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Detection of Edge-Conducting Channels in Quantum Hall Systems Using a Single-Electron Transistor

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We report detection of the edge channel of a two-dimensional electron gas (2DEG) in quantum Hall regime, through the measurement of the chemical potential variation and the compressibility of a 2DEG using a single-electron transistor (SET) on top of the 2DEG. The measurements at higher frequencies enabled us to detect the incompressible electronic states of the fractional quantum Hall effect (FQHE), the results of which indicate a method for resolving the edge channel of FQHE spatially.

KEYWORDS: single-electron transistor, quantum Hall effect, fractional quantum Hall effect, edge channel

1. Introduction

The importance of conductance channels at the edges (edge channels) in the integer quantum Hall effect (IQHE) is now well established, although the details (*e.g.*, current distribution, behavior at critical current) still leave room for discussion. In the fractional quantum Hall effect (FQHE), we know very little about the edge channel. The existence of a finite width edge state was experimentally observed.[1–5] However, there has been no report on the detailed spatial information on the edge channels in the FQHE.

A single-electron transistor (SET) can be a highly sensitive electrometer with spatial resolution comparable to its own size,[6,7] while it is usually insensitive to a magnetic field. Thus, an SET on a two-dimensional electron gas (2DEG) substrate can probe electronic properties of the 2DEG underneath with high spatial resolution. An experiment for IQHE by this method has already been reported.[8] In the experiment in ref. 8, the edge channels were detected through the amplitude of noise appeared in Coulomb oscillation by utilizing the incompressibility of quantum Hall liquid. To FQHE, however, this method cannot be applied directly because the energy gap is much smaller and dc measurement cannot detect the slight increase in the response time.

In this report, we applied SET sdetection of the edge channel in the FQHE, expanding such a measurement to the frequency domain. High-frequency measurement would not only enhance the detection capability but also increase the spatial resolution. We first discuss the results of static measurement, then present the results for the higher frequency region.

2. Device and Experimental Details

The 2DEG used in this experiment is at a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure grown by molecular beam epitaxy. The heterointerface is located 90 nm away from the sample surface. The 2DEG has a sheet density (n_e) of 2.0×10^{11} cm^{-2} and an electron mobility of 7.2×10^5 cm^{2}V^{-1}s^{-1} at 30 mK. A Hall-bar mesa was etched from the substrate with AuGe ohmic contacts.

On the top of the Hall-bar, an Al-AlO_x-Al SET was fabricated by standard electron beam lithography and two-angle evaporation techniques. The central island of the SET fabricated is 300 nm long, 80 nm wide and 25 nm thick, and connected to source and drain aluminum leads through two tunnel junctions of about 80 nm × 80 nm area. The tunnel resistances in series are 100 kΩ to 400 kΩ and the total charging energies $E_c = e^2/2C_\Sigma$ of the islands are between 30 and 100 μeV, depending on the samples. In our sample geometry, the 2DEG is used as a gate electrode for the SET island.

A top-side gate is placed about 0.65 μm away from the SET island in order to deplete the underlying 2DEG and control the distance from the SET island to the edge of the 2DEG.

All the measurements were performed in a dilution refrigerator at 30 mK. A magnetic field up to 15 T was applied perpendicular to the sample substrate by a superconducting solenoid. In order to minimize the direct cross talk between leads, which becomes severe at high frequencies, coaxial cables were introduced as the leads for the source and drain. Even with this setup, some background cross talk, *e.g.*, through the connection to the specimen, etc. is inevitable. To eliminate such spurious signal, we adopted a lock-in technique for detecting the double-frequency ($2f$) component utilizing the nonlinearity of the SET response. In the present system, double-frequency cross talk through a transducing process was below the noise level. The SET was driven by a voltage source and the source-drain current was detected by a battery-driven current amplifier placed close to the head of the cryostat. Hence, the drain was maintained at the ground level, although the resultant shift in the gate voltage was negligible.

3. Results and Discussion

Figure 1(b) shows the measured conductance oscillation versus gate voltage (i.e., the voltage between the SET and an electrode connected to the 2DEG), the so-called Coulomb oscillation, for different magnetic fields. The source-drain voltage is fixed at 100 μV. Mainly two local properties of the 2DEG can be probed in this measurement.

First, the chemical potential variation (here we distinguish chemical potential and electrochemical potential) of the 2DEG is detected as the shift in the phase of the Coulomb oscillation. The shift in the peak positions reflects the shift in the voltage between the 2DEG and the Al SET island. Since the magnetic field dependence of the chemical potential of aluminum is negligible, the variation in the contact voltage is mainly due to the variation in the chemical potential of the

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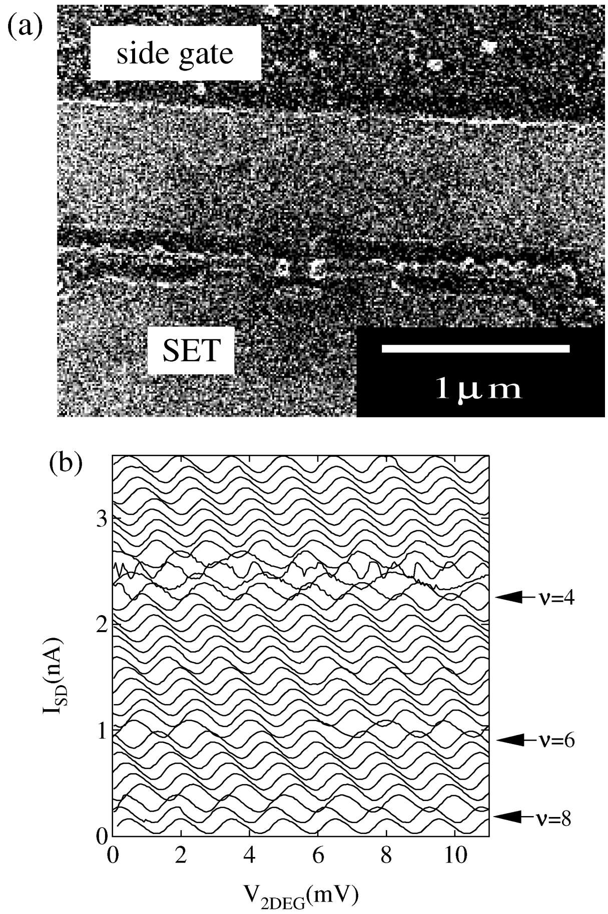

Fig. 1. (a) Scanning electron micrograph of the single-electron transistor (SET). The SET is located on the Hall bar made of a GaAs/AlGaAs heterostructure 2DEG. The side gate is used to deplete the underlying 2DEG. (b) Source-drain current vs V_{2DEG} for magnetic fields from 1.0 T to 2.7 T in the steps of 0.05 T, at $T = 30$ mK. The curves for the different magnetic fields are displaced along the ordinate for clarity.

2DEG induced by the external magnetic field.[9)]

Second, compressibility of the 2DEG is probed through the response time to the gate voltage. For example, in Fig. 1(b), low-frequency fluctuation (noise) in the source-drain current increased and Coulomb oscillations disappeared where the filling factor ν ($\equiv hn_e/Be$, B being the magnetic field) is approximately 4. This is interpreted as follows. When the 2DEG is in an incompressible quantum Hall state, $\sigma_{xx} \simeq 0$ and the bulk 2DEG behaves as an insulator. Hence, the 2DEG near the SET is almost decoupled from the ohmic contact and the Coulomb oscillation cannot be observed in an ordinal time scale for experiments. The increase in the noise is attributed to the loss of the screening property of the 2DEG and resultant charge fluctuations in the vicinity of the SET island.

In general, a metallic electrode placed on the 2DEG substrate affects the electron concentration of the underlying 2DEG and a bias voltage is necessary to compensate such inhomogeneity. To determine the optimum bias voltage, we measured the magnetic field dependence of the local chemical potential variation at different bias voltages. Figure 2 shows the trace of the Coulomb oscillation peak positions with the bias voltage as the parameter. The magnetic fields where the chemical potential drops sharply correspond to even integer filling factors. By comparing the result with the Shubnikov-de Haas measurement, we determined the bias voltage to be

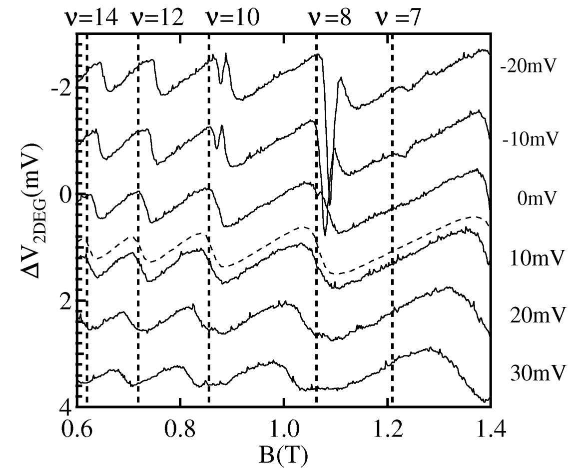

Fig. 2. Solid lines: local chemical potential variation versus magnetic field near different dc offset voltages from 30 mV to −20 mV in steps of 10 mV. Offsets are added for better presentation. Dashed line: calculated chemical potential variation of the 2DEG. Lorentzian broadening of the Landau levels with $\Gamma = 0.2$ meV is assumed. The curve near $V_{2DEG} = 10$ mV fits best to the calculation.

about 10 mV. This result is consistent with the calculated chemical potential variation assuming Lorentzian density of states of the Landau levels with the broadening $\Gamma = 0.2$ meV.

To detect edge channels of the IQHE, we measured Coulomb oscillations with a negative sidegate voltage (V_{side}) applied at the magnetic field at 8.4 T ($\nu = 1$). When no voltage is applied to the sidegate, Coulomb oscillations are not visible because the bulk 2DEG is in an incompressible quantum Hall state. At $V_{side} = -0.275$ V, the effective edge of the 2DEG comes under the geometrical edge of sidegate electrode (650 nm from the SET island), but there is still no change in the observed source-drain current. At $V_{side} = -0.45$ V (the edge is 600 nm from the SET), the Coulomb oscillations appeared taking the place of the noise, which is the sign that electrons in the vicinity of the SET island are compressible (metal-like), i.e., the edge channel existed under the SET.

In order to extract the information on compressibility of the 2DEG more quantitatively from such measurements, we use a Fourier power spectrum of the oscillation. The results are shown in Fig. 3. The distance between the SET island and the edge of the 2DEG is calculated by adopting a "frozen surface" model.[10)] The components around the frequency of Coulomb oscillation represent compressibility of the 2DEG under the SET, and the high-frequency noise components represent incompressibility. The edge channel is clearly visible in this analysis.

In spite of the above success in IQHE, this method cannot be applied directly to FQHE, as shown in the following. Figure 4 shows Coulomb oscillations measured at magnetic fields around $\nu = 2/3$. Although a well-developed fractional quantum Hall plateau is observed in σ_{xy}, there is no significant change in the Coulomb oscillations. This difference is attributed to the size the energy gap in the FQHE (typically $\simeq 0.2$ meV). Since the gap is small and the σ_{xx} is not small enough, the bulk 2DEG can follow thermodynamic equilibrium in the time scale accessible by these measurements (V_{2DEG} is swept at 0.1 mV/s). The situation is similar to an odd-integer IQHE, where we could observe clear

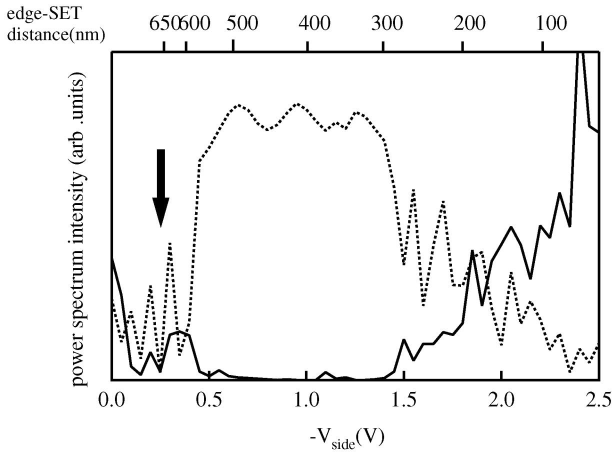

Fig. 3. Fourier power spectrum intensity of Coulomb oscillations versus side gate voltage measured at magnetic field $B = 8.4$ T ($\nu = 1$). The Coulomb oscillation component (dashed line) represents the compressibility of the 2DEG under the SET island. The high-frequency (noise) component (solid line) indicates that the 2DEG is incompressible. The negative sidegate voltage controls the depletion length of the 2DEG near the gate. The arrow indicates the voltage at which the 2DEG under the sidegate is completely depleted.

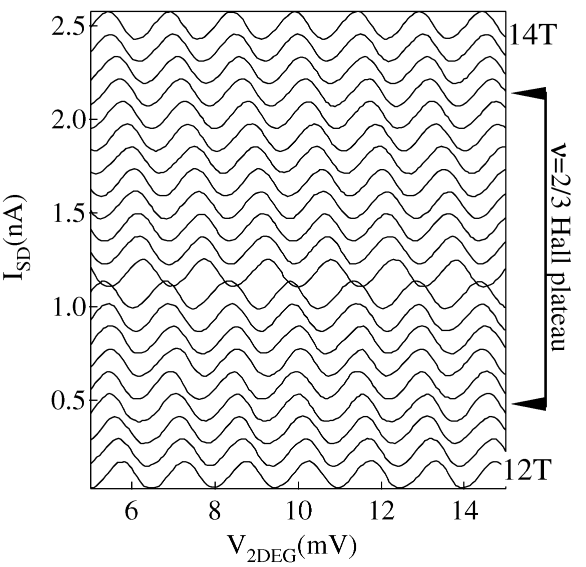

Fig. 4. Coulomb oscillations for magnetic fields from 12.0 T to 14.0 T with steps of 0.1 T. For better presentation, curves for different magnetic fields are displaced along the ordinate axis. The magnetic field of this range covers the observed Hall plateau coressponding to $\nu = 2/3$ FQHE.

Coulomb oscillations while Hall resistance showed an integer quantum Hall plateau. The problem is summarized that the time scale of the potential fluctuation due to the incompressibility of fractional quantum Hall liquid is too short to affect the static Coulomb oscillation.

The electric response of a 2DEG in QHE can be modeled as a distributed constant circuit. The resistance and the self-capacitance of the 2DEG consist an RC low-pass filter. Hence, the response time is characterized by the RC time constant. Diminution in σ_{xx} at the QHE thus results in the increase in the response time. Within this model, the disappearance of the Coulomb oscillation at the IQHE is interpreted as the divergence of the response time. This insight leads us to the inference that the measurement in the frequency domain

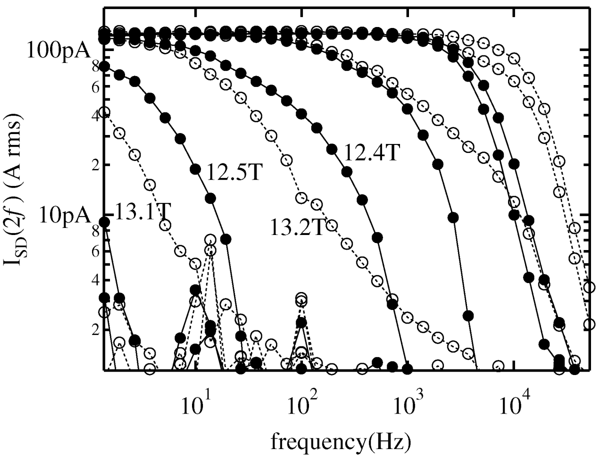

Fig. 5. Frequency dependence of the $2f$ SET current for different magnetic fields in the steps of 0.1 T. Solid circles: from 12.1 T to 12.7 T. Open circles: from 12.8 T to 13.4 T. Solid and dashed lines are a guide for the eyes. These lines show the response function of the bulk 2DEG to the ohmic contact.

would give more precise information on the incompressibility of the quantum Hall liquid and enable the resolution of the edge channel.

With the above inference, we performed measurements at higher frequencies. To eliminate the current due to cross talk, a double-frequency signal was measured in the following manner. The gate dc offset voltage was adjusted to the peak of the Coulomb oscillation, then ac modulation of amplitude 2.3 mV_{p-p} (the period of the Coulomb oscillations of this sample is 2.8 mV) and frequency (f) up to 10 kHz was applied. In this situation, the frequency of the SET source-drain current is twice that of the modulation. This $2f$ current was measured using a current amplifier and a lock-in amplifier. The measured signal corresponds to the local electrostatic potential modulation near the SET.

Figure 5 shows the measured frequency characteristics of the above experimental setup for different magnetic fields around $\nu = 2/3$ (12.8 T). The side gate was grounded through this measurements. The sharp decrease near 10 kHz is due to the characteristics of the current amplifier. As expected, it can be clearly observed that the cut-off frequency rapidly diminishes as the magnetic field approaches $\nu = 2/3$. Below 10 kHz and far from $\nu = 2/3$, the characteristic is almost flat at unity gain and we can attribute the decrease in the gain to the 2DEG. This result demonstrates that our method can be applied to the study of the edge channels in the FQHE.

If we assume simple RC relaxation, the response function is expected to decrease as f^{-1}. The observed response functions at magnetic fields smaller than $\nu = 2/3$ drops much more quickly than f^{-1}, while that of the higher magnetic fields decreases more slowly. On the contrary, similar measurements near $\nu = 2$ were performed and nearly f^{-1} behavior of the response function was observed at both higher and lower sides of $\nu = 2$. At the present stage, it is not clear whether this anomalous response is peculiar to the FQHE, and further investigation is now under way.

4. Conclusions

The spatial distribution of the IQHE edge channel around $\nu = 1$ was resolved by using a single-electron transistor as a sensor for the 2DEG and controlling the effective edge of the 2DEG by the sidegate placed near the SET central island. An incompressible electronic state of fractional quantum Hall effect was also detected through relaxation time measurements at higher frequencies. These results demonstrate that it is possible to resolve the edge channel of the FQHE spatially by a combination of these techniques.

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