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Short communication

Influence of series resistance and cooling conditions on I–V characteristics of SiC merged PiN Schottky diodes

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ABSTRACT

The paper presents the exemplary electro-thermal models of merged PiN Schottky diode – a diode with the parallel PiN junction, protecting the device against the uncontrolled voltage rise, causing so-called thermal runaway. In the presented models, the conductivity modulation effect in the PiN junction is taken into account. The influence of the PiN junction on the non-isothermal *I–V* characteristics of MPS diodes, for various cooling conditions, is discussed. It is shown, that the thermal runaway is possible, in spite of presence of protecting PiN junction.

1. Introduction

The silicon carbide devices are under intensive development. The laboratory tests show, that their operation temperature limit may exceed 500 °C [1,2], but such experiments are performed (also by the authors [3]) only in the laboratory tests and have no confirmation in the manufacturer declarations. So far, the operation junction temperatures given in the manufacturers data sheets do not exceed 175 °C – even for the 4th generation Cree SiC Schottky diodes [4]. If we would consider the MOSFET transistors, the maximum junction temperatures for such devices developed by the most popular manufacturers (Cree) are specified as 125 °C, but there exist data sheets from CISSOID, where the allowable junction temperature is declared as 225 °C [5].

The most mature SiC devices are merged PiN Schottky diodes (MPS) [6,7]. Some important limitations of operation conditions for those diodes are the result of the influence of the temperature on the parasitic series resistance. The considerations devoted to the mentioned limitations, with a special attention paid to the consequences of the self-heating phenomenon, may be found in [8–10]. In the case of true static characteristics [10], the increase of junction temperature often causes the uncontrolled rise of the voltage across the conducting device. In some circumstances it may lead to so called "thermal runaway" effect. As a protection against the thermal runaway, the additional PiN junction is formed in the structure of MPS diode [11,12]. On the basis of series of measurements, the authors have observed, that the PiN junction does not fulfil its protecting function for some combinations of operation conditions (thermal resistance, parasitic series resistance). Therefore, we consider the two principal cases. In the first case, described in Section 2 of this paper, the influence of PiN junction is neglected. In Section 3, the presence of PiN junction is taken into account, and the operation areas in which PiN junction visibly shapes the DC characteristics are specified.

2. Simplified description of Schottky diode

The forward characteristics of the Schottky diode are *I–V* dependence, where the voltage drop across the conducting device consists of two terms: the voltage on the ideal metal–semiconductor junction and the voltage drop across the parasitic series resistance R_S [9]. It is known, that the series resistance depends on the temperature and influences the shapes of *I–V* characteristics.

In general, the two cases of *I–V* dependence should be distinguished. The first – is so called isothermal case, where junction temperature is equal to the ambient temperature. The isothermal characteristics may be obtained by measurements, if the cooling conditions are nearly perfect, or if the measurements are performed with the use of the pulse method. The "nearly perfect" cooling conditions may be achieved, when the heat-sink provides fast and total disposal of the heat accumulated in the device. Such conditions are usually assumed by the manufacturers in the presentation of the thermal or electrical characteristics [4]. In the pulse method,

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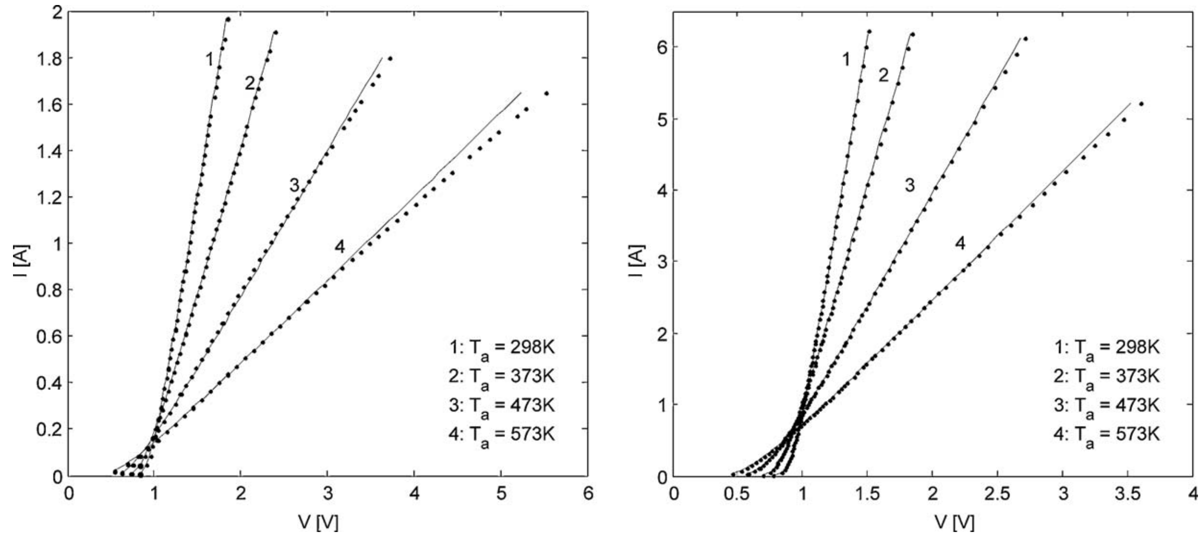

Fig. 1. The isothermal characteristics of SiC Schottky diodes: (a) CSD01060 and (b) CSD04060.

the measurements of the points on *I–V* characteristics are accomplished in a very short periods of time – the junction temperature rise is sufficiently low [13].

The analytical description of isothermal characteristics is taken from the standard PSPICE model (with the ambient temperature T_a taken as T) [14,15]:

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

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

$$R_S(T) = R_{S0} \cdot [1 + \alpha_1 \cdot (T - T_0) + \alpha_2 \cdot (T - T_0)^2] \quad (3)$$

where I_S is the saturation current; R_S is the parasitic series resistance, I_{S0}; R_{S0} is the saturation current and series resistance at the reference temperature T_0 (usually 298 K); V_{G0} is the barrier voltage; N is the emission coefficient, k; q is the physical constants and α_1, α_2 are the fitting coefficients. The parameters $I_S(T)$, $R_S(T)$, N, α may be identified on the basis of the measured characteristics. In the families of isothermal *I–V* curves, measured and calculated by the authors for various ambient temperatures are shown in Fig. 1. In the higher current area, the significant differences between the characteristics obtained for various ambient temperatures may be observed. The mentioned differences come from the dependence of the parasitic series resistance on the temperature.

It should be pointed out, that only the isothermal *I–V* characteristics are available in the manufacturer data sheets. Such characteristics do not include the self-heating phenomenon, and give the misleading information about the device behavior – e.g. the value of parasitic series resistance (at room temperature), estimated on the basis of isothermal characteristics is about 30% lower than the real value of this resistance in the electro-thermal steady-state [16]. Going further – the danger of thermal runaway occurrence is completely invisible on the isothermal characteristics.

In the more realistic conditions, when the cooling system does not provide the absolute heat removal and the significant temperature rise (with the self-heating phenomenon) occurs, the true-static *I–V* characteristics should be considered. Such characteristics give more reliable information about the device operating in the electronic circuit. The increasing junction temperature gives an increasing series resistance and voltage drop. Considering the Schottky diode, its non-isothermal characteristics, may be

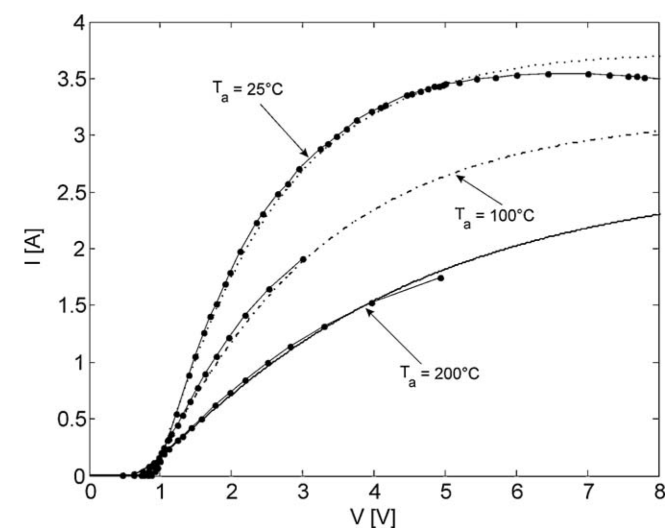

Fig. 2. The non-isothermal characteristics of an exemplary CSD01060 SBD at various ambient temperatures.

calculated on the basis of Eqs. (1)–(3), (with the junction temperature taken as T), and combined with the dependence [17–19]:

$$T = T_a + R_{th} \cdot I \cdot V \quad (4)$$

where R_{th} is the thermal resistance of the device and T_a is the ambient temperature.

The measured and calculated *I–V* characteristics of an exemplary SiC SBD, with the self-heating included are shown in Fig. 2. They are the true static characteristics, where each measurement point corresponds to the thermal equilibrium achieved. The shapes of non-isothermal characteristics of considered devices are strongly influenced by the series resistance and the thermal resistance. The electro-thermal interactions, in some conditions, may be interpreted as a positive feedback, which may lead to the "thermal runaway". The mentioned conditions are discussed in particular in [8,10,19,20].

3. Influence of PiN junction on MPS characteristics

In some areas of the MPS characteristics, the decrease of effective series resistance of the device may be observed. Such decrease

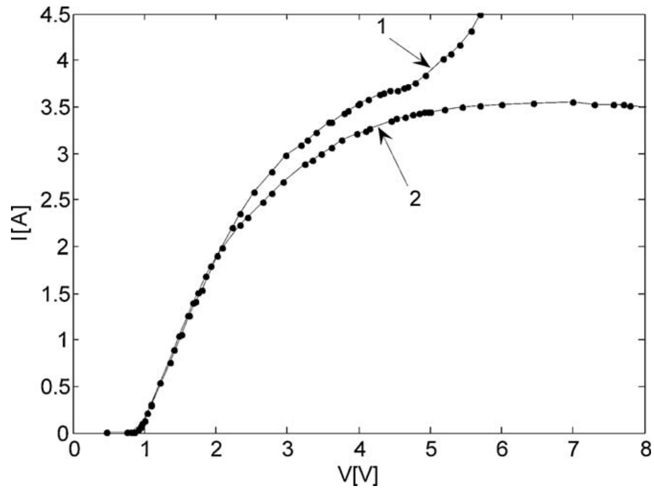

Fig. 3. The exemplary non-isothermal characteristics of CSD01060 MPS diode, measured for the two various heat-sinks: large RAD-A6405A/150 (1), medium RAD-A4062/100 (2).

is caused by the conductivity modulation in the PiN junction. As a consequence, the voltage drop does not achieve such large values, as in the case of absence of the PiN junction. The mentioned junction is "turned on" only for the sufficiently large values of diode current. On the other hand, we have observed, that the cooling conditions are the main factor determining the turning on of PiN junction, which stays inactive if the thermal resistance is relatively large.

The exemplary non-isothermal characteristics of MPS diode, measured for the two different types of heat-sinks, characterized with the different thermal resistances, are shown in Fig. 3.

The proper model of MPS diode should consist of the two parallel junctions: metal–semiconductor with the parasitic series resistance R_S and PiN junction with the series resistance R_{SP}. The total current in the MPS diode is of the form:

$$I = I_S(T) \cdot \exp \frac{q \cdot [V - R_S(T) \cdot I_M]}{N \cdot k \cdot T} + I_{SP}(T) \cdot \exp \frac{q \cdot [V - R_{SP}(I, T) \cdot I_P]}{N_P \cdot k \cdot T} \tag{5}$$

where I_M is the forward current in the M–S junction, I_P is the current in the PiN junction. The temperature-dependent saturation currents of M–S (I_S), and PiN junction (I_{SP}) are described by Eq. (3). It should be pointed out, that the values of saturation currents (I_{S0} and I_{SP0}) and barrier voltages (V_{G0} and V_{G0P}) should be different. In the presented electro-thermal model, the assumed barrier voltage of the PiN junction (V_{G0P} = 1.2 V) is about 15% higher than assumed barrier voltage of metal–semiconductor junction (V_{G0} = 0.87 V). Such difference is physically reasonable [14]. The parasitic series resistance in the PiN junction, with the I_H coefficient modeling the conductivity modulation, is of the form [17]:

$$R_{SP}(T) = \frac{R_{S0P}}{1 + (I/I_H)[1 + \alpha_{1P} \cdot (T - T_0) + \alpha_{2P} \cdot (T - T_0)^2]} \tag{6}$$

where R_{S0P} is the parasitic series resistance at the reference temperature and sufficiently low current. In the non-isothermal case, the DC characteristic is calculated from the set of Eqs. (2)–(6) [14,15,17].

4. Simulation examples

On the basis of the presented model, the series of simulations of MPS DC characteristics has been performed. In particular, the influence of the thermal resistance R_{th} on the shape of diode characteristics has been investigated. For the calculations, various values of R_{th} have been assumed, with the limiting values: R_{thj-c} (junction-to-case) and R_{thj-a} (junction-to-ambient, without heat-sink). The exemplary results obtained for the Cree diode CSD01060 are shown in Fig. 4. The dotted curves correspond to the measurement results, and the solid curves are the simulation results.

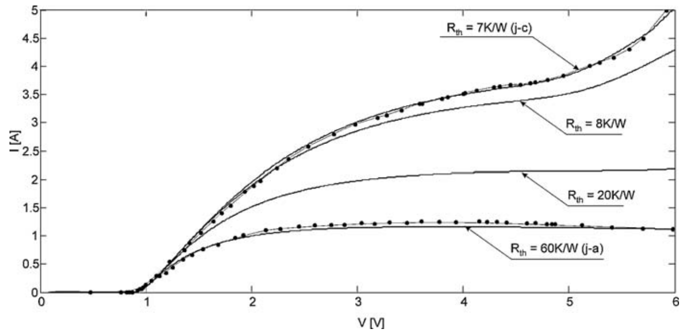

Fig. 4. The exemplary non-isothermal characteristics of CSD01060 MPS diode, measured (dotted lines) and calculated (solid lines) for the various values of the thermal resistance.

As it was described e.g. in [9], the thermal runaway effect may occur, when the device is supplied with the current source. In the more general case, the critical current value is only the maximum of the $I(V)$ function. In the case of PiN junction presence, the characteristics of MPS diodes may theoretically have the maximum point in the other region than in the case of pure metal–semiconductor junction, what may be seen in Fig. 5. The calculated characteristics shown in Fig. 5 are consistent with the measured characteristics – for the voltage range 0–12 V. For the forward voltages larger than 12 V, only the simulation results are available, because the predicted junction temperature is too high.

In the simulations, the maximum of the $I(V)$ dependence is achieved after the turning on the PiN junction. One may suspect, that such phenomenon is a result of perpetual increase of series resistance and for sufficiently high values of thermal resistance may be still dangerous, especially when the forward current is externally forced. As it was expected, the relatively small change of forward current forced in the device may cause the unacceptable increase of its voltage and junction temperature.

On the basis of simulations shown in Fig. 5, the values of forward voltage and, at which the PiN junction is turned on for various thermal resistances have been specified and shown in Fig. 6.

The parameters of the MPS models (5) and (6) have been identified on the basis of the characteristics measured by authors [3,13,16] with the use of least-square curve-fitting procedure, with the limits of each parameters imposed. Such limits have been assumed, to avoid obtaining of non-proper, physically unreasonable parameters. Such non-physical parameters may be found in the Cree models prepared for PSPICE [4].

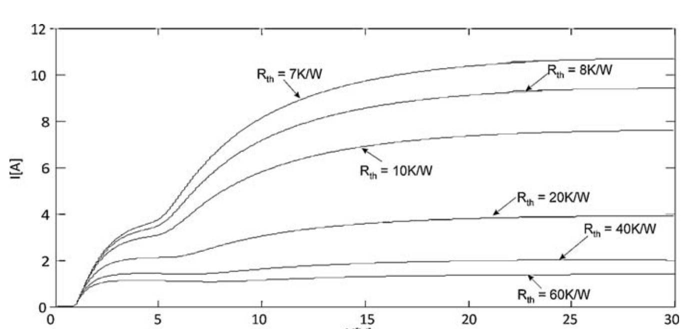

Fig. 5. The *I–V* characteristics of CSD01060 diode, calculated in the very wide range of forward voltage.

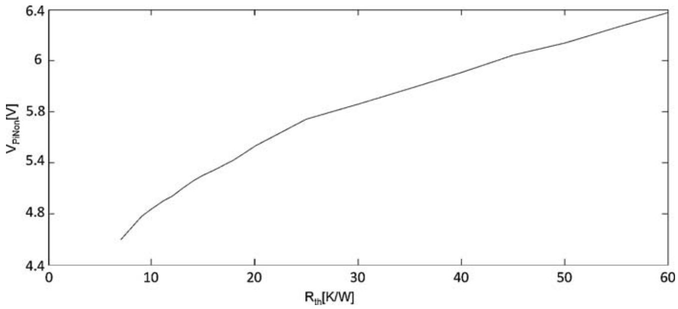

Fig. 6. The influence of thermal resistance on the PiN junction turning-on voltage.

In the presented example, the model parameters are as follows: $I_S = 3 \times 10^{-15}$ A; $R_S = 0.4\ \Omega$; $N = 1.2$; $V_{G0} = 1.05$ V; $I_{SP} = 2 \times 10^{-19}$ A; $R_{SP} = 0.1\ \Omega$; $N_P = 1.6$; $V_{G0P} = 1.2$ V; $I_H = 0.5$A; $\alpha_1 = 0.0072$/K; $\alpha_2 = 4.65 \times 10^{-5}/K^2$; $\alpha_{1P} = 0.005$/K; $\alpha_{2P} = 1.65 \times 10^{-5}/K^2$.

5. Summary

It is shown, that the temperature-dependent parasitic series resistance and the cooling conditions strongly influence the *I–V* characteristics of SiC MPS diodes. For some combinations of operating conditions, the dangerous effect, called "thermal runaway" may occur [8,10]. The possibility of thermal runaway has been recognized some time ago – and the manufactures have proposed the MPS devices with the protecting PiN junction. The average user may be convinced, that the Schottky diodes with merged PiN junction operate safely in the whole range of operation conditions. We have proved, that in some regions of operation conditions, the mentioned PiN junction does not fulfil its protecting function. In particular, the value of the thermal resistance is the factor determining the "turning-on" of PiN junction in the specified area of characteristics. The direct prediction of the thermal resistance limit, below which the influence of PiN junction on the *I–V* characteristics is visible is not possible without the detailed simulations of the non-isothermal characteristics of the device. Such simulations should be based on the models shown in this paper, including the self-heating phenomenon in both: PiN and M–S junction. After the comparison of the series of calculations and measurements, a good accuracy of the proposed model is observed.

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