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Investigation of spin state in a quantum dot by using strongly asymmetric tunnel barriers

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We investigate the spin state of a GaAs lateral quantum dot (QD) by using strongly asymmetric tunnel barriers. The saturated current depends on the current polarity, which switches the direction of the dominant tunneling transition that increases or decreases the total spin. With this technique, the spin polarization and the Coulomb interaction are investigated. We find that high spin states appearing in some magnetic field regions can be understood by considering simple Coulomb interactions.

1 Introduction Many-body effects in a semiconductor QD induce different total-spin states, which give rise to the intriguing properties in the Kondo effect [1] and the spin blockade [2]. Spin states in a few-electron QD with high circular symmetry can be deduced from the orbital effect in the magnetic field [3]. However, spin states of a lateral QD can only be investigated by limited methods, such as spin injection from the spin polarized edge states [4]. In this paper, we employ transport measurements through strongly asymmetric tunnel barriers, in which the change in the total spin during a single electron tunneling is reflected. The advantage of this method is that it is effective in the low magnetic field and even for low symmetry QDs. We find that the ratio of the saturation currents for positive and negative bias voltages goes back and forth between 2 and 2/3 in the magnetic field, indicating the alternate appearance of high spin state (S = 1) and low spin state (S = 0).

2 The ratio of saturated currents with different bias polarity The single electron tunneling is the tunneling transition between two different charge states, during which total spin, S, should increase or decrease by 1/2. When the transition decreases the total spin, the possible tunneling transitions are restricted by the spin selection rule. For instance, for the transition from S = 1/2 state to S = 0 state, only a spin-up (spin-down) electron can enter the dot and make a spin pair if the initial S = 1/2 state had an unpaired spin-down (spin-up) electron. However, either spin-up or spin-down electron can always enter the dot, when the transition increases the total spin. The difference can be clearly observable if the dot is connected to strongly asymmetric tunneling barriers. In this case, the current is approximately limited by the smaller tunneling rate of the thicker barrier. By changing the current polarity, the direction of the current-limiting tunneling transition can be reversed between increasing and decreasing the total spin. By assuming that only one spin-degenerated energy state for each of the two charge states contributes to the current, the ratio of the tunneling currents for different directions gives the ratio of the spin degeneracy for two charge states [5].

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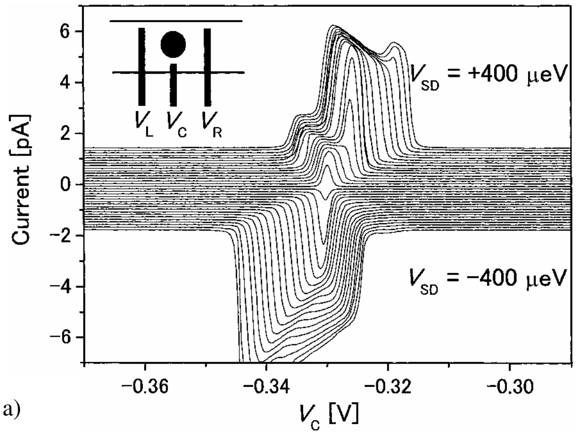
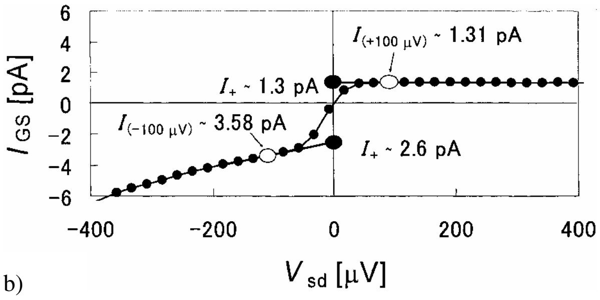


a)

Fig. 1 a) Current spectra as a function of center gate voltage (V_C) for the source-drain bias voltage from –400 to +400 μV. A magnetic field of 0.65 T was applied perpendicular to the sample plane. Each spectrum is shifted for clarity. The inset shows a schematic top view of the quantum dot device. b) Source-drain bias voltage dependence of the current I_{GS} corresponding to the transition between the ground states relevant to the tunneling transition.



b)

We studied a lateral QD fabricated in an AlGaAs/GaAs heterestructure (see the inset of Fig. 1a). The tunneling rate of the left and right barriers, Γ_L and Γ_R, are made significantly different, $\Gamma_L \sim 10^7$ s^{-1} $\ll \Gamma_R \sim 10^9$ s^{-1}. We define the saturation currents, I_+ and I_-, as the flows of electrons which are accompanied with the tunneling transition for increasing and decreasing the number of electrons in the QD, respectively. Therefore, $I_+/I_- = (2S_{N+1} + 1)/(2S_N + 1)$ at the tunneling transition between the total spin S_N state with N electrons and S_{N+1} state with $(N + 1)$ electrons [5]. The idea was first employed for the experimental investigation of spin states in a short carbon nanotube QD [6] and has been elaborated theoretically [5].

The center gate was used to change the electrostatic potential of the QD. The transport measurements of the QD were done by applying source-drain bias voltage V_{SD} between the left and right leads. For $V_{SD} > 0$, electrons flow from the left reservoir to the right reservoir. A magnetic field, B, was applied perpendicular to the sample plane. The Zeeman energy was negligibly small in the interesting magnetic field regime. The charging energy of the QD is about 1.5 meV and the energy level spacing is about 150 to 300 μeV.

We carefully measured I_+ and I_- in the condition where no excited states are involved in the transport. However, a slight dependence of saturation currents (I_+, I_-) on V_{SD} can bee seen in Fig. 1b. Therefore, we estimated them by the following two ways. In one method, the current values are measured at ±100 μV, where the current is just saturated. In the other method, the values are given by extrapolating the current to the zero bias from the positive and negative sides.

3 Magnetic field dependence of the spin polarization We employed the saturation current measurement in a magnetic field, where a few Landau levels (LLs) are developing. We find the spin polarization in some magnetic field regions.

We performed transport measurements at large bias (±1 mV) by changing B up to 1.5 T. The evolution of the addition spectrum with B reflects the formation of LLs in the QD [7]. States in the first LL fall in energy with increasing B while those in the second LL rise. According to the current spectra over more than six Coulomb oscillations, the positions of current peaks with respect to V_C mostly shift in pair with B, implying that each quantized state is two-fold spin degenerate. The number of electrons in each sate whether even or odd can be deduced. There are some minor differences between these pairs, which probably come from the Coulomb interaction between the electrons. Figure 2c shows the color scale

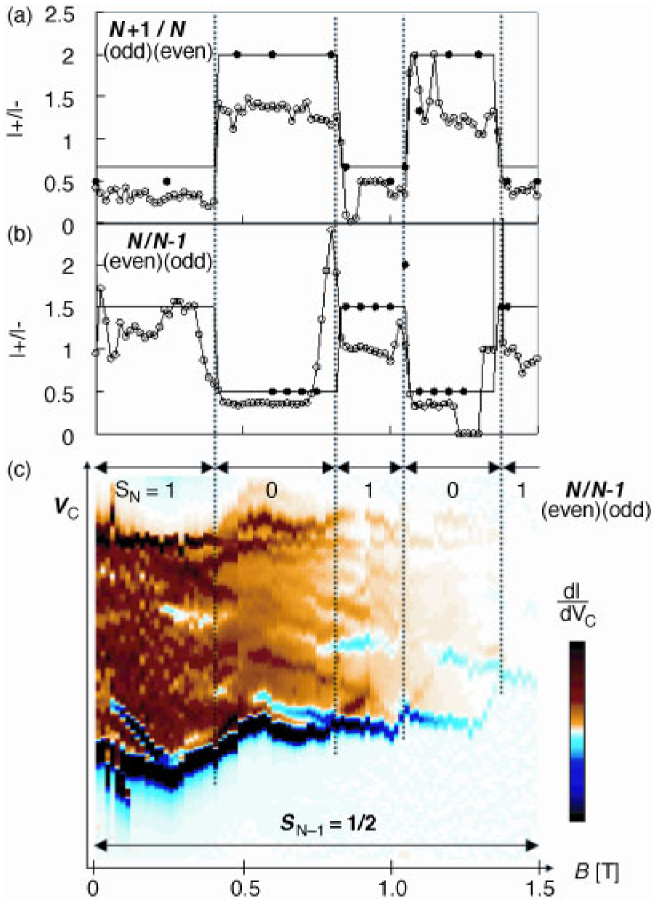


Fig. 2 Magnetic field dependence of the saturation current ratio, a) for the transition between Nth (even) state and $(N + 1)$th (odd) state, b) for the transition between $(N – 1)$th (odd) state and Nth (even) state. c) Color scale plot of dI/dV_g spectra for the transition between $(N – 1)$th (odd) state and Nth (even) state measured at $V_{SD} = –1$ mV. dI/dV_g is positive in black regions and negative in white regions.

plot of dI/dV_C spectra for the transition between $(N – 1)$th (odd) state and Nth (even) state measured at $V_{SD} = –1$ mV. The wiggling of the N-electrons ground state and some level crossings between the ground state and the excited states can be seen.

Figures 2a and b show magnetic field dependence of the ratios of the saturation currents. Figure 2a shows the transition between Nth (even) state and $(N + 1)$th (odd) state. Figure 2b shows the transition between $(N – 1)$th (odd) state and Nth (even) state. ○ is the ratio of the currents measured at $V_{SD} = \pm 100$ µV. On the other hand, ● is the ratio of the extrapolated values. $I_+/I_–$ shows step-like behavior for both of the tunneling transitions. Two ratios, $I_+/I_–$, jump in the opposite way at the same magnetic field values. For example, $I_+/I_–$ from 0.4 to 0.8 T in Fig. 2b is almost constant at ~0.5. When the excited state crosses the ground state around 0.8 T, Fig 2c, $I_+/I_–$ jumps up from ~0.5 to ~1.5. At the same magnetic field, $I_+/I_–$ in Fig. 2a jumps down from ~2 to ~0.67. In other words, the total spin of the N (even)-electron state suddenly changes around 0.8 T, while those of the $N – 1$ (odd)-electron and $N + 1$ (odd)-electron states remain the same. The same is true for the other jumps. The jumps are accompanied with the level crossings between the ground state and the excited state. Taking the even-odd behavior into account, it is deduced that the total spins of both odd-electron states (the $N – 1$ state and the $N + 1$ state) are 1/2 while the total spin of the even-electron state flips back and forth between 0 and 1. We drew the thick line in Figs. 2a and b to show their spin degeneracies. The absolute values of ● are in good agreement with the thick line.

The high-spin states ($S = 1$) for the even-electron state can be explained by a simple Coulomb interaction model [8], as shown in Fig. 3b. Suppose two different LLs intersect at a magnetic field B_0 ~ 1.0 T and two electrons fill in either level. When B is far from B_0, they occupy one of the two LLs, leading to the spin singlet state ($S = 0$). When B is close to B_0, one electron is in the one LL and the other is in the

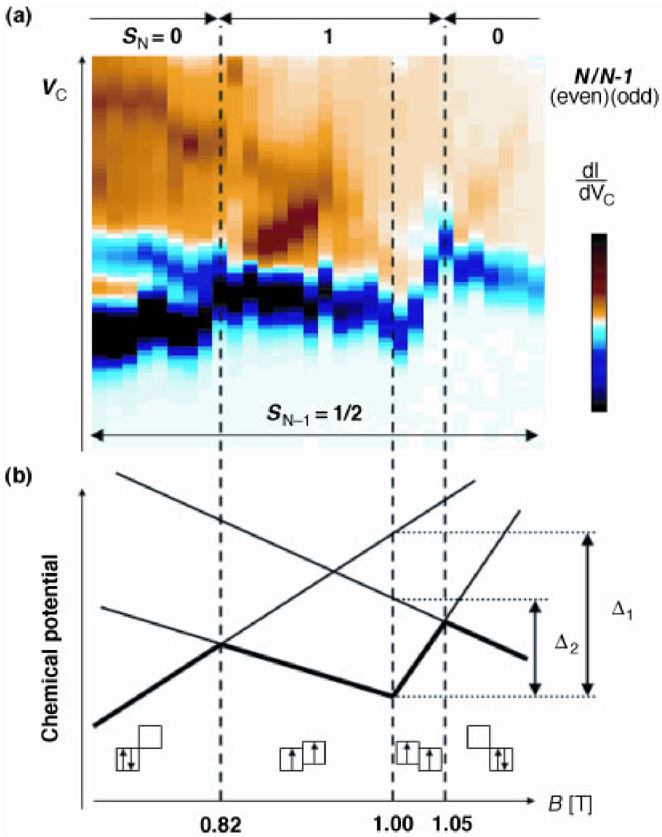


Fig. 3 a) Enlargement of Fig. 2c around one of the singlet-triplet-singlet transitions. b) Chemical potential for the *N*th electron. The thick line corresponds to the ground state energy and the thin lines correspond to the excited states.

other LL to reduce the Coulomb interaction energy between the two electrons. The function of chemical potential for the second electron has a downward cusp at B_0, which is clearly seen in Fig. 3a. The energy differences, Δ_1 and Δ_2, as defined in Ref. [8] to characterize the spin singlet-triplet-singlet transition, are estimated to be 240 and 130 μeV, respectively.

4 Conclusion We have demonstrated the experimental determination of the total spin for a lateral quantum dot by taking the ratio of the saturation currents together with the magnetic field dependence of the addition spectrum. The observed high-spin state (S = 1) for even-electron state is explained by a simple Coulomb interaction model.

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