An Optimization Method of Deep Submicron SOI Compact Model Parameter Extraction

Y. Mahotin and R. Mickevicius

Synopsys, Inc.
700 E. Middlefield Road, Mountain View, CA, USA, Yuri.Mahotin@synopsys.com

ABSTRACT

As Silicon-On-Insulator (SOI) rapidly advances to the vanguard of ULSI technology, compact model parameter extraction for SOI still relies on indirect methods. Floating body (FB) device parameter extraction is currently based on body contact (BC) device parameter extraction. However, the underlying physics of these two devices is quite different, and therefore, have distinctively different characteristics. In this work we report a novel method to directly extract parameters of a FB device. In addition to standard model parameters, we have been able to extract gate current, impact ionization current, GIDL current, as well as diode and parasitic BJT currents, using only a FB device.

Keywords: BSIMPD, SOI, parameter extraction, penalty function.

1 INTRODUCTION

SOI CMOS is becoming a mainstream technology for high-performance computing, such as IBM's new RISC processors [1]. At the same time the compact model parameter extraction for SOI devices lags behind and impedes further IC design. Recently, BSIMPD model and parameter extraction methods have been reported [2, 3]. However, these methods are indirect. Although target devices are FB SOI, most of the model parameters have to be extracted from BC SOI devices. These model parameters then must be validated on FB devices. Apart from the mere inconvenience of dealing with two separate devices and possible unavailability of BC devices, there are more serious issues with this method. Underlying physics in FB and BC SOI devices are quite different. The body potential of a FB device is defined by a delicate balance of hot carrier diffusion, impact ionization, band-to-band tunneling and recombination processes, as well as gate current, while the BC SOI physics is close to that of bulk MOS. As a result, it is very difficult to match BC and FB SOI characteristics before the extraction. Moreover, in deriving this indirect method many simplifying assumptions have been made [3].

We present here a novel direct method of FB SOI model parameter extraction. Our method does not require BC devices to extract the parameters of FB devices.

2 METHOD

The cornerstone of our approach is the notion that FB and BC SOI devices have fundamentally different underlying physics. For BC devices the extraction strategy is based on just 1 to 3 fitting parameters for some selected characteristics, or even specific part of the curve, while in FB devices the body potential depends on more than 45 model parameters. On the other hand, FB devices have only two degrees of freedom, gate and drain voltages (Vg and Vd), and two output currents, drain and gate current (Id, Ig) versus three degrees of freedom (Vg, Vd, Vb) and three output currents (Id, Ig, Ib) for BC devices, where Vb and Id are body voltage and body current. However, for FB devices the gate current, impact ionization current, gate-induced drain leakage current, diode and BJT currents all have an influence on the value of the body potential, which in turn strongly affects the drain current and its derivative with respect to Vd.

The conventional BC SOI extraction is based on the following idea. The body potential is fixed and known. Therefore, we have to adjust the model parameters to minimize the difference between measured and simulated data, which are almost the same as in the conventional bulk device model. In the case of the FB devices, the situation is much more complicated. The body potential is unknown. In addition to typical drain current model parameters, we have to determine the optimal value of the body potential which yields the best fitting of the drain current. On the other hand, this potential must be a result of balance of the different components of the body current. Considering the body potential equation at a fixed temperature, typically room temperature, the value of the body potential may be adjusted by any component of the body current that results in an ill-posed problem without a solution. To overcome this issue we used the data at different temperatures for the same bias conditions. Because the body current components have different temperature dependencies, and therefore, different temperature coefficients, it allows us to avoid ill-posed problems. In other words, to the two degrees of freedom (Vg and Vd) of FB device, we add the third degree of freedom, which is the temperature, intentionally complicating the extraction task. Therefore, the temperature-related model parameters have the same importance as the temperature-free parameters. This is not the case for the conventional extraction strategies, where the temperature-free parameters are extracted at room temperature first, and then, the temperature-related parameters are determined by fitting the drain current at different temperatures.

The FB device extraction task formulated above can not be solved using direct extraction methods or step-by-step extraction due to the complexity of the problem. Therefore, the only reliable way to extract the model parameters of the FB SOI devices is by applying the nonlinear numerical optimization techniques.

3 OBJECTIVE FUNCTION

Optimal data fitting is the mathematical task of finding the set of model parameters that achieves not only the best fit between the data and corresponding modeling results, but also provides the model which does not violate the laws of physics. The properly chosen objective function has to provide the desired properties of the final parameter set as well as to ensure fast and successful convergence of the optimization algorithm. The standard method is weighted least squares, i.e., the function to be minimized is the sum of the normalized residuals taken with user defined weight. Least squares are widely used in different fields of practical optimization due to their good mathematical properties which are similar to L_2-norm defined for function in L_2-Space. With our focus on the FB SOI extraction we chose the following objective function:

$$F(\vec{P}) = \sum_{Temperatures} \sum_{Devices} \sum_{Curves} W_c \times \left(\frac{Id_{meas} - Id_{sim}(\vec{P})}{Id_{meas}} \right)^2 + W_r \left(\frac{Rout_{meas} - Rout_{sim}(\vec{P})}{Rout_{meas}} \right)^2 + \Psi(\vec{P}) \quad (1)$$

where the first sum is over all temperatures, the second – over all devices, the third – over all curves for each device, Id_{meas} and Id_{sim} are the measured and simulated drain currents, $Rout_{meas}$ and $Rout_{sim}$ are the measured and simulated output resistances of the device, W_c and W_r are the user defined weight of drain current and output resistance for each particular curve, $\vec{P}$ is a vector of unknown model parameters and $\Psi(\vec{P})$ is a penalty function. The first two sums of the objective function (1) are well known and widely used in model parameter extraction, we just pick out the sum over temperature to point out the importance of using different temperatures for FB SOI device extraction. If these two sums measure the fitting accuracy between measured and simulated data, the last term, $\Psi(\vec{P})$ is designed to provide the physical meaning of extracted model parameters, which is one of the wishes of model development engineers. The penalty function approach applied to BSIM3 and BSIM4 model parameter extraction was reported in [4]. The part of the BSIMPD model related to the bulk device physics is based on the BSIM3 model, that allows us to use all the penalties developed for the BSIM3 model, and in addition, we introduce several penalty functions which are specific to partially depleted SOI device physics. We must stress that it is very difficult to keep the model parameter values related to the impact ionization current within a reasonable physical range, because it is a very non-linear function of the drain voltage and it depends on the channel drain current and parasitic BJT current which are functions of almost all model parameters. In this paper we consider only one example of penalty, impact ionization ratio defined in BSIMPD model as (for notation see [5]):

$$Ratio = \alpha_0 \times \exp\left(\frac{V_{diff}}{\beta_2 + \beta_1 V_{diff} + \beta_0 V_{diff}{}^2} \right)$$

The model limits the Ratio value to 10.0, which makes physical sense, and resets all Ratio derivatives with respect to voltages to 0.0, avoiding possible convergence problems of SPICE simulators. When the Ratio value exceeds 10.0, we apply the following penalty function:

$$\Psi(Ratio) = n_{Ratio}\left(Ratio - 10\right)^2, \quad if \quad Ratio > 10$$

where n_{Ratio} is a normalization factor for Ratio, chosen to be large enough to give a high value of penalty and small enough to provide a good convergence of the optimization algorithm. During the optimization process the penalty $\Psi(Ratio)$ plays a dual role. Firstly, it keeps the Ratio value at less than 10.0 which means it indirectly constrains the values of all model parameters related to the Ratio trying to keep them within physical range. Secondly, it improves the convergence of the optimization. As was mentioned above, Ratio is set to 10.0 if it is larger than 10.0. Hence, if the penalty functions are not used, the derivative $\partial F(\vec{P}) / \partial \alpha_0$ becomes zero. This point will be misinterpreted by optimization algorithm as minimum of the objective function and the optimization will fail, because in reality this point may be far away from the true minimum. If the penalty functions are used, the derivative $\partial F(\vec{P}) / \partial \alpha_0 \neq 0$ and has a large value. As a result, the optimization algorithm will be brought back to the feasible range for the parameter α_0 and optimization will continue.

4 RESULTS

The proposed optimization approach based on the objective function (1) has been applied to extract the BSIMPD model parameters of FB partially depleted SOI device with channel length 0.1um and oxide thickness of about 20A. We were using only IdVd curves for gate voltage from 0.0V to 1.5V with a step 0.1V. The data was obtained for five different temperatures: 27, 80, 110, 140 and 170 ºC. The extraction strategy consists of nine optimization steps. A brief description of each step is summarized in Table 1. The "Vd" and "Id" columns show the drain voltage and current ranges of data used at a particular extraction step. Almost for all extraction steps we are using the data at all available temperatures, as it is shown in "Temperature" column. The last two columns represent the number of model parameters optimized during each extraction step and the targets of optimization according to objective function (1).

Applying the presented extraction strategy we were able to achieve very good model accuracy: RMS error of drain current less than 5%, RMS error of Rout less than 15% for all temperatures and all bias conditions. The model accuracy at room temperature is demonstrated in Fig. 1. In order to provide an estimate of the model accuracy for all temperatures and all bias conditions we perform a very simple quality test: number of curves versus RMS error, which is shown in Fig.2. We simply calculate the RMS error of drain current for each curve and summarize the number of curves for each bin of size 1%. Please note that this distribution function does not exhibit the normal/Gaussian distribution because weighted least squares do not ensure the normal distribution of residuals.

As we mentioned above, our goal is not only the model accuracy but also physically meaningful model parameters. We illustrate the behavior of the body voltage and the components of body current, the data which is not available for FB device, in Fig 3, 4 and 5. The body voltage at Vg=0 (Fig.3) where the gate current is small, is defined by balance of the drain and source diode currents at low drain voltage, and at the source diode and impact ionization currents at high drain voltage. At Vg=0.8V (Fig.4) the body voltage is defined by gate and source diode currents at low Vd, and slightly increases at high drain voltage due to impact ionization current. At high gate voltage (Fig.5), the gate current is high and is compensated by source diode current keeping the value of body voltage almost constant. All other components of body current play an insignificant role. We believe that results shown in Fig. 3, 4, and 5 correspond to the real physics of FB SOI device.

5 CONCLUSION

We have presented a novel method for direct extraction of compact model parameters of partially depleted SOI devices. This method is based on the optimization of least squares function with penalties. Unlike other extraction approaches our method does not require body-contact SOI devices. All model parameters including impact ionization current, GIDL current, oxide tunneling current, diode and parasitic BJT current, temperature dependent parameters are extracted from a floating body SOI device.

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№	Vd	Id	Tempe-rature	Number of parameters	Target
1	<0.1V	>1e-9A	27	3	Id
2	<0.3V	>1e-9A	all	17	Id
3	<0.5V	>1e-9A	all	19	Id
4	<1.0V	>1e-9A	all	27	Id, Rout
5	all	>1e-10A	all	44	Id, Rout
6	all	>1e-11A	all	61	Id, Rout
7	all	>1e-11A	all	65	Id, Rout
8	all	>1e-11A	all	69	Id, Rout
9	all	>1e-11A	all	80	Id, Rout

Table 1: Summary of the FB SOI device extraction steps.

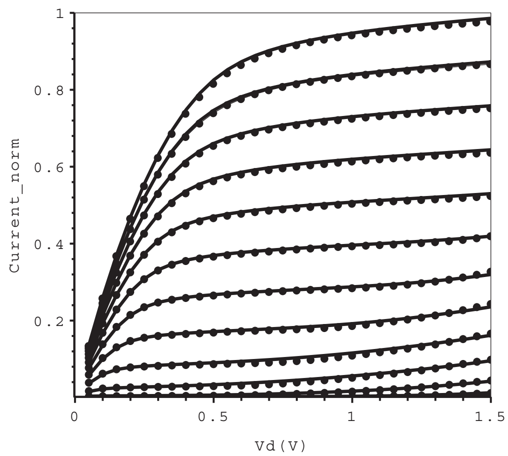

Fig. 1: Normalized drain current vs. drain voltage in linear scale (symbols–data, line–model).

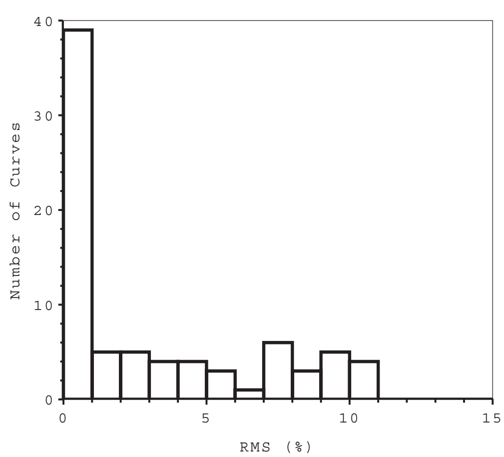

Fig. 2: Error distribution

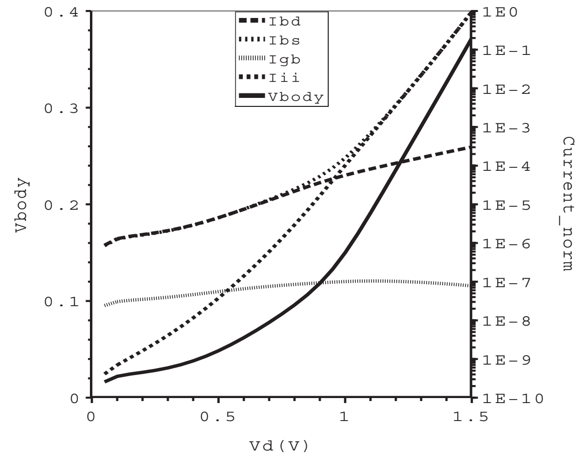

Fig. 3: Body voltage and normalized components of body current at Vg = 0.0 V.

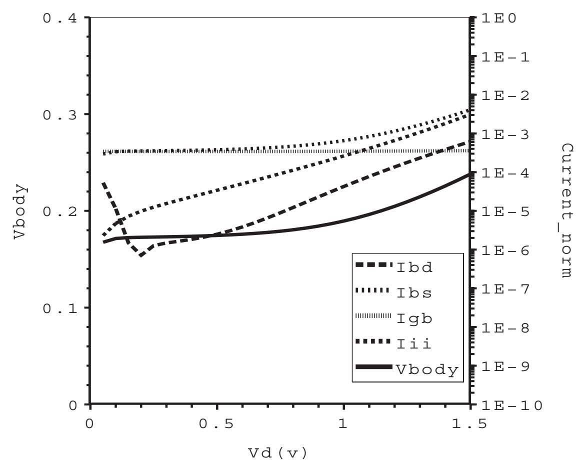

Fig. 4: Body voltage and normalized components of body current at Vg = 0.8 V.

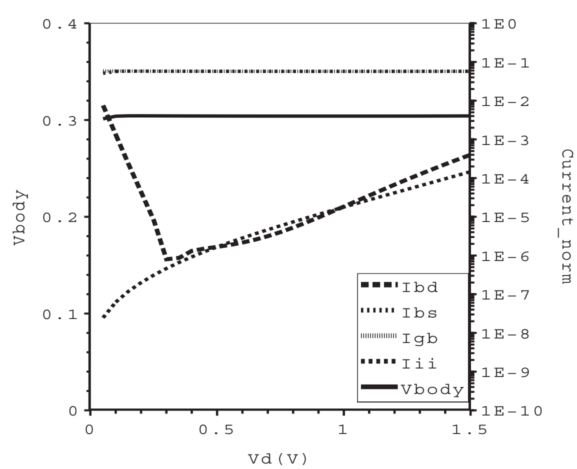

Fig. 5: Body voltage and normalized components of body current at Vg = 1.5 V.