Very low saturation densities in strained InGaAs/AlGaAs multiple quantum wells

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(Received 2 August 1993; accepted for publication 29 November 1993)

The saturation of excitonic absorption in strained InGaAs/AlGaAs quantum wells is systematically measured as a function of strain. By comparison with an unstrained GaAs/AlGaAs quantum well sample a reduction by a factor of up to 9 in the saturation carrier density is observed in strained samples with indium concentrations of 10% and 15%. Very low saturation densities, as low as 0.82×10^{17} cm^{-3}, are reported for the InGaAs/AlGaAs quantum wells with an indium concentration of 15%. The reduction in the saturation density is attributed to the change in the valence band density of states and the fact that these samples were designed to be fully strained. A novel method of measuring the absorption without antireflection coatings is described.

Recently, there has been increased interest in the application of strained layer materials in optical devices. Electro-optic modulators,[1,2] all-optical modulators,[3–5] and diode lasers, both surface[6] and edge[7] emitting, have been demonstrated. Strained diode lasers have been shown to have advantageous operating characteristics such as low threshold currents.[7] The low threshold current is believed to be a result of the change in the valence band density of states that occurs as a result of the strain from the lattice mismatch between the alloy layers and the substrate material.[8,9] Reductions by a factor of around 2 to 2.5 in the saturation carrier density in InGaAs/GaAs quantum well samples have been demonstrated in an InGaAs/GaAs asymmetric Fabry–Perot modulator (AFPM)[5] and an InGaAs/GaAs multiple quantum well sample.[10] This reduction is also attributed to the change in the valence band density of states with strain. However, the AFPM sample in Ref. 5 was subject to partial strain relief, as demonstrated by the presence of "crosshatching" when viewed under a Nomarski interference microscope. This suggests that if the strain is fully present a further reduction in the saturation density would be expected. In this letter a detailed investigation into the dependence of the saturation density on strain in a series of similar samples with varying but controlled amounts of strain is presented. The samples were designed and grown to be *fully strained* and we find a dramatic reduction, by a factor of up to 9, in the saturation density for the samples with indium concentrations greater than 10%.

Four samples, referred to as S1–S4, were grown by metal organic vapor phase epitaxy (MOVPE) for the purpose of this investigation. S1 is a GaAs/AlGaAs quantum well structure with no strain and hence is the control sample for the measurements. All the samples had identical structures apart from the indium content of the quantum wells. The samples were grown on the an undoped GaAs substrate on top of which was grown an epitaxial 0.5-μm GaAs layer followed by 0.5 μm of $Al_{0.35}Ga_{0.65}As$ and 0.5 μm of $Al_{0.2}Ga_{0.8}As$, the last 1 μm of which was grown as an etch stop layer. On top of these lattice matched layers was grown ten periods of 8 nm/8 nm $In_xGa_{1-x}As/Al_{0.2}Ga_{0.8}As$ well/barrier pairs. The indium fraction, x, was varied from 0.0 to 0.15 for samples S1 to S4, respectively, resulting in lattice mismatches of 0%, 0.36%, 0.71%, and 1.06%, respectively. The samples were capped with 0.5 μm of $Al_{0.2}Ga_{0.8}As$ and intrinsically doped. The sample design and growth programs were chosen on the basis of a thorough investigation on how to grow ten-period *fully strained* samples in the reactor used for the growth of these samples.[11] No crosshatching could be seen on samples S1 to S3 when viewed under a Nomarski interference microscope, implying the samples were fully strained. Sample S4 showed some light crosshatching indicating the onset of strain relief.

The position of the exciton in all the samples was either below or just on the tail of the GaAs substrate absorption. In order to do transmission measurements on the samples the removal of the substrate, using a freon plasma etching system, was necessary. A side effect of this etching system is that the etched surface of the sample remains smooth and mirrorlike resulting in the transmission and reflectivity spectra being dominated by Fabry–Perot effects, as seen in Fig. 1(a). Transmission and reflectivity measurements were taken using an argon-ion pumped titanium-sapphire laser. To avoid thermal affects at high intensities the output of the laser was modulated by an acousto-optic modulator (AOM) to give 1-μs pulses with a 100:1 mark space ratio. The output from the AOM was focused onto the sample, measured spot size of 24 μm, and collected on the other side by two 5× microscope objectives.

Figure 1(a) shows both the transmission and the reflection spectra for sample S2 (5% indium). The heavy-hole exciton can be seen at 854 nm in the transmission spectrum. In order to measure the absorption spectrum the samples could have been antireflection (AR) coated to suppress the Fabry–Perot effects, but there are problems with using AR coated samples as it is difficult to be sure of the exact value of the reflectivity of the coated surface which can lead to a signifi-

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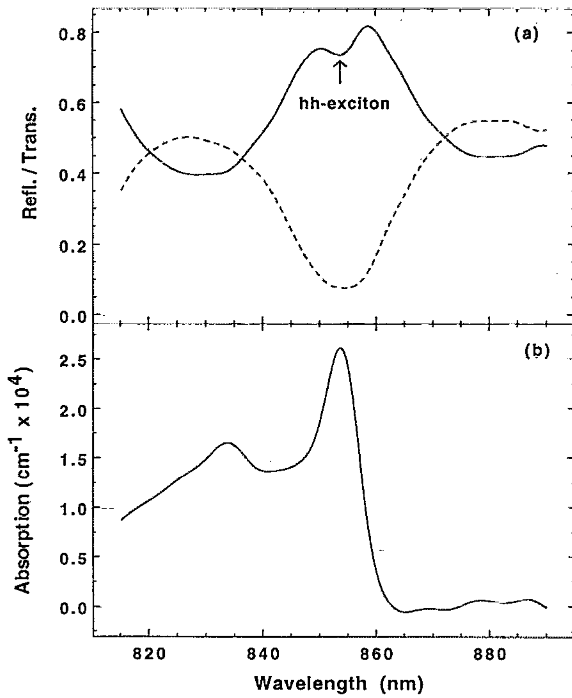

FIG. 1. (a) Shows the transmission (full line) and reflectivity (broken line) spectra for sample S2 with 5% indium in the quantum wells. (b) Shows an absorption spectrum calculated from the spectra in (a). Heavy-hole exciton is at 854 nm and light hole at 834 nm.

cant error when estimating the absorption. However it is possible to calculate the absorption without resorting to AR coating the sample. The transmission (T), reflection (R), and absorption (A) in any sample is governed by the equation

$$R+T+A=1. \tag{1}$$

Therefore, if

$$A=1-\exp(-\alpha d), \tag{2}$$

where α (cm^{-1}) is the absorption coefficient and d (cm) is the absorber thickness, then we can conclude that

$$\alpha=\frac{-\ln(R+T)}{d}. \tag{3}$$

Therefore by simply adding the reflectivity and transmission spectra, taking the log and dividing by the total well thickness the absolute value of the absorption coefficient can be determined. In Fig. 1(b) we see the absorption plot that is calculated from the spectra in Fig. 1(a) using this very simple method. The heavy hole can be clearly seen at 854 nm, with an absorption coefficient of about 26 000 cm^{-1}, and the light hole at 834 nm. The large splitting of the heavy and light holes is a result of the strain in the sample. To measure the saturation of the exciton absorption, spectra were taken at several different intensities, see Fig. 2. The carrier density, N (cm^{-3}), can be calculated from the steady-state equation;[12]

$$N=\frac{\alpha(I,\lambda)I\tau}{E(\lambda)}. \tag{4}$$

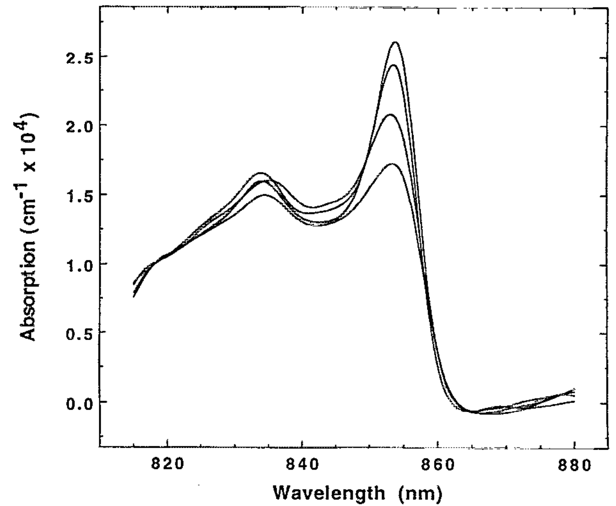

FIG. 2. Absorption spectra for S2 (5% indium) at different intensities: 0.009, 2.23, 9.45, and 14.15 kW cm^{-2} at 854 nm.

Here, $\alpha(I,\lambda)$ is the intensity dependent absorption coefficient, I is the intensity on the sample, τ is the carrier lifetime, and $E(\lambda)$ is the energy of the pump beam. The carrier lifetimes in samples S1–S4 have been measured using a pump-probe experiment which is reported elsewhere.[13] The lifetimes in the InGaAs samples are short, of the order of 0.5 ns, but have been shown to be independent of the strain. The origin of the short lifetime is unknown. The saturation of the absorption in a quantum well can be described by[12]

$$\alpha=\frac{\alpha_0}{(1+N/N_{\mathrm{sat}})}, \tag{5}$$

where α_0 is the saturable absorption and N_{sat} is the saturation carrier density. The absorption at the exciton wavelength, for samples S2 and S3, is plotted as a function of carrier density in Fig. 3. The solid lines show the fits to the data using the model in Eq. (5). The fit for S2 (5% indium) corresponds to a saturation density of 6.9×10^{17} cm^{-3}. This is not significantly different from that measured in the GaAs sample S1, namely 7.4×10^{17} cm^{-3}. However, when the experiment is repeated for S3 (10% indium) there is a marked decrease in the saturation density, i.e., $N_{\mathrm{sat}}=0.96\times10^{17}$ cm^{-3} in Fig. 3.

Average saturation densities for the four samples, as a function of the uppermost valence band density of states (DOS), are shown in Fig. 4. The two-dimensional DOS was calculated using a theoretical strain dependent heavy-hole effective mass[14] and is shown normalized to the GaAs DOS. The strain in each of the samples was estimated by fitting the exciton absorption positions with a strain varying band gap. The strain in the partially relieved 15% sample S4 was estimated to be just less than the strain in S3. The averaged saturation density of 7.4×10^{17} cm^{-3} for the GaAs sample, S1, is low but within the range of saturation densities measured for GaAs quantum wells.[15] The saturation density for the 5% indium sample, averaged over four measurements, is 7.083×10^{17} cm^{-3}. Although there is no significant difference in the saturation density between S1 and S2, it is important to note that in comparison to S1 there is a substantial de-

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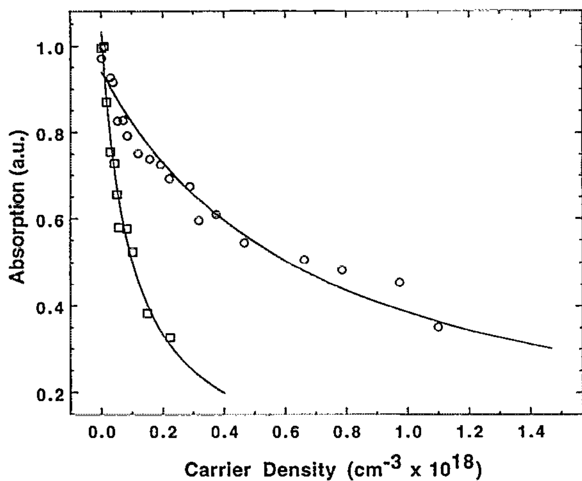

FIG. 3. Saturation curves for samples S2 (○: 5% indium) and S3 (□: 10% indium). Absorption values have been normalized for comparison purposes, normalization factors are 2.597×10^4 and 1.776×10^4 cm^{-1}, respectively. Lines show fits yielding saturation densities of 6.94×10^{17} and 0.96×10^{17} for S2 and S3, respectively. These measurements were repeated several times across the samples leading to average saturation densities of 7.75×10^{17} and 0.93×10^{17} for S2 and S3, respectively.

crease, by nearly an order of magnitude, in the saturation densities as the indium fraction is increased to 10%, S3, and 15%, S4. Small differences in the saturation density may be obscured by experimental limitations but the decrease in the saturation densities measured for S3 and S4 can only be explained by a major effect present in these samples. We believe that for indium concentrations of 10%, i.e., lattice mismatches of 0.71%, or greater, the change in the density of states in the valence band has a significant effect on the saturation of the band edge absorption. The average value of N_{sat} for S4, i.e., 0.82×10^{17} cm^{-1}, is the lowest yet measured for InGaAs multiple quantum wells grown on GaAs. As mentioned above, the strain in the partially relieved sample S4 has been estimated to be similar to the strain in the fully strained S3. This results in a similar density of states reduction and virtually identical values for N_{sat}. Although the sample in Ref. 10 has approximately the same overall thickness of InGaAs (15×5 nm well) as compared to S1–S4 (10×8 nm wells) we believe the smaller reduction in N_{sat} reported in Ref. 10 can only be explained if the sample is subject to some strain relief and therefore yields a smaller reduction in N_{sat}. However, it is worth noting that the strain relieved samples, in Refs. 5 and 10, still demonstrate a reduction in the saturation density in comparison to GaAs devices.

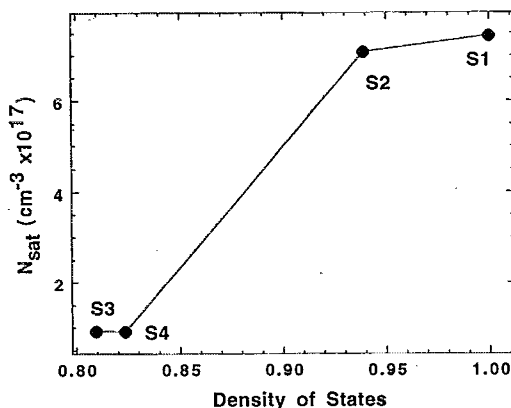

FIG. 4. Comparison of saturation densities averaged over three or four spectra for S1, S2, S3, and S4. Saturation densities are shown as a function of the strain dependent two-dimensional density of states of the uppermost valence band. A reduction in the saturation density for an increase in indium fraction and a resulting strain dependent decrease in density of states for the fully strained samples S2 and S3 is clearly seen in this figure.

In conclusion we have presented the first systematic investigation into the effect of strain on the carrier densities necessary to saturate the excitonic band edge absorption in four samples with varying indium concentration. A significant decrease in saturation densities, of nearly an order of magnitude, has been recorded for samples with lattice mismatches of 0.71% or greater. A very low saturation density of 0.81×10^{17} cm^{-3} was measured for a partially relieved sample with 15% indium multiple quantum wells. Lower saturation densities might be seen in fully strained 15% indium samples. These low saturation densities are attributed to the change in the valence band density of states with strain. All the InGaAs samples have lifetimes which are short, of the order of 0.5 ns, and independent of strain and strain relief.[13] If the source of the short lifetimes can be identified and eliminated then these strained materials promise to be suitable for very low power all-optical devices.

This work was carried out as part of FOCUS, ESPRIT Project 3180. Thanks go to Dr. Garreth Parry and the technical staff of the Digital Optics Group at University College London for their assistance with the sample etching.

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