Low-Temperature Photoluminescence of SiGe/Si Disordered Multiple Quantum Wells and Quantum Well Wires

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Low-temperature photoluminescence from disordered SiGe/Si quantum wells and quantum wires made from periodic quantum wells by electron beam lithography and reactive ion etching has been measured. No enhancement in luminescence is seen, compared to that in periodic quantum wells, in the disordered wells or quantum wires. New transitions are observed in the wire luminescence, including a possible no-phonon transition exhibiting a 32 meV blue shift compared to the same transition in the wells.

Key words: Photoluminescence, quantum well wires, SiGe/Si quantum wells

INTRODUCTION

In high quality Si and Ge due to the indirect nature of the bandgap, optical transitions occur by a second-order interaction involving phonons. As a result, the optical transitions can only be strengthened by increasing the lattice temperature. However, in the SiGe alloys, momentum conservation rules can be relaxed in a number of ways. A strong alloy disorder and a correspondingly high alloy scattering potential will strengthen the optical matrix elements. From analysis of high-field transport data in SiGe/Si heterostructures, we have recently calculated a value of the alloy scattering potential $U_0 = 0.6$ eV for holes and 0.2 for electrons in this alloy system.[1] We believe that these large values of U_0 are responsible for the observed no-phonon (NP) transition in the photoluminescence (PL) of bulk SiGe and SiGe/Si quantum wells.[2–14]

DISCUSSION

In general, the ratio of the optical transition rates in indirect bandgap materials to that in direct bandgap materials is approximately

$$\frac{W(\text{indirect})}{W(\text{direct})} \cong \frac{|M_{kk'}|^2}{(E_{g\Gamma} - \hbar\omega)^2} \qquad (1)$$

where $M_{kk'}$ is the matrix element corresponding to the scattering of electrons by phonons, alloy disorder, or interface disorder, and $E_{g\Gamma}$ is the direct bandgap. Near the bandedges, $E_{g\Gamma} - \hbar\omega$ is ~1.5 eV for Si while for pure Si, the value of $M_{kk'}$ is 0.1–0.2 eV at 300K. By increasing the disorder in the system, from that produced by alloying, the relative rate of the indirect transitions can be greatly increased.

Techniques of enhancing the oscillator strengths are to grow a random, or disordered quantum well (QW), or to fabricate disordered quantum wires. Recently reported work on porous Si suggests that optical processes can be enhanced in quasi-one dimensional (quasi-1D) systems.[15] It has been shown[16] that electronic states can be localized in quasi-1D systems even with little disorder. The disorder is expected to strongly localize electron states near the band edges and this will enhance the optical transition rates. We have, therefore, measured the luminescence properties of SiGe/Si regular and disordered QWs and quantum wires. The purpose of the study was to explore the effect of unintentional growth and processing induced disorder on the optical transitions in these lower dimensional quantum confined structures.

SiGe/Si undoped quantum well samples were grown in a RIBER 32 molecular beam epitaxy (MBE) system using Si_2H_6 (disilane) and solid Ge as sources. After substrate cleaning and oxide removal, the quantum well samples were grown on (100)-oriented, B-doped, p-type Si substrates at a temperature of 700°C. Growth is initiated after the observation of a clear (2 × 1) reflection high energy electron diffraction (RHEED) pattern. Multiquantum well (MQW) samples of SiGe well sizes L_z varying from 40–100Å and Si barrier sizes varying from 100–260Å were grown. The sample

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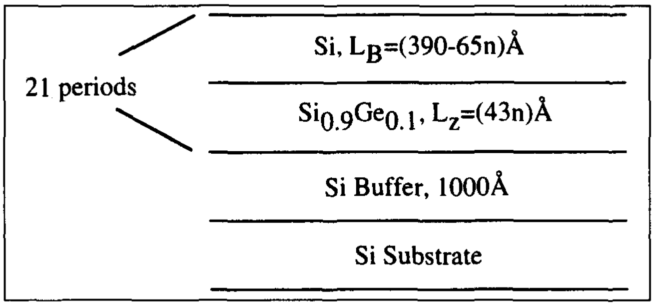

Fig 1. Heterostructure layer sequence of the disordered quantum well samples; n is an integer between 1 and 3.

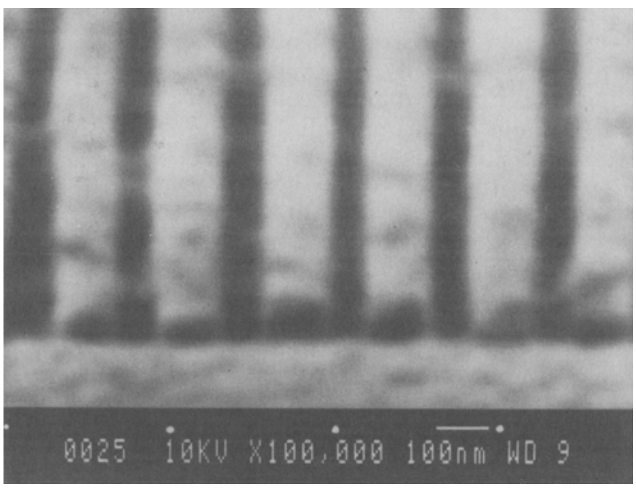

Fig. 2. Scanning electron photomicrograph of etched quantum wires. The nominal wire width in this sample is 300–400Å, produced by undercutting below the Ni mask. This photograph shows the exposed wires with the Ni removed.

from which quantum wires were fabricated consists of two periods of 85Å $Si_{0.88}Ge_{0.12}$ wells and 260Å Si barriers. The MQW were typically grown on a 1000Å Si buffer layer and then followed by a 200Å Si cap layer. The excellent crystalline quality of the materials is confirmed by double-crystal x-ray diffraction measurements.[17] Disordered quantum wells with multiple periods were also grown for photoluminescence (PL) measurements. The schematic of a typical disordered quantum well structure is shown in Fig. 1. For each period of the quantum wells, an integer n between 1 and 3 is randomly chosen to vary the well width. Each number is chosen seven times for the 21 periods. The average quantum well structure has 85Å SiGe wells and 260Å Si barriers.

Quantum wires were made from the two period multiquantum well samples. The quantum wires were defined by reactive ion etching (RIE) through 250Å Ni masks patterned by electron beam lithography. The RIE was performed in a SEMI 1000 parallel plate system. Pressure regulation was achieved using single stage regulators. Plasma was provided by a 13.56 MHz rf generator.[18] CF_4 and O_2 were used as the etch gases. At a selected chamber pressure of 40 mTorr and an rf power of 60 W, optimum gas flow rates of 20 and 7.5 sccm, respectively, were found to give etch rates of approximately 150Å/min for both Si and

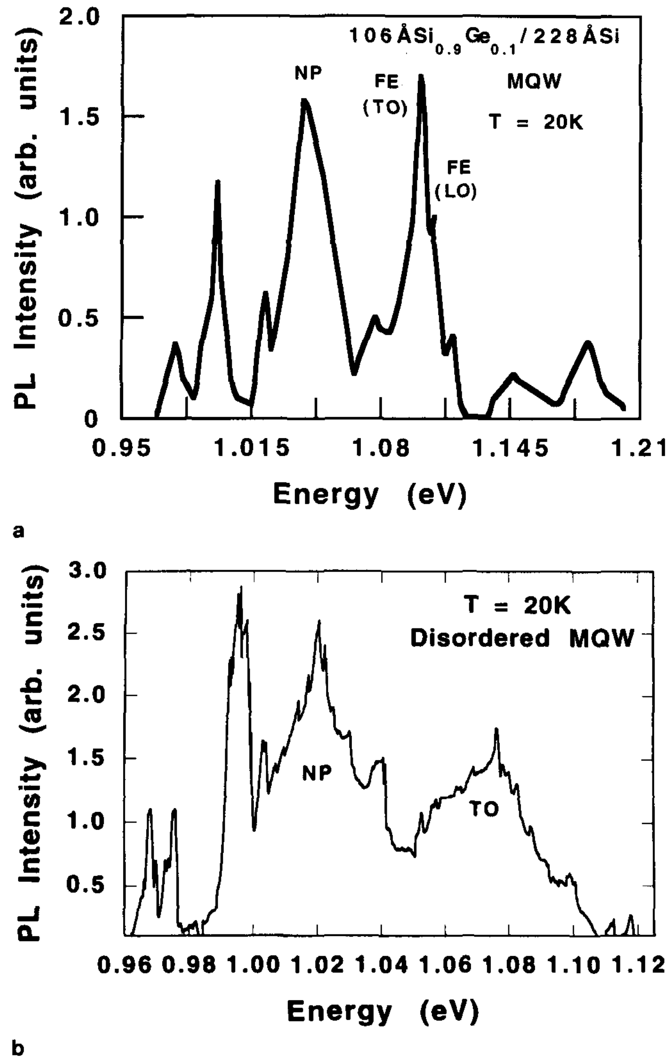

Fig. 3. Low-temperature PL spectra of (a) ten-period $Si_{0.9}Ge_{0.1}$/Si multiquantum well, and (b) disordered multiquantum well shown in Fig. 1.

$Si_{0.88}Ge_{0.12}$ without significant polymerization. Scanning electron microscopic (SEM) studies confirmed that etch profiles are fairly well-defined with some undercut. The free-standing wires so-defined in a sample are shown in the photomicrograph of Fig. 2. The width of such wires made in our laboratory varied from 400–1000Å.

High-resolution (~2Å) steady state PL spectra of the different samples were measured using the 488 nm line of an argon-ion laser of variable intensity. Luminescence signals were processed in a standard configuration using a 1m Jarell-Ash spectrometer and a lock-in detection system with a liquid N_2-cooled Ge detector. Samples were cooled to 20K with a closed-loop variable temperature He cryostat.

The low-temperature PL spectrum of a regular ten-period MQW sample consisting of 106Å $Si_{0.9}Ge_{0.1}$ wells and 228Å Si barriers is first briefly discussed, since this data will serve as a reference for the other samples that have been investigated. The various peaks in Fig. 3a have been identified by analogy with published data.[2] The NP transition from bound excitons is observed at 1.041 eV. The transition at 1.022

eV is possibly a doublet of the NP transition, or a transverse acoustic (TA) phonon replica. The transverse optical (TO_{Si-Si}) phonon replica is observed at 0.977 eV. The peak at 0.998 eV may be related to dislocations.[12] Luminescence from a disordered MQW sample is shown in Fig. 3b. Again, the spectrum contains the transitions mentioned above. No significant enhancement is observed in the overall low-temperature PL. It is, therefore, apparent that the role of QW size disordering is less significant than the role of alloy disordering.

The low-temperature (20K) PL spectrum observed from an exposed quantum wire sample is shown in Fig. 4. We estimate that the actual wire size, taking undercutting into account, is ~300Å. Two dominant sets of transitions are observed in the spectra. The double peak in the range of 0.9–0.98 eV is quite strong and is similar to the features at ~0.8 eV recently reported by Tang et al.[19] in the PL spectra of SiGe/Si multiple quantum wires defined by dry etching. However, the transition observed by these authors disappeared when the wire width was less than 2000Å. Therefore, we conclude that the transition observed by us in the range of 0.9–0.98 eV is a different one, which may have its origin in the interface or surface disorder and defects resulting from processing. The weak transition observed in the spectrum at 1.11 eV is also similar to a peak observed at 1.13 eV by Tang et al. The transition observed by these authors quenched with increasing temperature (totally disappearing for T > 8K) and excitation intensity (P > 50W/cm^2). The peak is observed in our quantum wire samples at a sample temperature of 20K and excitation intensity of 120 W/cm^2. Therefore, the origins of the two transitions are not the same. Tang et al. concluded that the 1.13 peak in their samples arise from ubiquitous impurities. We believe that the 1.11 eV transition observed in our samples is the NP transition in the quasi-1D system. In fact, when compared with the peak energy of the NP transitions in the quantum wells, from which the wires are made, a blue shift of ~32 meV is observed, indicating the existence of quasi-1D effects in a the wire. More work is in progress to characterize this transition. A small part of this blue shift could be due to etching and other extraneous effects. Taking into account the fill factor of the wires, a ~50% reduction in the intensity of the NP transition is observed. This may primarily be due to excessive surface recombination of the exposed wires.

CONCLUSION

In conclusion, we have characterized the luminescent properties of disordered SiGe/Si quantum wells and quantum wires made from periodic quantum wells by RIE. No significant luminescence enhancement is observed in the disordered MQW, compared to periodic MQW structures. New transitions are observed in the luminescence from the quantum wire sample, and one peak which is possibly related to a NP transition, is blue shifted by 32 meV from that of a quantum well.

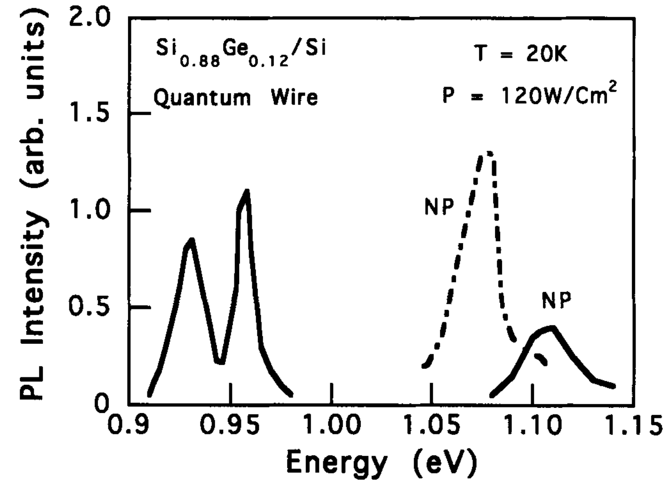

Fig. 4. Measured low-temperature PL spectrum from a quantum wire sample. The wire width is estimated to be ~300Å. The dashed peak represents the no-phonon transition observed from the quantum wells before etching.

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