A Model-Adaptable MOSFET Parameter Extraction System

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Abstract--- A model-adaptable parameter extraction system is developed to catch up with rapid development of new advanced MOSFET models. The model-adaptability relies on two techniques; a model-adaptable initial value estimation method and a design environment that stores and reuses extraction procedures. The system makes it easy to develop an extraction procedure for a new MOSFET model through the reuse of an existing procedure for a previous model. We have presently verified that the system can accommodate major SPICE models including Level2-3 and BSIM1-3.

I. Introduction

As the minimum feature size of MOSFETs goes into submicron and further, accurate MOSFET models for reliable circuit simulation becomes more and more important. Many advanced models have been developed for keeping up with the rapid progress of process technologies. The problem here is that the parameters of a new model, especially DC parameters, can not be extracted easily. The parameter extraction is indispensable to characterize the MOSFETs. However, conventional parameter extraction systems are suitable only for particular models since the development of a parameter extraction procedure is highly model-dependent. It is common to devise a dedicated extraction tool for each model, which is a time consuming and knowledge intensive task.

In this paper, we describe a parameter extraction system that is suitable for many MOSFET DC models including newly developed advanced ones. Two techniques are applied to build the system. The first one is a model-adaptable method for accurate estimation of DC model parameters[1]. This method contributes to eliminate the model-dependency of extraction procedures as much as possible. The second one is a design environment that can store and reuse extraction procedures[2]. This system makes it possible to reuse and modify an existing procedure for the development of a new procedure. These features reduce the time and cost for adopting a new MOSFET model. We describe extraction procedures for major SPICE models such as BSIM1-3[3, 4, 5] and Meta-MOS(Level28 in HSPICE)[6], and present the result of parameter extraction experiments.

II. Techniques for model-adaptability

In this section, two key techniques which are contributed to the model-adaptability of the parameter extraction system are described. They are a model-adaptable parameter value estimation method using a common intermediate model and a design system that stores and reuses extraction procedures.

A. Model-adaptable parameter value estimation method

A parameter extraction procedure usually relies on a numerical optimization technique. It consists of initial value estimation and curve fitting with a non-linear optimization algorithm. The optimization algorithm is model-independent and applicable to any MOSFET models. The initial value estimation procedure, however, is highly model-dependent. Hence, a dedicated extraction tool should be devised for each model one by one with a lot of effort and time.

We have proposed an initial value estimation method which is easily applicable to many MOSFET models including newly developed advanced models[1]. This method provides a framework for MOSFET parameter extraction that eliminates model-dependency as much as possible. The processing flow of the initial value estimation is summarized in Fig. 1. A key idea of the method is the decomposition of the process into two consecutive processes with the use of a common and simple intermediate model. The first process is the extraction of intermediate model parameters from measured I-V characteristics. This process is model-independent. The second process is the transformation from the intermediate model parameters into target model parameters. Although this process is model-dependent, it has been shown that a proper intermediate model has an ability to eliminate most of the model-dependency. Given a new MOSFET model, the only task a designer has to do is to derive a procedure for the parameter transformation which may be slightly different from procedures for other models.

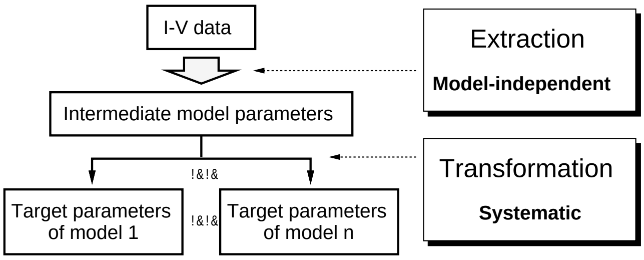

Fig. 1. : Processing flow for model-adaptable initial value estimation.

An intermediate model is shown below[1].

$$\begin{cases} \text{linear region :} \\ \quad I_{DS} = \beta \cdot \dfrac{\left(V_{GS} - Vth - \frac{1}{2}V_{DS}\right) V_{DS}}{1 + \theta (V_{GS} - Vth)} \\ \text{saturation region :} \\ \quad \text{not considered} \\ \text{subthreshold region :} \\ \quad I_{DS} = const \cdot exp\left(\dfrac{V_{GS} - Vth}{N}\right) \end{cases} . \quad (1)$$

It has four key parameters; threshold voltage Vth, gain β, mobility degradation θ, and subthreshold gate swing N. These parameters are functions of V_{BS}. They are analytically extracted by

$$\begin{cases} Vth = b - \frac{1}{2}V_{DS} \\ \beta = \dfrac{a}{\left(b - c - \frac{1}{2}V_{DS}\right) V_{DS}} \\ \theta = \dfrac{1}{b - c - \frac{1}{2}V_{DS}} \\ N = \left[\dfrac{d\,(lnI_{DS})}{dV_{GS}}\right]^{-1} \quad \text{(in subthreshold region)} \end{cases} \quad (2)$$

where a, b and c are calculated from three sets of measured (V_{GS}, I_{DS}) values with a fixed small V_{DS} and V_{BS} according to the equations shown in [7].

We can exploit the dependency of the intermediate model parameters on V_{BS} to transform them into target model parameters. Most models have similar structures for every intermediate model parameters as

$$P_i\,(V_{BS}) = \sum_{j}^{n_i} \left[p_{ij} \cdot f_{ij}\,(V_{BS})\right] + fh_i\,(V_{BS}). \quad (3)$$

P_i represents an intermediate model parameter, and it is a function of V_{BS}. The term p_{ij} is a target model parameter. Both f_{ij} and fh_i are functions of V_{BS} and known model parameters, which are derived directly from equations of the target model. As an example, we describe a method to transform V_{th} into target model parameters of BSIM1 model. The BSIM1 model calculates the V_{th} according to

$$Vth = V_{FB} + \phi_S + K_1\sqrt{\phi_S - V_{BS}} - K_2\,(\phi_S - V_{BS}) - \eta \cdot V_{DS}. \quad (4)$$

Target model parameters in this case are V_{FB}, K_1, and K_2. Parameter ϕ_S is a known process parameter which represents surface-inversion potential. The effect of η is negligible under small V_{DS}. Then, the following equations are derived for three different V_{BS} values.

$$\begin{cases} Vth_1 = V_{FB} + K_1\sqrt{\phi_S - V_{BS_1}} - K_2\left(\phi_S - V_{BS_1}\right) + \phi_S \\ Vth_2 = V_{FB} + K_1\sqrt{\phi_S - V_{BS_2}} - K_2\left(\phi_S - V_{BS_2}\right) + \phi_S \\ Vth_3 = V_{FB} + K_1\sqrt{\phi_S - V_{BS_3}} - K_2\left(\phi_S - V_{BS_3}\right) + \phi_S \end{cases} \quad (5)$$

If Vth_i is extracted under each V_{BS}, we can solve above simultaneous equations for V_{FB}, K_1, and K_2.

Many conventional parameter extraction tools also extract certain physical model parameters from measured I-V characteristics. A main advantage to use the intermediate model is that more parameters can be calculated accurately and systematically than the conventional tools.

B. System that stores and reuses extraction procedures

The initial value estimation method makes parameter extraction procedures systematic and less model-dependent. If the procedure is described in a simple manner, we can easily develop an extraction procedure for a new model through the reuse and modification of existing procedures for other models. This feature improves model-adaptability of the extraction system.

We can use GUIDE interactive design environment[2] to build a model-adaptable parameter extraction system. The GUIDE system stores and reuses design procedures operated by a designer. An design procedure is described by an Interactive Design Language(IDL) in a step-by-step manner, and stored in a script file. The stored design procedure is ready to reuse and modify if necessary.

III. Parameter extraction system

In this section, our parameter extraction system is presented. Extraction procedures for SPICE models and their re-usabilities are also discussed.

A. System overview

We have integrated a parameter extraction system using GUIDE design environment described in *2.2*. Fig. 2 shows the structure of the parameter extraction system. IDL was originally developed for LSI circuit and layout design[2]. We have extended the IDL for describing a parameter extraction procedure; from I-V measurement to final curve fitting. We have added new commands for initial value estimation and for controlling measuring instruments through the GP-IB interface.

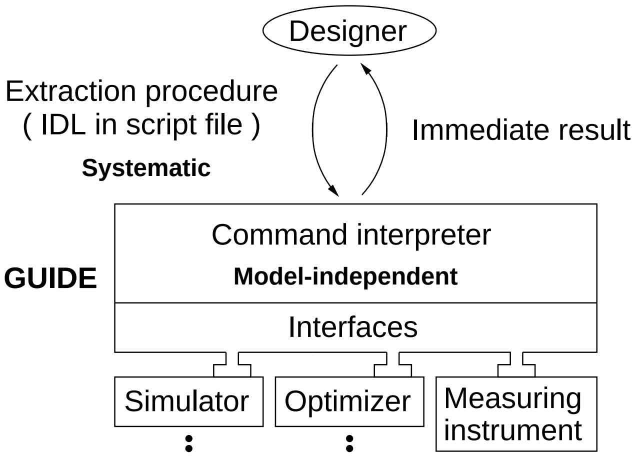

Fig. 2. : Parameter extraction system on GUIDE.

```
# Extraction procedure for BSIM1(Level13) model #
• • •                                         ............ Measurement etc.
extract_intModel( vgid | vth, beta, theta, n )

# Transformation from Vth
a11 = 1                                   \
a12 = sqrt( m1:phi0 - vbs1 )               |  Equation at VBS = vbs1
a13 = vbs1 - m1:phi0                       |
b1 = vth1 - m1:phi0                       /
• • •                                         ............ Equation at VBS = vbs2
• • •                                         ............ Equation at VBS = vbs3
transform_tarModel( a, b | m1:vfb0, m1:k1, m1: k2 )
• • •                                         ............ Transformation from &B, &H, #N

# Final curve fitting
optimizer( "npsol" )
optimize( "bsim1.opt" )
```

Fig. 3. : IDL description for BSIM1 extraction.

The intermediate model parameters are extracted by a specific command which solves (2). This process is common for all models. Then, each intermediate model parameter is systematically transformed into target model parameters through simultaneous linear equations based on (3). The procedure for the parameter transformation, therefore, is easily described in a step-by-step manner by the extended IDL. The procedure consists of two sections; the calculation of coefficients f_{ij} and fh_i, and a command to solve the simultaneous equations. The curve fitting procedure is also described by the IDL.

In our system, a parameter extraction procedure is completely described by the IDL and stored in a script file. The stored extraction procedure can be reused or modified easily to accommodate a new model into the system.

B. Extraction procedures for SPICE models

We have developed parameter extraction procedures for major SPICE models. Fig. 3 shows a part of IDL description to extract BSIM1 model parameters. The extract_intModel() command at the first line executes the extraction of intermediate model parameters from measured data. Calculation of coefficients to transform the intermediate model parameter Vth follows. Then, the transform_tarModel() command solves (5) using the calculated coefficients. Other target model parameters are similarly transformed from β, θ, and N. Finally, curve fitting is carried out through the optimize() command.

Extraction procedures for other SPICE models are also described using IDL. They are the same except for parameter names and several IDL lines for the parameter transformation. Table I explains re-usability of the transformation procedures. We define the re-usability as a ratio of the number of target model parameters that can be transformed by identical IDL description. For example, the procedure for the Level3 model is developed by the reuse of the one for the Level2 model. Four out of six target model parameters of the Level3 model can be calculated by the same transformation procedure for the Level2 model. We can also easily reuse and modify a stored procedure for the BSIM1 model to develop those for new models such as BSIM2,3 and Meta-MOS(Level28 in HSPICE).

TABLE I. : Re-usability of parameter transformation procedures

from ↓ to	Level2 ↓ Level3	BSIM1 ↓ BSIM2	BSIM1 ↓ Meta-MOS	BSIM1 ↓ BSIM3
Re-usability	$\frac{4}{6}$	$\frac{7}{11}$	$\frac{7}{9}$	$\frac{5}{10}$

$$\text{Re-usability} = \frac{\#\text{reusable parameters}}{\#\text{target parameters}}$$

IV. Experiments

First, we show the result of parameter extraction of an n-channel MOSFET with 0.6μm channel length. The target models in this case are BSIM1-3, and Meta-MOS. Table II summarizes the number of all target model parameters whose initial values can be derived according to the method shown in **2** with the total number of optimized parameters. The initial values of parameters that are not derived by the method in **2** are determined randomly within their possible ranges and 50 sets of initial parameter values are prepared for each model. Table III shows the distribution of rms-errors of I_{DS}-V_{DS} characteristics after optimization. We also show the average computation time for optimization in Table IV, which is measured on SPARCstation 10. In all trials we have reached to satisfactory solutions within practical caomputation time. The largest rms-errors of all trials is about 1.5% which occurred

TABLE II. : The number of target parameters and optimized parameters

	BSIM1	BSIM2	Meta-MOS	BSIM3
#target parameters	11	11	9	10
#optimized parameters	16	25	18	27

TABLE III. : Distribution of final I_{DS}-V_{DS} rms-errors (%) on an n-channel MOSFET(L=0.6μm)

	BSIM1	BSIM2	Meta-MOS	BSIM3
Ave.	1.44	0.81	1.04	1.26
Min	1.38	0.61	1.00	1.21
Max	1.47	0.88	1.06	1.38

for the BSIM1 model. The measured and simulated I_{DS}-V_{DS} data of this case are compared in Figure 4. Furthermore, the G_{DS}-V_{DS} data of the case are compared in Figure 5. Although we have not considered the G_{DS}-V_{DS} data during the optimization, we can see that good agreement is achieved even in the worst case.

Then, we have compared the results shown in Table III with those with conventional initial value estimation methods. The conventional methods considered are as follows.

method(1) All of initial parameter values are determined randomly within their possible ranges.

method(2) The V_{th} and β related parameters are calculated from measured I-V characteristics[8] and other parameters are determined randomly.

We have optimized parameters of the BSIM1-3 and Meta-MOS models from 50 sets of initial parameter values generated by these methods. Table V shows the probability of final rms-errors being less than 1.5%. The proposed method succeeds to obtain satisfactory results in all cases, while the conventional methods fail in many case.

TABLE IV. : Average computation time for optimization with SS10

	BSIM1	BSIM2	Meta-MOS	BSIM3
cpu-time	44.8s	85.9s	38.9s	90.3s

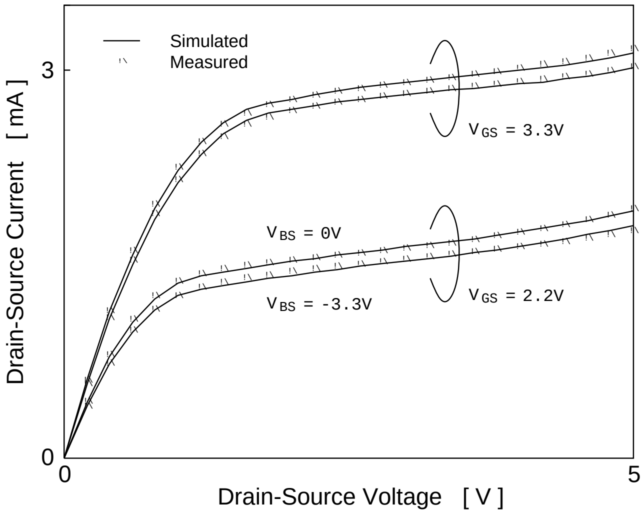

Fig. 4. : Comparison between measured and simulated I_{DS}-V_{DS} characteristics after optimization. This is the worst case out of 200 trials.

TABLE V. : The probability of final rms-errors being less than 1.5%

	BSIM1	BSIM2	Meta-MOS	BSIM3
proposed	100%	100%	100%	100%
method(1)	2%	8%	20%	6%
method(2)	0%	2%	8%	0%

V. Conclusions

We have presented a parameter extraction system which is suitable for many MOSFET models. The system is based on a model-adaptable initial value estimation method. We have implemented it in a GUIDE design system that stores and reuses extraction procedures. The extraction procedures are described by extended IDL. The stored procedures can be reused for the extraction of a new model. The re-usability on major SPICE models is experimentally shown. Also, the performance of the system is demonstrated.

Currently the system is targeted for the extraction of DC model parameters. Our future work includes the development of extraction capability for AC parameters.

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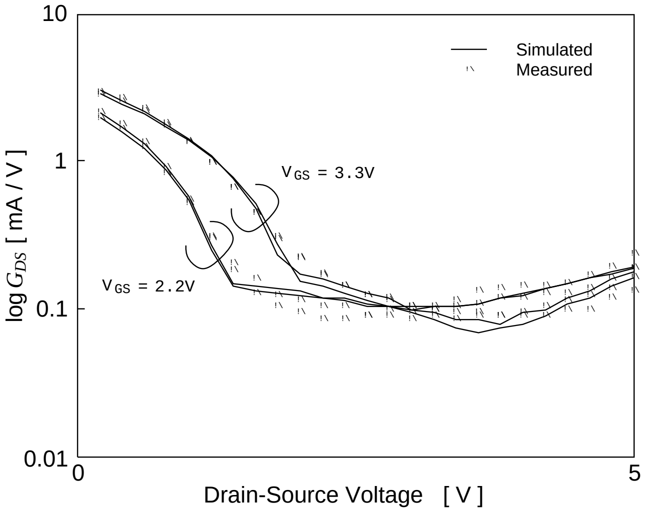

Fig. 5. : Comparison between measured and simulated G_{DS}-V_{DS} characteristics of the worst case.

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