Solid-State Electronics 62 (2011) 31-39

Contents lists available at ScienceDirect

# Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse



# A computationally efficient compact model for fully-depleted SOI MOSFETs with independently-controlled front- and back-gates

Darsen D. Lu\*, Mohan V. Dunga, Chung-Hsun Lin, Ali M. Niknejad, Chenming Hu

Dept. of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720-1770, USA

#### ARTICLE INFO

Article history: Received 14 September 2010 Received in revised form 22 November 2010 Accepted 21 December 2010 Available online 9 February 2011

The review of this paper was arranged by A. Zaslavsky

Keywords: Berkeley short channel insulated-gate FET model (BSIM) Compact modeling Double-gate MOSFET Fully-depleted SOI MOSFET Computational efficiency

## ABSTRACT

In this paper a computationally efficient surface-potential-based compact model for fully-depleted SOI MOSFETs with independently-controlled front- and back-gates is presented. A fully-depleted SOI MOSFET with a back-gate is essentially an independent double-gate device. To the best of our knowledge, existing surface-potential-based models for independent double-gate devices require numerical iteration to compute the surface potentials. This increases the model computational time and may cause convergence difficulties. In this work, a new approximation scheme is developed to compute the surface potentials and charge densities using explicit analytical equations. The approximation is shown to be computationally efficient and preserves important properties of fully-depleted SOI MOSFETs such as volume inversion. Drain current and charge expressions are derived without using the charge sheet approximation and agree well with TCAD simulations. Non-ideal effects are added to describe the *I–V* and *C–V* of a real device. Source-drain symmetry is preserved for both the current and the charge models. The full model is implemented in Verilog-A and its convergence is demonstrated through transient simulation of a coupled ring oscillator circuit with 2020 transistors.

Published by Elsevier Ltd.

# 1. Introduction

The scaling of conventional bulk CMOS has become more and more challenging due to increasing gate leakage and sub-threshold leakage [1]. Fully-depleted SOI (FDSOI) MOSFETs with superior control of short channel effects have emerged as a promising candidate to extend CMOS scaling. With a thin silicon body and an insulating buried oxide, unwanted leakage components are eliminated. Short channel effects can be further improved by scaling the buried oxide thickness as well. A heavily-doped back-gate serves as a ground plane which reduces the electrostatic coupling from the drain to the channel through the buried oxide [2]. In addition, a ground plane design allows dynamic threshold voltage  $(V_{TH})$ control through the back-gate. By selectively raising  $V_{TH}$  in idle circuit blocks, static leakage current can be significantly reduced without hurting the active-state performance [3]. Furthermore, multiple  $V_{TH}$  flavors in the same circuit can be achieved with back-gate biasing instead of channel doping. This reduces the variation due to random dopant fluctuation [4] and body thickness variation at the same time. In order to perform circuit simulation for the back-gated FDSOI technology, a computationally efficient and accurate compact model is required.

The back-gated FDSOI MOSFET is essentially an independent double-gate (DG) device. Several analytical compact models for independent DG MOSFETs are available in the literature [5-12]. Pei et al. [5] and Reyboz et al. [6] model the current and charge of independent DG MOSFETs with explicit expressions. Both models show good agreements with TCAD simulations. However, some formulations used in the models are known to violate source-drain symmetry, which is an important requirement for certain analog applications [13]. One way to maintain source-drain symmetry is through a surface-potential-based approach, as in [7-12]. However, in [7–12] the surface potential is described in implicit forms. Iterative techniques such as Newton Raphson are required inside the model, which from the authors' experience significantly degrades computational efficiency [14]. Recently, explicit approximations of surface potential have been developed for planar bulk MOSFETs [15] and symmetric (common) double-gate MOSFETs [16,17] and are robust and computationally efficient.

In this work, we develop a new explicit approximation to compute the surface potentials and the inversion charge density for back-gated FDSOI MOSFETs, based on the solution of the 1-dimensional Poisson's equation. To evaluate the computational efficiency of the new approximation, we implement it in C++ and measure the runtime of the compiled and optimized code. In addition, drain current and terminal charge expressions are derived without making the charge sheet approximation. The results are verified by comparing it with TCAD [18] simulations without the use of fitting



<sup>\*</sup> Corresponding author. Tel.: +1 510 642 1010; fax: +1 510 643 2636. *E-mail address:* darsen@eecs.berkeley.edu (D.D. Lu).

parameters. Non-ideal effects such as short channel and quantum effects, field dependent mobility, leakage currents and device parasitics are added to model real devices. The Gummel Symmetry Test [19,13] is performed to verify the symmetry of drain current and charge with respect to  $V_{ds}$  = 0. The full model including non-ideal effects is implemented in Verilog-A [20]. Good convergence is demonstrated through transient simulation of a large coupled ring oscillator circuit.

# 2. Core model

#### 2.1. Model framework

The basic model formulation for the independent double-gate FDSOI MOSFET is developed based on the 2-dimensional schematic cross section shown in Fig. 1. A silicon channel with thickness  $T_{si}$  is sandwiched between the front- and back-gate stacks. The two gate stacks are allowed to have different gate work functions ( $\Phi_{g1}, \Phi_{g2}$ ), dielectric thicknesses ( $T_{ox1}, T_{ox2}$ ), and dielectric constants ( $\varepsilon_{ox1}, -\varepsilon_{ox2}$ ). The energy band diagram of this system at the flat-band condition is shown in Fig. 2. Without loss of generality, we focus on an n-type device throughout this paper.

The silicon body is assumed to be lightly-doped and fully-depleted. Back-gated FDSOI MOSFETs will likely have a lightly-doped body to minimize random dopant fluctuation effects [4] and to



Fig. 1. Symbol definition and schematic cross section of the independent doublegate FDSOI MOSFET.



**Fig. 2.** Energy band diagram at flat-band condition corresponding to the A–A' cutline in Fig. 1.  $\chi$  is the electron affinity.

increase mobility. In addition, with a thin body, heavy doping is not needed for controlling short channel effects.  $V_{TH}$  is set by back-gate biasing or work function adjustment instead of channel doping.

#### 2.2. Explicit approximation for surface potential

In this section, we develop a method to approximately solve the Poisson's equation and obtain explicit analytical expressions for the surface potentials and the inversion carrier density per area  $(Q_{inv})$ . The results are verified with TCAD simulations.

Since there is no neutral body for fully-depleted devices, it is convenient to choose the quasi-Fermi level at the source as a reference for the potential ( $\psi$ ). In this paper we adopt the following definition for  $\psi$  in the silicon body:

$$\psi = -\frac{E_c - E_f(source)}{q} \tag{1}$$

where  $E_c$  is the conduction band energy and  $E_f(source)$  is the quasi-Fermi level at the source. The surface potentials,  $\psi_{s1} = \psi|_{x=-Tsi/2}$  and  $\psi_{s2} = \psi|_{x=+Tsi/2}$ , are the potentials at the front- and back-silicon/ oxide interfaces, respectively.

In the ideal long channel case, the potential distribution in the silicon channel is governed by the 1-dimensional Poisson's equation:

$$\varepsilon_{si} \frac{d^2 \psi(x, y)}{dx^2} = q N_c \exp\left(\frac{q(\psi(x, y) - V_{ch}(y))}{kT}\right)$$
(2)

where  $\varepsilon_{si}$  is the dielectric constant of silicon,  $N_c$  is the conduction band density of states of silicon, and  $V_{ch}(y)$  is the channel voltage (the electron quasi-Fermi potential relative to the source). The Boltzmann's approximation is used for the inversion carrier density. The charge contribution of ionized dopants is neglected since the body is lightly-doped. We focus on an n-type device and neglect the contribution of holes.

The continuity of displacement field at the front and back interfaces gives the following relation of the surface electric fields  $(E_{s1} = -\frac{d\psi}{dx}\Big|_{x=-Tsi/2}$  and  $E_{s2} = -\frac{d\psi}{dx}\Big|_{x=Tsi/2}$ ) and surface potentials:

$$C_{ox1(2)}(V_{fg(bg)} - \Delta \Phi_{1(2)} - \psi_{s1(2)}) = \varepsilon_{si} E_{s1(2)}$$
(3)

where  $C_{ox1(2)} = \varepsilon_{ox1(2)}/T_{ox1(2)}$  are the front(back) oxide capacitances and  $\Delta \Phi_{1(2)}$  are the work function differences of the front-gate (back-gate) and the N+ source.

Eq. (3) is the boundary condition for the ODE (2). Multiplying  $\frac{d\psi}{dx}$  on both sides of (2) and integrating from  $x = -\frac{T_{ai}}{2}$  to  $x = \frac{T_{ai}}{2}$ , we obtain:

$$E_{s1}^2 - E_{s2}^2 = \frac{2N_c kT}{\varepsilon_{si}} \left( \exp\left(\frac{q(\psi_{s1} - V_{ch})}{kT}\right) - \exp\left(\frac{q(\psi_{s2} - V_{ch})}{kT}\right) \right).$$
(4)

For FDSOI devices it is desired to have inversion carriers concentrated at the front surface, since short channel effects such as  $V_{TH}$  roll-off and drain induced barrier lowering (DIBL) are less prominent in such a condition. For this reason, we assume the carrier density at the back interface is negligible compared to that at the front interface, and the second exponential term in (4) can be neglected. Neglecting that term and substituting  $E_{s1}$  with (3), we obtain,

$$\left(\frac{C_{ox1}(V_{fg} - \Delta\Phi_1 - \psi_{s1})}{\varepsilon_{si}}\right)^2 - E_{s2}^2 = \frac{2N_ckT}{\varepsilon_{si}}\exp\left(\frac{q(\psi_{s1} - V_{ch})}{kT}\right)$$
(5)

In (5),  $E_{s2}$  is a function of  $\psi_{s2}$ , making it difficult to find an explicit approximation. To overcome this difficulty,  $E_{s2}$  is approximated by assuming a constant displacement field in the vertical direction

Download English Version:

https://daneshyari.com/en/article/753058

Download Persian Version:

https://daneshyari.com/article/753058

Daneshyari.com