Modelling the Influence
of Self-heating on Characteristics
# of IGBTs in the Sub-threshold Region

Krzysztof Górecki, and Paweł Górecki

Abstract—**The paper refers to modelling characteristics of IGBT in SPICE software with self-heating taken into account. The form of the electrothermal model of the considered transistor and equations describing this model are proposed. The correctness of the proposed model is verified experimentally during the operation of the examined transistor at different cooling conditions. Particular attention is paid to the non-typical course of characteristics of the considered device at weak excitation. The shape of the obtained characteristics is discussed and the influence of the sub-threshold effect in the input MOS structure on these characteristics is analysed.**

Index Terms—**IGBT, electrothermal model, self-heating, SPICE**

I. INTRODUCTION

POWER semiconductor devices are commonly used in switch-mode power supplies circuits and analogue electronic circuits operating in a continuous mode [1, 2, 3]. Within the range of high values of voltages and currents, IGBTs are practically used [2].

As it is commonly known, characteristics and technical parameters of semiconductor devices strongly depend on temperature [4, 5, 6]. As a result of thermal phenomena, among other things self-heating phenomena, the internal temperature T_j of semiconductor devices exceeds, sometimes considerably, the value of the ambient temperature T_a.

On the stage of designing electronic circuits, computer simulations are performed to verify correctness of the project. The reliability of the obtained results of calculations depends on the accuracy of the applied models [6, 7, 8, 9]. The highest accuracy characterizes the detailed models, but a high degree of their complication practically makes it impossible to use them in the analysis of networks containing a high number of semiconductor devices [5, 6, 7, 10]. Therefore, in the analysis of electronic networks, compact models of semiconductor devices describing dependences between voltages and currents on the connectors of these devices, are typically used.

More and more frequently in such analyses electrothermal compact models of the considered class of devices are used. Electrothermal models make it possible to calculate not only voltages and currents in the considered network, but also internal temperatures of the semiconductor devices. The collected electrothermal models have been formulated for many years for semiconductor devices [11 - 15].

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Due to widespread popularity of SPICE software, electrothermal models of semiconductor devices and integrated circuits dedicated for this software are important for designers of electronic circuits. Such models are proposed among others for power bipolar transistors in paper [12], for the power MOS transistor in [11], for the p-n diode in [16], or for monolithic integrated circuits dedicated for switch-mode power supplies in [15, 17, 18].

In this paper, which is an extended version of paper [19], the compact electrothermal model of IGBT for SPICE is proposed. In the second section the form of the worked out model is presented, and in the third section – the results of verification of its correctness are shown. Particularly, the influence of the sub-threshold effect on the dc characteristics of IGBTs is considered.

II. MODEL FORM

The structure of IGBT can be presented as the connection of the MOS transistor, the bipolar transistor and the p-n diode [20], shown in Fig. 1.
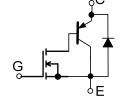

Fig. 1. The representation of the IGBT structure.

For the considered structure the electrothermal compact model dedicated for SPICE is formulated. Its network representation is shown in Fig. 2.

In the presented model two blocks can be distinguished: the electrical model and the thermal model. In the electrical model signals on the connectors G, C and E correspond to signals occurring on the connectors of the gate, the collector and the emitter of the real device. The device internal temperature is calculated in the thermal model and corresponds to the voltage in the node T_j. The value of this temperature is calculated using the following formula

$$T_j = T_a + R_{th} \cdot i_C \cdot v_{CE} \tag{1}$$

where R_{th} denotes thermal resistance of the investigated device, i_C is the collector current flowing through the voltage source V_C of the zero-value of the output voltage, while v_{CE} is the voltage between the connectors of the collector and the emitter.

Series resistances of the emitter and the collector are modelled by means of linear resistors R_E and R_C. The linear dependence of series resistance on temperature models the controlled voltage source E_{RC}. Resistors R_{CE}, R_{BE} and R_{GE} model leakages between the connectors of the transistor.
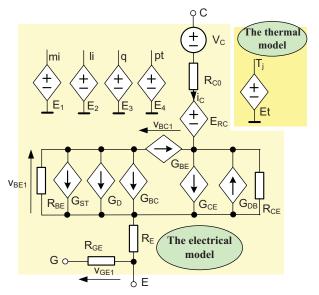

Fig. 2. The network representation of the compact electrothermal model of IGBT.

The drain current of the MOS transistor, existing in the structure of the considered IGBT, is equal to the sum of two components: the threshold current, modelled by the controlled current source G_{ST}, and the current of the MOS structure, represented by the controlled current source G_D. Currents of these sources are given by the formulas [11]

$$I_{GST} = I_{PO} \cdot \left(\frac{T_j}{T_0}\right) \cdot \exp\left(-\frac{U_{go}}{k/q \cdot T_j}\right) \cdot \left(\exp\left(\frac{LIMIT(v_{GE1} - v_{PH}, 0, v_{VT} - v_{PH})}{k/q \cdot n_{ST} \cdot T_j}\right) - 1\right) \quad (2)$$

$$I_{GD} = \frac{v_{BE1}}{|v_{BE1}|} \cdot B \cdot v_{mi} \quad (3)$$

In equations (2), (3) I_{PO}, n_{ST} and B are parameters of the transistor, whose values are estimated in the reference temperature T_0, U_{go} is equal to 1.206 V for silicon, k means the Boltzmann constant and q is the electron charge. LIMIT is a standard-function of SPICE software. The voltages v_{BE1} and v_{GE1} are marked in Fig. 2. In turn, v_{PH} and v_{mi} denote voltages between the connectors of the controlled voltage sources E_4 and E_1.

The controlled voltage sources E_1, E_2 are used for calculating values of the voltage v_{mi} according to the equations included in paper [11], whereas voltages on the controlled voltage sources E_3 and E_4 describe linear dependences of the threshold voltage and the Fermi's level on temperature.

The controlled current source G_{BE} describes the current flowing between the base and the emitter of the bipolar transistor included in the modelled structure. The current of this source is described by the dependence of the form

$$I_{GBE} = -\frac{I_O}{\beta_F} \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{U_{go}}{k/q \cdot n_1 \cdot T_j}\right) \cdot \left(\exp\left(\frac{-v_{BC1}}{k/q \cdot n_1 \cdot T_j}\right) - 1\right) \quad (4)$$

where I_0 and n_1 are parameters of the model, voltage v_{BC1} is marked in Fig. 2, while β_F is the current gain factor for the forward-active mode of the bipolar transistor and it is given by the formula [12]

$$\beta_F = \frac{\beta_{0F} \cdot (1 + a_F \cdot (T_j - T_0))}{1 + b_F \cdot (1 + c_F \cdot (T_j - T_0)) \cdot |i_C|} \cdot \left[1 - \sum_i \gamma_{iF} \cdot \exp(-\alpha_{iF} \cdot |i_C|)\right] \quad (5)$$

where a_F, b_F, c_F, γ_{iF}, α_{iF}, β_{0F} denote the model parameters in the forward active mode.

In turn, the controlled current source G_{BC} represents the current flowing between the base and the collector of the bipolar transistor included in the modelled structure. The current of its source is described by

$$I_{GBE} = -\frac{I_O}{\beta_R} \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{U_{go}}{k/q \cdot n_1 \cdot T_j}\right) \cdot \left(\exp\left(\frac{-v_{BE1}}{k/q \cdot n_1 \cdot T_j}\right) - 1\right) \quad (6)$$

where the voltage v_{BE1} is marked in Fig. 2, β_R is the current gain factor for the reverse-active mode of the bipolar transistor and it is given by

$$\beta_R = \beta_{0R} \cdot (1 + a_F \cdot (T_j - T_0)) \quad (7)$$

In equation (7) β_{OR} is equal to the value of the current gain factor for the reverse-active mode at the reference temperature T_0.

The main current of IGBT is modelled by the controlled current source G_{CE} described by

$$I_{GCE} = I_O \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{U_{go}}{k/q \cdot n_1 \cdot T_j}\right) \cdot \left(1 + \frac{v_{CE}}{V_{AN}}\right)$$

$$\cdot \left(\exp\left(\frac{-v_{BC1}}{k/q \cdot n_1 \cdot T_j}\right) - \exp\left(\frac{-v_{BE1}}{k/q \cdot n_1 \cdot T_j}\right)\right) \quad (8)$$

where V_{AN} denotes Early's voltage.

The dc characteristic of the reverse diode describes the controlled current source G_{DB}. The current of this source is given by the following formula

$$I_{GDB} = I_{OD} \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{U_{go}}{k/q \cdot n_D \cdot T_j}\right) \cdot \left(\exp\left(\frac{-v_{CE1}}{k/q \cdot n_D \cdot T_j}\right) - 1\right) +$$

$$+ I_{OG} \cdot \left(\frac{T_j}{T_0}\right) \cdot \exp\left(-\frac{U_{go}}{k/q \cdot n_{D1} \cdot T_j}\right) \cdot \left(\exp\left(\frac{-v_{CE1}}{k/q \cdot n_{D1} \cdot T_j}\right) - 1\right) \quad (9)$$

where I_{OD}, I_{OG}, n_D and n_{D1} are parameters of the presented model.

III. RESULTS

To verify the correctness of the model described in the second section, dc characteristics of the arbitrarily selected IGBT of the type IRG4PC40UD by International Rectifier are measured and calculated. This transistor is characterized with the admissible value of the reverse voltage $V_{CEmax} = 600$ V, with the admissible value of the collector current $I_{Cmax} = 20$ A and with the admissible value of dissipated power $P_{tot} = 65$ W [21].

In Figs. 3 - 11 the results of calculations and measurements of dc characteristics of the considered transistor obtained at different cooling conditions are collected. The values of parameters of the electrothermal model of IGBT used in the calculations are collected in Table I.

TABLE I.
PARAMETERS VALUES OF THE ELECTROTHERMAL MODEL OF THE TRANSISTOR IRG4PC40UD

parameter	V_{T0} [V]	α_T [K^{-1}]	B [A/V^2]	T_0 [K]	λ [V^{-1}]
value	5.62	1.4x10^{-3}	0.1	300	2x10^{-3}
parameter	PH_0 [V]	α_{PH} [K^{-1}]	I_0 [A]	n_1	β_{OF}
value	0.85	3x10^{-3}	10^3	1.4	65
parameter	β_{OF}	a_F [K^{-1}]	c_F [K^{-1}]	b_F [A^{-1}]	V_{AN} [V]
value	3	6x10^{-3}	2x10^{-3}	3	1000
parameter	I_{P0} [A]	n_P	I_{0D} [A]	n_D	I_{0G} [A]
value	4x10^3	5.8	500	1.5	5
parameter	n_{D1}	R_C [Ω]	R_E [Ω]	α_{RC} [K^{-1}]	
value	5	0.35	0.1	3x10^{-3}	

The value of thermal resistance R_{th} depends on cooling conditions of the transistor. Isothermal characteristics obtained at ideal cooling conditions are calculated for $R_{th} = 0$. Additionally, non-isothermal characteristics of the considered transistor operating without the heat-sink ($R_{th} = 35$ K/W) and the transistor situated on the aluminium heat-sink ($R_{th} = 6.5$ K/W) are calculated. The values of R_{th} are measured with the use of the method described in the paper [22].

In the figures included in the further part of this section, black dashed lines mean the results of isothermal calculations, blue solid lines – the results of electrothermal calculations for the transistor situated on the heat-sink, red solid lines – the results of electrothermal calculations for the transistor operating without the heat-sink, and points – the results of measurements. In order to illustrate the influence of taking into account the sub-threshold phenomena in the MOS input structure, in all the figures dashed red and blue lines denote the results of calculations obtained omitting this phenomena. The current-voltage characteristics are measured by means of the source meter Keithley 2612, and the case temperature of the transistor is measured by means of the thermo-hunter PT-3S by Optex. The calculated values of the case temperature are obtained on the ground values of the internal temperature with the use of the formula from paper [23].

In Fig. 3 the calculated and measured transfer characteristics of the examined transistor obtained at the voltage between the collector and the emitter $V_{CE} = 5$ V are presented, whereas in Fig. 4 - corresponding to them dependences of the case temperature of the transistor on the control voltage v_{GE}.
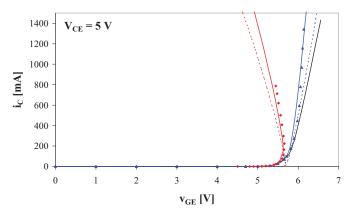

Fig. 3. Measured and calculated transfer characteristics of the investigated transistor at $V_{CE} = 5$ V.

As it can be noticed, the threshold voltage of the examined transistor exceeds 5.5 V. Together with worsening its cooling conditions the considered characteristic $i_C(v_{GE})$ moves left. It is worth paying attention to the calculated and measured characteristics of the transistor operating without any heat-sink, which for the current $i_C > 100$ mA show the negative slope. Omitting the sub-threshold part of the current of the input MOS structure results in understating the value of the collector current. It is very visible in the range of small values of the current i_C. In this case, the device case temperature T_C rises to 100°C, whereas for the transistor situated on the heat-sink - to 50°C.
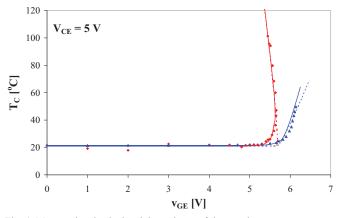

Fig. 4. Measured and calculated dependence of the transistor case temperature on the voltage v_{GE}.

Fig. 5 presents the output characteristics of the considered transistor obtained at the voltage $V_{GE} = 5.4$ V, lower than the threshold voltage, whereas Fig. 6 - corresponding to them dependences of the device case temperature on the voltage v_{CE}.

In the case of ideal cooling and for the transistor situated on the heat-sink the collector current has low values, resulting from the operation of the input MOS transistor in the sub-threshold range. For the transistor operating without any heat-sink the case temperature rise of this device equal to 18°C causes only a sharp increase of the collector current and a decrease of the voltage v_{CE}. In this range, the input MOS transistor passes from the sub-threshold range to the saturation

range. The case temperature of the transistor goes up to $120^{\circ}C$ and the value of the threshold voltage decreases under the value of the control voltage V_{GE}. When the sub-threshold phenomena is omitted, the transistor operates in the cut-off range and the i_C current is nearly zero, whereas the device case temperature is equal to the ambient temperature.
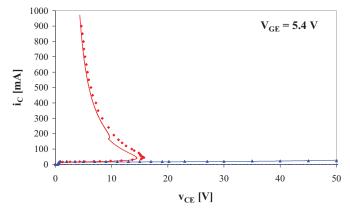

Fig. 5. Measured and calculated output characteristics of the investigated transistor at $V_{GE} = 5.4$ V.
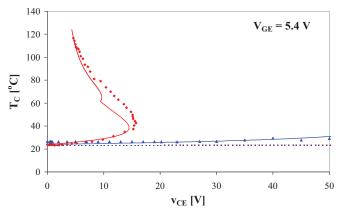

Fig. 6. Measured and calculated dependence of the transistor case temperature on the voltage v_{CE} at $V_{GE} = 5.4$ V.

Fig. 7 presents the output characteristics of the examined transistor obtained at the voltage $V_{GE} = 5.6$ V, lower by only just 20 mV from the threshold voltage, whereas Fig. 8 - corresponding to them dependences of the device case temperature on the voltage v_{CE}.

As it can be noticed, both for the transistor situated on the heat-sink and for the transistor operating without any heat-sink, there appear sections of the negative slope. The change of the sign of the slope of these characteristics appears when the case temperature of the device exceeds $40^{\circ}C$. Unfortunately, at the considered value of the voltage v_{GE}, only qualitative agreement between the calculated and measured characteristics for the transistor situated on the heat-sink is obtained. For the model without the sub-threshold phenomena, the collector current is near zero and the case temperature is practically equal to the ambient temperature.
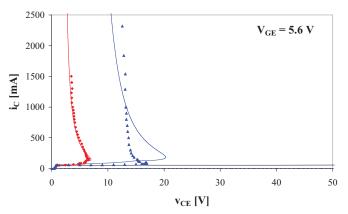

Fig. 7. Measured and calculated output characteristics of the investigated transistor at $V_{GE} = 5.6$ V.
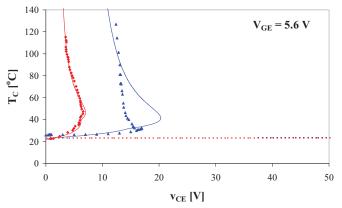

Fig. 8. Measured and calculated dependence of the transistor case temperature on the voltage v_{CE} at $V_{GE} = 5.6$ V.

Figs. 9 and 10 illustrate the output characteristics of the considered transistor and the dependence $T_C(v_{CE})$ at the voltage $V_{GE} = 6$ V. It is clearly visible that worsening the cooling conditions of the transistor causes an increase in the value of the collector current i_C at the fixed value of the voltage v_{CE}. In this case, the output characteristics have a positive slope in the whole examined range of voltages and currents.
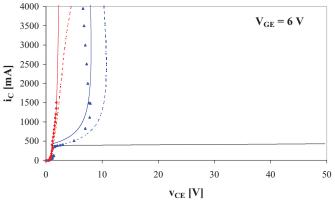

Fig. 9. Measured and calculated output characteristics of the investigated transistor at $V_{GE} = 6$ V.
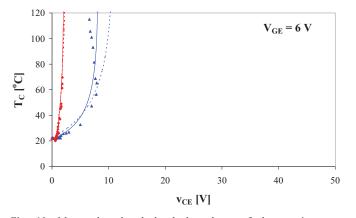
Fig. 10. Measured and calculated dependence of the transistor case temperature on the voltage v_{CE} at $V_{GE} = 6$ V.

For the transistor operating without any heat-sink the influence of the sub-threshold effect on the considered characteristics is not visible, whereas for the transistor situated on the heat-sink one can observe that the considered characteristics move to the right direction when the sub-threshold effect is not taken into account.
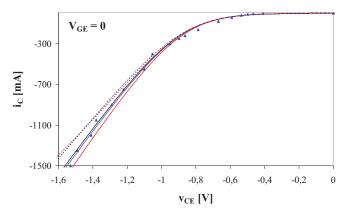

Fig. 11. Measured and calculated reverse output characteristics of the investigated transistor at $V_{GE} = 0$.

The output characteristic in reverse polarization of the examined transistor is shown in Fig. 11. This characteristic practically does not change the course for all the considered cooling conditions of the examined device. Series resistance of the transistor has essential influence on the course of the considered characteristic.

IV. CONCLUSIONS

In this paper, the electrothermal model of IGBT dedicated for SPICE is proposed. This model has a simple form, and, nonetheless, makes possible the correct calculation of non-isothermal characteristics of the considered device at different cooling conditions. Except terminal voltages and currents the proposed model makes it also possible to calculate the internal temperature and the case temperature of the examined device.

The presented results of calculations and measurements show that, as a result of self-heating phenomena, changes in the shape of characteristics of the considered device are visible. Particularly, the negative slope of the non-isothermal

transfer and output characteristics of the considered transistor while exciting this device with the voltage of the value not strider than the threshold voltage, is observed. This phenomenon results from the high value of the sub-threshold component of the drain current of the MOS structure existing in the analysed IGBT, being an exponentialy increasing function of the internal temperature of the transistor, and the decreasing dependence of the threshold voltage on this temperature.

It is worth noticing, that the sub-threshold phenomenon, typically omitted in classical IGBT models [24] is very important, when the considered device operates with low control signal. In this situation, the output characteristics of the IGBT can have a shape of the letter S and the collector current can attain values even some thousands higher than the values obtained without sub-threshold phenomena taken into account.

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