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(2/3)

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執行單位：國立交通大學電子物理系

中　華　民　國　98　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(2/3)
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(2/3)
Quantum pumping, rectification, and spin polarization of gate-confined open quantum dots and 1D channels (2/3)

計畫編號：NSC 96-2112-M-009-030-MY3
執行期限：97年8月1日至98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 $2e^2/h$。1996年，Thomas 等人在這些量子電導的行為上發現有額外的次平台，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[2-7]，二十多年來的探討，有幾個不同的論點，其中 kondo 效應[8-10]和局域電壓導致能態分裂都被熱烈地提及，迄今爭議仍然存在。我們針對此 0.7 結構，作一系列不同變因的探討，諸如藉由改變外加上電極施偏壓而控制載子濃度、改變量子線長度、或改變溫度等觀察到電導的不同行為展現，同時也深入探討這些變因對其微分電導能譜($G\text{-}V_{sd}$)的影響，我們認為在我們的一維窄通道系統展現此 0.7 結構似乎與微分電導能譜($G\text{-}V_{sd}$)的零偏壓異常無直接緊密關連性。

關鍵詞：閘極局域量子線、0.7 結構、熱激發行為、微分電導能譜、零偏壓異常。

Abstract

In high mobility $Al_xGa_{1-x}As/GaAs$ heterostructures, a negative bias on 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). In 1996, Thomas *et al*. reported that an additional shoulder in a value of $0.7(2e^2/h)$ below the first conductance plateau[1]. Spontaneous polarization was first proposed for this additional 0.7 structure[2-7]. After the advanced studies over two decades, several mechanisms are suggested. Among them, there are two separate effects, kondo effect[8-11] and gate-voltage induced subband splitting[2-7], attracting much more attentions. The origin of the anomaly is still under debate. In this work, we investigate the 0.7 structure by measuring differential conductance systematically as a function of a series of variables such as carrier concentration dependent top gate voltage, the length of quantum wire, and temperature. The response of source-drain spectroscopy to the mentioned above variables is also studied in detail. We conclude that the 0.7 structure and zero bias anomaly can be the separate effects.

Keywords: gate-confined quantum wire, the 0.7 structure, thermal activated behavior, differential conductance spectroscopy, zero bias anomaly.

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×($2e^2/h$) which has been observed in numerous 1D systems for more than two decades. In the first investigation to this shoulder-like (plateau) feature in the lowest transmission mode of conductance, the 0.7 structure, 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 subbands and the extra-shoulder arises from thermal contributions from the upper spin-band[2-7]. On the other hand, with the support of experimental data by Cronenwett *et al.* the kondo effect seems is predominantly responsible[8-9]. Nonetheless, no consistent agreement has been reached about the origin yet. Recently, Sfigakis *et al.* proposed that both the kondo-like effect in 1D wires and 0.7 structure are separate and distinct effects[10]. Moreover, they found that the kondo model and spin-polarization model cannot describe their observed zero bias anomaly spin splitting in the presence of magnetic fields[11].

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 is 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 numerous of submicron split gates of width (w) ~0.45μm and various lengths (ℓ). The geometry of four samples is displayed in Table 1. A quasi-one dimensional wire can be formed by the depletion of the 2DEG ~93nm beneath the negatively biased split gates. On top of the split gates, being isolated by a ~100nm thick dielectric layer of cross-linked Polymethylmethacrylate (PMMA), a top metallic gate (top) is fabricated to control the carrier concentration.

Sample	A	B	C	D
length(μm)	~0	0.2	0.5	0.8
width(μm)	0.5	0.45	0.45	0.45

Table 1 Geometry of four quantum point contacts.

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Differential conductance $G=\frac{\partial I}{\partial V_{sd}}$ is carried out by standard ac lock-in technique with a small ac voltage of 2~10μV in a ^{3}He cryostat. The base temperature of the cryostat is below 0.28K.

四、實驗結果

When the negative voltage is applied on a pair of split gates, the potential depletes 2DES to form the 1D channel resulting in the typically quantized conductance as the integer multiple of $2e^2/h$. As shown in Fig.1, there are conductance plateaus in units of $2e^2/h$ due to the transmission of 1D subbands for sample C. As known, 1D transport is sensitive to the carrier concentration. By biasing top gate voltage V_{top}, the carrier concentration can be effectively changed[11,12]. The more negative V_{top} is, the less concentration n is. The more positive V_{top} is, the more concentration n is. Quantized conductance behavior for a series of V_{top}'s is also demonstrated in Fig.1. The carrier concentration is smoothly decreased from left to right. The threshold V_{sg}^{P} for pinching off the split gate is more negative when n is larger. V_{sg}^{P} becomes less negative continuously with decreasing V_{top}. Moreover, when n is large the presence of the conductance plateau is more clear. Once n is severely reduced, the number of the observed plateau decreases and then, disappears.

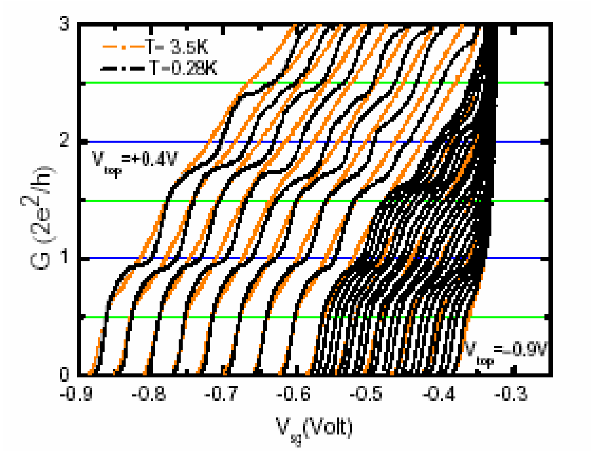

Fig. 1 Quantized conductance of sample C as a function of split gate voltage at T=0.28K (black) and T=3.5K (orange) for different top gate voltages. From left to right: V_{top} decreases from +0.4V to -0.9V in a step of 0.1V (left, +0.4V~–0.4V) and 0.02V (right, –0.4V~–0.9V).

It has been well known that no matter in either 1D or 2D device, the carrier concentration depends on top gate voltage. Fermi energy E_F is determined by n following $E_F = \pi^2\hbar^2 n_{1D}^2 / 8m^*$ in 1D and $E_F = \pi n_{2D} / 2m^*$ in 2D. The number of plateau implies the number of sub-band with energy less than E_F. Therefore, with decreasing V_{top}, n and E_F are reduced resulting in the decrease of observed plateau number. Moreover, the split gate voltage control the confining potential width associated with the energies of the available states. Simply for a hard wall model, the allowed energies are expressed as $E_N = N^2 \pi^2 \hbar^2 / 2m^* a^2$ where a is the width of infinitely confining potential. For low n and E_F, the pinch off split gate voltage V_{sg}^{P} becomes less negative in consistence with our findings. The similar scenario is also observed in all our samples. Figure 2 is the results of sample A. As displayed in Table 1, the channel length of sample A is near 0 while sample C is about 0.5μm. Comparison among all quantized conductance behaviors of four samples gives one interesting finding that 0.7 structure is hardly seen in sample A. For a finite length of quantum wire ($\ell \neq 0$), a clear shoulder ~$0.7(2e^2/h)$ is present for high n (positive V_{top}). It is more pronounced in sample D with ℓ=0.8μm. Theoretical calculation account for the spin-polarization using the Green's function within the density-functional theory gives that resonance conductance peaks are present in longer wires and the 0.7 structure is absent in shorter wires[13]. Later, the detailed calculation based on spin-density-functional theory does not reproduce the 0.7 structure observed in all quantum point contacts of various geometries.[14]

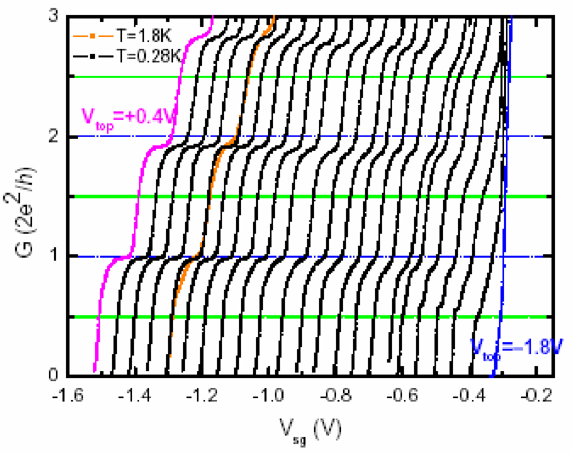

Fig. 2 Quantized conductance of sample A as a function of split gate voltage at T=0.28K (black) and T=1.8K (orange) for different top gate voltages. From left to right: V_{top} decreases from +0.4V to -1.8V in a step of 0.1V.

The results are quite different from the other previous studies by Reilly *et al*[15-17]. They found that the 0.7 structure is clearly present in quantum wires with ℓ=0 insensitive to n and the 0.7 structure can evolves to 0.5 with increasing n for quantum wires with non-zero ℓ's. They attributed the behavior to the many-body spin related effect in supporting their earlier conclusion that the 0.7 structure is a many-body spin state excited out of either the spin-polarized electron gas at low n or the spin-degenerate electron gas at high n. Later they also suggested a density dependent spin gap between E↑ and E↓. However, our findings are in contradiction with theirs but in consistence with the recent data by Hew *et al.*[18]. The discrepancy between ours and Reilly *et al.* may comes from the sample properties that theirs have much higher mobility and corresponding n. Hew *et al.*[18] suggested that the behavior characterizes the spin-incoherent transport proposed by Matveev[19] for a 1D charge-spin separation Wigner crystal (TLL, Tomonaga-Luttinger-Liquid.). The concentration of Hew *et al.*[16] is about 1×10^5/cm and the condition that $na_B<<1$ (where a_B is the Bohr radius) for 1D spin-incoherent regime holds. In our device, n is estimated to be 3.3×10^5/cm and $na_B\sim1$ for $V_{top}=0$ implying that the device may not qualify for TLL model. Except for very negative V_{top} with corresponding very low n, a plateau of $0.5(2e^2/h)$ lasts and $G(V_{sg})$ is nearly temperature–independent for all samples indicating that the spin sector with an infinitely large coupling strength J for an antiferromagnetic spin chain is possibly responsible.

The temperature dependence of the 0.7 structure has been intensely studied for a while, however the results are quite diverse. Among them two types are mostly be proposed, the Kondo-like and an activated temperature dependences. As mentioned above, our samples with very low n demonstrate a nearly temperature-insensitive conductance in the temperature range from 0.28K to 2K. While increasing V_{top} (n), conductance indeed depends on temperature. The trace of points in the inset of Fig.3(a) is the typical result of G(T) at a fixed n (with fixed V_{top} and V_{sg}). As expected for the evolution of the 0.7 structure, conductance declines with increasing temperature. In order to compare with the theoretical prediction, we fit the data with a modified formula,

$$G(T) = g_o\left(\frac{e^2}{2h}\right)\left(1+\gamma\exp\left(-\frac{T_S}{T}\right)\right)^{-1} \qquad (1)$$

Rearrange Equation (1), f_s defined as $\frac{1}{\gamma}\left(\frac{g_o/\left(2e^2/h\right)}{G(T)}-1\right)$ equals to $\exp\left(-\frac{T_s}{T}\right)$. Semilogarithmic plots of f_s versus 1/T are presented to confirm such typical activated behavior. It is important to note that our data does not favor the Kondo-like model over the activation model. Fig.3(a) and 3(b) summarize and the fit results for sample C with two different n's. As seen, all traces generally follow the linear relation in this semilogarithmic Arrhenius plot up to 5K. G(T) deviates from the activated form and seems to saturate at low temperatures. The slope of the linear fit represents the activated temperature T_s. T_s depends on the split gate voltage and increases from 0 near pinch-off to a few kelvin in the proximity of the first plateau. It has been proposed by Bruus *et al.* that the observed activated behavior in G is related to the thermal depopulation of a subband with a gate-voltage dependent subband edge. Reilly *et al.* suggested that exchange interaction between electrons in the quantum wire and the contacts lifts spin degeneracy of the sub-bands and the extra-shoulder (~0.7 structure) arises from thermal contributions from the upper spin-band[2]. The 0.7 structure is indeed separated from the Kondo effect.

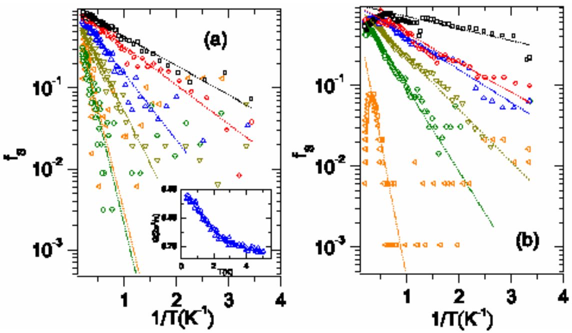

Fig. 3 Semilogarithmic plot of f_s versus T^{-1} for sample C with (a) $V_{top}=0V$ and $V_{top=}-0.6V$, respectively. Points are the experimental data and lines are the linear fits. Inset: Linear plot of one data G(T).

It has been known that the key evidence linking the 0.7 structure and the Kondo effect is the presence of a "zero-bias anomaly", a conductance peak at zero dc source-drain bias near the 0.7 structure. A gate voltage tuned conductance anomaly has been reported before. Both Fig.4(a) and Fig.4(b) are the evolutions of source-drain spectroscopy with split gate voltage for sample C of different carrier concentrations at T=0.28K. For each trace the split gate voltage is fixed, while going from one trace to the next represents an increase in V_{sg} of 3mV. As shown in Fig.1, there is a clear shoulder at ~0.7($2e^2/h$) for case (a) V_{top}=0.4V and ~0.8($2e^2/h$) for case (b) V_{top}=-0.7V, respectively. Zero bias anomaly appears in Fig.4(a) while it is absent in Fig.4(b). With decreasing the carrier concentration, zero bias anomaly weakens. This scenario has been observed in all our samples. One may argue that in very low n regime, 0.7 structure evolves to 0.5 and device may fall into different category such as TLL mentioned above. However, device of the intermediate n can has a shoulder ~(0.6~0.7) ($2e^2/h$) in zero bias conductance G(V_{sg}) but with no zero bias anomaly in source-drain spectroscopy G(V_{SD}) simultaneously. It leads to that 0.7 structure is not strongly correlated with the zero bias anomaly. Recently, other experiments also suggested that both the kondo-like effect in 1D wires and the 0.7 structure are separate and distinct effects[11].

Chen *et al*. found that zero bias anomaly may not split in a magnetic field up to 10 Tesla in contradiction to the prediction Kondo physics[20]. Moreover, a few zero bias anomalies splitting in a field were observed to evolve back to single peak by laterally shifting the confining potential. They claimed that the splitting of zero bias anomalies is related to disorder. The electron-electron interaction induced by disorder in the many body systems usually gives a so called "Coulomb cusp", a conductance dip instead of a conductance peak at zero bias due to the reduction of energy states near the Fermi energy. However, the only supportive finding was reported by Morimoto *et al.*[22] differing from others. Accompanied with the effect, conductance usually decreases with decreasing temperature in contrast to the experimental results in the ballistic quantum wires.

Simulations show that the zero bias anomaly can appears once when the subband energy is lifted by the source-drain voltage following a linear relation, $E_s\left(V_{SD}\right) = E_s\left(0\right) + \gamma V_{SD}$. Assuming that γ is reduced by thermal effect (temperature), simulations give a qualitative explanation for that the zero bias anomalies become broader and weaken with increasing temperature. Comparing Fig.4(a) with Fig.4(b), zero bias anomaly weakens and disappear in low n devices. It implies that γ decreases with decreasing n (V_{top}). It is reasonable to expect the impact of the carrier concentration on the shift of subband energy.

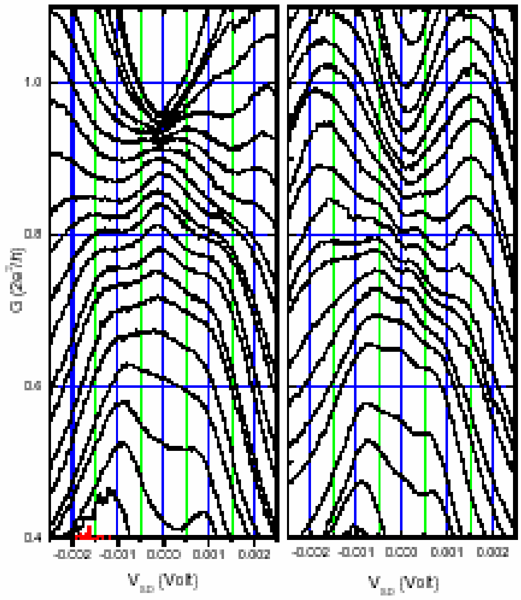

Fig. 4 Differential conductance as a function of source-drain voltage against a series of split gate voltage with V_{top}=+0.4V (left) and V_{top}=–0.65V (right), respectively, for sample C at T=0.28K. V_{sg} becomes more negative from top to bottom in steps of 3mV.

We have also checked the response of the zero bias anomaly to the split gate length.

In Fig.5(a) and Fig.5(b), we plot the evolutions of source-drain spectroscopy with split gate voltage for samples A and B at T=0.28K. Both demonstrate clearly visible zero bias anomalies for devices with ℓ~0 (a) and ℓ =0.25μm (b). Here, V_{top} is fixed at 0. At the same condition that V_{top}=0, zero bias anomaly of sample C is fuzzy with smaller amplitude while of sample D is absent. We conclude that the scattering induced by the long channel length is detrimental to the zero bias anomaly.

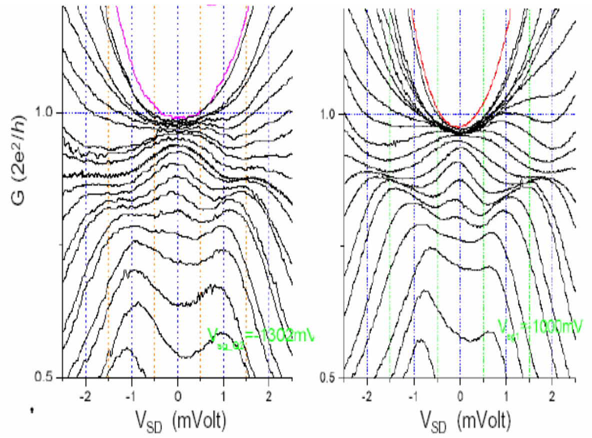

Fig. 5 Differential conductance as a function of source-drain voltage against a series of split gate voltage for two QPC devices with $\ell_{channel}$=0μm (left) and $\ell_{channel}$=0.25μm (right), respectively, at T=0.28K. V_{top}=0V. V_{sg} becomes more negative from top to bottom.

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. The 0.7 structure is more pronounced in the longer quantum wire implying that its origin may be related with boundary scattering. In very low electron concentration by negatively biasing the top gate voltage, 0.7 evolves to 0.5 and $G(V_{sg})$ is nearly temperature–independent in consistence of spin-incoherent transport of an antiferromagnetic spin chain proposed by Matveev.

For some devices with proper n (V_{top}), the 0.7 structure is present in $G(V_{sg})$ while the zero bias anomaly is absent in source-drain spectroscopy $G(V_{sd})$. This result indicates that 0.7 structure is not strongly correlated with the zero bias anomaly. Moreover, the zero bias anomaly weakens and may disappear in very low n devices. In addition, the scattering induced by the long channel length is found to weaken the zero bias anomaly.

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二、會議地點：Kobe(神戶), Japan(日本)

三、報告者：許世英

四、方式　：　壁報展示報告(Poster)

五、題目：

Density influenced electric transport of double quantum point contacts in series

摘要：

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 with lengths less than carrier's mean free path as called "quantum point contact". The conductance of such a device is known to be quantized in units of $2e^2/h$. With increasing interest in nanostructures and their scope for novel functionality, the study of the ballistic and coherent natures of transmission through these gated nanostructures is important. Here, we have measured the electric transport of double quantum point contacts (QPCs) in series at low temperatures to investigate the transmission coefficient T_d which represents the portions of electrons travelling ballistically from one QPC to the other.

Electron beam lithograph was used to pattern numerous pairs of split gates to define one dimensional wires in 2DEG. Different configurations were chosen to have a variety of edge-to-edge separation distance L between two pairs of identical split gates. Isolated from an insulating layer, a top gate was also fabricated on top of the quantum wires to modify the electron densities in the wires and the two dimensional electron gas as well. The transport is characterized by the direct transmission coefficient T_d. Based on theoretical work by Bennakker and Houten[1], the conductance through the serial QPCs can be written as $G_{series} = \frac{1}{2}\left(G + \frac{2e^2}{h} \mathrm{T_d} \right)$.

As shown in Fig.1 for a device with L=0.6μm, T_d decreases continuously from 0.5 to 0.1 with decreasing top gate voltage (carrier density) when both QPCs are confined with only one 1D channel (n=1). The transport is partially adiabatic in high electron densities and transits to nearly complete ohmic (T_d~0) in low densities. When both QPCs are confined with more than one 1D channel (n>1), T_d is smaller than that for n=1, but seems to be insensitive to n for n=2, 3, and 4. Moreover, T_d saturates at positive top gate voltages. The behaviour of T_d will be described in terms of the carrier density dependent mean free path and coherence length in the electron gas[2].

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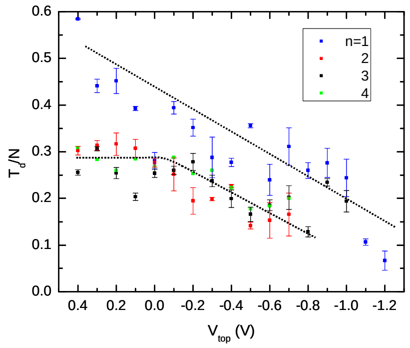

Fig.1 Transmission coefficient T_d versus top gate voltage for QPCs of different confined sub-band index n. Lines are guides to the eye.