Electronic Materials and Devices
Room 321/322 - Session EM+SC-MoA
Defects and Interfaces in Electronic Materials and Devices

Moderator: C.G. Van de Walle, Palo Alto Research Center

2:00pm **EM+SC-MoA1 Localized Defect States, Impurities, and Doping in Al@sub x@Ga@sub 1-x@N Epilayers**, ***S.T. Bradley***, Ohio State University **INVITED**

AlGaN and its heterojunction alloys are used in some of the most advanced micro- and optoelectronic devices today and rely on precise control of electronic properties in multilayer film structures on a nanometer scale. Deep level defects in these materials and at their interfaces can alter transport, recombination, contact formation, and doping, yet measuring such small structures is a challenge for conventional techniques. Al-rich AlGaN layers can enable many new applications but little is known of their deep level properties. Also, doping of AlGaN with high Al content is difficult and may be restricted by non-intentional impurities (such as oxygen) and their associated deep levels. We have used a near-surface version of cathodoluminescence spectroscopy (CLS), termed low energy electron-excited nanoluminescence (LEEN), to probe the electronic properties of thin HFET films as a function of lateral position and depth. LEEN spectroscopy can provide electronic properties of states that are localized at the surface, buried interface, and near the middle of these nanometer-scale films. For AlGaN/GaN structures, correlations have been made between deep level defects and the sheet charge density, AlGaN/GaN intermixing, surface roughness, and Ga/N ratio. We have also used LEEN with secondary ion mass spectrometry (SIMS) to correlate deep levels across the AlGaN alloy series with chemical impurities and spatial location at surfaces, interfaces, and in the bulk. Al-rich AlGaN exhibits deep level optical emissions that correlate with O and C impurities. Temperature-dependent CL of the Si-doped films reveal donor energy increases but activation energy decreases with Al content. Coupled with the appearance of an O deep level at mid-gap at highest Al concentrations, these changes can be seen to compensate the intentional Si doping. These results demonstrate how spatially-resolved CL combined with SIMS can provide new understanding of macroscopic III-nitride properties.

2:40pm **EM+SC-MoA3 Contactless Characterization of High Electron Mobility Transistor Structures using Surface Photovoltage Spectroscopy**, ***S. Solodky***, Tel Aviv University, Israel; *A. Khramtsov,* Ben-Gurion University, Israel; *T. Baksht,* Tel Aviv University, Israel; *M. Leibovitch,* Gal-El (MMIC), Israel; *Hava,* Ben-Gurion University, Israel; *Y. Shapira,* Tel Aviv University, Israel

GaN/AlGaN High Electron Mobility Transistor (HEMT), AlGaAs/InGAs/GaAs pseudomorphic HEMT (PHEMT), and InAlAs/InGaAs metamorphic HEMT (MHEMT) epitaxial structures have been characterized using surface photovoltage spectroscopy (SPS). The interplay between two opposite direction signals coming from the regions with opposite direction of electric fields define the shape of the spectra. The shape of the spectra is interpreted using self-consistent numerical simulations. The effects of the transistor delta-doping levels dtop, dbot and surface charge Qsur on the spectrum features have been studied using numerical simulations. Based on the latter, an empirical model has been developed, which allows extraction and comparison of dtop, dbot and Qsur and is applicable for both double-sided and single sided delta-doped structures. Effect of SiN passivation on GaN/AlGaN HEMT surface is shown. Applying of the model to passivated structure shows reduced Qsur. Prediction of the final device performance by the model is shown for two MHEMT structures. Applying of the model shows sensitivity of the methodology to 7.5% difference of dtop. Devices produced on these structures show relative difference of 8.2% in maximum drain currents, which correlate well with dtop values calculated using the model.

3:00pm **EM+SC-MoA4 Atomic Bonding and Electronic Changes at InGaAs/InP Heterojunctions**, ***P.E. Smith***, *S.H. Goss, S.T. Bradley, L.J. Brillson, M.K. Hudait, Y. Lin, S.A. Ringel,* The Ohio State University; *S.W. Johnson*, Sandia National Laboratories

Lattice-matched In@sub 0.53@Ga@sub 0.47@As/InP heterojunctions have attracted considerable interest for many opto- and microelectronic applications. Achieving abrupt interfaces is difficult since both group III and V elements must be switched at the interface during MBE growth. To minimize structural defects, growers often employ a sequence of source switching such that new group V elements are switched on for brief exposure times before growth of subsequent layers. Interface-specific atomic bonding and diffusion can occur that can alter local electronic properties. We combined secondary ion mass spectrometry (SIMS) depth profiling with micro-cathodoluminescence spectroscopy (CLS) in cross section to measure atomic bonding and compositional changes and their effect on electronic properties. SIMS and CLS measurements of InGaAs-on-InP interfaces subjected to exposure times of 40, 80, 110, 140, and 170 sec reveal: (1) interface broadening (both As and P) that increases from < 5 to 15 nm with the length of time the InP surface is exposed to As prior to InGaAs growth, (2) InGaAs near band edge (NBE) emissions at ~0.79 and 0.80 eV, whose intensities shift to higher energies with proximity to the heterojunction on a submicron scale and become more evident with increasing As exposure time. These electronic changes suggest either lower In interface concentration and/or local defect formation - the latter consistent with increasing trap densities with As exposure measured via photoconductivity decay. Overall, local electronic structure at a lattice-matched III-V compound heterojunction depends sensitively on the competition of atomic species in the transition region during growth.

3:20pm **EM+SC-MoA5 Nanoscale Electronic Characterization of Semiconductors: from Operating Devices to Atomic Scale Defects**, ***Y. Rosenwaks***, *R. Shikler,* Tel-Aviv University, Israel; *Th. Glatzel, S. Sadewasser,* Hahn-Meitner Institut, Germany **INVITED**

Scanning probe microscopy has opened new opportunities to image semiconductors electronic properties with unprecedented spatial resolution. The recently developed Kelvin probe force microscopy (KPFM) technique has already been demonstrated as a powerful tool for measuring nanoscale electronic properties and has found many diverse applications in recent years. In this talk several novel applications of the KPFM technique recently developed and demonstrated by our group will be presented. The long-range electrostatic force between the AFM tip and the semiconductor surface deteriorates drastically the KPFM spatial resolution, and poses the problem whether surface atomic scale defects can be quantitatively measured. In addition, the physical understanding of the observed contrast in atomic resolution images is still under discussion. We show that by combining ultrahigh vacuum (UHV) KPFM measurements with rigorous modelling of the tip-semiconductor electrostatic interaction it is possible to extract the surface charge density at the atomic steps of a GaP (110) surface. The third part of the talk will be devoted to the use of KPFM for direct measurement of surface states parameters in semiconductors. The method is based on the measurement of very asymmetric cleaved p++n or n++p junctions. The absolute surface band bending, Us, and the surface charge density, Nss, can can be extracted because one side of the junction is degenerate, and all the band bending is taking place in the low doped semiconductor. Methods to obtain the surface states energy distribution are also discussed.

4:00pm **EM+SC-MoA7 STM Observation of Subsurface Boron Dopants on the Si(001)-2x1 Clean Surface**, ***M. Nishizawa***, *L. Bolotov, T. Kanayama,* National Institute of Advanced Industrial Science and Technology, Japan

As the feature size of integrated circuits approaches nanometer dimensions, dopant distribution in device regions plays an increasingly larger role in determining device performance. This has motivated research in recent years to identify a suitable technique to profile dopant distribution with atomic scale resolution. Among the more promising technologies is Scanning Tunneling Microscopy (STM). While a number of studies have been made to measure individual dopants on cleaved compound-semiconductor surfaces and cleaved or hydrogen-terminated Si surfaces using STM, no studies have been made on the Si(001)-2x1 clean surface. From a surface science perspective, the Si(001)-2x1 is one of the most widely studied and documented surfaces. However, it has not received attention in dopant measurement studies, as it is believed that surface states in the band gap obscure observation of dopant features. In this report, we show that Boron-dopant features can be successfully observed on the Si(001)-2x1 surface using STM. On the Boron-doped Si(001)-2x1 surface (sheet resistance is 0.01 @ohm@ cm) we have observed a number of specific features which are a few nanometers in size and appear as round-shaped protrusions superimposed on the corrugation of surface reconstruction in the filled-state image. The appearance of these features is quite similar to the dopant images observed previously on the other surfaces. These features can be recognized starting at a sample bias voltage (V@sub s@) of -1.0 V and tunneling current (I@sub t@) of 0.2 nA, can be enhanced by increasing V@sub s@ to -0.4 V and I@sub t@ to 2.0 nA. Area density of these features changes with dopant concentration of the substrate. From these results, we conclude that the specific features

observed here are related to the Boron dopant located in a subsurface layer. This study was supported by NEDO.

4:20pm **EM+SC-MoA8 Surface Defects After the Growth of Highly P and Sb Doped Si***, **G.G. Jernigan**, P.E. Thompson,* US Naval Research Laboratory

Doping in semiconductors is crucial to the formation of electronic devices, but our knowledge of the physical characteristics of electrical interfaces, as they are formed during device fabrication, is limited. We will present a unique study of Si doping with P and Sb during MBE growth on Si (100) wafers using an in vacuuo STM. The process of doping affects the surface morphology, as compared to an undoped film, leading to surface defects. Under dopant flux conditions of ~10@super 12@ atoms/cm@super 2@/s and Si growth rates ~0.10 nm/s, we will report the changes to the Si surface morphology and the production of defects at growth temperatures of 500 °C. The segregation of the n-type dopants, P and Sb, is observed to affect Si adatom attachment at step-edges resulting in an increase in island formation. For thin films of P less than 50 nm, where less than 0.1 monolayers (ML) of P has segregated, the surface roughness is not increased significantly but line defects parallel to dimer rows can be observed. At high P surface coverages observed on films greater than 50 nm, there are blockages at step-edge sites to form pothole-like defects with a density of 2x10@super 10@ /cm@super 2@. For all Sb films grown, there is an increase in surface roughness with increasing film thickness (>2.0 nm) and Sb surface coverage (>0.01 ML). At high Sb surface coverages (0.8 ML), Si islands form into pyramid-like defects with a density of 8x10@super 10@ /cm@super 2@, and this casts concern for the use of Sb in surfactant assisted growth. The evolution of the surface morphology and defect appearance with film growth and dopant segregation will be discussed.

4:40pm **EM+SC-MoA9 The Effect of Strain on Impurity States in Si and Methods of Calculation Thereof***, **A. Rockett**, D.D. Johnson,* University of Illinois*; B.R. Tuttle,* University of Pennsylvania*; S.V. Khare,* University of Illinois

We propose a simple model for estimating the contribution of strain to the ionization energy of defect states in semiconductors. The model is illustrated for group III and V impurities in Si. The approach uses an extrapolation technique to determine the ionization energies from the results of density functional theory (DFT) calculations. The method is shown to produce reliable results for a range of dopants with no parameters and none of the usual corrections requried in DFT. The results are generalized through an analysis of the resulting energies based on a screened electrostatic interaction, strain, and a bonding localization term.

5:00pm **EM+SC-MoA10 New Mechanism for Coupling between Properties of Interfaces and Bulk Semiconductors***, **K. Dev**, E.G. Seebauer,* University of Illinois at Urbana Champaign

A new mechanism is described by which interface electronic properties can affect bulk semiconductor behavior. In particular, experimental measurements by photoreflectance of Si(100)-SiO2 interfaces show how a controllable degree of band bending can be introduced near the interface by ion bombardment and annealing. The resulting electric field near the interface can affect dopant concentration profiles deep within the semiconductor bulk by drastically changing the effective interfacial boundary condition for annihilation of charged interstitial atoms formed during bombardment. Kinetic measurements of band bending evolution during annealing show that the bending persists for substantial periods even above 1000 C. Unusually low activation energies for the evolution point to a distribution of energies for healing of bombardment-generated interface defects. The transformations take place at temperatures higher than those characterizing other defects known to exist at the Si-SiO2 interface. The findings have significant implications for pn junction formation during CMOS device processing.

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