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Ground State at Low Landau Level Filling Factors in Two-Dimensional Systems of GaAs/AlGaAs Heterostructures in Strong Magnetic Fields*

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Integer and fractional quantum Hall effects are interesting phenomena in two-dimensional electron systems (2DES) in strong magnetic fields. In this paper, breakdown of the integer quantum Hall effect (IQHE) at odd integer filling factors at 100 mK and temperature dependence of the fractional quantum Hall effect (FQHE) around the filling facor $\nu=1/2$ at temperatures between 100 mK and 1000 mK in magnetic fields up to 25 T are measured for the 2DES in two AlGaAs/GaAs heterostructures. The results in the IQHE measurements are compared with results at the even filling factors and derive the effective g-factor of about 10 in this system. The results in the FQHE measurements at $\nu = 1/2$ shows a logarithmic temperature dependence of the conductivity which is expected in a weakly localized Fermion system in zero magnetic fields.

KEYWORDS: two-dimensional electron system, integer quantum Hall effect, fractional quantum Hall effect

1. Introduction

In the integer quantum Hall effect (IQHE), the Hall conductivity is quantized as $\sigma_{xy} = -ie^2/h$ for an integer i with zero diagonal conductivity $\sigma_{xx}=0$ in degenerate two dimensional electron systems (2DES) at low temperaturres T and in strong magnetic fields B.[1] The IQHE may be observed near the filling factor $\nu=N_s\Phi_0/B=i$ where N_s is sheet electron concentration and $\Phi_0=h/e$ the flux quantum. The IQHE appears in a Hall bar sample as the Hall resistance is quantized as $R_H(i)=h/ie^2$ with zero diagonal resistance $R_{xx}=0$. The quantized Hall resistance(QHR) has been used as an international resistance standard since 1990.[2] In order to carry out high precision measurement of QHR, we must pass a high electric current through a Hall bar to generate a high voltage across the sample. When the current exceeds a critical value, however, the IQHE breaks down.

In very high mobility 2DES, the fractional quantum Hall effect(FQHE) may be observed as $\sigma_{xy} = -(q/p)e^2/h$, for integral p and q, where q is odd, accompanied minima in σ_{xx}.[3] Quite recently the idea of a "composite Fermion" (CF) has been introduced to describe the FQHE. The CF consists of an electron to which an even number ($2m$) of flux quanta are attached. In this approach the FQHE now appears as simply the Shubnikov-de Haas (SdH) effect and the IQHE of the CF arround the filling factor $\nu=m/2$.[4]

We have measured diagonal resistances R_{xx} and Hall resistances R_H of 2DES in AlGaAs/GaAs heterostructures with different electron concentrations and mobilities in magnetic fields up to 25 T and at temperatures down to 100 mK.

In this paper we present results of the breakdown measurements of the IQHE at the plateau for $i = 1$ and 3 in a high mobility sample which derive effective g-factor of the 2DES in strong magnetic fields and results of the FQHE measurements around $\nu=1/2$ in a low mobility sample which show logarithmic temperature dependence of the conductivity of the CF at zero effective magnetic field.

2. Breakdown of the integer quantum Hall effect

The QHE state is characterized by non-dissipative electric current whose direction is orthogonal to the direction of electric field, i.e. Hall electric field, where the diagonal resistance in the Hall bar is zero;i.e. $R_{xx}=0$. Such non-dissipative electronic state appears near the central part of the Hall bar sample only. Joule heat is always generated at both ends of the sample; i.e. transition regions between the 2DES and two current electrodes, the source- and the drain-electrode.[1] The breakdown of the QHE what we want to measure is the appearence of dissipation in a part of a Hall bar other than the parts near current electrodes. In order to do this, we have to eliminate effects of the source- and the drain-electrode.

In a series of our experiments we fabricated specially designed Hall bar samples (butterfly-type Hall bar) from $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure wafers by photo-lithography and wet chemical etching.[5~8] In the present experiments, we used a butterfly-type Hall bar which has the source- and drain-electrode width of $W = 400$ μm and the large length of $L = 2900$ μm between the source- and drain-electrode. The central part is 600 μm long and has the width $w = 120$ μm. The length of $\ell=600$ μm is distributed among three pairs of potential probes. The width of the sample is linearly narrowed from both current electrodes to the ends of the central part.[5~7]

Figure 1 shows a trace of diagonal resistivity and Hall resistivity against magnetic field B measured in a high mobility sample at 100 mK. In Figure 1, the FQHE is clearly observed at $\nu=3/5$ (B ≈ 21.5 T), $\nu=2/3$ ($B\approx 19$ T), $\nu=4/3$ (B ≈ 9.7 T) and $\nu=5/3$ (B ≈ 7.8 T). As we determined critical breakdown currents in the previous papers, the critical currents

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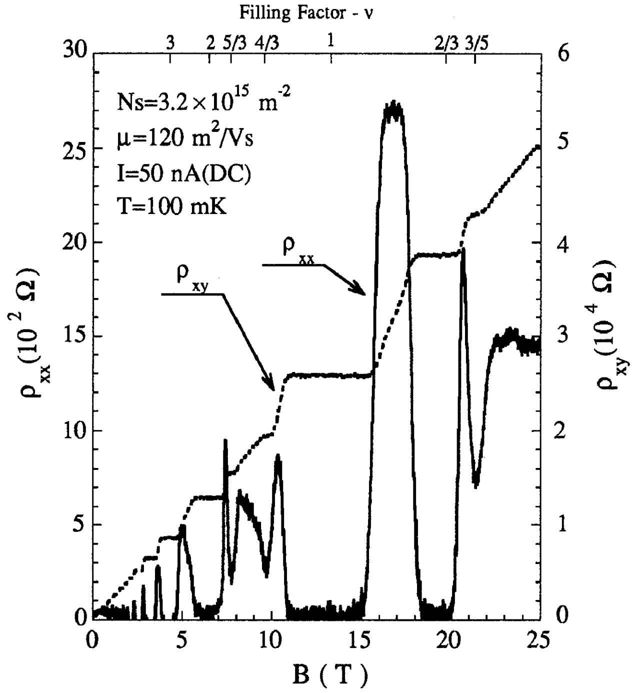

Figure 1. The diagonal resistivity ρ_{xx} and the Hall resistivity ρ_{xy} against the magnetic field B.

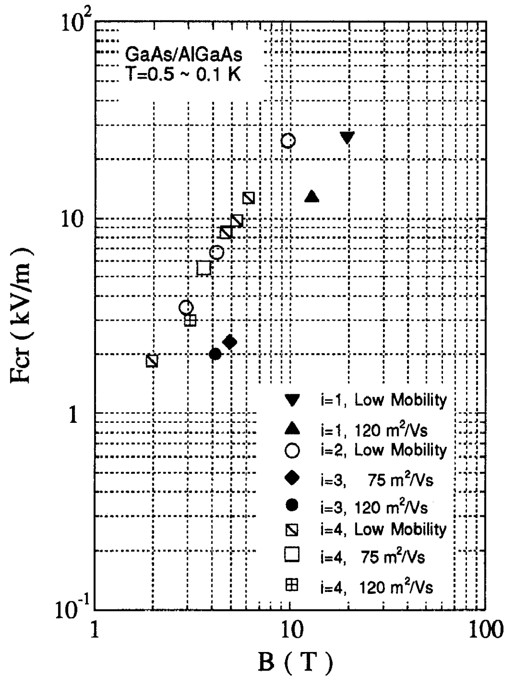

Figure 2. Critical Hall electric field in the breakdown F_{cr} versus the magnetic field at the center of the plateau B.

I_{cr} (i=1) and I_{cr} (i=3) were determined from the currents at which these plateaus disappear.

We add the results in the present experiments to the results reported in the previous work.[6-8] Experimental results of critical breakdown electric fields F_{cr} in the Hall plateaus with the plateau quantum numbers i= 1, 2, 3, 4 are plotted against the magnetic field B at the center of each plateau and shown in Figure 2. Figure 2 shows that F_{cr} (i = 2, 4) are lying on a single straight line and F_{cr} (i = 1, 3) are lying on another parallel single line in the log-log plot and their slopes are 3/2.

Magnetic field dependence of F_{cr} is a key which open the door to a possible mechanism for the breakdown. The mechanism of abrupt phonon emission analogous to Cerenkov radiation proposed by Stormer *et al.* [9] and an electron heating mechanism such as discussed by Komiyama *et al.*[10] lead to a dependence of $F_{cr} \propto B$. Our result of $F_{cr} \propto B^{3/2}$ suggests that a possible mechanism of the breakdown is production of dissipative carriers by inter-Landau-level transition of electrons due to small scatterers from the highest filled Landau level to the next empty Landau level. The reason is that the energy splitting between adjacent Landau levels is proportional to B and the spacial extent of the harmonic oscillator wave function is proportional to $B^{-1/2}$. Eaves and Sheard[11] have derived a simple expression for the critical breakdown field based on the inter-Landau-level transition. However, our experimental result is different from their theoretical result in the magnitude and in the dependence on the Landau level quantum number. Their expression leads a result which is more than one order of magnitude larger than our experiments. According to their expression, F_{cr} (i = 2) should be larger than F_{cr} (i = 4) while they are same in our experimental results. Higher order scattering may reduce the magnitude of F_{cr} given by Eaves and Sheard and make closer F_{cr} (calc) to our results.[12] The higher order scattering may also eliminate the dependence of the Landau level quantum number in the inter-Landau-level transition.[12] The enhancement of the inter-Landau-level transition by spacially extended scatterers propose by Trugman *et al.*[13] leads to a weaker magnetic field dependence of $F_{cr} \propto B$. Recently Ishikawa *et al.*[14] calculated the inter-Landau-level transition caused by Hall electric field based on von Neuman lattice model and derived the dependence of $F_{cr} \propto B^{3/2}$ independent of Landau quantum number and the magnitude of F_{cr}(i=2) close to Eaves and Sheard.[11]

Based on the inter-Landau-level tunneling mechanism, we can determine exchange-enhanced effective g-factor of electrons (g_{eff}) in the present 2DES. Strong spin-orbit interaction in GaAs allows spin-flip tunneling from the filled lower spin-split spin polarized Landau level to upper spin-split Landau level. Spin-splitting can be ignored in the breakdown in the plateaus with i=2 and 4 because g-factor of electrons in GaAs is very small.[15] However, the g-factor should be enhanced by exchange effect in observation of the plateaus with odd plateau quantum number i=1 and 3. Results in Figure 2 show that F_{cr} (i = 2,4)/F_{cr} (i = 1,3) $\approx$ 3. Then we have $g_{eff} \approx 10$. This result is consistent with Usher *et al.*'s g_{eff} =7.3 obtained by activation energy measurements[16] and a recent result in experiments on skyrmions by Barrett *et al.*[17] who have discussed the enhancement of Zeeman splitting by a factor of ~10 to explain temperature dependence of the Knight shift in optically pumped NMR measurements.

3. Composite Fermion in the fractional quantum Hall effect

Recent experiments which support the CF approach have been carried out to observe activation energies in ρ_{xx} minima[18] or to observe temperature dependence of the SdH effect [19] in the FQHE by using very high mobility 2DES in AlGaAs/GaAs heterostructures. However, we expect that low mobility 2DES would show properties of the "composite Fermions" in the weakly localized regime at the filling factor of $\nu = m/2$. It has been well known that the electrical conductivity of 2DES shows logarithmic temperature dependence in weakly localized regime.[20] A simple expression of the ln T dependent correction to the Drude conductivity due to weak localization is given by[20]

$$\sigma_L = \frac{\alpha p e^2}{2\pi^2 \hbar} \ln T \qquad (1)$$

where p is the exponent of the temperature dependence of the inelastic scattering time $\tau_\varepsilon \propto T^{-p}$ and α is a factor of order unity.

We have measured temperature dependence of the FQHE around $\nu = 1/2$ by using a low mobility sample. Figure 3 shows results of the FQHE oscillations at temperatures between 100 mK and 950 mK observed in a sample which has the electron mobility $\mu = 60$ m^2/Vs and the sheet electron concentration $N_s = 1.6 \times 10^{15}$ m^{-2}. Overall behaviour of the magneto-oscillations is described by the composite Fermion picture using the magnetic field dependent effective mass so far reported.[18, 19]

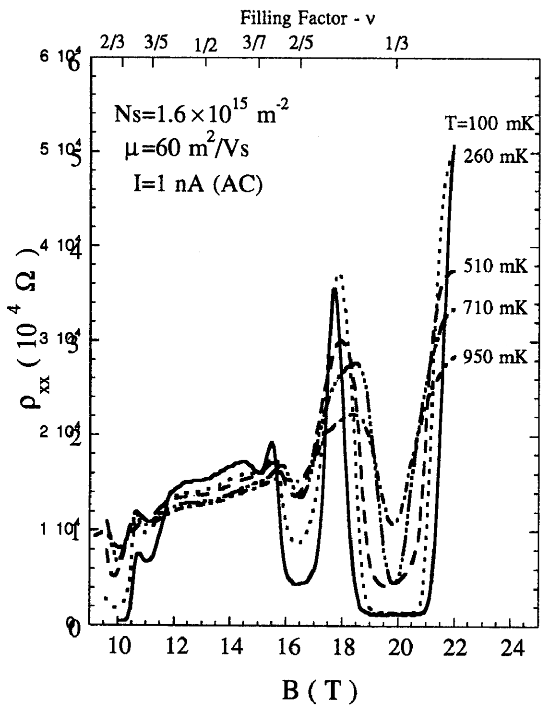

Figure 3. Magnetic field dependence of the diagonal resistivity around $\nu = 1/2$ at different temperatures.

Temperature dependence of the diagonal resistivity at the filling factor of 1/2 is shown in Figure 4. The temperature dependence is expressed as $\rho_{xx}(\nu = 1/2) = a + b \ln T$. If we assume $\alpha p \approx 0.5$, the temperature dependence of the diagonal resistivity in Figure 4 can be explained by eq. (1). In temperature dependences of resistivity in n-channel inversion

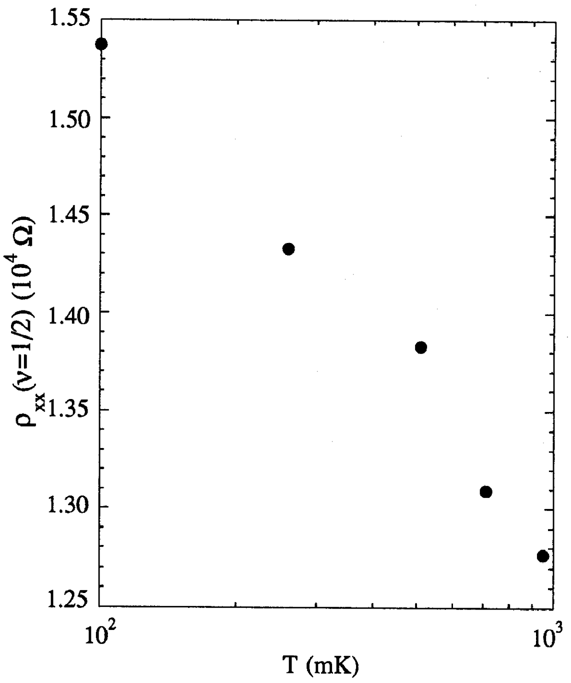

Figure 4. Temperature dependence of the diagonal resistivity at the filling factor $\nu = 1/2$.

layers in Cs-Si(111), it was found that $\alpha p = 0.9 \pm 0.3$.[20, 21] Bishop et al. [22] found that $\alpha p = 1.04 \pm 0.1$ in Si (100) and (111) MOSFETs. Therefore, the logarithmic temperature dependence of resistivity at the half Landau level filling we observed is a good evidence of the Fermi surface in zero effective magnetic field.

4. Conclusion

We have measured magnetic field dependence and temperature dependence of diagonal resistances and Hall resistances of two-dimensional electron systems in AlGaAs/GaAs heterostructures in magnetic fields up to 25 T and at temperatures down to 100 mK in integer and fractional quantum Hall effect regimes. In the integer quantum Hall effect, we have observed that the critical Hall electric field F_{cr} in the onset of the breakdown in the quantized Hall plateau with $i = 1$ and 3 is proportional to $B^{3/2}$ where B is the magnetic field at the plateau center. This magnetic field dependence is similar to that in the Hall plateau with $i = 2$ and 4. We have derived the effective g-factor of the two-diensional electron gas in GaAs in strong magnetic fielda as $g_{eff} \approx 10$ from the ratio $F_{cr}(i = 2$ and $4) / F_{cr}(i = 1$ and $3) \approx 3$. The value of g_{eff} is consistent with other authors' results. In the fractional quantum Hall effect, we have observed the logarithmic temperature dependence of diagonal resistivity at the Landau level filling factor of one half in a very low mobility sample. The observation is consistent with the composite fermion picture of the fractional quantum Hall effect.

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