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Photoluminescence and X-ray diffraction studies of MBE-grown compressively strained InGaAs and InGaAlAs quantum wells for 1.55 μm laser diode applications

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Compressively strained InGaAs and InGaAlAs multiple quantum wells were grown on InP by molecular beam epitaxy and their material qualities were investigated by double-crystal X-ray diffraction (DCXRD) and photoluminescence (PL). From the satellite peaks in a DCXRD scan, precise layer structures were determined. By comparing PL spectra of strained quantum wells having different well thicknesses, 75 Å thick quantum wells were found to be more suitable for laser diode applications than thinner wells. To achieve the required lasing wavelength of 1.55 μm with 75 Å wide strained quantum wells, quaternary InGaAlAs quantum wells were studied. It was also found that quaternary InGaAlAs strained quantum wells are less prone to strain relation than ternary InGaAs.

1. Introduction

In recent years, it has been very successfully demonstrated that pseudomorphically grown strained layers can greatly enhance the performances of electrical and optical semiconductor devices. In utilizing strained layers, one has to be careful not to reach a certain critical thickness, beyond which material qualities of the strained layer start to degrade due to strain relaxation and resulting dislocation formations. Although the strain relaxation by the formation of misfit dislocations has been explained long ago by Matthews and Blakeslee [1], there are still conflicting reports on how thick a pseudomorphic strained layer can be grown [2], and it is reported that the strain relaxation mechanism depends on the conditions under which strained layers are grown [3]. These uncertainties necessitate a careful study in which the optimal strained layer structures are experimentally determined for each specific device application.

The present goal is high performance 1.55 μm laser diodes based on the molecular beam epitaxy (MBE) grown, phosphorus-free InGaAlAs material system. We have already demonstrated that such devices with lattice-matched quantum wells have comparable device performances to more mature InGaAsP lasers [4], and now hope to improve them further by utilizing strained quantum wells.

To achieve this goal, a number of strained quantum wells with different thicknesses and compositions were grown, and they were characterized by double crystal X-ray diffraction (DCXRD) and photoluminescence (PL).

2. Material growth and characterization

Samples used in this study were grown by a Riber 2300 MBE system. The growth temperature was around 530°C as monitored by a calibrated pyrometer, except during the growth of strained layers when the growth temperature was lowered according to the amount of strain desired to be incorporated. The pyrometer was calibrated by setting the temperature at 530°C when

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the reflection high energy electron diffraction (RHEED) from the InP substrate under arsenic overpressure changed from the characteristic 2 × to 4 × patterns while the substrate temperature was ramped up.

Effusion cell temperatures were determined for the desired material compositions from flux beam equivalent pressure (BEP) measurements as well as the results of X-ray measurements on previously grown samples. Lattice matching to InP was achieved usually within 0.1%. The growth rate was about 0.6 um/h and the arsenic overpressure was maintained between 7×10^{-6} and 1×10^{-5} Torr of BEP. The indium cell temperature was fixed during the entire growth and the strained layer compositions were achieved by independently setting the two gallium and two aluminum cell temperatures for the desired compositions, and shuttering them as needed. Consequently, no growth interruption was required to adjust cell temperatures.

The layer structures used in this study were essentially those of laser diode devices, except that they lacked thick claddings and a contact layer. For some samples, in order to make X-ray analysis simpler, identical material compositions were used for both claddings and barriers.

Once a sample was grown, its layer thicknesses and compositions were determined by matching the result of DCXRD measurement with that of simulation. For the measurement, a Bede model 300 from the Bede Scientific Instruments with Cu-Kα radiation and an InP first crystal oriented for the (004) reflection was used. For the simulation, a software package, Rocking curve Analysis by Dynamic Simulation (RADS), supplied by the same company was used. Fig. 1 shows the results of DCXRD measurement and simulation of a strained multiple quantum well structure whose barriers and claddings are made of the same material composition. The estimated thicknesses for top and bottom claddings are 0.12 and 0.16 μm, respectively. The sharp peak located at zero arc second is from the InP substrate. The peak located about plus 1000 arc second corresponds to the unintentionally strained quaternary materials of the claddings and barriers. Since X-ray alone is not sufficient to determine the quaternary composition, the bandgap of this layer was measured from a low temperature PL measure-

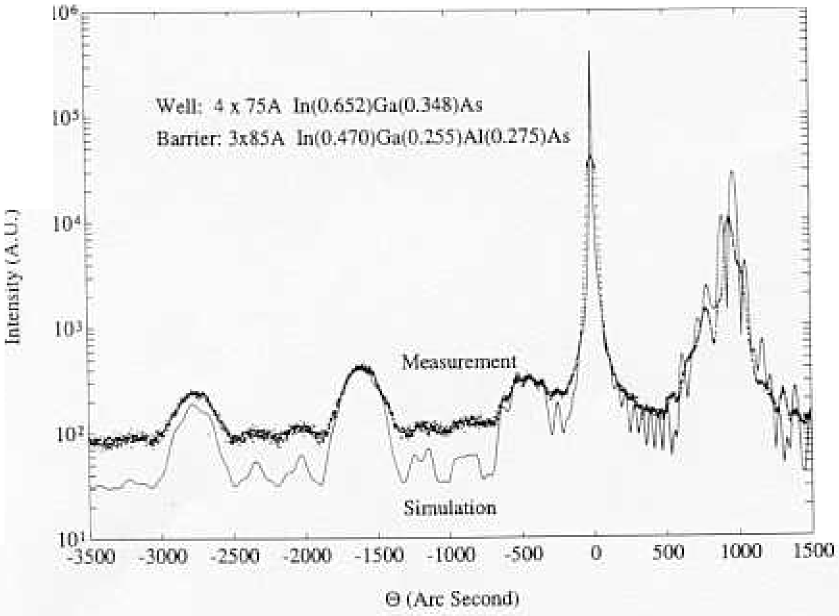

Fig. 1. Results of DCXRD measurement and RADS simulation. Layer structures given in the figure were used to obtain the matching simulation.

ment. With this additional information, we were able to determine the precise material composition. The most remarkable feature of fig. 1 is the satellite peaks located in the left side of the substrate peak. These well-defined satellite peaks indicate that the strained quantum wells are free of any major dislocations due to strain relaxation. From the positions of these satellite peaks along with the knowledge of growth time for well and barrier materials, the detailed information of the well composition, and well and barrier thicknesses can be easily determined, and are shown in the figure. The accuracy of layer structures so obtained is well manifested by the good matching between measurement and simulation. The layer structures of all the samples used in this study were determined in this manner.

For photoluminescence characterization, an Ar laser was used for excitation. Samples were cooled down to 15 K in a closed-cycle helium cryostat and the luminescence from the sample passed through a Spex 0.5 m monochromator and was detected by a lead-sulfide photoconductor.

3. Strained quantum well thickness dependence

For strained quantum wells in laser diodes, well composition and thickness must be well controlled in order to achieve the desired lasing wavelength. According to our calculation that accounts for the effects of strain on band-gap [5] and band-offset [6], but not on the effective masses of electrons and holes, the required well thickness for a quantum well made of 1% compressively-strained $In_{0.68}Ga_{32}As$ to have a room temperature optical transition of 1.55 μm between an electron and a heavy hole is about 35 Å. To confirm this calculation and to investigate the optical quality dependence on strained well thickness, samples with four multiple quantum wells of different thicknesses of 25, 50, and 75 Å were grown and characterized. To prevent any possible strain relaxation, especially for wider wells, relatively low growth temperature of 475°C was used for the well and barrier layers. Fig. 1 shows the result of X-ray analysis for the sample with 75 Å wells, and fig. 2 shows the PL spectra of all three

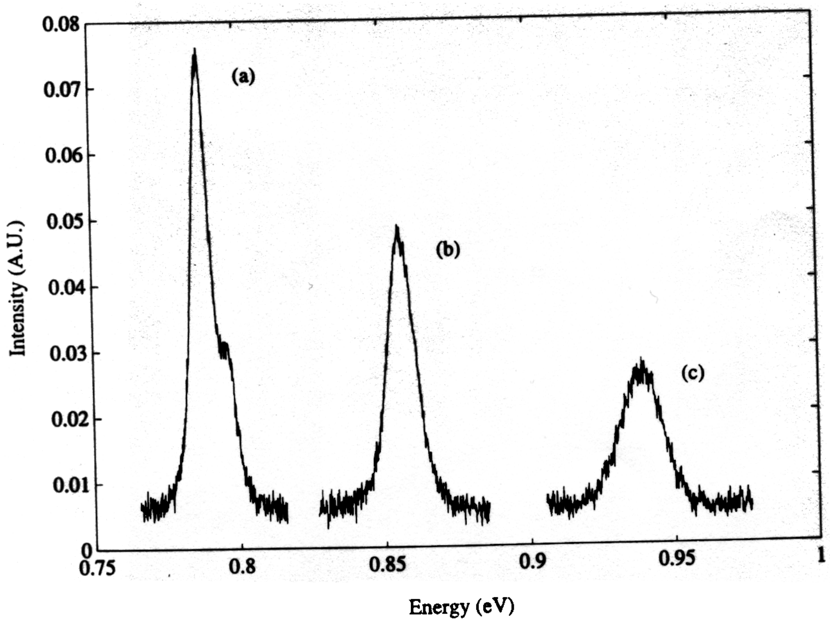

Fig. 2. 15 K PL spectra for four $In_{0.652}Ga_{0.348}As$ strained quantum wells with different well thicknesses: (a) for 75 Å, (b) for 50 Å, and (c) for 25 Å wells. The peak positions and FWHMs are 786 and 8.2 meV for (a), 855 and 10.0 meV for (b), and 938 and 18.2 meV for (c).

samples. From these, no evidence of major strain relaxation is observed.

The calculated 15 K PL peaks are 785, 831, and 938 meV for 75, 50, and 25 Å wells, respectively. With the exception of 50 Å wells, the agreement is excellent. The reason for the 24 meV difference between measurement and calculation for the 50 Å well requires more investigation.

It is clearly observed from the figure that thinner wells have larger PL full width at half maximum (FWHM). This is due to the fact that a slight interface roughness in a thinner quantum well causes a relatively larger electron-hole transition energy fluctuation than in a thicker well. For instance, a monolayer fluctuation in the total well thickness in the 25 Å well corresponds to almost 5% change in the calculated transition level as compared to less than 1% change in the 75 Å well. The significance of this result is that too thin wells are not optimal in an actual laser diode structure, since a slight nonuniformity in well thickness and/or well composition will result in a larger error in the resulting lasing wavelength. However, for the specification of room temperature lasing wavelength of 1.55 μm,the well thickness has to be fixed at the non-optimal value of 35 Å.

4. Quaternary strained quantum wells

To obtain strained quantum wells with wider well thickness and the lasing wavelength of 1.55 μm, we investigated quaternary InGaAlAs strained quantum wells in which a small amount of aluminum is added to the well resulting in a higher bandgap well material without a change in the amount of strain. Two samples were grown for this investigation. The first sample has three 80 Å $In_{0.67}Ga_{0.33}As$ quantum wells and the second has three 75 Å $In_{0.67}Ga_{0.27}Al_{0.06}As$ wells. The barrier material for both samples is estimated to be 80 Å thick $In_{0.52}Ga_{0.23}Al_{0.25}As$. Since claddings and barriers have different compositions for these samples, there is a small amount of uncertainty in this estimate. The growth temperature was 510°C for both samples. X-ray results show well-defined satellite peaks for both samples indicating no major strain relaxation.

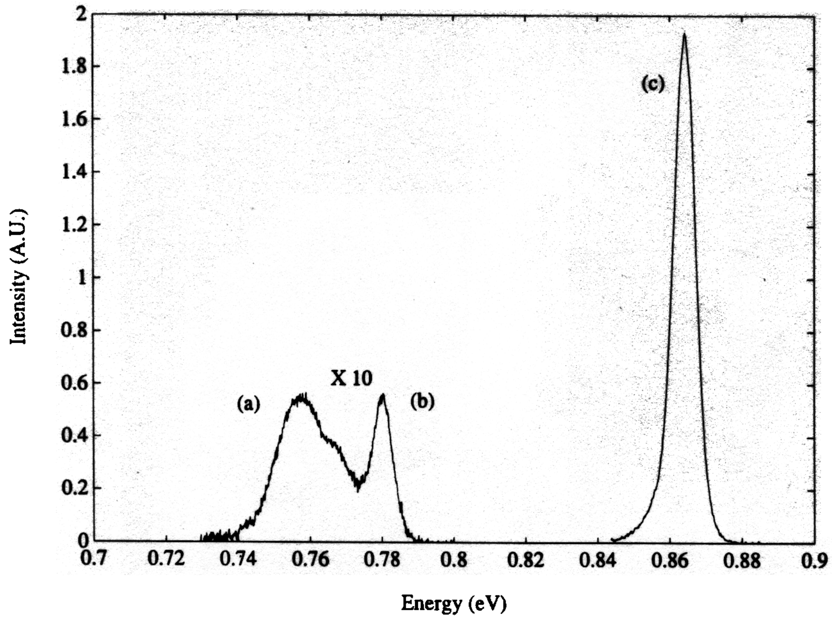

Fig. 3. 15 K PL spectra for 3×80 Å $In_{0.67}Ga_{0.33}As$ (a) and (b), and 3×75 Å $In_{0.67}Ga_{0.27}Al_{0.06}As$, (c). The peak positions and FWHM are 757 and 20.4 meV for (a), 781 and 7.6 meV for (b), and 864 and 7.2 meV for (c).

However, in PL, the two samples show a remarkable difference as shown in fig. 3. First, the PL peak for the quaternary sample is indeed at a desired position. The quaternary sample has the room temperature PL peak at 1.55 μm, as compared to 1.73 μm for the ternary.

Also, the quaternary sample has a single narrow (FWHM = 7.2 meV) and strong PL peak, whereas the ternary has two peaks: a narrow one (FWHM = 7.6 meV) and a broadened one (FWHM = 20.4 meV) at a lower energy. Broadening and shifting into a lower energy of PL peaks as well as the reduction in PL intensity have been identified as the sign of strain relaxation [7]. From this, we can identify the narrow peak as the luminescence from the portion of quantum wells that were grown pseudomorphically and the broad peak from somewhat relaxed layers. It is likely that a narrow PL peak from multiple strained quantum wells can be obtained only if at least one quantum well is grown pseudomorphically. From this, we can speculate that the relaxation in the ternary sample happened after the growth of the first quantum well. This puts the critical layer thickness of the ternary wells to be somewhere between 80 and 240 Å. On the other hand, quaternary wells have a critical layer thickness larger than 225 Å. For a comparison, the critical layer thickness from Matthews and Blakeslee's model [1] for the same amount of strain without considering the effects of lattice-matched barrier materials is about 100 Å. The exact cause for this improvement in the quaternary samples requires more detailed study, but it is consistent with our experience that growing pseudomorphic GaAs layers on InP is much more difficult than AlAs, both of which have about the same amount of strain.

It should be noted that wider strained quantum wells in laser diodes have the additional advantage of an enhanced electron–hole overlap integral resulting in higher values for optical matrix elements [8]. In fact, Bhat et al. have demonstrated that MOCVD-grown laser diodes with thicker InGaAlAs quaternary wells do show better device performances than those with thinner InGaAs ternary wells [9].

5. Conclusion

We have grown by MBE and characterized by DCXRD and PL a number of different compressively strained multiple quantum wells. From this, we have shown that the most optimal compressively strained quantum well structure for 1.55 μm laser diode applications is the one with the quaternary InGaAlAs quantum wells with a reasonable well thickness. It was also found that the addition of aluminum appears to make the strained layer less prone to strain relaxation.

Acknowledgements

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