MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS

VOLUME 298

Silicon-Based Optoelectronic Materials

EDITORS

M.A. Tischler

R.T. Collins

M.L.W. Thewalt

G. Abstreiter

MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS VOLUME 298

Silicon-Based Optoelectronic Materials

Symposium held April 12–14, 1993, San Francisco, California, U.S.A.

EDITORS:

M.A. Tischler

ATM
Danbury, Connecticut, U.S.A.

R.T. Collins

IBM T.J. Watson Research Center
Yorktown Heights, New York, U.S.A.

M.L.W. Thewalt

Simon Fraser University
Burnaby, British Columbia

G. Abstreiter

Walter Schottky Institut
Technische Universität München
Garching, Germany

MATERIALS RESEARCH SOCIETY
Pittsburgh, Pennsylvania

VISIBLE PHOTOLUMINESCENCE FROM $SI_{1-x}GE_x$ QUANTUM WELLS

T.W. STEINER[1], L.C. LENCHYSHYN[1], M.L.W. THEWALT[1],
D.C. HOUGHTON[2], J.-P. NOËL[2], N.L. ROWELL[2],
J.C. STURM[3], AND X. XIAO[3]
1 Simon Fraser University, Physics Department, Burnaby, British Columbia, Canada.
2 National Research Council Canada, Ottawa, Ontario, Canada.
3 Princeton University, Electrical Engineering Department, Princeton, NJ.

ABSTRACT

We have observed photoluminescence from strained SiGe quantum well layers at energies approximately equal to twice the SiGe band-gap energy. This luminescence is caused by the simultaneous recombination of two electron hole pairs yielding a single photon. Detection of luminescence at twice the band-gap has been previously used in Si to observe luminescence originating from electron-hole droplets, biexcitons, bound multiexciton complexes and polyexcitons. Time resolved spectra at twice the band-gap have been obtained from our SiGe samples prepared by molecular beam epitaxy (MBE) as well as rapid thermal chemical vapor deposition (RTCVD). This new luminescence clearly distinguishes multiexciton or dense e-h plasma processes from single exciton processes such as bound excitons, free excitons or localized excitons, which are difficult to separate in the usual near-infrared luminescence.

INTRODUCTION

The observation of infrared (IR) luminescence from quantum confined excitons in SiGe quantum wells has been achieved by several groups in the past two years[1-9]. Detailed investigation of the luminescence as a function of excitation density and temperature as well as time-resolved measurements indicate that several processes are responsible for the observed luminescence. Impurity bound excitons, free excitons, localized excitons and biexcitons can all play a role creating considerable complexity in the IR spectrum. However, as has been shown for bulk Si the visible luminescence technique allows the unambiguous identification of luminescence due to multiexcitonic species or dense plasmas[10,11]. This technique requires the simultaneous recombination of two electron hole pairs resulting in a photon with an energy close to twice the band gap. Such a recombination process is extremely unlikely and can occur only for a complex containing two or more electron hole pairs such as a biexciton. Ordinary bound excitons for example cannot give rise to any visible photoluminescence. It is important to appreciate that this is not a non-linear optical effect which, if it were allowed, would generate green photoluminescence from all excitonic species. We have observed visible luminescence in a variety of SiGe samples proving that biexcitons contribute significantly to the near edge luminescence from SiGe quantum wells.

EXPERIMENTAL

The SiGe samples were grown either by Rapid Thermal Chemical Vapour Deposition (RTCVD) or by Molecular Beam Epitaxy (MBE), as described previously [12,6]. The nominal growth parameters are used here to describe the samples. The actual parameters are expected to be within ± 10% and ± 1 nm for the Ge fraction and SiGe thickness, respectively. The IR luminescence was excited using an Ar ion laser and the photoluminescence (PL) spectra were measured using a Bomem DA8 Fourier transform interferometer with an InGaAs detector.

The visible luminescence was excited at 740 nm using a Ti:sapphire laser. The visible luminescence was dispersed by a single 3/4m spectrometer with a 300 groove/mm grating blazed at 500 nm and then imaged onto an imaging photomultiplier (ITT / Surface Science Laboratories Mepsicron) mounted on the spectrometer camera port [13]. The parallel collection capability of this photomultiplier, as well as its extremely low dark count, are essential in order to observe the extremely weak visible PL [11]. Furthermore, by picking off a timing signal from the photomultiplier [13], and cavity dumping the Ti:sapphire laser, time resolved measurements of the luminescence can be made with nanosecond resolution . By combining the output from the timing electronics with that from the photomultiplier position computer a complete three dimensional manifold of the luminescence can be collected with wavelength along the x-axis, time along the y-axis and intensity along z.

The samples were immersed in superfluid liquid helium. The dewar, spectrometer and optics were all enclosed in a light tight enclosure. The laser was filtered at the entrance of the enclosure using a long pass glass filter to remove any visible components from the beam. In order to reject the laser excitation a holographic rejection filter centered at 756 nm was used in conjunction with a stack of short pass glass filters.

RESULTS

The visible PL from an MBE SiGe sample with three quantum wells of width 2.8, 4.2 and 8.4 nm is shown in Fig. 1. The spectrum clearly exhibits contributions from all three wells as well as a small contribution from the electron-hole droplet (EHD) in the substrate at higher energy. For comparison purposes the IR spectrum at half the energy scale is plotted in the upper part of the figure. Note that the ordinary bound exciton (BE) luminescence from the substrate, which dominates the IR spectrum, is absent from the visible PL spectrum. The phonon replicas of the quantum well luminescence are also absent in the visible spectrum since the visible no-phonon (NP) transitions do not require the participation of a phonon [11]. Phonon less recombination can occur when the two constituent excitons have their electrons in opposite conduction band valleys resulting in zero net crystal momentum. Consequently, the intensity of phonon replicas should be much weaker than principal lines in the visible. The features in the visible spectrum are found to line up with the NP quantum well features in the IR after taking into account the factor of two difference in energy.

In Fig. 2 the visible and IR spectra of 6 different SiGe quantum well samples is shown. Sample a) contains three quantum wells but only two are seen in luminescence. The visible luminescence intensity as a function of excitation density in this sample was found to be close to linear over two orders of magnitude indicating that biexciton decay is the dominant quantum well recombination mechanism under high excitation conditions.

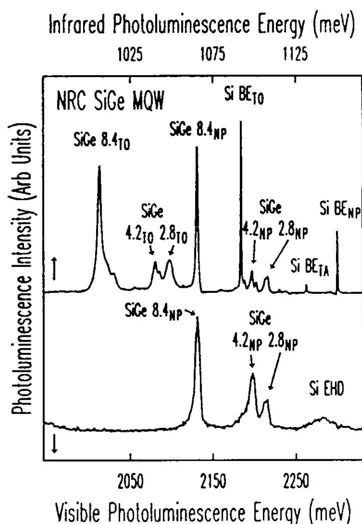

Figure 1. Comparison of the IR (top) and visible (bottom) spectra of a 3 well (2.8, 4.2, 8.4 nm, 14% Ge) MBE sample. The arrows point to the corresponding energy scale. The sample temperature was ≈1.7K. For the IR and visible spectra the excitation was ≈ 50 mW / cm^2 at 514.5 nm and ≈50 W / cm^2 at 740 nm respectively. Features labeled BE are bound exciton recombination from the Si substrate. Features labeled TO are TO phonon replicas of the corresponding no-phonon (NP) lines.

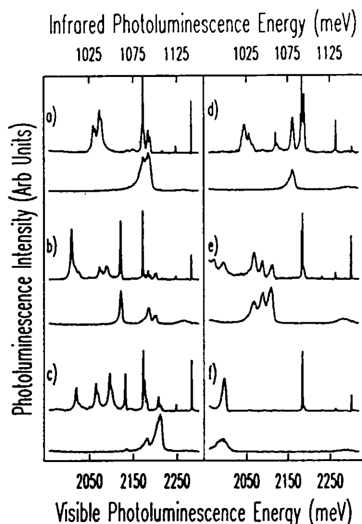

Figure 2. Comparison of the IR (upper) and visible (lower) spectra for 6 SiGe quantum well samples.
a) MBE, 2.8, 4.2, 8.4 nm, 14% Ge
b) MBE, 2.8, 4.2, 8.4 nm, 14% Ge
c) MBE, 8.4, 4.2, 2.8 nm, 14% Ge
d) MBE, 1.2 nm, 38% Ge
e) MBE 12 periods nominally identical
f) RTCVD 1.5 nm, 35% Ge

In other words the shallow alloy fluctuations are saturated with localized excitons at very low excitation densities in such samples (see Lenchyshyn et. al., these proceedings), so that at higher excitation the biexciton density increases linearly with excitation power. Sample b) is the same as the one presented in Fig. 1. Sample c) is similar to sample b); it also contains three wells of width 2.8, 4.2 and 8.4 nm. However, c) has the narrowest well closest to the substrate while b) has the widest well closest to the substrate. Since most of the excitons formed by the excitation originate in the substrate the well closest to the substrate is expected to have the greatest luminescence intensity. These expectations are borne out by the relative intensities of luminescence peaks shown in Fig. 2 b) and c). Sample d) has only a single very thin well which is 1.2 nm wide. Sample e) is a multiple quantum well sample in which all the well widths were intended to be the same. The spectra however shows three distinct peaks indicating that either the well widths or the Ge fraction is not uniform. The last sample f) is a single quantum well RTCVD sample whereas the others were all grown by MBE. This indicates that biexciton processes are important in samples grown by both techniques.

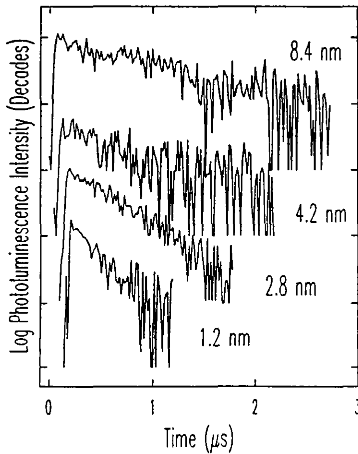

Figure 3. Biexciton lifetimes as determined from samples b) c) and d). The excitation used was cavity dumped 740 nm radiation with an average power of ≈ 4W / cm^2 at a repetition rate of 250 Khz and a pulse width of ≈ 10 ns. The sample temperature was ≈ 1.7 K.

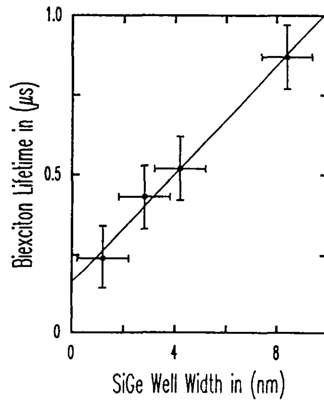

Figure 4. Biexciton lifetimes as a function of well width. The points are from the best fits to the data in Figure 3. The straight line is the best fit to the points.

By averaging together all counts over the spectral width of the individual peaks in the 3D luminescence manifold visible luminescence decay curves can be extracted for each well. The results are displayed in Fig. 3 and indicate that the biexciton lifetime decreases with decreasing well width. This is qualitatively as expected given the increased exciton-exciton overlap as the wavefunctions are increasingly confined and the consequent greater recombination probability. The observed lifetime as a function of well width is shown in Fig. 4 where the lifetime has been determined by the best straight line fit to the data in Fig. 3. The values obtained for the biexciton lifetimes ≈0.5μs are close to the fast lifetime components observed in the IR quantum well luminescence under high excitation conditions in the same samples (Lenchyshyn et. al., these proceedings).

CONCLUSIONS

We have clearly observed visible luminescence from a variety of SiGe quantum well samples. These results prove that a major component of the quantum well luminescence under high excitation conditions and low sample temperatures is due to biexcitons. Biexciton lifetime measurements indicate that the biexciton lifetime decreases with decreasing quantum well width.

REFERENCES

1. K. Terashima, M. Tajima, and T. Tatsumi, Appl. Phys. Lett. **57**, 1925 (1990)
2. J.C Sturm, H. Manoharan, L.C. Lenchyshyn, M.L.W. Thewalt, N.L. Rowell, J.-P. Noël, and D.C. Houghton, Phys. Rev. Lett. **66**, 1362 (1991).
3. D.J. Robbins, L.T. Canham, S.J. Barnett, A.D. Pitt, and P. Calcott, J. Appl. Phys. **71**, 1407, (1992).
4. V. Arbet-Engels, J.M.G. Tijero, A. Manissadjian, K.L. Wang, and V. Higgs, Appl. Phys. Lett., **61**, 2586 (1992).
5. N. Usami, S. Fukatsu, and Y. Shiraki, Appl. Phys. Lett. **61**, 1706 (1992).
6. J.-P. Noël, N.L. Rowell, D.C. Houghton, A. Wang, and D.D. Perovic, Appl. Phys. Lett. **61**, 690 (1992).
7. T.D. Steiner, R.L. Hengehold, Y.K. Yeo, D.J. Godbey, P.E. Thompson, and G.S. Pomrenke, J. Vac. Sci. Technol. **B10**, 924 (1992).
8. E.R. Glaser, T.A. Kennedy, D.J. Godbey, P.E. Thompson, K.L. Wang, and C.H. Chern, Phys. Rev. **B47**, 1305 (1993)..
9. J. Spitzer, K. Thonke, R. Sauer, H. Kibbel, H.-J. Herzog,and E. Kasper, Appl. Phys. Lett. **60**, 1729 (1992).
10. W. Schmid, Phys. Rev. Lett. **45**, 1726, (1980)
11. M.L.W. Thewalt and W.G. McMullan, Phys. Rev. **B30,** 6232, (1984)
12. J.C. Sturm, P.V. Schwartz, E.J. Prinz, and H. Manoharan, J. Vac. Sci. Technol. **B9**, 2011 (1991).
13. W.G. McMullan, S. Charbonneau and M.L.W. Thewalt, Rev. Sci. Instrum. **58**, 1626 (1987)