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Photoluminescence from Si/Ge Superlattices

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Short period strained-layer Si/Ge-superlattices grown by molecular beam epitaxy have been investigated by photoluminescence spectroscopy. In 16x4, 15x4 and 12x4 superlattices with 60-80 periods two new luminescence peaks appear. From their separation in photon energy, the two peaks are assigned to a no-phonon transition and its silicon transverse optical phonon replica. Detailed photoluminescence investigations have confirmed that the new peaks which appear at energies between 0.85 and 1.05 eV can be attributed to excitonic transitions in the superlattice.

1. INTRODUCTION

In spite of the fact that several investigations have claimed the observation of the direct transition from Si/Ge superlattices [1, 2] the conditions for the detection of any quasi-direct transition are still under debate [3]. However the interest in Si-based optoelectronic devices has recently gained support from well-resolved near-band gap luminescence detected in $Si_{1-x}Ge_x$-layers grown by various epitaxial techniques [4, 5]. Strongly enhanced radiative recombination from SiGe-quantum wells [6] as well as from Si/Ge-superlattices [7] have also recently been reported as a result of the improvement of molecular beam epitaxy of Si-Ge systems. Hydrogen plasma treatment of Si/Ge superlattices has also been shown to enhance the quantum efficiency of Si/Ge superlattices [8, 9].

In the present paper we report on high efficiency radiative recombination from strained-layer Si/Ge superlattices grown on a relaxed $Si_{1-x}Ge_x$ alloy buffer layers by molecular beam epitaxy.

2. EXPERIMENTAL DETAILS

The samples used for this study were grown in a modified Perkin-Elmer MBE-system. The superlattice (SL) was grown on a 2 μm thick $Si_{1-x}Ge_x$ relaxed buffer layer deposited on top of a *p*-type (100) silicon substrate. The superlattice is strain symmetrized with the average Ge concentration in the buffer layer. The set of samples used for this study consisted of 12x4, 15x4 and 16x4 superlattices grown on buffer layers with Ge concentrations of 25%, 21% and 20% respectively.

The luminescence was excited using an Ar^+ ion laser and a Nd:YAG laser with the samples mounted stress free and immersed in liquid helium (2–4.2 K). The excitation wavelength and power were varied from 351–1064 nm and 0.01-100 mW/mm^2. The PL spectra were recorded with a BOMEM DA8 or a Nicolet SX60 Fourier transform spectrometer fitted with a North Coast Ge diode detector.

3. RESULTS AND DISCUSSION

All of the superlattice samples investigated by us exhibit two strong luminescence peaks at energies between 0.85–1.05 eV. Similar peaks have been observed in a recent luminescence study on Si_m/Ge_n superlattices with $m/n=\frac{3}{2}$ [7]. In addition to these two peaks, which are observed in all our samples, the luminescence signal of the 16x4 and the 12x4 Si/Ge superlattice reveals broad bands in the spectral range from 0.7–0.9 eV. The luminescence of the 15x4 Si/Ge superlattice with 80 periods is shown in Figure 1. The excitation of the superlattice with the 457.9 nm line of an Ar^+-laser creates two strong photoluminescence peaks at 0.937 eV and 0.88 eV. According to their separation in photon energy the peaks can be described as a no-phonon transition and its transverse optical (TO) Si-Si phonon replica. The detection of a TO-phonon replica clearly rules out any correlation of the new peaks to a direct tran-

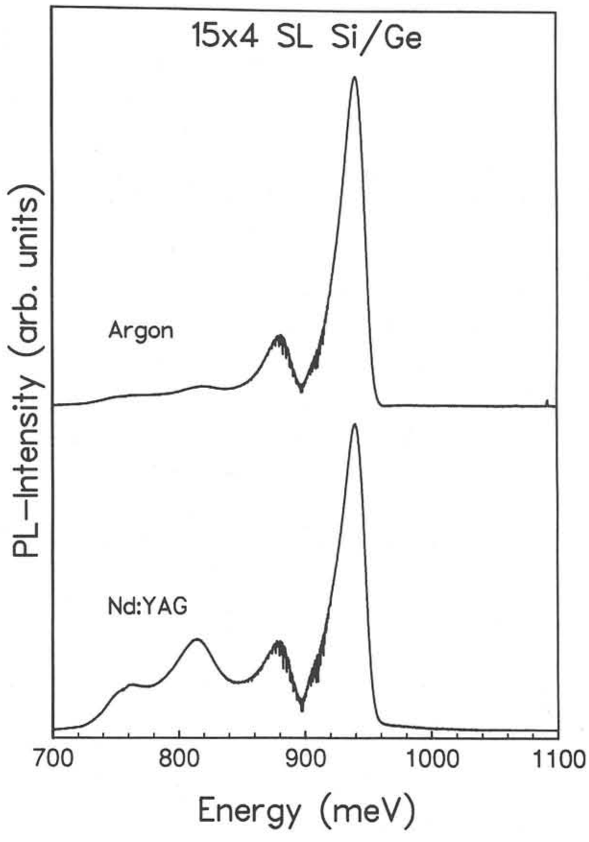

Figure 1: *Photoluminescence of the $Si_{15}Ge_4$ superlattice grown on a (100) Si-substrate with a $Si_{0.79}Ge_{0.21}$ buffer layer; the sample has been excited with a 457.9 nm Ar^+ laser line and the 1064 nm Nd:YAG-laser line.*

sition in a superlattice. The spectral line shape of the two peaks is slightly deformed due to an absorption dip in the beamsplitter used in Fourier transform spectrometer leading to a lower luminescence intensity at 0.893 eV at the intersect of both peaks. The undisturbed line shape is shown in the spectra of Figure 2, which have been measured using another beamsplitter of a different spectrometer. In the same spectral region the luminescence intensity is also slightly reduced by the absorption lines of water vapour. The intensity of the new peaks is much higher than the bound exciton luminescence from the silicon substrate at around 1.1 eV, which is also demonstrated in Figure 1. As additionally shown in Figure 1 the new peaks can also be observed when the sample is excited with photons of an energy smaller than the silicon band gap e.g. using a Nd:YAG laser. Due to the larger penetration depth of the infrared laser two broad peaks at 0.76 eV and 0.81 eV show up in the luminescence spectrum. They can be correlated to extended defects in the buffer-layer or the interface between the substrate and the buffer-layer. Similar peaks are also observed in the $Si_{12}Ge_4$- and $Si_{16}Ge_4$-superlattice samples.

In order to get information on the underlying recombination mechanism, the temperature dependence of the luminescence from the superlattice samples has been studied. With increasing temperature the intensity of both the no-phonon line and the TO-phonon replica decreases monotonically, Figure 2. The increase in sample temperature also causes a shift of the luminescence peaks to lower energies as known from free excitonic transitions. Before the two peaks disappear at a temperature of around 50 K they become superimposed on the low energy tail of a broad luminescence band centered at 780 meV, which appears at a temperature > 30 K. This broad band, which exceeds the low frequency cut off of the Ge-detector [10], has been reported in the literature to arise from strained $Si_{1-x}Ge_x$ alloys [11, 12]. Depth profiling by varying the excitation wavelength from the infrared to the ultraviolet results in an increased relative intensity of the two peaks with decreasing laser penetration. Reducing the excitation power density in the photoluminescence experiment leads to a shift of the two peaks to lower photon

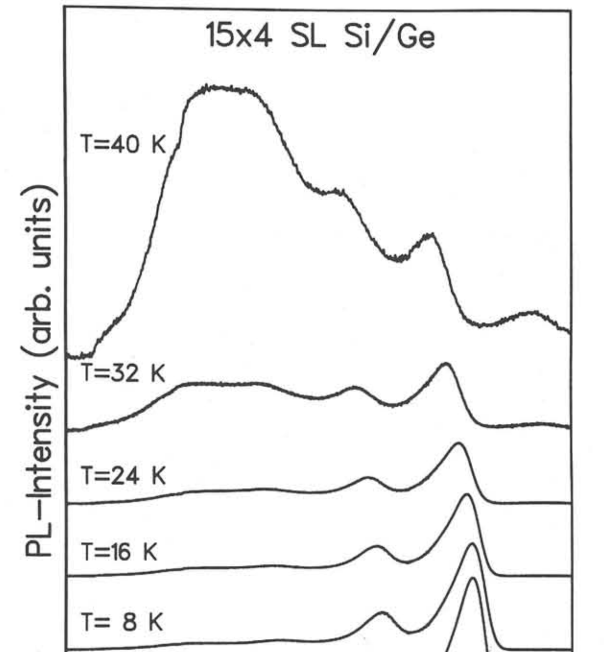

Figure 2: *Photoluminescence spectra of the Si_{15}/Ge_4 SL at different temperatures.*

energies. The two luminescence peaks show also a saturation at rather low excitation densities similar to luminescence peaks ascribed to localized excitons in $Si_{1-x}Ge_x$-layers [13]. All this, and the observation of the two peaks with Si subband gap excitation clearly indicates that the new features involve exciton recombination in the superlattice.

In addition to the investigation of the as grown samples we have studied the annealing behavior. The effect of annealing on the samples is shown in Figure 3. After annealing for 1 h at 650°C in an inert gas atmosphere the two luminescence peaks shift to higher energies by 10–30 meV for the 16x4, 15x4 and 12x4 SL, respectively – as shown in Figure 3. After annealing the $Si_{12}Ge_4$ sample at 750°C only the no-phonon peak can observed underlying the O^{Γ} phonon replica and the two hole transition of the bound excitons from the silicon substrate. Annealing at 850°C destroys the luminescence peaks completely.

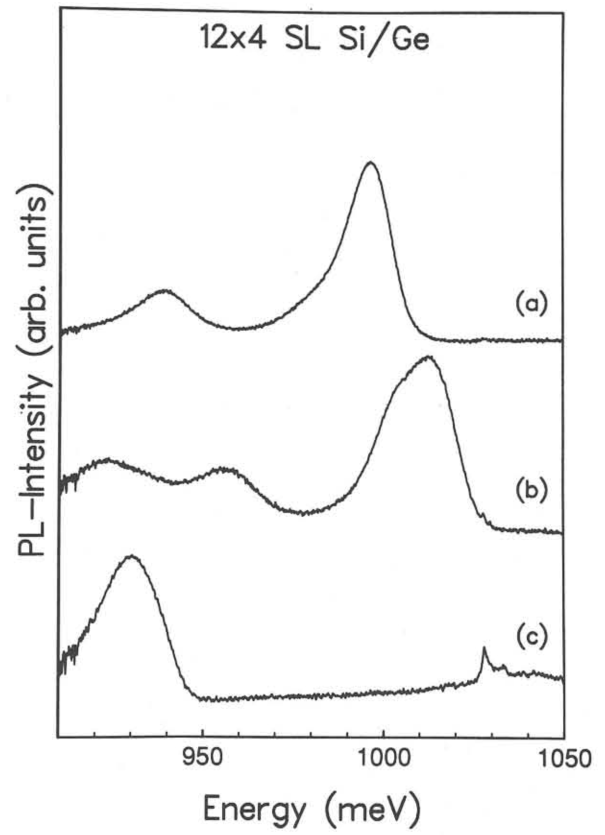

Figure 3: *Photoluminescence spectra of the $Si_{12}Ge_4$ superlattice from the as grown sample (a) and after subsequent annealing for 1 h at 650°C (b) and 750°C (c). The spectra were excited with a UV-laser and measured at T=4.2 K.*

4. SUMMARY

Strained-layer Si_m/Ge_n superlattices have been characterized using photoluminescence spectroscopy. Two new peaks separated in energy by the silicon transverse optical phonon energy have been observed. Depth profiling by variation of the excitation wavelength and excitation in the infrared clearly shows that the new peaks can attributed to excitonic transitions in the superlattices. The observed shift of the luminescence peaks to higher energies with increasing excitation power density additionally supports an excitonic recombination process responsible for the new peaks. Thermal annealing of the superlattice samples at temperatures between 650–750 °C causes a shift of the peaks to higher energies, while annealing at temperatures above 750°C destroys the luminescence peaks.

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