Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.170-171

G-2-4 Multi-Charge Turnstile Operation in Random-Multidot Channel FET

Hiroya Ikeda and Michiharu Tabe

Research Institute of Electronics, Shizuoka University,
3-5-1 Johoku, Hamamatsu 432-8011, Japan
TEL&FAX: +81-53-478-1317, e-mail: ikeda@rie.shizuoka.ac.jp

1. Introduction

Two-dimensional (2D) multidot single-electron/hole-tunneling (SET/SHT) devices are expected to be applicable to new functional devices such as high-density memory and photoimaging devices [1,2]. Another new function is single-charge transfer based on turnstile operation. A simple single-electron turnstile circuit is shown in Fig. 1(a), where n is the number of electrons in the center dot [3]. Figure 1(b) is its local stability diagram. By applying an alternating voltage to the gate (U), the circuit changes alternatively between n=0 and n=1 phases, resulting in one-by-one transfer of electrons.

We have investigated the turnstile operation for equivalent circuits corresponding to our fabricated Si multidot channel field-effect transistors (FETs) by Monte Carlo simulation. Recently, we indicated, for the first time, that the one-by-one transfer of carriers can be realized by the multidot channel FET [4], as briefly mentioned in this text. In the present paper, we study a possibility of multi-charge turnstile operation in the random-multidot channel FET and it will be clearly shown that two-by-two transfer of electrons can be operated, as well as the one-by-one transfer.

2. Simulation model

Figure 2(a) is a schematic diagram of our Si multidot channel FET fabricated using silicon-on-insulator substrates. The Si dots are random in size and position, as shown in an atomic-force microscope image of Fig. 2(b), and are connected to each other via a thin Si layer. The n^+-Si substrate serves as a backgate. The FET shows SET/SHT characteristics [5-7].

Figures 3(a) and 3(b) are simplified equivalent circuits of the 2D multidot channel FET for homogeneous and random multidot systems, respectively. The dots are arranged in a 5x3 system and they are connected to each nearest dot via a tunnel junction (capacitance C and resistance R). In this study, for the random-dot system, we introduce dispersion into only gate capacitance (C_g). All dots are simultaneously biased by backgate voltage (V_g) through each C_g. The V_g consists of an offset part (V_{g0}) and an alternating part (amplitude V_{g1}), as shown in Fig. 3(c). In this model, we take accounts of the rising (falling) rate of alternating V_g and choose 100mV/ns (V_{g1}=150 mV and $\Delta\tau$=3 ns) as the rising rate. We calculated the turnstile characteristics on the circuit at 0K by employing a Monte Carlo method. The calculation procedure was the same as in our previous work [2].

3. Results and discussion

The electron number per V_g period (n_e) is shown in Fig. 4, as a function of drain voltage (V_d). The bottom graph is for the uniform C_g case (C_g=0.05 aF). It is found that turnstile operation is realized around V_d=2 mV, as indicated by an arrow [4]. The middle and top graphs are for the random dot system with a mean C_g of 0.05 aF and a standard deviation of s=0.0348 aF. The difference between Types A and B is only the C_g arrangement. Nevertheless, the turnstile region for Type A expands and that for Type B vanishes [4]. It can be said that the 2D random multidot system has an ability of the turnstile operation under a wide bias condition.

For another C_g arrangement case of s=0.0348 aF (Type C), n_e-V_d curves are plotted in Fig. 5(a), in which the calculation was repeated five times for the same parameter. It is clearly found that there are two plateaus corresponding to single- and double-electron turnstile operation around V_d=1 mV (P_1) and 2.4 mV (P_2), respectively. As shown in Fig. 5(b), an electron is transferred from the source to drain via Dot 8 at V_d=1 mV. On the other hand, at V_d=2.4 mV, two electrons are transferred via Dots 3 and 14. Moreover, we confirmed that, for the homogeneous system, the two-by-two transfer is hardly found under the V_{g1}=150 mV condition.

Figure 6 shows a calculated drain-current (I_d) contour plot in the (V_{g0}, V_d) plane for the random multidot system (Type C). In this figure, dark region corresponds to large tunneling current and the bright gray region shows no current (Coulomb blockade region). Here, n is defined as the total number of electrons in the 15 dots, that is, n=1 means that one electron stably exists somewhere. From this figure, it is found that at Point P_1 (V_{g0}=300 mV and V_d=1 mV), the system has alternatively an n=0 phase (Point Q_1) and an n=1 phase (Point R_1). In this case, electrons move one by one from the source to drain via Dot 8. At Point P_2 (V_{g0}=300 mV and V_d=2.4 mV), the system has alternatively an n=0 phase (Point Q_2) and an n=2 phase (Point R_2). In this case, electrons move two by two via Dots 3 and 14. These results strongly suggest the realization of multi-charge turnstile operation of higher order.

4. Conclusions

We have investigated the turnstile operation in 2D random-multidot channel FETs using Monte Carlo simulation and showed that single- and double-electron turnstile operation can be realized in a random multidot system. These results indicate that 2D random multidot channel FETs have an ability to realize well-controlled multi-charge transfer.

[1] S. Muto, Jpn. J. Appl. Phys. **34** (1995) L210.
[2] M. Tabe, Y. Terao, R. Nuryadi, Y. Ishikawa, N. Asahi and Y. Amemiya, Jpn. J. Appl. Phys. **38** (1999) 593.
[3] D. Esteve, "Single Charge Tunneling, Coulom Blockade Phenomena In Nanostructure" eds. H. Grabert and M. H. Devoret, Chap.3 (Plenum Press, New York, 1992).
[4] H. Ikeda and M. Tabe, Abstr. on the 2005 Silicon Nanoelectronics Workshop, in press.
[5] R. Nuryadi, H. Ikeda, Y. Ishikawa and M. Tabe, IEEE Trans. Nanotechnol. **2** (2003) 231.
[6] H. Ikeda, R. Nuryadi, Y. Ishikawa and M. Tabe, Jpn. J. Appl. Phys. **43** (2004) L759.
[7] R. Nuryadi, H. Ikeda, Y. Ishikawa and M. Tabe, Appl. Phys. Lett. **86** (2005) 133106.

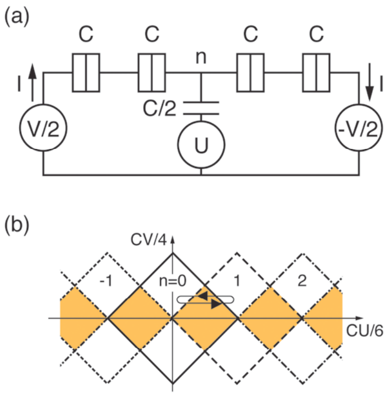

Fig.1 (a) Simple single-electron turnstile circuit and (b) its local stability diagram in (U,V) plane [3].

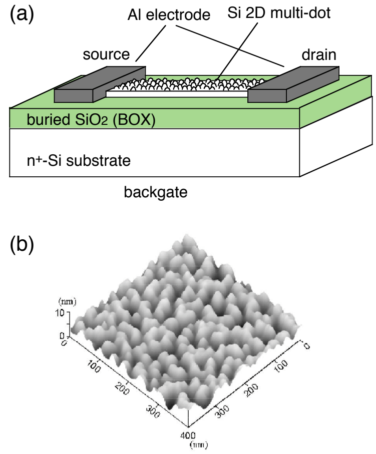

Fig.2 (a) Schematic diagram of 2D Si multidot channel FET and (b) AFM image of the multidot.

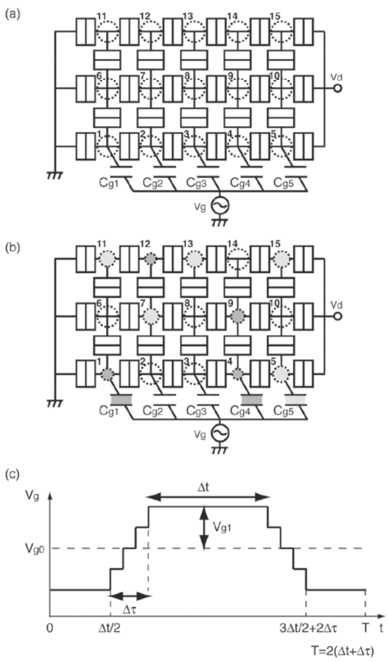

Fig.3 Equivalent circuits of multidot channel FETs for (a) homogeneous and (b) random multidot systems, and (c) applied periodic V_g.

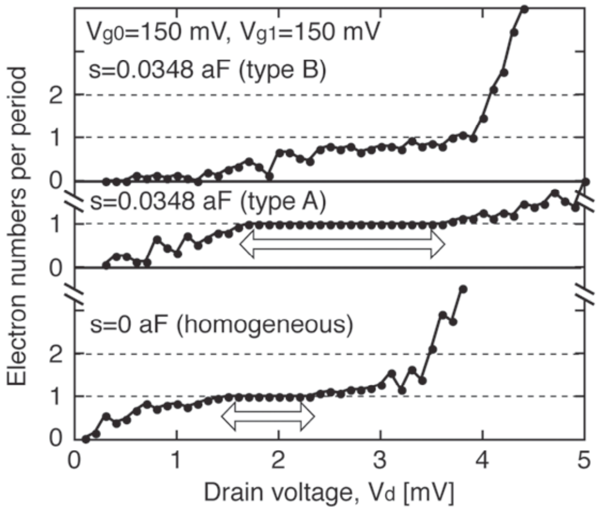

Fig.4 Electron number per V_g period as a function of V_d for homogeneous case (bottom) and random multidot cases (middle and top). Types A and B have different C_g arrangement each other.

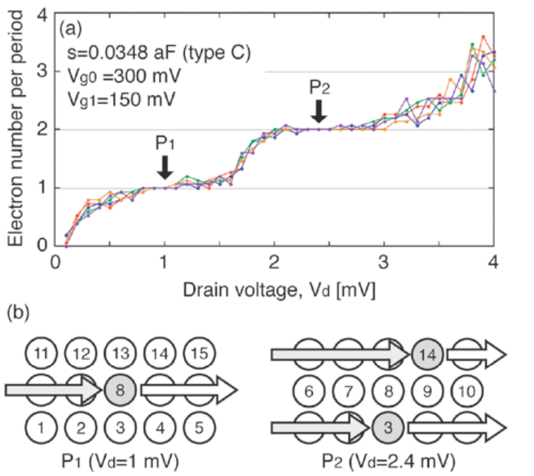

Fig.5 (a) Electron number per V_g period as a function of V_d for random multidot case (Type C) and (b) schematic electron movements under turnstile operation.

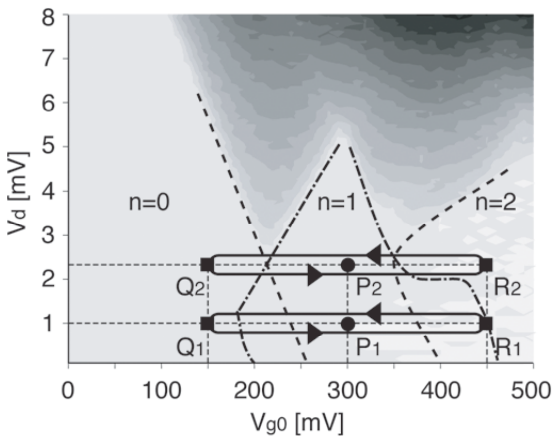

Fig.6 Calculated I_d contour plot in (V_{g0}, V_d) plane for random multidot system with s=0.0348 aF (Type C).