PCSI
Room Ballroom South - Session PCSI-1MoA
Device Interface Characterization

Moderator: Kimberly Thelander, Lund University

2:00pm **PCSI-1MoA-1 Sequential and In-Situ Atom Probe Tomography and Optical Spectroscopy on Single Luminescent Nanoscale Objects***, **Lorenzo Rigutti**,* University of Rouen Normandie, France **INVITED**

Correlating two or more microscopy and spectroscopy techniques on the same nanoscale object may yield an amount of information difficult to achieve by other means. In this contribution, we present selected studies of micro-photoluminescence (μ-PL), high-resolution scanning transmission electron microscopy (HR-STEM) and laser-assisted atom probe tomography (APT) performed *sequentially* on single nano-objects containing quantum confined systems based on III-V and II-IV materials. This approach can be applied to the study of heterostructure interface definition, presence of extended defects such as stacking faults or dislocations, carrier localization and optical emission in quantum confined systems [1-4]. Furthermore, the use of complementary techniques may be extremely helpful for a correct interpretation of atom probe results and for understanding its limitations [3,5]. Finally, we will show that the study of PL *in situ* in an atom probe opens up novel possibilities, such as the discrimination - with a spatial resolution beyond the diffraction limit - of the optical signal of two quantum wells (QWs) and the manipulation of the optical signal of color centers by the application of an electrostatically-induced stress [6].

[1] L. Rigutti et al., Nano letters, 14, 107–114 (2014). [2] L. Mancini et al. Appl. Phys. Lett., 108, 042102 (2016) [3] E. di Russo et al. Appl. Phys. Lett. 111, 032108 (2017) [4] L. Mancini et al., Appl. Phys. Lett. 111, 243102 (2017) and Nano letters 17, 4621 (2017) [5] L. Mancini et al. J. Phys. Chem. C 118, 24136 (2014).

[6] L. Rigutti et al. Nano letters 17, 7401 (2017)

2:30pm **PCSI-1MoA-7 The Three-dimensional Shape of Antiphase Domains in GaP on Si(001)***, **Pascal Farin**,* Technische Universität Berlin, Germany

The integration of III-V semiconductors on Si(001) has been a long standing research aim to lower the cost of optoelectronic devices and simultaneously improve their performance. As the lattice mismatch between Si and GaP is smaller than 4%, this particular III-V semiconductor is used preferentially. However, due to charged, three-dimensional defects called antiphase domains (APDs) in GaP arising at the interface, its integration has proven to be quite challenging. While the search for growth conditions to avoid pronounced formation of these defects has been successful, the exact shape of the remaining ones is not yet fully understood.

In this work, APDs in GaP on Si(001) are investigated by means of transmission electron microscopy (TEM) and cross-sectional scanning tunneling microscopy (XSTM), two methods that offer unique insight into the appearance of APDs' cross sections due to their high surface sensitivity and resolution. The progression of the cross sections of the antiphase boundaries (short: antiphase boundaries) that separate the crystal's mainphase from the antiphase could be analyzed all the way down to the atomic level, allowing for an identification of the individual crystal planes along which the antiphase boundaries form. The accurate analysis of their progression by means of XSTM is illustrated by Fig. 1. After a thorough investigation of the antiphase boundaries' appearances on plane-view TEM and on the (110) and the (1-10) cleavage planes by means of XSTM, it has been possible to develop a true-to-scale, three-dimensional model of antiphase domains.

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2:35pm **PCSI-1MoA-8 Atom Probe Tomography of GaN Vertical Power Diodes: Impurity Distribution near Regrowth Interfaces***, **Alexander Chang**,* Northwestern University*; M Nami, B Li, J Han,* Yale University*; L Lauhon,* Northwestern University

GaN has demonstrated its utility in lighting and RF application and are being considered as the next generations of vertical power devices. However, high leakage currents, current crowding followed by premature breakdown, and degradation of the device[1] have hindered the GaN technology from entering the market. For nonplanar vertical power diodes, active regions of the device are formed through ex-situ processes, e.g. regrowth and selective area growth. Therefore, precise control of intentional and unintentional impurity incorporation near these interfaces is essential for achieving high performance devices[2]. Analysis of the 3D spatial distribution and concentration of solute impurity atoms can be difficult, especially for nonplanar interfaces; thus, tomographic analysis becomes necessary. We describe atom probe tomography (APT) characterization of planar n/n and p/n GaN homojunctions with emphasis on detection sensitivity of dopants.

GaN homojunctions were grown by metal-organic chemical vapor deposition at Yale University, and analyzed using APT at Northwestern University. n-GaN templates were exposed to air prior to the regrowth of n-GaN or p-GaN to test subsequent cleaning procedures, and APT detection limits for impurities in GaN substrates and planar regrowth were analyzed by comparison with secondary ion mass spectroscopy (SIMS). Si impurities were observed with a surface density of $10^{12}cm^{-2}$ for both n/n and p/n homojunctions and attributed to contamination from reactor parts and air. However, detection of Si in GaN using APT was limited due to the overlapping $^{28}Si^{+}$ and $^{14}N_2^{+}$ mass to charge ratios. The detection limits of other intentional and unintentional impurities in APT varied from $10^{17}cm^{-3}$ to $10^{19}cm^{-3}$, depending on the peak positions relative to the Ga and N ion thermal tails. Analysis on spatial distribution of p-type dopant atoms did not reveal any evidence of clustering. Within the reconstructed APT data, the location of the regrowth interface of n/n homojunction was identified by spatial variations in charge states of evaporated Ga ions (Ga CSR). Although noticeable fluctuations in Ga CSR also coincided with the p/n homojunction, no clear correlation between Ga CSR and Mg concentration was observed. We will discuss efforts to extract the built-in field near p/n junctions and correlate with dopant concentrations.

[1] H. Nie, Q. Diduck, B. Alvarez, A.P. Edwards, B.M. Kayes, M. Zhang, G.F. Ye, T. Prunty, D. Bour, and I.C. Kizilyalli, *IEEE Electron Device Letters* **35**, 939-941 (2014).

[2] I.C. Kizilyalli, P. Bui-Quang, D. Disney, H. Bhatia, and O. Aktas, *Microelectronics Reliability* **55**, 1654-1661 (2015).

2:40pm **PCSI-1MoA-9 Surface/Subsurface Identification and Control of Ga_2O_3 Native Point Defects***, **Hantian Gao**, S Muralidharan, N Pronin, M Karim, S White, T Asel, G Foster, S Krishnamoorthy, S Rajan, L Cao,* The Ohio State University*; M Higashiwaki,* National Institute of Information Communications Technology, Japan*; H Von Wenckstern, M Grundmann,* Universität Leipzig, Germany*; H Zhao,* The Ohio State University*; D Look,* Wright State University*; L Brillson,* The Ohio State University

Ga_2O_3 has been considered a promising material for next generation high power devices due to its wide band gap enabling very high breakdown fields and n-type doping ranging from intrinsic to degenerate, both features of which lead to numerous solid-state electronic applications. However, surface/subsurface plays an important role in electronic applications of such material. Particularly, native point defects at surface/subsurface remain relatively unexplored. We used two surface sensitive techniques, depth-resolved cathodoluminescence spectroscopy and surface photovoltage spectroscopy to measure the optical signatures related to native point defects at surface/subsurface of Ga_2O_3.With near-surface treatments including plasma processing, annealing, and neutron irradiation on β-Ga_2O_3 grown by different methods, the near-surface sensitivity and depth resolution of these optical techniques enabled us to identify spectral changes associated with removing or creating these defects up to 180 nm below the material surface. This leads to measurement, identification, and control of one oxygen vacancy-related and two gallium vacancy – related energy levels in the β-Ga_2O_3 band gap. The combined near-surface detection and processing of Ga_2O_3 suggests an avenue for identifying the physical nature and controlling the density of native point defects in this and other semiconductors at surface and subsurface.

[1] T.J. Asel, et al., J. Vac. Sci. Technol. B 33, 04E103, (2015).

[2] J. B. Varley, et al., Appl. Phys. Lett. 97, 142106 (2010).

[3] Z. Zhang, et al., Appl. Phys. Lett. 108, 052105 (2016).

[4] H. Gao, et al. Appl. Phys. Lett. 112, 242102 (2018).

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2:45pm **PCSI-1MoA-10 Electrically Detected Magnetic Resonance Study of Leakage Currents in a-SiN:H***, **Ryan Waskiewicz**, P Lenahan,* Pennsylvania State University*; S King,* Intel Corp.

Electronic transport in dielectric thin films are important concerns in semiconductor device technology. We have initiated a study of the defects involved in electron transport through a-SiN:H thin films of various stoichiometries utilizing electrically detected magnetic resonance (EDMR) measurements at multiple frequencies. The primary defect responsible for electronic transport (the K center) through SiN films has been identified using conventional electron paramagnetic resonance (EPR), but a detailed understanding of the effects of varying nitrogen incorporation in very thin films is not complete on the atomic scale. The EDMR measurement involves spin dependent trap assisted tunneling (SDTAT) on a sample structure of p-Si/a-SiN:H/Ti where the N/Si ratio in the a-SiN:H film was varied from 0.432 (N poor) up to 1.268 (nearly stoichiometric). In EDMR, we detect spin-dependent changes in device current under the influence of a slowly varying magnetic field. When the resonance condition is met, defect spins "flip" and a forbidden tunneling event becomes allowed, resulting in a change in device current that allows us to identify the chemistry and local structure of the defect responsible for leakage current. These measurements were made at low frequency (ν=350MHz) and high frequency (ν=9.5GHz) over the entire range of film stoichiometries. Fig. 1 shows the EDMR results at low frequency (dashed line, filled squares) and high frequency (solid line, open diamonds). The trend of increasing linewidth with increasing N/Si ratio is observed in both sets of measurements. A comparison between the high and low frequency EDMR measurements allows us to determine the contribution to linewidth broadening from spin orbit coupling and electron-nuclear hyperfine interactions [1]. The linewidth broadening is nearly identical for both sets of measurements, so we can conclude that a majority of the linewidth comes from hyperfine interactions and not spin orbit coupling (we would expect a significant increase in broadening at high field compared to low field). This result is consistent with the prediction of increasing hyperfine interactions with increasing average number of nitrogen atoms in K center defects.

[1] M. J. Mutch, P. M. Lenahan, and S. W. King, Appl. Phys. Lett., vol 109, no. 6, 2016.

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2:50pm **PCSI-1MoA-11 Internal Mechanical Stresses Relaxation in the Si-SiO_2 System and its Influence on the Interface Properties**, ***Daniel Kropman**, *V Seeman,* Tartu University, Estonia*; A Medvids, P Onufrievs,* Riga Technical University, Latvia

It is known that internal mechanical stresses (IMS) due to the differences in the thermal expansion coefficients between films and substrates and lattice mismatch appear in the Si-SiO_2 system during the process of its formation and that point defects (PD) generation and redistribution could be used to reduce partially the surface stress. However, this process on the atomic scale is till not studied. The goal of the present report is to investigate the stress relaxation mechanism in the Si-SiO_2 system using EPR, IR absorption spectroscopy, scanning elektron microscopy (SEM) and samples deflection measurements. PD density and stresses in the Si-SiO_2 system were varied by oxidation condition (temperature, time, cooling rate, ambient) and by Si_3N_4 deposition on SiO_2. Different sign of the thermal expansion coefficient of the SiO_2 and Si_3N_4 on Si allow to modifay the IMS at the interface. It has been found that samples deflection decreases or increases simultaneously with EPR signal intensity depending on the oxidation condition (temperature).

At oxidation temperature 1100^0C the deflection of the samples(h) decreases with the increase of EPR signal intensity (vacancies),while at a oxidation temperature 1200^0C EPR signal (I) and deflection increase simultaneously. Those allows to suggest that at lower oxidation temperature PD (vacancies) reduce the tensil IMS in Si, while at higher oxidation temperature compressive IMS created PD in SiO_2 (E' centers).At an intermediate oxidation temperature tensil stresses in Si and compressive stresses in SiO_2 may bee equal and compensate each others (Fig.1).

It has been find that at oxidation temperature 1130^0C IMS at the Si-SiO_2. interface are lower than at 1100^0C and 1200^0C. Lower defect dencity on samples crossection microphotos obtained by SEM and PD density diminishing in samples oxidized at 1130^0C confirmed thise suggestion.In Fig,2 the EPR signal and IR absorbtion line-width dependence on the oxidation time is shown. It can bee seen ,that EPR signal and IR absorbtion line-width at 1100 cm^{-1} dependence on the oxidation time (oxide thickness) is nonmonotonous and depended on the cooling rate .In slowly cooled samples the increase of the EPR signal is accompanied by the decrease of $\Delta\nu$ but,in fast cooled samples EPR signal and $\Delta\nu$ increase simultaneously with increase oxidation time. Absent of the cooling rate influence on the PD density and $\Delta\nu$ dependence on the oxidation time at I(t) and $\Delta\nu(t)$ dependence intersection points show, that IMS by an appropriate choice of the SiO_2 film thickness dissapear.

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