Chapter 6
Application of Single Electron Devices Utilizing Stochastic Dynamics

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ABSTRACT

Single electron devices utilizing the Coulomb blockade phenomenon have attractive features such as extreme low power consumption, one by one electron flow controllability, small device size, etc. However, besides promising applications such as the current standard and charge detection, it is not easy to apply the single electron devices to conventional computational tasks due to its stochastic operation and low amplification capability. Therefore, it is important for us to consider suitable applications of single electron devices. In this paper, we show three applications such as a noise generator, a stochastic neural network, and a charge detector employing stochastic resonance. Through these applications, we see the advantages of single electron devices and study the direction of applications.

INTRODUCTION

The semiconductor integrated circuit technology has formed the basis of today’s information oriented society and supported its continuous progress. However, several problems such as high power density and quantum effects have been serious recently. On the other hand, recent development of nanotechnologies realizes the use of a nano-scale device for us. On such a tiny tunnel junction, electron tunneling is restricted by the Coulomb force between electrons, and this phenomenon is called Coulomb blockade. A single electron device based on the Coulomb blockade is one of the candidate devices which can overcome the difficulties of conventional LSIs. It has various advantages such as extreme low power consumption, high charge sensitivity, fine electron flow controllability, small area occupancy, and so on. Representative applications are charge detection, quantum computing, and current standard, etc. On the other hand, its low gain property and stochastic operation could be main obstacles when we apply it to a conventional
logic circuit. Therefore, a single electron device should be utilized for some specific fields where we can take its advantages reasonably.

In this paper, first we briefly show the theoretical background and simulation methods of single electron devices. Next, we introduce three application examples of single electron devices successively, and finally discuss those advantages in order to view the effectiveness of the single electron electronics. The first application is a random number generator. Though Coulomb blockade phenomenon is understood by the classical electromagnetism, electron tunneling is a quantum stochastic process, so that a single electron device has a stochastic property intrinsically. By constructing a symmetrical bistable circuitry with complementary single electron transistors (CSETs) proposed by Tucker (1992), and setting its initial state to an unstable equilibrium point, a random number is obtained. The second application is a hardware neural network. A huge number of neurons are required for its practical use, and it is said that artificial neural networks (ANNs) comprising about $10^3$ neurons are necessary for practical applications such as pattern recognition and classification problems (Dayhoff, 1990). We introduce a single electron neural network using stochastic logic proposed by Gaines (1969), in which a digital or an analog value is converted to the firing rate of a stochastic pulse sequence. Since multiplication can be done with a single AND gate, one can reduce the circuit size greatly. Furthermore, its power consumption is kept reasonably low thanks to the low power property of single electron transistors. The last one is related to charge detection. Stochastic resonance (SR) has been known as a nonlinear phenomenon whereby the addition of noise can enhance the detection capability of weak stimuli. An optimal amount of added noise results in the maximum enhancement, whereas further increases in the noise intensity only degrade detectability. The detection of weak signals in noisy environment becomes an important subject in the context of the development of nanotechnologies. Especially, it could be a critical subject for the practical application of quantum devices. As is well known, a single electron device operates as a good charge detector. Hence, we introduce the stochastic resonance with a single electron turnstile and discuss its performance as a charge detector.

THEORETICAL BACKGROUND AND SIMULATION METHODS

Coulomb Blockade

Operation of single electron devices is based on the Coulomb blockade phenomenon on ultra small tunnel junctions (Likharev, 1988; Averin & Likharev, 1991; Grabert & Devoret, 1992). Let us consider a junction whose electrostatic capacity is $C$. Its charging energy is given as $E = Q^2/2C$, where $Q$ is the charge on the junction. When an electron tunnels, the energy change is given as

$$\Delta E = \left(\frac{Q - e}{2C}\right)^2 - \frac{Q^2}{2C} = \frac{e^2}{2C} - eV,$$  \hspace{1cm} (1)

where $e$ and $V(=Q/C)$ denote the elementary charge and the voltage across the junction, respectively. The second term in the right side can be viewed as the work done by a voltage source. The fact that an electron tunneling accompanies energy dissipation gives the relation $\Delta E < 0$. Therefore tunneling does not occur if

$$-\frac{e}{2C} < V < \frac{e}{2C}.$$  \hspace{1cm} (2)

Therefore, this is called Coulomb blockade. There are two conditions required for us to observe a Coulomb blockade with a real device.
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