Microelectronics Journal 40 (2009) 543–546

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Electrical characteristics and modelling of multi-island single-electron transistor using SIMON simulator

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ARTICLE INFO

Available online 8 August 2008

Keywords:
MISET
SIMON
Orthodox theory
Coulomb oscillation
SET

ABSTRACT

In this paper, we present a multi-island single-electron transistor (MISET) model based on the orthodox theory and solving the master equation. Using SIMON simulator, we investigate the electrical characteristics of single-electron transistors (SETs) based on multiple islands and show the temperature dependence of the Coulomb oscillation of the SET with one to six islands as a function of gate voltage V_g in the temperature range from $T=5$ to 50 K. Values of current tend to increase proportionally with temperature. For a high drain voltage, the MISET behaved as a single-island device. This is probably because the multiple islands were electrically enlarged and merged into a single island owing to the high applied drain voltage. Finally, we compare the advantages of MISET face to single-island SETs with identical dimensions of islands.

1. Introduction

The multiple-island single-electron chains of tunnelling junctions are promising for the development of a variety of device structures for nanoelectronics [1,2]. Their main advantages in comparison to single-island single-electron transistors (SETs) with identical dimensions of islands and tunneling junctions are a higher threshold voltage of Coulomb blockade and, as a consequence, a higher operation temperature. As a rule, in the models of multiple-island single-electron chains, the parameters fitting the theory to the experiment are the capacitances and resistances of tunnelling junctions. Due to this circumstance, the relationship to the physics of processes in these device structures is lost to a great extent. The models of two-island and multiple-island single-electron chains on the basis of the solution of the Poisson equation, as well as on the basis of either the solution of the master equation or using the Monte Carlo method, were suggested previously [3,4]. These models are free of the above disadvantage to some extent. The purpose of this study is the theoretical analysis of the characteristics of the multiple-island single-electron chains.

In this paper, we describe firstly a new schematic double-island SET model and propose a compact, physically based, analytical SET circuit. Then, we investigate, using SIMON simulator, the electrical characteristics of SETs based on multiple islands and show the temperature dependence of the Coulomb oscillation of the SET with one to six islands as a function of gate voltage V_g in the temperature range from $T=5$ to 50 K. For a high drain voltage, the multi-island single-electron transistor (MISET) behaved as a single-island device. Finally, we expose some advantages of MISET in comparison to single-island SETs.

2. The double island SET

The orthodox theory of single-electron tunnelling succeeds in describing the electrical conduction to some extent. However, important elements such as cotunneling and tunneling into or out of quantum levels are not taken into account.

The double dot is modelled as a network of resistors and capacitors (Fig. 1). The number of electrons on dot 1(2) is $N_1(2)$. Each dot is capacitively coupled to a gate voltage $V_{g1}(2)$ through a capacitor $C_{g1}(2)$ and to the source (S) or drain (D) contact through a tunnel barrier represented by a resistor RL(R) and a capacitor CL(R) connected in parallel. The dots are coupled to each other by a tunnel barrier represented by a resistor R_m and a capacitor C_m in parallel. The bias voltage, V, is applied to the source contact with the drain contact grounded (asymmetric bias). In this section we consider the linear transport regime, i.e. $V \approx 0$. If cross-capacitances (such as between V_{g1} and dot 2), other voltage sources and stray capacitances are negligible, the double

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doi:10.1016/j.mejo.2008.06.089

dot electrostatic energy reads

$$U(N1,N2) = \frac{1}{2}N_1^2E_{c1} + \frac{1}{2}N_2^2E_{c2} + N_1N_2E_{cm} + f(V_{g1},V_{g2})$$

$$f(V_{g1},V_{g2}) = \frac{1}{-|e|}\{C_{g1}V_{g1}(N_1E_{c1}+N_1E_{cm}) + C_{g2}V_{g2}(N_1E_{cm}+N_2E_{c2}\} + \frac{1}{e^2}\left\{\frac{1}{2}C_{g1}^2V_{g1}^2E_{c1} + \frac{1}{2}C_{g2}^2V_{g2}^2E_{c2} + C_{g1}V_{g1}C_{g2}C_{g2}E_{cm}\right\}$$

where $E_{c1}(2)$ is the charging energy of the individual dot 1(2) and E_{cm} is the electrostatic coupling energy. The coupling energy E_{cm} is the change in the energy of one dot when an electron is added to the other dot. These energies can be expressed in terms of the capacitances as follows:

$$E_{c1} = \frac{e^2}{C1}\left(\frac{1}{1-C_m^2/C1C2}\right),\; E_{c2} = \frac{e^2}{C2}\left(\frac{1}{1-C_m^2/C1C2}\right),$$
$$E_m = \frac{e^2}{C_m}\left(\frac{1}{C1C2/C_m^2-1}\right)$$

here $C1(2)$ is the sum of all capacitances attached to dot 1(2) including C_m: $C1(2) = CL(R)+C_{g1}(2)+C_m$. Note that $E_{c1}(2)$ can be interpreted as the charging energy of the single, uncoupled dot 1(2) multiplied by a correction factor that accounts for the coupling. When $C_m = 0$ and hence $E_{cm} = 0$, Eq. (1) reduces to

$$U(N1,N2) = \frac{(-N1|e| + C_{g1}V_{g1})^2}{2C1} + \frac{(-N2|e| + C_{g2}V_{g2})^2}{2C2}$$

We note that tunnel barriers are characterized by a resistor and a capacitor, as indicated in the inset.

A linear array of three tunnel junctions forms a device with two islands; the DISET is presented in Fig. 2, a part from an increased parameter space due to an additional gate; the inter-island coupling gives rise to some new properties [6]. Starting with the electrostatics, the Coulomb blockade characteristics of the DISET are derived.

The two islands are biased by a source-drain voltage V_{ds}, and the occupation of the islands can be altered by gate voltages V_{g1} and V_{g2}. (Cross-capacitances C_{g1} and C_{g2} between gate 1 and island 2 and gate 2 and island 1, respectively, have been omitted for clarity.) The islands are coupled via tunnel junction with capacitance C_m and resistance R_m.

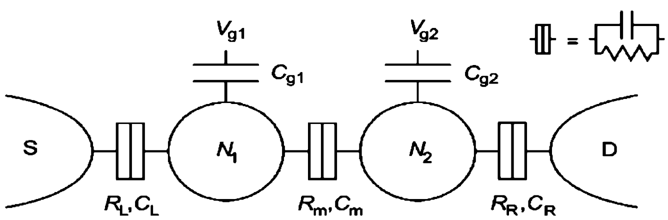

Fig. 1. Network of resistors and capacitors representing two quantum dots coupled in series [5].

3. Discussion and results

3.1. Simulation results using SIMON

We use this schematic circuit diagram of DISET in SIMON simulator, presented in Fig. 3; here we use only one polarisation source "V_d" because we choose the source potential at zero; after that we fix some parameters like temperature, mode of simulation, drain polarisation, capacitances and tunnel junction values and observe the charge and the current forms at $T = 5$ K.

The I_d–V_g characteristic obtained using SIMON is presented in Fig. 4.

At $T = 5$ K, we make the same hypothesis to DISET and 3ISET (capacities and resistors values) and simulate the current through tunnel junction 1 as a function of gate voltage (Fig. 5).

We note that, for a 4 Island SET, there are 4 picks, and two major peaks and two small peaks of the same value supply.

For a 5ISET, there are 2 picks left and 2 picks and a straight in the middle.

For a 6ISET, there are 3 major peaks and 3 small peaks.

We remark symmetric curves because we have chosen equals to the values of capacitances and tunnel junctions.

3.2. Temperature dependence

Fig. 6 shows the drain current I_d as a function of the gate voltage V_g at 5 K. Coulomb diamonds are clearly observed.

Figs. 6 and 7 show the temperature dependence of the Coulomb oscillation, respectively, for double-island SET and three-island SET in the temperature range from 5 to 50 K. Coulomb oscillations can clearly be observed up to 50 K. The temperature dependences of I_d at the peaks. It is noted that the value of central peak increases with increasing temperature. For large temperature, our structure tends to a structure with an island.

3.3. Drain polarisation influence

For a high drain voltage, the SET behaved as a single-island device. This is probably because the three islands are electrically enlarged and merged into a single island owing to the high applied drain voltage. The height of tunnel barriers is lowered at a high applied V_d. Owing to the various barrier heights in the

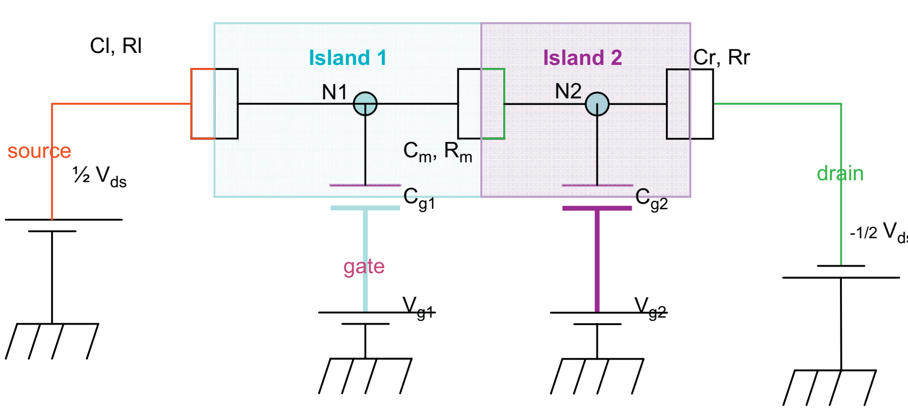

Fig. 2. Schematic circuit diagram of a DISET.