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Nanoampere charge pumping by single-electron ratchet using Si nanowire MOSFETs

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1. Introduction

Clocked transfer of a single electron (SE) is attracting much interest for the application to current standards [1]. Compared to the conventional metal-based SE devices using fixed tunnel junctions [2], the use of gate-induced tunable barrier in semiconductors has a significant advantage in terms of higher-frequency operation since the resistance of the barrier is tunable. Two-gate tunable-barrier SE turnstiles were reported using GaAs (15 MHz)[3], Si (100 MHz)[4], and GaAs (3.4 GHz) [5]. A larger current at nanoampere level, however, is favorable and still required for the so called metrological triangle experiment [6].

Ratchets [7] are known to generate a directional motion of particles when the spatial asymmetry of the ratchet is combined with an oscillating external field or nonequilibrium process. As a variation from the two-gate turnstile, we have recently reported on a SE ratchet that uses the asymmetric potential with a SE pocket, which produces a directional SE current with only one AC signal to one gate [8].

This paper reports on nannoampere charge pumping using the SE ratchet. We also discover an anomalous shape of the current steps, which can be ascribed to the nonadiabatic process of electron capture.

2. Device structure and operating principle

The ratchet comprises two-gate-array Si nanowire MOSFETs fabricated on a silicon-on-insulator wafer. Figure 1(a) shows the top-view SEM image of the device. A 30-nm wide Si-wire channel and fine poly-Si gates with a 40-nm gate length and 30-nm gap are formed. Double-layer gate structure is employed and a wide upper poly-Si gate (UG) is used as an implantation mask during the formation of n-type the source and drain. The thicknesses of the Si wire, the gate oxide under the fine gates, the one under UG, and the buried oxide are approximately 20, 30, 80 and 400 nm, respectively. Figure 1(b) describes the operating principle. AC pulse voltage (V_{G1}) with frequency (f) is applied to the source-side gate (G1) and thereby forms an oscillating barrier. To introduce asymmetry in potential, we applied a constant lower voltage (V_{G2}) to the drain-side gate (G2) and thereby formed a fixed low barrier. In the gap region, a potential pocket is dynamically formed so that it can capture electrons from the source and eject them into the drain. The estimated total capacitance of the pocket is several aF. It should be noted that cross capacitance between G1 and the pocket region is essential for the electron ejection. The number of transferred electrons per cycle (n) is controlled by the upper gate voltage (V_{UG}).

3. Experimental results and discussion

Figure 2 shows a contour plot for the ratchet current (I) at f=50 MHz, which is normalized by ef, as a function of V_{UG} and the drain voltage (V_D) where V_{G1} are -3 V (LOW) and 0 V (HIGH) and V_{G2}=-0.9 V. The measurement temperature is 20 K throughout the work. The current shows clear plateaus corresponding to $I=nef$ due to the SE pumping. What is striking here is that the current is directional in a wide V_D range and its dependence on V_D is small because we use gate-controlled electrostatic barriers of the MOSFETs. This is a unique feature of our device since it is difficult to obtain such a tolerance for a large V_D using conventional metal-based SE devices.

We found that the current steps as a function of V_{UG} have anomalous shapes as shown in Fig. 3. The first derivative of n on V_{UG} shows asymmetrically shaped peaks, which indicates that the system cannot be described by a orthodox SE-box model where thermal equilibrium is assumed. We discover that the anomalous shapes can be attributed to the nonadiabatic process related to the electron capture. Figure 4(a) shows our model. Let us assume that, at time (t)=0, the SE box is formed and the electron number is stabilized at P(n)=1 when the barrier height is at some low level, where P(n) is the probability that the charge pocket contains n electrons. As the barrier height is linearly increased with time, it pushes up the pocket potential so that the electrons likely escape to the source towards the thermal equilibrium. Then, the escape lifetime (τ_{out}) is exponentially increased with time, which is a result from the exponential gate-voltage dependence in the subthreshold current of MOSFETs. τ_{out} also depends on V_{UG} exponentially since it deepens the charge pocket. Thus, the rate equation for P is given as

$$\frac{dP}{dt} = -\frac{P}{\tau_{out}} \ , \quad \text{where} \quad \tau_{out} = \tau_0 e^{t/\tau_{inc}} e^{eV_{UG}/\varepsilon}. \quad (1)$$

Here τ_0 is constant and τ_{inc} and ε are prefactors of the exponential dependences. By solving (1), P is found to approach to P_∞=exp(-exp(-V_{UG}/ε+log$_e$(τ_{inc}/τ_0)) with time, which means that n electrons are nonadiabatically captured with P_∞. Figure 4(b) shows derivatives of the calculated P_∞ fitted to the experimental results. Note that the asymmetric shape is quite universal reflecting the double exponential form of V_{UG}/ε and can be fitted using one fitting parameter ε. Although the detailed analysis considering non-zero temperature is required, we believe that this model dictates the observed peak shapes. We think that this finding of the capture mechanism is important for improving the transfer accuracy of this device for the metrological application.

The advantage of the SE ratchet compared to the two-gate turnstile is its simple operation with one AC signal, which is suitable for high frequency operation. Figure 5 shows the nanoampere pumping using another device at f=2.3 GHz. The current of 1.1 nA is obtained using the 3*ef* plateau, which is the highest ever reported as far as we know.

4. Summary

Nannoampere charge pump is demonstrated at 20K using the SE ratchet. We discover the anomalous shapes of the current steps due to the nonadiabatic process of the electron capture.

References

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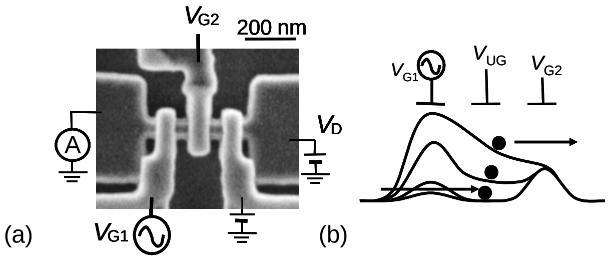

Fig. 1 (a) Top-view SEM image of the device before formation of the upper gate that covers a wide area. (b) Operating principle of single-electron ratchet.

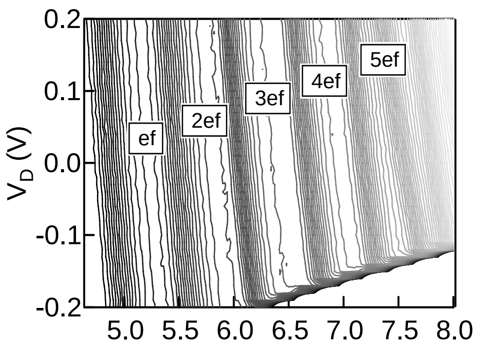

Fig. 2 Contour plot of SE ratchet current normalized by *ef* for V_D and V_{UG} at T=20 K and f=50 MHz. The triangular region in the lower right corner corresponds to the electron leakage from the drain because of the barrier lowering with respect to the drain.

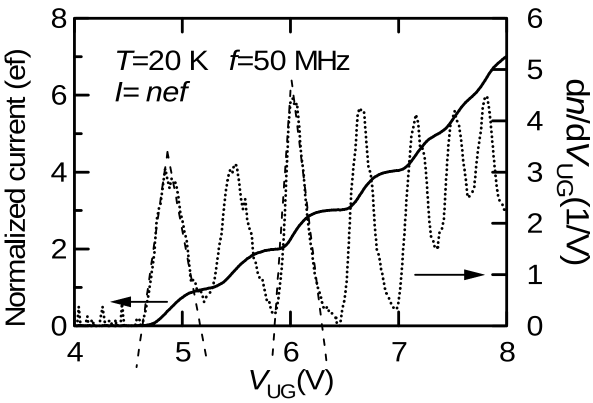

Fig. 3 Normalized current and its first derivative as a function of V_{UG} at V_D=0 V. Dashed lines are guide to the eye.

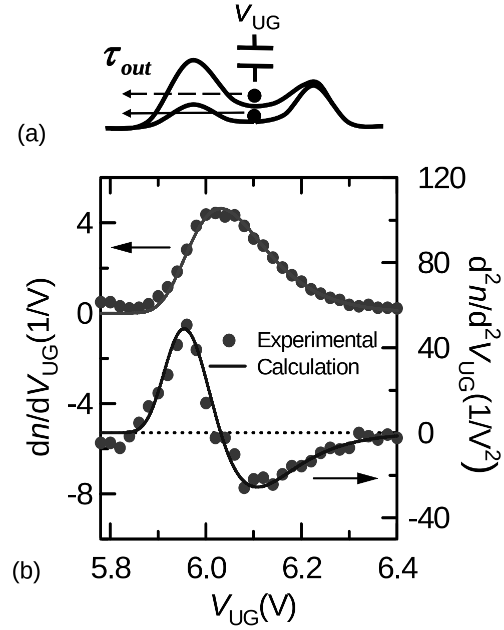

Fig. 4 (a) Model of nonadiabatic electron capture. (b) Calculation(ε=79 meV) fitted to the experimental curves for the first and second derivatives.

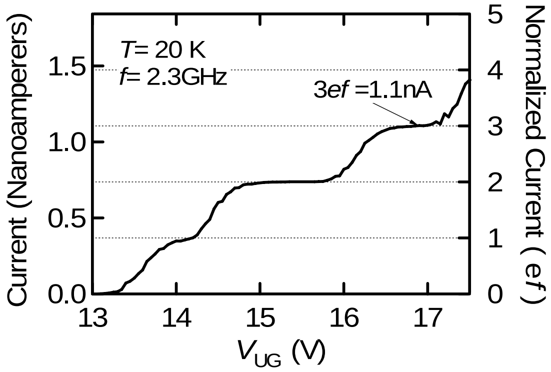

Fig. 5 Nanoampere single-electron pumping with another device when f=2.3 GHz, V_{G1}=-0.2 V (HIGH) and -3.8 V (LOW), V_{G1}=-2.6 V.