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Comparative Analysis of Giant Optical Fluctuations in GaAs Quantum Wells of Different Widths

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Abstract—A comparative analysis is performed of photoluminescence by two-dimensional electron systems with wide and narrow GaAs/AlGaAs quantum wells having close concentrations of electrons in the quantum Hall effect regime. Substantial differences in the intensity of fluctuations at occupation factor 2 are revealed. It is shown that the effect of great optical fluctuations of 2D electrons is much stronger for a wide quantum well. This is explained by the much stronger influence of electron–electron interaction on the energies and wave functions of 2D electrons.

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INTRODUCTION

A series of works in which results obtained experimentally and using a phenomenological approach were presented was devoted to the topic of giant optical fluctuations in quasi-two-dimensional electron systems in the quantum Hall effect regime [1–8]. The recombination of quasi-two-dimensional (2D) electrons with holes that arise during stationary photoexcitation of the system was studied for structures with GaAs/AlGaAs quantum wells and equilibrium electron concentrations of $n_s \propto 10^{11}–10^{12}$ cm^{-2}. Research on giant optical fluctuations also included experiments on Raman scattering [4, 7], which revealed giant fluctuations in the signal of intersubband Raman scattering that were similar to those in the intensity of photoluminescence (FL). One of the main goals of such research today is to study mechanisms that cause the coordinated 2D electron FL processes at occupation factor $\nu = 2$. In this work, we present new experimental data on giant optical fluctuations and attempt to construct a microscopic theory of this phenomenon. With a certain variety of methodological tools used in studying giant optical fluctuations, our experiments have so far lacked a comparative analysis of optical signal fluctuations that depend on the width of the 2D channel and quantum-dimensional effects. Let us recall that in our experiments, we detect only fluctuations of the optical signal as a consequence of a strongly correlated state in a 2D system. We have not detected any features in magneto-transport measurements (ρ_{xx}) made with the same magnetic fields. It is known that in magneto-transport and magneto-optical experiments, quantization of electron motion results in oscillations of the thermodynamic and kinetic characteristics of 2D systems. It was shown in [9] that magnetic oscillations of FL depend on the contribution from electrons of the first excited subband, and the origin of oscillations was associated with the elastic relaxation of carriers where the Landau levels of the main and excited subbands intersect. However, magneto-optical techniques and magneto-photoluminescence in particular are sensitive to the compressibility of an electronic system, since photoexcited holes can change its parameters [10]. When the magnetic field changes, a 2D electron gas passes through compressible and incompressible states. As a result, the electronic response to photoexcited holes differs, depending on the system's shielding, which is suppressed at the fully filled Landau level [11]. At the same time, high concentrations of 2D electrons exclude the possibility of exciton formation [12].

In this work, we assumed that a comparative analysis of fluctuations in FL intensity in structures with wide ($l = 250$ Å) and narrow ($l = 120$ Å) GaAs/AlGaAs quantum wells that have similar electron concentrations at $\nu = 2$ would reveal differences in the nature of giant optical fluctuations. We would expect changes in such parameters as the 2D electron wave functions of the main subband and the concentration of holes, which affect the intensity of FL and its correlations under the conditions of nonequilibrium occupation of the first excited subband.

EXPERIMENTAL

Our samples for measuring PL 2D intensity were structures with GaAs/$Al_xGa_{1-x}As$ ($x = 0.3$) quantum wells of different widths. The concentration and mobility of 2D electrons in narrow (l = 120 Å) quantum wells were $n_S = 3.38 \times 10^{11}$ cm^{-2} and $\mu = 2 \times 10^6$ cm^2/(V s). The corresponding values in wide (l = 250 Å) quantum wells were $n_S = 3.8 \times 10^{11}$ cm^{-2} and $\mu = 1.3 \times 10^6$ cm^2/(V s). Each test sample was placed in a helium cryostat with a superconducting solenoid that provided a magnetic field of 0 to 12 T. The experimental conditions, including the recording scheme, virtually corresponded to those used earlier to study structures with wide quantum wells. The optical scheme described in [6], which had a multi-light guide line recording the radiation from a spot of photoexcitation with a diameter of around 1 cm, was used to record the recombination radiation of Y2D electrons and study macroscopic spatiotemporal correlations of the radiation intensity. The spectra of PL 2D electrons near occupation factor $\nu = 2$ were measured to analyze the uniformity of electron density in the 2D layer. Pairs of seven light guides (2–8), arranged in a line with centers separated by approximately 1 mm and recording the signal from the corresponding points of each sample's surface, were selected for the simultaneous recording of spectra. Light guide 1 transmitted UV radiation from the laser to the sample. The spectra of FL in narrow quantum wells were studied in the range of magnetic fields $B = 6.9$–8.3 T ($B = 7$ T corresponds approximately to occupation factor $\nu = 2$) at T = 1.9 K. A laser with energy $E = 1.585$ eV and power $P = 50$ MW was used for photoexcitation. Photoexcitation close to resonant and corresponding to the energy of the electron transition from the hole zone to the first excited subband of the dimensional quantization (E_{1SB}) was also used as part of the experiment by employing a DLpro semiconductor laser with a tunable wavelength. A DFS-24 spectrometer (spectral resolution, 0.03 MeV) was used to record FL signals [6].

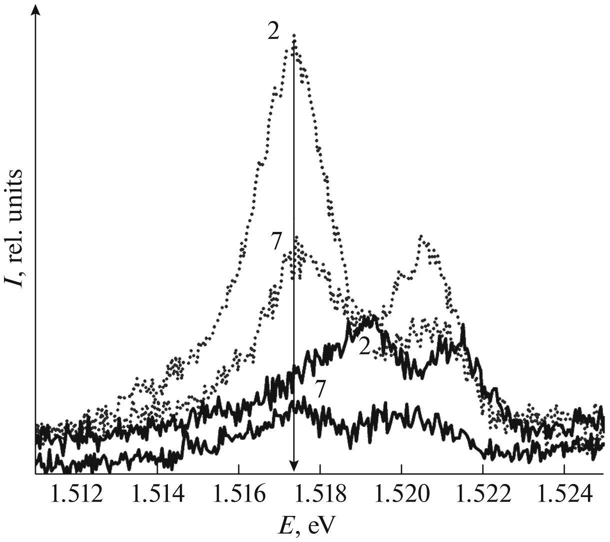

Fig. 1. PL spectra of a pair of light guides (2, 7) at (solid lines) $B = 7.55$ T and $\nu = 2.08$ and (dotted lines) $B = 7.78$ T and $\nu = 2$ for a 2D system with a wide (l = 250 Å) quantum well. The arrow shows the spectral coincidence of the maxima of the lines of main subband 0SB for the pair of optical fibers in the regime of the electron density macroscopic uniformity [8].

The FL signal of 2D electrons was recorded from the dimensional quantization main subband (E_{0SB}). The average intensity of radiation from 2D electrons for measuring fixed time $\langle I\rangle$, dispersion $\sigma^2 = \langle I^2\rangle - \langle I\rangle^2$, and ratio $\sigma^2/\langle I\rangle$ were estimated to determine the regime of giant optical fluctuations. A series of dependences of PL intensity on a magnetic field with small step ΔB in the above range of fields were recorded. Using the technique in [6] to record a signal from different points of a large sample in one plane allows us compare a system's spectral characteristics from different places of a sample simply and visually. In [7], this let us observe the mismatch of the position of the corresponding PL lines of 2D ground-state electrons upon resonant photoexcitation. When the field was scanned between factors $\nu = 3$ and $\nu = 2$, the positions of the 2D lines of any recorded pair of light guides converged as the field grew and coincided fully at the point of macroscopic uniformity ($\nu = 2$, $B = 7.78$ T) (Fig. 1). It was also found that the maximum noise of 2D electrons (giant optical fluctuations) is observed under the conditions of resonant photoexcitation in the first excited subzone. Upon the nonresonant excitation of systems with wide quantum wells, the positions of the 2D spectrum lines in different light guides coincided throughout the range of magnetic fields. Note that the effect of giant optical fluctuations in such systems at $\nu = 2$ was observed for resonant and non-resonant photoexcitation. In both cases, there was a state with macroscopic uniformity at $\nu = 2$ (within a sample's boundaries). Figure 2 presents the values of coefficient of correlation C_{ik} for different pairs of recording optical fibers in a non-resonant photoexcitation system with a wide quantum well:$\left\langle \Delta I_i \cdot \Delta I_k \right\rangle \Big/ \left(\sigma_i^2 \cdot \sigma_k^2\right)^{1/2}$ [8]. At temperatures of $T \leq 2$ K near factor $\nu = 2$, the FL signal of 2D electrons also displayed notable fluctuations in intensity (non-Poisson noise) in structures with narrow quantum wells. Figure 3a shows the spectrum recorded by light guide 5 for the line upon photoexcitation of the system by a laser diode with energy $E_1 = 1.585$ eV. The dispersion of σ^2 in these measurements had a maximum value of several tens (Fig. 3b), and the noise was distributed through a fairly wide range of $\nu = 2$ ($\Delta B > 0.5$ T). It should be noted that in a structure with a narrow quantum well, local inhomogeneities of the electron density of the ground state can play a much more prominent role than in struc-

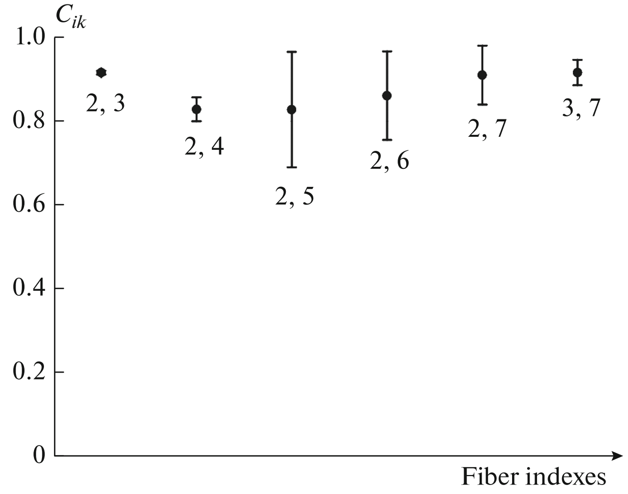

Fig. 2. Coefficient of correlation C_{ik} of PL intensity in the giant optical fluctuation regime for pairs of fibers (i, k) in a wide ($l = 250$ Å) quantum well [8].

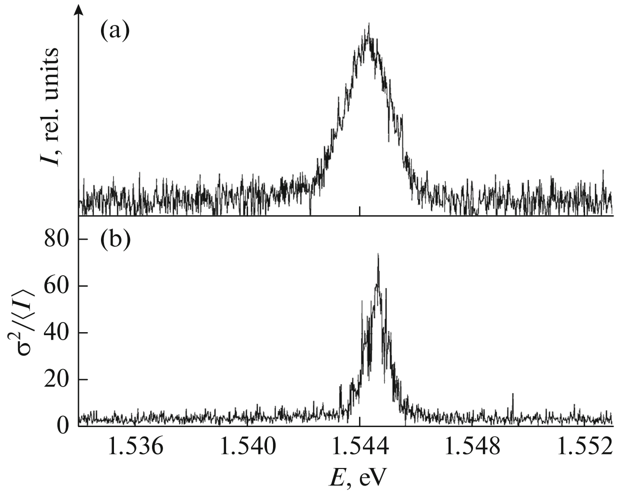

Fig. 3. (a) PL spectrum recorded by optical fiber 5 in a narrow (l = 120 Å) quantum well at B = 6.95 T (ν = 2.01); (b) ratio $\sigma^2/\langle I\rangle$ for this spectrum.

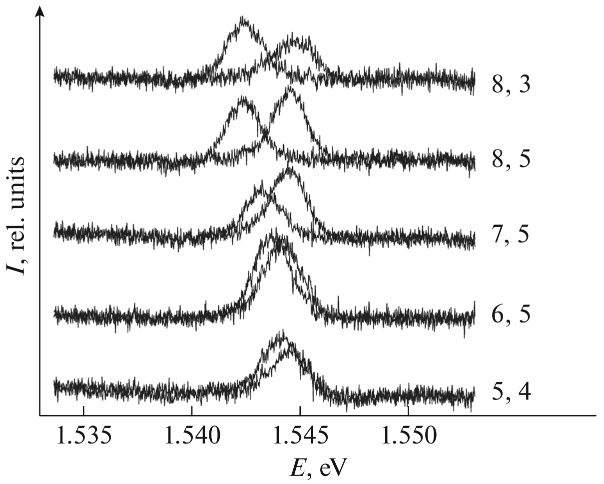

Fig. 4. PL spectra from different pairs of optical fibers at B = 6.95 T (ν = 2.01 and energy of photoexcitation E = 1.585 eV).

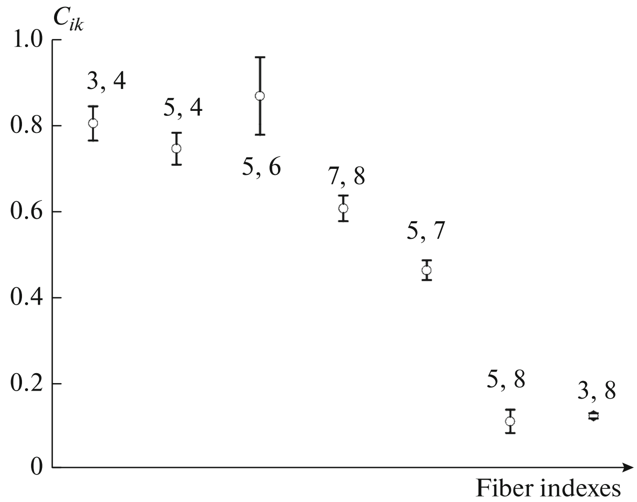

Fig. 5. Coefficient of correlation C_{ik} of integrated PL intensity in the giant optical fluctuation regime for the pairs of fibers (i, k) in a narrow (l = 120 A) quantum well.

tures with wide quantum wells. Under the conditions of a large photoexcitation spot, these local inhomogeneities are expressed by a considerable discrepancy of the spectral lines 0SB in different pairs of the recording light guides (Fig. 4). A comparison of the characteristic intensities of radiation in different pairs of recording light guides revealed local correlations at points corresponding to nearest pairs (Fig. 5). We may assume that the existence of a pronounced effect of macroscopic uniformity in a structure with a narrow quantum well depends on the magnitude of dimensional quantization. In such a system, the external potential seems to play a more important role than electronic correlations.

RESULTS AND DISCUSSION

Based on [5], we considered the system of interacting quasi-two-dimensional electrons in the structures with a wide (l = 250 Å) GaAs quantum well from the viewpoint of it being in one of two radiating states: (a) with homogeneous electron density in the 2D channel and (b) with inhomogeneous electron density in the 2D channel. In addition to telegraphic noise describing the change in the position of the PL line's maximum, there is instability that creates noise in the system near factor $\nu = 2$. Telegraphic noise is not a sufficient condition for the existence of such instability. As was shown in [7], however, the absence of telegraphic noise near $\nu = 2$ could indicate the system is divided into the local regions of extended states. According to our correlation analysis, these can be ring-shaped regions that enclose two maximally spaced recording light guides in a line. The diameter of such a ring is on the order of the lateral dimensions of a sample (1 cm). Or, so-called drops can form within one light guide (on the order of 1 mm). However, we emphasize that a characteristic feature of a structure with a wide well is the fundamental possibility of creating a state with homogeneous electron density. In structures with narrow quantum wells, we are probably dealing with an inhomogeneous 2D system throughout the range of magnetic fields, including $\nu = 2$. As noted in [13], the characteristic scale of potential spatial correlations is determined by properties of the scatterers. Long-range random potential is created by the layer of donors in a barrier; short-range random potential, by inhomogeneities in the plane of a channel (e.g., fluctuations in quantum well width). The maximum giant optical fluctuations effect (in terms of intensity fluctuations) is observed under conditions of resonant photoexcitation and the highest concentration of nonequilibrium electrons in the first subband. Indirect proof of the influence of the first subband electrons is the change in the intersubband splitting energy, which we discovered in experiments on inelastic light scattering in a wide well [4]. With a narrow quantum well, relaxation can be difficult because of the greater degree of intersubband splitting. This value for a narrow well exceeds the corresponding one for a wide well by 10–12 MeV. The maxima of the FL spectral lines for a narrow well are close only for neighboring pairs of recording optical fibers (see Fig. 4), testifying to the system's inhomogeneity in the plane even near $\nu = 2$.

The main difference between the 2D electrons in wide and narrow quantum wells is that the dependence on such basic parameters of the system as the levels of dimensional quantization E_n and the electron wave functions, which provide the distribution of the electron density in the direction of the normal to the well plane. For an estimate, we can compare the above values for two limiting cases: a rectangular quantum well with no Coulomb interaction and a triangular well. For a rectangular well without the final barrier height, we have

$$E_0(l) = \frac{\pi^2\hbar^2}{2m^* l^2}, \tag{1}$$

where m^* is the effective mass.

For narrow and wide quantum wells, energy E_0 has estimated values of around 40 and 9 MeV, respectively. Average distance of electrons $z_0 = l/2$ from the AlGaAs barrier is 60 and 125 Å, respectively (the electron density is concentrated in the quantum well center). For a triangular well modeling a system with l = 250 Å (a quantum well with unilateral doping), energy E_0 and distance z_0 depend on n_S [14]:

$$E_0(n_S) = \left(\frac{\hbar^2}{2m^*}\right)^{1/3} \left[\frac{9\pi^2 e^2}{2\varepsilon} n_S\right]^{2/3} \tag{2}$$

and

$$z_0(n_S) = \left(\frac{9\varepsilon\hbar^2}{16\pi m^{*2} e^2 n_S}\right)^{1/3}, \tag{3}$$

where ε is permittivity and e is the electron charge.

For $n_S = 3.8 \times 10^{-11}$ cm^{-2} we have $E_0 \sim 58$ MeV and $z_0 \sim 77$ A. It is obvious that the structures considered in this work are affected by both the width of the wells and the concentration of electrons. However, the rectangular well model is better for a narrow quantum well. The triangular well approximation, in which the electrons and holes are shifted to opposite edges and the effect of Coulomb interaction is stronger when the concentration of electrons changes, is better for a wide quantum well. At resonant photoexcitation, electron–hole pairs consisting of electron E_{1SB} and a two-dimensional hole from the valence band at the zero Landau level form in a quantum well. The concentration of such pairs is low, relative to n_S. Electron–hole luminescence relies on E_{0SB} electrons, of which there are many. Concentration of electrons E_{0SB} does not change appreciably. The lifetime of nonequilibrium carriers at the zero level of the first excited subband in such structures can be large enough to create a notable population on it. Elastic relaxation of the electrons from the first to the main excited subband has been confirmed by experiments on the optical detection of cyclotron resonance [13]. The intensity of luminescence is determined by the concentration of holes, which is equal to concentration of electrons E_{1SB}, and the transition matrix element. For a narrow quantum well, the matrix element is virtually independent of concentration of electrons E_{1SB}, along with other parameters of the 2D system. At the same time, the effect of electrons E_{1SB} can affect the transition matrix element and serve as an additional source of fluctuations for a wide quantum well in which recombining electrons and holes are separated in space.

CONCLUSIONS

A comparative analysis of fluctuations in FL intensity in quasi–two-dimensional electronic structures with wide (l = 250 Å) and narrow (l = 120 Å) GaAs/AlGaAs quantum wells that have close electron concentrations at $\nu = 2$ revealed considerable differences in the scale and nature of these changes. We suggest associating these differences with the greater dependence on the concentration of 2D electrons caused by Coulomb interaction for photoexcitation of the system under conditions of nonequilibrium occupation. A substantial factor affecting correlations of the intensity of radiation in the mode of giant optical fluctuations is the effect of electron–electron interaction, depending on the width of the quantum wells. Noise of non-Poisson intensity was observed when recording a FL signal in a 2D electron system with narrow quantum wells (the ratio of the dispersion to the average intensity $\sigma^2/\langle I\rangle$ was several tens). However, large-scale correlations of radiation intensity within a spot of photoexcitation (~1 cm), which are characteristic of systems with wider quantum wells, are not found in systems with narrow quantum wells. There are only local correlations at points of the 2D plane that correspond to the closest pairs of recording optical fibers (~1 mm). For a narrow quantum well, the giant optical fluctuation effect is observed in a wider range of magnetic fields near $\nu = 2$. The effect is noticeably stronger for a wide quantum well at $\nu = 2$, but quickly diminishes as we move away from it. The telegraphic noise of the spectral position, which characterizes two different states of the electronic subsystem, is weak. The response of the electronic 2D system under conditions of a large photoexcitation spot on the order of a sample's size depends largely on the system's uniformity. The electronic 2D system in structures with narrow quantum wells is obviously a spatially inhomogeneous state consisting of local regions with different occupation factors. Based on the model proposed in [7], 2D systems can be considered droplets of a dielectric Hall liquid surrounded by an electron gas. Noise exists in each of these regions in the absence of macroscopic correlations. Under the same conditions, experimental data on wide quantum wells indicate that at scales greatly exceeding those of long-range fluctuations of a random potential, a homogeneous state forms with $\nu = 2$ and the properties of an incompressible quantum fluid.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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