Type-I–type-II transition of GaAs/AlAs short-period superlattices investigated by photoluminescence spectroscopy under hydrostatic pressure

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The photoluminescence of $(GaAs)_m/(AlAs)_n$ short-period superlattices (SL's) with different period lengths ranging from $m,n=6$ to 17 is studied under hydrostatic pressure in the range of 0–50 kbar. The dependence of the energy separation between conduction-band Γ-like and X-like levels on the SL periodicity is obtained independent of which level is higher. The type-I–type-II transition is observed at atmospheric pressure and at room temperature in a $(GaAs)_{11}/(AlAs)_{11}$ SL. The pressure dependence of the luminescence intensities related to the transitions from both Γ-like and X-like states to heavy-hole states is also investigated. It is found that the ratio of the two transition probabilities only slightly increases from 1.4×10^{-4} for $(GaAs)_{17}/(AlAs)_{17}$ to 4.6×10^{-3} for $(GaAs)_6/(AlAs)_6$. This result demonstrates that the mixing between Γ-like and X-like states is quite small in these superlattices.

I. INTRODUCTION

Recent advances in molecular-beam-epitaxy technology made possible the growth of short-period $(GaAs)_m/(AlAs)_n$ superlattices (SL's) with very high quality. There have been quite a lot of theoretical[1–4] and experimental[5–10] studies on the interesting features of their band-structure and optical properties.

In GaAs/AlAs SL's the lowest energy level in the constituent GaAs layers is located at the Γ point in the center of the Brillouin zone, while it is at the X point at the edge of the Brillouin zone in the constituent AlAs layers. Due to the existence of band offset at GaAs/AlAs interfaces the X-valley energy in AlAs is lower than that of the X-valley in GaAs, and both Γ-like quantized states and X-like quantized states, which are localized mainly in the GaAs and AlAs layers, respectively, exist in GaAs/AlAs SL's and the system changes from a spatially direct (type-I) to a spatially indirect (type-II) SL depending on the SL period length. Therefore, the $(GaAs)_m/(AlAs)_n$ SL's with ultrathin layer thicknesses [for example, $(GaAs)_3/(AlAs)_3$] have X-like states as their lowest conduction-band energy level, while in the SL's with longer period lengths the lowest conduction-band states are Γ-like. However, there are still arguments about the question when the direct-indirect transition takes place, i.e., at which period length the anticrossing of the X-like and Γ-like states in a $(GaAs)_m/(AlAs)_n$ SL occurs. Nakayama and Kamimura[2] made calculations using a self-consistent pseudopotential method and suggested that the lowest conduction-band states are Γ-like for $m,n\geq2$. Gell *et al.*,[3] on the other hand, obtained the crossover point occuring at $m,n=8$ through a pseudopotential calculation. Finally, the empirical pseudopotential calculations made by Xia[4] showed that the crossing of Γ and X transition energies should take place when $m,n>10$. There are now also several experimental studies related to the direct-indirect transition in short-period GaAs/AlAs SL's, which are mainly based on the comparison of photoluminescence (PL) and photoluminescence excitation (PLE) spectra of the samples. The PLE threshold energy gives the direct absorption edge of the SL in contrast to the intrinsic peak energy of PL, which corresponds to the transition from the lowest conduction-band states to heavy-hole states. However, only when the lowest states are X-like can the energy separation between X-like and Γ-like states be distinguished by such a comparison. If the Γ-like states are lowest, the PLE threshold energy will only have a small Stokes shift away from the main PL peak, and then it is impossible to determine the X-Γ separation. Another interesting open question is how strong the state mixing induced by the folding effect of the Brillouin zone in SL is. The calculation of Gell *et al.*[3] indicates that the Γ-X mixing should be quite strong and thus the transition probabilities involving both X-like and Γ-like states to heavy-hole states (X-Γ and Γ-Γ transitions) should be of the same order of magnitude. However, Xia's results[4] show that the mixing should be weak, leading to a much smaller X-Γ transition probability than the Γ-Γ one.

The measurements of PL under hydrostatic pressure can be used as a powerful method for the investigation of semiconductor band structures and defect states. Recently, this technique has also been employed to study the electronic properties of the SL's and quantum wells. Owing to the pronounced differences of the pressure coefficients related to the Γ, X, and L valleys of bulk GaAs and other III-V compounds (e.g., the pressure coefficients of the Γ, X, and L valleys of GaAs are 10.7, −1.3, and 4.5 meV/kbar, respectively), it is possible to identify the nature of the lowest conduction-band states by measuring the pressure coefficients of the PL peak energies in short-period SL's.[7] In addition, an extrapolation of the pressure dependence of the X-like or Γ-like states to atmospheric pressure will give the value of the energy separation between Γ-like and X-like states at atmospheric pressure. The pressure dependence of the relative PL intensity will also provide information about the transition probabilities and of the state mixing. Wolford *et al.*[11] measured low-temperature PL on a $GaAs/Al_xGa_{1-x}As$ SL sample with a well thickness of 70 Å under hydrostatic pressure and discussed the Γ-X crossover and state mixing. Jones *et al.*[12] have investigated the low-temperature PL of a $(GaAs)_9/(AlAs)_9$ sample in the range of 0–4 kbar and found that the PL peak shifted to the low-energy side with increasing pressure at a rate of −2 meV/kbar. From this finding they concluded that the lowest conduction-band states should be X-like. Danan *et al.*[7] briefly reported the results of room-temperature measurements on five GaAs/AlAs short-period SL's under hydrostatic pressure.

In the present work we report the results of a systematic investigation of a series of $(GaAs)_m/(AlAs)_n$ short-period SL's with $(6,6) \le (m,n) \le (17,17)$ grown by molecular-beam epitaxy. The photoluminescence was measured at room temperature under hydrostatic pressure in the range of 0–50 kbar. At room temperature, due to the Boltzmann distribution of electrons in the conduction band, it is relatively easy to observe the luminescence related to both Γ-like and X-like states simultaneously under a wide pressure range and to obtain important information about the different luminescence lines and their relative intensities. Therefore, the room-temperature results are discussed here in detail. It is found that the type-I–type-II transition at atmospheric pressure takes place in the $(GaAs)_{11}/(AlAs)_{11}$ SL. To our knowledge, this is the first report on the direct evidence of the exact periodicity at which the direct-indirect transition occurs in $(GaAs)_m/(AlAs)_n$ SL's. From the investigation of the pressure dependence we found that at room temperature the ratio of the transition probabilities from X-like and Γ-like electron states to heavy-hole states increases gradually from 1.4×10^{-4} for $(GaAs)_{17}/(AlAs)_{17}$ to 4.6×10^{-3} for $(GaAs)_6/(AlAs)_6$. This small ratio indicates that the state mixing due to the folding effect of the Brillouin zone is not very pronounced.

II. EXPERIMENT

The undoped GaAs/AlAs SL's were grown by molecular-beam epitaxy at substrate temperature ranging from 530 to 550 °C. A 0.5-μm-thick GaAs buffer layer was first grown on the (001)-oriented semi-insulating GaAs substrate. On the buffer layer 100 to 200 periods of the $(GaAs)_m/(AlAs)_n$ SL's and subsequently a 20-Å-thick GaAs cap layer was grown. Details of the sample preparation have been described elsewhere.[13] The periodicity and layer parameters of the SL's, i.e., the monolayer equivalent thicknesses of constituent GaAs and AlAs layers in one period, m^+ and n^+, are measured by double-crystal x-ray diffraction and listed in Table I. For clarity, the SL configuration is represented by two numbers in a bracket, (m,n), where m and n are the layer thicknesses expressed in numbers of monolayers of GaAs and AlAs, respectively. The thickness of one monolayer is nearly 2.83 Å. m and n are the integer numbers which are closest to the measured thickness values.

A diamond anvil cell was used for the high-pressure studies. PL was excited with the 5145-Å line from an Ar^+ laser. The excitation power density was about 10^3 W/cm^2. The PL measurements were performed at room temperature. The experimental apparatus for measuring the hydrostatic pressure-dependent PL has been described elsewhere.[14] Most of the results reported here are derived from measurements performed at room temperature.

III. RESULTS AND DISCUSSIONS

The room-temperature PL spectra obtained from three representative SL configurations are shown in Fig. 1. The luminescence intensities have been normalized according to the strongest peak. In the figure E^Γ and E^X represent the luminescence transitions from the conduction-band Γ-like and X-like states, respectively, to the heavy-hole states. The measurements are made at room temperature and with relatively high excitation in-

TABLE I. Configurations of $(GaAs)_m/(AlAs)_n$ SL and the experimentally determined parameters of their electronic properties. E_0^i represents the peak energy at atmospheric pressure. a_i represents the pressure coefficient ($i=\Gamma,X,S$). p_0 denotes the pressure at which the energies E^Γ and E^X have reached the same level. $(I^\Gamma/I^X)_0$ denotes the extrapolated intensity ratio of I^Γ and I^X at $p=p_0$. P_Γ and P_X are the transition probabilities for Γ-like and X-like electrons to heavy-hole states. The meaning of m^+ and n^+ is explained in the text.

Sample (m,n)	m^+ (monolayers)	n^+	E_0^Γ (eV)	a^Γ (meV/kbar)	E_0^X (eV)	a^X (meV/kbar)	E_{S0} (eV)	a_S (meV/kbar)	$E_0^\Gamma - E_0^X$ (meV)	p_0 (kbar)	$(I^\Gamma/I^X)_0$	P_X/P_Γ
(6,6)	5.3	5.7	1.874	14.7	1.795	−1.6	1.433	10.8	79	−4.9	38.6	4.6×10^{-3}
(8,7)	8.2	6.6	1.765	11.1	1.748	−2.0	1.454	10.7	17	−1.3	118	1.5×10^{-3}
(9,11)	9.2	11.0	1.774	10.9	1.728	−2.2	1.434	10.7	46	−3.5	261	6.8×10^{-4}
(11,11)	10.9	10.5	1.708	10.0	1.699	−2.0	1.442	10.9	9	−0.8	516	3.4×10^{-4}
(17,17)	16.9	17.6	1.588	10.2	1.691	−2.2	1.448	10.5	−103	8.3	2736	1.4×10^{-4}

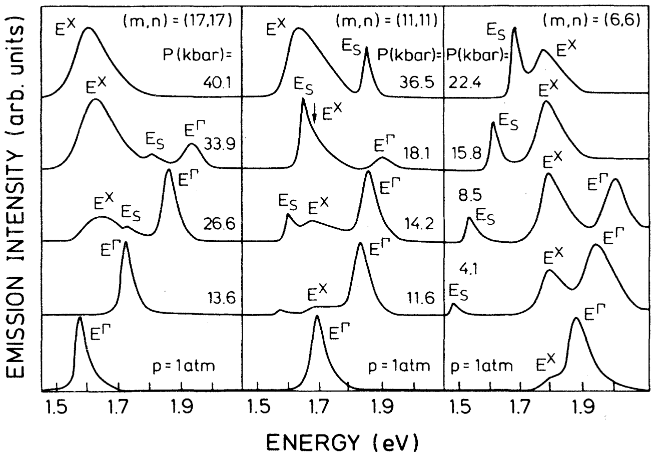

FIG. 1. Room-temperature PL spectra of three representative $(GaAs)_m/(AlAs)_n$ SL's obtained under different hydrostatic pressures indicated in the figure. For clarity, the baselines for the spectra have been offset and the intensities have been normalized according to the respective strongest peak.

tensity, thus both excitonic and band-to-band transitions may have contribution to the luminescence. E_S represents the luminescence transition coming from the GaAs substrate. The values of the hydrostatic pressure applied in the measurements are marked in the figure. For the (6,6) SL two luminescence peaks are observed at atmospheric pressure. The luminescence peak on the high-energy side has a rapid blue shift with increasing pressure, the pressure coefficient being nearly the same as that of the Γ-valley of bulk GaAs. On the contrary, the luminescence peak on the lower energy side shifts only slowly to lower energy, its pressure coefficient being similar to that of the X valley of bulk GaAs. Thus these two peaks can be directly identified as E^Γ and E^X related transitions without any ambiguity. The intensity of the peak E^Γ decreases rapidly with increasing pressure and finally only peak E^X is left. An additional peak labeled E_S appears on the lower energy side, and it grows stronger when a higher pressure is applied on the sample. This peak is assumed to be induced by the luminescence from the GaAs substrate based on its energy position and pressure coefficient.

For the (11,11) and (17,17) SL's only one peak is observed at atmospheric pressure, which is attributed to the SL peak E^Γ in the light of their pressure coefficient. Only after the pressure increases above a certain value does the peak E^X begin to appear on the lower energy side. Similar to the case of the (6,6) SL, the E_S peaks become also resolvable after a certain pressure has been applied to the samples.

For the (6,6) SL the energy separation between Γ-like and X-like states is considered to be given directly by the difference of the E^Γ and E^X peak energies, as the final states of the luminescence transitions are the same. (Here we neglect the difference of exciton binding energies. The error induced by this approximation is estimated to be smaller than 10 meV.) For the (11,11) and (17,17) SL's the peak energies E^X at atmospheric pressure are deduced by a linear extrapolation of the E^X versus p curves. Therefore, it is also possible to get the Γ-X separation for these samples at atmospheric pressure. For the three SL configurations, i.e., (6,6), (11,11) and (17,17), it is found that three characteristic cases exist. The Γ-like states of the (6,6) and the (17,17) SL's are either higher or lower in energy than the X-like states, respectively, while in the (11,11) SL the two states just cross over. Because the lowest X-like states and the lowest Γ-like states have the same symmetry, anticrossing may be expected. We should keep this fact in mind whenever we talk about the Γ-X crossover. (However, according to the calculation of Gell *et al.*[15] the level splitting arising from the anticrossing is sufficiently small, in the order of 1 meV, and will be difficult to observed in room-temperature measurements.) To our knowledge, this is the first time that such a crossover point is directly determined at atmospheric pressure and at room temperature and that it is exactly established when the type-I–type-II transition takes place in $(GaAs)_m(AlAs)_n$ SL's. Figure 2 shows the pressure dependence of PL peak energies at room temperature for E^Γ, E^X, and E_S. The linear relation $E^i = E_0^i + a^i p$ is used to fit the experimental data of the pressure dependence by least-squares fitting. In the formula $i = \Gamma, X, S$. E^i is the PL peak energy at different pressures. E_0^i represents the peak energy at atmospheric pressure, p is the applied hydrostatic pressure, and a^i is the pressure coefficient. The obtained values of E_0^i, of a^i, and of the energy separation $E_0^\Gamma - E_0^X$ are listed in Table I. Inspection of these data in Table I reveals that the pressure coefficients for E^Γ and E^X are close to their counterparts of bulk GaAs (10.7 and −1.3 meV/kbar, respectively). Since the pressure coefficients of bulk AlAs are not available, the bulk GaAs pressure coefficient for E^X is used for comparison which is presumably close to that of AlAs. Our result is in good agreement with that given by Jones *et al.*,[12] who obtained a pressure coefficient of −2 meV/kbar for the E^X peak at 4 K in a (9,9) SL sample. It is worthwhile to note that for our (6,6) SL the a^Γ value of the E^Γ peak is larger than for the other samples, while the absolute value of a^X of the E^X peak is smaller. Considering the state mixing between

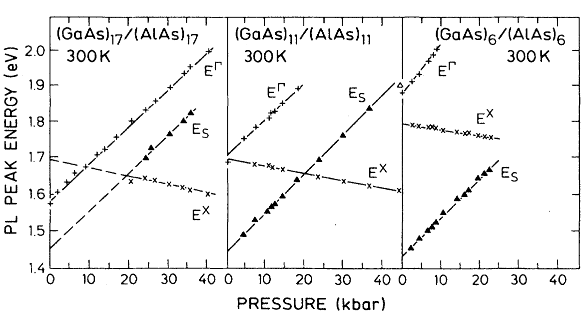

FIG. 2. Pressure dependences of the room-temperature PL peak energies obtained from three representative $(GaAs)_m/(AlAs)_n$ SL's.

Γ-like and X-like states, it can be expected that due to the incorporation of a certain part of Γ-like states into the X-like states the absolute value of a^X should decrease. However, the measured a^Γ value of the Γ-like states is even larger than the corresponding bulk value. This result is in contrast to the expectation based on the mixing effect. We therefore have to assume that other factors become important in the short-period SL's which may influence a^Γ of the E^Γ peak. A more detailed investigation of this phenomenon is needed.

The observed period-length dependence of the energy separation between Γ-like and X-like states, $E_0^\Gamma - E_0^X$, is depicted in Fig. 3, where the abscissa represents the monolayer equivalent thickness of the constituent GaAs layers m $(m=n)$. In this figure the experimental results reported by Moore *et al.*,[8] Jiang *et al.*,[9] and Nagle *et al.*[10] are also given for comparison. The authors determined the Γ-X separation in $(GaAs)_m/(AlAs)_n$ SL's at low temperature mainly from the difference between the PL peak energy and the PLE threshold energy of the same sample. Therefore they could provide data only if $E_0^\Gamma - E_0^X > 0$. Their data points are, in fact, strongly scattering so that the exact type-I–type-II transition point is difficult to determine. The data derived from the pressure dependence of the PL, on the other hand, are available for all period lengths and they do not depend on whether E_0^Γ is higher in energy than E_0^X. The period length corresponding to the type-I–type-II transition can then be determined more accurately. The energy separations between Γ-like and X-like states are calculated theoretically from a Kronig-Penney model, using the boundary conditions given by Bastard.[1] The calculated curve is drawn in Fig. 3 by the solid line. For short-period SL's we should realize that the energy-band calculation based on the assumption of a one-dimensional square well and the effective-mass approximation are not always justified. Nevertheless, inspection of Fig. 3 reveals that for $m,n>4$ the calculations agree well with the experimental results.[7,10] The formula used for the Kronig-Penney model calculation is described elsewhere.[9] The room-temperature GaAs and AlAs energy-band parameters used in the calculations are listed in Table II. It is found that if we take the band-offset parameter as $\Delta E_v = 0.35\Delta E_g$, the type-I–type-II transition takes place close to the configuration (10,10) which is in good agreement with our measurements.

Figure 4 shows the pressure dependence of the peak intensities I^Γ and I^X for the E^Γ and E^X transitions of a (8,7) SL. The inset in this figure depicts the pressure-dependent relative intensity I^Γ/I^X. The pressure dependence of the peak intensities obtained from the other SL configurations is similar. It is found that the luminescence intensity of E^Γ decreases rapidly with increasing pressure. In analogy to the case of bulk material, we assume that this decrease is induced by the change of the relative position of Γ-like states with respect to X-like states and, hence, the transfer of electrons from Γ-like states to X-like ones. Then the intensity I^Γ can be expressed as follows:

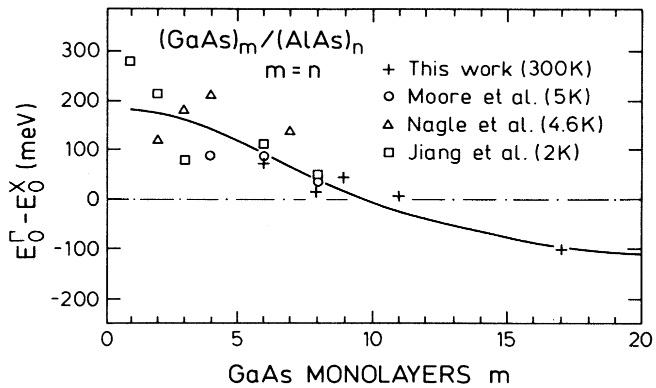

FIG. 3. Dependence of the energy separation $E_0^\Gamma - E_0^X$ on the constituent GaAs layer thicknesses (in monolayers m) in the $(GaAs)_m/(AlAs)_n$ SL's with $m=n$. The solid line represents the calculated result using the Kornig-Penney model.

$$I = I_0 \left[1 + A \exp \left[\frac{(a^\Gamma - a^X)(p-p_0)}{kT} \right] \right]^{-1}, \quad (1)$$

where I_0, A are constants and a^Γ, a^X are the pressure coefficients of E^Γ and E^X, respectively. p_0 is the pressure where $E^\Gamma - E^X = 0$, determined from the intersection point of the E^Γ versus p and E^X versus p curves. From the fitting of Eq. (1) to the measured pressure dependence we obtain $a^\Gamma - a^X = 13.1$ meV/kbar which is in good agreement with the value obtained from the direct measurement of the pressure coefficients of E^Γ and E^X ($a^\Gamma - a^X = 13.2$ meV/kbar). This result demonstrates the validity of the model of electron transfer from Γ-like to X-like states due to the change in the relative position of these two energy levels under pressure, and confirms that the direct recombination rate can be assumed to be a constant under different pressure.[16] On the other hand, the absolute intensity of the peak E^X, I^X, decreases with increasing pressure. The decrease is slow and not ex-

TABLE II. Parameters used in the Kronig-Penney model calculations.

	E_g^Γ (eV)	E_g^X (eV)	m_e^Γ (m_0)	m_e^{lX} (m_0)	m_e^{tX} (m_0)	m_{hh} (m_0)	m_{lh} (m_0)
GaAs	1.42	1.90	0.0665[a]	1.3	0.23	0.62	0.087
AlAs	3.02	2.17	0.15	1.1	0.19	0.76	0.15

[a] $m_e^\Gamma = 0.0665 + (0.0436\times10^{-3})E + (0.236\times10^{-6})E^2 - (0.147\times10^{-9})E^3$.

ponential. However, such a pressure dependence of I^X cannot be explained by the transfer of electrons, being just opposite to what is expected from the consideration of a carrier transfer. There are two reasons which possibly cause the decrease of I^X with increasing pressure. First, the direct absorption edge E^Γ rises with increasing pressure, making the absorption of the exciting laser light in the SL layers smaller and thus the total luminescence intensity from the SL weaker. This argument is supported by the fact that the luminescence from the substrate region becomes detectable and is enhanced only after the pressure is applied. Secondly, the energy separation between Γ-like and *X*-like levels increases with increasing pressure, thus reducing the state mixing between them. The diminished incorporation of the Γ-valley component into the *X*-like states causes a reduction of the transition probability and the decrease of the related luminescence intensity. Wolford *et al.*[11] have observed an increase of the recombination lifetime for the E^X transition induced by pressure in a GaAs/$Al_{0.24}Ga_{0.76}$Al SL sample, which has a 70-Å-thick well width. The increase of recombination lifetime in turn results in a decrease of the luminescence intensity under pressure.

When we compare the pressure dependences of the ratio I^Γ/I^X obtained for several SL's with different period lengths, some additional interesting results can be deduced. For the purpose of comparison, we choose the pressure point p_0 as the starting point of the pressure coordinate. p_0 is determined from the intersection point of the E^Γ versus p and E^X versus p curves. The p_0 values for the different SL configurations are listed in Table I. The dependence of I^Γ/I^X on $(p-p_0)$ for different samples is shown in Fig. 5, in which the solid lines are the least-squares fits to the experimental data by the exponential expression

$$\frac{I^\Gamma}{I^X}=\left[\frac{I^\Gamma}{I^X}\right]_0 \exp\left[-\frac{a'(p-p_0)}{kT}\right] . \tag{2}$$

The numbers marked in parentheses denote the period lengths of the corresponding SL's. Two distinct features can be extracted from the data of Fig. 5. (1) I^Γ/I^X decreases with increasing $(p-p_0)$ following nearly the same exponential law for all the SL configurations, which is mainly due to the electron transfer between Γ-like and *X*-like states under pressure. However, the value of I^Γ/I^X is also influenced by the pressure-induced Γ-*X* mixing, especially in the anticrossing region. In the figure the fitted a' is only nearly equal to the abovementioned value of $a^\Gamma - a^X$. (2) There is a regular shift between the lines, depending on the period length of the SL. The shorter the period length is, the more the corresponding line shifts to the left. The values of $(I^\Gamma/I^X)_0$ at which the extrapolated solid lines intercept the ordinate axis at $(p-p_0)=0$ are given in Table I. The extrapola-

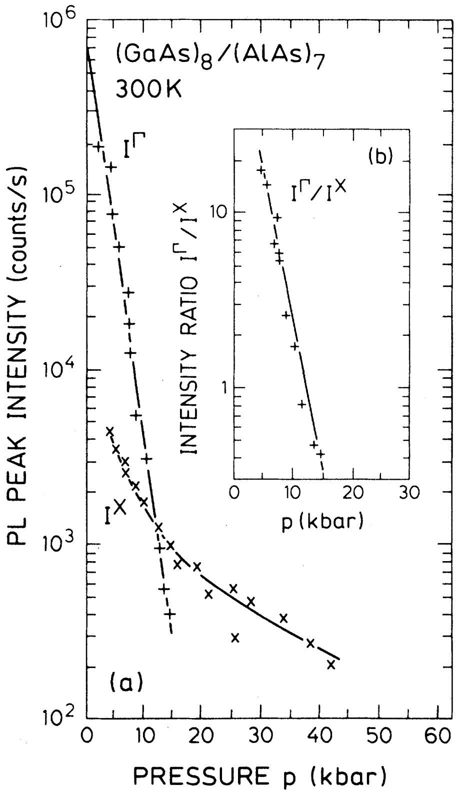

FIG. 4. Pressure dependence of room-temperature PL peak intensities I^Γ and I^X for a (8,7) SL. The inset displays the intensity ratio I^Γ/I^X.

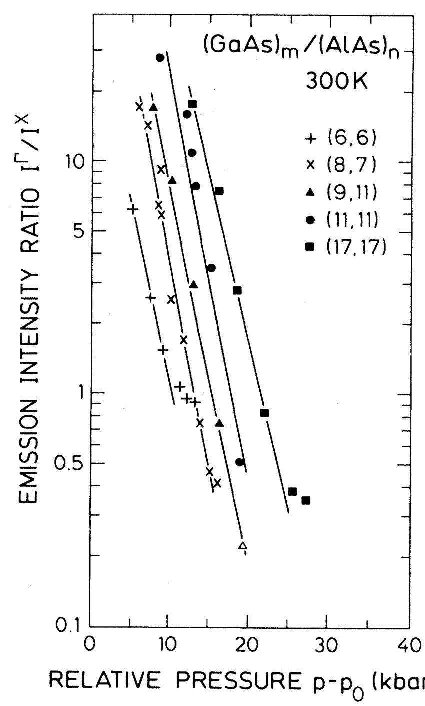

FIG. 5. Dependence of the room-temperature PL intensity ratio I^Γ/I^X on the relative pressure $(p-p_0)$, where p_0 denotes the pressure at which the energies E^Γ and E^X have reached the same level.

tion of the lines is made with an average slope common to all samples. Such extrapolation implicates that $(I^\Gamma/I^X)_0$ does not represent the intensity ratio at the real pressure-induced E^Γ-E^X crossing point. In fact, it is impossible to measure I^Γ/I^X at the crossing point directly from the PL intensities because when $E^\Gamma \approx E^X$ both transition peaks will overlap and become undistinguishable from each other. Here we are aware that we really confine our discussions on the state mixing away from the anticrossing region. The ratio of transition probabilities P_X/P_Γ is only a slowly-varying function of $E^\Gamma - E^X$, where P_Γ and P_X are the transition probabilities from Γ and X electrons to heavy-hole states, respectively. In such a case, we can approximately take the experimentally obtained value of $(I^\Gamma/I^X)_0$ as a constant, which is related only to the ratio of transition probabilities P_X/P_Γ and the influence of carrier statistics on the luminescence intensity is excluded. Assuming that the occupation probabilities of electrons on the two levels are comparable, in such a case the intensity ratio can be approximately expressed as follows:

$$\left[\frac{I^\Gamma}{I^X}\right]_0 = \frac{N_\Gamma P_\Gamma}{2N_X P_X} = \frac{m^\Gamma}{2m^{tX}}\frac{P_\Gamma}{P_X} , \quad (3)$$

where $N_\Gamma, N_X, m^\Gamma, m^{tX}$ represent the two-dimensional densities of states of Γ-like and X-like states and the effective masses of Γ- and X-valley electrons in the xy plane, respectively. P_Γ and P_X are the transition probabilities for Γ and X electrons to heavy-hole states. The factor 2 is induced due to the existence of two X valleys in the (001) direction. Taking $m^\Gamma = 0.0665 m_0$ and $m^{tX} = 0.19 m_0$, (P_X/P_Γ) values for the different SL configurations are calculated and listed in Table I. The relative error of fitted values is about 10%. From these data it is found that $P_X/P_\Gamma \sim 10^{-4} - 10^{-3}$, which is in the same order of magnitude as predicated by the calculations of Xia.[4] Thus our experimental results confirm the theoretical prediction of a weak state mixing. In addition, the fact that the pressure coefficients of Γ-like and X-like states are close to the corresponding values of bulk material gives further support to the weak mixing theory. The data of Table I show that the value of P_X/P_Γ increases from 1.4×10^{-4} [for (17,17)] to 4.6×10^{-3} [for (6,6)], indicating that the state mixing is relatively more pronounced for SL's with shorter period lengths. The larger mixing may also explain the relatively smaller absolute value of a^X obtained for shorter period SL's.

Meynadier *et al.*[16] recently reported the existence of mixing between Γ and X, which was probed by the measurements of the time decay of the indirect luminescence. The P_X/P_Γ values derived from their experiments are 4×10^{-5} and 1×10^{-3} for 78-Å period (with Γ-X spacing 200 meV) and 38-Å period (with Γ-X spacing 100 meV) GaAs/AlAs SL's, respectively. Our results are comparable with theirs in consideration of the fact that the configuration of GaAs/AlAs SL samples is not the same in both cases.

IV. CONCLUSION

The PL measurements under hydrostatic pressure provide an effective way to investigate the band structures and optical properties of $(GaAs)_m/(AlAs)_n$ short-period SL's. The nature of conduction-band states responsible for the luminescence transitions can be derived from their pressure dependence without any ambiguity. The energy separation between Γ-like and X-like states is thus determined independent of the relative position of these levels with respect to each other. The experimental results are in good agreement with the predictions of Kronig-Penney model calculations. The type-I–type-II transition at atmospheric pressure is observed in a $(GaAs)_{11}/(AlAs)_{11}$ SL. This is the first exact determination of period length at which the direct-indirect crossover takes place. According to the results on the relative PL intensity of transitions related to Γ-like and X-like states it is found that the transition probability from the conduction-band X-like state to the heavy-hole state is 3 to 4 orders of magnitude smaller than its counterpart related to Γ-like states. This finding indicates that the state mixing effects is quite weak in these superlattices.

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