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Well-Resolved Band-Edge Photo- and Electro-Luminescence in Strained $Si_{1-x}Ge_x$ Quantum Wells and Superlattices

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Well-resolved band-edge photoluminescence and electroluminescence of excitons in strained $Si_{1-x}Ge_x$ quantum wells and superlattices on silicon with a germanium fraction up to x=0.4 are reported. A characteristic no-phonon line due to alloy scattering dominates the emission process and allows an accurate determination of the bandgap. CW electro-luminescence has been observed for junction temperatures up to 300K.

Introduction

A long sought goal of microelectronics is to combine the worlds of silicon VLSI with high-speed optical data transmission and optical fibers. Integration of such optical interconnects onto silicon IC's would be a major advance towards removing the bandwidth limitations of electrical pinouts. It has been demonstrated that SiGe alloys on silicon can be used for integrated waveguides[1] and high speed 1.3 μm detectors[2]. Various theories for light emission from strained SiGe structures have been proposed[3,4], but have yet to be clearly demonstrated experimentally because of the high number of dislocations (up to 10^{10} cm^{-2} in many samples). In this paper, the first well-resolved band-edge photo- and electro-luminescence from strained $Si_{1-x}Ge_x$ layers, quantum wells, and superlattices is presented.

Experiments and Results

The experimental structures were grown by Rapid Thermal Chemical Vapor Deposition at temperature from 625 to 700 °C[5], and ranged from single uniform strained layers to superlattices with periods down to 45 Å. All samples discussed in this paper were fully strained, with misfit dislocation spacings greater than 10 μm, and threading dislocation densities under 10^3 cm^{-2}. A typical low temperature (2K) photoluminescence spectrum of a sample with multiple quantum wells (10 wells of 30-Å strained $Si_{0.8}Ge_{0.2}$) is shown in Fig 1(a)[6]. Note that several well-resolved peaks are observed, which as labeled correspond to a no-phonon (NP) transition and several phonon-emission replicas at lower energies, with the energy difference being the phonon energy. The TO phonon is split into 3 components because of the different nearest neighbor combinations possible in the random alloy. At helium temperature the photoluminescence signal is due to bound excitons; at higher temperatures (20K to 200K) the spectra are similar, but due to free exciton luminescence. Such well-resolved emission has not previously been observed in strained $Si_{1-x}Ge_x$ alloys, and reflects the uniformity and high quality of the RTCVD films. The strong no-phonon free exciton peak is especially significant since the $Si_{1-x}Ge_x$ has an indirect bandgap similar to Si, and such a signal is not seen in Si or Ge. The NP transition is not due to low temperatures or exciton localization since a similar signal is also observed in the same sample at 77K when the excitons are free (Fig. 1(b)). Qualitatively similar spectra with the NP feature are also seen in samples ranging from 45-Å superlattices to 0.1 nm single films, which indicates that the NP line is not a spatial quantization or superlattice effect. The no-phonon signal results since the alloy disorder breaks the long-range periodicity and mixes Bloch states[7], so that an electron nominally in the indirect minimum has some non-zero k=0 component for a direct no-phonon recombination process with a hole. Similarly, a hole at k=0 has a component near the X-point for a direct transition with an electron in the conduction band minimum. As the Ge content is raised, the spectra are similar but shifted to lower energy because of the lower bandgap. Furthermore, the no-phonon emission grows as the Ge content is raised and more disorder is introduced. From this NP peak in various samples, a plot of bandgap vs. composition can be obtained after correcting for quantum confinement effects and the exciton binding energies (Fig. 2). The results are in good agreement with previous results obtained by photocurrent spectroscopy[8].

Electro-luminescence (EL) experiments were performed by placing 10 $Si_{0.6}Ge_{0.4}$ quantum wells inside the i-region of a p-i-n diode (Fig. 3.). The device was fabricated by plasma-etching a 100 μm x 100 μm mesa, followed by a deposited oxide sidewall passivation, metallization, and a forming gas anneal. Photoluminescence spectra on this device were dominated by the usual NP and TO band-edge exciton features, with a peak at 1.34 μm (Fig. 4(a)). Under forward bias, excitons will be captured in the $Si_{0.6}Ge_{0.4}$ layers by the large valence band offset (~350 meV) where they can radiatively recombine. The EL results at a current of 10 mA resulted in an increased junction temperature due to the power dissipation in the diode and series resistance. The CW EL spectrum at a junction temperature of 200K (Fig. 4(b)) displays thermal broadening compared to the 77K PL spectrum, but is otherwise qualitatively similar. This is the first time that such band-edge EL in strained $Si_{1-x}Ge_x$ has been demonstrated. In similar structures grown by MBE, the luminescence is from not from the recombination of electrons and holes at the band edges, but due to some unidentified center 120 meV below the bandgap[9]. That center is clearly not present in the CVD material. Our results also differ from those of Ref. 9 in that our signal persists to high temperatures. Spectra similar to those of Fig. 4(b) have been observed in our samples for junction temperatures up to 300K. Since the increased thermal velocities can lead to the increased capture of carriers at deep level traps (leading to increased SRH recombination), that EL is seen at room temperature indicates a minimum of deep levels in our samples.

Summary

In summary, well-resolved band-edge photo- and electro-luminescence (up to 300K) in strained $Si_{1-x}Ge_x$ layers has been demonstrated for the first time. The results are dominated by a strong no-phonon line which is characteristic of the alloy and not seen in Si. Collaboration with M. Thewalt and L. Lenchyshyn (Simon Fraser University) and D. Houghton, J.P. Noel, N. Rowell, and J. McCaffrey (National Research Council, Canada) is acknowledged. The support of NSF, ONR, and the New Jersey Commission on Science and Technology is gratefully acknowledged.

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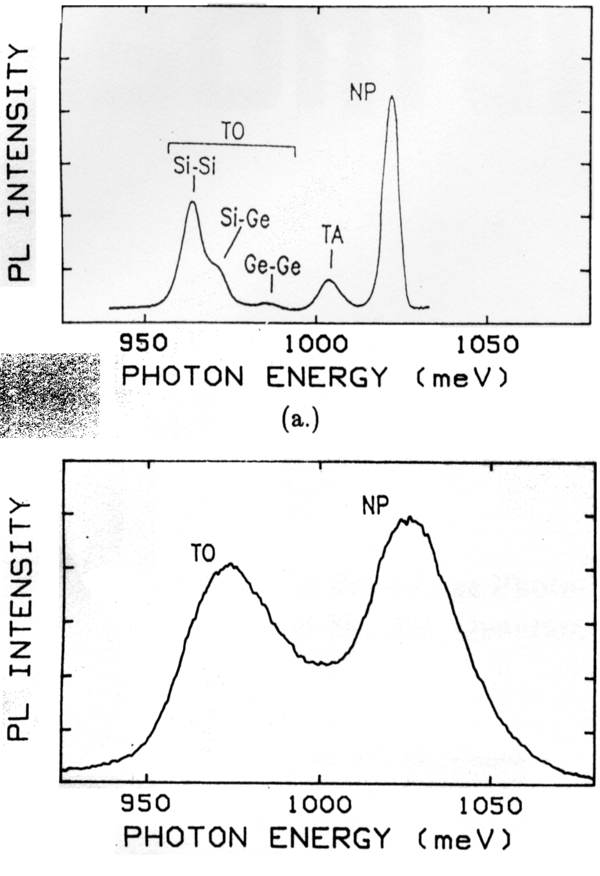

(b.)

Fig. 1. Photoluminescence spectra of a sample with ten 30-Å strained $Si_{0.8}Ge_{0.2}$ quantum wells at (a.) 2K and (b.) 77K. Note the no phonon (NP) peak and the various phonon-emission replicas at lower energy.

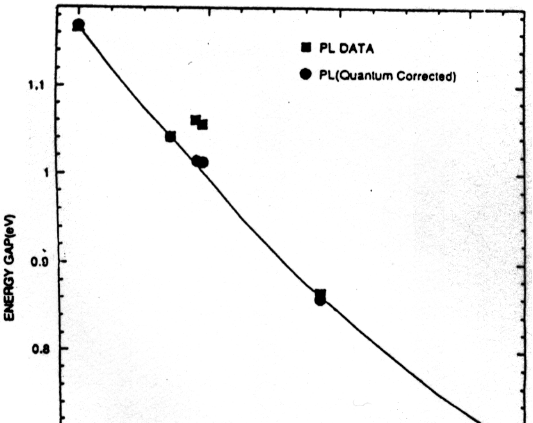

Fig. 2. Bandgap at 0K vs. germanium fraction x as determined from the no-phonon PL signal.

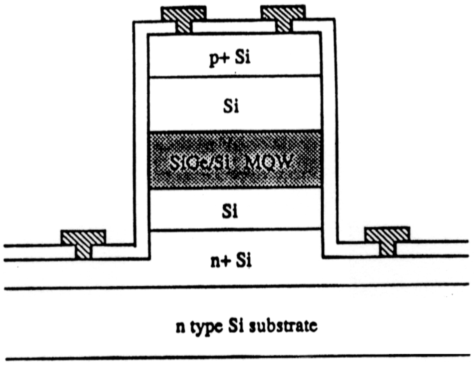

Fig. 3. Structure of a p-i-n diode containing ten strained $Si_{0.6}Ge_{0.4}$ quantum wells for electroluminescence experiments.

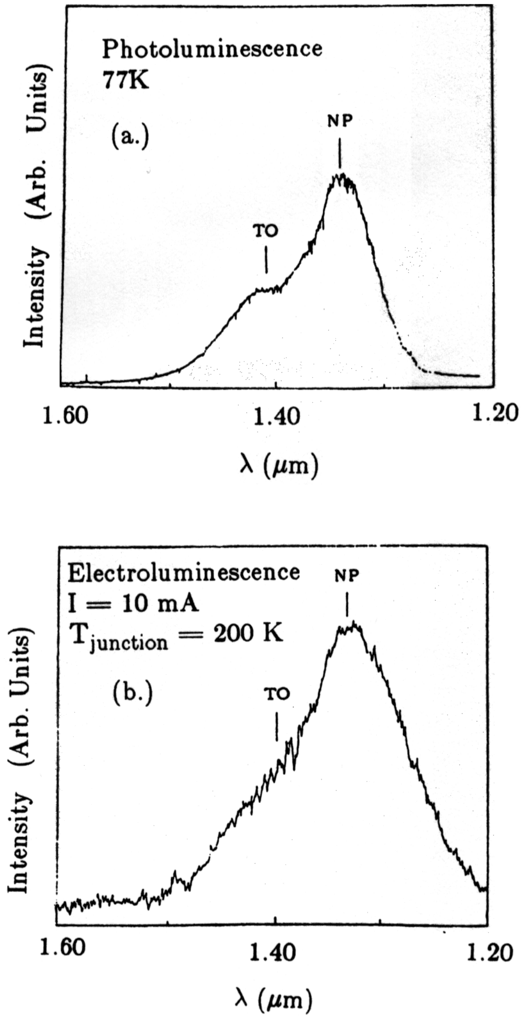

Fig. 4. (a.) Photoluminescence spectrum (77K) and (b.) electroluminescence spectrum (junction temperature = 200K) of the pin diode of Fig. 3.