Inclusion of body doping in compact models for fully-depleted common double gate MOSFET adapted to gate-oxide thickness asymmetry

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Since it is difficult to find the analytical solution of the governing Poisson equation for double gate MOSFETs with the body doping term included, the majority of the compact models are developed for undoped-body devices for which the analytical solution is available. Proposed is a simple technique to included a body doping term in such surface potential based common double gate MOSFET models also by taking into account any differences between the gate oxide thickness. The proposed technique is validated against TCAD simulation and found to be accurate as long as the channel is fully depleted.

Introduction: The body of the double gate MOSFETs is generally kept undoped (or lightly doped) in order to improve the carrier mobility and to reduce the random doping fluctuation effects. However, in order to fine tune the threshold voltage, body doping sometimes becomes necessary. The compact models for common double gate (CDG) MOSFETs are generally developed for undoped body devices as it is difficult to obtain an analytical solution of the governing Poisson equation if one includes the doping term. At the same time CDG models are based on the fundamental assumption of having equal oxide thicknesses for both gates. However, for practical devices, there will always be some amount of asymmetry between the gate oxide thickness owing to process variations and uncertainties, which can affect device performance significantly. An efficient technique to include the gate oxide thickness asymmetry in CDG compact models has been reported recently [1]. In this Letter we propose a simple technique to include the body doping in the surface potential based core compact model of CDG MOSFETs by taking into account any differences between the gate oxide thickness. The proposed technique has been validated against TCAD simulation [2] for a wide range of device geometries and found to be accurate as long as the channel is fully depleted. In passing, we note that a similar effort for symmetric devices has recently been reported in the charge based modelling approach [3].

Model development: Conventions used in this Letter are as follows: $C_{ox1(2)}$ is the oxide capacitance per unit area of the first (second)-gate defined as $\epsilon_{ox}/t_{ox1(2)}$, C_{si} is the silicon body capacitance per unit area defined as ϵ_{si}/t_{si}, where ϵ_{si}, ϵ_{ox} are the permittivities, and t_{si}, and t_{ox} are the thicknesses of Si and SiO_2, respectively. q is the elementary charge, β is the inverse thermal voltage, n_i is the intrinsic carrier density, N_a is the body doping concentration, $B = 2qn_i/\beta\epsilon_{si}$, $\psi_{1(2)}$ Si/SiO_2 is the surface potential at the first (second) gate, V is the electron quasi-Fermi potential (channel potential), and V_g is the effective gate voltage, i.e. $V_g = V_{gapp} - \delta\phi$, where V_{gapp} is the voltage applied at the gate terminal and $\delta\phi$ is the work function difference between the gate material and silicon. The effect of body doping is included in the model [1] through the following two steps.

Step 1: Perturbation of effective gate voltage: Neglecting the hole concentration for 'depletion-inversion' mode operation, the 1D Poisson equation for a long channel CDG MOSFET could be written as

$$\frac{\partial^2\psi}{\partial y^2} = \frac{qn_i}{\epsilon_{si}} e^{\beta(\psi - V)} + \frac{qN_a}{\epsilon_{si}} \tag{1}$$

with the boundary conditions

$$\left.\frac{\partial\psi}{\partial y}\right|_{y=\frac{-t_{si}}{2}} = \frac{C_{ox1}}{\epsilon_{si}}(V_g - \psi_1) \tag{2}$$

$$\left.\frac{\partial\psi}{\partial y}\right|_{y=\frac{t_{si}}{2}} = \frac{C_{ox2}}{\epsilon_{si}}(V_g - \psi_2) \tag{3}$$

Here y denotes the direction perpendicular to the channel and $y = 0$ represents the body centre. An analytical solution of (1) is difficult to obtain. However, in the weak-inversion, neglecting the inversion charge term, one can get the following solution for the surface potentials:

$$\psi_{1(2)} = V_g - \frac{\Delta\psi_{1(2)}}{2} \tag{4}$$

where

$$\Delta\psi_{1(2)} = \frac{qN_A t_{si}(2C_{si} + C_{ox2(1)})}{C_{ox1}C_{ox2} + C_{ox2}C_{si} + C_{ox1}C_{si}} \tag{5}$$

For an undoped CDG MOSFET, $\psi_{1(2)}$ at weak inversion, is close to V_g. Hence we see that the body doping lowers the value of $\psi_{1(2)}$ by $\Delta_{1(2)}2$. The effect of doping is now modelled as a lowering in gate overdrive, V_g. by a value $\Delta V_g = \frac{C_{ox1}\Delta\psi_1 + C_{ox2}\Delta\psi_2}{(C_{ox1} + C_{ox2})}$, which is the weighted average of $\Delta\psi_{1(2)}$ with the corresponding oxide capacitances. With this transformation on gate overdrive, the input voltage equation (IVE) for the doped DG MOSFET remains the same as that of the undoped DG MOSFET [4] with V_g modified to $\bar{V}_g = V_g - \Delta V_g$.

Step 2: Correction on coupling factor G: For doped body CDG MOSFETs, G_{Na}, the first integration constant (also known as coupling factor), is obtained integrating (1) once (similar to G in [4]), and could be given as

$$G_{N_a} = \frac{C_{ox1}^2(V_g - \psi_1)^2}{\epsilon_{si}^2} - Be^{\beta(\psi_1 - V)} - \Delta G \tag{6}$$

where $\Delta G = \frac{2qN_a}{\epsilon_{si}}\psi_1$ and ψ_1 is the exact solution of (1) at the first surface. As this cannot be obtained analytically, the following approximation is made:

$$G_{N_a} \simeq \frac{C_{ox1}^2(\bar{V}_g - \bar{\psi}_1)^2}{\epsilon_{si}^2} - Be^{\beta(\bar{\psi}_1 - V)} - \Delta G \tag{7}$$

where $\bar{\psi}_1$ is the solution of the undoped DG MOSFET IVE [4] with V_g modified to $\bar{V}_g$. In effect, while calculating DC current and terminal charges [1], V_g is replaced with $\bar{V}_g$, $\psi_{1(2)}$ with $\bar{\psi}_{1(2)}$ and G is replaced with G_{Na} . The perturbation in gate voltage ΔV_g, can be considered as a correction in gate work function that occurs due to body doping and the correction in coupling factor G is analogous to the 'equivalent-thickness concept' proposed in [3] (as in the exact drain current equation [1], the t_{si} term appears as a multiplication factor of G). In this way, the body doping effect is incorporated in all operating regimes without using any fitting parameters, interpolating functions or any transcendental operators.

Results and discussions: In Figs. 1–4, the proposed model is compared with the data obtained from TCAD simulation and very good agreement is observed for drain current, transconductance and transcapacitance characteristics. A constant electron mobility of 300 cm^2/V_s and the channel width and length are considered to be 1 μm each for all devices.

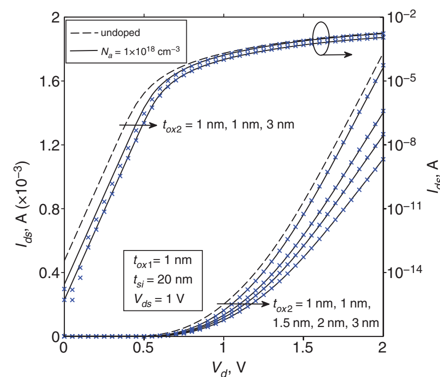

Fig. 1 *I_{ds}–V_g characteristics for doped and undoped body devices as obtained from model (lines) and TCAD simulations (symbol)*

Undoped body characteristic is shown only for symmetric device. To keep clarity of Figure, in log-scale data has been not been shown for all devices

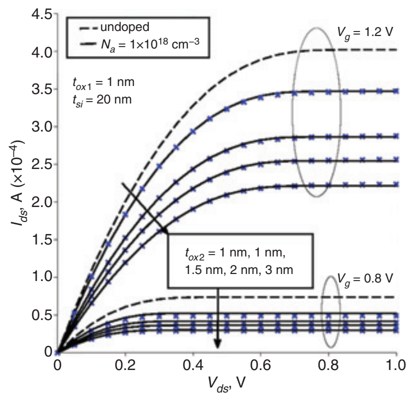

Fig. 2 *I_{ds}–V_{ds} characteristics for doped and undoped body devices as obtained from model (lines) and TCAD simulations (symbol) for two sets of gate voltages*

Undoped body characteristic is shown only for symmetric device

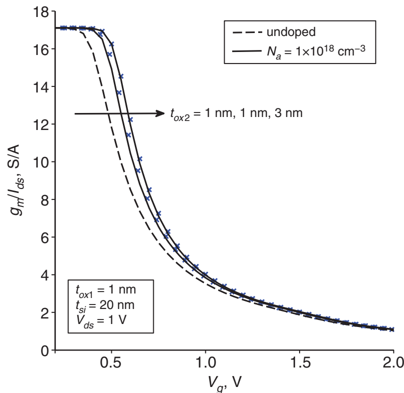

Fig. 3 *Comparison of g_m/I_{ds} by proposed model (lines) with values obtained from TCAD simulation (crosses)*

Undoped body characteristic is shown only for symmetric device

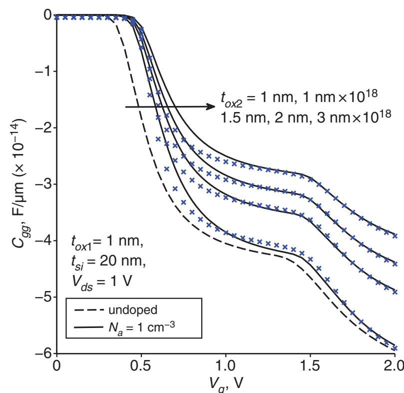

Fig. 4 *Variation of trancapacitance C_{gg} predicted by proposed model (lines) and TCAD simulation (symbols)*

Undoped body characteristic is shown only for symmetric device

Conclusion: A simple technique to include a body doping term in surface potential based common double gate MOSFET compact models is proposed by taking into account any differences between the gate oxide thickness. The proposed technique has been validated against TCAD simulation and found to be accurate for a fully depleted channel.

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One or more of the Figures in this Letter are available in colour online.

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