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Γ-X mixing in GaAs/$Al_xGa_{1-x}As$ coupled double quantum wells under hydrostatic pressure

J. H. Burnett, H. M. Cheong, and W. Paul
Department of Physics and Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138

E. S. Koteles and B. Elman
GTE Laboratories, Waltham, Massachusetts 02254

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We have investigated the energies of the electronic states of GaAs/$Al_xGa_{1-x}As$ strongly coupled double quantum wells and uncoupled multiple quantum wells as functions of hydrostatic pressure up to 35 kbar. The energies of the quantum-well states at 4 K were determined at each pressure by photoluminescence excitation spectra. The pressure coefficients of the energies of the allowed transitions between the valence-band and conduction-band quantized states of wide (200 Å) uncoupled wells were all equal to the pressure coefficient of the bulk GaAs band gap. For a strongly coupled double quantum well consisting of two 72-Å wells separated by an 18-Å barrier, the energies of the allowed transitions all showed a decrease in their pressure coefficients beginning near 20 kbar. These results are interpreted in terms of a drop in the conduction-band quantum-well confinement energy, due to Γ-X mixing, as the X valleys of the barrier materials are brought nearly equal to the energies of the confined electron states by pressure. An envelope-function-approximation model which includes Γ-X mixing at the interfaces is compared quantitatively with these results and found to be consistent for a certain range of the phenomenological mixing strength of the model.

I. INTRODUCTION

In the usual treatment of electronic energy levels in semiconductor heterostructures, the confined electronic states are assumed to be derived from bulk states of a given symmetry, e.g., for GaAs/$Al_xGa_{1-x}As$ quantum wells (for $x<0.4$) the lowest-energy conduction-band states are assumed to be derived from the Γ-like bulk states near the Γ edges of the constituent materials. With this assumption the other conduction-band relative minima of different symmetry of the component materials, e.g., L or X minima, would give rise to separate sets of noninteracting states, L- and X-confined states, built from bulk states of these symmetries. However, due to the broken periodicity in the growth direction, resulting in the breakdown of $\mathbf{k}$ conservation in this direction, mixing of states of the same energy but different symmetry is allowed; e.g., for a heterostructure grown in the [001] direction, a Γ state may have significant mixing-in of states associated with relative minima along the Δ axes in the [001] and [00$\bar{1}$] directions, if these are close in energy. This is clearly important for heterostructures for which the component bulk materials have conduction-band minima of different symmetry, as in GaAs/$Al_xGa_{1-x}As$ (with $x \gtrsim 0.4$) and Si/Ge heterostructures. However, even if the two component materials have conduction-band minima of the same symmetry, higher-energy relative minima of different symmetry can mix in by virtue of the components of their complex band structures at this energy, the mixing increasing with decreasing energy separation.[1]

Resonant tunneling experiments[2–8] have given evidence for such mixing, but they have been difficult to interpret quantitatively. Particularly vexing has been the fact that the envelope-function method, which has been quite successful in calculating the heterostructure band structures for the case of layers with equivalent band-edge symmetry, has generally been considered not capable of dealing with band-mixing effects.[9] Computational methods such as empirical tight-binding[1] and pseudopotential[10] schemes applied to heterostructures can take band mixing into account naturally, but they are not analytical, do not give the physical feel of envelope-function methods, and are not very accessible to the general researcher for the analysis of a specific experiment. It was only recently that the envelope-function formalism was shown to be capable of handling band-mixing effects, in a formal analysis by Ando and Akera.[11] This formalism was used by Pulsford *et al.*[12] to analyze anticrossing behavior between Γ and X states of a strongly coupled GaAs/AlAs superlattice with the application of a magnetic field. They extracted, within a simplified Bloch-function-mixed envelope-function model, a quantitative measure of the band mixing for this case. Whether this procedure is quantitatively accurate, or even qualitatively valid, is not settled.

The object of this work was to approach the question of band mixing in GaAs/$Al_xGa_{1-x}As$ quantum wells by the technique of using hydrostatic pressure as an external parameter to vary the heterostructure band structures. The rationale for this approach is that the pressure dependences of the bulk band structures of the constituent materials of the heterostructures are known. Since the envelope-function models of heterostructure band structures, including band-mixing effects, use only bulk band-structure parameters, the band offsets, and a few unknown band-mixing coefficients determining the boundary conditions of the envelope functions at the in-

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terfaces, then, assuming the band offsets and their pressure dependences are known, the measured changes under pressure of the heterostructure band structures should determine these band-mixing coefficients quantitatively in a simple model. At the least, these pressure measurements provide a straightforward test of the envelope-function band-mixing models. Specifically, the amount of mixing of the X states into the Γ states is expected, in these models, to vary strongly with their relative energy separations, and the effect of hydrostatic pressure on $Al_xGa_{1-x}As$ is to lower the energy of the X minima with respect to the Γ minimum.

There have been several previous reports of anomalous behavior of the pressure coefficients of the energy levels of narrow quantum wells for pressures approaching the Γ-X crossover pressure, which are not consistent with envelope-function models which neglect Γ-X mixing.[13,14] These results suggest that the simple envelope-function models are inadequate in this regime. Determining whether the extension of the simple envelope-function model to include band mixing resolves this inadequacy requires detailed comparisons of such measurements with these models.

II. EXPERIMENT

The basic idea of the experiment is summed up in Fig. 1. This shows, for a $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well, the positions of the conduction-band Γ and X minima for the well (GaAs) and barrier ($Al_{0.3}Ga_{0.7}As$) materials relative to the well valence-band maximum, as functions of hydrostatic pressure.[15] (For both materials, the minima along the Δ axis are close to but not actually at the X point.[16] We will nevertheless stick with convention and refer to these as X minima.) This figure assumes that the fraction of the band-gap discontinuity in the conduction band is 0.69.[17,18] For other fractions, the band edges are

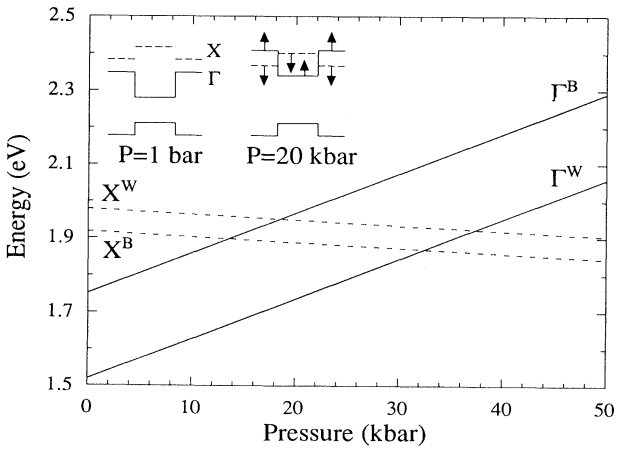

FIG. 1. Relative positions of the conduction-band Γ and X minima of the $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure as functions of hydrostatic pressure, assuming 69% of the band-gap discontinuity is in the conduction band. Energies are measured from the valence-band maximum of GaAs. Solid lines indicate barrier (B) and well (W) Γ minima, and broken lines indicate barrier and well X minima.

shifted relatively. The figure shows that for pressures (P) $\lesssim 10$ kbar a Γ-like electron is confined in the GaAs layer by the Γ barriers of constant height. For $10 < P \lesssim 30$ kbar and X minima of the barrier layers drop below the Γ minimum of these layers and pass through the energies of the confined electron states.

For $P > 30$ kbar the X minima of the $Al_{0.3}Ga_{0.7}As$ layers become the minimum-energy conduction-band states of the system, and the electrons are no longer confined to the GaAs layer. Since the holes are still confined in this layer, this causes a spatial separation of any optically created electrons and holes, with a dramatic reduction in recombination luminescence intensity. (The exact pressure where this luminescence reduction occurs depends directly on the band offset, and the band offset has been accurately determined from this pressure.[17–19]) For $P \gtrsim 40$ kbar the X minima are the lowest-energy states in the GaAs layer, and both the barrier and well materials become indirect.

For our measurements we chose $GaAs/Al_xGa_{1-x}As$ multiple-quantum-well structures with different barrier thicknesses designed to give different couplings between the wells at atmospheric pressure. The strategy was to measure the effects of hydrostatic pressure on these couplings, as determined by changes in the confinement energies and energy-level splittings, and compare these results with the predictions of two models which do and do not include Γ-X mixing, to investigate the strength of Γ-X mixing effects in these systems. The Γ-X mixing model includes a mixing strength parameter to be determined by comparison with measurement.

We will concentrate here on two samples, a strongly coupled double quantum well (CDQW) and a multiple quantum well (QW) consisting of wells uncoupled at atmospheric pressure. The samples were grown at GTE Labs by molecular-beam epitaxy on (001) GaAs substrates. The CDQW sample consisted of a single pair of 72-Å GaAs quantum wells separated by an 18-Å $Al_{0.27}Ga_{0.73}As$ barrier, and surrounded by two 850-Å $Al_{0.27}Ga_{0.73}As$ barriers. The uncoupled well sample consisted of 30 200-Å GaAs wells separated by 150-Å $Al_{0.3}Ga_{0.7}As$ barriers. In the second system, the coupling at atmospheric pressure between the wells was negligible due to the large barrier width.[20] The samples were thinned by lapping to a thickness of 30 μm, and cleaved to a 100×100-μm square. In separate experiments the samples were loaded into a steel gasketed diamond-anvil pressure cell (DAC) with liquid He as a pressure medium. Photoluminescence (PL) and photoluminescence excitation (PLE) spectra, with focused illumination power densities of 30 W/cm^2, were taken at 4 K at a number of pressures. The pressures were determined with an accuracy of ± 0.3 kbar using the fluorescence of a ~ 20-μm ruby chip in the DAC. The use of He as a pressure medium eliminated concerns about nonhydrostatic pressure components being introduced by the pressure medium.[21] Through the pressure range of the experiments, 0–35 kbar, there was no discernible broadening of the ruby or sample PL peaks.

Figure 2 shows a typical PLE spectrum, taken at 4 K and atmospheric pressure, of the CDQW with the param-

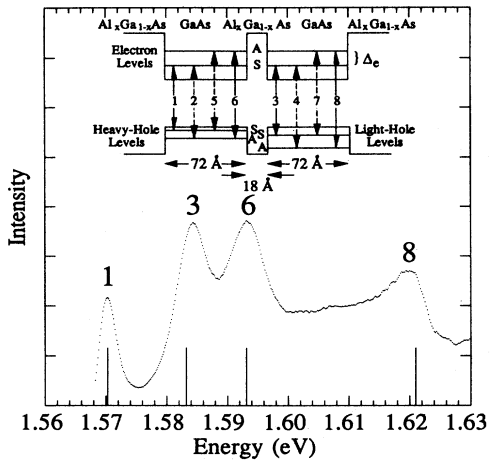

FIG. 2. PLE spectrum of a strongly coupled GaAs/$Al_{0.27}Ga_{0.73}As$ CDQW with parameters indicated in the schematic above, taken at atmospheric pressure and $T=4$ K. Illumination power density $=30$ W/cm^2. Resolution $=0.1$ meV. PL detection was set at 1.5650 eV. Identifications of the peaks are indicated with reference to the schematic. Calculated positions of peaks are shown by vertical lines below.

eters indicated. Since peaks in PLE spectra correspond to excitonic absorption transitions, the energies of the peaks give the energy separations between electron and hole states, including exciton effects, that give rise to allowed optical transitions. The vertical lines give the calculated energy levels, ignoring band mixing, using a three-band envelope-function model for the electron- and light-hole levels, consistent with $m_e^*(\text{GaAs})=0.067m_0$ (using parameters recommended in Adachi[22]), and a one-band model with an effective mass of $0.51m_0$ for the heavy-hole levels. The heavy- and light-hole exciton binding energies were taken from Greene, Bajaj, and Phelps.[23] The best fit required adjustment of the well and barrier widths 10% below their nominal values, which is within the uncertainties of these parameters.

The identification of the peaks of the spectrum can be understood with reference to the schematic diagram in Fig. 2, which shows the lowest ($n=1$) conduction- and valence-band levels of a CDQW. For this structure the electron, heavy-hole, and light-hole levels are split into doublets, and the size of the doublet splitting is a measure of the coupling between the wells. For a symmetrical CDQW the coupled electron and hole states must all be either symmetric or antisymmetric with respect to the center of the barrier. In this case transitions can only occur between electron and hole states of the same symmetry, i.e., transitions between symmetric and antisymmetric states are forbidden. As a result, of the eight possible transitions between the $n=1$ electron, heavy-hole, and light-hole levels shown in the diagram, only four (1,3,6,8) are optically allowed. These correspond to the four peaks shown in the spectrum. The electronic doublet splitting ($\Delta_e=E_5-E_1$) can be obtained directly by applying a small electric field which breaks the symmetry and makes the "forbidden" transitions slightly allowed, thus giving the energy of transition 5 when extrapolated to zero field.[24] We have used this technique to measure the $n=1$ electron levels and the doublet splitting (Δ_e) as functions of pressure.

If there were no Γ-X mixing, then one would expect no change in the Γ- confined levels as functions of pressure, other than that which would result from the known dependences of the well and barrier widths and the effective masses on pressure.[25,26] This is because the Γ-barrier height is approximately independent of pressure.[27] If there were some Γ-X mixing, then at pressures such that the barrier X minima are nearly coincident in energy with the well electron levels, one would expect a delocalization of the electrons via the barrier X states and thus a change in the electron confinement energies and the doublet splitting.

III. RESULTS

The measured pressure dependence of the lowest-energy transition of the wide, uncoupled quantum wells, with the pressure-dependent GaAs band gap subtracted out, is shown by squares at the bottom of Fig. 3. The value of the GaAs band-gap pressure dependence used was 10.7 ± 0.1 meV/kbar.[15] Also, 6.5 meV has been added to each point to correct for the exciton binding energy. The uncertainties of the energy values of the data points come from the uncertainties of the pressures and of the GaAs band-gap pressure dependence, and they enter the energy values through the subtraction of the pressure-dependent band gap. The figure shows that for this sample the energy of the transition relative to the GaAs band gap is independent of pressure within the error bars.

The measured pressure dependence of the lowest-energy transition of the CDQW, with the pressure-

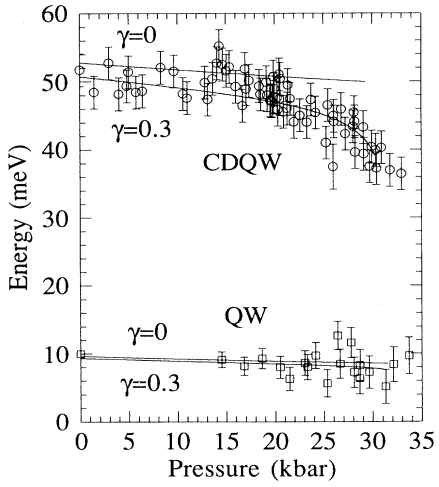

FIG. 3. Lowest-energy PLE peak energy of 200-Å-wide isolated GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells (squares) and of a strongly coupled GaAs/$Al_{0.27}Ga_{0.73}As$ CDQW (circles), with the pressure-dependent GaAs band gap (10.7 meV/kbar) subtracted out, vs pressure. Exciton binding energies have been corrected for by adding 6.5 meV to each point for the QW and 8.5 meV to each point for the CDQW. For each of the two plots, the upper (lower) solid curve is the calculated pressure dependence for $\gamma=0$ ($\gamma=0.3$), as explained in the text.

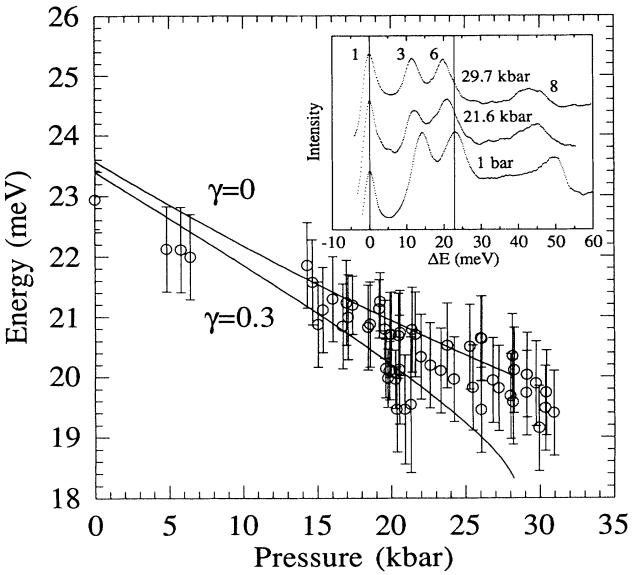

FIG. 4. Difference in energy between transitions 6 and 1 of the strongly coupled GaAs/$Al_{0.27}Ga_{0.73}As$ CDQW, indicated in Fig. 2, vs pressure. This energy difference is equal to the sum of the electron- and heavy-hole splittings, $\Delta_e+\Delta_{hh}$. The upper (lower) solid curve is the calculated pressure dependence for $\gamma=0$ ($\gamma=0.3$). The inset displays three PLE spectra of the CDQW taken at 4 K and the pressures indicated. The energies of the spectra are shifted so that the lowest-energy peaks of the three spectra line up, showing the relative spacings of the peaks.

dependent GaAs band gap subtracted out, is shown by circles at the top of Fig. 3. 8.5 meV has been added to each point to correct for the exciton binding energy. In contrast to the behavior for the wide, uncoupled wells, for this sample the transition energy relative to the GaAs band gap is nearly constant up to ~20 kbar, after which it begins to decrease with pressure, with a total decrease of ~15 meV by 30 kbar.

The splittings between the higher-energy PLE peaks and the lowest-energy peak also change with pressure for the CDQW, as can be seen by a comparison of the three PLE spectra taken at three different pressures, shown in the inset of Fig. 4. The pressure dependence of the splitting between peaks 6 and 1 ($E_6-E_1=\Delta_e+\Delta_{hh}$) of this CDQW sample is shown in Fig. 4. This is also seen to decrease with pressure, here linearly within the error bars. (We were able to measure the energies of peaks 2 and 5 for several pressures from 0–30 kbar by the method described in Sec. II, and thus we obtained the approximate pressure dependences of Δ_e and Δ_{hh} directly. We found that Δ_{hh} was independent of pressure within the error bars, ±0.3 meV, and thus Fig. 4 represents the pressure dependence of Δ_e with the approximately constant value of Δ_{hh} added.) All these results are corroborated by an independent set of measurements made on a similar sample.

IV. DISCUSSION

The energy of the lowest-energy absorption (or PLE) transition in a quantum well is given by the band-gap energy of the well material, plus the sum of the electron and heavy-hole confinement energies, less the exciton binding energy. The band gap of GaAs at 4 K increases linearly with pressure up to the Γ-X crossover pressure near ~41 kbar.[15] The pressure dependence of the GaAs heavy-hole mass has not been measured to our knowledge, but we estimate that its effects on the confinement energies are <1 meV for the CDQW and <0.1 meV for the QW.[28] The effects of the decrease in barrier and well thicknesses with pressure on the confinement energies tend to cancel, and over the pressure range of the experiment are calculated to affect the confinement energies by less than 0.5 meV. The exciton binding energy is in principle affected by pressure, due to the pressure dependences of the electron and hole masses and of the dielectric constant. In a simple hydrogenic exciton analysis the effect of pressure is to increase the exciton binding energy by no more than 1.5 meV over the pressure range of the experiment.

From the above, it can be concluded that Fig. 3 represents approximately the pressure dependences of the electron confinement energies for the two structures, shifted by small, approximately constant heavy-hole confinement energies. Within this analysis Fig. 3 shows that for the wide uncoupled quantum wells the electron confinement energy has no decrease with pressure from 0–30 kbar, within the error bars, while for the CDQW the electron confinement energy decreases by ~15 meV for pressures from 0–30 kbar, with most of the decrease taking place within the 20–30-kbar range.

The electron effective mass in GaAs increases approximately as the direct gap in $\mathbf{k}\cdot\mathbf{p}$ theory. Over the pressure range 0–30 kbar the band gap increases ~20%, giving rise to a ~20% increase in the electron effective mass.[25,26] This increased mass should lower the electron confinement energy roughly linearly with pressure. In Fig. 3, the upper solid curve ($\gamma=0$) for each structure gives the calculated effect of pressure on the lowest-energy conduction-band energy level due to this increasing mass effect, along with the very small effect of the changing well and barrier thicknesses. The assumed pressure-independent lowest-energy valence-band energy level and exciton binding energy have been added for comparison with the data. For the CDQW it is seen that the pressure dependence of the electron effective mass cannot account for the strong nonlinear decrease in confinement energy with pressure. In other words, the envelope-function model without band mixing cannot account for the observed behavior.

Comparing with Fig. 1, it should be noted that 20–30 kbar is the pressure range where the X minima of the barriers become near in energy to and cross the lowest conduction-band energy levels. This suggests that the behavior shown for the CDQW in Fig. 3 may result from Γ-X mixing. If the lowest-energy state in the well has a component of X character, then, as the bulk X minima of the barriers approach the energy of this state, an electron in this state can tunnel more strongly through the barrier separating the two wells via its X component, and tunnel out further through the barriers surrounding the well, thus lowering its confinement energy. The amount of this lowering would depend on the amount of X character in

the wave function.

A component of X character in the wave function would also be expected to affect the symmetric/antisymmetric doublet splitting of the conduction-band levels (Δ_e) as the X minima of the barriers approach these levels. Though the decreasing X-barrier height with increasing pressure would tend to increase the splitting, the heavy longitudinal effective mass of the X component of the wave function in the barrier ($m_x^* \sim$ bare electron mass)[22] has the opposite effect on the splitting. The net effect will depend on the precise value of the barrier X longitudinal effective mass.

This simple picture can be tested quantitatively within the Γ-X mixed envelope-function model of Ando and Akera.[11] For GaAs/$Al_xGa_{1-x}As$ heterostructures grown in the [001] direction, the broken periodicity in the growth (z) direction results in the breakdown of k_z conservation. This allows eigenstates of the system to be made up of linear combinations of bulk and evanescent states associated with the same k_x and k_y but different k_z. For pressures such that the X and Γ minima are close in energy, the mixtures consist principally of states associated with the Γ minimum and the X minima along the $\pm k_z$ directions. The total wave function is assumed to consist of linear combinations of three envelope functions multiplied by the basis Bloch functions associated with these Γ and X minima. In the Ando and Akera model, the boundary conditions on the envelope functions can be described by a 6×6 interface matrix, which gives a set of linear relations among the envelope functions and their derivatives for the two materials, at the interface. The components of the matrix are severely restricted by the requirement of the continuity of particle current across the interface. These components determine the amount of Γ-X mixing. Pulsford *et al.*[12] showed that if one makes the simplification that the minima along the Δ axes ("X minima") are exactly at the X point, then the total wave function for each material has the form $\Psi=\psi^\Gamma\sigma^\Gamma+\psi^X\sigma^X$, where σ^Γ and σ^X are the periodic Bloch functions of the specified symmetry for each material, and the 4×4 interface matrix, giving the connection rule for the envelope functions ψ^Γ and ψ^X and their derivatives at the interfaces, depends on a single phenomenological parameter γ, which governs the amount of Γ-X missing. The interface matrix used in their model, and used here, is given by

$$\begin{bmatrix} \psi^\Gamma \\ \psi^X \\ m_\Gamma^{-1}\nabla\psi^\Gamma \\ m_X^{-1}\nabla\psi^X \end{bmatrix}_{\text{GaAs}} = \begin{bmatrix} (1-\gamma^2)^{1/2} & -\gamma & 0 & 0 \\ +\gamma & (1-\gamma^2)^{1/2} & 0 & 0 \\ 0 & 0 & (1-\gamma^2)^{1/2} & -\gamma \\ 0 & 0 & +\gamma & (1-\gamma^2)^{1/2} \end{bmatrix} \begin{bmatrix} \psi^\Gamma \\ \psi^X \\ m_\Gamma^{-1}\nabla\psi^\Gamma \\ m_X^{-1}\nabla\psi^X \end{bmatrix}_{Al_xGa_{1-x}As} .$$

For symmetric CDQW's, using this model to connect the ψ^Γ and ψ^X envelope functions and their derivatives at the two inequivalent interfaces, we have calculated the conduction-band energy levels at $k_x,k_y=0$ as functions of pressure for different γ's. (This calculation could only be carried out for pressures below the barrier X/well Γ crossover pressure because beyond this the lowest-energy state is no longer confined.) In these calculations we used three-band model bulk dispersion relations for the Γ states and one-band model bulk dispersion relations for the X states. (The results were essentially the same when one-band model bulk dispersion relations for the Γ states were used.) These were consistent with atmospheric pressure band-edge effective masses of $0.067m_0$ for the well (GaAs) Γ states, of $0.090m_0$ for the barrier ($Al_{0.27}Ga_{0.73}Al$) Γ states, of $1.3m_0$ for the well (GaAs) longitudinal X states, and of $1.25m_0$ for the barrier ($Al_{0.27}Ga_{0.73}As$) longitudinal X states.[22] The pressure effects on the Γ states were included through the pressure effects on the bands, and the pressure dependences of the effective masses for the X states were neglected. The pressure coefficients used were $dE(\Gamma_{8v}\text{-}\Gamma_{6c})/dP=10.7$ meV/kbar and $dE(\Gamma_{8v}\text{-}X_{6c})/dP=-1.3$ meV/kbar, for both materials.[15]

In Fig. 3, the lower solid curve for each structure gives the calculated pressure dependence, including Γ-X mixing, of the lowest-energy conduction-band energy level for $\gamma=0.3$, with the assumed pressure-independent lowest-energy valence-band energy level and exciton binding energy added. Comparison with the data shows that this model gives a good fit for the CDQW for this value of γ. The range for a fit within the error bars is $\gamma=0.3\pm0.05$. Figure 4 shows that the pressure dependence of the splitting, $E_6-E_1=\Delta_e+\Delta_{hh}$, is not strongly dependent on γ.[29] Though the best fit to the data appears to be for values of γ closer to $\gamma=0$ than to $\gamma=0.3$, the fit for $\gamma=0.3$ is within the uncertainty of the measurements. All these results for the CDQW are confirmed for the corresponding light-hole transitions, 3 and 8 in Fig. 2, but with larger error bars. In principle, γ should be a function of pressure, since it should depend on the relative energies of the bulk Γ and X minima, which change with pressure. Thus this phenomenologically determined parameter is strictly only relevant for pressures near the crossover pressure, ~30 kbar, or for $Al_xGa_{1-x}As/Al_{x'}Ga_{1-x'}As$ systems with x and x' such that the bulk X minima in one material and the bulk Γ minima in the other have nearly the same energies.

Figure 3 shows that for the wide, uncoupled wells the energy levels are not strongly dependent on γ in this model. This is consistent, even with the strong Γ-X mixing implied by $\gamma=0.3$, with the general observation of a linear pressure dependence of the luminescence peak en-

ergies for wide uncoupled wells.[17,18]

Other types of experiments to investigate the amount of Γ-X mixing for GaAs/$Al_xGa_{1-x}As$ structures have been reported, including resonant tunneling,[2-8] luminescence under pressure[30,31] and electric field,[32] and magneto-optical[12] measurements, with mixing effects ranging from negligible to substantial. For example, Pulsford *et al.*[12] deduced a value of $\gamma=0.04$ for GaAs/AlAs superlattices from the anticrossing behavior of Γ and X states with magnetic field. However, these various measurements are difficult to compare because the effects are strongly dependent on the relative positions of the bulk Γ and X bands for each sample, and may be strongly barrier and well-width dependent.[33] Also, the Γ-X mixing may be dependent on the quality of the interfaces.[5] Nevertheless, our results suggest that confined Γ and X states in narrow, strongly coupled wells can strongly mix when they are near crossover, and that the envelope-function approach, extended by Ando and Akera[11] to include Γ-X mixing, can describe these effects quantitatively.

V. CONCLUSIONS

Our measurements of the effects of hydrostatic pressure on the energy levels of narrow CDQW's have shown that this regime displays behavior not seen in wider, uncoupled quantum wells, and behavior not consistent with the predictions of the simple envelope-function model. These results suggest that the discrepancy is due to neglect of strong Γ-X mixing effects. This work put to direct test a quantitative model that extends the envelope-function model to include Γ-X mixing effects. Our results are consistent with this model for a value of the phenomenological Γ-X band-mixing parameter of $\gamma=0.3\pm0.05$, for pressures where the Γ and X states are near crossover.

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the E_0 gap, the fractional change in the heavy-hole effective mass with pressure is $\lesssim 1.5/4.5 (\approx 0.33)$ times that in the electron effective mass, which is a $\sim 20\%$ increase for 0–30 kbar in $\mathbf{k}\cdot\mathbf{p}$ theory. Since the heavy-hole confinement energy of the CDQW is ~ 10 meV, the effect of this pressure dependence on the confinement energy (varying approximately as $1/m^*_{hh}$) over this pressure range is $\lesssim 0.33 \times 0.2 \times 10$ meV ≈ 0.7 meV.

[29]Comparing the $\gamma = 0$ and $\gamma = 0.3$ curves in Fig. 4, it may seem counterintuitive that the effect of having a component of X character in the wave function ($\gamma \neq 0$) is to *decrease* rather than *increase* the antisymmetric/symmetric splitting $E_6 - E_1 = \Delta_e + \Delta_{hh}$, relative to the splitting with $\gamma = 0$, with increasing pressure. However, this result is due to the heavy longitudinal effective mass ($m^* = 1.25 m_0$) (Ref. 22) of the X component of the wave function in the barrier used in the calculation. If the longitudinal X mass were as light as the electron mass [$m_e^* = 0.067 m_0$ (Ref. 22)] then the calculated splitting of the electron levels for $\gamma \neq 0$ *increases* relative to the splitting with $\gamma = 0$, with increasing pressure.

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