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Length Dependence of the Fractional Conductance Anomaly in Constricted Conducting Channels

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In addition to the integer conductance quantization in units of G_0 ($=2e^2/h$), a quantum point contact (QPC) often reveals a fractional conductance plateau, especially at $0.7G_0$, which is called the 0.7 anomaly. The one-dimensionality of the constriction (or QPC) has been debated as to whether or not it is a key element in the appearance of the anomaly. In this study, we specifically focused on the length dependence of the conductance anomaly in QPC's for a nominally identical width of nano-constrictions. The anomaly was shown to be more likely caused by the Kondo effect in a carrier-confining region formed inside a short QPC with its length comparable to its width while spontaneous spin polarization along with the opening of a spin gap better explains the anomalous conductance behavior in a longer QPC.

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I. INTRODUCTION

According to Landauer and Buttiker, the conductance is quantized in units of the universal conductance G_0 ($= 2e^2/h$) as $G = NG_0$ in a constricted structure like a quantum point contact (QPC), where N is the number of transverse channels through the constriction [1, 2]. The conductance plateaus can be experimentally obtained in QPC structures by varying the negative voltage of the QPC-forming split gates [3, 4], as the Fermi energy matches the quantized energy level of each channel, and the value of N changes accordingly. However, in addition to the usual integer conductance plateaus, an anomalous plateau is often observed at around $0.7G_0$, which is known as the *0.7 anomaly*, in a QPC [5]. Although several candidates [6–15] have been suggested to explain this anomaly, the Kondo-related model [14, 15] and the spontaneous spin polarization (SSP) model [5, 16] are considered to be the most plausible among them. To date, however, the origin of the 0.7 anomaly continues to be debated, as demonstrated, for instance, by our recent experimental result in a system consisting of a QPC prepared in proximity to a quantum dot [17]. It seems to suggest the irrelevance of the simple localized-electronic-state picture as a cause of the 0.7 anomaly.

In the Kondo-related model, an unpaired electron that is supposed to be localized within a QPC forms a singlet state with electrons of the opposite spin polarity in the source and the drain of a QPC. The transmission probability across a QPC increases due to the formation of the Kondo-induced zero-bias resonance state in the region of the electron localization, which results in a zero-bias conductance enhancement. The zero-bias conductance is maximum (the unitary limit) in the zero-temperature limit and decreases with increasing temperatures. According to this model, the 0.7 anomaly takes place at an intermediate finite temperature due to a suppression of the conductance from the unitary limit. In this sense, the 0.7 anomaly is not a ground-state property. The quantum-dot-like structure [18] (which gives the localized electronic state) may accidentally form inside a QPC due to the randomly, distributed impurity potential from the donors in the modulation doping layer. This quantum-dot-like structure is apt to form in a QPC that is wider than ∼100 nm. A recent experimental result [14] seems to support the forming of a localized state in a QPC, which leads to the Kondo-related 0.7 anomaly.

On the other hand, the integer G_0 ($= 2e^2/h$) plateau of a QPC evolves into two plateaus (an integer one and a half-integer one) by Zeeman splitting in a tesla-range high perpendicular magnetic field. These half-integer plateaus are expected to transform back into integer plateaus in the zero-field limit. In contrast to this expectation, however, fractional conductance plateaus of-

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ten persist around $0.7G_0$ in the zero-field limit. This indicates that even without an external magnetic field a finite spin polarization is spontaneously induced inside a QPC. Based on this finding, SSP is regarded as an adequate model for the 0.7 anomaly in a QPC. Reilly *et al.* suggested semiempirically [19] that *a spin gap* could open in a QPC with a relatively high electron density in the constricted region of a QPC, which would lead, even without an external magnetic field, to a spontaneous spin polarization caused by the strong correlation among conduction electrons.

In addition to the above two major models, the 0.7 anomaly in a QPC has been discussed in terms of a strong electron-electron correlation effect in a quasi-one-dimensional limit as in a relatively long QPC. Havu *et al.* [20] have also suggested that resonant peaks should be observed in ballistic quasi-one-dimensional wires with the opening of a spin gap.

The predictions of all the models introduced above are closely related with the extendedness of a QPC. In this study, we investigated the characteristics of the 0.7 anomaly while tuning the electron carrier density and the source-drain coupling strength by changing the length of the QPC between the source and the drain. A Kondo-related plateau was observed in a shorter QPC while a resonant peak was observed around a conductance of $0.5G_0$ in a longer QPC at the base temperature ($\sim$60 mK). This implies that, when the length of a QPC is varied, a crossover exists between the Kondo-related region and the SSP region of the conductance anomaly.

II. EXPERIMENTS AND DISCUSSION

In this work, the QPC devices were fabricated on GaAs/AlGaAs heterostructures containing a two-dimensional electron gas (2DEG) layer residing about 65 nm below the wafer surface. The electron density of the 2DEG was $n_s = 2.5 \times 10^{11}$ cm^{-2}, and the electron mobility was $\mu = 1.5 \times 10^6$ cm^{2}V^{-1}s^{-1} at 4.2 K. Three types of QPCs with different gate lengths (130, 320, and 920 nm for samples A, B and C, respectively) were fabricated with an identical spacing (165 nm) between two split gates.

Figure 1 shows a scanning electron micrograph (SEM) of the devices which were fabricated according to the procedure introduced in Ref. [21]. All the measurements of the differential conductance were made in a dilution fridge in corporation with the conventional lock-in technique by applying an excitation voltage of 10 μV rms at 17 Hz in a two-terminal configuration. The conductance of sample A (B, C) was taken by varying the gate voltage V_{g1} (V_{g2}, V_{g3}, respectively) while the drains D_2 and D_3 (D_1 and D_3, D_1 and D_2, respectively) were floated.

In the shortest QPC (Sample A) with a length/width (L/W) ratio of about 1, the conductance of the QPC is quantized in units of $2e^2/h$ at the base temperature,

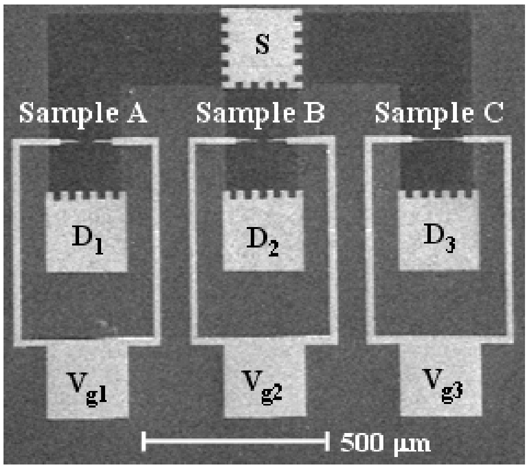

Fig. 1. Scanning-electron micrograph of the QPC devices used in this study. Three different samples were employed; samples A, B, and C had lengths of 130 nm, 320 nm and 920 nm, respectively, with nominally identical widths of 165 nm. The conductance of sample A (B, C) was taken by varying the gate voltage V_{g1} (V_{g2}, V_{g3}), while the drains D_2 and D_3 (D_1 and D_3, D_1 and D_2) were floated.

but the 0.7 anomaly takes place with increasing temperature and becomes most evident around 4.2 K [see Figure 2(a)]. More conspicuous 0.7 anomaly at finite temperatures around 4.2 K has been observed previously by other groups [14,22] in a constriction with an aspect ratio (about 1) similar to that for our sample A. The temperature dependence of the conductance in Figure 2(a) is in qualitative agreement with a previous observation that supports the Kondo-related model.

For the intermediate-legnth QPC (sample B) with a L/W ratio of about 2, in addition to an integer plateau, a weak 0.7 structure is observed at the base temperature, which again becomes clearer at higher temperatures [Figure 2(b)]. Furthermore, in sample B, the integer plateau has a slightly different shape from that of sample A at the base temperature. Namely, the G_0 plateau of this sample is not flat, but has a slightly upturned shape. In this sample, the temperature dependence of the conductance can be explained in terms of the phenomenological spin-gap model proposed by Reilly *et al.* [19]. According to the model, no spin gap is assumed to open for a low electron carrier density at a relatively high negative gate voltage while a spin gap should open with decreasing negative gate voltage. In addition to affecting the opening of the spin gap, the gate voltage also changes the electron carrier density and the corresponding Fermi level in the constricted channel; a higher Fermi level for a less negative gate voltage. In the low-temperature limit, the thermal smearing of the Fermi distribution would be much smaller than the spin-gap size at a finite gate voltage. Thus, the conductance plateaus in this case take place in units of the half-integer conductance (e^2/h), without other fractional conductance plateaus, as the

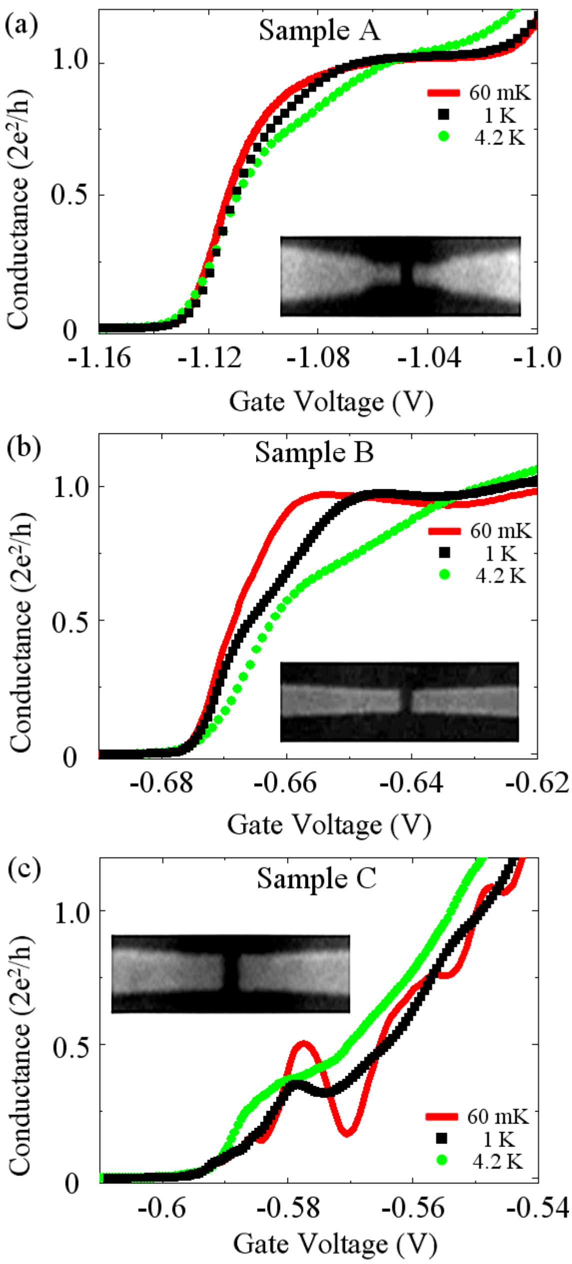

Fig. 2. Conductance as a function of the gate voltage at temperatures of 60 mK (solid curve), 1 K (squares), and 4.2 K (circles). (a) Conductance of sample A with the aspect ratio of $L/W \sim 1$. At the base temperature, the conductance is quantized in units of $G_0 = 2e^2/h$. As the temperature increases, an additional plateau at $0.7G_0$ (0.7 anomaly) is revealed. (b) Conductance of sample B with $L/W \sim 2$. A weak 0.7 anomaly is observed at the base temperature and becomes clearer with increasing temperatures. (c) Conductance of sample C with $L/W \sim 5$. Instead of the 0.7 structure, resonance-like peaks appear at the base temperature, which get smeared at higher temperatures.

Fermi level crosses the gap edge of each spin polarity with decreasing negative gate voltage. For a sufficiently high temperature, however, a much smeared Fermi level may distribute across the spin gap between the opposite spin polarities. This in turn smears both the integer and the half-integer conductance plateaus, leading to the 0.7 conductance plateau at a finite temperature around 4.2 K, as in our sample B. The temperature dependence of the anomaly in this sample is, thus, in qualitative agreement with the SSP (or the spin-gap) model.

In the longest QPC (sample C) with a L/W ratio of about 5, only the resonance-like peaks were observed [Figure 2(c)] without the conventional integer or fractional plateaus. The theoretical work [19, 20] suggests that the prominent electron resonance states can appear in a long QPC. As the length of the QPC increases, a gap opens between the spin-up and the spin-down states and becomes wide enough inside the constricted channel, which may lead to a conductance resonance with different spin states. Havu *et al.* [20] reported numerical results for systems with three different aspect ratios ($L/W = 1.2$, 1.4 and 1.6). The result shows that, at zero temperature, no anomalous plateaus exist in the shortest wire with $L/W = 1.2$ whereas the wire with $L/W =$ 1.4 (corresponding to our intermediate QPC) exhibits a $0.7G_0$ anomalous plateau. In contrast, the longest wire with $L/W = 1.6$ clearly exhibits a resonant peak at a conductance of $0.5G_0$. In our sample C, at high temperatures, the conductance shows only a monotonic decrease without any resonance or plateaus, but close to 1 K, the conductance has a plateau around $\sim 0.35G_0$. At a lower temperature around $\sim$60 mK, the resonance peaks become clearer and more sharpened. As in Figure 2(c), the height of the peak is $\sim 0.5G_0$ at the base temperature. This implies that a single polarized mode (spin-down state) contributes to the conductance. Although our length/width ratios do not exactly match with the ones discussed by Havu *et al.*, our results are in reasonable qualitative agreement with the numerical results [20]. This leads to a conclusion that a strong spin gap opens in our longest QPC ($L/W = 5$) at low temperatures and that a resonance with the spin-up and the spin-down states takes place inside a QPC. This in turn indicates that the spins of the conduction electrons can be spontaneously polarized by passing through a QPC, thus, spontaneous spin polarization better explains the 0.7 anomaly in a relatively long QPC.

One may wonder why no Kondo-related conductance anomaly takes place in the longest constriction (sample C), even though a quantum-dot-like charge confining region is more likely to form in the longer samples than in the shorter samples A and B. To clarify the reason, the conductances of samples A and C were also investigated (see Figure 3 for the data at the base temperature) for varying QPC gate voltages (V_g) as the bias of the source-drain was swept from $V_{sd} = -5$ to $+5$ mV for sample A and from -1.5 to $+1.5$ mV for a sample B. The conductance of sample A reveals peaks below the unity G_0 around zero bias in this low-temperature limit, which is known as the zero-bias anomaly [Figure 3(a)]. These zero-bias peaks in sample A become

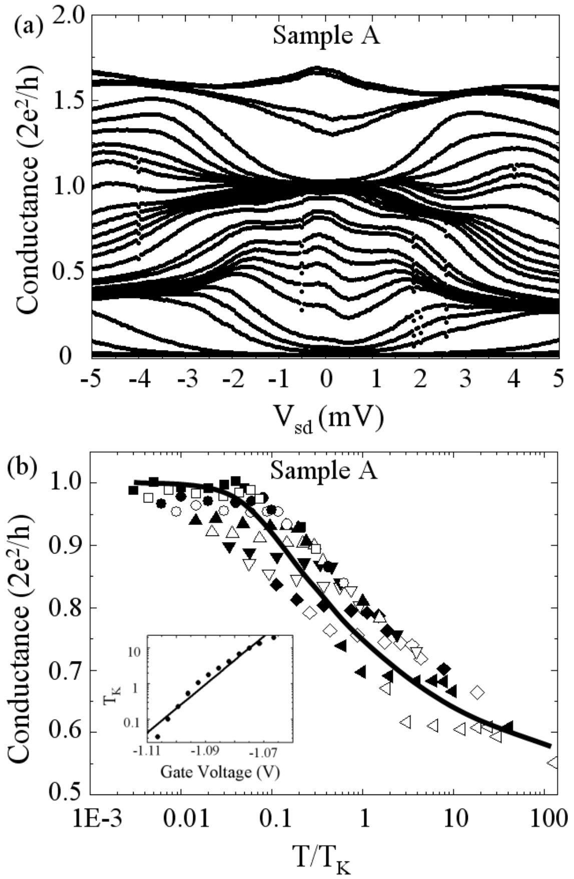

Fig. 3. Cascades of the conductance with altering gate voltages, V_g, as the source-drain bias is swept at the base temperature. (a) Conductance of sample A with the zero-bias peaks around $0.7G_0$. (b) Normalized zero-bias conductance of sample A as a function of temperatures scaled by the Kondo temperature T_K for various gate voltages. Inset: Gate-voltage dependence of the Kondo temperature.

weaker and result in $0.7G_0$ at higher temperatures [as seen in Figure 2(a)]. The temperature dependence of the zero-bias conductance is plotted in Figure 3(b) for various gate voltages. The best-fit solid curve represents the temperature dependence of the Kondo-conductance of a QD, $G(T)/(2e^2/h) = \frac{1}{2}[f(T/T_K) + 1]$, where $f = [1 + (2^{1/s} - 1)(T/T_K)^2]^{-s}$ with $s = 0.22$ for spin $\frac{1}{2}$ and T_K as a fitting parameter [14]. The overall temperature dependence of the observed conductance at different gate voltages follows the expected Kondo behavior well. The gate-voltage dependence of the Kondo temperature T_K, a quantity depending on the density of conduction electrons, reasonably well suits the known dependence of $\ln(T_K) \simeq aV_g + c$ [the inset of Figure 3(b)], where a and c are constants. The data shown in Figures 3(a) and (b) support the possible existence of a QD-like region of the electron confinement inside a QPC with unpaired electrons, thus leading to the Kondo-related behavior of the conductance anomaly.

However, in sample C (the longest QPC), the larger L/W ratio decreases the coupling between the electron-confining region and the source and/or drain across a QPC, which in turn weakens the Kondo-related effect. A relatively high coupling with the source and the drain is required for a QD to exhibit the Kondo conductance enhancement. In this long constriction of high aspect ratio, the QPC acts merely as a quasi-one-dimensional wire, without sufficient Kondo coupling of the constriction with the leads. No zero bias anomaly was observed for sample C. This explains the lack of the Kondo-related conductance anomaly in long QPCs.

III. CONCLUSIONS

In this study, we investigated the length dependence of the fractional conductance anomaly, which revealed that the anomaly may be caused by the formation of a carrier-confinement region inside a QPC and the spontaneous opening of a spin gap in a QPC with a high carrier density. Our study suggests that a crossover may take place from a Kondo-related region to a spontaneous spin polarization region (or a spin-gap region) with increasing a length of a QPC. The temperature and the source-drain-bias dependencies of the conductance for our shortest QPC support the Kondo-related picture as the origin for the 0.7 anomaly resulting from the formation of a region of carrier confinement. By contrast, the resonance states in our longest sample, without the zero-bias conductance enhancement in the conductance vs. source-drain bias, support opening of a wide spin gap. Weakening of the coupling between the source/drain and the carrier confinement region for a long QPC may explain the disappearance of the Kondo-related contribution to the conductance anomaly.

Our recent studies [17] employing a very short (~60 nm) QPC or, equivalently, very narrow split gates, prepared in conjunction with a QD structure seem to negate the existence of the carrier-confinement region inside the QPC. Since the split gates used in this study are much wider, the formation of a region of carrier confinement inside the QPC cannot be ruled out.

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