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The formation of bound states and the conductance modulation on 0.7 anomaly in a quantum wire

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Abstract. The electron transport in a short quasi-1D quantum wire is studied. In addition to the conductance quantization, several resonances are observed. Two of the resonances appear as extra plateaus below $2e^2/h$. A gate voltage offset is used to tune the local potential of the quantum wire. A robust resonance is seen and the resonances evolve continuously with respect to the offset. The conductance has opposite responses to temperature in successive regions of gate voltage V_g. In the source-drain bias spectroscopy, two more conductance peaks are observed in addition to the Zero-Bias-Anomaly. The locations of the extra peaks evolve with respect to V_g showing a pattern similar to that in a quantum dot. We suggest that a bound state forms in the quantum wire. The prominent 0.7 anomaly in our quantum wire is recognized as the residue of conductance resonance.

1. Introduction

In a 1D quantum wire(QW), the conductance is the integer multiple of $2e^2/h$ because of the quantized state in the direction transverse to the electron motion. It has been a while since an additional conductance plateau in a value of $\sim 0.7(2e^2/h)$ below the first conductance plateau was observed. The first proposed mechanism to this phenomenon was spontaneous polarization.[1] Many works have been intrigued afterward. Reilly *et al* proposed that exchange interaction between the electrons in the wire and the contacts leads to lift of spin degeneracy of the subbands, and the strength is density dependent.[2] Cronenwett *et al* associated the temperature dependence of the conductance with Kondo-like effect.[3] F. Sfgakis *et al* recently found that the temperature dependence on conductance of a tunable bound state in a quantum wire matches with the Kondo model in a quantum dot(QD).[4] In that work 0.7 anomaly and Kondo resonance are claimed to be two separate effects. However, the origin of the anomaly is still under discussion and not yet determined. In this paper, the local potential of a QW is tuned by a gate voltage offset ΔV_g. A robust conductance resonance along with mild resonances are observed. Temperature dependence of the resonances and source-drain-bias(SDB) spectroscopy of the QW are studied. The conductance has different temperature responses in successive regions of gate voltage V_g. In addition to the Zero-Bias-Anomaly(ZBA), two more conductance peaks are seen in the spectroscopy. The evolution of the peaks has similarity of the spectroscopy of a QD. We believe that a bound state exits in the QW. Moreover, conductance anomalies close to $0.7(2e^2/h)$ at high temperatures are observed as the remanence of resonances. Our result casts a light on the revelation of long indetermination.

2. Experimental Specification

A pair of Ti/Au split gates is fabricated on the surface of GaAs/AlGaAs heterostrucutre with the 2-Dimensional-Electron-Gas(2DEG) located 90nm beneath. The mobility and carrier density of the 2DEG are $2.2 \times 10^6 cm^2/V \cdot s$ and $1.4 \times 10^{11} cm^{-2}$, respectively. The device fabrication is accomplished by general electron-beam lithography and lift-off technique. The width of the slit is $\sim 0.4\mu m$. A quasi-1D quantum wire with length of $\sim 0.2\mu m$ is formed by the depletion of 2DEG beneath the negatively biased gates. Differential conductance $G = \partial I/\partial V_{sd}$ is carried out by ac lock-in technique with a small ac voltage of $15\mu V$ in a ^{3}He cryostat with base temperature of 0.3K. A serial resistance of $\sim 300\Omega$ due to the residual scattering of the wire and 2DEG is subtracted in all data.

3. Results and Analysis

When both gates are applied to the same negative voltage, the potential confining the wire is transversely symmetric and the transport is the typically quantized behavior. As shown in Fig.1(a), there are five conductance plateaus in units of $2e^2/h$ due to the transmission of 1D subbands. Besides the quantized conductance, several features are observed in the trace. Anomalous shoulders appears at 1.7, 2.6, and $3.5(2e^2/h)$ corresponding to extra plateaus below the 2nd, 3rd, and 4th plateaus. Two more additional plateaus occur at 0.6 and $0.78(2e^2/h)$. As known, 1D transport is sensitive to its environment such as temperature, external field, and confining potential. By differentially biasing both gates by ΔV_g, $V_{g1} = V_g$ and $V_{g2} = V_g + \Delta V_g$, the confining potential becomes asymmetric and conductance traces evolve differently. In Fig.1(a) we also plot other conductance traces with a finite ΔV_g. The QW is shifted and effectively narrowed, therefore the number of plateau reduced with increasing $|\Delta V_g|$. A robust conductance resonance appears near the pinch-off for finite ΔV_g. The location of this resonance along with the two extra plateaus move *continuously* with decreasing ΔV_g and depend on microconstrictions. This conductance resonance has the resemblance of Coulomb Blockade(CB) resonance, however there is *no sign of localized state by judging the physical geometry.*

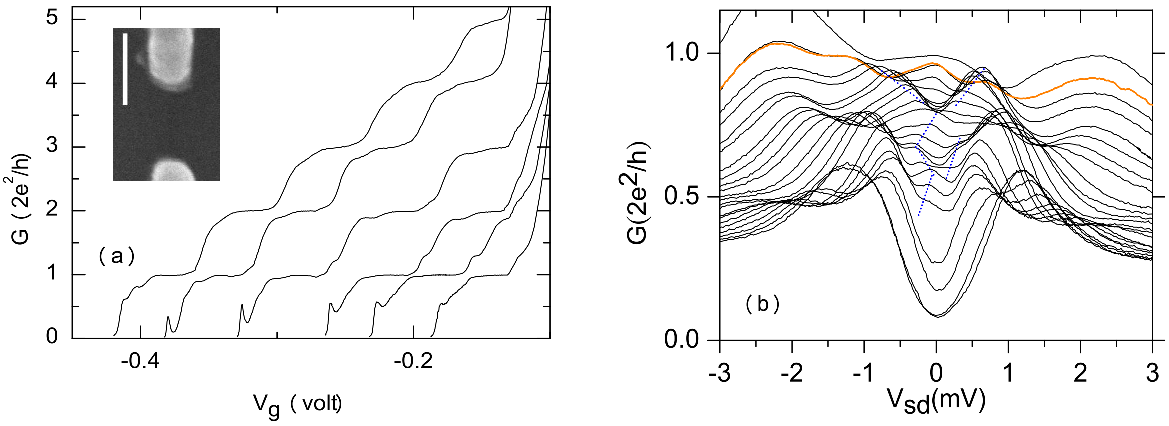

Figure 1. (a)Conductance as a function of gate voltage V_g. From left to right: $\Delta V_g = 0$ to $-0.5V$ in 0.1V steps at T=0.3K. Inset: The micrograph of the quantum wire with a scale bar of $0.4\mu m$. (b)Differential conductance $\partial I/\partial V_{sd}$ as a function of source drain voltage V_{sd} and V_g for $\Delta V_g = 0$, from $V_g = -0.380V$(top most) to the pinch-off voltage at T=0.3K. Orange: $V_g = -0.382V$. The locations of the satellite peaks are marked by the blue dotted lines.

Fig.1(b) is SDB spectroscopy. In addition to the ZBA close to $2e^2/h$, two satellite peaks are observed as well. While the ZBA is suppressed with decreasing V_g, the two peaks get closer and unite near $0.78(2e^2/h)$. The united peak tends to split away, get closer, merge again at

$0.6(2e^2/h)$, and split apart thereafter. The evolution of the peaks forms a pattern analogous to the diamond structure of QD excitation spectrum.[5] The energy level of a well defined quantum dot can be tuned by an external voltage. In the circumstance of small SDB, there is a maximum of density of state when the energy level of the dot is aligned with the fermi energy in the leads. Therefore a conductance peak appears corresponding to a maximized tunneling at zero bias. On the other hand, when the level of the dot is tuned away from the fermi level, a finite bias is required to align the chemical potential with QD energy level and hence, conductance peaks are present at finite V_{sd}. One thing worth being noticed is that the extra plateaus at 0.6 and $0.78(2e^2/h)$ on the trace of $\Delta V_g = 0$ in Fig.1(a) occur exactly where the peaks merge in the spectroscopy. This implies that the extra plateaus are actually CB resonances.

At finite V_{sd}, unexpected conductance resonances appear distinctly. For $V_{sd} \sim \pm 0.9, \pm 1.0,$ and $\pm 1.2mV$, the resonances appear in the values of $\sim 0.9, 0.77,$ and $0.6(2e^2/h)$, respectively. Similar phenomena is also observed by other authors.[2] According to the model for nonlinear transport through a QW, when V_{sd} is larger than one energy spacing of subband only the electrons coming from one lead can contribute to transport. Thus, *plateaus* of half integer are observed. However, the conductance is expected to decrease *monotonically* with decreasing V_g at a finite bias.[6, 7, 8] Models considering more than a quantum wire is required to explain the resonance here.

In order to further understand the abnormality, Fig.2 shows G versus V_g for various temperatures T for $\Delta V_g = -0.3V$. The valley conductance beside the resonance, G_{valley}, does not change much from 0.3 to 1.48K, and gradually increases for T>1.86K. On the other hand, the resonance conductance G_{res} decreases slightly with increasing temperature. The width of the resonance does not broaden until 1.48K. A QD is in resonant tunneling regime as long as $k_BT < h\Gamma \ll \Delta E, E_c$. Here ΔE, E_c, and Γ are level spacing, charging energy, and tunneling rate of a quantum dot, respectively. G_{valley} of the CB resonance does not increase much due to lack of thermal broadening and the resonance width is mainly determined by Γ. On the other hand, G_{res} decreases with increasing temperature.[9, 10] Our QW has a *short* length of $0.2\mu m$. If a bound state ever exists in the QW, it would be quite small in size and ΔE and E_c are very likely to exceed k_BT. The typical conductance of CB resonance in a QD is in order of a few $0.01(2e^2/h)$. In comparison G_{res} observed here is much larger implying a large Γ. The result is consistent with the scenario of resonant tunneling. Comparing the traces of 0.3 and 1.86K, besides the conductance increase in the valley, there is a conductance decrease in the region of $\mathrm{V}_g = -0.230$ to $-0.246V$. Along the traces, opposite conductance responses with respect to temperature in successive regions of V_g can be recognized. This is similar to the Kondo phase in a QD whereas enhanced conductance is found only in regions of voltage with odd number of electrons inside.[9, 11, 12] Armed with these evidences, we suggest that a bound state exits in our QW.

In addition, as shown in Fig.2, two conductance anomalies appear at T=5.05K. One of them has the value of $\sim 0.5(2e^2/h)$ and is clearly the remenant of the CB resonance at low temperatures. The other has a value of $\sim 0.7(2e^2/h)$ and is a remainder of a conductance shoulder which appears as soon as the enhanced conductance is suppressed for T>0.87K. The inset of Fig.2 shows the temperature response for $\Delta V_g = 0$. Two anomalies appearing at $\sim 0.6(2e^2/h)$ and $\sim 0.8(2e^2/h)$ at higher temperatures originate from the extra plateaus at low temperature. From the SDB spectroscopy(not shown for $\Delta V_g = -0.3V$), the two anomalies correspond to the unite of conductance peaks which has been mentioned in the previous paragraph. This result is a token that the conductance anomalies are the consequences of CB resonance while the Kondo resonance of the bound state induces enhance conductance.

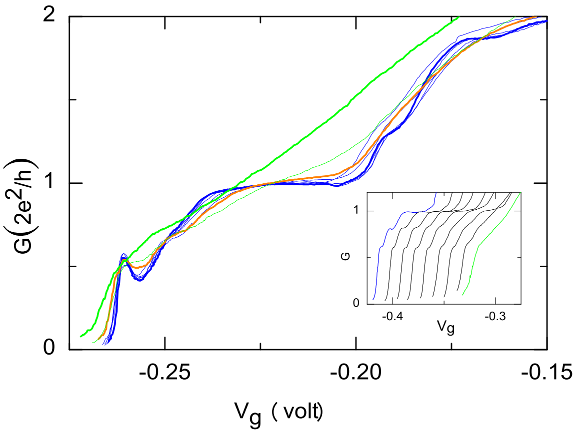

Figure 2. Conductance versus V_g for various temperatures from 0.3 to 5.05K with $\Delta V_g = -0.3V$. Temperature ranges are distinguished by colors: 0.3(thick blue), 0.50-1.48(blue), 1.86(thick orange) and 3.00-5.05K(green), respectively. Inset: Conductance versus gate voltage with $\Delta V_g = 0V$ for 0.30(blue), 0.50, 0.68, 0.87, 1.10, 1.48, 1.86, 3.00, and 5.00K(green) from left to right respectively

4. Conclusion

Coulomb blockade resonance is observed in a quantum wire coupled with a bound state. While the conductance at successive regions has different responses to temperature, the satellite peaks alongside the ZBA moves with V_g in the SDB spectroscopy. The pattern of evolution has similarity of excitation spectrum of a quantum dot. The root of bound state formation is beyond the scope of this paper and requires further study. Due to different temperature responses of Coulomb Blockade and Kondo resonances, they appear as conductance anomalies at high temperatures, which we propose to explain the long undetermined mechanism of 0.7 anomaly.

Acknowledgments

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