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# STATIC MODEL OF POWER SILICON MOSFET

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**Abstract.** This paper introduces a model of high-voltage long-channel MOS field-effect transistor. The new compact model is produced from a one-dimensional Shockley model of a MOSFET by introducing the dependence of the mobility of charge carriers on the electric field of the gate. Extensions are made for improved modeling of high-voltage MOSFETs, and one new parameter is introduced to correct the unsaturated region of the known model. The current in the saturated mode of the proposed model is obtained by non-linear extrapolation of the transistor current in the unsaturated mode by Padé approximant so that the current is maintained continuous along with its two first derivatives. The model has only four parameters, which are determined by the experimental current-voltage characteristics by the least squares method. The results of an experimental verification of the modeling accuracy of several high-power *n* and *p*-channel MOSFETs are presented.

**Keywords**: $C_2$-continuity, characterization, compact model, least squares, power MOSFET.

## Introduction

Implementing a compact device model into a circuit simulator takes on average one to two years for a new device model to become available to circuit designers in a commercial circuit simulator [1]. This sets a big barrier between model developers and circuit designers; on one hand, a lot of new models are created each year but only a small portion of them are implemented, while on the other hand, the need of using new models is increasing due to technological advances.

Difficulties of implementing new model in circuit simulation depend on a parameter-extraction procedure. This procedure relies on a numerical optimization technique that consists of two parts: initial estimation of model parameters and curve fitting with a nonlinear optimization method [2].

MOSFET's models with opened code, such as BSIM, implement an optimization separately for saturation and nonsaturation regions of *I*–*V* curves. So, they cannot get the minimum RMS error. Numerous new models, such as [3], use initial estimation of model parameters only, hence cannot get the minimum RMS error too.

Traditionally, sophisticated subcircuits have been used to duplicate the behavior of a power MOSFET [4, 5]. Obviously, the problems of accurately determining their parameters are exacerbated.

An ideal compact model should be $C_\infty$-continuous (a function is $C_n$-continuous if the function and its first *n* derivatives are continuous) [6]. In practice, the $C_1$-continuous model during transient analysis generates a small digital noise, which can be eliminated by reducing the *RELTOL* option. Fatal errors occur only when using the $C_0$-continuous model [7]. It would be logical to assume that the $C_2$-continuous model is relevant for the analysis of digital circuits, and in some cases for analog ones. The industry-standard BSIM-BULK MOSFET model uses Hermitian interpolation by the polynomial of the seventh order, to wit, is $C_3$-continuous [8].

When developing a power MOSFET's model, we place emphases on the physics of the simulated device and on the practicality of obtaining a complete and robust model for circuit simulator that allows its parameters to be measured most simply and reliably. The proposed $C_2$-continuous model is based on the well-known MOSFET model for the unsaturated regime and nonlinear extrapolation to the saturated region of the *I*–*V* characteristic.

## 1. Structure of the $C_2$-continuous model

The regional model of MOSFET has the form

$$I = \begin{cases} 0, & V_{GS} < V_{TH} \\ I_1, V_{DS} < V_{SAT} \\ I_2, V_{DS} \ge V_{SAT} \end{cases} \tag{1}$$

where $I$ is a drain current; $V_{GS}$ and $V_{DS}$ are gate-source, drain-source voltage, respectively. $V_{TH}$ denotes a threshold voltage. $V_{SAT}$ is a drain saturation voltage. For long channel MOSFET, in most models $V_{SAT}$ is equal to the cutoff voltage $V_{SAT} = V_{GS} - V_{TH}$, that depends on the threshold voltage $V_{TH}$.

The channel current of MOSFET in gradual channel approximation is delivered by

$$I = W\mu C_0 \left[V_{GS} - V_{TH} - V(y)\right] \frac{dV(y)}{dy} \tag{2}$$

where $W$ is a width of a channel; $\mu$ is a charge carriers' mobility; $C_0$ is a channel-gate capacitance per unit area. $V(y)$ denotes to a channel-substrate voltage at distant $y$ from source, at that the capacitance of the channel-substrate is assumed much less than $C_0$.

The mobility of charge carriers in a strong transverse electric field generally decreases. This degradation is technology dependent and can be approximated in one-dimensional model of transistor as

$$\mu = \frac{\mu_0}{1 + \left[V_{GS} - V_{TH} - V(y)\right] / V_K} \tag{3}$$

where $\mu_0$ is a mobility in week electric field; $V_K$ is an empirical constant. Given that $0 \le y \le L$, and $0 \le V(y) \le V_{DS}$, it follows from (2) and (3)

$$I_1 = \beta V_K \left[ V_{DS} - V_K \ln\left( \frac{V_K + V_{GS} - V_{TH}}{V_K + V_{GS} - V_{TH} - V_{DS}} \right) \right] \tag{4}$$

were $\beta = \mu_0 W C_0 / L$ is an intrinsic transconductance parameter; $L$ is a length of a channel

[9] .

In gradual channel approximation, it is assumed that:

$$dE_y/dy << dE_x/dx$$

where $dE_y/dy$ is the divergence of the electric field along the channel, while $dE_x/dx$ is the rate of change of the gate field in the channel normal to the surface [6]. With increasing voltage at the drain, this condition is violated, therefore, equations (2) and (4) are valid only when the $V_{DS}$ is less than the cutoff voltage. Hereafter we will assume $V_{SAT} = K_S(V_{GS} - V_{TH})$ , where $K_S$ is an empirical constant $(0 < K_S < 1)$.

In saturation mode, the transistor current monotonously and slowly grows. In the simplest case, the dependence $I_2(V_{DS})$ can be represented in the form

$$I_2 = (V_{GS}, V_{SAT})\frac{1 + a_1(V_{DS} - V_{SAT})}{1 + a_2(V_{DS} - V_{SAT})} \tag{5}$$

Parameters of (5) can be expressed explicitly in terms of the parameters $I_1(V_{GS}, V_{DS})$ from the conditions of current continuity of the current and its first and second derivatives at $V_{DS} = V_{SAT}$ as

$$a_2 = -\frac{1}{2}\frac{\partial^2 I_1}{\partial V_{DS}^2}\bigg|_{V_{SAT}} \bigg/ \frac{\partial I_1}{\partial V_{DS}}\bigg|_{V_{SAT}}, \quad a_1 = a_2 + \frac{\partial I_1}{\partial V_{DS}}\bigg|_{V_{SAT}} \bigg/ I_1(V_{GS}, V_{SAT}).$$

Thus, the expression for the current in saturated mode $I_2$ does not have a single new parameter.

At $V_{GS} >> V_K$ and small $V_{DS}$ drain current approximates by $I_1 = \beta V_K V_{DS}$. So, it is possible to obtain an estimate for the minimum differential resistance of the transistor in the form $r_{DS} = 1/(\beta V_K)$. Note that in datasheets manufacturers indicate static resistance $R_{DS(ON)}$, which is always a bit greater than differential resistance.

## 2. Parameter extraction procedure

Different parameters of BSIM-like models are extracted in two different regions of operation. Parameter extraction is a straightforward procedure here. It is convenient to determine physical parameters of the analytical MOSFET model by the least-squares minimum of the objective function as

$$S\,(\mathbf{x}) = \sum_{k=1}^{N} \left[ \frac{I_D(V_{DS,k}, V_{GS,k}) - I_k}{I_k} \right]^2 = \sum_{k=1}^{N} \delta_k^2 \tag{8}$$

where $\mathbf{x} = \{\beta, V_{TH}, V_K, K_S\}$ is the vector of physical parameters; $\{I_k, V_{DS,k}, V_{GS,k}\}$, $k = 1, 2, ..., N$ is the experimental $I$-$V$ curve of MOSFET in tabular form, $N$ is the number of points of the $I$-$V$ curves. Table 1 shows the results of parameters extraction for some power MOSFETs. It is worth noting that the measured values $r_{DS}$ and manufacturer data $R_{DS(ON)}$ are very close. Figure 1 shows residuals of the model and measured data. The maximum error values correspond to the maximum currents of the transistor.

**Table 1. Parameters of mosfet's model**

| MOSFET | channel | $\beta$ (A/V$^2$) | $V_{TH}$ (V) | $K_S$ | $r_{DS}$ (Ohm) | $R_{DS(ON)}$ (Ohm) | $s$ (%) | $\lvert\delta\rvert_{max}$ (%) |
|---|---|---|---|---|---|---|---|---|
| IPT020N | *n* | 571 | 3.969 | 0.857 | 0.001305 | <0.002 | 7.1 | 15 |
| BUK7Y3R5-40H | *n* | 150.5 | 3.7925 | 0.7979 | 0.00191 | 0.002–0.003 | 13 | 24 |
| 2SK3649-01MR | *n* | 43.71 | 4.842 | 0.8440 | 0.0553 | 0.054–0.07 | 3.0 | 7.3 |
| 2N7002KDV | *n* | 0.1958 | 2.2459 | 0.8616 | 1.958 | <7.5 | 5.7 | 12 |
| 2SJ474-01L | *p* | 6.212 | – 2.2314 | 0.7493 | 0.1329 | 0.15–0.2 | 5.0 | 15 |
| BSH205 | *p* | 4.011 | – 0.6554 | 0.7114 | 0.1897 | 0.18–0.4 | 1.7 | 3.2 |
| FQD5P20 | *p* | 6.766 | – 4.758 | 0.761 | 1.080 | 1.1–1.4 | 6,8 | 22 |
| 2SJ211 | *p* | 0.1836 | – 2.2023 | 0.6798 | 12.90 | <20 | 8.1 | 23 |

For solving curve-fitting problem we used standard Levenberg–Marquardt algorithm with the error control by variation of initials. To illustrate the effectiveness of the proposed method Table 1 shows the results of parameters extraction of some power MOSFETS. Accuracy of the experimental *I-V* curves approximation in each case was estimated by value of the relative root-mean-square (RMS) error $s = \sqrt{S(\mathrm{x}^*)/N}$ where **x*** is the vector of parameters of the model corresponding to the minimum of (8).

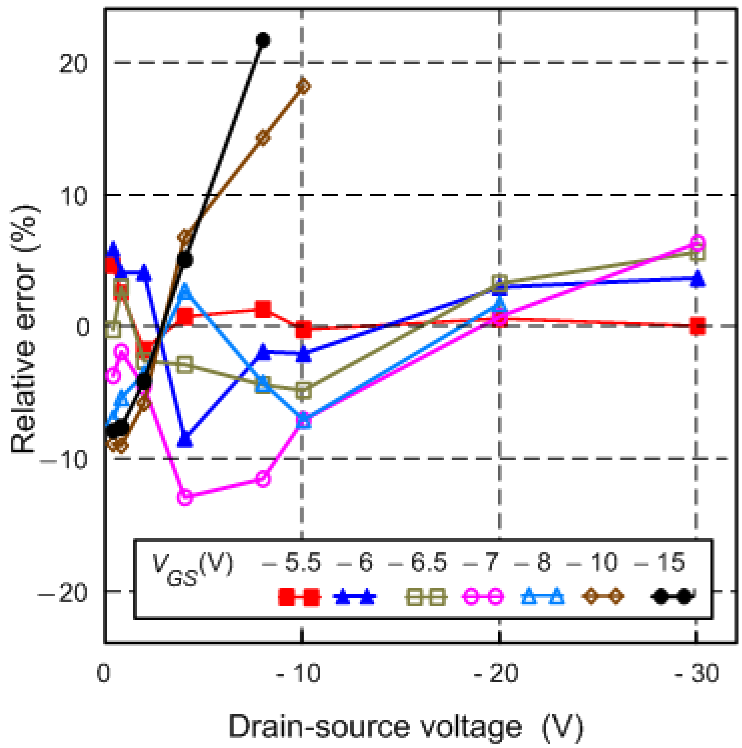


Fig. 1. Relative error as a function of applied voltages for *p*-channel MOSFET FQD5P20. All graphs of the function $\delta(V_{DS})$ intersect with the zero level, what indicates a good quality of the model (4) – (5).

Used technique minimizes the RMS error. Unfortunately, the standard error does not give a complete view of the quality of the approximation [7]. Therefore, along with the RMS error Table 1 gives the maximum relative error $|\delta|_{max}$ also. Instead of the parameter $V_K$, the table shows the resistance $r_{DS}$, since it is the main parameter of a power transistor. For comparison, the table shows the values of this resistance $R_{DS(ON)}$ indicated by the producers.

For PMOS and NMOS devices, drain-source current versus drain-source voltage curves were measured over a wide range of gate-source voltages. The ranges of $V_{DS}$ and $V_{GS}$ was selected according to the producers' datasheets. It should be noted that the limitation of the maximum currents of transistors reduces the simulation error.

Output characteristic $I$ – $V_{DS}$ are shown in Fig. 2. Fig. 2 also presents the characteristics that the Multisim simulator provides. The simulator uses a SPICE sub-circuit model with BSIM3 model as a core. In saturation mode, the accuracy of the proposed model is higher significantly, since the simulator model is intended only for digital circuits

Success in the numerical determination of model parameters by the least squares' method depends on the accuracy of the choice of initial conditions. Many trials and errors are usually required until we reach to proper parameter values. The most reliable is the method for determining part of the initial values using the simplest model [8]. For example, β can be roughly determined from one point of the $I – V$ characteristic in the saturation region with a minimum gate voltage according to the Shichman – Hodges model as $\beta \approx I/(V_{GS} - V_{TH})^2$ . The allowable range of threshold voltage is given in the datasheets of the manufacturer. $R_{DS(ON)}$ is also indicated there, which makes it possible to obtain the estimate $V_K \approx 1/(\beta R_{DS(ON)})$. The initial value of $k$, as follows from Table 1, is approximately 0.7.

## 3. Discussion

When determining the parameters of the transistor models of digital circuits, the objective function can be selected in the form

$$S = \sum_{k=1}^{N} \left( \frac{I_k - I(V_{GS,k}, V_{DS,k})}{I_{ref}} \right)^2$$

The value of reference current $I_{ref}$ can be set appropriately to obtain meaningful results. In case $I_{ref} = MAX\{I_k\}$ curve fitting is better for high currents then for low ones [9].

There is a simple opportunity to reduce the maximum error at the expense of a small increase in the mean square. To get an almost uniform approximation, it suffices to choose the objective function in the form $S=\sum_{k=1}^{N}\delta_k^8$ .

It should be noted that since the proposed model implicitly includes the parameter $R_{DS}$, the inclusion of an additional resistor $R_{DS}$ in the model is extremely undesirable, since the optimization problem becomes ill-conditioned. In models using the effective value of mobility, the differential resistance at low $V_{DS}$ decreases unlimitedly; therefore, such models need the introduction of parasitic resistors.

The MOSFET model (4) is physical; therefore, the threshold voltage and resistance of the switched-on transistor are of a physical nature. In the reference data, these parameters are determined for arbitrary current values. The threshold voltage in (4) has the same sense as in the Schichman-Hodges model, that is, it is extrapolated.

Model (4) doesn't used by *IC* designers, as it valid for long-channel FETs only. In MOSFET models with a short channel, the dependence of the mobility on the transverse field in the channel (3) is replaced by the dependence on the longitudinal field [13, 14], which significantly increases the accuracy of determining $V_{SAT}$. For this reason, the MOSFET's model with a short channel can be used not for silicon MOSFETs, but for transistors based on silicon carbide, since in them the decrease in carrier mobility in the transverse field is much weaker than in silicon. Unfortunately, it is impossible to obtain an explicit expression for the MOSFET drain current when taking into account the dependence of the mobility on the longitudinal and simultaneously on the transverse fields.

As a rule, the RMS error exceeds $|\delta|_{max}$ by 2-3 times. The large difference between $|\delta|_{max}$ and $S$ indicates a poor approximation of the derivatives of the *I-V* characteristic, therefore a sufficiently accurate determination of $|\delta|_{max}$ is desirable. During the procedure of descending in minimization of $S$ the RMS error varies monotonically, but $|\delta|_{max}$ varies no monotonically. Therefore, to obtain reliable results, it is desirable to rise the number of steps of descend until the value of the RMS error ceases to change. To improve the accuracy of the results, we can recommend the method of random descent [15].

## Conclusion

A simple long channel MOSFET model is put forward. The model determines the resistance of the turned-on transistor without introducing parasitic resistances. The proposed model takes into account the dependence of the carrier mobility on the transverse gate field and effective saturation voltage. In addition, the model is continuous along with its two derivatives, which is necessary for the effectiveness of the methods of numerical analysis of electronic simulators. A small number of parameters make it possible to quickly and reliably determine all parameters simultaneously from experimental volt-ampere characteristics.

## Appendix

$$\left.\frac{\partial I_1}{\partial V_{DS}}\right|_{V_{SAT}} = \beta V_K\left(1-\frac{V_K}{V_K+V_{GS}-V_{TH}-V_{SAT}}\right) \left.\frac{\partial^2 I_1}{\partial V_{DS}^2}\right|_{V_{SAT}} = \frac{-\beta V_K^2}{(V_K+V_{GS}-V_{TH}-V_{SAT})^2}$$

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