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Sensitive current measurement on a quantum antidot with a Corbino-type electrode

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Abstract

Quantum antidots (QAD), which is a potential energy hill in a quantum Hall state, offers an ideal test-bed to study bound states in the integer and fractional quantum Hall states. So far, electron transport in QAD devices has been investigated mostly by measuring a voltage between voltage probes, which, however, may not be suitable to detect small current on the order of pico-amperes or less. Here, we utilize a Corbino-type electrode to directly measure the current through the QAD. We observe Coulomb blockade oscillations by changing the magnetic field, which clarifies the formation of the QAD. Furthermore, we find the direct current measurement with a current-voltage converter provides more precise tunneling current than the voltage measurement with a voltage amplifier.

1. Introduction

A quantum antidot (QAD) is a small depleted region in a quantum Hall (QH) state. The Aharonov-Bohm (AB) effect quantizes the area of the electronic orbits as specified by the relation $BS = m\Phi_0$, where B is the magnetic flux density, S is the area, and m is the number of magnetic flux quanta $\Phi_0 = h/e$ inside the orbit. For a single occupied Landau level, the transport through the QAD is basically allowed periodically with the magnetic field period of $\Delta B = \Phi_0/S$. When n (> 1) Landau levels are populated, the Coulomb interaction between the orbits determines their energies, and thus the period becomes $\Delta B = \Phi_0/nS$ even when one of the Landau levels contributes to the transport [2, 3]. Since the Coulomb interaction dominates the transport [4], the oscillatory behavior is often referred to as Coulomb blockade (CB) oscillations [5]. Besides, many-body phenomena such as the Kondo effect [6] and the fractional QH effect [7-9] can appear in QADs. QAD thus is an attractive test-bed for understanding many-body physics.

Most of the QAD experiments have been carried out with voltage measurement as shown in Fig. 1(a). With finite voltage applied between the source and drain ohmic contacts, the diagonal voltage V_D between the opposite edge channels is widely investigated to study the transport through the QAD [1-4, 6, 9, 10]. When more than two transport paths are involved for the same QAD[5], the voltage drop between two nearby probes, V_{ij}, can be measured to determine the current $I_{ij} = (ne^2/h)V_{ij}$ through a path located between i and j-th probes [5, 7, 8]. One can also measure the current I_S or I_D at the ohmic contacts. However, these measurements may make it difficult to detect extremely small current because a large current is always flowing along the outer edge channel of the quantum Hall system. Such background edge current can be eliminated in a Corbino disk geometry in Fig. 1(b), where the current through the QAD is directly measured with a sensitive current meter.

In this study, we use a QAD with a Corbino-type electrode to show the advantage of the current measurement, where one can use a low-noise current-voltage converter that is designed for high-impedance devices like conventional quantum dots. Clear CB oscillations associated with the QAD are successfully observed with a small current on the order of pico-amperes. This is contrast to the noisy data taken with a nominally low-noise voltage amplifier that has finite leakage current at the inputs. The current measurement at Corbino-type electrodes is advantageous for studying small current through a small QAD.

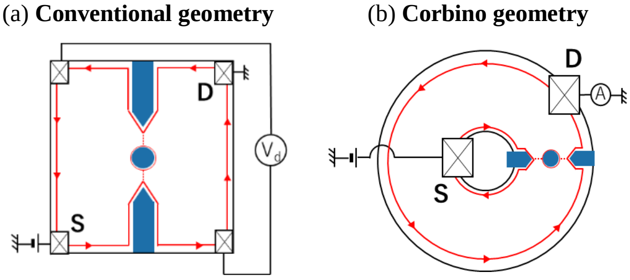

Fig. 1 (a) (b) Conventional and Corbino geometries. The circle indicates QAD. The arrowed lines show edge channels.

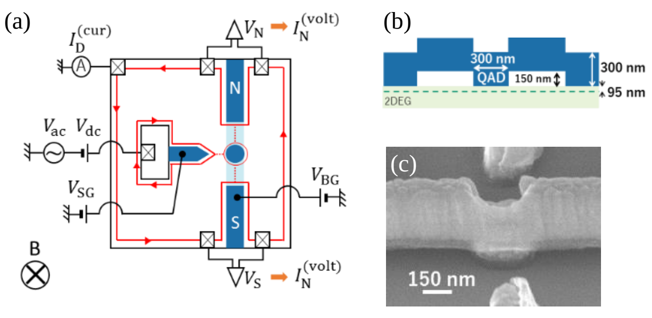

Fig. 2 (a) The schematic device layout and the measurement setup. Each arrowed line shows a bundle of n edge channels ($n = 2$ in our case). (b) Schematic cross section of the airbridge gate. (c) An SEM image of our sample.

2. Experimental setup

Figure 2(a) shows the fabricated device structure with a Corbino-type source electrode, which provides dc bias V_{dc} and ac voltage V_{ac} to the inner edge channel of the quantum Hall system. The QAD was fabricated with an airbridged gate BG and a side gate SG [Fig. 2(b) and (c)]. Ti (30 nm) and Au (270 nm) layers were patterned by electron-beam lithography with a triple layer resist [ZEP (150 nm), PMGI (500 nm), and ZEP (250 nm) from the bottom] [5]. The airgap and the large dielectric constant of GaAs allow the field effect on the 2DEG under the bridge to be much weaker than that under other directly metalized regions. Application of negative voltages V_{BG} and V_{SG} respectively on the bridge- and side-gates forms a potential hill under the pillar of diameter $D = 300$ nm and transport paths [the dashed lines in (a)]. We evaluate currents I_N to the noth channel and I_S to the south channel by measuring the voltage drop V_N and V_S between the probes with the relation $I_i = (ne^2/h)V_i$ for i = N and S. In the following, we fucus on I_S, as I_N is always negligible. Our interest is the total current I_D (= $I_N + I_S \sim I_S$) with an current voltage (I-V) converter. In this setup, we can directly compare the voltage and current measurements for the identical QAD.

3. Magnetic field dependence and Coulomb diamond

Measurements were carried out at 20 mK in a dilution refrigerator under a perpendicular magnetic field $B \sim 5.6$ T at the bulk filling factor $\nu \approx 2$ ($n = 2$). Clear CB oscillations were resolved in I_D with the I-V converter. Figure 3(a) is a color plot of the ac current $I_{D,ac}^{(cur)}$ induced by the ac source voltage $V_{ac} = 30$ μV at 37 Hz. Here, the superscript designates the method. The observed magnetic field period of $\Delta B = 20$ mT is equivalent to the orbital diameter of 360 nm, which is in agreement with the pillar diameter of 300 nm by considering the electron depletion around the pillar. We also observed Coulomb diamond feature in the V_{dc} - V_{BG} plane at B = 5.67 T and $V_{SG} = -1.5$ V [Fig. 3(b)]. We thus confirm the formation of QAD with airbridge gate from these observations.

4. Comparison between current and voltage measurement

To see the advantage of the current measurement, we compare the directly measured current $I_D^{(cur)}$ and the indirectly estimated current $I_N^{(volt)}$ from the voltage measurement. Note that the two measurements were performed separately as the voltage measurement influences the current measurement.

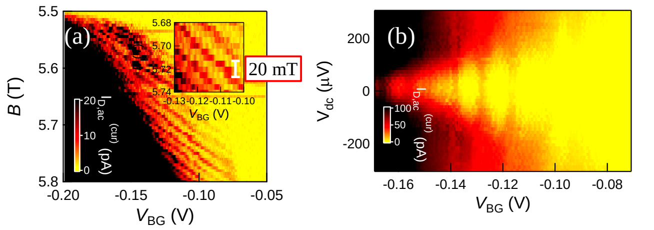

Fig. 3 (a) Color plot of ac current $I_{D,ac}^{(cur)}$ as a function of B and V_{BG} at $V_{SG} = -1.5$ V. The inset shows the expanded view of the color plot. (b) Color plot of $I_{D,ac}^{(cur)}$ as a function of V_{BG} and V_{dc} at B = 5.67 T and $V_{SG} = -1.5$ V, showing Coulomb diamond.

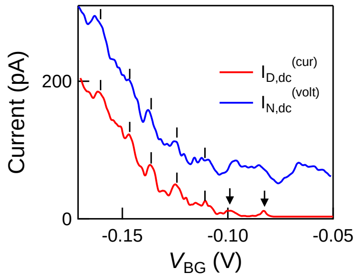

Fig. 4 The red curve is directly measured dc current $I_{D,dc}^{(cur)}$ with the I-V converter, while the blue curve is dc current $I_{N,dc}^{(cur)}$ evaluated from the voltage measurement with voltage amplifiers. The applied voltages are $V_{dc} = 100$ μV. The peaks marked by bars and arrows were reproduced in identical measurements, while other non-reproducing features are the noise discussed in the main text.

Figure 4 summarizes the CB oscillations in dc current of $I_{D,dc}^{(cur)}$ (red) and $I_{N,dc}^{(volt)}$ (blue), where peak positions of the CB oscillations are indicated by vertical bars. The noise in the conductive regions at $V_{BG} < -0.1$ V is almost the same in $I_D^{(cur)}$ and $I_N^{(volt)}$ traces. This noise is probably determined by the charge fluctuation in our device. In the non-conductive region at $V_{BG} > -0.1$ V except for the sharp CB peaks marked by the bars, $I_D^{(cur)}$ shows small noise level of about 0.5 $pA_{p\text{-}p}$ while $I_N^{(volt)}$ shows a large noise level of ~50 $pA_{p\text{-}p}$. Large leakage current in the inputs of the voltage amplifier (totally ~2 nA at the drain from the two amplifiers) and its fluctuation could be the source of the noise in $I_N^{(volt)}$. This hinders the observation of a small CB peak marked by the arrows in Fig. 4. The data clearly shows the advantage of the current measurement.

5. Summary

We have investigated QAD with Corbino-type electrodes and have observed its transport properties such as $h/2e$ magnetic field oscillation. We also have verified that the direct current measurement with the I-V converter enable us to observe the weak tunneling regime more clearly than the voltage measurement with the voltage amplifiers.

Acknowledgements

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