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DC characteristics of the SiC Schottky diodes

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Abstract. The isothermal and non-isothermal characteristics of silicon carbide Schottky diodes in the wide range of currents and ambient temperatures are investigated in this paper. The measurements of the diodes characteristics have been performed with the use of a pulse method, with fast registration of measurement points after the diode current turning on, or with the use of a fully static method, in which the self-heating phenomenon is taken into account. Apart from the measurements, the series of numerical experiments, giving the isothermal and non-isothermal characteristics as a result, were executed. The complex, accurate numerical procedures as well as simplified analytical calculations were implemented. A good conformity of all calculation and measurement results have been obtained.

In the presented investigations, for relatively high currents and ambient temperatures, the influence of self-heating on the SiC Schottky diodes static characteristics is significant. The large (even 4 V for the ambient temperature 300°C) values of voltages corresponding to the nominal diode currents have been observed.

Key words: silicon carbide, Schottky diodes, static characteristics, high temperature.

1. Introduction

Silicon carbide (SiC) is a very promising material for electronics (especially – power electronics), because of such qualities as the wide band-gap (3.23eV for 4H SiC) and high thermal conductivity. Because of a wide band-gap, the intrinsic carrier concentration for silicon carbide is very small, in relation to the concentration in silicon or gallium arsenide. This is the main reason, why SiC devices may work properly when the temperature achieves unacceptable values for other semiconductors. Another consequence of the wide band-gap of SiC is the high value of critical electric field, several times higher than for silicon. The natural result of high value of critical electric field is the possibility of achieving a high breakdown voltage of SiC devices. Because of good thermal conductivity, the cooling of silicon carbide devices is more effective, than for these ones of silicon or gallium arsenide.

Schottky Barrier Diodes (SBDs) are currently the most mature SiC devices and are delivered by several manufacturers (e.g. Cree, Infineon, Sensitron). SiC Schottky diodes exhibit very attractive features: fast switching and high values of reverse voltage ratings – impossible to simultaneously achieve by silicon- based diodes. They are also potentially able to operate in the range of very high ambient temperatures and power densities [1–4]. The forward current, reverse voltage and junction temperature rating approach 50 A, 2500 V and 250°C appropriately [5, 6]. The disadvantage of silicon carbide devices is the relatively large value of forward voltage (for example 2.4 V at forward currents 4 A (CSD04060) and 8 A (CSD08060) [5]). The operation of SiC devices in the wide range of ambient temperature have been studied by many authors [7–9], and it is believed that the ambient temperature limit for their operation may, in the future, exceed 600°C [7].

The relatively high differences between theoretical possibilities of high temperature operation and permissible values of the junction temperature of real devices have many causes. One of them is the phenomenon of electro-thermal interactions involved with the self-heating which, in some circumstances, may lead to “thermal runaway” and the possible damage of a device. According to analysis presented in [7–9], the critical value of junction temperature, at which the “runaway” begins is relatively low, depending on the assumed values of device parameters: 238°C or even 110°C [7].

Because of the influence of self-heating phenomenon on the electrical characteristics of SiC SBD’s, one should distinguish the isothermal and non-isothermal DC I-V characteristics of a device. The term “isothermal characteristic” denotes in this paper the I-V dependence obtained for constant junction temperature of a device. The isothermal conditions may be approximately achieved in measurements of I-V characteristics if a pulse method is applied and the junction temperature rise is sufficiently low. The standard I-V characteristics presented in data sheets are obtained in isothermal conditions. The non-isothermal DC characteristic is a sequence of points on I-V plane, each of them corresponds to steady-state conditions, in particular the fixed value of junction temperature. The difference between the isothermal and non-isothermal D.C. characteristics is a result of self-heating. The main purpose of the paper is to investigate the non-isothermal I-V characteristics of SiC SBD’s and to analyze the differences between the isothermal and non-isothermal characteristics. The examples of SiC SBD’s characteristics taken from manufacturer’s data sheet are compared in Sec. 2 with the results of the own measurements obtained in isothermal or non-isothermal conditions.

In Sec. 3, the basic formulas used in simulations of SiC SBD’s characteristics are presented and the procedure of the extraction of the parameters is outlined. It is observed that the

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parasitic series resistance of a diode strongly influences the I-V non-isothermal characteristics in high current values range, therefore the special attention is paid to the model of this resistance and its parameters.

In Sec. 4 the calculations of SiC SBD's characteristics are presented, corresponding both: to the isothermal or non-isothermal conditions. Apart from simulations based on MATLAB, the simplified analytical formula for I-V non-isothermal characteristic is presented and verified. Concluding remarks are given in Sec. 5.

2. Measurements of the I-V characteristics of silicon carbide Schottky diodes

The essential description of electronic device is usually its current-voltage characteristics, which may be acquired from manufactures data, from independent measurements or calculated with the use of available models.

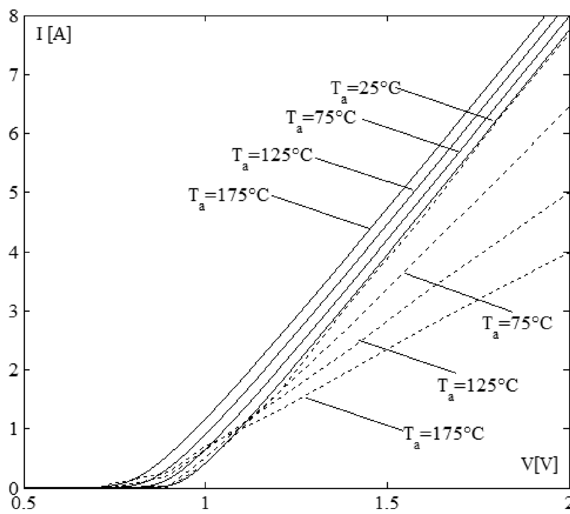

Fig. 1. Isothermal characteristics of an exemplary CSD04060 diode – measurements from Cree data sheet (dotted lines) and calculated from the Cree PSPICE model (solid lines)

The numerical models are especially popular in the case of electronic circuits designing, because of their applicability. Such models, dedicated to the work with popular circuit simulators (such as PSPICE), are often available on the manufacturers websites. Unfortunately, they are not always prepared in conformity with the real properties of considered devices. The example of such situation is shown in Fig. 1, where the measured by Cree [5] and calculated on the basis of Cree model [5] characteristics are compared. In the presented case (see Fig. 1), the Cree model prepared for PSPICE does not include the influence of the temperature on the parasitic series resistance, which increases substantially with the temperature rise. This is the reason, why the I-V curves calculated with the use of Cree PSPICE model differ considerably from those presented in the data sheets.

To obtain a reliable representation of exemplary SiC devices, the authors of this paper have performed series of SiC SBD's forward I-V characteristics measurements. In the case of isothermal characteristics, the current pulse width was equal to 0.1 ms – for each of the measurement points. The rise of the device junction temperature have never exceeded 0.1°C. In the case of non-isothermal characteristics, the time period required to achieve the electro-thermal steady-state was 60 s. Each of the points on the non-isothermal curve corresponds to a different value of junction temperature.

The values of the thermal resistances and the curves of transient thermal impedance have been obtained from another group of measurements [10].

The exemplary isothermal and non-isothermal characteristics of SiC SBD's – measured for the various ambient temperatures are shown in Figs. 2 and 3. For the rising values of current and ambient temperature – the differences between the isothermal and non-isothermal characteristics become more visible.

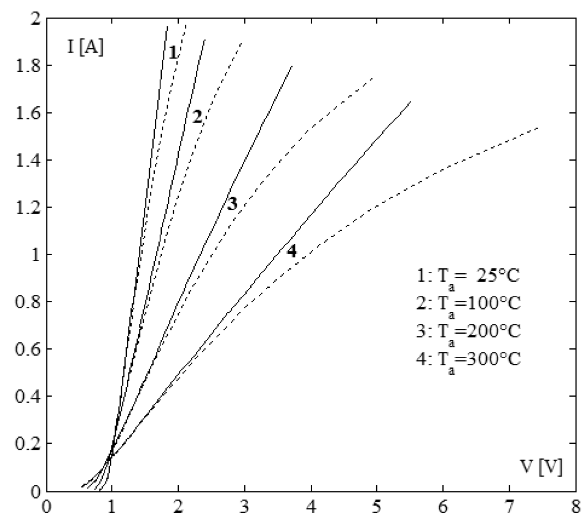

Fig. 2. Measurements of the isothermal (solid lines) and non-isothermal (dotted lines) characteristics of exemplary CSD01060 SiC SBD

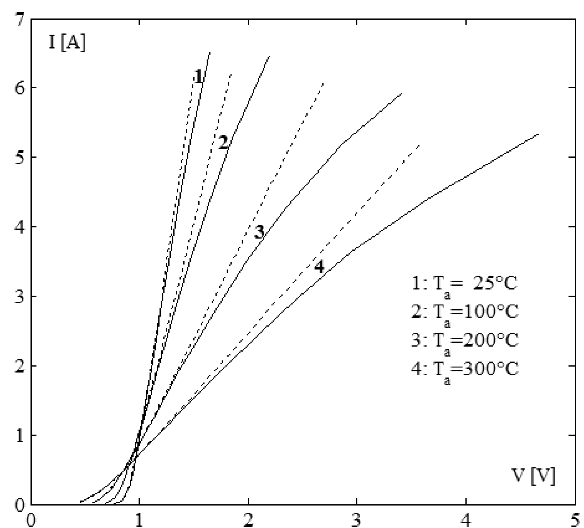

Fig. 3. Measurements of the isothermal (solid lines) and non-isothermal (dotted lines) characteristics of exemplary CSD04060 SiC SBD

3. Dependencies and parameters for the calculation of non-isothermal diode characteristics

The calculations of the DC diode characteristics are usually based on the model with the coefficients obtained from the measurement data. Authors of this paper have assumed the standard description of the current-voltage characteristic of a Schottky diode [11]:

$$I = I_S \cdot \left[\exp\left(q \cdot \frac{V - R_S(T) \cdot I}{N \cdot k \cdot T}\right) - 1\right], \tag{1}$$

where V – the voltage across a diode, I – the diode current, k – Boltzmann constant, q – elementary charge, I_S – saturation current, R_S – parasitic series resistance, T – junction temperature.

The saturation current is related to the junction temperature in a following way:

$$I_S(T) = I_{S0} \cdot \left(\frac{T}{T_0}\right)^D \cdot \exp\left(\frac{V_{G0} \cdot q}{N \cdot k \cdot T_0}\right) \cdot \exp\left(\frac{-V_{G0} \cdot q}{N \cdot k \cdot T}\right). \tag{2}$$

The parasitic series resistance depends on the temperature, that may be modeled by the linear, quadratic or power function [7, 12]:

$$R_S(T) = R_{S0} \cdot [1 + \alpha_0 \cdot (T - T_0)], \tag{3}$$

$$R_S(T) = R_{S0} \cdot \left[1 + \alpha_1 \cdot (T - T_0) + \alpha_2 \cdot (T - T_0)^2\right] \tag{4}$$

or:

$$R_S(T) = R_{S0} \cdot \left(\frac{T}{T_0}\right)^\kappa, \tag{5}$$

where T_0 – reference temperature, R_{S0}, I_{S0} – series resistance and saturation current at the reference temperature, V_{G0} – barrier voltage, N – emission coefficient, α_0, α_1, α_2, κ – fitting coefficients. Equations (3) and (4) are the standard description taken from PSPICE.

The additional dependence describing the self-heating effect is of the form:

$$T = T_a + K_t \cdot I \cdot V, \tag{6}$$

where K_t is the effective thermal resistance from junction to ambient, including heat sink.

For the identification of parameters in Eqs. (2)–(6), the particular procedure has been performed. First, on the basis of the family of isothermal diode characteristics, the values of series resistance $R_S(T_a)$ for different ambient temperatures are identified, what is shown in Fig. 3 (black dots). From such data one is able to assign values of α and κ coefficients in models (3), (4), (5). In Figs. 4 and 5, the curves representing dependencies $R_S(T_a)$, calculated with the use of Eq. (3) "linear function" and Eq. (4) "quadratic function" are also shown.

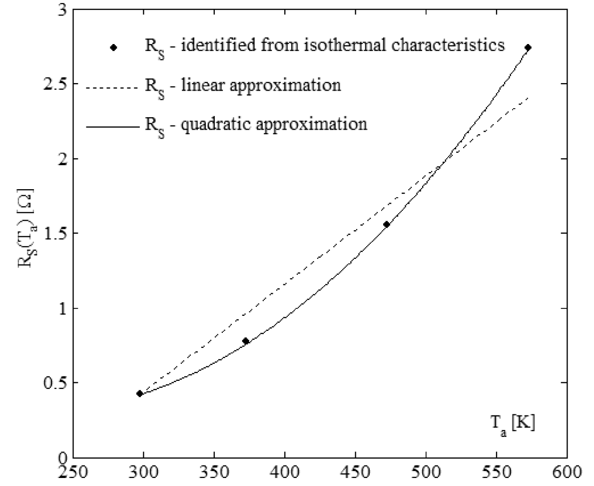

Fig. 4. The temperature-dependent parasitic series resistance of CSD01060 SBD

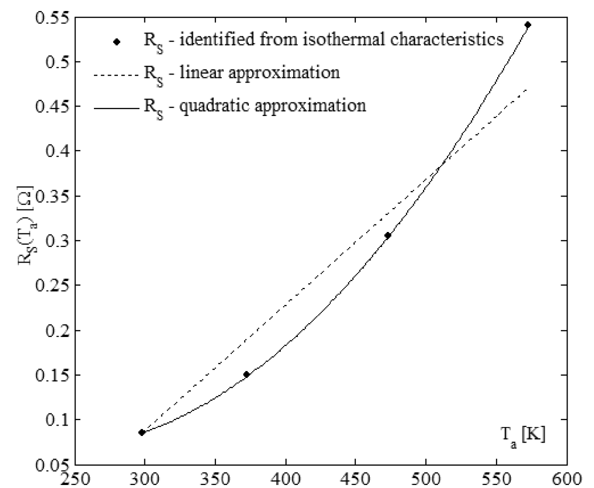

Fig. 5. The temperature-dependent parasitic series resistance of CSD04060 SBD

Afterwards, the parameters $I_S(T_a)$, N and V_{G0} are calculated by curve-fitting. The exemplary sets of coefficients describing some chosen SiC SBD's are shown in Table 1.

Table 1
Exemplary parameters of the SiC Schottky diodes models

	CSD01060	CSD04060
R_{S0} [Ω]	0.42	0.085
α_0 [1/K]	0.0172	0.0165
α_1 [1/K]	0.0072	0.0065
α_2 [1/K^2]	$4.65 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$
I_{S0} [A]	$3 \cdot 10^{-15}$	$21.6 \cdot 10^{-15}$
N	1.15	1.15
V_{G0} [V]	1.174	1.174
D	2.55	1.83
T_0 [K]	298	298
K_t [K/W]	6.4	2

In Figs. 6 and 7, the families of isothermal characteristics, calculated from Eq. (1), separately for various ambient temperatures are compared with measurement data. Very good consistency of measurements and calculations is obtained.

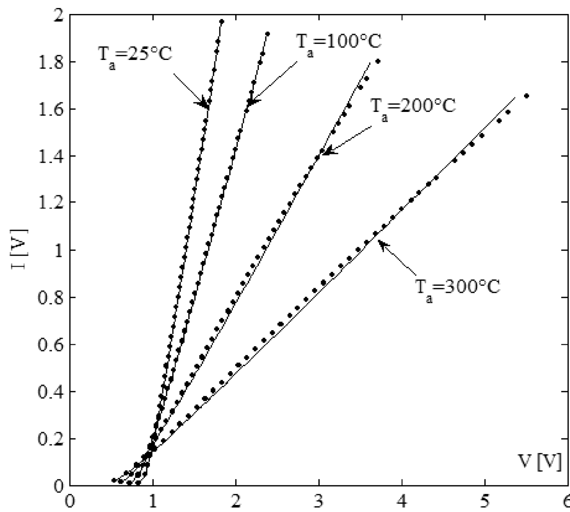

Fig. 6. Isothermal characteristics of an exemplary CSD01060 SBD at different ambient temperatures: measured (dots) and calculated (solid lines)

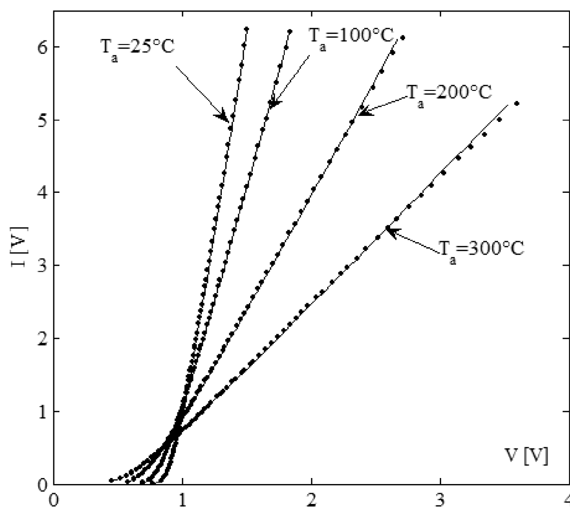

Fig. 7. Isothermal characteristics of an exemplary CSD04060 SBD at different ambient temperatures: measured (dots) and calculated (solid lines)

From the calculations presented in Figs. 5 and 6, and indirectly from Fig. 1, it may be observed that the parasitic series resistance of SiC SBD's strongly depend on the temperature. It is recommended to include this dependence as well in the isothermal as non-isothermal characteristics calculation.

The proper identification of the device parameters is quite important for the further simulation of its I-V characteristics.

4. The calculations of non-isothermal characteristics

The DC, non-isothermal Schottky diode characteristics may be calculated with the use of dependencies (1)–(6), using specific values of coefficients (for example from Table 1). Very accurate simulations may be performed using for example MATLAB program). In such case, the full set of Eqs. (1)–(6) is solved numerically.

A comparison of measured and calculated non-isothermal characteristics of an exemplary SBD (CSD01060) is presented in Fig. 8. The family of non-isothermal characteristics, calculated for an exemplary SBD (CSD04060) in the wide range of voltage and ambient temperature is shown in Fig. 9. The values of junction temperature, correspnding to the chosen points of I-V curves, are depicted in the figure.

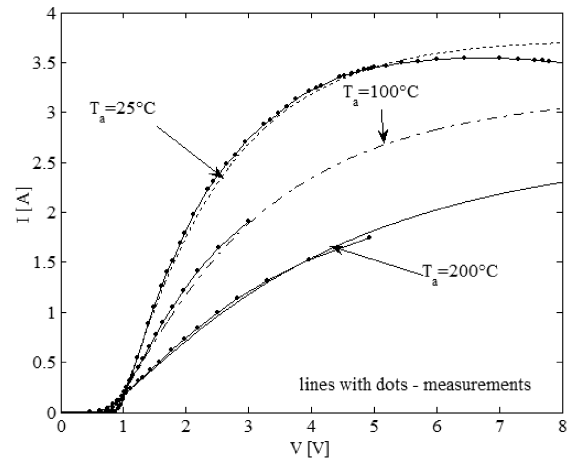

Fig. 8. Calculated and measured characteristics of CSD01060 SBD at various ambient temperatures

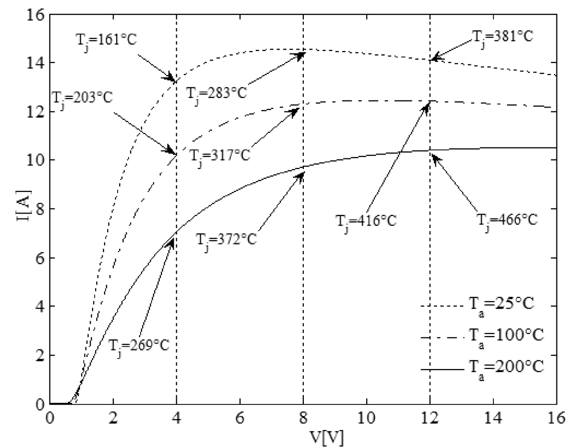

Fig. 9. Non-isothermal characteristics of an exemplary CSD04060 SBD, calculated in the wide range of voltage

It is seen, in Figs. 8 and 9, that in the case of non-isothermal characteristics, unexpectedly high values of forward voltage corresponding to relatively high values of current are obtained. It may be shown, that such increase of forward voltage is related mainly to the self-heating phenomenon in the parasitic series resistance of a diode. The influence of the series resistance on the non-isothermal I-V characteristics of SBD is shown in Fig. 10 [13]. The voltage drop on a diode, calculated with the real values of series resistance substantially differs from the voltage obtained for "ideal" diode without series resistance. The assumed parameters are the same as in Table 1 for the CSD01060 device, except the values of R_{S0}. The ambient temperature is 25°C. The typical values of the maximum operation temperatures, given by the manufactures in data sheets are marked with dots.

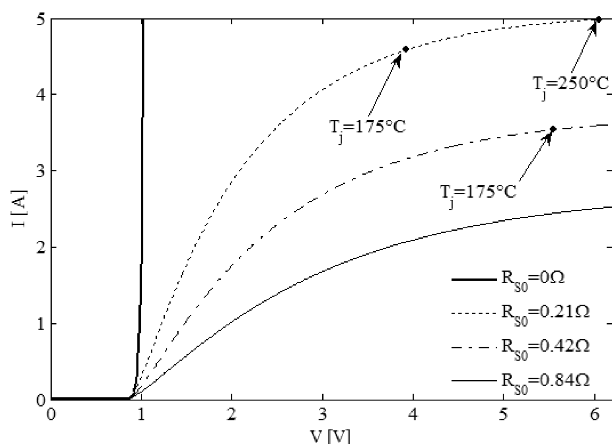

Fig. 10. Non-isothermal diode characteristics for various values of R_{S0} and $T_a = 25°$ C

It may be observed (see Figs. 8, 9), that for current-driven device, enough large value of current may cause the uncontrolled voltage rise. As it is seen, some of the I-V characteristics have a maximum, where the mentioned voltage rise may become dangerous and cause the device damage. On the other hand, voltage-driven SiC Schottky diodes still work "properly" for the wide voltage range, what may be observed in Figs. 8, 9 and e.g. in [14].

Apart from the numerical calculations of non-isothermal I-V characteristics based on the full set of Eqs. (1)–(6), the simplified analytical descriptions of such characteristics may be obtained. Using the linear approximation of $R_S(T)$ dependence, and assuming slight simplifications in (1)–(4), one obtains a non-isothermal characteristic in the form [15]:

$$V = \frac{\frac{N \cdot k \cdot T_a}{q}\left(\ln\left(\frac{I}{I_{S0}}\right) - \frac{q \cdot V_{G0}}{N \cdot k \cdot T_a}\right) + V_{G0} + R_{S0} \cdot I}{1 - \frac{N \cdot k \cdot R_{th} \cdot I}{q}\left(\ln\left(\frac{I}{I_{S0}}\right) - \frac{q \cdot V_{G0}}{N \cdot k \cdot T_a}\right) - \alpha_0 \cdot R_{S0} \cdot I^2 \cdot R_{th}}. \tag{7}$$

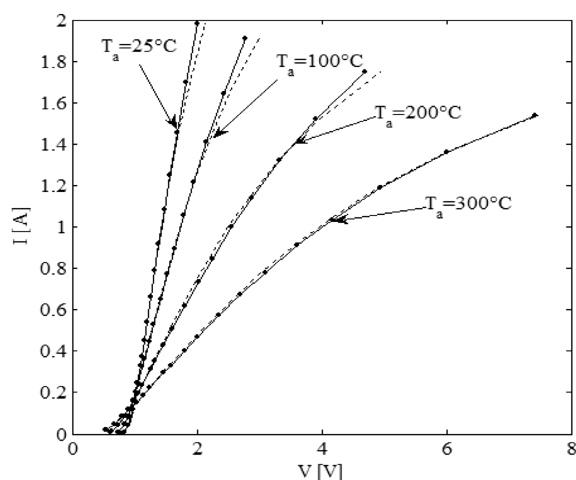

Fig. 11. A comparison of non-isothermal characteristics of CSD01060 SBD; measured (dotted lines), and calculated from Eq. (7) (solid lines with dots)

In Eq. (7) the ambient temperature is taken as a reference temperature. Equation (7) is useful in the simplified calculations of the approximated non-isothermal characteristics. Families of such characteristics of chosen SiC SBD's, for the specified set of parameters, have been calculated. The obtained curves do not differ substantially from those calculated with the more accurate procedure in MATLAB. In Figs. 11 and 12, the exemplary non-isothermal characteristics, compared with the measurement results, have been presented.

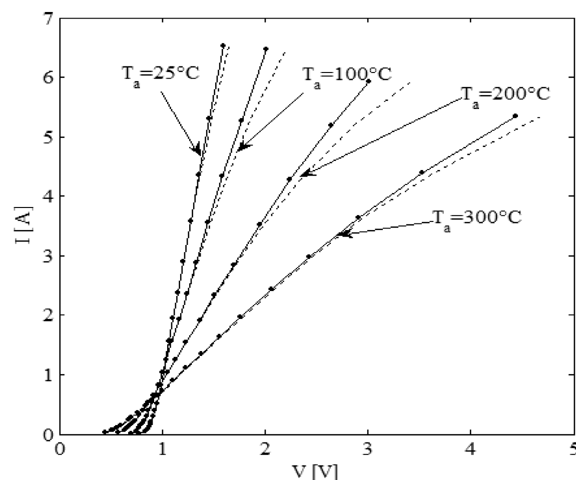

Fig. 12. A comparison of non-isothermal characteristics of CSD04060; measured (dotted lines), and calculated from Eq. (7) (solid lines with dots)

The results of calculations and measurements, presented in Figs. 11 and 12 are in relatively good conformity.

5. Conclusions

Isothermal and non-isothermal DC characteristics of SiC Schottky diodes in the wide range of ambient temperature have been shown in this paper. The mentioned characteristics have been obtained from the measurements and from the simulations based on the accurate procedure or on the simplified analytical description. The non-isothermal DC characteristics are the set of points corresponding to the thermal and electrical steady-states and substantially differ from the isothermal ones, given usually in the manufacturers data sheets. The main reason of mentioned differences is the self-heating phenomenon in the parasitic series resistance of a SiC SBD. As it is shown in the paper, the rise of junction temperature causes the relevant increase of series resistance. As a consequence, the voltage across a conducting diode strongly rises with the temperature rise. The maximum voltage, observed experimentally at the ambient temperature equal to 573K and without exceeding the maximum allowable current, achieves 4V. The results of self-heating in series resistance are especially dangerous in the case of current driven devices, in which, at a critical value of current, the uncontrolled rise of voltage may occur and cause the damage of a device.

The strong influence of the temperature-dependent series resistance on the I-V curves is one of the reasons of given by the manufacturers restrictions, such as surprisingly low allowable operation of currents and junction temperatures.

The procedures for proper prediction of the non-isothermal characteristics of SiC SBD's are the useful tool for specification of the device thermally induced limitations, especially that the measurements and calculations performed heretofore by authors, suggest the possibility of increasing the allowable temperatures and power densities even for the devices available commercially.

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