Semiconductors
Room 321/322 - Session SC-TuM

Narrow Gap Semiconductors
Moderator: P. Desjardins, École Polytechnique de Montréal, Canada

8:20am **SC-TuM1 Antimonide-Based Compound Semiconductors: From Interfaces to High-Speed Transistors**, ***B.R. Bennett***, *R. Magno, J.B. Boos,* Naval Research Laboratory*; R. Tsai, A. Gutierrez,* Northrop Grumman Space Technology **INVITED**

Future high-speed analog and digital systems that will benefit from reduced power consumption and high data transmission rates include wireless applications, space-based, and micro-air-vehicles used for communications, imaging, and sensing. The development of Sb-based electronics for use in low-noise high-frequency amplifiers, digital and mixed-signal circuits could provide the enabling technology to address these needs. Our group has been using MBE to grow heterostructures for Sb-based high electron mobility transistors (HEMTs), resonant tunneling diodes (RTDs) and heterojunction bipolar transistors (HBTs). In this talk, I will discuss the design, growth, and performance of these devices. Growth issues include interface formation, doping, and composition control of alloys containing both As and Sb. The attractive material properties of this system have been demonstrated by our development of high-speed, low-power AlSb/InAs HEMTs with an intrinsic f@subT@ value of 250 GHz at V@subDS@ = 600 mV and an f@subT@ of 90 GHz at 100 mV. Current work is focused on making the technology viable by reducing leakage currents and developing MMIC-compatible processing. We have also fabricated RTDs with InAs contacts, Al(Ga)Sb barriers, and GaSb wells. For barriers that are 9 Å thick, peak currents exceed 10@super4@A/cm@super2@ with peak-to-valley ratios of 10:1 at biases near 100 mV. Other HEMT and RTD technologies (e.g. GaAs and InP) cannot achieve comparable performance at such low voltages. HBTs using InGaSb for the base and InAlAsSb alloys for the collector and emitter are also being explored. The InGaSb base is attractive due to its narrow bandgap and good hole transport characteristics. In addition, a wide range of heterojunction design flexibility is available because of the various InAlAsSb alloys that can be used. Good diode characteristics with an ideality factor of 1.1 have been obtained for InGaSb/InAlAsSb p-n heterojunctions grown with a 6.2 Å lattice constant.

9:00am **SC-TuM3 Understanding the Electronic Properties of Diluted Nitrides Relevant to Optoelectronic Applications**, ***W.M. Chen***, Linköping University, Sweden*; I. Buyanova,* Linkoping University, Sweden **INVITED**

Dilute nitride semiconductors exhibits unusual physical properties, like a giant bowing in the bandgap energy, forming an attractive new material system promising for long wavelength light emitters operating within the optic-fiber communication wavelength window. A full exploration of the alloys potential in device applications requires, however, detailed knowledge of their fundamental physical parameters and material issues. In this talk we shall provide an overview of our present understanding of basic electronic properties of the dilute nitrides such as Ga(In)NAs alloys and some key material-related problems relevant to optoelectronic device applications, such as determination of dominant mechanism for carrier recombination, potential fluctuation and localization effect, identification and formation of non-radiative defects, effects of post-growth thermal annealing and hydrogenation, compositional dependence of the electron effective mass and band alignment in Ga(In)NAs/GaAs heterostructures.

9:40am **SC-TuM5 Nitrogen Incorporation and Strain Relaxation Mechanisms during Metalorganic Vapor Phase Epitaxy of GaAsN Layers on GaAs (001)**, ***J.-N. Beaudry***, École Polytechnique de Montréal, Canada*; G. Bentoumi,* Université de Montréal, Canada*; S. Guillon,* Bookham Technology, Canada*; R. Leonelli,* Université de Montréal, Canada*; R.A. Masut, P. Desjardins,* École Polytechnique de Montréal, Canada

GaAs@sub 1-x@N@sub x@ epilayers (x @<=@ 0.04), nominally 200-nm-thick, were grown on GaAs (001) by metalorganic vapor-phase epitaxy using trimethylgallium, tertiarybutylarsine (TBAs), and dimethylhydrazine (DMHy). We carried out a systematic investigation of N incorporation as a function of the J@sub DMHy@/J@sub TBAs@ flow rate ratio for growth temperatures T@sub s@ varying from 500 to 650°C. Quantitative secondary ion mass spectrometry measurements indicate that N incorporation increases initially linearly with J@sub DMHy@ with a temperature-dependent incorporation probability that decreases from 0.0036 at 500°C to 0.0005 at 600°C to nearly zero at 650°C. The use of very large DMHy flow rates results in larger incorporation probabilities but lower growth rates. High resolution x-ray diffraction (HR-XRD) shows that the GaAs@sub 1-x@N@sub x@ lattice parameter decreases approximately linearly with increasing x up to about 0.02, with a strain coefficient corresponding to a linear interpolation between the lattice constants of GaAs and cubic GaN. At higher N fractions, the lattice parameter decreases more rapidly. Films with x up to approximately 0.02 are perfect single crystals with smooth interfaces as judged by HR-XRD and cross-sectional transmission electron microscopy (XTEM). Atomic force microscopy and cross-sectional imaging by transmission electron microscopy of a 230 nm thick layer with x = 0.0375 show that crack formation is the most important tensile strain relief mechanism although extrinsic stacking faults and misfit dislocations were also observed. Optical absorption and photoluminescence analyses reveal that higher crystalline quality and lower impurity concentrations were obtained for growth between 575 and 600°C.

10:00am **SC-TuM6 Stress Evolution and Nitrogen Incorporation in GaAsN Films Grown by Reactive Molecular Beam Epitaxy**, ***M. Reason***, *W. Ye, X. Weng, G. Obeidi, V. Rotberg, R.S. Goldman,* University of Michigan

Narrow gap nitride semiconductors have shown significant promise for a wide range of applications including long-wavelength light-emitters, high performance electronic devices, and high efficiency solar cells. A consequence of the large N-As size difference is a predicted limited miscibility on the anion sublattice, which often leads to the formation of GaN-rich nanostructures.@footnote 1,2@ In the case of dilute GaAs@sub 1-x@N@sub x@, conflicting results have been reported regarding the mechanism of N incorporation, and recent optical studies have suggested that the shear deformation potential and/or the binary elastic constants have an unusual composition dependence.@footnote 3@ To date, studies of stress evolution in GaAsN have been limited to x-ray rocking curves (XRC), typically interpreted using a linear interpolation of elastic constants. We have investigated stress evolution in GaAsN films, using a combination of in-situ and ex-situ measurements. A comparison of Nuclear Reaction Analysis and Rutherford Backscattering Spectrometry in channeling and non-channeling conditions suggests significant composition-dependent incorporation of N into non-substitutional sites. Furthermore, a comparison of stresses measured via in-situ wafer curvature measurements, with those determined using a Vegard's Law interpretation of XRC, suggests a change in the mechanism of N incorporation for x@>=@0.015. The observed stress differences are likely the signature of significant bowing of the elastic properties of GaAsN. This work was supported in part by the DOE (Photovoltaics Beyond the Horizon Program), the Air Force Office of Scientific Research (MURI Program), and the TRW Foundation. @FootnoteText@@footnote 1@R.S. Goldman et al., Appl. Phys. Lett. 69, 3698 (1996), J. Electr. Mater. 26, 1342 (1997). @footnote 2@X. Weng, S.J. Clarke, W. Ye, R.S. Goldman, et al, J. Appl. Phys. 92, 4012 (2002). @footnote 3@Y. Zhang, A. Mascarenhas, H.P. Xin, and C.W. Tu, Phys. Rev. B 61, 4433 (2000).

10:20am **SC-TuM7 Electronic and Optical Properties of GaAsN/GaAs Quantum Wells**, ***N. Shtinkov***, *S. Turcotte, J.-N. Beaudry, P. Desjardins, R.A. Masut,* École Polytechnique de Montréal, Canada*; G. Bentoumi, R. Leonelli,* Université de Montréal, Canada

We present a theoretical and experimental investigation of the electronic structure and optical properties of GaAs@sub 1-x@N@sub x@/GaAs (001) quantum wells (QWs) with x < 0.045. The electronic structure is calculated using a recently developed empirical tight-binding (ETB) model, taking strain into account, for values of the GaN/GaAs valence band offset (VBO) from -4 to 4 eV. The valence band structure is found to be strongly influenced by the VBO and the strain-induced heavy hole-light hole splitting. At zero VBO only one heavy-hole and one light-hole state are observed. For VBO < 0 the ground hole state is localized in the barrier, but quasi-bound QW-localized heavy-hole states are observed in the continuum. For VBO > 0, the ground state is always a light-hole state localized in the QW, but there exist a number of excited heavy- and light-hole states. In spite of the significant influence of the VBO on the valence band structure, our results show that its effect on the transition energies is rather small for positive VBO. For example, changing the VBO from 0 to 4 eV in a QW with x = 0.04 shifts the ground state transition energy by only 16 meV. Therefore in simple rectangular QWs only the sign but not the value of the VBO can be unambiguously deduced from measurements of the transition energies. In order to compare our predictions with experimental results, we have measured low-temperature optical absorption spectra from fully coherent 7-period 7-nm-GaAs@sub 1-x@N@sub x@/15-nm-GaAs multiple quantum wells with x up to 0.04. We found that the measured ground-state and excited-state transitions are in

good agreement with our ETB calculations when considering a positive GaAsN/GaAs VBO.

10:40am **SC-TuM8 Growth of InN and Related Compounds by RF Plasma Molecular Beam Epitaxy**, ***W.J. Schaff***, *H. Lu,* Cornell University **INVITED**

InN is of interest for small bandgap, low effective mass applications. InN is grown with a remote RF plasma source of nitrogen using molecular beam epitaxy at substrate temperatures near 500C. GaN or AlN buffers on c-plane sapphire substrates are required for best InN quality. More than 200 wafers have been grown. All exhibit a direct bandgap near 0.7eV which is frequently measured for MBE grown InN@footnote 1@ and agrees with theoretical calculations.@footnote 2@ Bandfilling effects explain observations of increased energy of optical transitions at increased electron density.@footnote 3@ Control of electrical conductivity is limited. Undoped InN is n-type with electron densities that are usually high enough to be degenerate. Electron density falls with InN layer thickness and can be as low as 3E17cm-3 in layers beyond 5 microns thick. 300K mobility is beyond 1000 cm2/Vsec in 1 micron layers and is above 2000 in 5-7 micron thick layers.@footnote 4@ Dislocation density also decreases with InN layer thickness. A cause-effect relationship between electron and dislocation density is not established yet. Si is introduced as a shallow donor while unintentional shallow donors have not been identified. InN has not been made p-type. Mg and Be doping affects electron density and mobility, but net p-type conductivity has not been seen. InN can be grown in the a-plane direction when a-plane GaN or AlN buffers are used on r-plane sapphire.@footnote 5@ In contrast, direct growth on r-plane sapphire without a buffer layer creates predominantly a cubic form of InN.@footnote 6@ Mobility is lower and carrier density is higher in InN in the forms which are not c-plane wurtzite. @FootnoteText@ @footnote 1@V. Yu. Davydov, A. A. Klochikhin, R. P. Seisyan, et al, phys. stat. Sol. (b), 229, R1 (2002).@footnote 2@ F. Bechstedt, J. Furthmüller, M. Ferhat, L. K. Teles, L. M. R. Scolfaro, J. R. Leite, V. Yu. Davydov, O. Ambacher, and R. Goldhahn, phys. stat. sol. a 195, 628 (2003).@footnote 3@ V. Cimalla, Ch. Förster, G. Kittler, I. Popa, R. Kosiba, G. Ecke, O. Ambacher,R. Goldhahn, S. Shokhovets, A. Georgakilas, H. Lu, W. Schaff, Proc. ICNS-5 submitted to phys. stat. sol (a) 195, No. 1, 3-10 (2003).@footnote 4@ H. Lu, W.J. Schaff, L.F. Eastman, GaN and Related Alloys - 2001. Symposium (Materials Research Society Symposium Proceedings Vol.693) Mater. Res. Soc, 2002, xv+860 p. (9-14).@footnote 5@ H Lu, W.J. Schaff L F. Eastman, J. Wu, Wladek Walukiewicz, Volker Cimalla, Oliver Ambacher, submitted to Applied Physics Letters.@footnote 6@ V. Cimalla, J. Pezoldt, O. Ambacher, L. Spiess, and G. Teichert, H. Lu and W. J. Schaff, submitted for publication.

11:20am **SC-TuM10 Electronic Band Structure Ge(1-x)Sn(x) Alloys Grown on Silicon**, ***C.S. Cook***, Arizona State University*; S. Zollner,* Motorola*; M. Bauer, J. Kouvetakis, J. Menendez, J. Tolle,* Arizona State University*; C. Bungay,* J. A. Woollam Co., Inc.

The development of manufacturable direct band gap materials on Si is crucial for optoelectronic devices integrated with silicon circuits. Ge-Sn alloys with varying metastable compositions ranging from 2% - 18% were grown by UHV-CVD using a newly developed deuterium-stabilized Sn hydride with digermane. We use deep ultra violet and infrared spectroscopic ellipsometry to determine the optical properties of this new class of Si-based infrared semiconductors in the Ge1-xSnx system. Optical analysis of the energy derivatives in comparison with analytical lineshapes shows a Ge-like bandstructure that is substantially red-shifted compared that of elemental Ge. Tunability of these gaps with composition could have interesting optoelectronic applications.

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