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The Resonant Tunneling States in a Quantum Point Contact

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The resonant tunneling states formed in a relatively long and narrow quantum point contact have been observed. The conductance measurement as a function of bias and gate voltage shows the coulomb diamond structure, which is a typical fingerprint of a quantum dot. From the excited-state spectrum, the average energy-level spacing between the quantized energy states was found to be around 1 meV. Also, the shape of the resonant tunneling peak matched that of a quantum dot. The results support the evidence that a quantum dot can be formed in a relatively narrow quantum point contact.

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I. INTRODUCTION

The quantum dot (QD) has drawn immense attention from the scientific community, due to possible application for novel quantum devices such as a quantum bit [1] and also the fundamental interest in the quantum-mechanical nature of electrons. There are many different types of quantum dot, such as self-assembled QD [2–4], nanotube-based QD [5], GaAs/AlGaAs heterostructure-based vertical [6] and planar QD [7–10], *etc.* Among these, the planar-type quantum dot is an ideal candidate for quantum devices because electrons are coherent even outside the quantum dot. Hence, one can build fully coherent quantum-mechanical devices without suffering from the decoherence of the electrons. However, the disadvantage of such a quantum dot is that it only works at extremely low temperature, usually below a temperature of 500 mK, while other types of quantum dot can easily work at 4.2 K and even at room temperature. It has to be pointed out that a solid-state quantum dot working at 300 K does not have many applications for novel quantum devices, because the strong coupling between phonon and electron destroys the coherency of electrons totally. So, it has been of interest to make planar-type quantum dots which can work at a relatively higher temperature. Having a planar-type quantum dot system working at 4.2 K, which can be readily accessible by liquid helium, would just be good enough for most of the quantum-device applications. To make a planar-type QD work at such a temperature, the energy-level spacing between successive quantized levels inside the QD has to be much larger than k_BT at the operating temperature. The smallest planar-type quantum dot available up to now is around 150 nm by 150 nm in size, and the level spacing is around 100 μeV [11]. On considering that the thermal smearing of the Fermi energy level is around 4 k_BT, which is about 1.4 meV at 4.2 K, the size of the QD has to be much smaller than the previously mentioned one to get a much larger level spacing than the Fermi energy smearing. Due to the technical limit of the e-beam lithography technique, it is not so trivial to make a QD less than 100 nm by 100 nm in size.

Here, we report the observation of coulomb blockade peaks at 4.2 K, not from a QD but from a rather simple quantum point contact (QPC) [13] with slightly different geometry from the usual QPCs. We found coulomb blockade peaks in some of the QPCs when the QPCs are highly pinched. Surprisingly, these coulomb blockade peaks were observable even at 4.2 K and the conductance in the blockade regime was negligible. The conductance measurement as a function of bias and gate voltage showed the typical coulomb diamond structure of a quantum dot.

II. EXPERIMENTS AND DISCUSSION

QPCs having 100-nm, 300-nm, and 900-nm gate lengths have been fabricated. The width of the gap between split gates was kept the same for all three

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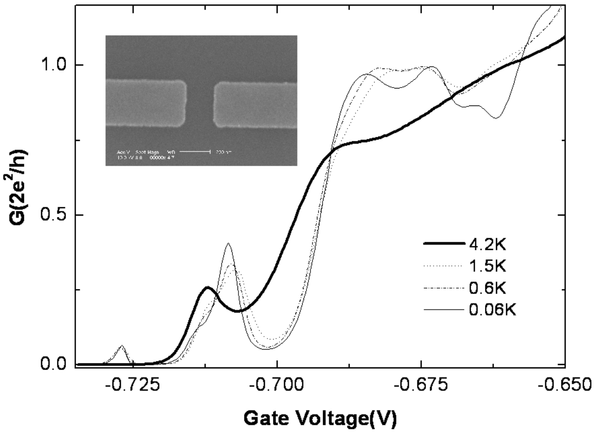

Fig. 1. Differential conductance as a function of gate voltage at different temperatures. The inset of the figure is a SEM image of the QPC. The gap between the gates was 165 nm and the width of the gates was 300 nm.

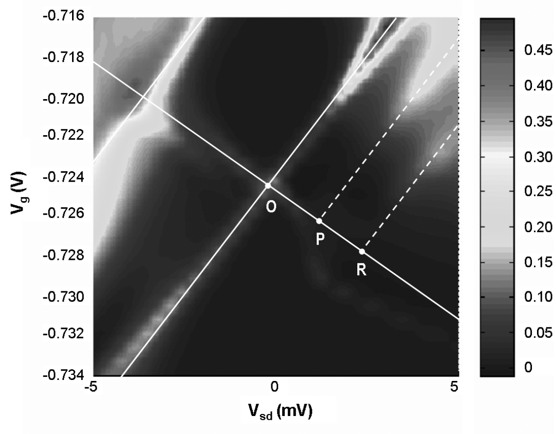

Fig. 2. Gray-scale plot of the differential conductance measured as a function of bias and gate voltage. For clarity, the shifts of the coulomb blockade peaks are marked as solid lines, while the shifts of the excited-state peaks are marked as dashed lines.

kinds of QPCs and measured to be around 165 nm. The devices were fabricated on the surface of a 65-nm-deep 2DEG layer based on GaAs/AlGaAs heterostructure with electron density of 2.5×10^{11} cm^{-2} and mobility of 1.5×10^{6} cm^2 V^{-1} s^{-1} at 4.2 K. First, a mesa was defined by etching away the unnecessary 2DEG layers in $H_2O_2 : H_3PO_4 : H_2O$ (1 : 1 : 50) solution, which gives around 100-nm/s etch rate at room temperature. To make ohmic contact to the 2DEG of the mesa, 30 Å of Ni, 2000 Å of Au, and 1000 Å of Ge, followed by 750 Å of Ni, were evaporated and annealed at 460 °C for 60 seconds. The QPCs were fabricated by electron-beam lithography. 200 k 3 % PMMA in anisole and 495 k 5 % PMMA in anisole were used to form a double e-beam resist layer to make lift-off easier and to give good resolution for very-fine-structure fabrications. Thermal evaporation of 150 Å of Ti to form a good Schottky contact with 2DEG and 150 Å of Au were placed on top of the Ti layer to prevent oxidation of Ti and to give good electrical contact to the next process layer. Finally, large electrical contact pads were fabricated by optical lithography.

The conductance measurements were made by applying constant voltage and measuring the current flowing through the sample. To measure the differential conductance, a small sine wave signal dV_{AC} was added to a DC bias V_{DC} to be fed into the source of the sample. While keeping the modulation voltage at the source constant, the current flowing through the device was measured from the drain of the sample. The differential conductance dI_{AC}/dV_{AC} at a finite DC bias was measured by the phase-sensitive measurement technique. Since the differential conductance is sensitive to the density of tunneling states in a quantum dot, the measurements of differential conductance as a function of bias reveal the energy spectra of a quantum dot. The modulation voltage was kept at 10 μV_{rms}, which is smaller than $4k_BT$ at 100 mK, throughout the experiment.

The samples were cooled to around 60 mK in a dilution fridge. The conductance measurements were made at various temperatures between 60 mK and 4.2 K. All three kinds of sample with different gate lengths were measured. All the samples with 100-nm-long gate show typical conductance quantization as a function of gate voltage at 60 mK and no conductance anomaly [14–16] was observed. We also measured typical conductance quantization behavior with some of the 300-nm-long QPCs. However, a few samples show resonant peaks when the QPCs are highly pinched, as shown in Figure 1. The inset of Figure 1 is a SEM image of the device. The width of the gap was 165nm and the length was 300nm, approximately. As is shown in the figure, a quantized plateau-like structure was observed at around −0.68 V. However, the plateau was not flat and we believe that this structure is the result of the superposition of many resonant tunneling peaks originating from conductance through the highly open quantum dot. When the quantum dot is very open, the conductance at coulomb blockade regime is not zero and the FWHM of the conductance peak is usually wide because the coupling between the energy states of the quantum dot and the reservoir is strong. Also, the energy spacing between the quantized energy states is relatively small, since the size of the dot is relatively large. If the energy spacing is comparable to or smaller than k_BT, the conductance peaks overlap each other. As a result, the superposed coulomb blockade peaks can form a plateau-like structure, as was observed in the experiment. This argument can be confirmed by the fact that the plateau-like structure looks more like two overlapped resonant peaks at lower temperature. The energy spacing between the quantized energy states becomes larger and the coupling between the energy states and the reservoir becomes smaller as we put

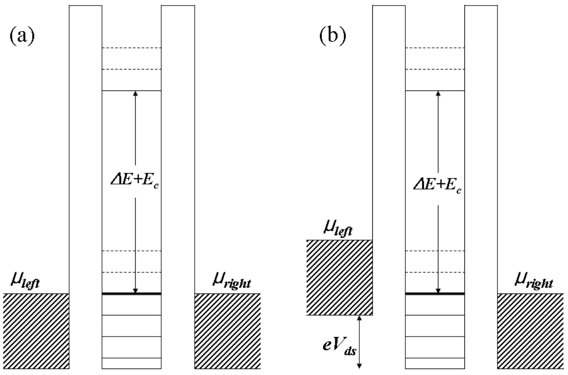

Fig. 3. Schematic diagram of energy states inside a quantum dot: (a) without bias, and (b) with a finite bias. The dashed sections on the left and the right of the quantum dot represent the electron reservoirs of source and drain. The solid line represents the ground state of a corresponding coulomb blockade peak and the dashed lines represent the excited states. The transport window in energy is between the chemical potentials of the left reservoir and the right reservoir.

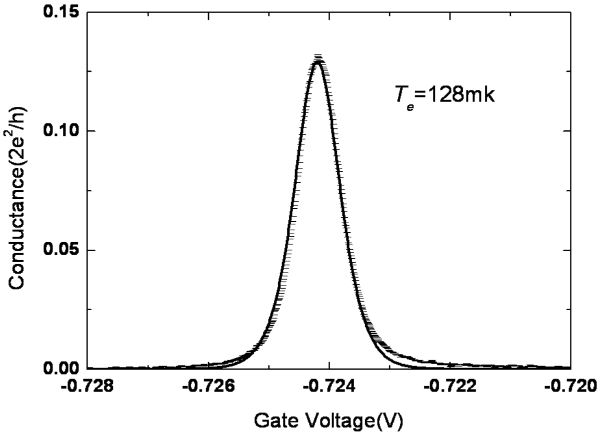

Fig. 4. The resonant peak measured experimentally was fitted to the derivative of the Fermi-Dirac distribution function. The horizontal bars are the experimental data points taken at 60 mK for the fridge temperature, and the solid line is the derivative of the Fermi-Dirac distribution function with 128-mK electron temperature.

more negative bias on the QPC. Hence, coulomb blockade peaks can be observed separately when the QPC is properly pinched. Two separate resonant peaks were observed at around -0.727 V and -0.719 V. These peaks were clearly observable at relatively high temperature. As can be seen from the figure, the conductance between the two peaks was totally suppressed below 1.48 K and was negligible at 4.2 K.

Figure 2 shows a stability diagram for the 300-nm-long QPC. The solid lines show the shift of coulomb blockade peaks as a function of bias and gate voltage. The conductance is totally suppressed in the black diamond-shaped region, which is surrounded by the solid lines. This is a typical fingerprint of a quantum dot. Additional conductance peaks are observed when the QPC is biased with finite voltages. The shifts of these peaks are marked as dashed lines in the figure. These additional peaks also shift in parallel with coulomb blockade peaks as a function of bias and gate voltage. These additional conductance peaks originate from tunneling through excited states of a quantum dot.

In Figure 3, we illustrate the energy states of a quantum dot with and without a bias on the sample. The thick solid line is the ground state of a quantum dot, which is responsible for a certain coulomb blockade peak. The dashed lines above the solid line are the excited states of a quantum dot. As can be seen from Figure 3(a), tunneling can happen only through the ground state when there is no bias between left and right reservoirs. However, when the bias is applied, tunneling can happen through the excited states lying within the transport energy window ($\mu_{left} \sim \mu_{left} + eV_{ds}$), which is defined by the bias applied on the sample. This tunneling event gives an additional conductance peak when the bias is applied on the sample. From this, one can get valuable information about the energy spacing between quantized energy states. Since the tunneling through the excited state starts to happen when the excited state is aligned to the chemical potential of the left reservoir, the bias applied to the sample is a direct measure of the energy spacing between the quantized states. As is shown in Figure 2, tunneling through the first excited state starts to happen at the point P. The corresponding bias of the point P is the energy spacing between the ground state and the first excited state. As the bias is increased, tunneling through the second excited state is observed at the point R. The average energy spacing between the energy states was about 1 meV. On considering that $k_B T$ at 4.2 K is about 0.36 meV, the energy spacing between the states is much bigger than the thermal smearing of the Fermi energy and this prevents the chance of having conductance through multiple energy states.

Finally, we compared the shape of the resonant peak with the derivative of the Fermi-Dirac distribution function. If the resonant peak originates from tunneling through a single monoenergetic state, the spectrum of the peak should fit to the derivative of the Fermi-Dirac distribution function. We compared the calculated result with the last peak shown in Figure 1. As is shown in Figure 4, the calculated result perfectly matches the experimental result. However, it has to be pointed out that the electron temperature used to fit the experimental data was 128 mK, while the data were taken at 60 mK. The discrepancy usually comes from the fact that the electron cooling in a high-purity 2-dimensional electron gas system is inefficient since there is almost no impurity scattering to cool the electrons. Moreover, the phonon scattering is also negligible, since the temperature is extremely low. As a result, the electron temperature is usually higher than the sample or fridge temperature. Nevertheless, since the shape of the peak measured experimentally matches perfectly that of the calculated result from a single energy state, it is reasonable to conclude that this resonance peak originates from tunneling through a monoenergetic energy state. It has to be pointed out that only formation of a quantum dot inside a QPC can provide such a tunneling state.

III. CONCLUSIONS

Resonant tunneling peaks were observed from relatively narrow and long quantum point contacts. The stability diagram of the QPC was measured and turned out to be the same as that of a quantum dot. From the excited-state tunneling spectrum, the energy spacing between the quantized energy states was found to be around 1 meV. This relatively large energy spacing between quantized levels allows coulomb blockade peaks observable even at 4.2 K. Finally, it is found that the shape of the resonant peak matches that of a quantum dot.

By judging from all the results mentioned earlier, it is reasonable to conclude that a quantum dot is indeed formed inside the quantum point contact. The only remaining question is that of how it is possible to have a quantum dot in a rather simple QPC. It is well known that the shape of the conduction-band potential profile does not need to be the same as that of the gate, due to the impurity states in the modulation doping layer. Hence, the slight distortion of the potential profile by the impurity states can accidentally create a quantum dot inside a QPC. This is the reason why the resonant peaks are observed in some 300-nm-long QPCs, but not in all QPCs.

In this work, we have demonstrated that a quantum dot can be formed in a QPC, and it works even at 4.2 K. Further studies are needed to increase the chance of having a quantum dot in a QPC. We believe that this can be achieved by slightly modifying the shape of the gates.

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