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A CAPACITANCE MODEL OF A SHORT CHANNEL DOUBLE-GATE FINFET INCLUDING A MOBILITY DEGRADATION EFFECT

A capacitance compact and explicit model is introduced for a short channel Double gate (DG) undoped FinFET including the mobility degradation effect. The capacitance model is developed on the basis of the channel charge partition, and is the generalization of previously developed capacitance model accounted only for constant mobility. The presented analytical compact model is validated with 3D Atlas simulations performed with the CVT mobility model.

Keywords: DGFinFET/MOSFET, capacitance model, mobility degradation, short channel effects, compact modeling

Introduction. Multigate FinFETs are recognized as the best candidates for down-scaling CMOS technologies. The key factors that limit how far a multi-gate MOSFET/FinFET can be scaled come from short-channel effects such as threshold voltage roll-off, drain-induced barrier lowering, velocity saturation followed by mobility degradation. Among the great variety of FinFETs the DG FinFET is recognized as the most stable to device variability. During the last decade a great number of scientific works have been published on modeling and characterization of DG FinFEts [1-5]. Compact models are critically important for circuit simulations. Based on the EKV formalism, the charge-based compact model was developed for a long channel, undoped DG MOSFET [4]. Further, this model was extended for a ultra-scalled DG FinFETs still being fully explicit and physics-based [5]. The static model accurately accounts for all short channel effects, and the model was validated down to 25 nm channel length. Based on the Ward channel charge partition [6], the trans-capacitance model was developed for a long channel DG FinFET [2], and further it was extended for short channel DG FinFETs [5], but at that stage of development, the mobility degradation effect was not considered in the capacitance model. However, the velocity saturation followed by mobility degradation is the dominating effect while shrinking the channel length. The scope of this work is to include the mobility degradation effect in the previously developed quasi-static model preserving the accuracy of the model. The paper is organized as follows: in Section 1, the trans-capacitance model for the DG FinFET is presented, in Section 2, the mobility dependence on the longitudinal electric field is introduced in trans-capacitance equations, Section 3 presents the validation and discussion of the developed model.

Methodology: Capacitance model

1. **A capacitance model considering the constant mobility.** For the subsequent clear introduction of the mobility degradation effect in the capacitance model, here we briefly introduce the main equations of the core capacitance model. In the following derivation we use normalized quantities, and for applied voltages, drain current, and charges, the following normalization factors are used:

$$V_{norm} = U_T = \frac{k \cdot T}{q},\ I_{norm} = 4 \cdot \mu \cdot C_{ox} \cdot \frac{H \cdot U_T^2}{L},\ Q_{norm} = 4 \cdot C_{ox} \cdot U_T .$$

The normalized gate charge (q_G) computed from two gates can be obtained by integrating the normalized mobile charge density (q_m) over the area of the gate region:

$$q_G = -H \int_0^L q_m dx, \tag{1}$$

where H and L are the device height and length respectively.

Following the channel charge partition proposed by Ward, the normalized drain charge (q_D) is defined as:

$$q_D = H \int_0^L \frac{x}{L} \cdot q_m dx. \tag{2}$$

The integration variables x and dx can be expressed by means of drain current and terminal voltages according to [7] :

$$x = -\frac{L}{i} \cdot \int_{v_s}^{v} q_m \cdot dv, \tag{3}$$

$$dx = -\frac{L}{i} \cdot q_m \cdot dv, \tag{3.1}$$

where $i(v)$ and $q_m(v)$ dependences are defined in the long channel charge based model [4].

For the sake of completeness, here we remind the main relationships of that model:

$$i = -q_m^2 + 2 \cdot q_m + \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right)\Bigg|_{q_{ms}}^{q_{md}} \text{ with } \alpha = \frac{C_{ox}}{C_{si}} \text{ and } q_m < 0, \tag{4}$$

$$v_g - v_{to} - v_{ch} = -2 \cdot q_m + \ln\left(-\frac{q_m}{2}\right) + \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right). \tag{5}$$

Differentiating (5) yields:

$$\frac{dq_m}{dv_g} = -\frac{dq_m}{dv} = -\frac{1}{2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m}}. \tag{6}$$

By substituting (6) into equations (3) and (3.1):

$$x = -\frac{L}{i} \cdot \left[q_m^2 - 2 \cdot q_m - \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right)\right]\Bigg|_{q_{ms}}^{q_m}, \tag{7}$$

and

$$dx = -\frac{L}{i} \cdot q_m \cdot \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m}\right) \cdot dq_m . \tag{8}$$

Further, by substituting (7) and (8) into (1) and (2), and by taking into account (5) and (6) the expressions for gate and drain charges are calculated and presented in the normalized form in the Appendix with equations (A1) and (A2) respectively. Once we have the expressions for q_G and q_D , the source charge is easy to compute as: $q_G + q_S + q_D = 0$.

The capacitances are defined as: $c_{kl} = \pm \frac{\partial q_k}{\partial v_l}$, where k , l refer to the gate, drain and source terminals. The corresponding equations derived for c_{gg}, c_{dd} and c_{dg} are presented in Appendix A with (A3), (A4), (A5). All the other capacitance expressions can be calculated by the same mechanism, also by using the relationships between the capacitances.

1. **A capacitance model including the mobility degradation effect.** The mobility dependence on the longitudinal electric field can be accurately modeled as $\mu_{eff} = -\frac{\mu_\perp}{1 + \mathrm{E}_{\|} / \mathrm{E}_c}$, where $\mathrm{E}_c = \frac{V_{sat}}{\mu_\perp}$ is the electric field at velocity saturation (V_{sat} is the carrier velocity saturation), $\mathrm{E}_{\|} = \frac{dV}{dx}$ is the longitudinal electric field,

$\mu_{\perp}$ - the transverse effective and is modeled by Mathias's rule. The degradation of transverse mobility is due to the scattering on the acoustic and optical phonons and on the surface roughness and becomes significant for thin body FinFets. The expressions for $\mu_{\perp}$ were presented in [5]. In the development of a static model, the mobility degradation due to the longitudinal electric field is modelled by the concept of the channel length modulation. However, in the development of the DC model, the mobility dependence on the longitudinal electric field should be accurately cinsidered in equations (1)-(2).

Thus equations (7) and (8) should be replaced by:

$$x = -\frac{L}{i}\left(q_m{}^2 - 2q_m - \frac{2}{\alpha}ln(1 - \frac{\alpha}{2}q_m)\right)\Big|_{q_{ms}}^{q_m} - \frac{\mu_{\perp}}{V_{sat}}U_T\left(2q_m + \ln(-q_m) - \ln(\frac{2}{\alpha} - -q_m)\right)\Big|_{q_{ms}}^{q_m}, \quad (9)$$

$$dx = \left(-\frac{L}{i}q_m - \frac{\mu_{\perp}}{V_{sat}}U_T\right)\left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m}\right)dq_m. \quad (10)$$

Then, for the gate charge we got:

$$q_{G\_mob} = q_G + H\frac{\mu_{\perp}}{V_{sat}}U_T\left(q_m{}^2 - 2q_m - \frac{2}{\alpha}ln(1 - \frac{\alpha}{2}q_m)\right)\Big|_{q_{ms}}^{q_{md}}, \quad (11)$$

where q_G is given by (A1) in Appenix A.

Similarly, for the drain charge from (2), (9) and (10) we calculate :

$$q_{Dmob} = q_D + q_{Dm}, \quad (12)$$

where q_D is defined with (A2) and q_{Dm} arises due to the velocity saturation effect and is calculated as:

$$q_{Dm} = \frac{H}{i}\frac{\mu_{\perp}}{V_{sat}}U_T(Int1 - Term1 * Int2 + Int33 - Term2 * Int22) + \\ + \frac{H}{L}\left(\frac{\mu_{\perp}}{V_{sat}}U_T\right)^2 Int3 - \frac{H}{L}\left(\frac{\mu_{\perp}}{V_{sat}}U_T\right)^2 Term2 * Int2,$$

where $Term1$, $Term2$, $Int1$, $Int2$, $Int22$, $Int3$, $Int33$ are the functions from the normalized mobile charge at the source and drain edges and are presented in Appendix B in the form of integrals. These integrals are easy to calculate, however for calculations of capacitances it is not required.

The source charge is calculated as $q_{G\_mob} - q_{Dmob} = q_{smob}$.

Further capacitances are calculated as derivatives of terminal charges. Taking into account (11), (12), (6) and (4), the following expression for capacitances are calculated:

$$c_{gg\_mob} = c_{gg} + H\frac{\mu_{\perp}}{V_{sat}}U_T(q_{md} - q_{ms}), \quad (13)$$

$$c_{dg\_mob} = c_{dg} - \frac{H}{i}\frac{\mu_{\perp}}{V_{sat}} U_T \Big(-Term3\big|_{q_{md}} + Term1 * (q_{md}) - q_{ms} * i - -Term4\big|_{q_{ms}}^{q_{md}} + Term2 * $$

$$* ({q_{md}}^2 - {q_{ms}}^2) + \frac{i * q_G}{H * L} \Big) - \frac{H}{L}\left(\frac{\mu_{\perp}}{V_{sat}} U_T\right)^2 (-Term5 - i + +(q_{md}) * Term2), \qquad (14)$$

$$c_{dd\_mob} = c_{dd} - \frac{H}{i}\frac{\mu_{\perp}}{V_{sat}} U_T \big(Term3\big|_{q_{md}} - Term1 \cdot (q_{md}) + Term4\big|_{q_{md}} - Term2 \cdot $$

$$\cdot ({q_{md}}^2) \big) - \frac{H}{L}\left(\frac{\mu_{\perp}}{V_{sat}} U_T\right)^2 (Term5 - (q_{md}) \cdot Term2), \qquad (15)$$

where c_{gg}, c_{dg} and c_{dd} are the capacitances calculated considering the constant mobility and are given by (A3), (A4) and (A5), Term3,Term4 and Term5 are defined in Appendix B. Consequently all the other capacitances can be defined in the same way.

2. **Discussion and model validation.** The capacitance model is important for the variation-aware design of FinFet. The trans-capacitances are very sensitive to random fluctuations caused by imperfect fabrication in IC fabrication process. The developed model is smooth, continuous and accurate throughout all operating regimes.

The capacitance in subthreshold regime is determined by inter-electrode coupling which is significant for short channel devices. According to Gauss' law, the inter-electrode coupling charge density is given by the perpendicular electric field terminating on the chosen electrode. Then corresponding capacitances are calculated as charge derivatives to corresponding terminal voltages and introduced in the developed model as it was described in [5]. Accordingly geometrical length of channel is replaced with effective channel length: (L-L_p), where L_p is responsible for inter-electrode charge coupling in subthreshold and saturation regimes and is given in [5]. The velocity saturation effect is introduced through equations (9) and (10) and so is included in (13) - (15).

The quantum mechanical effects (QME) are also included in the model as it was presented in [5].

The developed capacitance model is validated with 3D Atlas simulations, where CVT mobility model is considered. It is worth to note that there are only two empirical parameters in the model, which are included in transverse mobility expression [5]. Figs 1-3 present calculations for FinFET with a channel length of 40 *nm* and Fin thickness of 10 *nm*, analytical calculations are presented with lines and numerical simulations with symbols. The calculations are carried out both in linear and saturation regimes (V_g= 0.1 *V* and V_g= 1 *V*). The capacitance C_{gg} is presented in Fig.1, C_{sg} and C_{dg} are presented respectively in Fig. 2 and Fig. 3. Fig. 4 presents calculations for FinFET with a channel length of 25 *nm* and a Fin thickness of 3 *nm*. For thin Fins, QME become significant and in Fig.4 the calculations including QME are presented as well. The calculations excluding

QME are presented to make evident the accuracy of the mobility degradation effect introduction in the model. The good agreement of the model with 3D simulations makes it evident that the developed analytical model has good accuracy from a weak to a strong inversion.

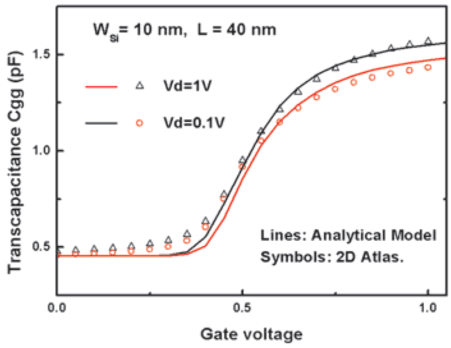

Fig. 1. Trans-capacitance C_{gg} obtained from the model and simulations

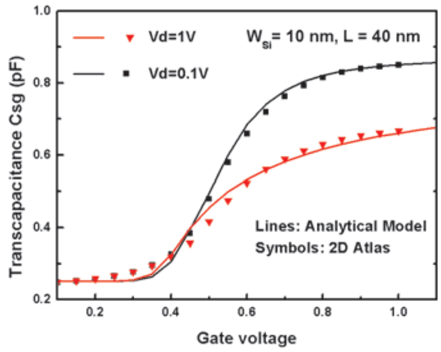

Fig. 2. Trans-capacitance C_{sg} obtained from the model and simulations

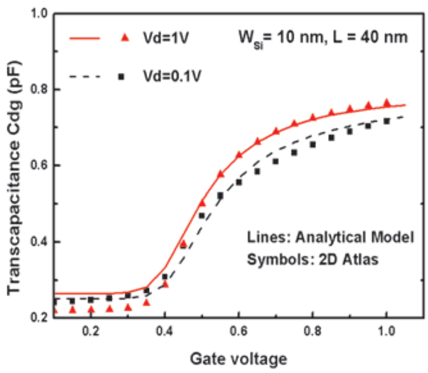

Fig. 3. Trans-capacitance C_{dg} obtained from the model and simulations

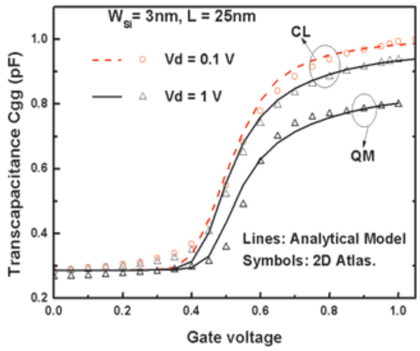

Fig.4. Trans-capacitance C_{gg} calculated with and without quantum mechanical effects, both from the model and simulations

Conclusion. In this work the trans-capacitance model is presented for a short channel DG MOSFET/FinFET accurately considered for the mobility degradation effect, quantum mechanical effects, as well as inter-electrode coupling, The model relies on the channel charge partition and is physics-based, thus the model is valid for a large range of FinFET geometrical parameters. The analytical capacitance model was validated with Silvaco 3D Atlas simulations for channel lengths varying from 50 to 25 (*nm*).

Appendix A

$$q_G = \frac{H \cdot L}{i} \cdot \left[\frac{2}{3} \cdot q_m^3 - q_m^2 - \frac{2}{\alpha} \cdot q_m - \frac{4}{\alpha^2} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) \right] \Bigg|_{q_{ms}}^{q_{md}}, \tag{A1}$$

$$q_D = \frac{H \cdot L}{i^2} \cdot \left\{ Int1 - \left[q_{ms}^2 - 2 \cdot q_{ms} - \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_{ms}\right) \right] \cdot \frac{i \cdot q_G}{H \cdot L} \right\}, \tag{A2}$$

where

$$Int1 = \left\{ \begin{array}{l} \frac{2}{5} \cdot q_m^5 - \frac{3}{2} \cdot q_m^4 + \left[\frac{4}{3} - \frac{2}{9 \cdot \alpha} - \frac{4}{3 \cdot \alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) \right] \cdot q_m^3 \\ + \left[\frac{1}{\alpha} - \frac{2}{3 \cdot \alpha^2} + \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) \right] \cdot q_m^2 \\ + \left[-\frac{8}{3 \cdot \alpha^3} + \frac{4}{\alpha^2} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) \right] \cdot q_m + \frac{304}{9 \cdot \alpha^4} - \frac{64}{5 \cdot \alpha^5} \\ - \frac{44}{3 \cdot \alpha^3} - \frac{16}{3 \cdot \alpha^4} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) + \frac{4}{\alpha^3} \cdot \left[\ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) \right]^2 \end{array} \right\} \Bigg|_{q_{ms}}^{q_{md}}$$

$$c_{gg} = -\frac{H \cdot L}{i} \cdot \left(q_{ms}^2 - q_{md}^2 \right) + \frac{q_G}{i} \cdot g_m, \tag{A3}$$

$$c_{dd} = -\frac{H \cdot L}{i} \cdot q_{md}^2 + \frac{2 \cdot q_D}{i} \cdot q_{md}, \tag{A4}$$

$$c_{dg} = -\frac{H \cdot L}{i} \cdot q_{md}^2 - \frac{q_{ms} \cdot q_G}{i} + \frac{2 \cdot q_D}{i} \cdot g_m. \tag{A5}$$

Appendix B

$Int1 = \int_{q_{ms}}^{q_{md}} q_m \left({q_m}^2 - 2q_m - \frac{2}{\alpha} ln(1 - \frac{\alpha}{2} q_m) \right) \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m} \right) \cdot dq_m,$

$Term1 = \left({q_{ms}}^2 - 2q_{ms} - \frac{2}{\alpha} \ln\left(1 - \frac{\alpha}{2} q_{ms}\right) \right),$

$Int2 = \int_{q_{ms}}^{q_{md}} q_m \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m} \right) dq_m,$

$Int33 = \int_{q_{ms}}^{q_{md}} {q_m}^2 \left(2q_m + \ln(-q_m) - \ln\left(\frac{2}{\alpha} - q_m\right) \right) \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m} \right) dq_m,$

$Int3 = \int_{q_{ms}}^{q_{md}} q_m \left(2q_m + \ln(-q_m) - \ln\left(\frac{2}{\alpha} - q_m\right) \right) \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m} \right) dq_m,$

$$Int22 = \int_{q_{ms}}^{q_{md}} {q_m}^2 \left(2 - \frac{1}{q_m} + \frac{1}{\frac{2}{\alpha} - q_m}\right) dq_m,$$

$$Term2 = \left(2q_{ms} + \ln(-q_{ms}) - \ln\left(\frac{2}{\alpha} - q_{ms}\right)\right),$$

$$Term3 = \left({q_m}^3 - 2{q_m}^2 - \frac{2}{\alpha} q_m \ln\left(1 - \frac{\alpha}{2} q_m\right)\right),$$

$$Term4 = \left(2{q_m}^3 + {q_m}^2 * \ln\left(-\frac{q_m}{\frac{2}{\alpha} - q_m}\right)\right),$$

$$Term5 = \left(2{q_{md}}^2 + q_{md} * ln(-q_{md}) - q_{md} * ln\left(\frac{2}{\alpha} - q_{md}\right)\right).$$

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ԵՐԿՓԱԿԱՆԻ, ԿԱՐՃ ՈՒՂԵՏԱՐՈՎ ՖԻՆՖԵՏ ՏՐԱՆԶԻՍՏՈՐԻ ՈՒՆԱԿՈՒԹՅԱՆ ՄՈԴԵԼԸ ՇԱՐԺՈՒՆԱԿՈՒԹՅԱՆ ԴԵԳՐԱԴԱՑԻԱՅԻ ՊԱՅՄԱՆՆԵՐՈՒՄ

Ներկայացված է կարճ ուղետարով երկփականի ՖինՖԵՏ տրանզիստորի ունակության մոդելը, որտեղ հաշվի է առնված լիցքակիրների շարժունակության դեգրադացիան: Ունակության մոդելը հիմնված է ուղետարի լիցքի տերմինալների միջև բաժանման գաղափարի վրա և հանդիսանում է հաստատուն շարժունակության համար նախկինում մշակված մոդելի ընդհանրացումը: Անալիտիկ հաշվարկների ճշգրտությունը ստուգված է 2D Atlas ստանդարտացված թվային գործիքով, որտեղ հաշվարկները կատարված են CVT շարժունակության մոդելով:

Առանցքային բառեր. DGFinFET/MOSFET, ունակության մոդել, շարժունակության դեգրադացիա, կարճ ուղետարի էֆեկտ, կոմպակտ մոդել:

А.Э. ЕСАЯН

МОДЕЛЬ ЕМКОСТИ КОРОТКОКАНАЛЬНОГО ФИНФЕТА С ДВОЙНЫМ ЗАТВОРОМ, ВКЛЮЧАЯ ЭФФЕКТ ДЕГРАДАЦИИ ПОДВИЖНОСТИ

Исследован короткоканальный, нелегированный FinFET полевой транзистор с двойным затвором. Разработана компактная модель емкости структуры, включая эффект деградации подвижности. Достоверность аналитических расчетов проверена сравнением с численными вычислениями с 2D Atlas инструментом с учетом CVT модели подвижности.

Ключевые слова: DGFinFET/MOSFET, модель емкости, деградация подвижности, короткоканальный эффект, компактная модель.