Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1231-1232

Coulomb diamonds and Two-electron Spin Blockade in Cotunneling Regime of Serial Vertical Triple Quantum Dot Device

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1. Introduction

Systems of two or more quantum dots (QDs) offer highly attractive spin and charge properties. For example two weakly coupled QDs in series show current rectification by Pauli spin blockade [1]. Spin blockade has played an important role in spin state initialization, and the detection and manipulation of spin for semiconductor qubits [2, 3]. It has also revealed hyperfine coupling to the host nuclei [4] potentially useful for quantum memories. Triple quantum dots (TQDs) constitute a non-trivial step towards more complex systems [4-15]. However, they are still challenging to fabricate, and experimental work has mostly focused on charge related phenomena.

Here we report the electronic properties of three vertically coupled QDs in series. This TQD system offers a well defined environment for studying new charge and spin related phenomena. We describe details of fine structure in the Coulomb diamonds which shed new light on charge and spin states of a TQD.

2. Device and Measurement details

Figure 1 shows a schematic of the device. The three QDs are embedded in a sub-micron circular mesa surrounded by a single Schottky gate. The device is fabricated from a GaAs/AlGaAs/InGaAs triple-quantum-well quadruple-barrier resonant tunneling structure. The three QDs (Dot 1, Dot 2, Dot 3) are well defined in the vertical direction because of the hetero-structure tunnel barriers, and they are confined in the lateral direction because of sidewall depletion which can be modulated by a voltage applied to the gate. We measure the DC current I flowing through Dot 1, Dot 2 and Dot 3 in series [Fig. 1 (b)] as a function of source-drain voltage V_{sd} and gate voltage V_g. Measurements are performed in a dilution refrigerator (<100mK).

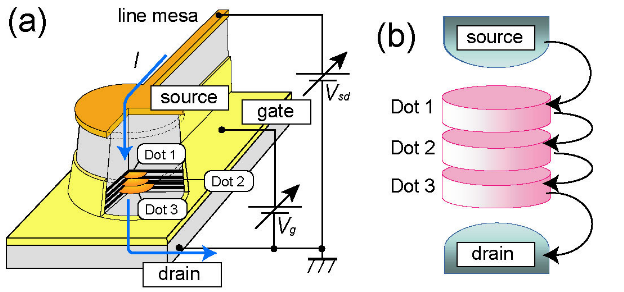

Fig. 1 (a) Schematic of vertical TQD device. The metal on top of the thin line mesa attached to the central circular mesa is connected to a large bonding pad (not shown). (b) Cartoon of current flow through TQD.

3. Results and Discussion

Figure 2(a) shows current I plotted in the V_{sd}-V_g plane. The less regular and even apparently open Coulomb diamonds near pinch-off are a signature, familiar for two weakly coupled double dots [1], of finite energy offset between adjacent dots at zero bias. By application of a simple constant interaction (CI) model for a TQD, we can reproduce in Fig. 2(b) key features in the measured current and can assign the electron numbers for Dot 1, Dot 2 and Dot 3 N_1, N_2 and N_3 respectively ($N = N_1 + N_2 + N_3$).

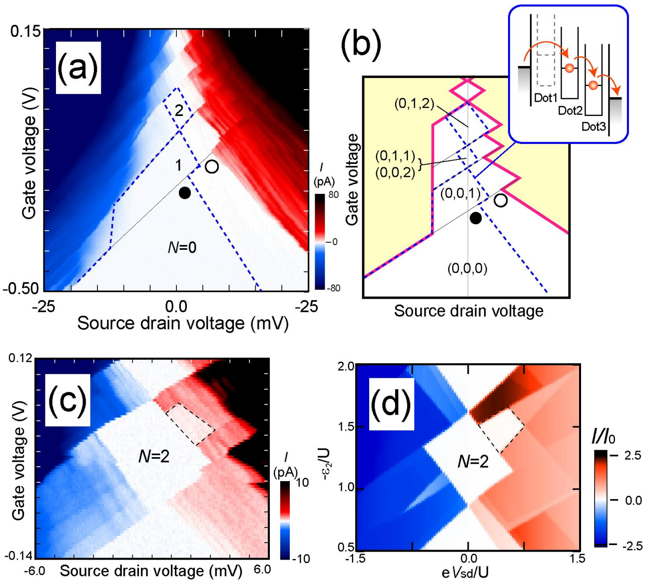

Fig. 2 (a) Measured current I in V_{sd}-V_g plane. (b) Coulomb diamond pattern, calculated by CI model, for TQD (solid line) and effective double QD (dashed line). Relative to Dot 3, Dot 1 and Dot 2 respectively are offset in energy by U and $U/2$ at zero bias where U is the onsite Coulomb energy. Inset: cartoon of effective double QD system relevant for discussion of N=2 Coulomb diamonds with co-tunneling from the source to Dot 2 via Dot 1. (c) Measured current I in the vicinity of the N=2 Coulomb diamond with co-tunneling. (d) Normalized current I calculated by master equation approach reproducing key features in (c). I_0 = $(e/\hbar)\,\Gamma_L\,\Gamma_R/(\Gamma_L + \Gamma_R)$, where Γ_L (Γ_R) is the hybridization strength between the left (right) lead and left (right) dot in the effective double dot model.

In Fig. 2(a) the current is strong when sequential charge transfer through all three dots is possible at sufficiently high V_{sd} [yellow shaded regions in Fig. 2(b)]. However, close to zero bias, weak structure is evident in the current (dashed blue lines) revealing irregular shaped Coulomb diamonds. To understand this structure we adopt an effective double QD CI model where electron transfer by co-tunneling between the source and Dot 2 via Dot 1 is treated as a tunneling process through an effective source-Dot 2 barrier, i.e., the dashed blue lines in Fig. 2(b) define the Coulomb diamonds for an effective double QD composed of Dot 2 and Dot 3. The weak structure evident in Fig. 2(a) is reproduced in Fig. 2(b).

To the immediate right of the N=2 Coulomb diamond in Fig. 2(c) current is determined by the charge transition (N_1, N_2, N_3)=(0,1,1)→(0,0,2). This is essentially the same as that instrumental in the familiar Pauli spin blockade effect for a double QD when the triplet state becomes occupied [1], and normally leads to strong current suppression everywhere inside a chevron shaped region. However, strong current suppression is only observed inside the rectangular-shaped region outlined, i.e., the appearance of the spin blockade is very different from that reported in Ref. 1. To understand this feature, we implemented a master equation approach for the effective double QD system to calculate the current as shown in Fig. 2 (d). It reproduces well the structure observed, in particular the rectangular-shaped region in Fig. 2 (c). Our model suggests asymmetry in the source-Dot 2 and Dot 3-drain barriers of the effective double QD is responsible for the observed current suppression in our TQD.

We also found that the structure evolves with in-plane magnetic field (not shown). From our model, we can understand the observed trends, as we will explain in more detail, in terms of a magnetic field induced decrease in the inter-dot coupling between Dot 2 and Dot 3.

4. Conclusions

We investigated the electronic properties of a serial vertical TQD with finite energy offset between adjacent dots. Weak fine structure in the Coulomb diamonds is observed, and can be well explained by an effective double QD picture. In this picture the appearance of the N=2 spin blockade region, including the presence of a rectangular-shaped region of strong current suppression is associated with the barrier asymmetry in effective double QD and the inter-dot coupling effect. These effects have not previously been reported in fabricated double dot devices where the dot-lead couplings are generally symmetric.

Acknowledgements

We thank R. Takahashi, H. Akimoto, T. Takakura, T. Kodera, Y. Nishikawa, A. Oguri, T. Kubo and Y. Tokura for discussions and comments. Part of this work is financially supported by JSPS Grant-in-Aid for Young Scientists B (No. 23740248), JSPS Grant-in-Aid for Scientific Research S (No. 19104007), MEXT Grant-in-Aid for Scientific Research on Innovative Areas (21102003), Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST), and IARPA grant W911NS-10-1-0330.

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