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CL imaging of Si/$Si_{1-x}Ge_x$/Si quantum wells grown by RTCVD

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ABSTRACT: Cathodoluminescence (CL) imaging and spectroscopy have been used to characterize fully strained SiGe quantum wells grown on Si. At T≈5 K, CL spectra contain well resolved band edge luminescence features. Monochromatic imaging with the no-phonon line attributed to the bound excitons in the quantum well, shows that the distribution of the luminescence from the wells was not uniform. The thinnest well (33 Å) contained a low density of non-radiative (luminescence reduction up to 100%) areas 40-100 μm in size. The thickest well (500 Å) contained non-radiative areas and also dark line features oriented along the <110> directions. These dark line features are areas of non-radiative recombination (up to 70%) and have been identified by TEM as misfit dislocations.

1. INTRODUCTION

Strained $Si_{1-x}Ge_x$ alloy layers and SiGe quantum well (QW) structures grown on Si have become the subject of extensive research interest due to the possibility of improved device performance and capabilities. There is a specific interest for the optoelectronic industry in Si/SiGe heterojunction technology with the potential for both Si based optoelectronic detectors and emitters. Photoluminescence (PL) spectroscopy has been used to characterize Si/SiGe heterostructures and quantum wells grown by molecular beam epitaxy (MBE). Very weak or simply broad features were observed with only a very limited number of reports of well resolved excitonic features.

The application of CVD growth techniques for SiGe epitaxial growth, has demonstrated that high quality fully strained SiGe quantum wells on Si can be grown. In addition, samples grown (growth temperature≈625°C) by a combination of rapid thermal processing and chemical-vapour deposition (RTCVD) show well-resolved band edge luminescence from excitons confined in the fully strained SiGe quantum wells (Sturm *et al* 1991). These recent advances have revitalized interest in the possibility of Si based optoelectronic devices. Therefore a detailed analysis of the optical properties of such structures is required.

We have recently begun to develop a SEM-CL system for mapping luminescence features both laterally and in depth. We show for the first time that SEM-CL can be used to characterize SiGe quantum wells at low temperatures. We report here the first low temperature CL spectra containing well-resolved band edge luminescence and CL images from SiGe quantum wells.

2. EXPERIMENTAL

CL spectra were recorded from both single (SQW) and multiple (MQW) quantum wells with different well widths grown by RTCVD on Si(100) substrates. In addition, CL measurements were made on SiGe/Si SWQs and MQWs grown by other variants of CVD growth for comparison; these results will be published elsewhere. In this study we concentrate on the CL measurements recorded from two single strained $Si_{1-x}Ge_x$ samples grown by RTCVD. The samples consisted of a single strained epitaxial $Si_{1-x}Ge_x$ quantum well on a Si buffer layer ($\approx 1\mu m$) with a thin $\approx$150 Å Si capping layer. Both samples had a germanium content of 20%, and well widths of 33 Å and 500 Å. These values were determined by high resolution transmission electron microscopy and Rutherford backscattering spectroscopy (Xiao *et al* 1992). PL measurements have also been carried out on these samples at 4.2 K.

CL measurements were made at T$\approx$5 K using a JEOL JSM 35C SEM fitted with an adjustable cold stage, a retractable off-axis paraboloidal collector mirror and a grating monochromator (Mono CL, Oxford Instruments). The detector employed was a North Coast germanium diode detector. CL spectra were recorded using beam energies (E_o) from 10-35 keV with different beam currents (I_b) between 0.1-100 nA. The CL spectra were recorded with a spectral resolution of 2 nm.

3. RESULTS AND DISCUSSION

CL spectra recorded from the 33 Å well sample and the 500 Å well sample are shown in Figures 1a and 1b respectively. The spectral features and band positions are the same as found in the PL spectra (Xiao *et al* 1992), although at much lower resolution. The spectral features are attributed to an exciton bound to a shallow impurity. The highest energy feature is a no-phonon (X_{NP}) transition and at lower energies are the phonon replicas. The transver-

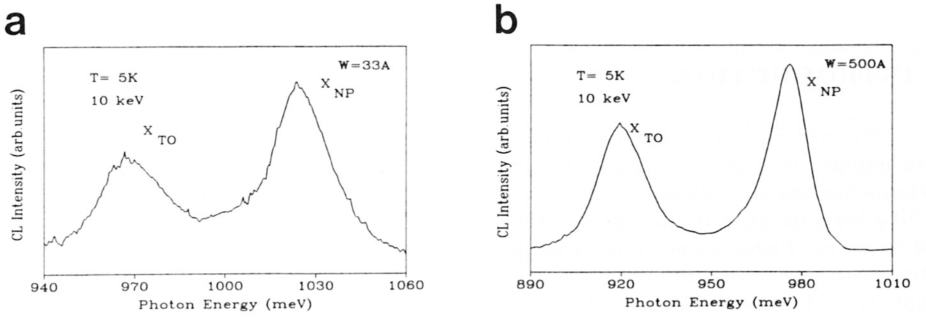

Figure 1. CL spectra recorded at T$\approx$5 K, E_o=10 keV, I_b=0.1 nA, a) QW $Si_{0.8}Ge_{0.2}$, thickness 33 Å, b) QW $Si_{0.8}Ge_{0.2}$, thickness 500 Å.

se acoustic (TA) phonon replica cannot be resolved in the CL spectra but can be seen on the low energy side of the X_{NP} band. Also the Si-Si transverse optical (TO) phonon assisted band (X_{TO}) can been seen clearly but the other two TO bands (Si-Ge and Ge-Ge) cannot be resolved.

The spectrum of the 500 Å sample shifts to lower energy due to reduced quantum confinement effects. The PL spectra recorded on the 500 Å sample showed wider linewidths compared to the 33 Å sample, whereas in the CL spectra the situation is reversed. These differences could be associated with the different carrier generation rates in the CL spectra and the PL spectra and local heating effects in the later.

CL imaging measurements were made using the X_{NP} feature. Figure 2a shows the CL image of the 33 Å well recorded at T≈5 K. On inspection of the image it is clear that the luminescence from the wells is not uniform, and contains a low density of "blobs" (30-100 μm). Monochromatic line scans showed that these "blobs" are areas of non-radiative recombination with luminescence reduction of up to 100%. Some areas show different levels of non-radiative recombination; the reduction in luminescence can vary from 65% to 100%. An estimate of the spatial resolution can be made assuming that the energy dissipation volume is a sphere of diameter equal to that determined by the Gruen range (Yacobi and Holt 1986). However we have observed previously that in both bulk Si and SiGe alloys the CL spatial resolution can be greatly affected by the large exciton diffusion lengths. CL spectra recorded as a function of beam energy show that bound exciton luminescence from the underlying Si substrate is only observed at $E_o \geq 15$ keV. The CL images were recorded at $E_o=10$ keV, the spatial resolution was estimated to be of the order of 1 μm, indicating that the shape of these "blobs" is not dependent on the spatial resolution.

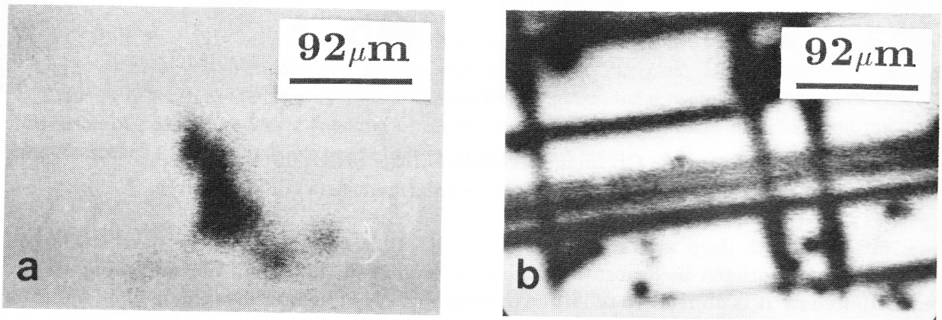

Figure 2. Monochromatic CL images recorded at T≈5 K, $E_o=10$ keV, $I_b=0.1$ nA, a) QW $Si_{0.8}Ge_{0.2}$, thickness 33 Å, b) QW $Si_{0.8}Ge_{0.2}$, thickness 500 Å.

On inspection of the CL image of the 500 Å well (see Figure 2b), the "blobs" can be seen but also dark lines oriented along the <110> directions. These dark line features are also areas of non-radiative recombination with a reduction in luminescence intensity by up to 70%. Such CL dark line contrast has been observed in CL imaging experiments on Si/SiGe epilayers containing misfit dislocations (Higgs and Kittler 1993). Transmission electron microscopy was used to examine the areas were the CL measurements were carried out, to establish if there was any correlation with the dark line features and the "blobs". A 1:1 correlation could be established between the dark line contrast and the misfit dislocations. However no unusual structural features could be correlated with the "blobs", suggesting that these areas of non-radiative recombination could be due to point defects trapped by the interfacial strain in the QW. This "blob" type defect has been observed by us with higher densities in CL mapping of QWs grown by other CVD techniques and these results will reported elsewhere.

To investigate the stability of the non-radiative recombination centres, the 500 Å well sample was annealed in the temperature range 100-400°C. CL images were recorded from the sample before and after annealing. The sample was cut into four sections, RCA cleaned then annealed in flowing argon in a RCA cleaned quartz tube. Below 300°C no differences were observed in the CL images. At 300°C and 400°C dramatic changes occurred in the CL images. There were two distinct effects. First the "blobs" became much larger. Figure 3a shows the CL micrograph of a typical region. On closer inspection it was clear there were three distinct regions. As already mentioned there was an area of larger "blobs", a second region with medium sized and small "blobs" (see Figure 3b) and a third region where there were no "blobs" observed.

The second effect which occurred over the whole sample was that the dark line CL contrast at the misfit dislocations had disappeared (see both Figures 3a and 3b). Preferential defect etching revealed that the misfit dislocations were still in the sample. This suggests that the dislocations have been passivated. There have been well documented cases of hydrogen

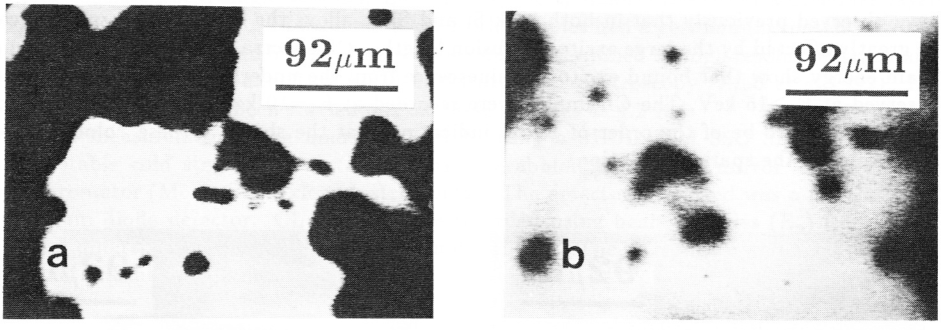

Figure 3. Monochromatic CL images recorded of the SiGe 500 Å sample, a) Annealing for 1 hour at T=300°C, b) same treatment as a) different area.

passivation of both deep and shallow levels in Si. It is possible that the passivation could be caused by hydrogen incorporated during layer growth, and that the annealing step has redistributed it. It is difficult to tell if the average density of "blobs" has changed on annealing, but in general there more areas without any "blobs" and dark line contrast. CL spectra were recorded in both regions. It was found that there was a reduction in CL intensity in the areas were the "blobs" became larger, and an increase in the areas were there were no large "blobs". PL spectroscopy revealed that the overall sample luminescence had increased after annealing. This increase in luminescence intensity is caused by a reduction in the non-radiative centres in the material.

This study has demonstrated the feasibility of using SEM-CL to obtain spatial information about the luminescence features and non-radiative processes occurring.

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