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An Analytic Circuit Model of Ballistic Nanowire MOSFET for Transient Analysis

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1. Introduction

Gate-all-around (GAA) MOSFETs have been explored extensively as a promising candidate in further scaling of CMOS owing to their excellent controllability of the electrostatic potential. Several computational techniques of the device properties based on the quantum transport such as non-equilibrium Green's function (NEGF) formalism have been reported [1], [2]. However, it is impractical to introduce them into the circuit simulator due to their tremendous amount of calculation time. Some compact models have been already reported [3]–[6], but these models have coupled equations to be evaluated numerically or parameters that have to be determined numerically in advance. Thus, there is a need to develop a fully analytic and explicit model at circuit level. In this work, we propose a fully analytic and explicit model for ballistic GAA-MOSFETs with a rectangular wire cross section and demonstrate a transient simulation with it.

2. Device Model Formulation

We consider GAA-MOSFETs with a rectangular wire cross section, as shown in Fig. 1 (a) and (b). Fig. 1 (c) shows the schematic potential profiles in the wire cross section. Firstly, the potential shape in the wire cross section is approximated by a parabolic function as follows:

$$w(x, y) = w_{\mathrm{s}}(\Delta U_{\mathrm{G}}) - 4\Delta U_{\mathrm{G}} f(x, y), \tag{1}$$

$$f(x, y) = \frac{x}{t_x + t_y}\left(1 - \frac{x}{t_x}\right) + \frac{y}{t_x + t_y}\left(1 - \frac{y}{t_y}\right), \tag{2}$$

where the potential shape is determined by ΔU_{G}, and $w_{\mathrm{s}}(\Delta U_{\mathrm{G}})$ represents electrostatic potential at the interface between the oxide and the channel. With (1) and (2), confined electron energy levels can be derived approximately with the perturbation theory, and those are obtained as a quadratic function of ΔU_{G} by considering the second-order term of the perturbation series. Then, the ballistic current is described as a function of ΔU_{G} using the derived energy levels and the Natori formula [3]. The quantity ΔU_{G} is determined by solving the coupled equation of the charge densities derived from the quantum statistics, Q_{q}, and electrostatics, Q_{e}, under each bias condition [7]. This equation for ΔU_{G} cannot be solved explicitly, so ΔU_{G} must be determined by either approximately or numerically. Fig. 2 shows a comparison of the ballistic current calculated from the numerical compact model in which ΔU_{G} is determined numerically and NEGF simulator [1], demonstrating a reasonable accuracy.

3. Analytic Model for Transient Analysis

A parameter ΔU_{G} determined numerically in the previous section can be derived analytically without a drain voltage dependence, which is considered in the next section, as shown in Table I (a) [8]. Then, characteristics of GAA-MOSFETs are calculated without any numerical calculations. This model for ballistic current demonstrates an excellent accuracy in Fig. 2. Transient circuit simulations with GAA-MOSFETs require fully analytic model of quantum gate-input capacitance C_{q}, which is defined by $\partial Q_{\mathrm{e}}/\partial V_{\mathrm{GS}}$. Then, C_{q} can be derived analytically with the fully analytic model of ΔU_{G} because of $Q_{\mathrm{e}} = -8\varepsilon_{\mathrm{ch}}\Delta U_{\mathrm{G}}$. Fig. 3 shows that the fully analytic models of ΔU_{G} and C_{q} demonstrate a reasonable accuracy comparing with those calculated by solving the coupled equation of charge densities numerically. We consider the circuit-compatible model, as shown in Fig. 4 (a). If we assume that the charge density distribution along z-axis in the channel is flat, both C_{GS} and C_{GD} in Fig. 4 (a) are obtained as $C_{\mathrm{q}} \times \frac{L_{\mathrm{G}}}{2}$ [9]. Finally, with those models, we demonstrate a transient circuit simulation of a GAA-MOSFET in Fig. 4 (b).

4. Drain Voltage Dependence

The quantum capacitance C_{q} depends largely on the drain voltage [10], and we introduce the drain voltage dependence into the fully analytic model of ΔU_{G}. When V_{DS} becomes sufficiently small, the coupled equation of charge densities can be solved approximately with the same technique mentioned in [8], considering electrons injected from the drain electrode to the channel on the lowest energy level. With the obtained solution, the ratio η of the number of electrons injected from the source and the drain electrodes on the lowest energy level is obtained analytically with the Aymerich-approximation [11]. Fig. 5 shows comparisons of η calculated with this model and the numerical compact model. Finally, substituting η back into the coupled equation, ΔU_{G} which has the drain voltage dependence can be derived as shown in Table I (b) with the same technique in [8]. Fig. 6 shows comparisons of ΔU_{G} and C_{q} which contain the drain voltage dependence, demonstrating a reasonable accuracy.

5. Conclusion

In summary, an analytic and explicit model of the GAA-MOSFETs has been reported with a high precision equivalent to the numerical compact model. With it, a transient simulation of a GAA-MOSFET could be demonstrated, introducing the fully analytic model to HSPICE as a Verilog-A script. The drain voltage dependence was considered to our model of ΔU_{G} and C_{q}, which agree well with the numerical compact model.

References

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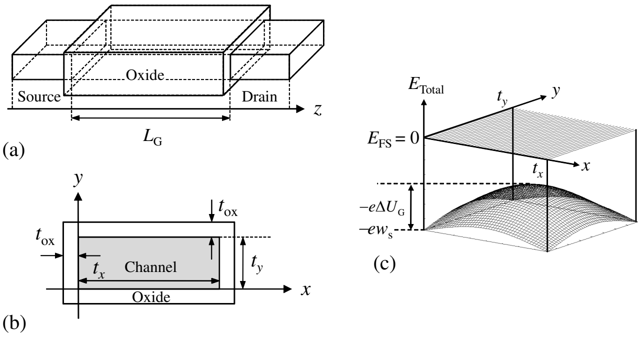

Fig. 1. (a) Schematic view of a GAA-MOSFET that has rectangular wire cross section with channel length L_G. (b) Wire cross section of channel width t_x, channel height t_y and oxide thickness t_{ox}. (c) Schematic potential distribution in the wire cross section at the barrier top in the channel region.

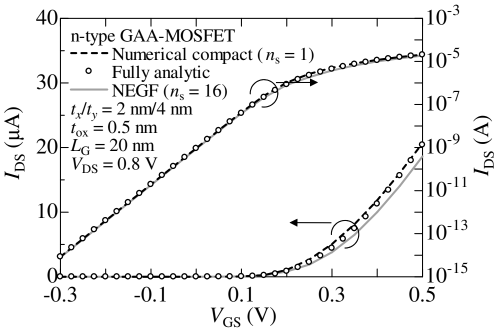

Fig. 2. Ballistic current characteristics calculated from numerical compact model (dashed line), fully analytic model (open circle) and NEGF simulation (solid line) as a function of V_{GS}. The channel and the oxide materials are intrinsic Si and SiO_2, respectively, and the transversal and the longitudinal effective masses are fixed at $m_t = 0.19m_0$ and $m_l = 0.91m_0$ in a (100)-oriented Si channel. We define n_s as the number of energy levels considered in the ballistic current.

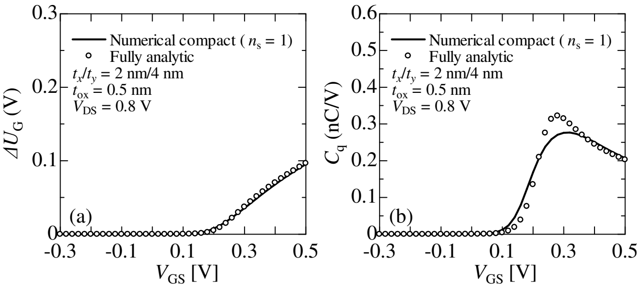

Fig. 3. Gate voltage dependences of (a) ΔU_G and (b) C_q calculated from numerical compact model (solid line) and the fully analytic model (open circle).

Table I
Quantity ΔU_G without (a) and with (b) the drain voltage dependence, where α, β and γ are determined by structural parameters and $\eta' = 1 + \eta$.

(a)	$\alpha\left\{1-\sqrt{1+\beta\ln\left[1+\exp\left[\frac{eV_{GS}}{k_BT}+\gamma\right]\right]}\right\}$
(b)	$\eta'^2\alpha\left\{1-\sqrt{1+\frac{\beta}{\eta'}\ln\left[1+\exp\left[\frac{1}{\eta'}\left(\frac{eV_{GS}}{k_BT}+\gamma\right)\right]\right]}\right\}$

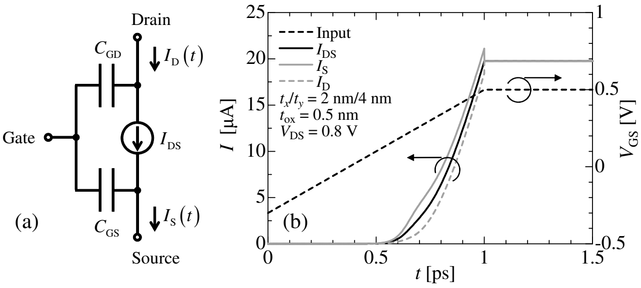

Fig. 4. (a) Circuit-compatible model of the GAA-MOSFET, where I_{DS} represents the steady-state current obtained analytically in [8]. (b) A transient analysis of a GAA-MOSFET. The fully analytic models are introduced to HSPICE as a Verilog-A script.

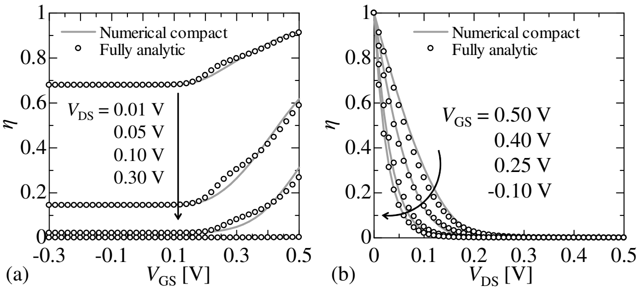

Fig. 5. A ratio of the number of electrons injected from the source and the drain to the channel on the lowest energy level as a function of (a) V_{GS} and (b) V_{DS}.

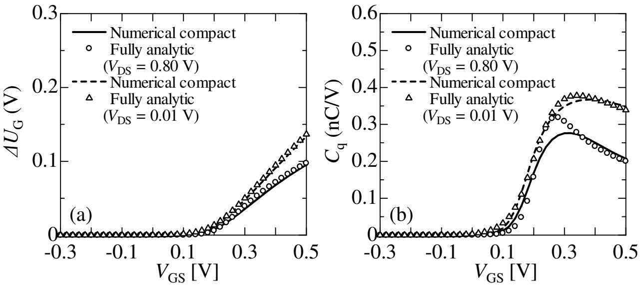

Fig. 6. Gate voltage dependence of (a) ΔU_G and (b) C_q calculated from numerical compact model (solid or dashed line) and the fully analytic model (open circle) with the drain voltage dependence.