**ROMANIAN JOURNAL OF INFORMATION
SCIENCE AND TECHNOLOGY**
Volume **10**, Number 2, 2007, 189–197

MOSFET Model with Simple Extraction Procedures, Suitable for Sensitive Analog Simulations

S. EFTIMIE[1], ALEX. RUSU[2], A. RUSU[2]

[1]Catalyst Semiconductor, Bucharest, Romania
E-mail: `sabin.eftimie@catsemi.ro`
[2]University "Politehnica", Bucharest, Romania

Abstract. In MOS modeling, the region between subtreshold and strong inversion, called moderate inversion region, has received little attention. Conventional models like BSIM or EKV use mathematical smoothing functions to model the moderate inversion. As the supply voltages are scaled down, this region becomes an increasingly larger fraction in the overall operation bias of MOSFETs. Because of this, the smoothing functions for moderate inversion increased in complexity and in number of parameters. The surface potential based models solve this problem by increasing the physical content of the model, thus using a small number of parameters. This paper proposes to present one such model and the extraction procedures for its parameters.

1. Introduction

Surface potential based models have been avoided for a long time because of the resources needed to calculate the drain current as function of biasing voltages. The time needed to calculate the surface potential is long because it can only be calculated iteratively. Classical models are based on threshold voltage, which is a conventional term, with no physical correspondent. They offer arithmetical approximations of the drain current using a lot of fitting parameters, with no physical meaning. This is why the development of IT technology made the interest in surface potential based models to increase. Surface potential is a physical value and has direct influence on the drain current. The models that are taking advantage of this can model the drain current precisely with a small number of parameters.

One such surface potential based model is in development at the University "Politehnica" Bucharest, in collaboration with Catalyst Semiconductor. This model, in its present form, proposes for the drain current an expression with only 4 parameters: impurity concentration in bulk (N_A), flat band voltage (V_{FB}), gain factor (β_0), and the coefficient of mobility reduction due to the gate electrical field (θ_G). Each parameter is describing a physical value or a physical effect. These 4 parameters allow a good modeling for the drain current of a long and wide MOSFET, in all regions of inversion, for small V_{DS}. This means that this is a base model, at which can be added in the future the other physical effects: saturation, short/narrow channel effects, bulk bias effects, etc. In order to verify this base model, an extraction procedure had to be implemented for its parameters. Because of the small number of parameters, the extraction process takes little time, comparing with other, more complex models, which can take several days.

2. Model description

The proposed model starts from the fact that the drain current has two components: diffusion current and drift current [1]

$$I_D = I_{D,\text{diff}} + I_{D,\text{drift}}. \tag{1}$$

The ratio of diffusion current in the drain current, r_d is defined as:

$$r_d = \frac{I_{D,\text{diff}}}{I_{D,\text{diff}} + I_{D,\text{drift}}}. \tag{2}$$

The expression for diffusion current is:

$$I_{D,\text{diff}} = \frac{\varphi_t}{R_{CH0}} \left(1 - \frac{Q_{IS}}{Q_{ID}} \right), \tag{3}$$

where R_{CH0} is the channel resistance when $V_{DS} \to 0$ and Q_{IS} and Q_{ID} are the inversion charges at the source and drain ends of the channel [2]. Their expressions are:

$$R_{CH0} = \frac{C_{ox} \left(1 + \theta_G \left|Q_{IS}\right|\right)}{\beta_0 \left|Q_{IS}\right|}. \tag{4}$$

The parameter β_0 in equation (4) incorporates a number of physical parameters:

$$\beta_0 = \frac{W}{L} \mu_0 C_{ox}, \tag{5}$$

where W and L are transistor's width and length, μ_0 is the channel's carrier mobility for zero electrical field and C$_{ox}$ is the gate's capacitance.

$$Q_{IS} = -\sqrt{2\varepsilon_s q N_A} \left(\sqrt{\varphi_{sS} + \varphi_t \exp\left(\frac{\varphi_{sS} - 2\varphi_F}{\varphi_t} \right)} - \sqrt{\varphi_{sS}} \right) \tag{6}$$

$$Q_{ID} = -\sqrt{2\varepsilon_s q N_A}\left(\sqrt{\varphi_{sD} + \varphi_t \exp\left(\frac{\varphi_{sD} - 2\varphi_F - V_{DS}}{\varphi_t}\right)} - \sqrt{\varphi_{sD}}\right) \tag{7}$$

Q_{IS} and Q_{ID} are dependent on the surface potential at the respective channel end: φ_{sS} is the source surface potential and φ_{sD} is the drain end surface potential. As it can be seen, besides the constants ε_s, C_{ox}, q and φ_F, which is N_A dependent, all three functions, R_{CH0}, Q_{IS} and Q_{ID}, have as parameters β_0, θ_G and N_A.

The drain current can be expressed as:

$$I_D = \frac{1}{r_d} \cdot I_{D,\mathrm{diff}} = \frac{1}{r_d} \cdot \frac{\varphi_t}{R_{CH0}}\left(1 - \frac{Q_{IS}}{Q_{ID}}\right). \tag{8}$$

The diffusion current ratio, r_d, is dependent only of the surface potential at the ends of the channel and V_{DS}:

$$r_d = 1 - \frac{\varphi_{sD} - \varphi_{sS}}{V_{DS}}. \tag{9}$$

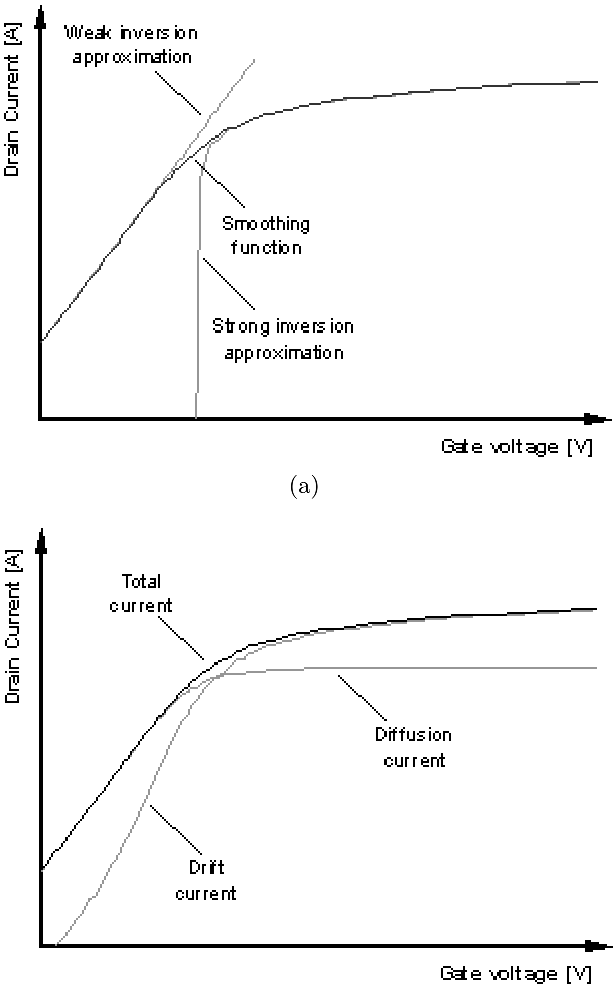
In conclusion, the drain current in present model has 3 parameters: β_0, θ_G and N_A. The drain current is not directly dependent on V_{DS} and V_{GS}, but through the surface potential at the ends of the channel. The fourth parameter of this model, V_{FB} is used only in calculating the surface potential at the ends of the channel as a dependence of bias voltages:

$$V_{GS} = V_{FB} + \varphi_s + \gamma\sqrt{\varphi_s + \varphi_t \exp\left(\frac{\varphi_s - 2\varphi_F - V_J}{\varphi_t}\right)}, \tag{10}$$

where V_J is the junction voltage. This equation is solved iteratively. For calculating the surface potential at the source end, φ_{sS}, V_J is considered 0 and for the drain end, φ_{sD}, $V_J = V_{DS}$.

Figure 1 shows the difference in calculating the drain current between the proposed model and a V_T based model with smoothing function for moderate inversion region. For the latter, a simple example was chosen (see Fig. 1 (a)). The smoothing function unifies the strong inversion and weak inversion approximations. The approximation functions are generally computed by fitting the curves on the measurements in the corresponding limited domain. This is done through a large number of fitting parameters, which, in general, have a mathematical meaning with no physical correspondent. Because the smoothing function has to cover the region that the approximation functions don't, the errors in this region are significant, because this function is purely mathematical, with no physical meaning.

As for the proposed model (Fig. 1(b)), the drain current is a sum of 2 physical components, diffusion current, $I_{D,\mathrm{diff}}$ and drift current, $I_{D,\mathrm{drift}}$. These 2 components are described on the entire V_{GS} domain. There is no approximation of the drain current and the curves are not obtained using fitting parameters.



(a)

(b)

Fig. 1. Drain current modeled by (a) smoothing function between weak inversion and strong inversion approximations; (b) proposed model, by summing the diffusion and drift components [3].

3. Extraction algorithms

The 4 parameters of the present model can be placed in two categories:

a) weak inversion parameters, that have greater influence for drain current in weak and moderate inversion, such as N_A and V_{FB}, and

b) strong inversion parameters, such as β_0 and θ_G.

In the extraction algorithms, for the ratio between Q_{IS} and Q_{ID}, the approximation

$$\frac{Q_{IS}}{Q_{ID}} = \exp\left(-\frac{r_d V_{DS}}{\varphi_t}\right) \tag{11}$$

will be used [1].

a) ***Weak inversion parameters.*** As it can be seen in Fig. 1(b), the diffusion current is preponderant in weak inversion, so r_d is very close to 1 [3]. The expression of the drain current in weak inversion becomes, taking into account approximation (11):

$$I_D = \frac{\varphi_t}{R_{CH0}}\left[1 - \exp\left(-\frac{V_{DS}}{\varphi_t}\right)\right]. \tag{12}$$

The slope of $\ln I_D(V_{GS})$ curve is:

$$m = \frac{\partial \ln(I_D)}{\partial V_{GS}} = \frac{\partial \ln(I_D)}{\partial \varphi_s} \cdot \frac{\partial \varphi_s}{\partial V_{GS}} = \frac{\partial \ln\left(\frac{1}{R_{CH0}}\right)}{\partial \varphi_s} \cdot \frac{\partial \varphi_s}{\partial V_{GS}}. \tag{13}$$

It can be demonstrated, leaving from this expression, that m (at a given V_{GS} in weak inversion) is dependent only on the Fermi potential, φ_F, and the surface potential corresponding to that V_{GS}, φ_s (φ_t is constant for a given temperature):

$$m = \frac{\dfrac{1+\exp(\varphi_s - 2\varphi_F/\varphi_t)}{2\sqrt{\varphi_s - \varphi_t + \varphi_t \exp(\varphi_s - 2\varphi_F/\varphi_t)}} - \dfrac{1}{2\sqrt{\varphi_s - \varphi_t}}}{\sqrt{\varphi_s - \varphi_t + \varphi_t \exp(\varphi_s - 2\varphi_F/\varphi_t)} - \sqrt{\varphi_s - \varphi_t}}. \tag{14}$$

So, if m is known, its expression is an equation with 2 unknown variables: φ_s and φ_F. It can be calculated only iteratively if one of the two variables is known.

The extraction algorithm for N_A and V_{FB} has the next steps:

1. Choose an $[I_D, V_{GS}]$ point in weak inversion region from the measured logarithmic curve and calculate the slope m in that point.
2. Calculate φ_F from equation (14), considering $\varphi_s = \mathrm{n}\varphi_F$, where n is chosen in the range from 1 to 2 (it is known that the surface potential in weak inversion is varying between φ_F and $2\varphi_F$).
3. Calculate N_A from equation

$$\varphi_F = \frac{kT}{q} \ln \frac{N_A}{n_i}, \tag{15}$$

and the substrate factor,

$$\gamma = \frac{\sqrt{2\varepsilon_s q N_A}}{C_{ox}}, \tag{16}$$

C_{ox} is usually known from the fab.

4. Calculate V_{FB} from equation (10) for V_{GS} and φ_s chosen and calculated, respectively, at first 2 steps.

b) *Strong inversion parameters.* The expression (8) of the drain current in strong inversion can be approximated as:

$$I_D = \frac{V_{DS}}{R_{CH0}} \Leftrightarrow \frac{V_{DS}}{I_D} = R_{CH0}, \tag{17}$$

but R_{CH0} is also

$$R_{CH0} = \frac{1 + \theta_G Q_{IS}}{\beta_0} \cdot \frac{1}{Q_{IS}} = \frac{1}{\beta_0} \cdot \frac{1}{Q_{IS}} + \frac{\theta_G}{\beta_0}. \tag{18}$$

So, the curve $V_{DS}/I_D(1/Q_{IS})$ is linear, with the slope $1/\beta_0$ and the origin θ_G/β_0 [1] (see Fig. 2).

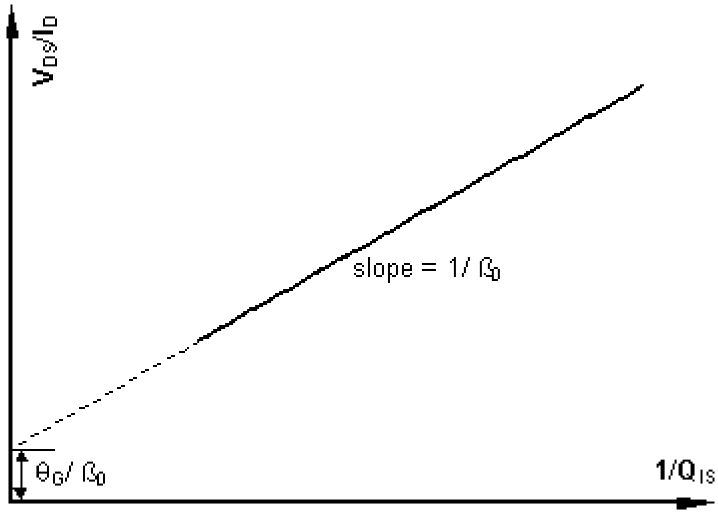


Fig. 2. Extracting strong inversion parameters from $V_{DS}/I_D(1/Q_{IS})$ curve.

The extraction algorithm for the strong inversion parameters, β_0 and θ_G, has the next steps:

1. Choose a deep strong inversion domain on the $I_D(V_{GS})$ measured curve (high V_{GS});
2. Calculate the corresponding V_{DS}/I_D and $1/Q_{IS}$ for every [I_D, V_{GS}] point in that domain. V_{DS} is the drain to source voltage used in measurements (which has to be smaller than 100 mV). Q_{IS} can be calculated using the N_A and V_{FB} values determined with the previous algorithm;
3. Calculate β_0 and θ_G from the slope and origin of the $V_{DS}/I_D(1/Q_{IS})$ curve.

At point a), an arbitrary value was considered for the surface potential, $\varphi_s = \text{n}\varphi_F$, where n is somewhere between 1 and 2. Figure 3 shows the extraction results using different values for n, by comparing the model $I_D(V_{GS})$ curves with the measured one. It can be seen that for different n values, the variation of the drain current in weak inversion is large, while in strong inversion is much smaller. This means that for any n value between 1 and 2, the strong inversion parameters, β_0 and θ_G will not change much. Taking advantage of this, a fitting algorithm can be developed to determine n:

1. Choose a point $[I_D,\ V_{GS}]$ in weak inversion and an arbitrary value between 1 and 2 for n.
2. Extract N_A, V_{FB}, β_0 and θ_G with the algorithms previously described.
3. Calculate I_D for V_{GS} chosen at point 1, using the model with extracted parameters. If I_D(model)$<$ I_D(measured), then choose another n value, higher than the previous one. If I_D(model)$>$ I_D(measured), then choose a smaller value for n (see Fig. 3). Repeat steps 1, 2, 3 until I_D(model) is close enough to I_D(measured).

This fitting algorithm is not much time consuming, because it can reach to less than 0.5% error between model and measurements in about 10 steps. Considering that one step takes about 0.3–0.4 seconds on a medium equipped computer, the entire extraction procedure takes less than 5 seconds for all 4 parameters.

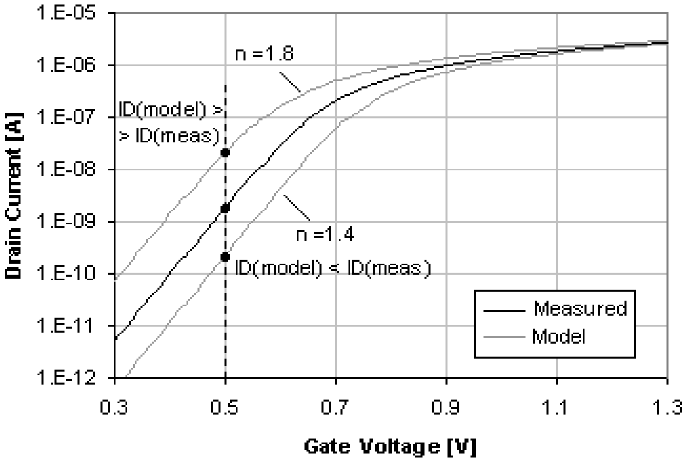
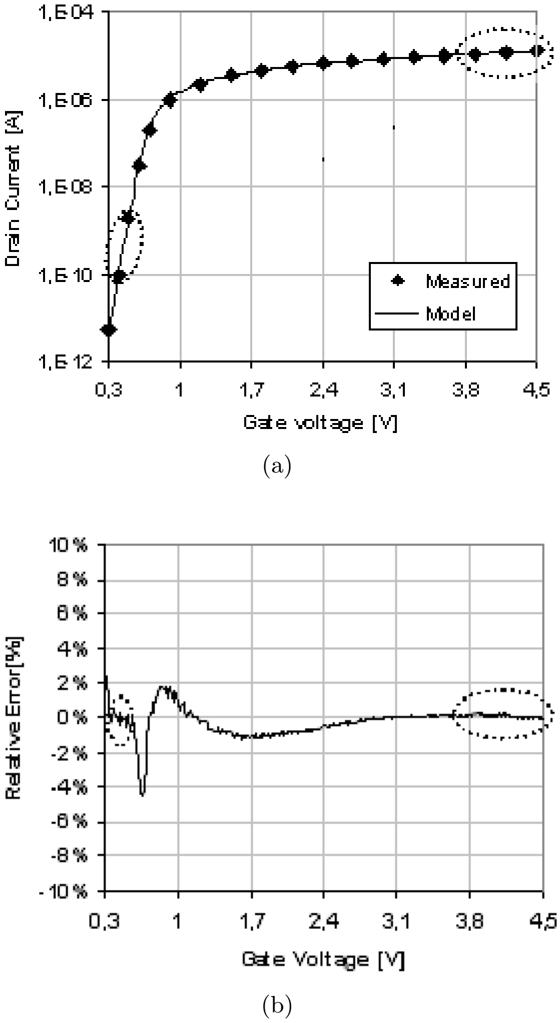


Fig. 3. Model *versus* measurements. Modeled current is calculated using parameters extracted with different values for n.

4. Results

The model, in the present form, does not include the short/narrow channel effects, V_{DS} related parasitic effects and bulk bias effects. This is why it can be considered a base model from which a complete model can be developed by just adding the desired effects.

The parameters were extracted from $I_D - V_{GS}$ curves measured at room temperature on a long and wide MOSFET with $W = L = 25$ μm, at low V_{DS} (70 mV) and $V_{BS} = 0$. The values extracted for parameters were: $N_A = 3.54\text{e}{+}21$; $\mathrm{V}_{FB} = -0.895$; $\beta_0 = 1.02\text{e-}4$ and $\theta_G = 8.48\text{e-}2$.



(a)

(b)

Fig. 4. Model *vs.* Measurements: (a) Drain current as a function of V_{GS} for $V_{DS} = 70$ mV; (b) Relative error.

Although limited data were used (marked in Fig. 4) to extract the parameters, a good agreement can be seen between the model and the measured drain current (see

Fig. 4(a)). A better view on the precision of the model is offered in Fig. 4(b), by the relative error of the model. Here, the marked regions correspond to the data used in the extraction process. The relative error is less than 0.5% in these regions and less than 5% in all regions of inversion. The performance is achieved through the model itself, which allows the good modeling of the drain current with only 4 parameters even in moderate inversion, combined with precise extraction algorithms adapted to obtain the best performance for the proposed model. This is realized by using in the extraction process very close approximations of the model itself.

5. Conclusions

The present model describes with a good precision the drain current using only 4 physical parameters. The model itself has no fitting parameters (only in the extraction procedure one is used). Because of this, the extraction process takes a couple of seconds, while in the case of other models it can take several hours or even days due to the large number of fitting parameters used. This promises to be a good base for a precise MOSFET model, with simple and fast extraction procedures. The only drawback is the computing time of the model itself, because the surface potential can be calculated only iteratively. This is common to the surface potential based models, but a slower and more precise simulation is sometimes preferred to a faster and less precise one, especially in sensitive analog circuits.

References

[1] RUSU A., *Non-Linear Electrical Conduction in Semiconductors* (in Romanian), Romanian Academy Press, 2000.

[2] RUSU A., IONESCU A., EFTIMIE S., *Private Communication.*

[3] EFTIMIE S., RUSU ALEX., *The Influence of Diffusion Current on the Zero-TC Point of a MOS Transistor*, *Proceedings of International Semiconductor Conference*, Sinaia, Romania, 2005, vol. **2**, pp. 401–404.

[4] BARSAN R. M., *Physics and Technology of Large Scale Integrated MOS Circuits* (in Romanian), Romanian Academy Press, 1989.