Escape dynamics of a few electrons in a single-electron ratchet using silicon nanowire metal-oxide-semiconductor field-effect transistor

Satoru Miyamoto,[1,2,a)] Katsuhiko Nishiguchi,[1] Yukinori Ono,[1] Kohei M. Itoh,[2] and Akira Fujiwara[1,b)]

[1]*NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan*

[2]*School of Fundamental Science and Technology, Keio University, 3-14-1 Hiyoshi, Yokohama 223-8522, Japan*

(Received 12 September 2008; accepted 23 October 2008; published online 1 December 2008)

Transport dynamics of a few electrons in a quantum dot are investigated in a single-electron ratchet using silicon nanowire metal-oxide-semiconductor field-effect transistors. Time-resolved measurements in a nanosecond regime are carried out to determine the escape times of the first, second, and third electrons from the quantum dot originally containing three electrons. The escape time strongly depends on the number of electrons due to the single-electron charging effect in the quantum dot, which makes it possible to achieve selective ejection of a desired number of electrons. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3028649]

Single-electron (SE) transfer and manipulation have been attracting much interest due to their potential applications to metrological current standards,[1] SE circuits,[2] charge qubits,[3] SE sources,[4] as well as single-photon sources.[5] In particular, the stringent criteria for the current standards require a nanoampere level current together with a transfer error of less than 10^{-8} to close the quantum metrological triangle through direct linking between ampere and frequency.[6] Inspired by the demonstration of SE pumps and turnstiles using multiple metal islands with fixed tunnel junctions,[7,8] the SE transfer in semiconductors has been extensively investigated toward the goal of higher-frequency operation by taking advantage of gate-induced tunable barriers or surface acoustic waves (SAWs).[9–12] Recently, a simpler transfer scheme called the SE ratchet employing the modulation of a single barrier[13,14] was demonstrated in a gigahertz frequency range to obtain a nanoampere level current. However, the transfer error is still large on the order of 10^{-2},[15] and the error mechanism in a tunable-barrier system is not fully understood. In general, the sources of the transfer error are the fluctuations in the electron number during the SE capture[13] as well as ejection into/from a quantum dot (QD). In order to open the route to a higher level of transfer accuracy, it is necessary to comprehend the dynamics of SEs.

In this letter, we investigate the escape dynamics of electrons in the SE ratchet using Si nanowire metal-oxide-semiconductor field-effect transistors (MOSFETs). It is shown that the voltage-controlled ejection of SEs can be achieved due to the Coulomb gap energy in the QD containing three electrons. Recently, the energy-dependent escape of a few electrons from SAW-defined dynamic QDs was observed on subnanosecond time scales.[16] We present here the direct time-resolved measurements of the characteristic times of the first, second, and third electrons to escape from the QD.

Figure 1(a) shows a top-view scanning electron microscope image of the device. A 30 nm wide and thick Si nanowire is defined on a (001) silicon-on-insulator substrate with a 400 nm buried oxide by electron beam lithography. Thermal oxidation to form an approximately 20 nm thick gate oxide is followed by the formation of triple poly-Si gates. Subsequently, further thermal oxidation results in the gate width and the separation of approximately 10 and 100 nm, respectively. After the deposition of a 50 nm thick SiO_2, the entire region is covered with a wide poly-Si upper gate (UG), which is used as an implantation mask for the formation of *n*-type source and drain regions. When the voltage applied to UG (V_{UG}) is positive, electrically induced source and drain are formed in the undoped silicon-on-insulator layers on both sides of the nanowire. For the operation of the SE transfer, an

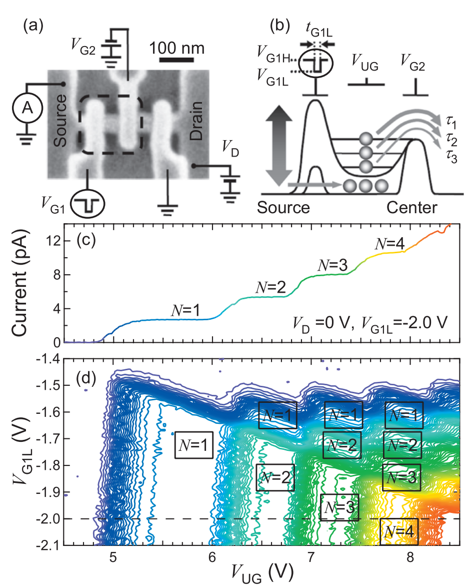

FIG. 1. (Color) (a) Scanning electron microscope image of the Si nanowire device mounted with triple gates before the UG formation. (b) Schematic of the SE ratchet employing the QD enclosed by the dashed line in the panel (a). (c) Quantization of the ratchet current observed at $V_{G2}=-1.0$ V. *N* denotes the transferred electrons that are obtained by normalizing the ratchet current by *ef*. (d) Contour plots of the ratchet current as a function of V_{UG} and V_{G1L}. The iridescent curve shown in (c) corresponds to the scan along the dashed line in (d).

[a)]Electronic mail: satoru@appi.keio.ac.jp.
[b)]Electronic mail: afuji@will.brl.ntt.co.jp.

ac-pulse voltage (V_{G1}) is applied to the source-side gate (G1) to form a time-modulated barrier in one-dimensional channel, while a steady barrier is formed underneath the center gate (G2) by a constant negative voltage (V_{G2}). The drain-side gate is grounded throughout the experiments. When V_{G1} is switched from $V_{G1H}=0$ V (high) to V_{G1L} (low), SEs are captured from the source into the QD formed between G1 and G2 due to the Coulomb blockade [Fig. 1(b)]. Furthermore, the lift of the QD potential via the capacitive coupling between G1 and the QD leads to the ejection of the captured electrons over the G2 barrier to the drain. Thus, the periodic modulation of the asymmetric potential produces a rectified current of SEs without any source-drain bias. When N electrons on average per cycle are conveyed from the source to the drain, the ratchet current I is quantized at Nef, where f is the clock frequency of the ac-pulse modulation. N is controlled predominantly using V_{UG} in order to deepen the QD potential during the SE capture. Figure 1(c) shows the ratchet current driven at $f=16.7$ MHz as a function of V_{UG}. The current plateaus are clearly observed corresponding to the discrete number of transferred electrons at 16 K. When V_{G1L} is -2.0 V, all captured electrons can be completely transferred to the drain. Figure 1(d) displays the contour plots of the ratchet current as a function of V_{UG} and V_{G1L}. When V_{UG} is set to approximately 7.3 V, three electrons are prepared in the capture process. However, the number of actually transferred electrons is reduced from three to zero by making V_{G1L} less negative since the lift of the QD potential is not sufficient for the captured electrons to escape over the G2 barrier.[13] Namely, the less negative V_{G1L} results in an incomplete ejection of the SEs, which motivates us to investigate their escape dynamics.

We expect that the number of escaped electrons depends on the time length of the low state of the V_{G1} pulse t_{G1L} since the surviving electrons tend to relax to the drain sooner or later. Therefore, we measure the average numbers of escaped electrons $\langle n_t \rangle = I/ef$ with varying of t_{G1L} at a constant time length of the high state of the V_{G1} pulse $t_{G1H}=10$ ns. The transfer operation is repeated about 10^6 times during the integration time for measuring the ratchet current. Figure 2(a) shows the time-resolved measurements of the escape of a few electrons from the bound states formed at a different V_{G1L}. The plateaus at $\langle n_t \rangle = 1$ and 2 are observed because of the incomplete SE ejection. Figure 2(b) shows a typical time-domain analysis at $V_{G1L}=-1.796$ V. Intriguingly, the first and second electrons escape within 10 ns after applying the G1 low-state pulse whereas the third electron remains for a relatively longer duration.

In order to determine the escape times of the electrons, we compare the experimental results with an analytical solution obtained from the following master equations. The escape time, the average time before the nth escape event to occur in one cycle, is defined as τ_n [see Fig. 1(b)], and the probability of m-electron survival in the QD is defined as $P_m(t_{G1L})$. The master equations of the survival probability are expressed as $dP_m/dt = P_{m+1}/\tau_n - P_m/\tau_{n+1}$ under the conditions of $n+m=3$ and $P_3(0)=1$.[17] Hence, the average numbers of escaped electrons can be obtained as the following expectation $\langle n_t \rangle = \Sigma_{n,m} n P_m(t_{G1L})$:

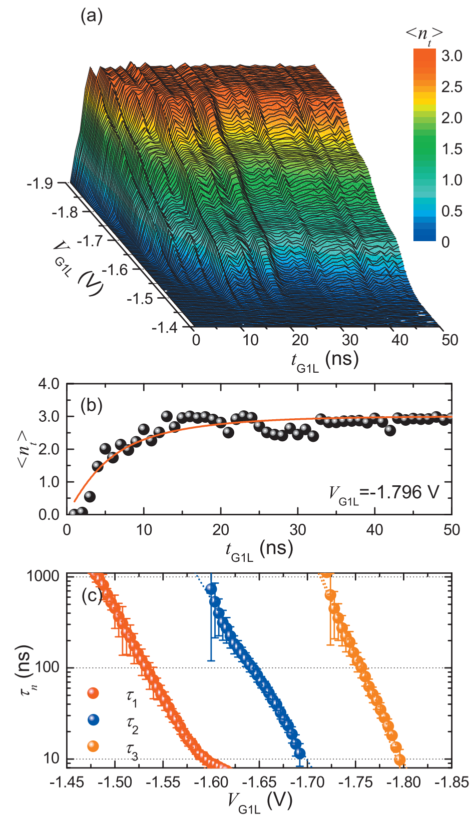

FIG. 2. (Color) (a) Average number of escaped electrons as a function of t_{G1L} and V_{G1L}. (b) Typical time-domain analysis at $V_{G1L}=-1.796$ V. (c) Exponential dependence of the escape time on V_{G1L}. The bars show the standard error included in the fitting routine.

$$\langle n_t \rangle = 3 - \frac{1}{\tau_2 - \tau_1}\left[\left(\frac{\tau_3\tau_1}{\tau_3 - \tau_1} + \tau_2 - 3\tau_1\right)\exp(-t_{G1L}/\tau_1) - \left(\frac{\tau_3\tau_2}{\tau_3 - \tau_2} - 2\tau_2\right)\exp(-t_{G1L}/\tau_2) + \left(\frac{\tau_3\tau_2}{\tau_3 - \tau_2} - \frac{\tau_3\tau_1}{\tau_3 - \tau_1}\right)\exp(-t_{G1L}/\tau_3)\right]. \quad (1)$$

We ignore the hopping back of the electrons from the drain over the high center barrier of ~160 meV. As shown in Fig. 2(b), the theoretical curve is well fitted to the experimental results. Figure 2(c) plots the escape times determined as the fitting parameters. Each escape time is exponentially extended by making V_{G1L} less negative. Naturally, a large negative V_{G1L} is needed for the purpose of a high-speed SE transfer. In addition, it should be noted that the escape times become longer by more than one order of magnitude for the latter turn of the escape event. Such a number-selective ejection of SEs is attributed to the SE charging effect in the QD. This is because the latter escaping electrons experience an additional energy barrier by the Coulomb gap energy.

The escape process can be explained by the classical thermal activation and/or quantum tunneling across a parabolic barrier since both can account for the exponential dependence of the escape time. Accordingly, we investigate the temperature dependence of escape rate Γ_n, which is the inverse of τ_n, in the temperature range between 16 and 28 K [Fig. 3(a)]. Another device comprising a 40 nm wide Si nanowire was measured at $V_{UG}=12.2$ V, where two electrons are initially bound within the QD. The slopes of Γ_1 and Γ_2 against V_{G1L} decrease as the temperature increases. In

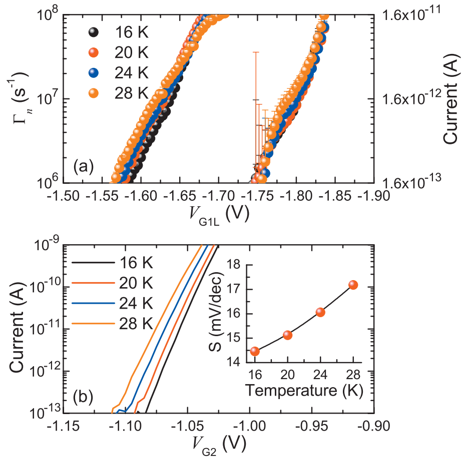

FIG. 3. (Color) Temperature dependence of (a) escape rate in the SE ratchet and (b) currents in the subthreshold regime of the MOSFET operated by G2 at $V_D = 100$ mV. In the upper panel (a), two series of plots show Γ_1 and Γ_2 from the left, and the right-side axis indicates the relevant current values. The inset in (b) shows the subthreshold swing (S-factor).

comparison to Fig. 3(b), this behavior is qualitatively consistent with the temperature-dependent current characteristic in the subthreshold regime of the MOSFET operated by G2. Therefore, we think the thermal activation rather than the tunneling[18] dominates the escape process of SEs at the temperature around 16 K. As a result, the Coulomb gap energy between m and $m+1$ electron states can be estimated to be several meV from $E_{Cm,m+1} = k_B T \ln(\tau_{n+1}/\tau_n)$, where k_B is the Boltzmann constant and T is the temperature.

Based on the exponential dependence of the escape time, we can obtain $\langle n_t \rangle$ from Eq. (1) as a function of V_{G1L} [Fig. 4(a)]. The calculated $\langle n_t \rangle$ and its first derivative with respect to $|V_{G1L}|$ reproduce the experimental results. The transition regions between the plateaus have a finite slope, which results from the thermally fluctuating number of escaping electrons. We also estimate the ejection accuracy from the escape probability of n electrons p_n [Fig. 4(b)]. Here, p_n is equal to P_{3-n}. The asymmetric variation in p_n, more specifically a gradual rise and a sharp fall, reflects the peak shape in the first derivative curve shown in Fig. 4(a). This is derived from the electron-number dependence of the escape time. Moreover, p_n and p_{n+1} cross each other in the transition regions. Then, the ejection accuracy is the lowest. In contrast, p_{n-1} and p_{n+1} are suppressed on the plateaus, where the accuracy of n-electron ejection is maximized. Hence tuning of V_{G1L} allows us to achieve highly accurate ejection of a desired number of electrons. It should be added that the ejection error can drop below 10^{-8} by making V_{G1L} sufficiently negatively large, for example, much less than -1.8 V in Fig. 4(b).

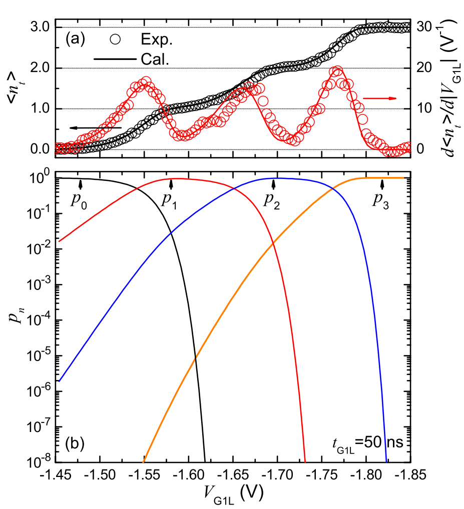

FIG. 4. (Color online) (a) Comparison of the experimental results with the calculated average number of escaped electrons and its first derivative with respect to $|V_{G1L}|$. (b) Escape probability of n electrons as a function of V_{G1L}.

In conclusion, we demonstrated the time-resolved measurements of the escape of a few electrons from the QD to determine both the escape times and the ejection accuracy in the SE ratchet. It was found that selective ejection of a desired number of electrons can be achieved by virtue of the SE charging effect in the QD. We believe that the observed electron-number dependence of the escape time also plays a role in the capture process, and thereby the present findings are important for building a complete model of SE transfer.

Different aspects of this work were supported by the Grant-in-Aid for Scientific Research (Grant Nos. 20241036, 19310093, and 18001002), Grant-in-Aid for the Global Center of Excellence for High-Level Global Cooperation for Leading-Edge Platform on Access Spaces from MEXT, and Special Coordination Funds for Promoting Science and Technology.

[1]M. W. Keller, J. M. Martinis, N. M. Zimmerman, and A. H. Steinbach, Appl. Phys. Lett. **69**, 1804 (1996).
[2]K. Nishiguchi, Y. Ono, A. Fujiwara, H. Inokawa, and Y. Takahashi, Appl. Phys. Lett. **92**, 062105 (2008).
[3]T. Hayashi, T. Fujisawa, H. D. Cheong, Y. H. Jeong, and Y. Hirayama, Phys. Rev. Lett. **91**, 226804 (2003).
[4]F. Fève, A. Mahé, J.-M. Berroir, T. Kontos, B. Plaçais, D. C. Glattli, A. Cavanna, B. Etienne, and Y. Jin, Science **316**, 1169 (2007).
[5]J. Kim, O. Benson, H. Kan, and Y. Yamamoto, Nature (London) **397**, 500 (1999).
[6]R. E. Elmquist, N. M. Zimmerman, and W. H. Huber, IEEE Trans. Instrum. Meas. **52**, 590 (2003).
[7]M. H. Devoret, D. Esteve, and C. Urbina, Nature (London) **360**, 547 (1992).
[8]J. P. Pekola, J. J. Vartiainen, M. Möttönen, O.-P. Saira, M. Meschke, and D. V. Averin, Nature Phys. **4**, 120 (2008).
[9]L. P. Kouwenhoven, A. T. Johnson, N. C. van der Vaart, and C. J. P. M. Harmans, Phys. Rev. Lett. **67**, 1626 (1991).
[10]A. Fujiwara, N. M. Zimmerman, Y. Ono, and Y. Takahashi, Appl. Phys. Lett. **84**, 1323 (2004).
[11]M. D. Blumenthal, B. Kaestner, L. Li, S. Giblin, T. J. B. M. Janssen, M. Pepper, D. Anderson, G. Jones, and D. A. Ritchie, Nature Phys. **3**, 343 (2007).
[12]J. M. Shilton, V. I. Talyanskii, M. Pepper, D. A. Ritchie, J. E. F. Frost, C. J. B. Ford, C. G. Smith, and G. A. C. Jones, J. Phys.: Condens. Matter **8**, L531 (1996).
[13]A. Fujiwara, K. Nishiguchi, and Y. Ono, Appl. Phys. Lett. **92**, 042102 (2008).
[14]B. Kaestner, V. Kashcheyevs, S. Amakawa, M. D. Blumenthal, L. Li, T. J. B. M. Janssen, G. Hein, K. Pierz, T. Weimann, U. Siegner, and H. W. Schumacher, Phys. Rev. B **77**, 153301 (2008).
[15]N. Maire, F. Hohls, B. Kaestner, K. Pierz, H. W. Schumacher, and R. J. Haug, Appl. Phys. Lett. **92**, 082112 (2008).
[16]M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper, Phys. Rev. Lett. **99**, 156802 (2007).
[17]The assumption that three electrons are exactly bound within the QD is not true because the error involved in regard to the capture process causes the other neighboring states. However, the discussion does not change significantly even if a fraction of the capture error of $\sim 10^{-2}$ at the level of the transfer error is taken into account.
[18]H. Kawaura, T. Sakamoto, and T. Baba, Appl. Phys. Lett. **76**, 3810 (2000).