Investigation on Stochastic Resonance in Quantum Dot and Its Summing Network

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ABSTRACT

Stochastic resonance behavior of single electrons in a quantum dot and its summing network is investigated theoretically. Dynamic behavior of the single electron in the system at finite temperature is analyzed using a master equation with a tunneling transition rate. The analytical model indicates that an input-output correlation has a peak as a function of temperature, which confirms the appearance of the stochastic resonance. The peak position and height depend on charging energy, tunnel resistance, and input signal frequency. It is also found that the correlation is enhanced by formation of a summing network integrating quantum dots in parallel. The present model quantitatively explains the stochastic resonance behaviors of the single electrons predicted by a circuit simulation (Oya, Asai, & Amemiya, 2007). [Article copies are available for purchase from InfoSci-on-Demand.com]

Keywords: Stochastic Resonance, Single Electron, Quantum Dot, Summing Network

INTRODUCTION

Single electron devices and their integrated circuits are expected to play important roles in future ultra-small and ultra-low-power nanoelectronics. However, there are several problems preventing their practical use. The most serious one is fluctuation, such as thermal and threshold voltage fluctuations. Decreasing the size for increasing operation temperature as well as increasing integration density, the device becomes very sensitive to various fluctuations. It is obvious that atomic-level imperfection of the structure is inevitable in large-scale integrated circuits (LSIs) integrating over million devices. This means that fluctuation of device characteristics is also inevitable. At this stage, a key issue in the single electron devices and circuits is to find a way to increase robustness against fluctuation rather than to remove or suppress it. Recently, it has been pointed out that stochastic resonance (SR) serves this purpose. It is a unique phenomenon in which response to a weak signal is enhanced by adding noise (Benzi, Sutera, & Vulpiani, 1981; Gammaitoni, Hänggi, Jung, & Marchesoni, 1998). It has been found to
work in various biological systems (Douglass, Wilkens, Pantazelou, & Moss, 1993; Funke, K., Kerscher, N. J., & Wörgötter, 2007; Moss, Ward, & Sannita, 2004) and contribute to the robustness of the systems against fluctuation, even having molecular-level fine structures. The SR is also known to occur artificially in various electronic systems, such as Schmitt trigger circuits (Fauve & Heslot, 1983), pn-junction diodes (Jung & Wiesenfeld, 1997), Josephson junctions (Hibbs, Singsaas, Jacobs, Bulsara, Bekkedahl, & Moss, 1995), carbon nanotubes (Lee, Liu, Zhou, & Kosko, 2006), and nanowire field effect transistors (Kasai & Asai, 2008). Recently, Kagaya, Oya, Asai, & Amemiya (2005) and Oya, Asai, & Amemiya (2007) predicted the appearance of the SR in single electron systems and demonstrated by circuit simulation. A noteworthy indication is that the response becomes robust against temperature by forming a summing network and high correlation value is kept even when temperature far exceeds the charging energy. In addition, the system can work even with threshold variation under finite thermal fluctuation. These behaviors agree with "without tuning" nature of the stochastic resonance indicated by Collins, Chow, & Imhoff (1995). However, at present, the mechanism of the single electron SR as well as physical parameters controlling the phenomenon have not been understood yet.

The purpose of this paper is to theoretically study the single electron SR in a quantum dot and its summing network. First, a system for the single electron SR is described and the behavior of the single electron is analyzed using a master equation with simple approximations. Then, the calculated results are presented and discussed. Comparison with simulation results reported by Oya, Asai, & Amemiya (2007) is also shown.

**MODELING AND ANALYSIS**

Figure 1 shows schematics of a quantum dot and its summing network studied in this paper. The quantum dot in Figure 1(a) consists of a normal capacitor, $C_n$, and a tunnel capacitor, $C_j$. The network in Figure 1(b) integrates quantum dots in parallel. Each connects to with a common voltage input and a summing circuit. The numbers of electrons in the dots are summed up using the summing circuit and it is measured as output of the system. When the capacitors of the dot are quite small, tunneling of a single electron into the dot results in non-negligible increase of electrostatic potential. This blocks the tunneling of another electron into the dot, called Coulomb blockade. Charging energy, $E_{c}$, is an energy to overcome the blockade, given by $E_{c} = q^2/C_n$, where $C = C_n + C_j$ and $q$ is the elemental charge. When positive voltage, $V$, is applied to the normal capacitance, potential of the dot decreases and the electron in the right-hand side of the tunnel capacitor is attracted to the dot. When $V$ exceeds $E_{c}/q$, the electron can tunnel into the dot. Then, the potential of the dot increases by $E_{c}/q$. Further increasing $V$, the system repeats the above process. Changes of the potential and the number of electrons in the dot are schematically shown in Figure 2. A total dot capacitance can be roughly estimated by $2 \times 8 \varepsilon R$, with a dielectric constant $\varepsilon$ and the size of junction $R$. The modern semiconductor technology can realize 10 nm-size structures. When $R = 10$ nm, the capacitance of 20 aF is obtained for a semiconductor dot. This results in the charging energy of 8 meV, which corresponds to 90 K in temperature. Thus, for room temperature operation of the single electron device, the dot size of a few nm or less is necessary. In this study, energy quantization due to the quantum mechanical effect is ignored for simplicity. It mainly affects on the threshold voltage in addition or removal of an electron. Usually the effect is considered an origin of the fluctuation of the threshold voltage. Here, it should be mentioned that such fluctuation should be canceled out when the SR takes place (Collins, Chow, & Imhoff, 1995).

In the present system, input is $V$ and output is the number of electrons in the dot, $n(t)$. When $V$ is smaller than $E_{c}/q$, it is enough for the analysis to consider a limited voltage range as shown in Figure 2 by un-hatched region, where $n = 0$ or
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