PCSI

Room Ballroom South - Session PCSI-ThM1

Wide Bandgap Materials

Moderator: Christopher Palmstrøm, University of California, Santa Barbara

8:30am **PCSI-ThM1-1 Surface Transfer - Modulation Doping at a Diamond-Dielectric Interface***, **Robert Nemanich,*** Arizona State University **INVITED**

Great strides in diamond wafer technology and diamond epitaxy have inspired new concepts for diamond electronics particularly for power conversion and RF applications.However, the highactivation energy of substitutional p- and n-type dopants in diamond has limited the development of field effect transistors (FET). An alternative approach of charge transfer doping at a diamond-dielectric interface, which results in the formation of a hole accumulation layer, is not limited by thermal activation [1].However, the hole transport shows a mobility that is much lower than predicted. It is widely accepted that the low mobility is due to scattering from the near interface negative charges transferred into the dielectric layer.

Following the concept of modulation doping at heterostructure interfaces [2], we have proposed and demonstrated (Fig. 1) a dielectric layer configuration that results in a nearly ten-fold mobility increase for the accumulated holes at the diamond interface [3]. In this approach MoO_3 is used as the charge transfer dielectric, and Al_2O_3 is employed as the modulation doping spacer layer. The charge transfer is driven by the energy difference between the diamond valence band and the charge transfer states in the MoO_3. The thickness of the spacer layer also affects the hole accumulation layer charge density.

In this study photoemission spectroscopy is employed to measure the band alignment and band bending throughout the multi -layer structure.The relative distribution of the charge near the interface is deduced from the band diagram. Another study developed a modulation doping approach using acceptor molecules (NO_2) to enable the charge transfer from the diamond valence band. They achieved results that were similar to the multi dielectric layer approach.

These experiments and the model of Surface Transfer - Modulation Doping demonstrates a new approach to FET channel doping for diamond field effect transistors. We also discuss options for improving modulation doping in diamond FET's.

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9:10am **PCSI-ThM1-9 Operation-Induced Short-Term Degradation Mechanisms of 275-Nm-Band AlGaN-Based Deep-Ultraviolet Light-Emitting Diodes Fabricated on a Sapphire Substrate***, **Shigefusa Chichibu,*** Tohoku University, Japan*; K. Okuno, M. Oya, Y. Saito, H. Ishiguro,* Toyoda Gosei Co. Ltd., Japan*; T. Takeuchi,* Meijo University, Japan*; K. Shima,* Tohoku University, Japan **INVITED**

The short-term degradation mechanisms of 275-nm-band AlGaN multiple quantum well (QW) deep-ultraviolet light-emitting diodes fabricated on a (0001) sapphire substrate were investigated under hard operation conditions with the current density of 66 A/cm^2 and the junction temperature of 105 °C. The optical output power (P_o) decreased by about 20 % within the operating time (t_{op}) less than 102 h and then gradually decreased to about 60 % by 484 h, as shown in Fig. 1. For elucidating the cause for the initial degradation (t_{op} < 102 h), complementary electrical, time-resolved photoluminescence (TRPL), and impurity characterizations were carried out making a connection with the energy band profiles.

The initial degradation was accompanied by the increases in both the forward current (I_F) below the turn-on voltage (V_D) and reverse leakage current (I_R). These results are consistent with those reported previously [1-5]. Because the weak-excitation room-temperature PL lifetime for the near-band-edge emissionusing the QW-selective TRPL showed only slight change by the operation at least until 1002 h, the initial degradation is attributed essentially to the decrease in carrier injection efficiency. From the correlation between the energy band profiles and H concentration profiles before and after the operation, the output power reduction is ascribed to be due to de-passivation of initially H-passivated preexisting nonradiative recombination centers (NRCs) in a Mg-doped p-type $Al_{0.85}Ga_{0.15}N$ electron blocking layer (EBL) caused by certain breaking of H bonds and the electric field induced drift of H^+. According to our database on the species of vacancy-type defects acting as NRCs in AlN [6] and GaN [7], vacancy clusters comprised of a cation vacancy (V_{III}) and nitrogen vacancies (V_N), such as $V_{III}(V_N)_{2-4}$, are the most suspicious origins of the NRCs in the Mg-doped p-type AlGaN layers [8].

This work was supported by MOE program for implementation of innovative infection-control and digital technologies with low CO_2 emissions and MEXT Crossover Alliance, Japan.

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9:50am **PCSI-ThM1-17 Impact of Interfacial Defects and Lattice Strain on NbN_x Films for Integration with Wide Bandgap Semiconductors***, **Annaliese Drechsler,*** University of Maryland College Park*; P. Shea,* Northrop Grumman*; A. Christou,* University of Maryland College Park

Niobium nitride (NbN) films have garnered significant attention due to their high critical temperature (T_c) and their usage in infrared-sensitive superconducting nanowire single photon detectors (SNSPDs). Devices fabricated from NbN have demonstrated single photon detection to mid-wave infrared wavelengths, which unlocks possibilities for novel applications such as long-range laser detection and ranging (LiDAR), interferometry of planetary emissions, quantum key decryption, and optical communications. To expand beyond a laboratory, however, these devices must be fabricated into focal plane arrays (FPAs), requiring integration with semiconducting device materials. In this work, we report progress on achieving a device structure comprised of a NbN SNSPD monolithically integrated with a wide bandgap semiconductor-based amplifier. This investigation is motivated by recent reports of monolithic integration of NbN with aluminum nitride (AlN) to provide a superconducting load for an amplifier [1].

NbN films for SNSPDs must be thin, typically <<100 nanometers. As a result, the film quality and defectivity, and ultimately SNSPD performance, are highly correlated to the interface between the NbN film and underlying lattice, lattice-mismatch strain, and deposition parameters of the NbN processing. In this talk, we investigate the impacts of the semiconducting interface on the NbN films utilized for SNSPD fabrication through XRD of grown films, AFM surface studies, cathodo-luminesce (CL), and TEM analysis.To optimize this interface, similar materials 6H-SiC (3.57% lattice mismatch) and wurtzite GaN (6.6% lattice mismatch) chosen to minimize intrinsic defect sources. XRD analysis of grown films indicates that growth on these substrates is possible with long range crystallinity, suggesting the presence of epitaxial growth for high quality films. Optimization of the stress of the film due to the lattice mismatch with the substrate is also investigated by modifying the growth temperature, pressure, and power to reduce lattice strain-induced defects. The presence of threading and other dislocations stemming from interface defects analyzed through CL and TEM will also be discussed.

9:55am **PCSI-ThM1-18 Impact of Unintentional Boron Supply on Sapphire Nitridation Process for GaN Growth by Rf-MBE***, **Tohru Honda,*** *K. Yajima, T. Yayama, T. Onuma, T. Yamaguchi,* Kogakuin University, Japan

GaN, InN and their related alloys grown by radio-frequency excited plasma-assisted molecular beam epitaxy (RF-MBE) [1] have investigated for the application to light-emitting devices operating in visible and infrared spectral regions [2]. Although the plasma assisted nitrogen source is a useful for III-nitrides by MBE, unintentional boron (B) supply, which is coming from the nitrogen cell, during the growth was reported [3]. The nitridation process was used for N-polar GaN growth on a sapphire substrate [4]. Although some nitridation models were reported [4], the boron incorporation during the nitridation is still unclear. Thus, the impact on unintentionally supplied boron incorporated during the nitridation is discussed.

Chemically cleaned (0001)sapphire substrates were used for the study. Thermal cleaning at 850 °C for 15 min. was performed before the nitridation. The nitrogen plasma (200 W, N_2 flow of 0.6 ccm) was used for the nitridation, whose temperature was fixed at 500 °C. The samples were taken out the growth chamber to air, subsequently, XPS and Auger electron spectroscopy (AES) spectra were observed. Boron 1s peaks (B-N and B) [5] were observed from the sapphire surface with the nitridation. This means that boron atoms or compounds were deposited on the sapphire. N 1s peaks related Al-N and B-N were also observed. To confirm the deposition

of boron related layers, AES was also observed for the samples. We observed B (KVV) signals from those. These indicate that the boron related layers were deposited on the sapphire substrates during the nitridation.

Generally, it was reported [6] that the suitable nitridation time led to the high quality GaN growth. We believed AlN coverage on the sapphire substrate by the nitridation was a key for the GaN growth with high crystalline quality. XPS results indicate that the amount of AlN is increased as a function of the irradiation time and it's saturated. On the other hand, the boron deposition is monotonically increased. The boron on the surface obstructs the GaN growth although the AlN enhanced it with high crystalline quality.

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10:00am **PCSI-ThM1-19 Photoluminescence Maps of Surface Defects in β-Ga_2O_3**, ***Matthew McCluskey***, Washington State University*; J. Huso,* Klar Scientific*; C. Remple, J. McCloy,* Washington State University*; S. Rebollo, S. Krishnamoorthy, J. Speck,* University of California at Santa Barbara

Monoclinic gallium oxide (β-Ga_2O_3) is an ultrawide bandgap semiconductor with potential applications in power electronics [1]. Photoluminescence (PL) spectroscopy is an important method to characterize dopants and defects in this material. Common features in the PL spectrum include the intrinsic UV band, blue and green bands that involve donor-acceptor pairs, and red emission due to Cr^{3+} impurities.

PL mapping with excitation wavelengths ranging from 266 to 532 nm reveals the spatial distribution of these features with micron resolution. In Czochralski-grown β-Ga_2O_3, the Cr^{3+} emission intensity shows striations that are attributed due to inhomogeneities during growth [2]. In addition to defects in the bulk, PL microscopy has revealed several specific defects on the surface. Some of these localized centers are very bright UV emitters [3].

Homoepitaxial layers show defects that are observed via the shifts in the PL band, likely due to the strain field around a dislocation core. Damage due to high-intensity laser pulses results in significant changes in the intensity and energy of the UV band. *In situ* PL spectroscopy performed with a pulsed 266 nm laser shows characteristic emission peaks attributed to Ga atoms ablated from the surface.

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10:05am **PCSI-ThM1-20 UPGRADED: Epitaxial Growth and Properties of Wide Bandgap *P*-Type $NiGa_2O_4$ on *β*-Ga_2O_3 for High Voltage *P-N* Heterojunctions with Superior Performance at Elevated Temperatures**, ***Kingsley Egbo***, *B. Tellekamp, W. Callahan, A. Zakutayev,* National Renewable Energy Laboratory

Gallium oxide (*β*-Ga_2O_3) is a promising wide bandgap oxide semiconductor material with properties well-suited for high-power electronics, and recent results show superior high-voltage performance compared to the commercial state-of-the-art [1],[2]. Due to the difficulty in the *p*-type doping of Ga_2O_3, unipolar devices based on Ga_2O_3 are prevalent. Several studies have explored bipolar devices using polycrystalline *p*-type oxides such as Nickel oxide and Tin (II) oxide grown on Ga_2O_3 to form heterojunctions[3][4]. However, resulting interface defects and grain boundaries decrease the electrical performance of these devices which directly affects the power device performances, such as breakdown characteristics, on-resistance, and mobility. Hence, the development of high-quality heteroepitaxy of a *p*-type layer with low structural defects on *n*-type Ga_2O_3 is essential to improve device performance in Ga_2O_3-based bipolar devices. For operation at high temperatures, thermodynamically stable interfaces are also critical. Recent observations show that $NiGa_2O_4$ forms as a thermodynamical reaction product between Ga_2O_3 and NiO at the p-n heterojunction interface during high-temperature operation. Hence the possibility of developing a *p*-type $NiGa_2O_4$ on Ga_2O_3 can circumvent this interface reaction and lead to the development of thermodynamically stable high-temperature devices. In this work, we demonstrate the epitaxial growth of wide bandgap *p*-type $NiGa_2O_4$ thin films on Ga_2O_3 and the device performance of vertical *p-n* heterojunction diodes processed using these heterostructures. Undoped $NiGa_2O_4$ thin films were grown on three different orientations of *β*-Ga_2O_3 wafers and on reference Al_2O_3 substrates by pulsed laser deposition. Structural characterizations of the $NiGa_2O_4$ thin films show that 002-oriented $NiGa_2O_4$ grows epitaxially on *β*-Ga_2O_3 (100) while $NiGa_2O_4$(220) was stabilized on *β*-Ga_2O_3 (010) orientation. But thin films of $NiGa_2O_4$ grown on Ga_2O_3(001) were polycrystalline. The reflection high energy diffraction (RHEED) patterns during growth were streaky indicating relatively flat surfaces. A bandgap of ~3.95 eV is obtained for $NiGa_2O_4$ thin films from spectroscopic ellipsometry. The fabricated $NiGa_2O_4$/β-Ga_2O_3 vertical p-n heterojunction devices demonstrated good specific on-resistance, excellent temperature-dependent reverse leakage current, and lower on-voltage compared to widely used NiO-Ga_2O_3 heterojunctions. These performances demonstrate that $NiGa_2O_4$/β-Ga_2O_3 p-n heterojunction diodes can be promising for high-power devices with low-on-state power dissipation capable of operating in extreme environments

10:25am **PCSI-ThM1-24 Quantum Oscillations in GaN/AlN 2D Hole Gas and Extraction of Light Hole Effective Mass**, ***Chuan Chang***, *J. Dill, Z. Zhang,* Cornell University*; S. Crooker, O. Valenzuela, R. McDonald,* Los Alamos National Laboratory*; D. Jena, G. Xing,* Cornell University

Gallium Nitride (GaN) has been a leading contender in commercial high-frequency and high power applications due to its internal polarization field and a wide bandgap of 3.4 eV [1]. However, while n-channel high-electron mobility transistors (HEMT) based on GaN's polarization-induced two-dimensional electron gas (2DEG) progress towards higher performance, its p-type counterpart has been lagging due to the low mobility of the polarization-induced two-dimensional hole gas (2DHG), hindering the development of GaN-based CMOS and an extraction of hole effective mass by Shubnikov de-Haas (SdH) oscillations and cyclotron resonance. In the absence of reliable and uniform experimental data, researchers have had to rely on theoretical calculations [3]. In this talk, we report the first observation of SdH oscillations in any p-type GaN platform and subsequent extraction of hole effective mass. Here, a technique pioneered by Chaudhuri et. al. [2] is used to form a high-density (~5×1013 cm-2 at 300 K) 2DHG at the heterointerface between GaN and a AlN substrate via the large internal electric fields induced by spontaneous and piezoelectric polarization. Magnetoresistance measurements up to 63 T is performed at the National High Magnetic Field Laboratory Pulsed Field Facility, showing

Shubnikov de-Haas (SdH) oscillations with an onset at around B=25 T (Fig. 1). Fig. 2a shows Rxx with a polynomial background subtracted plotted against B-1 and Fig. 2b shows its power spectrum. A strong peak is located at f =168 T in the power spectrum at all temperatures corresponding to a density of 8.2×1012 cm-2. In lower magnetic fields (< 9T), Rxx(B) and Rxy(B) are fitted to a classical two-band model (Fig. 3), revealing the coexistence of two carrier populations – low-mobility (~230 cm2/Vs) heavy holes with a density of 4.2×1013 cm-2 and high-mobility (~1400 cm2/Vs) light holes with a density of 7×1012 cm-2 in agreement with the density extracted from SdH frequency. Attributing the oscillations to the light holes, we extract their effective mass from the temperature dependence of the amplitudes, yielding a value of 0.48 ± 0.02 m0.

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Author Index

Bold page numbers indicate presenter