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Jim Sturm

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Technical Program with Abstracts

8:40 PM, F2 +

Effects of Boron Doping on Morphology of $Si_{1-x}Ge_x$ Films Grown on (001) Si: S. Vyas, R. Strong, T. Knight, D. W. Greve, Department of Electrical and Computer Engineering, and S. Mahajan, Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213

The effects of boron-doping on the morphology of $Si_{1-x}Ge_x$ films have been examined. Previous work has shown that thickness modulationsdevelop in undoped $Si_{1-x}Ge_x$ films after a period of planar growth. These undulations have been attributed to partial elastic relaxation of the strains resulting from the presence of germanium. This study is the first to assess the effect of boron addition on the morphology of $Si_{1-x}Ge_x$ films that have applications in infrared detector structures.

Films were grown at 600°C on (001) Si by UHV-CVD, and were characterized by cross-section TEM. Growths consisted of a 25-50 nm Si-buffer layer, 30-50 nm $Si_{1-x}Ge_x$, and a 60-100 nm Si cap. Films with 26% and 32% Ge were grown either heavily doped (~8 x 10^{19} cm^{-3}) or nominally undoped (~10^{17} cm^{-3}). Cross-sectional TEM was performed on a Philips 120 keV microscope.

In all cases no dislocations were observed, and the interface between the buffer layer and Si_1-xGe_x layer was planar. However, the interface between the $Si_{1-x}Ge_x$ layer and the Si cap exhibited undulations whose amplitude and wavelength depend on germanium fraction and boron concentration. Growth of the Si cap planarized the surface.

For the same Ge fraction, doped samples showed greater interfacial roughness than undoped samples. For 26% Ge, the undoped layer was planar, while the doped layer possessed a markedly rougher surface. For 32% Ge, the undoped layer was modulated with a period of 105-115 nm and an amplitude of 5 nm, while the doped layer possessed a period of 160-170 nm and an amplitude of 8-10 nm. Arguments based on the packing of $(Si)_4B$, $(Si)_4Ge$, and $(Si)_4Si$ tetrahedra having different volumes will be presented to rationalize these results.

9:00 AM, F3 +

Dislocation Related Carrier Trapping in Relaxed, Compositionally Graded RTCVD Grown $Ge_{0.3}Si_{0.7}$/Si: P.N. Grillot and S.A. Ringel Electrical Engineering Dept., The Ohio State University, 2015 Neil Ave., Columbus, Ohio 43210. E.A. Fitzgerald, G.P. Watson, and Y.H. Xie, AT&T Bell Laboratories, 600 Mountain Av., Murray Hill, New Jersey 07974

In recent years, interest in GeSi/Si and other lattice mismatched semiconductors has grown tremendously. Little is known, however, about the electronic trapping properties of the dislocations which are necessarily present in relaxed lattice mismatched heterostructures. In this study, relaxed, compositionally graded, RTCVD grown $Ge_{0.3}Si_{0.7}$/Si has been investigated with DLTS, EBIC, and XTEM. A single dominant electron trap ($\sigma \geq 2 \times 10^{-14}$ cm^2) and several hole traps have been observed in the undoped GeSi layers. All observed traps exhibit the logarithmic trapping behavior expected of extended defects and all observed trapping parameters compare favorably with traps reported in plastically deformed (PD) Si.[1,2] DLTS peak width is observed to broaden on the low temperature side with increasing fill pulse time, t_p, indicating that the observed traps are associated with a distribution of very closely spaced energy levels as opposed to a single level. For the electron trap, the FWHM is observed to nearly double from ~$0.08T_p$ for ms fill pulse times to ~ $0.15T_p$ for ms fill pulse times, where T_p is the peak temperature. Moreover, the maximum DLTS signal shifts slightly downward in temperature ($\Delta T \sim 10$ K) with increasing t_p, suggesting that the density of defect states is not uniformly distributed. These results are consistent with the observations of Omling et al. in PD Si, where the defect related DOS was modeled as a Gaussian distribution. Finally, optical and electrical DLTS depth dependence is correlated with the spatially varying dislocation network as observed by bias dependent EBIC and XTEM. This evidence indicates that the observed traps are associated with extended defects such as dislocations or Cottrell atmospheres. A detailed study of the trapping kinetics of these states will be presented in addition to preliminary results on a study of the doping effects on dislocation related trapping in UHVCVD GeSi/Si.

9:20 AM, F4

Gettering and Precipitation Behaviour of MBE Related Heavy Metal Impurities in Dependence on Silicon Self-Interstitial Supersaturation: G. Kissinger, G. Morgenstern, D. Knoll, P. Schley, Institut für Halbleiterphysik Frankfurt (Oder) GmbH, Walter-Korsing-Str. 2, D-15230 Frankfurt (Oder), Germany

MBE (molecular beam epitaxy) deposited Si layers are known to contain a relative high contamination level of heavy metals resulting first of all from hot metal containing components of the equipment. Typical contaminants identified by NAA (neutron activation analysis) are W, Ta, Mo, Cu, and Cr in concentrations up to 10^{16} cm^{-3}. Most of them diffuse slowly. This paper is concerned with the behaviour of these heavy metals in MBE grown SiGe- and Si-layers during annealing and device processing and with a possibility to getter them.

Precipitation of heavy metals was observed in a large number of SiGe- and Si-layers of different MBE equipments by etching of beveled sections. Even when the layers do not show any metal precipitate related etch figures after deposition a short annealing is sufficient in most cases to let the metals precipitate. More detailed studies of the metal precipitates were performed by TEM (transmission electron microscopy) and LST (laser scattering tomography).

Annealing experiments of Si-layers in oxygen and nitrogen have shown that at temperatures ≥800°C the precipitates start to dissolve. This is more effective in oxygen atmosphere because during precipitation of metalsilicides like tantalsilicide and titaniumsilicide, silicon self-interstitials are emitted. Subsequently, the Si_i supersaturation during oxidation of silicon increases the critical radius of such precipitate nuclei. Therefore, they dissolve more easily and precipitate more hardly after being dissolved.

Likewise, the gettering efficiency of an implantation layer is higher at low Si_i supersaturation because the critical radius of precipitate nucleation is lower. The gettering efficiency increases with temperature. Below 800°C it is ineffective. The gettering experiments were performed using layer systems for SiGe heterobipolar transistors.

After device processing, metal related etch figures were observed too. Implanted areas and the volume below them remained free of precipitates according to Si_i supersaturation. The higher the precipitate density outside of the active emitter-base region the higher is the current gain of the studied Si/SiGe transistors.

9:40 AM, F5

MBE-like Deep Photoluminescence in CVD Si/$Si_{1-x}Ge_x$/Si Quantum Wells Created by Ion Implantation and Annealing: J.C. Sturm, A. St. Amour, Dept. of Electrical Engineering, and S.L. Clark, Dept. of Chemical Engineering, Princeton University, Princeton, NJ 08544; Y. Lacroix and M.L.W. Thewalt, Dept. of Physics, Simon Fraser University, Burnaby, BC Canada V5A 1S6

In strained Si/$Si_{1-x}Ge_x$/Si quantum well structures, two basic types of photoluminescence (PL) are typically seen. The first is sharp, well-resolved, band-edge exciton luminescence, which is typically observed in CVD material but has also been observed in some MBE material. The second is a deep broad luminescence of unknown origin, which is typically 80 meV below the expected band edge and 100 meV wide, and which had been observed to date only in MBE material. In this work we show for the first time that the deep luminescence may be observed also in CVD material (after damage by ion implantation and annealing). By further annealing, one can switch the emission back to the original sharp band-edge emission.

The CVD samples were grown by RTCVD. They consisted of single strained Si/$Si_{1-x}Ge_x$/Si quantum wells with x from 0.10 to 0.25. As grown, all samples exhibited sharp well-resolved band edge luminescence. The samples were then implanted with 50 keV $^{29}Si^+$ ions with doses from 10^{10} to 10^{12} cm^{-2}. After implantation, no PL was visible except for implant damage. However, after a 600°C anneal, a broad deep luminescence which tracked the Ge fraction was observed. Its energy position, linewidth, temperature dependence, and pump power dependence were all similar to that in the MBE material. After 800°C annealing, the deep luminescence disappeared and sharp band-edge luminescence reappeared. This annealing behavior is also characteristic of the deep PL observed in MBE samples. In addition to the silicon implants, deep PL was also observed in CVD samples which were implanted with H. This is signigicant since the damage profiles and type of damage caused by H and Si are substantially different.

These results will be used to evaluate different theories for the the microscopic origin of the deep PL. Furthermore, they also suggest that radiation damage may be the cause of the deep PL commonly observed in many SiGe samples grown by MBE. This work was supported by NSF and ONR.

10:00 AM, BREAK

10:20 AM, F6

Growth and Characterization of High Quality $Si/Si_{1-x}Ge_x$ Quantum Well Structures Prepared by MBE: W.-X. Ni, A. Henry, M.I. Larsson, K. Joelsson, and G.V. Hansson, Department of Physics, Linköping University, S-581 83 Linköping, Sweden

High quality, strained $Si/Si_{1-x}Ge_x$ layered structures have been grown using a new solid-source MBE system (Balzers UMS 630). An important feature of the system is that a very precise growth rate is achieved using a mass-spectrometry-based control loop. As has been verified by RHEED intensity oscillations, deposition rates of 0.02-3 Å/sec, with rate fluctuations of $\leq 3\%$ and a day-by-day reproducibility of $\leq 5\%$, can be obtained for both Si and Ge. Sharp and intense high order satellite reflections were obtained in HRXRD rocking curves of $Si/Si_{1-x}Ge_x$ multiple quantum well (QW) structures, indicating flat interfaces with well-defined modulated structures. In addition, no mosaic broadening of the layer diffraction peak was observed in HRXRD reciprocal space maps, i.e., no occurrence of strain relaxation. Dynamic simulations of the rocking curves, using nearly unadjusted experimental structural parameters, were carried out with a good agreement to the experimental results, which is an evidence of very well controlled growth. In general, a deviation of $\leq$+2% from the desired values for both the Ge fraction and the layer thickness can be obtained. The high crystalline quality of MBE-SiGe layers has enabled material characterisation using PL measurements. Well-resolved luminescence features with FWHM of the NP peak $\leq$ 10 meV were observed from single and multiple QWs, and single SiGe epi-layers as well, grown at temperatures of 400-625°C. Very high PL intensities and very narrow peaks (FWHM=2.7 meV for the X^{NP} peak at low excitation level) were observed from the single QWs. There was no obvious decrease of PL intensities for narrow width single QWs grown at temperatures down to 400°C. The high luminescence intensity observed from samples grown at low temperatures implies firstly a high purity of the materials and secondly a low level of point defects. In general, for thick SiGe epi-layers, PL intensities were decreased to ~20% of those from narrow QWs when increasing the Ge fraction and the layer thickness was close to the metastable critical thickness value. However, no broad PL bands, as previously associated with MBE-grown SiGe materials, were ever observed in any of our samples. Moreover, PL from modulation doped single SiGe QW structures was studied. A special blue shift of the X^{NP} peak was observed due to the change of the band bending induced by δ-doped layers. Temperature-dependent and excitation-dependent PL measurements were carried out in order to understand the origin of the luminescence from SiGe layers. Our results obtained from HRXRD and PL measurements indicate that it is possible to obtain high quality SiGe materials using MBE technique without some particular defect problems at previously attributed to the growth process. This is of vital importance for the Si-based MBE technique and the future applications on devices.

10:40 AM, F7

Nature and Evolution of Interfaces in $Si/Si_{1-x}Ge_x$ Superlattices: J.-M. Baribeau and D.J. Lockwood, Institute for Microstructural Sciences, National Research Council Canada, Ottawa, K1A 0R6, Canada, and R. L. Headrick, Cornell High Energy Synchrotron Source and Department of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853-8001.

$Si/Si_{1-x}Ge_x$ strained heterostructures and superlattices are being widely investigated as an alternative materials system for novel microelectronic devices compatible with Si-based technology. The strain distribution in these structures has been investigated extensively and the thermal budget for processing strained $Si/Si_{1-x}Gex$ heterostructures has been mapped out as a function of both composition and thickness. In comparison, there have been relatively few studies of the physical (e.g., roughness) and chemical (e.g., intermixing) perfection of the interfaces in these heterostructures. In this work we present a systematic x-ray scattering and Raman spectroscopy study of the interfaces in $Si/Si_{1-x}Ge_x$ superlattices. A series of superlattices with the same unit period (~10 nm Si and 5 nm $Si_{0.65}Ge_{0.35}$) was grown by molecular beam epitaxy in the temperature range 250-750°C and with the number of periods varying from 5 to 20. For a set of 10-period structures, x-ray double crystal diffraction and Raman scattering from longitudinal optic phonons revealed that strain relaxation occurred above 620°C. X-ray specular reflectivity and Raman scattering from longitudinal acoustic phonons showed interesting variations in the nature of the interfaces with growth temperature. The interfaces in superlattices grown at 250°C are chemically abrupt, but exhibit a pronounced physical roughness that increases from ~0.3 nm near the substrate to 2 nm at the surface. Growth at intermediate temperatures (400-550°C) resulted in structures with physically smooth interfaces, but intermixed over at least two monolayers. The quality of the interfaces also showed no deterioration with increasing number of periods from 5 to 20. Higher growth temperatures further enhanced the intermixing (exceeding 1 nm at 750°C) in an asymmetric fashion, due to upward migration of Ge atoms from the alloy into the next Si layer. Radial scans and offset reflectivity measurements were also performed using synchrotron radiation. For 400°C growth, textured roughness aligned with the substrate miscut angle (~0.14° towards [001]) and with an in-plane length scale of ~ 1.2 mm is observed. Post-growth annealing had relatively little effect on the superlattices grown either in the low (roughness or defect limited) or high (already intermixed) temperature limits. However, at intermediate growth temperatures moderate annealing (e.g., 20 s at 750°C) caused substantial interfacial mixing (over ~1 nm) independent of the number of periods. This intermixing phenomenon can thus further restrict the thermal budget for $Si_{1-x}Ge_x$ device processing, in addition to that due to strain.

11:00 AM F8 +

Impact Ionization Coefficients in Si_xGe_{1-x}: J. Lee, K. Yeom, S-H. Li, J. Hinckley, A. Gutierrez-Aitken, J. Singh and P. Bhattacharya, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2122

Coherently strained $Si_{1-x}Gex$ alloys and SiGe/Si heterostructures are currently of interest due to their potentially useful electronic and optical properties and compatibility with existing Si technology. High-field induced breakdown is an important phenomenon, of which little is known for the SiGe alloys. Several mechanisms contribute or control the breakdown in a reverse-biased junction diode, the principal one being the avalanche multiplication process. Understanding and characterizing the latter process is therefore not only important for devices like junction photodiodes, but also for devices such as heterojunction bipolar transistors, where the collector breakdown will ultimately determine the limit of high power applications.

The impact ionization coefficients for electrons (α) and holes (β) in Si and Ge have been measured previously and it is generally agreed that $\alpha/\beta > 1$ in Si and $\beta/\alpha > 1$ in Ge. To our knowledge, there is no report on the measurement of impact ionization coefficients and multiplication factors in the SiGe alloys. We will present results obtained from theoretical calculations and measurements of these coefficients in $Si_{1-x}Ge_x$ ($0.2 \leq x \leq 0.3$).

The coefficients are being estimated by a Monte Carlo simulation taking into account the accurate bandstructure, bandgap narrowing and alloy scattering. The threshold energy in the unstrained $Si_{1-x}Ge_x$ is smaller than that in pure silicon due to the reduced bandgap energy. The strain causes band degeneracy lifting for both of conduction band and valence band. It gives an additional bandgap narrowing which leads to much smaller threshold energy. The reduced threshold energy is found to be the most dominant factor in determining a in the strained $Si_{1-x}Ge_x$. As a result, the strained $Si_{1-x}Ge_x$ has much larger a than pure silicon while the unstrained Si1-xGex does not, due to the effect of alloy scattering and relatively small change of the threshold energy. Calculations of b are in progress. p^+-n-n^+ photodiode structures for the measurement of a and b were grown on (100) Si substrates by gas-source MBE. The SiGe

THURSDAY AM