A new quasi-2D analytical threshold-voltage model for partially-depleted short-channel SOI MOSFET

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Abstract: — A new quasi-2D analytical model is presented for the threshold voltage of partially depleted silicon-on-insulator MOSFETs with effective channel lengths down to deep-submicrometer range. The model is based on the analytical solution for two-dimensional potential distribution in the silicon film approximated by the power series expansion method. A new approach is also proposed to improve the accuracy of the model. Good agreements are obtained between the results of the model and the 2-D numerical analysis with the devices scaling to the deep-submicrometer range. The derived threshold voltage is an explicit form and can be further implemented in the circuit simulator such as HSPICE.

Key-Words: —Threshold voltage model, silicon-on-insulator, MOSFET, transistor, HSPICE, SOI.

1 Introduction

The thin film fully depleted (FD) SOI MOSFETs are attracting considerable attentions as high-performance and low-power consumption IC devices due to their inherent properties such as improved short-channel effect, sharp subthreshold slope and high transconductance [1]. However, the threshold voltage is sensitive to the variation of the thickness of the SOI film across the wafer, and it may become uncontrollable. The partially depleted (PD) SOI MOSFET is easier to fabricate and control than the fully depleted one, and it is believed to be the most suitable for applications [2]. When the device is scaling down to the deep-submicrometer range, the short channel effects become significant, especially in the threshold voltage reduction. In the partially depleted SOI MOSFETs, in addition to the presence of the floating-body effect, the threshold voltage model is similar to that of the conventional bulk MOSFETs. The 2-D Poisson's equation for the silicon film has been solved by using power series expansion method [3] or the variable separation and the Green's function methods [4]. In the model of [3], the effects caused by the source/drain junctions were greatly under-estimated and only applicable to the MOSFETs with uniform substrate doping. In model of [4], although an explicit form of the threshold voltage model was obtained, the calculation was too complicated to be further implemented in the analytical current-voltage model for the circuit simulator.

In this paper, a simple and accurate quasi-2D analytical threshold voltage model is derived for the partially depleted SOI MOSFETs utilizing the power series expansion approach to solve the Poisson's equation in the silicon film. The model can be applicable for the non-uniform substrate doping. An explicit form of the threshold voltage model is obtained without involving an infinite series. The calculated results obtained by the present model are compared with the 2-D numerical MEDICI simulation results and good agreements are obtained.

2 Analytical threshold voltage model

The typical schematic cross-sectional view of the partially depleted SOI MOSFET is shown in Fig. 1. The 2-D Poisson's equation is written as

$$\frac{\partial^2\phi(x,y)}{\partial x^2}+\frac{\partial^2\phi(x,y)}{\partial y^2}=\frac{qN_B(y)}{\varepsilon_{si}} \quad (1)$$

where $\phi(x,y)$ is the potential distribution in the silicon film, $N_B(y)$ is the doping concentration of Si film and assumed to be one-dimensional and ε_{si} is the silicon permittivity.

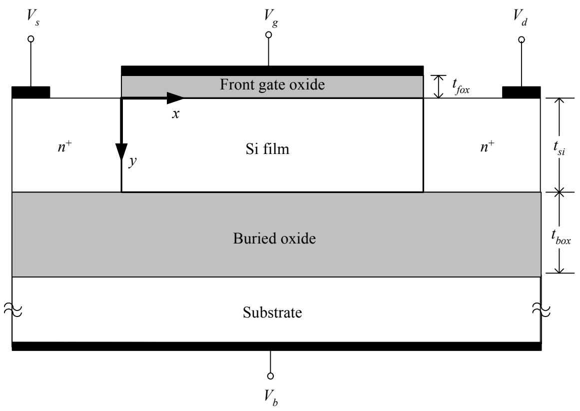

Fig.1. The schematic cross-sectional view of a partially depleted SOI MOSFET structure.

Firstly, we define the potential at the position x along the Si front surface $\phi(x,0)$ as $\phi_f(x)$. The boundary conductions for the equation (1) are assumed as

$$\begin{aligned}
&\phi_f(0)=V_{bi}\\
&\phi_f(L)=V_{bi}+V_{DS}\\
&\left[\frac{\partial\phi(x,y)}{\partial y}\right]_{y=y_d}=-E_y(x,y_d)=0\\
&\left[\frac{\partial\phi(x,y)}{\partial y}\right]_{y=0}=-E_y(x,0)=-\frac{C_{fox}}{\varepsilon_{si}}\left(V_{gs}-V_{FB,f}-\phi_f(x)\right)
\end{aligned} \quad (2)$$

where V_{bi} is the built-in potential of the source/drain junction, V_{gs} and V_{ds} are the gate and drain biases, respectively, y_d is the width of the bulk depletion region, $V_{FB,f}$ is the front-gate flatband voltage, C_{fox} is the front-gate capacitance and $E_y(x, 0)$ and $E_y(x, y_d)$ are the vertical electric fields at the position x along the Si front surface and along the edge of the depletion region, respectively. The equation $E_y(x, y_d) = 0$ is identical to the conventional bulk MOSFET due to the partially depleted property in the silicon film region. Using the power series expansion method, the 2-D potential distribution in the Si film can be expressed as

$$\phi(x,y)=a_0(x)+a_1(x)y+a_2(x)y^2+\ldots=\sum_0^\infty a_n(x)y^n \quad (3)$$

where the coefficients, a's, can be determined by the above boundary conditions. Because of the floating-body characteristic in the PD SOI MOSFET, the potential distribution along the edge of the back silicon depletion region cannot be definitely defined. Therefore, only three coefficients (a_0, a_1 and a_2) can be determined from the boundary conditions. By solving Poisson's equation (equation (1)) with the boundary conditions listed in the equation (2) and the potential distribution $\phi(x,y)$ in the equation (3), the surface potential $\phi_f(x)$ can be obtained as

$$\phi_f(x)=A\exp\left(-\sqrt{\alpha_f}\,x\right)+B\exp\left(\sqrt{\alpha_f}\,x\right)-\frac{\beta_f}{\alpha_f} \quad (4)$$

where

$$\alpha_f=\frac{\dfrac{C_{fox}}{y_d\varepsilon_{si}}}{1+\dfrac{y_dC_{fox}}{3\varepsilon_{si}}}$$

$$\beta_f=\frac{\dfrac{q}{y_d\varepsilon_{si}}\displaystyle\int_0^{y_d}N_B(y)dy-\dfrac{C_{fox}}{y_d\varepsilon_{si}}\left(V_{gs}-V_{FB,f}\right)}{1+\dfrac{y_dC_{fox}}{3\varepsilon_{si}}}$$

$$A=\frac{\left(V_{bi}+\dfrac{\beta_f}{\alpha_f}\right)\exp\left(\sqrt{\alpha_f}L\right)-\left(V_{bi}+V_{ds}+\dfrac{\beta_f}{\alpha_f}\right)}{2\sinh\left(\sqrt{\alpha_f}L\right)}$$

$$B=\frac{\left(V_{bi}+V_{ds}+\dfrac{\beta_f}{\alpha_f}\right)-\left(V_{bi}+\dfrac{\beta_f}{\alpha_f}\right)\exp\left(-\sqrt{\alpha_f}L\right)}{2\sinh\left(\sqrt{\alpha_f}L\right)}$$

Then, by differentiating the equation (4) and setting the resulting equation equal to zero, the position of the minimum front surface potential, x_{min}, can be obtained. The minimum front surface potential $\phi_{f,\min}$ can be determined by putting x_{min} into equation (4) and written as

$$\phi_{f,\min} = \frac{G}{\sinh\left(\sqrt{\alpha_f}L\right)} - \frac{\beta_f}{\alpha_f}$$

$$G = \left[2\left(V_{bi}+V_{ds}+\frac{\beta_f}{\alpha_f}\right)\left(V_{bi}+\frac{\beta_f}{\alpha_f}\right)\cosh\left(\sqrt{\alpha_f}L\right)-\left(V_{bi}+\frac{\beta_f}{\alpha_f}\right)^2-\left(V_{bi}+V_{ds}+\frac{\beta_f}{\alpha_f}\right)^2\right]^{1/2} \quad (5)$$

Through some mathematical manipulations, the following equation can be obtained

$$\lambda - \phi_{f,\min} = \frac{q\int_0^{y_d} N_B(y)dy - C_{fox}\left(V_{gs}-V_{FB,f}\right)}{C_{fox}} \quad (6)$$

where

$$\lambda = \frac{\left(2V_{bi}-2\phi_{f,\min}+V_{ds}\right)}{\cosh\left(\sqrt{\alpha_f}L\right)-1} + \frac{2\left(V_{bi}-\phi_{f,\min}\right)^{\frac{1}{2}}\left(V_{bi}-\phi_{f,\min}+V_{ds}\right)^{\frac{1}{2}}\cosh\left(\sqrt{\alpha_f}L/2\right)}{\cosh\left(\sqrt{\alpha_f}L\right)-1}$$

The threshold voltage V_{TH} can be taken as the value of V_{gs} for which $\phi_{f,\min} = 2\phi_{fp}$ (ϕ_{fp} is the Fermi potential of the silicon film). Therefore, the threshold voltage can be derived as

$$V_{TH} = V_{FB,f} + \frac{q}{C_{fox}}\int_0^{y_d} N_B(y)dy + 2\phi_{fp} - \lambda_{inv} \quad (7)$$

where

$$\lambda_{inv} = \lambda\big|_{\phi_{f,\min}=2\phi_{fp}} = \frac{\left(2V_{bi}-4\phi_{fp}+V_{ds}\right)}{\cosh\left(\sqrt{\alpha_f}L\right)-1} + \frac{2\left(V_{bi}-2\phi_{fp}\right)^{\frac{1}{2}}\left(V_{bi}-2\phi_{fp}+V_{ds}\right)^{\frac{1}{2}}\cosh\left(\sqrt{\alpha_f}L/2\right)}{\cosh\left(\sqrt{\alpha_f}L\right)-1}$$

Here, the bulk depletion width is approximated as

$$y_d = \left(\frac{2\varepsilon_{si}\phi_{f,\min}}{qN_B}\right)^{1/2} = \left(\frac{4\varepsilon_{si}\phi_{fp}}{qN_B}\right)^{1/2} \quad (8)$$

Additionally, in order to avoid the error resulted from the omission of the higher order terms in equation (3), a new approach to improve the accuracy of the present model is used. Observing the derivations of equation (4), it is easy to see that including the higher order terms in equation (3) will result in the increase of the number of terms in the parenthesis of the denominators in the α_f and β_f. The characteristic of the threshold voltage versus effective channel length is dominantly determined by α_f. Therefore, an empirical constant η_0 is assumed to account for the effects contributed by the higher order terms for simplicity and all the equations in the analysis remain unchanged except α_f and β_f. The modified equations of α_f and β_f are expressed as

$$\alpha_f = \frac{\dfrac{C_{fox}}{y_d\varepsilon_{si}}}{M}$$

$$\beta_f = \frac{\dfrac{q}{y_d\varepsilon_{si}}\int_0^{y_d} N_B(y)dy - \dfrac{C_{fox}}{y_d\varepsilon_{si}}\left(V_{gs}-V_{FB,f}\right)}{M} \quad (9)$$

where

$$M = 1 + \frac{y_d C_{fox}}{3\varepsilon_{si}} + \eta_0$$

It is noted that the derived threshold voltage model is applicable for the device with non-uniform doping concentration of the Si film.

3 Verification of the proposed model

To verify the accuracy of the derived equations, the analytical model of the V_{TH}, given in the equation (7), has been compared with the results obtained by the 2-D numerical device simulator Medici [5]. The threshold voltages of the results obtained by the 2-D numerical simulator are defined by the relationship between the drain current and external gate-source voltage as follows. In general, the drain current in the linear region can be expressed as

$$I_{DS} = \frac{W_{eff}C_{fox}\mu_{eff}}{L_{eff}}\left(V_{GS}-V_{TH}-\frac{1}{2}V_{DS}\right)\cdot V_{DS}. \quad (10)$$

For the long channel length devices operating at low V_{DS} (e.g., $V_{DS} = 50$ mV), using the extrapolation method on the I_{DS} - V_{GS} curve at V_{GS} equal to the voltage at which the maximum dI_{DS}/dV_{GS} occurs, the threshold voltage can be obtained by the intercept on the V_{GS} -axis.

$$V_{TH} = V_{GS,\mathrm{intercept}} - \frac{1}{2}V_{DS}. \tag{11}$$

Additionally, when $V_{GS} = V_{TH}$, the normalized drain current is defined as a reference current.

$$I_{reference} = I_{DS,normalized} = \frac{L_{eff}}{W_{eff}} I_{DS,longL} \tag{12}$$

where $I_{reference}$ is the reference current, $I_{DS,normalized}$ is the normalized drain current and $I_{DS,longL}$ is the drain current of the long channel device. When the channel length is very short, the maximum transconductance extrapolation method would fail due to the significant short channel effect. Thus, the threshold voltage of the short channel device is extracted by equating the normalized drain current to the reference current, which is determined by the long channel device.

In Fig. 2, the threshold voltage predicted by the present model is plotted as a function of channel length at two different drain biases. It is noted that when the device is scaling down to the deep submicrometer range, the model results without accounting for the higher order terms in equation (3) deviate from the 2-D numerical analysis obviously, but the model results that take into account the higher order terms agree closely with the 2-D numerical analysis results. In Figs. 3 and 4, the threshold voltages are plotted against the channel length with different front gate oxide thicknesses and channel doping concentrations. These comparison results explicitly indicate that the important influence of the higher order terms on predicting the threshold voltage correctly. It is noted that the channel doping profile is assumed to be uniform for simplicity and η_0 used in the equation (9) is 0.870 for all the cases.

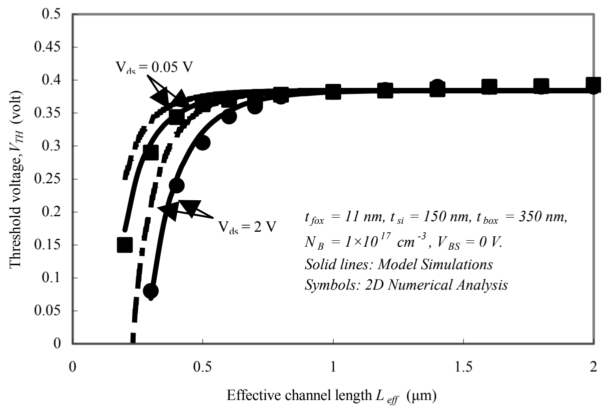

Fig. 2. The calculated threshold voltage as a function of effective channel length for two different drain biases.

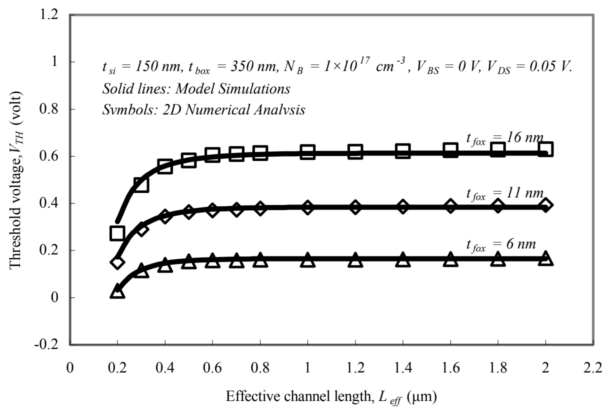

Fig. 3. The calculated threshold voltage as a function of effective channel length with the thickness of the front gate oxide as a parameter.

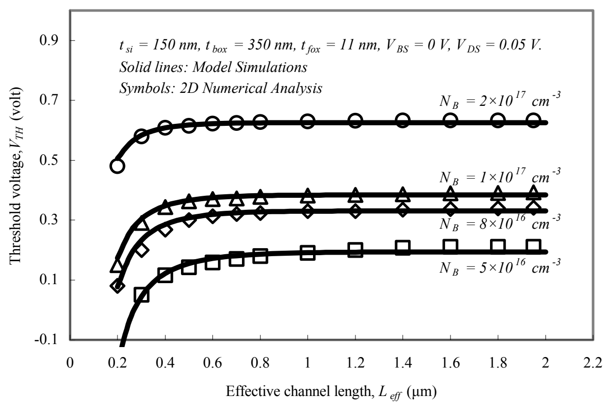

Fig. 4. The calculated threshold voltage as a function of effective channel length with the channel doping concentration as a parameter.

4 Conclusions

A simple quasi-2D analytical model is presented for the threshold voltage of the deep submicrometer PD SOI MOSFETs. The model uses the power series expansion approach with the appropriate boundary conditions to solve the 2-D Poisson's equation. To account for the complicated potential distribution in the Si film, a new approach for the modified model is proposed. The derived threshold voltage model has a simple and explicit expression without involving infinite series. Finally, the close agreements between the calculated results and the 2-D numerical analysis prove the validity of the present modified analytical model under different device structure parameter variations.

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