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FINE STRUCTURE IN A PHOTOLUMINESCENCE LINE OF A QUASI-2*D* 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 partially occupied second size quantized 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 size quantized electron subband in asymmetric δ-doped semiconductor heterostructures strongly affects their magnetooptical spectra [1-5]. A Landau fan of the first size quantized subband is far from linear in this case, and it exhibits well pronounced kinks at low temperatures [4]. This originates, to begin with, from the change in the potential profile in the vertical direction with magnetic field due to electron redistribution between the two subbands. The contribution of intersubband Coulomb interaction effects and sample inhomogeneities with carrier localization can be of importance. Usually these two effects can be hardly distinguished.

In our studies of asymmetric δ-doped AlGaAs/InGaAs/GaAs single quantum wells (QWs) abrupt kinks in the Landau fan have been observed at low temperatures. Moreover, 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 size quantized subband. This occurs in certain magnetic fields, H, at a small occupation of the second electron subband, n_2.

Similar fine structure has been reported earlier in δ-doped AlGaAs/GaAs heterojunctions with photoexcited holes localized at specially introduced acceptors [5]. It has been shown to originate from sample inhomogeneities. An alternative interpretation has attributed a similar 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 either initial or 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 an electron recombines with a single hole. This implies that the initial state in the discussed recombination transition cannot be split by Coulomb interaction, and sample inhomogeneities and

carrier localization should be taken into consideration. On the contrary, the final state splitting can be explained by the Coulomb interaction effects [6].

2. The idea of the experimental test is as follows. We excite carriers resonantly, with a photon energy, $\hbar\omega_{exc}$, below the QW barrier. The excitation intensity is weak. If the PL line components originate from different initial states, these can have different excitation resonances. In this case the relative number of photoexcited holes attracted by each state, as well as the relative intensities of the components in the spectrum, can be sensitive to a change in $\hbar\omega_{exc}$. On the contrary, 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 prehistory of photoexcited holes.

3. A molecular-beam epitaxy grown sample has the following design: 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 sample potential profile in the vertical direction at H=0 is presented in the inset to Fig.1.

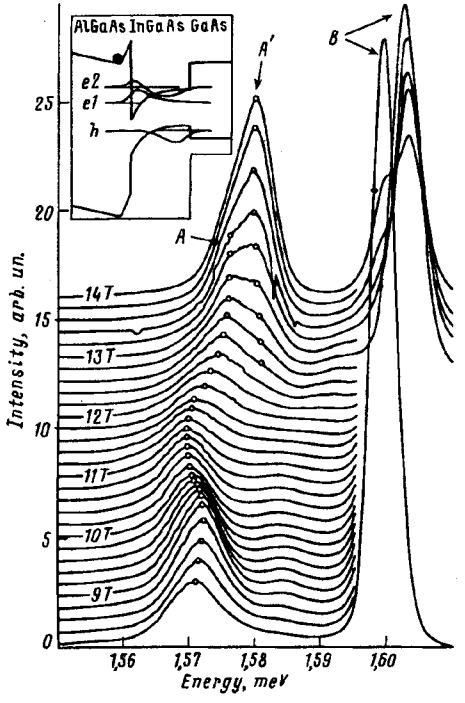

Fig.1. A set of typical photoluminescence spectra at P=20.9 kbar, T=2 K under He-Ne laser excitation vs magnetic field from 8.2 to 14 T (the step is 0.2 T). Solid circles indicate peak positions. Inset: self-consistent QW potential profile at H=0 with energy level positions and wavefunctions of two electron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

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

The sample in the high pressure cell was placed in a He cryostat with a superconducting solenoid generating a field up to 14 T. A weak He-Ne or Ti-sapphire laser excitation (about 10 mW/cm^2) was fed to the cell via a fiber, and a signal from the sample counterpropagated through the same fiber. 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 connected to a photon-counting system.

4. The second electron subband occupation, n_2, oscillates under normal H [1-3]. In our experiment we were interested in n_2 to turn to zero at some magnetic field intensities. In the sample studied this occurred under 18-25 kbar pressure. 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 presented in Fig.1 (at this pressure a $2D$-electron concentration is about 1.5×10^{12} cm^{-2}). 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. Due to small 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 one can clearly see a fall of the component A with H and a concurrent rise of the component A'. In some range of H the two components coexist, their maxima being clearly resolved. The rise of component A' correlates with the fall in the line B intensity. This behavior is typical of our samples in the case of small n_2.

In our test experiment, we first recorded photoluminescence excitation (PLE) spectra with the monochromator tuned to maxima of both A and A' components. A clear difference in PLE spectra could indicate that A and A' components originate from different initial states. Fig.2 shows two PLE spectra at H=12 T recorded at 1.576 eV and 1.582 eV. A strong peak at 1.606 eV in both spectra corresponds to the transition between zeroth LLs in first hole and second electron subbands. The spectra are very similar: there is a small shift in the peak energy position, but it might not be significant. Nevertheless if it is real the photoluminescence spectra should be sensitive to small changes in $\hbar\omega_{exc}$ just within the width of this PLE peak.

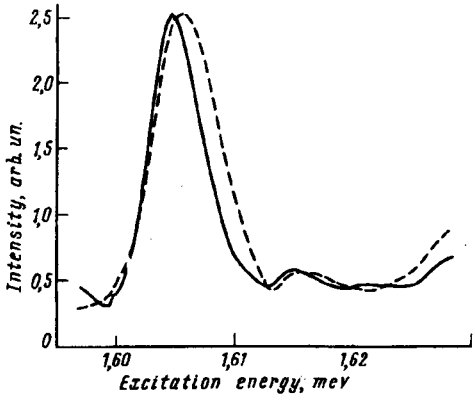

Рис.2

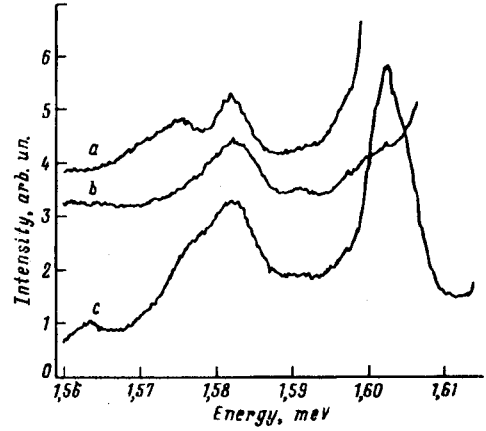

Рис.3

Fig.2. PLE spectra (smoothed) at H=12 T recorded at 1.576 eV (solid) and 1.582 eV (dashed)
Fig.3. PL spectra at H=12 T recorded under 1.603 eV (a), 1.609 eV (b) and 1.636 eV (c) excitation

Fig.3 shows the PL spectra at H=12 T, recorded under excitation detuned to the halfwidth 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 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 $\hbar\omega_{exc}$ if it is beyond the PLE peak in Fig. 2. Spectrum (c) in Fig. 3 is recorded under $\hbar\omega_{exc}$=1.636 eV, farther from resonance but still below 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 $\hbar\omega_{exc}$.

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 [6], the Coulomb interaction effects cannot lead to the observed fine structure. These effects can split the initial states of neither a hole (single on the Landau level) nor an electron (the completely occupied LL), hence sample inhomogeneities and carrier localization should be taken into account.

We can make some suggestions about the nature of the different initial states in terms of a sample inhomogeneity. The intensity of lines A and B falls with A'. This can be understood if we believe 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 non-zero or zero n_2. These regions result from the long-wave random potential fluctuations due to 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 [5] recombining holes are bound at acceptors).

In conclusion, the δ-doped asymmetric single quantum wells with weakly 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. Thus the fine structure should be attributed to the sample inhomogeneity and carrier localization, but not to the Coulomb interaction effects.

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