A Continuous Regional Current-Voltage Model for Short-channel Double-gate MOSFETs

Zhu Zhaomin, Yan Dawei, Xu Guoqing, Peng Yong, and Gu Xiaofeng

Abstract—**A continuous, explicit drain-current equation for short-channel double-gate (DG) MOSFETs has been derived based on the explicit surface potential equation. The model is physically derived from Poisson's equation in each region of operation and adopted in the unified regional approach. The proposed model has been verified with numerical solutions, physically scalable with channel length and gate/oxide materials as well as oxide/channel thicknesses.**

Index Terms—**Double-gate MOSFETs, short channel, surface potential**

I. INTRODUCTION

With the aggressive scaling of CMOS, future technology scaling will require novel device structures. Multiple-gate (MG) structures such as planar double-gate (DG) MOSFETs, vertical FinFETs, nanowire surrounding gate, and various 3D geometries [1] have been demonstrated. MG MOSFETs exhibit large inherent immunity to short-channel effects, sharper subthreshold slope, and higher drive current [2]. Intense efforts have been devoted to the development of compact models for DG-MOSFETs in the literature [3, 4]. Theoretical analysis of double-gate (DG) transistors dates back to 1967 [5], about the same time as bulk MOSFET models. Since 1980's many alternatives to the conventional bulk-

silicon MOSFET have been proposed and developed, such as the silicon-on-insulator (SOI) and double-gate MOSFETs [6-10]. Theoretically, this type of "generic" MOSFETs has a different boundary condition from bulk MOSFET due to the back-gate oxide. When the back-gate oxide thickness approaches that of the front gate, SOI conceptually becomes DG. Recently, there has been intense research interest in the development of compact models for SOI/DG MOSFETs [11-15]. Most of the models are integrable ones [7, 11, 13]; some are iterative [11, 15] and others are explicit [13, 14]. Undoped s-DG/a-DG MOSFETs were analyzed by Taur [11]. Ortiz-Conde *et al.* presented an approximate solution to the undoped s-DG surface potential [13] in comparison with the iterative one, and an implicit solution by numerical iteration [15] for generic doped MOSFETs with two gates. Undoped s-DG MOSFETs have been solved both implicitly [16-18] and analytically [18-20], while undoped asymmetric cases have only been solved implicitly in literature [11]. Subthreshold characteristics in short channel double-gate MOSFETs has also been solved analytically [26].

In this paper, we present a continuous, explicit drain-current equation for short-channel double-gate (DG) MOSFETs based on the explicit surface potential equation, physically scalable with independent applied gate biases and oxide/channel thickness variations. Explicit regional solutions are derived for the first time for DG and the unified regional solution shows an error in the mili-volts range with respect to the numerical solutions.

II. ANALYTICAL LONG-CHANNEL CURRENT-VOLTAGE SOLUTION

For long channel double-gate MOSFETs as shown in Fig. 1, the drain-current equation can be extracted from the Pao-Sah's integral, which is expressed as

$$I_D = \frac{W}{L}\mu\int_0^{Vds} Q_i(V)dV \qquad (1)$$

where I_D is drain current, W is gate width, L is gate length, u is mobility and $Q_i(V)$ is inversion charge in the channel. $Q_i(V)$ can be express by the Gauss's law

$$Q_i(V) = 2\varepsilon_{si}(\frac{d\phi}{dx})_{x=-t_{si}/2} \qquad (2)$$

where ϕ represents potential. After substituting (2) into (1) with boundary conditions, we get

$$I_D = \frac{2W}{L}\mu\int_0^{Vds}(\varepsilon_{ox}\frac{V_g - \Delta\phi_i - \varphi_s}{t_{ox}})dV \qquad (3)$$

where Vg is gate voltage, t_{ox} is gate oxide thickness, and φ_s is surface potential. After solving (3), a continuous, explicit drain-current equation is reached [21, 22]:

$$I_{ds} = \frac{2\mu W}{L}\frac{\varepsilon_{ox}}{t_{ox}}[\frac{1}{2}(V_{gf}-\varphi_s)^2 + \frac{2kT}{q}(V_{gf}-\varphi_s)$$
$$-\frac{t_{ox}}{2\varepsilon_{ox}}kTn_it_{si}(e^{\frac{q(\varphi_s-V)}{kT}} - \frac{\varepsilon_{ox}^2(V_{gf}-\varphi_s)^2}{2t_{ox}^2\varepsilon_{si}kTn_i})]\Big|_0^{V_{ds}} \qquad (4)$$

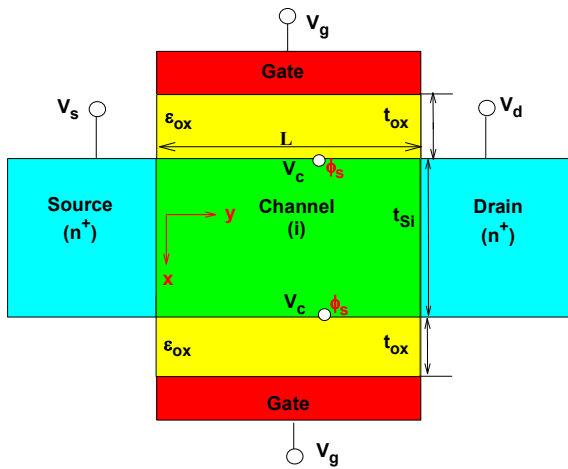**Fig. 1.** Schematic of a symmetric DG *n*-MOSFET.

where $V_{gf} = V_g - \Delta\phi_i$. ε_{ox} and ε_{si} are dielectric constant of oxide and silicon, respectively. q is the electron charge. n_i is the intrinsic carrier density. ϕ_s can be got approximately from the following expressions [23]:

$$\phi_{sub} = V_{gf}, \qquad (5a)$$

$$\phi_{str} = V_{gf} - 2v_{th}\mathcal{L}_+\left\{\frac{qt_{ox}}{\varepsilon_{ox}}\sqrt{\frac{n_i\varepsilon_{Si}}{2kT}}e^{(V_{gf}-V_c)/2v_{th}}\right\}, \quad (5b)$$

$$\phi_s = \vartheta_{eff}\{\phi_{sub}, \phi_{str}; \delta\}. \qquad (5c)$$

where $\mathcal{L}_+\{w\}$ is the *Lambert W* function [24] (principal branch), and

$$\vartheta_{eff}\{x_{sub}, x_{str}; \delta\} \equiv x_{str} - 0.5[x_{str} - x_{sub} - \delta$$
$$+\sqrt{(x_{str}-x_{sub}-\delta)^2 + 4\delta x_{str}}] \qquad (6)$$

where δ is a smoothing parameter [25], which is set as a constant 0.001 (which can be tuned for smoothness).

For symmetric case, we define the saturation voltage V_{dsat} at the point $\varphi_{sub} = \varphi_{str}(V) - \delta_1$, where δ_1 is a fitting parameter. Then we get

$$V_{Dsat} = V_{gf} + \frac{2kT}{q}\ln\frac{t_{ox}}{\delta\varepsilon_{ox}}\sqrt{2kTn_i\varepsilon_{Si}} - \delta_1 \qquad (7)$$

The subthreshold current is extracted by setting $V_{gf}=\phi_s$ in Eq. (6),

$$I_{dsub} = \frac{\mu W}{L}kTn_it_{si}e^{\frac{qV_{gf}}{kT}}(1-e^{\frac{-V_{ds}}{kT}}) \qquad (8)$$

III. ANALYTICAL SHORT-CHANNEL CURRENT-VOLTAGE SOLUTION

For short channel case, the drain-current equation can be expressed by [26]

$$I_D = \frac{W}{L}\mu_{eff}\int_0^{Vds}Q_i(V)dV = \frac{W}{L}\mu_{eff}\int_0^{Vds}Q_i(V)\frac{dV}{dy}dy \qquad (9)$$

Because $\quad \frac{dQ_i}{dx} = \frac{Q_i}{U_T}(\frac{d\varphi_s}{dy} - \frac{dV}{dy})$ [27], where

$$U_T = \frac{kT}{q}$$

So $\dfrac{dV}{dy} = \dfrac{d\varphi_s}{dy} - \dfrac{U_T}{Q_i}\dfrac{dQ_i}{dy}$, then we can get

$$I_D = \frac{W}{L}\mu_{eff}\int_0^{V_{ds}} Q_i(V)(\frac{d\varphi_s}{dy}dy - \frac{U_T}{Q_i}dQ_i)$$
$$= I_{D1} - \frac{W}{L}\mu_{eff}U_T(Q_d - Q_s) \tag{10}$$

where $\quad Q_s = \varepsilon_{ox}\dfrac{V_{gf}-\varphi_{ss}}{t_{ox}}\quad$, $\quad Q_d = \varepsilon_{ox}\dfrac{V_{gf}-\varphi_{sd}}{t_{ox}}\quad$,

φ_{ss} and φ_{sd} are the surface potential at source side and drain side, respectively.

$$I_{D1} = \frac{W}{L}\mu_{eff}\int_0^L Q_i(y)\frac{d\varphi_s}{dy}dy \tag{11}$$

Considering velocity saturation effect, μ_{eff} can be expressed by

$$\mu_{eff} = \frac{\mu_s}{[1+(E_y/E_{sat})^2]^{1/2}} \tag{12}$$

where $E_{sat} = \dfrac{v_{sat}}{\mu_s}$, μ_s is constant mobility.

$Q_i(y)$ can be extracted from Gauss' law,

$$Q_i(y) = \varepsilon_{si}(E'(y))t_{si} + 2\varepsilon_{si}E_s(y) \tag{13}$$

where

$$E_s(y) = -\varepsilon_{ox}\frac{V_{gf}-\varphi_s(y)}{\varepsilon_{si}t_{ox}} \tag{14}$$

In the linear region ($V_{DS}<V_{dsat}$), $E_y << E_C$, so after substituting (13) into (11) we get

$$I_{D1} = \frac{\mu_{eff}W}{L}\int_0^L \frac{d\varphi_s(y)}{dy}[2\varepsilon_{si}E(y)]dy$$
$$+ \frac{\mu_{eff}W}{L}\int_0^L \frac{d\varphi_s(y)}{dy}[\varepsilon_{si}(E'(y))t_{si}]dy \tag{15}$$
$$= I_{D2} + \frac{\mu_{eff}W}{L}[\varepsilon_{si}t_{si}](\frac{E(y)^2}{2})\Big|_0^L$$

where

$$I_{D2} = \frac{\mu_{eff}W}{L}\int_0^L \frac{d\varphi_s(y)}{dy}[2\varepsilon_{si}E(y)]dy \tag{16}$$

Suppose $\quad E(y) = -\dfrac{1}{\eta}\dfrac{d\varphi_s(y)}{dy} \tag{17}$

where η is a fitting parameter, and

$$E'(y) = -\frac{1}{\eta}\frac{d^2\varphi_s(y)}{dy^2} \tag{18}$$

From Eq. (13), we can get

$$\varepsilon_{si}(-\frac{1}{\eta}\frac{d^2\varphi_s(y)}{dy^2})t_{si} - 2\varepsilon_{ox}\frac{V_{gf}-\varphi_s}{t_{ox}} = qn_i\int_0^{t_{si}} e^{\frac{q\phi(x,y)}{kT}}dx \tag{19}$$

When in the volume inversion region (subthreshold region $V_G<V_T$), the inversion charge in the channel can be neglected. So

$$\varepsilon_{si}(-\frac{1}{\eta}\frac{d^2\varphi_s(y)}{dy^2})t_{si} - 2\varepsilon_{ox}\frac{V_{gf}-\varphi_s}{t_{ox}} \approx 0 \tag{20}$$

When in the strong inversion region ($V_G<V_T$), the inversion charge in the channel can be approximated by

$Q_i(y) = C_{ox}(V_{gf}-\varphi_s(y))$, So

$$\varepsilon_{si}(-\frac{1}{\eta}\frac{d^2\varphi_s(y)}{dy^2})t_{si} - 2\varepsilon_{ox}\frac{V_{gf}-\varphi_s}{t_{ox}} \approx C_{ox}(V_{gf}-\varphi_s(y)) \tag{21}$$

Let's set

$$a = \frac{\varepsilon_{si}t_{si}}{\eta}, \quad d = \frac{2\varepsilon_{ox}}{t_{ox}}, \quad c = 2\varepsilon_{ox}\frac{\varphi_s(y)}{t_{ox}} \tag{22}$$

After solving (21), we can get

$$\varphi_s(y) = \frac{c}{d} + \frac{[\varphi_s(V_D)-\frac{c}{d}]}{\sinh(\sqrt{\frac{d}{a}}L)}\sinh(\sqrt{\frac{d}{a}}y)$$
$$+ [\varphi_s(V_S)-\frac{c}{d}]\frac{\sinh[\sqrt{\frac{d}{a}}(L-y)]}{\sinh(\sqrt{\frac{d}{a}}L)} \tag{23}$$

Then

$$-\frac{d\varphi_s(y)}{dy} = \frac{\varphi_s(V_d)-\frac{c}{d}-e^{(-\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)}\sqrt{\frac{d}{a}}e^{(\sqrt{\frac{d}{a}}y)}$$

$$+\frac{\varphi_s(V_d)-\frac{c}{d}-e^{(\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)}\sqrt{\frac{d}{a}}e^{(-\sqrt{\frac{d}{a}}y)}$$

$$(24)$$

Meanwhile,

$$\varphi_s(0) = \frac{kT}{q}\ln\frac{N_{SD}}{n_i} , \quad \varphi_s(V_d) = \frac{kT}{q}\ln\frac{N_{SD}}{n_i}+V_{DS}$$

$$(25)$$

Now we can get I_{D2} after substituting (23) into (16)

$$I_{D2} = \frac{2\varepsilon_{si}\mu_s W}{\eta L}\int_0^L(\frac{d\varphi_s}{dy})^2 dy$$

$$= \frac{2\varepsilon_{si}\mu_s W}{\eta L}[\frac{1}{2}(\frac{\varphi_s(V_d)-\frac{c}{d}-e^{(-\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)})^2\sqrt{\frac{d}{a}}e^{(2\sqrt{\frac{d}{a}}y)}$$

$$-\frac{1}{2}(\frac{\varphi_s(V_d)-\frac{c}{d}-e^{(\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)})^2\sqrt{\frac{d}{a}}e^{(-2\sqrt{\frac{d}{a}}y)}$$

$$+2\frac{\varphi_s(V_d)-\frac{c}{d}-e^{(-\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)}$$

$$\times\frac{\varphi_s(V_d)-\frac{c}{d}-e^{(\sqrt{\frac{d}{a}}L)}(\varphi_s(0)-\frac{c}{d})}{2\sinh(\sqrt{\frac{d}{a}}L)}y]\Big|_0^L$$

$$(26)$$

Finally we can get I_{D1} after substituting (24) and (26) into (16), accordingly I_D after substituting (15) into (10).

In the saturation region, the gradual channel approximation (GCA) will not be valid near drain side. So we divide the channel into two regions. In the region

(0<y≤L-ΔL) GCA still applies, but in the region L-ΔL≤y<L we need to consider the effects of both vertical and lateral electrical fields.

Considering channel length modulation effect,

$$I_{ds} = I_D[1-\frac{\Delta L}{L}]^{-1} \qquad (27)$$

where ΔL is width of non-GCA region, which can be extracted as follows.

After we apply Gauss' law to the ABCD box in Fig. 2 (see Fig. 3), we can get the charge in the velocity saturation region (Q_{VS})

$$Q_{VS}(y) = \varepsilon_{si}(E_y'(y))t_{si} + 2\varepsilon_{si}E_s(y) \qquad (28)$$
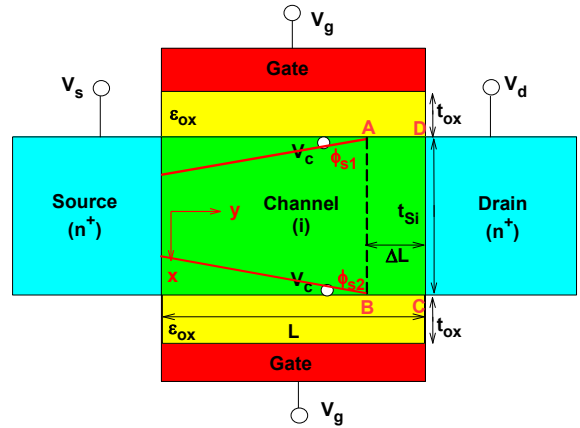
where

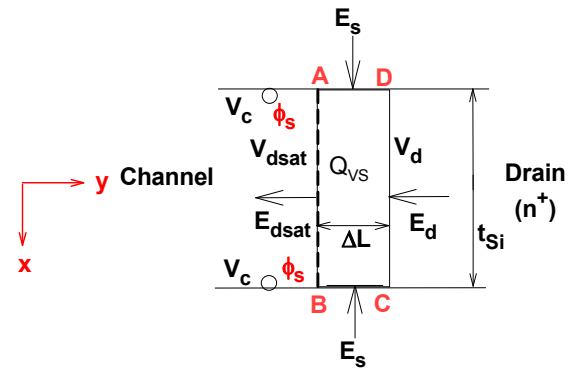**Fig. 2.** Schematic of a short-channel symmetric DG *n*-MOSFET.

Fig. 3. Velocity saturation region of a short-channel symmetric DG n-MOSFET.

$$E_s(y) = \varepsilon_{ox} \frac{V_{gf} - \varphi_{s0} - V(y)}{\varepsilon_{si} t_{ox}} \qquad (29)$$

Substituting (29) into (28), we can get (for symmetric undoped double-gate MOSFETs),

$$Q_{vs}(y) = \varepsilon_{si} E_y{'}(y)) t_{si} + 2\frac{\varepsilon_{ox}}{t_{ox}}(V_{gf} - \varphi_{s0} - V(y)) \qquad (30)$$

When y=0, according to gradual channel approximation,

$$Q_{vs}(0) = 0 + 2\frac{\varepsilon_{ox}}{t_{ox}}(V_{gf} - \varphi_{s0} - V_{dsat}) \qquad (31)$$

In the ABCD box (velocity saturation region),

$$Q_{vs}(y) = Q_{vs}(0) \qquad (32)$$

Then we can get $E_y{'}(y)$ by Eq. (30) and (31),

$$E_y{'}(y) = 2\frac{\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}(V(y) - V_{dsat}) \qquad (33)$$

The solution of the above equation is,

$$V(y) = V_{Dsat} + E_{sat}\sqrt{\frac{2\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}} \sinh\left(\frac{y}{\sqrt{\frac{2\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}}}\right) \qquad (34)$$

When y=ΔL,

$$V_D = V_{Dsat} + E_{sat}\sqrt{\frac{2\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}} \sinh\left(\frac{\Delta L}{\sqrt{\frac{2\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}}}\right) \qquad (35)$$

Then

$$\Delta L = \sqrt{\frac{2\varepsilon_{ox}}{\varepsilon_{Si} t_{Si} t_{ox}}} \operatorname{asinh}\left(\frac{\sqrt{\varepsilon_{Si} t_{Si} t_{ox}}(V_D - V_{Dsat})}{E_{sat}\sqrt{2\varepsilon_{ox}}}\right) \qquad (36)$$

IV. RESULTS AND DISCUSSION

In this section, results of the explicit solutions are compared with the numerical solutions for various operating conditions. Fig. 4 demonstrates Id-Vg curves when channel length is 1μm (long channel case). Fig. 5 plots Id-Vg curves when channel length is 0.1 μm (short channel case). Fig. 6 gives the comparison of the explicit, analytical drain current-drain voltage output characteristics and that from MEDICI results when channel length is 1 μm (long channel case). Fig. 7 compares the drain current-drain voltage output
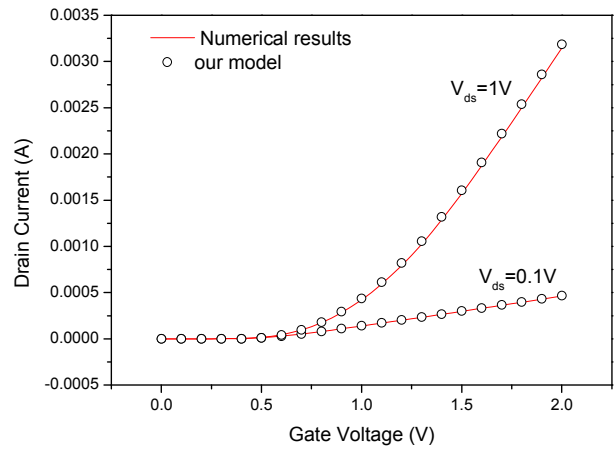

Fig. 4. Id-Vg curves for long-channel undoped double-gate MOSFETs. Symbols are from numerical results and line is from our model. Oxide thickness is 3 nm and channel thickness is 30 nm. Channel length is 1 um.
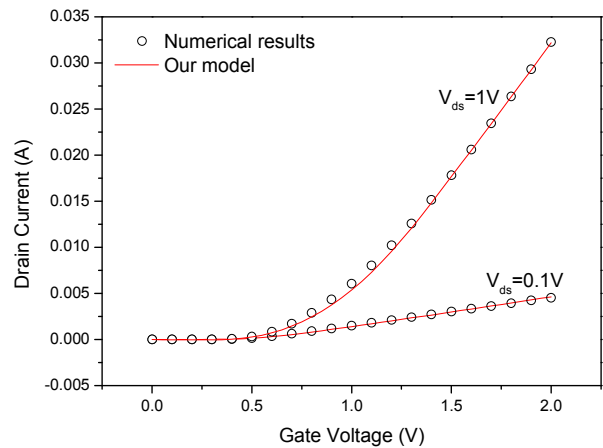

Fig. 5. Id-Vg curves for short-channel undoped double-gate MOSFETs. Symbols are from numerical results and line is from our model. Oxide thickness is 3 nm and channel thickness is 30 nm. Channel length is 100 nm.
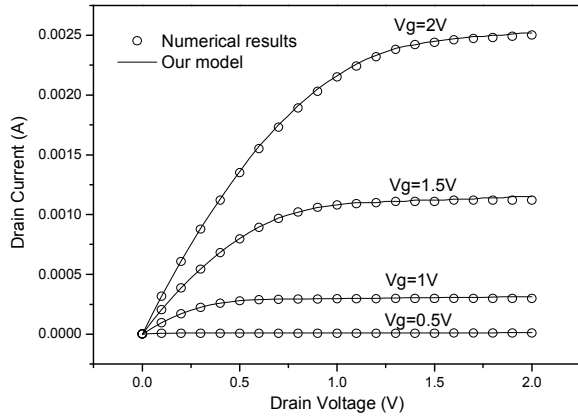
Fig. 6. Id-Vd curves for undoped double-gate MOSFETs. Lines are numerial results and symbols are our models. Oxide thickness is 3 nm and channel thickness is 30 nm. Channel length is 1 um.

Fig. 7. Id-Vd curves for undoped double-gate MOSFETs. Lines are numerial results and symbols are our models. Oxide thickness is 3 nm and channel thickness is 30 nm. Channel length is 100 nm.
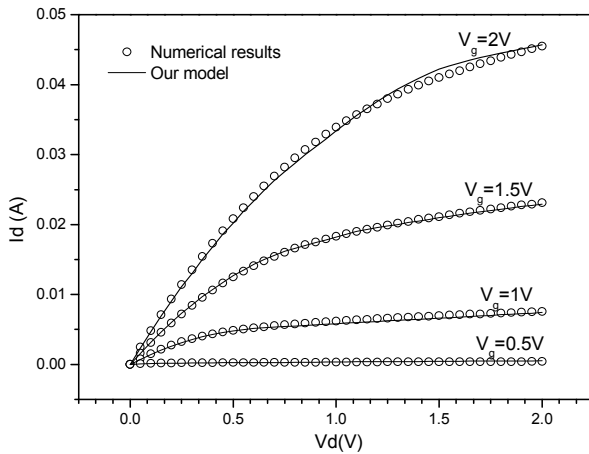
characteristics as calculated analytically with that from MEIDI results when channel length is 100 nm (short channel case), for four values of gate voltages. While we built our model, some fitting parameters are introduced for simplification and approximation of complicated equations, which otherwise cannot be solved analytically. The existence of the fitting parameters will produce some difference between MEDICI and our model. In general our model agrees very well with the simulated results. Fig. 8 gives the comparison of drain conductance (g_d) between our model and simulated results.
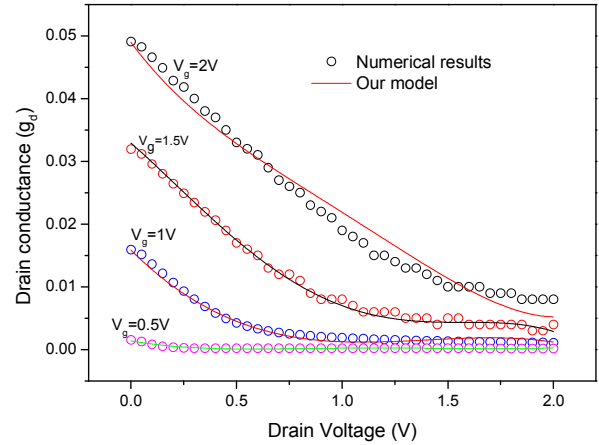

Fig. 8. g_d-Vd curves for undoped double-gate MOSFETs. Lines are numerial results and symbols are our models. Oxide thickness is 3 nm and channel thickness is 30 nm. Channel length is 100 nm.

V. CONCLUSIONS

An explicit unified regional short-channel drain current-drain voltage model has been derived for undoped symmetric double-gate. The V_{dsat} equation of undoped DG MOSFET has also been derived. The scalability of the model for different channel length and oxide thicknesses has been verified with the numerical solutions. The explicit solution is not only computationally efficient, more importantly, it is also easier to evaluate in compact drain-current formulations. The model has shown good accuracy compared with MEDICI result.

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