Optical observation of impurity localized states at the edges of Landau subbands in doped quantum wells

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We present experimental evidence for the existence of impurity localized electron and hole states in (in-well) p-type doped GaAs/$Al_{0.25}Ga_{0.75}As$ multiple quantum wells (MQW's) under applied magnetic fields ($B<14$ T) and at a temperature of $T=2$ K. We study the photoluminescence excitation (PLE) spectra with the monitored energy (E_m) varied throughout the inhomogeneously broadened photoluminescence (PL) band. The main effect is a broadening of the Landau PLE transitions as E_m decreases towards the low-energy side of the excitonic PL band. This effect is explained by an enhanced carrier relaxation rate between quantum states that are spatially localized in the vicinity of impurity centers. Also, the width of the observed transitions is nearly independent of the magnetic field. This confirms the long-range nature of the localizing extrinsic potential, which we suggest is due to compensated (charged) acceptors randomly distributed over the QW plane. We calculate the line shape dependence of the lowest Landau PLE band on E_m and obtain a good agreement with the experimental spectra. In contrast, for an undoped MQW of similar well width, the width of the Landau PLE transitions is independent of E_m and shows a $\sqrt{B}$ dependence. This demonstrates the short-range potential carrier scattering nature of the Landau-level broadening. [S0163-1829(96)02628-8]

I. INTRODUCTION

There is an on-going interest in the electrical and optical properties of two-dimensional electron systems under an applied magnetic field. In the most studied case of the quantum Hall effect it is generally accepted that the existence of plateaus in the dependence of the Hall conductivity on the filling factor is related to the presence of localized states in the electron spectrum.[1,2] The microscopic mechanism of this localization is still unclear. A full analytical description of the electron motion in two-dimensional disordered systems is not simple, even in the absence of interactions between carriers. A numerical study was done by Ando,[3] who calculated the wave functions and eigenenergies of electrons subjected to randomly distributed impurities. This study determined the extent of electron localization at the edges of the Landau subbands.

The carrier localization nature strongly depends on the impurity potential range, as compared to the scale of the magnetic length. For short-range potentials, the localization is weak and scattering theory can be applied. The simple Born approximation[4] gives the width of broadened Landau subbands to be proportional to $\sim\sqrt{B}$. Lyo[5,6] calculated the photoluminescence (PL) line shape in modulation-doped quantum wells (QW's) within the framework of multiple scattering. However, this approach neglects the localized nature of the broadened states. In the case of long-range potentials, the edge states of the Landau subbands can be described by perturbation theory.[7,8] The two-dimensional carrier motion is then separated into two parts: cyclotron rotation (unperturbed part) and a cyclotron center motion (perturbation). The eigenfunctions and eigenenergies of the decoupled Hamiltonian were explicitly derived.[9,10] However, until now there is no theory of the optical spectra based on the quantum states obtained in this way.

The present investigation is concerned with QW's, which are doped *within* the well. Then, the (quasi-) two-dimensional carriers are subjected to the potential of randomly distributed impurities (acceptors and donors). Experimentally (Sec. II), we used photoluminescence excitation (PLE) spectroscopy to study the spectrum of perturbed electron and hole states, as well as the relaxation processes that photogenerated carriers undergo.

A p-type multiple quantum well (MQW) is studied, since the broadening of the Landau transitions in this case is smaller than that of n-type MQW's with comparable doping levels.[11] Therefore, for acceptor doped MQW's, it is possible to resolve the structure of Landau transitions in the PLE spectra at relatively low magnetic fields. A comparison is made with the Landau transitions observed in an undoped MQW. In Sec. III, the experimental results are discussed and compared with the calculated line shape of the Landau transitions in the PLE spectra. A short summary concludes this paper.

II. EXPERIMENT

The GaAs/$Al_xGa_{1-x}As$ MQW structures used in this study were grown by molecular-beam epitaxy on (001)-oriented GaAs substrates. Results will be shown for two

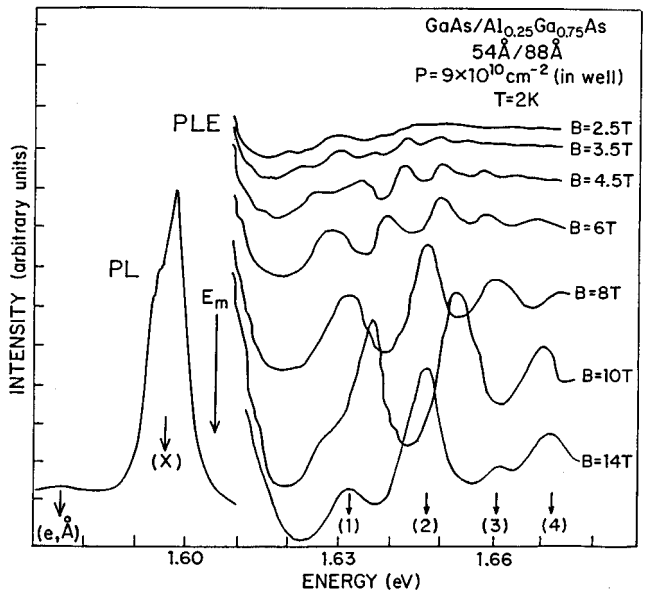

FIG. 1. The PL spectrum excited by above $e1$-hh1 band-gap radiation and the PLE spectra observed under different applied magnetic fields. The two bands in the PL spectrum are due to excitonic recombination (X) and to electron-acceptor bound hole transitions (e Å). The PLE spectra are monitored at $E_m=1.605$ eV (in the high-energy side of the excitonic PL band). For $B=14$ T, the observed bands are assigned to the Landau transitions (1) $n_{\mathrm{lh1}}=0\rightarrow n_{e1}=0$, (2) $n_{\mathrm{hh1}}=1\rightarrow n_{e1}=1$, (3) $n_{\mathrm{lh1}}=1\rightarrow n_{e1}=1$, (4) $n_{\mathrm{hh1}}=2\rightarrow n_{e1}=2$.

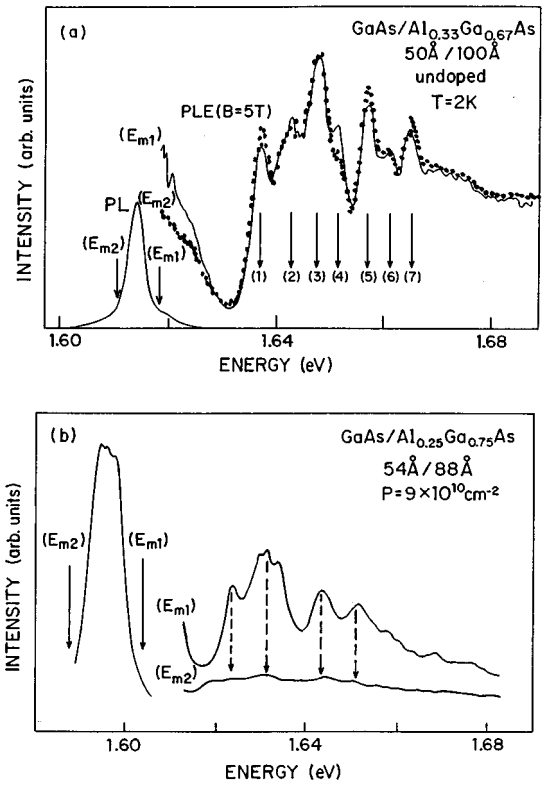

FIG. 2. The PLE spectra of (a) the undoped and (b) p-type doped MQW's under an applied magnetic field of 5 T monitored at the energies (a) $E_{m1}=1.618$ eV, $E_{m2}=1.611$ eV; (b) $E_{m1}=1.605$ eV, $E_{m2}=1.587$ eV. In (b), the dashed arrows indicate the evolution of Landau transitions, when E_m is tuned from the high-energy part of the excitonic PL band to its low-energy tail.

MQW's: (a) GaAs well widths of 54 Å, $Al_{0.25}Ga_{0.75}As$ barriers of 88 Å width, and 100 periods. This MQW is 3×10^{17} cm^{-3} Be-doped (p-type) in the central 30 Å of the wells. (b) An undoped $GaAs/Al_{0.33}Ga_{0.67}As$ MQW with well widths of 50 Å, barrier widths of 100 Å, and 200 periods.

All the spectroscopic studies were done with the samples immersed in liquid He at $T=2$ K and subjected to an external magnetic field ($0\leqslant B\leqslant 14$ T) oriented normal to the QW plane ($z\|[001]$). The excitation was done with a cw dye laser (linewidth of 0.15 meV). The light emitted from the crystals was dispersed through a double spectrometer (resolution of 0.05 meV).

Figure 1 shows the PL spectrum of the p-type doped MQW and a series of PLE spectra. The PL spectrum observed under above band-gap excitation consists of a strong emission from the inhomogeneously broadened ($e1$:hh1)1S exciton band (centered at $\simeq$1.597 eV) and a recombination band of electrons with acceptor bound holes (centered at $\simeq$1.575 eV). As was previously reported,[12,13] the excitonic band of doped QW's has a characteristic low-energy shoulder (in some cases even a separate peak), which corresponds to emission from acceptor bound exciton states. Under applied magnetic fields, the excitonic PL band shows a diamagnetic blueshift of $\simeq$4 meV for $B=14$ T, which is still smaller than the PL bandwidth. The PLE spectra shown in this paper were monitored at various energies E_m of the excitonic PL band. Those of Fig. 1 were all monitored at the same energy $E_m=1.605$ eV, corresponding to the upper energy part of the excitonic PL band for all values of the magnetic field. The PLE transitions between electron and heavy-hole Landau subbands are discernible for $B\geqslant 3.5$ T. Their Landau index identification is made by using the results of a MQW subbands structure calculation, where the Luttinger Hamiltonian[14] (with parameters taken from Ref. 15) is applied to the valence band, while the conduction band is considered in a simple parabolic approximation ($m_c\cong 0.067m_0$).

The problem presented in this paper is demonstrated in the next four figures. In Fig. 2, the PLE spectra of (a) undoped and (b) p-type doped MQW's are compared. The Landau transitions are clearly observed for all E_m throughout the inhomogeneously broadened PL band of the undoped MQW. For a given magnetic field, the PLE spectrum is independent of the monitored PL energy (apart from its overall intensity). In the case of the p-type doped MQW, the PLE Landau transitions are observed only for E_m in the high-energy wing of the PL band. The Landau transitions are then very similar in energy, but much broader than those observed in the undoped MQW. For E_m in the lower parts of the PL band, the Landau transitions are greatly broadened and can hardly be observed in the very low-energy tail of the PL band. Figure 3 shows the PLE spectra of the p-type doped MQW monitored at three different PL energies and observed under various magnetic fields. It is observed that for a given B, the width of the Landau PLE bands increases for E_m in the low-energy part of the PL band. We found that for $E_m=1.592$ eV [point (c) in Fig. 3], the Landau transitions are unobservable for $B\leqslant 8$ T.

In order to compare the dependence of the Landau PLE transitions on B, we measured their average width for both

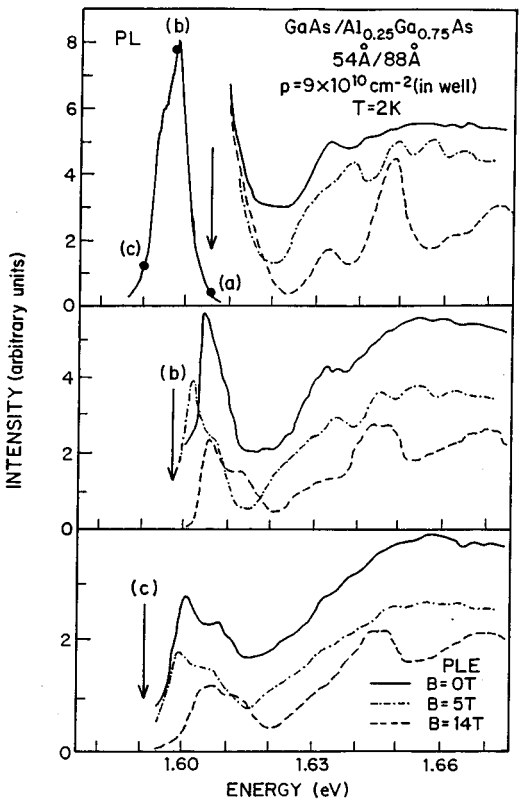

FIG. 3. The PLE spectra for the p-type doped MQW observed under the applied magnetic fields of 0, 5, 14 T and monitored at different energies (marked on the PL band): (a) E_m=1.605 eV, (b) E_m=1.597 eV, (c) E_m=1.590 eV.

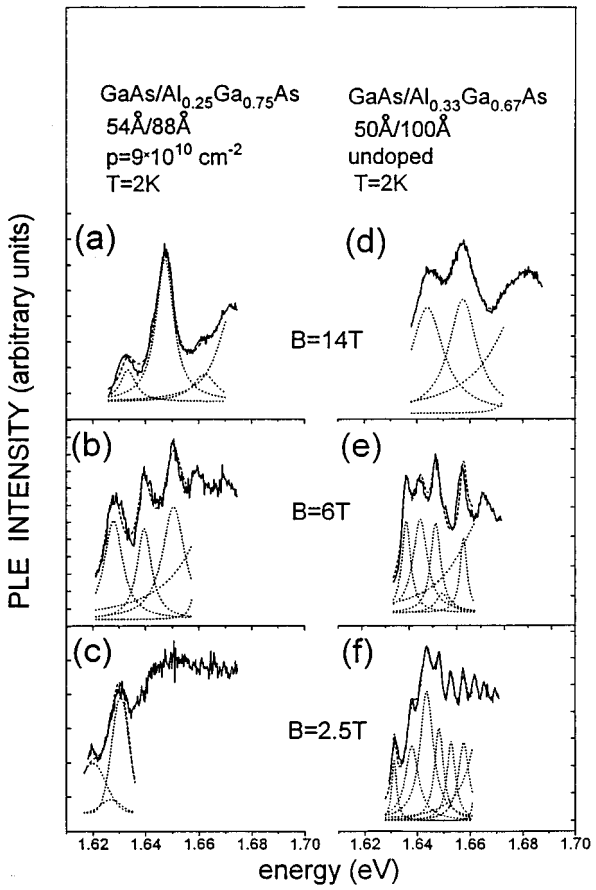

FIG. 4. The PLE spectra (full line) for the p-typed doped MQW [(a)–(c) with E_m=1.605 eV)] and for the undoped MQW [(d)–(f) with E_m=1.618 eV]. They are fitted to multiple Lorentzian functions (dotted line) at three indicated values of the magnetic field. The result of the fitting is shown by a dashed line (essentially coincident with the experimental curve).

the p-type doped and the undoped MQW's by resolving the PLE spectra, as shown in Fig. 4(a)–4(c) and 4(d)–4(f), respectively. We fit the PLE line shapes (full line) to multiple Lorentzian functions (dotted line) by adjusting the Lorentzian widths and positions. The results of the fitting are shown by a dashed line for three values of the magnetic field (essentially coincident with the experimental spectra). In Fig. 5, we present the measured width of the PLE transitions as a function of B for the p-type doped and undoped MQW's. For each value of B, the experimental bar center is the measured average width over the resolved transitions. The bar half length is the mean deviation of the different Landau transitions.

III. ANALYSIS

The experimental observations that are detailed in Sec. II, can be summarized as follows: In both undoped and p-type doped MQW's, the PLE spectra were observed in the spectral range above the ($e1$-hh1) gap and under an applied magnetic field. The monitored energy was varied throughout the PL band that is due to the radiative recombination of excitons. In the p-type doped MQW, the low-energy part of the excitonic PL band is due to excitons bound to impurities,[12,13] while the high-energy part arises mainly from the recombination of delocalized excitons scattered by intrinsic potential fluctuations.[16,17] The PLE spectra of the undoped MQW are independent of E_m and the Landau transition width shows an approximate $\sqrt{B}$ dependence. The PLE spectra of the p-type doped MQW show a significant broadening of the Landau transitions with decreasing E_m, but their bandwidth is almost independent of B.

The main difference between the p-type doped and the undoped systems is associated with different types of potentials acting on the photocreated carriers. In the undoped MQW, the $\sqrt{B}$ dependence of the Landau transition width indicates the short-range nature[4] of the intrinsic potential, which is probably due to interface roughness and local defects. For the p-type doped MQW, on the other hand, the doping produces a long-range potential that dominates over the intrinsic one, as confirmed by the Landau transition width being nearly independent of B. We suggest that this potential is due to randomly distributed charged acceptors appearing as a result of compensation by unintentionally incorporated donors. The presence of this strongly localizing Coulomb potential changes the character of the optical transitions between the electron and the hole Landau subbands, as well as the carrier dynamics during (phonon-assisted) energy relaxation. The transition rates of localized carriers are sensitive to the spatial separation between initial and final states. This results in appreciable dependence of the PLE spectra on E_m, as it varies from the high-energy excitonic PL band (essentially delocalized excitons) to its low-energy tail

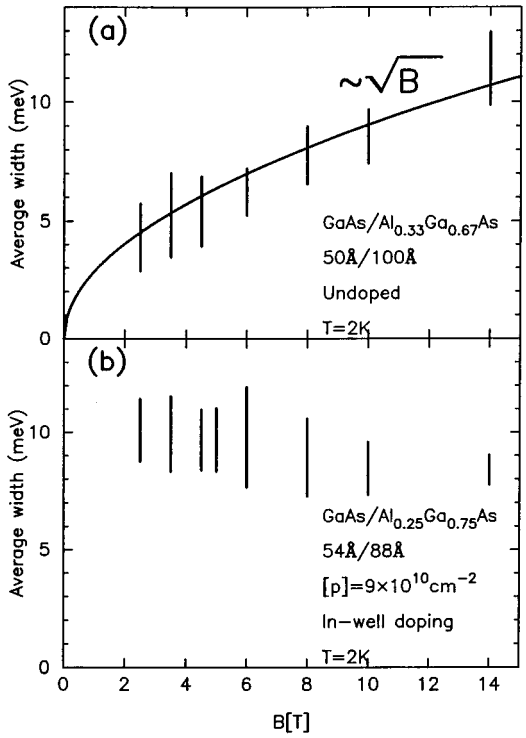

FIG. 5. The full width of the Landau PLE transitions, as a function of magnetic field for (a) the undoped MQW (the solid line is a fit to a $\sqrt{B}$ dependence) and (b) the p-type doped MQW. For each value of B, the center of the experimental bar is the average value over the resolved Landau transitions. The bar half length stands for the mean deviation.

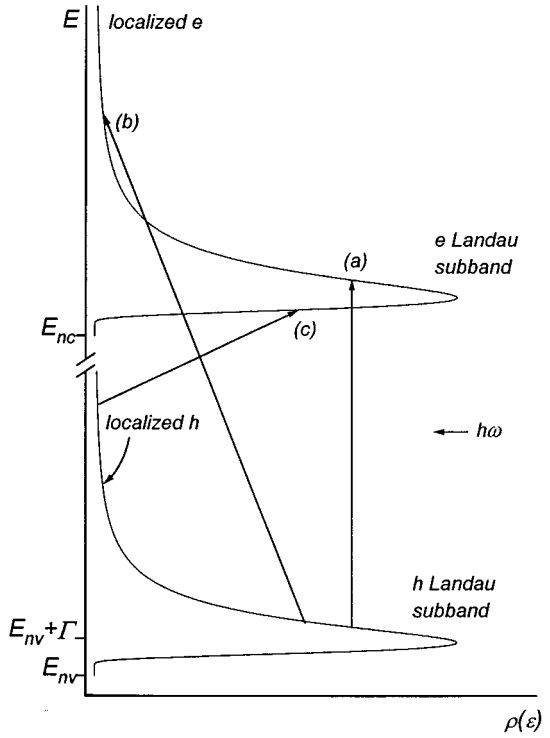

FIG. 6. A schematic description of the magneto-optical interband transitions between electron and hole Landau subbands in the presence of charged acceptors that are randomly distributed over the QW plane. E_{nc} and E_{nv} denote the respective Landau levels, Γ is the energy scale of the subband density of states $\rho(E)$ [see Eq. (1) in the text]. Three types of transitions are shown. (a) Vertical transitions with the photon energy $\hbar\omega \approx E_{nc}-E_{nv} \equiv E_{ng}$ corresponding to inter-Landau-level gap. These create mainly delocalized e-h pairs. (b) Transitions with $\hbar\omega > E_{ng}$ corresponding to the creation of acceptor-localized electrons and mainly delocalized holes. (c) Transitions with $\hbar\omega < E_{ng}$ corresponding to the creation of acceptor-localized holes and mainly delocalized electrons.

corresponding to the emission of strongly localized excitons.

In order to understand this point, let us consider optical transitions between electron and hole Landau subbands for a QW that contains charged acceptors, as shown in Fig. 6. In the limit of high magnetic fields, the subbands have the same structure: the high-energy edge states are localized on the charged acceptors, while the states of maximal density (close to the unperturbed Landau levels E_{nc} and E_{nv} for the electron and the hole, respectively) are extended or delocalized with respect to a single charged acceptor. Therefore, absorbed photons of energy $\hbar\omega \approx E_{nc}-E_{vc} \equiv E_{ng}$ corresponding to the inter-Landau-level gap [vertical transitions (a) in Fig. 6] create mainly delocalized e-h pairs. On the other hand, for photon energies $\hbar\omega \neq E_{ng}$ [transitions (b) and (c) in Fig. 6], at least one of the created carriers is strongly localized. Thus, the observed broadening increase of an individual Landau PLE transition with decreasing E_m essentially reflects the fact that e-h pairs photocreated at the transition peak relax mainly to the intrinsic exciton states monitored at high E_m, while those photocreated at the transition tails correspond to preferable relaxation into the low-energy extrinsic exciton states. For a quantitative evaluation of this effect, we consider the consecutive stages of the PLE process: (1) creation of an electron-hole pair by photon absorption and (2) relaxation of this pair into an excitonic state in which it recombines radiatively (at the monitored energy).

We assume a random distribution of charged acceptors, the limit of high magnetic fields and no excitonic effects. Then, the density of states (calculated in detail in Appendix A) for both electron and hole is

$$\rho(\epsilon) = \frac{1}{\pi\lambda^2}\frac{\Gamma^2}{\epsilon^3}\exp\left(-\frac{\Gamma^2}{\epsilon^2}\right), \tag{1}$$

where ϵ is the electron (ϵ_c) or hole (ϵ_v) subband energy measured from the respective unperturbed Landau levels and $\lambda \equiv \sqrt{hc/eB}$ is the magnetic length. $\Gamma \equiv 2e^2/\kappa\sqrt{\pi N}$ represents a characteristic subband energy scale, where N is the areal density of charged acceptors and κ denotes the GaAs dielectric constant. The states at the subband edge with $\epsilon \gg \Gamma$ are localized on a single charged acceptor, while for $0 < \epsilon \leqslant \Gamma$ the states have large, but finite (Anderson) localization lengths.[18] The degree of localization can be expressed, in the simplest form, by a Gaussian wave function with an effective length inversely proportional to ϵ, as follows:[3,7,8]

$$\Psi_\epsilon(r) = \frac{1}{\sqrt{\pi\alpha}}\,\epsilon\,\exp\left(-\frac{r^2\epsilon^2}{2\alpha^2}\right), \tag{2}$$

where α is the coupling constant that depends on the potential: $\alpha \sim (e^2/\kappa)$. Note, that, in this simplified model, the description of the Landau subbands is independent of the Landau index n.

This wave function can be used in order to obtain the dependence of inter-Landau-subband (conduction-valence) transition matrix element P_{vc} on the electron and hole subband energies as follows:

$$P_{vc}(\epsilon_c,\epsilon_v)\equiv|\langle\Psi_{\epsilon_c}\Psi_{\epsilon_v}\rangle|=\frac{2\epsilon_c\epsilon_v}{(\epsilon_c^2+\epsilon_v^2)}. \tag{3}$$

Note that if we used the exact electron and hole wave functions in the limit of a high magnetic field[9] [instead of the approximated ones, Eq. (2)], there would be no broadening of the Landau transitions, i.e., $P_{vc}(\epsilon_c,\epsilon_v)\sim\delta(\epsilon_c-\epsilon_v)$. This is a result of the identical Landau states for electrons and holes, when the respective long-range impurity potentials differ only in sign. The physical reason for a finite broadening is the impurity-induced Landau subband mixing that should be still effective at the range of applied magnetic fields. However, as B increases from 2.5 to 14 T, the admixture decreases and this leads to the small ($\simeq$10%) decrease in the observed transition width [Fig. 5(b)]. The analysis that explicitly deals with admixing the Landau subbands is much more complicated. For the present purpose, it is sufficient to take into account the localization property of the electron and hole subband edge states in order to obtain a qualitative agreement with the experiment.

Within the same framework of the approximate wave functions [Eq. (2)], the acoustic phonon-assisted relaxation rate between the carrier initial state $\Psi_\epsilon(r)$ ($\epsilon=\epsilon_c$ for an electron and $\epsilon'=\epsilon_v$ for a hole) and the final state $\Psi_{\epsilon'}(r)$ will be proportional to

$$M(\epsilon,\epsilon')\sim\sum_{\mathbf{q}_\parallel}\left|\int\Psi_\epsilon(r)\Psi_{\epsilon'}(r)e^{i\vec{\mathbf{q}}\vec{\mathbf{r}}}\mathbf{d}^2\vec{\mathbf{r}}\right|^2. \tag{4}$$

Here, $\mathbf{q}_\parallel$ is the in-plane phonon wave vector and the sum is over all energetically allowed $\mathbf{q}_\parallel$. Energy conservation requires $\hbar v_s\sqrt{\mathbf{q}_\parallel^2+q_z^2}=\Delta E$, where v_s is the sound velocity (for GaAs the average value[15] is 5×10^5 cm/sec). ΔE is the carrier energy transferred into the phonon field. The z component of the acoustic-phonon wave vector q_z is assumed to be unrestricted.

After integration and summation over $\mathbf{q}_\parallel$ from 0 to $\Delta E/\hbar v_s$ Eq. (4) yields

$$M(\epsilon,\epsilon')\sim\frac{4\epsilon^2\epsilon'^2}{\epsilon^2+\epsilon'^2}\frac{\eta^2}{(\Delta E)^2}\,(1-e^{-[(\Delta E)^2/(\epsilon^2+\epsilon'^2)\eta^2]}), \tag{5}$$

where $\eta\simeq(\hbar v_s/\alpha)$ is a dimensionless constant which characterizes the strength of the localized carrier-phonon coupling and has the value of $\eta\simeq10^{-2}$ for GaAs.

We note that, if the states $\Psi_e(r)$ and $\Psi_\epsilon(r)$ belong to the same Landau subband, i.e., $\Delta E=\epsilon-\epsilon'$, the transition rate given by Eq. (5) will decrease very quickly with increasing ΔE, namely, it becomes negligible for $[|\epsilon-\epsilon'|/(\sqrt{\epsilon^2+\epsilon'^2})]\geqslant\eta$. Therefore, acoustic phonon-assisted relaxations within a single Landau subband are essentially excluded. However, for relaxation into an excitonic state (or for inter-Landau-subband relaxation), where $\Delta E>\epsilon$ and $\Delta E>\epsilon'$, Eq. (5) is reduced to a simple form:

$$M(\epsilon,\epsilon')\sim\eta^2\frac{4\epsilon^2\epsilon'^2}{(\Delta E)^2(\epsilon^2+\epsilon'^2)}. \tag{6}$$

For the sake of simplicity, an excitonic state is considered within this model as a direct product of the decoupled electron and hole states with $n=0$.[19] We require, however, that the $n=0$ subband energy ϵ' be the same for the recombining electron and hole. It is different from the selection rule expressed by Eq. (3) and reflects, to some extent, the excitonic nature of the recombining state, where the Coulomb binding enhances the electron and hole spatial overlap.

The PLE spectrum is then taken to be proportional to the absorption efficiency between electron and hole Landau subbands [Eq. (3)] weighted by their direct relaxation rates [Eq. (6)], with energy $\Delta E\simeq E_{nc}+\epsilon'$ and $\Delta E\simeq E_{nv}+\epsilon'$, respectively:

$$\begin{aligned}I_{\epsilon'}(\omega)&\sim\int d\epsilon_v\int d\epsilon_c|P_{vc}|^2\delta(\epsilon_c-\epsilon_v+E_{gn}-\hbar\omega)\rho(\epsilon_v)M(\epsilon_v,\epsilon')\rho(\epsilon_c)M(\epsilon_c,\epsilon')\\&=K\int_0^{+\infty}dx\,\frac{x(x+\overline{\omega})\epsilon'^4\exp[-x^{-2}-(x+\overline{\omega})^{-2}]}{[x^2+(x+\overline{\omega})^2]^2(x^2+\epsilon'^2)[(x+\overline{\omega})^2+\epsilon'^2]\left(\frac{E_{nc}}{\Gamma}+\epsilon'\right)^2\left(\frac{E_{nv}}{\Gamma}+\epsilon'\right)^2},\end{aligned} \tag{7}$$

where $\overline{\omega}\equiv(|E_{nq}-\hbar\omega|/\Gamma)$, ϵ' is expressed in units of Γ, and the constant K lumps all the rest of the constants together.

Results of the numerical integration for different values of ϵ' are shown in Fig. 7. Note that there is a direct correspondence between the $n=0$ Landau subband energy ϵ' and the energy of an exciton bound to a charged impurity. It was shown by Dzyubenko[20] that, in a strong magnetic field, the binding energy of zero angular momentum excitons (which can recombine radiatively), in their ground state, is $\sim$0.94 times that of free carriers. Then, we relate them by this ratio and obtain the monitored exciton energy at the PL band. The calculated PLE Landau transition spectral line shapes show an increasing broadening with increasing ϵ', namely, with decreasing monitored exciton PL energy. The transition peak intensity reaches its maximal value for $\epsilon'\simeq0.5\Gamma$. This corresponds to the experimentally observed PL peak.

Figure 8 shows a comparison between the calculated line shapes width and the observed PLE band corresponding to the $n_{\mathrm{hh}1}=1\rightarrow n_{e1}=1$ transition. The best fit between the model and experiment is achieved for $\Gamma_{\mathrm{exp}}\approx7$ meV. Using the relation $\Gamma=(2e^2/\kappa)\sqrt{\pi N}$, we derive the density of charged acceptors $N\approx10^{10}$ cm^{-2}, which requires about 10%

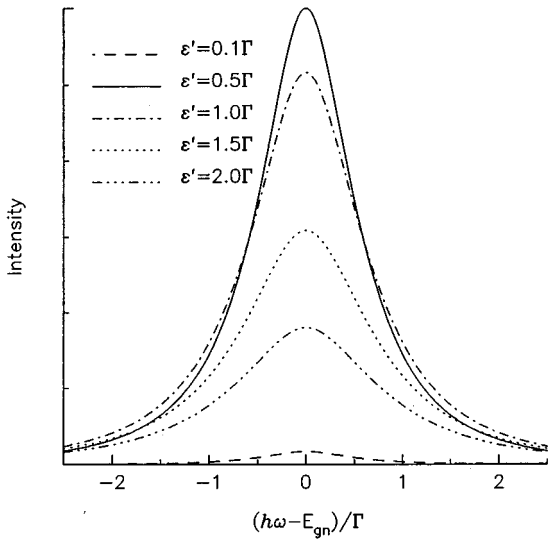

FIG. 7. The Landau PLE transition line shapes calculated by Eq. (7) for different values of carrier subband energy ϵ'. The line shapes are normalized to that calculated for $\epsilon' \simeq 0.5\ \Gamma$, which corresponds to the PL maximum.

compensation of the doping level. We emphasize that the calculated degree of compensation is probably overestimated. This is due to the approximation used in the model, to additional broadening mechanisms such as fluctuations in the acceptor location along the QW axis, compensated charged donors penetrating into the QW, intrinsic potential, or neutral acceptor scattering, and others.

It should be noticed that, at zero magnetic field, the influence of charged acceptors on the exciton states is apparently less appreciable than that of neutral acceptors. As it is well known,[21] the (A^-,X) complex is not stable in bulk GaAs, because of the small electron/hole mass ratio. In $GaAs/Al_xGa_{(1-x)}As$ QW's, this ratio is significantly larger, but until now there is no direct evidence for the existence of the (A^-,X) complex.

The situation is quite different in the presence of a strongly quantizing magnetic field. Neutral acceptors, contrary to charged ones, cannot produce a long range, strongly localizing potential, since the acceptor Bohr radius ($a_B \approx 20$ Å as deduced from the three-dimensional value[22]) is still smaller than the magnetic length $\lambda \approx 70$ Å at $B=14$ T. The potential of a single neutral acceptor can be obtained by the Gauss theorem and has the form

$$V(r)=(e^2/\kappa)(1/r+1/a_B)\exp(-2r/a_B).$$

For this potential, one can use scattering theory in the simple Born approximation[4] to evaluate the density of states energy width. Its upper limit is given by the short-range potential case[3,4] as

$$\Gamma_{\text{scatt}} < \sqrt{p/2\pi\lambda^2}\left|\int \mathbf{d}^2\mathbf{r}\ V(r)\right| \simeq 6.3(a_B/\lambda)\ \ (\text{meV}),$$

where $p \simeq 10^{11}\ \text{cm}^{-2}$ is the doping level. For a magnetic field of $B=14$ T it gives $\Gamma_{\text{scatt}} < 1.8$ meV, which is significantly smaller than the experimental value. Therefore, in spite of their large density, the neutral acceptors cannot produce the observed Landau transition broadening.

Finally, we conclude that the observed Landau PLE transition broadening is entirely due to the presence of strong localization centers—acceptor ions in the plane of confined carriers. In the undoped MQW, by contrast, there are intrinsic long-range potential fluctuations, which are due to interface roughness. These are, probably, too weak to localize the photogenerated high-energy electrons and holes, and, therefore, this effect is not observed in undoped MQW's.

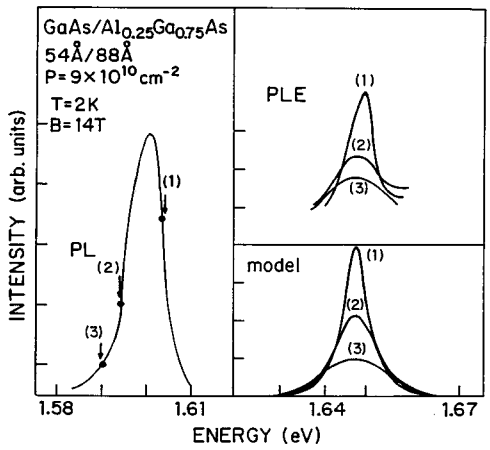

FIG. 8. A comparison between the experimentally observed PLE band (corresponding to the $n_{\text{hh1}}=1 \rightarrow n_{e1}=1$ Landau transition at $B=14$ T) and the calculated PLE line shapes at the three monitored energies marked on the PL spectrum.

IV. SUMMARY

We studied experimentally the Landau transition broadening for (in-well) p-type doped MQW's in PLE spectra monitored at E_m within the PL band and under applied B in the range 0–14 T. The appreciable increase of the observed Landau transition broadening with decreasing E_m within the exciton PL band evidences the presence of strongly localized electron and hole states at the edges of Landau subbands. The transition width is nearly independent of the applied B and this indicates the long-range nature of the localizing potential. By contrast, in an undoped MQW with similar well width, the Landau transition broadening does not show any effect of carrier localization, and thus the intrinsic potential fluctuations are of short-range type. It is suggested that in the p-type doped MQW, the carriers are localized by charged acceptors (which are present due to compensation) randomly distributed over the QW plane. Their density is low, so that the average distance between neighboring acceptors is larger than the magnetic length. Assuming the limit of high magnetic fields, we calculate the Landau subband density of states and the inter-Landau-subband acoustic phonon-assisted energy relaxation rates. The dependence of the PLE Landau transition line shape on the monitored exciton energy is obtained by calculating the absorption spectrum weighted by the relaxation rates into the exciton state recombining at E_m. It is shown that the increased Landau transition broadening is due to a preferred relaxation of impurity localized carriers into bound excitonic states. These excitons recombine radiatively in the low-energy part of the exciton PL band.

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APPENDIX: CALCULATION OF THE DENSITY OF STATES

Consider the motion of a photogenerated electron (or hole) of mass m and charge e in the plane of the QW when it is subjected to an impurity potential $V(x,y)$ and under a magnetic field B applied perpendicular to the QW plane. In the absence of impurities, the electron states are degenerate with respect to the different values of coordinates of the electron cyclotron rotation center (X,Y). However, even for a weak $V(x,y)$, this degeneracy is removed and each infinitely degenerate Landau level splits into a quasicontinuous (Landau) subband.

The density of states within one Landau subband will be obtained under the following assumptions: (a) The impurity potential is due to charged acceptors randomly distributed over the QW plane, where the mean interimpurity distance is much larger than the magnetic length. (b) The limit of high magnetic fields is assumed, namely, the width of Landau subbands is sufficiently small compared to the gaps between them. The Hamiltonian can be approximated by decoupled electron- and cyclotron-center-dependent terms as follows:[7,8]

$$H=\frac{\left(i\hbar\nabla+\frac{e}{c}\mathbf{A}\right)^2}{2m}+V(X,Y), \tag{A1}$$

where $\mathbf{A}$ is the vector potential. The commutation rule for the cyclotron center coordinates is $[X,Y]=-i\lambda^{-2}$, where λ is the magnetic length. This Hamiltonian can be exactly diagonalized for the case of an axially symmetric potential $[V(x,y)\equiv V(r)]$ and the energy eigenvalues are

$$E=E_n+V(\lambda\sqrt{2\nu+1}),\quad \nu=0,1\ldots, \tag{A2}$$

where E_n is the nth Landau level ($n=0,1...$). Substituting the Coulomb potential of a single charged acceptor $V(r)=(e^2/\kappa r)$ into Eq. (A2), we obtain the density of states at the edge of a given Landau subband,

$$\rho_{\text{edge}}(\epsilon)\equiv\frac{1}{S}\left|\frac{\partial\nu}{\partial E}\right|=\frac{e^4}{S\kappa^2\lambda^2}\frac{1}{\epsilon^3}. \tag{A3}$$

Here, $\epsilon\equiv E-E_n$ denotes the subband energy and S is the area per one impurity.

The next order of approximation takes into account the influence of neighboring (charged) impurity with a random distribution $P(l)=2\pi Nl\exp(-\pi Nl^2)$, where l is the interimpurity distance. The electron interaction with a nearest-neighboring impurity cuts off the subband spectrum by an energy $e^2/\kappa(l/2)$. Then, we have

$$\rho_l(\epsilon)\approx\rho_{\text{edge}}(\epsilon)\,\theta\left(\epsilon-\frac{2e^2}{\kappa l}\right). \tag{A4}$$

Averaging $\rho_l(\epsilon)$ over the impurity distribution and setting $S=(1/4N)$ in Eq. (A3), we finally obtain

$$\rho(\epsilon)=\frac{1}{\pi\lambda^2}\frac{\Gamma^2}{\epsilon^3}\exp\left(-\frac{\Gamma^2}{\epsilon^2}\right), \tag{A5}$$

where $\Gamma\equiv(2e^2/\kappa)\sqrt{\pi N}$.

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