行政院國家科學委員會補助專題研究計畫期中報告

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閘極局域的開放式量子點與一維窄通道的抽運傳輸、整流、與自旋極化機制(1/3)

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執行單位：國立交通大學電子物理系

中　華　民　國　97　年　05　月　31　日

行政院國家科學委員會專題研究計畫期中報告(1/3)
閘極局域的開放式量子點與一維窄通道的抽運傳輸、整流、與自旋極化機制(1/3)
Quantum pumping, rectification, and spin polarization of gate-confined open quantum dots and 1D channels (1/3)

計畫編號：NSC 96-2112-M-009-040
執行期限：96 年 8 月 1 日至 97 年 7 月 31 日
主持人：許世英　　國立交通大學電子物理系

一、中文摘要

在高 mobility $Al_xGa_{1-x}As/GaAs$ 異質結構的表面一對閘極施加負偏壓，將局域下層的二維電子氣在電子波長範疇寬的通道，形成類一維的量子系統，電子因而展現量子化的電性傳輸行為；由於一維量子化的能態與其環境（源、汲極）的量子穿透，電導值展現整數倍的 $2e^2/h$。近年來在其電導的行為發現有額外的平台發生在 0.7 的 $2e^2/h$[1]，一開始認為是由於瞬間極化(spontaneous polarization)所造成[2-3]，十年來的探討，有幾個不同的論點，但迄今仍在存在一些爭議，其中 kondo 效應和 bound state 都被熱烈地提及[2-8]。目前我們藉由改變閘極施加偏壓的方式，觀察到電導行為展現不同行為，有一電導共振(conductance resonance)會發生在 $2e^2/h$ 之下接近窄通道關閉(pinch-off)附近，深入探討溫度對其影響與其微分電導能譜(G-V_{sd})，我們認為在我們的一維窄通道系統有 bound state 才造成此額外電導共振，而觀察到的微分電導能譜似乎與量子點近似。

關鍵詞：閘極局域量子窄通道、0.7 異常、電子自旋極化、kondo 效應。

Abstract

In high mobility $Al_xGa_{1-x}As/GaAs$ heterostructures, a negative bias on surface split gates above 2DEG can be used to make constrictions comparable with electron wave length forming a “quasi-one-dimensional” quantum system. The conductance of such a device is known to be quantized in units of $2e^2/h$ because of the quantization of states and transmission via its environment (source and drain). It has been a while that an additional plateau in a value of $0.7(2e^2/h)$ below the first conductance plateau was reported[1]. Spontaneous polarization was first proposed for this additional 0.7 anomaly[2-3]. After the advanced studies over a decade, several mechanisms are suggested and the origin of the anomaly is still under debate. Among the proposed mechanisms, there are two separate effects, kondo effect and bound state, attracting much more attentions[2-8]. In this work, a gate voltage offset is used to tune the confined potential of the quantum wire asymmetrically. An additional conductance resonance appears below $2e^2/h$ near the pinch-off regime. Combined with the evolution of conductance resonance to temperature and the source-drain bias spectroscopy, we conclude that the conductance resonance results from a bound state in our quantum wire. Moreover, the observed differential conductance in our wires shows similarities to quantum dots.

Keywords: gate-confined quantum narrow channel, 0.7 anomaly, spin polarization, bound state, kondo effect.

二、緣由與目的

The quantization of conductance is a well known characteristic of ballistic quantum wires. However, a controversial exception to this electrical transport is the additional conductance feature below the first conductance plateau ($1\times 2e^2/h$) which has been observed in numerous 1D systems for a while[1]. In the first investigation to this shoulder-like (plateau) feature in the lowest transmission mode of conductance, the 0.7 anomaly, spontaneous spin polarization was proposed as the origin by Thomas *et al*[1]. Many works have been intrigued afterward. Reilly *et al*. suggested that exchange interaction between electrons in the 1D wire and the contacts lifts spin degeneracy of the sub-bands and the extra-shoulder arises from thermal contributions from the upper spin-band[2]. With the support of experimental data by Cronenwett *et al*.[6] the kondo effect seems is predominantly responsible[5]. Nonetheless, no consistent agreement has been reached about the origin yet. Recently, Sfigakis proposed that both the kondo-like effect in 1D wires and 0.7 anomaly are separate and distinct effects[7].

三、實驗方法

The two dimensional electron gas(2DEG) which forms at the interface of an $Al_xGa_{1-x}As$/GaAs heterostructure was grown using MBE by Dr. Umansky at Wiezmann institute in Israel. Shubnikov-de Haas and Hall measurements were used to determine the areal electron density n. Mobility μ is about 2.2×10^6 cm^2/Vs and n is $1.4\times10^{11}cm^{-2}$ corresponding to the elastic mean free path ℓ of ~15μm at low temperatures. Electron beam lithography was used to pattern the surface of $Al_xGa_{1-x}As$/GaAs heterostructures with a pair of metallic gates. In this work, we have fabricated submicron gate pattern of gate width 0.4μm (Inset of Fig.1(a)). A quasi-one dimensional wire of length ~0.2μm is formed by the depletion of the 2DEG beneath the negatively biased gates. Differential conductance $G=\dfrac{\partial I}{\partial V_{sd}}$ is carried out by ac lock-in technique with a small ac voltage of 15μV in a ^{3}He cryostat. The base temperature of the cryostat is below 0.3K.

四、實驗結果

When the same negative voltage is applied on both split gates, the potential confining the 1D wire is transversely symmetric and the conductance is typically quantized as the integer multiple of $2e^2/h$. As shown in Fig.1(a), there are five conductance plateaus in units of $2e^2/h$ due to the transmission of 1D sub-bands. As known, 1D transport is sensitive to its environment such as temperature, external field, and the 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 different conductance traces are observed. The evolution of the conductance trace with respect to finite ΔV_g's is also plotted in Fig.1(a). Comparing with the left-most one for $\Delta V_g=0$, several features appear in the trace in addition to integer quantized conductance. The confining potential is asymmetric shifted and effectively narrowed with increasing $|\Delta V_g|$, and hence, the number of plateaus decreases. For the right most one with ΔV_g=-0.5V, there are no plateaus of N=2 and bigger integers. A robust conductance resonance appears clearly below the first conductance plateau near the pinch-off regime for a non-zero ΔV_g. The location this conductance resonance moves continuously with ΔV_g indicating that it is associated with the micro-constrictions. Although this conductance resonance has the similarity of the Coulomb blockade resonance in a quantum dot, there is no sign of localized state by judging the geometry of our wire.

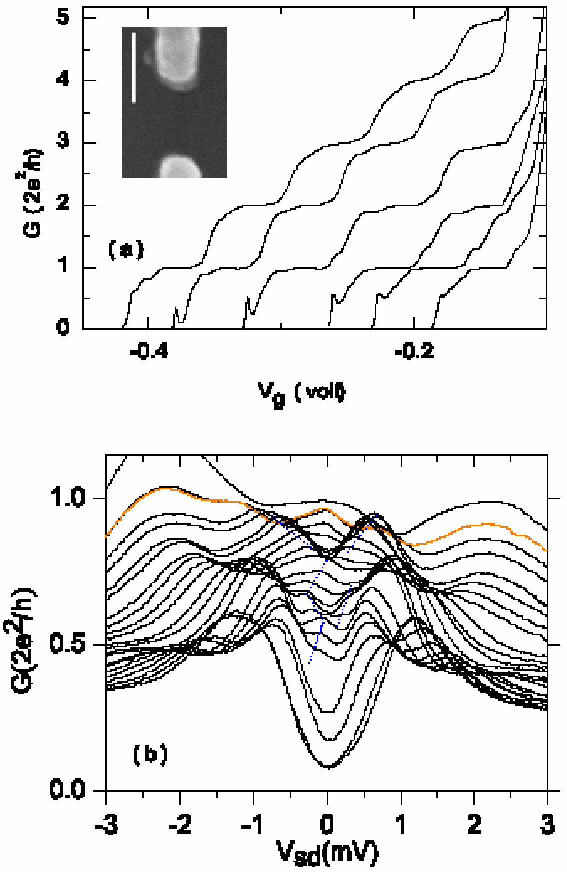

Fig. 1 (a) Zero bias conductance as a function of gate voltage at T=0.3K. From left to right : ΔV_g is from 0 to -0.5V in a step of 0.1V. Inset: The SEM picture of the pair of split gate with a scale bar of 0.4μm. (b) Differential conductance as a function of source-drain voltage for a series of gate voltage with ΔV_g=0 at T=0.3K. V_g=-0.38V for the top most curve and V_g becomes more negative from top to bottom. The locations of satellite peaks are marked by the blue dotted lines.

Source-drain spectroscopy, differential conductance $G = \dfrac{\partial I}{\partial V_{sd}}$ versus source-drain bias, for different V_g's is plotted in Fig.1(b). Beside the zero bias anomaly (ZBA) close to $2e^2/h$, two satellite peaks are observed as well (see the red curve V_g=-0.382V). With V_g becomes more negative corresponding the narrower wire, the ZBA is suppressed and the two satellite peaks get closer. The locations of satellite peaks are marked by the blue dotted lines. As shown, it seems that both peaks unite near $0.78\times(2e^2/h)$ and then, split away, get closer, and merge again at $0.6\times(2e^2/h)$, and split apart thereafter. This is consistent with two additional shoulders at 0.6 and 0.78 $(2e^2/h)$ observed for the left-most curve in Fig.1(a). The evolution of the peaks forms a pattern analogous to the diamond structure of quantum dot excitation spectrum[9]. The energy level of a dot can be tuned by an external gate voltage. When the energy level of the dot is aligned with that of the leads, there is a local conductance maximum. On other hand, when the energy level is shifted away by the gate voltage, a finite source-drain bias on leads can re-align the energy level with dot's to restore the conductance peak. Therefore, conductance peaks appear at a certain non-zero V_{sd}. This implies that the satellite peaks in the source spectroscopy and two extra shoulders in the zero bias conductance trance stem from the same origin revealing the signature of Coulomb blockade resonances.

Fig.2(a) the source-drain spectroscopy for a asymmetric confining potential with ΔV_g=-0.3V. In addition to ZBA, two satellite peaks are observed forming a triple-peak structure. Similar to the result for a symmetric confining potential in Fig.1(b), ZBA is suppressed and two satellite peaks get closer with decreasing V_g. A clear zero bias conductance peak is present in the green trace for V_g=-0.26V.The evolution of the conductance peak can be clearly demonstrated by the contour plot of $\dfrac{\partial G}{\partial V_{sd}}$ in Fig.2(b). A local conductance maximum (conductance peak) is recognized as the green are with red area at the left and blue area at the right. The evolutions of conductance peaks are marked by black dotted lines. They can get closer, merge, and split away by changing V_g. Here, the satellite peaks unite at V_g=-0.26V, exactly the place where Coulomb blockade resonance occurs. This is also a signature of a bound state.

A gate voltage tuned conductance anomaly has been reported by Chung *et al.* recently[8].There may be two possible mechanisms to explain the conductance variation induced by the spatial modification of confining potential. One is the quantum interference effect of electron proposed by Chung *et al*[8]. For their case, a “cavity-like” structure might be formed and hence, the backscattering is likely to occur in their device. However, taking adiabatic, coherent, and ballistic transport into account, this quantum interference effect can not apply to a short quantum wire like ours. The other is the coupling between a localized state and a quantum wire resulting in a conductance resonance. For our wires, the anomaly shall has connection with conductance resonances of a localized state.

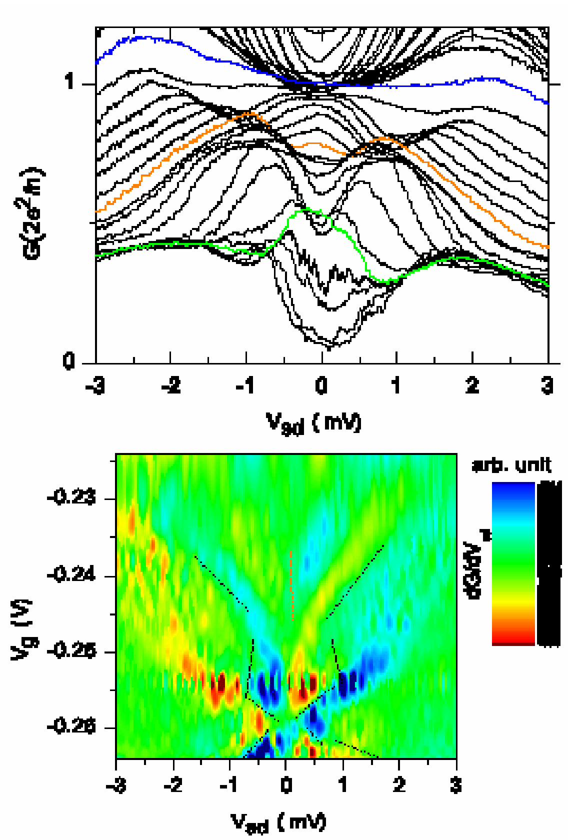

Fig. 2 (a) Differential conductance as a function of source-drain voltage for a series of gate voltage with ΔV_g=-0.3V at T=0.3K. V_g becomes more negative from top to bottom. Color lines are for certain V_g: -0.225V (blue), -0.244V (red), and -0.260V (green), respectively. (b) Contour plot of $\partial G/\partial V_{sd}$ as a function od V_{sd} and V_g. The colors indicate the signs of $\partial G/\partial V_{sd}$: red, blue, and green represent positive, negative, and zero, respectively.

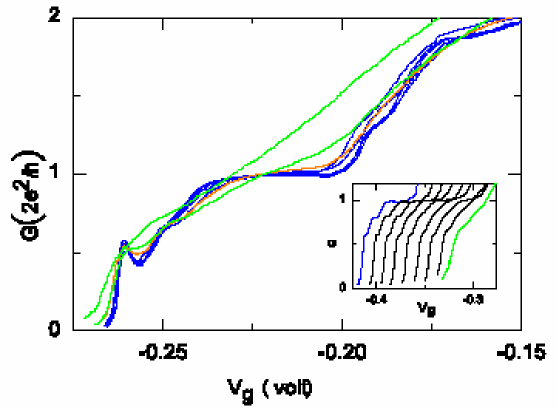

Fig. 3 Zero bias conductance versus gate voltage for a variety of temperature from 0.3K to 5.05K. ΔV_g=-0.3V. Temperature ranges are distinguished by color: 0.3K(thick blue), 0.5~1.48K(blue), 1.86K(orange), and 3~5.05K(green), respectively. Inset Zero bias conductance versus gate voltage with ΔV_g=0V for 0.3, 0.5, 0.68, 0.87, 1.10, 1.48, 3, and 5K (from left to right), respectively.

Fig .3 shows the zero bias conductance versus gate voltage for various temperatures from 0.3 to 5.05K, respectively. The confining potential is asymmetric with ΔV_g=-0.3V. The valley conductance close to resonance (G_{valley}) barely changes from 0.3K to 1.48K and increases gradually for T>1.86K. In contrast, the resonance conductance (G_{res}) decreases slightly with increasing temperature[10]. The width of the resonance does not broaden until 1.48K. It has been known that a quantum dot is in a resonant tunneling regime where $k_BT<h\Gamma<<\Delta E$, E_c[11]. Here, Γ, ΔE, and E_c are tunneling rate, energy level spacing, and charging energy of the dot, respectively. Due to the lack of thermal broadening, G_{valley} is insensitive to temperature and the resonance width is mainly determined by the tunneling rate Γ. Our wire has a mall dimension, 0.2μm in length. If a bound state ever exists in the wire, it would be pretty small in size resulting in large ΔE and E_c that are likely to exceed k_BT. The typical Coulomb blockade resonances of a quantum dot occur at very low conductance, ~$0.01\times(2e^2/h)$. The observed G_{res} of our wire is much larger implying a large tunneling rate Γ. Our results might be the scenario of the resonant tunneling. Comparing the traces between

0.3K and 1.48K, opposite conductance responses to temperature in successive regions can been recognized in Fig.3. This is indeed similar to the Kondo resonance in a quantum dot whereas enhanced conductance is found with odd number of electrons in the dot[12,13]. With the evidence, we suggest that there is locally bound state in our wire.

Moreover, there are two conductance anomalies appear at 5.05K as shown in Fig.3. One has a value of ~0.5×($2e^2/h$) and is clearly the remanence of the Coulomb blockade resonance at low temperatures. The other has a value of ~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.3 shows the temperature responses for a symmetrical confining potential with $\Delta V_g=0$. Two anomalies mentioned earlier, 0.6 and 0.78 ($2e^2/h$) at 0.3K, are still present at about the same locations up to 3K. This result indicates that the conductance anomalies are the consequences of Coulomb blockade resonances because that the Kondo resonance of the bound state will induce enhanced conductance.

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四、結論

In summary, we have investigated electric transport of a gate confined quantum wire system mediated by negative biasing a pair of split gate above 2DEG. In addition to the well known conductance quantization, several resonances are observed. Exploiting a voltage offset ΔV_g on one of the gate to tune the confining potential asymmetrically of the quantum wires, a robust resonance appears and the resonances evolve continuously with respect to ΔV_g. In the source-drain bias spectroscopy, two more conductance peaks beside the zero bias anomaly are observed. These additional peaks behave analogously to the prominent diamond structure of a quantum dot. Armed with all evidence, we suggest that there is a bound state in our quantum wires.

However, it has been theoretically proposed that the asymmetric build-in electric field at the heterostructure interface would induces spin-orbit interaction and the spatial modulation of such Rashba interaction can leads to the formation of purely bound state in a quasi-1D quntum wire. The model has also been associated with Kondo effect in some other aspects[14-16].

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