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Bang-Edge Photoluminescence of SiGe/strained-Si/SiGe Type-II Quantum Wells on Si(100)

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High-quality completely relaxed SiGe buffer layer is grown on Si(100) by gas source molecular beam epitaxy. Pseudomorphic Si layer is grown on this relaxed SiGe buffer to form SiGe/strained-Si/SiGe type-II (staggered) quantum wells. Intense band-edge photoluminescence is observed from these quantum wells for the first time. Quantum confinement effect in SiGe/strained-Si/SiGe type-II quantum wells is demonstrated from the systematic shift of photoluminescence energy peaks with the width of the quantum well.

1. INTRODUCTION

Epitaxial $Si_{1-x}Ge_x$ layers on Si are being studied extensively for potential use in Si-based optoelectronic device technology. Earlier report on the photoluminescence study of $(Si)_m/(Ge)_n$ SLS was controversial because of the poor quality of SiGe buffer [1,2]. With the recent development in SiGe buffer layer technology, however, enhanced luminescence from $(Si)_m/(Ge)_n$ SLS grown on graded SiGe buffer has been obtained [3]. The luminescence is described in terms of recombination of excitons localized at random potential fluctuations in SLS. However, no study on the properties of relaxed-SiGe/strained-Si/relaxed-SiGe quantum well, which forms type-II (staggered) heterostructure and acts as the basic block for many optical devices, has been reported. In this letter, we report for the first time a systematic study of band-edge photoluminescence characteristics of SiGe/strained-Si/SiGe quantum wells, which are grown on a thick relaxed $Si_{0.82}Ge_{0.18}$ buffer layer on Si(100). Quantum confinement effects and photoluminescence properties of excitons in this quantum well are presented.

2. EXPERIMENT

The basic requirement for the growth of strained-Si layer is to obtain a good quality relaxed SiGe buffer layer on Si substrates. Recently, it has been shown that a high-quality buffer layer can be grown by grading Ge concentration in the buffer layer [4-6]. In this study, we use step-graded buffer layer, which is grown by gas source MBE (Daido Sanso VCE-S2020) at 800°C [7]. The starting material consists of 3", p-type, 5-10 Ω-cm, Si(100) wafer, 3000 Å Si buffer, 3.8 μm step-graded SiGe buffer (0 to 18% Ge in 9 steps), and 2.5 μm $Si_{0.82}Ge_{0.18}$ buffer cap layer. Five quantum wells with equal well width were grown on this buffer layer at 700°C. The barrier between adjacent wells was 350 Å $Si_{0.82}Ge_{0.18}$, which eliminates any coupling between the quantum wells. All epitaxial layers were undoped.

PL spectra were recorded using a standard lock-in technique. A multi-line argon laser was used for excitation. Signal was monochromatized using a 1-m dispersive monochromator, and was detected by a liquid-nitrogen cooled Ge photodetector. Temperature control was achieved by a closed-cycle refrigerator.

3. RESULTS AND DISCUSSION

Figure 1(a) shows PL spectra from a thick (6.3 μm) step-graded relaxed $Ge_{0.18}Si_{0.82}$ buffer layer at 4.2K. A peak at 1.093 eV, denoted as SUB^{TO}, is due to TO assisted excitonic recombination in Si substrate. A sharp peak at 1.072 eV corresponds to NP transition from the relaxed buffer layer. Transitions from buffer (barrier) layer are denoted by "B". Full-width at half-maximum of this peak is 4 meV at 4.2K, which shows that the top region of the buffer is of good quality. Phonon-assisted momentum-conserving transverse-acoustical (TA) and transverse-optical (TO) replicas are found at lower energies, TA at 16 meV, TO(Ge-Ge) at 36 meV, TO(Ge-Si) at 51 meV, and TO(Si-Si) at 58 meV. Locations of these energy peaks agree well with PL measurement results on SiGe buffer layers by others [8]. Complete relaxation of the buffer layer was confirmed by x-ray diffraction measurements. Broad peaks at 0.880, 0.906 and 0.923 eV are identified as dislocation- and point defect-related transitions D2, D3 and D4 [9,10]. Dislocation-related transition at 0.81 eV, D1, appears only for thin buffer layers, but it disappears as the buffer layer thickness exceeds 3 μm. These dislocation-related PL, D1-D4, have been also reported for fully relaxed SiGe buffer layers grown by solid source MBE [6,10].

Five quantum wells with equal well width were grown on the above buffer layer at a lower temperature (700°C) in order to avoid thermal relaxation of strain and Ge/Si interdiffusion in the quantum well. PL spectra from the multiple quantum wells are shown in Figure 1(b). All transitions from the strained-Si quantum well are denoted by "X". Well and barrier widths were 10Å and 350Å, respectively. Figure 1(b) looks identical to Figure 1(a) except that two new peaks (as a pair) appear at 0.985 and 1.043 eV in Figure 1(b). We assign the peak at 0.985 eV to be TO phonon-assisted band-edge transition of confined excitons in strained-Si quantum well. As shown in Figure 2, type-II band alignment results at the strained-Si/relaxed-SiGe-buffer heterointerface [11]. Therefore, TO-assisted excitonic transition occurs between the confined conduction band state (lowest lying in energy) of strained-Si quantum well and the top of valence band of SiGe buffer layer (Figure 2). The peak at 1.043 eV in Figure 1(b) can be assigned to NP transition from the quantum wells, and always appears as a pair with the TO-assisted transition. These two peaks were separated by 58 meV, which corresponds to TO phonon energy of Si-Si bond. In case of this narrow strained-Si quantum well, the excitonic wave function penetrates considerably into SiGe barriers, where NP transition is allowed due to the randomness of alloying, resulting in NP transition from the confined conduction band state of strained-Si layer (Figure 2).

In order to demonstrate quantum confinement effect in the SiGe/strained-Si/SiGe quantum well, samples with different quantum well width were prepared. In these samples, the buffer layer structure was kept exactly the same. Well width dependent PL peak energy shifts for excitonic phonon-assisted as well as NP transitions are shown in Figure 3. Figure 3(f) is PL spectrum from the buffer layer without any quantum well. As before, transitions from strained-Si quantm well are marked by "X". For a given well width, the high-energy peak ("X") is NP free excitonic transition from the quantum wells, whereas the low-energy peak is its TO replica. Both these peaks move to lower energy as the quantum well width is increased, Figures. 3(a) and (b). As the well width is increased further, the relative intensity of NP peak becomes weaker with respect to its TO replica, Figures. 3(c), (d) and (e). This is because the penetration of excitonic wave function into SiGe barriers diminishes with increasing well width, and therefore, the NP transition probability becomes smaller. TO-assisted transition for the 10Å-well appears at 0.986 eV, and moves down to 0.947 eV for the 22Å-well. This shift of 39 meV can be used to estimate the conduction band discontinuity at the relaxed-$Si_{0.82}Ge_{0.18}$/strained-Si heterointerface. Using an envelope function calculation, this is found to be about 86 meV.

Temperature dependence of excitonic transitions from strained-Si quantum wells was found to be different from that of SiGe buffer (Figure 4). With increasing temperature, the NP transition intensity from the buffer layer, B^{NP}, diminishes rapidly. At 29K, the NP peak almost dissappear, while the transition from the quantum well, X^{TO}, remains unchanged compared to its 16K value. X^{TO} can be observed until 48K. This shows that free excitons are effectively confined into the quantum well and that strained-Si layer may have less nonradiative pathway for carrier recombinaton compared to its SiGe buffer counterpart.

4. SUMMARY

In summary, intense band-edge photoluminescence for SiGe/strained-Si/SiGe type-II (staggered) quantum wells is reported for the first time. Quantum confinement effect in this quantum well is clearly demonstrated from the systematic shift of PL energy peaks with the width of the quantum well. Transitions from the strained-Si quantum well are identified as radiative recombination of excitons, which are confined in the quantum well.

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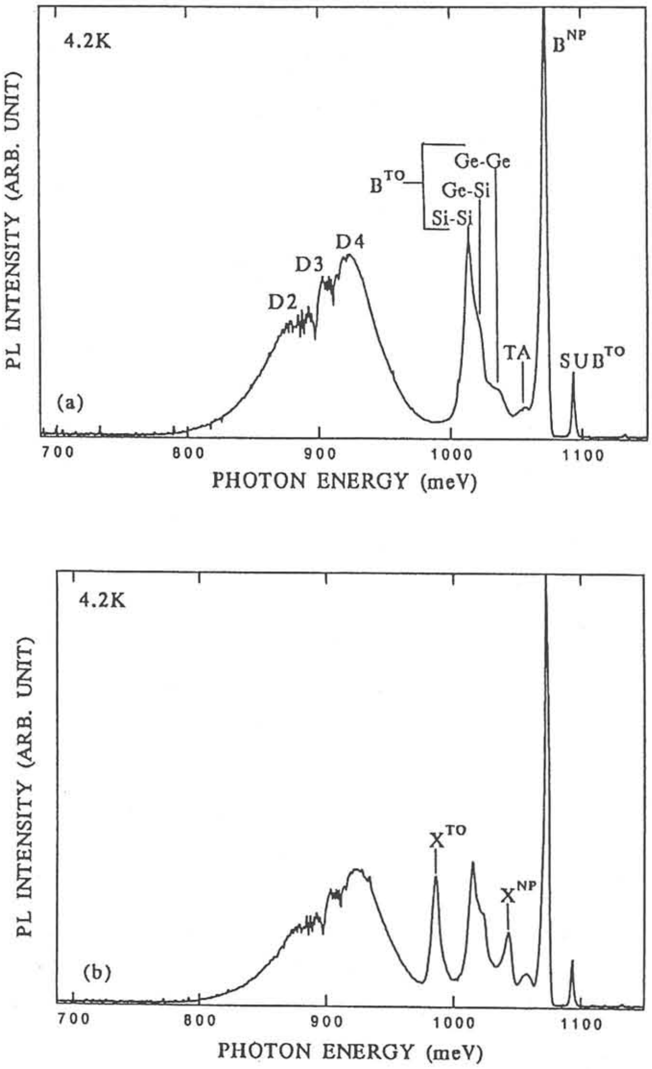

Figure 1 : (a) PL spectra at 4.2K from a fully relaxed thick (6.3 μm) step-graded SiGe buffer layer. (b) PL spectra at 4.2K from 10Å atrained-Si quantum wells grown on this buffer layer at 700ºC.

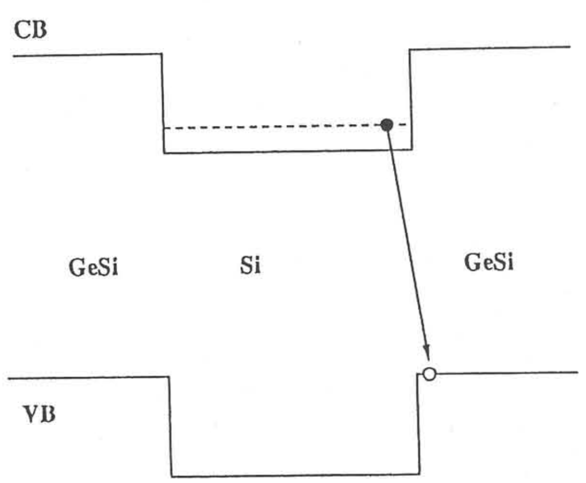

Figure 2 : Schematic type-II band alignment at relaxed-SiGe/strained-Si/relaxed-SiGe heterointerfaces.

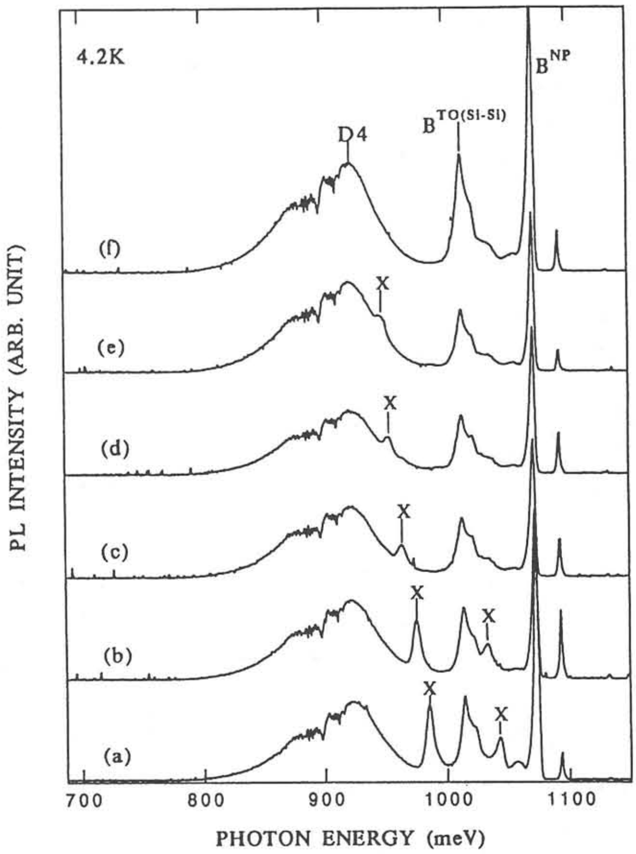

Figure 3 : PL spectra at 4.2K from five quantum well structures, which were grown on the buffer layer described in Figure 1. (a) 10Å, (b) 13Å, (c) 16Å, (d) 19Å, (e) 21Å and (f) no quantum well.

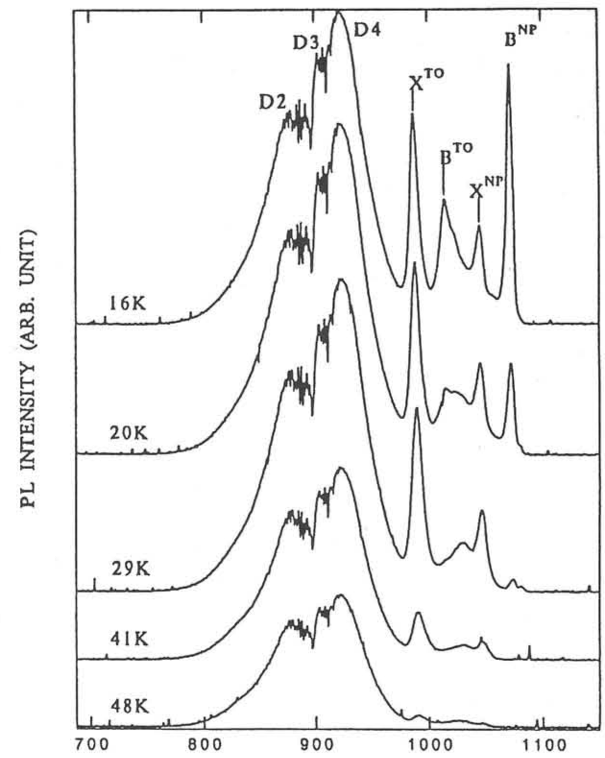

Figure 4: Temperature dependence of PL spectra at 16K, 20K, 29K, 41K, and 48K.