A critical examination of the molecular-beam-epitaxial growth of $In_xGa_{1-x}As/GaAs$ strained quantum well structures

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We have investigated the molecular-beam-epitaxial growth and optical properties of $In_xGa_{1-x}As/GaAs$ ($0.07 \leqslant x \leqslant 0.20$) single and multiple quantum well structures. Photoluminescence and absorption measurements were made to characterize the various structures. Low-temperature excitonic linewidths as small as 1.2–2.4 meV have been obtained in 80–120-Å $In_xGa_{1-x}As/GaAs$ ($0.07 \leqslant x \leqslant 0.20$) single and multiple quantum wells up to total thicknesses of 2.0 μm. The Stokes shift in these samples is $\sim$1–2 meV. This result is independent of the absence or presence of an intermediate composition buffer layer and indicates that the latter does not influence the optical properties of strained multiquantum wells. The growth kinetics and growth modes are more important factors in this respect.

There are three types of strained layer epitaxy[1] which are important for device applications. In the pseudomorphic regime, the thickness of the active region is below the critical thickness, and so no dislocations are generated. For larger thicknesses of strained layer, the mismatch is accommodated by the generation of misfit and threading dislocations upon reaching the critical thickness in the heterostructure. The dislocations may be generated in an intermediate or graded composition buffer layer or superlattice, in which case the active region is unstrained, or the active multiquantum well (MQW) or superlattice (SL) may be directly grown on the substrate, in which case the dislocations are generated within it. The misfit dislocations manifest themselves as surface undulations along the ⟨110⟩ directions, commonly known as cross-hatch patterns.[2] Finally, the nature of strained layer epitaxy and the resulting growth modes may have a profound influence on the nature of the heterointerfaces in the SL. An associated growth related problem is the low growth temperature necessary to remain in the unity incorporation regime of indium.

In the context of what has been mentioned above, we have critically examined the growth of InGaAs/GaAs single quantum wells (SQW) and *p-i*(MQW)-*n* diodes on (100) GaAs substrates. Photoluminescence (PL) and absorption measurements have been used as probes of the material quality. It will be evident that the results represent one of the narrowest PL linewidths, for 80–120-Å quantum wells, reported to date, indicative of the material quality achievable through controlled molecular-beam epitaxy (MBE).

The quantum well structures were grown on (100)-oriented GaAs substrates in a Varian Gen II system with computer controlled shutter operation. Preparation of the system prior to growth was similar to previous work.[3] The growth rate of the GaAs was maintained at 0.8 μm/h for the structures grown here the growth temperature was in the range 550 ± 10 °C. The group V versus group III ratio was held at approximately 30 to maintain an arsenic stabilized surface for both GaAs and $In_xGa_{1-x}As$. The reflection high-energy electron diffraction (RHEED) patterns were extremely sharp during the growth of the GaAs. During the growth of the $In_xGa_{1-x}As$ wells, the arsenic stabilized lines faded but the pattern did not turn spotty up to the critical thickness, indicating a near two-dimensional (2D) layer-by-layer growth mode in this regime.

A series of single and multiple quantum well structures

0.3 μm	p^+(Be):GaAs	2×10^{18}
600 Å	GaAs (L_Z = 30 Å)/ $Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	10 Period S.L.
1.98 μm	$In_xGa_{1-x}As$ (L_Z = 100 Å)/ GaAs (L_B = 200 Å)	66 Period MQW
900 Å	$In_xGa_{1-x}As$ (L_Z = 10 Å)/ GaAs (L_B = 20 Å)	30 Period S.L.
0.4 μm	n^+(Si):$In_yGa_{1-y}As$	2×10^{18}
0.2 μm	n^+(Si):GaAs	2×10^{18}
1200 Å	n^+(Si):GaAs (L_Z = 30 Å)/ n^+(Si):$Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	20 Period S.L. (2×10^{18})
200 Å	n^+(Si):GaAs	2×10^{18}

n^+(Si-Doped) GaAs Substrate

0.3 μm	p^+(Be):GaAs	2×10^{18}
600 Å	GaAs (L_Z = 30 Å)/ $Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	10 Period S.L.
1.98 μm	$In_xGa_{1-x}As$ (L_Z = 100 Å)/ GaAs (L_B = 200 Å)	66 Period MQW
780 Å	GaAs (L_Z = 30 Å)/ $Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	13 Period S.L.
0.2 μm	n^+(Si):GaAs	2×10^{18}
1200 Å	n^+(Si):GaAs (L_Z = 30 Å)/ n^+(Si):$Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	20 Period S.L. (2×10^{18})
0.2 μm	n^+(Si):GaAs	2×10^{18}
1200 Å	n^+(Si):GaAs (L_Z = 30 Å)/ n^+(Si):$Al_{0.3}Ga_{0.7}As$ (L_B = 30 Å)	20 Period S.L. (2×10^{18})
200 Å	n^+(Si):GaAs	2×10^{18}

n^+(Si-Doped) GaAs Substrate

FIG. 1. Schematics of *p-i*(MQW)-*n* diodes grown (a) with and (b) without an intermediate composition $In_xGa_{1-x}As$ buffer layer.

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up to a total MQW thickness of 2 μm were grown for the present study. Some of the structures had an intermediate composition buffer layer between the substrate and the MQW, with an average composition $\bar{x}$ given by

$$\bar{x} = xL_z/(L_b + L_z)\,, \tag{1}$$

where x represents the In composition in the well region of the strained MQW under study. The different structures are schematically shown in Fig. 1. It should also be noted from the figure that "smoothening" superlattices were incorporated in the buffer region. These were either GaAs/AlGaAs or strained InGaAs/GaAs. In the latter case, the average composition was made identical to that of the intermediate composition buffer. Growth was interrupted for 1 min while the temperature was reduced to 550 °C for growth of the active quantum wells, after the growth of GaAs or GaAs/AlGaAs SL buffer layers. In addition there was a 5-s interruption after each $In_xGa_{1-x}As$ well of the MQW structures in order to smoothen the growth front.

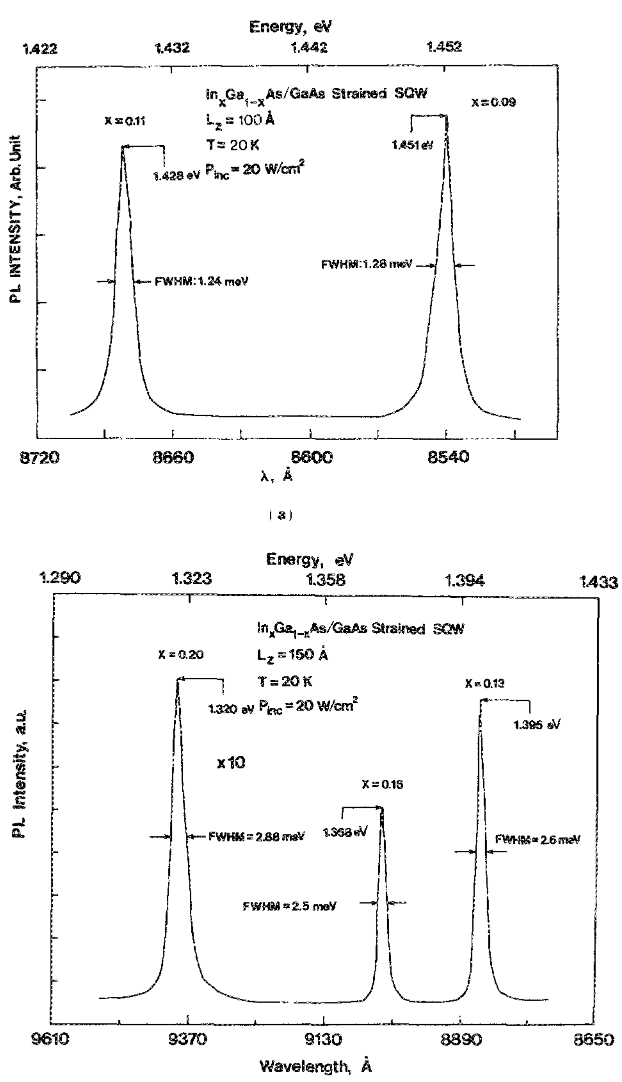

FIG. 2. Low-temperature photoluminescence spectra of $In_xGa_{1-x}As$/GaAs strained SQW having (a) $L_z = 100$ Å and (b) $L_z = 150$ Å obtained with 5145-Å excitation. In both cases, the well with the highest indium content was grown first, followed by wells with smaller x. The barriers in between the wells are ~ 0.45 μm.

Low-temperature (8 K) photoluminescence and absorption measurements were made with a 1-m Jarell–Ash spectrometer to ascertain the optical quality of the quantum wells. The PL spectra from the single quantum wells are shown in Figs. 2(a) and 2(b). The spectra are very sharp and excitonic in nature. There are several important aspects in the data of Fig. 2. The linewidths, which are the narrowest observed for the compositions and well widths indicated, approach those measured in high-quality GaAs/AlGaAs quantum wells,[3] and are almost a factor of 3 lower than that measured previously in identical structures.[4–6] We believe that the dramatic improvement in the optical quality results from (i) source and system preparation and purity, and (ii) the growth technique. With respect to the latter, the important factors are the incorporation of adequate buffers to trap impurities and dislocations, and smoothening of the growth front with an ideal growth rate and growth temperature.

An anomalous feature in the SQW data is a relatively narrower linewidth in wells of the same size but with a higher In content. Since by altering the growth conditions, we can grow near equilibrium or far from equilibrium with MBE, we can study the effect of strain on growth modes. Theoretical and experimental studies have been carried out by us in order to understand the initial stages of growth of InGaAs on GaAs.[7] From a thermodynamic standpoint, as strain increases, the free-energy minimum surface of the epilayer will not be atomically flat, as in the case of lattice matched heterostructures, but will be three dimensional in form, for misfits higher than 2%. Since in the sequence of growth the wells with higher In content were grown first, a plausible explanation may be that any form of three-dimensional growth initiated in the first well propagates and affects the interfaces of the subsequent wells, with smaller In content, in spite of the large barriers in between. This also explains the data of Fig.

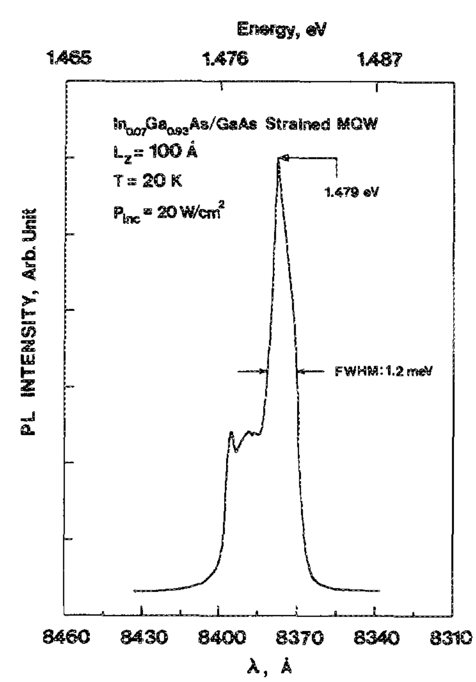

FIG. 3. Low-temperature excitonic photoluminescence spectrum measured in a strained $In_{0.07}Ga_{0.93}As$/GaAs MQW sample (15 periods) with $L_z = 100$ Å and $L_b = 250$ Å.

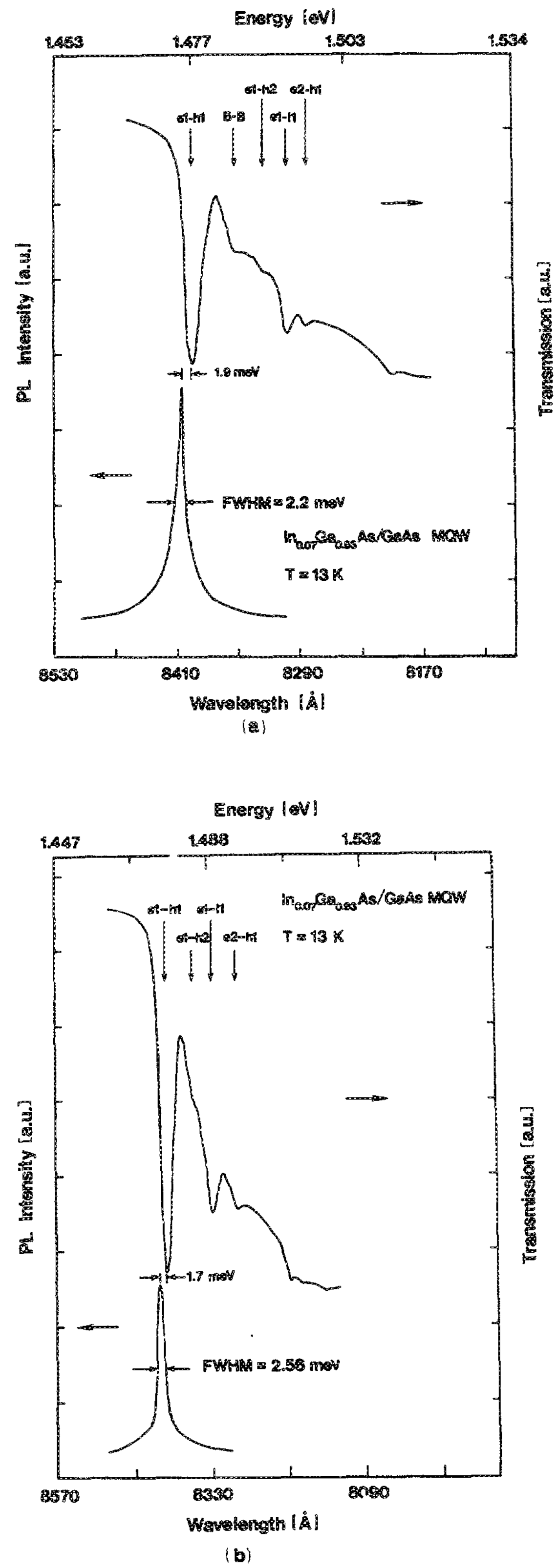

FIG. 4. Low-temperature photoluminescence and absorption spectra of p^+:GaAs-i:$In_{0.07}Ga_{0.93}As$/GaAs MQW (2 μm)-n^+:GaAs structures grown (a) directly on GaAs, and (b) on intermediate composition $In_{\bar{x}}Ga_{1-\bar{x}}As$ buffer layer. The different identified excitonic transitions in the absorption spectra are labeled. B-B in (b) represents band-to-band recombination.

2(b), where the first well with $x = 0.20$ degrades the optical quality of the two subsequent wells. The composition of the ternary wells are derived from the peak energy positions using a square-well model which takes into account the effects of strain.[8]

The PL data from the MQWs are equally impressive. Figure 3 shows low-temperature PL data of an MQW sample consisting of 15 periods of $In_{0.07}Ga_{0.93}As$ (100 Å) wells and GaAs (250 Å) barriers. The strained MQW was grown without an intermediate composition buffer. Again, the linewidth of the main excitonic peak is comparable to that of GaAs/AlGaAs for the same well size. The additional peaks at lower energies may, in part, be due to impurity or defect related bound excitons.

Figures 4(a) and 4(b) show low-temperature PL spectra from p-i-n modulator structures with 2-μm i-MQW regions. The linewidths for the two samples, grown with and without intermediate composition buffers are almost identical and so are the peak intensities. Low-temperature absorption spectra for the same two samples, in which the light- and heavy-hole (LH and HH) excitonic transitions are very well resolved, are also shown in the same figures. These results indicate that as far as optical properties are concerned, the incorporation of a buffer layer has little impact. The growth kinetics and growth modes play a more important role.

Finally, we make some observations regarding the surface morphology. The morphology of the SQW structures was featureless. In the MQW samples we observed a very slight cross-hatch pattern. There are important differences between the MQW with and without intermediate composition buffer layers. In the former, dislocations are generated in the buffer layer and the MQW is freestanding. In the latter, the dislocations are generated in the MQW. In both cases, these dislocations propagate with growth. Our results indicate that the optical properties of both types of samples were comparable. Detailed transmission electron microscopy (TEM) is under way to characterize the behavior of threading and misfit dislocations in these samples.

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