Hardware Implementation of a Single Electron Neural Network

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1. Introduction

Today, semiconductor integrated technology has developed remarkably and performance of an integrated circuit has improved more and more. Despite of such remarkable progress, there are many problems that are difficult to solve in real time operation such as combinatorial optimization problems. This is because that today's computers are designed to operate as a Neumann type computer which executes operations step by step. A neuro-computer is one of the candidate architecture to overcome these problems. In this architecture, computation is executed in parallel with very large number of processing units called a "neuron". Single electron devices are one of the most suitable device for hardware implementation of a neuro-computer. The reasons are as follow. First, it realizes ultimate low power consumption because it operates with only one or several electrons. Second, it must be made very small for high-temperature operation. Third, it has stochastic behavior due to an electron tunneling process. We investigate a single electron neural network by computer simulation and fabricate an ultra small tunnel junction required for single electron devices.

2. Principle of Single Electron Devices

A basic component of a single electron neural network is a single electron transistor (Figure 1). It consists of two tunnel junctions and a gate capacitor. An electrically isolated region between two tunnel junctions is called an "island". If free energy decreases after an electron tunneling, only such a tunneling process is allowed. This phenomenon is called "Coulomb Blockade". This is a classical phenomenon except for an electron tunneling. Figure 2 shows an I-V characteristic of a SET by computer simulation based on the Monte Carlo method[2]. Current flow has a peak when the number of electrons induced by the gate voltage V_G is a half integer, an electron can tunnel into the island. To observe Coulomb Blockade, electrostatic energy for one electron must be greater than thermal energy.

$$\frac{e^2}{2C} >> k_B T, \tag{1}$$

where, e is the electron charge, k_B is the Boltzmann constant, T is the absolute temperature, respectively. In order to satisfy these conditions at room temperature, a nano scale tunnel junction is required.

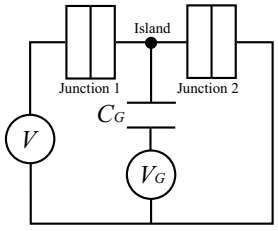

Figure 1: Single Electron Transistor

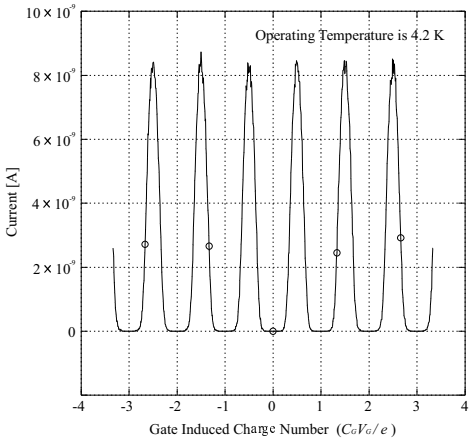

Figure 2: I-V Characteristic of a SET

3. Single Electron Neural Network

We design a single electron neuron with CSETs (Complementary Single Electron Transistor) suggested by Tucker[1]. A CSET consists of two SETs, a p-type SET and an n-type SET which works like as a p-MOS and an n-MOS in a CMOS, respectively. A CSET operates as an inverter. We investigate a characteristic of a CSET by computer simulation. Figure 3 shows the input-output characteristics of a CSET at 4.2 K. Stochastic behavior due to electron tunneling processes appears. Figure 4 shows the output distribution at $V_{in} = 0$.

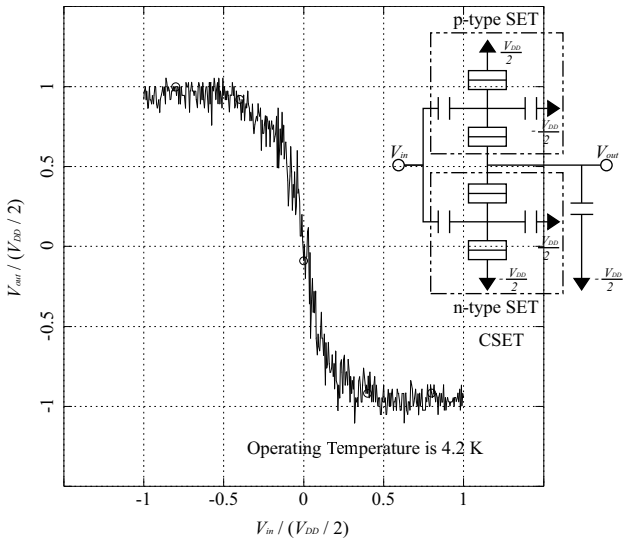

Figure 3: Input-Output Characteristics of a CSET

The distribution is almost like a Gaussian. Figure 5 shows the output spectrum at $V_{in} = 0$. The spectrum is almost a white (Side lobes at both ends are leakage errors of a FFT).

To implement a sigmoid function of a neuron, two CSETs are connected in series. From above results, it is said that a single electron neuron has an intrinsic noise source which distribution is like a Gaussian. We designed a single electron Hopfield network with single electron neurons and made it solve a 4-Queen problem in computer simulation[3]. In this simulation, we assume that an electron tunneling occurs at only one tunnel junction at the same time. But this assumption isn't correct strictly. There is high order tunneling processes called "co-tunneling phenomenon" in which several electrons tunnel at several tunnel junctions simultaneously due to quantum correlation[4]. The Monte Carlo based simulation can't treat co-tunneling phenomenon because its probability is very small. One of the method that can treat rare event precisely is to solve a master equation. In the simulation based on a master equation, first all transition probabilities between all possible states are calculated. Then state probabilities are renewed by multiplying the transition prob-

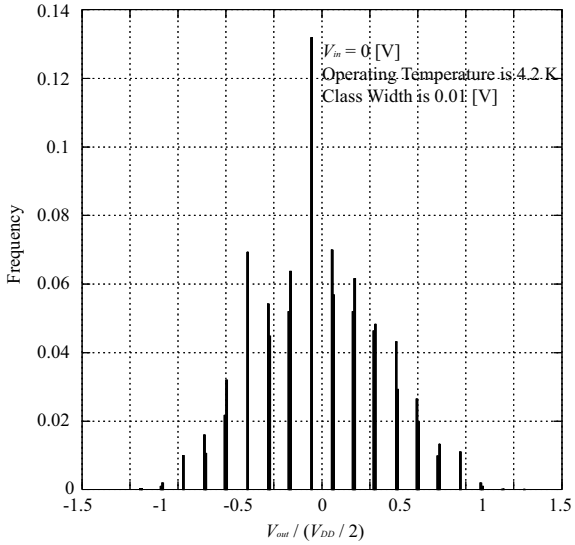

Figure 4: Output Distribution of a CSET

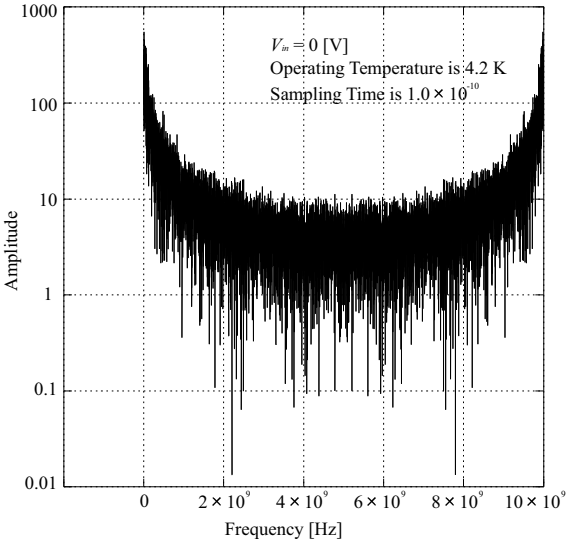

Figure 5: Output Spectrum of a CSET

ability matrix. Although this method is the most precise one, it can't treat a large system because required resources are enoumous. To avoid this difficulty, several methods that reduce the considered states have been suggested[5][6]. But a large scale simulation such as a neural network is as difficult as ever. Hence, we take co-tunneling phenomenon into the Monte Carlo based simulation roughly. In our method, all possible the 2nd order co-tunneling rates are calculated in a certain frequency and the 2nd order co-tunneling event that has the most shortest tunnel time is occurred. Figure 6 shows percentage of correct answer for the 4-Queen problem as a function of operating temperature. The more 2nd order tunneling occurs frequently, the more the peak of correct answer rises. It can be seen that these higher order tunneling enhances the performance as a neural network.

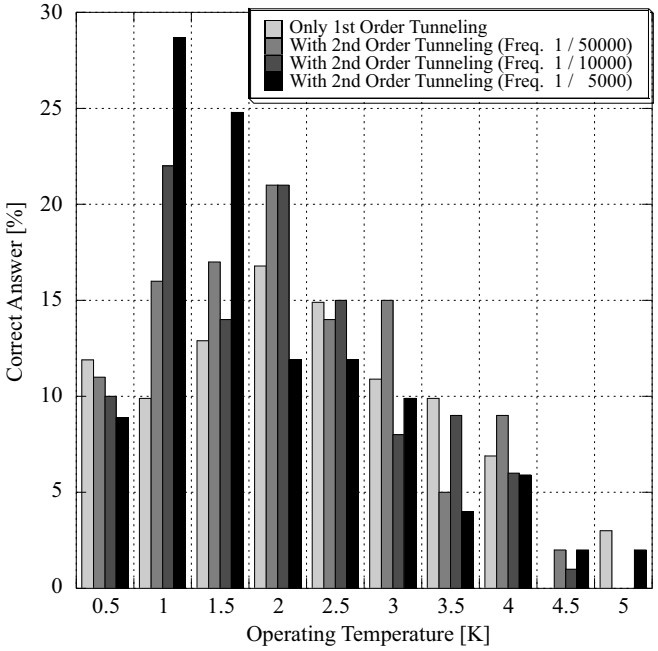

Figure 6: Percentage of Correct Answer as a Function of Operating Temperature

4. Device Fabrication

As mentioned in Section 2, nano scale tunnel junctions are required for single electron devices. We adopt shadow evaporation technique suggested by Dolan et.al[7]. It makes use of electron beam lithography to construct a resist bridge, and multiple angle metal deposition-oxidation-deposition to create narrow overlapping metal lines separated by thin tunnel barriers. Figure 7 (a) shows the SEM micrograph of a resist bridge fabricated by a MMA(8.5)MAA / PMMA(A7) multilayered EB resist process. Figure 7 (b) shows the Al overlapped pattern. The size of overlap can be easily controlled by modifying the size and shape of the resist bridge. Figure 8 shows double junctions for a SET and its enlarged SEM micrograph. Electrostatic capacity of the tunnel junction is about 200 aF. These devices are under fabrication and measured results will be given by the symposium.

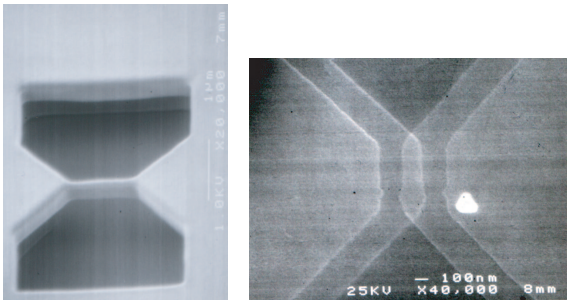

Figure 7: (a). Resist Bridge (b). Al Overlapped Pattern

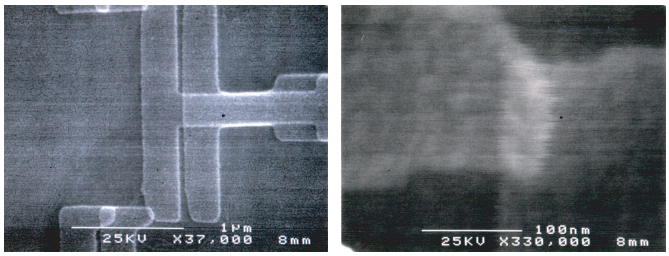

Figure 8: Double Junctions for a SET

5. Discussion

The connection between neurons is called a "synapse". The function of a synapse is multiplying an input signal and synapse weight. So far, we connect between single electron neurons with a capacitor. So a synapse weight is fixed depending on a capacitor. For general applications, we need a variable synapse weight, that is, a single electron multiplier. Using stochastic logic[8], a single electron multiplier may be made reasonably. To realize multiplier by stochastic logic, a random number generator is required. Figure 9 shows a 2-input multiplier using stochastic logic. By compared with random number, an input signal is encoded to a pulse sequence whose frequency is proportional to the value of the input. Multiplication is easily achieved with an AND gate. In a CMOS circuit, the area of a random number generator is relatively large. In addition, the generated random number is a pseudorandom number. On the other hand, a true random number can be generated with a small circuit area using

single electron devices. We now investigate a single electron random number generator almost like a CSET.

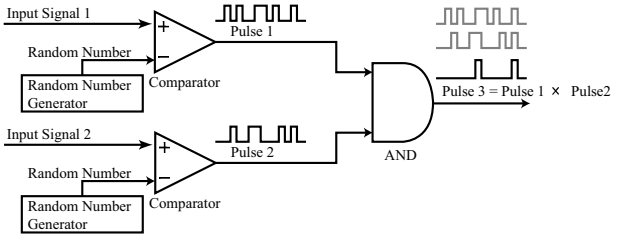

Figure 9: 2-Input Multiplier using Stochastic Logic

6. Conclusion

For practical applications using a neural network, a very large scale network is required. Although semiconductor integrated technology have developed remarkably, CMOS implementation for a neural network containing more than 1000 neurons is difficult because of enormous power consumption and a large circuit area. Single electron devices are one of the most candidate device that can achieve ultra low power consumption and a small circuit area. We investigate performance of a single electron neural network with computer simulation and find that the intrinsic noise of single electron devices can be used effectively. Co-tunneling phenomena, which are generally considered as a troublesome quantum effect, also contribute to improvement of network performance. We fabricate an ultra small tunnel junction whose electrostatic capacity is about 200 aF by shadow evaporation technique. Electrostatic energy of the junction is comparable with thermal energy of liquid helium.

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