Free-to-bound and interband recombination in the photoluminescence of a dense two-dimensional electron gas

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(Received 17 December 2001; published 29 May 2002)

Low-temperature photoluminescence (PL) measurements of a pseudomorphic modulation-doped GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ quantum well containing a dense two-dimensional electron gas ($n_s = 1.6 \times 10^{12}$ cm^{-2}) in a magnetic field are reported. Two well-defined high-energy cutoffs of the PL spectra are observed. Results of the magnetospectroscopic study indicate that these cutoffs are due to the recombination of free electrons from the vicinity of the Fermi level with localized and free holes, respectively. The localization energy of the bound hole is determined. It is shown that the free-to-bound recombination is much more effective that the interband recombination in the investigated structure.

DOI: 10.1103/PhysRevB.65.233307 PACS number(s): 78.67.De, 78.55.Cr

I. INTRODUCTION

Pseudomorphic modulation-doped GaAs/InGaAs/AlGaAs quantum wells (QWs) are ideal systems for studying the properties of dense two-dimensional electron gases (2DEG). This is due to the large conduction band offset in such structures which enables a high-density (well above 10^{12} cm^{-2}) single-subband occupation of the QW. The photoluminescence (PL) from such structures results from two coexisting radiative recombination schemes: (1) an interband recombination mechanism involving free electrons and free holes, which is a direct transition in the **k**-space, and (2) an ''indirect'' optical transition process.[1] Although the ''indirect'' process has been observed in QWs containing a dense 2DEG for several years, there is still no clear evidence what the process is behind it. It has been suggested that the **k**-vector conservation rule can be broken due to the scattering of carriers on randomly distributed impurities and/or alloy fluctuations.[1–5] Another explanation involves hole localization[6–12] due to alloy composition fluctuations, interface defects or residual impurities. The ''indirect'' recombination process dominates the PL spectrum of the QWs with high-density 2DEGs at low temperatures and under weak excitation.[1–12] The recombination of electrons from the vicinity of the Fermi energy in this process gives rise to a well-defined PL cutoff at high energy.[1,2,5–8,13] It should be noted, that a similar PL cutoff should be observed at the energy $E = E_g + (1 + m_e^*/m_h^*) \times E_F$, where E_g is the QW energy gap, E_F is the Fermi level energy, and m_e^* (m_h^*) is the electron (hole) effective mass, if the density of photoexcited holes is high enough. Although the presence of such an additional cutoff in the PL involving high-density 2DEG has previously been reported,[14] it was attributed to a recombination involving the upper $n = 2$ electron subband in the QW. In this paper we investigate the PL involving a high-density 2DEG in a magnetic field. We observe two high-energy PL cutoffs and we identify them as resulting from the recombination of electrons close to the Fermi level with localized holes (free-to-bound recombination) and with free holes (interband recombination) respectively. The localization energy is also determined.

II. EXPERIMENTAL PROCEDURE

The structure under investigation was grown by molecular beam epitaxy. The structure consisted of a 750 nm GaAs buffer layer, followed by 100 nm of a short period (5 nm $Al_{0.2}Ga_{0.8}As$/5 nm GaAs) superlattice, a 310 nm of $Al_{0.2}Ga_{0.8}As$ back barrier, an 11 nm $In_{0.2}Ga_{0.8}As$ QW, and a 205 nm GaAs top barrier. The Si δ-doping ($n_D = 1.5 \cdot 10^{12}$ cm^{-2}) was positioned 10 nm from the QW in the back $Al_{0.2}Ga_{0.8}As$ barrier. A similar δ-doping was introduced 5 nm below the structure surface to saturate surface states.

PL measurements were performed in a magnetic field up to 9 T. The same 600 mm thick optical fiber was both used for laser excitation (Ar^+ ion laser, $\lambda = 514.5$ nm) and emitted light collection. The sample was immersed in liquid helium and mounted in close proximity to the end of the fiber. The collected light was dispersed by a monochromator and focused on a N_2 gas cooled InGaAs photomultiplier. Standard lock-in techniques were used for the data acquisition.

III. RESULTS

A PL spectrum from the sample measured at $T = 4.2$ K is shown in Fig. 1. In this study we focus our attention on the high-energy part of the spectrum. Two PL cutoffs can be observed in the spectra at the energy E_1 and E_2 (see Fig. 1).

In order to identify the origin of the high-energy PL (E_1

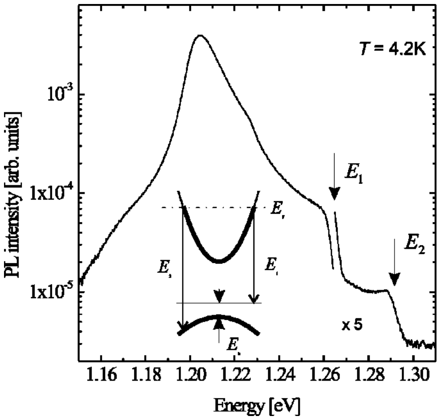

FIG. 1. Photoluminescence spectrum of the modulation doped GaAs/InGaAs/AlGaAs QW with a high density of the 2DEG measured at $T=4.2$ K in zero magnetic field. Two PL cutoffs at the energies E_1 and E_2 (see long arrows) are shown. Recombination scheme for the PL observed at E_1 and E_2 is shown in the inset.

$<E<E_2$) we performed measurements of the PL-intensity magneto-oscillations. The PL intensity is monitored at constant energy as a function of magnetic field. As can be seen from Fig. 2, at both the E_1 and E_2 detection energies the PL intensity oscillates as a function of B^{-1} with the same frequency. This is in contrast to lower frequency of magneto-oscillations detected at an intermediate energy E_3.

Measurements of the PL spectra at constant magnetic fields have also been performed. It was found that the PL spectra evolved into a series of peaks at high magnetic field. The spectrum at $B=4$ T is shown in Fig. 3. The peaks are characteristic for Landau level (LL) quantization of the 2D density of states. The separation of peaks in the main part of the spectrum ($E<E_1$) was smaller than at higher energies ($E_1<E<E_2$). Cyclotron resonance energies in the former and latter energy range were equal to 7.2 meV and 9.4 meV, respectively at $B=4$ T. Results of the PL spectra measurements at a constant magnetic field are summarized in Fig. 4.

IV. DISCUSSION

The PL cutoff observed at energy E_1 (see Fig. 1) is usually attributed to the recombination of electrons close to the Fermi level with holes from the top of the valence band, allowed due to scattering or localization effects. It is well known that the PL intensity measured at such a PL-cutoff energy oscillates with the characteristic frequency of the Shubnikov de Haas (SdH) oscillations.[2] Since the same frequency of the PL-intensity magneto-oscillations are observed in our experiment at E_2, this suggests that electrons close to the Fermi energy are also involved in the emission at E_2. The observation of the characteristic SdH frequency in the PL-intensity magneto-oscillations at two distinct detection energies can be explained in terms of separate processes involved in the recombination, which give rise to the PL at E_1 and E_2 energies. These, we suggest, are respectively the recombination of electrons close to the Fermi energy with localized holes and free holes. This also implies that the "indirect" process is a recombination of electrons with holes localized by a well-defined potential (free-to-bound recombination).

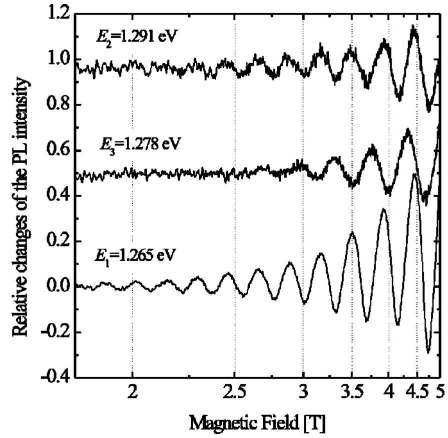

FIG. 2. Relative changes of the PL intensity $[I(B)/I(1\ \mathrm{T})]$ from the modulation doped GaAs/InGaAs/AlGaAs QW with a high density of the 2DEG measured at $T=4.2$ K at the PL cutoffs at the energies E_1 and E_2 as well as at an intermediate energy E_3. Linear background has been subtracted and offset has been added for more clarity.

In order to confirm our attribution, we analyze the behavior of the PL peaks due to the interband and the free-to-bound recombination processes in a magnetic field. If a parabolic dispersion of both conduction and valence bands is assumed, the interband recombination of free electrons from the nth electron LL and free holes from the nth hole LL in the 2DEG subjected to a perpendicular magnetic field results in emission at energy $E(n,n)$,

$$E(n,n)=E_g+(n+\tfrac{1}{2})\hbar\omega_c^*, \tag{1}$$

where $n=0,1,...$ is the number of LL, E_g is the energy gap, ω_c^* is the reduced electron cyclotron resonance frequency.

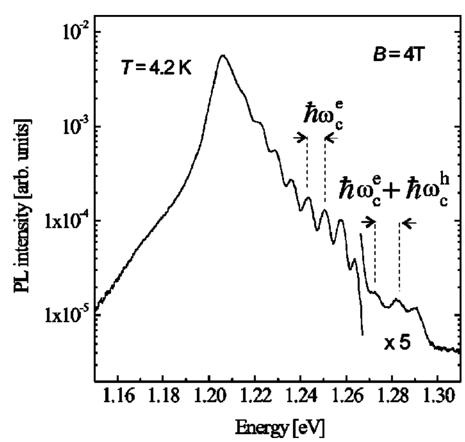

FIG. 3. Photoluminescence spectrum of the modulation doped GaAs/InGaAs/AlGaAs QW with a high density of the 2DEG measured at $T=4.2$ K in magnetic field $B=4$ T. Landau-level quantization with electron cyclotron energy $\hbar\omega_c^e$ (a sum of electron and hole quantization energies $\hbar\omega_c^e+\hbar\omega_c^h$) can be seen in energy range $E<E_1(E_1<E<E_2)$.

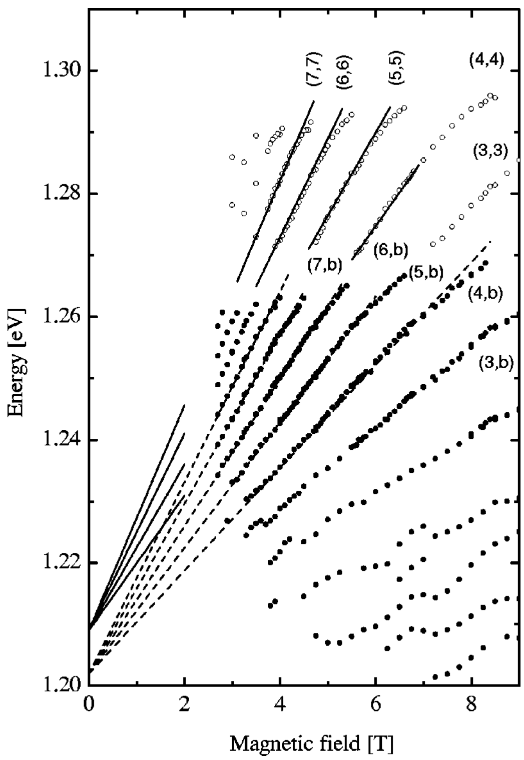

FIG. 4. Fanchart plot summarizing the results of magnetospectroscopic measurements of the PL from the modulation doped GaAs/InGaAs/AlGaAs QW with a high density of the 2DEG. Open circles represent the energies $E(n,n)$ of emission due to the interband recombination involving carriers from the nth electron and the nth hole Landau level. Closed circles represent the energies $E(n,b)$ of the emission due to the free-to-bound recombination involving electrons from the nth Landau level and bound holes.

Recombination of a free electron from the nth electron LL and a bound results in emission at energy, $E(n,b)$,

$$E(n,b)=E_g-E_b+(n+\tfrac{1}{2})\hbar\omega_c^e, \tag{2}$$

where E_b is the hole localization energy with respect to top of the valence band and ω_c^e is the electron cyclotron resonance frequency. Due to localization effects, the bound hole can provide a large dispersion of **k**-vectors.

Taking into account Eq. (1), it can be shown, that the density of states available for interband recombination at energy, $E'_{\rm det}=E_g+E_F(1+(m_e^*/m_h^*))$ peaks at magnetic fields B_n, where

$$E_F=\left(n+\frac{1}{2}\right)\hbar\,\frac{eB_n}{m_e^*}. \tag{3}$$

This results in the PL magneto-oscillations (as a function of inverse magnetic field) with a frequency of SdH oscillations. The electron density n_s found from the frequency of the PL-intensity magneto-oscillations at the energy E_1 was equal to $n_s=1.60\times10^{12}$ cm^{-2}.

Similarly, when the free-to-bound recombination is concerned, the density of states at $E''_{\rm det}=E_g-E_b+E_F$, also peaks in magnetic field given by Eq. (3). This means that the respective frequency of the PL-intensity magneto-oscillations is also equal to the frequency of the SdH.

Such an analysis explains why the same frequency of the PL-intensity magneto-oscillations can be observed at different detection energies. We therefore confirm that the PL cutoffs at energies E_1 and E_2 are due to the recombination of free electrons from the vicinity of the Fermi level with the bound holes and free holes, respectively. Note that $E_1=E_g-E_b+E_F$ and $E_2=E_g+E_F(1+(m_e^*/m_h^*))$, which leads to the following equation for the localization energy E_b:

$$E_b=E_2-E_1-E_F\frac{m_e^*}{m_h^*}. \tag{4}$$

In order to find the localization energy E_b, the values of electron and hole effective mass must be known, as well as the Fermi energy E_F. This information can be obtained from an analysis of the PL spectra measured at constant magnetic field (see Fig. 4).

Two sets of points can be identified in Fig. 4. The main PL emission ($E<1.27$ eV), ascribed to the free-to-bound recombination, is denoted with filled circles, whereas the PL emission ascribed to interband recombination ($E>1.27$ eV) is denoted by open circles. As can be seen from Fig. 4 the energies $E(n,b)$ of the PL spectrum ascribed to the free-to-bound process can be fitted well by straight lines. Significant deviations from the linear dependence can be seen at highest energies, when the Fermi energy is resonant with a particular LL. Such behavior has previously been observed, e.g., in InGaAs/InP QWs.[8] Departure from the linear magnetic-field dependence of the PL energy can also been observed at low energies ($E<E_1-E_{\rm LO}$) when hole-quasiparticle resonant polaron coupling takes place.[2–4,15,16] Fitted lines are separated by the electron cyclotron resonance energy $\hbar\omega_c^e$. The electron effective mass found from the fit was equal to $m_e^*=0.064m_0$ and the resulting Fermi energy, $E_F=60$ meV. Linear fits of the peaks due to the free-to-bound recombniation converge to a single energy $E(0)=1.202\pm0.001$ eV, which reflects the hole localization energy, i.e., $E(0)=E_g-E_b$.

A linear behavior of the emission energies $E(n,n)$ ascribed to the interband recombination can also be noticed in Fig. 4. The energy separation of those peaks is larger than for the case of the free-to-bound recombination and it must be equal to a sum of the electron and hole cyclotron energies $\hbar\omega_c^*=\hbar\omega_c^e+\hbar\omega_c^h$. The ratio of the electron to hole effective mass found from the separation was equal to 0.29. This leads to the hole mass equal to $m_h^*=0.19m_0$. Linear fits to the magnetic-field dependencies of the energies $E(n,n)$ give an extrapolated value of the energy gap in the QW equal to $E_g=1.209\pm0.002$ eV. The determination of the band gap energy E_g from such fits suffers from appreciable uncertainty. The linear part of the fan-chart is observed relatively far from the origin and its extrapolation to zero-field must be treated with some care. Moreover the likely dependence of the hole mass on the k-vector raises the question of the applicability of the parabolic approximation of the valence band. Both strain and confinement result in the splitting of the light hole and heavy hole valence bands.[17] It has been predicted that the heavy hole branch of the valence band in the InGaAs QW with ∼20% of In composition is higher in energy than the light hole band.[5] Mixing of both valence bands would occur in such a case, resulting in a complicated dependence of the hole mass on the hole *k*-vector.[17] In such a case the linear approximation of the PL-energies as a function of magnetic field may fail at lower energies. Nonparabolicity in the conduction band has also not been taken into account. Nevertheless the results of our analysis reflect a difference between the PL spectrum in the energy regions $E<1.27$ eV and $E>1.27$ eV and confirm its attribution to the free-to-bound and the interband recombination processes, respectively.

The confinement energy E_b of the bound hole state determined using Eq. (4) is equal to 10 meV, which is in agreement with previously reported values for similar systems.[11] This value agrees reasonably with that deduced from linear fits to the magnetic-field dependence of emission energies (7 ± 2 meV). In our opinion more sophisticated models of the valence band structure would very likely increase the precision of its determination.

Results of our study do not enable us to identify the hole localization potential. However the relatively small width of PL peaks due to free-to-bound recombination in magnetic field seems to favor its attribution to a potential with a well-defined energy, such as that of an ionized acceptor atom. There is also another experimental observation, which supports this argument. It was observed that the integrated PL intensity had pronounced dips around even LL-filling factors. Similar behavior has recently been observed in the PL from a QW with a high density of 2DEG purposely doped with acceptors.[18] It has been shown that the mean area of the localized-hole wave function determines the radiative lifetime of the free-electron and localized-hole recombination. The filling-factor dependent oscillations of the 2DEG screening of the acceptor potential result in changes to the extent of the bound-hole wave function and therefore to the PL intensity oscillations. In our opinion similar process occurs in our sample.

It needs to be mentioned that having focused our attention on the high-energy cutoffs, we do not address in this work the other details of the PL line shape. Our results can be explained in a simple one-particle model and many-body processes, which may be present in the investigated system, such as Fermi edge singularity[2,6,4,19] are not discussed. More theoretical effort is required to explain certain details of the PL, e.g., an apparent increase of the PL intensity near the PL cutoff at the energy E_2. This is however beyond the scope of the present experimental study.

V. CONCLUSIONS

In conclusion we have identified the interband and the free-to-bound recombination in the PL of a high-density 2DEG in the pseudomorphic modulation-doped GaAs/InGaAs/AlGaAs QW. We have shown that both recombination processes, which involve electrons close to the Fermi level give rise to the PL cutoff at distinct energies. The interband recombination is much less intense than the free-to-bound recombination in this energy region. The localization energy of the bound hole state involved in the latter process has been measured.

ACKNOWLEDGMENTS

A.B. kindly acknowledges valuable discussions with A. Sachrajda, Z. Wilamowski, and A. Wysmolek. Support from the EC under Contract No. HPRI-CT-1999-00069 (Access to Research Infrastructures) is kindly acknowledged.

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