Room-temperature 1.3 μm electroluminescence from strained $Si_{1-x}Ge_x$/Si quantum wells

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We report the first room-temperature 1.3 μm electroluminescence from strained $Si_{1-x}Ge_x$/Si quantum wells. The electroluminescence is due to band-edge carrier recombination, and its intensity increases linearly with the forward current up to 1700 A/cm^2. The internal quantum efficiency is estimated to have a lower limit of 2×10^{-4}. As the temperature is increased from 77 to 300 K, luminescence from the silicon increases relative to that from the $Si_{1-x}Ge_x$ wells. A minimum band offset is required to have effective room-temperature luminescence from the $Si_{1-x}Ge_x$ quantum wells.

One long sought goal is to combine very large scale integration (VLSI) electronics with fiber optics which could help to overcome the bandwidth limitations of electrical pinouts. Optical devices utilizing strained $Si_{1-x}Ge_x$ alloys would be promising candidates not only because the $Si_{1-x}Ge_x$ alloy band gap spans the wavelength range including both 1.3 and 1.55 μm, the two low loss optical windows for fiber optics communication, but also because its fabrication is more compatible with the standard Si VLSI processing technology compared with III-V optical devices.

It has been demonstrated that $Si_{1-x}Ge_x$ alloys can be used for integrated waveguides[1] and high-speed 1.3 μm detectors.[2,3] Various schemes for efficient light emission from strained $Si_{1-x}Ge_x$ structures have also been proposed.[4,5] There have been several reports of light emission from zone-folded short period superlattices which may result in a direct band gap.[6,7] However, because of the high dislocation densities present in those works and the known luminescence properties of dislocations, the interpretation of the results as due to zone folding is controversial.[8] In some thick strained $Si_{1-x}Ge_x$ layers grown by molecular beam epitaxy (MBE), intense photoluminescence (PL), and electroluminescence (EL) were observed at 4 K, but the emission peak was well below ($\sim$100 meV) the strained alloy band gap and of uncertain origin.[9,10]

For uniform, strained $Si_{1-x}Ge_x$ films, band-edge photoluminescence due to exciton recombination was first obtained by Terashima *et al.* (by MBE) for $x=0.042$.[11] This was extended to $x=0.2$, including quantum wells and superlattices by Sturm *et al.* [by rapid thermal chemical vapor deposition (RTCVD)].[12] Characteristic features of such luminescence are the usual phonon replicas found in indirect band gap semiconductors plus a signal near the bandgap due to direct electron–hole recombination without the requirement for a momentum-conserving phonon. At $T<20$ K the PL is dominated by shallow bound excitons (BE), while at $T>20$ K it is dominated by free excitons (FE). No-phonon (NP) emission from FE is an alloy effect and was first observed in bulk unstrained alloys.[13] It increases with the alloy randomness, having a maximum near $x=0.5$, where it is about 5 times stronger than the transverse optical (TO) phonon replicas.[13]

Such exciton emission was recently observed in electrically pumped strained $Si_{0.85}Ge_{0.15}$ quantum wells, with peak emission from the $Si_{1-x}Ge_x$ phonon replicas at 1.2 μm at 77 K.[14] At higher temperatures, however, luminescence from the silicon dominated the spectrum. In this letter, we report the first room-temperature EL from Si/$Si_{1-x}Ge_x$ quantum wells, with peak emission intensity from NP transitions at 1.3 μm.

The sample structure was grown epitaxially on *n*-type Si (100) substrates by RTCVD[15] at a pressure of 6.0 Torr and at 700 °C for growth of Si layers and 625 °C for growth of $Si_{1-x}Ge_x$ layers. Ten $Si_{0.65}Ge_{0.35}$ quantum wells were placed inside the *i* region of a *p-i-n* diode. Defect-etching revealed a misfit dislocation spacing of 10 μm. The device was fabricated by plasma-etching 60 μm$\times$60 μm mesas. A sidewall passivation oxide was deposited at 350 °C by plasma-enhanced CVD to a thickness of 0.6 μm. Contact holes were then etched and aluminum was evaporated. A third photolithography step and an aluminum etch defined the contact pad pattern and left a window on the top of the mesa for light emission (Fig. 1).

Shown in Fig. 2 are 4 and 77 K PL spectra of the sample before device processing. By comparison to earlier work,[12,13] the peaks near 896 and 842 meV in the 4 K spectrum have been identified as the NP peak and the TO replica, respectively. At higher pump powers, a higher ($\sim$924 meV) NP peak and its TO replica increasingly dominated the 4 K PL. The physical origin of these different peaks is not clear, but may be related to different well states, or to the energy difference between electrons in the well and electrons in the Si. The 77 K spectrum has a clear NP peak at 924 meV, but at very low power an 896 meV NP peak is again discernable.

Electroluminescence (EL) spectra were taken with the sample In-bonded to a copper heat sink. Also shown in Fig. 2 is the EL spectrum ($I=10$ mA, 400 Hz modulation, 50% duty cycle) for a heat sink temperature of 80 K. Based on the similarity of the EL and PL spectra, we conclude the physical mechanisms responsible for both are

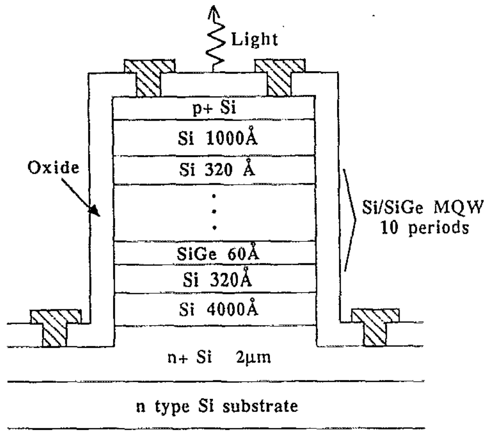

FIG. 1. Device schematic. The active regions consists of ten layers of Si—320 Å/$Si_{0.65}Ge_{0.35}$—60 Å.

similar, i.e., transitions of electrons directly from conduction band to valence band, not involving deep levels. At high injection levels, the recombination may actually be due to an electron-hole plasma, as opposed to discrete excitons.[16] Note that the peak emission from the NP line is at 1.34 μm.

Similar results with little change ($<50\%$) in absolute intensity were obtained with a room-temperature heat sink (Fig. 3). Although some emission due to the TO replica from recombination in the Si layer is now observed, well over 70% of the emitted spectrum is from the $Si_{1-x}Ge_x$. The dependence of the peak EL intensity on drive current at room temperature is shown in Fig. 4. The EL spectrum shape broadened slightly at higher drive currents, possibly due to sample heating or electron-hole plasma effects. The forward voltage for a current of 50 mA was ~3 V, implying a large parasitic contact resistance. Above a certain threshold (~300 mA/cm^2), the EL intensity is linearly proportional to the drive current up to 1700 A/cm^2. It is thought that the threshold is due to space-charge region recombination current at deep levels at low bias conditions.

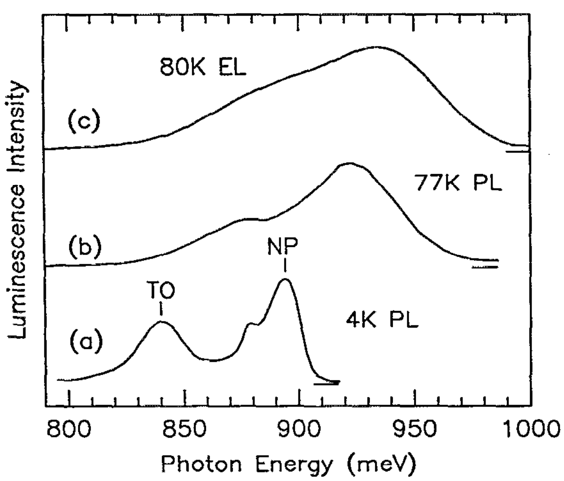

FIG. 2. Photoluminescence spectra at (a) 4.2 K and (b) 77 K, and (c) electroluminescence spectrum with 10 mA drive current and heat sink temperature at 80 K.

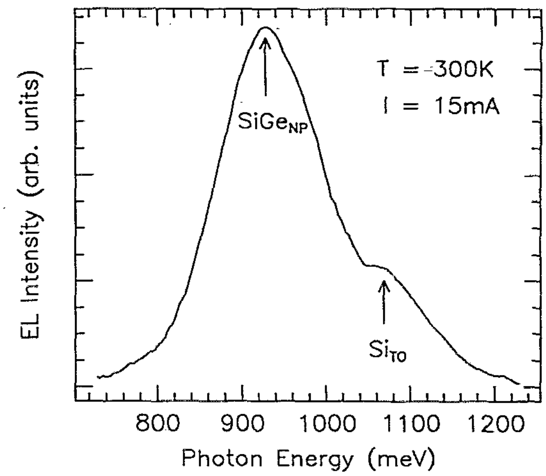

FIG. 3. Electroluminescence spectra with room temperature heat sink with 15 mA drive current.

The internal quantum efficiency of the *p-i-n* diode under constant current conditions was estimated by measuring the total infrared luminescence signal, using a calibrated InGaAs detector mounted close to the top of the device. The internal quantum efficiency could be obtained by

$$\eta_{\text{int}} = \frac{4\pi I_p e A_{\text{dio}} n_{\text{Si}}^2}{d\Omega I_d h\nu K T A_{\text{win}} n_{\text{air}}^2},$$

where I_p is the detector photocurrent and I_d is the drive current of the sample diode. $d\Omega$ is the solid angle spanned by the detector area, $h\nu$ is the average photon energy, K is the detector response in infrared which is 0.7 A/W, e is the electron charge, A_{dio} and A_{win} are the areas of mesa and contact window, and T is the transmission coefficient of light with average wavelength 1.3 μm through the 0.6 μm thick passivation oxide layer. The $n_{\text{Si}}^2/n_{\text{air}}^2$ term comes from the correction for refraction at the semiconductor surface. The estimated internal quantum efficiency of the device at room temperature is 2×10^{-4}, compared with a reported

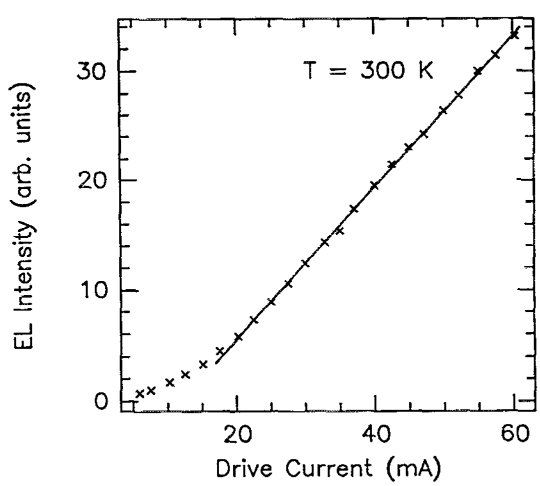

FIG. 4. Peak intensity of 1.3 μm emission with room temperature heat sink vs drive current.

efficiency of Si which is between 10^{-4} and 10^{-5}.[17] This calculated efficiency in our device should be taken as a lower limit however since it is known that due to the lateral resistance of the p^+ region, the current density is much lower in the window area than directly under the contact.

In the $Si_{0.8}Ge_{0.2}$ EL results of Robbins *et al.*,[14] emission from the $Si_{1-x}Ge_x$ dominated the spectrum at low temperature, but emission from silicon dominated at 220 K. In similar structures made in our labs with $Si_{0.8}Ge_{0.2}$ in the quantum wells, the room temperature EL signal was also nearly 100% from the silicon layers. A similar switch in the emitting layer from 77 K to room temperature was seen in PL on the same sample. We interpret this shift as due to the weaker carrier confinement effect at higher temperature. We find that the relative ratio of $Si_{1-x}Ge_x$ signal intensity to Si signal intensity of the $x=0.35$ sample is 100 times higher than the ratio of the $x=0.20$ sample at room temperature. This implies a minimum band-gap offset is required to have effective room-temperature luminescence from the $Si_{1-x}Ge_x$ quantum wells.

In conclusion, we have observed room-temperature 1.3 μm band-edge electroluminescence from strained SiGe quantum wells for the first time. The internal quantum efficiency is estimated to have a lower limit of 2×10^{-4}. The 1.3 μm peak intensity is relatively insensitive to temperature from 77 K to room temperature, and a minimum band offset is required for the design of an effective room-temperature $Si_{1-x}Ge_x$ luminescent device.

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[1] R. A. Soref and J. P. Lorenzo, Opt. Lett. **15**, 270 (1990).
[2] H. Temkin, T. P. Pearsall, and J. C. Bean, Appl. Phys. Lett. **48**, 963 (1986).
[3] T. P. Pearsall, H. Temkin, J. C. Bean, and S. Luryi, IEEE Electron Device Lett. **7**, 330 (1986).
[4] U. Gnutzmann and K. Clausecker, Appl. Phys. **3**, 9 (1974).
[5] S. Satpathy, R. M. Martin, and C. G. Van de Walle, Phys. Rev. B **38**, 13237 (1988).
[6] H. Okumura, K. Miki, S. Misawa, K. Sakamoto, T. Sakamoto, and S. Yoshida, Jpn. J. Appl. Phys. **28**, L1893 (1989).
[7] R. Zachai, K. Eberl, G. Abstreiter, E. Kasper, and H. Kibbel, Phys. Rev. Lett. **64**, 1055 (1990).
[8] U. Schmid and N. E. Christensen, Phy. Rev. Lett. **65**, 2610 (1990).
[9] J. -P. Noël, N. L. Rowell, D. C. Houghton, and D. D. Perovic, Appl. Phys. Lett. **57**, 1037 (1990).
[10] N. L. Rowell, J. -P. Noël, D. C. Houghton, and M. Buchana, Appl. Phys. Lett. **58**, 957 (1991).
[11] K. Terashima, M. Tajima, and T. Tatsumi, Appl. Phys. Lett. **57**, 1925 (1990).
[12] J. C. Sturm, H. Manoharan, L. C. Lenchyshyn, M. L. W. Thewalt, N. L. Rowell, J. -P. Noël, and D. C. Houghton, Phys. Rev. Lett. **66**, 1362 (1991).
[13] J. Weber and M. I. Alonso, Phys. Rev. B **40**, 5683 (1989)
[14] D. J. Robbins, P. Calcott, and W. Y. Leong, Appl. Phys. Lett. **59**, 1350 (1991).
[15] J. C. Sturm, P. V. Schwartz, E. J. Prinz, and H. Manoharan, J. Vac. Sci. Technol. B **9**, 2011 (1991).
[16] X. Xiao, J. C. Sturm, C. W. Liu, L. C. Lenchyshyn, and M. L. W. Thewalt, Appl. Phys. Lett. **60**, 1720 (1992).
[17] T. C. Ong, K. W. Terrill, S. Tam, and C. Hu, IEEE Electron Device Lett. **4**, 460 (1983).