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PHOTOLUMINESCENCE OF THIN $SI_{1-x}GE_x$ QUANTUM WELLS

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ABSTRACT

Well-resolved band edge photoluminescence spectra were obtained from SiGe quantum wells of various widths. In addition to the usual shallow bound exciton features, we observed a highly efficient deeper luminescence process, under conditions of low excitation density, in thick SiGe quantum wells. This luminescence band can be attributed to excitons localized by fluctuations in alloy concentration. The binding energy of the localized exciton feature is found to decrease with decreasing well width. In the thinnest quantum well samples only a single luminescence feature is observed at all power levels, while in several other thin quantum well samples having very sharp lines the localized exciton feature appears at higher energy than the bound exciton. Despite these changes in the spectra, the localized exciton luminescence could be identified in all cases by its characteristic intensity saturation at low excitation power density, as well as its slow decay time (~ 1 ms). The mechanism behind the changes in the localized exciton luminescence may originate from limiting the exciton motion to two dimensions in thin wells, which at low temperatures would hinder migration to the lowest energy alloy fluctuation centers.

INTRODUCTION

Since the initial observation of well-resolved band edge photoluminescence (PL) from strained SiGe on Si just a few years ago,[1,2] many other research groups have been successful in observing similar features in SiGe grown by various techniques.[3-9] While such luminescence provides important information about the SiGe band gap and crystal quality, as well as quantum confinement effects, the exact nature of the luminescence itself has not been studied in great detail as yet. One expects that the luminescence at low temperatures should be dominated by transitions due to free excitons or excitons bound to shallow impurities, such as phosphorus or boron,since this is the case for both pure Si and pure Ge. However, SiGe is in fact quite different from Si or Ge in that it is an alloy. This is manifested in a broadening of the PL peaks (typical linewidths are a few meV) because of the random variation in band gap in different regions of the crystal. The usual momentum conservation rules, which suppress the no-phonon (NP) transitions in indirect band gap materials, are relaxed so that relatively strong NP peaks are observed for the case of the SiGe alloy.

Besides the expected bound exciton (BE) PL features, we have observed a PL band at low excitation density in thick SiGe quantum well samples that is shifted to lower energy relative to the BE by roughly 15 meV.[10] This new PL band is unique to alloys and can be attributed to excitons localized by random fluctuations in Ge concentration. This process is particularly interesting since the localization reduces the chance for decay by non-radiative channels and thereby leads to an unusually high external quantum efficiency of > 10 %.

We have recently turned our attention to PL mechanisms in thin SiGe quantum wells.[11]

Although spectrally resolved BE and localized exciton (LE) peaks were not always observed, on close examination the PL in fact appeared to be consistent with the PL processes occuring in the thicker layers. A single sharp peak (and its phonon replicas), observed in several samples with very thin SiGe quantum wells, was found to behave at low excitation power density in a manner indicative of the LE process. In addition, we have very recently obtained some new results for other thin SiGe quantum wells which in fact show two sharp NP peaks. Like the thick wells, we can interpret these two peaks as a BE and an LE transition. However, the LE peak shifts to shallower energies relative to the BE, possibly due to the more limited 2D movement of the excitons in these quantum wells. In this paper we briefly describe the LE PL for thick SiGe layers and then study how this PL appears to be modified by the restriction of the excitons to two dimensions in the case of the thin SiGe quantum wells.

RESULTS

The SiGe samples were grown either by Rapid Thermal Chemical Vapour Deposition (RTCVD) or by Molecular Beam Epitaxy (MBE), as described previously.[5,12] The nominal parameters (ie. Ge fraction and well thickness) are used here to describe the samples. The luminescence was excited using an Ar ion laser and the PL spectra were measured using a Bomem DA8 Fourier transform interferometer with an InGaAs detector. The time resolved data was obtained by pulsing the Ar laser with an acousto-optic modulator and detecting the PL with a Varian (VPM159A3) photomultiplier tube operated in photon counting mode and coupled to a 3/4m double spectrometer. The samples were typically immersed in liquid He with temperatures between 1.7 and 4.2 K. For temperatures above 4.2 K a flowing He gas Varitemp dewar was used.

The LE and BE PL features are shown in Fig. 1a) for a thick (8.3 nm) CVD $Si_{0.8}Ge_{0.2}$ quantum well by the solid and dashed curves, respectively. In each spectrum we see the usual NP transition and the TA and TO phonon replicas to lower energy. The excitation power, I_0, was chosen to minimize the broadening of the features at high excitation and was of the order of a few W cm^{-2}. The BE PL dominates at high excitation power density (I_0), however these features drop linearly with excitation density until only the LE band remains at low power (10^{-3} I_0). At intermediate power densities both

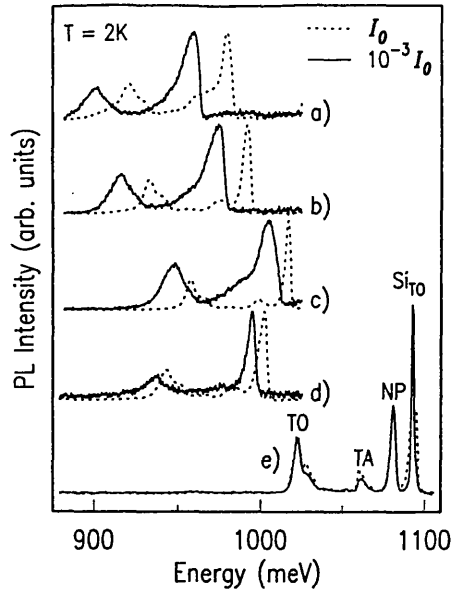

Figure 1 PL spectra for a) 8.3 nm CVD $Si_{0.8}Ge_{0.2}$, b) 5.8 nm CVD $Si_{0.8}Ge_{0.2}$, c) 3.3 nm CVD $Si_{0.8}Ge_{0.2}$, d) 1.5 nm CVD $Si_{0.65}Ge_{0.35}$, and e) 1.2 nm MBE $Si_{0.62}Ge_{0.38}$. Taken under conditions of high and low excitation power density, where I_0 is of the order of a few W cm^{-2}.

processes are resolved (see Lenchyshyn *et al.*[10]). The LE PL has been found to saturate at extremely low power densities (~ 100 μW cm^{-2}), consistent with the expectation that there are a limited number of regions rich enough in Ge to act as such deep localization centers. The exponential tail to low energy reflects the exponential dependence on energy of the density of states into the forbidden gap, which follows from an Anderson model of the alloy fluctuations.[13,14] At low temperatures excitons tunnel or hop so as to fill the lowest energy localization centers first. The exponential LE PL lineshape and low power saturation behaviour have been observed in other alloy semiconductors.[13,14] A band has also been observed by other workers in their MBE SiGe[15] which, because of its appearance only at low power density and spectral position relative to the BE, appears to be LE luminescence.

The remaining spectra in Fig. 1 (b-e) show the PL for high and low excitation power density for SiGe wells of b) 5.8 nm CVD $Si_{0.8}Ge_{0.2}$, c) 3.3 nm CVD $Si_{0.8}Ge_{0.2}$, d) 1.5 nm CVD $Si_{0.65}Ge_{0.35}$, and e) 1.2 nm MBE $Si_{0.62}Ge_{0.38}$. The peaks shift as expected with alloy fraction and quantum confinement effects. However, the spectra also show a decrease in separation between the LE and BE features with decreasing SiGe well width from 20 meV for the 8.3 nm well to 7 meV in the 1.5 nm well. This is consistent with our LE model if we consider that in the thinner layers the excitons cannot move freely in the growth direction and therefore are less likely to reach the deepest alloy localization centers. Instead they become trapped on the relatively more abundant, shallower alloy fluctuations. In the thinnest sample there is essentially no change between the high and low excitation spectra, indicating either approximately identical LE and BE binding energies or the absence of one of the processes. As outlined below, the PL for this sample is in fact found to behave at low power densities in a manner in agreement with an LE process

Evidence of the LE nature of the PL in the thin quantum wells is provided by studying the dependence of the PL intensity on excitation power density. Fig. 2 shows that in the case of thick (10 nm) CVD $Si_{0.75}Ge_{0.25}$ quantum wells the LE PL (+) begins saturating with only 10 μW cm^{-2} excitation, while the SiGe BE PL (■) varies as expected with a linear dependence on excitation power density. The solid curve is the power dependence of the

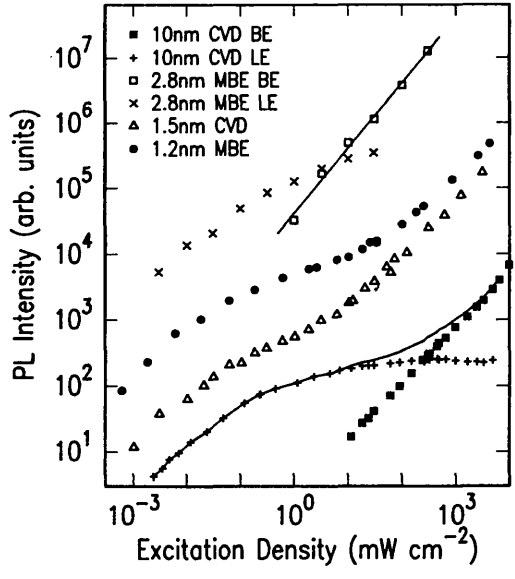

Figure 2 Dependence of PL intensity on excitation density for CVD and MBE SiGe quantum well samples at 2K. The BE PL depends linearly on power density, as indicated by the straight line fit for the 2.8nm MBE sample. The solid curve is the sum of the LE and BE signals for the 10 nm CVD sample. This curve is similar to the power dependence in the very thin (1.5nm and 1.2nm) wells. The curves do not reflect the relative intensities between different samples.

overall SiGe PL in the thick well sample, ie. the sum of the LE and BE signals. This solid curve is qualitatively in agreement with the intensity dependence of the single peak observed for the very thin (Δ 1.5 nm and ● 1.2 nm) SiGe quantum wells. The characteristic saturation at very low power levels suggests that the luminescence at low excitation density in the thin wells corresponds to the LE process seen in the thicker wells. The recovery of the linear dependence of the thin well PL intensity observed at high excitation could be due to a less efficient mechanism becoming dominant, possibly a BE or biexciton process.

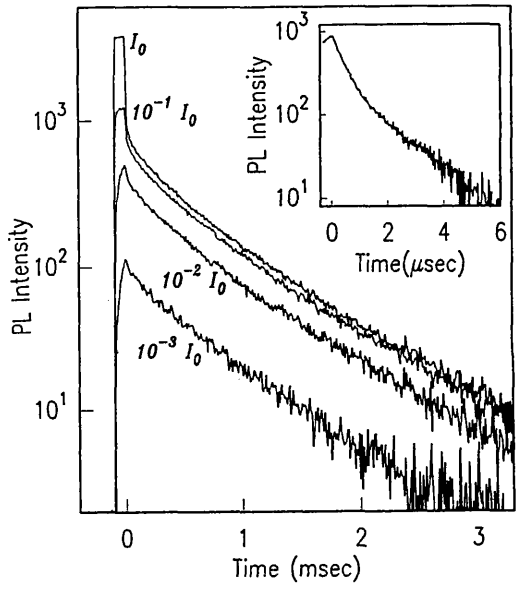

Figure 3 Time decay of the PL from the 1.2 nm MBE sample. As the excitation is increased by a factor of 1000 the contribution from the slow component (τ~750μs) saturates, while that from the fast component increases. The inset shows the non-exponential dependence (τ~0.35μs to τ~1.5μs) of the fast component at high excitation density on an expanded time scale. The four decay curves have not been shifted vertically.

Further support for the assignment of the low excitation PL in the thin quantum wells to an LE process is provided in Fig. 3 by the PL decay curves. Under very low excitation (10^{-3} I_0) the PL decay is a single exponential corresponding to a lifetime of 750 μs. This very slow decay is in agreement with observations for the LE process in the thick wells.[10] A long lifetime, corresponding to the free exciton radiative decay, is expected for the LE since the non-radiative (ie. fast) channels are eliminated. Such long lifetimes are difficult to reconcile with any other process. As the excitation power is increased by several orders of magnitude this slow component saturates, while a faster decay process becomes more obvious. As shown on an expanded time scale in the inset, the fast component is non-exponential with lifetimes of 0.35 to 1.5 μs. Again the origin for the PL observed at high excitation is not clear, however the fast decay times are consistent with processes in which non-radiative Auger decay dominates, and so would include BE or biexciton recombination. Thus even though the PL spectrum does not appear to change, the near gap PL of the very thin LE quantum well samples is dominated by the long lifetime, highly efficient process at low excitation and by a much less efficient, ~1μs lifetime process at high excitation.

Fig. 4 shows the PL spectrum of an MBE multiple quantum well sample with unusually small (~ 1.5 meV) linewidths. Luminescence from all three $Si_{0.86}Ge_{0.14}$ wells is observed, with the shifts to higher energy due to quantum confinement as expected given the nominal well widths of 2.8 nm, 4.2 nm, and 8.4 nm. The Si barriers between the wells are 30 nm, so that there should be no coupling between them. The unusual aspect of this luminescence is the sharp doublet for the 2.8 nm and 4.2 nm quantum wells. The peak separation of this doublet varies slightly with excitation power, but is typically ~2.5 meV. The doublet is shown on an expanded scale for the 2.8 nm well in Fig. 5 for excitation power densities of a) $3x10^{-5}$ I_0, b) $3x10^{-3}$ I_0, c) 10^{-2} I_0, and d) 10^{-1} I_0. Again, with varying excitation density the

spectra evolve from one luminescence peak at low excitation to the other peak at high excitation. However, in this case the higher energy component persists to low power density (curve 5a), suggestive of LE luminescence. This contrasts the situation observed earlier in the thick CVD wells, where the LE peak was always deeper than the BE. However this assignment is consistent with the characteristic LE (x) saturation and linear BE (□) dependence on excitation power shown in Fig. 2. It is also in agreement with PL decay measurements which indicated a fast (0.60 μs) decay for the BE peak, while the LE decayed with a very slow component of 270 μs plus a fast component of 0.26 μs. Fig. 6 shows the decrease in LE intensity with increasing temperature from a) 1.7 K, to b) 2.8 K, c) 4.2 K, d) 6.3 K, e) 8.3 K, and finally f) 15.3 K. The excitons gradually acquire enough thermal energy to escape the very shallow alloy fluctuation potential wells, so that at 4.2 K (curve 6c) the LE peak is essentially gone and BE PL dominates. An Arrhenius plot of the LE intensity between 1.7 and 4.2 K gives, as expected, a very small binding energy of ~0.4 meV. Above 4.2 K, the BE subsequently become dissociated from the impurities so that free exciton (FE) recombination dominates the spectrum at high temperatures (15.3 K).

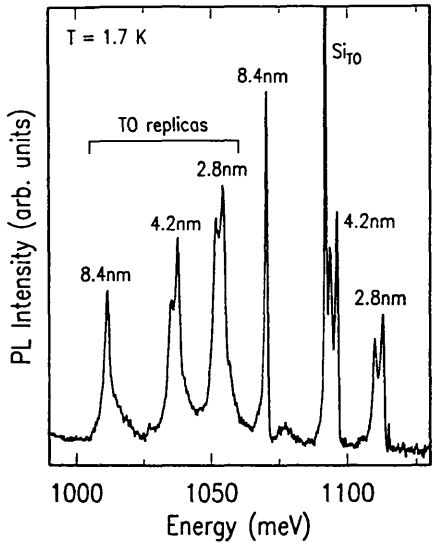

Figure 4 PL spectrum from an MBE sample with $Si_{0.86}Ge_{0.14}$ quantum wells of nominal thicknesses 2.8 nm, 4.2 nm, and 8.4 nm. The 2.8 nm and 4.2 nm quantum well PL shows a doublet structure with very small peak separations of roughly 2.5 meV.

In conclusion, we have studied SiGe quantum well samples grown by CVD or MBE techniques and found that the luminescence mechanisms are not limited to the usual FE and BE recombination found in Si and Ge PL spectra. Instead, the alloy nature of the SiGe plays an important role, with the observation of unique luminescence features at low excitation density that are consistent with a model based on excitons localized by fluctuations in alloy concentration. Clearly more work is warranted to better understand these processes and especially to determine the PL mechanism responsible for the luminescence in the thin quantum wells under high excitation conditions. We are currently working on an experiment based on the simultaneous recombination of two excitons with emission of a single photon to gain insight into these high excitation spectra (see Steiner *et al.*, this proceedings).

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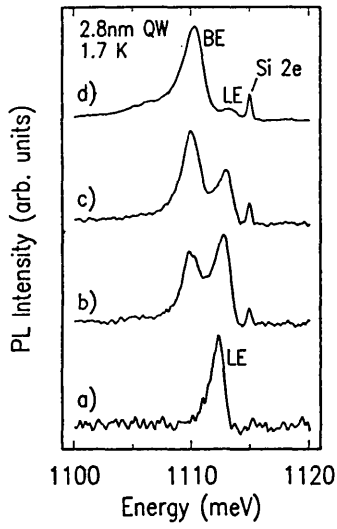

Figure 5 Evolution of the NP peak of the 2.8 nm quantum well PL, from the same sample as in Fig. 4, under increasing excitation power densities of a) $3x10^{-5}$ I_0. b) $3x10^{-3}$ I_0, c) 10^{-2} I_0, and d) 10^{-1} I_0.

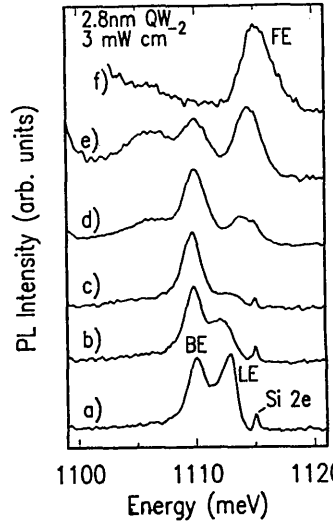

Figure 6 Evolution of the NP peak of the 2.8 nm quantum well PL from the same sample as in Fig. 4, with increasing sample temperatures of a) 1.7 K, b) 2.8 K, c) 4.2 K, d) 6.3 K, e) 8.3 K, and f) 15.3 K.

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