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

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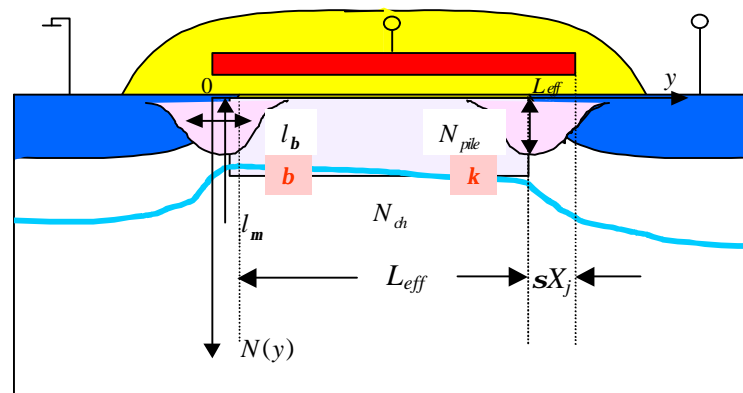
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# Physically-Based Approach to Deep-Submicron MOSFET Compact Model Parameter Extraction

## □ Motivation

- Demonstrates a physically-based approach to parameter extraction for compact  $V_t$  and  $I_{ds}$  model
- Regression approach for model parameters
- Optimization approach for physical parameters such as the pile-up charge centroid, LDD lateral diffusion, and saturation velocity
- Proposed *one-* and *two-iteration* parameter extraction scheme



# $V_t$ Model Parameter Extraction and Optimization

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Full Model

$$V_t = V_{FB} + f_s + g_{eff} \sqrt{f_{SO} - V_{bs}}$$

$$g_{eff} = g - \frac{l}{L_{eff}} \frac{2e_{si}}{C_{ox}} \left[ \sqrt{f_s - V_{bs}} + \frac{dV_{ds}}{\sqrt{f_s - V_{bs}}} \right]$$

$$f_s = f_{SO} - \Delta f_s$$

$$\Delta f_s = \frac{1}{\cosh(L_{eff}/2l_a)} \left[ (V_{bi} - f_{so}) \cosh\left(\frac{z}{2}\right) + \frac{jV_{ds}}{2} \frac{\sinh\left(\frac{L_{eff}}{2l_a} - \frac{z}{2}\right)}{\sinh\left(\frac{L_{eff}}{2l_a}\right)} \right]$$

$$N_{eff} = \frac{\sqrt{pk} N_{ch}}{L_{eff}/l_b} \left[ erf\left(\frac{L_{eff} - l_m}{l_b}\right) + erf\left(\frac{l_m}{l_b}\right) \right] + N_{ch}$$

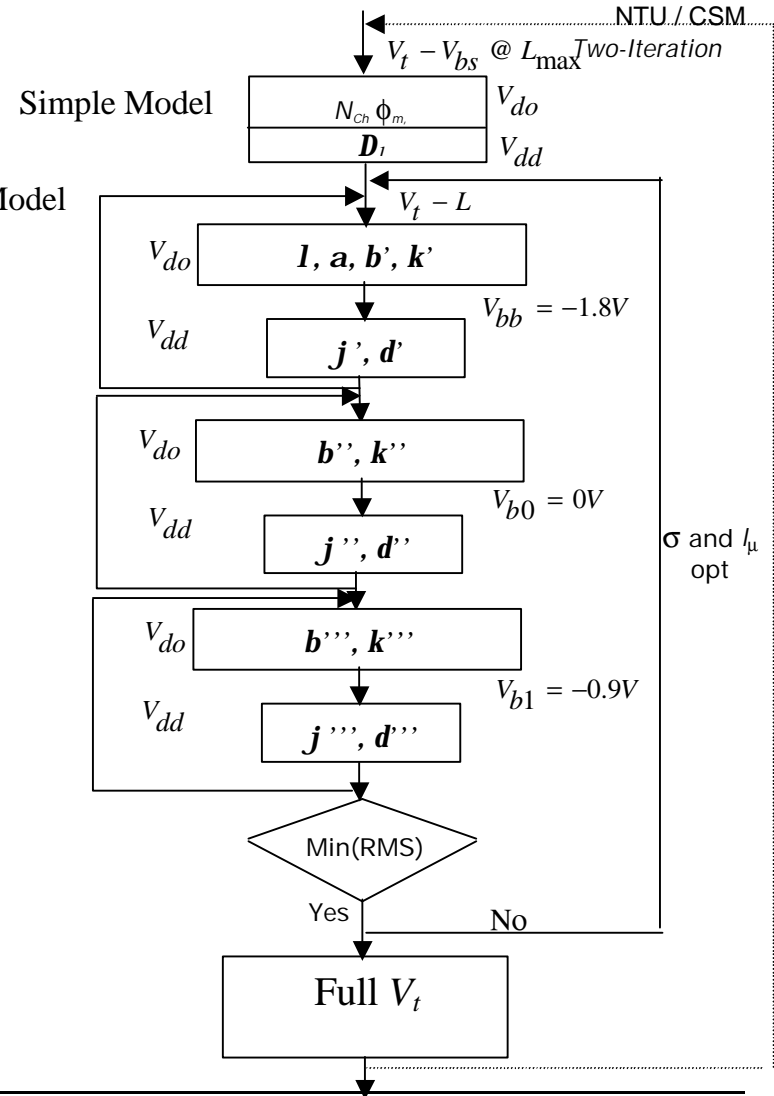
$$l_b = b (f_{so} - V_{bs})^{0.25}$$

$$L_{eff} = L - \Delta_{CD} - 2s X_j$$

Simple Model

$$g_{eff} \rightarrow g \quad f_s \rightarrow f_{SO} \quad N_{eff} \rightarrow N_{ch}$$

$$f_{SO} = 2f_f + \Delta_1 V_{ds}$$



# Model Extraction

## □ Semi-empirical approach (Body Bias Coefficient)

Semi-empirical parabolic equations for  $V_{bs}$  dependency are formulated

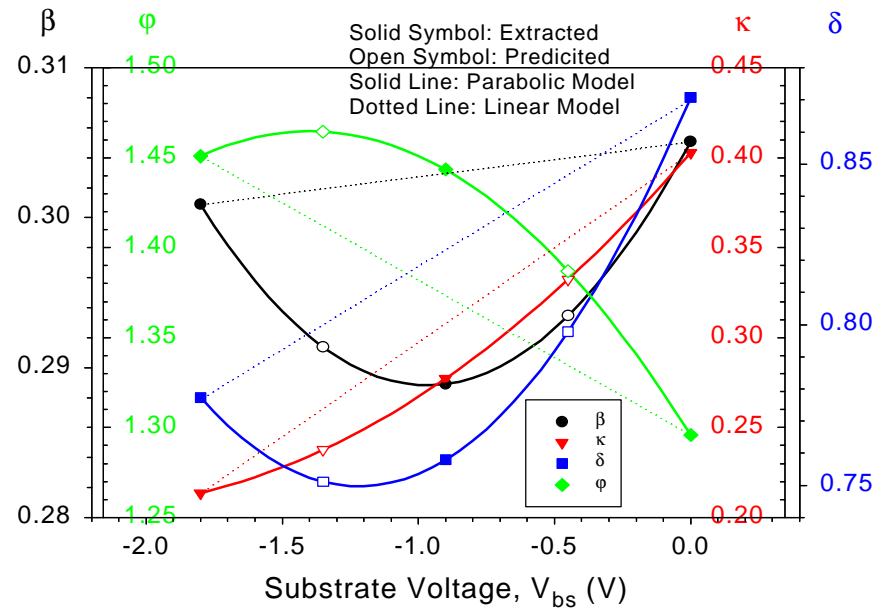
$$\mathbf{k} = \mathbf{k}_0 + \mathbf{k}_1 V_{bs} + \mathbf{k}_2 V_{bs}^2$$

$$\mathbf{b} = \mathbf{b}_0 + \mathbf{b}_1 V_{bs} + \mathbf{b}_2 V_{bs}^2$$

$$\mathbf{j} = \mathbf{j}_0 + \mathbf{j}_1 V_{bs} + \mathbf{j}_2 V_{bs}^2$$

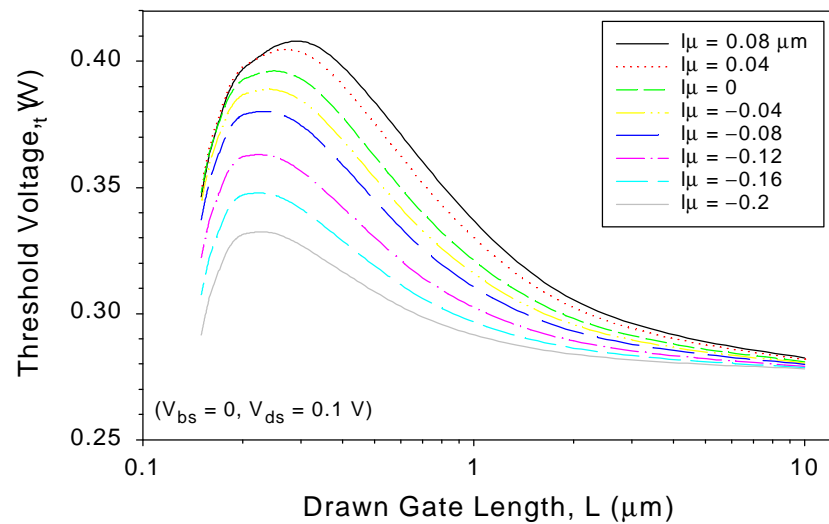
$$\mathbf{d} = \mathbf{d}_0 + \mathbf{d}_1 V_{bs} + \mathbf{d}_2 V_{bs}^2$$

- Calibrated at  $V_{bb}$ ,  $V_{bo}$  and  $V_{bl}$
- Accounted for different amount of RSCE and DIBL effects at different  $V_{bs}$  conditions
- Linear  $V_{bs}$  dependency calibrated only at  $V_{bb}$  and  $V_{bo}$

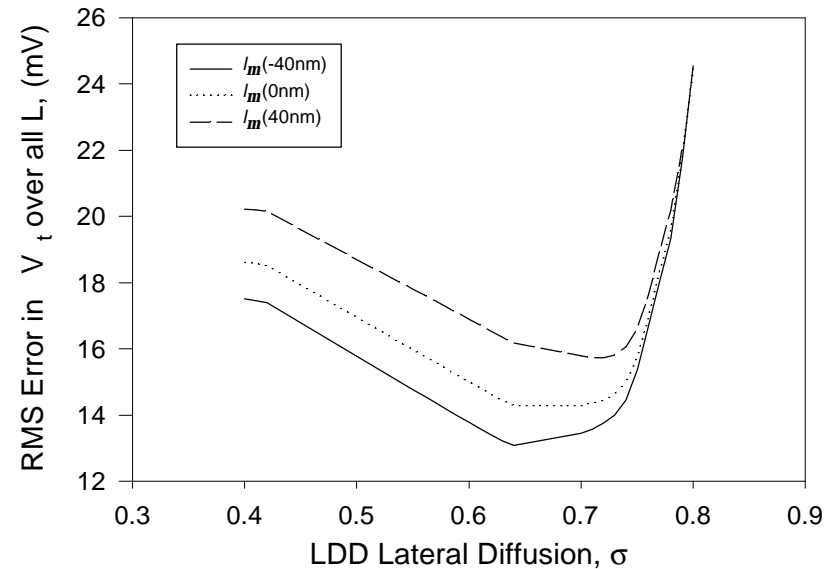


# Physical Parameter Behavior and Optimization

## □ Behavior



## □ Optimization

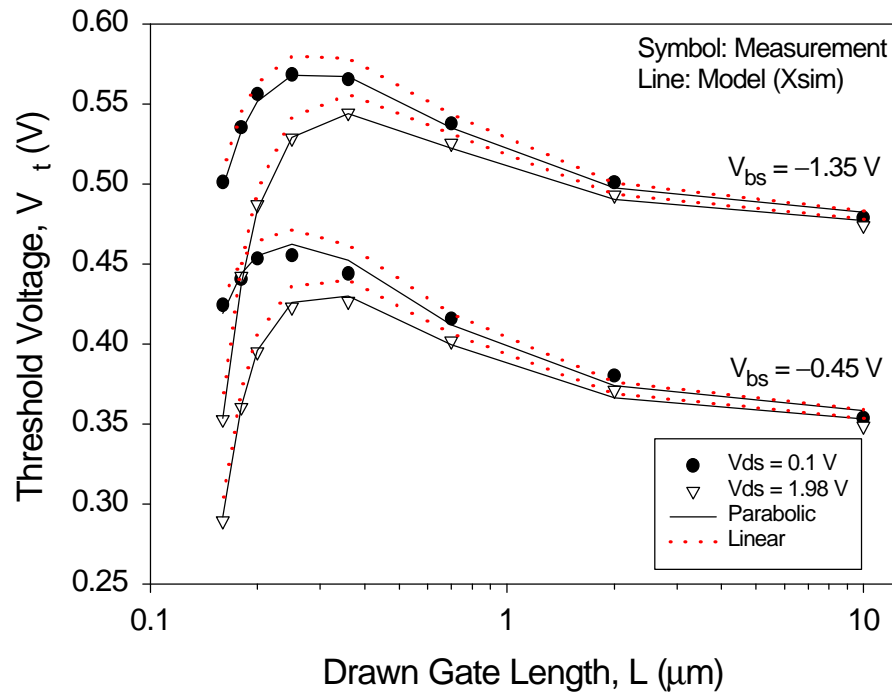


- **Optimized  $V_t$  is determined together with  $L_{eff}$  and  $N_{eff}$  by “tuning” two physical parameters,  $s$  (LDD lateral diffusion) and  $I_m$  (halo centroid), to obtain minimum RMS error for all geometry and bias ( $V_{bs}$ ,  $V_{ds}$ )**

# Model Prediction

## Predication

- Improvement in the parabolic- $V_{bs}$  over the linear- $V_{bs}$  model with excellent prediction of  $V_t - L_g$  measured data at  $V_{bs} = -0.45$  and  $-1.35$



# $I_{ds}$ Model Parameter Extraction and Optimization

## Model 1

$$I_{ds0} = m_{eff} C_{ox} (W/L_{eff}) [(V_{gs} - V_t)V_{ds} - 1/2 A_b V_{ds}^2]$$

## Model 2

$$V_{ds} \rightarrow V_{deff}, V_{deff} = f(V_{ds}, V_{dsat}) \quad V_{dsat} = \frac{E_{sat} L_{eff} (V_{gs} - V_t)}{V_{gs} - V_t + A_b E_{sat} L_{eff}}$$

$$A_b = 1 + V \frac{g}{2\sqrt{f_s - V_{bs}}}$$

## Model 3

$$I_{ds} = \frac{I_{dso}}{1 + (R_{sd} I_{dso})/V_{deff}} \quad R_{sd} = r_1 + \frac{r_2}{(V_{gs} - V_t)}$$

## Model 4

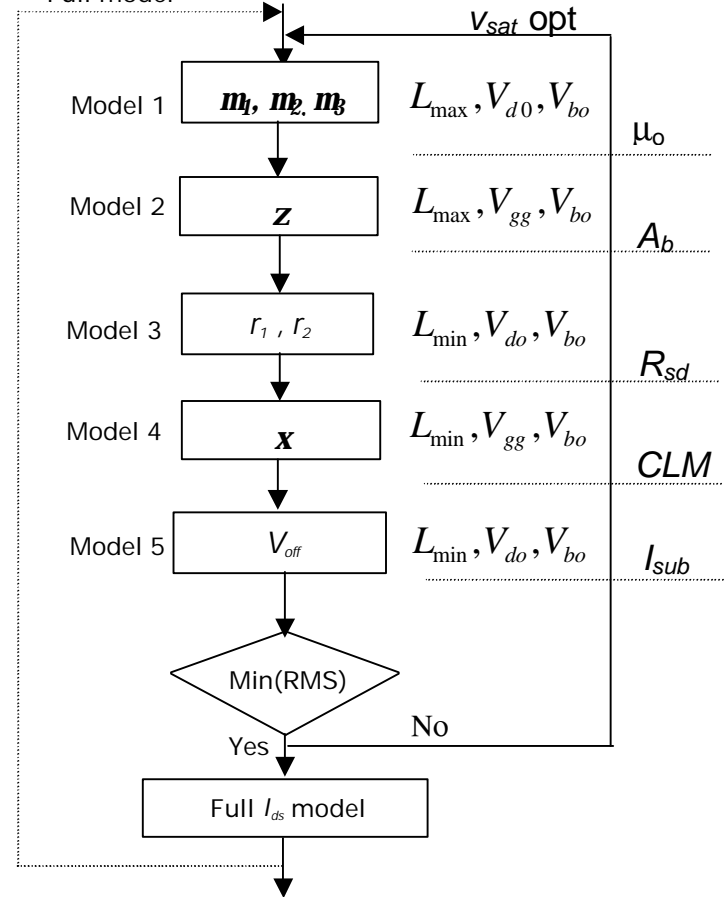
$$I_{ds} = \frac{I_{deff}}{1 + (R_{sd} I_{deff})/V_{deff}} \quad I_{deff} = \left(1 + \frac{V_{ds} - V_{deff}}{V_{Aeff}}\right) I_{dso}$$

$$V_{Aeff} = f(\mathbf{x}), V_{deff} = f(V_{ds}, V_{dsat}, v_{sat}) \quad V_{dsat} = f(V_{ds}, v_{sat}, R_{sd})$$

## Model 5

$$V_{gs} - V_t \rightarrow V_{geff} \quad I_{dso} = m_{eff} C_{ox} (W/L_{eff}) V_{ge} \quad V_{ge} = f(V_{off}, V_t)$$

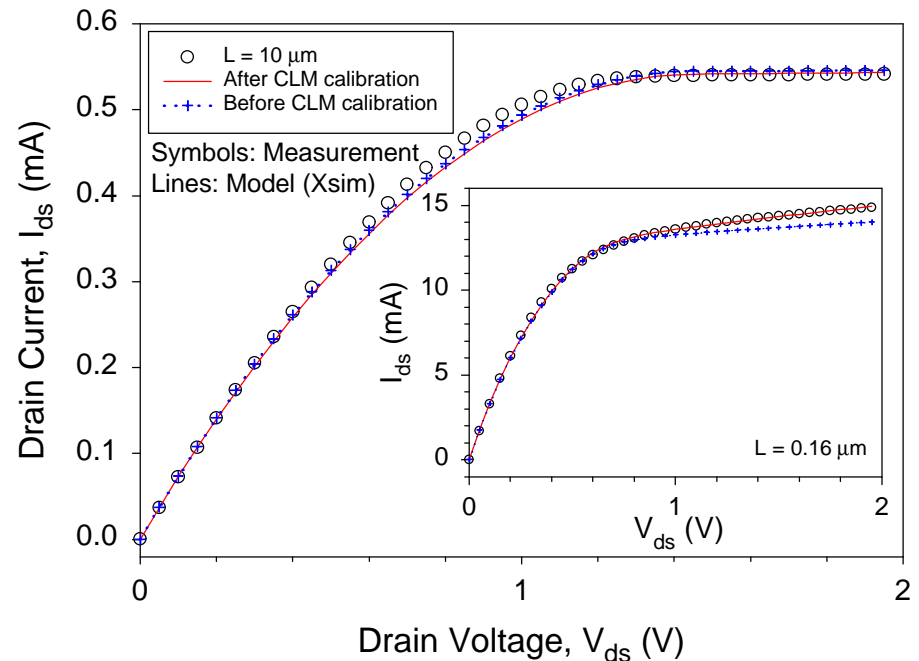
Two-Iteration:  
Full model



# CLM Extraction

## □ First Iteration

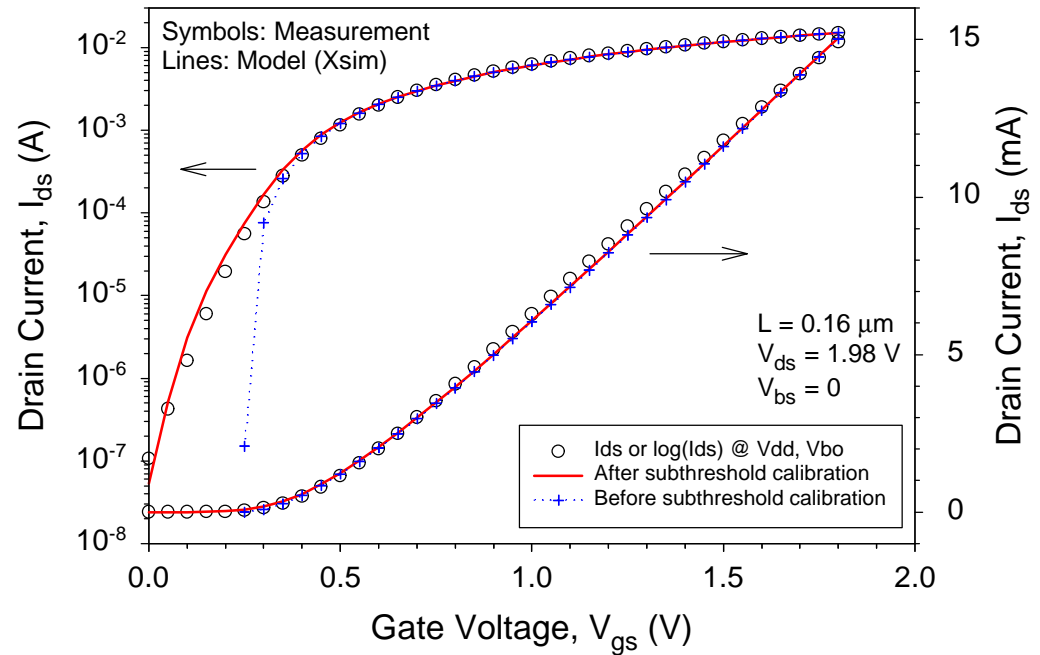
- De-couple the effect during the  $I_{ds}$  model parameter extraction
- Each calibration step calibrating each effect at its extreme condition
- Simple ideal long channel  $I_{ds}$  model is used for mobility and bulk charge calibration
- Ignore minor short-channel  $R_{sd}$  and CLM effect
- Modification of  $I_{ds}$  model to include  $R_{sd}$ , CLM,  $I_{sub}, \dots$



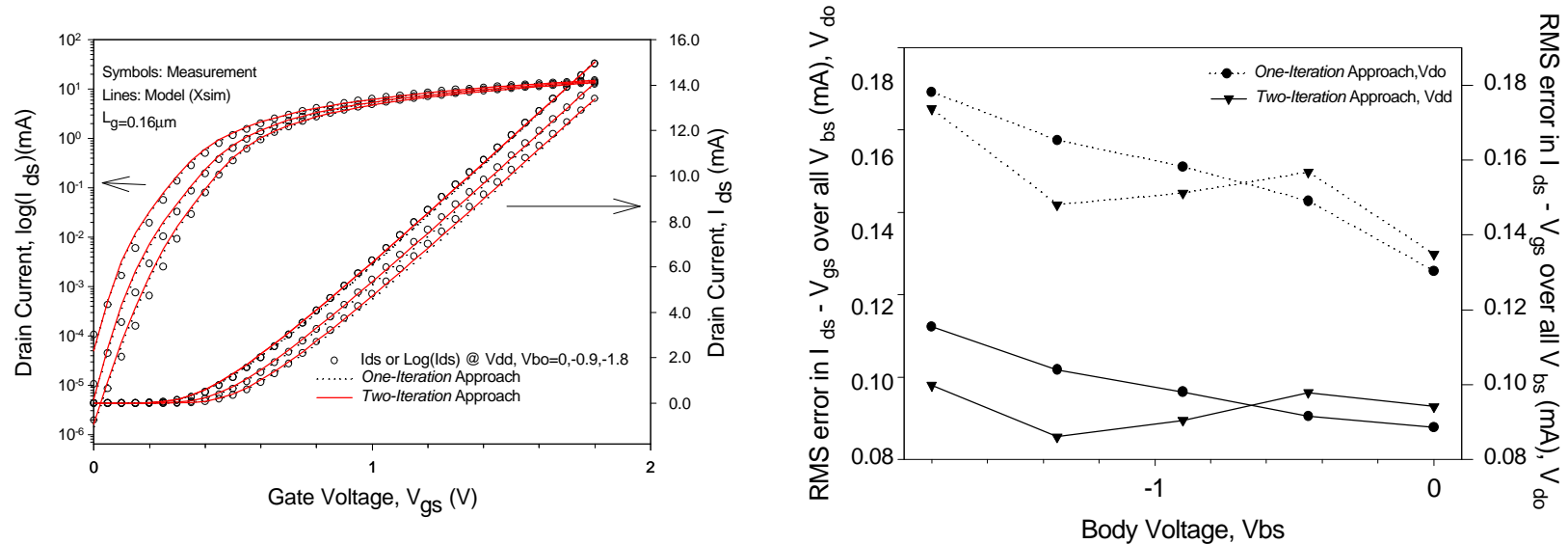
# Subthreshold Extraction

## □ First Iteration

Assumption:  
In each calibration step,  
the newly extracted  
parameter will not affect  
those that have been  
calibrated.



# One- vs Two-Iteration Extraction



## □ Two-Iteration

- Extracted parameter set from first iteration is used as initial guess
- Full compact  $I_{ds}$  model is used for each calibration step

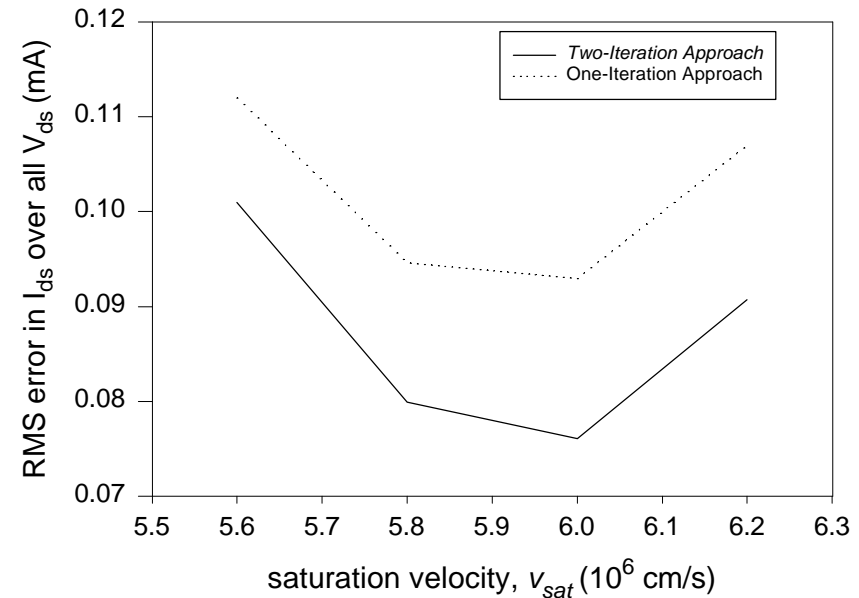
# Improvement and Optimization

## Improvement

- Improvement with *two-iteration* in term of RMS error for  $I_{ds} - V_{gs}$  over all  $V_{bs}$  and  $V_{ds}$  biases

## $v_{sat}$ Optimization

- $$y_{rms} = \left[ \frac{1}{n} \sum (y_{model} - y_{measured})^2 \right]^{1/2}$$
- RMS errors are computed in  $v_{sat}$  optimization over  $I_{ds} - V_{ds}$  at high  $V_{gs}$  and low  $V_{bs}$  for  $L_g = 0.16\mu\text{m}$  during CLM calibration. A minimum RMS error is observed at  $v_{sat} = 6 \times 10^6 \text{ cm/s}$



# Conclusions

## □ Approach

- New  $V_t$  calibration sequence allow either linear or parabolic- $V_{bs}$  dependent model and *one- or two-iteration* approach being incorporated during  $V_t$  model parameter extraction.
- This allows trade-off between accuracy and complexity based on the given technology data
- Model parameters are extracted through non-linear regression
- Physical parameter extraction is performed in more systematic way through optimization loops based on minimum RMS error criterion so as to reduce parameter dependency
- The *two-iteration* extraction approach effectively corrects the errors due to the assumptions made in *one-iteration* approach, which provides higher accuracy in deep-submicron device modeling

## □ Significance

- 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