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A photomodulated spectroscopy study of $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ superlattices and quantum wells

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We present here a detailed study of photomodulated transmission and reflectivity at room and liquid-nitrogen temperatures of a series of $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ superlattices and a single quantum well. Our samples span a variety of alloy compositions and quantum-well widths. We compare the results of our measurements with the predictions of an envelope-function calculation, which includes wave-vector dependence of the minibands. This comparison allows identification of several spectral features unmistakably arising from miniband dispersion. Also, accurate determination is made of the band-offset parameter, whose value is discussed in the context of those obtained by other authors.

I. INTRODUCTION

Strained-layer $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ multiple quantum wells and superlattices have been extensively studied by optical techniques. Most of the attention was concentrated on determining the band offset of the heterojunction $Q$, defined as

$$Q = \Delta E_c / (\Delta E_c + \Delta E^H_v).$$

where $\Delta E_c$ and $\Delta E^H_v$ are the conduction and heavy-hole valence-band discontinuities, respectively. The actual value of $Q$ is of particular importance because of the large strain-induced splitting between the heavy- and light-hole valence bands, which produces a different potential profile for each type of carrier. Thus, for some values of $Q$, it is possible to confine light holes in the GaAs layers and heavy holes (as well as conduction-band electrons) in the lower energy-gap layers. This leads to the potentially interesting situation of having a type-I superlattice for heavy holes and a type-II one for light holes. In spite of the importance of having an accurate value for this parameter, different authors have arrived at very different values for $Q$. Light-scattering experiments suggest $Q \approx 0.4$ (type-I behavior for both light and heavy holes), while measurements by other optical techniques suggest values of $Q$ between 0.6 and 0.8 (type-II behavior for heavy holes). In an attempt to reconcile this disparity, Joyce et al. suggested that $Q$ might be dependent on the indium molar fraction $x$, taking low values for small $x$ and vice versa. Recent photocurrent spectroscopy data seem to reinforce this interpretation. Even more recent photoreflectance data give values of $Q = 0.67$ for a sample with molar fraction $x = 0.19$ and $Q = 0.45$ for another with $x = 0.11$, which also supports the explanation proposed by Joyce et al. Still, in spite of the wealth of experimental information, the issue of the right value of $Q$ for a given $\text{InGaAs/GaAs}$ interface is far from settled. Other questions, such as the extent of coupling between wells and accompanying band dispersion, are only now beginning to be discussed.

In the present work, we report the results of studying the photomodulated reflection and transmission spectra of a series of $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ structures that include superlattices, where there is clear evidence of miniband dispersion, as well as multiple and single quantum wells. Our samples have different molar fractions, going from $x = 0.12$ to 0.22 and a variety of barrier and quantum-well thicknesses. We use Raman scattering to accurately measure the strain in each type of layer and photoreflectance data from thick, strain-relaxed alloy layers to obtain the bulk alloy band gap. We find that the values of $Q$ for all our samples are in the interval $0.59 < Q < 0.65$ with larger values of $Q$ corresponding to the samples with larger indium molar fraction (x). Although this result apparently supports the proposition of Joyce et al., the observed changes in $Q$ are well within the uncertainties in determining this quantity. The $Q$ values obtained by us produce a potential profile for light holes which confines these carriers to the GaAs layers. However, the energy necessary to overcome this confinement is always less than the exciton binding energy, so that this type-II behavior for light holes does not manifest itself in the absorption spectra.

II. EXPERIMENTAL DETAILS

The samples used in our experiments were grown by metalorganic vapor-phase epitaxy (MOVPE) on (001) GaAs substrates. The quality of the interface and the values of the different sample parameters were confirmed...
TABLE I. Main characteristics of the samples used in our experiments. Superlattice period \(d\) is the sum of the alloy \(d_a\) and barrier \(d_b\) layer thicknesses.

<table>
<thead>
<tr>
<th>Sample designation</th>
<th>Description</th>
<th>((d_a/d_b) \times n) ((d) in Å)</th>
<th>(x)</th>
<th>(10^5 e) InGaAs</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>Substrate material</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>TLA</td>
<td>Thick alloy layer on GaAs</td>
<td>...</td>
<td>0.12</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>TLB</td>
<td>Thick alloy layer on GaAs</td>
<td>...</td>
<td>0.16</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>SLA 100</td>
<td>Superlattice (50/50) (\times 20)</td>
<td>0.12</td>
<td>-0.703</td>
<td>0.167</td>
<td></td>
</tr>
<tr>
<td>SLB 100</td>
<td>Superlattice (50/50) (\times 20)</td>
<td>0.16</td>
<td>-1.047</td>
<td>0.103</td>
<td></td>
</tr>
<tr>
<td>SLA 200</td>
<td>Superlattice (100/100) (\times 20)</td>
<td>0.12</td>
<td>-0.558</td>
<td>0.310</td>
<td></td>
</tr>
<tr>
<td>SLA 300</td>
<td>Superlattice (200/100) (\times 20)</td>
<td>0.12</td>
<td>-0.599</td>
<td>0.269</td>
<td></td>
</tr>
<tr>
<td>QWC 80</td>
<td>Single quantum well (d_x = 80) Å</td>
<td>0.22</td>
<td>-1.650</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

by x-ray, transmission electron microscopy (TEM), and photoluminescence measurements.18 Table I lists all the samples used, designating by a different prefix the superlattices (SL), quantum wells (QW), and thick alloy layers (TL). The latter were grown so as to have the same composition as that of the well material in the superlattice samples. The letters A \((x = 0.12)\), B \((x = 0.16)\), and C \((x = 0.22)\) are used to designate the three different alloy compositions used. Finally, the number following these letters represents the period (quantum-well width) of the superlattices (quantum well) in Å. The strain present in each type of layer was determined by Raman-scattering experiments in the manner described in Ref. 17 and is also listed in Table I. The quantity \(e\) listed there is defined as

\[
e = (a - a_0)/a_0\]

where \(a\) is the in-plane lattice constant of the superlattice (QW) and \(a_0\) is the equilibrium lattice constant of the bulk material composing the layer.17

The photomodulated reflectivity and transmission spectra were taken both at room temperature \((300\) K) and with the sample immersed in liquid nitrogen \((77\) K). The experimental setup is standard for this type of spectroscopy,119 with the probe beam obtained from a 150-W tungsten-halogen lamp filtered by a 1-m SPEX monochromator with a 1200-lines/mm grating and \(\approx 1\)-mm slit width. The modulating beam comes from a 2-mW He-Ne laser attenuated by various neutral density filters and mechanically chopped at 200 Hz. The reflected (transmitted) light was detected by a Si photodiode whose output was fed into a Stanford SR 530 lock-in amplifier. Both ac and dc outputs were digitalized and stored in a PC-XT microcomputer, which also controlled the spectrometer scan.

III. RESULTS AND DISCUSSION

The photomodulated reflectivity \((\Delta R/R)\) and transmission \((\Delta T/T)\) spectra of our samples at 300 and 77 K are shown in Figs. 1 and 2, respectively. The former show peaks corresponding to the GaAs substrate and barrier material, while the latter show structure mostly produced by transitions in the InGaAs quantum wells. An exception to this rule is a peak located at energies of about 40 meV below the GaAs fundamental gap, which appears in most of our \(\Delta R/R\) and \(\Delta T/T\) spectra. This peak also appears in the GaAs substrate material [see top curve in Fig. 1(a)] and is identified as an impurity state whose binding energy varies between 36 and 42 meV depending upon donor concentration.20 Another structure appearing closely below the bulk GaAs gap in some superlattices [highest-energy features in the spectra of Fig. 2(b)] are related to absorption (reflectivity) by the stressed barrier material. Since both these transitions are not related to the electronic properties of the quantum wells, they shall not be discussed further. Also, because of the sharper features and more straightforward interpretation, most of our discussion will be centered on the 77-K transmission spectra [Fig. 2(b)]. An exception to this is the QWC 80 sample, where the active region is only 80 Å and for which a good signal was only obtained at room temperature [Figs. 1(a) and 2(a)]. In all other cases, the reflectivity spectra are used only for corroboration of results obtained from the transmission ones and to obtain values for the \(E_0\) optical transition in the bulk GaAs (substrate) and alloy (thick layers), as

![FIG. 1. Photoreflectance spectra of the samples listed in Table I at (a) 300 K and (b) 77 K.](image-url)
shown in Fig. 1. These values are listed in Table II. Since we did not have a bulk alloy with indium molar fraction \( x = 0.22 \), the value of \( E_0 \) listed in Table II for this composition was obtained by extrapolation from a quadratic fit of the \( E_0 \) values for the other three compositions. These values are used to construct the potential profiles for electrons and holes for a given \( Q \) [Eq. (1)], in the manner described in Ref. 2. Transitions originating in the quantum-well region have photon energies \( E_{\gamma} \), which can be written as

\[
E_{\gamma} = E_0 + E_{\text{exc}} + \delta E_0(e) + \lambda_k^e(k_x) + \lambda_k^h(k_y),
\]

(3)

where \( E_0 \) is the thick-alloy-layer value of Table II, \( \delta E_0(e) \) is the change in the alloy \( E_0 \) edge introduced by strain, and \( \lambda_k^e(k_x) \) (\( \lambda_k^h(k_y) \)) is the electron (hole) miniband measured from the bottom (top) of the conduction (valence) band of the bulk material. An exciton binding energy \( E_{\text{exc}} \) of \(-4\) meV was assumed in all cases. Sharp structure in the optical spectra will occur only at the mini-Brillouin-zone center (\( \Gamma \) point, \( k_z = 0 \)) or edge (\( \pi \) point, \( k_z = \pi/d \)), where the joint density of states has van Hove singularities. The term \( \delta E_0(e) \) is calculated from the values of \( e \) listed in Table I, in the manner described in detail in Ref. 2. The values for \( \lambda_j \) are calculated using an envelope-function model,\(^{21}\) from potential profiles obtained for different values of \( Q \) [Eq. (1)].\(^{2}\) In what follows we shall compare the results of these calculations with the observed spectral features for each one of the samples of Table I in an attempt to obtain reliable values for \( Q \). Since each sample has characteristics that differ from the others, the discussion is best carried out individually, reserving a general summary of our main results and conclusion for Sec. IV. In each case we shall concentrate our discussion on the spectral region containing the quantum-well transitions.

The 77-K photomodulated spectra of sample SLA 100 [Fig. 3(a)] exhibit an oscillatory behavior which has already been identified\(^{15}\) as Franz–Keldysh oscillations associated with the lowest-energy superlattice absorption: the transition between the first-quantized heavy-hole and conduction-band levels at the minizone center \( \Gamma (11) \). The inset of Fig. 3(a) shows a plot of the energy maxima and minima in these spectra versus \( x = \sqrt{(\pi(n - 1/2))/2} \), from which the presence of an electric field of \( F \approx 7\) kV/cm is deduced. A detailed analysis of these results has already been given in Ref. 15. Only two points of this previous discussion need be recalled here. The first is that from the linear plot of the inset of Fig. 3(a) we obtain the value of \( E_{\Gamma (11)} = 1.414\) eV, which coincides with the calculated value [Eq. (3) and explanations that follows it] for \( Q = 0.57 \), a value previously suggested in Ref. 2 on the basis of photoluminescence and simple absorption at 2 K. The second point relates to the fact that when the interface roughness of the sample was increased, the oscillatory behavior disappeared, giving way to two well-defined structures identified as the first heavy- and light-hole transitions at the minizone center, respectively. Quantitative comparison between theory and experiment for the transition energies, while possible,\(^{22}\) is not very helpful in determining \( Q \), since interdiffusion of In and Ga changes the potential profiles in ways that necessitate using additional adjustable parameters (other than \( Q \)). The spectrum of the annealed sample deserves further attention, since it illustrates important points about the line shapes of \( \Delta R/R \) and \( \Delta T/T \) spectra and their relation to interface quality. The question of the appropriate line shape required to fit electromodulated or photomodulated reflectivity or absorption spectra in quantum wells and superlattices is much debated.\(^{23,24}\) In bulk semiconductors, for weak fields and ignoring exci-

![FIG. 2. Photomodulated transmission spectra of the samples listed in Table I at (a) 300 K and (b) 77 K.](image)

![FIG. 3. 77-K photomodulated spectra of sample SLA 100 in the photon energy region of interest: (a) as grown and (b) annealed. The solid lines in (b) are fits to different line-shape functions (see text).](image)
tonic interactions, line shapes are related to the third derivative with respect to photon energy of the zero-field dielectric function. Exciting effects in three-dimensional (3D) materials produced line shapes best described by first derivatives of the excitonic dielectric function. For confined systems, such as single or multiple quantum wells, the modulated signal is best described by first-derivative line shapes (FDLSs), although third-derivative line shapes (TDLSs) usually give reasonable good fits with accurate determination of the energy of the optical transition responsible for the observed spectral feature under consideration. Glembocki and Shanabrook conclude that this result holds even in superlattices with considerable miniband dispersion because of the confinement produced by the electron-hole interaction. To further complicate matters, there is also the question of the appropriate profile for the dielectric function. It was observed that, in cases of high temperatures or in samples with large content of impurities (or even, as we shall argue, in superlattices or quantum wells with rough interfaces), the spectra are better fitted by TDLSs of a dielectric function with Lorentzian absorption profile than with the apparently more correct FDLSs obtained from the same profile. Glembocki and Shanabrook account for this discrepancy by noting that in such cases a Gaussian absorption profile describes better the physical situation and, thus, the FDLSs obtained from such profiles are the most adequate to describe such data. Following their line of thought, this type of line shape should also be the most appropriate one to describe the $\Delta T/T$ spectrum from our annealed SLA 100 sample. Figure 3(b) shows the relevant portions of this spectrum, taken at 77 K. From top to bottom, the spectra were fitted with a TDLS of a Lorentzian absorption profile (L3), a FDLS of the same profile (L2), and a FDLS of a Gaussian profile (G), respectively. The last (bottom curve) is seen to provide a much better fit to the data. This proves that in the case of rough interfaces, the FDLS of a Gaussian profile is to be preferred for fitting $\Delta T/T$ data, even for superlattices with large miniband dispersion and in the presence of a large electric field. The confinement of the carriers in this case is produced by the roughness of the interface, rather than by the Coulomb interaction between electrons and holes. For the rest of our samples, the spectra are also best fitted by first derivatives of Gaussian profiles, although TDLSs of a Lorentzian profile also provide a good fit to the data and give accurate values for the transition energies.

Next, we examine another superlattice of the same period ($d = 100 \, \text{Å}$) and different alloy composition ($x = 0.16$), labeled in Table I as SLB 100. In Fig. 4(a) we display the 77-K modulated transmission spectrum of this sample (open squares) fitted with the three types of line-shape functions described above (solid lines). Again, the best fit is obtained by the FDLS of a Gaussian profile (G, bottom curve). In all cases three transitions, the energies of which are indicated by arrows in Fig. 4, are needed to fit the spectra: two strong ones (A and C) and a weaker one (B) to account for the shoulder in the high-energy side of line A. The necessity of including the latter is illustrated by the dashed lines in the bottom spectra, which represents a fit where this weak transition is omitted. The inset in Fig. 4(a) shows the parity-allowed transitions calculated as a function of the offset parameter $Q$ (curves) and the transition energies (straight horizontal lines) obtained from fitting our spectrum. The electron and heavy-hole minibands, from which these transitions were calculated (for $Q = 0.60$), are shown in Fig. 4(b). Light holes remain largely unconfined, or weakly confined within the GaAs barriers, for all cases of interest. Strong transitions will result from the $M_0$ singularity at the zone center for both light- and heavy-hole valence-band states to the only electron miniband. Thus, it makes sense to assign the stronger lines in our spectra to these two transitions (upper and lower curves in the right-hand inset). Although the higher-energy line also coincides with the forbidden transition from the second-quantized hole level to the conduction band at the zone center [$H(21)$], assigning this transition to the allowed light-hole transitions is in consonance with the recent findings of Kaendrazov et al. These authors proved that, in spite of the type-II confinement of the light hole, the light-hole to conduction-band transition appears prominently in photomodulated spectra. The reason for this apparent anomaly will be discussed at the end of this section. Also, the competing $H(21)$ transition is not only forbidden by parity, but also gives rise to an $M_1$-type singularity because of the dispersion of the second heavy-hole miniband [Fig. 4(b)]. This would make it weak even if it were allowed by parity. The preceding discussion leads to the choice of $Q = 0.60$, as indicated by a vertical line in the inset of Fig. 4(a). With this choice, the light hole is only
weakly confined in the GaAs barriers. The assignment of the weaker line (B) in the spectrum of Fig. 4(a) leads to an interesting discussion. It appears in a region where no allowed or forbidden transitions occur at the center of the minizone. Its position, however, is in the neighborhood of a \( (M_1) \) saddle-point singularity occurring at the edge of the minizone (\( \pi \) point at \( k_z = \pi/d \)). Such transitions are predicted theoretically and have been reported to manifest themselves in the photoluminescence and photoreflectance spectra of \( \text{Al}_x\text{Ga}_1-x\text{As/GaAs} \) superlattices\(^{27-30} \) and in the photoconductivity spectra of the type of superlattice under discussion.\(^{14,16} \) The miniband dispersion discussed by these authors results in an absorption spectrum containing a strong excitonic peak at the \( M_0 \) singularity at the zone center and an absorption band which extends up to the saddle-point \( (M_1) \) exciton at the zone edge. The latter would produce only a weak peak in the derivative spectrum. Such a feature, manifesting itself as a shoulder on the strong excitonic line from the zone center transition, is reported by Shen et al. in the photoreflectance spectrum of a 100-Å-period \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{As/GaAs} \) superlattice.\(^{30} \) The weakness of the zone-edge feature, when compared to that originating a zone-center transition, is justifiable in view of the concentration of oscillator strength characteristic of \( M_0 \) excitons, a property which is not shared by the \( M_1 \) exciton.\(^{27} \) Another distinguishing feature between the photomodulated line at the \( \Gamma \) and \( \pi \) points in the minizone is pointed out by Shen et al.,\(^{30} \) namely that the modulation produced by an electric field at these two points should have opposite phases. Our fittings with FDLSs of Gaussian profiles result in a phase for line B which is opposite to those of lines A and C. On the basis of the miniband scheme of Fig. 4(b), the zone-center \( M_0 \) and the zone-edge \( M_1 \) singularities should be separated by an energy of 33 meV. The energy separation of our spectral features is 25 ± 4 meV. The calculated energy separation, however, is very sensitive to small changes in \( d \). This is shown in the inset of Fig. 4(a), where the shaded area corresponds to the energy of the \( M_1 \) saddle point for ±5% deviations of the period from its nominal value. In view of this, we regard the agreement between the observed and calculated values for the zone-edge transitions as satisfactory. Thus, careful analysis of the photomodulated transmission spectrum of sample SLB 100 leads us to conclude that (a) the appropriate line shapes to describe our spectra are FDLSs of a Gaussian profile, a feature common to all our samples; (b) there is convincing evidence for spectral features arising from transitions at the minizone edge (\( \pi \) point at \( k_z = \pi/d \)); and (c) the best choice for the offset parameter is \( Q = 0.60 \).

In Fig. 5(a) we show the 77-K \( \Delta T/T \) spectrum of a sample with twice the period of the previous two \( (d = 200 \text{ Å}) \), namely, SLA 200 (Table 1). The spectral region (see Fig. 2) where the GaAs impurity and strained barrier peaks appear is omitted for the sake of clarity. The calculated minibands (for \( Q = 0.59 \)) are shown in Fig. 5(b). The spectrum is fitted (solid line) in the manner previously described with five transitions (labeled A, B, C, D, and E, in order of increasing energy) indicated by arrows in Fig. 5(a). These are shown in the inset of Fig. 5(a) as horizontal straight lines, while the curves represent the energies, as a function of \( Q \) for the various possible transitions arising from the theoretical miniband scheme [Fig. 5(a)]. Following the discussion of the previous samples, it is easy to assign lines A and C to transitions from the first heavy- and light-hole states to the first conduction-band state. No distinction is needed here as to the point in the minizone where these transitions take place, since these minibands are essentially dispersionless [see Fig. 5(b)]. These transitions pinpoint the value of the offset parameter at \( Q = 0.59 \). The photon energy position of line B is not very accurately determined by our fit, since it appears in the spectrum of Fig. 5(a) as a weak shoulder on the high-energy side of line A. We assign it to the parity forbidden \( H(21) \) transition, whose energy is in reasonable agreement with that of line D [see inset of Fig. 5(a)]. The remaining two lines (D and E) deserve more careful study. They are both relatively strong and well-defined lines which cannot be attributed to any allowed or forbidden zone-center transitions. A look at the miniband dispersion of Fig. 5(b) shows that the second electron miniband is strongly dispersive, having a minimum at the minizone edge and increasing its energy with decreasing wave number in such a way that it merges into the continuum long before it reaches the minizone center. Since the first and second heavy-hole minibands are virtually dispersionless, transitions from these bands into the second conduction miniband at the zone edge \([H^e(12)\text{ and } H^e(22), \text{ respectively}]\) would give rise to \( M_0 \) singularities in the joint density of states. These transitions would appear strongly in the absorption spectra because of the excitonic concentration of oscillator strength at this type of singularity.\(^{47} \) In contrast, these same transitions at the zone center should not contribute to the absorption because of the \( M_1 \) character of the singularity and, even more important, because the electron
state is unconfined [Fig. 5(b)] at this point of the minizone. Identifying lines D and E in the $\Delta T/T$ spectrum of our sample with these two zone-edge transitions is also coherent from the energy point of view, as shown in the inset of Fig. 5(a). The only weak point in the previous argument is that it would be expected that the parity-allowed $H^{\prime}(22)$ line should be stronger than the forbidden $H^{\prime}(12)$ line, while the opposite is seen to happen in our spectra. However, the overall consistency of our assignment is so great that we feel safe in claiming to have seen yet more clear evidence of miniband dispersion in the form of modulated absorption peaks arising from transitions at the minizone edge.

The next sample, SLA 300, has an even larger period ($x = 0.12, d = 300 \, \text{Å}$). Here, the minibands are practically dispersionless and the two features (A and B) observed in the photomodulated transmission spectra [Fig. 6(a)] are accounted for by three allowed transitions: $H(11)$ (A) and the almost coincidental $L(11)$ and $H(22)$ transitions, to which we attribute the second spectral feature (B). Our assignment is consistent with the choice of $Q = 0.59$, although the energy positions of these features are rather insensitive to the choice of $Q$. However, the fact that the B peak is stronger than the A one suggests that indeed the $H(22)$ and $L(11)$ transitions coincide in energy and reinforce one another. Looking at the inset of Fig. 6(a), we see that (within our spectral resolution) this pinpoints the offset parameter rather effectively at $Q = (0.59 \pm 0.03)$.

Finally, the room-temperature photomodulated signal of a single quantum well, QWC 80 (Table I), is shown in Fig. 6(b). No modulation signal from this sample could be obtained at low temperatures. The spectra show three features A, B, and C in order of increasing energy, which can easily be attributed to parity-allowed transitions $H(11)$, $L(11)$, and $H(22)$, respectively. Comparison of the photon energies at which these lines occur with calculated values [see inset in Fig. 6(b)] yields values for $Q$ of 0.65, 0.69, and 0.61 for lines A, B, and C, respectively. This leads to $Q = (0.65 \pm 0.04)$ as a suitable compromise.

The photon energies of the observed lines for all our samples as well as their calculated values for each assignment are listed in Table III, where we also list the best choices of the offset parameter for each case. These cluster around $Q = 0.60$ with very little dependence on sample composition. The crucial point about this choice is whether the light hole is confined in the GaAs barriers or in the InGaAs quantum wells. This depends on the sign (and magnitude, as we shall see) of the confining potential for light holes, $V_h$, that can be written as

$$V_h(Q) = \Delta E_h^L - q\Delta E_0^H,$$

(4)

where $\Delta E_h^L$ ($\Delta E_0^H$) is the difference in the $E_0$ gap for light (heavy) holes between GaAs and In$_x$Ga$_{1-x}$As, taking into account the strain-induced changes in these quantities [which we shall call $\delta E_h^L(e)$ and $\delta E_0^H(e)$, respectively, following the notation of Ref. 2]. Thus, if $V_h > 0$ ($V_h < 0$), the light holes are confined in the alloy (GaAs) layers. The material changes from type-I to -II behavior for light holes at a value $Q_0$ obtained by making $V_h = 0$ in Eq. (4), given by

$$Q_0 = \frac{\Delta E_h^L - \delta E_h^L(e)}{\Delta E_h^L - \delta E_0^H(e)},$$

(5)

where $\Delta E_h^L$ is the difference in gaps between GaAs and In$_x$Ga$_{1-x}$As in the absence of strain. With this definition, type-I (-II) behavior for light holes occurs with $Q < Q_0$ ($Q > Q_0$). All quantities to the right of the equality in Eq. (5) have a predominantly linear behavior with the indium molar fraction. Thus, $Q_0$ should be a quantity which is roughly independent of $x$. The small quadratic dependence of $\Delta E_h^L$ with $x$ and of $\delta E_h^L(e)$ with $e$ should not greatly affect this result. Using the data of Ref. 2, we calculate

$$Q_0 = (0.60 \pm 0.04),$$

(6)

for all values of $x$. The uncertainty is caused by different choices of the deformation potentials and the aforementioned quadratic terms. In Eq. (3) we assumed a superlattice commensurate within the GaAs substrate. If strain relaxation occurs, the strain shifts on the GaAs side of the gap must also be included. Since deformation potentials for both types of layers are apt to be very similar and quadratic terms are of little importance, this strain relaxation should not change very much the result of Eq. (6). A calculation of $Q_0$ for each one of our samples, whose strain distribution is given in Table I, is shown in Table III. All values are contained in the interval 0.56 < $Q_0 < 0.60$. Comparison of $Q$ and $Q_0$ in Table III shows that these two values are very close to one another, with $Q$ always slightly larger than $Q_0$. This gives the value of $V_h$ given in the last column of Table III, where we also list (in brackets) the light-hole binding energy, i.e., the energy necessary to remove it from the GaAs layer ($|E_{\text{excl.}}| = |V_h| - \lambda_h^L$), where it would be confined by this negative value of $V_h$. This binding energy is always smaller than the exciton binding energy ($|E_{\text{excl.}}| > 4 \, \text{meV}$). Hence, in spite of the fact that the light holes
are formally confined by the superlattice potential into the GaAs layers, the Coulomb interaction between this hole and the conduction-band electrons is more important than this confinement. This results in a strong spectral feature arising from transitions from the light-hole state to the first-quantized conduction-band state \( [L(11)] \), a feature common to all our spectra. If \( Q \) were sufficiently large so that \( \Delta E_L > |E_\text{exc}| \), this spectral feature would not be observed. In practice, this would mean \( Q > 0.70 \) for all our samples. This feature is also prominent in the spectra of Ksendzov et al.\(^\text{13}\) for samples with \( x = 0.11 \) and 0.19, respectively. This fixes the value of \( Q \) to be close to \( Q_0 \) for samples in this composition region, \( 0.11 < x < 0.22 \). While this reasoning places an upper limit to \( Q (Q < 0.70) \), it does not place a lower limit since the \( L(11) \) feature would be present for all values of \( Q < Q_0 \) (when light holes are confined in the alloy layers). This lower limit is placed by other observations. Transitions such as the \( H(22) \) in sample QWC 80 Fig. 6(b)\(^\text{7842}\) and all zone-edge transitions [Figs. 4(a) and 5(a)] in the superlattices only start for sufficiently deep conduction-band wells, which in our case means \( Q > 0.50 \). Thus, we place the limits

\[ 0.50 < Q < 0.70, \quad \text{for} \quad 0.11 < x < 0.22. \]  

(7)

Best values for our samples are given in Table III and, as already remarked, are close to \( Q \approx 0.60 \). A look at these values would allow us to believe that a dependence of \( Q \) upon \( x \) of the type proposed by Joyce et al.\(^\text{11}\) is possible. However, the changes observed in \( Q \) are too small to draw this conclusion. The main reason to postulate such a dependence is the desire to compatibilize the results of Ref. 3, obtained for low values of \( x \) (0.05), with most other results obtained for \( x > 0.11 \). On the basis of the present results, one would be tempted to offer a conjecture to the contrary, namely, that there is a close correlation between \( Q \) and \( Q_0 \) and that the former should always be just a little larger than the latter. Since \( Q_0 \) is virtually independent of \( x \) and always of the order of \( Q_0 \approx 0.60 \), the same should happen with \( Q \). Although concluding this from our data would be rash, the state of uncertainty about the value of \( Q \) is such that we feel this possibility should be mentioned anyway.

### IV. SUMMARY AND CONCLUSIONS

From the discussion in the previous section we would like to summarize the following points

(a) The question of the appropriate line shape for the photomodulated signal was discussed in relation to the results obtained for the annealed SLA 100 sample [Fig. 3(b)] and the SLB 100 one [Fig. 4(b)]. It was shown there that the carriers in these samples are confined by the excitonic effects and interface roughness. These factors determined that the best line shape to describe our results for \( T > 77 \) K was a first-derivative line shape of a Gaussian profile, although the more usual third-derivative line shape of a Lorentzian dielectric function, while not formally correct, also gives a good fit with reliable values for the energies of the optical transitions.

(b) Much evidence of miniband dispersion was presented. They appear in the shorter-period superlattices SLA 100, SLB 100, and SLA 200. In the first sample, the large dispersion in the only electron miniband allows the
built-in electric field to produce tunneling of the electrons throughout the microstructure, leading to the unmistakable appearance of Franz–Keldysh oscillations in the photomodulated spectrum [see Fig. 3(a)]. In the remaining two samples, there are structures in the photomodulated transmission and reflectivity spectra that can be unambiguously attributed to transitions at the minizone edge. In the SLB 100 sample, a clearly identifiable shoulder arises at an energy of about 25 meV higher than the zone-center (Γ-point) transition from the first heavy hole to the first electronic state at the minizone center. The energy separation, relative intensities, and relative phases of these two lines identify the shoulder as arising from the weak $M_1$-type singularity at the minizone edge (π point). In the SLA 200 sample, the second electronic miniband has a strong negative dispersion which produces confined states only at wave-vector values close to the minizone edge. This results in two strong $M_1$-type singularities for a π-point transition in a photon energy region where no other allowed or forbidden center transitions occur. The appearance of two strong lines at these photon energies gives direct proof of this calculated miniband dispersion.

(c) The band offsets (Table III) obtained by fitting the spectra of our samples cluster around $Q = 0.60$. Although looking at Table III a slight increase in $Q$ with increasing indium molar fraction could be inferred, in agreement with the proposal of Joyce et al.,11 the actual difference in the values listed there is well within the uncertainty in the determination of this parameter. A rather curious correlation appears to exist between the chosen value of $Q$ and the binding energy of the light hole in the GaAs layer has always clearly observable, both in our spectra and in those of Joyce et al.11 (0.11 < $x$ < 0.22). For this to be so, the binding energy of the light hole in the GaAs layer has to be smaller than that of the exciton, which, in turn, implies that $Q$ cannot be much larger than $Q_0$. If this were so in all cases it would lead to the result that $Q$ is $x$ independent and close to 0.60 for all alloy compositions, contrary to the proposal of Joyce et al.11 This, however, is mere speculation based on the fact that the transition from the light hole to conduction band is only allowed or forbidden zone-center transitions occur. The appearance of two strong lines at these photon energies gives direct proof of this calculated miniband dispersion.

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1 Some of this work is discussed in a recent review by H. Pollak, Superlatt. Microstruct. (to be published).