Design of new single-electron information-processing circuit mimicking behavior of swarm of honeybees

Toshihiko Tanabe, Takahide Oya
Graduate School of Engineering, Yokohama National University,
Tokiwadai 79-5, Hodogaya-ku, Yokohama 240-8501, Japan
Email: tanabe-toshihiko-mv@ynu.jp
TEL: +81-45-339-4125 FAX: +81-45-338-1157

ABSTRACT

We propose a new single-electron (SE) circuit that shows a unique information-processing by mimicking a foraging behavior of a swarm of honeybees. It is known that the foraging behavior of honeybees can be assumed to be a certain type of information processing. In this study, we focus on the behavior of the honeybees as nature-inspired information processing to apply to the SE circuit that is a target device in this study. For this, there are three important points to mimic the behavior for the SE circuit: 1) "random flying (walk)" to find foods, 2) "sharing information about discovered nectar sources" and 3) "updating information by repeating process." At the first stage of this study, we designed a SE circuit that expressed the behavior of performing random search and discovering nectar source. By using computer simulation, we confirmed that the design circuit operated correctly as desired. That is, the "honeybee-inspired SE circuit" that can show unique information-processing can be realized.

Keywords: single-electron, information-processing, nature-inspired, nanoelectronics, nonlinear-problem

1 INTRODUCTION

Nano-scaled devices, e.g., single-electron (SE) devices, single molecule devices and so on, have been proposed and developed as results of the advances in nanotechnology. It is known that such emerging devices consist of nano-scaled elements and show unique functions. Therefore, many researchers have tried to design and develop useful and functional systems for the construction of novel information-processing devices. Actually, as a unique approach, the "nature-inspired" or "biomimetic" technique based on natural world phenomena and biological behaviors has been proposed for the purpose of developing novel functional nanodevices. This is because the living things and nature can often be assumed to be a certain type of information processing.

In this study, we focus on a foraging behavior of a swarm of honeybees as the nature-inspired information processing to apply the SE circuit that is the targeted device in this study. It is known that the honeybees that are social insects form a nest, live in herds, and forage for foods. These behaviors, especially the foraging, can be assumed to be a certain type of information processing that is the solving nonlinear problems. For example, the honeybees fly around in random to discover nectar sources firstly. They return to the nest after discovery. Secondly, they share information about the place and the amount of the nectar sources in the nest if necessary. This sharing is expressed by a dance called the "waggle dance." The waggle dance tells important information of the place, the distance, and the quality of the nectar sources. Finally, after the sharing information, appropriate numbers of the honeybees go to the better nectar sources. By repeating the process, the honeybees optimize the process. To materialize an "artificial honeybee circuit," these are at least three important points should be focused. One is the "random flying (walk)" to find foods. The second is the "sharing information" in the swarm. The last one is the "updating information by repeating process." We here try to mimic these three behaviors. However, it is difficult to express at once all of the honeybees foraging behavior on the SE circuit. Therefore, as the first stage of this study, we designed the SE circuit that expressed the foraging behavior of performing random search and discovering nectar sources.

2 SINGLE-ELECTRON CIRCUIT

In this section, we describe the basis of the SE circuit and a SE oscillator and a SE memory that are two of the SE circuits utilized in this study. In addition, we describe the application of each of the circuit.

2.1 Basis of single-electron circuit

The SE circuit that is a certain type of a quantum device can control an individual electron by controlling a quantum effect. A main component of the circuit is a tunneling junction. The electron can pass through the junction under a special condition, although the junction is a certain type of a capacitor, i.e., the junction has a threshold value for the electron to tunnel.

2.2 Single-electron oscillator

A SE oscillator (SEO) is one of the SE circuits. The SEO consists of a bias voltage source V_d, a high resistance R, and the tunneling junction C_j in series, as shown in Fig. 1. The SEO operates as a threshold element because of the contained tunneling junction. When the bias voltage V_d that is set to higher than the threshold value is applied to the SEO, the electron tunneling occurs with a probabilistically.

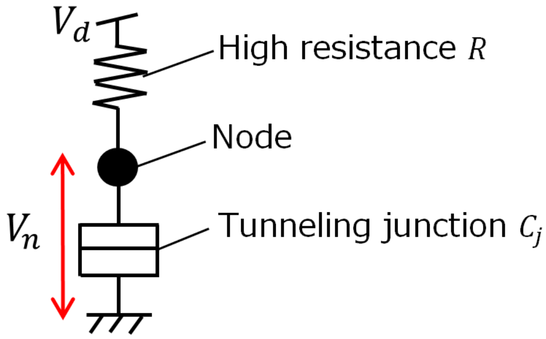

Figure 1 Single-electron oscillator.

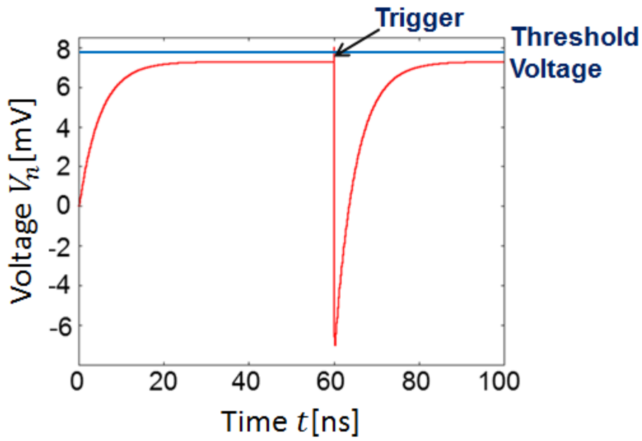

Figure 2 Sample operation of SEO.
(V_d = 8 mV, R = 500 MΩ, C_j = 10 aF)

Then, the node voltage V_n changes sharply. A sample operation the SEO is shown in Fig. 2.

In Fig. 2, the bias voltage V_d was set to a subthreshold value to the SEO. When a trigger was inputted, then node voltage V_n exceeded the threshold value. After that, the electron tunneling occurred and the node voltage of V_n dropped steeply. Therefore, it is possible to control the electron tunneling by a trigger input. Moreover, the voltage change can be propagated by connecting the SEOs. Because the change in a SEO can be a trigger input for neighbor SEOs. In concrete, when the SEOs are connected with each other in a two-dimensional as shown in Fig. 3, the voltage change can propagate in the circuit like a wave because of a certain chain reaction of the electron tunneling.

We utilize a two-dimensional arrayed SEO system[2] to mimic the "random flying (walk)" behavior. Because the system can generate spatiotemporal patterns, i.e., "voltage waves," and the pattern propagates with randomness on the system as shown in Fig. 4.

Figure 4 represents the voltage changes of the SEO in gray scale. The black color indicates a low voltage and the white color represents a high voltage. This wave-like propagation is caused by the chain reaction of the electron tunneling with probability. We can assume this operation as the "random flying (walk)" behavior of our SE honeybees.

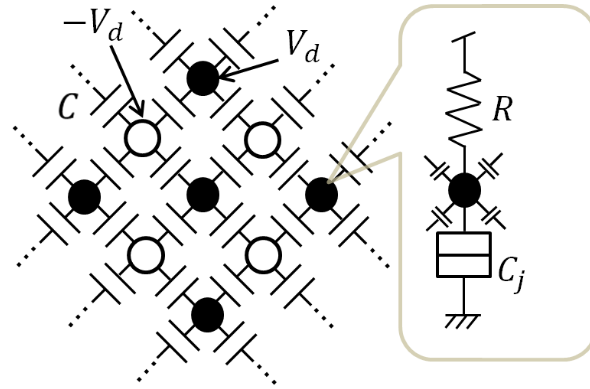

Figure 3 Two-dimensional arrayed SEO system.

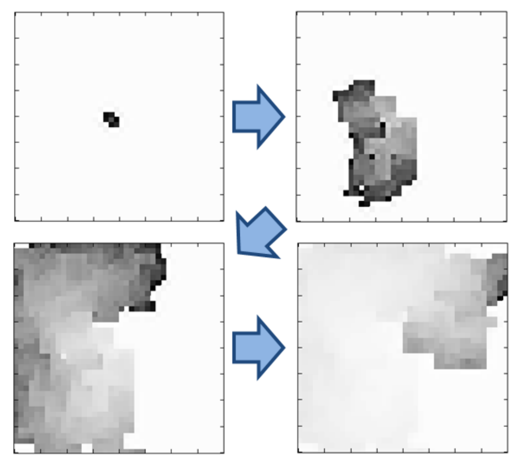

Figure 4 Sample operation of two-dimensional SEO system.
(V_d = 3.89 mV, R = 34 MΩ, C_j = 10 aF)

2.3 Single-electron memory

A single-electron memory (SEM) is also one of the SE circuits. The SEM consists of a bias voltage source V_d, a capacitor C_L, and two tunneling junctions C_j in series, as shown in Fig. 5. The SEM also operates as a threshold element. A sample operation of the SEM is shown in Fig. 6.

A special feature of the SEM (the differences of the SEM and the SEO) is that the voltage V_n of the SEM shows a hysteresis characteristic as a function of the bias voltage V_d. Therefore, it is possible to hold the value of the two states (voltages). Thus, it is possible to keep the value of the two states as a memory element by controlling the electron tunneling. For the aiming honeybee circuit, we consider the SEOs and the SEMs must be connected. Figure 7 is an example of a circuit diagram as a demonstration of the connection of the SEO and the SEM by using a coupling capacitor C.

Figure 8 shows a sample operation of the connected SEO and SEM circuit. The red colored line indicates an operation of the SEO and, the green colored line represents an operation of the SEM, respectively. The bias voltage for the SEM is set to subthreshold for the electron tunneling negative to positive that is indicated by the black colored line in Fig. 6. In this case, when the electron tunneling

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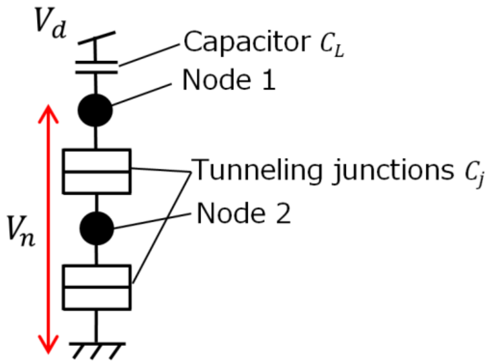

Figure 5 Single-electron memory.

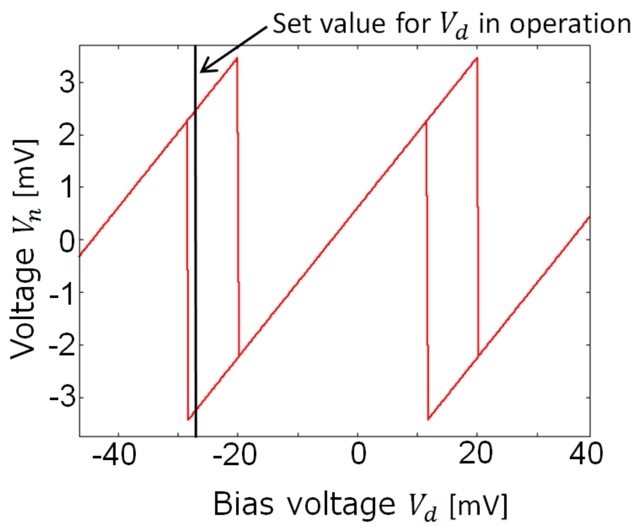

Figure 6 Sample operation of SEM.
(C_L = 4 aF, C_j = 40 aF)

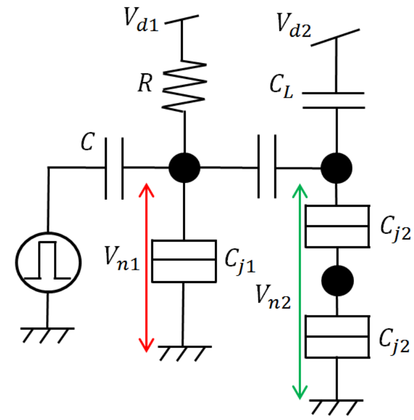

Figure 7 Sample construction of connecting SEO with SEM.

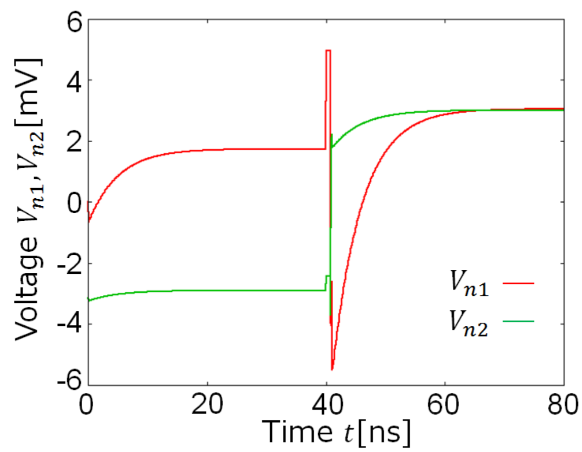

Figure 8 Sample operation of demonstrated circuit shown in Fig. 7.
(V_{d1} = 4.3 mV, V_{d2} = -22 mV, R = 500 MΩ, C_{j1} = 10 aF, C_{j2} = 40 aF, C_L = 4 aF, C = 4 aF)

occurs in the SEO, the sudden voltage change of the SEO induces the electron to tunnel in the SEM as a trigger signal. Then, the occurred electron tunneling in the SEO is memorized by the connected SEM.

3 DESIGNED SE HONEYBEE CIRCUIT

In this study, we express the honeybee behavior on the SE circuit by the combination of the SEO and SEM. As the first stage of this study, we design a SE circuit that expressed the foraging behavior of honeybees performing random search and discovering nectar source.

3.1 Circuit structure

Figure 9 shows a schematic of the designed circuit structure. The circuit consists of a search (random walking) layer, a nectar-dotted layer, a discovery and buffer layer, and an output layer. The search layer consists of the two-dimensional SEO system, the nectar-dotted layer consists of the arrayed SEM. The discovery and buffer(D&B) layer consists of the arrayed SEO, and the output layer consists of the arrayed SEM, respectively. The basic structure of the honeybee circuit is shown in Fig. 10.

The SEO in the search layer connects to the SEO in the D&B layer and the SEM in the nectar-dotted layer by using the coupling capacitors, respectively. Furthermore, the SEO in the D&B layer and the SEM in the nectar-dotted layer connect to the SEM in the output layer by using the coupling capacitors as same as described above.

The search layer expresses the random search behavior of the honeybees. The propagation of the voltage wave in the search layer (the two-dimensional SEO system) regards as the current positions of the travelling honeybees. The nectar-dotted layer represents the positions of the nectars and a state whether the honeybees visit or no. The D&B layer determines detecting the nectar and inputs signal for the SEM in the output layer, probabilistically. Here, a demonstrated operation of the designed circuit is described as follows. Firstly, in the search layer, the voltage waves perform the random search on the two-dimensional SEO system. i.e., our SE honeybees travel in the circuit. Secondly, in the nectar-dotted layer, when the SE honeybee reaches the position of a nectar, the electron tunneling occurs in the SEM at the position (“visited” information is

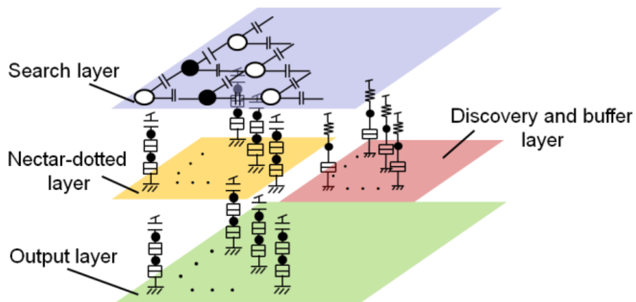

Figure 9 Schematic of circuit structure.

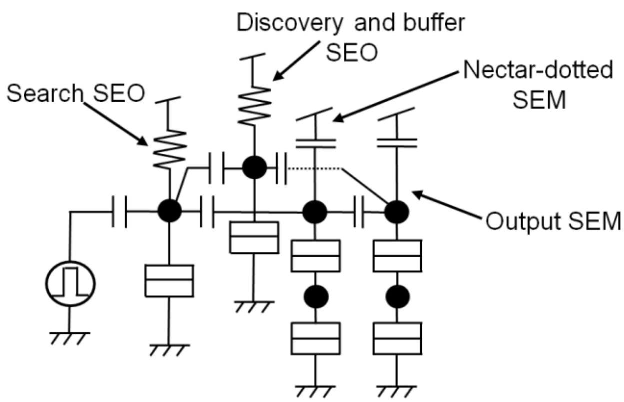

Figure 10 Basic structure of honeybee circuit.

memorized). Thirdly, in the D&B layer, when the electron tunneling occurs a position of the SEO in the search layer, the electron tunneling also occurs in the position in the D&B layer (a nectar is discovered). This tunneling also becomes an input signal for the SEM in the output layer. Finally, only if two electron tunnelings occur at both the SEM in the nectar-dotted layer and the SEO in the D&B layer, the electron tunneling occurs at the SEM in the output layer.

3.2 Simulation results

Figure 11 shows the simulation result of the designed circuit. In this demonstration, we set the circuit parameters as follows. For the SEOs in the search and D&B layers, capacitance of the tunneling junction C_j: 10 aF and the resistance R: 30 MΩ. The bias voltage V_d: 2.305 mV for the search layer and -4.3 mV for the D&B layer. For the SEMs in the nectar-dotted and output layers, capacitance of each tunneling junction C_j: 40 aF and the capacitor C_L: 4 aF. The bias voltage of V_d: -26 mV for the nectar-dotted layer and 21 mV for the output layer. In addition, capacitance of the coupling capacitor C between the layers was set to 4 aF. As the results of the simulation, it was confirmed that our SE honeybees operated correctly, i.e., the circuit shows the foraging behavior.

4 CONCLUSION

In this study, we aimed to design unique SE circuit that mimicked the foraging behavior of the honeybees in the natural world. It is known that the foraging behavior of the honeybees can be assumed to be a certain type of information processing that is the solving nonlinear problems. Therefore, we considered that mimicking the foraging behavior on the SE circuit provides the new functional information-processing device having the solving ability of the nonlinear problems. By relating the foraging behavior of the honeybees to the behavior of the SE circuit, we designed our honeybee circuit. From the simulation results, it was confirmed that the designed circuit operated as desired, i.e., the "honeybee-inspired SE circuit" can show unique information-processing. Moreover, it is expected to be a candidate of the next-generation information-processing devices.

In near future, we are going to modify our system to operate more efficiently. Because we designed circuit only for mimicking the "foraging behavior" in this time. To complete this study, we must realize the "sharing information about discovered nectar sources" and the "updating information by repeating process" operations as the SE circuits, respectively.

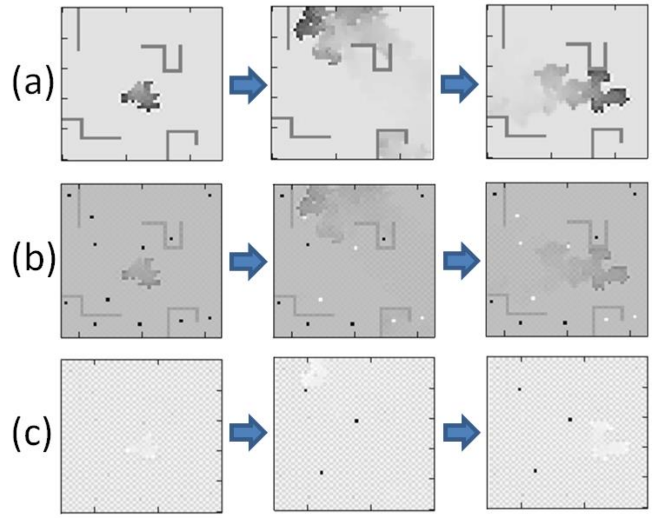

Figure 11 Snapshots of simulated operation in (a) search, (b) nectar-dotted, and (c) output layers.

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