行政院國家科學委員會專題研究計畫 期末報告

閘極局域之介觀系統的自旋相關物理性質探討

計畫類別：個別型
計畫編號：NSC 100-2112-M-009-008-
執行期間：100年08月01日至101年10月31日
執行單位：國立交通大學電子物理學系（所）

計畫主持人：許世英

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公開資訊：本計畫可公開查詢

中華民國 102年03月18日

中文摘要：

以負偏壓閘極局域的量子線與其他電子介觀系統研究其自旋相關的物理參數，一般認為即使在沒有鐵磁性接點和外加磁場下，自我存在的自旋束縛態或自旋軌道耦合都有可能產生自旋極化電流；我們將釐清二維電子氣與類一維量子線各自之自旋相關的物理參數如何隨電子濃度而改變，以此控制自旋軌道耦合強度並系統性探討其對0.7電導異常與零偏壓電導異常的影響，在微結構中的局域電子自旋極化來自多體之間的交互作用，當電子密度減少，多體之間的交互作用就越強，之前實驗結果歸納得知電子的背向散射會受微結構的幾何形狀影響，像量子線的長度就會增加其內部電子的背向散射，因此量子線的自旋極化值會因電子密度、幾何長度與其閘及電壓在空間的相對分佈而有所不同。我們系統性將樣品依展現的自旋相關物性歸類，並藉此也一併釐清0.7結構與一維量子線的基態；希望藉由此研究工作，學會以電性測量有效地製造、操控、與偵測自旋極化電流。

中文關鍵詞：

Rashba自旋軌道耦合，自旋極化，量子線、介觀系統，磁場聚焦技術。

英文摘要：

We have investigated spin-related physical quantities systematically in negatively biased gate-confined quantum wires and other mesoscopic electron systems. It has been suggested that either intrinsic spin bound state or spin-orbit coupling may generate spin polarization current in nanostructures without ferromagnetic contacts and applied magnetic fields. The dependence of spin orbit interaction parameters on carrier density in a two dimensional electron gas and a quasi-one dimensional wire are explored independently. The influence of spin-orbit interaction on 0.7 anomaly and zero bias anomaly is studied. Spin polarization of carriers in nanostructures can results from strongly enhanced many-body interactions, which arise when the carriers are confined in a quantum wire or a quantum dot. Many body interactions are predominantly influenced by carrier density in quantum wires. Our earlier work showed that electron backscattering depends on the wire geometry. Meanwhile, quantum wires of different carrier density and geometry with different arrangements of gate voltage will have different values of spin polarization. The degree of spin polarization among samples will be cataloged. Through this, we would figure out the origin of 0.7 structures and ground state of a one dimensional interacting wire. Through this work, we expect to learn how effectively create, manipulate, and detect spin polarized currents by electrical means.

英文關鍵詞： Rashba spin-orbit interaction, spin polarization, quantum wires and mesoscopic systems, magnetic focusing technique.

行政院國家科學委員會補助專題研究計畫 ■成果報告 □期中進度報告

閘極局域之介觀系統的自旋相關物理性質探討

計畫類別：■個別型計畫　□整合型計畫
計畫編號：NSC100－2112－M－009－008
執行期間：100 年 8 月 1 日至 101 年 10 月 31 日

執行機構及系所：國立交通大學電子物理系

計畫主持人：許世英
計畫參與人員：黃馨慧（碩士畢）
柯昇（碩士班二年級生）
廖婉婷(碩士班二年級生)
王漢賢(碩士班二年級生)
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黃鉦凱(碩士班一年級生)
留逸杰(碩士班一年級生)

成果報告類型(依經費核定清單規定繳交)：□精簡報告　■完整報告

本計畫除繳交成果報告外，另須繳交以下出國心得報告：
□赴國外出差或研習心得報告
□赴大陸地區出差或研習心得報告
□出席國際學術會議心得報告
□國際合作研究計畫國外研究報告

中華民國 102 年 1 月 30 日

行政院國家科學委員會專題研究計畫成果報告

閘極局域之介觀系統的自旋相關物理性質探討
Spin-related physical properties of gate confined mesoscopic system

計畫編號：NSC 100-2112-M-009-008
執行期限：100 年 8 月 1 日至 101 年 10 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

以負偏壓閘極局域的量子線與其他電子介觀系統研究其自旋相關的物理參數，一般認為即使在沒有鐵磁性接點和外加磁場下，自我存在的自旋束縛態或自旋軌道耦合都有可能產生自旋極化電流；我們將釐清二維電子氣與類一維量子線各自之自旋相關的物理參數如何隨電子濃度而改變，以此控制自旋軌道耦合強度並系統性探討其對0.7電導異常與零偏壓電導異常的影響，在微結構中的局域電子自旋極化來自多體之間的交互作用，當電子密度減少，多體之間的交互作用就越強，之前實驗結果歸納得知電子的背向散射會受微結構的幾何形狀影響，像量子線的長度就會增加其內部電子的背向散射，因此量子線的自旋極化值會因電子密度、幾何長度與其閘及電壓在空間的相對分佈而有所不同。我們系統性將樣品依展現的自旋相關物性歸類，並藉此也一併釐清 0.7 結構與一維量子線的基態；希望藉由此研究工作，學會以電性測量有效地製造、操控、與偵測自旋極化電流。

關鍵詞：Rashba 自旋軌道耦合，自旋極化，量子線、介觀系統，磁場聚焦技術。

Abstract

We have investigated spin-related physical quantities systematically in negatively biased gate-confined quantum wires and other mesoscopic electron systems. It has been suggested that either intrinsic spin bound state or spin-orbit coupling may generate spin polarization current in nanostructures without ferromagnetic contacts and applied magnetic fields. The dependence of spin orbit interaction parameters on carrier density in a two dimensional electron gas and a quasi-one dimensional wire are explored independently. The influence of spin-orbit interaction on 0.7 anomaly and zero bias anomaly is studied. Spin polarization of carriers in nanostructures can results from strongly enhanced many-body interactions, which arise when the carriers are confined in a quantum wire or a quantum dot. Many body interactions are predominantly influenced by carrier density in quantum wires. Our earlier work showed that electron backscattering depends on the wire geometry. Meanwhile, quantum wires of different carrier density and geometry with different arrangements of gate voltage will have different values of spin polarization. The degree of spin polarization among samples will be cataloged. Through this, we would figure out the origin of 0.7 structures and ground state of a one dimensional interacting wire. Through this work, we expect to learn how effectively create, manipulate, and detect spin polarized currents by electrical means.

Keywords: Rashba spin-orbit interaction, spin polarization, quantum wires and mesoscopic systems, magnetic focusing technique.

二、緣由與目的

In a ballistic quasi-one-dimensional (1D) channel, the linear conductance is quantized into integer multiples of $G_o=2e^2/h$ due to the transmission of spin-degenerate 1D sub-bands within a non-interacting electron picture.[1,2] Peculiar phenomena, however, such as a 0.7 anomaly and a zero-bias Anomaly (ZBA), referred to as the conductance peak centered at zero bias in source-drain bias spectroscopy, are often observed near the first quantization plateau and have attracted much attention.[3,4] Some may argue that the spin polarization is originated from the spin-orbit coupling and may be responsible for the 0.7 structure.[5] The electron-spin-precession is theoretically expected in quasi-one dimensional electron gas system in the presence of spin-orbit interaction.[6,7] For a GaAs based two dimensional electron gas (2DEG), the spin-dependent part of the Hamiltonian is given by

$$H_{SO}=\alpha\left(\sigma_x k_y-\sigma_y k_x\right)+\beta\left(\sigma_x k_x-\sigma_y k_y\right)$$

The first term is called the Rashba spin-orbit interaction which originates from the asymmetry of the electron confinement in the z-direction (normal to the 2DEG plane). The second term is named the Dresselhaus spin-orbit interaction which originates from the absence of inversion symmetry in the bulk GaAs. Both interactions can result in the spin splitting of band giving rise to a variety of spin-dependent phenomena. It has reported that the spin-orbit interaction related parameter can be tuned by carrier density for a high mobility GaAs/AlGaAs two dimensional electron gas.[8]

During the past decades, the quantum devices have attracted considerable interest providing important insights in topics of electron-electron interaction, wavefunction interference, decoherence, and localization effects in addition to the charge and size quantization.[9] Moreover, both spin orbit interactions can result in the spin splitting of band giving rise to a variety of spin-dependent phenomena. Much greater sensitivity to spin properties can be achieved by measuring pure spin currents resulting from spin-resolved charge transport, but such measurements have not yet been integrated with gate-defined mesoscopic systems.

三、實驗方法

The 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 $1.2\sim0.8\times10^6$ cm^2/Vs and n is $1.6\sim1.7\times10^{11}$cm^{-2} corresponding to the elastic mean free path ℓ of 5~12μm at low temperatures. There are slight variations among devices.

Electron beam lithography along with thermal deposition were used to fabricate metallic gates on (100) plane of the substrate. There are numerous configurations employed in this work as shown in Fig.1: (a) a quasi-zero and a 1μm long QWs with edge_to_edge spacing D=1μm, (b) two 0.25μm long and a 2μm long QWs with spacing D=0.5μm and D=1.0μm. (c) four metal gates to form a two QWs coupled by a ~0.8 long QW. (previous design) (d) six metal gates to form four QWs coupled by a longer QW (current design). Isolating from an insulating layer (PMMA), a top gate is also fabricated on top of the quantum wires to modify the electron densities in the quantum wires and the two dimensional electron gas as well.

Measurements were performed in a pumped ^{3}He cryostat with base temperatures of 0.27K. Differential conductance measurement was carried out using standard four terminal ac lock-in techniques at 17 Hz with a small excitation voltage of 5μV.

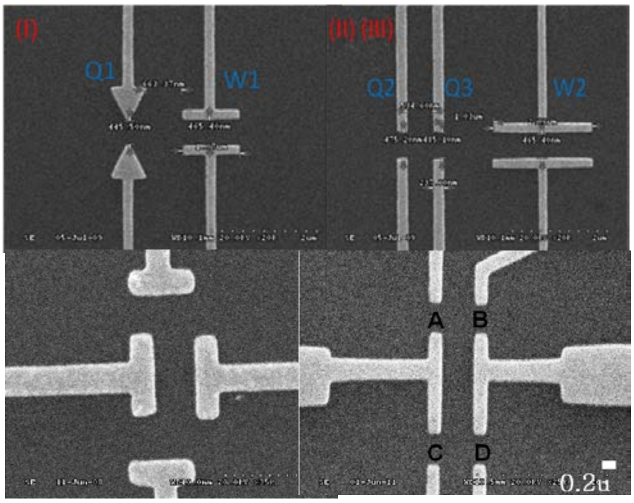

Fig 1. SEM images of two metal gate configurations. (a) A quasi-zero and a 1μm long QWs. (b) Three QWs of two 0.25μm and one 2μm long QWs. (c) Four metal gates to form a two QWs coupled by a ~0.8 long QW. (d) Six metal gates to form four QWs coupled by a longer QW.[10]

四、實驗結果

When a negative voltage is applied on a pair of split gates, the potential depletes 2DEG to form the 1D channel and the conductance is typically quantized as the integer multiples of $2e^2/h$ due to the transmission of 1D sub-bands. In the other hand, by biasing top gate V_{tp}, the carrier concentration can be effectively changed. As shown in top panel of Fig.1, the quantized conductance curve can be obtained by sweeping V_{tp} instead of V_{sg}. The leftmost curve represents the zero bias conductance. The carrier concentration n_{1D} decreases smoothly with decreasing V_{tp}. Fermi energy is determined by n_{1D} following that $E_F = \pi^2 \hbar^2 n_{1D}^2 / 8m^*$ for a 1D QW.

When a dc voltage is applied across a QW, the energy of the source relative to drain opens up and IV characteristic becomes non-linear and a new plateau at the half integer multiples of $2e^2/h$ would appear. These can be described in terms of a model proposed by Glazman incorporating the effect of bias on the chemical potentials on either side of the 1D channel in the adiabatic regime.[11] As shown in Fig.1, at large enough V_{sd}, the conductance plateau occurs at $(n+1/2)\ 2e^2/h$ due to the sub-band number difference below the chemical potentials at two ends of QW. The bottom panel of Fig.1 exhibits the grey-scale plot of dG/dV_{tp} as a function of V_{tp} and V_{sd}. The large black areas are plateaus that $dG/dV_{tp}=0$. The source drain bias at which two bands intercept is about the energy level spacing of closest nearby sub-bands. Our data conclude that $\Delta E_{12}=2.33mV$, $\Delta E_{23}=2.13mV$, $\Delta E_{34}=2.10mV$, and $\Delta E_{45}=1.99mV$, respectively.

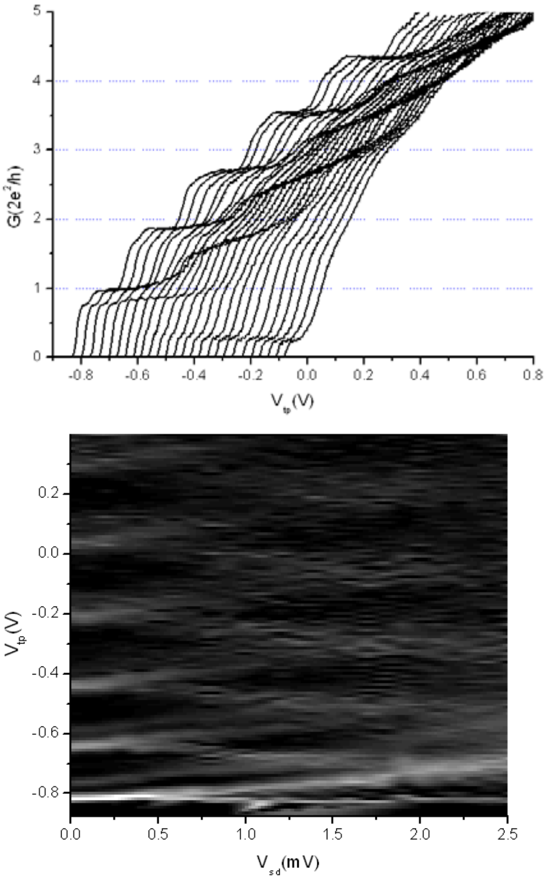

Fig. 2 (Top) Conductance G versus the top gate voltage V_{tp} against the source drain voltage for a 2μm long QW (W2) at T=300mK. V_{sd} is from 0 to 2.5 mV in 0.1 mV steps. Curves are horizontally offset for clarity. (Bottom) Grey-scale diagram of dG/dV_{tp} as a function of V_{tp} and V_{sd}. Dark line represents conductance plateau while white line correspond to the sharp conductance change.[10]

Since the top gate voltage V_{tp} indeed influences the carrier concentration of our QWs and 2DEG, the transport properties are expected to change due to the carrier concentration dependent spin-orbit interaction. In the top panel of fig.3, we plot the conductance of a narrow QW as a function of V_{R-B} ($V_R = V_B = V_{R-B}$) while gate L and A have no function in device C. G_{12} shows several plateaus. When a gate voltage V_A is applied in addition to V_{R-B}, a wider QW is formed next to the narrow QPC. In contrast to devices A and B, the 2DEG separating both QWs is absent and the two QWs are coupled via another QW directly. In the quantum regime, G_{12} should be sensitive to the nearby environment.

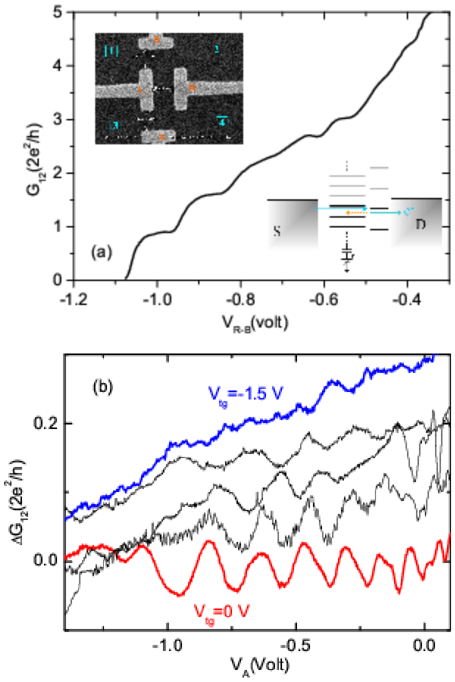

Fig. 3 (Top) Zero bias conductance of a single QW confined by gates B and R of Device C as a function of gate voltage V_{B-R}. Lower inset: illustration of energy states when two QWs coexist. (Bottom) The conductance variation measured by lead 1 and 2 as a function of V_A for various V_{tp} while two QWs are next to each other. The imposed V_{B-R} is for G_{12} ~2.67 $(2e^2/h)$ when V_A is not functioning. V_{tp} = 0, –0.5, –0.8, –1.2, and –1.5 V, respectively. Curves are vertically offset for clarity.[10]

Keeping V_{R-B} a constant value, the conductance G_{12} oscillates as a function of V_A. The bottom panel of Fig.3 demonstrates the conductance variation $\Delta G_{12} = G_{12} - \overline{G_{12}}$ against V_{tp} while V_{R-B} is set to keep the conductance of the narrow QW at G_{12}~ $2.7(2e^2/h)$. For V_{tp}=0, ΔG_{12} has about seven conductance oscillations of ~ $0.067(2e^2/h)$ in amplitude. With reducing the density by decreasing V_{tp} from 0 to -1.5 V, the oscillations are getting weaker and smoother. For V_{tp}=–1.5 V, oscillations almost disappear except a slight peak at V_A ~ –0.35 V. Since quantum interference requires the coherence of electrons, the data conclude that the coherence is strongly destroyed in low carrier concentration (large negative V_{tp}).

Various types of impurity potential have been employed for studying resonant electric transport in QWs. It was proposed that there are self-consistently realized bound states in strongly pinched-off QWs.[12,13] The bound states may give rise to a robust confinement of single spins. Earlier work of Bird group suggest that a resonant conductance of detector QW appears due to the interaction between spin polarized bound state and a quasi-one dimensional QW.[12,14] A special arrangement of six metal gates is chosen as shown in Fig.1(d) that there are numerous configurations with different distances between bound state and the quasi-one dimensional narrow QW.[10]

As sketched in the inset of Fig.4, the pair of blue gates which are biased at a fixed voltage serve as a detector QW of a constant channel width. Conductance of this detector QW is measured by sweeping bias on the red metal gate. Three gates on left are floated with no function on the device. Because the middle blue gate is already negatively biased, the sweeping QW becomes narrower by applying more negatively Vs on the red one. A spin polarized bound state is expected to form as the sweeping QW close to pinch off. In fig.4 the red curve (right axis label) represents the conductance of the sweeping QW against V_s. Although the plateaus are smeared out, the confinement of QW is present and pinch off of the sweeping QW occurs at Vs~ –0.15V. Six black lines (left axis label) are conductance traces of the detector QW G_D against V_s for different widths. From top down the detector QW is set to narrower. Even taking a closer look at each line, The detector QW conductance stays almost constant, $\sim G_D(1\pm 0.4\%)$ no matter the channel width. In addition, no resonant conductance peak of the detector NC appears when nearby bound state is created for different channel widths.

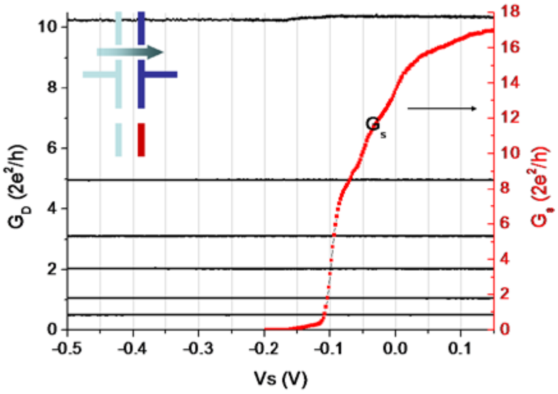

Fig.4 Conductances G_s (red trace-right axis) and G_D (black traces-left axis) versus sweeping QW gate voltage V_s for the device sketched in the inset. The measurement details are indicated in the text.[10]

Moreover, there is no significant change of the QW conductance in the presence of nearby bound state, insensitive to the channel width and the distance between the bound state and the narrow QW. It is quite surprising for the disagreement with the observation of Bird's group.[12,14] This indeed requires further investigation.

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四、結論

In summary, when the two QWs are coupled directly to each other, the conductance oscillations reveal the interference between the incident and backscattered electrons. The quantum interference is suppressed by either decreasing the electron density or increasing the bias voltage V_{sd}. We suggest that low carrier density may enhances electron-electron interaction resulting in short coherence length which is detrimental to ballistic transport. On the other hand, there is no evidence that spin polarization play important role in this work.

ACKNOWLEDGEMENTS

We acknowledge the high mobility samples from V. Umansky at Wiezmann institute.

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國科會補助計畫衍生研發成果推廣資料表

日期:2013/03/17

國科會補助計畫	計畫名稱: 閘極局域之介觀系統的自旋相關物理性質探討
	計畫主持人: 許世英
	計畫編號: 100-2112-M-009-008- 學門領域: 半導體物理－實驗

無研發成果推廣資料

100 年度專題研究計畫研究成果彙整表

計畫主持人：許世英	**計畫編號：**100-2112-M-009-008-
計畫名稱：閘極局域之介觀系統的自旋相關物理性質探討	

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	1	0	100%	篇	Journal of Superconductivity and Novel Magnetism
		研究報告/技術報告	0	0	100%		
		研討會論文	1	0	100%		2012 年第三屆國際超導與磁學會議(ICSM2012) oral presentation
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
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		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	無

🟥	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標
□未達成目標（請說明，以 100 字為限）
　　□實驗失敗
　　□因故實驗中斷
　　□其他原因
說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：□已發表 □未發表之文稿 ■撰寫中 □無
專利：□已獲得 □申請中 ■無
技轉：□已技轉 □洽談中 ■無
其他：（以 100 字為限）

由於原本申請為多年期計畫, 但僅獲得一年合約且經費大幅刪減, 不僅原先該添置作磁電聚焦的設備未購置, 且在經費不足下, 從事低溫實驗的次數限縮且也無法使用超導磁鐵作高磁場下實驗, 只能維持樣品的微影製作的好品質, 得到各項初步結果, 待下次機會.

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

由於目前以量子元件發展為量子計算元件有其潛力，同時也是資料儲存工具之一，角色越趨重要，隨著製成技術的不斷進步，元件的尺度不斷地遞減，奈米尺度的結構元件的製作已不再是問題，其在科技應用上扮演著重要角色，然其物理性質仍有許多為揭露的機制，因此有必要及時且深入探討。奈米尺度的量子結構的波函數量子干涉效應在電性傳輸機制扮演重要角色，是現在一熱門的研究題材，從能源、效益與經濟的角度上，奈米尺度的結構元件一定是未來科技應用的主角。

就參與計畫的學生，即使未繼續物理學術研究，由於光微影與電子束微影技術的熟練，在目前科技產業仍是非常仰賴的製成工程師，他(她)們將是台灣未來重要人才。