Novel blockade due to spin-filtering with spin-orbit interaction

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Abstract. We report experimental finding of current blockade in a quantum dot (QD), which effect originates from spin-filtering in a quantum point contact (QPC) with spin-orbit interaction (SOI). Our QPCs made of In$_{0.1}$Ga$_{0.9}$As showed clear $G_q/2$ plateaus ($G_q \equiv 2e^2/h$), which suggest the spin-filtering. The effect has been further confirmed in the conduction of a QD defined by two such QPCs. The Kondo effect has been utilized for the clarification of the spin states in the QD and an ordinal Coulomb valley with spin 1/2 has been chosen for the stage to test the filtering. One of the bounding Coulomb peaks disappears with the application of a finite source-drain voltage $V_{sd}$ while the other grows in height. The sign reversal of $V_{sd}$ transposes the heights of the two peaks. Further increase in $|V_{sd}|$ recovers the dual peak configuration. Every aspect of the above characteristics behavior is explained under the hypothesis of spin-filtering in the QPC at the plateau of $G_q/2$. From the peak height ratio, the lower bound of the filtering efficiency is estimated to be above 80%.

An important step for the semiconductor spintronics is the creation of spin-polarized current in non-magnetic materials. A candidate of such mechanism is the spin-orbit interactions (SOIs), which, in many cases, works as effective magnetic fields on electron spins. However because plain SOIs bring about no energy splitting in average over the $k$-space, some additional symmetry breaking is required for spin polarization. Numbers of schemes have been proposed for the spin current creation with SOIs though no sound experimental confirmation has been reported. On the other hand, a clear plateau at half conductance quantum, which suggests possible spin-polarization, has been reported in an InAs quantum point contact (QPC). [1] The result suggests that spin current can be created with this kind of simple structure with an SOI through it should be confirmed that the electron spins are really polarized.

The purpose of this paper is to report the finding of a new type current blockade effect in a QD with SOI, through which the spin-filtering effect in QPCs is confirmed.

We adopt a pseudomorphic In$_{0.1}$Ga$_{0.9}$As quantum well placed next to a GaAs/AlGaAs interface, as a material to constitute QPCs and QDs. The layered structure shown in Fig.1(a) was grown with molecular beam epitaxy (MBE) on a (001) GaAs substrate. The 2DES carrier concentration is $1.2 \times 10^{12}$/cm$^2$, and the Hall mobility is $8.2 \times 10^4$cm$^2$/Vs at 4.2K. QPCs and QDs defined by Ti/Au split gate were fabricated with electron-beam lithography. The specimens were cooled down to 50mK in a dilution fridge.

Figure 1(b) is an electron beam micrograph of a QPC. The conductance of the QPC as a function of the gate voltage. A clear plateau at half conductance quantum ($0.5G_q$, $G_q \equiv 2e^2/h$) is observed. The result is similar to that in ref.[1], suggesting the spin-filtering in the QPC.
We hence proceed to the transport in a QD. As shown in Fig.2(a), the QD is connected to the electrodes through two QPCs (QPC1, QPC2). As depicted in Fig.2(b), QPC1 also shows the 0.5 plateau, which is, however, significantly distorted by surrounding gate structures. In forming a QD, QPC1 was set on 0.5 plateau while QPC2 was on 1.0 plateau. Therefore if we apply the spin-filtering hypothesis, the transport through QPC1 is spin-selective while that though QPC2 is not.

Here we utilize the Kondo effect to clarify the spin states in the dot. [4] The Kondo effect in QDs is characterized by anomalous enhancement of conductance in Coulomb valleys with decreasing temperature below the Kondo temperature $T_K$ and also by zero-bias conductance peaks in the I-V characteristics. We looked for such a Coulomb valley among few tens of Coulomb oscillation periods.

Four Coulomb peaks are observed in Fig.3(a) and the Kondo effect has been observed in the valley indicated as C. The much higher conductances in peaks $p_c$, $p_d$ and C mean that $T_K$ in C is comparatively higher. In the I-V characteristics shown in Fig.3(b) double peak structure around zero-bias is observed. The peak splitting, which veils the center zero-bias sharp peak, is attributed to the spin-selection at QPC1. The conductance of this shoulders increases with decreasing temperature (the inset of Fig.3(b)). If we fit well known temperature dependence of conductance to obtain reasonable $T_K$ of 995mK. The above result leads to the fact that the QD has spin 1/2 in valleys C and A, while a closed shell structure is realized in valley B.
As shown in Fig.3(c), at a small positive bias ($V_{sd}=100\mu V$) where broadening and height growing of the coulomb peaks are expected, peak $p_a$ vanishes while $p_b$ shows ordinary growth. When the sign of $V_{sd}$ is reversed to negative, peak $p_b$ vanishes whereas $p_a$ grows. The anomalous behavior disappears and ordinary Coulomb oscillation is restored when the absolute value of $V_{sd}$ exceeds about 250$\mu V$.

Because $p_a$ and $p_b$ arise from the same orbital level, the major difference between them is the total spin in the dot. In the following we discuss that the spin-selectivity (SS) at QPC1 is the origin of the anti-symmetric blockade. For simplicity we henceforth assume that only up spin ($\uparrow$) electron can transmit through QPC1 without losing generality. The following discussion also holds if an entanglement between the direction of the electron transmission and the spin (e.g., left-$\uparrow$ and right-$\downarrow$) is assumed instead of the simple SS. Therefore we cannot go into the comparison of the present results with existing theoretical proposals for such spin-selectivity in quantum constrictions with SOI.

The explanation based on the spin-selectivity in QPC1 and the Pauli exclusion principle as summarized in Fig.4. At peak $p_b$ with a small positive bias only $\uparrow$-electrons can escape through QPC1 with $\uparrow$-spin-selectivity(SS) but $\downarrow$-electrons can be supplied through QPC2(Fig.4(b)). Hence $p_b$ survives for the positive bias. On the other hand the positive bias kills peak $p_a$ because once an $\uparrow$-electron enters the dot it cannot escape neither through $\uparrow$-SS QPC1 nor through QPC2 and blocks the successive tunnelling. When the bias is reversed, electrons should
**Figure 4.** (a) At peak $p_a$ with a positive bias, sooner or later the topmost level is occupied by a $\downarrow$-electron, which cannot go out to the source due to the spin-selectivity in QPC1, and the current is blocked. (b) At peak $p_b$ with a positive bias, the topmost level is once occupied with a singlet pair and the $\uparrow$-electron can go out to the source through QPC1. (c) At $p_a$ with a negative bias, the topmost electron can go out to the drain regardless of the spin direction and the current flows. (d) At $p_b$ with a negative bias, QPC1 can supply only $\uparrow$-electrons and sooner or later a $\downarrow$-electron goes out to the drain and successive tunneling is blocked by the Pauli exclusion principle. (e) Summarized schematic stability diagram.

come in through QPC1 and go out through QPC2. At $p_b$, the entrance of $\uparrow$-electron through QPC1 is blocked due to the Pauli exclusion principle (Fig.4(d)). The blockade does not take place for $p_a$ because $\uparrow$-electrons can escape through QPC2 (Fig.4(c)). When $eV_{sd}$ exceeds the spacing of single-electron orbital levels or the gap between up and down channels, the blockade is lifted along a line parallel to an edge of a Coulomb diamond as illustrated in Fig.4(e). This anti-symmetric blockade arises, in summary, from the spin-filtering effect in a QPC with SOI and the Pauli exclusion principle, and the deduction perfectly agrees with the observation in Fig.3. The peak height ratio in the blockade region gives the lower bound of spin-filtering efficiency in QPC1, which should be above 80% in Fig.3.

This work is supported by Grant-in-Aid for Scientific Research and Special Coordination Funds for Promoting Science and Technology.

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