Imaging of current distribution in GaAs/AlGaAs quantum Hall devices

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Abstract. We have measured the current distribution in GaAs/AlGaAs two-dimensional electron system (2DES) at quantum Hall effect (QHE) regime to investigate the mechanism of QHE breakdown. A Hall-bar device on the scanning stage is locally illuminated by an infrared laser light guided by polarization maintaining optical fiber at QHE condition. We have tried to map the QHE breakdown critical current with local photo-excitation. The mapping of breakdown critical current shows the current concentration at the center region of 2DES channel in the sample where the critical current shows sub-linear dependence on the channel width. We have also tried to measure the Hall potential imaging in the electric current flowing 2DES by means of Pockels effect in GaAs/AlGaAs sample. The experimental techniques of the optical fiber based current distribution imaging in the high magnetic field up to 9 T have been reported in detail.

1. Introduction

The characteristics of quantum Hall effect (QHE) breakdown is closely related with the properties of two-dimensional electron system (2DES) and the spatial current distribution in the QHE condition [1]. Two types of the QHE breakdown have been known: one is that the critical current scales linearly with the channel width (linear type) and the other is that the breakdown current increases sub-linearly with the channel width (sub-linear type), as shown in figure 1. In the sub-linear type samples, a low critical current with weak dependence on the channel width and unstable I-V characteristics are observed, which are distinct properties in the conventional linear type QHE breakdown. The sub-linear dependence, which is often observed in rather high mobility 2DES samples, suggests that the current density is locally concentrated in the sample. The small value of critical current was explained with the current concentration near the sample edge region [2]. However, the value of breakdown current is scarcely affected by changing side gate bias voltage, which suggests that the QHE breakdown is independent of the confinement potential at the 2DES edge [3].

In this paper, we studied the spatial current distribution in the GaAs/AlGaAs 2DES by means of imaging technique, and possible mechanism of QHE breakdown in the sub-linear type 2DES was discussed. We also report the experimental details of local potential imaging system by means of Pockels effect of GaAs samples [4-6] working in the high magnetic field up to 9 T.
2. Sub-linear type Hall-bar sample

The samples were made from a modulation doped GaAs/AlGaAs heterostructure wafer, whose electron density and the mobility was $2.2 \times 10^{11} \text{ cm}^{-2}$ and $5.2 \times 10^5 \text{ cm}^2/\text{Vs}$ at 4.2 K, respectively. The conventional 6-terminal Hall-bar samples were fabricated by using UV photolithography and wet chemical etching. We measured DC four terminal current-voltage profiles around the Landau level filling factor 2 ($\nu=2$). The 2DES channel width dependence of the breakdown current shows sub-linear relation, and the critical current tends to saturate with increasing channel width. In the wider channel samples, the critical current shows plateau around the filling factor 2, as shown in the inset of figure 1. These experimental results suggest that there is some narrow strip in the 2DES bulk region, where the current is concentrated, as schematically shown in figure 2.

3. Current mapping by spot illumination at QHE plateau

To investigate the origin of sub-linear type QHE breakdown, we investigated the current distribution of the GaAs/AlGaAs 2DES Hall-bar devices by means of a critical current mapping technique with local photo-excitation. The sample on the scanning stage is locally illuminated by using an infrared laser light ($\lambda=1.5 \text{ \mu m}$) guided by single-mode optical fiber, where the excitation spot size is 4 $\mu$m at $\nu=2$ QHE conditions ($T=1.7 \text{ K}$, $B=6 \text{ T}$). The persistent photoconductivity, which is usually used to increase the carrier density in 2DES, is absent at the $\lambda=1.5 \text{ \mu m}$ light, and unexpected photo-excitation due to the stray light is completely eliminated in our optical windowless imaging system. In the illuminated spot, the photo-excited hot electrons act as ‘seeds’ of QHE breakdown and the number of excited electrons drastically increase if the strong Hall electric field (i.e., the current concentration) exists at the illuminated spot. The value of critical current should be considerably reduced while the excitation spot hits the current concentrated region in the 2DES, as shown in figure 2. From the photo-excitation mapping of QHE breakdown critical current, we can obtain the image of current concentration region in quantum Hall regime.

In the sub-linear type 2DES Hall-bar ($W=0.5 \text{ mm}$), remarkable reduction of the critical current is observed when the photo-excitation point approaches center line of the Hall-bar (arrow in figure 3). The imaging data of breakdown critical current show the evidence of current concentration at the

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**Figure 1.** Channel width ($W$) dependence of the breakdown critical current at $\nu=2$ measured in Hall-bar shaped samples made from the sub-linear type GaAs/AlGaAs wafer. Upper inset: Filling factor dependence of the critical current $I_c$ in the samples of those width are 10(●), 20(●), and 80(▼) $\mu$m, respectively. Lower inset: Schematic view of the Hall-bar sample.

**Figure 2.** Schematic view of the current flowing state in the sub-linear type sample at QHE plateau. The current mainly flows in the incompressible (IC) electronic state which is located at the inner region of the 2DES channel. The current flowing IC state may be narrow channel (dotted area in the figure).
center region of 2DES channel, not along the sample edge, in the sub-linear type QHE devices. It is consistent to the experimental results that the value of breakdown current is scarcely affected by voltage of side gate along the sample boundary [3].

4. Imaging of Hall potential in GaAs 2DES by Pockels effect

Since the diagonal conductivity $\sigma_{xx}$ becomes zero at QHE plateau, the local current density is $\sigma_{xy} E_{\text{Hall}}$, where $\sigma_{xy}$ is Hall conductivity and $E_{\text{Hall}}$ is a Hall electric field, respectively. At the current concentrating 2DES position, the strong Hall electric field exists, i.e., the steep Hall potential variation should be observed. To investigate the detail of spatial current distribution in QHE devices, we tried to measure the Hall potential profile directly by means of the Pockels effect in GaAs/AlGaAs, which is a contactless electro-optical potentiometry. A Hall-bar shaped sample on the scanning stage is locally illuminated by using a polarized infrared laser light ($\lambda = 1.5 \mu m$) guided by a polarization maintaining (PM) single-mode optical fiber, where the illumination spot diameter is 5 $\mu m$ using high

**Figure 3.** Critical current at $\nu=2$ measured with local photo-excitation by 1.5 $\mu m$ infrared laser light. The position of spot illumination is scanned across the Hall bar channel (see inset). The critical current reduces almost zero at the laser spot hits the current concentrating position (arrow).

**Figure 4.** Schematic view of the Pockels effect measurement system. The wavelength of 1.5 $\mu m$ laser light is polarized by Glan Taylor (GT) calcite polarizer and focused into the polarization maintaining (PM) optical fiber. The incident laser beam is reflected by the back gate made of aluminum film and collimated by objective lens into the PM fiber. The light from the sample has elliptical polarization due to the Pockels effect in GaAs sample, and is lock-in detected as the difference of the two photo-detector signal through the polarization beam splitter (PBS) and $\lambda/4$ wave plate. To make the PM fiber as duplex channel, the half beam splitter (BS) is used between light source and photo detectors. The local potential voltage of 2DES at the laser spot is evaluated from the degree of elliptical polarization due to the Pockels effect.
NA objective lens. The reflected light from the Al back gate is focused into the optical fiber core, the confocal optics improves spatial resolution of the imaging system. Figure 4 shows the schematic diagram of the Pockels imaging system operating at 4.2 K and up to 9 T, the 2DES local potential voltage at the illuminated spot can be evaluated from polarization analysis of the reflected light. In GaAs sample, the refraction index shows anisotropic feature due to the Pockels effect. The phase retardation between 100 and 010 polarized light (ΔΓ) is proportional to the voltage difference between 2DES and back gate (V). The incident beam is polarized to 110 direction, the reflected return light has an elliptical polarization due to the Pockels effect with the phase retardation of 2ΔΓ.

Figure 5 shows the voltage versus detected Pockels signal, where the incident laser power is about 100 μW on the sample surface. We confirmed that the measured signal intensity is linear to the applied modulation voltage between 2DES and back gate, and the voltage difference below a few mV can be detected from the Pockels signal. We have observed Hall potential profile across the 2DES channel at QHE plateau, which shows also the current concentration in the bulk 2DES [7]. However, it is necessary to stabilize the Pockels signal while the light spot is scanning across the sample for detailed mapping of Hall potential distribution. We are trying to improve the signal to noise ratio in this system: long time stabilization of the laser intensity and polarization, and using optical bridges for polarization analysis. By using this optical fiber based system, it is possible to extend the experimental conditions to investigate the Hall potential distribution in QHE devices in a narrow sample space, at low temperatures and high magnetic fields.

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