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D.C. CHARACTERISTICS OF SiC POWER SCHOTTKY DIODES MODELLING IN SPICE

Janusz Zarębski, Jacek Dąbrowski

Gdynia Maritime University, Department of Marine Electronics

Key words: Silicon Carbide (SiC), Schottky Barrier Diodes (SBDs), modelling, self-heating, electrothermal macromodel, SPICE

Abstract: In this paper the problem of SPICE modelling of the class of silicon-carbide (SiC) Schottky diodes with thermal effects (self-heating) taken into account is considered. Since April 2001 the SiC Schottky diodes made by Infineon Technologies have been commercially attainable. In the paper the SPICE electrothermal (including self-heating) macromodel of Infineon Technologies SiC Schottky diode is presented and in detail investigated. The considered macromodel has been verified experimentally. The silicon-carbide SDP04S60 rectifier has been tested. The nonisothermal characteristics obtained from measurements and SPICE calculations of SDP04S60 diode are compared. Due to the unacceptably large differences between measurements and calculations, some modifications of the macromodel have been proposed.

DC karakteristike močnostnih SiC Schottky diod – modeliranje s programom SPICE

Kjučne besede: Silicijev karbid (SiC), Schottky diode, modeliranje, pregrevanje, elektrotermični model, SPICE

Izvleček: V prispevku obravnavamo probleme pri modeliranju SiC Schottkyjevih diod s programom SPICE z upoštevanjem termičnih efektov. Od aprila leta 2001 so SiC Schottky diode izdelane pri podjetju Infineon Technologies tudi komercialno dosegljive. Tako v prispevku predstavimo in natančno obravnavamo SPICE elektrotermični model prav teh diod. Predastavljeni model smo preverili tudi eksperimentalno in sicer smo testirali SiC diodo z oznako SDP04S60. Primerjali smo izmerjene in izračunane neizotermične karakteristike. Zaradi velikih razlik med meritvami in napovedmi, predlagamo določene spremembe pri parametrih makromodela.

1. Introduction

The silicon carbide (SiC) is a great promising semiconductor material for manufacturing of power devices. It occurs in over 170 polytypes, the most common of which are cubic 3C, hexagonal 4H and 6H structures. A number of most important physical aspects of SiC compared to other semiconductors one can find in the literature, e.g. /1,2,3/. As results from the cited papers, silicon carbide has an order of magnitude higher breakdown electric field and an electron mobility only about 20% lower (for 4H-SiC) than silicon. A high breakdown electric field allows to design the SiC power devices with 10-times thinner and about 100-times higher dopend voltage blocking layers. Smaller dimensions of SiC material result in higher device switching frequency.

Nowadays, a lot of SiC devices, as transistors, diodes, thyristors, LED's, thermistors etc. are manufactured and investigated in laboratories /4,5/. In the case of the power SiC devices a high breakdown voltage is needed. So far, the SiC power diodes, have been the class of semiconductor devices having the greatest values of the breakdown voltage equal to 10 kV for Schottky diodes /6/ and 19 kV for PiN diodes /7/. Since 2001 SiC Schottky diodes made by Infineon Technologies have been available in the market /8/.

A very important feature of all semiconductor devices, including SiC SBDs, is a strong influence of the temperature on their characteristics. Due to the self-heating resulting from the change of the device dissipated power into the heat in the case of nonideal cooling conditions, the junction temperature (often much greater than the ambient one) affects the device characteristics, called the nonisothermal ones. In order to take into account the self-heating, the models of the special kind, called the electrothermal models (ETM) have to be used for the device simulations.

Infineon Technologies, on their web-side /9/, offers the SiC Schottky's electrothermal macromodel for SPICE, indicated as Level 3.

In the paper the Level 3 Infineon's SPICE macromodel is presented, in detail discussed and experimentally verified. The SDP04S60 diode: 4A/600V, has been chosen for investigations, instead of 6A/600V SiC Schottky diode (SDP06S60) considered in /10/. Due to the fact, that obtained results between measurements and calculations differ from each other significantly, therefore some modifications of the macromodel were introduced.

2. The Macromodel Form of The SiC Schottky Diode

To derive the electrothermal macromodel of the considered device, the following dependencies have to be used /11/:

- the current-voltage-temperature dependence (isothermal model),

- the dependence of the inside (junction) temperature T_j on the electrical power dissipated in the device, along with the dependence of this electrical power on the device terminal currents and voltages (thermal model).

The structure of such a macromodel is shown in Fig. 1.

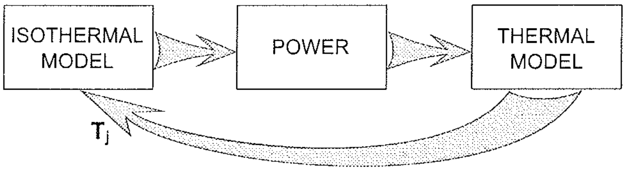

Fig. 1. The structure of the electrothermal macromodel of the SiC Schottky diode

Next, the detailed form of the isothermal model and the thermal model, forming the considered electrothermal macromodel are presented and discussed.

The network form of the isothermal model of the SiC Schottky diodes is presented in Fig. 2. /9/.

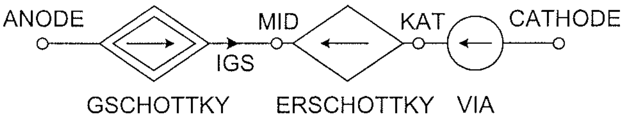

Fig. 2. The network form of the isothermal model of the SiC Schottky diode

As seen, the model is composed of three elements: the controlled current GSCHOTTKY source, the controlled voltage ERSCHOTTKY source and the independent source VIA of the efficiency equal to zero. Due to the d.c. dependencies considered here, the wire inductance and junction capacitance are not taken into account in further considerations.

The control current source GSCHOTTKY is of the efficiency

$$I_{GS}(T,V) = I_{bw} \cdot \left[\exp\left(\frac{V \cdot q}{k \cdot (T_0 + T)} \right) - 1 \right] \qquad (1)$$

where T - the analysis temperature ($T \equiv TEMP$) in Celsius degrees, V - voltage between ANODE and MID nodes, I_{bw} - reverse (saturation) current, q - electron charge, k - Boltzmann's constant, T_0 - the reference temperature.

The saturation current is expressed by the formula

$$I_{bw} = AREA \cdot A_0 \cdot (T_0 + T)^2 \cdot \exp\left(\frac{-q \cdot \phi_{SiC}}{k \cdot (T_0 + T)} \right) \cdot K \qquad (2)$$

where $AREA$ - relative device area, A_0 - Richardson's constant, ϕ_{SiC} - metal-semiconductor barrier height.

In Eq.(2) the factor K models the lowering effect existing in the reverse range of the Schottky diode operation which is given by the following expression

$$K = \exp\left(\frac{q \cdot \sqrt{\beta \cdot EFLD_{(V)}}}{k \cdot (T_0 + T)} \right) \cdot$$
$$\frac{1}{2} \cdot \left(1 + \exp\left(AA + AB \cdot (T - 127) + AC \cdot (T - 127)^2 + \frac{\alpha_1 \cdot EFLD_{(V)}}{EFLD_{\left(\frac{-VPT}{5}\right)}} \right) \right) \qquad (3)$$

where b, AA, AB, AC, α_1 and VPT are the model parameters.

The description of the electric field ($EFLD$) dependent on the junction reverse voltage is divided into three ranges according to the value of the anode-cathode voltage, up to the pattern (4), where V denotes the voltage on the diode, EPT denotes the critical electrical field, whereas x and g are the model parameters. $LIMIT$ denotes the SPICE standard function.

$$EFLD = \begin{cases} 0 & if \quad V > 0 \\ \sqrt{\xi \cdot \mathrm{LIMIT}(-V, 0, VPT)} & if \quad -V < VPT \\ \mathrm{EPT} \cdot \gamma \cdot \left(\frac{V}{VPT} + 1 \right) & if \quad -V \geq VPT \end{cases} \qquad (4)$$

In turn, the voltage source ERSCHOTTKY controlled by the current of VIA source models the influence of the diode series resistance on the i(u) characteristics. Thus

$$U_{ERS} = I_{(VIA)} \cdot R_{S(T)} = \frac{I_{(VIA)} \cdot R_{0SQ}}{AREA \cdot V_j^2} \cdot \left(\frac{T_0 + T}{T_0} \right)^{\chi} \qquad (5)$$

where $R_{S(T)}$ is the series resistance dependent on the temperature, R_{0SQ} is the specific series resistance at the reference temperature T_0, whereas $I_{(VIA)}$ is the zero voltage source current and χ, V_j are the model parameters. The isothermal model parameter values of the diode are collected in Table 1 /9/.

The thermal model of the considered diode has been presented in the network form (Cauer leader) consisting of four resistors (*RTHD*) and capacitances (*CTHD*), representing the junction-to-case thermal impedance of the diode (Fig. 3.) /9/. The values of those elements are given in Table 2. The nodes TJ and TCASE represent the junction and the case temperatures respectively, whereas the potential value of the node TREF representing the ambient temperature, can be fixed by the efficiency of the voltage source VREF. This form of the thermal model is not acceptable by SPICE due to the fact, that the TREF node has not d.c. connection with the other one. Therefore, in the case of the ideal conditions of the case cooling, the nodes TREF and TCASE have to be shorted. Otherwise, between the nodes TCASE and TREF, the *RC* network of the Cauer leader, representing the phenomena of heat removing from the case to the ambient (e.g. by means of a heat-sink), has to be added.

Table 1 The parameters values of the isothermal model of the SDP04S60 diode

Parameter	Value
q [C]	$1.602 \cdot 10^{-19}$
k [J/K]	$1.38 \cdot 10^{-23}$
T_0 [K]	273
A_0 [$A \cdot cm^{-2} \cdot K^{-2}$]	110
ϕ_{SiC} [eV]	1.3
AA, AB, AC	$-1.5, \ -12.95 \cdot 10^{-3}, \ 91 \cdot 10^{-6}$
α_1	3.8
R_{0SQ} [$m\Omega \cdot cm^2$]	0.9
VPT [V]	400
EPT [V/cm]	$1.05 \cdot 10^6$
β	$1.49 \cdot 10^{-8}$
ξ	$2.811 \cdot 10^9$
γ	$5.33 \cdot 10^5$
χ	1.5
$AREA$	0.0116
V_j	0.75

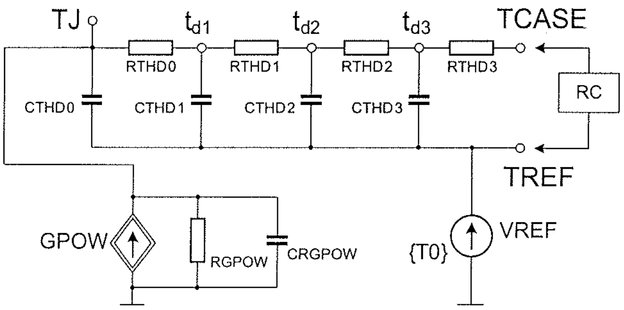

Fig. 3. The general form of the thermal model of the SiC SDP04S60 Schottky diode

Table 2 The parameter values of the thermal model of the SDP04S60 diode

Parameter	Unit	Value
$RTHD0$	[K/W]	1.756
$RTHD1$		1.717
$RTHD2$		0.545
$RTHD3$		0.094
$CTHD0$	[J/K]	$5.243 \cdot 10^{-4}$
$CTHD1$		$1.076 \cdot 10^{-3}$
$CTHD2$		0.044
$CTHD3$		2.025
$RGPOW$	[Ω]	$100 \cdot 10^6$
$CRGPOW$	[F]	$10 \cdot 10^{-12}$

The controlled current source GPOW represents the real power dissipated in the diode. Its efficiency is described by

$$I_{GPOW} = \begin{cases} ABS\left(I_{(VIA)} \cdot V_{(ANODE,CATHODE)}\right) & if \ t > 25ns \\ 0 & if \ t \le 25ns \end{cases} \tag{6}$$

where $I_{(VIA)}$ is the total current flowing through the diode, $V_{(ANODE,CATHODE)}$ is the voltage on the diode, whereas ABS is the standard SPICE function denoting the absolute value of any function.

In the case of the analysis at the steady-state the simplified, shown in Fig. 4, thermal network is used. In this figure the resistance R_1 denotes the junction-to-case thermal resistance represented by the sum of $RTHD_i$ (i = 0÷3) and equal to 4.112 K/W, whereas the resistance R_2 represents the case-to-ambient resistance of the value depending on the case cooling conditions. Note, that the thermal model can be used in d.c. analysis, if the time limitations in Eq.(6) are eliminated.

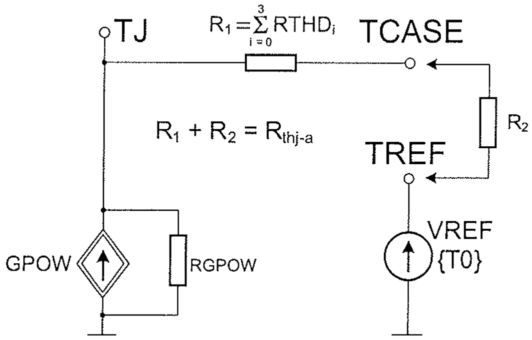

Fig. 4. The thermal model of the SiC Schottky diode for d.c. analysis

3. The Macromodel Verification

To estimate the correctness of the macromodel described in the early chapter, SPICE simulations of the forward and reverse characteristics of the diode SDP04S60 have been compared to the measurements. The diode has been operated without the heat-sink. The value of the measured thermal resistances R_{thc-a} is equal to 59.26 K/W.

The results of measurements (points) and SPICE simulations (lines) in the wide temperatures range are shown in Fig. 5 (the forward range) and Fig. 6 (the reverse range), respectively. As seen in Fig. 5, the simulation results based on the original macromodel (the broken lines) differ from the measurements even more than 60 %.

To improve the agreement between simulations and measurements the following modification of the parameter χ (existing in Eq.(5)) has been proposed /10/

$$\chi = 1.58 + \left(35 \cdot 10^{-5} \cdot T^1\right) + \left(32 \cdot 10^{-7} \cdot T^2\right) \tag{7}$$

After these modifications the considered characteristics obtained both from measurements and SPICE calculations fit well and the error of the current estimation at the given voltage is not greater than a few per cent.

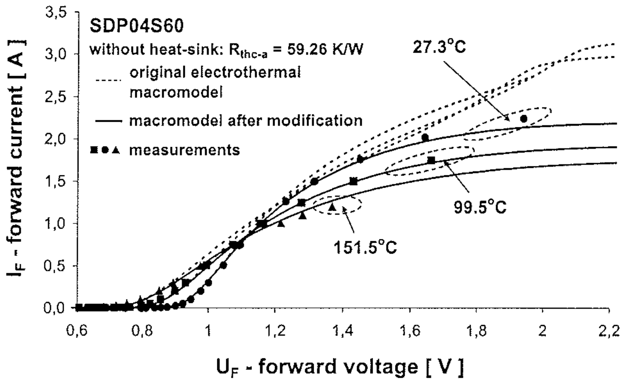

Fig. 5. The forward characteristics of the SDP04S60 diode without the heat-sink

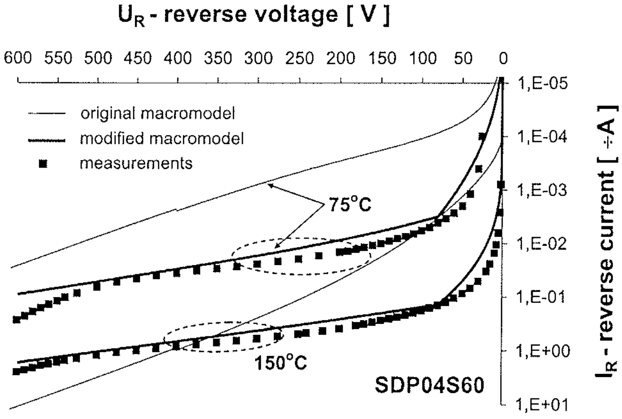

Fig. 6. The reverse characteristics of the SDP04S60 diode

The considered macromodel along with the author's additional modifications presented in Table 3, has also been used for modelling the diode characteristics operating in the reverse range /10,12/. Note, that for the considered two ambient temperature values, different values of the selected parameters are required.

As seen, also in this case a very good agreement between the results of measurements (points) and electrothermal calculations has been obtained. One can notice, that in the considered voltage range the dissipated power in the diode can be omitted. Thus, the obtained characteristics can be treated as the isothermal ones.

Table 3 The macromodel modifications for the SDP04S60 diode operating in the reverse range

<table>
<tr><th colspan="2" rowspan="2">Parameter</th><th colspan="3">Value</th></tr>
<tr><th>Original</th><th>75°C</th><th>150°C</th></tr>
<tr><td colspan="2">α_1</td><td>3.8</td><td>2</td><td>1.75</td></tr>
<tr><td colspan="2">β</td><td>$1.49 \cdot 10^{-8}$</td><td>$2.24 \cdot 10^{-7}$</td><td>$1.60 \cdot 10^{-7}$</td></tr>
<tr><td rowspan="2">ϕ_{LS}</td><td>$V \leq VPT/5$</td><td rowspan="2">$\frac{q \cdot \sqrt{\beta \cdot EFLD_{(V)}}}{k \cdot (T + T_0)}$</td><td colspan="2">$\frac{q \cdot \sqrt{\beta \cdot EFLD_{(V)}}}{k \cdot (T + T_0)}$</td></tr>
<tr><td>$V > VPT/5$</td><td>$\phi_{LS(VPT/5)} = 10.87$</td><td>$\phi_{LS(VPT/5)} = 7.55$</td></tr>
</table>

4. Conclusions

In the paper the electrothermal macromodel of the SiC Schottky diode has been investigated and verified experimentally. As was proved, the original macromodel is of poor accuracy, whereas after the author's modifications the characteristics obtained from measurements and calculations fit very well. Note, that to perform the simulations the value of the thermal resistance from the case to the sourrounding had to be additionally measured.

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Prof. Janusz Zarębski; M.Sc. Jacek Dąbrowski
Gdynia Maritime University,
Department of Marine Electronics
Morska 83, 81-225 Gdynia, POLAND,
Tel. ++48 58 6901599, ++48 58 6901609,
fax ++48 58 6217353
E-mail: zarebski@am.gdynia.pl, oakjack@am.gdynia.pl

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