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Floating-Body Effect in Partially/Dynamically/Fully-Depleted DG/SOI MOSFETs Based on Unified Regional Modeling of Surface and Body Potentials

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Abstract—A compact terminal current/charge model for partially/dynamically/fully-depleted (PD)/(DD)/(FD) double-gate (DG) and SOI MOSFETs with floating-body effect (FBE) based on unified regional modeling (URM) of the surface and body potentials is presented. The model accurately describes the physical behavior of the impact-ionization current that gives rise to the “hump” in the C – V characteristics and the body thickness- and doping-dependent “kink effect.” The floating-body potential at the zero-field (ZF) location in the body is the key to model the electrical characteristics of PD/DD/FD devices with complete body doping and thickness scalability. The model is validated by comparison with I – V and C – V data of the numerical devices in a given range of body doping, body thickness, and temperature. Such a scalable model is important for physical and variability modeling of DG/SOI FinFETs with doped body.

Index Terms—compact model (CM), double gate (DG), dynamically-depleted (DD), floating body (FB), fully-depleted (FD), impact ionization, MOSFET, partially-depleted (PD), SOI, surface potential, unified regional modeling (URM).

I. INTRODUCTION

MOS TRANSISTORS fabricated in SOI technologies have a generic structure with a silicon body thickness T_{Si} , a (top) gate oxide thickness T_{ox1} , and a (back) gate buried-oxide thickness T_{ox2} . The top-gate bias (V_{g1}) is used to control the inversion layer, whereas the back-gate bias (V_{g2}) is usually grounded to form a typical SOI MOSFET. The silicon body may be connected to a body bias (V_b) [“body-contacted” (BC)] or floating [“floating-body” (FB)]. The SOI device may be operated in the partially-depleted (PD), fully-depleted (FD), or dynamically-depleted (DD) mode depending on the maximum depletion widths at the source/drain (S/D) ends ($X_{dm,s/d}$) at a given body doping (N_A) in comparison with T_{Si} . This generic structure can be extended to the independent-gate ($V_{g1} \neq V_{g2}$) asymmetric double-gate (ia-DG) FinFETs on bulk-Si (with BC) or SOI (only FB). With $V_{g1} = V_{g2}$ and $T_{ox1} \neq T_{ox2}$, it gives

the generic structure for common-gate asymmetric-DG (ca-DG) FinFETs. The symmetric-DG (s-DG) FinFET is a special case of ca-DG with $T_{ox1} = T_{ox2}$, for which the zero-field (ZF) location is always in the middle of the body and it can be modeled as two FinFETs in parallel each having a body thickness of $T_{Si}/2$. This s-DG structure also has the same boundary conditions as the generic SOI structure when $T_{ox2} \rightarrow \infty$, for which the electric field at the back gate approaches zero. In both devices, when the body doping is high and operating in PD or DD mode, the ZF location is the maximum depletion width. In this paper, we restrict our discussions to the s-DG or SOI (with $T_{ox2} \rightarrow \infty$) nMOSFETs, which can be generalized to the generic ca-DG and ia-DG device structures.

In the emerging SOI and FinFET technologies, doped body becomes ultrathin body (UTB) and FinFETs are also doped for threshold-voltage adjustments. Thus, body thickness and doping dependencies have to be modeled physically in a compact model (CM). This poses one of the most challenging tasks for developing a CM that is scalable with body thickness and doping. Moreover, the well-known floating-body effect (FBE) such as the kink effect [1], important in PD-SOI devices, is mostly modeled without body-thickness scaling. In contemporary UTB-SOI and DG-FinFETs, device operations may undergo PD to FD [2] as well as DD [3], [4] transitions. FBEs in DC and AC, together with body-doping/thickness as well as bias/temperature scaling, become important to be included in a CM that is physical, smooth, and symmetric.

Compact models for SOI MOSFETs have been proposed by several research groups. The model [5] widely used by industries solves the FB potential through iteration by the SPICE circuit simulator with body-source built-in potential lowering [6]. Other approaches have proposed to solve the accumulated charge [7] through three equations [8] iteratively, or to solve the front- and back-gate surface potentials through its coupling effect for modeling FBEs in SOI MOSFETs.

In this paper, the body potential at ZF location, ϕ^* , is proposed to be the key parameter in the “ground-referenced” [9] unified regional modeling (URM) [10] of surface and body potentials for FBEs in PD/DD/FD devices. Our previous URM for s-DG/SOI MOSFETs [10] as well as the DD modeling [11] is extended to include the impact-ionization current for

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modeling the FBEs with physical body doping/thickness and temperature scaling. The model is validated by comparison with numerical simulations of the generic s-DG devices with body thickness ranging from 20 to 150 nm, body doping concentration ranging from 1×10^{17} to $2 \times 10^{18} \text{ cm}^{-3}$, and temperatures from 27 to 300 °C. The “hump” observed in the numerical $C_{gg} - V_{gs}$ data in the depletion region of PD/DD devices as well as the body-doping/thickness- and temperature-dependent “kink effect” in the $I_{ds} - V_{ds}$ characteristics are physically modeled.

II. MODEL EQUATIONS

A. Impact-Ionization Current

The impact-ionization current induced at the drain side flowing into the body of a s-DG/SOI MOSFET raises the body potential. This gives rise to the observed increase in the drain current at high drain biases in PD devices, which is the well-known kink effect. The impact-ionization current is generally expressed as [12]

$$I_{ii,c} = I_{ds} \frac{A_{ii}}{B_{ii}} \Delta V_{ii,c} \exp\left(\frac{-I_{ii} B_{ii}}{\Delta V_{ii,c}}\right) \quad (1)$$

$$\Delta V_{ii,c} = (V_c - V_r) - C_{ii} (V_{c,eff} - V_r) \quad (2)$$

in which the subscript c stands for s or d at the source or drain end, respectively. V_c and $V_{c,eff}$ [9] are the channel and effective channel voltages, respectively. I_{ii} is the characteristic length. V_r is the ground-referenced voltage at the flatband ($V_{gr} = V_{FB}$) and equilibrium ($V_{ds} = 0$) conditions, which is equal to V_b (for BC) or $\min\{V_s, V_d\}$ (for FB). A_{ii} and B_{ii} are the impact-ionization coefficients. C_{ii} in (2) has been proposed by [13] as

$$C_{ii} = C_0 \left[C_1 + C_2 [V_c - V_{c,eff}] + C_3 (V_c - V_{c,eff})^2 \right] \quad (3)$$

for better matching to the measurement data, where C_0 , C_1 , C_2 , and C_3 are fitting parameters.

In this work, the B_{ii} expression in (1) is revised for PD/DD/FD devices for a scalable body thickness and doping with smooth transitions between different operating modes at any operating temperature and terminal biases. The newly proposed B_{ii} model in (1) is given by

$$B_{ii} = B_0 \left[1 - \frac{X_{dep,c} - X_{dm,c} + \sqrt{(X_{dep,c} - X_{dm,c})^2 + \delta_B (4X_{dep,c} + 1)}}{2X_{dep,c}} \right]^{B_1} \quad (4)$$

where B_0 , B_1 , and δ_B are fitting parameters.

$$X_{dm,c} = \sqrt{\frac{2\epsilon_{Si}}{qp_0}} (2\phi_F + V_{cr}) \quad (c = s, d) \quad (5)$$

is the maximum depletion width at the S/D end, in which ϵ_{Si} is the permittivity of Si and

$$p_0 = n_i e^{\phi_F / V_{th}} = n_i \exp\left[\sinh^{-1}\left(\frac{N_A - N_D}{2n_i}\right)\right] \quad (6)$$

is the hole concentration at equilibrium (or at flatband). n_i is the intrinsic carrier concentration, ϕ_F is the Fermi potential, given by the Kingston equation [14], and $v_{th} = kT/q$ is the thermal

voltage.

For a T_{Si} -scalable model, a linearly-interpolated depletion width

$$X_{dep,c} = \frac{X_{FD,c} - X_{PD,c}}{T_{Si,PD} - T_{Si,FD}} (T_{Si,PD} - T_{Si}) + X_{PD,c} \quad (7)$$

between two “boundaries” ($X_{PD,c}$ and $X_{FD,c}$) with the corresponding body thicknesses ($T_{Si,PD}$ and $T_{Si,FD}$) is assumed [used in (4)], given by

$$X_{PD/FD,c} = \sqrt{\frac{2\epsilon_{Si}}{qp_0}} (2\phi_F + B_{ii,PD/FD} V_{cr}) \quad (8)$$

where $B_{ii,PD}$ and $B_{ii,FD}$ are two fitting parameters to be extracted from the onset of the kink effect in the $I_{ds} - V_{ds}$ data for the two “boundaries” devices.

The final expression for the multiplication factor is given by

$$M_{ii} = \frac{I_{ii}}{I_{ds0}} \quad (9)$$

where I_{ds0} is the drain current without impact ionization and

$$I_{ii} = I_{ii,s} + I_{ii,d} \quad (10)$$

is the total impact-ionization current based on ground-reference for model symmetry.

B. Floating-Body Effect

The FBE model for the FB potential with impact-ionization current has been presented in Eq. (78) of [10], which is based on current balance between the impact-ionization current (10) and the S/D PN-junction diode currents. In this work, we use the notation $\phi_{o,ii}$, given by

$$\phi_{o,ii} = nv_{th} \left(\ln[2 + (I_{ii}/I_s)] - \ln(e^{-V_s/nv_{th}} + e^{-V_d/nv_{th}}) \right) \quad (11)$$

$\phi_{o,ii}$ in (11) reduces to the one without impact ionization as

$$\phi_o = nv_{th} \left[\ln 2 - \ln(e^{-V_s/nv_{th}} + e^{-V_d/nv_{th}}) \right] \quad (12)$$

where I_s is the S/D PN-junction diode reverse saturation current, which is dependent on the S/D and body doping concentrations, junction cross-sectional area (T_{Si} dependent), and temperature, and n is the diode ideality factor, taken as a fitting parameter. In the absence of any impact ionization, (12) is needed to correctly model the FB potential in PD devices without body contact (such as SOI/FinFETs) in the Gummel symmetry test (GST). If ϕ_o is set to the reference voltage $V_r = \min(V_s, V_d)$, it would give incorrect slopes in the third- and higher-order harmonic-balance tests, as explained in [10] and [15].

The final FB potential, which is the key result of this work that extends our previous models [10], [11], [15] for FBE modeling, is given by $\phi_{o,c}^* = \phi_{o,c} + \phi_{o,ii}$. Details for the $\phi_{o,c}^*$ model will be given in the ensuing sections.

C. URM for the Surface Potential

The input-voltage equation as obtained by solving the Poisson–Boltzmann equation and Gauss’ law in a generic DG/SOI MOSFET is given by

$$V_{gf} - \phi_s = \text{sgn}(\phi_s - \phi_o^*) Y \sqrt{f_\phi(\phi_s, \phi_o^*, V_c, V_r)} \quad (13)$$

$$f_\phi = e^{-(2\phi_F + V_{cr})/V_{th}} \underbrace{\left[v_{th} e^{-V_r/V_{th}} \left(e^{\phi_s/V_{th}} - e^{\phi_o^*/V_{th}} \right) - (\phi_s - \phi_o^*) \right]}_{(n)} + \underbrace{v_{th} e^{V_r/V_{th}} \left(e^{-\phi_s/V_{th}} - e^{-\phi_o^*/V_{th}} \right)}_{(p)} + \underbrace{(\phi_s - \phi_o^*)}_{(p_0)} \quad (13a)$$

where ϕ_s is the surface potential and ϕ_o^* is the body potential at ZF location. $V_{gf} \equiv V_g - V_{FB}$ is defined as the flatband (V_{FB}) shifted gate voltage.

$$r = \frac{\sqrt{2q\epsilon_{Si}p_0}}{C_{ox}} \quad (13b)$$

is the body factor and $C_{ox} = \epsilon_{ox}/T_{ox}$ is the gate-oxide capacitance (per unit area), where ϵ_{ox} is the permittivity of SiO₂ and T_{ox} is the gate-oxide thickness. p_0 in (6) (rather than N_A) being used in the body factor (13b) is the key to body-doping scaling from high to zero doping (“undoped” body).

The URM approach considers only one dominant charge, either p , p_0 (due to N_A), or n in the accumulation, depletion, or strong-inversion regions, respectively, to solve the surface potential in (13) explicitly by considering its asymptotic *piecewise regional* solutions, and using two complementary smoothing functions

$$\mathcal{G}_f\{x; \sigma\} = 0.5 \left(x + \sqrt{x^2 + 4\sigma} \right) \quad (14a)$$

$$\mathcal{G}_r\{x; \sigma\} = 0.5 \left(x - \sqrt{x^2 + 4\sigma} \right) \quad (14b)$$

and a transition function

$$\mathcal{G}_{eff}\{x, x_{sat}; \delta\} = x_{sat} - 0.5 \left[x_{sat} - x - \delta + \sqrt{(x_{sat} - x - \delta)^2 + 4\delta x_{sat}} \right] \quad (14c)$$

to obtain *unified regional* solutions and joining them to form *single-piece unified* solutions, as given by [10]

$$\phi_{acc} = \mathcal{G}_r(V_{gf}; \sigma_a) + 2v_{th}\mathcal{L}\left\{ \frac{r}{2\sqrt{v_{th}}} e^{-(V_{gf}-V_r)/2v_{th}} \right\} \quad (15)$$

$$\phi_{sub} = \phi_{o,ii} + \left(-\frac{r}{2} + \sqrt{\frac{r^2}{4} + \mathcal{G}_f(V_{gf} - \phi_{o,ii}; \sigma_f)} \right)^2 \quad (16)$$

and

$$\phi_{str} = \mathcal{G}_f(V_{gf}; \sigma_s) - 2v_{th}\mathcal{L}\left\{ \frac{r}{2\sqrt{v_{th}}} e^{(V_{gf}-2\phi_F-V_{cr})/2v_{th}} \right\} \quad (17)$$

in accumulation (ϕ_{acc}), depletion (ϕ_{sub}), and strong-inversion (ϕ_{str}) regions, respectively, where σ_a , σ_f , and σ_s are smoothing parameters. $\mathcal{L}\{W\}$ is the *Lambert W* function, which can be considered as an explicit library function in implementation.

The key to obtaining a smooth transition between PD and FD regions in FD devices is to determine the *FD voltage*, $V_{g,FD}$, which is defined as the gate voltage at which FD occurs, given for s-DG/SOI MOSFETs by

$$X_o(V_{g,FD}) = \begin{cases} T_{Si}/2 & (\text{s-DG}) \\ T_{Si} & (\text{SOI}) \end{cases} \quad (18)$$

which can be obtained from

$$X_o(V_{g,FD}) = X_o(V_g) \Big|_{V_g=V_{g,FD}} = \sqrt{\frac{2\epsilon_{Si}}{qp_0}} (\phi_s - \phi_{o,ii}) \Big|_{\phi_s=\phi_{FD}} \quad (19)$$

$$= \sqrt{\frac{2\epsilon_{Si}}{qp_0}} \left(-\frac{r}{2} + \sqrt{\frac{r^2}{4} + V_{gf,FD} - \phi_{o,ii}} \right)$$

where $V_{gf,FD} \equiv V_{g,FD} - V_{FB}$. Thus, the FD voltage can be obtained from (19) as

$$V_{g,FD} = \phi_{o,ii} + \left[\sqrt{\frac{qp_0}{2\epsilon_{Si}}} X_o(V_{g,FD}) + \frac{r}{2} \right]^2 - \frac{r^2}{4} \quad (20)$$

The corresponding FD potential is given in (19) as

$$\phi_{FD} = \phi_{o,ii} + \left(-\frac{r}{2} + \sqrt{\frac{r^2}{4} + V_{gf,FD} - \phi_{o,ii}} \right)^2 \quad (21)$$

The unified piecewise ϕ_s solution in the depletion region for FD devices in the range of $V_{FB} < V_g < V_{g,FD}$ follows the depletion piece (ϕ_{sub}) in (16) until FD is reached at $V_g = V_{g,FD}$, and it is pinned at ϕ_{FD} for $V_g > V_{g,FD}$, as given by the unified solution

$$\phi_{dep} = \mathcal{G}_{eff}\{\phi_{sub}, \phi_{FD}; \delta_d\} \quad (22)$$

If strong inversion is not reached beyond $V_g > V_{g,FD}$, ϕ_s follows

$$\phi_{dv} = V_{gf} - r\sqrt{\phi_{dep} - \phi_{o,ii}} \quad (23)$$

in the “volume-inversion” region, in which the Si body is fully depleted with a fixed bulk charge, $Q_b = -C_{ox}r(\phi_{FD} - \phi_{o,ii})^{1/2}$. A unified single-piece surface potential valid from depletion to strong inversion can be obtained as

$$\phi_{ds} = \mathcal{G}_{eff}\{\phi_{dv}, \phi_{str}; \delta_s\} \quad (24)$$

which follows the V_c -independent ϕ_{dv} for PD and FD devices with a smooth transition between PD and FD modes, and connects to the V_c -dependent strong-inversion piece ϕ_{str} smoothly. It approaches zero below V_{FB} . The sum of ϕ_{acc} and ϕ_{dv} solutions

$$\phi_{sa} = \phi_{acc} + \phi_{dv} \quad (25)$$

gives a single-piece V_c -independent ϕ_s solution valid from accumulation to depletion and volume-inversion regions. Finally, a unified single-piece solution valid in all regions, including impact ionization, can be written as

$$\phi_{seff} = \phi_{acc} + \phi_{ds} \quad (26)$$

D. URM for the Body Potential

One of the key advantages of the URM approach is to obtain asymptotic physical surface/body-potential solutions that are otherwise difficult when both n and N_A terms in (13a) need to be considered. Similar to obtaining undoped-body ϕ_s and ϕ_o solutions in [16], when only electrons are considered, Poisson’s equation (including the nonzero N_A -dependent ϕ_F) can be integrated twice, from which asymptotic ϕ_s and ϕ_o solutions can be obtained rigorously. Consistent with the URM approach, the body potential at ZF location valid from depletion to strong inversion for s-DG/SOI MOSFETs is given by [10]

Fig. 1. Modeled FB potential at ZF location $\phi_{o,c}^*$ (lines), which is the sum of $\phi_{o,ii}$ (solid symbols) and $\phi_{o,c}$ (open symbols), as a function of (a) gate voltage and (b) drain voltage for various body thicknesses as indicated.

$$\phi_{o,ds} = v_{th} \ln \left(\frac{B_{ds,c}}{A_{ss,c}} \right) - 2v_{th} \ln \left[\cos \left(\arccos \left(\sqrt{\frac{B_{ds,c}}{A_{ss,c}}} e^{-(\phi_{ds} - \phi_{FD})/v_{th}} \right) + \frac{\sqrt{B_{ds,c}}}{2v_{th}} X_{o,c} \right) \right] \quad (27a)$$

$$A_{ss,c} = (2qp_0 v_{th} e^{-(2\phi_f + V_{cr})/v_{th}}) / \epsilon_{Si} \quad (27b)$$

$$B_{ds,c} = A_{ss,c} e^{(\phi_{ds} - \phi_{FD})/v_{th}} - \left[C_{ox} (V_{gf} - (\phi_{ds} - \phi_{FD})) / \epsilon_{Si} \right]^2 \quad (27c)$$

where $X_{o,c} = \min\{X_{dm,c}, X_o(V_{g,FD})\}$, with $X_{dm,c}$ and $X_o(V_{g,FD})$ given in (5) and (18), respectively. ϕ_{ds} and ϕ_{FD} are given in (24) and (21), respectively. Equation (27) gives a physically N_A/T_{Si} -scalable ϕ_o solution important for modeling FBEs, which is not available in those models based on the fixed depletion charge for surface/body potentials in strong inversion.

E. Compact Terminal Charge/Current Models

The terminal-charge models [10], together with the DD modeling in the URM formalism [11], are listed below:

Fig. 2. Modeled first-order derivative of the effective surface potential versus gate voltage for various (a) body thickness and (b) body doping at $V_c = 0 \text{ V}$ (thin lines) and $V_c = 2 \text{ V}$ (thick lines), as indicated, with impact ionization turned on (lines) and off (dotted lines).

$$Q_b = -C_{ox} \left[q_{b,acc} + q_{b,sub} - \frac{(\overline{A_{b,DD}} - 1) \Delta \phi_s^2}{12H_{DD}} \right] \quad (28)$$

$$Q_d = -\frac{C_{ox}}{2} \left[\frac{\overline{q_i}}{q_i} - \frac{\overline{A_{b,DD}} \Delta \phi_s}{6} \left(1 - \frac{\Delta \phi_s}{2H_{DD}} - \frac{\Delta \phi_s^2}{20H_{DD}^2} \right) \right] \quad (29)$$

$$Q_s = -\frac{C_{ox}}{2} \left[\frac{\overline{q_i}}{q_i} + \frac{\overline{A_{b,DD}} \Delta \phi_s}{6} \left(1 + \frac{\Delta \phi_s}{2H_{DD}} - \frac{\Delta \phi_s^2}{20H_{DD}^2} \right) \right] \quad (30)$$

$$Q_g = -(Q_b + Q_d + Q_s) \quad (31)$$

where

$$\overline{A_{b,DD}} \equiv -\frac{\Delta q_i}{\Delta \phi_s} = \frac{q_{i,s} - q_{i,d}}{\phi_{s,d} - \phi_{s,s}} \quad (32)$$

is based on the revised bulk-charge linearization [4], with

$$q_{i,s} = \mathcal{J}_f(V_{gf}; \sigma_f) - \phi_{s,s} - \gamma \sqrt{\phi_{s,s} - \phi_{o,s}^*} \quad (32a)$$

$$q_{i,d} = \mathcal{J}_f(V_{gf}; \sigma_f) - \phi_{s,d} - \gamma \sqrt{\phi_{s,d} - \phi_{o,d}^*} \quad (32b)$$

$$H_{DD} = (\overline{q_i} / \overline{A_{b,DD}}) + v_{th} \quad (33)$$

$\Delta \phi_s$ is defined as

Fig. 3. Modeled gate capacitance versus gate voltage for various body thicknesses as indicated, with impact ionization (a) turned off (dotted lines) and (b) turned on (solid lines), compared with the numerical data (open/solid symbols) from the corresponding s-DG MOSFETs.

$$\Delta\phi_s = \phi_{s,d} - \phi_{s,s} \quad (34)$$

where

$$\phi_{s,c} = \phi_{ds}(V_{c,eff}) \quad (c = s, d) \quad (35)$$

and

$$\phi_{o,c} = \phi_{o,ds}(V_{c,eff}) \quad (c = s, d) \quad (36)$$

$$\phi_{o,c}^* = \phi_{o,c} + \phi_{o,ii} \quad (c = s, d). \quad (37)$$

The above terminal charges (per unit area) in (28)–(31) are extended for modeling FBEs with

$$q_{b,sub} = \mathcal{Q}_f(V_{gf}; \sigma_a) - \mathcal{Q}_f(V_{gf}; \sigma_f) + Y\sqrt{\phi_s - \phi_o^*} \quad (38)$$

and

$$\bar{q}_i = V_{gf} - \bar{\phi}_s - Y\sqrt{\phi_s - \phi_o^*} \quad (39)$$

where

$$\bar{\phi}_s = (\phi_{s,d} + \phi_{s,s})/2 \quad (40)$$

$$\bar{\phi}_o = (\phi_{o,d} + \phi_{o,s})/2 \quad (41)$$

$$\bar{\phi}_o^* = \bar{\phi}_o + \phi_{o,ii}. \quad (42)$$

(37) and (42) are the key models for FBEs in the URM formalism, including the contributions from the Poisson's solution (27) and impact-ionization current (11).

The drain-current model for FBEs, with the multiplication factor in (9), is given by

$$I_{ds} = I_{ds0}(1 + M_{ii}) \quad (43)$$

Fig. 4. Modeled gate capacitance versus gate voltage for various body doping as indicated, with impact ionization (a) turned off (dotted lines) and (b) turned on (solid lines), compared with the numerical data (open/solid symbols) from the corresponding s-DG MOSFETs.

Fig. 5. Modeled gate capacitance versus gate voltage for various body doping as indicated for the thin-body (20 nm) device, with impact ionization turned on (lines), compared with the numerical data (symbols) from the corresponding s-DG MOSFETs.

where the drain current, including DD effects, is given by [10], [11]

$$I_{ds0} = \bar{\beta}_0 (\bar{q}_i + \bar{A}_{b,DD} v_{th}) V_{ds,eff}. \quad (44)$$

The effective field in the transverse-field dependent mobility is modified for FBEs as

TABLE I
MODEL PARAMETERS FOR IMPACT-IONIZATION EFFECT

Model	Symbol	Unit	Default	Fitted
Impact Ionization Model	C_0	—	1	1
	C_1	—	1	1.05
	C_2	V^{-1}	0	1.36
	C_3	V^{-2}	0	-0.06
	B_0	V/cm	1×10^7	0.341×10^7
	B_1	—	0	-0.5
	δ_b	—	0	0.05
	$B_{ii,PD}$	—	1	1.98
	$B_{ii,FD}$	—	10	2.78
	A_{ii}	cm^{-1}	0	0.037×10^7

Fig. 6. Modeled drain current versus drain voltage for various body thickness as indicated at 150 °C (and 27 °C, large square), with impact ionization turned off (dotted lines) and turned on (solid lines), compared with the numerical data (open/solid symbols) from the corresponding s-DG MOSFETs.

$$E_{eff} = \frac{\zeta_n C_{ox}}{\epsilon_{Si}} \left(\overline{V_{gt}} + \frac{\zeta_b}{\zeta_n} R \sqrt{\phi_s - \phi_o^*} \right) \quad (45)$$

$$\overline{V_{gt}} = (V_{gt,s} + V_{gt,d})/2 \quad (46)$$

$$V_{gt,c} = R \sqrt{\phi_{s,c} - \phi_{o,c}^*} + v_{th} e^{(\phi_{s,c} - 2\phi_{o,c} - V_c)/v_{th}} - R \sqrt{\phi_{s,c} - \phi_{o,c}^*} \quad (c = s, d). \quad (47)$$

where ζ_n and ζ_b are fitting parameters.

III. RESULTS AND DISCUSSION

For validating the FBE model for physical scalability under various PD/DD/FD operating modes, a generic s-DG nMOSFET with ideal gate ($L = 10 \mu m$, $T_{ox} = 3 nm$) and uniformly-doped S/D ($N_{D,S/D} = 10^{20} cm^{-3}$) and body is simulated by the Medici device simulator with a range of body thickness, body doping, and temperatures. Common mobility models (Arora, phonon, surface-roughness, and lateral-field) as well as generation-recombination models are used. The post-processing method for impact-ionization analyses is used to calculate the generation rate of electron-hole pairs as a result of impact ionization, which can be turned on or off to study its effects. The CM (named Xsim) uses all the given physical parameters from the numerical devices, and its smoothing

Fig. 7. Modeled drain current versus drain voltage for (a) various body doping and (b) temperature as indicated, with impact ionization turned off (dotted lines) and on (solid lines), compared with the numerical data (open/solid symbols) from the corresponding s-DG MOSFETs.

parameters are tuned with smooth second-order derivatives, which are fixed in all models. The impact-ionization model and its fitted parameters used in this work are listed in Table I together with the default values. When the default parameter $A_{ii} = 0$ is used, the impact-ionization current is turned off.

Figure 1 shows the modeled FB potentials $\phi_{o,c}$ in (36) and (27) by the open symbols and $\phi_{o,ii}$ in (11) by the solid symbols in a s-DG nMOSFET as a function of V_{gs} and V_{ds} with body thicknesses of 150, 100, 80, and 20 nm and a body doping of $10^{18} cm^{-3}$. $\phi_{o,c}^*$ in (37) shown by the lines is the sum of $\phi_{o,c}$ and $\phi_{o,ii}$. It is observed that $\phi_{o,c}^*$ follows $\phi_{o,c}$ for thin-body and $\phi_{o,ii}$ for thick-body devices, the latter being the FBE due to impact-ionization current. Although it is difficult to extract an equivalent ϕ_b from the corresponding numerical device for model validation, the results in Fig. 1 demonstrate the captured FBEs, which happen whenever the device meets the following 3 conditions: (i) FB, (ii) PD or DD, and (iii) with impact ionization. In other words, there is no FBE if the device is BC, FD, or no impact ionization. This FB-potential model is key to

Fig. 8. (a) Modeled drain current (right axis) and drain conductance (left axis) versus drain voltage, and (b) modeled subthreshold drain current (right axis) and transconductance (left axis) versus gate voltage, with impact ionization turned off (dotted lines) and turned on (solid lines), compared with the numerical data (open/solid symbols) from the corresponding s-DG MOSFETs.

modeling FBEs with body thickness/doping and temperature scalability, as will be validated in the results shown below.

The first-order derivative of the surface potential ϕ_{seff} in (26) with respect to V_g is shown in Fig. 2(a) by the different line types with impact ionization, and compared with those by the dotted lines without impact ionization. It can be observed that when the device is PD, there is a “hump” around $V_g = 0.5 \text{ V}$, which becomes more pronounced for thicker body. This can be attributed to the FBE modeled by the onset of $\phi_{o,c}^*$ rise as shown in Fig. 1(a). Similar “humps” are also observed in PD/DD devices with varying body doping, as shown in Fig. 2(b), with the hump peaks shifted at increasing N_A for both $V_c = 0 \text{ V}$ (thin lines) and $V_c = 2 \text{ V}$ (thick lines). These “hump” behaviors are expected to be observable in the $C_{gg} - V_{gs}$ characteristics when the impact-ionization current is large in PD/DD FB devices.

Indeed, this “hump” behavior in C_{gg} is captured as validated by comparison with numerical $C - V$ data by turning off and on the impact ionization, as shown by the open and solid symbols in Figs. 3(a) and (b), respectively. It is worth mentioning that the observed “hump” is due to the increase in $\phi_{o,ii}$ [Fig. 1(a)], which is different from the hump in C_{gg} due to PD-to-DD

Fig. 9. Modeled drain current versus drain voltage for various gate length as indicated with 50-nm body thickness at 27°C , with impact ionization turned off (dotted lines) and turned on (solid lines), compared with the numerical data without impact ionization (open symbols) from the corresponding s-DG MOSFETs.

transition (see, e.g., Fig. 3 in [11]). DD is also modeled in Fig. 3 (without and with impact ionization), as shown by the triangles of the $T_{Si} = 100 \text{ nm}$ device for the decreasing C_{gg} in saturation, which is attributed to the PD-to-DD transition as captured in the “second hump” in $-d\phi_{seff}/dV_g$ around $V_g = 2.5 \text{ V}$ at $V_c = 2 \text{ V}$, shown by the dashed line in Fig. 2(a).

Similar C_{gg} “hump” behaviors are also observed when the body doping is varied from 5×10^{17} to $2 \times 10^{18} \text{ cm}^{-3}$ for a given $T_{Si} = 150 \text{ nm}$, as shown in Fig. 4(b) when the impact ionization is turned on and the devices are PD or DD; while the “hump” is diminishing when the maximum depletion width is approaching the body thickness, as shown in Fig. 4(b) by the diamond symbol for $N_A = 1 \times 10^{17} \text{ cm}^{-3}$, and there is no “hump” when the impact ionization is turned off, as shown in Fig. 4(a). A visible decreasing C_{gg} in saturation can be seen in Fig. 4 (squares, with or without impact ionization), a signature of DD, which is confirmed by the “second hump” in $-d\phi_{seff}/dV_g$ around $V_g = 2.5 \text{ V}$ at $V_c = 2 \text{ V}$ due to the PD-to-DD transition, as shown by the dashed line in Fig. 2(b).

In a device with ultra-thin body and high doping, there is no C_{gg} “hump” even with the impact ionization turned on in both the model and numerical data, as shown in Fig. 5 for the $T_{Si} = 20 \text{ nm}$ device with varying body doping, which is confirmed by the “flat” signature in $-d\phi_{seff}/dV_g$ as shown by the dash-double-dotted line in Fig. 2(a). The absence of the FBEs and the presence of the doping effect (threshold-voltage shift) in such FD devices are correctly captured.

Figure 6 shows the modeled T_{Si} -dependent “kink effect” validated by numerical data at 150°C (and for the $T_{Si} = 50 \text{ nm}$ device at 27°C). When the impact ionization is turned off (dotted lines), there is no kink effect and the saturation current increases when volume-inversion (FD) occurs, as modeled by (36) and (27) in Fig. 1(b) by the open symbols. When the impact ionization is turned on (solid lines), the FBE is modeled by $\phi_{o,c}^*$ in (42), as shown in Fig. 1(b) by the lines, in which the onset of I_{ds} increase is modeled by the increase in $\phi_{o,ii}$, as shown

Fig. 10. Modeled Gummel symmetry test for the s-DG MOSFET at 3 gate voltages for the (a) drain current, (b) first derivative, (c) second derivative, and (d) third derivative. The GST circuit is shown in the inset of (a).

in Fig. 1(b) by the solid symbols whenever the device is in PD or DD mode.

Similar N_A -dependent “kink effect” is also well captured by the FB $\phi_{o,c}^*$ model, as validated by numerical data shown in Fig. 7(a). When impact-ionization current is significant, the onset of “kink effect” will occur when the body is PD or DD depending on the body doping and thickness as well as the gate/drain biases. These FBEs are temperature dependent, which are well modeled as shown in Fig. 7(b) in comparison with the numerical data.

The output (current and conductance, g_{ds}) and transfer (current and transconductance, g_m) characteristics are plotted in Figs. 8(a) and (b), respectively. The increases in g_{ds} and g_m when the impact ionization is turned on are accurately captured by the model with smooth transition across regions of operation.

The long-channel model including FBEs is extended to short-channel devices using the same set of impact-ionization model parameters, as shown in Fig. 9 (solid lines) for gate lengths ranging from 10 μm to 60 nm, with $T_{Si} = 50$ nm, $N_A = 10^{18} \text{ cm}^{-3}$, and $T = 27^\circ\text{C}$.

Finally, the model with FBEs has been tested to pass the Gummel symmetry test (GST) up to the third-order derivative, as shown in Fig. 10 for the $T_{Si} = 100$ nm and $N_A = 10^{18} \text{ cm}^{-3}$ s-DG MOSFET.

IV. CONCLUSION

Floating-body effects with complete body-thickness/doping dependencies are known to be difficult to model in a physically-scalable compact current/charge model. Although they are undesirable effects and may not show up in undoped thin-body devices, it becomes important to model them for emerging DG FinFETs and UTB-SOI MOSFETs with doped

FB. In this paper, the FBEs are modeled through the FB potential at ZF location by inclusion of the impact-ionization induced current together with the T_{Si}/N_A -dependent body potential within the URM formalism. The model has been validated by comparison with the corresponding numerical devices. The “hump” in C_{gg} and the T_{Si}/N_A -dependent “kink effect” when the device is operating in the PD or DD mode are physically captured in the FB-potential model, which is due to the combined contributions from Poisson’s solution and impact-ionization current.

REFERENCES

- [1] S. C. Lin and J. B. Kuo, “Temperature-dependent kink effect model for partially-depleted SOI NMOS devices,” *IEEE Trans. Electron Devices*, vol. 46, no. 1, pp. 254–258, Jan. 1999.
- [2] J. W. Sleight and R. Rios, “A continuous compact MOSFET model for fully- and partially-depleted SOI devices,” *IEEE Trans. Electron Devices*, vol. 45, no. 4, pp. 821–825, Apr. 1998.
- [3] J. Zhang, L. Zhang, J. He, and M. Chan, “A noncharge-sheet channel potential and drain current model for dynamic-depletion silicon-on-insulator metal-oxide-semiconductor field-effect semiconductor field-effect transistors,” *J. Appl. Phys.*, vol. 107, 054507, 2010.
- [4] W. Wu, W. Yao, and G. Gildenblat, “Surface-potential-based compact modeling of dynamically depleted SOI MOSFETs,” *Solid-State Electron.*, vol. 54, pp. 595–604, 2010.
- [5] *BSIMSOIv4.4 MOSFET MODEL User’s Manual*, University of California, Berkeley, CA, Dec. 2010.
- [6] P. Su, S. K. H. Fung, P. W. Wyatt, H. Wan, A. M. Niknejad, M. Chan, and C. Hu, “On the body-source built-in potential lowering of SOI MOSFETs,” *IEEE Electron Device Lett.*, vol. 24, no. 2, pp. 90–92, Feb. 2003.
- [7] M. Miura-Mattausch, S. Amakawa, M. Miyake, H. Kikuchi, H. Baba, and H. J. Mattausch, “HiSim-SOI: Complete surface-potential-based model valid for all SOI-structure types,” in *Proc. IEEE Int. SOI Conf.*, Oct. 2010.
- [8] M. Miyake, S. Kusu, H. Kikuchi, A. Tanaka, Y. Shintaku, M. Ueno, J. Nakashima, U. Feldmann, H. J. Mattausch, and M. Miura-Mattausch, “The flexible compact SOI-MOSFET model HiSIM-SOI valid for any structural types,” in *Proc. SISPAD*, 2011, pp. 167–170.
- [9] G. Zhu, G. H. See, S. Lin, and X. Zhou, “‘Ground-referenced’ model for three-terminal symmetric double-gate MOSFETs with source/drain symmetry,” *IEEE Trans. Electron Devices*, vol. 55, no. 9, pp. 2526–2530, Sep. 2008.
- [10] X. Zhou, G. Zhu, G. H. See, K. Chandrasekaran, S. B. Chiah, and K. Y. Lim, “Unification of MOS compact models with the unified regional modeling approach,” *J. Comput. Electron.*, vol. 10, no. 1, pp. 121–135, 2011.
- [11] X. Zhou and S. B. Chiah, “A simplified model for dynamic depletion in doped UTB-SOI/DG-FinFETs,” in *Proc. Nanotech*, 2012, vol. 2, pp. 784–787.
- [12] B. Iniguez and T. A. Fjeldly, “Unified substrate current model for MOSFETs,” *Solid-State Electron.*, vol. 41, no. 1, pp. 87–94, Jan. 1997.
- [13] L.-A. Yang, Y. Hao, C.-L. Yu, and F.-Y. Han, “An improved substrate current model for ultra-thin gate oxide MOSFETs,” *Solid State Electron.*, vol. 50, no. 3, pp. 489–495, Mar. 2006.
- [14] R. H. Kingston and S. F. Neustadler, “Calculation of the space charge electric field, and free carrier concentration at the surface of a semiconductor,” *J. Appl. Phys.*, vol. 26, no. 6, pp. 718–720, 1955.
- [15] X. Zhou, G. J. Zhu, M. K. Srikanth, S. H. Lin, Z. H. Chen, J. B. Zhang, C. Q. Wei, Y. F. Yan, R. Selvakumar, and Z. H. Wang, “Xsim: benchmark tests for the unified DG/GAA MOSFET compact model,” in *Proc. Nanotech*, 2010, vol. 2, pp. 785–788.
- [16] W. Z. Shanguan, X. Zhou, K. Chandrasekaran, Z. M. Zhu, S. C. Rustagi, S. B. Chiah, and G. H. See, “Surface-potential solution for generic undoped MOSFETs with two gates,” *IEEE Trans. Electron Devices*, vol. 54, no. 1, pp. 169–172, Jan. 2007.

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