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Nonuniversal Conductance Quantization Observed in a Gate-defined 1D Wire

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A new method of fabricating a one-dimensional (1D) electron system using a conventional GaAs/AlGaAs heterostructure with metallic gates has been demonstrated. The transport properties of 1D wires with various lengths up to 6400 nm have been studied. A clear conductance quantization, which has never before been observed in a gate-defined 1D wire system, was observed. This confirms that the 1D wire is indeed clean without a significant local resonant state in the conduction channel. Also, the conductance step height was found to be less than $2e^2/h$ for wires longer 3200 nm. Such nonuniversal conductance quantization is regarded as a fingerprint of a Luttinger liquid. The result confirms that a 1D electron system can be fabricated by using a conventional method.

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I. INTRODUCTION

The transport properties of multi-dimensional electron systems are well understood with the Fermi liquid theory, which considers interacting electrons as non-interacting quasiparticles based on many-body perturbation theory. However, such a theoretical treatment is not applicable in 1D electron systems where even a weak interaction is not ignorable due to the geometrical peculiarity. Such electron systems are called Luttinger liquids, and their transport properties are very much different from those of Fermi liquids [1, 2]. Because the electrons are constrained to move only in 1D, any perturbation will collectively affect a large number of electrons in the wire [3]. Such a collective behavior causes the total suppression of tunneling into the Luttinger liquid at zero temperature and bias. At finite temperature and bias, the tunneling conductance becomes proportional to a power of the temperature and the bias [4]. Such behaviors are not expected in Fermi liquids and are regarded as a distinct property of a 1D electron system. Also, spin-charge separation, which is the separation of the charge and the spin excitations of an electron (known as the holon and the spinon), is the unique property of a 1D electron system [5]. Recently, the power-law behavior [6] and the spin-charge separation [7] were observed experimentally in carbon nanotubes and cleaved edge overgrown 1D wires, respectively. Even though the theoretical predictions had been made a few decades earlier, the experimental observations were delayed due to difficulties in realizing clean 1D electron systems.

Among many 1D electron systems, the cleaved edge overgrown (CEO) 1D wire [7] is regarded as the cleanest 1D electron system. However, making such a wire is extremely difficult because it requires in-situ cleaving of a GaAs/AlGaAs wafer in a Molecular Beam Epitaxy (MBE) chamber and regrowth of a GaAs/AlGaAs layer on a cleaved edge [8]. Also, using a CEO 1D wire to make complex quantum devices, which incorporate other quantum structures such as a quantum dot, an electron interferometer and so on, is not easy.

In our previous work, we reported that a 3-gate quantum point contact (QPC) structure could increase the subband energy spacing of the QPC up to 7 meV, which would make it possible to observe clear conductance quantization at 4.2 K [9]. Also, we showed the possibility of fabricating a 1D wire by using the 3-gate QPC structure. In this work, 1D wires with various lengths up to 6400 nm were fabricated, and their transport properties were studied as a function of wire length. The length dependencies of the so-called nonuniversal conductance quantization in a 1D wire and the subband energy level spacings were studied. Nonuniversal conductance quantization was observed for devices longer than 3200 nm, which is regarded as a fingerprint of a Luttinger liquid. Also, the subband energy spacings were found to be constant, regardless of the number of subbands in the wire, for the 6400-nm-long 1D wire. This work demonstrates that the conventional method for making a planar quantum device can be used to fabricate a clean 1D wire. This allows the a possibility of combining a 1D wire with

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other quantum structures, such as quantum dots, electron interferometers *etc.*, to develop more complex quantum structures.

II. EXPERIMENT

A conventional QPC employs a split gate to squeeze a 2-dimensional electron gas (2DEG) electrostatically to make a short quasi-1D conduction channel. Such a device shows conductance quantization at integer multiples of $G_0 = 2e^2/h$ as a result of ballistic transport through constriction [10, 11]. Extending the gate length of the split gate does not allow the making of a 1D wire due to the impurity potentials caused by the ionized donor impurities, which are randomly distributed in the modulation doping layer. Typically, a conventional QPC has a gap of around 300 nm between the gates of a QPC, and the 2DEG lies around 100 nm below the surface of the wafer. In a conventional QPC, the potential on the channel is not zero due to the potential caused by the nearby QPC gates. Hence, the potential on the channel is lifted above the conduction band minimum, and the depth of the 1D potential well becomes shallow. This makes the potential profile of the 1D channel prone to be affected by the relatively weak potential fluctuations caused by the ionized donor impurities. Such a potential fluctuation renders the potential profile of the 1D channel as a series of potential puddles, hence closing the 1D channel locally to create local resonant states, as shown in Fig. 1(a). This makes it difficult to fabricate a clean, long, 1D conduction channel by using the conventional QPC method. To remove such unwanted local blockages, we adopt a 3-gate QPC structure [9], which has an extra gate between the split gate, to fabricate 1D wires, as shown in Fig. 1(b). By a positive gate voltage is applied to the middle gate, the bottom of the potential well can be pushed down to unclog the local blockages in the wire, as is illustrated in the figure.

The conventional uniform doped GaAs/$Al_{0.34}Ga_{0.66}As$ heterostructure grown by using molecular beam epitaxy was used to fabricated 1D wires. The 2DEG was buried 77 nm below the surface of the heterostructure. The carrier density and the mobility were 1.9×10^{11} cm^{-2} and 1.1×10^6 cm^2/Vs, respectively, at 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. Figure 1(c) show the fabricated 1D wires with various lengths (100 nm, 200 nm, 400 nm, 800 nm, 1600 nm, 3200 nm, and 6400 nm). The width of the middle gate and the gap between gates were fixed to 100 nm for all the devices. All the measurements were done at a temperature of 4.2 K in liquid helium. The conductance $G = dI_{\mathrm{SD}}/dV_{\mathrm{SD}}$ was measured by applying an excitation voltage of 100 μV$_{\mathrm{rms}}$ between the source and the drain and measuring the current through the device by using a standard lock-in technique at 970 Hz.

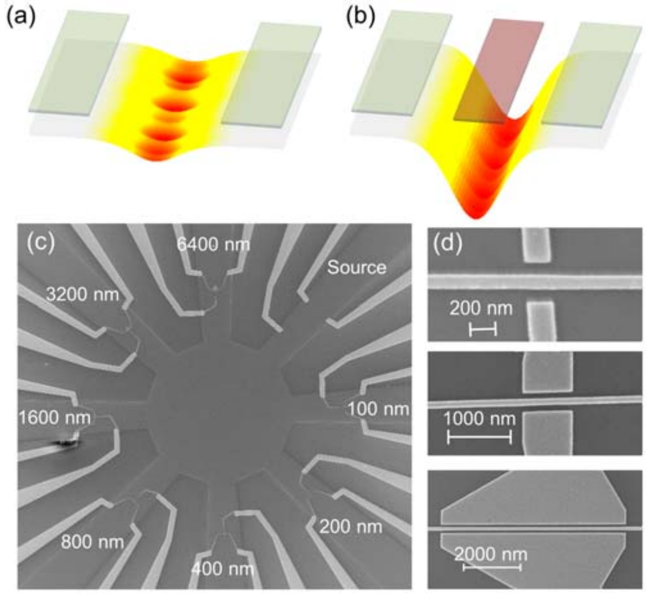

Fig. 1. (Color online) Schematic diagrams of (a) a conventional QPC and its potential profile and of (b) a 3-gate QPC and its potential profile. An extra gate (transparent red part) is inserted in the middle of a conventional split gate. (c) SEM picture of 1D wires with various lengths. (d) SEM pictures of 200-nm, 800-nm, and 6400-nm (top to bottom) 1D wires.

III. RESULT AND DISCUSSION

Figure 2 shows the conductance quantization measured through 1D wires as a function of the source-drain bias at various QPC gate voltages. Figures 2(a) and (b) are the results measured with 200-nm- and 800-nm-long 1D wires, which show the typical conductance of a quantum point contact (QPC). The first quantized plateau shows a conductance very close to $G_0 = 2e^2/h$, which is the theoretical conductance of a single electron transport channel. As the number of channels n in the wire increases, the quantized conductance deviates from the theoretical values, $n \times 2e^2/h$ (denoted as the blue dashed lines in the figure). Usually, such a deviation is regarded as the contribution from the series resistance added to the 1D wire resistance, which cannot be avoided in a two-terminal measurement. When a 1D wire is connected to a series resistance R_{s}, the two-terminal conductance is given by $1/(1/nG_0 + R_{\mathrm{s}})$, where n is the number of channels in the wire. For a fixed series resistance, the deviation from the theoretical value gets bigger as the number of channel increases, because the contribution by the series resistance become important as the channel resistance become smaller.

For 200 nm-long 1D wire, the 200 Ω series resistance must be subtracted from the raw data to fit the second and the third plateaus to the theoretical values. Similarly, 500 Ω must be substracted for a 800 nm-long 1D wire (Fig. 2(b)).These series resistance values exceed the measured series resistance values in our experiment. The

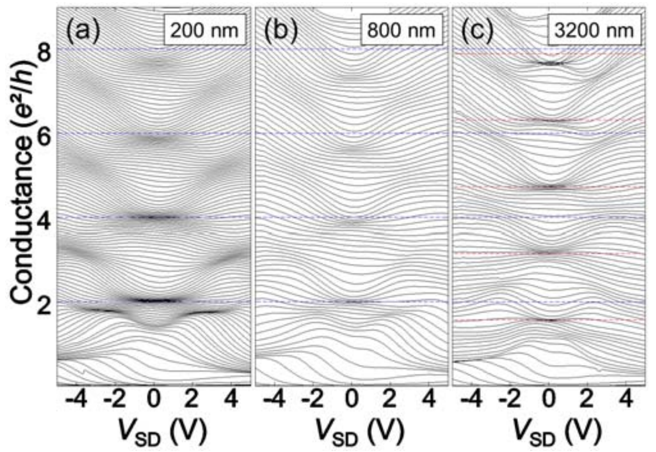

Fig. 2. (Color online) Conductance quantization measured through 1D wires as a function of source-drain bias at various QPC gate voltages. The middle gate was set to +600 mV for the measurements. The blue and the red dashed lines are guidelines for the universal conductance $n \times 2e^2/h$ and the nonuniversal conductance $n \times 0.79 \times 2e^2/h$, respectively.

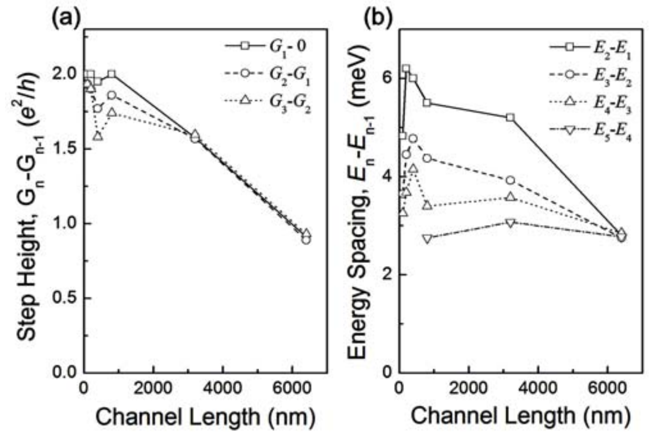

Fig. 3. Length dependences of (a) the conductance step heights between consecutive conductance plateaus and (b) the subband energy spacings between consecutive subband energy states measured for 1D wires with various lengths (100 nm, 200 nm, 400 nm, 800 nm, 3200 nm, and 6400 nm).

typical series resistances of our samples were usually less than 100 Ω, which included the resistances of two ohmic contacts (source and drain) and the mesa (2DEG) resistance. Subtracting the experimentally observed resistance (100 Ω) will shift the conductance for the third plateau only to $2.93 \times 2e^2/h$, which is very close to the theoretical value. The origin of the extra resistance required to fit the data is unclear and remains to be understood.

Figure 2 shows the data measured for a 3200-nm-long 1D wire. As can be seen from the figure, the conductance for the first plateau is around $0.79 \times 2e^2/h$, which is well below the theoretical value $2e^2/h$. Moreover, the subsequent plateaus seem to quantize at integer multiples of $0.79 \times 2e^2/h$ (red dashed guidelines) up to the fourth plateau. A similar behavior was observed for the 6400-nm-long 1D wire with nonuniversal quantization at integer multiples of $0.46 \times 2e^2/h$. This cannot be explained by compensating for the fixed series resistance. Such nonuniversal conductance quantization was first observed in a cleaved edge overgrown (CEO) 1D wire by Yacoby *et al.* [8]. They explained the phenomena by introducing phenomenological scattering in a 1D wire. By assuming that the conducting modes in the wire were completely uncoupled from each other and that the scattering rates associated with each mode were the same, they showed that the nonuniversal conductance quantization was plausible in 1D electron system. Also, their experiment on the temperature and the bias dependence behaviors showed that such nonuniversal conductance quantization was related to the properties of the Luttinger liquids. The replication of the nonuniversal conductance quantization in our gated-defined 1D wire on a conventional 2DEG proves that our proposed method can be used to realize a 1D electron system showing a Luttinger liquid behavior. Note that nonuniversal conductance quantization is only observed in a long 1D wire while universal conductance quantization [10] is observed in a QPC (a short 1D wire). Figure 3(a) shows the conductance step heights between consecutive conductance plateaus measured for 1D wires with different lengths. The quantized conductance step for the first subband ($G_1 - 0$) is very close to the universal conductance quanta $2e^2/h$ for wires up to 800 nm in length. The other conductance step heights ($G_2 - G_1$ and $G_3 - G_2$) are noticeably smaller for 400-nm and 800-nm 1D wires, in contrast to the results for 100-nm and 200-nm wires. The reasons for the decreases in step heights for the 400-nm and 800-nm wires are unclear, as mentioned earlier. Clear nonuniversal quantization can be seen for the wires with 3200-nm and 6400-nm lengths. Even though 1600-nm-long wires have been fabricated, the data are not available due to defects in the devices. Thus, we can only say that nonuniversal quantization starts to appear in 1D wires with lengths around 1000 $\sim$ 2000 nm.

The subband energy spacings between consecutive subband energy states have been measured. As shown in Fig. 4, the subband energy spacings can be obtained by finding the values of eV_{SD} at the first intersections of the light straight lines (dashed lines in the figure) [9]. The results are summarized and shown in Fig. 3(b) as a function of wire lengths. Naturally, the subband energy spacings in a QPC is expected to decrease as the number of subband is increasing. The transverse (perpendicular to the direction of the electron flow) potential well, which gives the energy quantization in the wire, needs to be wider to accommodate more subbands below the Fermi level. This makes the energy spacing between confined states smaller for multiple subbands. Such behavior was observed in our results for wires shorter than 6400 nm and has also been reported in other experiment [12]. However, for the 6400-nm-long wire, the subband spacings

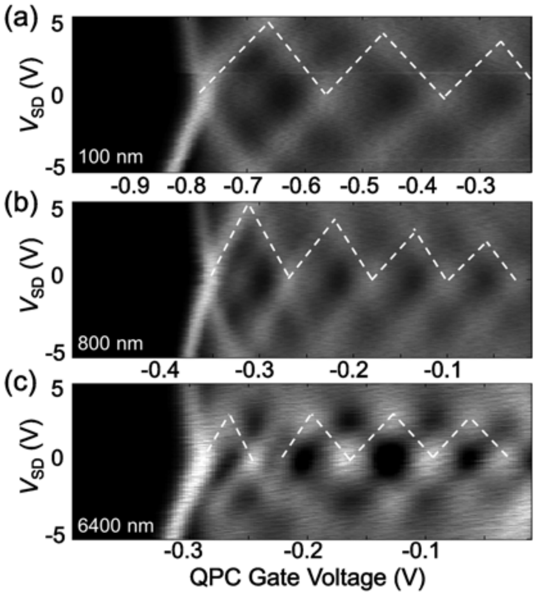

Fig. 4. Grey-scale plots of the transconductance traces (dG/dV_{QPC}) obtained by numerical differentiation of the measured data for (a) 200-nm, (b) 800-nm, and (c) 6400-nm 1D wires. The subband energy spacings can be obtained by finding the V_{SD} values of the intersections of the dashed lines.

were the same regardless of the subband population in the wire. As can be seen in Fig. 4, the subband spacing gradually decreases as the subband index gets higher for 100-nm- and 800-nm-long wires. For the 6400-nm 1D wire, almost no significant changes in subband spacings are seen. The subband spacing ($E_3 - E_2$) between the second and the third subbands for the 6400-nm-wire was difficult to determine due to an unexpected conductance anomaly in the second conductance plateau, as can be seen from the figure. Ignoring the ($E_3 - E_2$) data point does not change the picture because the rest of the subband spacings, are almost equal. Whether is not clear because the observed equal subband spacing is related to the nonuniversal conductance quantization, the 3200-nm-long 1D wire does not show equal subband spacings.

IV. CONCLUSION

Gated-defined 1D wires with various lengths have been fabricated with a 3-gate QPC structure. A clear conductance quantization, which has never before been observed in a gate-defined 1D wire system, was observed. The nonuniversal conductance quantization, which is the signature of a Luttinger liquid, was observed for wires longer than 3200 nm. This implies that 1D wires can be fabricated by using a conventional 2DEG with the proposed technique. In addition, equal subband spacings were observed for a 6400-nm-long 1D wire, which could be related to the nonuniversal conductance quantization in a 1D wire. We believe that our method can be used to combine a 1D wire with other quantum structures such as quantum dots, electron interferometers *etc.* to develop more complex quantum structures.

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