Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp35-36

Quantum Antidot with Fully and Partially Depleted Regions in the Quantum Hall Regime

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Abstract

A quantum antidot (QAD) in a two-dimensional electron gas (2DEG) is an interesting tool for research on electron-electron interaction and quasiparticle excitations in a high magnetic field. In contrast to the QAD with a fully depleted region, we find that the QAD with a partially depleted region shows short-period Coulomb blocakde oscillations associated with the compressible region.

1. Introduction

An antidot is a small depleted region in a 2DEG [1]. An antidot is formed by applying negative voltage to a small gate electrode above 2DEG. In a magnetic field, the Aharonov-Bohm (AB) effect quantizes charge orbitals around the antidot with the relation $BS = m\Phi_0$, where B is the magnetic flux density, S is the area that a charge orbital encircles, m is the number of magnetic flux quanta, and Φ_0 is the magnetic flux quantum. Thus, an antidot in a magnetic field has discrete levels and is called a quantum antidot (QAD). Interestingly, a QAD can also bind quasiparticles called fractional charges induced by electron-electron interaction [2].

Many researchers have investigated QADs with a fully depleted region (FDR) at the center, and explained their natures with the interplay of the AB effect and the Coulomb blockade (CB) effect [1-3]. Here, we investigate the QAD with a partially depleted region (PDR) forming a compressible liquid at the center. The observed short-period CB oscillations cannot be explained with the AB effect.

2. QAD with fully and partially depleted regions

We use an air-bridge gate on an AlGaAs/GaAs heterostructure to form a QAD. Fig. 1(b) shows the schematic design of our QAD device for this experiment. The air-bridge gate is placed horizontally. By applying sufficient voltage V_{GB} to the air-bridge gate, a QAD is formed beneath the central pillar. Two side gates are placed at north and south sides of the pillar to form extended edge channels (ECs) close to the QAD. We measured tunneling current from west ECs to east ECs tunneling under the air-bridge for investigating the FDR, and current from north ECs to south ECs for the PDR while applying voltage V_{GN} and V_{GS} to the gates on north and south.

These tunneling current is evaluated by measuring voltage drop V_i (i = N, S, W, E) between the adjacent voltage terminals across each gate while applying ac voltage V_{ac} to the sample. In the integer quantum Hall regime (IQHR) where

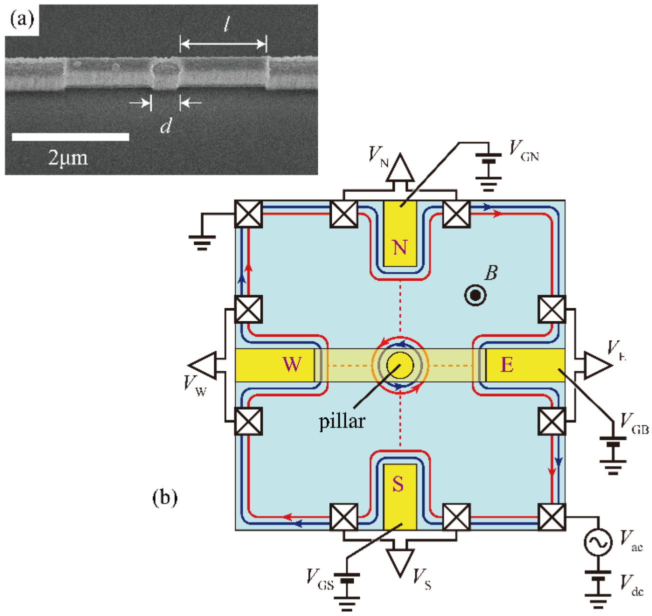

Fig. 1 (a) A scanning electron micrograph of the air-bridge gate structure with d = 0.5 µm, l = 1.5 µm. The device with d = 0.2 µm, l = 3.0 µm is used in this measurement. (b) The schematic diagram of the device and the measurement setup. The air-bridge gate forms an QAD beneath the pillar. By measuring voltage drop V_i (i = N, S, W, E) between the adjacent voltage terminals across each gate, we detect tunneling current through the QAD.

the Hall conductance is quantized as ne^2/h with n (~bulk filling factor ν_B) being the number of the ECs. Each tunneling current through the QAD is proportional to voltage drop V_i. We performed this measurement at 30 mK in a perpendicular magnet field where the system is on the IQHR.

At first, the QAD with a FDR was prepared at $\nu_B \sim 2$ (n = 2) and $V_{GN} = V_{GS} = 0$, and we observed CB oscillations in V_E as a function of B and V_{GB} as shown in the color-scale plot of Fig. 2(a). Because V_{GB} is lower than the pinch-off voltage of the 2DEG, we estimate that the 2DEG beneath the pillar is fully depleted and that both spin-up and -down states form circular orbits as shown in the inset of Fig. 2(a). With the idea that n spin-resolved Landau levels contribute the oscillations by the AB effect, magnetic field period ΔB = 30 mT is equivalent to the 0.3 µm of the QAD diameter [1]. This is a reasonable value considering that the pillar diameter is 0.2 µm. In addition, we confirmed that ΔB decreases with increasing n (tested for 1, 2, and 4) and observed clear Coulomb diamonds as a function of B and dc bias voltage V_{dc}. We confirmed the formation of QAD with air-bridge gate.

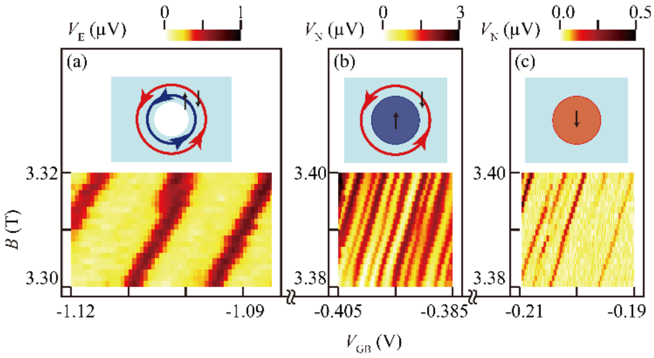

Fig. 2 (a) Color-scale plots of V_E as a function of B and V_{GB}. Both spin-up and -down electrons around the QAD are fully depleted. Inner and outer states form circular orbitals. (b) Color-scale plots of V_N as a function of B and V_{GB} at V_{GN} = -1.9 V and V_{GS} = -1.825 V. While the inner spin-up state forms a PDR, the outer spin-up state forms a circular orbitals enclosing the spin-up PDR as described in the inset. (c) Color-scale plots of V_N as a function of B and V_{GB} at V_{GN} = -1.9 V and V_{GS} = -1.82 V. Only the spin-down state forms a PDR as described in the inset. All data were measured with V_{ac} = 30 μV and V_{dc} = 0 V for n = 2. We removed the linear offset in each color-scale plot.

Secondly, in order to form a PDR at the center of the QAD, we carry out the measurement on the condition where V_{GB} is around or higher than the pinch-off voltage of the 2DEG (~ -0.4 V). We observed the CB oscillations in V_N as a function of B and V_{GB} as shown in the color-scale plots of Fig. 2(b) and (c). These periods ΔB = 5-10 mT and ΔV_{GB} = 2-3 mV are smaller than those in Fig. 2(a). This does not follow the AB effect where the period ΔB should increase with reducing the size of the QAD. We suggest that the PDR is filled with a whole compressible liquid without forming a FDR inside. In this case, the oscillation period should be determined by the Coulomb blockade effect on the PDR. There should be no AB effect in the charging of the FDR. We note that, in the case of a standard QAD with a FDR, an increment of the FDR is associated with depleting an electron from the innermost bound state with the AB period.

For the condition of Fig. 2(b), where the 2DEG beneath the pillar of air-bridge gate is almost pinched off, the inner spin-down state forms a PDR and the outer spin-up state forms a circular orbitals as shown in the inset of Fig. 2(b). For the condition of Fig. 2(c), where the 2DEG beneath the pillar gate is depleted approximately by half, only the spin-down electrons form a PDR as shown in the inset of Fig. 2(c).The period of the oscillations in Fig. 2(b) and (c) are similar by ignoring the irregular oscillation amplitude in Fig. 2(c). This implies the formation of multiple islands in the PDR.

3. Summary

We have investigate a QAD with fully and partially depleted regions. A QAD with PDRs showed different properties from one with FDRs. By using the CB model, we explain the behavior of a QAD with FDRs and PDRs.

Acknowledgements

We thank Masayuki Hashisaka and Tokuro Hata for discussions. This work was supported by JSPS KAKENHI (JP26247051, JP15H05854), and Nanotechnology Platform Program of MEXT.

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