

## Electrical Current Generation by Sorting Thermal Noise

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### Abstract

We have achieved the operation of Maxwell's demon with an electrical device, which is a feedback operation based on single-electron motion. Maxwell's demon is related to the lower bound of energy consumption in electrical devices and power generation efficiency in small systems. We therefore anticipate that this achievement will contribute to creating nanoscale energy-efficient electrical devices.

*Keywords: thermal noise, silicon transistor, Maxwell's demon*

### 1. Second law of thermodynamics and Maxwell's demon

The second law of thermodynamics states that every physical system eventually becomes random. This law prohibits us from creating ordered motion of electrons, or electrical current, from thermal noise unless we modify the electrons externally. Maxwell's demon is a thought experiment created by Scottish mathematician James Clerk Maxwell to contradict the second law of thermodynamics; it is an ideal entity that can perform a feedback operation by observing objects at the level of thermal noise and can create ordered motion of electrons using energy from thermal noise without our having to modify the electrons.

Maxwell's demon has been vigorously discussed among physicists for more than 150 years because it appears to violate the second law. The discussions have clarified that Maxwell's demon uses information about the thermal motion of electrons, which requires energy. This means that we need a certain amount of energy to obtain the information, and we can create the same amount of energy at maximum from it.

This idea leads to the concept of information thermodynamics, in which the role of information is on the same footing as energy. Information thermodynamics reveals the lower bounds of the thermody-

amic cost of information processing [1] and provides us knowledge about small heat engines such as molecular motors whose motions are driven by thermal fluctuations. Maxwell's demon is the epitome of information thermodynamics, which is considered to be related to energy-efficient biological systems.

In this study, we succeeded in generating electrical current and power with Maxwell's demon in one of the most natural ways: observing electron thermal motion, sorting electrons with the obtained information, and outputting the sorted electrons that had large energy.

### 2. Silicon nanotransistors and operation of Maxwell's demon

In the experiment, we used a silicon nanodevice on a silicon-on-insulator wafer. In our device, a single-electron box electrostatically defined by two transistors provides doors through which electrons can enter and exit the box, and a capacitively coupled detector with single-electron sensitivity detects thermal fluctuation in the box at the single-electron level (**Fig. 1**) [2]. By switching the transistors on and off, we can open and close the entrance to the box and the exit from it individually. The number of electrons in the box was observed in real time at a frequency of about 14 Hz by measuring the current flowing through the detector. All the measurements were done at room

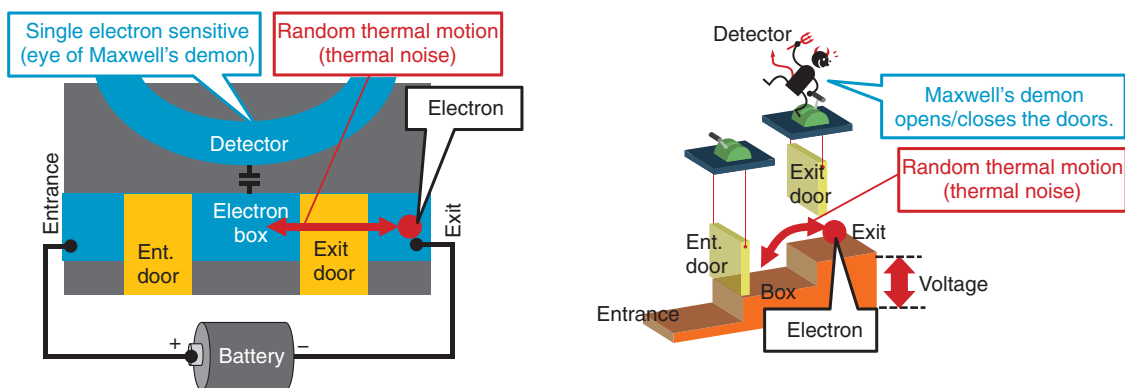


Fig. 1. Device structure. A schematic illustration of the structure of our device (left), and a corresponding schematic illustration of Maxwell's demon (right). The nanometer-scale silicon transistors serve as doors that control the motion of electrons. Electrons move in a direction determined by the voltage as an average flow. However, at the single-electron level, the motion is random because of thermal noise. The detector can observe the random motion.

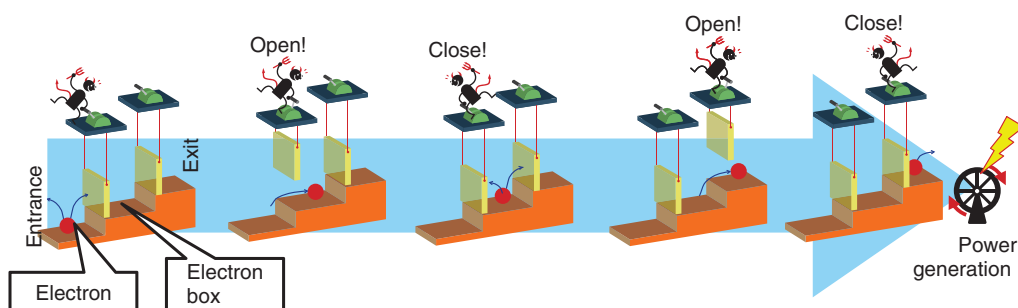


Fig. 2. Operation of Maxwell's demon. Maxwell's demon opens and closes the entrance and exit doors based on the number of electrons in the electron box, which thermally fluctuates.

temperature.

We performed feedback control based on the number of electrons in the box [3] as follows (Fig. 2). First, we open the entrance and observe random electron motion between the entrance and the box. After electrons have entered the box, we close the entrance. Then, we open the exit and observe random electron motion between the exit and the box. Finally, after the electrons have exited the box, the exit is closed. By repeating these procedures, we can move electrons from the entrance to the exit. We carefully calibrated the experimental setup to achieve the operation of Maxwell's demon without doing any external work on the electrons [4].

### 3. Rectification of thermal noise with Maxwell's demon

Carrying out the above procedures enables sorted electrons to flow as electrical current. They can even climb up the potential energy across the entrance and exit (Fig. 3); this climbing is the power generation. When the source-drain bias voltage  $V_{SD}$  is  $\sim 30$  mV, the generated power shows the maximum value of  $0.5$  zW ( $10^{-21}$  W). The quantitatively estimated information-to-energy conversion efficiency is 18%, which is reasonably high and consistent with our theoretical simulation. This consistency indicates that silicon nanodevices are an ideal platform for studying Maxwell's demon and information thermodynamics. The simulation also demonstrated that the power output increases as the detector becomes faster and the box becomes smaller. Therefore, further advances in

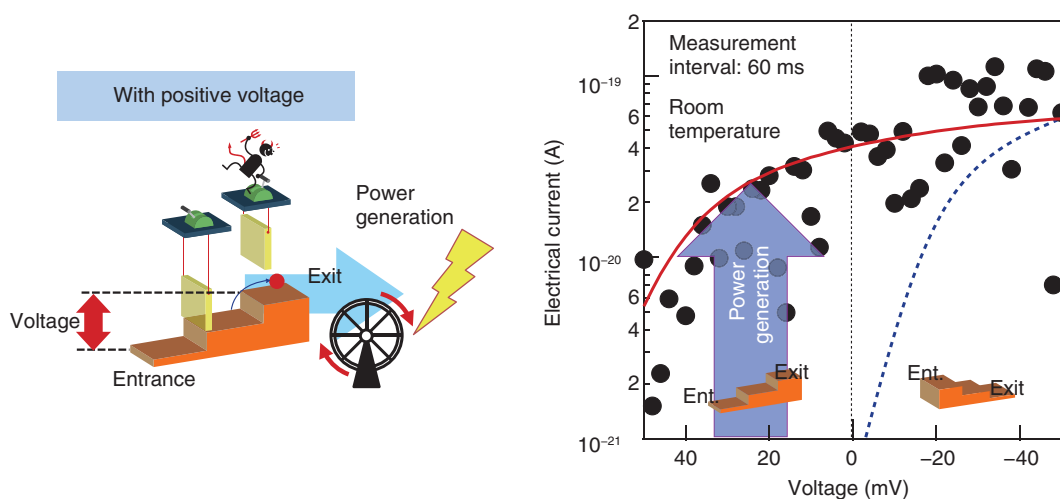


Fig. 3. Power generation with Maxwell's demon. On the left is a schematic illustration of power generation with Maxwell's demon. Maxwell's demon sorts electrons with large energy and outputs them. The energy can be utilized as electrical power as depicted. The right graph shows the electrical current (in the direction corresponding to electron motion from the entrance to the exit) as a function of the voltage. The voltage represents the height of the exit relative to that of the entrance (when the exit is higher than the entrance, the voltage is positive). The dotted blue line is the expected electrical current without Maxwell's demon. In this situation, electrons flow from the entrance to the exit only when the voltage is negative. In contrast, with Maxwell's demon, electrons are expected to flow from the entrance to the exit even when the voltage is positive, which is shown by the red line. The experimentally obtained electrical currents, plotted as black circles, are similar to the expected value with Maxwell's demon. When the voltage is positive, electrons climb up the voltage, and Maxwell's demon generates electrical power as illustrated on the right.

transistor technology will lead to an increase in the demon's power output.

#### 4. Future work

The results in this work are closely related to the lower bound of energy consumption in electrical devices and the efficiency of small heat engines. To achieve high energy-to-power conversion efficiency, biomolecules, for example, molecular motors, are thought to use information about themselves to perform their operation at proper timings. Such an efficient process in biomolecules can be modeled and analyzed in the framework of Maxwell's demon. We will attempt in the future to deepen our understanding

of the mechanism responsible for the high efficiency in biological systems and thereby make an electrical device that mimics their high efficiency.

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