Physically-Based Approach to Deep-Submicron MOSFET Compact Model Parameter Extraction

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ABSTRACT

This paper demonstrates a physically-based approach to parameter extraction of the compact I_{ds} model we have developed for deep-submicron technology development. A *two-iteration* parameter-extraction scheme is described, which improves the previous *one-iteration* approach. Parameter calibration for the V_t model is revisited. Comparison of parabolic and linear body-bias dependency with new calibration sequence for the V_t model is carried out, which shows higher accuracy in V_t modeling for the new parabolic interpolation. Optimization for the halo pile-up centriod, LDD lateral diffusion as well as saturation velocity is carried out to improve the overall V_t and I_{ds} modeling. This has been verified with the experimental data from a 0.18-µm CMOS technology wafer.

Keywords: Deep-submicron MOSFET, compact model, parameter extraction, nonlinear regression, optimization.

1 INTRODUCTION

A unified compact I_{ds} model [1] from subthreshold to saturation region, which conforms to the well-known long-channel characteristics and encapsulates all major short-channel effects (SCEs) and reverse short-channel effects (RSCEs) in deep-submicron MOSFETs, has been formulated through physics-based effective transformation. Simple *one-iteration* parameter-extraction method has been introduced, which covers full range of channel lengths (without "binning") and bias conditions. In the one-iteration approach, there are several assumptions made. First, simple equation is used before extraction of non-calibrated parameters at each step. This is based on the assumption that the effect of non-calibrated parameters can be ignored at the condition when the parameter in the current step is being extracted. Secondly, fixing the parameter value after extraction is based on the assumption that the calibrated effect will not be affected by subsequent extraction. Finally, if a fitting parameter is found to have different values at different bias conditions, a linear bias dependence of that parameter is assumed and extracted at two extreme bias conditions.

These assumptions have been validated by the application of the model to the 0.25-µm technology data with reasonable accuracy [1]. However, when the same approach is applied to the 0.18-µm technology data, error due to these assumptions becomes fairly large.

In this paper, the approach to physically-based parameter extraction is revisited. The threshold-voltage parameters are calibrated with parabolic-V_{bs} dependency for increased accuracy. A *two-iteration* extraction scheme is followed, in which the first iteration result is used as the initial guess. Together with local optimization of a few physical parameters (such as LDD lateral diffusion σ, the pile-up charge centriod l_μ as well as saturation velocity v_{sat}), we show that the new extraction approach can provide more physical and accurate parameters for the compact model.

2 PARAMETER EXTRACTION

The V_t model conforms to the well-known long-channel model with effective quantities for SCEs and RSCEs:

$$V_t = V_{FB} + \phi_s + \gamma_{eff}\sqrt{\phi_{s0} - V_{bs}} \tag{1}$$

$$\gamma = \sqrt{2q\varepsilon_{si}N_{eff}} \Big/ C_{ox} \tag{2}$$

$$\phi_s = \phi_{s0} - \Delta\phi_s = 2\phi_F + \Delta - \Delta\phi_s \tag{3}$$

in which Δ is introduced to model long-channel drain-induced barrier lowering (DIBL) effect with an assumed linear dependency on V_{ds} ($\Delta = \Delta_1 V_{ds}$).

Charge-sharing effect is modeled by λ:

$$\gamma_{eff} = \gamma - \frac{\lambda}{L_{eff}}\frac{2\varepsilon_{si}}{C_{ox}}\left(\sqrt{\phi_s - V_{bs}} + \frac{\delta V_{ds}}{\sqrt{\phi_s - V_{bs}}}\right) \tag{4}$$

Barrier-lowering effect is modeled by α:

$$\Delta\phi_s = \frac{1}{\cosh\left(L_{eff}/2l_\alpha\right)}\left[\left(V_{bi} - \phi_{s0}\right)\cosh\left(\frac{z}{2}\right) + \frac{\varphi V_{ds}}{2}\frac{\sinh\left(\frac{L_{eff}}{2l_\alpha} - \frac{z}{2}\right)}{\sinh\left(\frac{L_{eff}}{2l_\alpha}\right)}\right] \tag{5}$$

$$l_\alpha = \alpha\left(\phi_{s0} - V_{bs}\right)^{0.25} \tag{6}$$

where the short-channel DIBL effect is modeled by δ and φ in γ_{eff} and $\Delta\phi_s$ at high V_{ds}. RSCE is modeled by κ and β [2]:

$$N_{eff} = \frac{\sqrt{\pi}\kappa N_{ch}}{L_{eff}/l_\beta}\left[\operatorname{erf}\left(\frac{L_{eff}-l_\mu}{l_\beta}\right)+\operatorname{erf}\left(\frac{l_\mu}{l_\beta}\right)\right]+N_{ch} \qquad (7)$$

$$l_\beta = \beta\left(\phi_{s0}-V_{bs}\right)^{0.25} \qquad (8)$$

where the pile-up charge centroid l_μ is taken as an optimization parameter together with the LDD lateral diffusion parameter σ in the effective channel length:

$$L_{eff} = L_g - 2\sigma x_j = L - \Delta_{CD} - 2\sigma x_j \qquad (9)$$

where Δ_{CD} is the critical-dimension correction and x_j is the LDD junction depth.

The V_t model has 3 long-channel fitting parameters, V_{FB}, N_{ch}, and Δ_1, which are extracted from the long-channel $V_t - V_{bs}$ data using simple equations (without SCE parameters) at low V_{ds} (extracting V_{FB} and N_{ch}) and high V_{ds} (extracting Δ_1 with V_{FB} and N_{ch} fixed). The short-channel V_t model has 6 fitting parameters, $\lambda, \alpha, \kappa, \beta, \delta$, and φ, which are extracted for a given technology from the measured $V_t - L$ data, where the measured V_t is based on constant-current definition [3] in which only $6 \times N$ point (I, V) data plus one $I_{ds} - V_{gs}$ curve are required (where N is the number of different gate-length devices).

The V_t model includes all major SCEs and RSCEs that can be appropriately modeled by fitting $\lambda, \alpha, \kappa, \beta, \delta$, and φ to a given $V_t - L$ data at any biases for the given σ and l_μ values (see Section 3 for the $\sigma - l_\mu$ optimization). It has been observed that charge-sharing and barrier-lowering parameters (λ and α) are relatively independent of V_{bs} and, thus, extracted at high $|V_{bs}|$ when the effects are largest. In the previous one-iteration approach, DIBL effect (δ and φ) is first ignored when λ, α, κ, and β are being extracted at low $V_{ds} = V_{do} = 0.1$ V, then δ and φ are calibrated at high $V_{ds} = V_{dd} = 1.98$ V with the extracted λ, α, κ, and β values fixed. $\kappa, \beta\ \delta$, and φ are assumed to be linearly dependent on V_{bs} and are calibrated at low $V_{bs} = V_{bo} = 0$ and high $V_{bs} = V_{bb} = -1.8$ V. While these assumptions have been valid for the 0.25-μm data, it is found that they are no longer accurate for the 0.18-μm technology data.

In the new two-iteration approach, we take the extracted δ and φ from the first iteration as the initial guess values and re-calibrate λ, α, κ, and β with the full V_t model where the minor DIBL effect at V_{do} is accounted for. Also, we assume that κ, β, δ, and φ have parabolic V_{bs} dependence:

$$\begin{aligned}
\kappa &= \kappa_0 + \kappa_1 V_{bs} + \kappa_2 V_{bs}^2 \\
\beta &= \beta_0 + \beta_1 V_{bs} + \beta_2 V_{bs}^2 \\
\delta &= \delta_0 + \delta_1 V_{bs} + \delta_2 V_{bs}^2 \\
\varphi &= \varphi_0 + \varphi_1 V_{bs} + \varphi_2 V_{bs}^2
\end{aligned} \qquad (10)$$

They are calibrated at V_{bo}, V_{bb}, and $V_{bs} = V_{b1} = -0.9$ V to account for different amount of RSCE and DIBL effects at different V_{bs} conditions, while λ and α are still assumed to be V_{bs} and V_{ds} independent.

Excellent fitting of the parabolic-V_{bs} dependent V_t model at the extreme V_{ds} and V_{bs} conditions is demonstrated in Fig. 1. The improvement of the parabolic-V_{bs} model over the linear-V_{bs} model is shown in Fig. 2 with the excellent prediction of the measured $V_t - L$ at $V_{bs} = -0.45$ and -1.35 V, in which none of the data has been used in parameter extraction.

Similarly for the I_{ds} model, the ideal long-channel MOSFET is described by the simple equation:

$$I_{ds0} = \mu_0 C_{ox}\left(W/L_{eff}\right)\left[\left(V_{gs}-V_t\right)V_{ds} - \tfrac{1}{2}A_b V_{ds}^2\right] \qquad (11)$$

$$A_b = 1 + \zeta\,\frac{\gamma}{2\sqrt{\phi_s - V_{bs}}} \qquad (12)$$

$$\mu_{eff} = \frac{\mu_0}{1+V_{ds}/\left(E_{sat}L_{eff}\right)} \qquad (13)$$

where the parameters such as vertical-field mobility (μ_0) and bulk-charge factor (A_b) are well defined. For the short-channel I_{ds} model, Eq. (11) is modified to include SCEs such as series resistance (R_{sd}), channel-length modulation (CLM), and subthreshold modeling.

In the one-iteration approach, we start from long-channel equation to extract μ_0 parameters at low V_{ds}, assuming that the minor bulk-charge effect can be ignored by setting $\zeta = 1$. This is followed by calibrating A_b using the long-channel $I_{ds} - V_{ds}$ data at high gate voltage $V_{gs} = V_{gg} = 1.796$ V (with fixed μ_0). V_{ds} in Eqs. (11) and (13) is changed to V_{deff} using the BSIM smoothing function [4] with long-channel saturation voltage:

$$V_{dsat0} = \frac{E_{sat}L_{eff}\left(V_{gs}-V_t\right)}{V_{gs}-V_t+A_b E_{sat}L_{eff}} \qquad (14)$$

Then, Eq. (11) is modified to include R_{sd} in the short-channel I_{ds} model with a consistent solution for V_{dsat} [1]:

$$I_{ds} = \frac{I_{ds0}}{1+\left(R_{sd}I_{ds0}\right)/V_{deff}} \qquad (15)$$

where I_{ds0} is the drain current without the R_{sd} effect. R_{sd} is calibrated from short-channel $I_{ds} - V_{gs}$ at low V_{ds} (with fixed μ_0 and A_b). This is then followed by CLM calibration for short-channel $I_{ds} - V_{ds}$ at high V_{gs} using

$$I_{ds} = \frac{I_{deff}}{1+\left(R_{sd}I_{deff}\right)/V_{deff}} \qquad (16)$$

$$I_{deff} = \left(1 + \frac{V_{ds} - V_{deff}}{V_{Aeff}}\right) I_{ds0} \tag{17}$$

where V_{Aeff} is an effective Early voltage with one fitting parameter (ξ) extracted with an optimization loop for the saturation velocity (v_{sat}). Finally, $V_{gs} - V_t$ in the “simple” equations is replaced by an effective gate overdrive (V_{ge}) [5] for subthreshold modeling with one fitting parameter (V_{off}) for the full range of geometry and biases.

In the one-iteration approach, it is assumed that for each calibration step, the newly extracted parameter will not affect those that have been calibrated. Fig. 3 illustrates this assumption by comparing the $I_{ds} - V_{ds}$ characteristics using the simple I_{ds0} model (11) without CLM to the full compact I_{ds} model (16) with CLM for long- and short-channel devices. Both simple and full I_{ds} models simulate accurately for the long-channel $I_{ds} - V_{ds}$ behavior, while the full I_{ds} model can predict short-channel CLM effect without affecting what has been characterized at the long-channel. Similar idea is shown in Fig. 4 during the subthreshold calibration, which does not affect the calibrated behavior in the strong inversion.

In the new two-iteration approach, the above scheme is still followed, in which the extracted parameter set is used as the initial guess for the full model equations in the second iteration. Comparison between one- and two-iteration approaches is shown in Fig. 5 for the root-mean-square (RMS) error in $I_{ds} - V_{gs}$ over different V_{bs} biases at high and low V_{ds}.

3 OPTIMIZATION

The philosophy of our model parameter extraction is based on separation of fitting and physical parameters, where process-dependent fitting parameters are extracted using nonlinear regression method [6] at the “given” physical parameter values, which are optimized through optimization loops for minimum RMS error in the target being fitted. This is to avoid extraction of unphysical values of these physical parameters if they were used as regression parameters.

V_t model parameters are extracted together with σ and l_μ optimization loops. RMS errors are calculated with the full V_t model over all gate lengths at four combinations of V_{bs} and V_{ds} conditions (V_{bo}, V_{bb}, V_{do}, V_{dd}). Total RMS errors are computed and plotted against different σ and l_μ values as shown in Fig. 6. Minimum RMS error in V_t over all gate lengths falls on $\sigma = 0.63$ and $l_\mu = -40$ nm, which is chosen to be the optimum values for L_{eff} and N_{eff}.

The I_{ds} CLM parameter is extracted together with the v_{sat} optimization loop. RMS errors are computed in v_{sat} optimization over $I_{ds} - V_{ds}$ at high V_{gs} and low V_{bs} for $L = 0.16$ μm during CLM calibration. A minimum RMS error is observed at $v_{sat} = 6\times10^6$ cm/s, as shown in Fig. 7, which also shows further improvement in RMS error with two-iteration for I_{ds} model extraction during v_{sat} optimization.

4 CONCLUSION

In conclusion, the proposed new V_t calibration sequence allows either linear-V_{bs} or parabolic-V_{bs} dependent model and one- or two-iteration approach being incorporated during the V_t model parameter extraction, which can be selected based on available process data to trade off accuracy and complexity.

Physical parameter extraction is performed in a more systematic way, in which the parameters are extracted through optimization loops of physical parameters based on minimum RMS error criteria. The two-iteration extraction approach effectively corrects the errors due to the assumptions made in the one-iteration approach, which provides higher accuracy in deep-submicron device modeling.

The potential impact of our improved calibration approach on V_t and I_{ds} lies in more accurate and physical device parameter extraction, which would lead to more meaningful statistical modeling in circuit simulation and deep-submicron technology development.

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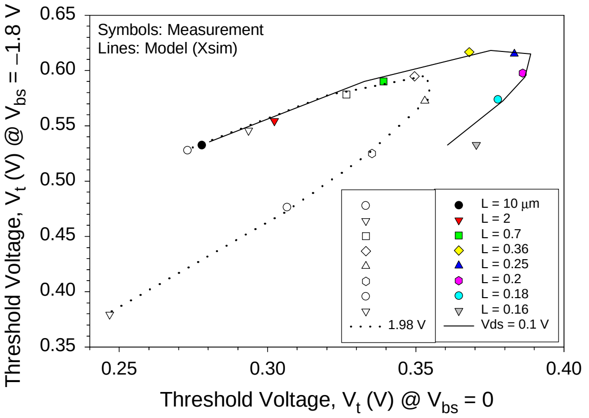

Figure 1: Measured (*symbols*) and modeled (*lines*) $V_t(V_{bb}) - V_t(V_{bo})$ behaviors at V_{do} (*solid*) and V_{dd} (*dotted*) for the indicated gate-length devices.

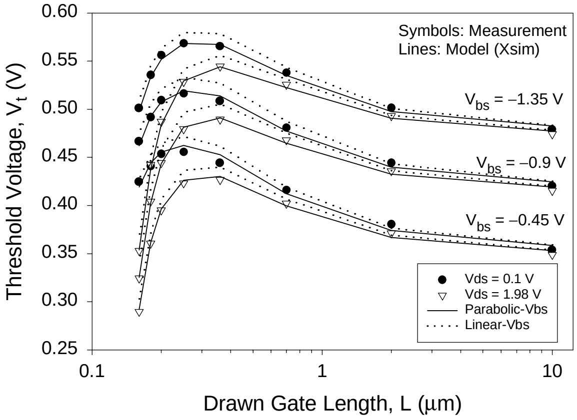

Figure 2: Measured (*symbols*) and modeled (*lines*) $V_t - L$ characteristics for the linear-V_{bs} (*dotted*) and parabolic-V_{bs} (*solid*) models at the indicated bias conditions.

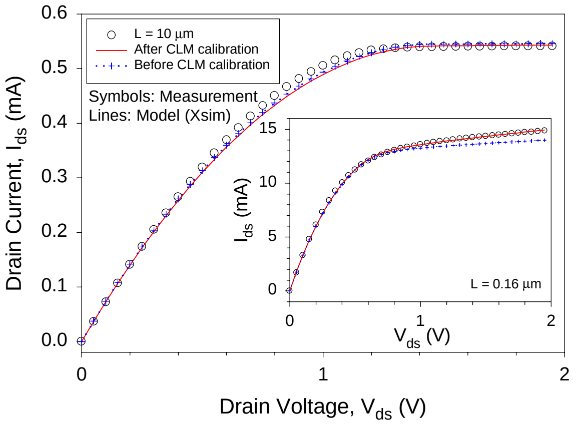

Figure 3: Measured (*symbols*) and modeled (*lines*) $I_{ds} - V_{ds}$ characteristics before (*cross-dotted*) and after (*solid*) CLM calibration for L = 10-µm and L = 0.16-µm (*inset*) devices.

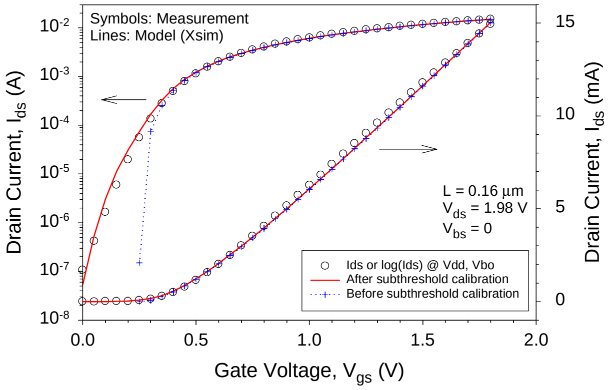

Figure 4: Measured (*symbols*) and modeled (*lines*) $I_{ds} - V_{gs}$ characteristics before (*cross-dotted*) and after (*solid*) subthreshold calibration for the L = 0.16-µm device.

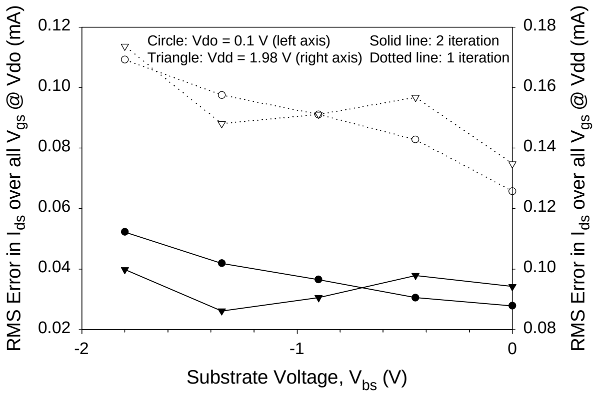

Figure 5: RMS error in I_{ds} over all V_{gs} for one-iteration (*dotted lines*) and two-iteration *(solid lines)* at V_{do} = 0.1 V (*circles*, *left axis*) and V_{dd} = 1.98 V (*triangles*, *right axis*).

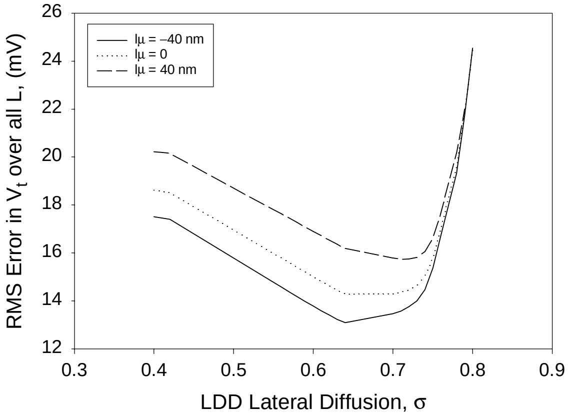

Figure 6: RMS error in V_t over all L for $\sigma - l_\mu$ optimization. The optimal condition σ = 0.63 and l_μ = −40 nm is chosen.

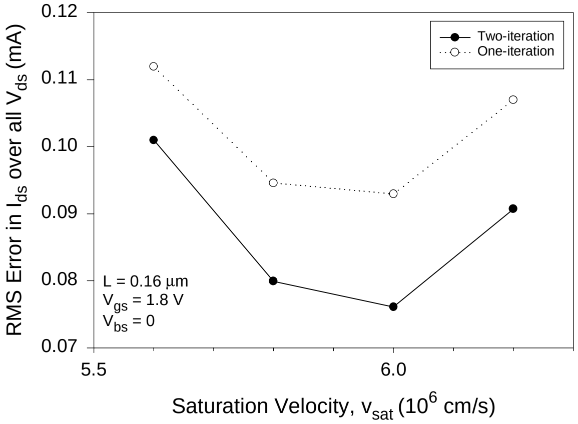

Figure 7: RMS error in v_{sat} optimization over all $I_{ds} - V_{ds}$ for one-iteration (*dotted lines*) and two-iteration (*solid lines*) during CLM calibration (at V_{gs} = 1.796 V, V_{bs} = 0, and L = 0.16 µm). The optimal v_{sat} = 6×10^6 cm/s is chosen.