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Multifunctional device by using a quantum dot array

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1. Introduction

Single-electron transistors (SETs) have been attracted for use with future very low power and highly integrated LSIs [1]. However, the size of the device should be in the order of a few nano-meters for room-temperature operation. Although this size can be achieved by using recent nanotechnologies, tight control is difficult to achieve. Because the electrical characteristics of the SETs depend on the island size (or gate capacitance), we have to control it if we use the device as a switching device, like a MOS transistor. Here, we describe a new concept for a nano-dot array device, which positively uses the size fluctuation of the dots, and we show the principal functionality of the device using a simulation.

2. Device concept

A schematic image of the nanodot array device is shown in Fig. 1. Here, we assume a two-input-gate device. Each gate is coupled capacitively to many dots because the dots are small. The voltage applied to each gate changes the electrical potential of the dots according to the coupled capacitance. The current I_d flows only when the Coulomb blockade conditions of the dots lying between the source and drain are lifted. Because the array contains many dots, which enable electrons to select many tunneling paths, we can obtain complicated functions. If the drain current flows only when both the two input gate voltages, V_{g1} and V_{g2}, are "High", the function corresponds to an AND gate. If the current flows when at least one of the gates is "High", the function corresponds to an OR gate. Here, as shown in Fig. 1(c), the device also has another gate, a top gate, by which we can change the charging condition of all the dots at once. Thus, we can change the function of the array, for example, from an AND gate to an OR gate. The device can act with a selectable logic function.

3. Simulation

To determine the operation principle of the nanodot array device, we examined the smallest size of the array, shown in Fig. 2(a), by using a Monte Carlo simulation where the randomness of single-electron tunneling was taken into account. Figure 2(b) shows an equivalent circuit used for the simulation. We selected the average of the capacitances between each island and gates to be 2 aF and the average of the tunnel capacitances between the dots to be 1 aF. We assumed the standard deviation of these capacitances to be 0.2. We also assumed a tunnel resistance of 1 MΩ and a temperature of 10 K. We simulated the characteristics 20 times for different sets of arrays with the same average capacitances.

4. Results and Discussion

Some of the simulation results are shown in Fig. 3. The drain current I_d oscillates as a function of top gate voltage V_{g3}, and it shows quite different characteristics according to the combination of the two input gate voltages, V_{g1} and V_{g2}. Here, "1" corresponds to a "High" input voltage of 30 mV, and "0" corresponds to a "Low" input voltage of 0 V. The important point of the results is that the current switching characteristics change as a function of V_{g3}. For example, if we set the current threshold to 0.15 nA, the current level is "High" for (0,0) and (1,1), and it is "Low" for (0,1), (1,0) when the V_{g3} is between 0 and 0.045 V. This is exactly the function of an XNOR gate. But the function changes to a NOR gate when the V_{g3} is between 0.07 and 0.085 V.

In Fig. 4, we summarize the switching function for the typical logic functions of AND, OR, NAND, NOR, XOR, and XNOR, when we set the threshold drain current of 0.1 nA. The frequency of occurrence of the six logic functions is almost uniformly distributed.

To make the tendency clear, the relationship of the frequency of occurrence for each logic function is plotted as a function of the threshold current in Fig. 5. OR and NAND mainly appear when the threshold is low, and NOR and AND appear when it is high. XOR and XNOR appeared in the middle threshold. To clarify the feature, we checked all of the 20 trials of the simulations, where the nanodot arrays have different sets of capacitances —although the averages of the capacitances are the same. Among these, 17 simulations gave all of six typical logic functions, like those shown in Fig. 4. However, a few functions did not appear in the other three simulations. These are due to some special combination of capacitances in the small array. To achieve all six of the major logic functions consistently, we should enlarge the array somewhat.

5. Conclusion

We described a nanodot array device, in which we used the size fluctuation in the nanodots, and we clarified its basic operation using a simulation. The results show that controlling the gate voltage even in the small array size can change the logic function, although the performance is not sufficient to get all of the important functions. We believe that slightly enlarged arrays will enable them all to work properly.

6. Acknowledgements

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References

[1] Y. Takahashi, Y. Ono, A. Fujiwara, and H. Inokawa, Journal of Physics: Condensed Matter, **14**, 995 (2002).

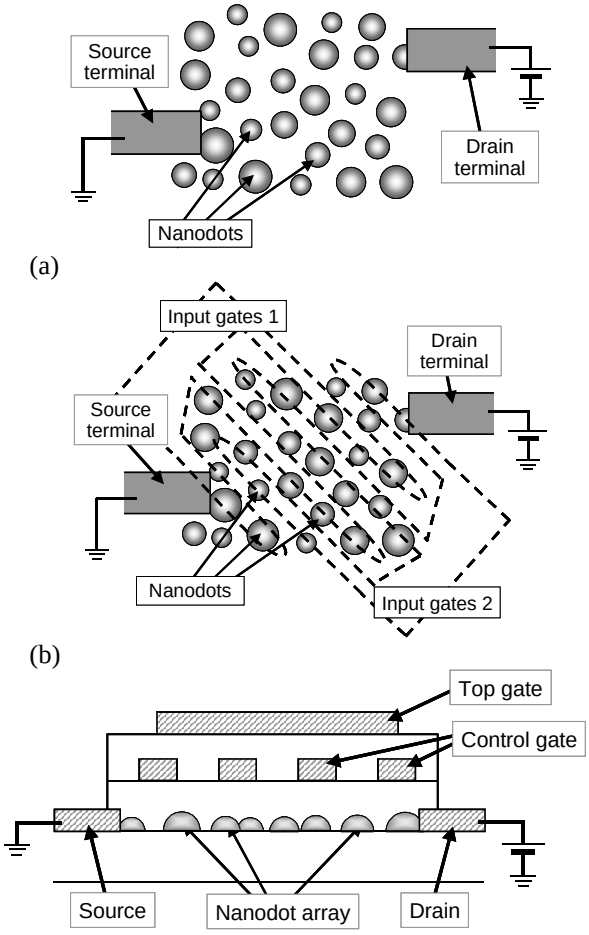

Fig. 1. Schematic top view of nanodot array (a), after attaching the control gates (b), cross section of the device (c).

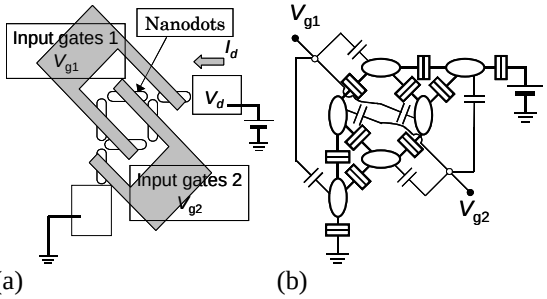

Fig. 2. Schematic top view of nanodot array used for simulation (a), and equivalent circuit (b).

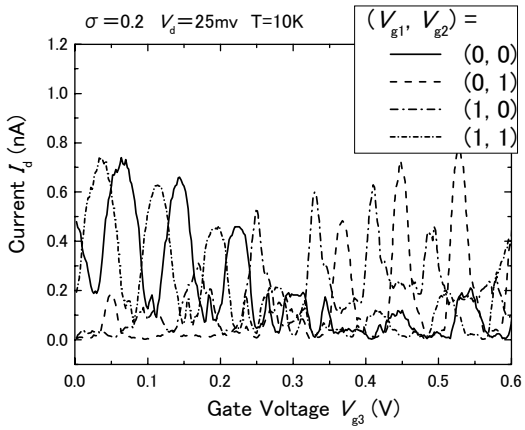

Fig. 3. Relationship between drain current and top gate voltage with V_{g1} and V_{g2} as parameters. “1” corresponds to a “High” input voltage of 30 mV, and “0” corresponds to a “Low” input voltage of 0 V.

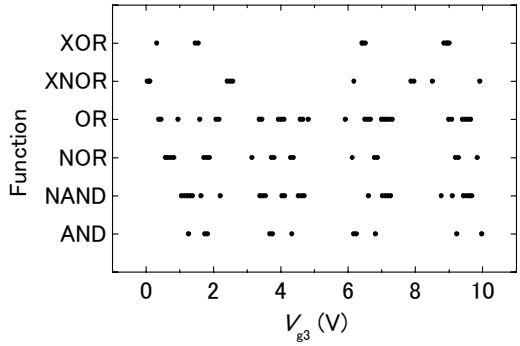

Fig. 4. Logic functions operated with two input gate as a function of top voltage V_{g3}. We rank the function as usable one only when the function is stable for a V_{g3} period of 10 mV.

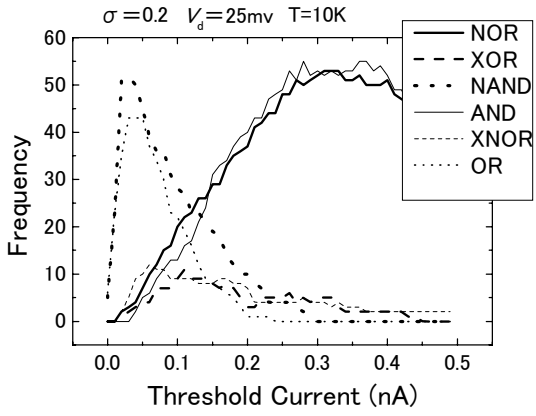

Fig. 5. Frequency of occurrences of typical logic functions of AND, OR, NAND, NOR, XOR, and XNOR when we change V_{g3} from 0 to 10 V. We rank the function as a usable one only when the function is stable for a V_{g3} period of 10 mV.