Γ-X mixing effects on pseudodirect exciton transitions in GaAs/AlAs type-II superlattices

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We report on an experimental study of Γ-X mixing effects on the optical transition of the no-phonon-assisted (pseudodirect) exciton consisting of the $n=1$ AlAs-X_z electron and the $n=1$ GaAs-Γ heavy hole in [001]-$(GaAs)_m/(AlAs)_m$ type-II superlattices ($m=8$–13 monolayers) by using cw- and time-resolved-photoluminescence spectroscopies and photoluminescence-excitation spectroscopy. We have estimated the relative oscillator strength of the pseudodirect transition to the direct transition between the $n=1$ Γ electron and Γ heavy-hole states from the relative photoluminescence-excitation intensity, the relative photoluminescence intensity, and the relative photoluminesence decay rate. The values of the relative oscillator strength estimated from these three kinds of experimental results, which are around 1×10^{-4}, are mutually consistent, and they are almost independent of the layer thickness. We evaluate the Γ-X mixing factor from the relative oscillator strength, using a first-order perturbation theory, as a function of the layer thickness and show that the mixing factor is mainly determined by the overlap of the envelope functions of the Γ and X_z electrons.

I. INTRODUCTION

In the past several years much attention has been focused on electronic and optical properties of GaAs/AlAs short-period superlattices (SL's).[1] Finkman, Sturge, and Tamargo reported on a long-lived exciton photoluminescence (PL) with an indirect-transition nature in $(GaAs)_m/(AlAs)_m$ SL's with $m=3$, 7, and 10 monolayers (1 monolayer=0.283 nm).[2] It is now well known that the lowest conduction-band state of $(GaAs)_m/(AlAs)_m$ SL's with $m\lesssim13$ monolayers is the X valley of AlAs; therefore, the band structure is an indirect type, and the X electrons and Γ holes are spatially separated; this is called a type-II alignment. Although the X valley is threefold degenerate in bulk AlAs, confinement effects in SL's split the X valley into two states: the X_z state along the growth direction ($z=[001]$), and the X_{xy} one perpendicular to it. A simple effective-mass picture predicts that the X_z state ($m_z^*=1.1m_0$) lies lower in energy than the X_{xy} state ($m_{xy}^*=0.19m_0$). Several experimental studies have clearly supported the effective-mass picture:[3–8] the lowest-energy type-II exciton consists of the $n=1$ X_z electron state of AlAs and the $n=1$ Γ heavy-hole state of GaAs, which is denoted by $11HX_z$. In PL measurements of GaAs/AlAs type-II SL's at low temperature, we observe a strong no-phonon-assisted PL band of the $11HX_z$ exciton. This indicates that the transition is a pseudodirect type with a finite oscillator strength resulting from a Γ-X mixing in the conduction band. Meynadier *et al.*[9] reported evidence of the Γ-X mixing from the electric-field-induced anticrossing of the PL band of the $11HXz$ exciton, and that of the $11H\Gamma$ direct exciton with the $n=1$ Γ electron and $n=1$ Γ heavy hole in a $(GaAs)_{12}/(AlAs)_{28}$ SL. The appearance of the anticrossing originates from the Γ-X mixing, and the estimated mixing potential is very small, on the order of 1 meV. Skolnick *et al.*[10] observed a change of the $11HX_z$-PL intensity and decay rate induced by hydrostatic pressure, which varies the energy spacing between the X_z and Γ electron states, in a $(GaAs)_{12}/(AlAs)_8$ SL, and analyzed the energy-spacing dependence of the oscillator strength of the $11HX_z$ transition by using a first-order perturbation theory. Theoretical studies[11–15] suggest that the Γ-X mixing drastically changes as a function of the number of the AlAs monolayers because of the symmetry change of the wave function of the X electron. According to Refs. 11 and 13 (12 and 14), the Γ-X mixing occurs only at an odd (even) number of AlAs monolayers. Dawson *et al.*[16] and Minami, Nakayama, and Inoue[17] reported on the layer-thickness dependence of the $11HX_z$-PL decay rate in $(GaAs)_9/(AlAs)_n$ SL's (Ref. 16) and $(GaAs)_m/(AlAs)_m$ SL's.[17] Although the results of Ref. 17 indicate that the decay rate depends slightly on the parity of m, there has been no experimental evidence for the drastic change of the Γ-X mixing predicted theoretically above.

In the present work, we have investigated Γ-X mixing effects on the pseudodirect $11HX_z$ transition in a series of [001]-$(GaAs)_m/(AlAs)_m$ type-II SL's ($m=8$–13 monolayers) from the viewpoints of PL intensity, PL-excitation (PLE) intensity, and PL decay rate. In our previous paper[18] we reported the PL and PLE results. In the PLE measurements, we detected an $11HX_z$-exciton band with a very weak intensity in addition to the $11H\Gamma$-exciton band. In the PL measurements, we focused on the temperature dependence of the PL intensities of the $11HX_z$ and $11H\Gamma$ bands. We estimated the relative oscillator strength of the $11HX_z$ transition compared to the $11H\Gamma$ one from the relative PLE intensity, the relative PL intensity at infinite temperature extrapolated from the temperature dependence, and the relative PL decay rate. Analyzing the relative oscillator strength from the first-order perturbation theory,[10] we discuss here the Γ-X mixing effect as a function of the layer thickness. In addition, we discuss the PL decay profiles of the $11HX_z$ exciton.

II. EXPERIMENTAL PROCEDURES

The samples of $(GaAs)_m/(AlAs)_m$ type-II SL's with $m=8$, 9, 10, 12, and 13 monolayers, which are denoted

as (m,m) SL hereafter, were grown on a (001) GaAs substrate at ~560 °C by molecular-beam epitaxy (MBE). The total thickness of the SL layer in each sample is ~600 nm. The layer thickness was controlled by monitoring the intensity oscillation of reflection high-energy-electron diffraction (RHEED) patterns during the MBE growth. The RHEED-oscillation period corresponds to the growth time of one monolayer; therefore, the inaccuracy of the layer thickness is within ±1 monolayer.

The PLE measurements were performed at 10 K by using an excitation light (~1 μW) produced by combination of a 100-W tungsten lamp and a 32-cm single monochromator with a resolution of 0.5 nm. The emitted light was analyzed with a 25-cm double monochromator (0.5-nm resolution), and detected with a photon-counting system. The PL measurements were performed in the temperature range of 5–200 K, with the 514.5-nm line of an Ar^+ laser (~0.5 W/cm^2) and a double monochromator (0.5-nm resolution). For time-resolved PL measurements, which were carried out at 5 K, excitation pulses were obtained from the 632.8-nm line of a He-Ne laser using an electro-optic modulator: the pulse width was 25 ns, and the power was ~40 pJ (~100 nJ/cm^2). The PL transients were analyzed by using a gated photon counter with a gate time of 25 ns. In all optical measurements, the samples were mounted in a contact-type cryostat.

III. RESULTS AND DISCUSSION

A. PL and PLE spectra

Figure 1 shows PL and PLE spectra of (9,9), (10,10), (12,12), and (13,13) SL's at 10 K. In each PL spectrum, the strongest band originates from the no-phonon-assisted $11HX_z$ exciton recombination, and the weak bands on the lower-energy side are attributed to the phonon-assisted recombination. Each PLE spectrum, which is detected near the peak energy of the $11HX_z$-PL band, clearly shows the absorption features of the direct heavy- and light-hole excitons labeled $11H\Gamma$ and $11L\Gamma$. Noticing the magnified PLE spectrum on the low-energy side of the $11H\Gamma$ band, we observe a very weak PLE band starting 6–10 meV above the peak of the $11HX_z$-PL band. The PLE band is attributed to the no-phonon-assisted absorption of the $11HX_z$ exciton, because it is well known that the Stokes shift is due to weak localization of the exciton resulting from random potentials at interfaces. If we assume that the PLE spectrum is equivalent to the absorption one, the relative PLE intensity of the $11HX_z$ band compared to the $11H\Gamma$ one corresponds to $D_{X\text{-}\Gamma}S_{X\text{-}\Gamma}$, where $D_{X\text{-}\Gamma}$ is the relative density of states of the $11HX_z$ exciton to the $11H\Gamma$ one, and $S_{X-\Gamma}$ is the relative oscillator strength. Although the estimation of the relative PLE intensity is fairly ambiguous because of the continuum-transition background; the value, which is around 0.5×10^{-3}, hardly depends on the layer thickness.

Next we describe the temperature dependence of the PL properties. Figure 2 shows the PL spectra of (8,8) and (13,13) SL's at various temperatures. The relative intensity of the $11HX_z$ band compared to the $11H\Gamma$ one decreases with increasing temperature, which is due to the thermal electron transfer between X_z and Γ states. Figure 3 shows the relative integrated PL intensity of the $11HX_z$ band compared to the $11H\Gamma$ one, $I(11HX_z)/I(11H\Gamma)$, for all samples as a function of the inverse of temperature $(1/T)$. As is evident from our previous work,[7] the proportional relation between the logarithm of the relative intensity and $1/T$ demonstrates that the X_z electrons are in quasithermal equilibrium

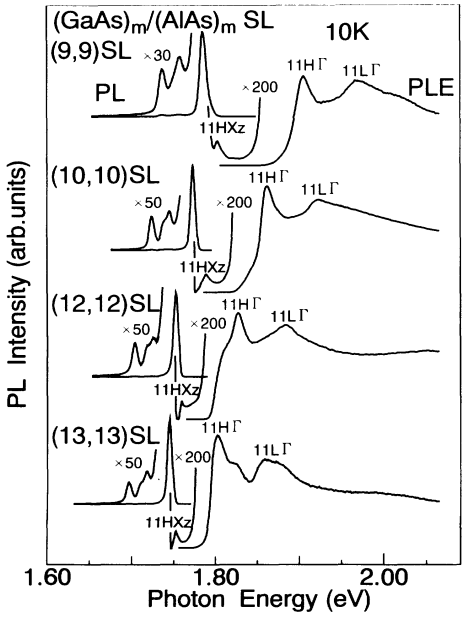

FIG. 1. Photoluminescence and photoluminescence-excitation spectra of the (9,9), (10,10), (12,12), and (13,13) SL's at 10 K.

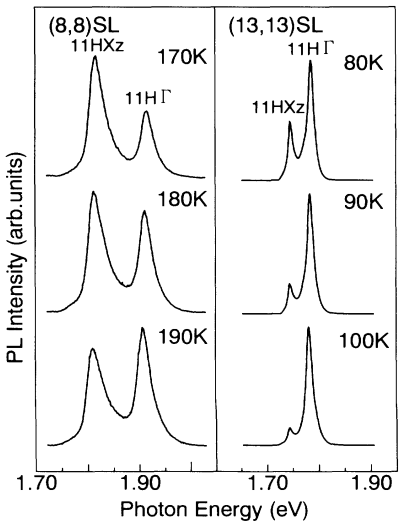

FIG. 2. Photoluminescence spectra of the (8,8) and (13,13) SL's at various temperatures.

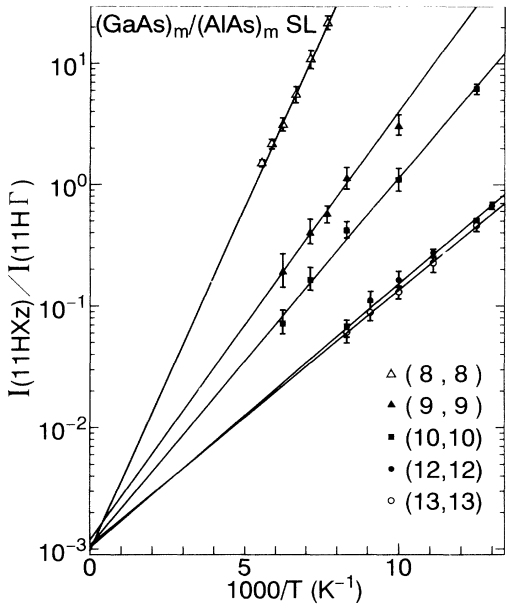

FIG. 3. Relative integrated PL intensity of the $11HX_z$ band to the $11H\Gamma$ one, $I(11HX_z)/I(11H\Gamma)$, of all the samples as a function of the inverse of temperature.

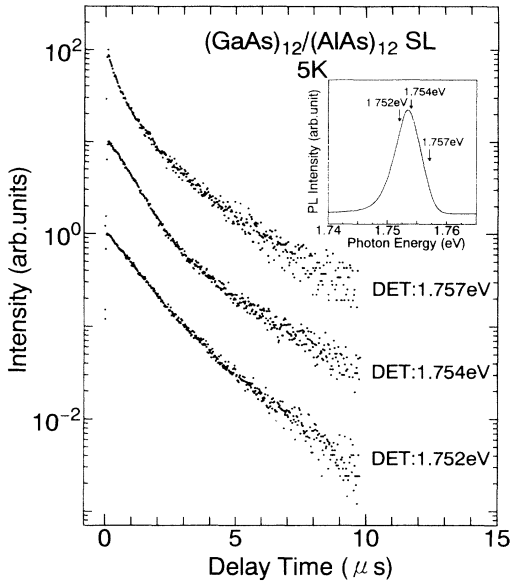

FIG. 4. Photoluminescence-decay profiles of the $11HX_z$ exciton detected at different energies in the (12,12) SL at 5 K, where the inset shows the integrated PL spectrum, and the arrows indicate the detection energies.

with the Γ electrons in the recombination process. Therefore, we can postulate the following equation for the relative PL intensity:

$$I(11HX_z)/I(11H\Gamma)=D_{X\text{-}\Gamma}S_{X\text{-}\Gamma}\exp(\Delta E/kT)\ , \quad (1)$$

where ΔE is the energy difference between the $n=1$ Γ and X_z electron states. From Fig. 3 it is obvious that the extrapolated relative PL intensity at $1/T=0$ (infinite temperature), which corresponds to $D_{X\text{-}\Gamma}S_{X\text{-}\Gamma}$, is an almost constant value of $\sim 1\times 10^{-3}$ for all the samples. This is consistent with the relative PLE intensity above. Thus the results obtained from PL and PLE measurements indicate that the oscillator strength of the $11HX_z$ exciton resulting from the Γ-X mixing effect hardly depends on the layer thickness, which is contrary to the theoretical prediction[11–15] that the Γ-X mixing producing the oscillator strength drastically changes as a function of number of AlAs monolayers because of the symmetry change of the wave function of the AlAs-X_z electron.

B. PL-decay properties

Figure 4 shows the PL-decay profiles of the $11HX_z$ exciton detected at different energies in the (12,12) SL at 5 K, where the inset shows the integrated PL spectrum, and the arrows indicate the detection energies. The detection resolution is 1 meV. It is obvious that the decay profiles change remarkably with the detection energy. On the high-energy side of the *PL* band, the decay is clearly nonexponential, while the nonexponential character is reduced on the low-energy side. Similar results have been reported by Dawson *et al.*;[16] however, Sturge *et al.*[19] criticized the results of Ref. 16 from PL-decay measurements of the same samples used by Dawson *et al.* as a function of excitation intensity (10^{11}–10^{16} photons/cm^2). In Ref. 19 it is reported that the decay profile at the lowest excitation intensity of $\sim 10^{11}$ photons/cm^2 is a nonexponential type, and that it becomes an exponential type with increasing the excitation intensity. In several works,[1,17,19–22] nonexponential decay profiles have been observed. In Ref. 19 it is concluded that the intrinsic character of the PL decay is nonexponential, which is given by

$$I(t)\propto \exp(-w_c t)(1+2w_r t)^{-3/2}\ , \quad (2)$$

where w_r is the mean decay rate due to random scattering by interface disorder, and w_c is the decay rate due to coherent scattering. The major mechanisms of the coherent scattering seem to be electron-phonon interactions and band-folding effects. This equation has been used to fit the decay profile of the $11HX_z$ exciton.[17,19,20,22] These fits indicate that w_c is much smaller than w_r; therefore, the exponential (coherent scattering) component can be neglected. Although the excitation intensity of ~ 100 nJ/cm^2 ($\sim 3\times 10^{11}$ photons/cm^2) in the present work is comparable to the lowest intensity in Ref. 19, the decay profile is remarkably different from that given by Eq. (2). As shown in Fig. 4, the fast component of the PL decay decreases as the detection energy is lowered, and the slow component, whose decay time is independent of the detection energy, becomes dominant. In addition, the decay profile at the lowest detection energy exhibits a delayed rise (~ 0.2 μs range). Similar decay features have been observed in all the samples. From the above results we consider that the fast component of the PL decay is related to relaxation processes of exciton localization, and that the slow component corresponds to the intrinsic PL decay. The random scattering process in the radia-

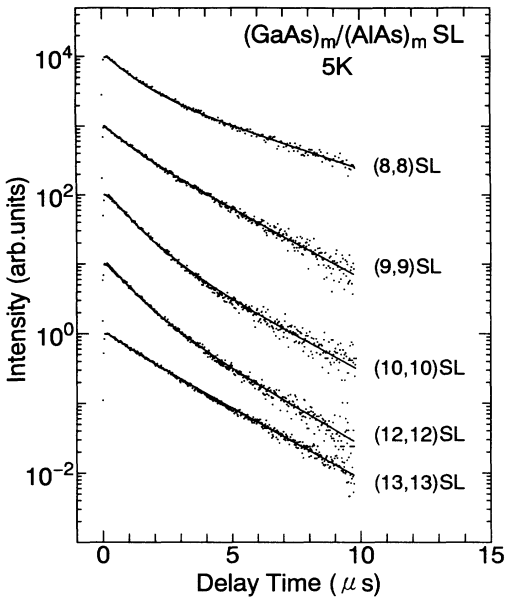

FIG. 5. Photoluminescence-decay profiles on the low-energy side of the $11HX_z$ exciton band of all the samples at 5 K. The solid lines represents the least-square fits based on the double exponential model given by Eq. (3).

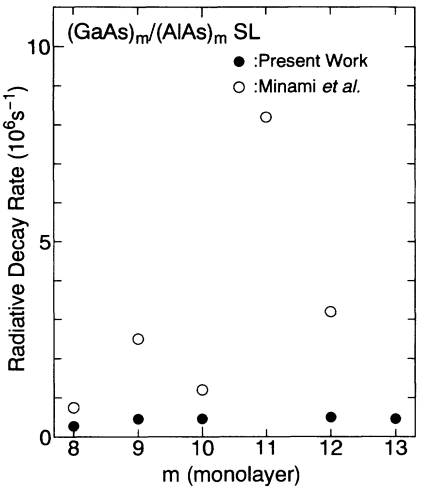

FIG. 6. Photoluminescence-decay rates of the $11HX_z$ exciton obtained in the present work (closed circles) and in Ref. 17 by Minami, Nakayama, and Inoue (open circles) as a function of the layer thickness. Our data are the decay rate of the slow component, w_s, given by Eq. (3), while the data in Ref. 17 are the decay rate of the random scattering, w_r, given by Eq. (2).

tive recombination is negligible for our samples. Although the radiative recombination mechanism is now controvertible, further details of the PL-decay properties are beyond the scope of this paper.

Figure 5 shows PL-decay profiles on the low-energy side of the $11HX_z$ exciton band of all the samples at 5 K. The solid lines indicate the least-square fits based on a double-exponential model:

$$I(t)=A_f\exp(-w_f t)+A_s\exp(-w_s t)\ , \tag{3}$$

where the subscripts f and s mean the fast and slow components, respectively. The PL-decay profiles are successfully explained by Eq. (3). The values of w_f and w_s are listed in Table I, with the values of $I(11HX_z)/I(11H\Gamma)$ at $1/T=0$ estimated from Fig. 3. As mentioned above, we assume that w_s is attributed to the radiative decay rate of the $11HX_z$ exciton corresponding to the oscillator strength. It is evident that the decay rate is almost independent of the layer thickness. This suggests that the oscillator strength is hardly affected by the layer thickness in the range of 8–13 monolayers, which is consistent with the inference from PL and PLE data.

TABLE I. Decay rates of the fast and slow components (w_f and w_s) of the $11HX_z$ exciton at 5 K estimated from the decay profiles shown in Fig. 5 on the basis of Eq. (3) and the relative PL intensity of $I(11HX_z)/I(11H\Gamma)$ at infinite temperature ($1/T=0$) estimated from the temperature dependence shown in Fig. 3.

Sample	w_f (10^6 s^{-1})	w_s (10^6 s^{-1})	$I(11HX_z)/I(11H\Gamma)$ at $1/T=0$ (10^{-3})
(8,8)	0.95	0.28	0.97
(9,9)	1.1	0.46	1.2
(10,10)	1.2	0.46	1.1
(12,12)	1.2	0.50	1.0
(13,13)	1.1	0.46	1.1

Minami, Nakayama, and Inoue carried out similar PL-decay measurements of (m,m) SL's with $m=8-12$ monolayers.[17] The decay profiles exhibit the nonexponential character given by Eq. (2). Figure 6 shows the values of the w_r (open circles) taken from Ref. 17, and w_s (closed circles) obtained in the present work as a function of the layer thickness. The decay rates of Ref. 17, which are much faster than our results, depend remarkably on the layer thickness, and they are relatively enhanced for the odd numbers 9 and 11 of the layer thickness in monolayer units. It is concluded that the Γ-X mixing is relatively enhanced in the monolayers 9 and 11, which is quite different from the layer-thickness dependence of the decay rate in the present work. This difference suggests that the decay rate depends remarkably on the sample quality. To reveal the experimental discrepancy for the decay profile and the decay rate described above, intensive measurements of various samples grown by different groups are needed.

C. Γ-X mixing

We analyze the experimental results above from the viewpoint of Γ-X mixing. According to the first-order perturbation theory,[10] the relative oscillator strength $S_{X-\Gamma}$ is given by the following equation:

$$S_{X\text{-}\Gamma}=|\langle\Psi_\Gamma|V|\Psi_X\rangle|^2/\Delta E^2\ , \tag{4}$$

where Ψ_Γ and Ψ_X are the total wave functions of the $n=1$ Γ and X_z electrons, V is a Γ-X mixing potential, and ΔE is the energy difference between the two states. Here we evaluate $S_{X\text{-}\Gamma}$ from the decay rate of the slow component, w_s, of the $11HX_z$ exciton, and the relative PL intensity of $I(11HX_z)/I(11H\Gamma)$ at infinite temperature extrapolated from the temperature dependence, which are listed in Table I. The relative PLE intensity is more ambiguous than the relative PL intensity because the continuum-state absorption overlaps the exciton band in the PLE spectrum; therefore, we omit the PLE data in this evaluation.

According to Eq. (1), $S_{X\text{-}\Gamma}$ corresponds to the relative PL intensity at $1/T=0$ divided by the relative density of states ($D_{X\text{-}\Gamma}$). We assume that $D_{X\text{-}\Gamma}$ is given by D_X/D_Γ, where D_X is the density of states of the AlAs-X_z electron, and D_Γ is that of the GaAs-Γ electron, because we suppose a quasithermal equilibrium between the X_z and Γ electrons. In all the samples the miniband widths of the $n=1$ X_z-electron state calculated by using an effective-mass approximation, in which the parameters used are standard values listed in Ref. 23, is less than 1 meV; therefore, the approximation of a two-dimensional condition is appropriate. On the other hand, the miniband width of the $n=1$ Γ-electron state ranges from 1 meV in the (13,13) SL to 25 meV in the (8,8) SL. Although the miniband dispersion should be taken into account to calculate the density of states, which is very complicated, we simply assume a two-dimensional condition because the PL bandwidth of the $11H\Gamma$ exciton is sufficiently larger than the calculated miniband width in the temperature range of the quasithermal equilibrium of the Γ and X_z electrons, as shown in Fig. 2. Therefore, $D_{X\text{-}\Gamma}$ is approximately given by $2m_{X,t}/m_\Gamma$, where $m_{X,t}$ is the transverse (in-plane) X-electron mass of AlAs, m_Γ is the Γ-electron mass of GaAs, and the factor of 2 is the degeneracy of the in-plane X-electron state. The values of $m_{X,t}$ and m_Γ are $0.19m_0$ and $0.0665m_0$, respectively: $D_{X\text{-}\Gamma}=5.7$. Thus the value of $S_{X\text{-}\Gamma}$ estimated from the relative PL intensity is around 1.7×10^{-4}.

From the viewpoint of the radiative decay rate, $S_{X\text{-}\Gamma}$ is given by w_X/w_Γ, where w_X is the radiative decay rate of the $11HX_z$ exciton, and w_Γ is that of the $11H\Gamma$ exciton. We use the decay rate of the slow component, w_s, of the $11HX_z$ exciton as w_X. On the other hand, we cannot measure w_Γ in GaAs/AlAs type-II SL's because of the very fast Γ-X scattering time of subpicosecond order.[24] In direct-transition-type SL's (Ref. 21) and multiple quantum wells[25] with a GaAs-layer thickness of ~10 monolayers, the observed decay time ranges from ~100 to ~400 ps, so that we assume that $w_\Gamma=4\times10^9$ s^{-1}. It is considered that w_Γ gradually decreases with decreasing the layer thickness in our samples because the increase of the miniband width of the Γ-electron state, which is described above, reduces the oscillator strength of the $11H\Gamma$ exciton, though there are no available data. The value of $S_{X\text{-}\Gamma}$ estimated from the PL decay rate is around 1.1×10^{-4}, which almost agrees with the value estimated from the relative PL intensity. It is noted that the values of $S_{X\text{-}\Gamma}$ are comparable to those calculated by Ando.[15]

Figure 7 shows the values of the Γ-X mixing factor, $\langle\Psi_\Gamma|V|\Psi_X\rangle$, evaluated from the relative oscillator strength (circles for the relative PL intensity and triangles for the PL-decay rate) on the basis of Eq. (4) and the overlap integral of the envelope functions of the Γ and X_z states, $\langle\phi_\Gamma|\phi_X\rangle$ (solid line), as a function of the layer thickness, where the dashed line represents the relative change of the overlap integral. The uncertainty of the mixing factor estimated from the relative PL intensity increases as the layer thickness is decreased, because the uncertainty of the relative PL intensity increases owing to the increase of the slope of the temperature dependence shown in Fig. 3. In this calculation, the values of ΔE for the relative PL intensity are different from those for the PL-decay rate because the temperature dependence of the direct-band-gap energy of GaAs is larger than that of the indirect-band-gap energy of AlAs, which has been demonstrated in Ref. 7. For the decay rate the energy difference between the $11H\Gamma$ and $11HX_z$ bands of the PLE spectra at 10 K is used as ΔE, while for the relative PL intensity the slope of the temperature dependence is used. The envelope function is calculated by using the effective-mass approximation.

As shown in Fig. 7, the values of the Γ-X mixing factor estimated from the relative PL intensity almost agree with those from the PL decay rate, and they exhibit an increment feature with decreasing layer thickness. The values are comparable to those reported previously: ~1 to ~2 meV.[9,16,17] It is evident that the layer-thickness dependence of the Γ-X mixing factor almost agrees with that of the overlap integral of the envelope functions. For the envelope functions varying slowly on the scale of

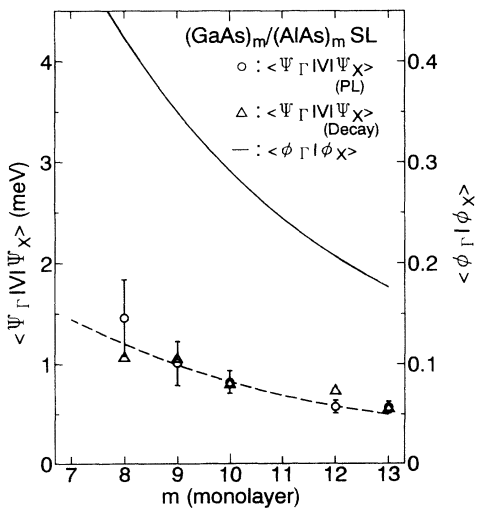

FIG. 7. Values of the Γ-X mixing factor, $\langle\Psi_\Gamma|V|\Psi_X\rangle$ estimated from the relative PL intensity of $I(11HX_z)/I(11H\Gamma)$ at $1/T=0$ (circles) and the decay rate of w_s (triangles), and the overlap integral of the envelope functions of the Γ and X_z states, $\langle\phi_\Gamma|\phi_X\rangle$ (solid line), as a function of the layer thickness, where the dashed line represents the relative change of the overlap integral.

the Bloch functions, we can approximately rewrite the mixing factor in Eq. (4) as follows:[16]

$$\langle \Psi_\Gamma | V | \Psi_X \rangle = \langle \sigma_\Gamma | V | \sigma_X \rangle \langle \phi_\Gamma | \phi_X \rangle \ , \quad (5)$$

where σ_Γ and σ_X are the Bloch functions of the Γ and X_z electrons. The values of $\langle \sigma_\Gamma | V | \sigma_X \rangle$ estimated from the decay rates are 3.1, [(13,13)], 3.5 [(12,12)], 2.7 [(10,10)], 3.0 [(9,9)], and 2.5 [(8,8)] in meV. Thus the Bloch-function term of the Γ-X mixing is almost independent of the layer thickness. This is similar to the results estimated from the PL decay rate of the $11HX_z$ exciton of $(9,m)$ SL's with $m=7$, 10, and 15 monolayers:[16] the values are ~ 3.5 meV.

Theoretical studies[11–15] predict that the Γ-X mixing depends on the number of AlAs monolayers because of the symmetry change of the wave function of the X-electron state: References 11 and 13 suggest that the mixing occurs only at an odd number, while Refs. 12 and 14 suggest that it occurs only at an even number. According to Ref. 13 (Xia and Chang), the difference of the theoretical predictions is due to the choice of the base function of X electrons. Our results suggest that Γ-X mixing does not depend on the parity of the AlAs monolayers, but on the overlap of the envelope functions of the Γ- and X_z-electron states. The Bloch-function term in Eq. (5) is almost independent of the layer thickness. This is contrary to the theoretical prediction of the layer-thickness dependence; however, the values of the relative oscillator strength obtained in the present work are comparable to the calculated results reported by Ando.[15] Although the decay rates reported by Minami, Nakayama, and Inoue[17] shown in Fig. 6 are relatively enhanced for the odd number in (m,m) SL's, the enhancement is not so large. One possible reason for the inconsistency between theoretical predictions and experimental results is that the imperfection of interfaces, so-called monolayer fluctuation, breaks the symmetry of the Bloch wave functions at interfaces.

IV. CONCLUSIONS

We have investigated Γ-X mixing effects on the pseudodirect $11HX_z$-exciton transition in $(GaAs)_m/(AlAs)_m$ type-II SL's ($m=8$, 9, 10, 12, and 13 monolayers) by using cw and time-resolved PL spectroscopies and PLE one. We have estimated the relative oscillator strength of the $11HX_z$ transition to the $11H\Gamma$ transition from the following data: (1) the relative PLE intensity of the two bands, (2) the relative PL intensity at infinite temperature extrapolated from the temperature dependence, and (3) the relative PL-decay rate. It is found that the relative oscillator strength is almost independent of the layer thickness: the values are around 1×10^{-4}. The analysis of the relative oscillator strength based on first-order perturbation theory indicates that the Γ-X mixing factor of the order of 1 meV, which slightly increases with decreasing the layer thickness, is mainly determined by the overlap of the envelope functions of the Γ and X_z electrons, and that the Bloch-function term of the mixing is almost independent of the layer thickness. This is inconsistent with the theoretical prediction that the Γ-X mixing depends on the parity of the AlAs monolayers. In addition, it is demonstrated that the PL-decay profile of the $11HX_z$ exciton is an exponential type, which is different from the reported typical feature of a nonexponential type. The exponential-type PL decay suggests that coherent scattering dominates the recombination process.

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