Thursday Morning, November 3, 2005

Electronic Materials and Processing
Room 310 - Session EM2-ThM
Heteroepitaxy and Low-Dimensional Structures
Moderator: R.S. Goldman, The University of Michigan

8:20am **EM2-ThM1 Materials Integration of III-V Heterostructures***, **M. Goorsky**, S.L. Hayashi, A. Noori,* University of California, Los Angeles*; R.S. Sandhu,* University of California, Los Angeles and Northrop Grumman Space Technology*; A. Cavus, C. Monier, M. Lange, M. Wojtowicz, T. Block, A. Gutierrez-Aitken,* Northrop Grumman Space Technology **INVITED**

III-V wafer bonded structures satisfy requirements for electronic device structures that simultaneously possess a large surface lattice parameter (e.g., near that of InAs) and a high substrate resistivity. The objectives of the research are to address the fabrication of III-V composite wafer bonding with the ultimate goal of producing virtual substrates for advanced III-V devices. Graded buffer layers are one key technological step. Very thin InAlAs graded buffer layer structures were produced for virtual InAlAs substrate applications. The rapid kinetics of strain relaxation in In@sub x@Al@sub 1-x@As graded buffer layers (GBLs) was exploited to produce thin (0.21 µm - 0.90 µm) buffer layers graded from the InP substrate to 6.0 Å. GBL layers as thin as 0.21 µm showed full strain relaxation and GBL layers as thin as 0.45 µm showed similar growth mode, surface roughness, and strain relaxation as thicker GBL structures. The threading dislocation density was low (mid-10@super 6@ cm@super -2@) for the 0.45 µm and the 0.90 µm buffer layers but there was evidence of non-uniform threading dislocation distribution for the 0.21 µm buffer structures. The feasibility of aggressive grading for other III-V systems will also be addressed. For some applications, even a thin GBL - upon which device structures are grown - is not feasible for device applications. To address the issue of limited GBL thickness, hydrogen exfoliation ("Smart-Cut") has been assessed to transfer thin films of InP, InAs, or 6.0Å lattice parameter layers to high resistivity substrates. We have developed a strategy for implantation and exfoliation based on the nucleation and growth of mechanical cracks at the projected range of the implant. This method has led to reproducible exfoliation and successful transfer of a wide variety of semiconductor materials. Damage-free chemical-mechanical polishing (CMP) has also been developed to produce low roughness (< 1 nm r.m.s) surfaces for subsequent epitaxial deposition. Another issue associated with composite wafers is the coefficient of thermal expansion (CTE) differences between the bulk substrate and the transferred layer. We have incorporated the temperature-dependent CTE values into force-balance equations to determine the thermodynamic stability of heterostructures based on these materials. The stability criteria have been experimentally confirmed. Examples of device structures on graded buffer layers and transferred layers will be shown to demonstrate the feasibility of this approach for the integration of III-V heterostructures.

9:00am **EM2-ThM3 Interfacial Bond Formation in W-structured type-II IR Detectors as Revealed by Cross-Sectional Scanning Tunneling Microscopy***, **J.C. Kim**, J.G. Tischler, I. Vurgaftman, J.R. Meyer, E.H. Aifer, L.J. Whitman,* Naval Research Laboratory*; C.L. Canedy, E.M. Jackson,* SFA Inc.

W-structured type-II superlattices (W-SLs) were originally developed to enhance the gain of mid-wave infrared lasers, but also have desirable properties for the design of infrared detectors. We are currently investigating ternary (and quaternary) W-SL structures composed of InAs, InGaSb (InGaAsSb), and AlInSb (AlInAsSb) layers for use in long-wave and very long-wave infrared photodiodes. Interfaces play a significant role in W-SLs because there are twice as many interfaces in each period than in a typical two-constituent SLs such as InAs/Ga(In)Sb, and therefore more options to engineer interfaces in order to compensate strain. We use x-ray diffraction to determine the overall strain in the W-SLs, and cross-sectional scanning tunneling microscopy (XSTM) to directly image the atomic-scale structure of the SLs, including the interfacial bonds, as a function of growth conditions. Differences in the local bond length of different interfaces (e.g., AlAs vs. InSb) result in specific contrast in XSTM images, making it possible to directly identify the interfacial bond types. We find that "unforced" AlSb/InAs interfaces, where both shutters are switched simultaneously with the intention of creating a neutral mix of interfacial bonds, actually consist predominantly of AlAs bonds, leading to undesirable strain. In contrast, InGaSb/InAs interfaces form as intended. We will discuss the surface science underlying the formation of these interfacial bonds, along with their effects on the optical properties and device characteristics.

9:20am **EM2-ThM4 Control of InAs/GaAs Quantum Dot Density and Positioning Using Modified Buffer Layers***, **W. Ye**, S. Hanson, M. Reason, X. Weng, R.S. Goldman,* The University of Michigan

Recently, strain-induced self-assembled quantum dots (QDs) have enabled the development of high performance light-emitters and detectors. Further advances in optoelectronics and quantum computing will require a narrowing of the density of states and achievement of periodic charge distributions, both of which necessitate the fabrication of high density, nearly monodispersed, highly ordered QD arrays. Various efforts have been made to achieve high densities of laterally ordered InAs/GaAs QDs. However, the mechanisms of lateral ordering of QDs are the subject of continued debate. A significant remaining question concerns the effects of buffer layers on the QD density and lateral ordering. Therefore, we have examined the patterning effects of buffer layers during the growth of QD SLs. Our QD SLs consisted of 2.6 ML InAs and 5 nm GaAs grown by molecular beam epitaxy at 500°C. Prior to QD deposition, GaAs buffer layers were grown under several different conditions, involving growth and/or annealing at 580°C and 500°C. High temperature grown buffers consist of relatively flat surfaces, while lower temperature grown buffers contain "mound-like" features elongated along the [1-10] direction. Isotropic distributions of QDs are observed for QD growth on flat buffers. Interestingly, QD alignment along the [1-10] direction is observed for QD SL growth on buffers containing mounds. This anisotropic QD alignment is enhanced as the number of QD SL increases and is dependent on the density of mounds. For flat buffers, the density of QDs decreases with stacking, consistent with the model of Tersoff. However, for buffers containing mounds, this effect is compensated by an increase in QD density. We propose a new mechanism for QD nucleation, which is based upon patterning by undulated In-enriched GaAs spacer layers following the initials sets of QD SLs.

9:40am **EM2-ThM5 Implantation-Defect-Mediated Intermixing of InAs/InP Quantum Dot Layers***, **C. Dion**,* École Polytechnique de Montréal, Canada*; S. Raymond, G. Ortner, P.J. Poole,* National Research Council of Canada, Canada*; F. Schiettekatte, M. Chicoine,* Université de Montréal, Canada*; P. Desjardins,* École Polytechnique de Montréal, Canada

The reduced dimensionality provided by quantum dots (QDs), which leads to atom-like discrete energy levels and @delta@-function-like density of states, offers possibilities for considerable improvements in optoelectronic device applications. However, the use of these nanostructures relies on achieving precise tunability of QDs luminescence emission through QDs size and composition. Since InAs/InP QDs growth is complicated by the rapid exchange of group V species at the InAs/InP interfaces, a post-growth method to fine tune the electronic properties of this particular system is of great relevance. We have investigated the effect of post-growth P implantation followed by rapid thermal annealing on the low-temperature photoluminescence (PL) spectra of self-assembled InAs/InP(001) QDs grown by chemical beam epitaxy (CBE) and metal-organic vapor phase epitaxy (MOVPE). In untreated samples, threshold temperature for intermixing was found to be 725 °C with blueshifts of the PL peaks of up to 90 meV after RTA at 800 °C for 210 s, while preserving emission bandwidth. In order to obtain larger blueshifts, we studied the effect of introducing point defects into InP cap layers by implanting P at energies sufficiently low to insure that the InAs QDs were not damaged. Implantation with fluence as low as 10@super 12@ P/cm@super 2@ followed by annealing at 500 °C were sufficient to induce a 275 meV blueshift. These observations give important insights into the role of defects generated in InP-based structures on the As/P intermixing and reinforce the applicability of ion implantation for the fabrication of monolithically integrated devices. Implantation-defect-mediated intermixing for wavelength tuning of InAs/InP QDs-based laser structures was investigated.

10:00am **EM2-ThM6 Modeling of InAs/GaAs Self-Assembled Heterostructures: Quantum Dot to Quantum Ring Transformation***, **I. Filikhin**,* North Carolina Central University*; E. Deyneka,* North Carolina A&T State University*; B. Vlahovic,* North Carolina Central University

It is possible to directly observe discreet energy spectra of self-assembled quantum dots (QD) and quantum rings (QR) by means of capacitance-voltage (CV) spectroscopy.@footnote 1,2@ Related theoretical studies, however, had some difficulties interpreting the experiments. Acquired values of the electron effective mass in QD@footnote 1@ and QR@footnote 2,3@ were significantly larger than the bulk mass. Also, the value of the energy-gate-voltage conversion coefficient was in disagreement with experimental conditions.@footnote 2,3@ In presented work we use relatively simple single subband model for InAs/GaAs QD(QR)

where the energy dependence of electron effective mass is defined by the Kane formula.@footnote 4@ Model assumptions lead to the non-linear Schrodinger equation in 3D space.@footnote 5@ Model geometrical parameters are based on the fabrication process for InAs/GaAs QD/QR,@footnote 6@ for which the experimental CV data is available.@footnote 1,2@ We assume that the QD to QR transformation occurs without the loss of InAs material. Energies of confinement states of QD(QR) are calculated. Obtained results for single energy levels are in good agreement with the CV spectroscopy.@footnote 1,2@ Our calculations reproduce experimental value for the energy-gate-voltage conversion coefficient as 7. Magnitude of the non-parabolic contribution to the electron effective mass is also evaluated. @FootnoteText@ @footnote 1@ B. T. Miller, et al., Phys. Rev. B 56, 6764 (1997).@footnote 2@ A. Lorke, et al., Phys. Rev. Lett. 84, 2223 (2000).@footnote 3@ A. Emperador, et al., Phys. Rev. B. 62, 4573 (2000).@footnote 3@ E. Kane, J. Physics and Chemistry of Solids 1 249 (1957).@footnote 4@ Li Y, et al., Journal Applied Physics 90 6416 (2002).@footnote 5@ I. Filikhin, E. Deyneka and B. Vlahovic, Model. Simul. Mater. Sci. Eng. 12, 1121 (2004).@footnote 6@ J.M. Garsia et al., Appl. Phys. Lett. 71, 2014 (1997).

10:20am **EM2-ThM7 Relaxed Coupling Conditions between Quantum Dots and Photonic Crystals***, **P. Petroff,*** University of California, Santa Barbara **INVITED**

The possibility of controling the photon emission directionality and enhancing their emission rate by using quantum dots (QDs) coupled to a high Q photonic crystal (PC) opens important technological applications e.g. single photon emitters and detectors. Hence, understanding and controling this coupling is essential if the weak or strong coupling regime is to be routinely achieved. Coupling conditions are however, very demanding, since both the position of the QD and its frequency must be tuned to the PC the mode location and the ultra sharp resonant frequency. We will demonstrate using the InAs/GaAs system a strategy which allows for the deterministic coupling of a single QD to an S1 PC. This technique is general and can be applied to other PC types.@footnote 1@ We report high Purcell factors and non-trivial relaxation dynamics for off resonance lines in all fabricated structures.. We will discuss the coupling of an L3 PC with a dilute InAs/GaAs QD system which shows an ultra low threshold stimulated emission. This "threshold-less" laser is realized even for off - resonance coupling conditions between the QDs and the L3-PC. This new body of experimental observations suggests a relaxation of the coupling conditions which is specific to the QDs. We will present evidence that the continuum of states associated with the wetting layer together with acoustic phonons are involved in these relaxed coupling conditions. Acknowledgments: This work has been carried out in collaboration with A. Badolato, K. Hennessy, S. Strauf, M. Atature, J. Dreiser, M. Rakher, L. Andreani, E.Hu, A. Imamoglu and D. Bouwmeester. The support of an NSF-NIRT no: 0304678 and DARPA no: 972-01-1-0027. @FootnoteText@@footnote 1@A.Badolato et al., Science 308, 1158 (2005).

11:00am **EM2-ThM9 Formation of Flat, Relaxed Si@sub 1-x@Ge@sub x@ Alloys on Si(001) Without the Use of Buffer Layers***, **S. Hong**, H.-W. Kim, D.K. Bae, S.C. Song, G.-D. Lee, E. Yoon,* Seoul National University, South Korea*; C.S. Kim,* Korea Research Institute of Standards and Science*; Y.L. Foo, J.E. Greene,* University of Illinois at Urbana-Champaign

Flat, fully-strained Si@sub 1-x@Ge@sub x@ layers with thicknesses ranging from 40 to 240 nm were grown on Si(001) at 450 @super o@C by ultrahigh vacuum chemical vapor deposition and subjected to furnace annealing at 1000 @super o@C for 20 min to induce relaxation. In order to suppress the thermally-activated surface adatom diffusion leading to surface roughening, while simultaneously promoting misfit dislocation formation, SiO@sub 2@ capping layers were deposited prior to annealing. The degree of strain relaxation R and the root-mean-square surface roughness w are determined as a function of layer thickness. For Si@sub 1-x@Ge@sub x@ layers annealed without SiO@sub 2@ cap layers, the primary relaxation mechanism is strain-induced roughening leading to the formation of a self-organized mound structure with high w and R. However, for capped layers, strain-relaxation occurs through the formation of misfit dislocations and surface roughening is controlled by the resulting cross-hatch. Detailed analysis using atomic force microscopy line scans show that the crosshatch patterns consist of slip steps produced by misfit dislocations at the Si@sub 0.77@Ge@sub 0.23@/Si(001) interface. The presence of oxide cap layers during annealing changes the mechanism of strain relaxation from strain-induced to misfit dislocation induced roughening and inhibits surface diffusion such that the evolution of crosshatch ridges from slip steps is limited. As a result, with oxide capped 240-nm-thick films, we obtain smooth, relaxed Si@sub 0.77@Ge@sub 0.23@ layers with w = 0.68 nm and R = 68% without the necessity of using several-µm-thick compositionally-graded buffer layers.

11:20am **EM2-ThM10 Formation of Epitaxial Ge Nanorings on Si by Self-assembled SiO@sub 2@ Particles and Touchdown of Ge Through a Thin Layer of SiO@sub 2@***, **Q. Li**, S.M. Han,* University of New Mexico

We demonstrate that hexagonally packed single-crystalline Ge rings can be grown around the contact region between self-assembled SiO@sub 2@ spheres and 1.2-nm-thick chemical SiO@sub 2@ on Si. When the oxide-covered Si substrate is pulled from a colloidal suspension of SiO@sub 2@ spheres, the SiO@sub 2@ spheres self-assemble into a hexagonally packed monolayer on the substrate. These SiO@sub 2@ spheres provide a surface diffusion path to guide the Ge adspecies to reach the substrate. We have previously determined that the Ge adspecies readily desorb from the bulk SiO@sub 2@ surface with a desorption activation energy of 42±3 kJ/mol. This low desorption activation energy gives rise to a low surface diffusion barrier, which in turn leads to a high diffusion length on the order of several micrometers, exceeding the dimension of the SiO@sub 2@ spheres. With a flux of Ge impinging at 45° from the surface normal, the Ge beam cannot directly impinge on the underlying substrate through the openings between SiO@sub 2@ spheres. The Ge adspecies diffuse around the SiO@sub 2@ spheres and "touchdown"[Li et al., APL, 85(11), 1928 (2004)] through the chemical SiO@sub 2@, forming epitaxial ring structures. The touchdown process anchors nanoscale Ge seed pads to the underlying Si substrate. The ring formation uniquely takes advantage of the SiO@sub 2@ sphere self-assembly; the weak interaction between Ge adspecies and SiO@sub 2@; and the touchdown where Ge densely nucleate on Si surface through the 1.2-nm-thick chemical oxide. We will also demonstrate that ring dimension and geometrical arrangement can be precisely controlled by the size of the SiO@sub 2@ spheres and by the artificially introduced surface corrugation, respectively.

11:40am **EM2-ThM11 Local Origins of Catalytic and Sensor Activity in 1D Oxide Nanostructures: From Spectromicroscopy to Device***, **A. Kolmakov,*** SIUC*; U. Lanke,* University of Saskatchewan, Canada*; S.V. Kalinin,* Oak Ridge National Laboratory

When nanowire radius (or nanobelt's thickness) is comparable with its Debye length, the adsorption/desorption of donor/acceptor molecules on the surface of the nanowire (nanobelts) drastically alters the bulk electron density inside the nanowire manifesting superior performance of nanostructure as a chemical sensor as an example. For the nanostructures which are functionalized with catalytic particles this appears to be an oversimplified picture. The sensing effect of such 1-D metal oxide chemiresistor or chemi-FET can have completely different origins like spillover effect from catalyst particles, gas induced barrier modulations of the local electroactive element (nanoparticles, defects etc)or transient processes in the gate oxide. To explore the relative importance of these phenomena on catalytic and sensing performance of 1D nanostructures, adsorbate specific, microscopic techniques have to be developed. We have tested a range of imaging techniques to address local transport behavior in the working metal oxide nanostructure wired as chemiresitor and chemi-FET. In particular, we have developed the experimental techniques and preparative protocols for implementation of synchrotron radiation based spectro-microscopies (SPEM and X-PEEM) to individual 1D nanostructures. Using X-PEEM in NEXAFS mode we demonstrated the ability to reveal submicron lateral compositional and electronic (work function) inhomogeneouties in individual nanowire. We were also complemented our results with Scanning Impedance Microscopy (SIM) and Scanning Surface Potential Microscopy (SPPM) to acquire ac and dc potential distributions in an operating nanowire device. These results open new avenue to visualize the adsorption /desorption phenomena on the surfaces of the individual nanostructure both in real time and at nano- and mesoscopic level.

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