Journal of the Korean Physical Society, Vol. 60, No. 11, June 2012, pp. 1907∼1910

Anomalous Conductance Quantization Observed in a Quantum Point Contact with an Asymmetric Confinement Potential

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(Received 26 March 2012, in final form 17 April 2012)

The conductance through a quantum point contact with an asymmetric confinement potential has been studied. Multiple anomalous conductance plateaus were observed, around $0.5\mathrm{G}_0$ and $0.9\mathrm{G}_0$, when the confinement potential of the QPC was set to be asymmetric. Also, resonance-like conductance peaks were observed in some devices for highly asymmetric confinement potentials while some of the peaks evolved into anomalous conductance plateaus when the asymmetry was reduced. We found that the spin polarization model based on spin-orbit coupling in an asymmetric confinement potential could not directly explain our data.

PACS numbers: 73.23.-b, 72.15.Qm, 71.70.Ej
Keywords: Conductance quantization, Quantum point contact, 0.7 structure, Spin-orbit coupling, Spin polarization
DOI: 10.3938/jkps.60.1907

I. INTRODUCTION

The conductance through a quantum point contact (QPC) is quantized at integer multiples of $\mathrm{G}_0 = 2e^2/h$ due to ballistic transport through a spin-degenerate non-interacting conduction channel [1,2]. The phenomenon is well explained by using quantum transport theory based on a single-particle picture developed by Landauer and Buttiker [3]. In addition to the usual integer conductance plateaus, an anomalous plateau was observed at around $0.7\mathrm{G}_0$ [4]. The phenomenon is called the '0.7 structure' and cannot be explained by using the single-particle picture. To explain this unusual conductance plateau, theoretical explanations based on electron-electron interactions, spin effects, luttinger liquids, and others effects have been suggested [5–10]. Among them, the spontaneous spin-polarization model [5,6] and the Kondo-related model [8], which were supported experimentally by Thomas *et al.* [4] and Cronenwett *et al.* [11], respectively, are the most popular. Thomas *et al.* have shown that the 0.7 plateau observed at zero magnetic field evolves into a 0.5 plateau when a magnetic field strong enough to lift spin degeneracy is applied. From the result, they concluded that the electron spin in a QPC is partially polarized to lift the spin degeneracy even at zero external magnetic field.

Recently, Crook *et al.* observed a 0.5 plateau, which is the signature of full spin polarization, when the electrostatic potential nearby a QPC was locally modified by the scanning-probe tip [12]. They suggested that the technique could be used to generated spin-polarized electrons without an external magnetic field, which is very useful for spintronics applications. Another observation of a 0.5 plateau has been reported in an InAs-based QPC where the spin-orbit coupling is much higher than that of GaAs [13]. It has been shown that a completely spin-polarized current can be generated by a QPC without an external magnetic field when its lateral confinement potential is made highly asymmetric. These observations make the possibility of using a QPC as a spin-polarizer very high. However, to use a QPC as a possible spin polarizer, more systematic research has to be done because the 0.7 structure is not always observed in a QPC although the phenomenon is regarded to be an intrinsic property of a 1D conduction channel. In this work, we have studied the 0.7 structure formed in a new kind of QPC [14] with an asymmetric confinement potential. We found that the 0.7 plateau could be tuned on and off by changing the symmetry of the confinement potential. Also, multiple conductance plateaus below $2e^2/h$, which cannot be explained by the spin-polarization model [13], have been observed.

II. EXPERIMENT AND DISCUSSION

A new kind of QPC that has an extra gate in the gap of a conventional QPC [14] has been used for the experiment. Figure 1(a) is a SEM picture of the 3-gate QPC device. In a conventional QPC, the shape of the

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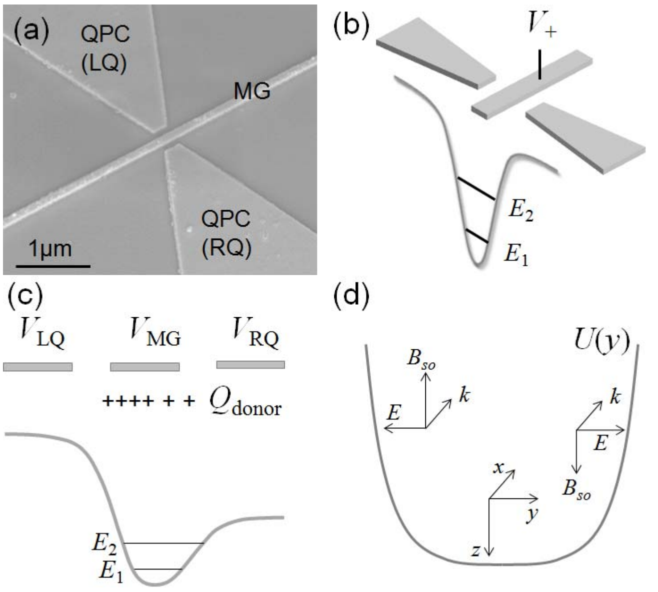

Fig. 1. (a) SEM picture of a 3-gate QPC device. (b) Schematic diagram of the 3-gate QPC used in our experiment. An extra gate is placed in the gap of a conventional QPC to control the potential in the channel. (c) The asymmetry of the transverse confinement potential can be adjusted by using the gate voltages on the QPC. (d) Schematic representation of the effective magnetic field induced by the spin-orbit coupling in a QPC [13]. The U-shaped line represents the transverse confinement potential of a QPC.

confinement potential of the device is determined by the potential drawn by both gates on a QPC. Thus, it is not easy to control the asymmetry of the confinement potential independently. In a 3-gate QPC, the middle gate sets the potential in the channel and helps to separate the potentials drawn by the left and the right QPC gates, as shown in Fig. 1(b). This scheme helps us to control the potential gradients on the edges of the channel separately. In addition, it is easier to observe conductance quantization at higher temperature in a 3-gate QPC than in a conventional QPC. If a positive voltage is applied on the middle gate, the shape of the confinement potential can be made deeper and sharper to make subband energy spacings larger than those of a conventional QPC.

The QPC was fabricated on a conventional uniform doped GaAs/GaAlAs heterostructure grown by molecular beam epitaxy (MBE). The 2DEG is buried 77 nm below the surface of the GaAs/$Al_{0.34}Ga_{0.66}As$ heterostructure. The carrier density was 1.9×10^{11} cm^2 and the mobility was 1.1×10^6 cm^2/Vs at a temperature of 4.2 K. The 3-gate QPC structure was defined by using electron beam lithography, and 15/30-nm-thick Ti/Au were used for the gates. The length of QPC gate was 200 nm, and the width of the middle gate was 100 nm. The gaps between the middle gate and the QPC gates were 100 nm. All the measurements were done at a temperature of 4.2 K in liquid helium. The conductances G = dI_{sd}/dV_{sd} were measured with an excitation voltage of 100 μV_{rms} by using the standard lock-in technique.

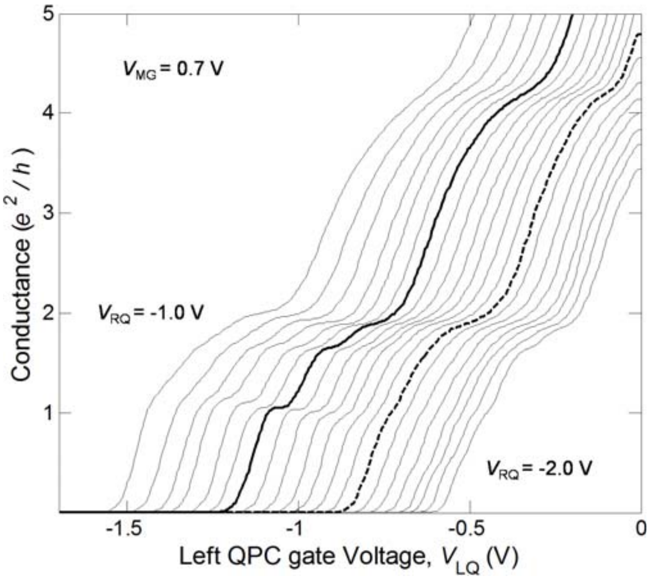

Fig. 2. Conductance through a 3-gate QPC device as a function of the left QPC gate voltage V_{LQ}. The middle gate voltage is fixed at +0.7 V, and the right QPC gate voltage V_{RQ} is varied from −1.0 V to −2.0 V (left to right) in 0.05 V steps. The thick solid line ($V_{RQ} = -1.3$ V) shows anomalous conductance plateaus while the dashed line ($V_{RQ} = -1.65$ V) shows no conductance anomaly.

Figure 2 shows the quantization of the conductance observed at 4.2 K. The conductances were measured as a function of the left QPC gate voltage (V_{LQ}) at various fixed right QPC gate voltages (V_{RQ}) to change the degree of the asymmetry in the confinement potential. The degree of asymmetry increases as the right QPC gate voltage V_{RQ} become more negative. The middle gate voltage was set to +0.7 V to make the conductance quantization observable at 4.2 K [14]. Two-terminal measurement technique was used to measure the conductance through a QPC. The two-terminal conductance is given by $1/(R_{QPC} + R_s)$, where R_s and R_{QPC} are the series and QPC resistance, respectively. The sources of the series resistance are the electrical contacts, the measurement wires *etc.* These series resistances are measured together with QPC resistance and cannot be distinguished during the measurement. Hence, the two-terminal measurement does not give the correct conductance through a QPC. To compensate for the series resistance, a finite resistance, which makes the conductance of the first quantized plateau $2e^2/h$, is subtracted from the raw data [15].

As it can be seen from the Fig. 2, the usual conductance plateaus at G_0 and $2G_0$ are observed. However, the conductance traces measured at some certain fixed right QPC voltages show unusual conductance plateaus below G_0. When the right gate voltage V_{RQ} is set to −1.3 V, two anomalous conductance plateaus, around $0.5G_0$ and $0.9G_0$, are observed. Since the right QPC gate voltage

V_{RQ} is set to −1.3 V and the 0.5 plateau appears around −1.055 V for the left QPC voltage. We expect that the confinement potential is asymmetric when the 0.5 plateau is formed. Debray *et al.* observed a 0.5 plateau in an InAs-based QPC when the transverse confinement potential of the QPC was set to be asymmetric [13]. They explained that the origin of the 0.5 plateau was the spin polarization caused by the asymmetric confinement potential of the QPC. Figure 1(d) shows a schematic of the potential profile of the confinement potential formed in the transverse direction (y direction) of a QPC. The Hamiltonian describing the spin-orbit (SO) coupling interaction is given by $H_{SO} = \beta\vec{\sigma}\cdot(\vec{k}_x \times \vec{\nabla}U(y))$,where β is the intrinsic SO coupling parameter of the channel material and $\vec{\sigma}$ is the vector of the Pauli spin matrices. Because the spatial gradients of the potential on the edges of the conduction channel are opposite in direction, the effective magnetic fields induced by the SO coupling are opposite at different edges. For a symmetric confinement potential, the population of spin up and down electrons will be the same; thus, the net spin will be zero. However, the net spin for an asymmetric potential will be non-zero even though the resulting net spin is not big enough to cause full spin polarization in a QPC. Debray *et al.* took a strong repulsive electron-electron interaction into consideration and found that the spin could be fully polarized to give a 0.5 plateau when there was a finite net spin due to spin-orbit coupling. According to their explanation, strong SO coupling is one of the key ingredients that causes spin polarization in a QPC. In our experiment, the QPC was fabricated on a 2DEG based on GaAs/GaAlAs heterostructure in which the 2DEG lies in GaAs layer. The intrinsic SO coupling in GaAs is an order of magnitude smaller than that of InAs. Hence, it is quite difficult to explain the 0.5 plateau observed in our device by using the spin-orbit coupling model. The conductance measured for V_{RQ} = −1.65 V (marked as the dashed line in the figure) shows no signature of an anomalous conductance plateau except for the regular subband plateaus. The degree of asymmetry in the confinement potential is much higher for the dashed trace because V_{RQ} is −1.65 V and V_{LQ} for 0.5G$_0$ is −0.73 V. According to the model suggested by Debray *et al.*, the 0.5 plateau should be more pronounced due to the higher asymmetry in the confinement potential. Also, the additional plateau around 0.9G$_0$ cannot be explained by using the spin-polarization model because the spin has only two species.

The gray-scale plot of the transconductance dG/dV_{LQ} for various fixed source-drain voltages are shown in Fig. 3. The black region surrounded by the diamond in Fig. 3(c) is the conductance plateau region formed between the first and the second subband of the confinement potential when there is no conductance anomaly in a QPC. When the right QPC gate voltage is set to V_{RQ} = −1.3 V, three diamond-like structures were found, as denoted by the arrows in Fig. 4(d). The structures correspond to the 0.5G$_0$, 0.9G$_0$, and G$_0$ conductance plateau regions, respectively. The observations of these multiple anomalous plateaus may be thought to be the result of transport through multiple subbands. From the transconductance plot, the subband energy spacings can be estimated [15]. The first subband energy spacing (E_2 − E_1) has been found to be around 7 meV while (E_3 − E_2) and (E_4 − E_3) were around 5 meV and 4 meV. If the thermal excitation $k_B T$ (k_B is the Boltzmann constant and T is the temperature) of electrons is much small than the subband energy spacings, transport through multiple subbands will be suppressed. At 4.2 K, $k_B T$ is around 0.36 meV, which is an order of magnitude smaller than the subband energy spacings in our sample. Hence, the transport through multiple subbands is highly unlikely in our device.

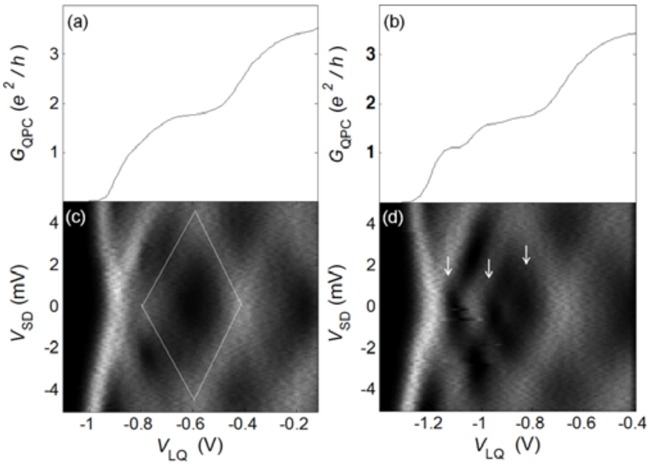

Fig. 3. The differential conductance traces $G(V_{QPC})$ were measured for various fixed source-drain voltages V_{sd}. The gray-scale plot of the transconductance traces dG/dV_{LQ} were obtained by numerical differentiation of the measured data. The transconductance is higher for the lighter colors. The conductance were measured when the right QPC gate voltage was set to (a) V_{RQ} = −1.65 V and (b) V_{RQ} = −1.3 V for zero source-drain bias. The gray-scale plot of the transconductance traces are shown for the right QPC gate voltages of (c) V_{RQ} = −1.65 V and (d) V_{RQ} = −1.3 V.

Several 3-gate QPC devices have been measured, and similar results have been observed. However, in some devices, resonance-like peaks have been observed when the confinement potential is highly asymmetric, as shown in Fig. 4. At V_{RQ} is −2.0 V, where the asymmetry of the confinement potential is the highest, a few resonance-like peaks are observed while some of the peaks evolve into conductance plateaus as the asymmetry is reduced. It is well known that randomly-distributed ionized donor impurities (depicted as Q_{donor} in the Fig. 1(c)) in the modulation doping layer can cause potential fluctuations along the channel, thus creating local scattering barriers. If there are multiple barriers along the longitudinal direction of a QPC, fabry-perot type interference can happen in a cavity formed between two local barriers. Hence,

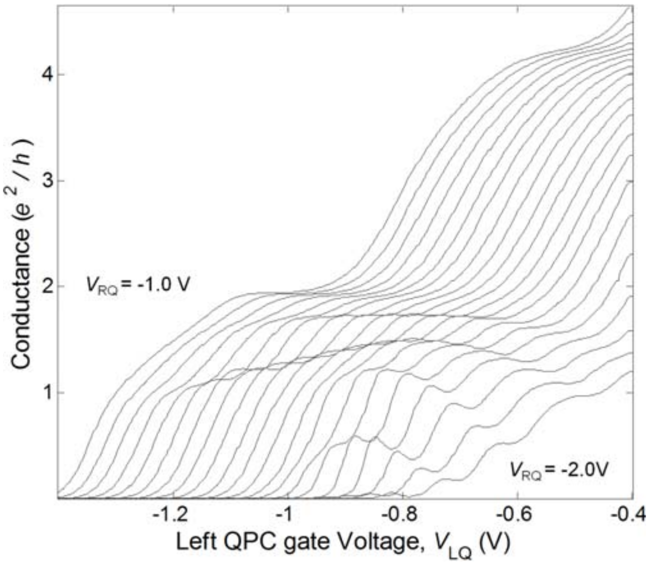

Fig. 4. Conductance through another 3-gate QPC device as a function of the left QPC gate voltage. The middle gate voltage is fixed at 0.7 V, and the right QPC gate voltage is varied from −1.0 V to −2.0 V (left to right) in 0.05 V steps.

unwanted interference can be observed in a QPC device if the potential fluctuation along the channel is significant. However, it is not clear why these resonance-like peaks appear only for a highly asymmetric confinement potential, not for a less asymmetric confinement potential with the same average conductance through a QPC. A similar phenomenon is reported in a very open quantum dot system when the gates of a quantum dot are set to work as weak local potential barriers [10]. Also, it is not clear why some of these resonance-like peaks evolve into anomalous plateaus when the asymmetry is reduced. Even though the origin of the anomalous conductance plateau is not clear, it is important to note that the anomalous plateaus form around $0.5G_0$ and $0.9G_0$ consistently, not at random conductance values. The existence of a consistent $0.5G_0$ plateau still leaves the possibility of spin polarization in a QPC.

III. CONCLUSION

The conductance through a QPC with an asymmetric confinement potential has been studied. Multiple plateaus are found to be formed around $0.5G_0$ and $0.9G_0$ when the confinement potential of a QPC is asymmetric. Our result differs from the result measured for an InAs-based QPC [13] where only a single conductance plateau around $0.5G_0$ is observed. The existence of the extra plateau around $0.9G_0$ makes it difficult to explain the results only by spin-orbit coupling in an asymmetric confinement potential. We believe that unwanted fabry-perot interference, occurring due to unwanted local potential barriers in a QPC, is partially responsible for the anomalous conductance plateaus observed in our device.

ACKNOWLEDGMENTS

We thank M. Heiblum, V. Umansky, D. Mahalu for helpful discussions and experimental support. This work was supported by the Financial Supporting Project of Long-term Overseas Dispatch of PNU's Tenure-track Faculty, 2009.

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