Transport Characteristics in GaAs/AlGaAs Quantum Structures

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論文内容要旨

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学位論文の 題　　　目	**Transport Characteristics in GaAs/AlGaAs Quantum Structures** **(GaAs/AlGaAs 量子構造における伝導特性)**		

The role of semiconductor becomes more important. Especially, quantum computing attracts more interest. The semiconductor spin qubit is one of the candidate to achieve the quantum computing. This is because the spin qubit has longer coherent time, fast rotations and established fabrication techniques of semiconductor. Therefore, spin qubit is suitable for an element in quantum processor and quantum memory.

GaAs has very high-quality electron system in III-V semiconductors, and it also can form hole system. Moreover, the heterostructure of GaAs/AlGaAs achieves high-mobility 2 dimensional (2D) system by utilizing MBE method and so on. Carrier density and potential shape can be controlled by metal Schottky gates in the 2D system, then we can form nano-structure device. One of the simplest device is quantum point contact (QPC), which forms quasi 1D system. The QPC is utilized not only for fundamental physics research but also for application such as charge detector of quantum dot (QD). The QD has a more complicated confinement structure than QPC, and it forms 0 dimensional system. These nano-structure devices are expected for the next generation's element of spin qubit.

At very low temperature (less than 4 K), the conductance of QPC as a function of gate voltage shows step-like feature, which is so-called quantized conductance. The conductance characteristics strongly depend on potential shape of the confinement. Landauer-Büttiker (LB) model [1] is well known to reproduce the effective potential shape. Therefore, one can evaluate the potential shape from comparison between LB model and experimentally obtained conductance curve. Recently, there was a surprising report where random potential induced by impurity dominate the potential shape, thus affected effective length (L_{eff}) of the channel even in high mobility QPC devices [2]. One possibility to solve such problem is triple-gated structure. It can show clearer quantization with utilizing additional gate, so-called center gate, even for rather lower mobility device [3]. Therefore, I estimated potential shape of triple-gated QPC and L_{eff}.

At first, I fabricated devices with triple-gated structure QPC. My devices were fabricated on GaAs/AlGaAs heterostructure with a 20-nm-wide modulation-doped quantum well. The center of the quantum well is located 175 nm from the surface. The low temperature electron mobility of the starting wafer is $\mu = 84.5\ \mathrm{m^2/Vs}$ at $n = 1.0 \times 10^{15}\ \mathrm{m^{-2}}$. Although the mobility is not as high as wafer used in the reference [2], it is much higher than that used in reference [3] and enough to see clear qauntized characteristics in a wide range of gate bias parameters as discussed later. In addition, I fabricated two lengths of split gate width, 400 and 800 nm, which is fabricated length (L_{fab}) to compare the differences with effective potential shape.

Devices I fabricated work well and quantized plateaus appeared even higher than 10th. Furthermore, the conductance curves shift almost equally depending on the center gate voltage (V_{cg}). It is noteworthy that the shift of pinch-off split gate voltage (V_{sg}) values with V_{cg} step is not equal in some parts of the results in 400 nm device. This is because reflecting electron capture or escape from the defect (probably surface defect) nearby QPC.

There are two components to fit based on LB model; separation between plateaus and slope of conductance curvature. The separation between plateaus can be estimated from transconductance plots, which is the differential conductance with respect to the V_{sg}, because the separation energy is determined by the channel confinement. A relation between energy and gate voltage can be estimated from these comparisons. I confirmed the energy separation as a function of V_{cg} shows linear dependence. Moreover, the dependences show that energy separation became smaller at higher quantized plateaus. This is because the confinement of split gates changed at the higher quantized plateau, which is corresponding to the smaller value of V_{sg}. And then, the potential shape of channel width became wider, which results in the smaller energy separation.

I simulated LB model by using estimated energy separation. I utilized two method to fit the simulated results to the experimental results. One is the height of peak estimated from differential conductance curve. The height of simulated results is corresponding to the slope of conductance curvature. However, the experimentally obtained maximum is not always appear at the half integer of quantized conductance. Therefore, I also fitted the results by utilizing full width of half maximum method. Actually, these two methods showed almost the same results.

The slope of conductance is determined by the effective channel length, therefore I calculated L_{eff} as a function of V_{cg}. For the 400 nm device, L_{eff} was almost independent as a function of V_{cg}. However for the 800 nm device, estimated L_{eff} obviously shows systematic change with increasing V_{cg}. The L_{eff} value finally reaches to higher than 30 nm, clearly higher than reported results without center gate structure [2] in spite of the slightly lower mobility of our device. This result suggests effect of the center gate which weaken the impurity-induced potential.

The reason why L_{eff} is almost constant for V_{cg} for the shorter device can be explained by the fact that fabricated length is 400 nm and the fabricated channel width is 300 + 200 + 300 = 800 nm. It means the confinement near the pinch-off is close to the "point" and the L_{eff} at the saddle point becomes small in dependent of V_{cg}. In the case of 800 nm device, the L_{fab} is equal to the fabricated channel width, therefore it is possible that the results really observed the effect of center gate for the potential shape.

On the other hand, double quantum dot (DQD) with hole system also has interest in as a spin qubit device. Hole system has some advantages compared with electron system. For example, hole system of GaAs/AlGaAs has large spin-orbit interaction, and results in spin-flip tunneling [4]. It is possible to control spin rotation by radio frequency of electric field with spin-orbit interaction, which process is so-called electric dipole spin resonance (EDSR). The observation of EDSR is reported in some hole nanowire devices [5, 6], however it is not observed in hole system of a lateral

GaAs/AlGaAs DQD device. The gated DQD device has more controllability to apply for spin qubit device. Here we report single hole EDSR measurements over the 10-50 GHz range taking advantage of the strong spin-orbit coupling.

To manipulate hole spins, it is required to reach to single hole regime identified at first. I controlled 7 gates to confine hole dot. 2 of them can control the barrier between DQD and leads, other 2 gates modify inter potential of DQD, 2 gates placed at the center of DQD can changed the coupling between dots, and 1 of them is charge detector. To identify the single hole regime, I changed the barrier between DQD and leads and checked it by charge detection. I confirmed single hole regime, and its spin-conserving tunneling was about 60 μeV. After this identification, I controlled inter potential of DQD.

When we apply the high bias gradient to the leads, the transport diagram shows triangle structure. Along the lower edge of triangle structure, the single-hole ground spin state is below the Fermi level of both leads, and the current is energy blocked. In a case of a small micro-wave voltage is applied to a gate, the hole spin is excited from the ground spin state (GS) to the 1st excited spin state (ES1), which allows the hole to tunnel out to one lead. These reasons result in the additional peak current confirmed as an EDSR signal at the point below triangle structure. The EDSR signal as functions of magnetic field and micro-wave frequency also obviously shows linear dependence. I estimated g-factor from this line, and the result is 1.25 which is reasonable to compare with the number of bulk g-factor 1.44.

However, it is strange because the "simple" EDSR signal should appear not at the point but along the edge of triangle. If the signal appeared depending on only the Zeeman splitting, the signal would be observed along the edge of triangle everywhere. I measured magnetic field dependence to clarify that. The EDSR signal as a function of magnetic field and dot detuning at a constant micro-wave frequency continuously changes. Especially, the value of effective g-factor changes almost 30 % lower.

This is because of the transition from "Spin-like" to "Charge-like" with increasing magnetic field. At lower magnetic field regime, the spin rotation changes between GS (spin-down) and ES1 (spin-up) because of spin-orbit interaction. In a constant micro-wave frequency, the EDSR signal appears in any detuning, which is a "simple" EDSR regime. Therefore, the effective g-factor is constant. At intermediate magnetic field regime, ES1 and ES2 levels interact each other, then the EDSR signal does not appear anywhere. Especially near zero detuning region, the EDSR signal depends on not only magnetic field but also detuning. At higher magnetic field regime, the spin rotation doesn't change between GS and ES1. This is because spin-up state shifts more than another spin-down state by large Zeeman splitting. Therefore, the EDSR signal does not depend on magnetic field. This controllability of "Spin-like" and "Charge-like" states by a gate can be applied for spin qubit device.

References

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論 文 目 次

別　紙

論文審査の結果の要旨

GaAs（砒化ガリウム）をベースにした高品質メゾスコピック構造は、低次元構造における輸送特性を研究する格好の材料であり、特に最も単純なメゾスコピック構造である量子ポイントコンタクト（QPC）はその中核をなしている。しかし、QPC における量子化コンダクタンスが発見されて30 年以上経つが、まだ未解明な部分も多い。また、QPC をチャージセンサとして用いる二重量子ドット構造は、半導体スピン量子ビットの担い手であり、特に正孔を用いた量子ビットは緩和時間が長く、半導体量子ビットの有力な候補となっている。このような状況の中で、高橋基氏提出の本学位論文は、QPC の中でも欠陥などによる不均一ポテンシャルの影響を受けにくいと考えられるセンターゲート付きトリプルゲート QPC について、擬一次元チャンネル内のポテンシャル形状を明かにした。また、所属するスピントロニクス国際共同大学院の海外インターンシップで滞在したカナダ NRC で、正孔二重量子ドットの EDSR（Electric Dipole Spin Resonance）測定に挑戦し、スピン軌道相互作用が大きい正孔に特徴的な振る舞いを発見した。これら二つの研究について、具体的に得られた成果を以下にまとめる。

第一の研究では高品質なトリプルゲート QPC の作製に成功し、電極の長さで決まるチャンネル長が 400nm と 800nm のデバイスについて、センターゲートバイアスに依存した明瞭な量子化コンダクタンスを観測した。さらに、得られた特性を Landauer-Buttiker（ランダウアー・ブティカー）モデルに当てはめることで、実効的なチャネル長を導出した。センターゲートがない通常の QPC では、電極で決まるチャネル長に関係なく実効的なチャネル長は一定で、欠陥によるランダムポテンシャルが QPC の特性を支配していることが 2016 年に主張されていた。これに対し、本論文ではセンターゲートバイアスに正のバイアスを加えたときに、実効チャネル長が徐々に増加することを確認し、トリプルゲート構造が欠陥によるランダムポテンシャルを抑制し、良好な QPC を作製するのに大変有効であることが確認された。QPC の実効チャネル長は、量子化されたコンダクタンス間の遷移の急峻さを決定し、チャージセンサとしての性能を支配するため、得られた知見は QPC の物理としても、また応用としても重要なものである。

第二の研究では、二重量子ドット構造での正孔の EDSR に成功した。まず、二重量子ドットのそれぞれのドットに正孔を正確に 1 個ずつ制御して入れることができることを確認し、スピン反転により電気伝導が促進される状況を実現した。通常の ESR では交流磁場を印加してスピン反転を実現するが、正孔ではスピン軌道相互作用が強いため交流電界をゲートの一つに加えることで、スピン反転を起こす EDSR が可能になる。本研究ではこの EDSR 信号を明確に測定するとともに、磁場を変化させた時に、スピンギャップとチャージギャップが等しくなる領域で準位の反交差が生じ、これに伴い EDSR の信号から評価されるｇ因子が大きく変調できることを確認した。この実験結果は高橋君が丁寧な実験の中で NRC の研究者の予想を超えて測定に成功したもので、正孔二重量子ドット構造をスピン量子ビットに応用する際に、量子ビットごとに制御周波数を調整できることを示しており、大きなインパクトのある成果である。

本論文は５つの章から成る。第一章では序論として本研究の目的などを紹介し、第二章では本研究で用いたトリプルゲート QPC の作製について述べられている。第三章では本研究によって得られたトリプルゲート QPC の伝導特性から実効的なチャネル長の導出が行われ、トリプルゲート QPC の有用性が確認されている。第四章では、正孔二重量子ドット構造における EDSR 実験と変調可能なｇ因子の特性が述べられている。第５章では各章で得られた結果についてまとめている。

以上の内容は、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、高橋基氏提出の博士論文は，博士（理学）の学位論文として合格と認める。