Single-electron switching effect in graphene parallel-coupled double quantum dots

M. Arai1, S. Masubuchi1,2, and T. Machida1,2,3

1Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, Japan
2Institute for Nano Quantum Information Electronics, University of Tokyo, Tokyo 153-8505, Japan
3PRESTO, Japan Science and Technology Agency, Saitama 332-0012, Japan

E-mail: msatoru@iis.u-tokyo.ac.jp

Abstract. We have fabricated parallel-coupled quantum dots on single-layer graphene. The tunnel coupling between the quantum dots can be tuned by a graphene in-plane gate. Owing to the tunnel coupling, the Coulomb blockade oscillation peaks exhibit periodic shifts as the number of electron in the non-conducting side-coupled QD is changed. The result suggests the observation of the single electron switching effect, which is a prerequisite for a single photon detection scheme using parallel-coupled quantum dots.

1. Introduction

In a parallel-coupled double quantum dot (QD) system, where a non-conducting QD is coupled to a main QD on a current path through a tunable tunnel barrier, the electrostatic energy of the main conducting QD is modulated by the charge state of the other QD[1, 2]. When the two QDs are weakly coupled, the addition of an extra electron to the side-coupled QD leads to an abrupt change in the conductance of the main QD. This phenomenon is called as the single electron switching effect. Since the main conducting QD acts as an ultra-sensitive electrometer of the non-conducting QD, the single electron switching effect has been utilized for the detection of a far-infrared single photon absorption in GaAs/AlGaAs parallel QDs[3, 4].

In order to extend the range of detection wavelength and operation temperature in parallel QD single photon detectors, graphene can be a promising material[5]. This is because (i) the large Fermi velocity of the Dirac fermion induces large energy-level spacing in a quantum dot[6], which makes high-temperature single electron transistor (SET) operation of the quantum dot easier as compared to the conventional materials with massive carriers; (ii) the dipole-allowed transition energy in a graphene QD is expected to be about ten times larger than that in a GaAs quantum dot with the same size, which implies the detection wavelength of mid-infrared range for the parallel graphene QDs[7]. To date, however, the parallel QDs on a single-layer graphene have not been realized yet, although a single QD and series double QDs have been realized on a single-layer graphene[6, 8, 9, 10, 11]. Therefore, the fabrication of parallel QD system will be a fundamental step necessary for the development of graphene parallel QD single photon detectors.

In this work, we fabricated parallel-coupled quantum dots in a single-layer graphene. The tunnel coupling between the quantum dots can be tuned by a graphene in-plane gate. In a
Figure 1. Atomic force microscopy image of the device studied in this work. The outlines of graphene regions are highlighted by white dashed lines. The size of the two quantum dots labeled QD1 and QD2 are 200×200 nm². The QD1 is connected to the source (S) and drain (D) regions through the two 100-nm-wide graphene constrictions. The QD2 is connected to QD1 through another constriction, which serves as a tunable tunnel barrier. The graphene in-plane gates labeled SG, PG1, and PG2 are defined 100 nm away from the graphene conducting channel. (b) The equivalent circuit of the parallel QD system using classical capacitance model. \( C_{\text{int}} \) is the interdot capacitance between QD1 and QD2. \( C_{12}, C_{11}, C_{22}, \) and \( C_{21} \) are the gate capacitances. \( C_S (C_D) \) is the capacitance between QD1 and source (drain) region.

weak tunnel coupling regime, the observed Coulomb blockade oscillation peaks exhibit periodic shifts as the number of electron in the non-conducting side-coupled QD is changed. The result suggests the observation of the single electron switching effect, which is a prerequisite for a single photon detection scheme using parallel-coupled quantum dots.

2. Experimental

Single-layer graphene flakes were deposited on a heavily-doped silicon substrate covered with a 290-nm-thick SiO\(_2\) layer by the mechanical exfoliation of Kish graphite. The number of graphene layers was identified by the optical microscopy and the Raman spectroscopy. The graphene flakes were patterned by electron-beam lithography (Elionix ELS-7500) and reactive ion etching using argon and oxygen. The metal electrodes Au/Ti (40 nm/4 nm) were fabricated by the electron-beam lithography and lift-off process.

Figure 1(a) shows an atomic force microscopy image of the device studied in this work. The device consists of two quantum dots labeled QD1 and QD2. The lithographic size of each QD is 200×200 nm². The main QD1 is connected to the source and drain electrodes through the 100-nm-wide constrictions. The side-coupled QD2 is connected to QD1 through another constriction. In the constrictions, lateral confinement of charge carriers induces transport gap [12], hence the constrictions function as tunable tunnel barriers. The graphene in-plane gates labeled PG1 and PG2 are used to change the electrostatic potential of each QD by applying gate bias voltages \( V_{\text{PG1}} \) and \( V_{\text{PG2}} \), respectively. The in-plane gate labeled SG is used to tune the tunnel coupling between QD1 and QD2. The measurements were performed in a dilution refrigerator at \( T = 100 \) mK. The back-gate bias voltage of \( V_{BG} = +3.5 \) V was applied to adjust the Fermi level of the graphene flake to the charge neutrality point. The current through QD1 is recorded by using the conventional low-frequency (18 Hz) lock-in technique with a small excitation voltage of \( V_{\text{ac}} = 10 \mu\text{V} \).
Figure 2. Charging diagram for the side-coupled quantum dot system. \(N_1\) and \(N_2\) indicate the electron numbers in QD1 and QD2, respectively. Thick solid (thin solid) lines correspond to the boundaries associated with the changes of the electron number in QD1 (QD2). Dotted boundaries indicate internal redistribution of the electrons between QD1 and QD2. Direction of the \((V_{PG1}', V_{PG2}')\) axis is shown by the black arrows.

The parallel-coupled QD system can be modeled using classical capacitance picture as illustrated in Fig. 1(b)[1, 2]. By minimizing the total electrostatic energy of the classical capacitance model, we can construct the phase diagram that yields ground states of the parallel QD system as shown in Fig. 2. Each honeycomb cell corresponds to a different charging state of the parallel-coupled QD system with independently quantized electron numbers \(N_1\) and \(N_2\) in QD1 and QD2, respectively. The shapes of the honeycomb cells are determined by the capacitance values \(C_S\), \(C_D\), \(C_{int}\), \(C_{11}\), \(C_{12}\), \(C_{21}\), and \(C_{22}\) defined in Fig. 1(b). When \(V_{PG1}\) and \(V_{PG2}\) are in a region within a honeycomb cell, the QD1 and QD2 are in a Coulomb blockade regime, hence the conductance of the parallel QD system is completely suppressed. When \(V_{PG1}\) and \(V_{PG2}\) are changed across a boundary between honeycomb cells shown by thick solid lines, the number of electrons in QD1 is changed by one and the Coulomb blockade effect of the QD1 is lifted. Due to the tunnel coupling between QD1 and QD2, the position of the resonance line changes periodically as the number of electrons in QD2 is changed. Thus, the conductance of the main QD1 can be switched by the addition of a single electron to the non-conducting QD2, i.e. the single-electron switching effect, which is a characteristic transport phenomenon observed in GaAs/AlGaAs parallel-coupled quantum dot systems[1, 2].

3. Results and discussion

Figure 3(a) shows the differential conductance of the main conducting QD1 as a function of \(V_{PG1}'\) at incremented values of \(V_{PG2}'\). The side-gate bias voltage applied to SG is \(V_{SG} = -2.65\) V, which corresponds to the case in which the two quantum dots are very weakly coupled. \(V_{PG1}'\) and \(V_{PG2}'\) are defined by \(V_{PG1}' = 0.86V_{PG1} + 0.51V_{PG2}\), \(V_{PG2}' = +0.51V_{PG1} - 0.86V_{PG2}\), which correspond to the directions indicated by the black arrows in Fig. 2. In this plot, \(V_{PG2}'\) is changed from -55 mV to +40 mV from the bottom curve to the top curve. In the scanned range of \(V_{PG1}'\) and \(V_{PG2}'\), the change in the tunnel coupling between QD1 and QD2 due to the capacitive crosstalk between PG1/PG2 and 100-nm-wide graphene constriction is negligibly small.

For \(V_{PG2}' = -55\) mV (the bottom curve), we observe periodic modulation of the differential conductance as a function of \(V_{PG1}'\). The periodic oscillation of the differential conductance is the Coulomb blockade oscillation in QD1. The observed peak corresponds to the thick solid phase boundaries between honeycomb cells in Fig. 2, across which the electron number in the main
Figure 3. (a) Differential conductance $dI/dV$ of the main conducting quantum dot as a function of $V'_{PG1}$ and $V'_{PG2}$ for (a) $V_{SG} = -2.65$ and (b) -2.35 V at $T = 100$ mK.

QD1 is changed by one.

When $V'_{PG2}$ is increased, the positions of the Coulomb blockade oscillation peaks shift discontinuously toward the larger $V'_{PG1}$ direction as the number of electron in QD2 is changed. The peak shifts occur periodically for further increasing of $V'_{PG2}$. The successive shifts of the Coulomb blockade oscillation peaks in the main conducting QD1 correspond to the pronounced periodic jumps of the resonance line in Fig. 2. The result suggests that the conductance of the main QD1 can be switched by the addition of a single electron to the non-conducting QD2, i.e. the single-electron switching effect, which is a characteristic transport phenomenon expected in parallel-coupled quantum dot systems. Here we emphasize that this is the first experimental demonstration of the single-electron switching effect in graphene-based parallel-coupled quantum dots.

Figure 3(b) shows the differential conductance of the main conducting QD1 as a function of $V'_{PG1}$ at incremented values of $V'_{PG2}$ from -55 mV (bottom) to +40 mV (top). The side-gate bias voltage is $V_{SG} = -2.35$ V, which corresponds to the case where the tunnel coupling between QD1 and QD2 is strong. We observe the Coulomb-blockade oscillation in the differential conductance as a function of $V'_{PG1}$. As we change $V'_{PG2}$, the position of conductance peaks changes continuously. The result indicates that the interdot coupling between the QDs is strong and that the observed conductance peak occurs when the total number of electron in QD1 and QD2 is changed by one. Thus, the change of the charge stability diagram suggests that the coupling between two quantum dots is modulated by the in-plane graphene side gate.

4. Summary
We have fabricated parallel-coupled quantum dots in a single-layer graphene. The tunnel coupling between the quantum dots can be tuned by a graphene in-plane gate. In a weak tunnel coupling regime, the observed Coulomb blockade oscillation peaks exhibit pronounced periodic shifts as the number of electron in the non-conducting side-coupled QD is changed, which is the first experimental observation of single-electron switching effect in graphene-based parallel-coupled quantum dots. Since a single-electron switching effect is a prerequisite for a
single photon detection scheme using parallel-coupled quantum dots, this is a fundamental step for developing graphene-based parallel QD single photon detectors.

5. Acknowledgements

The authors acknowledge S. Katsumoto and T. Otsuka for helpful discussions. This work is supported by the Grant-in-Aid from MEXT, the Special Coordination Funds for Promoting Science and Technology, and Japan Science and Technology Agency.

[1] F. Hofmann, T. Heinzel, D. A. Wharam, J. P. Kotthaus, G. Bohm, W. Klein, G. Trankle, and G. Weimann, Physical Review B 51, 13872 (1995).
[2] A. S. Adourian, C. Livermore, R. M. Westervelt, K. L. Campman, and A. C. Gossard, Superlattices and Microstructures 20, 411 (1996).
[3] O. Astafiev, S. Komiyama, and T. Kutsuwa, Applied Physics Letters 79, 1199 (2001).
[4] O. Astafiev, S. Komiyama, T. Kutsuwa, V. Antonov, Y. Kawaguchi, and K. Hirakawa, Applied Physics Letters 80, 4250 (2002).
[5] A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, Reviews of Modern Physics 81, 109 (2009).
[6] L. A. Ponomarenko, F. Schedin, M. I. Katsnelson, R. Yang, E. W. Hill, K. S. Novoselov, and A. K. Geim, Science 320, 356 (2008).
[7] H-Y. Chen, V. Apalkov, and T. Chakraborty, Physical Review Letters 98, 186803 (2007).
[8] C. Stampfer, J. Guttinger, F. Molitor, D. Graf, T. Ihn, and K. Ensslin, Applied Physics Letters 92, 012102 (2008).
[9] J. Guttinger, C. Stampfer, S. Hellmuller, F. Molitor, T. Ihn, and K. Ensslin, Applied Physics Letters 93, 212102 (2008).
[10] F. Molitor, S. Droscher, J. Guttinger, A. Jacobsen, C. Stampfer, T. Ihn, and K. Ensslin, Applied Physics Letters 94, 222107 (2009).
[11] J. Guttinger, C. Stampfer, F. Libisch, T. Frey, J. Burgdorfer, T. Ihn, and K. Ensslin, Physical Review Letters 103, 046810 (2009).
[12] M. Y. Han, B. Ozyilmaz, Y. Zhang, and P. Kim, Physical Review Letters 98, 206805 (2007).