Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp816-817

Thermal-noise suppression in nanometer-scale Si field-effect transistors by feedback control with single-electron resolution

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1. Introduction

Maxwell's demon is a feedback controller who can measure the motion of microscopic particles. Feedback means a control protocol in which information measured in the past controls the measured system in the present or future. With the feedback protocol, the demon makes the system gain free energy without exerting any work on the system [1]. The free energy comes from the information obtained by the measurement [2]. In other words, Maxwell's demon is a device that converts information into energy.

In this paper, we report the realization of Maxwell's demon for suppressing thermal noise in a nanometer-scale Si nanodevice. We effectively reduce the thermal noise by 60 % through a feedback operation based on real-time monitoring of the thermal fluctuation of single electrons. As a result, the free energy of the Si nanodevice increases by 11 meV.

2. Thermal noise with single electron resolution

Figure 1 shows device schematics. A nanometer-scale node is separated from a reservoir electrically by applying a negative voltage to a gate [3]. Thermal energy makes electrons shuttle one by one randomly between the reservoir and the node. The number of electrons in the node (N) therefore fluctuates in a range determined by the thermal energy [see Fig. 2(a)], which corresponds to thermal noise. The fluctuating N is monitored in real time by means of drain current (I_d) flowing through a detector based on a field-effect transistor capacitively coupled to the node. All measurements are carried out at room temperature.

Figure 3(a) shows I_d as a function of time. I_d fluctuates among discrete values, which means that N fluctuates with time because of the thermal noise as indicated by the right axis. To discuss the fluctuation of N, we estimate probability p_i from the total time when N-N_{ave} = i, where N_{ave} is the average of N. As shown in Fig. 3(b), p_i characteristics follow the Gaussian distribution given by $P_0\exp(-i^2E_c/2k_BT)$, where P_0 is the prefactor of the distribution, E_c ($=e^2/C$ =17 meV) is the charging energy of the node, C is the capacitance of the node, k_B is the Boltzman constant, and T is the temperature. Additionally, the average energy $U = \Sigma_i\, \varepsilon_i p_i$ of the node is $k_BT/2$ when $k_BT < E_c$, where $\varepsilon_i(=i^2E_c/2)$ is the charging energy of the node with i electrons at the equilibrium. These features mean that the N fluctuation originates from the thermal noise.

3. Feedback operation to suppress thermal noise

To suppress the thermal noise by feedback control, voltage V_{res} applied to the reservoir is adjusted so that N becomes N_{ave}: when N is smaller (larger) than N_{ave}, the reservoir potential is raised (lowered) by decreasing (increasing) V_{res} by V_{FB} and thus the rate for electrons to enter the node is increased (decreased) according to V_{FB}, which makes N closer to N_{ave} [see Figs. 2(b), (c)]. As a result, N fluctuation, i.e., the thermal noise, is suppressed from the pristine fluctuation determined by the thermal energy.

Figure 4(a) shows I_d as a function of time under the feedback control. The feedback control reduces the fluctuation of I_d, i.e., N, and the distribution of p_i is suppressed from the Gaussian distribution originating from the thermal noise [see Fig. 4(b)]. As a result, U becomes smaller than $k_BT/2$ when V_{FB} is increased as shown in Fig. 5. These features mean that the feedback control suppresses thermal noise substantially, e.g., by 60 % at V_{FB} of 80 mV.

4. Discussion

To discuss the feedback operation from the viewpoint of Maxwell's demon, we estimate the free energy $F = U - TS$ of the node, where $S(=-k_B\,\Sigma_i\, p_i\ln p_i)$ is the entropy of the system composed of electron number states. U and TS become smaller when V_{FB} increases [see Fig. 5]. Since the change of TS is larger than that of U, F increases by 11 meV at V_{FB} = 80 mV, which means that the thermal-noise suppression by the feedback control generates free energy from the information. The fundamental mechanism for the suppression is modulation of the rate at which electrons enter the node so that N becomes N_{ave}. Therefore, the thermal-noise suppression originates from the information with single-electron resolution and is achieved by Maxwell's demon. It should be noted that the work done by the reservoir is dissipated to the phonon heat bath and also plays a minor role in the noise suppression.

5. Conclusions

In conclusion, we performed a feedback operation based on the outcome of measurement with single-electron resolution to realize Maxwell's demon in a Si nanodevice at room temperature. As a result, the thermal noise in the nanodevice is suppressed by 60 %, which corresponds to free energy gain of the node of 11 meV. This is the first experimental demonstration of information-to-energy conversion in semiconductor nanodevices.

Acknowledgements

We thank K. Kanazawa, H. Tanaka, and H. Nakano for helpful discussions and comments. This work was partially supported by the Funding program for Next Generation World-Leading Researchers of JSPS (GR 103).

References

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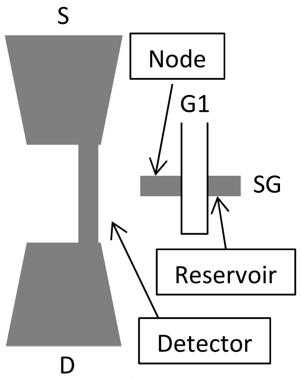

Fig. 1. Schematic illustration of Si field-effect transistor made of silicon-on-insulator on a 400-nm buried oxide.

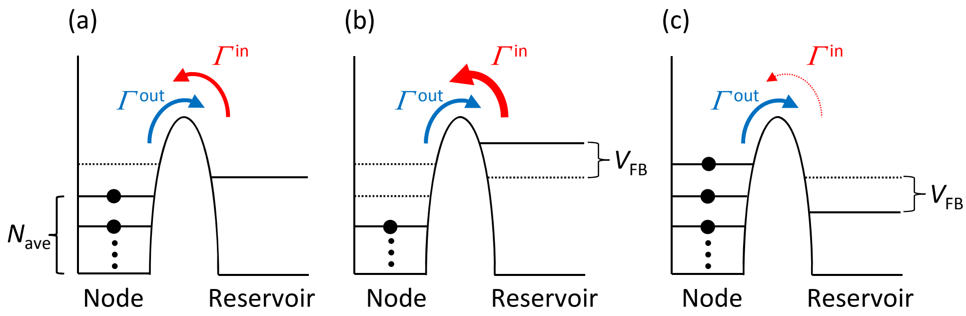

Fig. 2. (a) Electrons shuttle one by one randomly between the node and reservoir because of the thermal fluctuation, where Γ^{in} (Γ^{out}) is the rate at which electrons enter (exit) the node. (b) When $N < N_{ave}$, in the feedback scheme, $-V_{FB}$ is applied to the reservoir to enhance Γ^{in}. The enhanced Γ^{in} is indicated as the red bold arrow. (c) When $N > N_{ave}$, in the feedback scheme, $+V_{FB}$ is applied to the reservoir to reduce Γ^{in}. The reduced Γ^{in} is indicated as the narrow arrow.

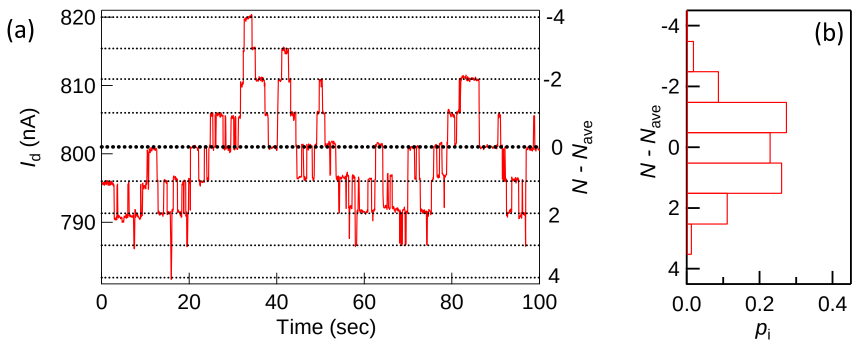

Fig. 3. (a) I_d as a function of time. N-N_{ave} is indicated in the right axis. (b) p_i as a function of N-N_{ave} obtained from a data set including Fig. 3(a).

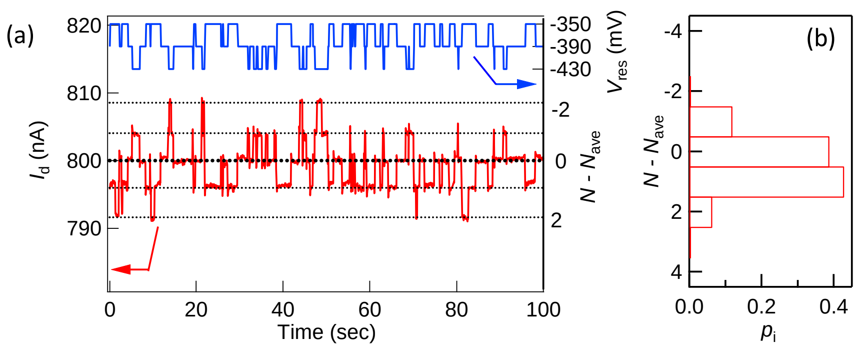

Fig. 4. (a) I_d and V_{res} as a function of time under the feedback control with V_{FB} = 40 mV. The right axis indicates V_{res} and N-N_{ave}. (b) p_i as a function of N-N_{ave} obtained from a data set including Fig. 4(a).

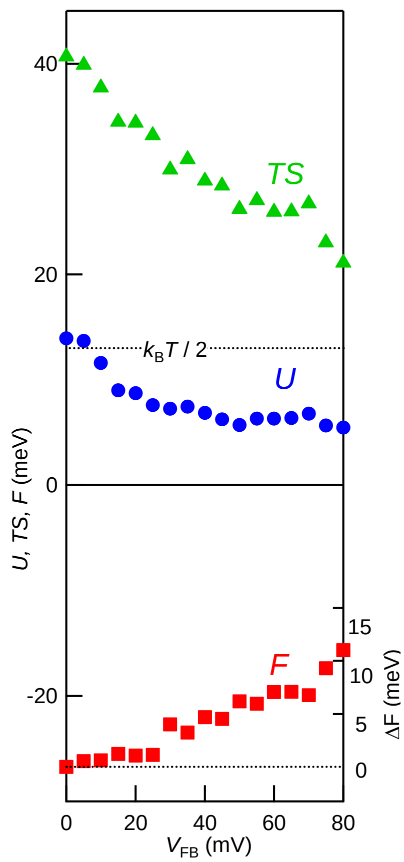

Fig. 5. U, TS, and $F(=U - TS)$ as a function of V_{FB}. The right axis indicates the free energy gain ΔF.