Semiconductors
Room 326 - Session SC-ThM

Heteroepitaxy and Strain Engineering

Moderator: R.S. Goldman, University of Michigan

8:40am **SC-ThM2 Strain Engineering of SiGe/Si Structures*, P.M. Mooney,*** IBM T.J. Watson Research Center **INVITED**

Heteroepitaxy allows the growth of semiconductor structures for a wide variety of device applications. When the materials are also lattice mismatched, the strain can be tailored to enhance the electronic properties of the active device layers. At the same time, however, misfit dislocations and other defects that tend to degrade device characteristics may be present. Strained Si MOSFETS are being developed for high-speed logic applications. These devices are built in a Si layer under biaxial tensile strain that is grown pseudomorphically on a so-called virtual substrate, typically a thick, strain-relaxed SiGe buffer layer on a Si(001) substrate. Key to the success of this application is the control of the misfit dislocations required to relieve the strain in the SiGe layer to achieve a low density of threading dislocations in the active device layers. Two types of SiGe/Si structures will be discussed. Strain-relaxed SiGe buffer layers produced by the implantation of He below the interface between a pseudomorphic SiGe layer and the Si(001) substrate and subsequent annealing are significantly more relaxed compared to layers of the same thickness that were not implanted. Platelet defects that are formed near the top of the Si substrate during annealing serve as dislocation nucleation sources. Elastic (defect free) strain relaxation of SiGe/Si structures is also under investigation. We have recently demonstrated that a pseudomorphic SiGe layer grown on free-standing Si relaxes elastically. The strain is shared with the free-standing Si layer resulting in Si under biaxial tensile strain.

9:20am **SC-ThM4 Strain Relaxation of Step-graded InAsP Buffers on InP Grown by Molecular Beam Epitaxy*, M.K. Hudait*,** *Y. Lin, S.A. Ringel,* The Ohio State University

Compositionally graded metamorphic buffers grown on InP substrates to increase the substrate lattice constant are of interest to support a range of high-speed electronic and infrared optoelectronic devices based on the InGaAsP material system. Recent work by our group has shown that grading the composition of the anion sublattice using InAsP buffers as opposed to the group-III cation sublattice using In(Al,Ga)As buffers is advantageous for such applications since decoupling the growth rate (Indium flux) from the composition control (As:P flux ratio) results in superior morphological properties of relaxed layers. Here, we discuss the strain relaxation properties of step-graded InAs@sub y@P@sub 1-y@ out to a nominal composition of y = 0.4, representing a total misfit of ~ 1.2% with respect to InP. For this study, InAs@sub y@P@sub 1-y@ buffers were grown on both on-axis and 2° off-cut (001) InP substrates under identical solid source MBE growth conditions with an average grading rate of 20% As/µm. The relaxation of each layer within each buffer was measured along [1-10] and [110] directions using TAXRD to evaluate asymmetric relaxation and tilt relative to the initial substrate orientation. For both substrate types, the strain relaxation was found to be symmetric and greater than 90% for the top InAs@sub 0.4@P@sub 0.6@ layer. This indicates that @alpha@ ([1-10] direction) and @beta@ ([110] direction) slip systems have similar activation energies for dislocation nucleation. Moreover, a small epilayer tilt of ~190 arcsec was observed for both substrate orientations, which indicates that tilt generated by @alpha@ and @beta@ dislocations will be in proportion to the substrate offcut resolved in [110] and [1-10] directions, respectively. The relation between these observations and properties of group-V and group-III core dislocations, and a comparison to cation based graded layers will be made to optimize the growth of these buffers.

9:40am **SC-ThM5 Effects of InAlSb Buffer Layers on the Structural and Electronic Properties of InSb Films*, X. Weng*,** *N.G. Rudawski, R.S. Goldman,* University of Michigan*; D.L. Partin, J. Heremans,* Delphi Research and Development Center

InSb is useful for a variety of device applications, including long wavelength light sources and magnetoresistive sensors. InSb films are generally grown on GaAs substrates, with a 14.6% lattice mismatch which results in a high density of threading dislocations. In earlier work, we showed that electron scattering from the strain field associated with threading dislocations is the primary mobility-limiting mechanism in highly mismatched InSb films.@footnote 1@ The electron mobility of InSb films increases with the film thickness due to the decrease of threading dislocation density. Recently, highly mismatched resistive buffers such as InAlSb showed promise for increasing the electron mobility of thin InSb films.@footnote 2@ However, the mechanisms of buffer strain relaxation and the consequent increase in InSb electron mobility are not well understood. Thus, we have studied the effects of In@sub0.94@Al@sub0.06@Sb buffers on the structural and electronic properties of InSb films. We find a significant increase of electron mobility for InSb films grown on In@sub0.94@Al@sub0.06@Sb buffers, in comparison with those grown directly on GaAs. Cross-sectional transmission electron microscopy (TEM) reveals bending of threading dislocations at the InSb/In@sub0.94@Al@sub0.06@Sb interface, suggesting that the InSb/In@sub0.94@Al@sub0.06@Sb heterojunction plays an important role in suppressing the propagation of threading dislocations. Plan-view TEM shows a more than 50% decrease of threading dislocation densities in InSb films grown on In@sub0.94@Al@sub0.06@Sb layers compared with those grown directly on GaAs, suggesting that the electron mobility increase is likely due to the reduction in dislocation density. The effects of the buffer composition on the structure and properties of the InSb films will also be discussed. @FootnoteText@@footnote 1@ X. Weng, R.S. Goldman, D.L. Partin, and J.P. Heremans, J. Appl. Phys. 88, 6276 (2000). @footnote 2@D.L. Partin, J. Heremans, and C.M. Thrush, J. Vac. Sci. Technol. B 17, 1267 (1999).

10:00am **SC-ThM6 Heteroepitaxy of III-Se Materials: Compatibility to Si and Their Growth Studied by In-situ Scanning Probe Microscopy*, T. Ohta*,** *A. Klust, J.A. Adams, Q. Yu, M.A. Olmstead, F.S. Ohuchi,* University of Washington

Heteroepitaxy of semiconductors on silicon is essential for expanding Si-based technology beyond standard microelectronics. Materials consisting of Group III (Ga and Al) and selenium (Se) are of particular interest, combining Si compatibility with structural versatility and optical band gaps (Eg(Ga@sub x@Se@sub y@)=1.8-2.6eV and Eg(Al@sub x@Se@sub y@)>3.1eV). We present a study of heteroepitaxy of layered GaSe on Si(111) using scanning tunneling microscopy (STM). GaSe is composed of a stack of iono-covalently bonded quad layers (QL) of Se-Ga-Ga-Se with van der Waals interactions between the layers. Of general interest for the growth of layered materials whether the full QL is required for layer nucleation. During growth, we observed: (1) formation of a pseudomorphic GaSe-bilayer, (2) development of triangular QL nuclei, followed by (3) layer-by-layer growth of GaSe layers. The first GaSe bilayer perfectly passivates the Si(111), making its surface environmentally inert. Triangular islands, one QL thick, nucleate on this passive surface with their edges aligned to of Si(111). Nuclei with two orientations, rotated by 180°, are observed, leading to orientational domains in thicker layers. We characterized their electronic structures and the type of defects incorporated in the domains. In thicker films, GaSe layers often extended over substrate atomic steps, showing a "carpet-on-steps" morphology. This work is supported by NSF Grant DMR 0102427 and the M. J. Murdock Charitable Trust. T. O. further acknowledges support by UIF Nanotechnology fellowship of the University of Washington, and A. K., the Alexander von Humboldt-Foundation, Germany.

10:20am **SC-ThM7 Characterization of High Quality GaAs(100) Films Grown on Ge(100) Substrates*, A. Wan*,** *V.M. Menon, D. Wasserman, A. Kahn, S.R. Forrest, S.A. Lyon,* Princeton University

We have grown GaAs (100) films by MBE on off-axis Ge(100) substrates cut 6° towards the (110) plane and 6Âº towards the (111) plane. The motivation for this work is the integration of GaAs and lattice matched InGaAsN on Si and SiGe. Vicinal surfaces with regular arrays of double steps are crucial in eliminating anti-phase domains in III-V/elemental systems.@footnote 1@ We used electron diffraction, STM, AFM, X-ray and ultraviolet photoemission, electron channeling, photoluminesence (PL) and Raman spectroscopy to investigate the quality of the GaAs films. We observed two domains (1 x 2 and 2 x 1) on the surfaces of the Ge substrates both after annealing and after Ge buffer growth, on each of the off-cut orientations. GaAs films grown on Ge substrates cut towards the (110) exhibited poor morphology, with evidence of faceting and polycrystalline domains, whereas films grown on substrates cut towards the (111) exhibited much higher crystalline quality with a (4 x 2) recontruction. Low temperature PL exhibited a sharp narrow peak at 1.51 eV on samples grown on substrates cut towards (111), indicative of high quality material. We also investigated the effects of using different growth conditions including migration enhanced epitaxy, which have been reported to reduce both the APD and doping at the GaAs/Ge.@footnote 2,3@ We conclude that high quality GaAs can be grown at a variety of growth temperatures and conditions on off axis Ge(100) substrates cut 6° towards the (111). @FootnoteText@ @footnote 1@J.M. Zhou et al., Appl. Phys Lett. 68, 628 (1996) @footnote 2@R.M. Sieg et al., J. Vac. Sci. Technol. B 16, 1471 (1998) @footnote 3@J.A. Carlin et al., Appl. Phys Lett. 76, 1884 (2000).

10:40am **SC-ThM8 In Situ Monitoring of Stress Relaxation in Semiconductors*, E. Chason,*** Brown University **INVITED**

Understanding stress relaxation in heteroepitaxial semiconductors is important if we want to be able to control surface morphology and dislocation density. Because the relaxation process is a complex interaction of many kinetic processes, it is useful to be able to monitor the evolution of the stress and surface morphology in real time. We have developed several optical diagnostics that can be used during growth without interrupting the growth process. Stress relaxation is monitored by measuring the curvature induced in the substrate by the strained film. The technique is robust and has been used in a number of processing environments including MBE, MOCVD and sputter deposition. Examples of stress relaxation due to islanding and dislocation motion will be presented. Spectroscopic light scattering is used to measure the power spectral density of the surface height distribution without having to rotate the sample or detector. This has enabled us to measure the density of strain-relieving islands in heteroepitaxial layers and to understand the effect of elastic interactions between islands on their shape and alignment.

11:20am **SC-ThM10 Strain Effects in Si-Ge Growth on Vicinal Si Surfaces Prepared by Laser Texturing*, F. Watanabe,*** *D.G. Cahill, J.R. Serrano, S. Hong, T. Spila, J.E. Greene,* University of Illinois at Urbana-Champaign

Growth of Si-Ge strained layers on Si substrates is of great interest because of its multiplicity of growth modes. These growth modes are a complicated function of temperature, alloy content, growth rate, and substrate vicinality. Laser texturing of Si provides contamination- and defect-free curved surfaces for our studies of how the morphology depends on vicinality. The surface features produced by fluid flow in the laser melt are approximately 5 µm in diameter and 200 nm in depth, and contain vicinal surfaces with orientations 0-10 degrees off (001). SiGe layers are grown by gas-source MBE. At high strain (~80% Ge), film growth is similar to that of 100% Ge, but the formation of dislocated islands at high coverage is less pronounced. At a growth temperature of 600 °C, nucleation of dome-shaped three dimensional islands takes place preferentially on vicinal surfaces with orientations within one degree of (001). Island nucleation is suppressed on surfaces oriented more than a degree off (001). At these higher vicinalities, ripple shaped morphologies form along directions. The preferred regions for these instabilities are 5-10 degrees miscuts in the directions inside and outside the laser dimples.

Author Index

Bold page numbers indicate presenter