A Technology-Based Compact Model for Predictive Deep-Submicron MOSFET Modeling and Characterization

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ABSTRACT

This paper presents new development results of our compact model (Xsim) for deep-submicron MOSFETs. Although a threshold-voltage-based and source-referenced regional model, Xsim meets the basic requirements of continuity (to third-order derivatives), scalability (entire geometry range), and symmetry, with a single-piece unified equation that approaches the ideal long/wide-channel expression. Model calibration requires minimum measurement data with one-iteration parameter extraction, which can be extrapolated to predicting characteristics of extremely-scaled devices with severe threshold voltage roll-off, a regime in which most common models do not (or cannot) model.

Keywords: Compact model, deep-submicron MOSFETs, scalability, symmetry, technology development.

1 INTRODUCTION

Compact models (CMs) for circuit simulation have been at the heart of CAD tools for circuit design over the past decades, and are playing an ever increasingly important role in the very-deep-submicron (VDSM) era. The current practice is to use the industry standard model, BSIM [1], on the golden die of a given technology by fitting a large number of parameters on a large set of measured electrical data. The model is optimized at the designed feature geometry, and not meant to be extrapolated outside the fitted range. To meet the increasing demand in accurate and continuous (in higher-order derivatives) modeling in the weak-inversion regime, “surface-potential-based” (as opposed to “threshold-voltage-based”) approach is becoming popular [2]–[4]. Another basic requirement for MOS CM is source–drain symmetry, for which a “bulk-referenced” (as opposed to “source-referenced”) model is generally favored. However, unlike in the “old” (micron) technology generations, in the VDSM era, geometry dependence (scalability) of a CM becomes extremely important due to strong lateral nonuniformity (such as halo) in a MOSFET since even a small gate-length variation is having a similar effect as due to drain-source voltage variation. Single-transistor-based models that are based on solving the surface potential (physically, iteratively, or approximately) would need empirical relations (at best, with simplified assumptions) to account for geometry effects. Moreover, a bulk-referenced model does not necessarily guarantee symmetry if lateral-field mobility and velocity saturation are not handled correctly [5]. Finally, if a CM’s fitting parameters (no matter how many) have to be obtained through global optimization without physical relation to process variations, it may fit one transistor perfectly but may lose predictability for other transistors of the given technology.

The essence of MOS compact modeling is essentially a tradeoff among accuracy, continuity, symmetry, scalability, predictability, and efficiency. The ability of a CM in predicting electrical characteristics with accuracy in the second-/third-order derivatives from long/wide-channel down to the threshold-voltage ($V_t$) roll-off regime is a major challenge, which is important for capturing geometry variations due to process fluctuations, for predicting new technologies, as well as for analog circuit design. This paper presents our approach to CM development (named Xsim [6]–[11]), which has a small number of (dc) fitting parameters that requires a one-iteration extraction procedure using minimum measurement data, and demonstrates its predictive capability in modeling short-channel effects (SCEs) in the $V_t$ roll-off regime, accurate higher-order derivatives, as well as symmetry.

2 MODEL OVERVIEW

Xsim is a single-piece, source-referenced, threshold-voltage-based, regional model developed by adding SCEs to the well-known long-channel equations with physical modeling in the respective strong/weak-inversion and linear/saturation regions joined by smoothing functions. The main features include: physical modeling of $V_t$ [6]–[8] by technology characterization (fitting $V_{t-L}$ data at corner bias) that includes charge sharing and barrier lowering from quasi-2D solution, together with halo centroid modeled by two Gaussian lateral nonuniform doping profiles and LDD lateral diffusion for effective channel length ($L_{eff}$) extraction; semi-empirical vertical-field mobility ($\mu_v$) modeling and new velocity–field and effective field ($E_{adv}$) formulations for lateral-field and bulk-charge ($A_s$) effects; bias-dependent series resistance ($R_{dd}$) modeling; channel-length modulation (CLM) formulated with energy-balance equations for overshoot effect with a single fitting parameter ($\xi$) in the effective Early voltage ($V_{A_{eff}}$) for all
length/bias conditions [9]; a novel analytical “drift +
diffusion” formulation with smooth weak/strong-inversion
transition for all length/bias with one fitting parameter ($V_{\text{eff}}$)
[10]; and poly-gate depletion effect. Our new
developments on the narrow-width effects [11] include a
unified $V_i$ model to account for the fringing capacitance,
surface-potential lowering, and effective doping for the
pile-up charge in shallow-trench isolated structures, as well
as width-dependent phonon mobility correlation and dog-
bone geometry for the external series resistance.

The complete $I_{ds}$ equation [11] is extremely clean and
compact with each internal term representing the respective
physics, which also resembles (and approaches) the ideal
long-channel equation (in the long-channel limit):

$$ I_{ds} = I_{\text{eff}} \left[ 1 + \left( R_{sd} I_{\text{eff}} \right)/V_{\text{eff}} \right] $$

$$ I_{\text{eff}} = I_{i-d} + \left( V_{ds} - V_{\text{eff}} \right)/V_{\text{eff}} $$

$$ I_{i-d} = \beta_i V_{gs} = \mu_{\text{eff}} C_{ov} (W/L)_{\text{eff}} (V_{gs}^2 + V_{gd}) $$

where $V_{\text{eff}}$ (BSIM smoothing function [1]) links linear ($V_{ds}$)
and saturation ($V_{\text{dsat}}$) regions (with a smoothing parameter,
$\delta_i$). $V_{gs}$ (effective gate/drain-voltage product) represents the
sum of drift ($V_{gs}$) and diffusion ($V_{gd}$) components, including
a bulk-charge term $V_{dc} = (1 - A_s V_{dsat}^2 V_{\text{eff}}) V_{\text{eff}},$
linked by $V_{i-d}$ (BSIM interpolation function [1]), which approaches
$V_{gs} \rightarrow V_{gd} \rightarrow I_{i-d} = (V_{gs} - V_i^2 [1 - A_s V_{dsat}^2 (V_{gs} - V_i)]) V_{\text{eff}}$
and $V_{gs} \rightarrow V_{gd} \rightarrow I_{i-d} = \alpha_h (C_{ov}) (V_{gs}^2 + V_{gd}) \ln(1 - e^{-V_{gd}/\alpha_h})$
in strong and weak inversions, respectively, with the correct
asymptotes and smooth transitions. The effective Early
voltage ($V_{\text{eff}}$) incorporates all length/bias dependencies of
CLM/velocity overshoot effects and expressed in the
familiar form of the “pinch-off” model. All fitting
parameters are extracted at the corner conditions at which
they are defined in a one-iteration procedure.

3 RESULTS AND DISCUSSION

Figs. 1–3 show Xsim results (in comparison with BSIMv3) for three devices from the 0.18-µm technology,
where Xsim used only the $V_i-L$ data (in Fig. 5) plus 5
$I_{ds}$-$V_{ds}$ data at low/high $V_{ds}$ (zero $V_{gs}$) for the 0.16/10µm and
at low-$V_{ds}/high-V_{gs}$ for the 10µm devices, as well as $I_{ds}-V_{ds}$
for each device; whereas BSIM used all available $I_{ds}$-$V_{gs}$
and $I_{ds}$-$V_{ds}$ data (all 0.18–10µm devices). Xsim’s approach is
to “bracket” the optimized device (0.18µm), thus,
geometry variation (down to 0.16µm) can be accurately
modeled. Direct extrapolation to 0.15µm (no data used),
as shown in Figs. 1, 2, 3(c), demonstrates the physics built
into the model. The discrepancy is mainly due to $V_i$ not being
fitted, which can be improved if calibrated down to 0.15µm
(shown in Fig. 5, cross-dotted); while a full re-calibration
for the 0.15µm device (using three $I_{ds}$ data) can well model
the MOSFET in deep $V_i$ roll-off (see Fig. 4). The $g_{ds}$ and
$V_{\text{eff}}$ calibration uses $g_{ds}$ data to determine the optimized $\delta_i$
value (related to the $V_{gs}$ location of linear/saturation
transition determined by the peak of $g_{ds}$), and optimizes $v_{ds}$
on $I_{ds}$ data and $\zeta$ on $g_{ds}$ data for each device. This assigns
“physical” meanings to the smoothing function parameter $\delta_i$ and the $v_{sat}$ and $V_{\text{eff}}$
interpretations (see Figs. 6 and 7), which are empirically modeled by
length-dependent functions. The novel “$I_{\text{eff}}+I_{i-d}$”
formulation provides smooth and physical modeling in
weak inversion, as shown in Fig. 8. Smooth derivatives are
evident in $g_{ds}/I_{ds}$ and $g_{ds}$ vs. log($I_{ds}$) characteristics, as
shown in Fig. 9. Source-drain symmetry is shown in Fig.
10, with smooth first/second derivatives at zero $V_{ds}$, which
is attributed to the correct physical modeling of $g_{ds}$
for all geometry/bias conditions.

4 CONCLUSION

The Xsim model has demonstrated predictive capability
for modeling VDSM technologies, as the model is scalable
and technology-based, with minimum parameter and
measurement data requirements. As SOI and double-gate
technologies are entering the mainstream, source-
referencing will find its advantage over bulk-referenced
models. Although still under development/improvement,
this regional/source-referenced/$V_i$-based model has already
demonstrated smooth transitions and symmetry (as
compared to popular surface-potential-based models), and
especially its validity and predictability in large geometry
range. It will have significant impact on modeling VDSM
MOSFETs for circuit simulation that combines the essential
features of model accuracy, continuity, scalability,
predictability, symmetry, and simplicity.

REFERENCES

Figure 1: Measured (symbols) and modeled (Xsim: solid lines, BSIM: dotted lines) strong-inversion drain characteristics ($V_{DS} = 1.8 \text{ V}$, $V_{GS} = 0$) of $I_{ds}$ ($\bigcirc$, mA), $g_{m}$ ($\nabla$, mS), $r_{on}$ ($\Box$, kΩ), $g_{ds}^{''}$ ($\bigtriangleup$, mS/V), and $g_{ns}^{''}$ ($\bigtriangleup$, mS/V) for the three gate-length devices.

Figure 2: Measured (symbols) and modeled (Xsim: solid lines, BSIM: dotted lines) saturation gate characteristics ($V_{DS} = 1.98 \text{ V}$, $V_{GS} = 0$) of $I_{ds}$ ($\bigcirc$, mA), $g_{m}$ ($\nabla$, mS), $r_{on}$ ($\Box$, kΩ), $g_{m0}$ ($\bigtriangleup$, mS), $g_{m0}^{''}$ ($\bigtriangleup$, mS/V) for the three gate-length devices.

Figure 3: Measured (symbols) and modeled (Xsim: solid lines, BSIM: dotted lines) linear gate characteristics ($V_{DS} = 0.1 \text{ V}$, $V_{GS} = 0$) of $I_{ds}$ ($\bigcirc$, mA), $g_{m}$ ($\nabla$, mS), $g_{m0}$ ($\bigtriangleup$, mS), $g_{m0}^{''}$ ($\bigtriangleup$, mS/V) for the three gate-length devices.

Figure 4: Measured (symbols) and modeled (lines) current/conductance characteristics of the 0.15-μm device for (a) output characteristics: $I_{ds}$ ($\bigcirc$, mA), $g_{m}$ ($\nabla$, mS), $r_{on}$ ($\Box$, kΩ) at high (solid symbols) and low (open symbols) $V_{DS}$, (b) saturation and (c) linear transfer characteristics: $I_{ds}$ ($\bigcirc$, mA), $g_{m}$ ($\nabla$, mS), $g_{m0}$ ($\bigtriangleup$, mS) at low (solid symbols) and high (open symbols) $V_{DS}$. The solid lines are Xsim model with a re-calibration of the $V_{I}$ model including the 0.15-μm $V_{I}$ data (dotted lines in Fig. 5) and the $I_{DS}$ model using the three $I_{DS}$ data shown in solid circles plus $I_{DS}$ at $V_{DS} = 0.1 \text{ V}$, $V_{GS} = -1.8 \text{ V}$ for bulk-bias calibration, which demonstrates Xsim’s capability of modeling devices with severe SCEs ($V_{TSS} = 0$).
Figure 5: Measured (symbols) and modeled (lines) threshold-voltage (constant-current definition) characteristics at the corner $V_{TH}$ and $V_{DS}$. Solid lines are fitted with the hard corner 0.16-$\mu$m (used in Figs. 1-3, solid lines), and dotted lines are for the hard corner 0.15-$\mu$m (used in Fig. 4).

Figure 6: Individually fitted (symbols) (on $I_{DS}$-$V_{GS}$ at $V_{DS} = 1.8$ V, $V_{TH} = 0$) and empirically modeled (lines) (using data $L = 0.16$-$10$ $\mu$m) saturation velocity ($v_{sat}$), CLM ($\xi$, $\nu$), and $V_{TSS}$ smoothing ($\delta_{TSS}$) parameters. Model extrapolation for $L = 0.15$-$\mu$m is used in prediction in Figs. 1,2,3(c).

Figure 7: Modeled $I_{DS}$-$V_{GS}$ characteristics using (1)-(3) with different components (using $V_{ds}$, $V_{ds}$ or $V_{ds}$), showing the smooth transition from linear to saturation mode for both $I_{DS}$ and $\delta_{TSS}$ (inset, dotted line: without CLM) with $V_{DS}$ and $\delta_{TSS}$ optimized for $I_{DS}$ and $\delta_{TSS}$, respectively; and $\delta_{TSS}$ based on $\delta_{TSS}$ data.

Figure 8: Modeled $I_{DS}$-$V_{GS}$ characteristics using (1)-(3) with different components (using $V_{ds}$, $V_{ds}$, $V_{ds}$, and $V_{ds}$), showing the smooth transition from strong inversion to subthreshold, which is built in for all length and bias with a single $V_{TH}$. The inset shows the smooth derivatives, which supports the model results in Figs. 2,3 ( $\bigcirc$ ) and Fig. 9.

Figure 9: Measured (symbols) and modeled (Xsim: solid lines, BSIM: dotted lines) $g_{m}/I_{DS}$ and $\log(g_{m})$ versus $\log(I_{DS})$ characteristics, showing the smooth transitions in strong/weak-inversion and linear/saturation regions.

Figure 10: Measured (symbols) and modeled (Xsim: solid lines, BSIM: dotted lines) symmetry test around $V_{DS} = 0$, showing Xsim accuracy in higher-order derivatives (similar behavior is also observed in true Gummel test at various $V_{DS}$, which is uncommon for source-referenced models).