Adding Physical Scalability to BSIM4 by Meta-Modeling of Fitting Parameters

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Abstract— **A new approach for improving physical scalability of existing compact models is proposed. The behavior of internal BSIM4 model parameters in response to a change in fabrication process condition is modeled by physics-based meta-model equations. By recovering missing links between the fitting parameters and device design parameters, the model parameter sets for variant transistors with different channel implant dose can be predicted starting from a parameter set of existing reference transistors.**

Keywords: compact model, V_{th} model parameter, channel impurity profile, halo

I. INTRODUCTION

MOSFET compact models usually have many fitting parameters to meet the demand for high accuracy. As a result, considerable effort is required for the parameter extraction procedure. Moreover, since there are many variant transistors (multiple V_{th}, multiple T_{ox}) in advanced CMOS technologies, the effort becomes huge. Physical scalability of the compact model often helps saving this effort, because crude parameter sets for variant transistors can be created by simply changing the relevant device design parameters. It is also useful for creating alpha models without silicon data for performance predictions. However, this is not possible with BSIM4, though it is still widely used in the industry [1]. In this work, a new approach for adding physical scalability to BSIM4 is proposed. Physics-based meta-model equations are developed and their effectiveness is demonstrated.

II. MODELING

A. Concept of meta-modeling

Fig.1 shows the concept of the meta-modeling. Ideally, the characteristics of devices should be linked with device design parameters, such as channel impurity concentration N_{ch}, gate oxide thickness T_{ox}, etc thorough physics based models. However, in BSIM4, some of internal parameters, which are originally physics based, lost their links with the design parameters. This results in the loss of proper correlation between the internal parameters, and loss of scalability. In our approach, the missing links are re-constructed by external add-on meta-models. Using such meta-models, a model parameter set for the transistors with a modified fabrication process condition can be easily predicted from existing reference transistors.

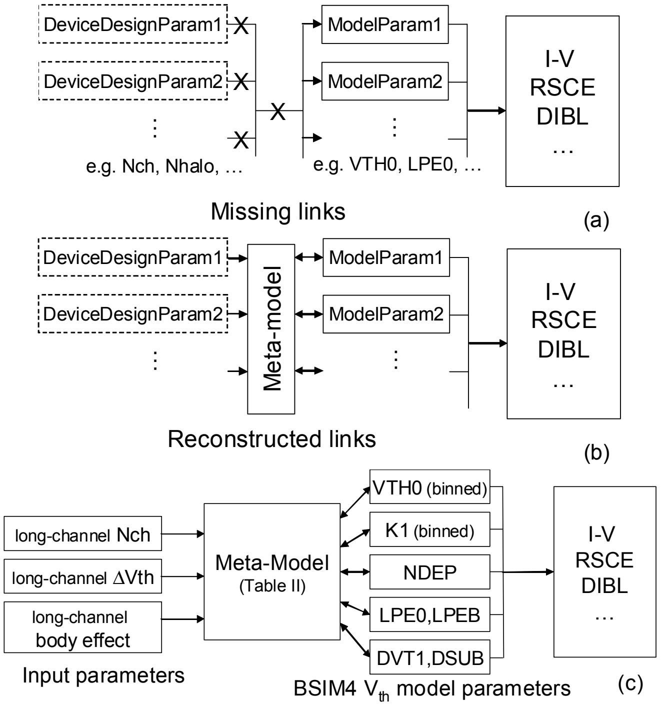

Figure 1. Concept of meta-modeling. Missing links between device design parameters and model parameters (a) are reconstructed by physics-based add-on meta-models (b). (c) Specific meta-models for BSIM4 Vth-rerated model parameters.

B. Meta-model for BSIM4 Vth model parameters

Meta-model equations for key parameters in BSIM4 V_{th} model are developed. Dominant terms in BSIM4 V_{th} equations are summarized in Table I.

BSIM4 channel impurity concentration parameter NDEP is one of the model parameters which are tightly linked to device design parameters. When the channel impurity concentration N_{ch} is altered by a modification of fabrication process condition, NDEP directly follows the change of N_{ch}, i.e.,

$$\boldsymbol{NDEP'} = N_{ch}' \, . \tag{9}$$

Parameters with prime represent model parameters or device design parameters for the modified process condition.

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On the other hand, a reverse short channel effect (RSCE) parameter LPE0 is a typical example of an internal parameter which lost its scalability. In BSIM4, RSCE caused by halo is modeled based on a step-like 1-D lateral channel doping profile [2] shown in Fig. 2 where N_{halo} is doping concentration in halo, L_{halo} is lateral expanse of halo, L_{eff} is effective channel length. V_{th} is determined by the average concentration in the channel N_{av}, which changes as a function of L_{eff}. According to this model, V_{th} should scale as

$$V_{th} = const\cdot\sqrt{N_{ch}\left(1+\frac{2N_{halo}L_{halo}}{N_{ch}}\frac{1}{L_{eff}}\right)}+\ldots \qquad (10)$$

In BSIM, increase of V_{th} due to RSCE is modeled as (2) in Table I. It is clear from (10) and (2) that LPE0 should be a function of N_{ch} as

$$LPE0 \;=\; 2N_{halo}L_{halo}/N_{ch}\,. \qquad (11)$$

However, in BSIM4 parameter extraction, there is no link between LPE0 and N_{ch}. Rather, LPE0 is specified independently as a fitting parameter. However, the lost link can be easily recovered by scaling LPE0 according to the following equation.

$$\boldsymbol{LPE0'} = LPE0\cdot\left(N_{ch}/N_{ch}'\right). \qquad (12)$$

Meta-model equation for another RSCE parameter LPEB which appears in (3) is similarly derived as follows.

$$\boldsymbol{LPEB'} = LPEB\cdot\left(N_{ch}/N_{ch}'\right). \qquad (13)$$

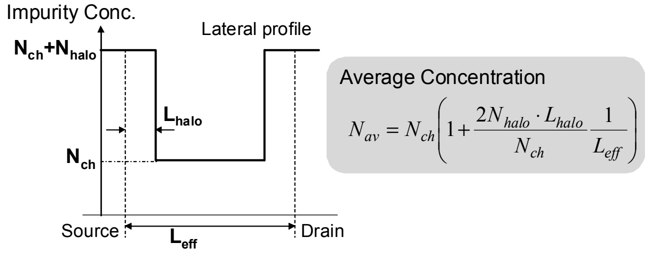

Figure 2. Simplified 1-D lateral impurity profile to model RSCE parameters.

Meta-model equations for DIBL and short channel effect (SCE) model parameters are derived to recover their link with RSCE. As shown in (4), (7) and (8), DIBL is described using characteristic length l_{t0} in BSIM4. Characteristics of short channel devices will be determined by N_{av}, not N_{ch}. However, l_{t0} in BSIM4 is proportional to $NDEP^{-1/4}$. A DIBL model parameter DSUB is used to compensate for this discrepancy, i.e., DSUB can be modeled to be proportional to $(N_{av}/NDEP)^{1/4}$ $\propto \left[1+\left(LPE0/L_{eff}\right)\right]^{1/4}$.

To model DIBL, the influence of non-uniform vertical doping profile should also 1be taken into account. The simple 1-D doping profile model (Fig. 2) is modified to 2-D model as shown in Fig. 3. Average impurity concentration for the surface region N_{av1} and that for the deep region N_{av2} are separately considered in this model. N_{av1} and N_{av2} can be associated with RSCE parameters LPE0 and LPEB, respectively. This is because V_{th} which affected by LPE0 is determined by the impurity profile in surface region (inside of

TABLE I. DOMINANT TERMS IN BSIM4 VTH EQUATION.

$\mathbf{BodyEffect} = \left(K_{1ox}\cdot\sqrt{\Phi_s - V_{bseff}} - K1\cdot\sqrt{\Phi_s}\right)\sqrt{1+\frac{\boldsymbol{LPEB}}{L_{eff}}} - K_{2ox}\cdot V_{bseff}$ (1)	$l_t = \sqrt{\frac{\varepsilon_{Si}\cdot TOXE}{EPSROX}}X_{dep}\left(1+DVT2\cdot V_{bseff}\right.$ (5)
$\mathbf{RSCE} = K_{1ox}\left(\sqrt{1+\frac{\boldsymbol{LPE0}}{L_{eff}}}-1\right)\sqrt{\Phi_s}$ (2)	$X_{dep} = \sqrt{\frac{2\varepsilon_{Si}\cdot\left(\Phi_s - V_{bseff}\right)}{q\cdot \boldsymbol{NDEP}}}$ (6)
$\mathbf{SCE} = -\frac{1}{2}\frac{DVT0}{\cosh\left(\boldsymbol{DVT1}\cdot\frac{L_{eff}}{l_t}\right)-1}\left(V_{bi}-\Phi_s\right)$ (3)	$l_{t0} = \sqrt{\frac{\varepsilon_{Si}\cdot TOXE}{EPSROX}}X_{dep0}$ (7)
$\mathbf{DIBL} = -\frac{1}{2}\frac{1}{\cosh\left(\boldsymbol{DSUB}\cdot\frac{L_{eff}}{l_{t0}}\right)-1}\left(ETA0+ETAB\cdot V_{bseff}\right)\cdot V_{ds}$ (4)	$X_{dep0} = \sqrt{\frac{2\varepsilon_{Si}\cdot\Phi_s}{q\cdot \boldsymbol{NDEP}}}$ (8)

TABLE II. META-MODEL EQUATIONS FOR VTH-RERATED MODEL PARAMETERS.

$\boldsymbol{VTH0'} = VTH0+\Delta V_{th\_longchannel}$	(18)	$\boldsymbol{DSUB'} = DSUB\cdot\frac{1}{2}\left[\left[\frac{1+\left(LPE0'/L_{eff}\right)}{1+\left(LPE0/L_{eff}\right)}\right]^{1/4}+\left[\frac{1+\left(LPEB'/L_{eff}\right)}{1+\left(LPEB/L_{eff}\right)}\right]^{1/4}\right]$	(16)
$\boldsymbol{K1'} = k\cdot K1$	(19)		
$\boldsymbol{NDEP'} = N_{ch}'$	(9)		
$\boldsymbol{LPE0'} = LPE0\cdot\left(N_{ch}/N_{ch}'\right)$	(12)	$\boldsymbol{DVT1'} = DVT1\cdot\frac{1}{2}\left[\left[\frac{1+\left(LPE0'/L_{eff}\right)}{1+\left(LPE0/L_{eff}\right)}\right]^{1/4}+\left[\frac{1+\left(LPEB'/L_{eff}\right)}{1+\left(LPEB/L_{eff}\right)}\right]^{1/4}\right]$	(17)
$\boldsymbol{LPEB'} = LPEB\cdot\left(N_{ch}/N_{ch}'\right)$	(13)		

the depletion layer) whereas V_{th} shift due to body effect which affected by LPEB is determined by that in deep region (near the depletion layer edge).

According to the discussions above, meta-model equations for DSUB considering only surface region:

$$DSUB'1 = DSUB \cdot \left[\frac{1+\left(LPE0'/L_{eff}\right)}{1+\left(LPE0/L_{eff}\right)} \right]^{1/4}, \tag{14}$$

and that considering only deep region:

$$DSUB'2 = DSUB \cdot \left[\frac{1+\left(LPEB'/L_{eff}\right)}{1+\left(LPEB/L_{eff}\right)} \right]^{1/4}, \tag{15}$$

are derived. Appropriate value for DSUB' is expected to lie between DSUB'1 and DSUB'2. As the simplest estimation, (16) in Table II is derived. Meta-model equation for SCE parameter DVT1 is also derived as (17) in Table II according to similar discussion.

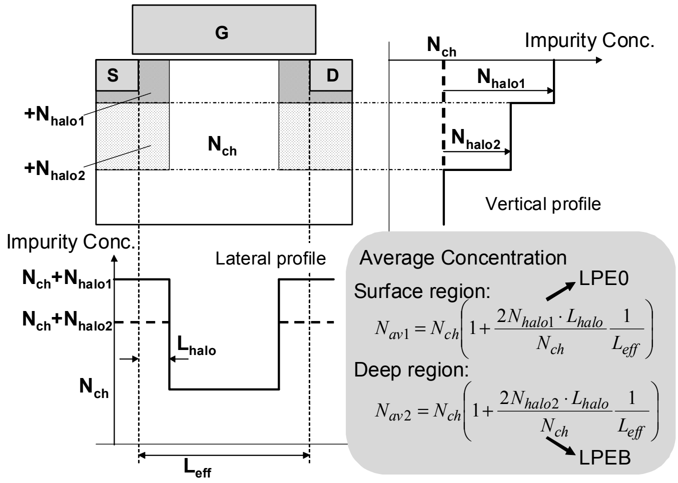

Figure 3. Simplified impurity profile to model SCE and DIBL parameters. Vertical distribution is introduced.

A long-channel V_{th} parameter VTH0 and a body effect parameter K1 are modeled by following simple equations,

$$\boldsymbol{VTH0'} = VTH0 + \Delta V_{th\_longchannel} \tag{18}$$

$$\boldsymbol{K1'} = k \cdot K1 \tag{19}$$

where $\Delta V_{th\_longchannel}$ is V_{th} difference and k is ratio of K1 in long-channel transistors. Table II summarizes Meta-model equations for V_{th}-related model parameters. Only three input parameters (Fig. 1 (c)) other than a V_{th} model parameter set for existing devices are required to generate a V_{th} model parameter set for the modified devices. Meta-model for mobility model parameters U0 and UA is also developed using the ratio of mobility.

III. RESULTS

To test the effectiveness of this method, model parameter sets for low- and high-dope channel devices were derived by meta-models. The model parameter set for existing medium-doped channel devices is used as a reference. Figs. 4(a) and 4(b) show the V_{th}-L_g characteristics and Fig. 5 shows DIBL-L_g characteristics. Model parameters generated by meta-model equations adequately predicts measured result, whereas the case simply changing NDEP and VTH0 does not follow measured result. Figs. 6(a) and 6(b) show I_d-V_{gs} and I_d-V_{ds} characteristics of low-dope channel NFET with L_g ~ 55 nm. I_d is well estimated with a maximum error less than 3% by meta-model-based parameter set.

These results show that by simply modifying the V_{th}-related parameters, moderately accurate variant parameter sets can be obtained. Though fine tuning of the parameters is still required in some cases as shown in Fig. 7, only a small number of parameters (in this case three parameters) are required for additional fitting. Fig. 8 summarizes the reduction of maximum I_d error with parameter tuning from reference model parameter set. In this work nine parameters are modified in a batch using meta-models, and maximum Id error is automatically reduced to less than 6%.

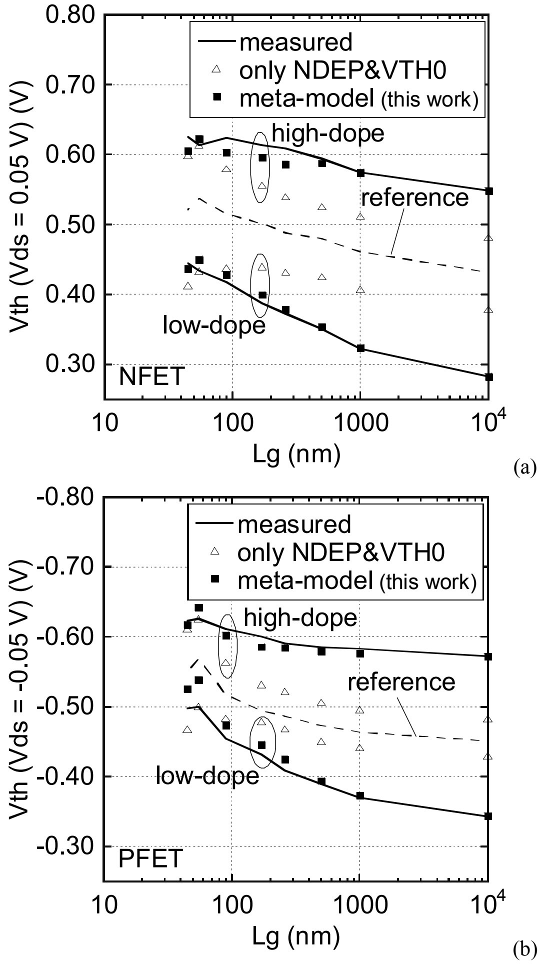

Figure 4. Vth-Lg characteristics of (a) NFET and (b) PFET. Amount of VTH0 shift is determined by Lg ~ 55 nm transistor in the case of "only NDEP&VTH0."

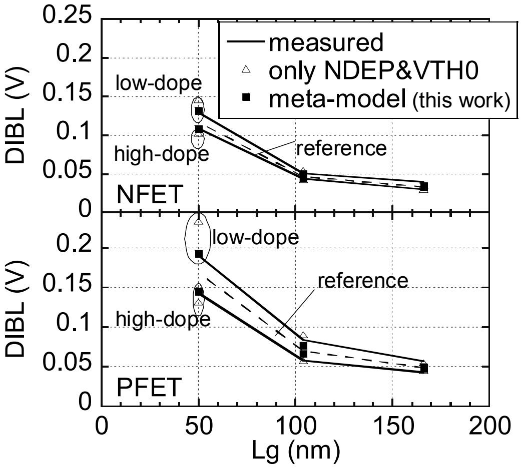

Figure 5. DIBL-Lg characteristics of NFET and PFET. DIBL is defined by Vth difference between |Vds| = 0.05 V and 1.2 V.

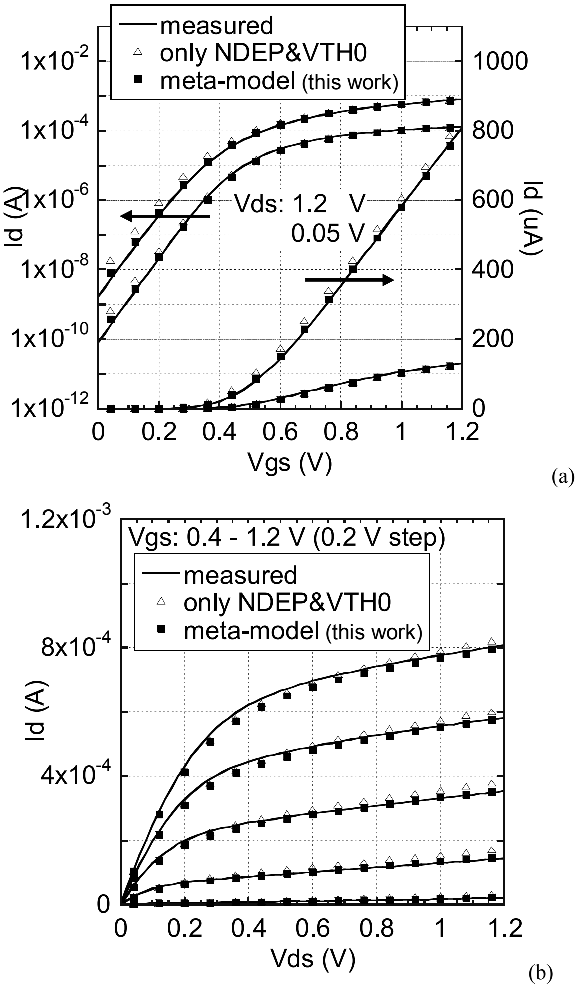

Figure 6. (a) Id-Vgs and (b) Id-Vds characteristics of low-dope channel NFET (Lg ~ 55 nm).

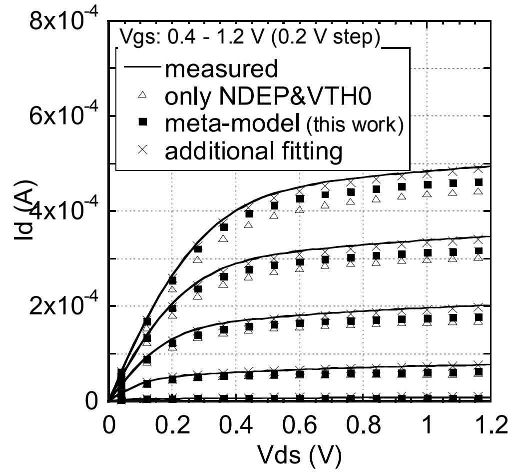

Figure 7. Id-Vds characteristics of low-dope channel NFET (Lg ~ 170 nm). Additional fitting is performed using three model parameters.

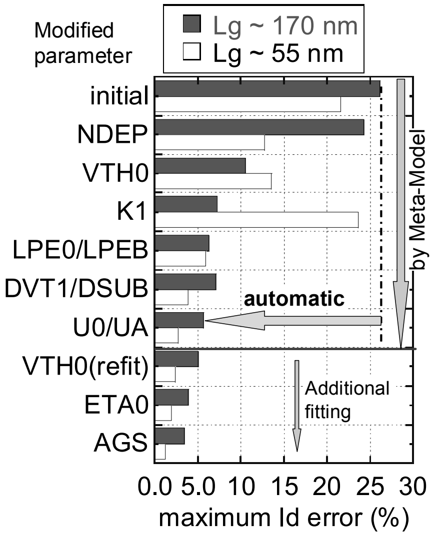

Figure 8. Reduction of error in Id by tuning each parameter sequentially from top to bottom. Note that the order of parameters is not important. Upper nine parameter values are set automatically by meta-models.

IV. CONCLUSION

The concept of meta-modeling for improving BSIM4 physical scalability was proposed. Basic meta-model equations were developed and applied to 65nm technology devices for deriving parameter sets for different channel doping. The errors of the obtained models were reduced to 6%, as compared with 13% for simple VTH0 tuning. The concept is practically useful for improving efficiency of parameter extraction.

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