Photoluminescence and photoconductivity measurements on band-edge offsets in strained molecular-beam-epitaxy-grown $In_xGa_{1-x}As/GaAs$ quantum wells

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Structure has been observed in the photoluminescence and photoconductivity spectra of $In_xGa_{1-x}As/GaAs$ ($x \leq 1$) strained quantum wells grown by molecular-beam epitaxy onto GaAs(001)-oriented substrates. Features in the spectra at energies larger than the energy gap of $In_xGa_{1-x}As$ are interpreted as the allowed excitonic transitions between electron and hole subbands (including the strain-split-off valence band) in $In_xGa_{1-x}As$. The spectra were analyzed with the conduction-band offset and the energy gap of $In_xGa_{1-x}As$ as adjustable parameters. No strain relaxation in quantum wells with thickness smaller than the critical one was observed. The strain-split-off valence subband in $In_xGa_{1-x}As$ is found to be below the valence band of unstrained GaAs. The ratio of the conduction-band offset to the energy-gap discontinuity was determined to be 0.83 ± 0.06.

I. INTRODUCTION

Recently, considerable interest has developed in semiconductor heterostructures of the lattice-mismatched $In_xGa_{1-x}As/GaAs$ system because of their potential for high speed and optoelectronic device applications. They also provide a convenient system for investigating the physics of strained quantum-well (QW) structures and strained superlattices. The built-in elastic strain in these systems is due to the $\sim 7\%$ lattice mismatch between GaAs and InAs. High-quality strained single- and multiple-QW structures as well as superlattices can be grown by different methods, provided that the thickness of the strained layers are kept small enough to avoid misfit dislocation generation.[1,2] For such layers the lattice mismatch is entirely taken up by elastic strain. The critical thickness, L_c, for dislocation generation has been found to be approximately inversely proportional to the In content and about 200 Å for an $In_{0.15}Ga_{0.85}As$ QW in GaAs.[3,4]

One of the basic parameters characterizing the properties of heterostructures is the ratio of the conduction- to valence-band discontinuity ($\Delta E_c/\Delta E_v$) across the interface. The determination of this quantity is still a difficult and controversial subject. For (AlGa)As/GaAs the offset has been studied intensively since 1974 when Dingle and co-workers[5] found that 85% of the band-gap difference was at the conduction-band edge. Since that several values (down to 55%) have been reported without providing a conclusive result.[6] For the $In_xGa_{1-x}As/GaAs$ system measurements have been reported in a few papers[3,7,8] but the obtained estimates are not very accurate. Therefore we have investigated the photoluminescence (PL) and photoconductivity (PC) of a set of undoped single-QW (SQW) and multiple-QW (MQW) heterostructures in the $In_xGa_{1-x}As/GaAs$ system for x values up to 1. The structures were grown by molecular-beam epitaxy (MBE) and the experimental procedure is described in Sec. II.

In SQW's we have observed the ground state transition in the PL measurements and three allowed transitions in the PC measurements, all at energies larger than the energy gap of the strained QW. These lines correspond to excitonic transitions between the ground states of electrons and $j_z = \pm\frac{3}{2}$ holes, transitions between their first excited states, and transitions between the QW electronic ground state and the strain-split-off $j_z = \pm\frac{1}{2}$ hole subband of the Γ_8 band (Secs. III A and III B). In Sec. III C we analyze the observed transition energies, with the conduction-band offset and the energy gap of strained $In_xGa_{1-x}As$ as adjustable parameters. We have taken into account the change of the hole and electron effective masses due to the strain in the QW as well as the energy dependence of the electron effective mass. Our results show that QW's in $In_xGa_{1-x}As$ layers are present in the conduction band and the upper of the strain-split valence bands. We also found that the $In_xGa_{1-x}As$ valence-band splitting is as expected due to lattice mismatch and therefore no strain relaxation is present in the SQW and MQW structures for thicknesses smaller than the critical one (Sec. III D). The ratio of the conduction-band offset, ΔE_c, to the energy-gap discontinuity across the interface, ΔE_g, is found to be independent of the In content, for $x \leq 0.36$, and equal to $\Delta E_c/\Delta E_g = 0.83 \pm 0.06$ ($= 0.8 \pm 0.1$ for InAs/GaAs).

II. EXPERIMENTAL

Single and multiple $In_xGa_{1-x}As$ QW's in a GaAs matrix were grown by MBE in a Varian MBE-360 system. We used (001)-oriented substrates of semi-insulating GaAs on which a GaAs buffer layer was grown with a thickness of 0.5 μm. The growth temperature was 530–550 °C and the growth rate about 1 μm/h for GaAs and 0.3 μm/h for InAs. Growth and calibration procedures are described in Ref. 4. The top layer of GaAs covering the QW structure is about 500 Å. In the MQW structures the thinnest QW is grown first and the wells

are separated by 200 Å of GaAs. None of the investigated samples was intentionally doped. The estimated concentration of shallow impurities is about 10^{15} cm^{-3}. Sample parameters are shown in Table I.

The photoluminescence experiments were performed at 2, 77, and 300 K with He-Ne laser excitation. The PL of the samples was dispersed by a Jobin-Yvon H-25 grating monochromator (grating, 0.7–1.2 μm; blaze, 1 μm) and detected with an S-1 cathode photomultiplier cooled to liquid-nitrogen temperature. The photoconductivity measurements were carried out using excitation light from a tungsten-halogen projector lamp via the same monochromator. The light beam was chopped at 12.5 Hz and the induced ac photocurrent was amplified and detected by conventional lock-in techniques. The PC experiments were run from 77 to 300 K. No correction of the PC spectra has been made for the spectral variation in source intensity. In all measurements of PL and PC the light propagation was perpendicular to the QW plane (z axis).

Electrical connections to the layers were made by alloying indium at 400 °C, giving good contacts both to the QW's and the buffer layer. The PC measurements exhibited some low-temperature anomalies due to QW capture of electrons excited from impurity centers in the buffer layers of GaAs. This is further discussed in III B.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Photoluminescence of single and multiple quantum wells

Figure 1 represents typical PL spectra recorded at 2 K for a SQW and a MQW (four wells) heterostructure. In the SQW spectrum there is a single strong low-energy line, α, and two very weak lines—BE and D^0A^0—at higher energies. The spectral position of these two weak lines is the same for all investigated samples. They are due to the PL from the thick barrier layers of GaAs and correspond to the well-known emission lines of bound excitons (BE) and neutral donor-acceptor pairs (D^0A^0) in unstrained GaAs. For fixed In content the strong α line moves to higher energies with a reduction of the QW thickness. It is caused by the emission of QW excitons between the electron and hole ($j_z = \pm\frac{3}{2}$) ground states.

The PL spectrum of a MQW structure in Fig. 1(b) shows strong emission lines of the same origin (α transitions) from all QW's with different thickness because the large thickness of the GaAs barriers prevents tunneling of free carriers and excitons into a nearby thicker QW with smaller confinement energy. The intensity of the QW emission, with the thickest layer closest to the surface, monotonically increases with thickness, $L < L_c$. The relative position of the peaks in Fig. 1 is consistent with the width and depth (composition and strain) of the wells and the relative position of them. The α lines have a low-energy tail due to the emission of excitons bound to impurity centers in the QW or localized at potential minima due to inhomogeneity in the In concentration.[9] In accordance with the expected behavior of the emission of localized excitons, the relative intensity of the tail decreased with increased excitation (due to filling of localizing centers) and temperature (due to the thermal excitation of localized excitons). The tail disappears when the temperature is raised to 77 K.

The half-width of the excitonic emission peak and the strength of its tail is usually smaller for thinner QW's. In particular the half-width of the exciton emission peak at 2 K is about 3 meV for the QW's with $L = 30$–40 Å

TABLE I. Sample parameters.

(a) Single QW's

Sample number	x	L (Å)
SQW-1 (1179)	0.16	100
SQW-2 (1180)	0.18	130
SQW-3 (1181)	0.158	150
SQW-4 (1182)	0.165	180
SQW-5 (1177)	0.306	90
SQW-6 (1208)	1	10
SQW-7 (1209)	1	10
SQW-8 (1210)	1	14

(b) Multiple QW's

Sample number	x	L_1 (Å)	L_2 (Å)	L_3 (Å)	L_4 (Å)
MQW-1 (1188)	0.175	160	120	80	40
MQW-2 (1187)	0.187	160	110	70	30
MQW-3 (1199)	0.21	90	50	25	
MQW-4 (1198)	0.073	300	120	80	40
MQW-5 (1207)	0.36	30	20	10	
MQW-6 (1217)	1	10	15		

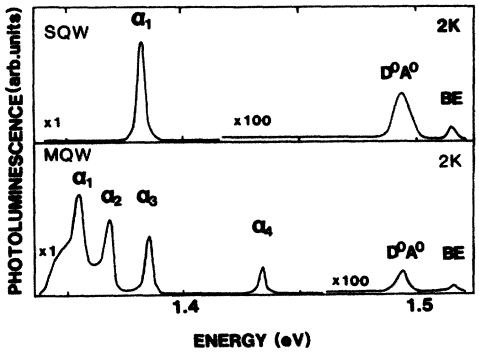

FIG. 1. The photoluminescence spectra of $In_xGa_{1-x}As$ single and multiple quantum wells in a GaAs matrix at 2 K. Sample SQW-3, $L = 150$ Å; sample MQW-1, $L = 160$, 120, 80, and 40 Å.

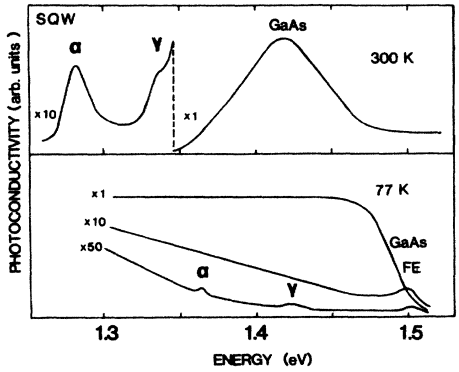

FIG. 2. The photoconductivity spectra of an $In_xGa_{1-x}As$/GaAs sample, SQW-2, at 300 and 77 K. The spectra at 77 K were recorded after 0, 10, and 20 min of white-light illumination.

while it is 3–5 times larger in the case of unstrained bulk $In_xGa_{1-x}As$ layers grown on GaAs under the same conditions. One reason for this is that In inhomogeneities have less influence on the energy gap of strained QW's (the energy gap decreases with x but increases with strain[4]) than in unstrained bulk $In_xGa_{1-x}As$. Note that the variation in well width should lead to an additional broadening of the emission line. The absence of this for $L > 30$ Å shows that the QW width variation in our samples does not exceed one atomic layer.

When the thickness of the $In_xGa_{1-x}As$ layer is very close to the critical one for misfit dislocation generation a large broadening of the exciton emission line has been observed accompanied by a strong decrease in its intensity. The observed critical thickness decreases[4] from ~500 Å for $In_{0.1}Ga_{0.9}As$ to ~16 Å for InAs QW's. These values are well described by the theoretical expression proposed by Matthews and Blakeslee.[1,4]

B. Photoconductivity of single-quantum-well structures

The observed photoresponse is a superposition of the QW and the buffer-layer contributions, since both regions are contacted. At room temperature the bulk response is large in the spectral region of the GaAs exciton absorption as shown in Fig. 2. The long low-energy tail obscures the observation of the QW excitonic transitions between the excited electronic and hole quantum levels. Decreasing the temperature leads initially to a reduction of this tail. However, after cooling to ~120 K a very strong increase in a parasitic photoresponse is observed spreading into the entire spectral region below the energy gap of GaAs (cf. Fig. 2).

We found that this photoresponse can be suppressed with a long additional illumination by white light from a tungsten lamp. The change of the PC spectrum with time is shown in Fig. 2. After some time (0.5–1 h) the PC spectra became reproducible with a well-pronounced structure in the region of the allowed QW excitonic transitions and a weak photoresponse in the spectral region below the QW energy gap. No such behavior has been found in homoepitaxial bulk GaAs grown under similar conditions. Therefore we ascribe this unusual behavior in the PC structures to a change in charge state of the deep levels in the GaAs within the carrier diffusion length from the QW. Indeed, the nonequilibrium carriers excited from these defects (and absorbed by the QW) cannot quickly return at low temperatures, i.e., when $kT \ll \Delta E_c$.

The observed reduction in GaAs photoresponse with time suggests that free carriers are captured by traps which are not excited by light in the spectral region under consideration. The additional illumination strongly stimulates the process of redistributing electrons between such crystal traps. As a result, the bulk photoresponse disappears and the QW photoresponse becomes dominating. A relaxation time of about 5 min is usually needed after white-light excitation in order to get the most pronounced structure in the PC spectra. In contrast to the $Al_xGa_{1-x}As$/GaAs heterostructures,[10] the $In_xGa_{1-x}As$/GaAs ones do not exhibit any appreciable persistent PC. The difference in the conductivity of the samples at 77 K before and after illumination is less than 20%.

The PC spectra recorded at 77 K are shown in Fig. 3 for two samples. The main peak has the same spectral position as the α peak in the PL spectra. In photocon-

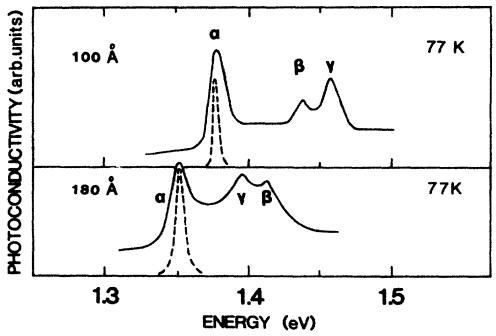

FIG. 3. The photoconductivity spectra of $In_xGa_{1-x}As$/GaAs SQW samples with $L = 100$ Å (SQW-1) and $L = 180$ Å (SQW-4) at 77 K. The dashed lines show the photoluminescence spectra of these samples at the same temperature.

ductivity the position of maximum photoresponse should differ from the free-exciton energy with its dissociation energy (the excitons effectively dissociate at 77 K). Therefore the close spectral position of α lines in the PC and PL spectra supports the interpretation of the PL peak as a free-excitonic transition indicating that excitonic localization effects are small enough to be neglected.

Two additional lines β and Y are at energies smaller than that of the free exciton in GaAs, as shown in Fig. 3. With decreasing QW thickness the Y-peak moves to the high-energy side significantly faster than the main α peak. In addition, it disappears after reaching the position of the GaAs free exciton. This agrees with the expected behavior for an excitonic transition between the excited QW levels belonging to the same conduction and valence bands, as in the case of the α transition. This fact together with the large strength of the peak make us interpret Y as the next allowed transition involving the first excited QW sublevels for electrons and holes as shown in Fig. 4.

The β peak moves to higher energy slightly slower than the α peak when decreasing the width of the QW (at constant composition). Therefore the β peak cannot be associated with the excited sublevels of the electron and hole states responsible for the α transition or transitions involving forbidden selection rules, e.g., $\Delta n \neq 0$. The spectral position of the β peak and the different observed energy shifts suggest that it may be connected with the excitonic transition involving an electron from the QW ground state and a hole from the valence subband split off by strain as proposed by Marzin *et al.*[8]

In biaxially compressed $In_xGa_{1-x}As$ the z component of the hole effective mass is significantly smaller for the split-off ($j_z=\pm\frac{1}{2}$) valence subband than for the $j_z=\pm\frac{3}{2}$ band, as shown in Fig. 4. For this reason the observed decrease in energy difference between the β and α lines, with reduction in L, could indicate a nonconfinement of the holes belonging to the strain-split-off valence subband. Hence the valence-band offset in $In_xGa_{1-x}As$/GaAs heterostructures should be smaller than the strain-induced valence-band splitting, ∂E_v, as shown in Fig. 4.

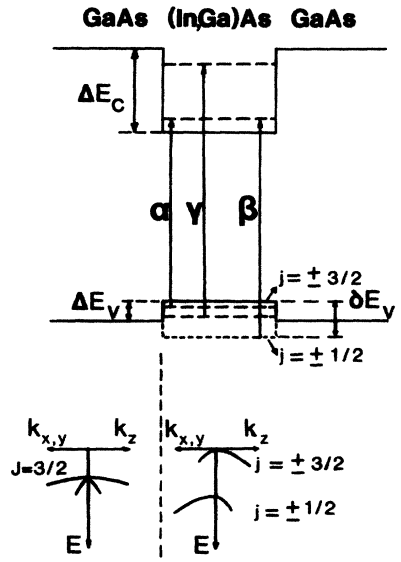

FIG. 4. Energy-band configuration of a strained $In_xGa_{1-x}As$/GaAs QW. In the (In,Ga)As layer the valence band is split into $j_z=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ hole bands with the $E(k)$ dependence as shown. The observed allowed excitonic transitions are shown by arrows.

C. Band-edge offsets

To calculate the energies, E, of the electron and hole sublevels in a QW with width L we have used a standard quantum-mechanical approach. For the one-dimensional case the values of E are determined from the transcendental equation

$$\sin(k_zL)=2\beta/(\beta^2-1)\cos(k_zL)\ , \tag{1}$$

where $k_z=(2m_zE/\hbar^2)^{1/2}$, $\beta=[M_zE/m_z(V-E)]^{1/2}$, V is the QW depth, and m_z and M_z are the z components of the electron (or hole) effective masses in the well and barrier, respectively. It is not possible to accurately calculate the energy gap of a grown $In_xGa_{1-x}As$ QW because of uncertainties in the measured In content and the estimated magnitude of strain. For this reason we use in our calculations the energy-gap offset at the $In_xGa_{1-x}As$/GaAs interface, $\Delta E_g=E_g(\text{GaAs})-E_g(In_xGa_{1-x}As)$, as an adjustable parameter in addition to the discussed one, $\Delta E_c/\Delta E_v$.

There are two possibilities to determine the ratio $\Delta E_c/\Delta E_v$. One can either measure the energies of the main transition for QW's with different thicknesses in MQW structures or measure the energy difference of sublevels involved in a SQW. We have used both these methods to determine the offsets, and because of the minimizing of the relative importance of the band gap of (InGa)As the sensitivity to the parameters used will be optimized. It is a general problem that the combination of simple QW calculations and the relative insensitivity to barrier heights have resulted in a large discrepancy in the determination of the offset for the widely studied (AlGa)As/GaAs heterostructure.[6] Unless more elaborate measurements and calculations are performed we think that our results are useful in designing QW devices. As pointed out by Miller and co-workers[6] all determinations of the band offset have in common an uncertainty because of uncertainties in the value of the parameters used, e.g., the masses.

The effective mass of the electrons in strained $In_xGa_{1-x}As$ and its energy dependence, needed in Eq. (1), have been obtained from Kane's approximation.[11] The strained $In_xGa_{1-x}As$ has a nondegenerate valence band, cf. Fig. 4. In a biaxially compressed $In_xGa_{1-x}As$ layer the heavy m_z component, of the hole effective mass for the ground $j_z=\pm\frac{3}{2}$ valence band, depends weakly on the energy. We therefore neglect this dependence and use the value obtained from a linear extrapolation between the known values of m_z in strained GaAs and InAs [$m_z=(0.36-0.04x)m_0$].[12] The electron and hole effective masses outside the QW layer are those of the unstrained GaAs,[12] namely, $0.066m_0$ and $0.36m_0$.

Figure 5(a) shows the results of comparing experimen-

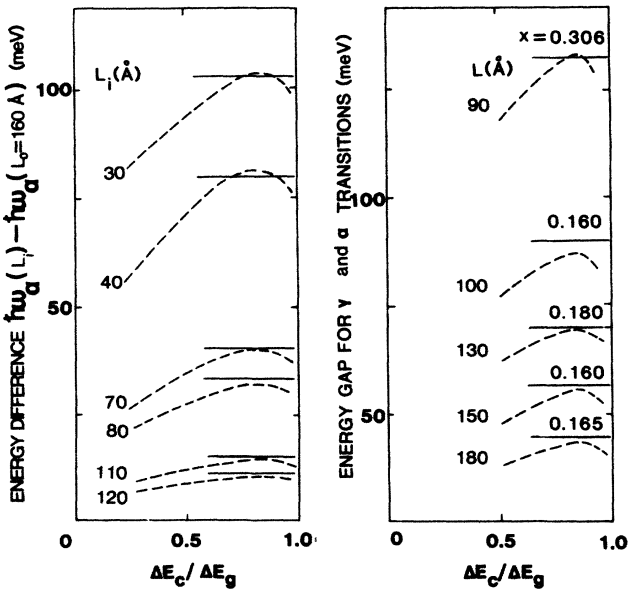

FIG. 5. (a) Comparison of measured energy differences $\hbar\omega_\alpha(L_i)-\hbar\omega_\alpha(L_0)$ (solid lines) for the α transitions in QW's with different widths (samples MQW-2 and MQW-1) and the calculated ones (dotted lines) as a function of $\Delta E_c/\Delta E_g$ for the same QW's. (b) Comparison of measured energy separations (solid lines) for Y and α transitions with calculated ones (dotted lines) as a function of $\Delta E_c/\Delta E_g$.

tal (solid lines) and calculated (dashed lines) energies of the α transition in the MQW structures. The experimental values have been taken from the PL spectra recorded at 2 K, where the emission lines have the smallest half-width. As the observed transitions are all excitonic, the conduction-to-valence QW subband separations were found by adding the appropriate excitonic rydberg to each transition energy. As no experimental or theoretical values of the excitonic rydberg in $In_xGa_{1-x}As$ QW's are available at present, the GaAs QW results[13,14] have been used with correction for the small effective-mass difference of electrons and holes in GaAs and $In_xGa_{1-x}As$: $m_{e,\text{GaAs}}=0.067m_0$, $m_{\text{LH,GaAs}}=0.087m_0$, $m_{\text{HH,GaAs}}=0.36m_0$; $m_{e,\text{InAs}}=0.023m_0$, $m_{\text{LH,InAs}}=0.094m_0$, $m_{\text{HH,InAs}}=0.40m_0$.

The calculated transition energies as a function of $\Delta E_c/\Delta E_g$ were obtained from Eq. (1) in the following way. First we calculate the energy gap of the strained $In_xGa_{1-x}As$ QW's as a function of $\Delta E_c/\Delta E_g$ with $\hbar\omega_\alpha(L_0)$ as a reference energy [$\hbar\omega_\alpha(L_0)$ is the α-transition energy for the largest well in a MQW]. The obtained values of $\Delta E_g=E_g(\text{GaAs})-E_g(In_xGa_{1-x}As)$ were then used to calculate the energies of the α transitions, $\hbar\omega_\alpha(L_i<L_0)$, as a function of $\Delta E_c/\Delta E_g$ for the other QW's. For all QW's the dependencies, $\hbar\omega_\alpha(L_i)-\hbar\omega_\alpha(L_0)$, show similar behavior. The results for two MQW structures are shown in Fig. 5(a) (dashed lines). Evidently the best agreement between experimental and calculated values is for $\Delta E_c/\Delta E_g=0.83\pm0.06$.

Figure 5(b) represents the observed and calculated energy separation between the ground-state (α) and excited-state (Y) transitions for five SQW structures. Experimental energy values were taken from the PC spectra recorded at 77 K. The values of $E_g(In_xGa_{1-x}As)$ as a function of $\Delta E_c/\Delta E_g$ were obtained with the use of α energies as described above. The calculated $(\hbar\omega_Y-\hbar\omega_\alpha)$ values for the SQW's show dependencies on $\Delta E_c/\Delta E_g$ that are similar to the previous data for the MQW's. Again we find the best agreement between measured and calculated values for $\Delta E_c/\Delta E_g\approx0.83$. In order to obtain higher precision in the conduction- and valence-band offsets a more accurate determination of the QW thickness is necessary.

The obtained ratio for $\Delta E_c:\Delta E_v\approx0.83:0.17$ is different from the value recently reported by Marzin *et al.*,[8] $\Delta E_c:\Delta E_v\approx0.7:0.3$. However, these authors used the calculated value E_g (based on the x-ray-measured In content in the $In_xGa_{1-x}As$) for the QW and did not obtain a good fit to the spectral positions of the α and Y lines.

The ratio of the conduction to valence-band discontinuities is nearly independent of the In content in $In_xGa_{1-x}As$ QW's. This is expected for $x<0.4$ because the positions of the conduction and valence bands in the QW are almost linear functions of x (linear dependence on the In content as well as strain connected with lattice mismatch). The x dependence of the alloy band gap $E_g(x)$ is given by the expression[8]

$$E_g(x)=E_g(0)-1.47x+0.375x^2\ \text{eV}\ . \tag{2}$$

The change of the conduction, ∂E_c^s, and valence, ∂E_v^s, band-edge positions due to strain (biaxial compression) of the $In_xGa_{1-x}As$ in the QW along the $\langle 100\rangle$ axis can be written as[15]

$$\partial E_c^s=-a_c e_{A1}\ , \tag{3}$$

$$\partial E_v^s(j_z=\pm\tfrac{3}{2})=-a_v e_{A1}+b_v e_\theta\ , \tag{4}$$

where

$$e_{A1}=e_{xx}+e_{yy}+e_{zz}=2[(C_{11}-C_{12})/C_{11}]\ , \tag{5}$$

$$e_\theta=e_{zz}-\tfrac{1}{2}(e_{xx}+e_{yy})$$
$$=-[(C_{11}+2C_{12})/C_{11}]\ , \tag{6}$$

e_{ij} are components of the strain tensor, and a_c, a_v, and b_v are the hydrostatic and axial deformation potentials [for GaAs, $a_c+a_v=8.4$ eV, $a_v=2.7$ eV, and $b_v=1.7$ eV; for $In_xGa_{1-x}As$, $a_c+a_v=(8.4-2.4x)$ eV (Refs. 12 and 16)], ε $(=e_{xx}=e_{yy})$ is the lattice mismatch (for the GaAs/$In_xGa_{1-x}As$ system $\varepsilon=0.07x$), and finally C_{ij} are the elastic constants [$C_{11}/C_{12}=2.22$ for GaAs (Ref. 12)].

Using Eqs. (1)–(6) and the observed ratio $\Delta E_c/\Delta E_v$ we can calculate the spectral position of excitonic transitions for QW with any thickness and In content. Figure 6 shows that the calculations of $\hbar\omega_\alpha(L)-E_g(\text{GaAs})$ for all investigated MQW structures are in good agreement with the measurements.

The accuracy in the determined $\Delta E_c/\Delta E_v$ ratio strongly decreases in the case of wells with large In content because they have no excited states for electrons or holes at $L<L_c$. Therefore we did not consider the cases

with In content $x > 0.5$ except for $x = 1$ when the uncertainty in the InAs QW energy gap is only due to inaccuracy in the experimental values of the deformation potentials. The critical thickness[4] of InAs in GaAs is as small as 16 Å. The inset in Fig. 6 shows a comparison between the observed α energies for InAs QW's with $L = 10, 14, 15$ Å $< L_c$ and calculated ones for different $\Delta E_c/\Delta E_v$ ratios. The ratio $\Delta E_c/\Delta E_v = 0.8 \pm 0.1$ obtained from Fig. 6 for the InAs/GaAs heterostructure is similar to the value found for $x < 0.4$.

Using Eqs. (2)–(6) allows us to find a relation between $\Delta E_c/\Delta E_g$ both for a hypothetical unstrained GaAs/InAs heterojunction and also for a strained QW. The estimated value of $\Delta E_c/\Delta E_g \approx 0.9$ for the unstrained GaAs/InAs system is in good agreement with earlier results, 0.8–1, obtained by other methods.[17–19]

D. Valence-band split in the $In_xGa_{1-x}As$ quantum well

As was previously discussed the spectral position of the β line in the PC spectra and its dependence on the QW thickness indicates that this line is associated with a transition from the strain-split-off $j_z = \pm\frac{1}{2}$ valence band. Therefore we can use this line to determine the strain-induced splitting of the valence band in a QW and in addition estimate the magnitude of the strain relaxation in the QW. The calculated dependence $\partial E_v(x)$ (on In content) for the $In_xGa_{1-x}As$ QW's in GaAs is shown in Fig. 7. At subcritical thickness for the generation of misfit dislocations it is given by the expression[15]

$$\partial E_v = 1.5 b_v e_\theta + 0.5 \partial_{s.o.} - 0.5[\partial_{s.o.}{}^2 - 2 b_v e_\theta \partial_{s.o.} + 9(b_v e_\theta)^2]^{1/2} . \quad (7)$$

Here $\partial_{s.o.}$ is the spin-orbit splitting. The values of $\partial_{s.o.}$ and b_v were taken from a linear interpolation between the known values for GaAs and InAs, namely, $\partial_{s.o.} = 340 + 50x$ meV and $b_v = 1.7$ eV.[20] The calculated values of ∂E_v are larger than the experimental ones for the valence-band offset. This result is in agreement with the above conclusion that holes involved in the β transition are not well confined. Therefore ∂E_v should be equal to a sum of the confinement energy for the $j_z = \pm\frac{3}{2}$ holes and the difference in energies of the α and β lines. The experimental dependence $\partial E_v(x)$ obtained in this way is shown in Fig. 7. The good agreement between experimental and calculated values, obtained without any adjustable parameters, is taken as evidence for no strain relaxation in our $In_xGa_{1-x}As$-GaAs QW structures.

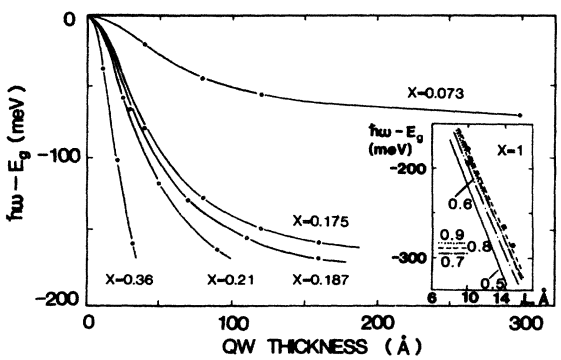

FIG. 6. Comparison of measured and calculated energy positions for α lines in MQW samples; $\Delta E_c/\Delta E_g = 0.83$, solid points correspond to QW's chosen for the determination of ΔE_g. The inset shows the comparison between measured α energies for InAs QW's with $L < L_c$ and calculated ones with different parameters $\Delta E_c/\Delta E_g$ shown at calculated curves.

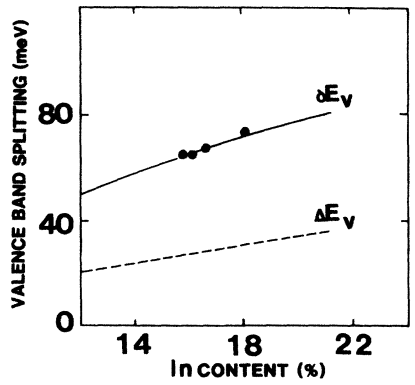

FIG. 7. Comparison of measured (points) and calculated (solid line) $In_xGa_{1-x}As$ QW valence-band splitting induced by lattice-mismatch strain. The $j_z = \pm\frac{3}{2}$ hole band offset is shown by the dotted line.

IV. CONCLUSION

The determination of the conduction- and valence-band offsets for strained $In_xGa_{1-x}As$/GaAs quantum structures, grown on GaAs substrates, is complicated because it is difficult to estimate the energy gap of the $In_xGa_{1-x}As$ QW accurately. There are two reasons for this, namely, the inaccuracy in the In content and the possible relaxation of strain due to dislocation generation. The use of both PL and PC measurements showing the excitonic transitions between the electron and hole subband, including the strain-split-off valence band, allows us to overcome these difficulties. Strain relaxation has been found to be absent in QW's with thickness smaller than the critical one which decreases from about 500 Å for $x = 0.1$ to 17 Å for InAs QW's. In such QW structures with $x < 0.4$ the ratio $\Delta E_c/\Delta E_v$ has been found to be nearly independent of In content and equal to 0.83 ± 0.06. The accuracy in determining the $\Delta E_c/\Delta E_v$ ratio decreases for QW's with larger In content because they have no excited states. For InAs/GaAs QW's $\Delta E_c/\Delta E_v$ is found to be about 0.8. The offsets are in agreement with (AlGa)As/GaAs (Ref. 6) and (AlGa)As/(InGa)As (Ref. 21) heterostructures.

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