Photoluminescence excitation spectroscopy of as-grown and chemically released $In_{0.05}Ga_{0.95}As/GaAs$ quantum wells

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Chemically released and as-grown $In_{0.05}Ga_{0.95}As/GaAs$ single quantum wells were studied with use of low-temperature photoluminescence and photoluminescence excitation spectroscopy. The good quality of the lifted material allowed excellent excitation spectra to be observed, with both allowed and forbidden transitions being evident. The small strains induced in the chemically released layers allowed light-hole- and heavy-hole-related transitions to be easily differentiated. In addition, the layer thicknesses in the chemically released films were inferred from optical-transmission measurements and growth rates. The conduction-band offset ratio was thereby determined to be 0.57±0.05 for these quantum wells, with the light holes being borderline between type-I and type-II alignment.

I. INTRODUCTION

The recently developed technique of preferentially etching and chemically releasing epitaxially grown layers[1–3] has been demonstrated to have much potential in device applications[3,4] and in the study of the physical properties of epilayer materials.[5,6] This paper describes photoluminescence (PL) and photoluminescence excitation (PLE) measurements made on $In_{0.05}Ga_{0.95}As/GaAs$ single quantum wells (QW's), some of which have been chemically released and bonded to quartz or sapphire substrates. Small strains are induced in the released layers at temperatures other than room temperature due to the different thermal expansion of the epilayer and substrate material.[5] This novel feature of chemically released films is used to unambiguously identify the light- and heavy-hole-related transitions in the PLE spectra.

In using optical techniques to characterize QW's and superlattices, it is important to distinguish heavy-hole- and light-hole-related features. It is generally not possible to unambiguously assign spectral features solely on the basis of a theoretical model, and some independent measure is required. In the $In_xGa_{1-x}As/GaAs$ system, this has been achieved in the past by exploiting the spin-induced polarization differences between the light- and heavy-hole bands,[7] either in absorption,[8] luminescence,[9] PLE (Refs. 10 and 11) or photoreflectance[12] (PR) spectra. The application of strain, using a diamond anvil cell has also been utilized to study $In_xGa_{1-x}As/GaAs$ quantum wells.[13,14] We present here a much simpler technique whereby we exploit the presence of small strains induced in chemically released films to determine the nature of the observed QW transitions. The light-hole transitions are shifted much faster as a function of the strain, making identification of these transitions straightforward.

Because of recent controversy surrounding the $In_xGa_{1-x}As/GaAs$ band offset,[9–12,15–22] especially at low In concentration, we chose to study QW's with only 5% indium in the well layer. The total QW depth ΔE_T (equal to the sum of the conduction-band offset ΔE_c and the valence-band offset ΔE_v) is only $\sim$ 60 meV in this case, so it is important to determine the QW excited-state transition energies accurately. For this reason, the samples were studied using low-temperature PLE. The QW thickness was determined very accurately using the sample growth times and the total film thickness, which is determined by optical transmission. Both allowed and forbidden transitions were observed. The conduction-band offset ratio $Q_c = \Delta E_c/\Delta E_T$, was found to be 0.57±0.05, with the light-hole transitions being borderline between type I and type II in nature. That is, the light holes are either weakly bound in the $In_xGa_{1-x}As$ layer, or just unbound.

II. EXPERIMENTAL

Five $In_xGa_{1-x}As/GaAs$ single-QW samples were prepared. They were grown by molecular-beam epitaxy on (100)-oriented, undoped semi-insulating GaAs substrates. The sample for chemical release consisted of a 0.25-μm GaAs buffer layer followed by a 500-Å AlAs release layer, then 0.5-μm GaAs, 180-Å $In_{0.05}Ga_{0.95}As$ and a further 0.5-μm GaAs. The remaining four samples consisted of a 0.25-μm GaAs buffer layer, a layer of $In_{0.05}Ga_{0.95}As$ of thickness d, and a 500-Å capping layer of GaAs. The well thickness d was nominally 160, 140, 100, and 70 Å for the four samples. The substrate temperature was 530 °C for the $In_xGa_{1-x}As$ layers and the 500-Å GaAs capping layers and 600 °C for all other layers.

The details of the chemical release technique have been described elsewhere,[6] and will only be outlined here. After the growth, two 5 mm × 5 mm squares were cleaved from the sample grown for liftoff. These were coated with

"Apiezon W" wax, and the AlAs layer was selectively removed using a 10% HF etch at a temperature a few degrees below 0 °C. One of the lifted-off layers was then bonded to a quartz substrate (sample No. 2) using uv-cured Norland optical adhesive number 81, and the other was "van der Walls bonded" to sapphire (sample No. 3). Finally, the wax was removed with trichloroethylene.

For the PL and PLE measurements, the samples were cooled in a closed-cycle, variable-temperature helium cryostat, generally to 9 K. The excitation source was either a He-Ne laser (633 nm) or an Ar^+-ion-pumped Ti:sapphire tunable laser. Incident powers varied from about 1 to 10 mW (0.1–1 W/cm^2). The luminescence was dispersed by a 0.75-m Spex monochromator, or a 1-m Chromatix monochromator, and detected with either a Si *p-i-n* detector or a GaAs photomultiplier tube, using a synchronous detection technique. Room-temperature transmission measurements of one of the lifted films were performed using a tungsten lamp, a monochromator, and the Si detector. PR measurements were also carried out, again at room temperature using a similar setup, with the He-Ne laser as a pump.

III. PRELIMINARY ANALYSIS

An accurate determination of the QW thickness of sample No. 2 was made by measuring the transmission of the film beyond the GaAs band edge. The refractive index of the $In_xGa_{1-x}As$ layer is virtually the same as that for GaAs (since the In content is so low), so the resulting interference fringes are determined by the total thickness of the lifted film. Using known values for the GaAs refractive index,[23] this thickness was found to be 1.055±0.008 μm. The individual $In_xGa_{1-x}As$ and GaAs layer thicknesses h_x and h_0 can be related to the respective growth times t_x (=64 sec) and t_0 (=1912 sec), and the perpendicular lattice constants $a_x^\perp$ and $a_0^\perp$ ($=a_{\rm GaAs}$) of the layers via[24]

$$\frac{h_x}{h_0}=\frac{t_x}{t_0}\frac{a_x^\perp}{a_{\rm GaAs}(1-x)}\ , \qquad (1)$$

where x is the indium fraction of the $In_xGa_{1-x}As$ layer. Since $2h_0+h_x=1.055$, the thicknesses can be found if the x fraction is known. Even allowing this x fraction to vary from 4.5% to 5.5%, the QW layer thickness is determined very accurately by this process. The resulting thickness of 184±4 Å is very close to the target thickness.

The critical thickness for epitaxial growth of $In_xGa_{1-x}As$ on GaAs has not been exceeded in these samples, so the $In_xGa_{1-x}As$ layers are (biaxially) compressively strained to match the GaAs, which is unstrained. Since the total GaAs thickness in the lifted films is much larger than the $In_xGa_{1-x}As$ layer thickness, the GaAs remains unstrained after liftoff (at room temperature) and the strain in the $In_xGa_{1-x}As$ layer remains constant. PR measurements confirmed there was no energy shift of the GaAs or the QW band gaps between the lifted and unlifted samples at room temperature. At low temperatures, however, the different thermal expansion of the epilayer and the substrate of the lifted films induces a small biaxial tension, $\Delta\epsilon$, in the films. This tension can be estimated from the thermal expansion of the materials involved,[5,6] to be $\sim 3\times10^{-4}$ for sample No. 3 and 10^{-3} for No. 2, however, in the experimental arrangement used, the substrates were constrained by the aluminium sample holder, and so the observed strain appears to be a few percent smaller than the above estimates. The GaAs layers in the lifted samples are hence under a small tensile strain, and the $In_xGa_{1-x}As$ layers are under a smaller compressive strain than before liftoff. Since we are interested in determining the effects of liftoff on the transition energies, we will describe this situation by saying that both layers (GaAs and $In_xGa_{1-x}As$) are under a small (positive) biaxial tension $\Delta\epsilon$ relative to the corresponding unlifted layer.

This thermally induced tensile strain shifts the electron–to–heavy-hole band gap by an amount $\delta E_H-\delta E_U$, and the electron–to–light-hole band gap by $\delta E_H+\delta E_U$, where

$$\delta E_H=2a\left(\frac{C_{11}-C_{12}}{C_{11}}\right)\Delta\epsilon \qquad (2)$$

and

$$\delta E_U=b\left(\frac{C_{11}+2C_{12}}{C_{12}}\right)\Delta\epsilon. \qquad (3)$$

C_{11} and C_{12} are the elastic constants and a and b are the hydrostatic and uniaxial deformation potentials, respectively (the biaxial strain is analyzed into a hydrostatic and a uniaxial contribution). The hydrostatic contribution δE_H shifts the transitions to lower energy and the (smaller) uniaxial component δE_U additionally shifts the electron–to–light- (heavy-) hole transitions to lower (higher) energy. Now the deformation potentials and elastic constants for the $In_xGa_{1-x}As$ layer are very close to those for GaAs, since the In fraction is small. Hence, to a first approximation, these hydrostatic and uniaxial shifts will be identical for the two layers. For the GaAs layer, where the light- and heavy-hole band gaps are initially degenerate, the strain causes a splitting of the light and heavy holes by an amount $2\,\delta E_U$, as previously reported for GaAs thin films.[5,6] For the QW layer, the strain causes the light-hole band to shift to a higher energy relative to the heavy-hole band also by $2\,\delta E_U$. Thus if the electron–to–light-hole transitions are type I, then ignoring perhaps a small change in the quantum confinement energy, these transitions will also shift down in energy, relative to the heavy-hole transitions, by $2\,\delta E_U$. Again, if they are type-II transitions, we expect them to move to lower energy by the same amount. Therefore, it is a very simple task to identify the light- and heavy-hole-related transitions using the liftoff samples.

IV. RESULTS AND DISCUSSION

Figure 1 shows PLE spectra, taken at 9 K, of the 180-Å sample before liftoff (sample No. 1), and the lifted samples, No. 2 and No. 3. PL (at 9 K) is also shown for sample No. 1, and consists of a strong peak at 1.463 eV, and a weaker peak 6 meV higher in energy. Similar PL was observed from the other samples, and no Stokes shift between the PL and PLE peaks was found for any of the samples. The stronger PL peak corresponds to a first electron to first heavy hole transition, $e1$-hh1, and the higher energy PL peak corresponds in energy to a peak in the PLE spectrum of this sample (In this paper, en-hh$m$ denotes the nth electron to mth heavy-hole transition, and en-lh$m$ likewise for light holes). This weaker PL peak was observed to increase in intensity relative to the ground-state luminescence as the temperature increased, and several other higher energy peaks also became visible.[25] The linewidth of the PLE peaks is very narrow, being ~2 meV for the unlifted sample, and ~3 meV for the lifted samples. Thus, the material quality of the films after liftoff is very similar to before. The spectra in this figure are displaced in energy to align the $e1$-hh1 transition for each sample, which occurs at 1.463, 1.462, and 1.459 eV, respectively, for samples No. 1, No. 3, and No. 2. Plotted in this way, the hydrostatic contribution to the strain-induced energy shifts is removed, and heavy-hole-related transitions should all occur at the same energy. Electron-to-light-hole transitions will appear at progressively lower energies as the strain increases.

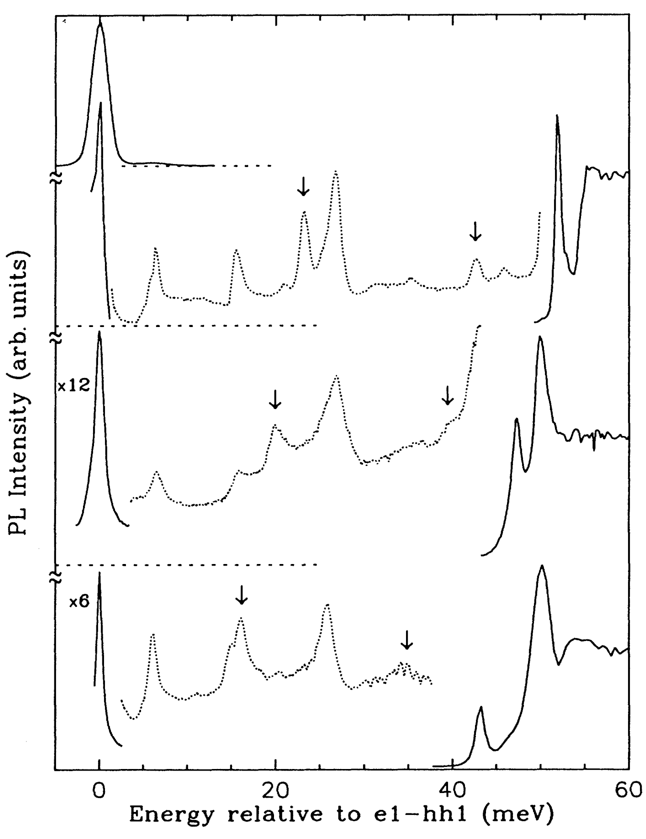

FIG. 1. 9-K PL and PLE spectra of a single 180-Å $In_{0.05}Ga_{0.95}As$/GaAs QW. The top two curves are PL and PLE, respectively, of the as-grown sample. The two lower curves are for the sample mounted on sapphire (No. 3) and quartz (No. 2), respectively. Dotted sections of the PLE curves are magnified approximately 24 times with respect to the GaAs peaks on the right-hand side. The lowest energy peaks ($e1$-hh1) are magnified as indicated. The arrows show the position of the light-hole-related peaks as a function of the strain.

The strong peaks above ~40 meV correspond to GaAs transitions.[5,6] For sample No. 1, only one such peak is observed, whereas for the lifted samples, two GaAs-related peaks can be seen, the peak at higher (lower) energy being due to the strain-split heavy- (light-) hole transition. Note that the highest energy peaks in each case are roughly coincident in energy, since they are electron-to-heavy-hole transitions. The small relative energy shifts are due to slight differences (inhomogeneities) in the indium fraction or well width of the samples. The weaker peaks correspond to QW transitions. It can be seen that, to a good approximation, most of these peaks align in energy, with fairly strong peaks at ~6, 16, and 27 meV being observed from each sample. These peaks are therefore identified as electron-to-heavy-hole transitions. The two peaks marked with vertical arrows clearly shift to lower energy (relative to the heavy-hole transitions) as the strain in the samples increases and therefore are identified as electron-to-light-hole transitions.

Having identified the light- and heavy-hole transitions, and having an accurate measure of the quantum-well width, we can identify the individual peaks by fitting the observed energies to an envelope function model.[9,26] The relative intensity of the transitions can also be used as confirmation that our assignment is reasonable, as described later. We concentrate on the unlifted sample No. 1, since this sample yielded a spectrum with narrower, more clearly resolved peaks than the lifted samples. Initially, a finite square-well potential is assumed, and the material parameters used are shown in Table I. Nonparabolicity of the electron effective mass was ignored because of the shallow well being studied. The unstrained $In_xGa_{1-x}As$ band gap is taken as $E_{GaAs} - 1.5387x + 0.475x^2$ (Ref. 27), where the GaAs band gap E_{GaAs} is determined by adding a bulk exciton energy to the observed excitonic peak. The QW exciton binding energy is taken as 6.5 meV (Ref. 28), and is assumed to be the same for all the transitions. This assumption is discussed later. The band offset ratio Q_c is allowed to vary in fitting the observed transitions. Figure 2 shows the calculated energies (relative to $e1$-hh1) as a function of Q_c. The observed, allowed ($\Delta m = 0, \pm 2, \ldots$) transitions are shown as vertical lines, and dashed lines correspond to electron-to-light-hole transitions. The $e1$-hh2 transition is also shown since it is quite strong in this spectrum even though it is forbidden. The In fraction is chosen at each value of Q_c such that the calculated position of the $e1$-hh1 transition matches correctly to the observed value. The range of x is 4.9–5.1 %.

Clearly, $Q_c = 0.57$ provides an excellent fit to the observed transition energies, with all the peaks fitted to within 0.5 meV, except for the highest energy peak $e2$-hh4. The total QW depth ΔE_T is found to be 59.6±0.5 meV. It should be noted that for Q_c above ~0.5,

TABLE I. Various parameters used in the calculation of the QW energy levels. They are taken from Ref. 27, except the GaAs deformation potentials (indicated by †), which are from Ref. 5.

	a (eV)	b (eV)	C_{11} (10^{11} dyn/cm^2)	C_{12} (10^{11} dyn/cm^2)	m_e^*	m_{hh}^*	m_{lh}^*
GaAs	$-8.5^{\dagger}$	$-1.92^{\dagger}$	11.88	5.38	0.0665	0.34	0.094
InAs	-5.9	-1.8	8.33	4.53	0.023	0.34	0.032

the fourth heavy-hole level is not bounded in the well, so the discrepancy in the fit here may arise from the simple model used to calculate this resonance level. The allowed transitions can be seen to be the strongest in intensity, with the forbidden transitions generally being quite weak. An exception, as mentioned previously, is the $e1$-hh2 transition. The unexpected strength of this transition is probably due to its being coincident in energy with the $e1$-hh1 continuum. The observation of forbidden transitions in the spectra of this sample indicates that the QW potential is not symmetrical. This may be due to In fluctuations or gradations in the well, or to the presence of an electric field across the well.[29] The effect of this uncertainty in the exact potential profile is discussed later. It is obvious from Fig. 2 that the correct identification of light- and heavy-hole peaks is essential if one is to attempt a fit of this kind. For example, if the $e2$-hh2 and $e1$-lh1 peaks were confused, a satisfactory fit could be obtained with $Q_c \sim 0.4$.

We consider now the uncertainties in the calculation of the band offset, looking first at the electron-to-heavy-hole transitions. First, as mentioned above, there is some uncertainty as to the potential profile of the QW. The above calculation assumes a finite square potential for which the forbidden transitions will have zero overlap and hence not be observed. The relative intensity of the forbidden transitions are small compared to the allowed transitions, however, so the square-well approximation will be quite good. The model used to calculate the well energy levels itself contains several approximations which introduce inaccuracy into the calculated levels,[16] and there are uncertainties in the values of the input parameters. Most important of these are the effective masses and well width, but the deformation potentials and the In fraction must also be known. In this study, the well width has been accurately determined, and the appropriate effective masses are known to good accuracy, since these are well known for GaAs (Ref. 27) and our In fraction is small. Nevertheless, taking into account all the possible error sources mentioned here, the uncertainty in the theoretical energies is as much as a few meV for the higher-lying levels. The experimental accuracy in determining the exciton positions is very good, the relative energy positions being known to ± 0.2 meV; however the band offset ratio is not found to high accuracy just using the heavy-hole transitions. The uncertainty in Q_c is about ± 0.1.

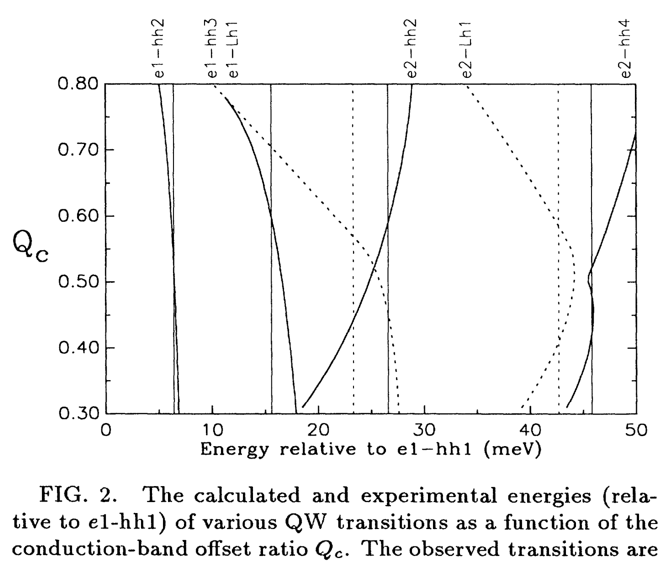

FIG. 2. The calculated and experimental energies (relative to $e1$-hh1) of various QW transitions as a function of the conduction-band offset ratio Q_c. The observed transitions are shown as vertical lines, the dashed vertical lines corresponding to transitions that have been shown to be light hole in origin (Fig. 1). The dashed curves correspond to calculated energies of electron-to-light-hole transitions.

Yet another approximation made above is the assumption that the exciton binding energies of all the transitions are equal. The observation of all the possible transitions between the two electron and the four heavy-hole levels allows this to be checked. For example, under this assumption, the energy difference between the observed positions of the $e2$-hh1 and the $e1$-hh1 transitions, $E_{e2\text{-hh1}} - E_{e1\text{-hh1}}$, should be the same as $E_{e2\text{-hh2}} - E_{e1\text{-hh2}}$, being equal to ΔE_{12}^e, the intersubband energy difference between the first and second electron levels in the quantum well. We find values, however, of 21.0 and 20.2 meV, respectively. This discrepancy may be due to band-mixing effects, but it can be adequately explained simply by allowing for a different exciton binding energy for the different transitions. In terms of this explanation, we can write

$$E_{e2\text{-hh1}} - E_{e1\text{-hh1}} = \Delta E_{12}^e - X_{21} + X_{11} = 21.0 \text{ meV} , \tag{4}$$

$$E_{e2\text{-hh2}} - E_{e1\text{-hh2}} = \Delta E_{12}^e - X_{22} + X_{12} = 20.2 \text{ meV} , \tag{5}$$

where X_{nm} is the exciton binding energy of the nth electron to mth heavy-hole exciton. Hence,

$$(X_{11} + X_{22}) - (X_{12} + X_{21}) = 0.8 \text{ meV}. \tag{6}$$

One expects X_{nm} to reduce as n or m increases, since the respective wave functions spread out and so the exciton potential energy decreases. This energy goes as the inverse square of the effective radius of the electron-hole pair, which implies, qualitatively, that the left-hand side of Eq. (6) will be positive. Comparing this result with calculations of the exciton binding energy for various electron–to–heavy-hole transitions in $GaAs/Al_xGa_{1-x}As$ QW's,[26] good qualitative agreement is again found. Thus variation in the exciton binding energy appears to account for the observed effect, although this question is under further investigation.[30] Lack of a quantitative explanation for this effect contributes a further significant uncertainty to the above estimate of Q_c.

The electron–to–light-hole transitions, especially the e1-lh1 transition, allow a much more accurate estimate of the band offset to be made. As shown in Fig. 3, the $In_xGa_{1-x}As$ potential will form either a well (type I) or a barrier (type II) for the light holes, depending on the relative magnitude of the (heavy-hole) valence-band offset ΔE_v and the strain-induced splitting of the light-hole and heavy-hole bands $S_{\text{lh-hh}}$. Similarly to Eq. (3), this splitting depends on the uniaxial deformation potential, the elastic constants of the well layer, and the strain in the layer. The latter is determined by the x fraction of the well, assuming coherent epitaxial growth. Uncertainty in the value of this strain is dominated generally by uncertainty in this x fraction, and in the value of the deformation potential b. Recent measurements[5] determine b to be -1.92 ± 0.04 eV for GaAs, very close to the value for InAs (see Table I). The splitting $S_{\text{lh-hh}}$ is thus determined for this sample to be 25.5 ± 0.5 meV. The energy of the lowest heavy-hole level, E_{hh1}, is almost independent of the valence-band depth, and has the value 2.2 ± 0.1 meV. The observed energy difference between the e1-hh1 and the e1-lh1 transitions is 23.3 ± 0.2 meV, which leads to a band alignment in which the light-hole band is completely flat — borderline between type-I and type-II behavior. This situation corresponds to $\Delta E_v = 25.5$ meV, and $Q_c = 0.57$. We now consider the uncertainties associated with this value. To the small uncertainties quoted above, one must add a further error to account for the difference in the e1-hh1 and e1-lh1 exciton binding energies. The light-hole binding energy should be somewhat larger than that for the heavy-hole transitions, due to the larger reduced mass of the light-hole exciton,[26] but the large spatial extent of the light-hole wave function will reduce this energy, making the actual value difficult to predict. We expect the e1-lh1 binding energy to lie somewhere between about 4.2 meV—a bulk GaAs exciton binding energy—and 7.5 meV. The latter value is based on the observation that the light-hole exciton binding energy is $\sim$1 meV larger than the heavy-hole one in a wide ($>$ 50 Å) $GaAs/Al_xGa_{1-x}As$ QW.[26] This range in the exciton binding energy leads to a range in ΔE_v spanning from 23 meV (light holes are type II, barrier $\approx$ 2.5 meV) to 28 meV (light holes are type I, well $\approx$ 2.5 meV). Q_c lies in the range 0.52–0.62.

As a further test on the band offset thus determined, four samples grown under identical conditions but with different well widths were studied using PL and PLE. The PLE spectra are shown in Fig. 4. All samples showed

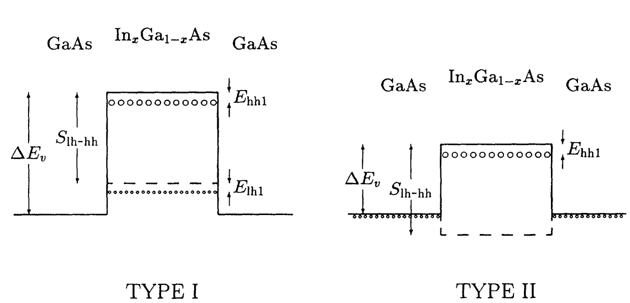

FIG. 3. Alternative valence-band alignments for an $In_xGa_{1-x}As/GaAs$ QW. ΔE_v is the heavy-hole valence-band offset, $S_{\text{lh-hh}}$ is the strain-induced light-hole–heavy-hole band splitting, and E_{hh1} (E_{lh1}) is the energy of the first heavy-hole (light-hole) level. The type of band alignment depends on the relative magnitude of ΔE_v and $S_{\text{lh-hh}}$.

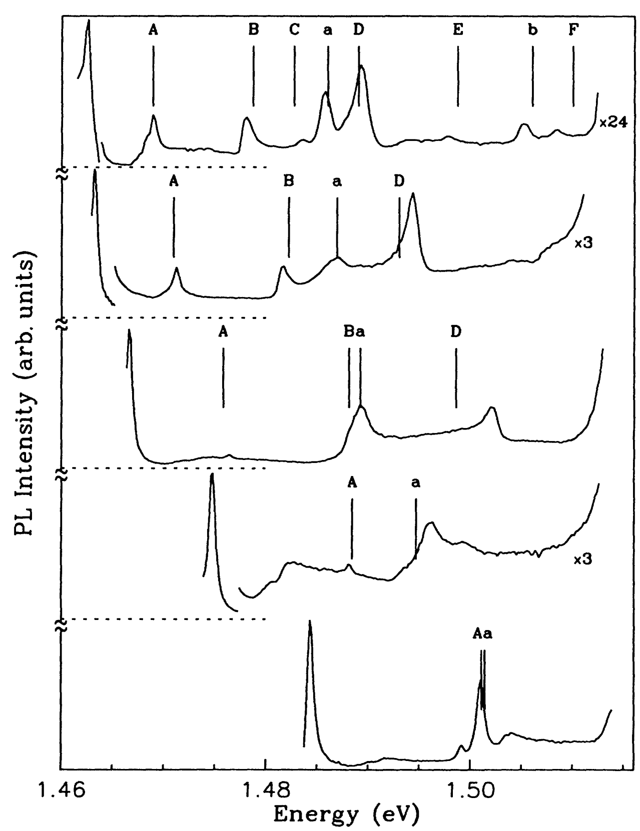

FIG. 4. 9-K PLE spectra of five different $In_{0.05}Ga_{0.95}As/GaAs$ QW's. The wells widths, from the uppermost spectrum down, are 184, 164, 143, 102, and 72 Å, respectively. The vertical lines mark the calculated position of various transitions, assuming a conduction-band offset ratio Q_c of 0.57. The letters above these lines identify the transitions, as follows: A, e1-hh2; B, e1-hh3; C, e2-hh1; D, e2-hh2; E, e2-hh3; F, e2-hh4; a, e1-lh1; b, e2-lh1.

a small (< 1 meV) Stokes shift between the PL and PLE peak positions. The samples are all fitted with a conduction-band offset ratio of $Q_c = 0.57$, and the well width was taken as the target thickness from the sample growth, d, multiplied by the ratio 184/180, since the well targeted to be 180 Å had a well width of 184 Å. The x fraction was allowed to vary slightly (from 4.9% to 5.2%) between samples. The exciton binding energy was taken as 6.5 meV for all the transitions. Agreement of the model fit to the observed data is very good, with all the light-hole peaks being fitted to within ~ 1 meV, and heavy-hole transitions being accurate to within ~ 3 meV, in agreement with the magnitude of the uncertainty in our simple model. Of course, for these samples, we have not independently identified the electron–to–heavy-hole and light-hole transitions, but the small width difference between samples allows the movement of the various peaks to be tracked, since they have been clearly identified in the first sample.

Previously we reported a band offset ratio of $Q_c = 0.36\pm0.12$ for an $In_{0.04}Ga_{0.96}As/GaAs$ QW.[9] This result was based on what appears to be an incorrect assignment of the observed transitions. In obtaining the present result, we have unambiguously determined all the electron–to–heavy-hole and electron–to–light-hole transition energies in a number of QW's of well-known thicknesses, and have thus accurately determined the band offset as $Q_c = 0.57\pm0.05$. Several groups have suggested[9,12,19–21] that Q_c may be x dependent for this system, while others[11,15–18] find a constant ratio. There is perhaps general agreement that a conduction-band offset ratio of ~ 0.6—0.7 is appropriate for In compositions above about 10%, however reported values at lower x fractions vary from 0.4 (Ref. 22) to 0.83 (Ref. 17). Therefore, the question of whether the band offset ratio is constant or varying is really just a question of what the ratio is at low x fraction. The results of this study suggest a value intermediate between these two extremes.

In conclusion, a method for applying small strains to QW layers by chemically releasing them from their as-grown substrates and bonding them to different substrates has been demonstrated. The samples were studied using low-temperature PLE spectroscopy, and both allowed and forbidden transitions were observed. The use of chemically released samples provides a straightforward method of unambiguously identifying the light- and heavy-hole-related transitions in the PLE spectra, and allows the layer thicknesses to be easily found. The band offset ratio is determined from these measurements to be 0.57 ± 0.05 for these $In_{0.05}Ga_{0.95}As/GaAs$ QW's.

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