Negative differential conductance in a quantum dot and possible application to ESR detection

K Hitachi, A Inoue, A Oiwa, M Yamamoto, M Pioro-Ladriere, Y Tokura and S Tarucha

1Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
2QPEC & Department of Applied Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
3ICORP-JST, 3-1 Wakamiya, Morinosato, Atsugi-shi, Kanagawa 243-0198, Japan
4NTT-BRL, 3-1 Wakamiya, Morinosato, Atsugi-shi, Kanagawa 243-0198, Japan
5INQIE, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

E-mail: hitachi@meso.t.u-tokyo.ac.jp

Abstract. We propose a new scheme of detecting electron spin resonance (ESR) using a single quantum dot (QD). Suppose up-spin (down-spin) electrons can only transport through the ground (excited) state with a large (small) tunnel coupling. Negative differential conductance (NDC) appears when both states enter the transport window because of dynamical population of the excited state. This NDC can be restored by ESR when the dot-lead coupling of the ground and excited states is asymmetric between the two tunnel barriers. We first experimentally characterize the conditions of NDC, which appears when edge states are formed in the leads, to derive the parameters of tunnel coupling. We finally calculate the modulation of QD current induced by ESR to lift the NDC characteristic.

1. Introduction
Detection of spin rotation is one of the key elements for constructing spin-based quantum computation, and has been demonstrated using Pauli spin blockade (P-SB) in a double quantum dot (DQD) [1-4]. This technique uses electron transport through the two-electron states in a DQD via transitions of the charge states \((N_1, N_2)\), where \(N_1\) and \(N_2\) denote the electron occupation in the left, and right dot, respectively: \((0,1) \rightarrow (1,1) \rightarrow (0,2) \rightarrow (0,1)\). This transition is allowed if the \((1,1)\) state is spin-singlet, while it is blocked by Pauli exclusion if the \((1,1)\) state is spin-triplet [5]. In the transition from \((0,1)\) to \((1,1)\), an extra electron is added to the QD to form either the singlet or the triplet, and once the triplet is formed, P-SB is immediately established. If electron spin resonance (ESR) occurs, P-SB is dynamically lifted to restore the electron transport through DQD. This scheme is skillful but very subtle, because all of the gate voltages should carefully be adjusted to prepare a DQD in the P-SB.

Here we propose an alternative but simpler technique for detecting ESR using a single QD. We utilize difference of the dot-lead tunnel coupling between the two different spin states. We consider the case when the ground state (GS) with an up-spin electron has a stronger tunnel coupling to the leads than the excited state (ES) with a down-spin electron (See figure 1(a)) for a single quantum dot (QD) coupled to the leads made in a two-dimensional electron gas (2DEG). The large difference in the
tunnel coupling between the opposite spins can occur when spin-resolved edge states are formed in the 2DEG leads. The lowest edge state with up-spin electrons is located closer to the dot than the second lowest edge state with down-spin electrons, and therefore more strongly coupled to the dot [6-9]. If GS (ES) is only available for up-spin (down-spin) electrons, the current, \( I_{\text{dot}} \), through the dot is decreased to generate negative differential conductance (NDC) when a source-drain voltage, \( V_{\text{sd}} \), is increased such that both GS and ES enter the transport window (figure 1(a)). On the other hand, positive differential conductance (PDC) appears if GS (ES) is only available for down-spin (up-spin) electrons (figure 1(b)) [8]. This NDC can be lifted by ESR, because ESR works to depopulate the ES. We actually measured the QD current when the edge states are formed in the leads, and studied the detailed condition for PDC/NDC. With knowledge extracted from this experiment, we finally calculate the ESR effect on NDC, and show that NDC can be used for ESR detection when the tunnel coupling for GS and ES is asymmetric between the two tunnel barriers.

![Figure 1](image-url)

Figure 1. Schematic diagram of electron transport through GS (ES), which only holds for up-spins (down-spins) (a) and down-spins (up-spins) (b). When the first ES enters the transport window, either PDC \((dI_{\text{dot}}/dV_{\text{p}} > 0)\) or NDC \((dI_{\text{dot}}/dV_{\text{p}} < 0)\) appears, depending on the asymmetry of the dot-lead coupling in (a), whereas PDC appears in (b). (c) SEM picture of the sample.

2. Device

Our device consists of a QD defined by L, P, R, and T gates made in a 2DEG at the n-AlGaAs/GaAs heterostructure. The other gates are not used in the present experiment (figure 1(c)). The 2DEG has a sheet carrier density of \(3 \times 10^{11} \text{ cm}^{-2}\) and a mobility of \(8 \times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}\) at 1.5K. The charging energy is 1 to 2 meV, evaluated from measurement of Coulomb diamond. We measured the conductance of the sample placed in a dilution refrigerator with the base temperature of 30 mK and electron temperature of 180 mK. A tilted magnetic field is applied with the angle of 16 degrees measured from the in-plane direction, to increase the spatial separation of the two different edge states.

3. Experiment

First we study the GS tunneling by measuring the current \( I_{\text{dot}} \) in response to a small \( V_{\text{sd}} \) as a function of \( V_{\text{p}} \) and \( B \) field. Coulomb oscillations measured for \( V_{\text{sd}} = 50 \mu\text{V} \) are shown in figure 2(a). The Coulomb peak amplitude is modulated alternately with \( B \) field. This feature can be explained by taking into account the spin-dependent tunnel coupling [6, 9], i.e. high (low) peak corresponds to transport of up-spin (down-spin) electrons through the dot. The difference of the tunnel coupling strength between the opposite spins arises from formation of edge states in the leads as explained before.

Next we measure the excitation spectrum as a function of \( V_{\text{p}} \) and \( B \) to examine the contributions from ES(s). Figure 2(b) shows the excitation spectrum measured for \( V_{\text{sd}} = 0.6 \text{ mV} \). We observe two kinds of Coulomb peaks or current stripes. The width of each current stripe is equivalent to \( eV_{\text{sd}} \), and the lower boundary guided by the solid line indicates GS, and the ES is identified by the dashed lines inside the stripe. The dashed line labeled A (B) indicates the transconductance \( dI_{\text{dot}}/dV_{\text{p}} \) to be positive in dark (negative in bright) when the first ES enters the transport window. Comparing figure 2(b) to
figure 2(a), we find that PDC (NDC) always appears when the GS transport is only allowed for downspins (up-spins) and the ES transport is only allowed for up-spins (down-spins).

For the other $V_{sd}$ polarity, we only observe PDC, as shown in figure 2(c). This indicates that not only the difference in the tunnel coupling between GS and ES but also the asymmetry of dot-lead coupling between the two tunnel barriers affects the characteristic of PDC and NDC.

To make clear the conditions for PDC and NDC, we solved the rate equation, and plot the phase diagram in figure 3(a). $p$ represents the ratio of dot-lead tunnel coupling between GS and ES as $p = \Gamma_{ES}^L/\Gamma_{GS}^L = \Gamma_{ES}^R/\Gamma_{GS}^R$, and $k$ represents the ratio of dot-lead tunnel coupling between the left and right barriers as $k = \Gamma_{ES}^L/\Gamma_{ES}^R = \Gamma_{GS}^L/\Gamma_{GS}^R$. The superscripts L, and R indicates the left, and right tunnel barriers, respectively. In this figure PDC always appears for $p > 1$, i.e. $\Gamma_{ES} > \Gamma_{GS}$. If $p < 1$, the PDC/NDC boundary strongly depends on the thickness of the two barriers. NDC appears for $k > 1$, i.e. when the left barrier is thinner than the right one, while PDC appears for $k < 1$. Note NDC is still possible for $p << 1$, even if $k < 1$. Large NDC appears for $p < 1$ and $k > 1$. This result strongly suggests that NDC only appears in the positive $V_{sd}$ in figure 2(b), because the positive (negative) bias corresponds to the case of $k > 1$ ($k < 1$).

![Figure 2](image-url)

Figure 2. $B$ field dependence of Coulomb peaks measured for (a) $V_{sd} = 50 \mu \text{V}$, (b) $V_{sd} = 0.6 \text{ mV}$, and (c) $V_{sd} = -0.6 \text{ mV}$, respectively. In (a), large (small) amplitude of Coulomb peaks specifies the up (down) spin state. In (b), PDC/NDC appears at each dashed lines, associated with the difference in the tunnel coupling between the two spin states. For the negative bias of $V_{sd}$ in (c), only PDC appears.

4. Proposal for ESR detection

Finally, we discuss a scheme of detecting ESR. If the edge states are equally formed between the two leads, time-averaged electron occupation should be the same between GS ($\rho_{GS}$) and ES ($\rho_{ES}$). Then $I_{\text{dot}}$ is not affected by ESR, because ESR just works to make $\rho_{GS} = \rho_{ES}$. $I_{\text{dot}}$ can be changed by ESR if $\rho_{GS} \neq \rho_{ES}$ in the absence of ESR. This condition is achieved when formation of the edge states is asymmetric between the two leads or when a quantum wire is used as a contact lead for filtering spins [9].

Consider that GS with an up-spin electron has a stronger tunnel coupling to the leads than ES with a down-spin electron, for instance $\Gamma_{ES}^R/\Gamma_{GS}^R = 1/10$, which is the minimum evaluated from the experiment in figure 2(b). Then, NDC appears if $k > 1$ as discussed above. We calculate the QD current in the presence or absence of ESR with the ratio of $s \equiv (\Gamma_{ES}^L/\Gamma_{GS}^L) / (\Gamma_{ES}^R/\Gamma_{GS}^R)$ as a parameter. $s \neq 1$ is the case when the formation of edge states is asymmetric between the two leads. The result is shown in figure 3(b), where $I_{\text{dot}}^{\text{ESR}}$ is the QD current in the presence of ESR whose Rabi frequency is assumed to be the half of $\Gamma_{GS}^R$, and $I_{\text{dot}}^{\theta}$ is the QD current in the absence of ESR. In this figure increasing $s$ exceeding $s=1$ makes larger the ratio of $I_{\text{dot}}^{\text{ESR}}/I_{\text{dot}}^{\theta}$, because population of ES in the dot is efficiently decreased by ESR to favour the transport through GS. This can be observed as an
increase in the QD current to lift NDC (figure 3(b) inset). In the absence of ESR, $I_{\dot{d}t}$ decreases when the first ES state enters the transport window. The decreased $I_{\dot{d}t}$ is restored by ESR as shown by the dashed line in figure 3(b). For example, we obtain $I_{\dot{d}t}^{\text{ESR}}=120\text{fA}$ and $I_{\dot{d}t}^{0}=50\text{fA}$ if $\Gamma_{\text{GS}}=5\text{MHz}$ and the Rabi frequency $= 2.5\text{MHz}$ when $s=10$ and $k=10$. The ratio of $I_{\dot{d}t}^{\text{ESR}}/I_{\dot{d}t}^{0}$ can be resolved in the actual experiment.

Figure 3. (a) Schematic diagram showing the spin-dependent tunnel coupling between GS and ES with $p > 1$ and $k > 1$, and numerical calculation of PDC/NDC as a function of $p$ and $k$. The value larger (smaller) than 100% shows PDC (NDC). (b) Numerical calculation of $I_{\dot{d}t}^{\text{ESR}}/I_{\dot{d}t}^{0}$ as a function of $k$ with $s$ as a parameter. NDC is restored by ESR as schematically shown in the inset.

In conclusion, we propose a new scheme of detecting ESR using a single QD. When QD is tunnel-coupled to the spin-resolved edge states in the leads, up-spin (down-spin) electrons can only tunnel through GS (ES) in the QD with a large (small) tunnel coupling. This causes NDC when both GS and ES enter the transport window. When the tunnel coupling of GS and ES is asymmetric between the two tunnel barriers, NDC can be restored by ESR. We experimentally characterize the conditions of NDC to derive the parameters of tunnel coupling, and calculate the performance of ESR detection.

We acknowledge financial support from the Grant-in-Aid for Science Research S (No. 40302799) and B (No. 18340081), and CREST-JST. We also thank K. Ono for helpful discussions.

References
[1] Koppens F H L, Buizert C, Tiroloij K J, Vink I T, Nowack K C, Meunier T, Kouwenhoven L P, and Vandersypen L M K 2006 Nature 442, 766.
[2] Nowack K C, Koppens F H L, Nazarov Yu V, and Vandersypen L M K 2007 Science 318, 1430.
[3] Laird E A, Barthel C, Rashba E I, Marcus C M, Hanson M P, and Gossard A C 2007 Phys. Rev. Lett. 99, 246601.
[4] Pioro-Ladriere M, Obata T, Tokura Y, Shin Y S, Kubo T, Yoshida K, Taniyama T, and Tarucha S, arXiv:0805.1083.
[5] Ono K, Austing D G, Tokura Y, and Tarucha S 2002 Science 297, 1313.
[6] Ciorga M, Sachrajda A S, Hawrylak P, Gould C, Zawadzki P, Jullian S, Feng Y, and Wasilewski Z 2000 Phys. Rev. B 61, R16315.
[7] Ciorga M, Wensauer A, Pioro-Ladriere M, Korkusinski M, Kyriakidis J, Sachrajda A S, and Hawrylak P 2002 Phys. Rev. Lett. 88, 256804.
[8] Ciorga M, Pioro-Ladriere M, Zawadzki P, Hawrylak P, and Sachrajda A S 2002 Appl. Phys. Lett. 80, 2177.
[9] Hitachi K, Yamamoto M, and Tarucha S 2006 Phys. Rev. B 74, 161301.
[10] Hitachi K, Inoue A, Oiwa A, Pioro-Ladriere M, Tokura Y, and Tarucha S, in preparation.