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A novel surface potential-based short channel MOSFET model for circuit simulation

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ABSTRACT

In this paper a novel analytical approximation method for surface potential (ψ_s) calculation in compact MOSFET model is presented. It achieves excellent accuracy and good calculation speed over all regions from accumulation to strong inversion. With this approximation method, a surface potential-based compact model for short channel MOSFET is developed. Comparison with measured data is also presented to validate the new model.

1. Introduction

Many different methods have been developed for MOSFET compact modeling, result in models with various degrees of complexity and accuracy. At present, surface potential-based models have engaged more interest, and tend to be the mainstream of MOSFET compact models.

However, there is a critical building block for developing surface potential-based models: the surface potential ψ_s has to be evaluated from an implicit surface potential equation [1], which may lead to complicated computation. The surface potential calculation methods can be divided into two categories: numerical iteration [2–5] and analytical approximation. The iteration method is used in the latest MM11 [6] and HiSIM [7], and the most accurate values of ψ_s can be computed with them. However, the iteration method requires a special care in programming and coding, otherwise, it is likely to cause convergence issues or lower the simulation efficiency.

Consequently, for ψ_s calculation, a proper analytical approximation would be a better method. In literatures several analytical approximation methods have been reported. The analytical approximation model reported in Ref. [8] is used in previous levels of MM11 [9,10]. But the accumulation region is not included in this model, and the model's absolute error of ψ_s is about 2–3 mV, which is not good enough for reproducing derivatives of current in the moderate inversion region [11]. The analytical approximation method used in PSP [12] has been reported in Refs. [11,13,14], which achieves good accuracy in all operation regions [14]. However, the ψ_s computation in PSP becomes very complicated. In Ref. [15], the analytical approximation reported is also very complicated. In the analytical surface potential model reported in Ref. [16], only subthreshold region is considered.

In this paper, a novel analytical method for ψ_s computation is presented, which achieves both excellent accuracy and good computation speed. In the calculation speed comparison, the model shows a better performance than PSP. It also keeps validity over all regions from accumulation to strong inversion. Though different equations are used for different operation regions, it still keeps the continuity of ψ_s and it's derivatives even on the region boundaries.

With the new surface potential model, a charge sheet model is presented. A new linearized bulk charge equation is developed, which keeps the model symmetry with respect to source and drain. For short channel devices, velocity saturation model is derived. New subthreshold models are also developed, which provide model parameter that affect operation regions separately, and lead to easier extraction work and better accuracy. At last, comparison of the model result with the measured result is presented, in which the new model shows an accurate description for the actual short channel MOSFET devices.

2. Surface potential model

Solved from one dimensional Poisson equation, the original surface potential equation was first developed in Ref. [17], then

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the equation was discussed again and modified by Refs. [18,19]. According to Refs. [18,19], a physically based well-conditioned version of the surface potential equation can be expressed as follows:

$$V_{GB} = V_{FB} + \psi_s \pm \gamma\sqrt{e^{(-2\phi_F-\phi_n)/\phi_t}(\phi_t e^{\psi_s/\phi_t} - \psi_s - \phi_t) + \phi_t e^{-\psi_s/\phi_t} + \psi_s - \phi_t} \tag{1}$$

where V_{GB} is the gate-to-bulk voltage, V_{FB} is the flat band voltage, $\phi_t = kT/q$ is the thermal potential, ϕ_F is the Fermi potential, $\gamma = \sqrt{2q\epsilon_s N_{sub}}/C_{ox}$ is the body factor, N_{sub} is the substrate concentration, C_{ox} is the oxide capacitance per unit channel area, q is the magnitude of electronic charge, ϵ_s is the permittivity of silicon, the $+$ sign before γ is used with $\psi_s > 0$ and $-$ sign is used with $\psi_s < 0$, the bulk-referenced quasi-Fermi potential ϕ_n is equal to V_{SB} and V_{DB} at the source and drain end, respectively. Eq. (1) is valid for all values of gate-bulk voltage V_{GB} and gives an accurate description in all operation regions (accumulation, depletion and inversion). With some notations, it can be reformed as follows:

$$z = x \pm a\sqrt{e^{x-A} - xe^{-A} - e^{-A} + e^{-x} + x - 1} \tag{2}$$

where $x = \psi_s/\phi_t$, $z = (V_{GB} - V_{FB})/\phi_t$, $a = \gamma/\sqrt{\phi_t}$, $A = (2\phi_F + \phi_n)/\phi_t$.

The analytical approximation of surface potential in our model is derived from Eq. (2).

2.1. The ψ_s approximation equations

To simplify the expression of our analytical approximation, following notations are used for ψ_s calculation:

$$vt = A + a\sqrt{A} \tag{3}$$

$$td = \frac{\sqrt{A}}{\sqrt{A} + a} \tag{4}$$

$$tds = -\frac{a(A-2)}{2(\sqrt{A}+a)^3} \tag{5}$$

$$fd = \frac{\sqrt{2}}{(\sqrt{2}+a)} \tag{6}$$

$$fds = \frac{2a}{3(\sqrt{2}+a)^3} \tag{7}$$

Thus the computation of ψ_s is divided into three pieces according to the value of z.

2.1.1. For $z \geq vt$

When $x \geq A$, $z \geq vt$. By assuming $A \gg 1$, Eq. (2) can be simplified as:

$$z = x + a\sqrt{e^{x-A} + x - 1} \tag{8}$$

As described in Appendix A, the approximation calculation of ψ_s can be derived as follow:

$$x_0 = \ln[1 + td(z - vt) + \tfrac{1}{2}(td^2 + tds)(z - vt)^2] + A \tag{9}$$

$$x_1 = \ln\left[\frac{x_0^2}{a^2} - \left(1 + \frac{2z}{a^2}\right)x_0 + \frac{z^2}{a^2} + 1\right] + A \tag{10}$$

where x_0 and x_1 are both approximation values of x. For value of z near vt, x_0 in Eq. (9) have better accuracy than x_1; for $z \gg vt$, the accuracy of x_1 in Eq. (10) is better. Combine x_0 and x_1 yields

$$x_2 = x_1 - (x_1 - x_0)e^{-0.1\cdot(z-vt)} \tag{11}$$

As an approximation of x in Eq. (2), the accuracy of x_2 in Eq. (11) is good enough for MOSFET compact modeling in a regular parameter range ($t_{ox} > 2$ nm, $N_{sub} > 2 \times 10^{17}$ cm^{-3}). In order to achieve adequate accuracy for wider parameter range, further computations can be executed as:

$$z_2 = x_2 + a\sqrt{e^{x_2 - A} + x_2 - 1} \tag{12}$$

$$\psi_s = \phi_t\left[x_2 + \frac{(z - z_2)}{z_2'}\left(1 - \frac{(z - z_2)z_2''}{2z_2'^2}\right)\right] \tag{13}$$

where z_2' and z_2'' are the first and second derivatives of z_2 in Eq. (12). The calculation method in Eq. (13) is similar with the second-order Newton–Raphson iteration method in Ref. [3], but in our model, only one time computation is needed for Eq. (13).

2.1.2. For $z \leq 0$

When $x \leq 0$, $z \leq 0$. By assuming $A \gg 1$, Eq. (2) can be simplified as:

$$z = x - a\sqrt{e^{-x} + x - 1} \tag{14}$$

With the similar method used in the derivation of Eqs. (9)–(13), the following equations can be derived as

$$x_0 = -\ln[1 - fd \cdot z + \tfrac{1}{2}(fd^2 + fds) \cdot z^2] \tag{15}$$

$$x_1 = -\ln\left[\frac{x_0^2}{a^2} - \left(1 + \frac{2z}{a^2}\right)x_0 + \frac{z^2}{a^2} + 1\right] \tag{16}$$

$$x_2 = x_1 - (x_1 - x_0)e^{0.1\cdot z} \tag{17}$$

$$z_2 = x_2 - a\sqrt{e^{-x_2} + x_2 - 1} \tag{18}$$

$$\psi_s = \phi_t\left[x_2 + \frac{(z - z_2)}{z_2'}\left(1 - \frac{(z - z_2)z_2''}{2z_2'^2}\right)\right] \tag{19}$$

where z_2' and z_2'' are the first and second derivatives of z_2 in Eq. (18).

2.1.3. For $0 < z < vt$

When $0 < x < A$, $0 < z < vt$. By assuming $A \gg 1$, Eq. (2) can be simplified as:

$$z = x + a\sqrt{H(x,A) \cdot e^{x-A} + I(x,A) \cdot e^{-x} + x - 1} \tag{20}$$

where functions H and I are added to keep continuity with Eqs. (8) and (14) on the region boundaries. They are introduced as:

$$H(a,b) = 1 - \left(\frac{1}{2} + \frac{1}{2}\cos\frac{\pi \cdot a}{b}\right)^4 \tag{21}$$

$$I(a,b) = 1 - \left(\frac{1}{2} - \frac{1}{2}\cos\frac{\pi \cdot a}{b}\right)^4 \tag{22}$$

As described in Appendix B, the approximation method of ψ_s calculation can be derived as follow:

$$F(z) = 1 - H(z,vt) \cdot e^{td(z-vt) + (1/2)tds(z-vt)^2} - I(z,vt) \cdot e^{-fd\cdot z - (1/2)fds\cdot z^2} \tag{23}$$

$$x_1 = z + \frac{a^2}{2} - \frac{a}{2}\sqrt{4z + a^2 - 4F(z)} \tag{24}$$

$$G(x_1) = 1 - H(x_1,A) \cdot e^{x_1 - A} - I(x_1,A) \cdot e^{-x_1} \tag{25}$$

$$\psi_s = \phi_t\left[z + \frac{a^2}{2} - \frac{a}{2}\sqrt{4z + a^2 - 4G(x_1)}\right] \tag{26}$$

Thus, according to the value of z, we get the value of ψ_s with Eqs. (13) and (19) or Eq. (26).