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HiSIM Methodology for the Parameter Extraction in Accordance with the Model Derivation

I. Introduction

HiSIM (Hiroshima university STARC IGFET Model) is one of the surface potential based Spice models [1], [2] and pioneered the iterative approach to obtain the surface potential applicable in compact models. The model aims for MOSFET technology of 100 nm or below. The parameter extraction procedure was introduced first by the model developers: Semiconductor Technology Academic Research Center (STARC) [3], [4]. Silvaco ***UTMOST-III*** introduced the first version of the local optimization strategies for HiSIM-1.1 in 2002 [5]. Since then, the parameter extraction methodology has been reviewed thoroughly. This article is meant to provide significant aspects on the HiSIM version 1.2 parameter extraction for ***UTMOST-III*** users.

Since the surface potential is obtained by solving Poisson equation, and the geometric effects are directly related to the electric field calculated from the potential, establishing the HiSIM model parameter extraction methodology forces traditional SPICE modeling engineers to refresh their understanding of device physics. Moreover, making the HiSIM model to be scalable over the wide geometric region challenges the experienced manner of this tradition. In this paper, each step of the developed HiSIM model parameter extraction is discussed from the model derivation point. The model parameters are symbolized with the capital, bold and italic letters. Also, the HiSIM-1.2 equations and the numbers used herein are based on HiSIM1.2.0 user's manual [3]. The detailed ***UTMOST-III*** local optimization strategies with the practical application results will be covered in a future edition of simulation standard issued by Silvaco International.

II. HiSIM Methodology

A. Substrate Model Parameters

MOSFET threshold voltage parameter (Vth) is very popular in MOSFET Spice models such as in the Level-1, 2, 3 and in the UC Berkeley BSIM3 models. The threshold voltage parameter extraction comes at the very first of the extraction procedures. In contrast, HiSIM calculates the surface potential by applying Poisson equation to the channel region and the potentials are used for the drain current computation with no explicit threshold voltage parameter. The followings are the HiSIM formulas of the drain current with the surface potentials.

$$I_{\rm ds} = \frac{W_{\rm eff}}{L_{\rm eff}} \mu \frac{IDD}{\beta}$$

$$\begin{aligned} IDD = {} & C_{\rm ox}(\beta V'_{\rm G}+1)(\phi_{\rm SL}-\phi_{\rm S0}) - \frac{\beta}{2}C_{\rm ox}(\phi_{\rm SL}^2-\phi_{\rm S0}^2) \\ & - \frac{2}{3}\left(qN_{\rm sub}L_{\rm D}\sqrt{2}\right)\Big[\left\{\beta(\phi_{\rm SL}-V_{\rm bs})-1\right\}^{\frac{3}{2}} \\ & \qquad - \left\{\beta(\phi_{\rm S0}-V_{\rm bs})-1\right\}^{\frac{3}{2}}\Big] \\ & + (qN_{\rm sub}L_{\rm D}\sqrt{2})\Big[\left\{\beta(\phi_{\rm SL}-V_{\rm bs})-1\right\}^{\frac{1}{2}} \\ & \qquad - \left\{\beta(\phi_{\rm S0}-V_{\rm bs})-1\right\}^{\frac{1}{2}}\Big] \end{aligned} \tag{23}$$

$$C_{\rm ox} = \frac{\epsilon_{\rm ox}}{T_{\rm ox}} \tag{11}$$

$$V'_{\rm G} = V_{\rm gs} - V_{\rm fbc} + \Delta V_{\rm th} \tag{12}$$

$$\beta = \frac{q}{kT} \tag{13}$$

$$\Delta V_{\rm th} = \Delta V_{\rm th,SC} + \Delta V_{\rm th,R} + \Delta V_{\rm th,P} + \Delta V_{\rm th,W} - \phi_{\rm Spg} \tag{73}$$

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V_{th} represents the threshold voltage shifts referring to the long channel device including the short channel (ΔVth,SC), the reverse short channel ($V_{th,R}$ and $V_{th,P}$), and the reduced channel width ($V_{th,W}$) effects. Most of them are related to the electric field gradients for the lateral direction.

Therefore, the substrate parameters such as the substrate impurity concentration (***NSUBC***), the flat-band voltage (VFBC), the maximum pocket concentration (***NSUBP***), and the pocket penetration length (***LP***) are to be determined first. At the same time, the oxide thickness (***TOX***) is also to be fixed as the source of the vertical electric field.

$$N_{\mathrm{sub}} = \frac{N_{\mathrm{subc}}(L_{\mathrm{eff}} - L_{\mathrm{p}}) + N_{\mathrm{subp}} L_{\mathrm{p}}}{L_{\mathrm{eff}}} \quad (39)$$

Effective impurity concentration used in the HiSIM equation is the averaged value using ***NSUBC, NSUBP,*** and ***LP*** parameters (eq.39). The eq.39 was supposed to limit the ***LP*** value less than the Leff value. However, the formula enables it become larger than the Leff. There is no structural constraint, which was found through the trial parameter extraction applied for 90 nm technology [6]. For long and wide channel devices, the ***NSUBP*** and ***LP*** have less influence and the initial value determination appears to be arbitrary. But, the ***LP*** must be defined and the remaining substrate parameters should be extracted under the fixed value at the first step of the extraction. The reasonable approach to define the LP is under investigation.

The ***TOX*** requires a capacitance voltage curve (CGG) for the determination. The substrate related parameters could be fixed using Ids versus Vgs curve for the large geometry transistor. Also, the capacitance curve could be appropriate for the initial value findings. Naturally, gate current contribution must be considered for very thin gate oxide devices.

With those initial values, the sub-threshold drain current region is used for the substrate parameter optimization. Since HiSIM has no body effect coefficient parameters like in the previous generation models, the substrate parameter determination at the very first stage almost destines the body bias behavior of the HiSIM model.

B. Carrier Mobility: Low Field Mobility

HiSIM low field mobility model follows the mobility universality [7]. Three scattering mechanisms such as Coulomb, phonon, and surface roughness effects are taken into account.

$$\frac{1}{\mu_0} = \frac{1}{\mu_{\mathrm{CB}}} + \frac{1}{\mu_{\mathrm{PH}}} + \frac{1}{\mu_{\mathrm{SR}}} \quad (50)$$

$$\mu_{\mathrm{CB}}(\mathrm{Coulomb}) = MUECB0 + MUECB1 \frac{Q_{\mathrm{i}}}{q \times 10^{11}} \quad (51)$$

$$\mu_{\mathrm{PH}}(\mathrm{phonon}) = \frac{MUEPH1}{(T/300\mathrm{K})^{MUETMP} \times E_{\mathrm{eff}}^{MUEPH0}} \quad (52)$$

$$\mu_{\mathrm{SR}}(\mathrm{surface\ roughness}) = \frac{MUESR1}{E_{\mathrm{eff}}^{MUESR0}} \quad (53)$$

The gate bias region of Ids versus Vgs should be properly selected with this mobility universality in mind for the parameters (***MUECB0, MUECB1, MUEPH1, MUESR1***) using the wide channel width and the long channel length (large) device. Although the target I-V curve for the large device is easily expressed with the rough bias selections, the scalable model would become difficult to be achieved. Some parameters are related with the electric field component. The low field mobility characterization with split C-V method might provide an insight for the bias selection.

In addition, the surface roughness effect might be indistinguishable from the HiSIM pocket resistance parameter effect. The Ids degradation at the high Vgs could be expressed only with the surface roughness parameter. However, it might be an overestimation of the decreasing mobility. And the short channel length devices might show the smaller Ids current for the target curves.

C. Geometric Effects: Reverse Short Channel Effect

HiSIM geometric effects toward the MOS channel length such as the reverse short channel (RSC) and the standard short channel (SC) effects need the careful approach. The HiSIM RSC expression is based on the impurity inhomogeneity in the lateral direction and the lateral electric field strength is modified as following.

$$\Delta V_{\mathrm{th,P}} = (V_{\mathrm{th,R}} - V_{\mathrm{th0}}) \frac{\epsilon_{\mathrm{Si}}}{C_{\mathrm{ox}}} W_{\mathrm{d}} \frac{dE_{y,\mathrm{P}}}{dy} \quad (35)$$

$$V_{\mathrm{th,R}} = V_{\mathrm{fbc}} + 2\Phi_{\mathrm{B}} + \frac{\sqrt{2qN_{\mathrm{sub}}\epsilon_{\mathrm{Si}}(2\Phi_{\mathrm{B}} - V_{\mathrm{bs}})}}{C_{\mathrm{ox}}} \quad (36)$$

$$V_{\mathrm{th0}} = V_{\mathrm{fbc}} + 2\Phi_{\mathrm{BC}} + \frac{\sqrt{2qN_{\mathrm{subc}}\epsilon_{\mathrm{Si}}(2\Phi_{\mathrm{BC}} - V_{\mathrm{bs}})}}{C_{\mathrm{ox}}} \quad (37)$$

$$\frac{dE_{y,\mathrm{P}}}{dy} = \frac{2(V_{\mathrm{bi}} - 2\Phi_{\mathrm{B}})}{PARL1 \cdot L_{\mathrm{p}}^2} \left(SCP1 + SCP2 \cdot V_{\mathrm{ds}} + SCP3 \cdot \frac{2\Phi_{\mathrm{B}} - V_{\mathrm{bs}}}{L_{\mathrm{p}}} \right) \quad (38)$$

The four model parameters such as ***PARL1, SCP1, SCP2***, and ***SCP3*** in addition to the substrate related parameters (***NSUBC, NSUBP***, and ***LP***) are included in the equation.

$$N_{\mathrm{sub}} = \frac{N_{\mathrm{subc}}(L_{\mathrm{eff}} - L_{\mathrm{p}}) + N_{\mathrm{subp}} L_{\mathrm{p}}}{L_{\mathrm{eff}}} \quad (39)$$

The ***NSUBP*** under the fixed ***LP*** should be mainly used to express a shift of Ids versus Vgs curve to the larger Vgs (Vth roll-up) of the RSC devices. And it should be modified carefully to have the small effect on the SC device curves. Too much change on the SC device characteristics at this step means the shift of Ids versus Vgs toward the smaller Vgs (Vth roll-off) couldn't be expressed later with any effort. It means the pre-defined ***LP*** is too small to assign the larger contribution to the ***NSUBP*** for the averaged Nsub. The ***LP*** must be redefined, other substrate parameters also must be extracted according to the previous description. So that the ***NSUBP*** value could become reasonable compared to the ***NSUBC***, and the RSC effect could be expressed clearly [8].

One of remaining four parameters, ***PARL1***, is fixed to unity. ***SCP1*** appears to be used for the slight tuning of the RSC effect expression. And ***SCP3*** could be used to modify the body bias effect for the RSC devices. Finally, ***SCP2*** which relates the RSC effect with the drain bias needs to be optimized for Ids versus Vgs under the saturation condition.

D. Geometric Effects: Standard Short Channel Effect

The standard short channel effect is expressed with the similar formula for the reverse short channel effect.

$$\Delta V_{\mathrm{th,SC}} = \frac{\epsilon_{\mathrm{Si}}}{C_{\mathrm{ox}}} W_{\mathrm{d}} \frac{dE_y}{dy} \quad (28)$$

$$W_{\mathrm{d}} = \sqrt{\frac{2\epsilon_{\mathrm{Si}}(2\Phi_{\mathrm{B}} - V_{\mathrm{bs}})}{qN_{\mathrm{sub}}}}. \quad (29)$$

$$\frac{dE_y}{dy} = \frac{2(V_{\mathrm{bi}} - 2\Phi_{\mathrm{B}}^{'})}{PARL1(L_{\mathrm{eff}} - PARL2)^2} \left(SC1 + SC2 \cdot V_{\mathrm{ds}} + SC3 \cdot \frac{2\Phi_{\mathrm{B}} - V_{\mathrm{bs}}}{L_{\mathrm{eff}}} \right) \quad (30)$$

$$\Phi_{\mathrm{B}}^{'} = \Phi_{\mathrm{B}} + PTHROU \cdot \left(\Phi_{\mathrm{B}}^{''}(V_{\mathrm{gs}}) - \Phi_{\mathrm{B}} \right) \quad (31)$$

However, such four parameters as ***PARL2, SC1, SC2,*** and ***SC3*** should be optimized carefully to obtain the standard short channel (SC) effect. ***PARL2*** has the length dimension, modifies the effective channel length used in the SC effect equation and shows much influence on the effect. ***SC1*** parameter has also the great effect to pull the overshot Ids versus Vgs curves resulted by the RSC expression toward the Vth roll-off (SC effect) direction. Also, ***SC2*** influences the higher drain bias region of Ids versus Vgs curves, and expresses the SC effect dependency on the drain bias. The extraction of the standard short channel parameters requires the software optimizer to be used with much care. Especially, both the ***SC1*** and ***SC2*** values spread widely between 0 and 200 depending on the device characteristics of RSC and SC effects.

E. Carrier Mobility: High Field Mobility

Now that such parameters as the substrate, the low field mobility and the RSC and SC effect parameters are fixed using the Ids versus Vgs at the low Vds, HiSIM high field mobility parameters should be extracted. The HiSIM high field mobility is obtained by modifying the low field component with the lateral electric field in association with the modulated maximum velocity parameter.

$$\mu = \frac{\mu_0}{\left(1 + \left(\frac{\mu_0 E_{\mathrm{y}}}{V_{\mathrm{max}}}\right)^{BB}\right)^{\frac{1}{BB}}} \quad (60)$$

$$V_{\mathrm{max}} = \frac{VMAX}{1.8 + 0.4(T/300\mathrm{K}) + 0.1(T/300\mathrm{K})^2} \quad (61)$$

$$V_{\mathrm{max}} = \frac{V_{\mathrm{max}}}{1 - \frac{VOVER}{L_{\mathrm{eff}}^{VOVERP}}} \quad (62)$$

The HiSIM maximum velocity (***VMAX***) modulation adopts a nonlinear expression with two model parameters which are related to the channel length. The lateral electric field is also the function of channel length. Therefore, the high field mobility dependency on the channel length could become complex and hard to be predicted. Therefore, tuning over the wide range of the channel length would be the most critical step to obtain the scalable model parameters over the channel length.

In order to trace the drain bias influence, Ids versus Vgs curves under the various drain voltages appear to be suitable as the target characteristics for the parameter optimization. Whether the equation could be capable of depicting the scalability for 100 nm below technology, or not, requires the verification with various technology devices.

F. Geometric Effects: Narrow Width Effect

HiSIM-1.2 narrow width effect description which takes the shallow trench isolation (STI) technology into account looks simple, and has waited for the validation using the actual and practical devices.

$$\Delta V_{\mathrm{th,W}} = \left(\frac{1}{C_{\mathrm{ox}}} - \frac{1}{C_{\mathrm{ox}} + 2C_{\mathrm{ef}}/(L_{\mathrm{eff}} W_{\mathrm{eff}})} \right) qN_{\mathrm{sub}} W_{\mathrm{d}} \quad (71)$$

$$C_{\mathrm{ef}} = \frac{2\epsilon_{\mathrm{ox}}}{\pi} L_{\mathrm{eff}} \ln \left(\frac{2T_{\mathrm{fox}}}{T_{\mathrm{ox}}} \right) = \frac{WFC}{2} L_{\mathrm{eff}} \quad (72)$$

A trial report on this methodology reveals the effectiveness of HiSIM approach [6].

G. Geometric Effects: Wide Width Effect

The second STI effect expression in HiSIM-1.2 is the mobility reduction assuming the STI induced mechanical stress. The wider device is supposed to suffer the mobility degradation.

$$MUEPH1 = MUEPH1 + MUEPH2 \cdot \log(W_{\mathrm{gate}}) \quad (72)$$

$$\log(W_{\mathrm{gate}}) \geq W0$$

H. Geometric Effects: Hump in Sub-Threshold Current

Another STI induced effect in HiSIM-1.2 is the drain current hump in the sub-threshold region. As far as the parameter extraction for the varied channel length is concerned, further validation seems to be required.

V. Summary

The methodology on HiSIM-1.2 model parameter extraction was discussed from the model derivation point. HiSIM-1.2 incorporates other effects such as Poly-Depletion, Quantumn-Mechanical, Channel-Length Modulation, etc.. The readers of interest should refer to HiSIM-1.2.0 user's manual [3]. The practical procedure was applied to the actual N-channel MOS devices and the HiSIM-1.2 model parameter set was obtained. The simulated result demonstrated the geometrical scalability down to 100 nm from 10 um channel length with no binning at all. The UTMOST-III local optimization strategies with the applied result will appear on a future issue of Simulation Standard from Silvaco International.

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