Letters

Silicon Carbide Power MOSFET Model: An Accurate Parameter Extraction Method Based on the Levenberg–Marquardt Algorithm

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***Abstract*—This letter proposes an accurate parameter extraction method based on the Levenberg–Marquardt algorithm for a silicon carbide (SiC) power MOSFET model. An improved compact model uses this method to study the static behavior of SiC power MOSFETs according to the temperature and the input voltage. The simulation results obtained with this proposed method fit perfectly the measurements and accurately describe the static behavior of 1200 V Gen 2 SiC MOSFETs. The extracted model parameters (threshold voltage, saturation region transconductance, and transverse electric field parameter) are evaluated to analyze the temperature impact and understand the physical behavior of 1200 V Gen 2 SiC power MOSFET.**

***Index Terms*—Levenberg–Marquardt (L–M), model, physical behavior, silicon carbide (SiC) MOSFET , static behavior.**

I. INTRODUCTION

NOWADAYS, the increasing performance request has urged researchers to develop new "wide band gap" technologies based on silicon carbide (SiC) and gallium nitride semiconductors [1]. Nevertheless, the SiC MOSFET reliability study remains a complex problem in terms of temperature and electrical effects [2]. In this context, MOSFET models are needed in circuit and system simulation tools in order to understand these problems. Several research works propose various approaches to model the power MOSFETs and to understand their physical behaviors, these models can be classified into three categories [3]: tabulated models [4], subcircuit or macromodels [5], [6], and compact models [7]–[12]. These last models are based on physical

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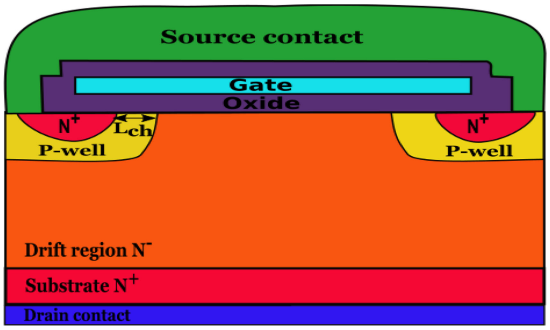


Fig. 1. *N*-channel 4H-SiC VDMOSFET structure.

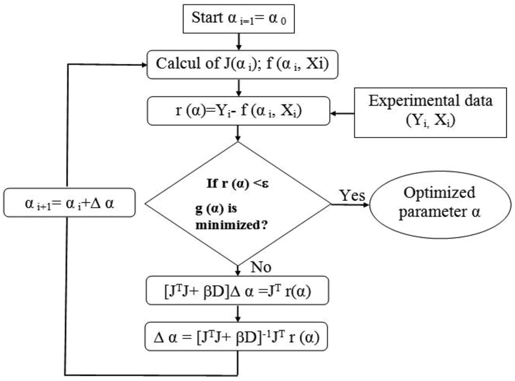


Fig. 2. Flowchart of the Levenberg–Marquardt algorithm.

The improved model describes the drain–source current $I_{\rm ds}$ in two operating regions by the following equations.

1) In linear region $0 \le V_{ds} \le \frac{V_{gs}-V_{th}}{P_{vf}}$

$$I_{\rm ds}=\frac{K_f K_p}{1+\theta\left(V_{\rm gs}-V_{\rm th}\right)}\left[\left(V_{\rm gs}-V_{\rm th}\right)V_{\rm ds}-\frac{P_{\rm vf}^{y-1}V_{\rm ds}^{y}\left(V_{\rm gs}-V_{\rm th}\right)^{2-y}}{y}\right]. \tag{1}$$

2) In saturation region $0 \le \frac{V_{gs}-V_{th}}{P_{vf}} \le V_{ds}$

$$I_{ds}=\frac{K_p\left(V_{gs}-V_{th}\right)^2}{2\left(1+\theta\left(V_{gs}-V_{th}\right)\right)}\left(1+\lambda V_{ds}\right) \tag{2}$$

where K_p is the saturation region transconductance expressed in (A/ V^2). θ is the transverse electric field parameter (V^{-1}) introduced to take into account the mobility reduction generated by a transversal electric field resulting from the input voltage $V_{\rm gs}$. $V_{\rm th}$ is the threshold voltage. $P_{\rm vf}$ and K_f are the pinch-off voltage and the linear region transconductance factors, respectively, and y is the pinch-off voltage exponent expressed by

$$y=\frac{K_f}{K_f-\frac{P_{vf}}{2}}. \tag{3}$$

III. PROPOSED PARAMETER EXTRACTION METHOD

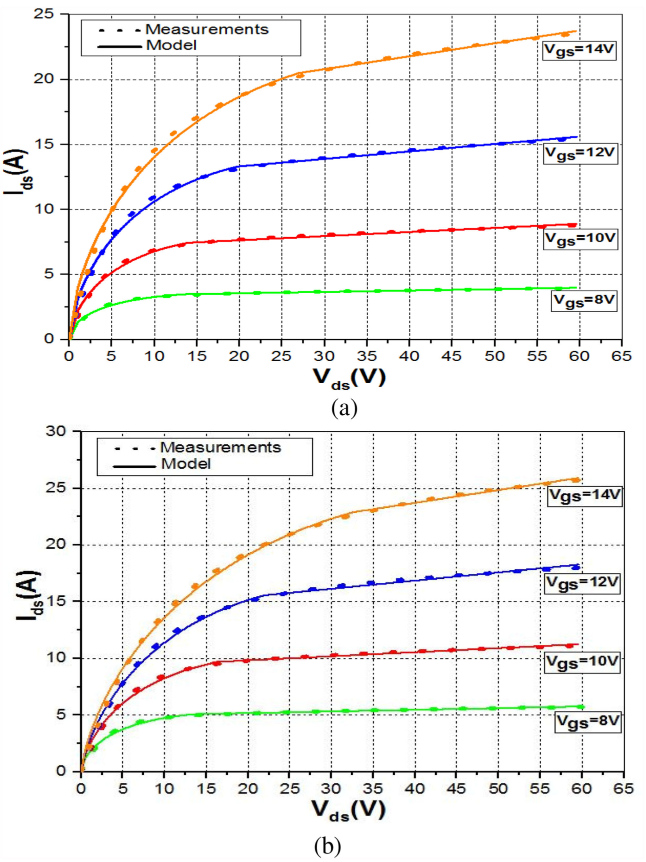
The L–M algorithm is proposed by Levenberg and Marquardt [15]–[17]. The L–M algorithm flowchart is shown in Fig. 2. It is an efficient iterative method for estimating nonlinear regression parameters of models. The L–M algorithm is an improvement of the classical Gauss–Newton method for solving nonlinear least squares regression problems. Consider the nonlinear model fit $Y_i = f\left(\alpha,\, X_i\right)$, where X_i ($V_{\rm gs}$ or $V_{\rm ds}$) and Y_i ($I_{\rm ds}$) are the data extracted from the *I–V* measurements, and α is a vector of dimension n that represents the parameters of the model ($V_{\rm th}$, K_p, θ, $P_{\rm vf}$, K_f, y, λ). The L–M method searches for (α_1, α_2, $\alpha_3, \ldots, \alpha_n$), which are the solutions of α (locally) minimizing $g(\alpha)$ defined by

$$g\left(\alpha\right)=\sum_{i=1}^{m}\left(Y_i-f\left(\alpha,X_i\right)\right)^2. \tag{4}$$

The L–M algorithm finds the solution by using

$$\alpha_{i+1}=\alpha_i-\left(J^T J+\beta D\right)J^T r\left(\alpha\right) \tag{5}$$

where $r(\alpha) = Y_i - f(\alpha,\, X_i)$, J is the Jacobian matrix for $f(\alpha,\, X_i)$, J^T is the transposed matrix of *J*, β is a regularization parameter, and *D* is the identity matrix, whose dimension is equal to that of $J^T J$ to adjust the scales factors.



(a)

(b)

Fig. 3. Simulated and measured output characteristics for 1200 V Gen 2 SiC MOSFET at two temperatures. (a) 25°C. (b) 100°C.

IV. EXPERIMENTAL VALIDATION

The proposed extraction method is validated and applied on the improved model in order to describe the static behavior of 1200 V Gen 2 SiC power MOSFET according to temperature.

TABLE I
RELATIVE VARIATIONS BETWEEN THE IMPROVED MODEL RESULTS AND MEASUREMENTS FOR 1200 V GEN 2 AND FOR 2-KV, 5-A 4-H SIC POWER MOSFET [9]

	1200V Gen 2 SiC MOSFET				2-kV, 5-A 4-H SiC power MOSFET [9]			
Region	Linear		Saturation		Linear		Saturation	
T(°C) V_{gs}(V)	25	100	25	100	25	100	25	100
8	4.69 %	5.06 %	0 %	0 %	15 %	17.69 %	18 %	16.13 %
10	4.09 %	2.89 %	1.16 %	1.83 %	10.61 %	12.5 %	11.58 %	7.95 %
12	1.53 %	0.1 %	0.06 %	0.12 %	11.97 %	4.9 %	7.5 %	-
14	0.6 %	2.9 %	0.13 %	0.28 %	7.44 %	4.68 %	3.37 %	-

The static *I–V* characterizations have been performed using a bench generating a pulse measurement duration not exceeding 7 μs in order to avoid self-heating of the device under test. The measurements are conducted on a temperature range from 0°C to 135°C. The temperature is controlled by a Peltier module. Fig. 3 shows the simulated and measured output characteristics of SiC power MOSFET. The relative variations of I_{ds} between model simulation ($I_{\text{ds(sim)}}$) and measurements ($I_{\text{ds(mes)}}$) have been calculated by

$$\text{Relative variation} = \left(\frac{I_{ds(sim)} - I_{ds(mes)}}{I_{ds(sim)}}\right) \times 100. \qquad (6)$$

Table I shows the relative variations resulting from our proposed method performed on 1200 V Gen 2 SiC MOSFET, and the relative variations calculated from [9] and applied on 2-kV, 5-A 4-H SiC power MOSFET.

By analyzing the obtained results of Fig. 3, it is obvious that the improved model is more accurate and matches very well the measurements. The comparison between the relative variations (see Table I) of our proposed method and those deduced from [9] shows that the proposed parameters extraction method is very efficient over the temperature range from 0°C to 135°C and for various values of V_{gs} voltage.

V. PHYSICAL PARAMETERS ANALYSIS

The proposed parameters extraction method has been studied in order to understand the impact of the temperature and the voltage V_{gs} on the SiC-MOSFET static behavior.

A. Threshold Voltage

V_{th} is extracted from the improved model based on the L–M optimization algorithm and input characteristics defined as the gate–source voltage at which significant drain current starts to flow. Fig. 4 shows V_{th} evolution according to temperature. V_{th} decreases as the temperature is increased. Indeed, the increase of temperature generates the appearance of charges in the oxide (the mobile ion charge, the trapped oxide charge, and the interface state charge). The presence of the oxide charges produces band bending at the semiconductor surface. The band bending for the case of a p-type semiconductor creates a depletion region. This reduces V_{th} for the MOS structure [18].

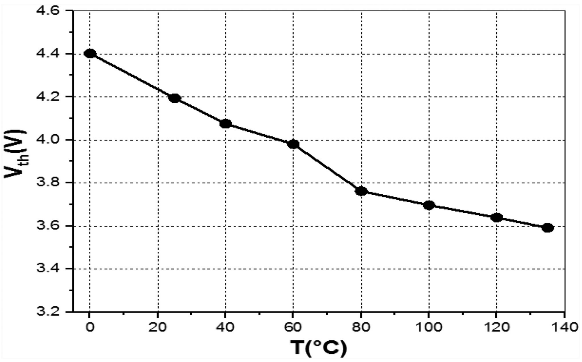


Fig. 4. Threshold voltage as a function of temperature at $V_{\text{ds}} = 20$ V for 1200 V Gen 2 SiC MOSFET.

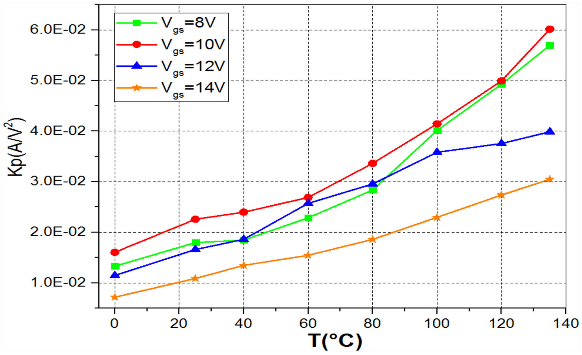


Fig. 5. Saturation region transconductance K_p as a function of temperature at V_{gs} (8, 10, 12, and 14 V) for 1200 V Gen 2 SiC MOSFET.

B. Saturation Region Transconductance and Electron Mobility

The saturation region transconductance K_p is an image of the electron mobility according to [19]

$$K_p = \frac{N_{cell} Z C_{ox} \mu_n}{L_{ch}} \qquad (7)$$

where N_{cell} is the transistor cells number, Z is the cell length, L_{ch} is the channel length, and μ_n is the electron mobility.

Fig. 5 shows the saturation region transconductance K_p variation extracted from the improved model as a function of temperature and input voltage V_{gs}. The dependence of K_p on temperature and input voltage V_{gs} is mainly due to the impact of these factors on the electron mobility μ_n. Indeed, the μ_n

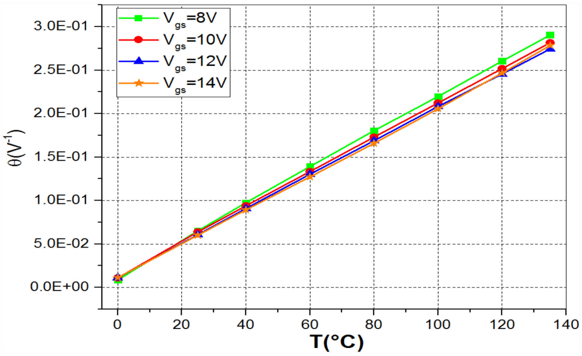


Fig. 6. Transverse electric field parameter θ as a function of temperature at V_{gs} (8, 10, 12, and 14 V) for 1200 V Gen 2 SiC MOSFET.

in the channel increases with temperature because the Coulomb scattering dominates on the other degradation mechanisms [20], [21]. The dependence of μ_n to the input voltage V_{gs} is described by [22]

$$\mu_n = \frac{\mu_0}{1 + \theta\left(V_{gs} - V_{th}\right)} \tag{8}$$

where μ_0 presents the electron mobility at low electrical field. Fig. 6 shows the θ factor variations as a function of temperature and voltage V_{gs}. The factor θ increases with temperature, but its value remains unchanged with V_{gs} variations.

VI. CONCLUSION

In this letter, an accurate parameter extraction method is developed based on the *I–V* static measurements in the pulsed mode and the L–M optimization algorithm of SiC power MOSFETs. The improved compact model uses this L–M method to describe accurately and efficiently the static behavior of SiC MOSFETs as a function of temperature and input voltage variations. The extraction of physical parameters shows that the static behavior of the device is related, on one hand, to the dependence of threshold voltage on temperature, and on the other hand to the dependence of electron mobility on temperature and input voltage. This improved model could be an effective way to study the reliability of these MOSFETs and the interpretation of data resulting from aging tests to identify the failure mechanisms like the doping concentration and the oxide capacitance variations during the aging test.

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