JETP Letters, Vol. 77, No. 6, 2003, pp. 295–299. Translated from Pis'ma v Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki, Vol. 77, No. 6, 2003, pp. 345–349.

Spatial Correlations of Recombination Radiation Intensities of Two-Dimensional Electrons under the Conditions of the Quantum Hall Effect

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Received February 11, 2003

Correlations have been studied between the recombination radiation intensities of a two-dimensional electron gas measured at different points of the sample with giant luminescence fluctuations in the quantum Hall effect regime. It has been found that the correlation of the radiation intensities measured under these conditions at different points of the sample separated by a distance of 1–3 mm is close to unity and disappeared in a threshold way with increasing temperature. It is shown that macroscopic spatial correlations also disappear if the electron system is artificially divided into two subsystems not connected with each other. *© 2003 MAIK "Nauka/Interperiodica".*

PACS numbers: 73.20.-r; 73.43.-f; 78.66.-w

1. Giant fluctuations that we observed previously in the luminescence intensity of a two-dimensional electron gas under the conditions of the quantum Hall effect [1] exhibit a number of completely unusual properties pointing to the fundamentality of the new phenomenon. Among these are the following properties: (a) the dispersion of radiation intensity fluctuations is anomalously high, (b) fluctuations are observed exclusively in the quantum Hall effect regime, (c) the range of magnetic fields at integer filling factors in which fluctuations can be observed is extremely narrow (less than 0.01 T), (d) fluctuations rapidly disappear as the temperature is raised above a critical one, and (e) the critical temperatures for even and odd filling factors are essentially different. The very possibility of observing giant intensity fluctuations in the radiation collected by a light guide from the surface of the sample about 1 mm in size already points to the existence of mechanisms in the system determining that recombination processes proceed consistently at macroscopic distances. The nature of these mechanisms is not clear at present; however, the necessity of studying spatial correlations in radiation fluctuations is evident. It is not inconceivable that luminescence intensity fluctuations are due to the effect of additional background illumination on the two-dimensional electron system. This background illumination serves to excite the luminescence signal, and although it creates a negligibly small concentration of electrons as compared to their dark concentration in the two-dimensional channel, it can nevertheless become significant because of an extremely fast variation of system parameters in the immediate vicinity of an integer filling factor. Another explanation is of a more fundamental character. It may be believed that the electron system undergoes a phase transition; that is, a new coherent macroscopic state of two-dimensional electrons described by a common wave function arises. In this case, the unity of wave function provides an exceptionally high degree of the uniformity of the concentration of electrons at macroscopic distances, which is manifested in the abnormally narrow peak of noise localized at an integer filling factor (the peak width at the filling factor scale is less than 0.001). In the case of this scenario, an analogue of the Josephson effect in the two-dimensional electron system in the quantum Hall effect regime and a manifestation of the phase of the common wave function of the coherent state should be sought. From the viewpoint of the theory of dynamic systems (see, for example, [2, 3]), it is appropriate to raise the question of whether the observed fluctuations are a random process or a manifestation of the deterministic chaos of the dynamic system with the phase space of a finite dimension. In the latter case, an effort can be made to determine the phase space dimension and to find the form of the strange attractor of the system. It is of course hardly probable that studies of this sort can unambiguously elucidate the microscopic reasons for the fluctuations; however, these can strongly help in constructing the theory of this phenomenon, because the phase space dimension is directly related to

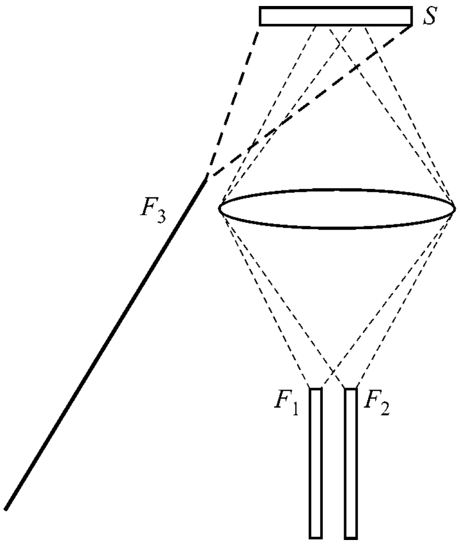

Fig. 1. Schematic diagram of the experiment.

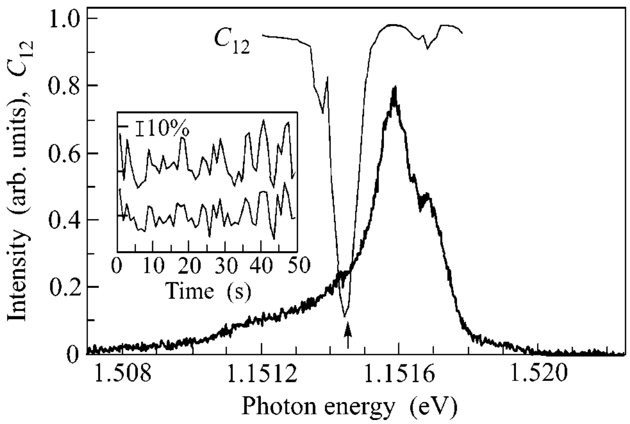

Fig. 2. Luminescence spectrum of two-dimensional electrons measured in a single quantum well with a width of 25 nm under conditions of the quantum Hall effect ($\nu = 2$, $n_s = 3.85 \times 10^{11}$ cm^{-2}, $B = 7.95$ T) at $T = 1.5$ K. Curve C_{12} corresponds to the spectral dependence of the correlation coefficient of luminescence intensities measured simultaneously in two different sections of the sample spaced at 1 mm (the inset shows time dependences of these luminescence signals). The arrow indicates the spectral position of the luminescence line from the GaAs buffer layer.

the number of independent differential equations describing the dynamic system. This work is devoted to a study of correlations between luminescent signals measured from two spatially separated regions of the sample surface under conditions of giant fluctuations of the radiation of two-dimensional electrons in the vicinity of the filling factor equal to 2. It is found that virtually complete correlation is observed for the radiation intensities measured at different points of the sample separated by a distance of 1–3 mm. It is shown that macroscopic spatial correlations disappear if the electron system is divided into two subsystems unconnected with each other.

2. Measurements were performed with high-quality samples containing a single GaAs quantum well, in which the radiative recombination of 2D electrons with photoexcited holes was studied. The samples were grown by molecular-beam epitaxy on a GaAs substrate by the following scheme: GaAs buffer layer 3000 Å thick, undoped GaAs/AlGaAs (30/100 Å) superlattice 13000 Å in total thickness, GaAs quantum well 250 Å thick, AlGaAs spacer 400 Å thick, and doped AlGaAs : Si layer (doping level, 10^{18} cm^{-3}) 650 Å thick. The characteristic mobility of 2D electrons in these structures at 3.8×10^{11} cm^{-2} was 1.3×10^6 cm^2 V^{-1} s^{-1}. The optical excitation of the sample was carried out by a laser light-emitting diode with a photon energy of 1.653 eV and the time instability of the radiation power less than 10^{-4}. A Monospec monochromator with a spectral resolution of 0.03 meV served as the spectral instrument. A semiconductor charge-coupled device (CCD) matrix was used for detecting the radiative recombination signal and for analyzing its intensity fluctuations. This allowed the entire luminescence spectrum to be measured simultaneously in the wavelength region of our interest. At the same time, the CCD matrix response speed (1 spectrum per minute) was quite sufficient for studying signal fluctuations, because the fluctuations at hand are predominantly of a low-frequency character with characteristic times on the order of tens of seconds. Sufficiently long sequences of spectra were recorded at a step of 1 s for studying the fluctuations. The characteristic duration of a series of spectra was 3000 s. The sample was placed in a helium cryostat inside a superconducting solenoid. The exciting radiation was delivered and the luminescence signals were collected using light guides as shown in Fig. 1. The radiation of the pumping laser was supplied to the sample through light guide F_3 0.4 mm in diameter, which gave a spot about 2–3 mm in diameter on the sample surface. Short-focus lens L constructed an image of the sample with a magnification close to unity in the plane where the ends of receiving light guides F_1 and F_2 were arranged. This symmetric optical scheme is the least critical with respect to the accuracy of the arrangement of the light guides and, therefore, minimizes the effect of misalignment, which inevitably arises on cooling to helium temperatures. The receiving light guides were 1 mm in diameter and were arranged right up to each other. As a result, we had the possibility of recording signals from two sections of the sample surface 1 mm in diameter each with distances between their centers of about 1.2 mm, which did not overlap with each other. The accurate alignment of the whole system was carried out in the following way. The sample was illuminated through the receiving light guides and the lens using a filament lamp. A screen of thin white paper was placed on the surface of the sample, and the sample and the screen were transferred along the optical axis until a sharp image of light guide ends F_1 and F_2 appeared on the screen. As a result, we could be assured that the sections of the sample surface from which signals were recorded did not actually overlap.

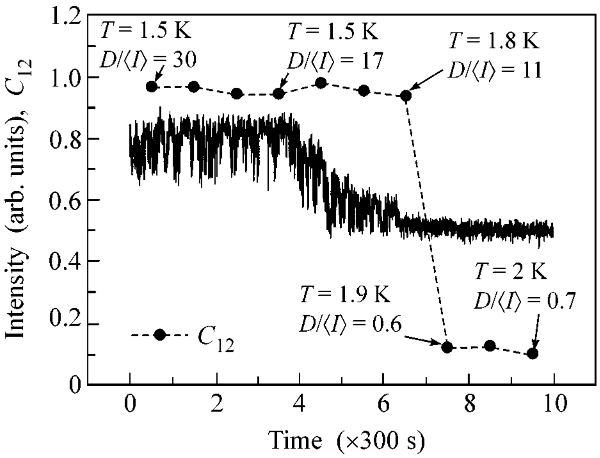

Fig. 3. Temperature dependence of the luminescence intensity measured at a maximum of the recombination line of two-dimensional electrons (1.516 eV) under conditions of the quantum Hall effect ($\nu = 2$, $n_s = 3.85 \times 10^{11}$ cm^{-2}, $B = 7.95$ T) at $T = 1.5$ K. Points in the figure indicate how the correlation coefficient C_{12} of two radiative recombination intensities of two-dimensional electrons measured simultaneously at two spatially distant points of the sample. The value of the ratio $D/\langle I \rangle$ is indicated for each point.

3. Figure 2 demonstrates the luminescence spectrum measured in a single quantum well with a concentration of 2D electrons of 3.85×10^{11} cm^{-2} in a magnetic field of 7.95 T, which corresponds to a filling factor $\nu = 2.00$. It is important that under these conditions the radiative recombination spectra measured from two different points of the sample with the use of two light guides spaced at about 1 mm coincided. This fact indicates that a 2D-electron system under conditions of the integer quantum Hall effect becomes uniform and the local electron concentrations at different points of the sample coincide with a high accuracy. This result is in good agreement with the fact that anomalous radiation intensity fluctuations are observed within an extremely narrow range of magnetic fields in the vicinity of integer filling factors that corresponds to the change in the filling factor by less than 0.005. Measuring with the use of two light guides allowed us to record the time evolution of radiation spectra from different points of the sample simultaneously, because the signals from the light guides were detected simultaneously by two different sections of one CCD matrix. This allowed us to perform a quantitative comparison of the parameters of giant radiation intensity oscillations at different points of the sample and to study spatial correlation effects. With this purpose, we calculated the correlation coefficient (see, for example, [3]) between the radiation intensities (I_1 and I_2) measured simultaneously from two different light guides

$$C_{12} = \langle \Delta I_1 \Delta I_2 \rangle / (D_1 D_2)^{1/2},$$

where $\langle I_i \rangle$ is the average intensity over the whole measurement time and $\Delta I_i = I_i - \langle I_i \rangle$, $D_i = \langle \Delta I_i^2 \rangle$ is the variance of I_i. A comparison of the results measured from different light guides showed that giant intensity fluctuations are observed simultaneously in the same narrow range of magnetic fields in the vicinity of an integer value of the filling factor equal to 2 (and also in the vicinity of $\nu = 4, 6, 8$). Therefore, it was possible to measure the correlation coefficient of fluctuating signals and its dependence on the wavelength in the emission spectrum. A typical example of measurements of anomalous radiation intensity fluctuations carried out with the use of two light guides under conditions of the quantum Hall effect at a maximum of the luminescence line is shown in the inset in Fig. 2. It is evident that strong correlation (phase coherence) is observed under these conditions for fluctuations of the two intensities. The spectral dependence of the coefficient C_{12} under conditions when the filling factor equals 2 ($B = 7.95$ T) is shown in Fig. 2 (curve C_{12}). It is evident that the coefficient C_{12} is rather close to unity for all the wavelengths corresponding to the luminescence of the 2D electron gas and drops virtually to zero in the vicinity of 1514.66 meV, where the contribution of bulk luminescence from the GaAs buffer layer (shoulder in the luminescence spectrum marked by an arrow in Fig. 2) dominates. Note that we identified luminescence lines from bulk GaAs by an analysis of the behavior of these lines upon varying the magnetic field and the concentration of 2D electrons [4]. It is directly followed from Fig. 2 that sections of the two-dimensional electron system spaced at about 1 mm can emit light in a strongly correlated way.

Tracing the temperature dependence of the correlation coefficient is of interest. We measured giant fluctuations under conditions when all the macroscopic parameters were fixed with the greatest possible accuracy and the temperature varied slowly with time. The results of the corresponding measurements are shown in Fig. 3. As the temperature increases, the luminescence signal somewhat decreases; however, it is more important that giant fluctuations disappear with increasing T. This is reflected in Fig. 3, where it is shown how the luminescence intensity measured at the line maximum (1.516 eV) varies. In addition, it is indicated in the same figure how the ratio $D/\langle I \rangle$ varies with temperature. In is evident that the ratio $D/\langle I \rangle$ takes an anomalously high value of about 30 at 1.5 K and sharply drops down to normal Poisson values (0.5–1) at $T > 1.9$ K. As to the correlation coefficient, it is evident

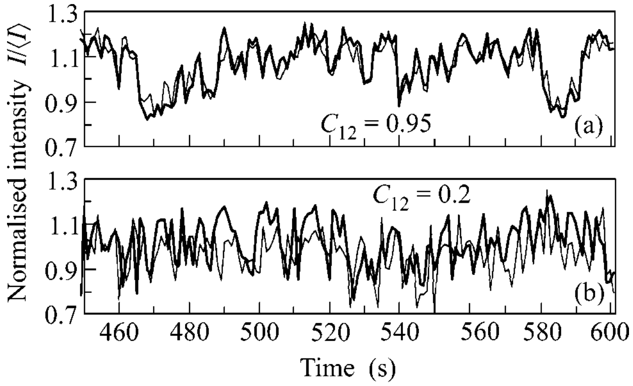

Fig. 4. Comparison of giant fluctuations of luminescence intensities measured under the same experimental conditions (a) without and (b) with a strip dividing the system of two-dimensional electrons into two subsystems. It is evident that dividing the sample into two subsystems completely suppresses the effect of correlations between luminescence intensity fluctuations and decreases the correlation coefficient from 0.95 down to 0.2. Measurements were performed under conditions of the quantum Hall effect at $\nu = 2$, $n_s = 3.85 \times 10^{11}$ cm^{-2}, $B = 7.95$ T, and $T = 1.5$ K.

in the figure that it remains close to unity down to the critical temperature $T_c = 1.9$ K, at which giant fluctuations disappear, and then sharply drops down to its background value (less than 0.1). Thus, it may be argued that the occurrence of spatial correlations of luminescence signals at macroscopic distances is a characteristic feature of the regime of giant fluctuations under conditions of the integer quantum Hall effect at $T < T_c$.

In order to check whether the existence of a common excitation spot is essential for the observed correlations, the following experiment was set up. A thin strip (0.5 mm) of black paper was placed on the sample so that it divided the excitation spot into two parts and the signal arrived at each of the light guides from its own part of the excitation spot. It should be noted that the signals from the same two parts of the sample measured in the absence of the black strip at $\nu = 2$ exhibited in-phase giant fluctuations with a correlation coefficient of 0.95. In the presence of the black strip correlations between the signals were not observed even at $\nu = 2$, though the signal from each light guide still exhibited giant fluctuations (ratio $D/\langle I\rangle > 10$). The results obtained under the same experimental conditions with the dividing strip and without it are compared in Figs. 4a and 4b, respectively. It is evident that dividing the sample into two subsystems completely suppresses the effect of correlations between luminescence intensity fluctuations. Small residual correlations that are seen in Fig. 4b can be explained by insufficient magnetic field stability, because these correlations were observed even in the absence of giant intensity fluctuations. It is known that the magnetic field strongly affects the shape of the luminescence spectrum of a 2D electron gas, especially under conditions of the quantum Hall effect [4, 5]. By virtue of this fact, the insufficient stability of the field can give rise to residual correlations of the signals. In the case when the luminescence spectrum only weakly depends on the field strength, as takes place for bulk luminescence, the magnitude of residual correlations is close to zero. The suppression of correlations in intensity fluctuations observed in this work on artificially dividing the 2D electron system into two subsystems allows us to exclude unambiguously the possible interpretation of giant fluctuation according to which the fluctuations are due to the anomalous enhancement of instabilities of the magnetic field or the photoexcitation source. Actually, it is possible to suggest that, because of the sharp stepwise character of the magnetic-field dependence of the spectral position of the luminescence line in the vicinity of integer filling factors [1], even weak magnetic field fluctuations can be manifested under these conditions as a strong instability of the luminescence intensity. If this were so, it would be reasonable to expect in-phase fluctuations in both parts of the sample upon dividing the 2D electron system into two subsystems (with the use of a thin black strip), because the source of fluctuations is similar in both cases and specifies a common phase. However, it is evident in Fig. 4 that correlations in intensity fluctuations disappear upon dividing the electron system into two subsystems, which most likely points to the occurrence of a common single phase in the macroscopic wave function of 2D electrons under conditions of the quantum Hall effect. Upon artificially dividing the electron system into two subsystems, the unity of the wave function disappears and a phase difference appears between the wave functions of two subsystems, which leads to disturbance of the phase coherence of fluctuations measured in different parts of the sample. The occurrence of a phase difference in the wave functions must lead to phenomena analogous to the Josephson effect. Therefore, it may be expected that oscillations associated with phase periodicity must arise in the correlation coefficient C_{12} if the parameters of the barrier (its width and the potential height) dividing the electron system into two subsystems are smoothly varied.

Thus, correlations between recombination radiation intensities of a 2D electron gas measured at different points of the sample with giant luminescence fluctuations in the regime of the quantum Hall effect have been investigated in this work. It has been found that extremely strong correlations are observed in intensity fluctuations under these conditions. These correlations most likely point to the macroscopic coherence of the electron system in the regime of the quantum Hall effect. It has been shown that these correlations disappear as the temperature increases or if the electron system is artificially divided into two subsystems unconnected with each other.

This work was supported by the Russian Foundation for Basic Research and by the program Physics of Solid-State Nanostructures.

REFERENCES

1. O. V. Volkov, I. V. Kukushkin, M. V. Lebedev, *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **71**, 558 (2000) [JETP Lett. **71**, 383 (2000)].
2. H. G. Schuster, *Deterministic Chaos* (Physik, Weinheim, 1984; Mir, Moscow, 1988).
3. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge Univ. Press, Cambridge, 1995; Nauka, Moscow, 2000).
4. O. V. Volkov, V. E. Zhitomirskiĭ, I. V. Kukushkin, *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **65**, 38 (1997) [JETP Lett. **65**, 38 (1997)].
5. O. V. Volkov, V. E. Zhitomirskiĭ, I. V. Kukushkin, *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **66**, 539 (1997) [JETP Lett. **66**, 575 (1997)].

Translated by A. Bagatur'yants