Fine structure in the photoluminescence line of a quasi-2D electron Landau level: Initial or final state origin?

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Magnetophotoluminescence spectra of modulation-doped AlGaAs/InGaAs/GaAs asymmetric single quantum wells with a partially occupied second quantum-well electron subband exhibit a pronounced fine structure in a recombination line of electrons from the completely occupied zeroth Landau level of the first subband with photoexcited holes. The test experiment has shown that this structure originates from different initial states in the electron–hole recombination transition.

1. Occupation of the second quantum-well electron subband in asymmetric δ-doped semiconductor heterostructures strongly affects their magnetooptical spectra.[1–5] A Landau fan of the first quantum-well subband is far from linear in this case, and it exhibits highly pronounced kinks at low temperatures.[4] This behavior is attributable, first of all, to the change in the potential profile in the vertical direction with magnetic field due to the electron redistribution between the two subbands. The contribution of the intersubband Coulomb interaction effects and the sample inhomogeneities with carrier localization can be of importance. Usually, these two effects are virtually indistinguishable.

In our studies of asymmetric δ-doped AlGaAs/InGaAs/GaAs single quantum wells (QWs) we have observed abrupt kinks in the Landau fan at low temperatures. Additionally, a well-resolved structure was found in the recombination line of electrons and photoexcited holes in their ground states, i.e., the zeroth Landau level (LL) in the first quantum-well subband. This occurs in certain magnetic fields, H, in the case of a small occupation of the second electron subband, n_2.

The presence of such a fine structure has been reported earlier in δ-doped AlGaAs/GaAs heterojunctions, whose photoexcited holes are localized at specially introduced acceptors.[5] This fine structure was shown to originate from the inhomogeneities of the sample. An alternative interpretation has attributed such a structure in single AlGaAs/InGaAs/GaAs quantum wells to the effects of magnetoplasmon interaction.[6]

A fine structure in a photoluminescence (PL) line can result from the splitting of

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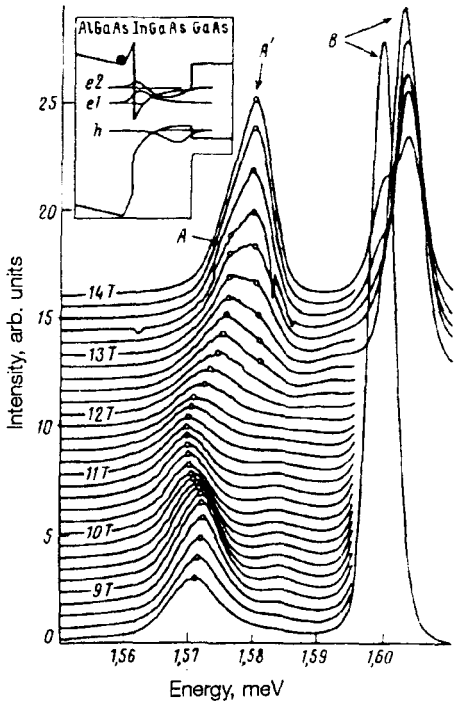

FIG. 1. A set of typical photoluminescence spectra at $P=20.9$ kbar, $T=2$ K under He–Ne laser excitation vs magnetic field from 8.2 to 14 T (the step is 0.2 T). Solid circles indicate peak positions. Inset: self-consistent QW potential profile at $H=0$ with energy level positions and wavefunctions of two electron (e1, e2) and one hole (h) quantum-well levels. Crossed circle indicates the spatial position of the Si δ-layer.

either the initial or the final state in the recombination transition. In this letter we report an experimental test of whether the observed fine structure originates from the initial or final state. A background information is that the zeroth electron LL in the first subband is completely occupied, and that an electron recombines with a single hole. This implies that the initial state in the recombination transition which we are discussing cannot be split by the Coulomb interaction, and that the sample inhomogeneities and carrier localization should be taken into consideration. In contrast, the final-state splitting can be explained by the Coulomb interaction effects.[6]

2. The experimental test can be described as follows. We excite carriers resonantly, with a photon energy, $\hbar\omega_{\rm exc}$, below the QW barrier. The excitation intensity is weak. If the PL line components originate from different initial states, they can have different excitation resonances. In this case the relative number of photoexcited holes attracted by each state and the relative intensities of the components in the spectrum can be sensitive to a change in $\hbar\omega_{\rm exc}$. In contrast, if the line splitting results from different final states, the spectra should be nonsensitive to the excitation energy, because the transition probabilities to each of the final states cannot depend on the history of photoexcited holes.

3. A molecular-beam-epitaxy grown sample has the following structure: i-GaAs substrate–1 μm GaAs buffer layer–250 Å $In_xGa_{1-x}As$ layer, $x=0.15$ (QW)–40 Å undoped $Al_yGa_{1-y}As$ buffer layer, $y=0.25$–δ-layer of 2.5×10^{12} cm^{-2} Si donors–250 Å undoped $Al_yGa_{1-y}As$ layer–100 Å GaAs cap layer. The potential profile of the sample in the vertical direction at $H=0$ is shown in the inset of Fig. 1.

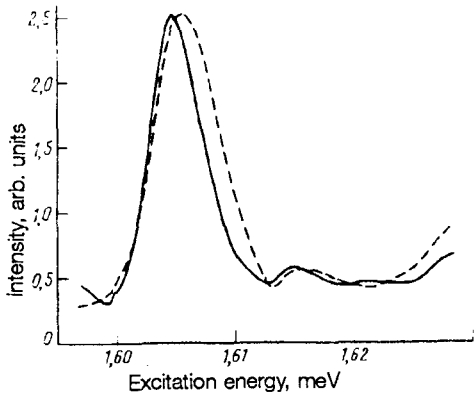

FIG. 2. PLE spectra (smoothed) at $H=12$ T recorded at 1.576 eV (solid curve) and at 1.582 eV (dashed curve).

A powerful method to control the density of 2D electrons, n_{2D}, is to apply a high quasi-hydrostatic pressure, P, in a low-temperature diamond-anvil cell.[7] The value of n_{2D} falls with pressure due to the electron redistribution between the QW and the deep localized states (mostly at the sample surface). The pressure was estimated from the energy of the quantum well PL lines.

The sample in the high-pressure cell was placed in a He cryostat, in which a superconducting solenoid generated a field up to 14 T. A weak He–Ne or Ti-sapphire laser excitation (about 10 mW/cm^2) was applied to the cell via a fiber, through which counterpropagated a signal from the sample. The luminescence was dispersed by a double monochromator RAMANOR (gratings with 1800 lines/mm, dispersion 1.4 Å/mm) and detected by a photo-electron multiplier which was connected to a photon-counting system.

4. The second electron subband occupation, n_2, oscillates in a normal H.[1–3] In our experiment we wanted to reduce n_2 to zero at certain magnetic field intensities. In the sample studied by us this occurred at a pressure in the range 18–25 kbar. A typical set of spectra vs H at $P=20.9$ kbar under He–Ne laser excitation (above the QW barrier, i.e., the GaAs gap) is shown in Fig. 1 (at this pressure a 2D electron concentration is about 1.5×10^{12} cm^{-2}). The lines A and B correspond to the recombination of electrons on the zeroth LL in the first and second subbands, respectively, with a hole on the zeroth LL in the first hole subband. Because of the small value of n_2, the initial state in the latter transition (line B) should have a single-particle excitonic character.[8]

In the H range from 10 to 14 T we clearly see a decrease of the component A with H and a concurrent increase of the component A'. In a certain range of H the two components coexist; their maxima are clearly resolved. The increase of the component A' correlates with the decrease in the intensity of the line B. This behavior is typical of our samples in the case of small n_2.

In our test experiment we first recorded the photoluminescence excitation (PLE) spectra with the monochromator tuned to the maxima of the A and A' components. A clear difference in the PLE spectra could indicate that A and A' components originate from different initial states. Figure 2 shows two PLE spectra at $H=12$ T recorded at 1.576 and 1.582 eV. A strong peak at 1.606 eV in both spectra corresponds to the

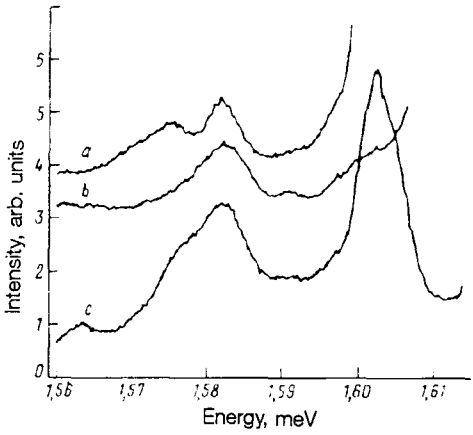

FIG. 3. PL spectra at $H = 12$ T recorded at 1.603 eV (a), 1.609 eV (b), and 1.636 eV (c).

transition between zeroth LLs in the first hole subband and the second electron subband. The spectra are very similar: there is a small shift in the position of the peak energy, but this might not be significant. Nevertheless, if this is the case, the photoluminescence spectra should be sensitive to small changes in $\hbar\omega_{\text{exc}}$ only within the width of this PLE peak.

Figure 3 shows the PL spectra at $H = 12$ T, recorded at an excitation detuned to the half-width of the PLE peak: 1.603 eV (a) and 1.609 eV (b). The difference between the two spectra is obvious. The relative intensities of the A and A' components are consistent with the small shift in the PLE peak position in Fig. 2. The 1.603-eV excitation is in resonance with the state that emits at 1.576 eV (A): more carriers (holes) are created and they recombine in this state. Similarly, the 1.609-eV excitation is in resonance with the state that emits at 1.582 eV (A').

The PL spectra are much less sensitive to $\hbar\omega_{\text{exc}}$ if it is beyond the PLE peak in Fig. 2. Spectrum (c) in Fig. 3 is recorded at $\hbar\omega_{\text{exc}} = 1.636$ eV, farther from the resonance but still below the barrier. The ratio of A and A' intensities is about an average of the spectra (a) and (b). This is typical for a wide range of $\hbar\omega_{\text{exc}}$.

5. From our results we draw an unambiguous conclusion that the fine structure in the PL line originates from different initial states in the electron–hole recombination transition. This implies that, contrary to Ref. 6, the Coulomb interaction effects cannot lead to the observed fine structure. These effects cannot split the initial states of either a hole (single on the Landau level) or an electron (the completely occupied LL). The sample inhomogeneities and carrier localization should therefore be taken into account.

We can make several suggestions about the nature of the different initial states in terms of the sample inhomogeneity. The intensity of the lines A and B decreases with A'. This behavior can be understood if we assume that for the line A (as well as B) a recombining hole is bound in an exciton with a second subband electron, while for the line A' a hole is unbound. Since the exciton binding energy contributes to the transition energy in the former case, the two components are shifted with respect to each other. Two types of holes correspond to two types of regions in the sample with nonzero or zero n_2. These regions are attributed to the long-wave random potential fluctuations due to the

density fluctuations of the δ-layer Si donors or the residual donors. On the scale of these fluctuations the localization of photoexcited holes is required (in Ref. 5 the recombining holes are bound at acceptors).

In conclusion, the δ-doped, asymmetric, single quantum wells with a slightly occupied second electron subband exhibit the fine structure in the recombination line of an electron in the completely occupied Landau level with a photoexcited hole. By means of magnetophotoluminescence experiments with resonant excitation we have proved that this structure results from different initial states in the electron–hole recombination transition. The fine structure should therefore be attributed to the sample inhomogeneity and carrier localization, but not to the Coulomb interaction effects.

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