Electronic Materials and Processing
Room 309 - Session EM-WeA

Contacts to Semiconductors

Moderator: S.E. Mohney, The Pennsylvania State University

2:00pm **EM-WeA1 Effect of Si on the Ohmic Behavior of Ti/Al/Mo/Au Metallization for AlGaN/GaN HEMTs***, **F.M. Mohammed**, L. Wang, H.J. Koo, I. Adesida,* University of Illinois at Urbana-Champaign

The high breakdown voltage and high saturation current of AlGaN/GaN HEMTs present great potential for applications in power amplification. High performance devices for such application require low parasitic ohmic contact resistance. We present an investigation on the study of the effects of Si incorporation in Ti/Al/Mo/Au metallization scheme. Si is a commonly used n-type dopant in GaN alloys systems, and implantation and diffusion doping are utilized to increase carrier concentration at the surface of epilayers. In Ti/Si-based contact metallizations, the formation of TiSi@sub x@ at the interface is believed to lower the barrier height for conduction of current across the metal/GaN junction. In this study, we have carried out experiments to optimize the thicknesses of Si introduced in the metallization scheme. Impact of the place of insertion within the metallization scheme (e.g. Ti/Si/Al/Mo/Au vs. Ti/Si/Al/Si/Mo/Au) has also been studied. Si incorporation, surface treatment, and annealing are collectively optimized to induce a reduction in contact resistance. An example is the optimized Ti/Si/Al/Si/Mo/Au metallisation annealed at 850 @super o@C for which a contact resistance (R@sub c@) and specific contact resistivity (@rho@@sub c@) as low as 0.16 ± 0.02 @OMEGA@.mm and 6.77 ± 0.7 x 10@super -7@ @OMEGA@.cm@super 2@ were obtained, respectively. This represents a significant reduction when compared to what was correspondingly obtained for Ti/Al/Mo/Au at 0.41 @OMEGA@.mm and 4.78 x 10@super -6@ @OMEGA@.cm@super 2@, respectively. Atomic force microscopy (AFM) and Auger electron spectroscopy (AES) characterization are utilized to reveal the nature of ohmic contact formation and the evolution in surface morphologies of the metallization schemes and epilayers.

2:20pm **EM-WeA2 Non-uniform Interfacial Reactions of Ti/Al/Mo/Au Ohmic Contacts on n-AlGaN/GaN Heterostructure and its Effect on Carrier Transport***, **L. Wang**, F.M. Mohammed, I. Adesida,* University of Illinios at Urbana-Champaign

Ti/Al/Mo/Au multilayer metallization scheme has been demonstrated to have low ohmic contact resistance, high thermal stability, and sharp edge acuity on AlGaN/GaN high electron mobility transistors (HEMT). Transmission electron microscopy (TEM) is used to elucidate the cross-sectional interfacial microstructure and to gain insight into the formation mechanism of low-resistance ohmic contacts. It has been observed that reactions between the metallization and the AlGaN layer did not proceed uniformly. Localized penetration through AlGaN layer up to a depth of 130 nm was observed. Thinning of the AlGaN layer was noted where there was no penetration. Energy dispersive x-ray spectroscopy (EDS), and high resolution TEM (HRTEM) analysis confirmed that the reaction products were TiN. A strong correlation between the appearance of TiN islands and threading dislocations in the epitaxial layers was observed. Further analysis indicated that threading dislocations served as short-circuit diffusion channels, and thus are responsible for the non-uniform reaction. TiN islands have a large total area of intimate contact with the two-dimensional electron gas (2DEG), and since no tunneling of electron through the AlGaN is required, a low resistance ohmic contact is obtained. Methods for promoting and controlling the non-uniform interfacial reaction are proposed.

2:40pm **EM-WeA3 Polarization-enhanced Ohmic Contacts to GaInN-based Blue Light-Emitting Diodes***, **T. Gessmann**, Y.A. Xi, H. Luo, J.K. Kim, J.Q. Xi, K. Chen, E.F. Schubert,* Rensselaer Polytechnic Institute

Thin p-type Ga@sub 1-x@In@sub x@N cap layers have been grown on p-type GaN contact layers of blue light emitting diodes (LEDs) using metal-organic vapor phase epitaxy (MOVPE) with an AIX 200/4 RF-S reactor. The Ga@sub 1-x@In@sub x@N cap layers have thicknesses smaller than 4 nm and In-contents varying between x = 0.1 and 0.2. The LED structure consists of a GaN nucleation layer grown on c-oriented sapphire, a 2 µm-thick n-type GaN layer, 5 Ga@sub 0.86@In@sub 0.14@N quantum wells embedded in GaN-barriers, and a 0.2 µm-thick p-type GaN layer. Having a cap layer thickness below the critical thickness of Ga@sub 1-x@In@sub x@N on GaN, a piezoelectric field will be present in the cap layer resulting in increased carrier tunneling probabilities through the metal-semiconductor barrier. The In-content and the strain status of the cap layers have been analyzed using HR X-Ray diffractometry. For cap layer thicknesses smaller than 4 nm, pseudomorphic Ga@sub 1-x@In@sub x@N has been obtained for three different In-contents x = 0.1, 0.15 and 0.2. LEDs have been fabricated using standard photolithograpy processes, CAIBE mesa etching and electron beam deposition of Ni/Au and Ti/Al/Ni/Au contact metals. The specific contact resistance, diode series resistance, ideality factor and optical output power of the LEDs are determined and compared to devices without capping layer. A specific contact resistance @rho@@sub c@ = 1.8 x 10@super -4@ @Ohm@ cm@super 2@ has been obtained for samples with InGaN cap layer; this value is significantly smaller than @rho@@sub c@ of a sample without cap layer. The results will be discussed in terms of a model relating the cap layer thickness and In-content to the p-type contact resistance.

3:00pm **EM-WeA4 Indium-based Ohmic Contacts to n-GaSb and the Influence of Surface Passivation***, **J.A. Robinson**, S.E. Mohney,* The Pennsylvania State University

Gallium antimonide and related ternary and quaternary semiconductors have shown great potential for electronic devices as well as optoelectronic devices in the 0.3 - 8 µm wavelength range. High quality ohmic contacts help ensure device reliability and improve performance by providing a low resistance, a uniform interface morphology, and minimal semiconductor consumption. Pd-based contacts to n-GaSb that do not include In provide specific contact resistance values as low as 5 x 10@super -6@ @Omega@-cm@super 2@. However, by adding In, the specific contact resistance is reduced by 80%. We present two high quality In-based contacts that include Pd. Initial experiments included a Pd/In/Pd/Pt/Au contact that provides a specific contact resistance of 1.8 x 10@super -6@ @Omega@-cm@super 2@ using a modified pre-metallization surface treatment that involves 2.1% (NH@sub 4@)@sub 2@S. However, the surface and interfacial reaction morphology of the Pd/In/Pd/Pt/Au contact was less than optimal. As a result, sputtered Pd@sub 3@In@sub 7@/X/Au (X = Pt,W,WSi@sub 2@, or WSiN) contacts were explored as a means to improve reaction morphology and thermal stability. Contacts utilizing WSiN provide a specific contact resistance of approximately 3 x 10@super -6@ @Omega@-cm@super 2@ using a conventional surface treatment, and 1.8 x 10@super -6@ @Omega@-cm@super 2@ when the modified surface treatment is used. While the Pd@sub 3@In@sub 7@/WSiN/Au contact provides specific contact resistance values comparable to the best reported In-based contacts, this contact exhibits an improved reaction morphology and better thermal stability compared to other contacts.

3:20pm **EM-WeA5 Controlling Interfacial Reactions in Ferromagnetic Metal / GaAs Heterostructures***, **B.D. Schultz**,* University of Minnesota **INVITED**

Growth of epitaxial ferromagnetic metal contacts on compound semiconductors with atomically abrupt interfaces is often a challenge due to thermodynamic instabilities at the interface between the two materials and the subsequent formation of solid state reaction products. Elemental ferromagnetic metals, such as Fe and Co, can be grown by molecular-beam epitaxy (MBE) as single crystal films on GaAs; however, they are not thermodynamically stable and reacted phases form at the interface. The initial nucleation of Fe on GaAs surfaces is strongly influenced by the GaAs surface reconstruction, but results in little disruption of the reconstruction itself. Fe/GaAs reactions are reduced at lower MBE growth temperatures with a reacted layer thickness of approximately three monolayers at 15°C. Post-growth anneals at 250°C do not result in the reaction of additional GaAs, but the anneals significantly alter the electronic properties of the interface. Co is more reactive than Fe on GaAs and forms a reaction region composed of Co@sub 2@GaAs, CoGa, and CoAs. Thermodynamically stable metals such as ErAs can be used as epitaxial diffusion barriers to minimize Fe-Ga-As and Co-Ga-As interfacial reactions for growth temperatures as high as 225°C. This paper will emphasize the correlation between the structure, chemistry, magnetism and transport properties of Fe@sub x@Co@sub 1-x@/GaAs and Fe@sub x@Co@sub 1-x@/ErAs/GaAs contacts as determined by STM, RHEED, LEED, XPS, RBS, XRD and TEM. Supported by: ONR, DARPA, NSF/DMR, and AFOSR.

4:00pm **EM-WeA7 Molecular Beam Epitaxial Growth of Sc@sub x@Er@sub 1-x@Sb on III-V Compound Semiconductors***, **S.G. Choi**,* Univerrsity of Minnesota*; B.D. Schultz, C.J. Palmstrom,* University of Minnesota

Epitaxial metallic or semimetallic layers in semiconductors have potential application in novel electronic devices. Rare-earth group-V (RE-V) compounds have received much attention since they are thermodynamically stable and epitaxial on III-V semiconductors. In particular, Sc@sub y@Er@sub 1-y@As alloys have been employed successfully in GaAs-based materials, however, application of Sc@sub y@Er@sub 1-y@As alloys to other III-V's has been less fruitful due to large lattice-mismatches. Therefore, RE-V alloys with lattice parameters close to InP or GaSb are of considerable interest and Sc@sub x@Er@sub 1-x@Sb is one of the promising candidates. The lattice parameter of Sc@sub x@Er@sub 1-x@Sb ranges from 5.85Å (ScSb) to 6.11Å (ErSb), and can therefore be lattice-matched to InP, InAs, and GaSb by controlling the Sc to Er ratio. In this work, Sc@sub x@Er@sub 1-x@Sb alloys have been grown on various III-V semiconductors by molecular beam epitaxy (MBE). The surface ordering was monitored in-situ by RHEED and LEED. ErSb grown on GaSb(100) exhibited a (1x1) surface ordering with high Sb incorporation and a mixed (1x4)/(4x1) with low Sb incorporation. In-situ XPS data showed no significant differences in Er and Sb coverage between the two surfaces, however, the amount of Ga riding on the two surfaces was different, which may cause the different surface ordering. One possible mechanism for Ga atoms to segregate on a 500Å-thick ErSb film can be explained in terms of an embedded growth model. Growth of Sc@sub x@Er@sub 1-x@Sb on InAs and InP is more challenging since intermixing of the different group-V elements at the interface would be expected to degrade the quality of interface. Different methods for minimizing the intermixing at the interface will be discussed. Supported by ONR, DARPA, and ARO.

4:20pm **EM-WeA8 Chemically-Induced Point Defects and Schottky Barrier Formation at Metal/4H-SiC Interfaces***, **L.J. Brillson**, S. Tumakha, M. Gao,* The Ohio State University*; S. Tsukimoto, M. Murakami,* Kyoto University, Japan*; D.J. Ewing, L. Porter,* Carnegie Mellon University

We have used depth-resolved cathodoluminescence and Auger electron spectroscopies, DRCLS and AES, respectively, to determine the role of chemically-induced defects on 4H-SiC barrier formation on a nanometer scale. DRCLS of 5 nm Au, Ag, Ti, and Ni overlayers reveal formation of mid-gap defect transitions at ~1.8 eV and 2.85 eV extending only nanometers away from the junction. These states vary in their ranges of depth and depend sensitively on interface reactivity and subsequent UHV annealing. Their pervasive appearance near morphological defects and the absence of new gap states indicates that native defects rather than metal-specific states produce the dominant interface levels. For thicker TiAl Ohmic contacts with 5 min 1000 C anneals, cross-sectional scanning electron microscopy, AES, and DRCLS reveal a continuous ternary Ti-Si-C interfacial layer ~100 nm thick, a 1.9 eV sub-band gap transition localized within this depth and a 2.8 eV emission extending into the SiC, indicating both reaction-induced compound and defect formation, respectively. Within annealed NiTiAl Ohmic contacts, Ni silicide and Ti carbide form with a qualitatively different ~ 1.6 eV transition extending beyond the reaction zone. AES showing C movement from SiC into the metal overlayer indicate formation of a C-deficient SiC point defect. Thus the major difference in TiAl and NiTiAl interfacial reactions induces different interfacial gap states. For Ni/SiC reacted diodes, DRCLS and current-voltage measurements show a close correspondence between the Schottky barriers and deep level defect energies from diode to diode. Furthermore, the range of energies bounded by these defects corresponds with Schottky barrier heights reported previously via electrical measurements. This correspondence between chemically-induced deep levels at bulk defect energies and the range of macroscopic Schottky barriers for SiC appears to be a more general phenomenon, extending to other compound semiconductors as well.

4:40pm **EM-WeA9 Metal Germanide Schottky Contacts to Relaxed and Strained Germanium***, **A. Khakifirooz**, O.M. Nayfeh, M.L. Lee, E. Fitzgerald, D.A. Antoniadis,* Massachusetts Institute of Technology

Significant mobility enhancement offered by germanium channel MOSFETs and especially strained-Ge devices makes them very attractive for the deca-nanometer transistor scaling. A low resistivity contact to the S/D junctions is, however, the key to successful integration of such devices. Since high doping levels are difficult to achieve in Ge, Schottky S/D MOSFET is considered as an interesting option that also relaxes the constraints on the S/D junction abruptness. A systematic study of the formation of different metal germanide phases has been recently performed and they were characterized in terms of their electrical resistivity.@footnote 1@ In this work we study the Schottky barrier formed between germanium and Ni, Pd, and Pt germanides that were previously identified as the low-resistivity phases and offer a relatively wide processing window. Metal germanide is formed by annealing a very thin layer of metal (~15 nm) deposited onto HF-last Ge samples and patterned by lift-off. Samples are annealed in a furnace for 15 min. or in an RTA chamber for 1 min at different temperatures in the range of 350-500°C. Some diodes are also fabricated on strained Ge epitaxially grown on relaxed Si@sub 0.4@Ge@sub 0.6@ buffer with an ultrathin silicon cap. In this case, the metal thickness is selected in a way to consume the Si cap and almost the entire strained-Ge layer without touching the SiGe buffer layer to avoid excessive leakage. XRD and XTEM analysis are performed to study the crystallinity and morphology of the germanide layers, whereas I-V and C-V measurements are used to characterize the Schottky barrier. While nearly ideal barriers (ideality factor as good as 1.01), with a barrier height of 0.55-0.57 eV are obtained on bulk germanium, diodes fabricated on strained-Ge samples show excessive leakage current and high ideality factor (~1.8). Possible mechanisms responsible for this non-ideality are discussed. @FootnoteText@ @footnote 1@S. Gaudet et al., AVS 51st Int. Symp., 2004.

5:00pm **EM-WeA10 Ni Diffusion Studies From NiSi/Hf-based High-K Dielectric Stack Into Si***, **P. Zhao**, M.J. Kim, B.E. Gnade, R.M. Wallace,* University of Texas at Dallas

Fully silicided NiSi has been studied as a metal gate electrode due to low resistivity, scability and work function tunability.@footnote 1,2,3@ However, there remain many challenges for the integration of NiSi metal gates, such as phase stability, incomplete silicidation and possible Ni diffusion. The interdiffusion of Ni from NiSi through dielectrics into the underlying Si substrate (channel) has not yet been reported in the literature to our knowledge. We have investigated the Ni diffusion from NiSi through SiO@sub X@N@sub Y@ and Hf-based gate dielectrics into the Si channel. SIMS profiles show that interdiffusion of Ni from NiSi through a 13Å SiO@sub X@N@sub Y@ into the Si channel can be observed after thermal anneal budgets even as low as 350°C for 60min, representative of a typical backend process. It is also found that the Ni penetration increases with temperature and time. Although the penetration is reduced for a stack with thicker HfSiON dielectrics (23Å), the diffusion is observed when the stack is annealed for 60min at 400°C. Compared to N@sub 2@ annealing, deuterated forming gas annealing appears to enhance the Ni penetration. Both backside and front side SIMS, XRD, and HRTEM results will be presented. The possible diffusion mechanism will be discussed. This work is supported by Texas Instruments and the Semiconductor Research Corporation. @FootnoteText@ @footnote 1@ Z. Krivokapic, W. Maszara, F. Arsnia, E. Patron, Y. Kim, L. Washington, et al., VLSI 2003, p. 131-132 (2003)@footnote 2@ J. Kedzierski, E. Nowak, T. Kanarsky, Y. Zhang, D. Boyd, R. Carruthers, et al., IEDM 2002, p.247-250 (2002)@footnote 3@ C. Cabral, Jr., J. Kedzierski, B. Linder, S. Zafar, V. Narayanan, S. Fang, A. Steegen, P. Kozlowski, R. Carruthers, and R. Jammy. 2004 Symposium on VLSI Technology Digest of Technical Papers, p.184-185 .

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