Scanning electrometer using gate effect for a quantum Hall device by a charged nano-probe

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1. Electrostatic potential imaging

Observation of electrostatic potential landscape in low-dimensional systems is crucially important for microscopic understanding of matters of electron transport, such as where and how electron flows in devices. Especially, in quantum Hall effect (QHE) devices, the issue is very of interest. Because it has been revealed that the systems have spatially dependent transport properties, for example, one-dimensional edge channel, macroscopically nonlocal transport in the breakdown regime of the QHE, etc. However, a satisfactory understanding of their origins remains elusive. Attraction of such issues has driven experimental efforts for obtaining electrostatic potential images to produce such techniques as use of electro-optical effect [1] and application of AFM cantilever [2]. In these techniques, however, one can not rule out a possibility that illumination of the intense laser beam and vibration of the AFM tip disturb real potential distributions.

Recently we have successfully developed a simple and powerful method for mapping electrostatic potential distributions, where small QHE devices are exploited as local electrometer [3]. In the present work, we have improved drastically the previous system through introduction of a nano-probe. Thanks to the novel technique, we have achieved spatial resolution of sub micrometer (about 0.8μm), which is significant improvement (by a factor of about 13), compared to our earlier setup.

2. Experimental scheme

The experimental scheme is described in Fig. 1(b), compared to our earlier setup in Fig. 1(a). In both systems, basic mechanism for detecting local electrostatic potential is similar and explained as follows: Sensors and samples are capacitively coupled. Therefore, when source-drain voltage is applied to samples, an excess charge ΔQ is induced and consequently the magnetoresistance, R_{sen}, of sensors changes. Here, ΔQ is proportional to local electrostatic potential in samples. Therefore, by translating sensors over the surface of samples and monitoring the variation of R_{sen}, one can image the spatial distribution of electrostatic potential in samples.

In the previous scheme, spatial resolution is limited by the size of two-dimensional electron gas (2DEG) channel in the sensor. The resolution we obtained was about 10μm. To overcome the restriction, in this work, we have introduced a T-shaped probe with a tip diameter of 0.7μm,

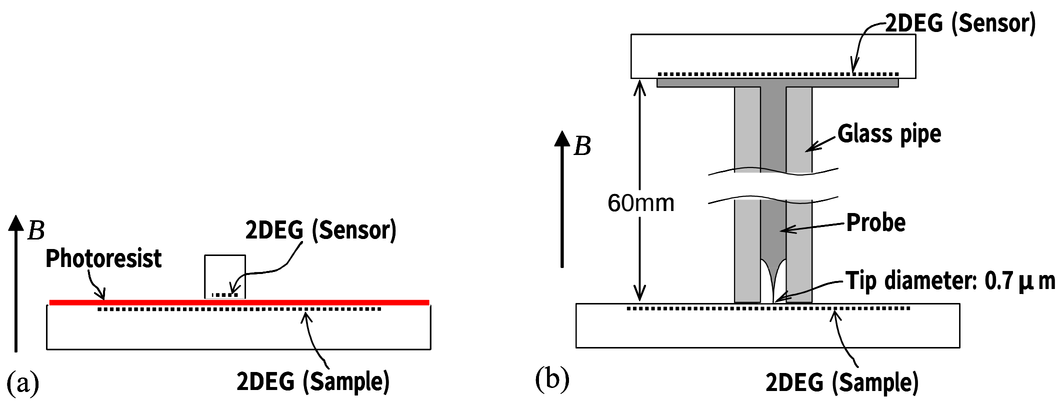

Fig. 1 Schematics of the experimental setup for electrostatic potential imaging in (a) the previous scheme and (b) the presently developed scheme.

between the sensor and the sample. The probe is fabricated from tungsten. The probe not only detects local electrostatic potential by the tip but also plays a role as a gate electrode for the sensor. In this scheme, the resolution is determined by the tip diameter. In the present measurements, we have achieved a resolution of about 0.8μm. Moreover, application of this technique allows us to use a Hall bar with large aspect ratio of 2DEG channel as a sensor, leading to large magnetoresistance changes.

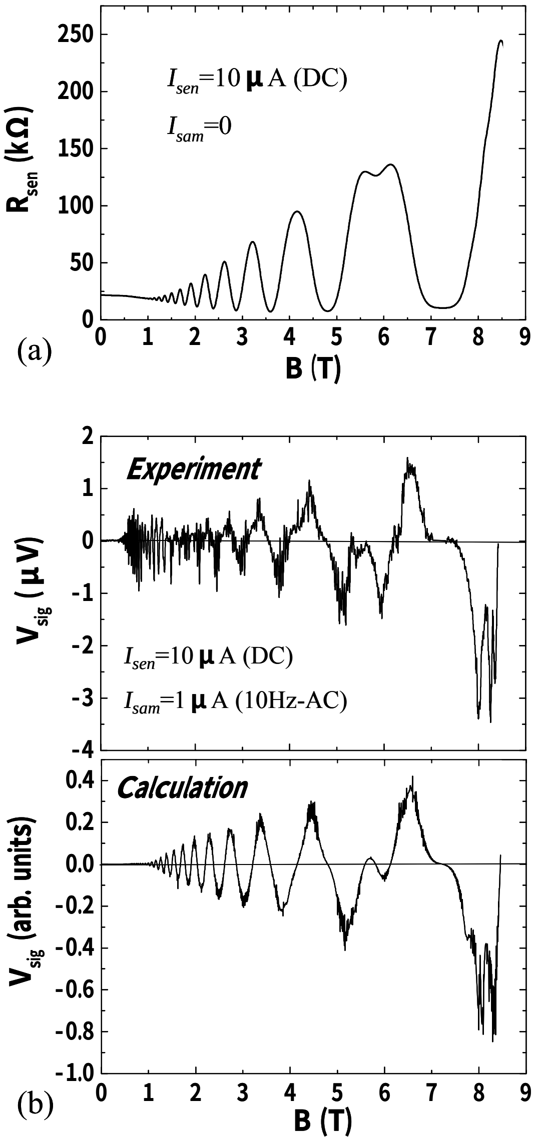

Fig. 2

(a) Two-terminal resistance, R_{sen}, of the sensor as a function of magnetic field B at current I_{sen}=10μA.

(b) B-dependence of detected voltage signal, V_{sig}, of the sensor. Upper and lower panels show experimental result and calculation, respectively.

3. Detection of local electrostatic potential

In the configuration shown in Fig. 1(b), the magnetoresistance R_{sen} and detected voltage signal, V_{sig}, of the sensor are measured and displayed, respectively, in Fig. 2(a) and the upper panel of Fig. 2(b). Here, the sensor and the sample are fabricated on a GaAs/AlGaAs heterostructure into Hall bar. The length L and the width W of the 2DEG channel are L=66mm, W=0.18mm (L/W=367) for the sensor, and L=3mm, W=1mm for the sample. V_{sig} is measured by means of a lock-in technique, where a 10Hz rectangular current is transmitted through the sample.

If V_{sig} is induced by ΔQ as mentioned above, the dependence of V_{sig} on magnetic field B is expressed as

$$V_{sig}(B) = \frac{\partial(R_{sen}I_{sen})}{\partial Q} \times \Delta Q$$

$$= \frac{\partial(R_{sen}I_{sen})}{\partial Q} \times (C \times R_{sam}I_{sam}) \propto \frac{\partial R_{sen}}{\partial Q} \times R_{sam}$$

Here, R_{sam} is the magnetoresistance of the sample, between a spot just below the probe tip and the current-exit contact of the sample. C is capacitance between the probe tip and the 2DEG of the sample at a spot just below the probe tip. On this basis, the B-dependence of V_{sig} is calculated. The result is displayed in the lower panel of Fig. 2(b). The calculated curve reproduces well the experimental data. This indicates that the probe tip senses local electrostatic potential in the sample and as a consequence of gate effect by the charged probe, the magnetoresistance of the sensor is varied.

At the present stage, the spatial resolution is about 0.8μm. In the near future we will improve much better the resolution and the voltage sensitivity by reducing tip diameter and increasing aspect ratio, L/W, of sensor, and provide detailed profiles of electrostatic potential distributions throughout samples.

[1] P. F. Fontein et al., Phys. Rev. B **43**, 12090 (1991).
[2] K. L. McCormick et al., Phys. Rev. B **59**, 4654 (1999).
[3] Y. Kawano and T. Okamoto, Proceedings of the 15th international conference on High Magnetic Fields in Semiconductor Physics, 5 - 9 August 2002, Clarendon Laboratory, Oxford, UK.