Spatial imaging of noise voltages by a quantum Hall scanning electrometer

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Abstract. We present a new application of the quantum Hall effect (QHE): a scanning sensor for imaging the spatial distributions of noise voltages. This technique is based on a scanning electrometer employing a QHE device, which utilizes capacitive coupling between electrometer and sample. By measuring local voltage fluctuations with the QHE electrometer, we have been able to produce the first image of a noise-voltage distribution in a QHE sample. We found that a high noise level occurs in the lower magnetic field region of a QHE plateau of Landau-level-filling factor 2, and that it is concentrated in a high-potential edge region of the Hall bar sample. These results show that our noise-imaging system serves as a useful tool for probing edge-state electrons in QHE systems.

1. Introduction

The quantum Hall effect (QHE) [1,2] in a two dimensional electron gas (2DEG) under a high magnetic field has provided researchers with rich opportunities for developing functional devices using its unique electronic properties. In addition to a well-known application as an international resistance standard [3], practical applications so far devised include Terahertz detector [4], quantum bit [5], and relaxation oscillator [6].

Recently, the study of the spatial properties of the electrical noise has become an important topic in the field of solid-state device engineering. This issue is of particular relevance to the development of charge-based quantum computers that are extremely sensitive to charge fluctuations. Scanning electrometer technique provides a direct and effective method for addressing this issue. Until now, scanning electrometers using single electron transistor (SET) [7] and atomic force microscope (AFM) cantilever [8] have been developed. However, the SET electrometer has to be operated in a very low temperature (below a few hundred milliKelvin), since it requires observing clear Coulomb oscillations. Though the AFM technique is available over a wider range of temperature, it has the disadvantage that applying a high electric field between the AFM tip and the sample easily disturbs the real electronic state of the sample. Using a SET electrometer, Buehler et al. [9] have made local observation of telegraph switching noise in metal-oxide-semiconductor devices. However, their technique is not a scanning-type system and hence is not able to provide images of noise-voltage distributions.
Previously, we have developed a new type of scanning electrometer that is based on a QHE device [10]. Based on this QHE scanning electrometer, we have recently succeeded in constructing a novel imaging system for mapping out noise-voltage distributions, in which mean square voltages of local voltage fluctuations are measured with a lock-in amplifier [11]. Compared to the other earlier electrometers [7-9], our technique has the following three merits: (i) Since our device exploits the integer QHE, the temperature range accessible to it is much wider (up to several Kelvin). (ii) As described in detail later, no external voltage needs to be applied between electrometer and sample. (iii) Our scanning technique, in contrast to the SET electrometer of Buehler et al., enables the imaging of noise-voltage distributions. These advantageous properties make the QHE electrometer a powerful noise-characterization system.

Here, we have applied the present noise-imaging system to a QHE sample, and have for the first time obtained the maps of the noise voltage distribution in the QHE sample. We found that noise largely occurs in the lower magnetic field region of a QHE plateau of Landau-level-filling factor 2, and that the most of the noise is concentrated in a higher-potential edge region of the sample. These features can be reasonably understood as being due to the unsteady electron transfer between the outer edge state and the inner bulk state. The present noise-imaging experiment opens up a new way to study spatial properties of charge fluctuations in solid-state devices.

2. Functional principle of the quantum Hall scanning electrometer

The experimental setup of the QHE scanning electrometer is schematically represented in Fig. 1(a). A sensor (electrometer) is in contact with a sample. In order to prevent the two devices from being damaged, the surface of the sensor is coated with a 50 nm-thick SiO₂ film. A magnetic field \( B \) is applied perpendicular to the 2DEG planes. In this scheme, voltage distributions are imaged through the following process: Since the distance between the two adjacent 2DEG layers is very short, they are capacitively coupled. Therefore, as shown in the equivalent circuit of Fig. 1(b), when a source-drain current \( I_{\text{sam}} \) is passed through the sample, excess charges \( \Delta Q \) are induced into the 2DEGs, accordingly to \( CV(x,y)=\Delta Q \). Here, \( V(x,y) \) is a local voltage in the sample right below the sensor, and \( C \) is the capacitance between the two 2DEG layers. The generation of \( \Delta Q \) leads to the change, \( \Delta R_{\text{sen}} \), in the longitudinal resistance, \( R_{\text{sen}} \), of the sensor. By moving the sensor throughout the surface of the sample and simultaneously measuring \( \Delta R_{\text{sen}} \times I_{\text{sen}} \), one can obtain a two-dimensional image of \( V(x,y) \) in the sample (\( I_{\text{sen}} \) is the bias current for the sensor).

Based on the above sensing mechanism, we observe the spatial distribution of the noise voltage as follows: Using a lock-in amplifier, we measure the mean-square voltage, \( S_V \), of the voltage fluctuations \( \Delta V \), which is expressed as \( S_V=|\Delta V(f)|^2/\Delta f \). Here, \( f \) is a central frequency for the noise detection and \( \Delta f \) is a frequency bandwidth. In this experiment, we set \( f=1\text{kHz} \) and \( \Delta f=10\text{Hz} \) in the lock-in amplifier. The \( S_V \) value of the pre-amplifier is about \( 4 \times 10^{-16}\text{V}^2/\text{Hz} \) at \( f=1\text{kHz} \), a level which is
low enough to measure only sample noise. In order to remove the noise of the sensor itself, we subtract \( S_V \) at a sample current \( I_{\text{sam}} = 0 \) from that at \( I_{\text{sam}} \neq 0 \).

| Sensor 1 | \( \mu_{\text{th}} \) (m²/Vs) | \( n_s \) (10¹⁵ m⁻²) | \( L_1 \) (μm) | \( L_2 \) (μm) | \( W_1 \) (μm) |
|----------|----------------|----------------|-------------|-------------|-------------|
| Sensor 2 | 60            | 2.5            | 0.8         | 0.7         | 1.5         |
| Sensor 2 | 22            | 2.4            | 1.0         | 0.7         | 1.8         |

**Table 1.** Characteristics of the sensors. Values of the 4.2K-mobility \( \mu_{\text{th}} \) and the 4.2K-electron density \( n_s \). For the notations of \( L_1, L_2, \) and \( W_1 \), see Fig. 2.

| Sample 1 | \( \mu_{\text{th}} \) (m²/Vs) | \( n_s \) (10¹⁵ m⁻²) | \( L \) (μm) | \( W \) (μm) |
|----------|----------------|----------------|-------------|-------------|
| Sample 1 | 11            | 2.6            | 500         | 30          |
| Sample 2 | 80            | 2.5            | 200         | 50          |

**Table 2.** Characteristics of the samples. Values of the 4.2K-mobility \( \mu_{\text{th}} \), the 4.2K-electron density \( n_s \), the length \( L \), and the width \( W \) of the 2DEG channel.

The sensors and samples are fabricated from GaAs/AlGaAs heterostructure wafers, where the 2DEG layers are located 0.1 μm beneath the crystal surface. In Tables 1 and 2, we show the characteristics of the sensors and the samples. As depicted in Fig. 2, the sensors have the four metallic contacts that are extended to the side surfaces of the GaAs wafer, to each of which a wire is attached. In the sensors, small square region of 1.5 μm x 2.3 μm for sensor 1 and that of 1.8 μm x 2.7 μm for sensor 2 correspond to the effective sensing areas. The samples are standard rectangular Hall bar devices. We used sensor 1 and sample 1 for the voltage imaging experiment, and used sensor 2 and sample 2 for the noise-voltage imaging experiment.

For spatially resolved measurements, the samples are moved by a two-axes translation stage, while the sensors are spatially fixed. The whole system is immersed in a ⁴He cryostat, and all the measurements are carried out at 4.2K.

### 3. Experimental results

#### 3.1. Basic features of the quantum Hall scanning electrometer

![Figure 3. (a) B-dependence of the longitudinal resistance, \( R_{\text{sen}} \), of the sensor at \( I_{\text{sen}} = 0.3 \) μA (upper panel) and the detected voltage signal, \( V_{\text{sig}} \), of the sensor at \( I_{\text{sen}} = 0.3 \) μA and \( I_{\text{sam}} = 4 \) μA (lower panel). The two broken lines indicate the peak positions where large signals show up. (b) Schematic illustration of the density of states of Landau levels.](image-url)
Figure 4. Hall voltage profiles at $I_{\text{sen}}=0.3\mu\text{A}$, $I_{\text{sam}}=4\mu\text{A}$, and $B=5.51\text{T}$ ($\nu_{\text{sam}}=2$). Two broken lines indicate the positions of the 2DEG boundaries. As represented in the inset, the respective data were taken by translating the sensor along four dotted lines, (1)-(4), in the sample.

The upper panel of Fig. 3 (a) shows the four-terminal resistance $R_{\text{sen}}$ as a function of $B$ at $I_{\text{sen}}=0.3\mu\text{A}$ and $I_{\text{sam}}=0$. In the lower panel of Fig. 3 (a), the detected signal, $V_{\text{sig}}$, with a sweep of $B$ is displayed at $I_{\text{sen}}=0.3\mu\text{A}$ and $I_{\text{sam}}=4\mu\text{A}$. Comparing these two data shows that large signals systematically appear slightly outside QHE plateaus. This feature suggests that the large occurrences of $V_{\text{sig}}$ originate from the following electronic property of the QHE device: As schematically illustrated in Fig. 3 (b), in the presence of $B$, discrete energy levels (Landau levels) are formed, each of which has localized and extended states. Therefore, when the Fermi level $E_F$ is located at the boundary between these two states, it follows that even a slight rise in $E_F$ caused by the generation of $\Delta Q$ in the sensor leads to an enhancement of the resistance change $\Delta R_{\text{sen}}$.

By scanning this electrometer over the sample surface, we observe voltage distribution profiles along the width direction of the 2DEG channel, and show them, as in Fig. 4; these measurements were done at $I_{\text{sen}}=0.3\mu\text{A}$, $I_{\text{sam}}=4\mu\text{A}$ and Landau-level-filling factor, $\nu_{\text{sam}}=2$, of the sample ($B=5.51\text{T}$). As illustrated in the inset of Fig. 4, the four data are taken, respectively, (1) on the boundary between the current source contact and the 2DEG, (2) in the middle between two current contacts, (3) on the boundary between the 2DEG and the ground terminal, and (4) on the ground terminal. The voltage images obtained show: (1) the occurrence of Hall voltage along the whole boundary, (2) a gradual slope in the interior 2DEG region, (3) a steep increase at hot spot, and (4) no voltage on the ground terminal. These features are consistent with voltage distribution expected for a Hall bar in the QHE state [12]. The above results confirm that the present system works properly as a scanning electrometer for imaging voltage distributions.

3.2. Noise-voltage imaging

To examine the basic features of the sample noise, we measure a longitudinal resistance, $R_{\text{sam}}$, of the sample, and a corresponding noise voltage, $S_V$, with the sweep of $B$ at $I_{\text{sam}}=0.05$, 0.1, 0.3, 0.5, and 0.7$\mu\text{A}$, and plot them, as in Fig. 5. It should be noted that these data are taken in four-terminal measurements for the sample itself, as represented in the inset of Fig. 5. The $R_{\text{sam}}$ spectra between $\nu_{\text{sam}}=4$- and $\nu_{\text{sam}}=2$-QHE plateaus in the upper panel of Fig. 5 show that, when $I_{\text{sam}}<0.5\mu\text{A}$, the amplitude of the oscillations normally observed in $R_{\text{sam}}$ vs. $B$ is strongly reduced, whereas as the current increases, the amplitude of $R_{\text{sam}}$ recovers. These are well-known phenomena, which are due to the nonequilibrium edge state decoupled from the bulk state and its quenching for the current above 0.5$\sim$1$\mu\text{A}$ [13,14]. The data of $S_V$ vs. $B$ show that, with increasing the current beyond $I_{\text{sam}}=0.5\mu\text{A}$, $S_V$ rapidly grows in the region of $2<\nu_{\text{sam}}<4$. Comparing the $B$ dependence of $S_V$ with that of $R_{\text{sam}}$, suggests that the enhancement of $S_V$ arises from the unstable electron transfer taking place when the nonequilibrium edge state equilibrates, as the current increases, with the bulk state.
Figure 5. The longitudinal resistance, $R_{sam}$, of the sample (upper panel) and the corresponding noise voltage $S_V$ (lower panel) versus magnetic field $B$ at $I_{sam}=0.05, 0.1, 0.3, 0.5, \text{and } 0.7 \mu A$.

Figure 6. Image of $S_V$ distribution at $B=4.41 \, T$ ($\nu_{sam}=2.38$) and $I_{sam}=0.7 \mu A$. The white broken line shows the 2DEG boundary.

Figure 7. Schematic representations of electron flow (left panel) and spatial profile of Landau levels (right panel) in the lower $B$ region of the $\nu_{sam}=2$ QHE plateau.

Figure 6 displays an image of $S_V$ distribution for the same sample as that used in the measurements shown in Fig. 5 at $I_{sam}=0.7 \mu A$ and $B=4.41T$ ($\nu_{sam}=2.38$); this image is obtained with the experimental system described in Fig. 1 (a). The value of $B=4.41T$ corresponds to the maximum peak position of $S_V$ with the sweep of $B$ at $I_{sam}=0.7 \mu A$, shown in the lower panel of Fig. 5. The $S_V$ map shows that the most of the noise is concentrated in a higher-potential (lower Hall voltage) edge region of the Hall bar sample. This result provides clear evidence that the high noise levels occur as a result of the equilibration process of the electrons from the nonequilibration edge state to the bulk state, as schematically shown in Fig. 7. This consistency between the transport data of Fig. 5 and the mapping data of Fig. 6 makes sure that the image obtained with the present measurement corresponds to the noise-voltage distribution. The spatial resolution obtained from the data is about $2 \mu m$, which is almost the same as the size of the sensing 2DEG area of the sensor.

4. Remarks and Summary

We would like to make two remarks on the present noise-imaging system. First, we note the spatial resolution of our system. Its spatial resolution, $2 \mu m$, is determined by the size of the sensing area, i.e. the values of $L_1$, $L_2$, and $W_1$. Therefore, the resolution can be improved by reducing the 2DEG size of the sensing area. We expect that a further enhancement would be achieved with the improved system.
illustrated in Fig. 8. Here, a metallic probe with a tip diameter of below 100nm is combined with the gate electrode of the QHE electrometer. In this system, the resolution will be mainly determined by the tip diameter, because local noise voltage is detected via capacitive coupling between the probe tip and the sample. However, this system has the disadvantage that the sensitivity is reduced because the capacitance with the sample is smaller than that in the system of Fig. 1(a).

Figure 8. Schematic of the concept of the system as improved from that in Fig. 1(a).

Second, we point out that as shown in Fig. 3 (a), the sensitivity of the sensor depends strongly on $B$. One might think that imaging voltage or noise voltage distributions for various magnetic fields would be impossible. We can resolve this problem the following way: As the magnetic field is varied, one could tune $n_s$ of the sensor with the application of a back gate voltage.

In summary, as a novel application of the QHE, we have developed a scanning electrometer, enabling us to map the spatial distributions of the voltage and the noise voltage. The noise-voltage map obtained for a QHE sample showed that noise, largely occurring for $2 < v_{\text{sam}} < 4$ and $I_{\text{sam}} > 0.5 \mu \text{A}$, is concentrated in the higher-potential edge region of the QHE sample. These findings lead us to understand that the high noise levels are generated due to an unstable equilibration between the nonequilibrium edge state and the bulk state. The present experiments demonstrate that the noise-imaging technique provides a powerful probe for investigating spatial electronic properties in solid-state devices.

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