Two-Dimensional Model for the Subthreshold Slope in Deep-Submicron Fully-Depleted SOI MOSFET's

Hans van Meer and Kristin De Meyer
STDI division, IMEC, Kapeldreef 75, B-3001 Leuven, Belgium
ESAT, K.U. Leuven, Kasteelpark Arenberg 10, B-3001 Leuven, Belgium
vanmeer@imec.be

Abstract

A 2D analytical model for the calculation of the subthreshold slope has been derived for deep-submicron Fully-Depleted SOI MOSFET's using a Green's function solution technique. The accuracy of the equations has been verified by a 2D numerical device simulator. It is shown that the analytically derived model for the subthreshold slope is in good agreement with 2D numerical simulation data.

1 Introduction

Fully-Depleted (FD) Silicon-On-Insulator (SOI) CMOS has shown to be a promising technology for deep-submicron circuit applications. The analytical modelling of the subthreshold slope of FD SOI MOSFET's has already been reported by several authors [1]-[3]. However, since the coupling effects between front- and back-gate become more complicated for short-channel FD SOI devices, the subsequent analytical models for the subthreshold slope have become more complicated and inaccurate as well. This paper presents a two-dimensional analytical approach which is able to model the subthreshold slope of deep-submicron FD SOI MOS transistors accurately.

2 Analytical model

Since for deep-submicron MOSFET's the short-channel effects can not be neglected, the calculation of the subthreshold slope S should take into account the *drift component* of the *drift-diffusion equation* [4]

$$J_{DS} = \underbrace{q\mu_{eff} V_{th} \frac{\partial n}{\partial x}}_{\text{diffusion component}} - \underbrace{q\mu_{eff}\, n \frac{\partial \psi}{\partial x}}_{\text{drift component}} \tag{1}$$

Normally, only the diffusion component is analysed, which results in accurate predictions for the subthreshold slope of long-channel FD SOI MOS devices only [1]. If the drift-diffusion equation is combined with the continuity equation, $\partial J/\partial x = 0$, a general expression for the free carrier concentration, which relates the electrical potential $\psi(x,y)$ in the 2D device architecture to the carrier density, can be found. If this expression is introduced into the drift-diffusion equation again, an integral equation form for the current density can be obtained, namely

$$J_{DS} = q\mu_{eff}\, V_{th}\, N_{SD}\, \frac{\exp\left(-\frac{V_{DS}}{V_{th}}\right)-1}{\int\limits_{0}^{L} \exp\left(-\frac{\psi(x,y)-\psi(0,y)}{V_{th}}\right)dx} \tag{2}$$

which is valid for any bias regime and for any device architecture. From Eq. (2), it follows that the subthreshold slope S, which is defined as $S = \partial V_{GS}/\partial \log(I_{DS})$, can be obtained for deep-submicron FD SOI MOS transistors if an accurate 2D model for the electrical potential $\psi(x,y)$ is available. In our calculations, we used a 2D analytical model for the electrical potential, which is based on an exact solution of the 2D Poisson's equation for FD SOI MOSFET's (Fig. 1).

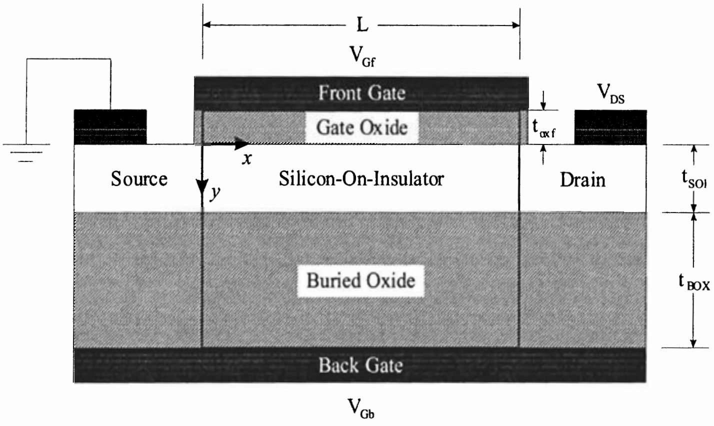


Fig. 1. Schematic diagram of a Fully-Depleted SOI MOSFET. The bold lines indicate the domain over which the Poisson's equation is solved.

The solution has been obtained by using the Green's function solution technique [5]. By combining the results on the Green's functions for the 2D Poisson's equation, shown in Fig. 2a, and Green's theorem, presented in Fig. 2b, a 2D model for the electrical potential in an FD SOI MOSFET can be derived. The final result is shown in Fig. 3.

3 Results and discussion

By combining the obtained integral equation for the carrier density and the 2D analytical model for the electrical potential, the carrier concentration can be calculated as function of the lateral position along the front Si/SiO$_2$ interface of a FD SOI MOSFET. The results, which are presented in Fig. 4, are obtained 1) by using the 2D device simulator MEDICI [6]; 2) by using a 1D model which only evaluates the *diffusion component* in the *drift-diffusion equation* [1] and 3) by using our proposed 2D analytical model. Figure 4 clearly shows that the carrier concentration

$$G_x(x,y;x',y')=\frac{2}{L}\sum_{m=1}^{\infty}\sin k_m x\,\sin k_m x'\times\frac{\cosh k_m y\,\cosh k_m\left(t_{SOI}-y'\right)}{k_m\sinh k_m t_{SOI}}$$

$$G_y(x,y;x',y')=\frac{c}{t_{SOI}}\sum_{n=0}^{\infty}\cos k_n y\,\cos k_n y'\times\frac{\sinh k_n x\,\sinh k_n\left(L-x'\right)}{k_n\sinh k_n L}$$

$c = 1$ for $n = 0$; $c = 2$, for $n > 0$

with $k_m=\frac{m\pi}{L};\ k_n=\frac{n\pi}{t_{SOI}}$

(a)

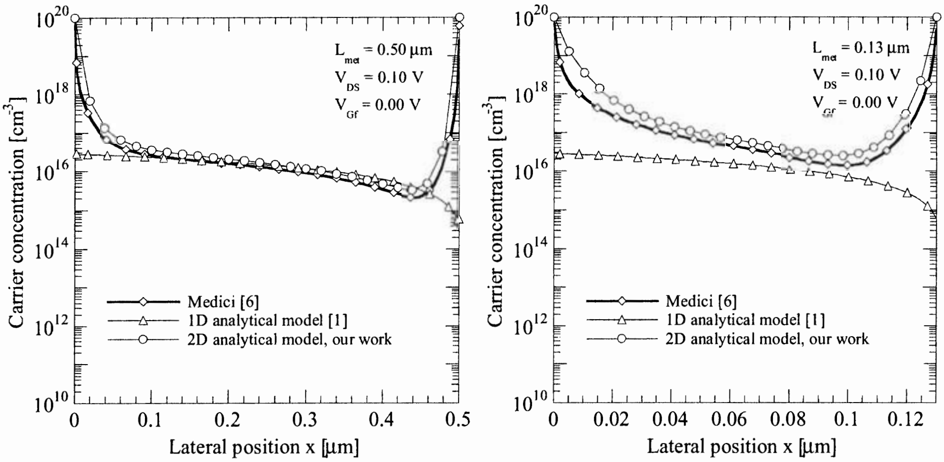
$$\psi(x,y)=\iint_V\frac{\rho(x',y')}{\varepsilon}G(x,y;x',y')\,dx'dy+\oint_S\frac{\partial\psi(x',y')}{\partial n'}G(x,y;x',y')\,dS'-\oint_S\psi(x',y')\frac{\partial G(x,y;x',y')}{\partial n'}\,dS'$$

(b)

Fig. 2. (a) The Green's functions for the silicon film of the Fully-Depleted SOI MOS transistor. (b) Green's theorem, used for the calculation of the 2D analytical solution of the potential.

$$\psi(x,y)=-\frac{qN_{chan}}{2\varepsilon_{Si}}x\left(L-x\right)+V_{bi}+\frac{V_{DS}}{L}x+\sum_{m=1}^{\infty}\frac{D_{sf}^{m}\cosh k_m\left(t_{SOI}-y\right)-D_{sb}^{m}\cosh k_m y}{\varepsilon_{Si}k_m\sinh k_m t_{SOI}}\sin k_m x$$

Fig. 3. 2D analytical solution of the electrical potential in the Fully-Depleted SOI MOS transistor shown in Fig. 1.



(a) (b)

Fig. 4. Carrier concentration as function of lateral position *x* at the front Si/SiO$_2$ interface for a (a) 0.5 µm and a (b) 0.13 µm long FD SOI transistor. The silicon thickness t_{SOI} = 25 nm; the front gate oxide t_{oxf} = 3 nm; the buried oxide t_{BOX} = 400 nm. The substrate doping $N_{chan} = 5\cdot10^{17}$ cm^{-3}.

should indeed be calculated by taking into account the *drift component*. The approaching S/D areas result in a significant increase of the carrier concentration in short-channel FD SOI MOSFET's, resulting in a large error in the subthreshold slope model of the 1D model [1].

Finally, the results obtained on the subthreshold slope S are summarised in Fig. 5. The subthreshold slope has been calculated for both a 'long'- (0.5 μm) and a 'short'- (0.13 μm) channel SOI device, as well as at 'low' (0.1 V) and 'high' (1.5 V) drain bias. Besides the data acquired from our proposed 2D model, also the data obtained from the 1D model and the 2D device simulator MEDICI are shown in Fig. 5. It can be concluded that the proposed 2D analytical model agrees well with the 2D device simulator MEDICI, while the 1D model shows clearly to be unusable for deep-submicron dimensions.

	$S(V_{DS} = 0.1\text{ V})$ [mV/dec]			$S(V_{DS} = 1.5\text{ V})$ [mV/dec]		
Gate length	MEDICI [6]	1D model [1]	2D model (our work)	MEDICI [6]	1D model [1]	2D model (our work)
0.50 μm	60.7	60.0	60.9	60.7	60.0	60.9
0.13 μm	67.7	60.0	67.1	72.1	60.0	68.8

Fig. 5. Subthreshold slope for a 'long' (0.5 μm) and a 'short' (0.13 μm) Fully-Depleted SOI MOSFET at different drain biases: comparison between the 1D, 2D analytical models and the 2D device simulator MEDICI.

4 Conclusions

We have presented a 2D analytical model for the calculation of the subthreshold slope for deep-submicron Fully-Depleted SOI MOSFET's using a Green's function solution technique. The accuracy of the equations has been verified by a 2D numerical device simulator. From the results presented, it can be concluded that the analytically derived model for the subthreshold slope is in good agreement with 2D numerical simulation data.

References

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