Spatial mapping of potential fluctuation in GaAs/AlGaAs and graphene by a scanning nanoelectrometer

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Abstract. We present observations of potential fluctuation distributions in two-dimensional systems of a GaAs/AlGaAs interface and of a graphene surface. We have exploited scanning electrometers based on gate effects for the sensor via capacitive coupling with a sample. The experimental data for the GaAs/AlGaAs sample show that the temporal potential fluctuation (noise voltage) largely occurs in the transition region between two adjacent quantum-Hall plateaus and that it is concentrated on a sample boundary. This fluctuation can be understood as arising from unstable electron relaxation in the non-equilibrium edge state. For the graphene sample, a Hall potential profile was imaged and a potential fluctuation with the period of 50-100nm was observed.

1. Introduction
Electric potential fluctuations in space and/or time domains play important roles in quantum electron transport of meso- and nano-scopic devices, such as electron localization and delocalization. Interest in such phenomena has attracted much interest, and several scanning probe techniques for obtaining potential images have been developed, such as electro-optic effect imaging [1,2], a Kelvin force microscope (KFM) [3], and a scanning single-electron transistor (SET) [4,5]. Although the KFM and the SET are useful methods for obtaining high-resolution images, one can not rule out the possibility that the application of high voltage between a KFM tip and a sample may disturb the actual potential distribution. The SET is only used in a dilution or 3He refrigerator, because observations of clear coulomb oscillations are required. This condition restricts the range of measurements that are feasible with this method.

We have developed two types of scanning electrometers; a two-dimensional electron gas (2DEG) sensor in GaAs/AlGaAs heterostructure [6] and a cantilever-integrated 2DEG sensor [7]. The sensing mechanism is that local potential is detected through gate effects for the 2DEG sensor via capacitive coupling with a sample. Using this technique, we have demonstrated mapping of the potential distribution in other 2D systems of a GaAs/AlGaAs interface and of a graphene surface. We have imaged spatial distribution of the temporal potential fluctuation (noise voltage) in the GaAs-based 2DEG sample. The experimental data revealed linear distribution, which results from unstable relaxation of edge-state electrons. For the graphene sample, the potential amplitude was shown to fluctuate with the period of 50-100nm. This feature has not been obtained for the 2DEG in the GaAs/AlGaAs heterostructure. We discuss relevant mechanisms of charge dynamics.

2. Experimental setup
Figures 1(a) and (b) schematically depict the two types of potential imaging systems. 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 SiO$_2$ film. A magnetic field $B$ was applied perpendicular to the 2DEG planes. In this scheme, since the distance between the 2DEG sensor and the sample is very short, they are capacitively coupled. It follows that when a source-drain current $I_{\text{sam}}$ is passed through the sample, excess charges $\Delta Q$ are induced into the 2DEG, 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 sensor and the sample. The generation of $\Delta Q$ results in the change, $\Delta R_{\text{sen}}$, in the sensor resistance, $R_{\text{sen}}$. By moving the sensor over the sample surface and simultaneously measuring $\Delta R_{\text{sen}} \times I_{\text{sen}}$, a two-dimensional distribution of $V(x,y)$ in the sample is imaged ($I_{\text{sen}}$ is the current for the sensor).

Based on the above mechanism, we carried out spatial mapping of the potential fluctuation (noise voltage). Using a lock-in amplifier, we measured the mean-square voltage, $S_V$, of the voltage fluctuations $\Delta V$, which is expressed as $S_V = \left[ \Delta V(f) \right]^2 / \Delta f$. Here, $f$ is a central frequency for the noise detection and $\Delta f$ is a frequency bandwidth. In this experiment, we set $f = 1$ kHz and $\Delta f = 10$ Hz in the lock-in amplifier. The $S_V$ value of the pre-amplifier was about $4 \times 10^{-18}$ V$^2$ Hz$^{-1}$ at $f = 1$ kHz, a level which is low enough to measure only sample noise. In order to remove the noise of the sensor itself, we subtracted $S_V$ at a sample current $I_{\text{sam}} = 0$ from that at $I_{\text{sam}} \neq 0$.

The spatial resolution of the above system was about 2 $\mu$m. In this scheme, the resolution is restricted by the size of the 2DEG sensing area. In order to resolve this problem and improve the resolution, we constructed the second type of electrometer system, as illustrated in Fig. 1(b). Here, a metal-coated cantilever probe with a tip diameter of 20 nm is integrated with the gate contact of the 2DEG sensor. In this system, local potential is detected by the following processes: (i) The metallic probe tip senses local potential through capacitive coupling with the sample; (ii) As a result, the tip region of the probe is electrically charged, leading to electrical polarization of the gate contact of the 2DEG sensor according to charge conservation law; (iii) The polarization of the gate contact results in generation of excess charges, $\Delta Q$, in the 2DEG of the sensor, and thereby the sensor resistance changes. With this system, we were able to obtain a much higher resolution (24 nm), which was primarily determined by the tip diameter (20 nm).

The sensors were fabricated from GaAs/AlGaAs heterostructure wafers, where the 2DEG layers are located 0.1 $\mu$m beneath the crystal surface. As samples, we used two types of 2D systems; GaAs/AlGaAs and graphene. We used an exfoliated graphene on a SiO$_2$/Si substrate. The GaAs/AlGaAs (graphene) sample is a rectangular Hall bar with a length of 200 (10) $\mu$m and a width of 50 (0.9) $\mu$m.

For potential imaging measurements, the samples were moved by an X-Y translation stage, while the sensors were stationary. The whole system was immersed in a 4 He cryostat, and all the measurements were performed at 4.2K.
3. Experimental results

3.1. GaAs/AlGaAs

![Figure 2.](image)

**Figure 2.** (a) The longitudinal resistance, $R_{\text{sam}}$, of the GaAs/AlGaAs sample (upper panel) and the mean-square voltage, $S_V$, of the temporal potential fluctuations (lower panel) as a function of magnetic field $B$. (b) Two-dimensional $S_V$ map in the GaAs/AlGaAs sample at $B=4.41$T ($\nu_{\text{sam}}=2.38$) and $I_{\text{sam}}=0.7\mu$A. The value of $B=4.41$T corresponds to the peak position of $S_V$ vs $B$, as indicated by the broken line in (a). The length and width of the Hall bar sample are 200$\mu$m and 50$\mu$m, respectively.

First, we studied the basic features of the sample noise with conventional four-terminal transport measurements. Figure 2 (a) displays 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$\mu$A. The $R_{\text{sam}}$ spectra between $\nu_{\text{sam}}=4$- and $\nu_{\text{sam}}=2$-quantum Hall plateaus in the upper panel of Fig. 2(a) show that, when $I_{\text{sam}}<0.5\mu$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. ($\nu_{\text{sam}}$ is Landau-level filling factor of the sample.) These are well-known phenomena, which originate from the non-equilibrium edge transport decoupled from the bulk transport and its quenching for the current above 0.5–1$\mu$A [8,9]. The data of $S_V$ vs. $B$ show that, with increasing the current beyond $I_{\text{sam}}=0.5\mu$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 $S_V$ enhancement is related to the unstable electron transfer taking place when the non-equilibrium edge state equilibrates, as the current increases, with the bulk state.

![Figure 3.](image)

**Figure 3.** Schematic representation of spatial profile of Landau levels and electron dynamics in the region of $2<\nu_{\text{sam}}<4$. 

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Figure 2(b) displays $S_V$ mapping for the same sample as that used in the measurements shown in Fig. 2(a) at $I_{sam}=0.7 \mu A$ and $B=4.41 T$ ($\nu_{sam}=2.38$). The value of $B=4.41 T$ 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. 2(a). The $S_V$ map reveals that the most of the noise is concentrated in a higher-potential (lower Hall voltage) edge region of the Hall bar. This result provides clear proof that the $S_V$ enhancement in the region of $2<\nu_{sam}<4$ results from the equilibration process of the electrons from the non-equilibration edge state to the bulk state, as schematically represented in Fig. 3.

This data was taken at $f=1 kHz$ and the dynamics with the time constant of 1ms was investigated. The $S_V$ distribution should strongly depend on the time constant characteristic of the charge dynamics and hence on the $f$ value. The $S_V$ mapping in the frequency domain is an interesting next step.

3.2. Graphene

Using the second electrometer system with much higher resolution (24nm), we performed the potential imaging in the graphene Hall bar device. Figure 4 shows a line-scan plot of the Hall potential profile along the channel-width direction at $I_{sam}=0.4 \mu A$. The graphene device has a channel length of 10$\mu$m and a channel width of 0.9$\mu$m. The data of Fig. 4 revealed that the potential amplitude fluctuates with the period of 50-100 nm. We observed that such potential fluctuation in space was also seen for different positions of the graphene device. This feature has not been obtained on the 2DEG in the GaAs/AlGaAs heterostructure. At present we interpret that the potential fluctuation may arise from topological variation in the graphene surface and resulting change in Hall effect or from trapped charges in the SiO$_2$ substrate. The elucidation of this feature requires further investigation, including a comparison with potential imaging for epitaxial graphene.

4. Remarks and Summary

We would like to make two remarks on the potential imaging. First, we note future improvement in the detection sensitivity and the spatial resolution of our system. It is known that a quantum point contact (QPC) device works as an ultra-sensitive electrometer [10]. We anticipate that the use of the QPC electrometer would result in the large enhancement of the sensitivity. In our second type of electrometer system, the resolution is determined by the tip diameter. Based on this fact, using a carbon nanotube probe with a smaller tip diameter is expected to lead to more improvement in the resolution. Second, the potential variation in graphene and its effect on transport and optical properties are still questions to be resolved. Miller et al. have reported that the peak position of Landau level obtained with scanning tunneling spectroscopy varies with the tip location relative to the graphene
surface [11]. We plan to investigate the screening of the potential and the charge redistribution with our scanning electrometer.

In summary, we have studied the potential fluctuations in the 2D systems of GaAs/AlGaAs and of graphene by using two types of scanning electrometers. We have imaged the spatial distribution of the temporal potential fluctuation (noise voltage) in the GaAs-based 2DEG sample. The experimental data revealed linear distribution resulting from unstable relaxation of non-equilibrium edge-state electrons. For the graphene sample, we observed that the potential amplitude fluctuates with the period of 50-100nm. Studying the potential fluctuation and its effect on macroscopic transport properties is our next target.

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