gate-insulators to reduce the leakage current [6]. For these *n*-$Al_{0.65}Ga_{0.35}N$-$Al_{0.4}Ga_{0.6}N$ MOSHFETs perfectly linear ohmic contacts were achieved with a resistivity as low as 1.6 Ω-mm. A record peak current as high as 0.6 A/mm was measured for devices with a gate-length of 1.75 µm in a 6 µm source-drain opening. In addition, the gate-leakage currents at room-temperature were four orders of magnitude lower than Schottky-gate devices. The ON/OFF current ratio which was more than 10^8 at room-temperature, remained as high as 10^4 for operation up to 250 C. Using temperature-dependent I_{DS}-V_{DS} and (C_{GS}-V_{GS}) characteristics, we show n_s to be (~1×10^{13} cm^{-2}) and nearly temperature independent. The room temperature mobility was around 430 cm^2/V-s and decreased with increasing temperature and n_s. These mobility values were considerably higher than those predicted by the theoretical model in [7]. We believe the discrepancy to be from a smaller contribution of alloy scattering than the one used in the model of reference 7. In this paper we will present the detailed results of the comparative study of AlGaN channel MOSHFETs with PECVD SiO_2 and ALD TiO_2 and ZrO_2 gate-insulators. Initial results of a comparative study of breakdown voltages for passivated and un-passivated devices will also be discussed.
We gratefully acknowledge the support from the DARPA-DREAM program (ONR Contract N00014-18-1-2033, Program Manager Dr. Paul Maki). Many thanks to Virginia Wheeler and Charles Eddy for the ALD oxide depositions.

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8:45 AM EP08.08.02
Enhancement-Mode, High Al-Content HEMTs Using Epitaxial Gate Oxides Peter T. Dickens[1], Brianna Klein[1], Erica Douglass[1], Andrew Armstrong[1], Andrew Allerman[1], Albert Baca[1], Michael Brumbach[1], Rebecca Chow[1], Jon Ihlefeld[2] and Elizabeth Paisley[1]; [1]Sandia National Labs, Albuquerque, New Mexico, United States; [2]Department of Materials Science and Engineering, Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, Virginia, United States.

The development of ultra-wide-bandgap (UWBG) transistors for next generation power electronics is promising owing to their higher breakdown field, thermal conductivity, and saturated electron velocity over traditional silicon insulated gate bipolar transistors. Currently however, the improvement of UWBG transistors is sometimes limited by non-ideal gate performance leading to normally-on operation, high leakage currents, and frequency dispersion. Gate oxide introduction may improve the performance, but many oxides are insufficient for UWBG transistors due to low conduction band offsets and/or poor chemical and structural interface quality. In this work, we will demonstrate that MgO gate insulators are promising gate insulator candidates for high Al-content AlGaN transistors. We have previously shown that MgO provides a sufficient band offset to 85% AlGaN, a high dielectric constant, and epitaxial, chemically abrupt interfaces with AlGaN. In this presentation, we will show our recent data demonstrating that 3 nm MgO provides enhancement-mode transistor performance on 85% Al-content AlGaN by utilizing a fluorine interface treatment prior to oxide growth. Channel currents of 17 mA/mm at +6 V gate bias were achieved with a +0.5 V threshold voltage. We will show the transistor device performance for MgO gated devices compared to normally depletion mode Schottky gated devices on similar device architecture.

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SAND2018-6427A

9:00 AM EP08.08.03
Design and Modeling of III-Nitride HEMTs for Extremely Linear RF Operation Kexin Li and Shaloo Rakheja; New York University, Brooklyn, New York, United States.

To enhance the dynamic range of high-frequency wireless technologies, it is important to develop new transistor architectures with new material systems that display high RF linearity, with high efficiency and power density. High-electron mobility transistors (HEMTs) using III-nitride materials can provide the foundational capability needed to push the performance of next-generation wireless systems [1]. Current designs of III-nitride HEMTs suffer from transconductance (g_m) degradation which leads to intermodulation signal distortion (IMD) at the circuit level. The two-tone IMD signal is proportional to the second derivative of g_m and interferes with the fundamental output signal, thereby compromising the dynamic range of the system. It is understood that g_m degradation results from a combination of factors such as self-heating, electron scattering with hot phonon populations [2], and an increase in nonlinear access region resistances at high current drive [3].

In this work, we design and model new transistor geometries to overcome the intrinsic device limits related to gm degradation. Through our numerical simulation approach based on a non-equilibrium hydrodynamic model in Sentaurus, we optimize the transistor heterostructure (materials, dimensions) for linearity and power density. We compare the performance of (i) dual channel heterostructures [4-5], (ii) gate self-aligned channels with implanted access regions [3], and (iii) GaN FinFETs with different fin structures including T-gate FinFETs [6], InAlN/GaN nanoribbons [7], and nanowire channel InAlN/GaN HEMTs [8]. Our numerical modeling will allow us to identify the most promising material options and transistor architectures for extreme RF linearity and will also serve as guidelines for experimentalists. We also use a compact self-consistent current-voltage (I-V) and charge-voltage (C-V) model based on Landauer transport theory [9-10] to validate the numerical results obtained in this work as well as previously published experimental data demonstrating linear III-nitride HEMTs. The transport in the channel is quasi-ballistic in nature. The model interprets non-ideal effects such as non-linearity of access regions, self-heating, and traps. The compact model will provide a physical and intuitive insight into device operation and will bridge the gap between device technology and circuit design.

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9:15 AM EP08.08.04
Reverse-Bias-Induced Virtual Gate Phenomenon in N-Polar GaN HEMTs Tetsuya Suemitsu[1], Kiattiwut Prasertsuk[2, 3], Tomoyuki Tanikawa[2], Takeshi Kimura[2], Shigeyuki Kuboya[2] and Takashi Matsuoka[2]; [1]Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai, Japan; [2]Institute for Materials Research, Tohoku University, Sendai, Japan; [3]Thai Microelectronics Center, National Electronic and Computer Technology Center, Chachoengsao, Thailand.

N-polar GaN high-electron-mobility transistors (HEMTs) are a promising candidate for high-frequency power transistors for millimeter-wave and beyond because of its stronger carrier confinement by the natural back-barrier and its potential to achieve lower ohmic resistance by means of the direct contact between the GaN channel and ohmic electrodes in comparison with conventional Ga-polar HEMTs. A grand challenge in N-polar GaN HEMTs is to achieve a high-performance and highly-stable MIS (metal-insulator-semiconductor) gate structure because Schottky gates suffer from a large gate leakage current due to the low barrier height and a large background charges by oxygen impurities in the GaN channel layer so far. In Ga-polar GaN HEMTs, a reverse bias annealing (RBA) is reported as an effective approach to stabilize the MIS interface and to reduce anomalous behaviors such as hysteresis in the

current-voltage and capacitance-voltage characteristics. We confirmed, however, that RBA causes a significant decrease in the maximum drain current density and the transconductance in N-polar GaN HEMTs which were not observed in Ga-polar counterparts. In this study, in order to understand the physics behind such a difference between Ga- and N-polar GaN HEMTs, a 2D numerical analysis was performed to calculate the potential profiles inside the devices.
The device structure of the N-polar GaN HEMTs consists of a 30-nm-thick GaN channel, a 25-nm-thick AlGaN back barrier with an Al mole fraction of 0.32, and a 2-μm-thick GaN buffer on a 0.8°-offcut sapphire substrate from top to bottom. For comparison, the Ga-polar GaN HEMTs consisting of a 7.7-nm-thick AlGaN barrier with an Al mole fraction of 0.33, a 1-nm-thick AlN spacer, and a 2-μm-thick GaN channel/buffer on a sapphire substrate are also prepared. For both samples, a 10-nm-thick SiN is utilized as a gate dielectric film. The gate length and width are 10 and 50 μm, respectively. RBA was performed at 200°C for 1 h with a negative gate bias voltage of –10 V. The source and drain electrodes were grounded during RBA. The 2D analysis of the potential profile inside the devices revealed that the electrons injected from the gate electrode are able to accumulate near the SiN/GaN interface at the access region adjacent to the gate electrode in the N-polar GaN HEMTs. This could cause the electron trapping in deep levels at the SiN/GaN interface and the resulting negative charges of the trapped electrons act as a virtual gate to increase the access resistance of HEMTs. In contrast, in Ga-polar GaN HEMTs, the AlGaN barrier layer prevent electrons from accumulating near the SiN/GaN interface. Based on this finding, an AlGaN cap layer on the GaN channel could be a possible way to minimize such a RBA-induced virtual gate phenomenon and to achieve more stable N-polar GaN HEMTs.
This work is partly supported by the funding from JSPS KAKENHI JP16H04341.

9:30 AM EP08.08.05
Investigation on the Trap States at p-GaN MO(I)S Interface with Different Gate Dielectric Layers Liwen Sang; NIMS, Tsukuba, Japan.

Recent progresses in the GaN-based electronic devices have demonstrated them as excellent candidates for the high power supply and switching systems, due to their unique characteristics, such as the high blocking voltage, wide bandgap, large electron saturation velocity and high thermal stability. Compared to Si or GaAs electronic devices, higher output currents can be achieved at higher frequencies by using GaN system. To fulfill the potential of GaN electronic devices, integration of GaN power devices and their gate driving circuits is needed to minimize the chip-to-chip parasitic inductance, thus reduce the switching loss, ringing and reliability issues. Monolithic complementary metal-oxide (insulator)-semiconductor (MO(I)S) transistors with both n-channel and p-channel for the integrated circuits is desirable to ultimately reduce the power consumption. However, the development of p-channel field effect transistors (FETs) is still in its infancy in comparison to the n-channel ones. Recently, our group has achieved p-channel MOSFETs based on polarization induced two dimensional hole gas at the InGaN/GaN heterojunctions. It is found that the performance of p-channel FET was restricted by the poor-quality p-GaN MOS interface. As a result of Mg accumulation to the p-GaN surface, a large surface band bending of 1.2-1.6 eV was observed for the native p-GaN, which lead to in an interfacial Mg-Ga-O disordered region with high-density trap states on the order of 10^{13} cm^{-2} using Al_2O_3 gate dielectric layer. The high-density traps resulted in the serious electrical hysteresis in both current-voltage (I-V) and capacitance-voltage (C-V) characteristic, bringing about the threshold voltage instability. The surface pre-treatment could not effectively remove the surface oxides on p-GaN as a result of re-oxidation in the following atomic-layer deposition process for Al_2O_3. Therefore, to ultimately enhance the performance and stability of p-channel FETs, proper oxygen-free gate dielectric layer and high-quality p-GaN MIS interface with lower interface state density and less trapping states is in great demand.
In this paper, we investigated the p-GaN MIS and MOS capacitors with different gate dielectric layer such as CaF_2, SiN_x, SiO_2, and Al_2O_3. The interface quality and traps behaviors are evaluated with regard to the microstructure and electrical characteristics. The oxide and oxygen-free gate dielectric layers were compared for the performance of p-GaN electronic devices.

9:45 AM EP08.08.06
Hyperspectral Quantum Rod Thermal Imaging of GaN Electronic Devices Bahar Oner, James W. Pomeroy, Serge Karboyan and Martin Kuball; University of Bristol, Bristol, United Kingdom.

The peak junction temperature in electronic devices is a key parameter in determining the mean time to failure (MTTF). However, accurate temperature measurement becomes increasingly more challenging as devices are miniaturised and operating power densities increase, generating large temperature gradients on the sub-micron length-scale. Existing thermography methods either have limitations in spatial resolution, e.g., IR thermography, or require time consuming complex calibration and specialised equipment, e.g., Raman thermography, transient thermoreflectance or SThM. There is a clear need for high resolution, fast, simple and low cost thermal imaging technique. To address this, we have developed a high spatial resolution and cost-effective thermography technique, Hyperspectral Quantum Rod Thermal Imaging (HQTI), demonstrated on GaN high electron mobility transistors (HEMTs), with sub-micrometer spatial resolution.
The technique exploits the temperature dependent emission wavelength of nanoparticles, i.e. quantum rods or dots deposited onto the device under test, using a low cost hyperspectral camera. Quantum dots/rods are ideal temperature sensors for this application because they have low thermal mass and surface area, quickly reaching thermal equilibrium with the surface. Core/shell nanoparticles also have a high quantum efficiency and bright emission, enabling short image acquisition times. Temperature images are obtained by imaging the nanoparticle emission wavelength in the unbiased (reference) state and biased (on) state, and applying the known emission wavelength temperature dependence of the particles used. In this way the measurement is generic and does not require any re-calibration when the particles are deposited onto different materials.
The HQTI technique has been applied to GaN HEMTs for demonstration; a technology where high temperature gradients are generated in the channel region due to the localised high power dissipation density. An optical resolution of ~0.6 μm has been achieved using an 0.5 numerical aperture objective lens and temperature resolution of ~2ºC, which can be further improved by numerical image processing techniques. Measured temperatures were within ~15% of a three dimensional finite element model. In comparison, the temperature was underestimated by ~50% using the lower resolution IR thermography method. This new generic measurement technique is expected to be a step-changing characterisation tool not only for micro-electronic devices, but also for any other micro/nano scale thermal measurement applications, such as biomedical devices and nanocomposites.

10:00 AM BREAK

10:30 AM *EP08.08.07
Point Defect Management in Ultra-Wide Bandgap Materials Zlatko Sitar[1, 2], Pramod Reddy[2] and Ramon Collazo[1]; [1]North Carolina State University, Raleigh, North Carolina, United States; [2]Adroit Materials, Apex, North Carolina, United States.

Achieving control of electrical conductivity in n- and p-AlGaN over all doping levels of interest has proven to be challenging. AlGaN exhibits a decrease in free carrier concentration as the dopant concentration increases above a critical doping concentration. This behavior is attributed to the formation of compensating defects due to lowering of their formation energy during doping. These compensators also contribute to impurity scattering, limiting the carrier mobility.
A novel scheme to control point defects in wide bandgap semiconductors is presented. The scheme uses above bandgap UV-illumination to change the position of the quasi Fermi levels in a semiconductor, and, thus, increase the formation energy of compensating defects leading to a decrease in incorporation. Using AlGaN as a model system, we demonstrated that over an order of magnitude improvement in the electrical properties could be achieved in these materials by using this scheme for controlling the incorporation of point defects.

In n- and p-doped AlGaN films grown by MOCVD, point defects such as hydrogen, carbon, nitrogen or metal vacancies and their corresponding complexes lead to dopant compensation, resulting in a high resistivity and a low mobility in these films. Generally, the energy of formation of a point defect is a function of the process conditions, as described by the chemical potentials of the species involved. In addition, the energy of formation of charged point defects is also a function of the Fermi energy, or the electrochemical potential. We have developed a non-equilibrium process scheme in which the Fermi level is controlled by external excitation in a steady-state condition. We introduce above-bandgap illumination as the excitation source for enhancing the doping capabilities, by controlling the energetics of point defects via Fermi level control during growth.
This presentation will focus on the details of the theoretical background and related calculations. In addition, the discussion will also focus on the used experimental setup and influence of UV-light on the growth condition and possible gas-phase interaction. The proposed point defect control scheme is of great interest for all semiconductors in which compensation is the main limiting factor in obtaining the desired free carrier concentrations and conductivity.

11:00 AM EP08.08.08
Impact of Ge Doping on Growth Stress and Dislocation Microstructure in AlGaN Anushka Bansal and Joan M. Redwing; The Pennsylvania State University, University Park, Pennsylvania, United States.

Intentional n-type doping of $Al_xGa_{1-x}N$ has been widely studied given its critical role in light-emitting diodes and ultra-wide bandgap devices. Silicon has been the most intensively investigated donor in $Al_xGa_{1-x}N$ since it enables low resistance *n*-type films, however, Si doping induces bending of edge-type threading dislocations which generates tensile stress and cracking with increasing film thickness. Germanium (Ge) has been investigated as an alternative to Si for n-type doping of GaN. Its impact on dislocation inclination and film stress, however, is unclear particularly for the growth of $Al_xGa_{1-x}N$ alloys. In this study, we employ *in-situ* wafer curvature measurements combined with post-growth structural and electrical characterization to investigate the impact of Ge doping on film stress and doping efficiency in $Al_xGa_{1-x}N$ (x=0-0.51) layers grown by metalorganic chemical vapor deposition (MOCVD) as compared to Si doping.
$Al_xGa_{1-x}N$ layers were grown on semi-insulating Si-face (0001) 6H-SiC substrates in a vertical cold wall MOCVD reactor equipped with *in-situ* wafer curvature measurements. The precursors used for growth and doping included trimethylaluminum, trimethylgallium, NH_3, SiH_4 and GeH_4. Growth of $Al_xGa_{1-x}N$ was carried out at 1150ºC and 100 Torr reactor pressure using a thin (~90 nm) AlN buffer layer. SiH_4/group III inlet ratio of 2×10^{-3} resulted in an electron concentration of ~8.2×10^{18} cm^{-3} for Si doping while a GeH_4/group III ratio of 0.5 was required to achieve a similar Ge doping level. The film microstructure was investigated on cross-sectional samples using bright field imaging and [110] and [0002] weak-beam dark-field imaging. High resolution X-Ray Diffractometry (HRXRD) in a triple-axis geometry was used to measure the film composition and threading dislocation density. Room temperature (RT) Hall measurements were used to measure the carrier concentration and mobility of Ge doped $Al_xGa_{1-x}N$ layers.
In-situ wafer curvature measurements employed during growth provided information on the evolution of film stress with doping. It was observed that Ge doping does not induce additional tensile stress into the film in contrast to Si doping. This is consistent with the inclination angle of the edge dislocations which was measured to be 6.9°and 7.5° for undoped and Ge doped $Al_{0.30}Ga_{0.70}N$ films, respectively, indicating only a minor change in dislocation bending with doping. The electron concentration decreased a small amount going from GaN to $Al_xGa_{1-x}N$ (x=0.21-0.41). However, at x=0.51, the resistivity increased by a factor of 40, and the electron concentration decreased sharply consistent with theoretical predictions of the onset of DX centers in Ge doped high Al content $Al_xGa_{1-x}N$.
The results demonstrate that Ge is a viable n-type dopant for $Al_xGa_{1-x}N$ (x<0.5) enabling the growth of highly doped, low resistivity layers without significant modification of film stress.

11:15 AM EP08.08.09
Heteroepitaxy of Thick GaN on Si and Improvement of Electrical/Material Characteristics by Defect Annihilation Atsunori Tanaka, Woojin Choi, Renjie Chen, Ren Liu and Shadi Dayeh; Univ of California-San Diego, La Jolla, California, United States.

A major challenge in vertical power devices in GaN and other large bandgap materials is the high defect density that compromises the performance, reliability and yield. We are developing selective area growth approaches that have successfully reduced the densities of these defects on scalable and cheap substrates to a comparable level of native substrates. With these new approaches to material growth, we are able to demonstrate devices whose performance correlates well with the improved material quality. Our choice of material for studying these growth approaches is GaN that while have been extensively studied for decades suffer from large defect densities on large-scale commercially viable Si substrates. Recently, bulk GaN crystal growth techniques such as Na-flux, Hydride Vapor Phase Epitaxy and ammonothermal methods have been developed and, homoepitaxial vertical GaN devices have made it possible to achieve thick drift layers and low dislocation densities but at significant cost. Issues of reliability and uniformity over large areas remain challenging for market adoption of these bulk GaN technologies. For GaN growth on Si, since the GaN cannot be typically grown thicker than 3-4 µm on Si, the dislocation density at the surface cannot be lowered below 10^8 cm^{-2} due to lattice and thermal mismatches. In contrast, we are able to grow over 20 µm thick GaN on Si [Tanaka et al., Adv. Mat. 29, 1702557, 2017], and report here systematic studies on GaN Schottky barrier diodes with different thicknesses from 5 µm to 20 µm of unintentionally doped GaN on Si substrates and a newly commercialized QST substrate (Qromis Inc.) and reference GaN substrates. We observed a number of dislocations generated at GaN/Si interface were annihilated with thickness and decreased from 1.89×10^7 cm^{-2} in 5 µm thick GaN to 3.39×10^6 cm^{-2} in 20 µm thick GaN at the surface. The improvement of the material quality in thick GaN lowered the Schottky diode leakage current 2 orders of magnitude compared to thin GaN and made it possible to fabricate a vertical trench gate field effect transistor(FET) on Si with comparable leakage current as devices on GaN substrate. Similarly, GaN Schottky diodes on QST substrate successfully resulted in comparable leakage current with devices on GaN substrate and showed breakdown voltage of 400 V without edge termination. Vertical devices with optimized edge termination will be reported in the talk.

11:30 AM EP08.08.10
Rehybridization Enhanced Incorporation of Boron at GaN and AlN (0001) Surfaces—A Novel Route to Grow High B Content Alloys Liverios Lymperakis and Jorg U. Neugebauer; Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany.

Boron containing GaN and AlN materials constitute emerging members of the III-Nitrides alloys family. They are candidate materials for a number of technological applications such as a back barrier in AlGaN/GaN high electron mobility transistors or to achieve lattice matched InGaN layers to SiC or GaN. However, a major challenge towards exploiting the full potential of B containing III-Nitride alloys is the limited B incorporation. More specifically, the B bulk solubility does not exceed 2% and 3% in GaN and AlN at 1000 ºC, respectively. A potential route to overcome the limit set by bulk solubility is to employ surface engineering. Surfaces break the bulk translational symmetry, offer efficient strain relaxation and may provide different coordination and rehybridization than bulk [1]. The key idea underlying surface engineering is to employ surface structures with compositions higher than the bulk solubility limit which are kinetically stable and do not change their composition when overgrown. Therefore, understanding the atomistic mechanisms at surfaces is a prerequisite to fully control the composition of epitaxially grown alloys.
In the present work a potential route to achieve B contents well above the bulk solubility limit is investigated and identified. We employ total energy and force calculations within density functional theory (DFT). Specifically, we investigate the effect of surfaces on the properties and composition of epitaxially grown BGaN and BAlN alloys. In total more than 200 different B containing and B free surface structures have been implemented. Based on these calculations phase diagrams for both BGaN and BAlN surfaces are derived. These diagrams reveal that under typical MOCVD growth conditions as

well as under metal-rich MBE growth none of the calculated B containing surfaces is energetically favourable and the maximum B content at the surfaces does not exceed the bulk solubility limits at typical growth temperatures. However, under N-rich MBE growth a hybridization enhanced B incorporation mechanism dominates [2]: B which adopts the hexagonal ground state when alloyed with N, is favourably incorporated at the low coordinated and sp^2 hybridized cation site of the 2×2 N adatom reconstruction. This mechanism allows to incorporate B content well above the bulk solubility limits and as high as 25%. Furthermore, an interesting outcome is that ordering in the form of 2×2 and $2\sqrt{3}\times2\sqrt{3}R30^{o}$ patterns is introduced at the surface. Based on the aforementioned calculations we will present and discuss in detail the physics governing the above mentioned mechanism. Specifically, we will elaborate on RHEED and/or HRTEM fingerprints of B induced ordering as well as possible routes to optimize the growth of BGaN and BAlN alloys with high B content.

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[2] L. Lymperakis, AIP Advances **8**, 065301 (2018)

11:45 AM EP08.08.11
Direct Determination of AlN and GaN Native Surface Oxide Structures J. Houston Dycus[1], Kelsey J. Mirrielees[1], Everett D. Grimley[1], Seiji Mita[2, 1], Ronnie Kirste[2, 1], Zlatko Sitar[1, 2], Ramon Collazo[1], Douglas L. Irving[1] and James M. LeBeau[1]; [1]North Carolina State Univ, Raleigh, North Carolina, United States; [2]Adroit Materials, Cary, North Carolina, United States.

Reactive broken bonds at pristine material surfaces often promote the formation of surface oxides. These surface oxides can then have structures and properties that differ dramatically from bulk. These structure of these surface oxides is, however, often difficult to determine. For example, X-ray photoelectron, Auger electron spectroscopies, electron diffraction can provide key insights into surfaces, but are indirect. Furthermore, scanning tunneling microscopy and atomic force microscopy largely probe the outer most layer. A rich set of structural details, however, can lie just below the surface.

Here, we investigate the formation and structure of native surface oxides of Al/Ga-nitride. These oxides have yet to be unambiguously determined, even though they play a major role incontrollingthe properties of buried AlGaN/GaN interfaces for high-power devices. Using aberration corrected scanning transmission electron microscopy, we show how these layers can be directly measured, and as a function of depth. The native oxide structure is found to be exceedingly thin, about 1.5 nm. When viewed along multiple high symmetry projections, we construct a three dimensional model of the layer that is used for input into theory calcualtions. We find a number of key features that define these layers. First, there is a tetrahedral—octahedral—tetrahedral arrangement of cation--oxygen units that build the layer, in contrast to the tetrahedral coordination of the substrate and octahedral configuration found in Al_2O_3. The combination of local bounding environments is reminiscent of bulk β-Ga2O3. In addition, a polarity inversion is found across the oxide layer, which contribute to the surface stability. Combining our structural model with density functional theory, we explore the surface formation energy relative to prior surface oxide models, and find that it is lower in energy across all conditions considered. Finally, we will discuss how this structure can play a key role in seeding inversion domain boundaries, high quality ZnO/GaN interfaces, and how the structure shares similarities to the recently discovered two-dimensional GaN stabilized by graphene.

Dycus, J. H., et al., "Structure of Ultrathin Native Oxides on III-Nitride Surfaces" *ACS Applied Materials and Interfaces*10, 10607–10611. (2018) doi:10.1021/acsami.8b00845

SESSION EP08.09: III-Nitrides II
Session Chair: Rachael Myers-Ward
Thursday Afternoon, November 29, 2018
Hynes, Level 2, Room 209

1:30 PM *EP08.09.01
Transition Metal Nitrides—Avenue to Ultra-Wide Bandgap Semiconductor Devices? David J. Meyer, D. S. Katzer, Brian Downey, Matthew T. Hardy, Neeraj Nepal, David Storm, Shawn Mack and James G. Champlain; Naval Research Laboratory, Washington, District of Columbia, United States.

The emerging class of ultra-wide bandgap semiconductor (UWBGS) materials, including AlN, diamond, Ga_2O_3, and cubic BN, have been of recent interest to electron device developers because of their desirable ability to withstand high electric fields. Despite numerous experimental demonstrations of this breakdown strength, UWBGS materials still generally suffer from the fundamental challenge of being able to get large densities of mobile carriers into their conduction or valence bands. In cases where impurity doping is possible, there is typically only one impurity type (donor or acceptor) with small ionization energy in the material system, and this prevents or limits bipolar device realization.

Given the difficulties associated with impurity doping in UWBGS materials, our team has been investigating the epitaxial integration of lattice-matched crystalline conductors and superconductors to replace heavily doped semiconductor layers in device heterostructures. To accomplish this task, we have used an RF plasma-assisted molecular beam epitaxy system equipped with an electron beam evaporator source to study the thin film growth of single crystal transition metal nitride (TMN) materials, such as NbN_x and TaN_x, and their integration with AlN and GaN. Cross-sectional transmission electron microscopy shows that TMN/III-N interfaces are atomically abrupt with no evidence of interdiffusion of the host elements. We anticipate that the device applications of these metallic films are quite broad ranging from selective etching of sacrificial layers for epitaxial lift-off of processed III-N devices, to buried metallic or superconducting electrodes for Josephson junction devices, to optical mirrors and waveguides for improved optoelectronics. This talk will present our latest work involving TMN development and applications that will enhance wide and ultra-wide bandgap semiconductor devices.
This work was supported by the Office of Naval Research.

2:00 PM EP08.09.02
Gadolinium-Doped Gallium Nitride for Room Temperature Spintronic Applications Vishal Saravade, Amirhossein Ghods, Naishadh Raval, C. Zhou and I. T. Ferguson; Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, Missouri, United States.

Gallium nitride (GaN) is a candidate material for room temperature (RT) spintronic applications considering its electrical and magnetic properties. MOCVD-grown Gd-doped GaN (GaGdN) exhibited RT ferromagnetism and anomalous Hall effect (AHE) in which the mechanism seems to be free carrier-mediated [1]. Observation of ferromagnetism only in GaGdN from a $(TMHD)_3Gd$ precursor that contains oxygen points to the role of oxygen especially oxygen interstitials in stabilizing the ferromagnetism. GaGdN from a Cp_3Gd precursor that does not contain oxygen did not show ferromagnetism. In this work, the mechanism for the ferromagnetism in GaGdN will be further investigated. The role of oxygen in the magnetic properties

will be examined using GaGdN implanted with oxygen. Carbon-implanted GaGdN will also be studied as carbon can also introduce interstitial sites in GaGdN [2]. AHE measurement will be done and relationship between the anomalous Hall resistivity and longitudinal resistivity will be determined to better understand the responsible mechanism for the ferromagnetism. Furthermore, GaGdN based spin-LEDs will be fabricated and difference between the left and right circularly polarized light intensities will be determined using magnetic circular dichroism measurement. These would help towards understanding spin injection in GaGdN devices and to determine the suitability of GaGdN for spintronic applications.

References:

1. M. Kane, S. Gupta and I. Ferguson, "Transition metal and rare earth doping in GaN", Rare Earth and Transition Metal Doping of Semiconductor Materials: Synthesis, Magnetic Properties and Room Temperature Spintronics, 2016

2. R. Xie, H. Xing, Y. Zeng, Y. Liang, Y. Huang and X. Chen, AIP Advances 7, 115003, 2017

2:15 PM EP08.09.03
MOCVD Growth and Characterization of Er Doped III-Nitride Epilayers and Quantum Well Structures Talal Al Tahtamouni[1], Hongxing Jiang[2] and Jingyu Lin[2]; [1]Qatar University, Doha, Qatar; [2]Texas Tech University, Lubbock, Texas, United States.

Er doped materials have attracted much attention for their applications in photonics, especially in the area of optical communications. Doped in a solid host, Er^{3+} ion has allowable intra-4*f* shell transition from its first excited state ($4I_{13/2}$) to the ground state ($4I_{15/2}$) and the transition corresponds to a wavelength of minimum optical loss in silica based optic fibers at 1.54 µm.Thus, Er-doped materials are ideal candidates to make amplifiers for optical communications.
It has been observed that the 1.54 µm emission from Er doped semiconductors of smaller bandgaps has a low efficiency at room temperature due to a strong thermal quenching effect. In general, the thermal stability of Er emission increases with an increase of the energy gap and ionicity of the host materials. III-nitride semiconductors are excellent host materials for Er-ions due to their structural and thermal stabilities. III-nitride wide bandgap semiconductors have demonstrated excellent performance for electronic and optoelectronic devices.
AlN has a large bandgap (6.1 eV). Therefore, it is expected that AlN as a host material will result in lower thermal quenching of Er emission. AlN is of great technological significance because of its physical and chemical properties such as low dielectric constant, excellent thermal conductivity, electrical resistivity, excellent mechanical strength and chemical stability. These reasons make AlN an excellent host material for device applications.
Despite the reports of fabrication of light emitting diodes based on Er doped III-nitride epilayers operating in the infrared region. However, further improvements in the quantum efficiency of the 1.54 µm emission in Er-doped III-nitrides are still needed to enable practical photonic devices. One way to improve the quantum efficiency of these device structures is to improve the excitation efficiency of the Er ions via the enhancement in the carrier density around Er^{3+} ions. This could be achieved by implementing quantum well structures.
A-plane AlN epilayers doped with erbium (AlN:Er) have been grown on r-plane sapphire substrates by MOCVD. The 1.54 µm emission properties were probed by photoluminescence (PL) emission spectroscopy and compared with those of c-plane AlN:Er. It was found that the emission intensity from a-plane AlN:Er is higher than that from c-plane AlN:Er for above and below energy gap, as well as resonant excitation. The intensity of the 1.54 µm emission was found to increase with increasing Er molar flux. A-plane Er-doped AlN epilayers exhibit a smaller thermal quenching effect.

Erbium doped GaN/AlN multiple quantum wells (MQWs:Er) have been grown by MOCVD. The 1.54 µm emission properties from MQWs:Er were probed by PL and compared with those of GaN:Er epilayers. It was found that the emission intensity from MQWs:Er is 9 times higher than that of GaN:Er epilayers. The influence of the well and the barrier widths on the PL emission at 1.54 µm was studied

2:30 PM EP08.09.04
Coalesced, Centimeter-Scale GaN Films on Amorphous Substrates via MOCVD Growth on a Silicon Seed Layer Fabricated by Aluminum-Induced Crystallization Mel Hainey[1], Yoann Robin[2], Hiroshi Amano[2] and Noritaka Usami[1]; [1]Materials Process Engineering, Nagoya University, Nagoya, Japan; [2]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan.

The fabrication of III-nitride semiconductor thin films on substrates such as glass and oxidized Si(001) is of significant interest for LED and CMOS integration applications. However, direct epitaxy on these substrates is difficult because their amorphous structure offers no template for III-nitride thin film growth.
In recent work, the growth of GaN on amorphous and polycrystalline substrates was demonstrated by using a silicon seed layer fabricated by aluminum-induced crystallization (AIC)[1]. While c-axis oriented GaN with threading dislocation densities of ~$5x10^9/cm^2$ was demonstrated, the coalesced area realized was only ~$1mm^2$ on a $1cm^2$ fused quartz substrate, and was even smaller for other substrates. For large-scale applications, scalable fabrication of fully coalesced GaN films is required, and methods for evaluating the crystal quality of the underlying AIC-Si thin film prior to GaN growth should be developed.
In this report, GaN films with reduced tilt and improved coalescence are grown from AIC-Si seed layers on cm-scale fused quartz and oxidized Si(100) substrates. In the first part of this process, optimized annealing conditions producing the most uniformly oriented AIC-Si silicon thin films are developed. Based on pole figures taken from electron backscatter diffraction of the AIC-Si films, reducing annealing temperatures from 500°C to 425°C results in reduced Si(111) surface misorientation and increased grain size. In the second part, AIC-Si films with reduced Si(111) misorientation are used as seed layers for GaN growth, and the reduced Si misorientation translates into reduced GaN in-plane misorientation. Full-width at half maximum values (FWHM) of x-ray rocking curves measured on the GaN (00.2) peak were found to be reduced from >3° to roughly 2° on fused quartz substrates, and <1° on oxidized Si(100) substrates. Note that this marks a significant improvement over previous reports of GaN growth on glass, where (00.2) FWHM values of over 3° were reported[1,2].
While the initial GaN growth process was able to produce highly oriented films, these films remained heavily pitted and grew as islands on their underlying AIC-Si grains. However, by increasing the growth temperature, GaN films became smooth and formed nearly coalesced films over areas of ~$1cm^2$. These coalesced films should enable device fabrication using conventional III-nitride device processing processes.
[1] M. F. Hainey, Z. Y. Al Balushi, K. Wang, N. C. Martin, A. Bansal, M. Chubarov, J. M. Redwing, *Phys. Status Solidi - Rapid Res. Lett.* **2018**, *12*, 1.
[2] J. H. Choi, A. Zoulkarneev, S. Il Kim, C. W. Baik, M. H. Yang, S. S. Park, H. Suh, U. J. Kim, H. Bin Son, J. S. Lee, M. Kim, J. M. Kim, K. Kim, *Nat. Photonics* **2011**, *5*, 763.

2:45 PM EP08.09.05
Thermal Stress Analysis of AlN/Sapphire Templates Fabricated by Sputtering and High Temperature Annealing Yusuke Hayashi, Kenjiro Uesugi, Shuichi Tanaka, Kentaro Tanigawa, Shojiki Kanako and Hideto Miyake; Mie University, Tsu, Japan.

High temperature annealing of sputtered AlN is a promising approach to produce high quality AlN templates for AlGaN-based light emitting devices. High temperature annealing at 1600 – 1700 °C enables the significant improvement in crystal orientation in twist component. In our previous works, we were

able to achieve a FWHM value of (10-12) X-ray rocking curve (XRC) of less than 300 arcsec, owing to the solid phase epitaxy enhanced at high temperature annealing. Although the crystallinity was improved, compressive stress as large as 2.0 GPa and wafer curvature around 20 km^{-1} were observed owing to the large thermal mismatch. Hence, the investigation and the suppression of these drawbacks are crucial for the DUV LED applications.
2-inch AlN templates were prepared by sputtering onto vicinal c-plane sapphire substrates. The sputtering conditions were an RF power of 700 W, a chamber temperature of 600 °C, and a chamber pressure of 0.20 Pa. Subsequently, the templates were annealed at 1700 °C for 3 hours. X-ray rocking curve (XRC) measurement of 200-nm thick AlN templates showed high crystallinity, and FWHM values of about 11 arcsec in (0002) diffraction and about 270 arcsec in (10-12) diffraction were achieved. From lattice constant measurement by 2θ-ω scan, biaxial stress σ_{xx} was calculated to be 2.0 GPa in compressive direction. Curvature $1/r = \Delta\omega/\Delta x$ was also estimated to be -27 km^{-1} from the variation of the AlN (0002) XRC angle $\Delta\omega$corresponding to the variation of the measurement position Δx.
In order to quantitatively evaluate biaxial stress and curvature, thermal stress analysis was performed in elastic multilayer system proposed by Hsueh, where stress distribution is determined by thermal expansion $\alpha_i \Delta T$, Young's modulus E_i, and thickness t_i of each layer. In this analysis, it is assumed that no lattice mismatch exists during growth and residual stress results from the thermal mismatch. This assumption might agree with our AlN templates because solid phase epitaxy occurs at 1700 °C and an AlN layer probably turns into be freestanding on a sapphire substrate. For a calculation of thermal stress and curvature, following parameters were assumed. E_{AlN}, E_{sap}, t_{AlN} and t_{sap} were set to be 374 GPa, 460 GPa, 200 nm, and 430 μm, respectively. Thermal expansion coefficients depending on temperature were estimated from literature values. Consequently, the calculation of thermal stress indicated 2.0 GPa in compressive direction, while the calculated curvature was -21 km^{-1}, which indicates our thermal stress analysis well agrees with experimental values. Therefore, it was found that biaxial stress and curvature were determined by thermal mismatch between AlN and sapphire in this case. These findings can be beneficial information for making use of the AlN template for DUV LEDs.

3:00 PM BREAK

3:30 PM EP08.09.06
Improved Performance UVC LEDs at 235nm Based on Pseudomorphic AlGaN/AlN Leo J. Schowalter[1], Akira Yoshikawa[2], Tomohiro Morishita[2], Kazuhiro Nagase[2], James Grandusky[1] and Chris Scully[1]; [1]Crystal IS, Green Island, New York, United States; [2]Asahi Kasei, Fuji, Japan.

Ultraviolet LEDs, which emit in the UVC wavelength range shorter than 280nm, have steadily improved over the last 15 years. Commercial UVC LEDs with wavelengths longer than 250nm are now being used for both instrumentation and disinfection applications but applications that require emission wavelengths shorter than 250 nm are inadequately addressed. These short wavelength applications include the monitoring of nitrate concentrations in water, NO_x in emissions, DNA purity analysis, and high performance liquid chromatography (HLPC). All of these applications could benefit from the introduction of LEDs with wavelengths at or shorter than 235 nm.

Two-inch, high quality c-face AlN substrates are now available with threading dislocation densities below 10^5 cm^{-2} and short wavelength UVC LEDs can be fabricated from AlGaN layers grown pseudomorphically on the Al-polarity side of these substrates. The lattice mismatch in these pseudomorphic layers is entirely accommodated by compressive strain parallel to the interface and the threading dislocation densities in the epitaxial layer replicates that of the substrate. In this work, LEDs targeting a wavelength of 235nm were pseudomorphically grown on free-standing, single crystal aluminum nitride substrates using an Aixtron close-coupled shower head MOCVD system. A Si-doped, $Al_{.85}Ga_{.15}N$ was used for the n-contact and the active region consisted of five quantum well structures consisting of $Al_{.75}Ga_{.25}N$ wells sandwiched between AlGaN barriers with 85% or higher Al concentration. As predicted in prior work,[3-5] light extraction is hindered at wavelengths shorter than 240 nm as the emission mode on c-face AlN substrates switches from TE to TM mode at these high Al concentrations.[6]Unfortunately, photons produced with TM polarization will tend to propagate parallel to the emission surface (because the electric field is parallel to the c-axis). While no special effort was made to aid photon extraction, UVC LEDs at 238 nm and 235 nm have been demonstrated with 0.5 mW and 0.4 mW of output power, respectively at 20 mA. The output power drops 0.2mW at 231nm. These devices have demonstrated over 1,000h of lifetime operating at 20mA. Higher power can be obtained at higher currents but the lifetime is reduced. We also anticipate higher output powers as the photon extraction is improved.

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[5] M. Kneissl et al., *Semicond. Sci. Technol.*, **26**, no. 014036, (2010).
[6] S. Bharadwaj et al., presented at CSW 2018.

3:45 PM EP08.09.07
Luminescence Dynamics of Indirect Excitons in h-BN Epitaxial Films Grown by BCl_3-NH_3 Chemical Vapor Deposition on a *c*-Plane Sapphire Substrate Shigefusa F. Chichibu[1], Naoki Umehara[2], Kohei Shima[1], Kazunobu Kojima[1] and Kazuhiko Hara[3]; [1]Tohoku University, Sendai, Japan; [2]Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan; [3]Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan.

Hexagonal (h-) BN crystallizes in a 2D honeycomb structure based on three sp^2 bonds and exhibits unique properties. Arising from the large bandgap energy (6 eV), h-BN has attracted increasing attention as an UV/DUV light-emitting semiconductor, since Watanabe *et al*. have observed intense near-band-edge (NBE) emissions in DUV wavelengths at around 5.4-6.0 eV [1]. Despite their observation [1], h-BN has been calculated to have an indirect bandgap [2] and Cassabois *et al*. [3] have shown experimental evidences that h-BN has an indirect bandgap. Because the samples measured [1,3] were high crystalline quality single crystals, we thought that the concentrations of nonradiative recombination centers (NRCs) in the samples were sufficiently low, exciton-phonon interaction [3] in h-BN is quite strong [3,4], and indirect bandgap may give rise to high light-extraction efficiency [4]. However, low-purity (99%) h-BN microcrystals (MCs) [5] also exhibited cathodoluminescences at 5.5-5.9 eV and at around 4 eV even at 300 K [4,5], and the NBE and 4 eV emissions did not show a remarkable thermal quenching up to 300 K [4]. Therefore, h-BN is a potential material for low-cost DUV emitters and is an interesting indirect bandgap semiconductor to learn.
Because the growth of large-size bulk h-BN crystals [1,3] is challenging, heteroepitaxial growths of h-BN films have been studied by many researchers recently. Umehara and Hara *et al*. [6] have also grown (0001) h-BN films on a (0001) sapphire substrate by means of low-pressure CVD using the BCl_3-NH_3-N_2 gas system at 1300-1400 °C. In this presentation, the results of spatially and temporary resolved luminescenece measurements on these films [6] will be shown.
The h-BN films routinely exhibited the NBE emission peaks: similar to the cases for single crystals [1,3] and annealed MCs [4], present CVD films exhibited ZA(T), TA(T)/LA(T), and TO(T)/LO(T) phonon replicas [3] of the **MK** indirect excitons (iXs) at approximately 5.92, 5.86, and 5.76 eV, respectively. Also, the 5.5-eV band due to the stacking defects and the 4.0-eV band were observed. Among them, the NBE emissions and 4.0eV-band did not lose their intensities up to room temperature. Consistently, the luminescence lifetimes for those non-quenching emissions did not change remarkably

with the measurement temperature. The results will be discussed in terms of strong excitonic effects indicating the strong exciton-phonon interaction in h-BN [3,7].
We thank K. Kikuchi for help with the experiments. This work was supported in part by the Five-Star Alliance and JSPS KAKENHI Nos. 16K14222, 16H06427, and 17H02907. [1] Watanabe *et al* , Nat. Mater. 3, 404 (2004). [2] Arnaud *et al*., PRL 96, 026402 (2006); Wirtz *et al*., arXiv:cond-mat/0508421. [3] Cassabois *et al*., Nat. Photon. 10, 262 (2016). [4] Chichibu *et al,*. JAP 123, 065104 (2018). [5] Hara *et al*., PSS(c) 8, 2509 (2011). [6] Umehara *et al*., JJAP **55**, 05FD09 (2016). [7] Cassabois *et al*., PRB 93, 035207 (2016).

4:00 PM EP08.09.08
Quantification of Indium Fluctuations in InGaN/GaN Quantum Well LEDs Using Electron Energy-Loss Spectroscopy Sarah A. Goodman[1], Akshay Singh[1], Zhibo Zhao[1], Dong Su[2], Kim Kisslinger[2], Rob Armitage[3], Isaac Wildeson[3], Parijat Deb[3], Eric A. Stach[2] and Silvija Gradecak[1]; [1]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [2]Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, New York, United States; [3]Lumileds LLC, San Jose, California, United States.

InGaN/GaN quantum well (QW) light emitting diodes (LEDs) have high efficiencies and demonstrate wide wavelength tunability, but their internal quantum efficiency (IQE) decreases with increasing current – a phenomenon known as efficiency droop – which limits the use of these devices for high power applications. Mitigating efficiency droop requires a thorough understanding of inhomogeneities within the QWs, including indium fluctuations and crystalline defects. Electron energy-loss spectroscopy (EELS) within the scanning transmission electron microscope (STEM) is well-suited to probe material composition and optoelectronic properties on the sub-nanometer scale. However, it has been shown that electrons with energies above the knock-on threshold for indium (~120 keV) induce indium fluctuations within the QWs. As such, it is critical to obtain imaging conditions that do not induce artifacts into the sample. Furthermore, despite the widespread use of EELS to characterize InGaN, no standard approach has been developed to extract relative In and N composition from the raw EELS spectra.
Here, we use an aberration-corrected STEM at low accelerating voltage (80 kV and 120 kV) to map the composition of high-efficiency InGaN/GaN QW LEDs using EELS with high spatial resolution. We develop methodology to extract In and N signal from the raw spectra, separating this signal from the plasmon tail background and the neighboring carbon K-edge, which results from deposition of carbon contamination within the chamber onto the sample through interaction with the electron beam. Additionally, we investigate the effect of spectroscopic and imaging conditions on the apparent indium composition within the QWs. We observe an artificial decrease in In signal along the EELS scan direction when the spectrum image is collected at high electron doses. We attribute this artifact to an increase in the carbon K-edge resulting from a build-up of carbon deposition along the scan, which prevents accurate background subtraction in the region preceding the N K-edge and In M-edge. We optimize the imaging and spectroscopic parameters to reduce carbon deposition and therefore produce pristine EELS spectra unaffected by artifacts. In addition, we provide a robust methodology to decouple carbon-induced artifacts from intrinsic materials properties.
Although carbon deposition particularly impacts characterization of InGaN due to the proximity of the C edge to the In and N edges, this artifact impacts STEM imaging and spectroscopy of all materials systems. Therefore, our work is generally applicable to other high-resolution EELS studies that require precise quantification.

4:15 PM EP08.09.09
Correlation of Structural and Optoelectronic Properties of V-pits in InGaN/GaN Quantum Well Heterostructures Grown on Silicon Substrates via Cathodoluminescence in Scanning Transmission Electron Microscopy Zhibo Zhao[1], Sarah A. Goodman[1], Akshay Singh[1], Govindo J. Syaranamual[2], Saurabh Srivastava[2], Jing Y. Chung[2, 3], Abdul Kadir[2], Li Zhang[2], Soo-Jin Chua[2, 3], Eugene Fitzgerald[1, 2], Stephen Pennycook[2, 3] and Silvija Gradecak[1, 2]; [1]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [2]Low Energy Electron Systems Interdisciplinary Group, Singapore-MIT Alliance in Research and Technology, Singapore, Singapore; [3]Department of Materials Science and Engineering, National University of Singapore, Singapore, Singapore.

Over the past two decades, InGaN/GaN quantum well (QW) heterostructures have set the industry standard for high-efficiency inorganic blue light emitting diode (LED) devices. The highest quality InGaN/GaN-based LEDs are grown on sapphire substrates as opposed to silicon substrates, to overcome difficulties associated with thermal expansion mismatch and decrease the density of crystalline defects in the QW region. Growth of these devices on Si substrates would allow for their incorporation into integrated circuits, expanding their range of potential applications. A shift from sapphire to cheaper Si substrates would also allow cost reductions between 40-60% at the die level and enable the development of large-area LEDs using semi-automated CMOS processes.[1] Despite recent advances in GaN-on-Si epitaxy, commercial adoption of GaN-on-Si technology remains limited due to a degradation in crystalline material quality in comparison to incumbent sapphire technologies. Although InGaN-based LEDs are highly resilient to non-radiative recombination at dislocations and V-pits, local optical properties around such defects remain ambiguous. Correlating optoelectronic properties with nanoscale defects remains critical to improved GaN-on-Si LEDs.

In this work, we use cathodoluminescence in scanning transmission electron microscopy (CL-STEM) to map nanoscale optical properties around V-pit defects found in InGaN/GaN QW heterostructures grown on Si substrates. The heterostructures consist of 13 periods of 2.5 nm InGaN QWs separated by 10 nm GaN barriers and emit at 472 nm. We find that the radiative recombination localized around the V-pits in the QW region is blue shifted compared to the QW emission, occurring at 375-395 nm. We attribute the blue-shift to radiative recombination in the QWs near the V-pit which are thinner and are hypothesized to contain fluctuations in indium concentration. Dislocation analysis in the TEM shows that the V-pits luminesce regardless of dislocation character (screw, edge, or mixed). In addition, hyperspectral CL-STEM mapping reveals strong spatial variations in the wavelength and emission intensity from the V-pit core to the facet.

This work provides a foundation for identifying how defects in the InGaN/GaN QW heterostructure region of an LED can influence the optoelectronic properties of the device. Understanding the correlation between structure and emission of V-pits on the nanoscale will be critical to further development of both incumbent GaN-on-sapphire and next-generation GaN-on-Si LED technologies.

1. L. Zhang, *et al*., *J. Electron Devices Soc.*, vol. 3, no. 6, pp. 457-462, Nov. 2015

4:30 PM DISCUSSION TIME

4:45 PM EP08.09.11
AlN Capacitors for High Temperature Systems Pijush K. Ghosh[1], Mirsaeid Sarollahi[1], Rahul Kumar[2], Samir K. Saha[2], Gregory J. Salamo[2] and Morgan E. Ware[1]; [1]Electrical Engineering, University of Arkansas-Fayetteville, Fayetteville, Arkansas, United States; [2]Physics, University of Arkansas–Fayetteville, Fayetteville, Arkansas, United States.

The recent trend towards higher power and smaller size has necessitated a renewed attention to the thermal budget in power conversion systems. Increased temperatures can reduce efficiency and ultimately can lead to failure. Capacitors are particularly sensitive to high temperature failure and are in many cases

held remotely from the main power devices increasing system size and complexity. Currently, off-the-shelf, general purpose capacitors limit their operating temperature range to below ~100°C. Newly developed ceramic capacitors based on $BaTiO_3$ and $CaZrO_3$ demonstrate very good properties at temperatures up to >200°C, however still suffer at high temperatures from both break down and instability. Their capacitance, although very large, changes by several times and subsequently vanishes at high temperature as the ferroelectric dielectric undergoes a phase change. Although, these do have very good properties for applications in high power modules which may see very high temperatures, there are two main factors we would like to improve upon by the introduction of AlN deposited by MBE on n-type 4H-SiC as the dielectric material of the capacitor. 1) The AlN capacitors should be able to operate at high temperature, high voltage, and high frequencies in a single device, whereas the ceramic devices have different constructions optimized for each. 2) More importantly, with a look to the future of integration, the AlN based capacitors could in principle be directly integrated at the chip level with high power transistors and the associated control electronics based on GaN and SiC materials and technology. AlN is an ultrawide band gap semiconductor with very stable dielectric properties up to at least 600°C and well suited for both RF and high-power devices. At the same time there are no known phase changes within usable operating temperatures. We will present the extreme temperature stability of these AlN based capacitors over the wide temperature range from 240K to 600K, along with their high capcitance density of ~ 10μF/cm^2. Finally, current efforts to increase the usable voltage range and at the same time reduce leakage current will be presented.

SESSION EP08.10: Poster Session: Ultra-Wide-Bandgap
Session Chair: Robert Kaplar
Thursday Afternoon, November 29, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

EP08.10.01
Substrate Induced Chemically Stabilized Large Area *Wurtzite*-BN Epitaxial Thin Film Badri Vishal[1, 2] and Ranjan Datta[1, 2]; [1]International Centre for Materials Science, Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru, India; [2]Chemistry and Physics Of Materials Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru, India.

We report for the First time on chemically stabilized the metastable wurtzite phase boron nitride (*w*-BN). Single crystalline epitaxial wurtzite *w*-BN thin film grown on *c*-plane sapphire by pulsed laser deposition (PLD) under slow kinetic condition. Wurtzite phase boron nitride have wide band gap of 5.81 eV (Γ→X). Experimental investigation into the properties of *w*-BN is scarce because of the difficulty in synthesizing sufficiently large and pure crystals of it, which usually requires extremely conditions (1730-3230°C, ~10^8 torr) in various methods e.g. static high-pressure, shock-wave compression method, direct conversion from *h*-BN. We have grown *w*-BN phase on a thin film under relatively low temperature (800°C) and pressure (~10^{-5} torr). The thin film shows no traces of other allotropes such as cubic (*c*) or hexagonal (*h*) BN phases and confirms by high-resolution transmission electron microscopy (HRTEM), X-ray diffraction and Raman spectroscopy. Sapphire substrate plays a significant role to stabilize metastable *w*-BN in unusual PLD growth condition, and explained based on density functional theory (DFT) calculation using Quantum Espresso (QE). DFT confirms the phase transition occurred due to a chemical interaction between Boron and Oxygen atoms leading to staggering in flat *h*-BN layer transforming to the *w*-BN structure at the O-terminated (0001) plane of sapphire. HRTEM and electron diffraction confirms film is relaxed and the lattice parameters of *w*-BN are approximately a = 2.58 Å and c = 4.29 Å. Epitaxial relationship is *w*-BN<01-10> || Al_2O_3 <2-1-10> with -6.1 % lattice mismatch. Theoretical predictions indicate that *w*-BN is the second hardest material (114 GPa) after lonsdaleite (-152 GPa). The hardness (H) and the elastic modulus (E) of the *w*-BN film are 37 & 339 GPa, respectively measured by indentation along <0001> direction. The hardness of the film is 37 GPa lower than theoretical prediction due to indention along a soft direction, thin film geometry and defects present in the film. It is also possible that structure may not have undergone bond flipping intermediate structural transitions during indentation and gives lower H. wide bandgap *w*-BN is a new unexplored phase which can open the opportunities as an active material for the energy applications and optoelectronic as its 2D layered counterpart *h*-BN to improve properties of graphene and 2D MoS_2, WS_2, ReS_2, heterostructures in various device application. On the other hand, the results are extremely promising in advancing the microelectronic and mechanical tooling industry.

EP08.10.02
Current Transient Study of RF GaN HEMTs Biased at 100 mA/mm and 28 V Yen-Pin Lin, Yi-Nan Zhong and Yue-Ming Hsin; National Central University, Taoyuan City, Taiwan.

AlGaN/GaN HEMTs have been widely used in RF power amplifiers especially for mobile base station transmitters because of high electron mobility and breakdown field characteristics in GaN based wide bandgap materials. However, current dispersion from trapping is an important issue in GaN HEMTs. In this study, on-state stress in AlGaN/GaN HEMTs is to investigate the current transient characteristics while transistors are biased at different quiescent points (Q-points) and under different substrate temperatures.

AlGaN/GaN HEMTs with two 0.25-μm T-gate fingers and width of 125-μm were investigated in this study. All HEMTs were grown on 4-inch SiC substrates and fabricated by a commercial foundry. SiN stack layers were used for passivation and source field-plate was adopted.

The transient study (on-state stress) includes two parts, one is to measure the current transient at fixed Q-points for 100 sec, another one is to measure the current transient while switching back to Q-point of 100 mA/mm and 28 V for 100 sec. All transient measurements were done under different temperatures (25, 40, 50, and 60 °C) for activation energy analysis.

In the fixed Q-points study, the transient currents decrease with time at high current Q-points (230 ~ 450 mA/mm) showing a significant trapping effect. The transient currents increase or decrease with time at medium current Q-points (~ 100 mA/mm) showing both trapping and detrapping effects. At low current Q-points (< 80 mA/mm), most transient currents increase then decrease with time. Based on the measurements, the trapping effect dominates at high current Q-points which hot carriers would inject into adjacent layers (AlGaN and/or GaN) for trapping. And the trapping effect is not strong function of temperatures indicating tunneling behaviors.

In the switching back to Q-point of 100 mA/mm and 28 V study, if the previous biased current (pre-stressed) is larger than 100 mA/mm, the transient currents decrease with time showing trapping effects. If the previous biased current (pre-stressed) is smaller than 100 mA/mm, the transient currents increase with time showing detrapping effects. Bot trapping and detrapping behaviors are not strong function of temperatures too.

All current transient measurements (on-state stress) in this study showed complicate trapping and detrapping behaviors at different Q-points and substrate

temperatures. This observation would strongly relate to the performance of GaN HEMT power amplfiers, further investigation and correlation are necessary.

EP08.10.03
Temperature Dependence of Gate Leakage Current in p-GaN/AlGaN/GaN HEMTs Ming-Yan Tsai[1], Yi-Nan Zhong[1], Chen-Ting Chiang[2] and Yue-Ming Hsin[1]; [1]National Central University, Taoyuan City, Taiwan; [2]Delta Electronics, Taoyuan City, Taiwan.

AlGaN/GaN HEMTs have been widely applied in power switching devices due to superior GaN properties including high breakdown field, high switching frequency, and good-thermal characteristics. A two dimensional electron gas (2DEG) with high electron mobility is formed as a channel at the interface of the AlGaN and GaN layers to further improve on-resistance because of polarization effects. However, enhancement-mode (E-mode) transistor is preferred in the power switching circuits, therefore AlGaN/GaN HEMTs with p-GaN gate to deplete the underneath 2DEG channel is currently used as the major technology to achieve E-mode operation.

If a p-type ohmic contact metal for gate electrode is used, the p-GaN/AlGaN/GaN forms a pin diode. This pin diode starts to turn on at high positive gate voltages and induces high gate leakage current, which limits the E-mode operation and input gate voltage swing. Alternatively, a p-type Schottky contact metal for gate electrode is used to reduce the gate leakage current and maximize the gate voltage swing. In spite of that, the Schottky diode formed at the gate metal and p-GaN dominates the gate leakage current at high positive gate bias owing to the reverse voltage drop on Schottky diode. This study investigates the temperature dependence of gate leakage current in E-mode p-GaN/AlGaN/GaN HEMTs with Schottky gate metallization.

E-mode p-GaN/AlGaN/GaN HEMTs were grown on 6-inch Si substrate and fabricated by a commercial foundry. Devices with gate width of 2×400 μm were studied. The I_G-V_{GS} characteristics at V_{DS} of 0 and 10 V were measured under various temperatures (25, 50, 75, 100, 125, and 150 °C). The gate structure is consisted of a Schottky diode (D1) formed by metal/p-GaN and a p-GaN/AlGaN/GaN diode (D2) in series.
At V_{GS} = 7V and V_{DS} = 0V, which Schottky diode (D1) dominates the leakage current, the gate leakage current increases with increasing temperatures. The possible leakage current mechanisms include Thermionic emission, Fowler-Nordheim tunneling, and Poole-Frenkel effect.
By using Thermionic emission equation to approximately estimate the Schottky gate diode, an effective barrier height of 0.26 eV was obtained. The 0.26 eV is much lower than Schottky barrier height. By using Poole-Frenkel effect, the barrier height for hole emission from the trap state is about 0.6 eV. The measurements show Fowler-Nordheim tunneling and Poole-Frenkel effect dominate the gate leakage current at V_{GS} = 7V or an Ohmic-like gate electrode.
At V_{GS} = -8, -9, and -10 V, which p-GaN/AlGaN/GaN diode (D2) dominates the leakage current, the gate leakage currents show less temperature dependence.

In this study, gate leakage currents at various temperatures were investigated on p-GaN/AlGaN/GaN HEMTs. The results show the major leakage is dominated by Schottky diode in high positive gate bias.

EP08.10.04
Physical and Electrical Properties of ALD-Al_2O_3/GaN MOS Annealed by High Pressure Water Vapor Yuta Fujimoito, Mutsunori Uenuma, Tubasa Nakamura, Masaaki Furukawa, Yasuaki Ishikawa and Yukiharu Uraoka; Graduate School of Materials Science, Nara Institute of Science and Technology, Nara, Japan.

GaN-based field effect transistors with metal oxide semiconductor have attracted much attention as power devices that enable low-loss and high-power driving. Gate dielectric layers have the ability to suppress the gate leakage current owing to their large conduction band offset with the nitride semiconductor. Controlling the interface state density between the gate dielectric and GaN is a key issue. We propose a post-deposition treatment that is called high pressure water vapor annealing (HPWVA).[1] This study focuses on the effect of HPWVA on Al_2O_3/GaN by evaluating the electrical characteristics of the MOS structure and the physical analyses of HPWVA, especially the reaction mechanisms which remain unclear.
Al_2O_3 films (40 nm) were deposited on n-GaN epitaxial layer by ALD at 300ºC using TMA and O_3. After the Al_2O_3 deposition, the samples were treated with HPWVA at 400ºC for 0.5 h at 0.5 MPa. Then, upper and lower electrodes were deposited. For comparison, we prepared w/o HPWVA samples.
Current density-electric field characteristics show that the breakdown electric field was improved from 7.5 MV/cm to 9.3 MV/cm by HPWVA.
Capacitance-voltage characteristic (C-V) show flat band shift voltage of 2.01 V and 0.83 V, respectively. The C-V curve of the HPWVA sample is the closest to theoretical C-V curve. The fixed charge density improved from 4.2×10^{11} to 2.9×10^{11} (cm^{-2}) and interface state density which were calculated by using Hi-Low method improved from ~2.0×10^{12} to ~7.0×10^{11} ($eV^{-1}cm^{-2}$) (at Ec-Et: 0.2 eV). The reliability by time dependent dielectric breakdown shows that the maximum allowable electric field was increased by about 25 % at room temperature.
From thermal Desorption Spectrometry profiles, HPWVA sample shows higher desorption of H_2O and smaller desorption of C_xH_y and CO_2 than the w/o HPWVA. Therefore, HPWVA leads to improvement of the termination with OH group to defect of Al_2O_3 films and reducing the residual hydrocarbon. In addition, X-ray Photoelectron Spectroscopy profile of Ga2p at the Al_2O_3/GaN interface shows that the Ga-O binding increased after HPWVA. Therefore, it is considered that a thin $AlGaO_x$ transition layer is formed by HPWVA.
Finally, through defect termination of OH groups and reduction of residual carbon by HPWVA, high quality Al_2O_3 were produced leading to reduction of N_f and improvement of reliability. The low Dit is considered to be due to the termination of defects at the Al_2O_3/GaN interface by oxidizability of HPWVA. This research would contribute to realizing GaN MOSFET including high quality Al_2O_3/GaN interface for power semiconductor devices.
[1] T. Sameshima, and M. Satoh, Jpn. J. Appl. Phys., 36, L687 1997.

[Acknowledgements]
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EP08.10.05
Ultrahigh-Yield Growth of GaN via Halogen-Free Vapor-Phase Epitaxy Daisuke Nakamura and Taishi Kimura; Toyota Central R&D Labs Inc, Nagakute, Japan.

To realize commercially feasible vertical GaN-based power devices, a sustainable supply of high-quality, large-diameter GaN wafers at low cost is required. Particularly, the cost of GaN wafers should be made comparable to that of Si and SiC wafers. Therefore, efficient incorporation of Ga into GaN crystals in the growth process (i.e., a high material yield of Ga) is critically important for reducing the total cost of GaN wafers as it would minimize Ga consumption in the production of GaN wafers. We demonstrated the HF-VPE GaN growth of high-quality thick GaN layers at the relatively high growth rate of ~100 μm/h. HF-VPE employs a simple reaction scheme [Ga (g) + NH_3 → GaN (s) + $3/2H_2$], it can lead to an efficient reaction, a low reverse reaction rate, or both. The present study investigates the critical growth parameters and mechanisms that govern the material yield of Ga in HF-VPE GaN growth, and demonstrates ultrahigh-yield HF-VPE GaN growth.
The setup employed here for HF-VPE GaN growth was almost the same as that described in previous reports. A total of 27 growth experiments were

carried out using a 2”-diameter sapphire substrate as a seed. The growth parameters of concern were the seed substrate holder temperature, the Ga crucible temperature, the background pressure p, the gas flow rates, and the seed-to-crucible-outlet distance d; their effects on the material yield of Ga, Y_{Ga}, during HF-VPE GaN growth were investigated. A linear multivariate analysis was conducted to find the critical growth parameters that govern Y_{Ga}.
The Y_{Ga} values are in the range of 14—23%, which are considerably higher than those for conventional HVPE GaN growth (5—10%). The critical growth parameters identified in the best model for the multivariate analysis were d, p, $Q_{carrier}$, Q_{sheath}, $Q_{dilution}$, and Q_{NH3}. Based on the regression coefficients for the critical growth parameters, the regression equation for calculating Y_{Ga}^{cal} was formulated.
The dependence of Y_{Ga} on d suggests that the gas-stream pathways for Ga vapor nearer to the seed substrate surface are a dominant factor in achieving a higher Y_{Ga}. With a low p and a small d, most of the gas-stream pathways for Ga vapor (denoted by blue arrows) almost reach the seed surface owing to their high gas-stream velocity and the short seed-to-source distance. Considering the above discussion on the gas-stream pathways of Ga vapor, we employed larger-diameter seed substrates (3”- and 4”-diameter sapphire substrates) to demonstrate the suppression of Ga vapor escape and the resultant higher Y_{Ga}. Y_{Ga} increases almost linearly with increasing seed substrate diameter, with an ultrahigh Y_{Ga} of ~47% obtained for the 4”-diameter substrate. With this ultrahigh material yield, we believe that HF-VPE can be used to produce a sufficient number of GaN wafers for high-power vertical GaN devices at moderate prices without depleting the global Ga supply.

EP08.10.06
Aluminum Nitride Nanowire Flexible Ultraviolet Photodetectors Yassir A. Ali and Kasif Teker; Electrical and Electronics Engineering, Istanbul Sehir University, Istanbul, Turkey.

One-dimensional nanostructured wide bandgap (WBG, typically[endif]-->between 3 eV – 6 eV) semiconductor materials are good candidates as building blocks for photosensitive device applications such as UV photodetectors, phototransistors, and photodiodes. Furthermore, high UV light sensitivity, small size, very short response time, low power consumption, and high efficiency are the most important features of nanodevices for new and superior applications photonics. AlN nanostructures, an important III-V WBG semiconductor, have aroused significant interest due to its large direct bandgap (6.28 eV), low electron affinity, high thermal conductivity, high melting point (above 2300ºC), and chemical stability. Despite its intrinsic superior properties, challenges in synthesis of defect free and uniform morphology AlN nanostructures persist, thereby limiting the number of electronic and photonic device studies.

This paper presents the fabrication of a flexible ultraviolet (UV) photodetector from free-standing catalyst-free AlN nanowire (AlNNW) films via a direct transfer method through a very low-cost non-lithographic fabrication scheme. The device has demonstrated very fast photoresponse rise and decay times of 0.27 s and 0.41 s to the deep-UV light illumination, respectively. The photocurrent measurements have been conducted for bias voltages from 1V to 20V. In fact, the flexible AlNNW photodetector is very sensitive to the UV illumination even at low bias voltages (as low as 1V) indicating very high sensitivity and capability of operating at low voltages. Moreover, the photocurrent has decayed to the dark current value rapidly, after the exposure ended, suggesting the absence of defect-related traps. Consequently, the facile fabrication scheme is very cost-effective, readily scalable; and offers broad integration capabilities in various flexible photonic and electronic applications including wearable devices.

EP08.10.07
Solid-Phase Heteroepitaxy and Synchrotron Radiation Analyses of β-Ga_2O_3 Thin Films Fabricated by Room-Temperature Laser Processes Akifumi Matsuda[1], Hiroyuki Morita[1], Tomoaki Oga[1], Yanna Chen[2], Okkyun Seo[2], Osami Sakata[2, 1], Nobuo Tsuchimine[3], Satoru Kaneko[4, 1] and Mamoru Yoshimoto[1]; [1]Tokyo Institute of Technology, Yokohama, Japan; [2]Synchrotron X-ray Station at SPring-8, National Institute for Materials Science, Sayo, Japan; [3]TOSHIMA Manufacturing Co., Ltd., Higashi-matsuyama, Japan; [4]Kanagawa Institute of Industrial Science and Technology, Ebina, Japan.

Semiconductor β-Ga_2O_3 has bandgap of E_g~4.9 eV wider than SiC and GaN. There have been reports to grow epitaxial β-Ga_2O_3 thin films by MBE, PLD, MOCVD, Mist-CVD at substrate temperature above 400°C; those high-quality and highly oriented films have applications to deep-UV optoelectronics and high-efficient power transistors. On the other hand, reduction of the epitaxy temperature should also contribute to advance device development owing to suppressed interfacial roughness and compositional deviation. The low-temperature process would also support epitaxial Ga_2O_3 nanomaterials to be integrated with flexible materials and devices in addition. In this study, β-Ga_2O_3 epitaxial thin films was obtained via amorphous film deposition and subsequent solid-phase epitaxy by sequential room-temperature laser processing; and its crystallization mechanism was studied through structural analyses and morphological evaluation.
The precursor amorphous Ga_2O_3 thin films were grown on atomically stepped α-Al_2O_3(0001) substrates with ultra-thin rocksalt-type or wurtzite-type buffer layers by PLD at room-temperature in 10^{-3} Pa of O_2 using a β-Ga_2O_3 sintered target. The amorphous Ga_2O_3 films were subsequently irradiated 500–1000 pulses of the KrF laser beam for excimer laser annealing (ELA). A six-axis diffractometer in SR-XRD was used to evaluate the lattice parameters and to measure the reciprocal space map, such as out-of-plane -201 and in-plane 002 for Ga_2O_3 thin film, 111 and 1-11 including reflectivities for NiO seed layers, 0006 and 11-23 for α-Al_2O_3(0001) substrates. The epitaxial β-Ga_2O_3(-201) thin films with six-fold in-plane symmetry were obtained on rocksalt-type buffer layers after the ELA procedure, while the films on wurtzite-type buffer remained uniaxial oriented and planarly isotropic. Although, the crystallization did not propagate to the surface in case of excessive precursor thickness, while insufficiently thick films remained amorphous. The d-spacing of NiO seed layers having different thickness shows a constant value because of the high-quality epitaxial growth of their layers on sapphire substrates. On the other hands, the d-spacing of the β-Ga_2O_3 thin films shrunk in the in-plane direction and expanded in the out-of-plane direction. β-Ga_2O_3 thin film with NiO of 2 nm thick showed the best epitaxial quality when we judged from FWHM values of rocking curves.The results suggested importance of total consumption of energy above a threshold via photothermal process as well as a trigger of effective absorption of the reached excimer laser at the interface between amorphous and crystallized regions or the buffer layer, that optical absorption of the precursor amorphous Ga_2O_3 films well agreed the Lambert-Beer Law.
[1] M. Higashiwaki et al., *Appl. Phys. Lett.* **100** (2012) 013504.
[2] F.B. Zhang et al., *J. Cryst. Growth* **387** (2014) 96–100.
[3] D. Shiojiri et al., *Appl. Phys. Exp.* **9** (2016) 105502.

EP08.10.08
Solid-State Synthesis of Hexagonal Boron Nitride Crystals Clint D. Frye[1], James H. Edgar[2] and Rebecca Nikolic[1]; [1]Lawrence Livermore National Laboratory, Livermore, California, United States; [2]Chemical Engineering, Kansas State University, Manhattan, Kansas, United States.

Ultrawide bandgap (UWBG) semiconductors such as diamond, AlN, Ga_2O_3, and AlGaN are emerging electronic and optoelectronic materials. However, material quality and availability remain immature and lag conventional semiconductors such as silicon or even silicon carbide and gallium nitride. Hexagonal boron nitride (hBN) has many of the same advantages of other UWBG materials such as low chemical reactivity, high temperature operation, and high critical electrical field, but it also has a layered 2D structure and been shown to emit light at 215 nm. These properties are valuable for a wide array of applications such as deep ultraviolet (DUV) optoelectronics, neutron detection, electronics in harsh hot environments, and as the preferred substrate and dielectric for 2D electronics (graphene, MoS_2, etc.). Crystal growth of hBN, however, is relatively unexplored, and a lack of high quality crystals has limited device fabrication. In this work, hBN crystals were grown by a wholly solid-state process. 300 nm of NiCr was sputter deposited onto

pyrolytic BN and then annealed in a rapid thermal annealer in Ar at 980 °C for 3-15 min. During the annealing, B and N from the pyrolytic boron nitride substrate dissolved into and diffused across the NiCr film. As the samples cooled, hBN precipitated on the top side of the NiCr film. The NiCr metal serves simultaneously as a solvent, template, and catalyst. hBN platelets up to 1 um in diameter were grown as confirmed by Raman analysis. NiCr was selected because it has been used as a liquid solvent for hBN growth and has a small lattice mismatch of 0.4%. Cr, which has a strong affinity for N, was alloyed with Ni to increase N solubility as pure Ni has a very low N solubility. The chromium content in the NiCr films was varied from 0-40 mol%. This growth technique uses readily available materials, common vacuum processing equipment, relatively low temperatures, and has the potential to be scaled up to wafer scales or made into a steady state crystal growth process. A roadmap will be presented on how to scale up the size of the crystal platelets to wafer scales.

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EP08.10.09
Fabrication of MIM Diodes by Atmospheric Pressure Spatial Atomic Layer Deposition (AP-SALD) System Abdullah Alshehri[1, 2], Kissan Mistry[1], Khaled Ibrahim[1], Viethuong Nguyen[3], David Munoz[3], Mustafa Yavuz[1] and Kevin Musselman[1]; [1]Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada; [2]Mechanical Engineering, Prince Sattam bin Abdulaziz University, Alkharj, Saudi Arabia; [3]Laboratoire des Matériaux et du Génie Physique, Grenoble, France.

A novel quantum metal-insulator-metal (MIM) diode is fabricated by atmospheric pressure spatial atomic layer deposition (AP-SALD) system. This scalable method was used to produce MIM diodes with high-quality, pinhole-free Al_2O_3 film more rapidly than by conventional ALD. MIM diode fabricated by AP-SALD system shows lower effective barrier height (1.27 eV) between electrode-insulator interface than that of MIM by conventional ALD (1.44 eV) resulting lower turn on voltage (V_{ON}= 1V) and better asymmetry and nonlinearity values 4.5, 8 respectively, and demonstrate that clean room fabrication is not a prerequisite for quantum-enabled devices.

EP08.10.10
Atomic Layer Etching for Selective Area Doping of GaN Kevin A. Hatch, Houqiang Fu, Jesse Brown, Xingye Wang, Mei Hao, Yuji Zhao and Robert J. Nemanich; Arizona State University, Tempe, Arizona, United States.

The development of high efficiency GaN power devices using vertical architectures is hindered by the ability to achieve selective area doping of the *p-n* junction. This process may be improved by the removal of surface damage caused by the conventional inductively coupled plasma (ICP) etching and regrowth method, which may create defects, impurities, and surface states that impact the junction properties. We have demonstrated surface etching of GaN allowing controlled material removal. Our technique uses *in situ* remote plasma-enhanced atomic layer oxidation of the ICP etched surface followed by oxide removal through H-plasma etching. The removal of damaged layers at the surface resulted in an increase of the surface band bending to a value 0.5 ± 0.1 eV for previously ICP etched n-type GaN and 0.7 ± 0.1 eV for non-etched n-type GaN. The variation in band bending indicates continued removal of damage over several cycles of this repeated process for the etched material whereas the non-etched GaN displayed no change in the band bending after the first cycle, consistent with dry cleaning of surface contamination.
This work was supported by ARPA-E, grant No. DE-AR0001691.

EP08.10.11
Observation of Slow and Controllable Growth of Filament in Conducting-Bridge Memory Atsushi Shimizu[1], Hiroshi Sato[1], Sohta Hida[2] and Kentaro Kinoshita[1]; [1]Faculty of Science, Tokyo University of Science, Katsushika, Japan; [2]Tottor University, Tottori, Japan.

Resistive switching memories are drawing attention as memories that can overcome miniaturization and other performance limits facing conventional memories. Among them, filament growth-based resistive switching memories especially show high performance and are largely categorized into anion diffusion-type, which is generally called resistive random access memory, ReRAM, and cation diffusion-type, which is called conducting-bridge RAM, CBRAM. Although they tend to be mixed up in the category of a filament type resistive switching memory and both of them are expected as a non-volatile memory for next generation, it is important to elucidate intrinsic difference of their performances to select appropriate applications. In this paper, the difference of filament growth characteristics between them are discussed using ReRAM and CBRAM of top electrode(TE)/metal oxide(MO)/bottom electrode(BE) structures which were fabricated sharing the same MO and BE layers.
A ZrO_2 layer with a thickness of 25 nm was deposited on a Pt(100nm)/Ti(20nm)/SiO_2(100nm)/Si(650nm) substrate using an RF sputtering method. Then, both Cu and Pt top electrodes were deposited on the ZrO_2 film by an RF magnetron sputtering method. Accordingly, Cu/ZrO_2/Pt CBRAM structures (ZrO_2-CBRAM) and Pt/ZrO_2/Pt OxReRAM structures (ZrO_2 -ReRAM) were fabricated sharing the same ZrO_2 layer as a memory layer.
We succeeded in observing the transient of the resistance from high resistance state, HRS, to low resistance state, LRS, of the CBRAM device, by inserting a load resistance. The load resistance should have an appropriate resistance value to divide a voltage applied to the CBRAM device, V_{device}, to the load resistance when set switching is caused. It is noticeable that CBRAM resistance continues to decrease even when V_{device} is decreasing unless a current is also decreasing, which is consistent with a widely received picture that the growth of filaments is rerated to ionic current, i.e., the flow of cupper ions in the present case. On the other hand, the increasing rate of a resistance is too rapid to be detected within the sampling rate of 10 μs, meaning that the resistance of ReRAM device decreases to the resistance value lower than the load resistance within 10 μs after the occurrence of set switching. The difference of the observability of the transient state between CBRAM and ReRAM devices strongly suggests the difference of the switching speed between them. Fast switching speed of ReRAM causes large surge current through the parasitic capacitance of a measurement circuit, although the same measurement circuit was used for both devices. The large surge current enhances the growth of filaments and makes a reset current, I_{reset}, large. On the other hand, slow switching speed of CBRAM highly enhances the controllability of I_{reset} ranging more than six orders of magnitude, 0.1 nA - 1.0 mA.

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[2] A. Chen, Proc. IEEE IRPS, MY.2, 2012.

EP08.10.12
Theoretical Study on Oxygen Vacancies in Crystal Grains in Polycrystalline HfO_2 Thin Firm Sohta Hida[1, 2], Takumi Morita[2], Takahiro Yamasaki[3], Jun Nara[3], Takahisa Ohno[3] and Kentaro Kinoshita[2]; [1]Graduate School of Sustainability Science, Tottori University, Tottori, Japan; [2]Faculty of Science, Tokyo University of Science, Katsushika, Japan; [3]National Institute for Materials Science, Tsukuba, Japan.

Metal oxides such as HfO_2 are widely received as materials for the fabrication of memory layers of Resistive Random Access Memory (ReRAM) [1]. It is theoretically reported that electric characteristics were changed by introducing vacancies into HfO_2 single crystal or grain boundary [2, 3]. In these studies, they suggested that resistive switching is caused by diffusion and aggregation of oxygen vacancies (V_O's). However, no one demonstrates the whole of the process during the resistive switching, i.e., detailed movement of V_O's between high and low resistance states.

In this paper, the first principles molecular dynamics (FPMD) program PHASE/0 [4] was used to discuss the generation and movement of V_O's. We calculated the generation energy of V_O (E_{Vo}) on the surface and far from the surface of HfO_2 periodic slab which was modeled based on our experimental results [5]. E_{Vo} for the former and the latter are 9.043 eV and 9.807 eV, respectively. Therefore, V_O's are easily generated near the surface than far from the surface.
We theoretically observed the process of structural relaxation and the effects of changing charge states of V_O's and raising a temperature to 1000 K, by FPMD. When the charge state of V_O's changes from divalent (V_O^{2+}) to neutral (V_O^0), V_O's are attracted each other and aggregate. On the other hand, when the charge state of the V_O's changes from V_O^0 to V_O^{2+}, V_O's are repelled against each other and disperse. The difference of the static energy between the aggregated and dispersed states was 0.67 eV. In addition to the result above, we previously reported that slight displacements of small amounts of atoms alter the surface electric state from conductive to insulating or vice versa [6]. Therefore, resistive switching of ReRAM can be caused by aggregation and dispersion of V_O's depending on the charge state of V_O's, with the assistance of Joule heat. The location at which resistive switching takes place is near the surface of crystal grains where V_O's are expected to move easily due to the symmetry of bulk crystal is broken. This type of resistive switching can be caused by applying voltage to a metal/metal oxide structure, which changes Fermi level and causes injection (extraction) of electrons from (to) the metal to (from) the metal oxide layer.
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[5] in preperation
[6] Moriyama et al., Journal of Applied Physics, 56, 04CE12 (2017)

EP08.10.13
The Nitrogen Impurity in Wide-Band-Gap Oxide Semiconductors Intuon Chatratin[1], Pakpoom Reunchan[1, 2] and Anderson Janotti[3]; [1]Department of Physics, Kasetsart University, Bangkok, Thailand; [2]Thailand Center of Excellence in Physics (ThEP Center), Commission on Higher Education, Bangkok, Thailand; [3]Department of Materials Science and Engineering, University of Delaware, Newark, Delaware, United States.

Wide-band-gap oxide semiconductors are promising for various device applications, yet controlling the electrical conductivity and achieving p-type doping remain challenging. Among the possible acceptor impurities, N would be the most promising due to atomic size considerations. We use hybrid density-functional calculations to study the effects of the nitrogen impurity on the electronic and optical properties of the wide band-gap oxides ZnO, SnO_2, In_2O_3, TiO_2, $SrTiO_3$ and $BaTiO_3$. In ZnO, SnO_2, In_2O_3, and TiO_2, we find that N incorporating on the O site (N_O) introduces donor and acceptor levels in the gap, with the donor level below the acceptor level, as in an AX center. In $BaTiO_3$ and $SrTiO_3$, N_O is, however, a negative-U center, with a (+/-) level in the gap and an unstable neutral charge state. In the donor charge state, elongated metal-N bonds are observed in ZnO, SnO_2 and TiO_2, but not in In_2O_3, $SrTiO_3$ and $BaTiO_3$. The formation of the AX-like configurations makes it difficult to achieve p-type conductivity due to self-compensation. The optical absorption and emission peaks of $N_O$are calculated by constructing configuration coordinate diagrams based on the Franck-Condon principle, and the results are compared to the available experimental data.

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Preparation of Wide Gap n-Type $Sn_2Ta_2O_7$ Polycrystalline Films by Magnetron Sputtering Shunichi Suzuki[1, 2], Naoto Kikuchi[2], Yoshihiro Aiura[2] and Keishi Nishio[1]; [1]Materials Science and Technology, Tokyo University of Science, Katsushika, Japan; [2]Electronics and Photonics Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.

Transparent conductive oxides (TCOs) have a potential in various applications to electronic devices. Actually n-type TCOs such as tin-doped indium oxide (ITO) have been used for displays, solar cells and so on. On the other hand, p-type TCOs have not been practicable due to low hole mobility. The reason for low hole mobility for many transparent oxides is localized valence band maximum (VBM) composed of O2p. For realizing the p-type TCOs, the VBM composed of delocalized orbitals of metal elements is essential. Our group focused on $Sn_2Ta_2O_7$ of which VBM is composed of Sn5s and succeeded in preparation of p-type and n-type $Sn_2Ta_2O_7$ bulks depending on annealing condition. Hole and electron carriers were also found to be generated by Sn^{4+} -on-Nb^{5+} substitutional defects and oxygen vacancies, respectively. For the application of new transparent electronic devices based on the p-n junction, preparation of $Sn_2Ta_2O_7$ films is indispensable. However there is no report on conductive $Sn_2Ta_2O_7$ films as of today. In this study, we report the preparation of n-type polycrystalline thin films of $Sn_2Ta_2O_7$, and the effect of annealing conditions on their electrical properties.
$Sn_2Ta_2O_7$ polycrystalline thin films were fabricated by magnetron sputtering. Dense $Sn_2Ta_2O_7$ was used as a target. The sputter deposition was performed at an Ar gas pressure of 0.5 Pa with an rf power of 100 W. $Sn_2Ta_2O_7$ films were deposited on SiO_2 glasses at a substrate temperature of 848 K and followed by annealing under N_2 gas flow at 773-973 K for 6 h in tubular furnace. Crystalline phases were identified by X-ray diffraction (XRD). Band gap (E_g) of the films were estimated from the transmission spectra using the Tauc plot. Resistivity and Hall measurements were carried out at room temperature.
E_g of the films was estimated to be 3.2 eV, indicating high transparency in visible range. After the annealing over 873 K for 6 h under N_2 gas flow, the thin film samples showed n-type conductivity. Electrical resistivity, carrier density and mobility were 1.2 ohm cm, 5.4×10^{18} cm^{-3}, 9.9×10^{-1} $cm^2V^{-1}s^{-1}$.
$Sn_2Ta_2O_7$ with small amount of $Sn_2Ta_2O_{8+x}$ and SnO_2 as impurity phases was found in XRD patterns. The amount of impurity phases increased with increasing temperature. In summary, we succeeded in preparation of wide-gap, n-type $Sn_2Ta_2O_7$ films which showed both p- and n-type conductivity in powder samples.

EP08.10.15
Surface Band Bending of Polar ZnO by Hard X-Ray Photoemission Combined with X-Ray Total Reflection Shigenori Ueda; National Institute for Materials Science, Hyogo, Japan.

ZnO is known as a polar semiconductor due to an alternative stacking of Zn and O layers along the c-axis. Ohashi *et al*. [1] showed that the valence band spectral shapes of ZnO single crystals strongly depended on the crystalline orientation from hard X-ray photoemission spectroscopy (HAXPES) measurements. In general, HAXPES is a bulk-sensitive probe [2], and take-off angle (TOA) dependent of photoelectron gives depth information [3]. However, the decrease of the photoemission intensity occurs in lower TOA, and the valence band spectra depend on TOA [3] due to the matrix element effect [4].
In this work, HAXPES combined with X-ray total reflection (TR-HAXPES) [5] was used to obtain a depth-resolved electronic structure instead of TOA dependent measurements. We have measured the core-level and valence band HAXPES spectra of commercially available bulk single crystalline ZnO for Zn- and O-polar faces in the case of effective inelastic mean free path of 2.0, 4.1, and 8.0 nm by tuning the X-ray attenuation length. Undoped *n*-type ZnO crystals with fine polished surfaces were used. The valence band spectra of ZnO showed the clear polarity dependence as reported in Ref. [1]. The depth dependence of the valence spectra showed the nearly flat band behaviors for the Zn- and O-polar ZnO faces, in contrast to those for the Ga- and N-polar GaN faces [5]. The Zn 3s and O 1s core-level spectra also showed the nearly flat band behaviors for both the Zn- and O-polar faces. These nearly flat band behaviors are attributed to the pining by the states located at the Fermi-level. We will discuss the band bending behaviors and electronic structures of ZnO in comparison with those of GaN.

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Fabrication of Rocksalt-Structured MgZnO/MgO Layered Structures and Their DUV Light Emission Properties Kyohei Ishii[1], Mizuki Ono[3], Takeyoshi Onuma[3], Kentaro Kaneko[2] and Shizuo Fujita[2]; [1]Electronic Science and Engineering, Kyoto University, Kyoto, Japan; [2]Photonics and Electronics Science and Engineering Center, Kyoto University, Kyoto, Japan; [3]Applied Physics, School of Advanced Engineering, Graduate School of Engineering, Kogakuin University, Tokyo, Japan.

Recently, deep ultraviolet (DUV) light sources using wide bandgap materials attract much attention because they can substitute for gas sources due to their small-size, low cost, and capability of arbitrary tuning the emitting wavelength. Our group has been focusing on rocksalt-structured MgZnO (RS-MgZnO), possessing the maximum bandgap energy of 7.8 eV[1], as a candidate capable of emitting DUV light of the wavelength range shorter than 200 nm, which cannot be realized by AlGaN.
At first, MgZnO thin films were grown on MgO (001) substrates by the mist CVD method. Magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$) and zinc chloride ($ZnCl_2$) were used as precursor sources of Mg and Zn, respectively. The source molar ratio of [Mg]:[Zn] was 90:10. Then, MgZnO/MgO layered structure samples were fabricated. The structure consists of four periods of MgO barrier and MgZnO well layers.
X-ray diffraction (XRD) 2θ/ω scan profile of the MgZnO thin film indicated that the RS-MgZnO without other crystalline phases was successfully grown. Atomic force microscopy (AFM) observation showed a smooth surface with a root-means-square (RMS) roughness of 0.20 nm. Additionally, step-terrace structure was observed on the film surface, where the step height was 0.42 nm corresponded to the diatomic length. Cross-sectional transmission electron microscope (TEM) observation do not show the generation of misfit dislocation at the interface, i.e., only dislocation lines originated from the MgO substrate exist in the MgZnO film. The dislocation density in the MgZnO film is estimated to be less than 10^7 cm^{-2}. The improvements of crystalline quality resulted in the observation of predominant DUV emission peak at 5.86 eV (212 nm) at 6 K and 5.71 eV (217 nm) at 300 K in the cathodoluminescence (CL) spectra. Other peaks at the longer wavelengths, which were remarkable in our previous report [2], were negligibly reduced. The improvements in optical quality may be attributed to the use of carbon-free sources instead of the acetate sources as used in the previous study[2]. Spectrally integrated CL intensity at 300 K over that at 6 K (I_{300}/I_6) was estimated to be 2.5%. CL spectra of MgZnO/MgO layered structure exhibited a peak at 5.96 eV (208 nm) at 6 K and 5.90 eV (210 nm) at 300 K. Apparent increase in the peak energies of 0.1 eV (0.19 eV) at 6 K (300 K) were confirmed. Moreover, I_{300}/I_6 of 16% was 6 times higher than that of the MgZnO thin film. Further research toward the vacuum ultraviolet (VUV) emission at the wavelength range shorter than 200 nm is in progress.
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Novel P-Type Oxide Semiconductors of α-Ir_2O_3 in Gallium Oxide Electronics Kentaro Kaneko[1], Shinichi Kan[1], Shu Takemoto[1], Isao Takahashi[2], Masahiro Sugimoto[2], Takashi Shinohe[2] and Shizuo Fujita[1]; [1]Kyoto University, Kyoto, Japan; [2]FLOSFIA INC., Kyoto, Japan.

Gallium oxide (Ga_2O_3) electronics, owing to ultra-wide bandgap of Ga_2O_3, is one of the most emerging fields in electronic materials research because some of the materials properties of Ga_2O_3 are advantageous over SiC and GaN for power device applications. Ga_2O_3 takes several different crystal structures, among which monoclinic Ga_2O_3 (β-Ga_2O_3) is the thermally stable phase, and marked progress for device applications are reported [1].
On the other hand, rhombohedral corundum-structured Ga_2O_3 (α-Ga_2O_3) is attractive in view of bandgap engineering from 3.7 to ~9 eV by alloying with corundum-structured α-Al_2O_3 and α-In_2O_3. With mist CVD growth, high-quality α-Ga_2O_3 is grown on sapphire (α-Al_2O_3) substrates [2], followed by evolution of Schottky barrier diodes with extremely low on-resistance [3]. However, the lack of p-type oxide semiconductors acting as a counterpart of n-type α-Ga_2O_3 has obstructed high-performance power devices based on α-Ga_2O_3.

Our attention has been focused on corundum-structured α-$(Rh,Ga)_2O_3$ [4] and α-Ir_2O_3. An α-$(Rh,Ga)_2O_3$ thin film showed clear p-type conductivity by Hall-effect measurements with the hole mobility of 1.0 cm^2/Vs and the hole concentration of 7.6×10^{17} cm^3. On the other hand, α-Ir_2O_3 was reported as a p-type oxide confirmed by thermoelectric power measurement with a band gap of 2.6 eV[5]. Almost reports about α-Ir_2O_3 were poly crystals, multi-domain crystals, or oxidation layer generated at Ir metal surface[5-6].
Single-crystalline α-Ir_2O_3 thin films were fabricated on c-plane sapphire (α-Al_2O_3) substrates by mist CVD technique. The growth rate was accomplished up to 7.5 mm/h. A lattice mismatch between α-Ir_2O_3 and α-Ga_2O_3 was calculated as 0.3% along a-axis from cross-sectional TEM observations. Obtained α-Ir_2O_3 and α-$(Ir,Ga)_2O_3$ showed clear p-type conductivity, especially for α-$(Ir,Ga)_2O_3$, it has a hole density and a mobility of $3.7\times10^{20}/cm^3$ and 2.9 cm^2/Vs, respectively.
These results pave the way to fabricate pn junctions with an n-type α-Ga_2O_3 layer and a p-type α-Ir_2O_3. Highly-doped α-Ga_2O_3 (n+) and α-Ga_2O_3 (n-) layers were fabricated on α-Ir_2O_3 (p+) thin film on sapphire substrate. The junction showed rectification properties. From the current-voltage measurement, depletion layer was mainly spread into the α-Ga_2O_3 (n-) from α-Ga_2O_3 (n-)/α-Ir_2O_3 (p+) interface because of the large value of hole concentration in the α-Ir_2O_3 (p+).
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Controlled p-Type Doping of CuSCN Ajith DeSilva[1, 2], G. R. A. Kumara[3], K. Tennakone[2] and Unil Perera[2]; [1]University of West Georgia, Carrollton, Georgia, United States; [2]Physics and Astronomy, Georgia State University, Atlanta, Georgia, United States; [3]National Institute of Fundamental Studies (NIFS), Kandy, Sri Lanka.

Solution processable optically transparent p-type semiconductors are rare. Copper (I) thiocyanate (CuSCN) having a direct band gap of ~ 3.9 eV has been identified as one of the most promising materials of the above category. CuSCN is extensively studied as the hole collector material for perovskite and dye-sensitized solid state solar cells and simple techniques are available for casting thin films under ambient conditions. The p-type semiconductivity of CuSCN depends on stoichiometric excess of SCN normally introduced during the method of preparation via reaction of aqueous solutions $CuSO_4$ and KSCN in the presence of a reducing agent. Ultraviolet irradiation and chlorination introduce excess SCN enhancing the conductivity, but drawback here introduction of impurities. A methods developed for controlled doping of CuSCN, using solutions of $Cu(SCN)_2$ in organic solvents will be discussed giving the details of the procedures and results of conductivity measurements of thin film. The method enable introduction of measured quantities of excess SCN into CuSCN without introduction of impurities.

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Controlling the Polarity of Aluminum Nitride Thin Films Using Si-Based Dopants Sri Ayu Anggraini, Masato Uehara, Hiroshi Yamada and Morio Akiyama; AIST, Fukuoka, Japan.

Aluminum nitride (AlN) is a promising wide band-gap material particularly for various electronic applications due to its unique combination of electrical, thermal, acoustic and piezoelectric properties. The functionality of AlN-based thin film can be tuned not only by having a highly c-oriented thin film but also by controlling its polarity. Stacking two AlN-based thin films with different polarities has been reported to improve the performance of a solid mounted BAW resonator [1]. Thin films with an inversed polarity could be obtained by controlling the deposition parameter, such as oxygen concentration [2], sputtering pressure [3], cathode power [4], or it can be also obtained by employing seed a layer to promote the growth of AlN thin films in a certain direction [5]. However, since these techniques often resulted in crystallinity deterioration and require precise control, we propose the use of Si or MgSi dopants to control the polarity of AlN thin film as an alternative method to control the polarity of AlN thin films.
The polarity of the thin film was investigated by examining the piezoelectric response (d_{33}) of the resulting thin films. Incorporating 1-14 at.% of Si could inverse the polarity of AlN thin films from positive (Al-polar) to negative (N-polar) without massively reducing the magnitude of the piezoelectric response. The piezoelectric response of non-doped AlN thin film is 6.9 pC/N, while that of $Si_{0.03}Al_{0.97}N$ was found to be -6.2 pC/N. In case of MgSi-codoped-AlN, the polarity of the thin films is governed by the ratio of Mg to Si. When the Mg/Si ratio is lower than 1, the negative d_{33} values suggest that the thin films are predominantly N-polar. On the contrary, higher Mg/Si ratio (> 1) yielded a positive d_{33} value which indicates that the thin films are mainly Al-polar. Despite of polarity changes, significant enhancement in piezoelectric response by alloying AlN with MgSi was not observed. The effect of Mg and Si addition into AlN is further investigated and elucidated by investigating the change of chemical states, morphology and crystallinity of the thin films.

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Solution-Processed Cubic GaN for Potential Lighting Applications Aakash K. Jain[1], Sushma Yadav[4], Meenal Mehra[3], Sameer Sapra[2] and Madhusudan Singh[1]; [1]Electrical Engineering, IIT Delhi, New Delhi, India; [2]Chemistry, IIT Delhi, New Delhi, India; [3]Momentive Performance Materials (India) Pvt. Ltd., Bengaluru, India; [4]Institut für Physikalische Chemie und Elektrochemie, Leibniz University, Hannover, Germany.

Cubic gallium nitride (GaN) is a wide bandgap semiconductor exhibits high crystallographic symmetry resulting in a lower inbuilt polarization which is useful for more efficient phosphor-free green light-emitting diodes. It has been grown using molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD), which produce highly ordered thin films on compatible substrates. In this work, we report the chemical synthesis of cubic GaN using chemical metathesis reaction in diethyl ether with lithium nitride and anhydrous gallium chloride as precursors, inside a nitrogen glove box at the room temperature. The resulting product was washed to remove lithium chloride and dried before vacuum annealing in a furnace at 850°C. Powder X-ray diffraction (XRD) scans of the as-prepared and annealed product reveal cubic phase of GaN. Energy dispersive X-ray spectroscopy (EDX) measurements show a nitrogen-poor product, which correlates well with the nearly black color of the powder. Diffuse reflectance spectroscopy (DRS) measurements were carried out with the product on a barium sulfate substrate in a Perkin-Elmer 1050 spectrophotometer to obtain strong absorbance below 400 nm, and the Tauc plot for the bandgap estimate of 3.3 eV, which is good agreement with the known excitonic bandgap of cubic GaN. Initial photoluminescence (PL) measurements with an excitation wavelength of 310 nm reveal a weak emission at 440 nm corresponding to the known defect centers (D^0X) in GaN. Further development of this process to form an ink is expected to provide an alternate pathway to producing flexible phosphor free lighting devices.

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Heteroepitaxial Growth of Sn-Doped Ga_2O_3/Sapphire(0001) Thin Films Using Powder Sputtering Methodβα Ha Ram Lee[1], Su Yong Lee[2] and Hyon Chol Kang[1]; [1]Chosun University, Gwangju, Korea (the Republic of); [2]PAL, Pohang University of Science and Technology, Pohang, Korea (the Republic of).

Ga_2O_3 thin films have been widely investigated for use in optoelectronic and photonic devices as well as gas sensors because of a wide bandgap of 4.9 eV and good thermal stability up to its melting point (~1800 °C). Many efforts have focused on demonstrating the performance of electronic devices by varying the doping elements and concentrations. We reports the heteroepitaxial growth of Sn-doped Ga_2O_3 thin films deposited using radio frequency magnetron sputtering onto sapphire(0001) substrates. The crystalline orientation of the films was examined using high-resolution synchrotron x-ray diffraction. The Sn-doped Ga_2O_3 thin films were grown with remarkably high crystallinity and negligible mosaic structure. We found that the corundum α- and monoclinic β-phases of Ga_2O_3 coexisted in the as-grown samples. Azimuthal angle scans of the in-plane β(020) and α(30-30) Bragg peaks revealed that the α-Ga_2O_3 and β-Ga_2O_3 both showed 12-fold in-plane rotational symmetry and, in particular, that the 30° rotated α-Ga_2O_3 domains in the in-plane direction were tilted ±3° to the sapphire direction. It is noteworthy that only 6-fold symmetry has previously been reported for most α- and β-Ga_2O_3 thin films. Finally, the optical bandgap of the as-grown film with a thickness of 185 nm was estimated at 5.03 eV, and it gradually decreased to 4.52 eV as the film thicknesses increased to 1.6 μm, which is attributed to the increased amount of Sn atoms. This might also be affected by the crossover of the dominant phases from the initial alpha phase to the later beta phase.

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Growth Mechanism of In-Doped β-Ga_2O_3 Nanowires Deposited by Radio Frequency Powder Sputtering Su Yong Lee[2] and Hyon Chol Kang[1]; [1]Chosun University, Gwangju, Korea (the Republic of); [2]PAL, Pohang University of Science and Technology, Pohang, Korea (the Republic of).

In the last decade, various techniques have been proposed for synthesizing one-dimensional nanostructures such as nanowires (NWs) and nanobelts, In particular, monoclinic gallium oxide (β-Ga_2O_3) has received considerable attention for use in NWs owing to its wide bandgap of 4.9 eV, high breakdown field (> 8 MV/cm), and high optical transparency to visible and ultraviolet radiation. Recently, applications of β-Ga_2O_3 NWs in optoelectronic and photonic devices, as well as gas sensors, have been widely explored. Moreover, doped β-Ga_2O_3 NWs have attracted even greater interest as doping is an effective way to tune the physical properties of such structures. Many of these efforts have focused on demonstrating the performance of NW-based devices by varying the types and concentrations of the doping elements used, with Eu, Cr, Mn, Sn, and In having been examined. Among them, In is regarded as a promising dopant for significantly enhancing the sensitivity and quantum efficiency in nanobelt-based photodetectors, The synthesis of In-doped β-Ga_2O_3 NWs is typically carried out by thermal evaporation and vapor transport, using a mixture of either In and Ga_2O_3 powders or Ga and In_2O_3 powders as source materials.
Recently, we reported the growth of β-Ga_2O_3 NWs using radio frequency (RF) powder sputtering. The deposition of non-stoichiometric Ga_2O_{3-x} under an oxygen-deficient atmosphere was essential for facilitating the growth of β-Ga_2O_3 NWs by a self-catalytic vapor-liquid-solid (VLS) process using self-assembled Ga seeds. In this work, we examine the growth mechanism of In-doped β-Ga_2O_3 NWs synthesized by powder sputtering. In particular, the role of In atoms in determining the growth mechanism and the structure of NWs is investigated. Although the growth sequence of the doped NWs is similar to that of the undoped β-Ga_2O_3 NWs, the formation of self-assembled In clusters is more favorable compared to Ga clusters. Clusters of In act as seeds for initiating the growth of In-doped β-Ga_2O_3 NWs through a self-catalytic VLS mechanism, while Ga seeds initiate the growth of undoped β-Ga_2O_3 NWs by the same mechanism. We also observed zigzag NWs formed by alternating NW growth directions.

EP08.10.23
Investigation of Luminescence Characteristics of ZnO with Cycled Exposure to Electron Beams Using Cathodoluminescence in Transmission Electron Microscopy Young-Woon Kim[1], Yonghee Lee[1], Sungdae Kim[3], Samdong Kim[2] and Mi-Hyang Sheen[1]; [1]Seoul National University, Seoul, Korea (the Republic of); [2]Dongguk Uinversity, Seoul, Korea (the Republic of); [3]Korean Institute of Materials Science, Changwon, Korea (the Republic of).

ZnO is one of the strong candidates for the electrodes, sensors and detectors for the UV emission. Luminescence characteristics of nano-wire and thin-film ZnO was investigated using cathodoluminescence in transmission electron microscopy (TEM-CL). Ultraviolet (UV) emission revealed reduction with time under electron beam, while the visible light did not show degradation of the luminescence intensity. UV luminescence decreased exponentially leaving 30% of intensity after 200 seconds exposure with electrons of 200keV, 12 pA/cm^2 current density. The luminescnece intensity was partially recovered when the electron beam was temporarily off. Half-life of the luminescence was measured by turning electron beams ON and OFF for a fixed duration. For the first and second cycles of the electron beam showers, half-life time was measured as 26 seconds. Luminescence degradation from near-band-edge emission (3.29 eV), donor-acceptor-pair transition(3.17 eV), and emission from defects (~2.33 eV) were compared. In-situ luminescence of electrically biased ZnO thin film was characterized using TEM-CL, where localized luminescence was observed.

EP08.10.25
Epitaxial Growth and Band Offset Measurement of β-Ga_2O_3/GaN Heterojunction Sunan Ding; Suzhou Institute of Nano-Tech and Nano-Bionics, CAS, SuZhou, China.

Ga_2O_3 is a kind of ultra-wide-bandgap oxide semiconductors, which have been attracting more and more interests due to its super chemical and thermal stabilities. Since the band gap of β-Ga_2O_3 is about 4.9eV, corresponding right to ultra-valet (UV) emission, β-Ga_2O_3 has been considered as the most promising candidate for UV/deep-UV (DUV) LED and detectors. On the other hand, GaN-based devices are being well developed and widely used in high power electronics and photo-electronics. If combining Ga_2O_3 with GaN together in one structure, it will be possible to greatly promote their applications in the devices. However, the major challenges for Ga_2O_3 are material quality and p-type doping.

In this work, we have successfully grown crystalline β-Ga_2O_3 on GaN (0001) thin films by using plus laser deposition (PLD) and atomic layer deposition (ALD) techniques respectively. The atomic structure, interface properties, morphology, and composition of the oxide films were characterized by X-ray diffraction (XRD), atomic force microscope (AFM), transmission electron microscope (TEM) and X-ray photoelectron spectroscope (XPS), which confirmed the epitaxial growth of highly orientated β-Ga_2O_3 thin films on GaN films in a wide range of temperature. By using our unique UHV connected system, the MOCVD grown GaN films were directly transferred through an UHV tube from its glove box to the ALD chamber for quick β-Ga_2O_3 deposition, without exposing the as-grown GaN surface to air. Therefore, a clear interface between Ga_2O_3 and GaN was achieved and the band offset of the β-Ga_2O_3/GaN heterojunction was directly measured by using XPS core levels and valence band spectra, which also indicate that the band offset value varies with the interface conditions and the Ga_2O_3 crystallization.

As the recent progress in our studies, we demonstrated high quality epitaxial growth of β-Ga_2O_3 films on GaN(0001) by using PLD and ALD techniques at various temperatures, and experimentally determined the valence band offset of 1.40±0.06eV at the β-Ga_2O_3/GaN heterojunction. All of these results should be benefit to explore DUV devices based on Ga_2O_3/GaN heterojunctions.

EP08.10.26
High-Performance of Low-Voltage Flexible UV Photodetectors Assembled with ZnO-$ZnGa_2O_4$ Heterostructure Qianqian Du, Kun Tang, Shunming Zhu, Jiandong Ye, Youdou Zheng and Shulin Gu; Nanjing University, Nanjing, China.

Over the past decade, many efforts have been made to optimize the photoelectric devices because of their promising potential for biological and environment detection, optical communication and so on[1-3]. Photodetectors based on low-dimensional nanostructures exhibit superior performance owing to the large surface to volume ratio and tunable surface morphologies. Zinc gallate ($ZnGa_2O_4$) is an ultra-wide band gap semiconductor with a direct band gap of 4.4-4.7 eV. And it has attracted significant attention because of its high chemical stability and outstanding optical properties, which is the potential candidate of the deep ultraviolet photodetectors[4, 5]. In this study, we have fabricated ZnO-$ZnGa_2O_4$ heterojunction microwires by a simple chemical vapor deposition(CVD) method. Firstly, as evidenced from EDX, XRD and SEM analyses, we find the component of ZnO and $ZnGa_2O_4$ can be modulated by changing the ratio of the source materials(ZnO: Ga_2O_3) or the flow of O_2. The ZnO-$ZnGa_2O_4$ heterojunction photodetectors are fabricated on both the rigid SiO_2/Si and the flexible polyethylene terephthalate (PET) substrates, exhibiting excellent photoresponsivity to UV light illumination with high photoconductive gain. And it is noteworthy that the prepared flexible devices show good flexibility, high stability, reproducibility, and folding endurance.

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Structural Tuning and Photocatalytic Performance of Three-Dimensional Ga_2O_3 a-b Hetero-Phase Junction Arrays for Solar Water Splitting Can Cui, Liaoyong Wen and Puxian Gao; University of Connecticut, Willimantic, Connecticut, United States.

Widely studied and utilized wide-bandgap semiconductors such as SiC and GaN have met the intrinsic bottle-neck of electronic performance due to the limit in break-down strength and thermal stability. As a result, even wider bandgap and thermally stable semiconductors are called upon to replace these semiconductors. An emerging candidate, Gallium Oxide (Ga_2O_3) has drawn much attention lately due to its superb stability[1] and wider band gap (~4.9 eV), as well as its five polymorphic structures in nature, i.e., α-, β-, γ-, δ-, and ε phases [2-3]. Up to date, the full understanding of Ga_2O_3 is still lacking on their structural evolution, physical and chemical characteristics, as well as functional properties, calling for more and more studies.
In this work, the tuning of the crystal structure and morphology of Ga_2O_3 has been investigated via a facile solution preparation of Ga_2O_3 based nanowire arrays on planar surfaces that could carry various functions such as sensing, catalysis, and others. A hydrothermal deposition process has been successfully carried out with controllable parameters to produce GaOOH nanorod arrays with adjustable diameter and length. The phase evolution of Ga_2O_3 nanorods was studied starting from precursor GaOOH nanostructures under thermal annealing in detail. As a result, the pure a, the a-b hetero-phase junction, and the pure b Ga_2O_3 arrays have been realized with mesoporous surface structure and adjustable porosity by such a well-controlled post-annealing process. The relationship of evolution of these nanostructure ensembles and the resulting photocatalytic performances are verified via a demonstration of solar water splitting reaction. The results revealed a higher photocatalytic efficiency (~ 4.27 $mmolh^{-1}cm^{-2}$) in a-b hetero-phase junction arrays, as compared with that of pure alpha (~2.13 $mmolh^{-1}cm^{-2}$) and pure beta (~ 1.78 $mmolh^{-1}cm^{-2}$) phases, respectively. The catalytic performance enhancement through these phase junctions may be due to a charge carrier separation caused by an offset of electronic structure between alpha and beta Ga_2O_3, which allows a more efficient charge utilization for the hydrogen evolution.

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