Coulomb-like mesoscopic fluctuations in a two-dimensional electron gas near filling factor $\nu=\frac{1}{2}$

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In the present work we report an experimental investigation of mesoscopic fluctuations in AlGaAs/GaAs microstructures in the vicinity of the Landau level filling factor $\nu=1/2$. Mesoscopic fluctuations in this regime have been studied both in magnetoresistance and in resistance versus gate voltage dependencies. The ratio of the correlation magnetic field to the correlation electron density for all experimental curves investigated turns out to be close to $2\Phi_0$ which suggests the existence of a universal relation between the two types of mesoscopic fluctuations in the fractional quantum Hall regime. [S0163-1829(97)04336-1]

More than a decade since its discovery the fractional quantum Hall effect (FQHE) still remains in the focus of attention in the solid state physics. Recently a new approach to the FQHE, the composite fermion theory, has been proposed.[1,2] According to this approach strongly interacting two-dimensional (2D) electrons at a fractional filling of the first Landau level can be viewed as a gas of novel weakly interacting quasiparticles, the so-called composite fermions (CF's), that have a renormalized effective mass and are expected to exhibit a number of quasiclassical properties. The FQHE for electrons is then explained as an IQHE for CF's moving in an effective magnetic field $B_{\mathrm{eff}}=B-B_{1/2}$, where B is the applied magnetic field and $B_{1/2}$—the magnetic field corresponding to the half filling of the first Landau level. It is noteworthy that all the main predictions of the CF theory have been shown to be basically true in numerous and diverse experiments.[3–10] The described approach to the FQHE raises a number of questions concerning quantum interference and, in particular, the nature and properties of universal conductance fluctuations (UFC's) at a fractional Landau level filling. Recently a theory has been proposed[11] which deals with UCF's in the presence of a random magnetic field. The results of this theory have been used to describe the behavior of a gas of CF's in a system with random potential fluctuations. The authors[11] come to the conclusion that in the case of CF's the Fermi energy dependence of UCF is radically different from that of electrons at $B=0$. The gate voltage dependence of CF conductance fluctuations at $\nu=1/2$ is predicted to be similar in some respect to aperiodical Coulomb-like oscillations with an effective charge $e/2$.

It appears that the first observation of conductance fluctuations in magnetoresistance dependencies in the vicinity of $\nu=1/2$ has been made in a ballistic microbridge in Ref. 12. However the absence of any analysis of these fluctuations in Ref. 12 makes it difficult to completely exclude the possibility of these fluctuations being some kind of noise. A more detailed experimental study of the magnetoresistance conductance fluctuations in the vicinity of $\nu=1/2$ has been reported recently in Ref. 13. The authors performed a comparison analysis of these fluctuations and of the UCF around $B=O$ and came to the conclusion that the fluctuations observed at $\nu=1/2$ could indeed be described as UCF of CF. The latter experiment, however, was limited to the study of magnetoresistance dependences and lacked measurements of CF conductance versus Fermi energy necessary for testing the important theoretical prediction mentioned above.[11]

In the present work we have investigated the behavior of mesoscopic samples in the vicinity of the half filling of the first Landau level. Both magnetic field and gate voltage dependencies of mesoscopic fluctuations near $\nu=1/2$ have been studied. It has been found that in contrast to the case of mesoscopic fluctuations in weak magnetic fields, in the vicinity of $\nu=1/2$ there exists a special relation between the R_{xx} fluctuations in the resistance versus magnetic field and in the resistance versus gate voltage dependencies. Namely, the ratio of the correlation magnetic field to the correlation electron density is found to be equal with good enough precision to $2\Phi_0$ (where Φ_0 is the magnetic flux quantum), i.e., to be determined solely by the Landau level filling factor. To our opinion this experimental evidence collaborates the prediction of Ref. 11 and mesoscopic conductance fluctuations in the vicinity of $\nu=1/2$ can indeed be viewed as Coulomb-like aperiodical fluctuations with a corresponding effective charge $e/2$.

Our two experimental samples were microbridges with the lithographical length $L=2$ μm and lithographical width $W=1$ μm. The actual width of the microbridges determined from Shubnikov–de Haas oscillations in weak magnetic fields is $(0.3-0.5)$ μm. The microbridges were fabricated by means of electron lithography and plazma chemical etching on top of a 2D electron gas in AlGaAs/GaAs heterolayer with the spacer thickness 60 nm. The electron density and electron mobility in the original heterolayers were $(1-2)\times10^{11}$ cm^{-2} and $(2-4)\times10^{5}$ cm^2/V s correspondingly. The microbridges were etched in the middle between the voltage probes of a conventional rectangular Hall bar with the dimensions 100×50 μm^2. At the final stage of preparation the structures were covered by a Au/Ni metal gate. The schematic top view of the structures is shown in the inset to Fig. 1. The measurements were carried out at temperatures 30 mK–4.2 K in magnetic fields up to 15 T. The alternative driving current of frequency 3–6 Hz was

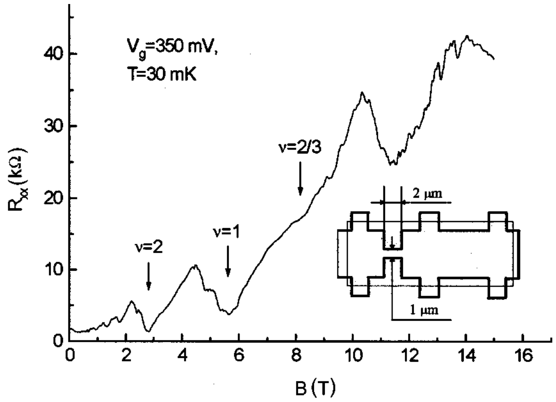

FIG. 1. Sample I, $R_{xx}(B)$; $T=30$ mK, $V_g=350$ mV. Inset: schematic top view of the experimental samples; hatched is the region under gate.

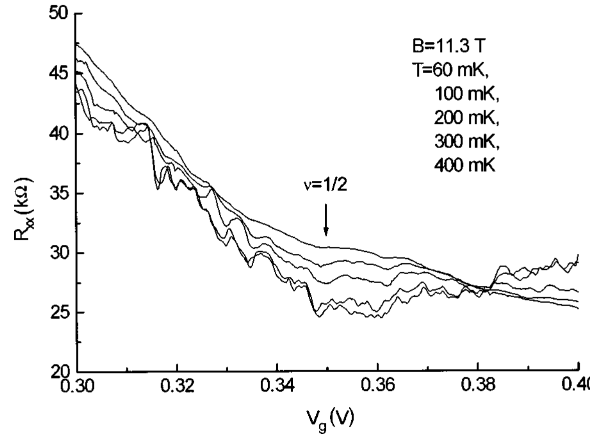

FIG. 3. Sample I, $R_{xx}(V_g)$ near $\nu=1/2$ for several temperatures.

kept as low as (0.5–1) nA to preclude electron heating.

Figure 1 shows a typical $R_{xx}(B)$ curve for sample I at a gate voltage of $+350$ mV. One can see distinct minima corresponding to $\nu=1$ and $\nu=2$ and a weaker minimum at $B=8.5$ T corresponding to $\nu=2/3$ in the microbridge. The fact that R_{xx} does not turn to zero at $\nu=1$ and $\nu=2$ testifies that there are potential barriers at the entrances to the microbridge. The positions of the minima $\nu=1$ and $\nu=2$ provide a means of determining the electron density in the microbridge and its dependence on the gate voltage. In the electron density range studied $(1-2)\times 10^{11}$ cm^{-2} this dependence for samples I and II is linear, the transport regime is metallic and the values of dN_s/dV_g for the two samples are 5×10^8 cm^{-2}m V^{-1} and 5.6×10^8 cm^{-2}m V^{-1} correspondingly. In the vicinity of $\nu=1/2$ in Fig. 1 there is a deep minimum that occurs at the same magnetic field as the $\nu=2/3$ minimum in the macroscopic part of the sample. The topology of our samples may be responsible for this feature in magnetoresistance since, as one can see in the inset to Fig. 1, the properties of the macroscopic regions at the entrances to the bridge can influence the results of transport measurements in the microstructure.

Apart from the above-mentioned magnetoresistance features, in the vicinity of $\nu=1/2$ in Fig. 1 there are also fluctuations of R_{xx} that are similar to those reported in Ref. 13. These fluctuations can be seen in more detail in Figs. 2 and 3 that show series of $R_{xx}(B)$ and $R_{xx}(V_g)$ dependencies taken at different temperatures in the vicinity of $\nu=1/2$ for small variations of magnetic field and gate voltage.

Figures 2 and 3 demonstrate a good reproducibility of the R_{xx} fluctuations at different measurements. There was as good a reproducibility in all our measurements provided the state of the sample did not change. At the same time the pattern of the fluctuation could become completely different following an illumination or warming up of the sample. Similar behavior has been known for mesoscopic resistance fluctuations of electrons in weak magnetic fields and is described in detail in a number of publications.[14,15] As the temperature increases the amplitude of the fluctuations decreases and at $T>400$ mK they die out completely. Figure 4 shows the temperature dependence of the average amplitude of the fluctuations. One can see that the average amplitude and its variation with temperature are practically the same for the fluctuations in magnetic field and gate voltage dependencies of R_{xx}. At the same time the temperature dependence itself is different from that observed for mesoscopic fluctuations of electrons in weak magnetic fields[15] where in one-dimensional systems the average amplitude changes with temperature as $T^{-1/2}$. In Fig. 4 a very weak temperature dependence observed at temperatures lower than 100 mK changes to a much stronger one $\Delta R_{xx}\sim T^{-(1\pm 0.5)}$ at higher temperatures. Such a temperature dependence might be at-

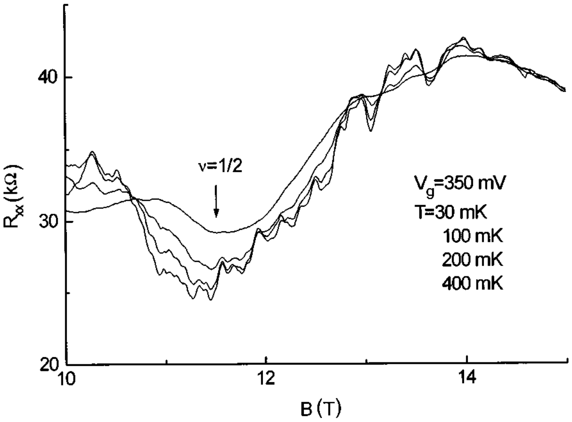

FIG. 2. Sample I, $R_{xx}(B)$ near $\nu=1/2$ for several temperatures.

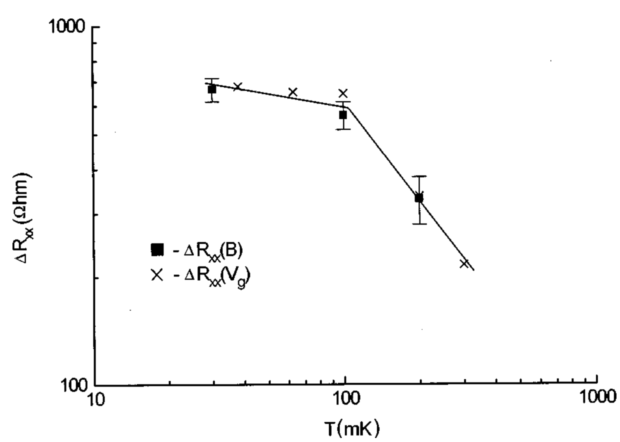

FIG. 4. The fluctuations average amplitude temperature dependence derived from $R_{xx}(B)$ and $R_{xx}(V_g)$ curves in Fig. 2 and Fig. 3.

tributed to some unusual behavior of the CF coherence length which however we cannot at present account for. We notice that for samples with a considerably higher disorder no such anomaly in the fluctuations amplitude temperature dependence has been reported.[13]

The relation between mesoscopic fluctuations in magnetic field and gate voltage dependencies of composite fermion resistance has first been theoretically investigated in Ref. 11. The composite fermions are quasiparticles with charge e, each carrying two magnetic flux quanta attached to it.[1,2] If, then, in a fixed external magnetic field B one changes the electron density, it will result in a corresponding change in $B_{1/2}$ and, therefore, in a change of the effective magnetic field $B_{\mathrm{eff}}=B-B_{1/2}$ experienced by CF. As with bare electrons, the typical period of the magnetoresistance mesoscopic fluctuations of CF is determined by the ratio Φ_0/S,[16] where S is the sample area and Φ_0 is the magnetic flux quantum. Hence, at $\nu=1/2$ a variation of gate voltage that results in one electron more or one electron less under the gate should be accompanied by approximately two fluctuations in $R_{xx}(V_g)$ dependence. In other words if the variation of gate voltage is converted into the variation of electron density, the ratio of the correlation magnetic field B_c to the correlation electron density N_{sc} is expected to be $2\Phi_0$:

$$B_c/N_{sc}=2\Phi_0. \tag{1}$$

As regards the feasibility of the experimental study of relation (1) it should be noted that it is likely to remain valid even at $T>0$. Indeed, according to what is said above, a gate voltage variation resulting in a change of electron density in the sample at $\nu=1/2$ is but an alternative means of changing the effective magnetic field of CF. In that sense mesoscopic fluctuations of CF in magnetoresistance should be equivalent to those in gate voltage dependencies. It may be expected therefore that at $T>0$ both B_c and N_{sc} would have the same temperature dependence and the ratio (1) would not change.

An experimental test of Eq. (1) has been the aim of the present work. For this purpose several different states of sample I and one state of sample II have been investigated. The state of a sample could be altered either by LED illumination or by changing the electron density with gate voltage. By means of the latter the microbridge resistance at $\nu=1/2$ could be varied in the range 30–60 kΩ. In a state thus obtained the dependencies $R_{xx}(B)$ and $R_{xx}(V_g)$ were measured in a narrow interval of filling factor ($\sim$0.1) around $\nu=1/2$. The values of B_c and N_{sc} derived from these dependencies were then used to determine the ratio (1) for a given state and sample. The values of B_c/N_{sc} obtained in this manner are shown in Table I. The observed scatter of the values may be due to the error associated with the procedure of separation of mesoscopic fluctuations from the background of smooth nonmonotonic components. As seen in Figs. 1–3 these components remain unaltered at temperatures where the mesoscopic fluctuations are already completely suppressed and therefore we infer that they must have some different origin. On the whole the experimental values of B_c/N_{sc} for the two samples and for different states of sample I agree closely with the theoretically predicted value $2\Phi_0$ and on the strength of this evidence we conclude that the ratio (1) for CF is indeed universal.

TABLE I. The values of B_c/N_{sc}.

Sample	T (mK)	$R_{1/2}$ (kΩ)	B_c/N_{sc}, Φ_0
I	30	23	2.38
I	30	23	1.85
I	30	24	2.37
I	30	27	2.04
I	40	57	2.3
I	100	27	2.18
II	40	50	1.83

If the notion of a Fermi surface is applicable to CF, then apart from the R_{xx} fluctuations in gate voltage dependencies described in Ref. 11 there might still be another and more conventional type of mesoscopic fluctuations near $\nu=1/2$ resulting from the CF wavelength variation. The contribution of this latter mechanism to the ratio (1) has not been analyzed in Ref. 11 but it seems likely that it would be sensitive to the state and parameters of a sample. Since no such sensitivity was observed in our experiment we will not discuss the second mechanism in this work though it should be taken into account in further investigations of the problem. In weak magnetic fields, where for bare electrons only the second mechanism works, the ratio (1) in our samples is about an order of magnitude less than for fluctuations at $\nu=1/2$.

Results in some sense similar to those described here, have been recently reported in Ref. 17 where at $\nu=1/3$ the resonance tunneling via a state bound to an antidot in the center of a microstructure has been studied. The ratio of the resonance tunneling periods in magnetic field and in gate voltage has been found to be equal $3\Phi_0$. So in two different physical situations (the 1/3 state of the FQHE in Ref. 17 and a gapless energy spectrum at $\nu=1/2$ in our case) the ratio of B_c to N_{sc} is found to be equal to the magnetic flux quantum multiplied by the inverse of the filling factor. To our opinion this fact is not a coincidence and can be taken to mean that in the conditions of FQHE the interference effects are determined by the value of the filling factor regardless of the character of the energy spectrum. Yet further experimental and theoretical studies are needed to prove it conclusively.

In conclusion we have investigated mesoscopic resistance fluctuations in electron microstructures in the vicinity of $\nu=1/2$. The mesoscopic fluctuations have been studied both in the gate voltage and in magnetic field dependencies of R_{xx}. It is established that the fluctuations in these two types of dependencies have the same average amplitude and temperature dependence. The latter is found to be different from the one observed in Ref. 13. We have experimentally proved the theoretically predicted[11] universal relation between these two types of fluctuations, according to which the ratio of the correlation magnetic field to the correlation electron density should to be equal to the magnetic flux quantum multiplied by the inverse filling factor.

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