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Two-Dimensional Analytical Subthreshold Model and Optimal Scaling of Fully-Depleted SOI MOSFET Down to 0.1 μm Channel Length

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New two-dimensional analytical models for the potential distribution and the subthreshold factor in SOI MOSFET are developed and extensive study of 0.1 μm SOI MOSFET design is performed. It is shown that the ultra-thin SOI films and high doping concentrations are necessary to obtain high subthreshold slopes in SOI MOSFETs.

1 Introduction

The analytical two-dimensional modeling of the short-channel SOI MOSFET has been reported by many authors. In [1] an analytical two-dimensional model was developed under the assumptions that the potential distribution inside the buried oxide is linear and the potential in SOI film can be described by the parabolic function. However, these assumptions underestimate the effect of the source/drain junctions and may cause significant error when the channel length approaches 0.1 μm. The model [1] was further developed and used to study the SOI MOSFET subthreshold behavior in number of works [2] - [7]. In [3], [4] the assumption of the linear potential distribution inside the back oxide was removed, however parameters, which have to be determined from numerical device simulations, were introduced. Analytical potential distribution models based on the infinite series methods were developed in [5], [6]. However, such models require iterative calculations, which reduce the physical insight provided by the infinite series models. An analytical model based on empirical expressions for the device capacitances was developed in [7].

We are presenting a new analytical two-dimensional model which accurately describes the subthreshold behavior of SOI MOSFET without use of fitting parameters.

2 New Analytical Model

A cubic potential distribution in the transverse direction in the silicon film and parabolic distribution in the buried oxide of the SOI MOSFET are assumed. The potential at arbitrary point in the silicon film is expressed as a function of the front- and back-surface potentials. The two-dimensional Poisson's equation, the boundary conditions and the depletion approximation are used to derive a system of two ordinary second-order differential equations in the front- and the back-surface potentials:

$$\frac{\partial^2 \psi_s}{\partial y^2} + A\psi_s + B\psi_b = C, \quad (1)$$

$$\frac{\partial^2 \psi_b}{\partial y^2} + F\psi_s + G\psi_b = H, \quad (2)$$

where y is the distance in the horizontal direction, $\psi_s(y)$ is the front-surface potential, $\psi_b(y)$ is the back-surface potential and A, B, C, F, G, H are independent of y coefficients which are functions of device parameters:

$$A = -\frac{1}{t_{si}^2}\left(6 + 4\frac{C_f}{C_{si}}\right); \quad (3)$$

$$B = \frac{1}{t_{si}^2}\left(6 + 4\frac{C_b}{C_{si}}\right); \quad (4)$$

$$C = \frac{qN_A}{\epsilon_0 \epsilon_{si}} + 4\frac{1}{t_{si}^2}\frac{C_b}{C_{si}}V_{SUB} - 4\frac{1}{t_{si}^2}\frac{C_f}{C_{si}}V_G; \quad (5)$$

$$F = \frac{1}{t_{si}^2}\left(6 + 2\frac{C_f}{C_{si}}\right); \quad (6)$$

$$G = -\frac{1}{t_{si}^2}\left(6 + 8\frac{C_b}{C_{si}}\right); \quad (7)$$

$$H = \frac{qN_A}{\epsilon_0 \epsilon_{si}} - 8\frac{1}{t_{si}^2}\frac{C_b}{C_{si}}V_{SUB} + 2\frac{1}{t_{si}^2}\frac{C_f}{C_{si}}V_G; \quad (8)$$

where t_{si} is the silicon film thickness, N_A is the doping concentration, and C_f, C_b, C_{si} are the front gate oxide, the buried oxide and the depleted silicon film capacitances, respectively. Analytical solution of the system is obtained in the following form:

$$\vec{\psi} = \vec{\psi}_p + c_1\vec{z_1}\exp(\sqrt{\lambda_1}y) + c_2\vec{z_1}\exp(\sqrt{-\lambda_1}y) +$$
$$c_3\vec{z_2}\exp(\sqrt{\lambda_2}y) + c_4\vec{z_2}\exp(\sqrt{-\lambda_2}y), \qquad (9)$$

where $\vec{\psi} = (\psi_s(y), \psi_b(y))^T$ is the solution vector, $\psi_s(y)$ is the front-surface potential, $\psi_b(y)$ is the back-surface potential,

$$\vec{\psi}_p = \begin{pmatrix} \frac{BH-CG}{BF-GA} \\ \frac{CF-AH}{BF-GA} \end{pmatrix}, \qquad (10)$$

$$\lambda_{1,2} = -\frac{A+G}{2} \pm \sqrt{\frac{(A-G)^2}{4} + BF}, \qquad (11)$$

and c_1, c_2, $\vec{z_1}$, $\vec{z_2}$ are known functions of the applied voltages and device parameters, analytical expressions for which are derived. Good accuracy is obtained for front- and back-surface potentials as is shown in Fig. 1 and Fig. 2. Analytical

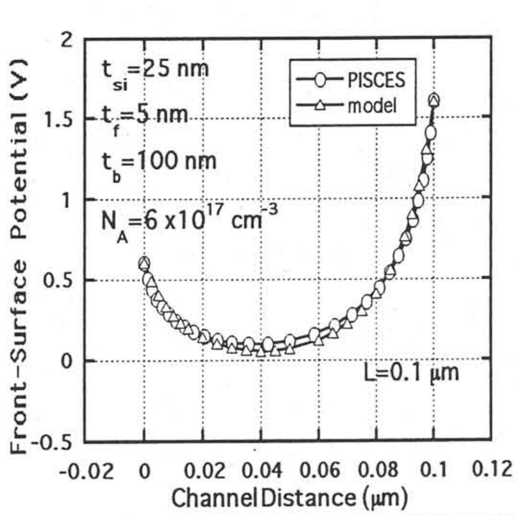

Fig. 1. Front-surface potential of SOI MOSFET as function of distance in channel

expression for position of the potential barrier in the channel is obtained, and analytical expressions for minimum front- and back-surface potentials are derived. As distinguished from [3], [4], our analytical potential approximation does not use any fitting parameters and does not require iterative calculations as in infinite series methods [5], [6]. It also correctly reflects the fact [5] that the potential rise in the channel of SOI MOSFET can not be described accurately by a single exponential function. Using an approach described in [8] with our new two-dimensional potential approximation, we have developed a new model for subthreshold factor

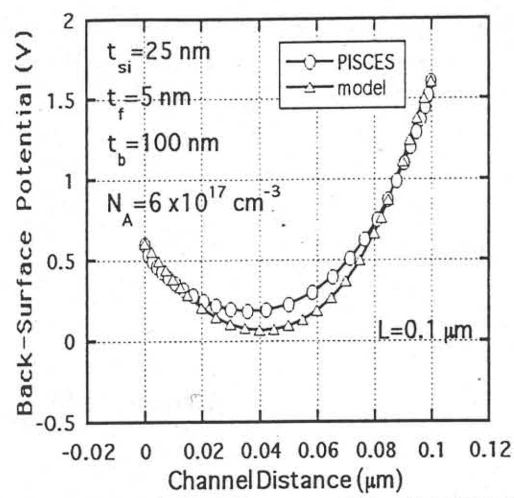

Fig. 2. Back-surface potential of SOI MOSFET as function of distance in channel

of the fully-depleted SOI MOSFET. For the front-surface conduction case the subthreshold factor is

$$\frac{1}{S} = \frac{1}{\ln 10}\times\frac{q}{kT}\times\left(\frac{\frac{1}{2C_b}+\frac{1}{C_{si}}}{\frac{1}{C_f}+\frac{1}{2C_b}+\frac{1}{C_{si}}} + \frac{z_{21}}{\sqrt{c_3c_4}}\frac{\partial(c_3c_4)}{\partial y}\right) \qquad (12)$$

where C_{si}, C_f, C_b are the depleted silicon film, the front gate oxide and the buried oxide capacitances, respectively, and z_{21}, c_3, c_4 are the coefficients of the solution (5).

3 Subthreshold Characteristics of 0.1 μm SOI MOSFET

An extensive study of subthreshold behaviour of fully-depleted SOI MOSFETs was performed using our analytical model and numerical simulation (PISCES). In Fig. 3. the front-channel threshold

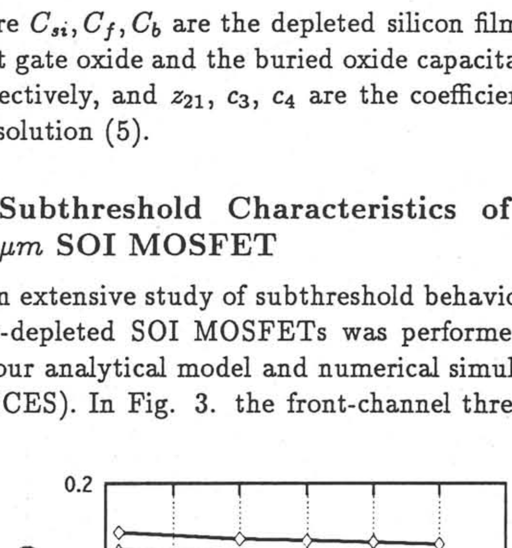

Fig. 3. Dependence of threshold voltage on drain voltage for 0.1, 0.2 and 0.3 μm devices

voltage dependence on the drain voltage is shown for SOI MOSFETs with the channel length from 0.1 to 0.3 μm. Doping concentrations higher than $6 \times 10^{17}\ cm^{-3}$ have to be used to obtain positive threshold voltage in 0.1 μm SOI MOSFET. In Fig. 4. the front- and back-surface potential barrier difference is shown. The positive difference values indicate that the back-surface potential is higher than the front-surface, and that the subthreshold current flows at the back interface. High doping concentrations and reduction of the silicon film down to the ultrathin dimensions are necessary to suppress the back-surface conduction. The back-surface conduction is responsible for severe degradation of the subthreshold factor of the 0.1 μm SOI MOSFET as is shown in Fig. 5. In Fig. 6. influence of doping concentration on subthreshold factor is analysed. When the silicon film thickness $t_{si} > 25\ nm$, the back-surface conduction dominates for both doping concentrations. When $t_{si} < 25\ nm$, the 10^{17} doped device switches from the back- to the front-surface conduction and the subthreshold factor improves dramatically. In summary, the ultra-thin SOI films and high doping concentrations are necessary to obtain high subthreshold slopes (low subthreshold factors) in SOI MOSFETs.

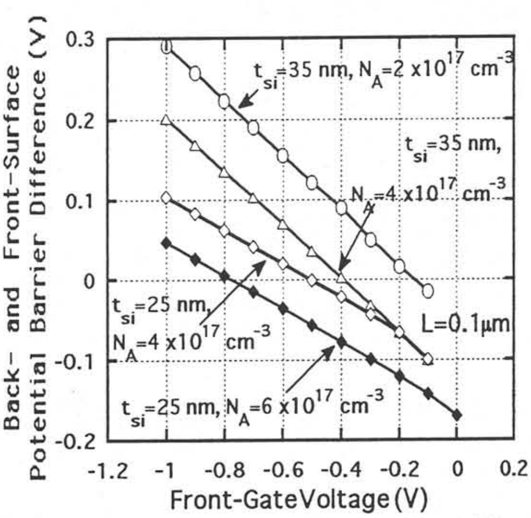

Fig. 4. Back- and front-surface potential barrier difference for 0.1 μm SOI device

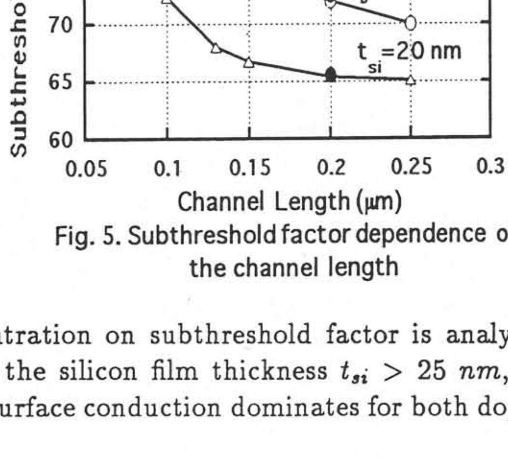

Fig. 5. Subthreshold factor dependence on the channel length

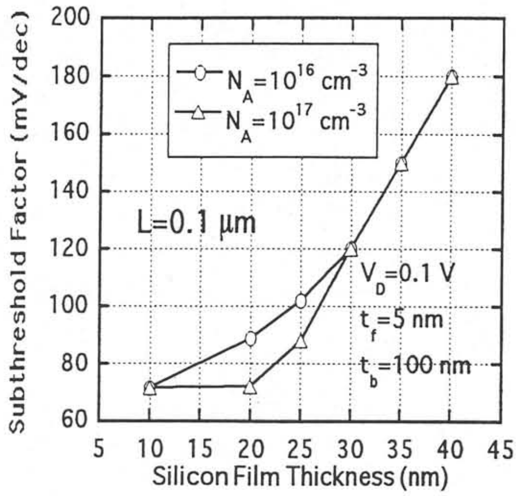

Fig. 6. Subthreshold factor dependence on silicon film thickness

4 Conclusion

A new two-dimensional model for potential distribution and subthreshold factor in SOI device was developed and rules of scaling SOI MOSFET down to 0.1 channel length were extensively studied.

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