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Tunable 0.7 conductance plateau in quantum dots

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A consistent approach in forming the 0.7 structure by using a quantum dot rather than a quantum point contact is demonstrated. With this scheme, it was possible to tune on and off the 0.7 structure. The 0.7 structure continuously evolved into a normal integer conductance plateau by varying the tuning condition. Unlike the conventional 0.7 plateau, the new 0.7 structure was observed even at low electron temperatures down to 100 mK, with unprecedented flatness. From our results, it is concluded that electron interference should be taken into consideration to explain the 0.7 structure.

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The quantization of conductance in units of $G_0(=2e^2/h)$ through a quantum point contact (QPC) was first observed experimentally by two groups.[1,2] The phenomenon is a result of adiabatic transmission of electrons through spin-degenerate noninteracting one-dimensional (1D) channels. Shortly after the discovery, an additional plateau was observed at around $0.7G_0$, which has been known as the *0.7 structure*.[3] Many other experiments followed to confirm the existence of this unusual plateau and to investigate its physical origin.[4–10] Since this anomalous conductance plateau cannot be explained in a single-particle picture, theoretical explanations based on electron-electron interaction, spin effect, and others have been suggested.[11–15] The spontaneous spin-polarization model[11,12] and the Kondo-related model[14] are most popular among them, which were supported experimentally by Thomas *et al.*[3] and Cronenwett *et al.*,[7] respectively.

Nonetheless, no consensus has been reached about its origin yet, and still contradicting experimental and theoretical results are reported. Furthermore, the 0.7 structure is not always revealed in a QPC although the phenomenon is regarded as intrinsic properties of 1D conduction channels. In most studies, however, the absence of the 0.7 structure was simply ignored and the condition for the occurrence of this structure has not been systematically investigated. We report an approach to the formation of the anomalous 0.7 structure by using a quantum-dot structure. This unique approach allows one to tune to the formation condition of the 0.7 plateau at one's disposal. This tunable 0.7 structure showed characteristics that were similar to the conventional ones in a QPC, but with additional features. We believe that our results will provide an insight into the nature of this ever-controversial phenomenon.

The quantum dots were fabricated on two-dimensional electron-gas (2DEG) wafers based on a GaAs/AlGaAS heterostructure. The electron densities were around 2.5×10^{11} cm^{-2} with the mobilities higher than 1.5×10^{6} cm^2 V^{-1} s^{-1} at 4.2 K. The 2DEG layer resided 65 nm below the surface of the wafers. Two different types of quantum dots (types A and B) were fabricated (Fig. 1). The electron temperature was estimated to be around 100 mK (140 mK) for the type-A (type-B) sample. For convenience, all the gates were named individually as in Figs. 1(a) and 1(b). Conductance quantization behavior for individual QPC's was examined by applying negative voltages on the nose gate and one of the other three gates (QPC, side, and plunger gates) separately while keeping the rest of the two gates at zero voltage. In each of these usual QPC geometries, only the normal integer conductance quantization was observed without any anomalies including the 0.7 structure. We believe the absence of anomalies was caused by the extreme narrowness (less than 50 nm in its width) of our gates. The zero-bias anomaly suggesting the Kondo character[7] was not observed either even at 100 mK, the base electron temperature used.

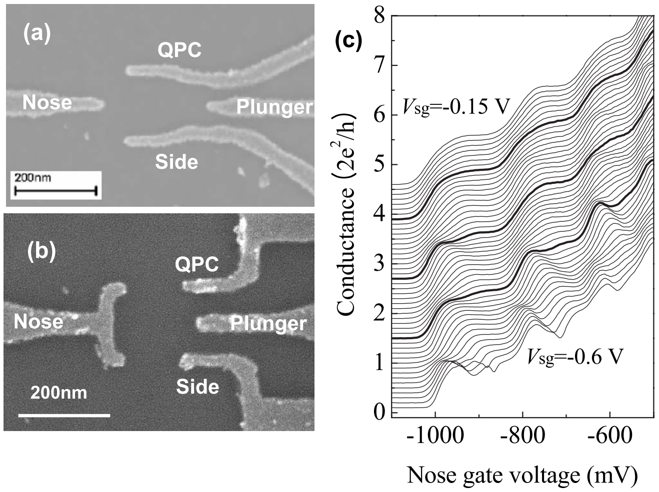

FIG. 1. Scanning electron microscope pictures of two different types of quantum dots; (a) type A and (b) type B. (c) The conductance measured for the type-B sample, with the QPC-gate and the plunger-gate voltages fixed at −0.7 and −0.23 V, respectively, as a function of nose-gate voltages V_{ng} while varying the side-gate voltages V_{sg} from −0.15 to −0.6 V at intervals of 0.01 V. The 0.7 structure is present at $V_{sg}=-0.46$ and −0.34 V (lower solid curves). Weak 0.7 anomaly is also seen at $V_{sg}=-0.22$ V (upper solid curve). Data for V_{sg} from −0.24 to −0.41 V are shown in more detail in Fig. 2.

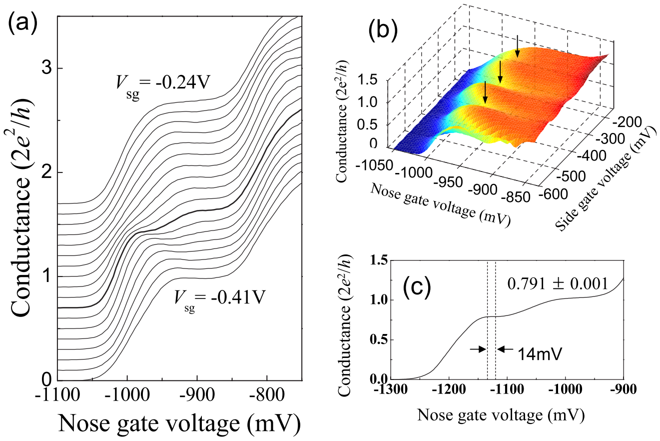

FIG. 2. (Color online) (a) The evolution of the 0.7 plateau of the type-B sample to and from the normal integer plateaus for varying V_{sg} from −0.24 to −0.41 V at intervals of 0.01 V. The thick curve is the conductance taken for −0.34 V. (b) The conductance as a function of V_{sg} and V_{ng} put in a three-dimensional–pseudocolor plot. The positions of the 0.7 structure are marked by arrows for clarity. (c) The conductance as a function of the V_{ng} for the type-A sample at the electron temperature of 100 mK, with the side and the QPC gates set at −0.19 and −0.85 V, respectively.

As in Fig. 1(c), the conductance anomaly started to appear only when certain negative voltages were applied to all the gates concurrently. To induce the conductance anomaly, we first applied small fixed negative voltages to the QPC and the plunger gates, which were just strong enough to pinch the 2DEG under the gate. Only the nose gate was then varied to observe conductance quantization. For a fixed nose-gate voltage V_{ng}, the side-gate voltage V_{sg} was scanned from −0.15 to −0.6 V to tune on and off the conductance anomaly. Figure 1(c) shows the conductance variation for the type-B sample at the electron temperature of 140 mK. The 0.7 structures are seen for V_{sg} around −0.46 and −0.34 V. Thus, controlling V_{sg} in the above circumstances provides a very convenient means to tune to the formation of the 0.7 structure. Higher-order anomalies such as 1.7 and 2.7 structures, observed in ordinary QPC's, are also revealed with clearer features. Similar features were obtained in the type-A sample.

Figure 2(a) shows in detail how the 0.7 plateau for the type-B sample evolves to and from the normal integer plateaus as V_{sg} varies between −0.24 and −0.41 V. The 0.7 plateau becomes most pronounced for V_{sg}=−0.34 V (the thick curve). For V_{sg}=−0.24 V and above, however, no appreciable conductance anomalies were observed (see Fig. 1). The width of G_0 plateau reduces as a more negative voltage is applied to the side gate. For V_{sg}=−0.34 V, it reduces to almost one-half of that for −0.24 V, with the concurrent development of a clear plateau just below $0.8G_0$. Further increasing the negative voltage to the side gate, the plateau reduces to a broad local maximum and transforms back to the G_0 plateau for V_{sg}=−0.41 V. As shown in Fig. 1(c) these generic processes repeat for varying V_{sg}. The width of the G_0 plateau changes noticeably with V_{sg} varying from −0.24 to −0.41 V, while the pinch-off voltage remains almost unaltered. This implies that the recurrent change of the width of the normal integer plateaus for varying V_{sg} was not caused by the possible electrostatic coupling between the side and the QPC gates.

Figure 2(b) shows the modulation of the width of the G_0 plateau for the type-B sample as a function of V_{sg}. The strong modulations are shown for V_{sg} lower than −0.3 V, along with clear 0.7 plateaus (two front arrows). At V_{sg}=−0.22 V, a faint 0.7-like structure (the rear arrow) is also evident. Both samples show well-formed plateaus for the conductance just below $0.8G_0$. For the type-A sample, with the average spacing between the side and the QPC gates closer than in the type-B sample, the plateau is substantially flatter. Figure 2(c) shows the flatness of the 0.7 structure of the type-A sample. The average conductance for V_{ng} between −1.120 and −1.134 V is $0.791G_0$, with the conductance deviation less than 0.1% of the averaged value. No 0.7 structures reported to date have the flatness as high as this. It is highly unlikely that such high flatness is induced by the suppression of the Kondo resonance peak.[14] The flatness can hardly be explained without introducing an energy gap in the model. Along this line, the spin-gap model[11,12] may be the best candidate to interpret the data. It, however, does not explain the repeated occurrence of the 0.7 structure for varying V_{sg}. According to the model, the spin gap widens monotonically with increasing the electron carrier density in a QPC. The electron carrier density inside our QPC gate supposedly decreased monotonically for more negative V_{sg}, the trend of which was in contradiction to the clear occurrence of the 0.7 structure.

In this study, the electron carriers were intended to be weakly localized inside the quantum dot formed by the carrier-confining gates, mimicking the Kondo[16] configuration that was claimed to cause the 0.7 structure.[14] The side-gate voltages in the presence of the 0.7 structure [denoted by two front arrows in Fig. 2(b)], V_{sg}=−0.34 and −0.46 V, corresponded to opening of 5.9 and 3.1 conducting channels between the nose and the side gates, respectively. Thus, the carriers were not effectively confined inside the quantum dot even in the presence of the 0.7 structure. The localization of electrons inside the quantum dot, if any, must have been very weak. A weak 0.7 structure [denoted by the rear arrow in Fig. 2(b)] was also observed even for much less confining side-gate voltage, V_{sg}=−0.22 V, which corresponded to opening of more than 100 conducting channels. In this case, it is thus highly unrealistic to expect localization of electrons inside the quantum dot.

The temperature dependence of the 0.7 structure of the type-A sample is shown in Fig. 3. Before varying the temperature, the side gate was set at the optimum voltage (V_{sg}=−0.19 V) for the formation of the 0.7 structure at the base electron temperature. As shown in Fig. 3(a), the tunable 0.7 plateau gets weaker as the temperature increases and eventually vanishes for T=800 mK. The temperature dependence of the conductance in Fig. 3(b), similar to the one in Fig. 3(a) but taken for a slightly more negative side-gate voltage (V_{sg}=−0.20 V), reveals a local conductance maximum rather than a plateau at the base electron temperature. As the temperature increases, the local maximum gets smeared and gradually transforms into the 0.7 structure, forming a perfect plateau at the temperature around 520 mK.

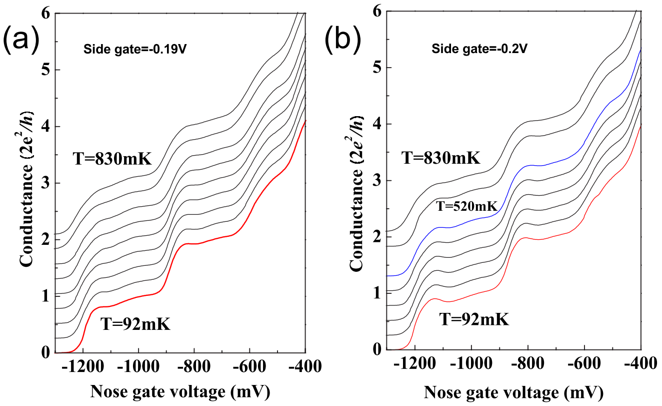

FIG. 3. (Color online) The temperature dependence of 0.7 structure for the type-A sample. The nose and the QPC gates were set to show (a) the 0.7 structure and (b) a resonancelike local conductance maximum rather than a plateau at 92 mK. The fridge temperatures were 92, 152, 250, 365, 420, 520, 630, 730, and 830 mK from bottom to top [without the data for 630 mK in (b)].

This temperature-dependent evolution of the plateau is similar to the feature of the regular 0.7 structure observed in the conventional QPC's,[3,7] where it has been known that the 0.7 structure develops only at relatively high temperatures around 1 K. Thus, the temperature dependence in Fig. 3 appears to indicate that the 0.7 anomaly observed in the conventional QPC structure is a particular subset of the tunable 0.7 anomaly in our quantum-dot structure.

The source-drain bias dependence of the conductance at different V_{ng} was examined with V_{sg} set to show an almost normal integer conductance plateau. As seen in Fig. 4(a), the measured conductance curves around zero bias are somewhat asymmetric due to the imbalance of the potential buildup around each gate. The 0.7 structures are seen for the bias around 0.87, 0.46, −0.36, and −0.87 mV. One also notices that the 0.7 structure is a little clearer in negative biases, which correspond to the situation where electrons were injected to the side gate first. Since the side gate was more open than the QPC gate, the carrier density in this case was higher in the quantum-dot region between the side and the QPC gates than in the case of electrons injected to the QPC gate first. The clearer appearance of the 0.7 anomaly for higher carrier concentration is consistent with some models of the conventional 0.7 anomaly based on electron correlations.[11]

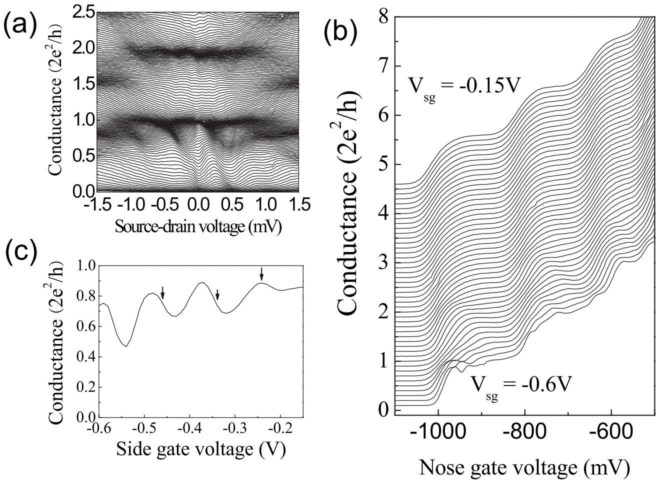

FIG. 4. (a) The differential conductance of the type-B sample, measured as a function of the source-drain bias voltage for varying V_{ng} from −632 to −1061 mV at intervals of 3 mV. The QPC and the plunger gates were set at −0.7 and −0.23 V, respectively, while the side gate was at −0.39 V. (b) The tunable 0.7 structure taken in the same measurement condition as the data in Fig. 1(c) but in a perpendicular magnetic field of 0.15 T. (c) The conductance as a function of V_{sg} with V_{ng} set at −0.964 V. The 0.7 structures were observed at V_{sg} marked by the arrows.

Measurements similar to the ones leading to Fig. 1(c) were repeated in a magnetic field of 0.15 T applied perpendicular to the plane of the 2DEG. As shown in Fig. 4(b), in this relatively low magnetic field, the 0.7 structures were almost entirely suppressed, leaving only normal integer conductance plateaus. A very weak field such as 0.05 T was high enough to considerably weaken the 0.7 structures. No such behavior has been reported in the conventional 0.7 conductance anomaly.[17]

With two carrier-confining gates (the side and the QPC) arranged in series in the direction of electron transport, the interference may have taken place for the electrons moving back and forth between the gates. Thus, it can be inferred that such an interference may have caused the 0.7 plateau in our measurements. In Fig. 4(c), the conductance is plotted as a function of V_{sg}, with the nose gate fixed around the middle of the 0.7 plateau. A clear interference pattern is revealed as V_{sg} varies. Marked by arrows in Fig. 4(c) are the positions of V_{sg} where the 0.7 structures were observed. Although the interference is evident, not much correlation exists between the 0.7 structure and the interference pattern. The 0.7 structure formed at $V_{sg}=-0.22$ V is located at the local conductance maximum, while those formed for V_{sg} at −0.46 and −0.34 are located somewhat away from the local conductance maxima. This indicates that the 0.7 structure cannot be explained by a simple interference effect with a single transmission mode. With multiple transmission modes in the interference, no direct correlation can exist between the 0.7 structure and the interference pattern as in Fig. 4(c).

Also, the recurrence of the 0.7 structure as a function of the side-gate and bias voltages resembles the electron interference effect. However, the extreme flatness of the 0.7 structure over a wide range of V_{ng} as in Fig. 2(c) cannot be explained by the simple electron interference effect, because varying V_{ng} continuously alters the electron phases, resulting in the change of the conductance. Sharpening of the 0.7 anomaly at high temperatures around 1 K is not explained by the simple electron interference effect either due to the enhanced electron decoherence at high temperatures.

Recently, it has been reported that a 0.5 plateau can be realized by changing the potential landscape of 1D wire by using a scanning probe tip.[18] The 0.5 structure was observed when the potential away from the main confinement potential landscape was perturbed. In this case, electrons scattering back and forth between the main and perturbed potentials possibly resulted in the interference. Even in conventional QPC's, the electron interference is likely to happen since the shape of the quasi-1D wire formed by QPC gates is usually distorted by the formation of the unintended impurity potential. An exception takes place for an extremely short QPC formed by narrow gates. In this study, no conductance anomaly was observed for QPC's, the widths of which were shorter than 50 nm. We believe that the 0.7 structure has not been observed consistently in ordinary QPC's due to the varying distortion of the potential landscape from sample to sample. The difference in features of the 0.7 structure between our samples and conventional QPC's can be a result of the difference in the detailed shape of the potential landscape. Although we consider that the electron interference is the main cause of the 0.7 anomaly, all of its features are not explicable in terms of the electron interference only. Thus, both the interference and the interaction effect are believed to play essential roles in causing the 0.7 anomaly.

In summary, we have demonstrated a unique approach in forming the 0.7 plateau in tunable quantum-dot structures. In our scheme, it was possible to tune on and off the 0.7 structure. The 0.7 structure was demonstrated to evolve into a normal integer conductance plateau by varying the negative side-gate voltage. In clear contrast to the conventional one in an ordinary QPC structure, however, the 0.7 plateau in our study was observed even at very low electron temperatures with unprecedented flatness. The tunable 0.7 plateau occurred in our quantum-dot structure even when carriers were not fully confined in the quantum-dot region. The interference feature shown in Fig. 4(c) strongly suggests that, in addition to the generally accepted electron correlation effect, the interference effect should also be taken into account for the cause of the 0.7 anomaly. The tunable 0.7 anomaly provides implications to the cause of the 0.7 anomaly in the ordinary QPC structure. The tuning, however, turns out to be somewhat subtle, which explains the reason why the conventional 0.7 structure is not always observed in ordinary QPC's.

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