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BSIM5: An advanced charge-based MOSFET model for nanoscale VLSI circuit simulation

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Abstract

This paper outlines the charge-based core and the model architecture of the BSIM5, an advanced charge-based MOSFET model for nanoscale VLSI circuit simulation. Compared with the previous charge-based models with an assumption of the linearization of the bulk and inversion charges with respect to the surface potential at a fixed gate bias, the BSIM5 model is directly derived from the solution of the Poisson equation coupled to the current density equation. The comparisons of the inversion charge and the channel current between the BSIM5 and the Pao–Sah model indicate that the BSIM5 model maintains the inherent device physics and high accuracy of the Pao–Sah model. BSIM5 model is further extended to include the short-channel effects, narrow-width-effects, and the wide comparison with the experiment data demonstrates its validity to simulate the nanoscale circuits. Moreover, the symmetry and RF function of BSIM5 have also been demonstrated in the Gummel tests and high-order distortion analysis.

Keywords: MOSFETs; Device physics; Compact model; Surface potential-based model; Charge-based model

1. Introduction

Compact models are one of the most critical roles in the design of IC design and production manufacturing. The semiconductor industry's dependence on accurate and computation efficient compact models continues to grow as circuit frequencies increase, device sizes scale down, and mixed signal content enhances. Although the BSIM (Berkeley Short-Channel IGFET Model) series of compact MOSFET models such as BSIM3 and BSIM4 are industry standard compact models successfully used throughout the semiconductor industry and the research community for digital and analog circuit design, they still have some limitations. These limitations include their being source-referenced, threshold voltage based models, and as such, having asymmetries and discontinuities in derivatives, such as capacitance and the derivative of conductance, at $V_{ds} = 0$. These asymmetries and discontinuities preclude modeling of distortion, e.g., IP3. With the rising importance of CMOS used for RF applications, these inadequacies have become showstoppers for design [1]. Under such a background, advanced CMOS models addressing the industry's need for modeling RF performance of beyond 65 nm MOSFET node are expected to be fully symmetric, model all intrinsic capacitances, and pass all circuit tests. Such a model is critical for analog and RF CMOS simulation.

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The present advanced compact models of CMOS can be categorized into two classes based on the approach they take to solving the input and output equations [2]. One approach is to solve for the input equation surface potential at the two ends of the channel. The terminal charges, currents and derivatives are then calculated from the surface potential. These models are called surface potential models. Gildenblat, Van Langevelde, and Miura-Mattausch are involved with development of such models such as SP, MOS-11, HiSIM, and PUNSIM [3–6]. Another approach is to find the density of the inversion charge at the two ends of the channel and formulate the model outputs in terms of these charge densities. Enz, Galup-Montoro, and Gummel are involved with the development of charge-based models such as EKV, ACM, USIM, and BSIM5 [7–10]. The results from the surface potential-based models involve the surface potential evaluation with high precise, thus need complex iterations or the approximation mathematic algorithm. On the other hand, the result from the charge-based models achieves complete analytical model to improve the computation efficiency and circuit simulation speed while retaining the essential physics of the MOSFET via the appropriate approximations to offer adequate accuracy for compact MOSFET modeling. The analytical framework of the charge-based models also leads to an elegant and compact large signal and small-signal analysis.

Preliminary investigation into charge-based models was initialed by Maher and Mead [11]. They showed that the drain current could be expressed as a function of the area densities of the inversion charge at the source and the drain although the general relationship between the inversion charge and the terminal bias had not been obtained. Shur's group proposed the unified charge control model [12] and introduced an equation for the charge densities as a function of terminal voltages. The charge-based model in its current form began to take shape in the EKV model put forth by Enz [7]. In this model, the key step is use of the normalized method and showed that the drain current can be expressed as a function of the area densities of the inversion charge that is a function for the terminal biases at the source and the drain. Cunha et al. [8] derived expressions for the ACM model of the total charges and small signal parameters as a function of the source and drain channel charge densities. These models rely on the gradual channel and charge sheet approximations and an addition assumption of the linearization of the bulk and inversion charges with respect to the surface potential at a fixed gate bias. The former approximations had to be adopted for an analytic model to de-composite the two-dimensional (2-D) problem into two one-dimensional (1-D) problems and get closed-form current equation. The latter assumption, however, has a little special difference compared with the basic device physics. The different methods involving this assumption result in the different inversion charge equation that leads to the different models. Thus, this assumption is a key in the previous charge-based models. Gummel et al. [9] recently provided a theoretical derivation for basically the same charge equation and then developed a charge-based model called USIM [9]. This USIM model has some different characteristics compared with the previous charge-based models, e.g. it starts from the basic Poisson equation solution and the charge partition between the depletion and inversion charge; it, however, still needs some extrapolations for the bulk and the inversion charge related terms in deriving the final master charge equations.

In order to incorporate new physical effects and enhance RF and analog functions of BSIM model without fundamental problems of the asymmetry, which represent a critical semiconductor industry need for designs utilizing single gate bulk CMOS, the next generation BSIM model, BSIM5 [10], an advanced charge-based MOSFET model with the symmetry, continuity, scalability, computational efficiency, and a minimal number of parameters, has been developed in BSIM team in the past five years. This paper outlines the charge-based core equations and the model architecture of the BSIM5. Compared with the previous charge-based models, the BSIM5 model is directly developed from the solution of the Poisson equation coupled to the Pao–Sah current formulation [10,15,27] without need for the extrapolation pinch-off voltage and the assumption of the linearization of the bulk and inversion charges with respect to the surface potential at a fixed gate bias. BSIM5 model starts with the fundamental 1-D MOSFET physics to derive the basic charge and channel current equations, and then extend results to quasi-2-D case and three-dimensional (3-D) case to include short-channel effects, narrow-channel effects and quantum-mechanic effects.

2. Derivation of BSIM5 core equations

BSIM5's core equations include the inversion charge equation and current equation. The theory derivation starts with one-dimensional current density and drain current equations in terms of the quasi-Fermi-potential. The general MOSFET channel current density is written as

$$J_n = q\mu n \frac{\mathrm{d}V_{\mathrm{ch}}}{\mathrm{d}y} \tag{1}$$

where V_{ch} is the electron quasi-Fermi-potential, n and μ are the electron concentration and the effective mobility, respectively.

The MOSFET is inherently a two-dimensional (2-D) electronic device. Its input voltage is applied in the x-direction perpendicular to a semiconductor surface in order to modulate the current which flows near the surface in the y-direction when a voltage is applied to the two ends of the device [2]. An "exact" analytic drain current equation for the MOSFET does not exist since the 2-D spatial variation of the quasi-Fermi-potential splitting in a MOSFET (as opposed to the case of a MOS capacitor) does not allow analytic forms of the first integral of the 2-D Boltzmann–Poisson equation [13,14] and the current density integration [15]. In order to make the 2-D MOSFET problem