Continuous and Symmetric Trans-Capacitance Compact Model for Triple-Gate Junctionless MOSFETs

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ABSTRACT

In this work, a continuous and symmetric trans-capacitance compact model for triple-gate junctionless MOSFETs is presented, valid in all regions of operation. Initially, the expressions of the gate, drain and source total charges are analytically derived based on a continuous and symmetric drain current compact model already developed. Then, the intrinsic capacitances are calculated via the differentiation of the terminal charges, verified against TCAD simulation data. The AC symmetry tests of the trans-capacitance compact model are thoroughly investigated.

Keywords: Junctionless triple-gate MOSFETs, trans-capacitance compact model, AC symmetry tests.

1. Introduction

Junctionless (JL) transistors have attracted much attention lately posing as candidates in the continuation of Moore's Law. Attributes provided include short-channel effects (SCE) immunity, absence of p-n junctions that leads to a much more simplified fabrication process and improved reliability compared with the conventional MOSFETs [1].

JL transistors have recently been evaluated with regards to their analog performance. Studies have shown that JL transistors present superior analog properties, when compared to their inversion-mode (IM) counterparts and thus, their use in analog-based circuits is encouraged [2]. Generally, in order to design circuits, compact analytical models are required. These models should not only be in terms of the drain current of the respective devices, but also should describe the dynamic behavior of the devices through the inclusion of trans-capacitances.

Although there are numerous compact drain current models reported for JL transistors for long-channel [3-10] and short channel devices [11-16], the literature reveals only a handful of intrinsic capacitance models. For double-gate junctionless transistors, a charge based analytical model for long-channel devices has been developed in [17]. For gate-all-around (GAA) junctionless devices, [18] is presenting an analytical model for trans-capacitances for long-channel devices whereas [19] is referring to a gate length of 100 nm. For triple-gate JL MOSFETs, an analytical trans-capacitance model has been developed only in [20], which is described in terms of the potential at the gate interface and the potential at the buried oxide/silicon interface. It includes short channel effects (SCE) and tests the dynamic behavior of devices with gate length down to 30 nm. However, this model requires partial derivatives of multiple intermediate variables making it complicated, whereas AC symmetry tests of the model are missing.

An attribute of the analytical models often not considered is the symmetry condition around the drain voltage $V_{ds} = 0$ [21]. Specifically, any modern compact model should be able to succeed both the DC and AC source-drain symmetry tests. This behaviour is important for analogue and digital designs, since it dictates the suitability of the device model for a plethora of circuit applications. A few compact models have achieved the DC source-drain symmetry test for double-gate [22,23] and triple-gate [15,24] junctionless transistors so far. However, there is a lack of investigation on the AC symmetry of those models.

In this work, to acquire analytical expressions of the total terminal charges in triple-gate (TG) JL MOSFETs required to develop a trans-capacitance compact model, we take advantage of our DC symmetric and continuous drain current compact model in the depletion operation region [24], adequate for circuit applications of JL transistors [16]. The novel contribution of the work is to formulate an analytical and symmetric trans-capacitance compact model for short-channel triple-gate JL transistors, valid in the depletion operation region where bulk conduction determines the drain current. Its AC symmetry is validated through numerical simulation data of long and short channel devices.

2. Trans-capacitance compact model

The total gate charge is obtained by integrating the normalized mobile charge q_y over the channel length L (y-direction):

$$Q_g = -W_{eff} C_{ox} V_{th} \int_0^L q_y dy, \quad (1)$$

where $W_{eff} = N_{fin} (2H_{fin} + W_{fin})$ is the effective width, N_{fin} is the number of fins, H_{fin} and W_{fin} are the fin height and fin width respectively, L is the channel length, C_{ox} is the gate oxide capacitance per unit area and V_{th} is the thermal voltage. The normalized charge at coordinate y along the channel, $q_y = -Q_{mobile}/(2C_{ox}V_{th}/\beta)$ is given by Eq. (2) in terms of the threshold voltage V_t and the ideality factor η defined in [24] for JL TG MOSFETs. It is noted that the parameter β corresponds to the total capacitance reduction given by $\beta = 1 + C_{ox}X_{dep}/\epsilon_{si}$, where ϵ_{si} is the silicon permittivity and X_{dep} is the depletion width which is fraction of the silicon thickness t_{si} [3].

Fig. 1. Graphic representation of the simulated junctionless FinFET.

$$q_y = \text{LambertW} \left[\exp \left(\frac{V_g - V_b - V_t - \eta(V_y - V_b)}{\eta V_{th}} \right) \right], \quad (2)$$

where V_g is the gate voltage and V_y is the quasi-Fermi potential at a position y in the channel ($V = V_s$ at the source and $V = V_d$ at the drain), referenced to the bulk potential V_b of the four terminal device presented in Fig. 1. The term “four terminal device” refers to the drain current compact model of [24]. The trans-capacitance model developed in this work is practically three-terminal, ignoring the total charge of bulk, Q_b . In Eq. (1) dy is defined from the current continuity equation as:

$$dy = -W_{eff} \mu_{eff} C_{ox} V_{th} q_y \frac{dV_y}{I_{ds}(y)}, \quad (3)$$

where μ_{eff} is the effective carrier mobility. Considering the derivative of the Lambert function $W(x)$ defined as $dW(x)/dx = W(x)/[x(1+W(x))]$, from the derivative dq_y/dV_y of Eq. (2) dV_y is obtained as:

$$dV_y = -\frac{V_{th}(q_y + 1)dq_y}{q_y}. \quad (4)$$

Considering Eqs. (3) and (4) and the drain current defined in terms of the normalized charges at the source (q_s) and drain (q_d) [24]:

$$I_{ds} = \frac{W_{eff} \mu_{eff} C_{ox} V_{th}^2 \eta}{(1+F)L_{eff}\beta} \left[(q_s - q_d) + \frac{1}{2}(q_s^2 - q_d^2) \right], \quad (5)$$

the final analytical expression for the gate charge is:

$$Q_g = A \times \frac{\frac{1}{2}(q_s + q_d) + \frac{1}{3}(q_s^2 + q_s q_d + q_d^2)}{1 + \frac{1}{2}(q_s + q_d)}, \quad (6)$$

where

$$A = \frac{W_{eff} L_{eff} C_{ox} V_{th} \beta (1+F)}{\eta}. \quad (7)$$

The factor F is defined as $F = W_{eff} C_{ox} \mu_{eff} V_d R_{sd}/L$, R_{sd} is the series resistance, $L_{eff} = L - \Delta L$ and ΔL is the channel length shortening due to short-channel effects. Both μ_{eff} and ΔL are expressed in terms of the normalized charges q_s and q_d [24]. In JL transistors, the channel is buried in the center of the nanowire and the association of the gate oxide capacitance per unit area C_{ox} with the depletion capacitance C_{dep} due to the depletion formed between the gate oxide and the mobile charges, reduces the total capacitance that drives the drain current. The normalized charges q_s and q_d are obtained from Eq. (2) with $V_y = 0$ at the source ($y = 0$) and $V_y = V_d$ at the drain ($y = L$). We note that the velocity saturation is incorporated into the factor F through the effective carrier mobility.

Following the Ward-Dutton channel charge-partitioning scheme [25], the total charge at the drain is obtained by integrating the normalized mobile charge q_y over the channel length L (y -direction) as:

$$Q_d = -W_{eff} C_{ox} V_{th} \int_0^L q_y dy. \quad (8)$$

Due to the current continuity requiring constant drain current at any point y of the channel, considering that $I_{ds}(y) = I_{ds}(y=L)$ and using the proportional partitioning method, for constant mobility in the channel direction y can be expressed by:

$$\frac{y}{L} = \frac{(q_s - q_y) + \frac{1}{2}(q_s^2 - q_y^2)}{(q_s - q_d) + \frac{1}{2}(q_s^2 - q_d^2)}. \quad (9)$$

By introducing Eqs. (3) and (9) in Eq. (8), the analytical expression for the drain charge is:

$$Q_d = -\frac{A}{\left[1 + \frac{1}{2}(q_s + q_d)\right]^2} \cdot (\varphi_1 + \varphi_2 + \varphi_3), \quad (10)$$

where

$$\varphi_1 = \frac{1}{6}q_s + \frac{5}{24}q_s^2 + \frac{1}{15}q_s^3, \quad (11)$$

$$\varphi_2 = \frac{1}{3}q_d + \frac{3}{8}q_d^2 + \frac{1}{10}q_d^3, \quad (12)$$

$$\varphi_3 = q_s q_d \left(\frac{5}{12} + \frac{2}{15}q_s + \frac{1}{5}q_d \right). \quad (13)$$

Considering the charge conservation equation, the total charge at the source is given by the relation:

$$Q_s = -Q_g - Q_d = -A \times \frac{\frac{1}{2}(q_s + q_d) + \frac{1}{3}(q_s^2 + q_s q_d + q_d^2)}{1 + \frac{1}{2}(q_s + q_d)} +$$

$$A \times \frac{(\varphi_1 + \varphi_2 + \varphi_3)}{\left[1 + \frac{1}{2}(q_s + q_d)\right]^2}. \quad (14)$$

It is noted that the terminal charges Eqs. (6) and (10) are continuous at $V_{ds} = 0$.

The analytical equations of the total charges at the gate, drain and source electrodes are generally complex for every trans-capacitance model developed in literature. This feature is also present here in Eqs. (6), (10) and (14). However, these analytical equations can become quite compact in the linear ($q_s \ll q_d$) and saturation ($q_d \gg 0$) regions. Therefore, for the total gate and drain charges in the linear region, Eqs. (6) and (10) are simplified as:

$$Q_{g,lin} = A \cdot q_s = A \cdot q_d, \quad (15)$$

$$Q_{d,lin} = \frac{A \cdot q_s \cdot (1 + q_s)}{2} = \frac{A \cdot q_d \cdot (1 + q_d)}{2}, \quad (16)$$

For the saturation region, Eqs. (6) and (10) can be written as:

$$Q_{g,sat} = \frac{A \cdot q_s}{3} \cdot \left(\frac{2q_s + 3}{q_s + 2} \right), \quad (17)$$

$$Q_{d,sat} = \frac{A \cdot q_s}{30(q_s + 2)^2} \cdot (8q_s^2 + 25q_s + 20). \quad (18)$$

It is apparent that the total source charge in the linear ($Q_{s,lin}$) and saturation ($Q_{s,sat}$) regions can be analytically obtained by adding Eqs. (15), (16) and (17), (18) respectively.

Parasitic capacitance (C_p in F/ μm), including overlap and fringe capacitances must be considered as a serious problem on trans-capacitances [10]. Taking into account C_p , then the total terminal charges of the gate, drain and source can be, respectively, expressed as:

$$Q_{t,g} = Q_g + C_p W_{eff} V_{gs} + C_p W_{eff} V_{gd}, \quad (19)$$

$$Q_{t,d} = Q_d - C_p W_{eff} V_{gd}, \quad (20)$$

$$Q_{t,s} = Q_s - C_p W_{eff} V_{gs}. \quad (21)$$

Having acquired the analytical expressions of the total charges for gate, source and drain, the intrinsic capacitances can be obtained from Eq. (22):

$$C_{ij} = - \left. \frac{\partial Q_{t,i}}{\partial V_j} \right|_{i \neq j}, \quad C_{ij} = \left. \frac{\partial Q_{t,i}}{\partial V_j} \right|_{i=j}, \quad (22)$$

where i and j stand for the source, drain and gate.

3. Trans-capacitance model validation

To verify the accuracy of the trans-capacitance compact model, TCAD numerical simulations were performed using Silvaco (Atlas) tool, considering the drift-diffusion transport mechanism. In simulations, models for the bandgap narrowing, Shockley-Read-Hall generation-recombination and field-dependent mobility have been used. The simulated device has channel length $L = 1 \mu\text{m}$ and 30 nm , fin height $H_{fin} = 30 \text{ nm}$, fin width $W_{fin} = 10 \text{ nm}$, equivalent gate oxide thickness $t_{ox} = 1.3 \text{ nm}$ and doping concentration $N_d = 6 \times 10^{18} \text{ cm}^{-3}$. The source/drain regions used for simulations were short to reduce the effect of parasitic resistances. Quantum confinement effects are not considered here, since these effects become significant when the silicon thickness is smaller than 10 nm [25].

Fig. 2. Transfer characteristics of a long-channel ($L = 1 \mu\text{m}$) TG JL MOSFET with different drain voltages V_{ds} in logarithmic and linear scales. Symbols and lines correspond to TCAD simulation and model results, respectively. The model results were obtained using the parameters: $\eta = 1.01$, $V_t = 0.713 \text{ V}$, $\mu = 145 \text{ cm}^2/\text{Vs}$ and series resistance $R_{sd} = 3 \text{ k}\Omega$.

Fig. 3. Gate voltage dependence of trans-capacitances for a long-channel ($L = 1 \mu\text{m}$) TG JL MOSFET at drain voltages $V_{ds} = 50 \text{ mV}$ (a) and 1 V (b) in the depletion operation region. Symbols and lines correspond to TCAD simulation and model results, respectively. The model results were obtained using the parameters of the drain current model and the parasitic capacitance $C_p = 5 \times 10^{-12} \text{ F}/\mu\text{m}$.

Figs. 2 and 3 show the transfer characteristics in logarithmic and linear scales and the trans-capacitances of a long-channel ($L = 1 \mu\text{m}$) JL TG MOSFET at $V_{ds} = 0.05$ and 1 V . In order to acquire the best possible results, an optimization technique was performed to fit the transfer characteristics and the trans-capacitances models simultaneously to the TCAD data at drain voltages 0.05 and 1 V .

Fig. 4. Transfer characteristics of a short-channel ($L = 30 \text{ nm}$) TG JL MOSFET with different drain voltages V_{ds} in logarithmic and linear scales. Symbols and lines correspond to TCAD simulation and model results, respectively. The model results were obtained using the parameters: Ideality $\eta = 1.01$, $V_t = 0.7 \text{ V}$, $\mu = 98.2 \text{ cm}^2/\text{Vs}$, series resistance $R_{sd} = 2.87 \text{ k}\Omega$ and channel length modulation parameter $\delta = 0.121 \text{ V}^{-2}$ [24].

Fig. 5. Gate voltage dependence of trans-capacitances for a short-channel ($L = 30 \text{ nm}$) TG JL MOSFET at drain voltages $V_{ds} = 50 \text{ mV}$ (a) and 1 V (b) in the depletion operation region. Symbols and lines correspond to TCAD simulation and model results, respectively. The model results were obtained using the parameters of the drain current model and the parasitic capacitance $C_p = 5 \times 10^{-13} \text{ F}/\mu\text{m}$.

The results of the symmetric drain current compact model [24] are in good agreement with the Silvaco simulation data. The model parameters are presented in the caption of Fig. 2. Fig. 3 shows the trans-capacitances obtained from numerical simulations and the proposed analytical compact model using a

parasitic capacitance $C_p = 5 \times 10^{-12} \text{ F}/\mu\text{m}$. All the modeled trans-capacitances show good agreement with the simulated data, indicating the good accuracy of the proposed trans-capacitance compact model. It is noticed that the models results for both drain current and trans-capacitances fit the simulation data for depletion width $X_{dep} = t_{si}/7$ in the model parameter β .

Figs. 4 and 5 present the transfer characteristics and the trans-capacitances of a short-channel ($L = 30 \text{ nm}$) JL TG MOSFET for different drain voltages. Good agreement between numerical and model results has been obtained indicating that the charge-based trans-capacitance model is valid for short-channel JL TG MOSFETs in the depletion operation region. Using the capacitances presented in Figs. 3 and 5, all other capacitances can be obtained by means of the following relationships derived according to the charge conservation law: $C_{ss} = C_{ds} + C_{gs}$, $C_{dd} = C_{ds} + C_{dg}$, $C_{gd} = C_{gg} - C_{gs}$, $C_{sd} = C_{dd} + C_{gd}$.

4. AC symmetry test

In addition to the drain current symmetry [24], the terminal charges and, therefore, the trans-capacitances should also satisfy the symmetry condition. According to [21], AC symmetry tests of the gate and source/drain charge models were performed by calculating the quantities δ_{cg} and δ_{csd} , respectively, defined as:

$$\delta_{cg} = \frac{C_{gs} - C_{gd}}{C_{gs} + C_{gd}} \quad (23)$$

and

$$\delta_{csd} = \frac{C_{ss} - C_{dd}}{C_{ss} + C_{dd}}. \quad (24)$$

The trans-capacitance compact model succeeds in the AC symmetry test when Eqs. (23) and (24) are odd functions of V_x , which is a voltage that is generally given low values. In this work, the drain voltage is rendered equal to V_x and the source voltage equal to $-V_x$. Then V_x is swept from -0.2 to 0.2 V , while the gate voltage V_g maintains a constant value. In Figs. 6 and 7, we show that the model satisfies the condition for AC gate and source-drain symmetry, respectively, for typical long-channel TG JL transistor with parameters: $L = 1 \mu\text{m}$, $H_{fin} = 30 \text{ nm}$, $W_{fin} = 10 \text{ nm}$, $t_{ox} = 1 \text{ nm}$ and $N_d = 6 \times 10^{18} \text{ cm}^{-3}$. In these figures, we also show the first derivatives $d\delta_{cg}/dV_x$ and $d\delta_{csd}/dV_x$, which highlight the smoothness and continuity of our trans-capacitance compact model. Symmetry and continuity of the second order derivatives $d^2\delta_{cg}/dV_x^2$ and $d^2\delta_{csd}/dV_x^2$ is confirmed in Fig. 8 for a long-channel devices ($L = 1 \mu\text{m}$) at $V_{ds} = 0$ and 1 V , as it was also confirmed for higher order derivatives. The symmetry and continuity of $d^2\delta_{cg}/dV_x^2$ and $d^2\delta_{csd}/dV_x^2$ for short-channel device ($L = 30 \text{ nm}$) for $V_{ds} = 0$ and 1 V is confirmed in Fig. 9.

Fig. 6. AC symmetry test δ_{cg} of the gate charge and its first derivative versus V_x for (a) $V_g = 0$ and (b) $V_g = 1$ V of a long-channel ($L = 1 \mu\text{m}$) TG JL MOSFET. δ_{cg} and its derivative have been normalized to their absolute maximum values.

Fig. 8. Second order derivatives of AC symmetry test $d\delta_{cg}^2/dV_x^2$ (a) and $d\delta_{csd}^2/dV_x^2$ (b) versus V_x for $V_g = 0$ and 1 V of a long-channel ($L = 1 \mu\text{m}$) TG JL MOSFET. The derivatives have been normalized to their absolute maximum values.

Fig. 7. AC symmetry test δ_{csd} of the source/drain charge and its first derivative versus V_x for (a) $V_g = 0$ and (b) $V_g = 1$ V of a long-channel ($L = 1 \mu\text{m}$) TG JL MOSFET. δ_{csd} and its derivative have been normalized to their absolute maximum values.

Fig. 9. Second order derivatives of AC symmetry test $d\delta_{cg}^2/dV_x^2$ (a) and $d\delta_{csd}^2/dV_x^2$ (b) versus V_x for $V_g = 0$ and 1 V of a short-channel ($L = 30 \text{ nm}$) TG JL MOSFET. The derivatives have been normalized to their absolute maximum values.

5. Conclusion

A physics-based compact model for trans-capacitances has been developed in this work for long-channel and short-channel TG JL MOSFETs, valid in all regions of operation. The trans-capacitances model was derived based on the Dutton-Ward channel linear charge partition method and its development was thoroughly described. The model has been validated against TCAD data, demonstrating good agreement. AC symmetry tests were performed in order to verify the continuous and symmetric nature of the trans-capacitance compact model. The model is shown to pass the AC symmetry condition tests and thus the compact trans-capacitance model developed seems suitable for implementation in circuit design simulators.

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