Modeling of Single-Electron Transistor in Advanced Design System

Huong Thi Thu Tran, Manh Duy Luong, and Nguyen Huy Hoang
Dept. Radio and Electronics Engineering
Le Quy Don Technical University
Hanoi, Vietnam
saohom10385@gmail.com

***Abstract*— Single-electron transistor (SET) was successfully modeled in Advanced Design System (ADS) software. Simulation of the model in ADS (modeled SET) showed typical characteristics of SET including Coulomb blockade (CB) region and Coulomb oscillations. The simulated results of the modeled SET were compared with those of a commercial SIMON simulator in certain ranges of drain-source voltage and temperature validating accuracy of the modeling method.**

Single-electron transistor, Advanced Design System, modeling.

I. Introduction

Single-electron (SE) devices with salient features of nanometer-scale sizes and low power consumption are prospects of large-scale integrated (LSI) circuit [1]. Single-electron transistor (SET) is one of the most important devices in this field [2]. It is worth analyzing characteristics of SET. One of the most common commercial simulators for simulation of SET is SIMON. SIMON basically using Monte Carlo method provides a good way to look insight fundamental phenomena of SET such as Coulomb blockade (CB) and Coulomb oscillations. However, the drawback of the SIMON simulator is that it takes time for calculation. In addition, it has components limited to SE devices [3]. To overcome these issues and to widen realistic application of SET in the trend combining with conventional semiconductor devices, it is urgent to find out a useful program for this purpose. Advanced Design System (ADS) developed by Keysight is the electronic design software which provides plentiful libraries and powerful simulation technologies [4]. This simulator incorporates a variety of semiconductor devices libraries including BJT, CMOS, HEMT, and HBT. This paper aims to model the SET in such a conventional circuit simulator.

For simplicity and convenience of analyzing LSI circuits, an analytical model is more useful than a numerical simulator such as SIMON. To obtain not only accuracy over a relatively wide range of drain-source voltage V_{DS} and temperature T but also coverage for both cases of symmetric and asymmetric SETs, the analytic model developed by H. Inokawa and Y. Takahashi is used for modeling SET in ADS [5]. Using this analytic model, drain current I_D is calculated as a summation of currents for different numbers of electrons on the island of SET to observe Coulomb oscillations.

II. Single-Electron Transistor Model

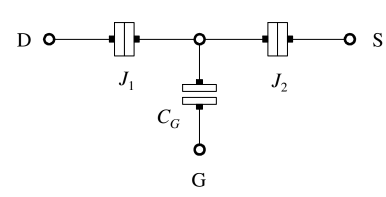
Figs. 1(a) and (b) describe a schematic diagram of SET in SIMON and modeling of SET in ADS (modeled SET), respectively. In Fig. 1(a), the SET is composed of two tunnel junctions J_1 (capacitance C_1 and resistance R_1) and J_2 (capacitance C_2 and resistance R_2) and a gate capacitor C_G. Three terminals of the SET (Fig. 1(a)) and the modeled SET (Fig. 1(b)) called Source (S), Drain (D), and Gate (G) are supplied by source, drain, and gate voltages V_S, V_D, and V_G to ground. Let assume that $V_S = 0$, $V_D = V_{DS}$, $V_G = V_{GS}$; n is the number of electrons on the island.

Calculation of the modeled SET is implemented by using following equations [5].

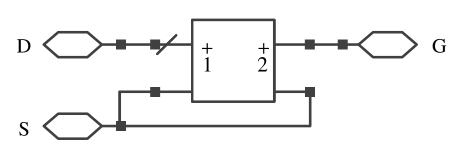
$$I_n = \{[e/(4C_\Sigma R_T)] \times[(1-r^2)(V_{GS\_norm}{}^2 - V_{DS\_norm}{}^2)\sinh(V_{DS\_norm}/T_{norm})]/A\}, \quad (1)$$

$$A = \{V_{GS\_norm}\sinh(V_{GS\_norm}/T_{norm}) - V_{DS\_norm}\sinh(V_{DS\_norm}/T_{norm}) + r[V_{DS\_norm}\sinh(V_{GS\_norm}/T_{norm}) - V_{GS\_norm}\sinh(V_{DS\_norm}/T_{norm})]\}, \quad (2)$$

$$V_{GS\_norm} = 2C_GV_{GS}/e - (C_G + C_2 - C_1)V_{DS}/e - 2n - 1. \quad (3)$$



(a)



(b)

Figure 1. (a) Schematic diagram of SET in SIMON. (b) Modeled SET in ADS.

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Here, total capacitance C_Σ of the SET is $C_1 + C_2 + C_G$; harmonic mean of tunneling resistances R_T is $2R_1R_2/(R_1+R_2)$; asymmetric factor r is $(R_1–R_2)/(R_1+R_2)$. $V_{DS\_norm} = V_{DS}C_\Sigma/e$, V_{GS_norm}, and $T_{norm} = 2k_BTC_\Sigma/e^2$ are normalized drain-source voltage, normalized gate-source voltage, and normalized temperature, respectively; e is the elementary charge; k_B is the Boltzmann constant. I_D is the summation of I_n with different n.

In this paper, we consider both SET structures including symmetry and asymmetry. Parameters of two tunnel junctions are the same in a symmetric SET whereas they are different in an asymmetric SET. In the below simulation, we assume that the symmetric SET has parameters: $C_1 = C_2 = 0.1$ aF, $R_1 = R_2 = 5$ MΩ, $C_G = 0.1$ aF; the asymmetric SET has parameters: $C_1 = 0.01$ aF, $C_2 = 0.13$ aF, $R_1 = 1$ MΩ, $R_2 = 13$ MΩ, $C_G = 0.16$ aF. As an example, the modeled SET is calculated with n from –3 to +3.

Current-voltage characteristics of the symmetric and asymmetric SET at 300 K are described in Figs. 2 and 3.

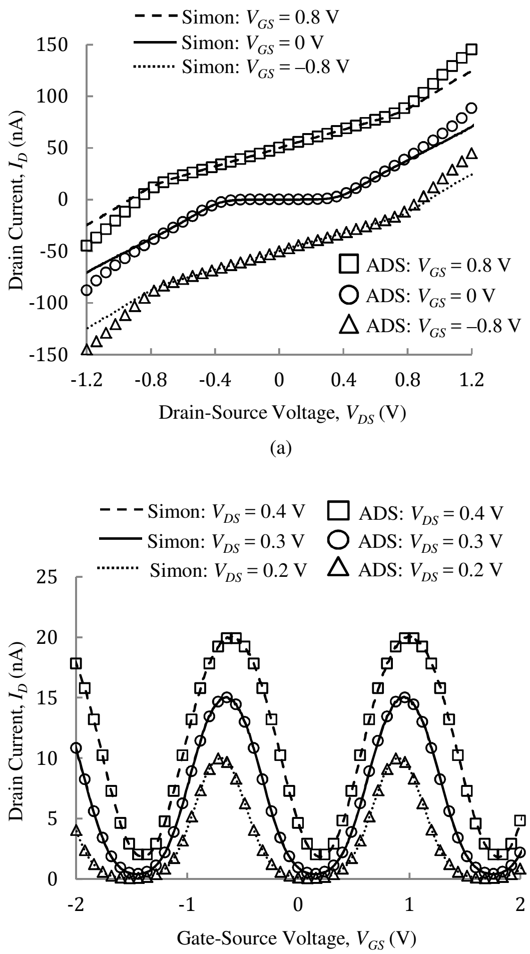

Figure 2. Current-voltage characteristics of the symmetric SET at 300 K. (a) I_D versus V_{DS} when V_{GS} varies from –0.8 V to 0.8 V in 0.8 V steps. For clarity, the curves for V_{GS} = –0.8, 0.8 V are respectively shifted by –50, 50 nA. (b) I_D versus V_{GS} as V_{DS} varies from 0.2 V to 0.4 V in 0.1 V steps.

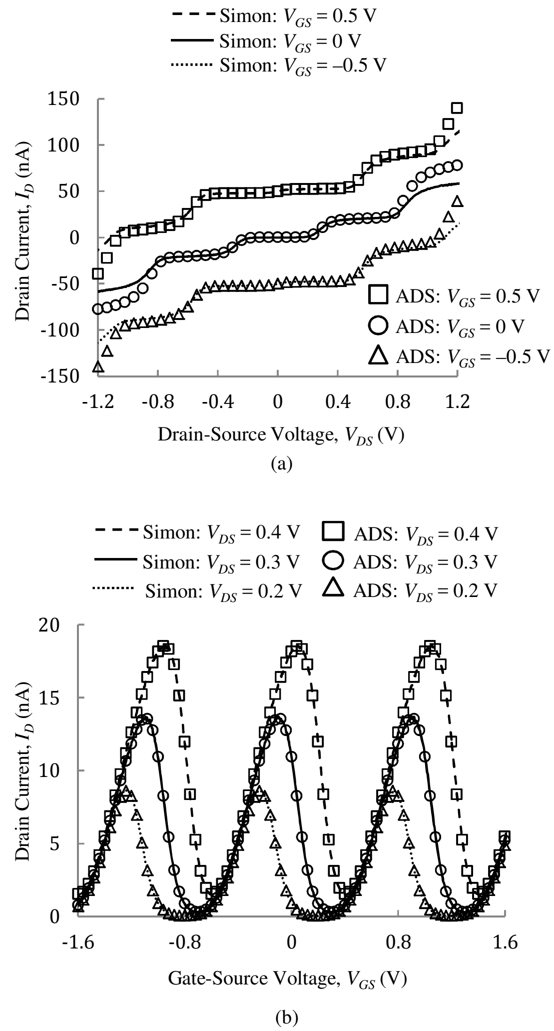

Figure 3. Current-voltage characteristics of the asymmetric SET at 300 K. (a) I_D plotted as a function of V_{DS} when V_{GS} changes from –0.5 V to 0.5 V in 0.5 V steps. For clarity, the curves for V_{GS} = –0.5, 0.5 V are respectively shifted by –50, 50 nA. (b) I_D plotted as a function of V_{GS} when V_{DS} changes from 0.2 V to 0.4 V in 0.1 V steps.

The lines (dot, solid, and dash) and symbols (triangle, circle, and square) represent results simulated by SIMON simulator and ADS software, respectively. Fig. 2(a) and Fig. 3(a) show $I_D – V_{DS}$ characteristics with different V_{GS}. The modeled SET can reproduce the SET characteristics with a Coulomb blockade (CB) region at V_{GS} = 0 V and disappearances of the CB region at $V_{GS} = \pm e/2C_G$ (±0.8 V in Fig. 2(a) and ±0.5 V in Fig. 3(a)). However, accuracy of the modeled SET is satisfied in certain condition of voltage and temperature due to the accuracy of the analytic model in [5]. In this paper, at V_{GS} = 0 V, deviation between drain currents simulated by ADS and SIMON, $|(I_{ADS} – I_{SIMON})/ I_{SIMON}| \times 100\%$, is less than 5% providing that $V_{DS\_norm} < 1.4$. T_{norm} is relatively high, which is approximately 0.1.

Fig. 2(b) and Fig. 3(b) describe $I_D – V_{GS}$ characteristics with various V_{DS}. Coulomb oscillations observed in the $I_D – V_{GS}$ characteristics of the modeled SET coincide well with those of

SIMON. The modeled SET exhibits typical phenomena of the asymmetric SET with Coulomb staircase outside the CB region (Fig. 3(a)) and asymmetric shapes in Coulomb oscillations (Fig. 3(b)).

III. CONCLUSIONS

The SET, a nanoscale device, is successfully modeled in the conventional circuit simulator ADS with a relatively high accuracy. The modeled SET exhibits the typical characteristics of SET including CB region and Coulomb oscillations in both symmetric and asymmetric structures. The modeled SET will bring promising prospects in further study of nanoscale devices with conventional semiconductor devices.

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