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Technical Program with Abstracts

dislocation density $Si_{1-x}Ge_x$ strained layers and layered microstructures. However, the photoluminescence spectra of electron beam evaporated MBE deposited $Si_{1-x}Ge_x$ films do not resemble spectra obtained from bulk materials or films grown by other techniques such as chemical vapor deposition. Our electron beam evaporated MBE material has shown very strong, although broad, no-phonon photoluminescence with unresolved phonon components. The distinguishing aspect(s) of material having more conventional spectra exhibiting phonon replicas is not yet clear. Grown-in compositional and/or strain inhomogeneities inherent to electron-beam evaporation, however, appear to have created regions in the epilayers that served as exciton wells, similar to isoelectronic centers in silicon. These inhomogeneities, which have been observed in cross-sectional transmission electron microscopy, can give rise to photoluminescence with Characteristics such as those observed for our MBE material. We have observed reproducible, intense low temperature PL in the range 1.2-1.7 µm from MBE grown $Si_{1-x}Ge_x$ structures on Si(100) substrates for $0.1 < x < 0.5$. In addition to shifting consistently and predictably with x, the PL peak's higher energy edge was just below the $Si_{1-x}Ge_x$ strained bandgap. When samples grown above the equilibrium critical thickness were forced to relax by annealing, the luminescence was either quenched by deep, dislocation related states in the heterostructure or it shifted to higher energies toward the unstrained bandgap. For samples with a germanium concentration, x, near 0.25, up to ~ 10% of exciting photons were converted into longer wavelength photons. When the germanium concentration was changed from 0.25, the quantum efficiency declined, although the broad $Si_{1-x}Ge_x$ photoluminescence was observed over a large concentration range. Zone folding and other atomic layer superlattice effects were not significant since the alloy well thickness was at least 5 nm. Photoluminescence spectra have been observed from a variety of samples, e.g., from capped or uncapped epilayers, single quantum wells (SQW), and multiple quantum wells (MQW) with the $Si_{1-x}Ge_x$ thickness dependent on Ge concentration. The $Si_{1-x}Ge_x$ peak widths were all of the order of 80 meV and the shapes of the $Si_{1-x}Ge_x$ features showed a similar degree of asymmetry in the low energy sides of the peaks. In some cases a smaller, convoluted peak was observed ~ 60 meV lower than the main peak. This energy difference is close to the TO phonon energy in Si (58 meV), suggesting that our $Si_{1-x}Ge_x$ peaks were due to no-phonon optical transitions. Photoluminescence excitation spectroscopy of an efficiently emitting sample (x ~ 0.25) supported this observation. Assuming a Gaussian distribution of germanium concentrations arising from growth fluctuations during electron beam evaporation, and that excitons preferentially bind in regions with x greater than the average value (determined by x-ray diffraction and electron microscopy), a numerical model was developed predicting $Si_{1-x}Ge_x$ photoluminescence spectra that were greatly broadened compared to conventional spectra. With a distribution in germanium concentration of width 0.05, the lineshape obtained from this model resembled experimental lineshapes. Further evidence confirming that the luminescence was band-edge related was obtained from samples that had partly relaxed (due to annealing), where the $Si_{1-x}Ge_x$ peak shifted upward toward the unstrained bandgap, similar to that observed in epitaxial samples grown by CVD. Thus, the trends for our photoluminescence data show that the observed $Si_{1-x}Ge_x$ peak occurs due to bound exciton self-annihilation starting at energies near the strained alloy bandgap energy, with broadening to lower energies from growth induced inhomogeneities. A study of MBE growth rate fluctuations appears to support this conclusion.

11:20 AM, R9

Band-Edge Exciton Photoluminescence in Strained Silicon-Germanium Alloy Films Grown by Rapid Thermal Chemical Vapor Deposition: J.C. Sturm, Q. Mi, P.V. Schwartz and H. Manoharan, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544; L.C. Lenchyshyn and M.L.W. Thewalt, Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada; N.L. Rowell, J.-P. Noël and D.C. Houghton, National Research Council, Ottawa K1A 0R6, Canada.

Attention has been focussed on silicon-germanium ($Si_{1-x}Ge_x$) strained layer structures and atomic layer superlattices for several years as potential optical emitters. However, all photoluminescence experiments to date (except for x = 0.04) have yielded either no signal or signals from defects, impurities, dislocations, or other unidentified centers from below the bandgap. We recently have observed the first clear, strong, well-resolved band-edge photoluminescence in strained $Si_{1-x}Ge_x$ layers, quantum wells, and superlattices grown by any technique. The samples were grown by Rapid Thermal Chemical Vapor Deposition, with alloy layers grown from 600 to 625 °C and silicon barriers for quantum wells or superlattices grown at 700 °C. The germanium atomic fraction ranged up to x = 0.4, and strained layer thicknesses were up to 1000 Å depending on composition. Superlattices periods were as small as 45 Å, and had an interface abruptness of a few Å on high-resolution TEM. Except for quantum confinement energies, the spectra for superlattices, quantum wells, and single layers are qualitatively similar. Typical photoluminescence spectra at low temperatures (2 K) showed a strong no-phonon line from bound excitons, and then several phonon replicas. A weak TA replica was seen in all samples (as in silicon), and three TO replicas (Si-Si, Si-Ge, and Ge-Ge) were observed. The relative strengths of the different TO replicas accurately followed the sample composition. At higher temperatures (>20 K), free exciton luminescence was seen, again with a strong no-phonon line and the same phonon replicas. It should be pointed out that the no-phonon free-exciton signal, which results from alloy scattering, is not typically seen in elemental indirect semiconductors such as silicon. Band-edge luminescence allows accurate direct measurement of the bandgap of the strained silicon-germanium alloys. The method is more direct than that of absorption measurements, since the determination of the bandgap in absorption measurements depends on knowledge of the phonons (if any) involved in the absorption process. This ambiguity has led to a large (~ 45 meV) discrepancy in the reported bandgaps of bulk unstrained SiGe alloys measured by absorption measurements and photoluminescence, with the photoluminescence energies lying *higher* than those of the bandgaps inferred by absorption measurements (and supposedly corrected for phonon effects). From our measurements, we have established a free exciton bandgap of 1027, 995, and 848 (± 10) meV for compositions of x = 0.14, 0.18, and 0.37 (± 0.02), respectively, at liquid He temperatures. (These energies will be lower than the bandgap by the excitonic binding energies, which range from 15 meV for Si to 4 meV for Ge.) These results are in relatively good agreement with the absorption data (photocurrent) of Lang, which reported the absorption edge without correction for phonon effects. This suggests that the dominant absorption in the alloys is by a no-phonon process.

11:40 AM, R10

Exciton Luminescence and Quantum Confinement in $Si_{1-x}Ge_x$ Alloys: D.J. Robbins, L.T. Canham, S. Barnett and A.G. Cullis, Royal Signals & Radar Establishment, St. Andrews Road, Malvern, WR14 3PS, United Kingdom.

A series of thin, nominally undoped pseudomorphic $Si_{1-x}Ge_x$ alloy layers capped by silicon have been grown on p-silicon substrates at 610°C by low pressure chemical vapour deposition in a cold-wall reactor with UHV background. Each sample is a single alloy well, and the germanium fraction was varied in the range $0.11 < \xi < 0.22$ at a constant nominal well thickness of 50 nm. In one case the well width was reduced to 6.3 nm to investigate quantum confinement effects. Strong photoluminescence spectra were measured at 4.2 K using an Ar ion laser and cooled Ge photodetector. The principal alloy-related features in each spectrum are a no-phonon line (NPL) and a momentum-conserving TO-phonon replica (TOR) resulting from exciton (electron-hole) recombination near the alloy band gap energy. The intensity ratio NPL/TOR increases as x increases in the measured range $0.11 < x < 0.22$, presumably due to an increasing perturbation from the random distribution of germanium atoms which breaks the momentum-conservation selection rule in the indirect-gap alloy. The energies of the NPL photoluminescence peaks for layers

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