Study of single-electron DOMINO logic circuit

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Abstract—A single-electron (SE) circuit, which is just one type of nanodevice, has been attracting attention in the nanotechnology research area. However, we have yet to determine the most appropriate information processing architecture for the SE circuit. So, as a candidate for the architecture, we are proposing the application of DOMINO logic theory to the SE circuit. DOMINO logic circuit is a logic circuit that is based on the behavior of a domino. To make sure that the DOMINO logic circuit is the most appropriate information processing architecture for the SE circuit, we designed and evaluated an actual SE calculator that is based on the DOMINO logic circuit. To do this, we designed basic logic circuits, e.g., OR, AND, and XOR, using the SE DOMINO logic circuit, and evaluated them by first conducting a Monte Carlo simulation. As a result, we confirmed that our circuit performs correctly.

Keywords: single-electron circuit, domino logic circuit, single-electron oscillator

1. BACKGROUND AND MOTIVATION

Nanodevices have recently been attracting attention for use as novel devices having unique nonlinear phenomena in nanotechnology research area. Single-electron (SE) circuits, which are just one type of nanodevice, have also been attracting attention because of their unique behavior, i.e., the Coulomb blockade phenomenon [1, 2]. We can control individual electrons by harnessing the phenomenon in the SE circuit. Various useful applications of SE circuits have already been proposed by many researchers. However, we have yet to determine the most appropriate information processing architecture for SE devices. In this study, we propose a new logic circuit design for the SE circuit for consideration as a candidate for the most appropriate architecture. In particular, we apply the “DOMINO logic” [3] theory to the SE circuit. The DOMINO logic circuit is based on the behavior of dominoes. When a domino falls in the DOMINO logic circuit, we can assume it represents a logical “1.” In contrast, when a piece does not fall, it represents a logical “0.” It was previously clarified that basic logic circuits, e.g., OR, AND, and XOR, can be designed using the DOMINO logic circuit as described in Ref. [3]. Mimicking the behaviors of dominoes, i.e., “speeds of falling dominoes are constant” and “when two falling lines of dominoes collide head-on, both lines will stop falling,” is important when using DOMINO logic circuits in electrical devices. We use the SE circuit in this study to mimic the behaviors of the dominoes. We appropriately named this circuit a SE DOMINO logic circuit. We propose our SE DOMINO logic circuit as a candidate for consideration as a new SE circuit in this study. Moreover, we aim to design a practical SE calculator, e.g., a full adder. The SE calculator will be a novel information processing device. We will clarify here that the DOMINO logic circuit is the most appropriate information processing architecture for an SE device. We will present our basic SE DOMINO logic circuit, i.e., OR, AND, and XOR, and that by conducting a Monte Carlo simulation as a first step in this study, we confirmed that their operations are feasible.

2. THEORY

We use a SE oscillator (SEO) that consists of a bias voltage \( V_b \), a resistance, and a tunneling junction in series to mimic the behaviors of dominoes in this study. The tunneling junction has a threshold value for the electrons to tunnel through it, i.e., we can control the flow of electrons by changing the bias voltage. Our SEO also has a threshold value for changing the voltage at both ends of the tunneling junction caused by the electron tunneling. Figure 1 shows a schematic of the SEO. Figure 2 shows an example of its operation when \( V_b \) is bigger than the threshold value of the tunneling junction. We can see in Fig. 2 that the voltage at both ends of the tunneling junction in a SEO rapidly changes at regular time intervals, because electron tunneling occurs.
We use arrayed SEOs connected together using coupling capacitors to mimic “falling domino lines” on the SE circuit. Figure 3 shows a schematic of a one-dimensional chain of six SEOs as an example. Each polar character of the bias voltage of the SEOs is inverted to alternating. In Fig. 3, when the signal is inputted at SEO V1 as a trigger, the electron tunnels in V1, and the node voltage $V_{\text{node}}$ of the tunneling junction in V1 rapidly changes. In addition, the drastic voltage change of V1 becomes the input trigger for V2 through the coupling capacitor. In this way, the electron tunneling occurs one after another. Figure 4 shows the sample operation of Fig. 3. We can assume this operation is the “falling DOMINO lines” one. However, the electron tunneling occurred due to a quantum phenomenon with randomness. Therefore, the spreading speed of the mimicked falling is not constant, as shown in Fig. 4. We propose the use of multiple tunneling junctions (multiple-junction SEO (Fig. 5)) instead of a single tunneling junction in a SEO \cite{4}.

![Fig. 1: Schematic of SEO (R=77[\mu\Omega], C_l=4[\text{aF}], C_j=10[\text{aF}], R_j=0.2[\mu\Omega])](image1)

![Fig. 2: Sample operation of Fig. 1 (V_d=5.7[mV])](image2)

![Fig. 3: Schematic of one-dimensional chain of six SEOs (R=77[\mu\Omega], C_l=4[\text{aF}], C_j=10[\text{aF}], R_j=0.2[\mu\Omega])](image3)

![Fig. 4: Sample operation of Fig. 3 (V_d=5.0[mV])](image4)

![Fig. 5: Schematic of multiple tunneling junctions SEO (R=77[\mu\Omega], C_j=500[\text{aF}], R_j=0.2[\mu\Omega], 50 layers)](image5)

We can set the falling speed to almost constant in the lines by using the multiple-junction SEO. Figure 6 shows the sample operation of Fig. 5. We can confirm from Fig. 6 that the voltage change occurs due to multiple electron tunnelings. If multiple tunneling junction SEOs are arrayed with coupling capacitors just like in Fig. 3, the
operating principle does not change. However, we determined that the spreading speed of mimicked falling was almost constant.

The SEO cannot generate the second electron right after the first tunneling occurred because the first drew the change in $V_{node}$. As a result, the second cannot occur until the $V_{node}$ is recharged by $V_d$. Therefore, we can also mimic the “stopping falling dominoes by collision.”

Figure 7 shows the sample operation of Fig. 3, when the input trigger provides SEOs from both ends. For an easy explanation of Fig. 7, the node voltages of negative biased SEOs were multiplied by -1. We can see from Fig. 7 that the two signals from both ends of Fig. 3 collide at V3 and V4, and the propagation of the electron tunneling stops. These techniques give us a hint for how to apply the DOMINO logic to the SE circuit.

3. SIMULATION

We designed the basic logic circuits, e.g., OR, AND, and XOR, using our SE DOMINO logic circuit to demonstrate the SE calculator. We used multiple tunneling junction SEOs (containing 50 tunneling junctions in series) to design a basic logic circuit. We designed a multi-function logic circuit that can operate as an OR, AND, and XOR circuit, and changed its function by changing the bias voltage on one circuit in this study. By using the multi-function logic circuits, the structure of the circuit could be simplified to design the SE calculator.

Figure 8 shows a schematic of the multi-function SE DOMINO logic circuit. In Fig. 8, each blue circle represents one SEO, and the coupling capacitor between each SEO is omitted. For easy explanation of Fig. 8, we assigned a number to each SEO as based on X-Y coordinate (X,Y). For example, the SEO connected to trigger $A_{in}$ was numbered (2,4). In the multi-function SE DOMINO logic circuit, the input parts were (2,4) and (6,4) and the output part was (4,1). We used the Monte Carlo simulation to confirm the validity of our multi-function SE DOMINO logic circuit.

![Fig. 6: Sample operation of Fig. 5 (V$_{in}$=8.2[mV])](image)

![Fig. 7: Sample operation of Fig. 3 when two input triggers are provided from both ends (R=77[MΩ], C=2[aF], $C_{in}$=500[aF], $R_j$=0.2[MΩ], 50 layers, V$_{in}$=±8.1[mV])](image)

![Fig. 8: Schematic of multi-function SE DOMINO logic circuit (R=77[MΩ], C=2[aF], $C_{in}$=500[aF], $R_j$=0.2[MΩ], 50 layers)](image)
finally arrives at the output part. Figure 10 shows the simulated operation if $A_{in}$ was set to logical “1” and $B_{in}$ was set to logical “0”, and also if $A_{in}$ and $B_{in}$ were both logical “1.” We could confirm from the results that the OR mode of our SE DOMINO logic circuit operated correctly.

![Fig. 9: OR mode of SE DOMINO logic circuit](image)

Fig. 9: OR mode of SE DOMINO logic circuit
($R=77\,M\Omega$, $C_{l}=2\,aF$, $C_{j}=500\,aF$, $R_{j}=0.2\,M\Omega$, 50 layers)

Next, we confirmed the AND-mode operation of our SE DOMINO logic circuit. Figure 11 describes how to set the bias voltage of each SEO for an AND. In Fig. 11, a plus or a minus in the circle represents the polarity of the bias voltage of each SEO, and a blank circle represents a zero biased SEO that is a power-off just like shown in Fig. 9. Moreover, the bias voltage of only (4,4) was set lower than the others. In the lower biased SEO, two trigger signals from neighboring SEOs were required to produce electron tunneling at the SEO. In the AND mode, the path for the signal flows that the input signals from $A_{in}$ and $B_{in}$ followed was the same as that in the OR mode. Figure 12 shows the simulated operation if $A_{in}$ was a logical “1” and $B_{in}$ was a logical “0,” and also if $A_{in}$ and $B_{in}$ were both logical “1.” We confirmed from the results that the AND mode of our circuit operated correctly.

![Fig. 11: AND mode of SE DOMINO logic circuit](image)

Fig. 11: AND mode of SE DOMINO logic circuit
($R=77\,M\Omega$, $C_{l}=2\,aF$, $C_{j}=500\,aF$, $R_{j}=0.2\,M\Omega$, 50 layers)

![Fig. 12: Simulated operation of AND mode](image)

Fig. 12: Simulated operation of AND mode
($V_{d}=\pm 8.0[mV]$, $V_{d}$ at (4,4)=7.4[mV])
Finally, we confirmed the XOR-mode operation. Figure 13 describes how to set the bias voltage of each SEO for XOR. For the XOR-mode operation, the bias voltage of (2,2) and (6,2) was set lower than the others. In an XOR operation, a signal from $A_{in}$ follows the paths $(2,4)\rightarrow(1,3)$ and $(2,3)\rightarrow(2,2)\rightarrow(3,2)\rightarrow(3,3)\rightarrow(4,3)\rightarrow(5,3)\rightarrow(5,2)\rightarrow(6,1)\rightarrow(5,1)\rightarrow(4,1)$, and finally arrives at the output part. On the other hand, a signal from $B_{in}$ follows the paths $(6,4)\rightarrow(6,3)$ and $(7,3)\rightarrow(6,2)\rightarrow(5,2)\rightarrow(5,3)\rightarrow(4,3)\rightarrow(3,3)\rightarrow(3,2)\rightarrow(2,1)\rightarrow(3,1)\rightarrow(4,1)$, and finally arrives at the output part. Figure 14 shows the simulated operation if $A_{in}$ is a logical “1” and $B_{in}$ is a logical “0,” and if $A_{in}$ and $B_{in}$ were both logical “1.” If both input signals from $A_{in}$ and $B_{in}$ were a logical “1,” the two signals would collide at (4,3) and stop propagating as a result of the collision. We could confirm from the results that the XOR mode of our circuit operated correctly.

![Fig. 13: XOR mode of SE DOMINO logic circuit (R=77[\text{M} \Omega], C_{in}=2[\text{aF}], C_{in}=500[\text{aF}], R_{in}=0.2[\text{M} \Omega], 50 layers)](image)

![Fig. 14: Simulated operation of XOR mode (V_{dc}=\pm8.0[\text{mV}], V_{dc} at (2,2) and (6,2)=7.4[\text{mV}])](image)

We confirmed the multi-function SE DOMINO logic circuit can operate as OR, AND, and XOR circuits. However, the multi-function SE DOMINO logic circuit was based on the premise that there was no time interval between two input signals of $A_{in}$ and $B_{in}$. In other words, if there was time interval, the multi-function SE DOMINO logic circuit was not able to operate as OR, AND, and XOR circuits correctly. For example, when there was time interval between the two input signals of $A_{in}=\text{“1”}$ and $B_{in}=\text{“1”}$ in XOR mode, two input signals should not collide at (4,3) and we may fail to get correct output signal “0”. To solve this problem, we have to design the circuit which adjusts the time interval of two signals in future work.

4. CONCLUSION AND FUTURE WORK

We aimed at designing a new type of SE information processing circuit in this study. For this propose, we proposed the application of DOMINO logic theory to the SE circuit. Mimicking the behaviors of dominos is required in the circuit in order to use the DOMINO logic in the circuitry. For this, we used a SEO chain because we can mimic the DOMINO behavior by using SEO chains. To make sure that the DOMINO logic circuit was a suitable information processing architecture for the SE circuit, we designed and demonstrated the basic SE DOMINO logic circuits. In particular, we designed a multi-function SE DOMINO logic circuit and confirmed its correct operation. The multi-function SE DOMINO logic circuit can act as OR, AND, or XOR by changing the bias voltage. In our future work, we will design the circuit which adjusts the time interval of two signals. Then, we will combine the adjusting circuit and the multi-functions of SE DOMINO logic circuits, and design and demonstrate the SE calculator, e.g., a full adder by using a simulator.

We must consider the influence of noise for effective operation of our SE circuit. We did not simulate noise in this study, because we aimed to design a new type of SE information processing circuit. However, we believe we can overcome the influence of noise because previous studies [5,6] on the relation between the SE circuit and the influence of noise have been ongoing. Therefore, the proposals and demonstrations in this study showing that the DOMINO logic circuit is a viable candidate for use as the most appropriate information processing architecture for the SE circuit should be significant.
5. ACKNOWLEDGMENT

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6. REFERENCE