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Compact model for undoped symmetric double gate comprising quantization effect

By

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Abstract:

In this paper we propose an analytical modification for Hu's model which is an analytical model for undoped symmetric double gate MOSFETs. This modification targets to include the energy states quantization effect on the drain current. This leads to correct the model behavior for ultra thin double gate. Moreover, we introduce a simple method to include the velocity saturation effect in the current equation. Comparison with device simulator results is finally presented to validate the proposed modifications.

Keywords:

double gate MOSFETS, compact models, quantization effect, velocity saturation

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1. Introduction:

The short channel effects become an obvious obstruction to the shrinkage of the gate length of bulk MOSFETs below 45nm. Double-gate structures introduce better control over the channel reducing the short channel effects. So, double-gate structures are strong candidates below 45nm despite the complexity needed to build such structures [1].

For undoped symmetric double gate, published compact models are based on either surface potential or charge distributions [2]. The model introduced by Taur et al. [3] is an example for surface potential based models. The model introduced by Chenming Hu et al. [4] is an example for charge based models. Hu's model considered the quantum confinement effect occurred for ultra thin double gate (below 10nm) on the electron distribution. However it is not enough to consider the effect of the quantum confinement on the energy states quantization which affects the threshold voltage. To include such effect, Schrödinger's equation has to be solved in the perpendicular direction to the gates. However, this is too complex to be done for compact models. This shortcoming also appears in Taur's model. Moreover, Hu's model assumed the mobility is constant. For the small dimensions of the double gate, this assumption is not correct due to the effect of velocity saturation. The model mentioned that the effect of velocity saturation can be included using the unified mobility module used in Surface-Potential-Plus (SPP) approach [5]. However the model did not illustrate specifically how to apply this module for double gate MOSFETs.

In this work we introduce a simple way to include the energy states quantization effect for Hu's model without the need to solve Schrödinger's equation. In addition, we will present how to include the velocity saturation effect in the current equation of this model with a similar way that used in Surface-Potential-Plus approach [5].

2. Proposed Model:

First, we will introduce our technique to include the energy quantization effect on the drain current. We will insert the energy quantization caused by the quantum confinement to the semiconductor work function as follows:
The positions of the energy levels above the conduction band edge of the bulk material due to the quantum confinement effect can be approximated as [6]:

$$E_n = \frac{\hbar^2}{2m^*}\left(\frac{n\pi}{t_{si}}\right)^2 \tag{1}$$

where n=1,2,3,…, $\hbar$ is the reduced Planck constant, m^* is the electron effective mass and t_{si} is the body thickness. We can get the position of the minimum energy of the lowest conduction subband by posing n=1 in equation (1)

$$E_c = E_{c0} + \frac{\hbar^2}{2m^*}\left(\frac{\pi}{t_{si}}\right)^2 \tag{2}$$

where E_{c0} is the original conduction band minimum of bulk silicon. Consequently, the semiconductor work function will be changed to be:

$$\phi_{snew} = \phi_s - \alpha_1\left[\frac{\hbar^2}{2m^*}\left(\frac{\pi}{t_{si}}\right)^2\right] + \alpha_2 \tag{3}$$

where ϕ_s is the original semiconductor work function, α_1 and α_2 are model parameters. So, the work function difference can be expressed as follows:

$$\Delta\phi_i = \phi_m - \phi_{snew} \tag{4}$$

where ϕ_m is the metal work function.
By replacing the work function difference in Hu's model with equation (4), the energy quantization effect is considered in the model.

Second, we will describe our method to include the velocity saturation effect in the current equation of this model. Figure (1) presents a schematic structure of an undoped symmetric double gate n-MOSFET, where x is the direction across the channel thickness and y is the direction along the channel.

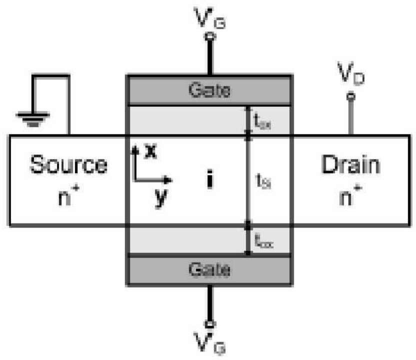

Figure (1): *Schematic structure of a symmetric DG n-MOSFET.*

Starting with the current equation used in Hu's model:

$$I_{ds} = 2\mu w C_{ox}\left(\frac{KT}{q}\right)^2 q_{in}\frac{dv_{ch}}{dy} \tag{5}$$

where μ is the mobility, w is the gate width, C_{ox} is the oxide capacitance, K is the Boltzman constant, q is the electron charge, T is the temperature, q_{in} is the inversion charge normalized by $C_{ox}\frac{KT}{q}$ and v_{ch} is the channel voltage normalized by $\frac{KT}{q}$.
We will insert the velocity saturation effect in the mobility by putting [7]:

$$\mu = \frac{\mu_o}{1+\frac{\mu_o}{2v_{sat}}\left|\frac{d\psi_s}{dy}\right|} \tag{6}$$

where v_{sat} is a model parameter which presents the value of velocity saturation, μ_o is a model parameter which presents the value low field mobility and ψ_s is the surface potential.

From Hu's model we can deduce that

$$\frac{d\psi_s}{dy} = -\frac{KT}{q}\frac{dq_{in}}{dy} \tag{7}$$

Using equations (5), (6) and (7) we can get:

$$I_{ds}\left[1+\frac{\mu_o}{2v_{sat}}\frac{KT}{q}\left|-\frac{dq_{in}}{dy}\right|\right]dy=-2\mu_o wC_{ox}\left(\frac{KT}{q}\right)^2\times q_{in}\left(\frac{1}{q_{in}}+1\right)dq_{in} \quad (8)$$

Integrating equation (8) from the source to the drain

$$I_{ds}\int_0^L\left[1+\frac{\mu_o}{2v_{sat}}\frac{KT}{q}\left|-\frac{dq_{in}}{dy}\right|\right]dy=-2\mu_o w\left(\frac{KT}{q}\right)^2 C_{ox}\int_{q_s}^{q_d}(1+q_{in})dq_{in} \quad (9)$$

Then we can get the drain current equation:

$$I_{ds}=\frac{2\mu_o w\left(\frac{KT}{q}\right)^2 C_{ox}\left[\frac{1}{2}\left(q_s^2-q_d^2\right)+\left(q_s-q_d\right)\right]}{L+\frac{\mu_o}{2v_{sat}}\frac{KT}{q}\left|\left(q_s-q_d\right)\right|} \quad (10)$$

Where the normalized source and drain charges are given by [4]:

$$q_s=W_0\left[\exp\left(v_g-\Delta\phi_i-v_s+f\ln\left(\frac{q^2 n_i T_{si} t_{ox}}{2KT\varepsilon_{ox}}\right)\right)\right] \quad (11)$$

$$q_d=W_0\left[\exp\left(v_g-\Delta\phi_i-v_d+f\ln\left(\frac{q^2 n_i T_{si} t_{ox}}{2KT\varepsilon_{ox}}\right)\right)\right] \quad (12)$$

where v_g is the gate voltage normalized by $\frac{KT}{q}$, v_s is the source voltage normalized by $\frac{KT}{q}$, v_d is the drain voltage normalized by $\frac{KT}{q}$ and f is a dimensionless correction factor.

In the saturation region, the drain current can be expressed as follows [7]:

$$I_{dsat}=2w\times C_{ox}\times\frac{KT}{q}\times q_{dsat}\times v_{sat} \quad (13)$$

So we can get q_{dsat} by equating equation (10) and equation (13)

$$q_{dsat} = \frac{\frac{q_s^2}{2} + q_s}{\frac{v_{sat} L}{\frac{KT}{q}\mu_o} + \frac{q_s}{2} + 1} \tag{14}$$

From Hu's model, we can calculate the saturation drain voltage

$$v_{dsat} = v_g - \Delta\phi_i + f\ln\left(\frac{q^2 n_i T_{si} t_{ox}}{2KT\varepsilon_{ox}}\right) - \ln q_{dsat} - q_{dsat} \tag{15}$$

Now, we will define the effective drain voltage v_{deff} by which we can merge the normal drain voltage and the saturation drain voltage using the following equation [8]:

$$v_{deff} = \frac{v_d}{\left(1 + \left(\frac{v_d}{v_{dsat}}\right)^{AX}\right)^{\frac{1}{AX}}} \tag{16}$$

where AX is a fitting model parameter
So we can get the effective drain inversion charge using the effective drain voltage:

$$q_{deff} = W_0\left[\exp\left(v_g - \Delta\phi_i - v_{deff} + f\ln\left(\frac{q^2 n_i T_{si} t_{ox}}{2KT\varepsilon_{ox}}\right)\right)\right] \tag{17}$$

Substituting with equation (17) in equation (10) we can get:

$$I_{ds} = \frac{2\mu_o w\left(\frac{KT}{q}\right)^2 C_{ox}\left[\frac{1}{2}\left(q_s^2 - q_{deff}^2\right) + \left(q_s - q_{deff}\right)\right]}{L + \frac{\mu_o}{2v_{sat}}\frac{KT}{q}\left|\left(q_s - q_{deff}\right)\right|} \tag{18}$$

Equation (18) presents the final formula of our proposed model for the drain current which covers both the linear and saturation regions.

3. Results:

In this section we will verify our proposed model (equation 18) results compared with Hu's model and nanomos [9] device simulator as a reference. According to the ITRS roadmap function ϕ_m =4.45 eV to achieve the required threshold voltage. In addition the following technological parameters were used: $W = 1\mu m$ $L = 40\,nm$ $t_{ox} = 1.5\,nm$ and S/D doping=$10^{20}\,cm^{-3}$.

Figure (2) depicts the transfer characteristics for t_{si} =5nm and t_{si} =1.5nm at V_d =0.8V It is clear that Hu's model doesn't show a good fitting for the subthreshold region because it didn't consider the energy states quantization. Moreover Hu's model shows a poor fitting for the strong inversion region because it didn't consider the velocity saturation effect. On the other hand, our proposed model presents a good fitting for both the subthreshold and strong inversion regions when the model parameters $\alpha_1 = 0.65$ $\alpha_2 = 0.007$ $v_{sat} = 0.57 \times 10^5\, m/s$ $AX = 1.7$ and $\mu_0 = 200 cm^2 / V.sec$

It should be noted that we neglect the correction factor f , which is applicable for ultra thin double gate as mentioned in Hu's model.

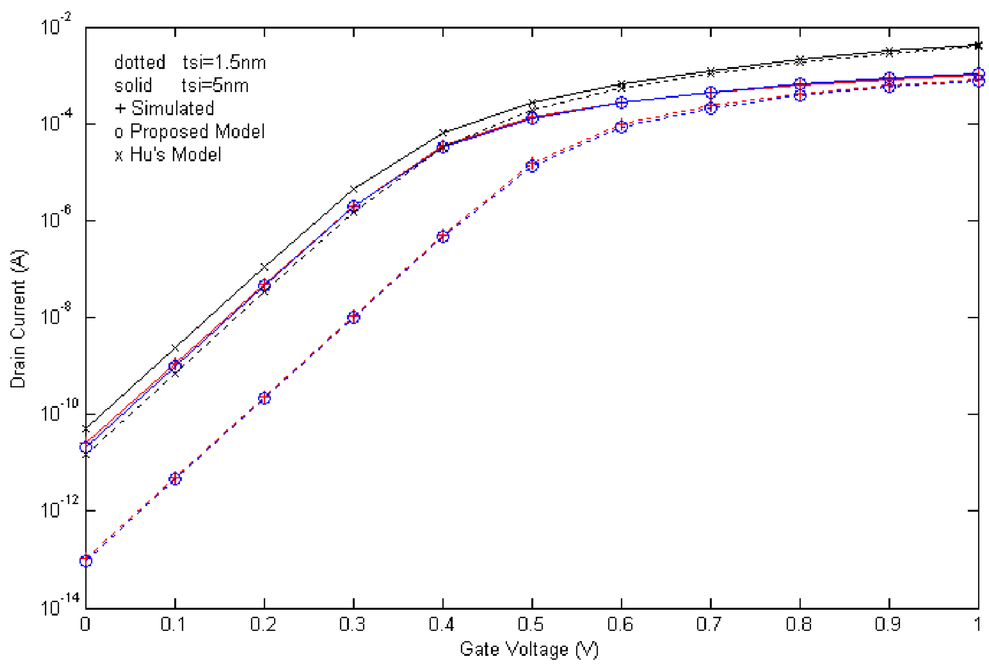

Figure (2): I_d *versus* V_g *for* t_{si} *=1.5nm and 5nm*

It is well known that the correct value of the threshold voltage is an important parameter for digital applications. Figure (3) shows the variation of the threshold voltage versus the body thickness. The threshold voltage is extracted at constant current level equals $1\mu A$ for V_{ds} =0.8V. The device simulator shows that the body thickness has a strong effect on the threshold voltage. This is due to the significant effect of the energy state quantization on the threshold voltage. As the body thickness decreases below 10nm, a quantum well is formed between the two gates. In the subthreshold region, the quantum well can be considered as square. As a result, for electrons, the quasi-continuous conduction band of bulk silicon material is replaced by a series of discrete energy subbands. The energy states that the electrons occupy in the quantum well are higher than those in the bulk material, which means that more voltage is needed to reach the inversion case as compared with the bulk case. Thus, If the body thickness decreases, the energy states are raised due to narrower quantum well. Consequently, the threshold voltage increases with decreasing body thickness [10]. It can be deduced from Figure (3) that Hu's model has a high fitting error reaches to 23%. On the other hand, our proposed model introduces a fitting error below 0.5% as a result to taking into account the energy state quantization. This leads to have a good fitting for the subthrehold current for this range of t_{si} .

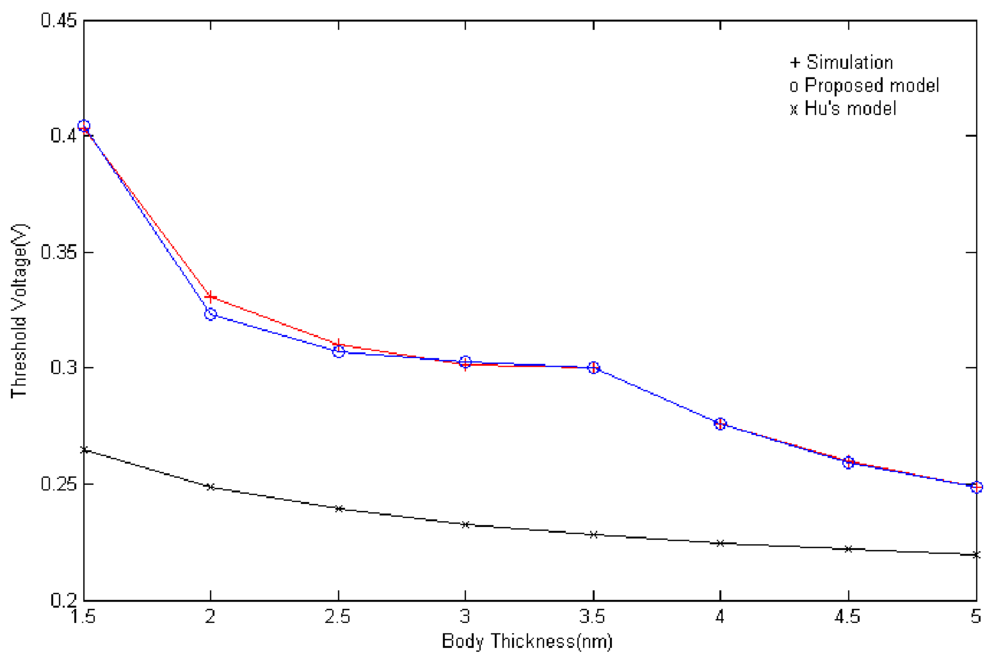

Figure (3): *Threshold Voltage versus Body Thickness*

In order to verify that our method includes the velocity saturation effect correctly, the $I_d - V_d$ characteristic is shown in Figure (4). It is obvious that the unified drain current presented in equation (18) shows a good fitting for all regions of operation.

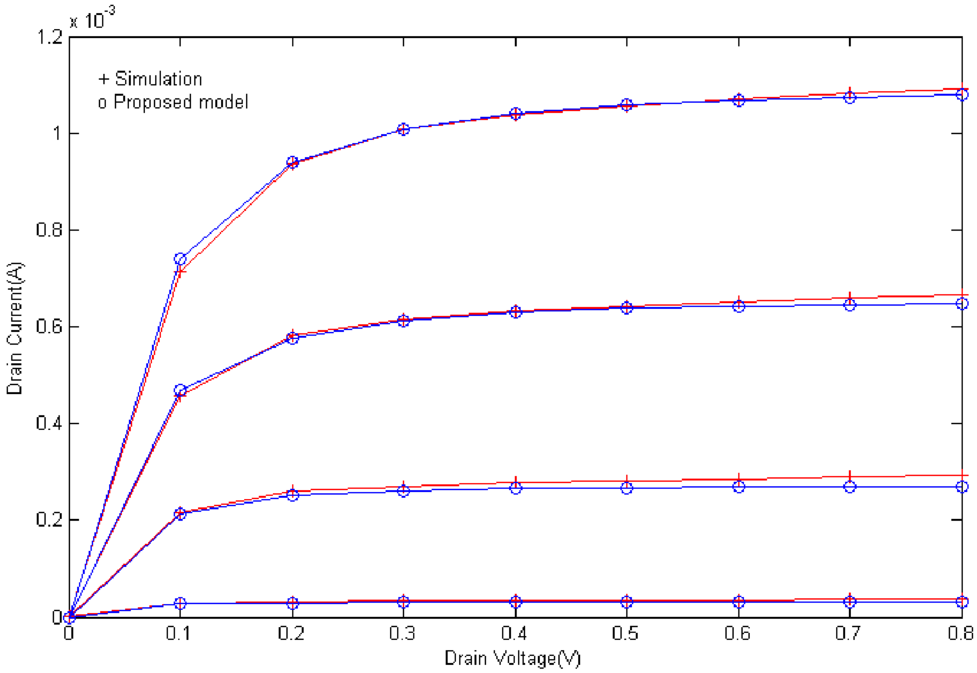

Figure (4): I_d *versus* V_d *for different* V_g

4. Conclusions:

A method to include the energy states quantization effect inside the drain current of Hu's model is presented. This method leads to enhance the fitting error of the threshold voltage from 23% to 0.5% for ultra thin double gate. Consequently our proposed model introduces a good fitting for the drain current in the subthreshold region. This method is also very simple and can be extended to other models like Taur's model. Furthermore, we proposed a method to have a unified drain current equation which includes the velocity saturation effect. This leads to have a good fitting for the drain current in strong inversion region.

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