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Isothermal current–voltage characteristics of high-voltage silicon carbide rectifier p–i–n diodes at very high current densities

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Abstract
It is shown that, at high current densities corresponding to current surges, the isothermal current–voltage characteristics of high-voltage silicon carbide diodes cannot, *in principle*, be measured experimentally if the lifetime of nonequilibrium carriers is high enough for effective modulation of the base resistance. In such cases, isothermal current–voltage characteristics must be 'reconstructed' from experimental pulse current–voltage curves by comparison with an adequate analytical or numerical model. A procedure of this kind is performed for high-voltage 4H-SiC rectifier diodes with a record-breaking high carrier lifetime τ of 3.7 μs at room temperature.

1. Introduction

Silicon carbide (SiC) as a base material for high-power, high temperature and high-frequency devices has demonstrated its great potential over recent years. In particular, a considerable progress has been achieved in design and development of high-voltage SiC rectifier p–i–n diodes. Recently, the fabrication of diodes of this kind, with a blocking voltage of 10, and even 19 kV, has been reported [1, 2]. To block a voltage of 10 or 19 kV, it is necessary to have a base width W of 100 or 200 μm, respectively. In turn, to provide an effective modulation of the base resistance during the forward current flow, it is necessary to have rather high non-equilibrium carrier lifetimes τ in the base of the p–i–n diodes.

Thanks to the modern techniques of SiC purification, very impressive results have been achieved in this field in recent years. Room temperature lifetimes as long as $\tau = 2.5$ μs [3] and $\tau = 3.7$ μs [4] have been observed in SiC high-voltage diodes. It is well known that, in SiC, τ increases with temperature (see, for example, [5–7]). At elevated temperatures of about 500 K, τ can be as high as 10 μs and even more. It is noteworthy that, with *any* method used to measure τ (open circuit voltage decay or current recovery time technique), the duration t_0 of the forward current pulse that injects non-equilibrium carriers into the base of a diode must be much longer than τ. It is usually assumed that, to provide the full base modulation, the condition $t_0 \geqslant (2–3)\tau$ should be satisfied.

The ability to withstand current surges is one of the most important requirements for p–i–n rectifier diodes. Surge currents appear rather frequently due to short circuits or high-power electromagnetic discharges. The current densities that correspond to loss of thermal stability in SiC diodes are rather high. For example, the limiting overload current density j_{ol} is ~6000 A cm^{-2} for 4.5 kV SiC diodes at ~2-ms forward current pulses [8]. In our preliminary experiments with high-voltage 4H-SiC rectifier diodes ($W = 70$ μm and diameter $a = 400$ μm) at 8 ms forward current pulses, the limiting overload current density j_{ol} was found to be ~9000 A cm^{-2}.

To measure the static current–voltage (I–V) characteristic, it is necessary to pass through the sample a pulse of a forward current of duration $t_0 \geqslant (2–3)\tau$. However, the temperature of the diode strongly increases due to self-heating, and such I–V characteristics cannot be considered isothermal. Meanwhile, just isothermal (I–V) characteristics should be used to calculate self-heating effects in both static and transient modes [8–12].

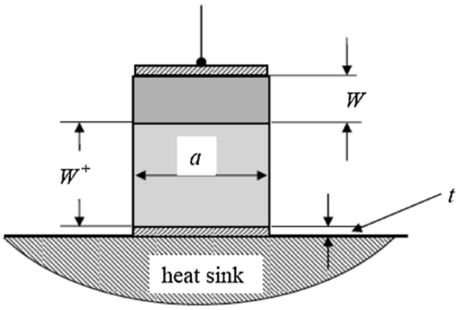

Figure 1. Schematic of the thermal model for a high-voltage SiC rectifier diode. W is the width of the blocking base; W^+ the width of the highly doped substrate; t the total thickness of the contact layer, solder, and thermo-compensating layers, and a is the diameter of the structure.

In this paper, we analyse the situation in which isothermal *I–V* characteristics cannot be measured experimentally *in principle*. As shown below, the isothermal current–voltage characteristics should be 'reconstructed' in such cases from experimental pulse *I–V* curves by using an adequate simulation. The procedure for a reconstruction of this kind is illustrated by the example of high-voltage 4H-SiC rectifier diodes with a record-breaking high carrier lifetime τ of 3.7 μs at room temperature.

2. Statement of the problem

Let us consider, as an example, a simplified heat sink model for a high-voltage SiC rectifier diode [13] (figure 1). The diode is soldered, with its bottom contact layer down and temperature-compensating layers of total thickness t placed in between, to a massive, supposedly semi-infinite copper heat-sink.

In the static situation (dc current), heat is released into the active layer of the structure, which has thickness W (W is virtually equal to the thickness of the blocking base of the diode), and, through a highly doped substrate of thickness W^+ and an intermediate layer of thickness t, dissipates into the copper heat-sink.

In the opposite limiting case of a 'short' current pulse, heat does not have enough time to reach the heat-sink during the time interval t_0, and the device overheating ΔT can be estimated as

$$\Delta T \approx \frac{j_{\mathrm{ol}} \cdot V_{\mathrm{ol}} \cdot t_0}{C_P \cdot \rho \cdot (W + L_{\mathrm{T}})} \tag{1}$$

where j_{ol} is the overload current density; V_{ol} is the forward voltage drop across the diode for j_{ol}; C_P is the specific heat; ρ is the density; $L_{\mathrm{T}} = \sqrt{\chi t_0}$, the characteristic length of heat diffusion during a pulse of width t_0; $\chi = K/\rho C_P$, the thermal diffusivity; and K, the thermal conductivity. When making such an estimation, we assume that the whole amount of thermal energy (per unit area) $P_0 = j_{\mathrm{ol}} \times V_{\mathrm{ol}} \times t_0$ is released in the blocking base of the diode and extends over a length L_{T}. Equation (1) is valid at $L_{\mathrm{T}} \leqslant W^+$ (at $t_0 \leqslant (W^+)^2/\chi$), e.g., at

$$\tau \leqslant \frac{(W^+)^2}{3\chi}. \tag{2}$$

In most cases, the substrate thickness W^+ in high-voltage SiC rectifier diodes is $\sim$300–350 μm. Hence, the pulse duration that allows use of expression (1) for such diodes is limited to $t_0 \leqslant 10^{-3}$ s, and $\tau \leqslant t_0/3 \leqslant 3 \times 10^{-4}$ s. (The value of χ for highly doped n$^+$-substrate is taken to be $\chi = 0.8$ cm^2 s^{-1}, which corresponds to $K = 1.8$ W cm^{-1} K^{-1}, $C_P = 0.69$ J g^{-1} K^{-1} and $\rho = 3.21$ g cm^{-3} [13].)

It is usually assumed that the optimal ratio W/L_{a} for high-voltage rectifier diodes can be estimated as (W/L_{a} $\sim$(2–3)). Here,

$$L_{\mathrm{a}} = \sqrt{2b/(b+1)D_{\mathrm{p}}\tau} \tag{3}$$

is the ambipolar diffusion length; $b = \mu_{\mathrm{n}}/\mu_{\mathrm{p}}$, where μ_{n} and μ_{p} are electron and hole mobilities, respectively; and D_{p} is the hole diffusion coefficient. With $\mu_n = 800$ cm^2 V s^{-1}, $\mu_p = 120$ cm^2 V s^{-1} [13], $D_{\mathrm{p}} = kT\mu_{\mathrm{p}}/q = 3$ cm^2 s^{-1} and $\tau = 3 \times 10^{-4}$ s, L_{a} is 390 μm. With $W/L_{\mathrm{a}} \sim 2$, the maximum value of $W_{\max}$ that allows use of formula (1) is $W_{\max} \sim 780$ μm. It is usually supposed for SiC rectifier diodes that, to block a voltage of 1 kV, it is necessary to have a base width of $\sim$10 μm. Hence, expression (1) can be used for SiC rectifier diodes with a blocking ability of up to $\sim$80 kV.

Let us estimate now the inevitable overheating of a SiC diode with a blocking voltage of 10 kV and record-breaking high minority carrier lifetime of 3.7 μs [4] at $j_{\mathrm{ol}} = 10$ kA cm^{-2} (room temperature). To estimate analytically the forward voltage drop $V = V_{\mathrm{ol}}$ at a current density j_{ol}, we can use the approach described in detail in [14]. In this approach, we have

$$V = V_{\mathrm{pn}} + V_{\mathrm{L}} + V_{\mathrm{eh}} + jR_S + jR_C, \tag{4}$$

where

$$V_{\mathrm{pn}} = \frac{kT}{q} \ln\left(\frac{p(0) \cdot p(W)}{n_{\mathrm{i}}^2}\right) \tag{5}$$

is the voltage drop across the emitter–base junctions;

$$V_{\mathrm{L}} = \frac{j}{q(\mu_{\mathrm{n}} + \mu_{\mathrm{p}})} \int_0^W \frac{\mathrm{d}x}{p(x)} = \frac{\pi}{2} \frac{jL_{\mathrm{a}} \exp(W/2L_{\mathrm{a}})}{q(\mu_{\mathrm{n}} + \mu_{\mathrm{p}})\sqrt{p(0) \cdot p(W)}}, \tag{6}$$

the ohmic voltage drop across the base n-layer, associated with all the scattering mechanisms except electron–hole scattering (EHS);

$$V_{\mathrm{eh}} = \frac{j}{q} \int_0^W \frac{\mathrm{d}x}{p\mu_{\mathrm{np}}} = \frac{jW}{qGp_0}, \tag{7}$$

the ohmic voltage drop across the base n-layer, associated with EHS; R_S, the substrate resistance; and R_C, the total contact resistance.

Here

$$p(0) = n_{\mathrm{i}}\sqrt{\frac{b}{b+1}\frac{j}{j_{\mathrm{sn}}}}, \qquad \text{and} \qquad p(W) = n_{\mathrm{i}}\sqrt{\frac{1}{b+1}\frac{j}{j_{\mathrm{sp}}}}, \tag{8}$$

are the boundary concentrations of carriers at $x = 0$ (p$^+$–n junction) and $x = W$ (interface between the n-base and the substrate), respectively; n_{i}, the intrinsic carrier concentration;

$$j_{\mathrm{sn}} = \frac{qD_{\mathrm{n}}^+ n_{\mathrm{ie}}^2}{L_{\mathrm{n}}^+ N_{\mathrm{A}}}, \qquad j_{\mathrm{sp}} = \frac{qD_{\mathrm{p}}^+ n_{\mathrm{ie}}^2}{L_{\mathrm{p}}^+ N_{\mathrm{D}}} \tag{9}$$

the effective saturation leakage currents determined at high injection levels by recombination in the emitters [15, 16],

D_n^+ and L_n^+ are the electron diffusion coefficient and electron diffusion length in the highly doped p$^+$-emitter layer, respectively, N_A, the doping level in the p$^+$-emitter; D_p^+ and L_p^+, the hole diffusion coefficient and hole diffusion length in the highly doped n$^+$-emitter layer, respectively; N_D, the doping level in the n$^+$-substrate;

$$n_{ie}^2 = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right), \qquad (10)$$

ΔE_g is the narrowing of the band gap due to the high doping level, and G and p_0 are constants characterizing the EHS (see, e.g., [17]).

Note that the parameters j_{sn} and j_{sp} enter into expression (6) as $\sqrt{j_{sn} j_{sp}}$. Our estimates based on numerous simulations of SiC power rectifier diodes (see, for example, [7, 14, 18]) give $j_s = \sqrt{j_{sn} j_{sp}} \approx 2.8 \times 10^{-47}$ A cm^{-2} at room temperature. The EHS parameters were found for SiC in [14]: $qGp_0 = 9.3\ \Omega^{-1}\ \mathrm{cm}^{-1}$.

With $j = 10^4$ A cm^{-2}, $\tau = 3.7\ \mu$s ($L_a = 44\ \mu$m), $W = 100\ \mu$m, $n_i = 1.3 \times 10^{-8}$ cm^{-3}, $R_S = W^+/\sigma^+ \approx 7.5 \times 10^{-5}\ \Omega$ cm^2 ($W^+ = 300\ \mu$m, $N^+ = 5 \times 10^{19}$ cm^{-3}, $\mu_n{}^+ = 50$ cm^2 V s^{-1}) and $R_C = 10^{-4}\ \Omega$ cm^2, we have $V_{pn} \approx 3.03$ V, $V_L \approx 10.2$ V, $V_{eh} \approx 10.75$ V, $V_s = jR_s \approx 0.75$ V, and $V_c = jR_c \approx 1$ V. Hence, the total forward voltage drop corresponding to $j_{ol} = 10$ kA cm^{-2} can be estimated to be $V_{ol} \approx 25.7$ V.

As mentioned above, we cannot use a forward pulse of duration t_0 shorter than $t_0 \geqslant 3\tau \approx 11\ \mu$s to measure correctly the steady-state forward I–V characteristics. The characteristic length of heat diffusion during the pulse time t_0, $L_T = \sqrt{\chi t_0}$, is equal to $L_T \approx 30\ \mu$m. Hence, (1) gives $\Delta T \geqslant 100$ K. It is clear that such measurements cannot be considered 'isothermal'. It should be emphasized again that there is no way to avoid this fundamental problem.

Meantime, to solve the very important problem of thermal stability of a rectifier diode, including that of surge currents, it is necessary to know its isothermal I–V characteristics at high current densities. That is why, development of a technique that would allow extraction of isothermal I–V characteristics from pulsed experimental measurements is very important for high-power wide-band electronics.

3. Experimental details

The device structures investigated here were 4H-SiC p$^+$nn$^+$ diodes manufactured by CREE, Inc. Mesa-structures of 400 μm in diameter were fabricated on a 350 μm n-type substrate doped to 5×10^{19} cm^{-3}. The voltage-blocking n-base had width W of 70 μm and effective donor doping concentration $N = N_d - N_a = 2 \times 10^{14}$ cm^{-3}. The doping level in the 2 μm thick p$^+$-emitter was 3×10^{18} cm^{-3} at the p$^+$–n interface and increased to $\geqslant 8 \times 10^{18}$ cm^{-3} at a distance of 1.7 μm from the interface.

The lifetime τ in the n-base has been measured using the open circuit voltage decay (OCVD) technique and found to be 3.7 μs at room temperature [4].

Forward I–V characteristics were measured using a pulse generator with a pulse rise time of 30 ns and pulse width of 12 μs (1 Hz repetition rate), up to a current density $j \sim 8000$ A cm^{-2}.

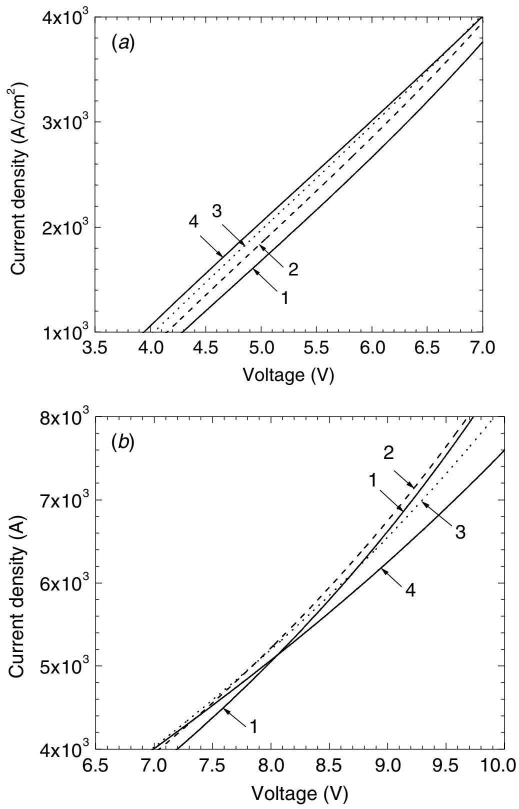

Figure 2. Experimental current densities versus forward bias dependences for the diode under study at different ambient temperatures: (*a*) j–V characteristics in the range from 1.0 to 4.0 kA cm^{-2}; (*b*) j–V characteristics at high current densities up to 8.0 kA cm^{-2}. Temperature T (K): 1–292; 2–352; 3–421; 4–472.

4. Results and discussion

Figure 2 shows experimental forward j–V characteristics of the diode under study at different ambient temperatures. Figure 2(*a*) presents j–V characteristics for current densities j from 1.0 to 4.0 kA cm^{-2}. Figure 2(*b*) shows j–V characteristics for current densities ranging from 4 to 8 kA cm^{-2}. As can be seen from figure 2(*a*), curves 1 and 2 have no inversion point at current densities in the range $1.0 \leqslant j \leqslant 4.0$ kA cm^{-2} [18]. Curves 3 and 4, measured at ambient temperatures of 421 and 472 K, respectively, intersect at $V \approx 6.6$ V ($j \approx 3.8$ kA cm^{-2}). It can be seen in figure 2(*b*) that there is no inversion point for curves 1 and 2 up to the maximum achieved current density $j = 8.0$ kA cm^{-2}). However, curves 3 ($T = 421$ K) and 4 ($T = 472$ K) intersect with all of the other pulse I–V characteristics.

As was emphasized above, the experimental pulse characteristics *are not isothermal*. The main idea of correct reconstruction of isothermal I–V characteristics from the experimental curves consists in thorough fitting of experimental dependences in the wide range of current densities, in which the self-heating effect can be neglected ($j \leqslant 4$–5 kA cm^{-2}), at widely varying ambient temperatures. Such a fitting requires that the temperature dependences of all the main parameters of silicon carbide should be taken into account, including the temperature dependences of the energy gap, intensity of electron–hole scattering (EHS), carrier mobilities and diffusion coefficients, lifetimes in the base layer and emitter layers, substrate resistivity and contact resistance. That is why we believe that such a procedure can be performed only by means of computer simulation.

The 'INVESTIGATION' ('ISSLEDOVANIE') software package [19] was used to fit the experimental *I–V* characteristics for a p^+–n–n^+ structure with the parameters listed above. This software package solves numerically a fundamental system of equations comprising two continuity equations (for electrons and holes) and a Poisson equation. The continuity equations are written in a form that takes into account all the main nonlinear phenomena in bipolar devices: electron-hole scattering, semiconductor band gap narrowing and Auger recombination. The program also takes into account the decrease in the carrier lifetime and mobilities in the highly doped p^+ and n^+ layers. A detailed description of the software can be found in [20]. The Investigation software has already been used to analyse steady-state and transient processes in high-voltage Si and SiC diodes and thyristors (see, for example, [7, 14, 21]).

We used in the calculations the same SiC parameters and their temperature dependences as those in [18]. So, we discuss here only the parameters that were directly used to extract the isothermal characteristics from the experimental results.

The lifetime in the blocking layer, τ, can be written as [21]

$$\tau(T) = \tau(T_0)\exp\left[\frac{\Delta}{kT_0}\left(1 - \frac{T_0}{T}\right)\right], \tag{11}$$

where $T_0 = 300$ K, $\Delta = 0.11$ eV, $\tau(T_0) = 3.7$ μs [4].

The dependence of life time in highly doped emitter layers, τ^+, on the doping level was taken into account in the form suggested in [22]:

$$\tau^+ = \frac{\tau}{1 + (N/N_\tau)^\alpha}. \tag{12}$$

It was assumed that the temperature dependence of τ^+ is described by an expression similar to equation (11):

$$\tau^+(T) = \tau^+(T_0)\exp\left[\frac{\delta}{kT_0}\left(1 - \frac{T_0}{T}\right)\right]. \tag{13}$$

For the temperature dependence of the contact resistance $R_c(T)$ a simple power dependence was used [14]:

$$R_C(T) = R_C(T_0)\left(\frac{T}{T_0}\right)^\beta. \tag{14}$$

Two different situations may occur in reconstruction of isothermal *I–V* characteristics. In the first case, the contact resistance $R_c(T_0)$ and its temperature dependence are safely known from independent TLM measurements. Then only the emitter parameters N_τ, δ and α in expressions (12) and (13) can be used for fitting. In the second case, which occurs much more frequently, $R_c(T_0)$ and its temperature dependence are not known and should be determined from experimental *I–V* characteristics. In this study, we deal with just the second case.

It is noteworthy that the parameters of the p^+-emitter, N_τ, δ and α, should be determined by comparison with experimental *I–V* characteristics at relatively small current densities, where the contribution of the terms V_{eh}, jR_S and jR_C, which are proportional to the current density, to the total voltage drop V is comparatively small (see equation (4)). (For the structures in question, this range of current densities is 500 A cm$^{-2} \leqslant j \leqslant$ 2000 A cm^{-2}.) By contrast, the contact resistance parameters can be conveniently determined from data for relatively large current densities (2000 A cm$^{-2} \leqslant j \leqslant$ 5000 A cm^{-2} for the structures in question), where the contribution to V from terms linear in current prevails.

When determining the emitter parameters (see expressions (12) and (13)), we assumed that, according to [22], the decrease in the lifetime in highly doped layers is caused by additional traps that appear on doping. Apparently, the trap concentration is independent of temperature at a given doping level N. The temperature dependence of the lifetime is due to temperature dependences of the cross-sections of traps and their position within the band gap with respect to the conduction (valence) band edges. Accordingly, N_τ and δ are considered to be temperature-independent parameters, and the value of α and its temperature dependence are extracted by fitting of experimental *I–V* characteristics.

The coordinate dependence of the doping level N along the p^+-emitter was taken into account. It was assumed that N increases linearly from 3×10^{18} cm^{-3} at the p^+–n interface to 8×10^{18} cm^{-3} at a distance of 1.7 μm from the interface and then remains constant within the remaining 0.3 (with the total emitter thickness equal to 2 μm).

The best fitting was achieved at $N_\tau = 10^{16}$ cm^{-3} and $\delta = 0.27$ eV. It is noteworthy that this value of N_τ falls well within the known interval of N_τ in Si 7×10^{15} cm$^{-3} \leqslant N_\tau \leqslant 10^{17}$ cm^{-3}. The value obtained for δ is close to $\delta = 0.22$ eV, found earlier for 10 kV SiC p–i–n diodes. The temperature dependence of α is well described by a simple power function:

$$\alpha(T) = \alpha(T_0)\left(\frac{T}{T_0}\right)^{-\nu} \tag{15}$$

where $\alpha(T_0) = 1.4$ and $\nu = 0.495$. The decrease in α, observed as the temperature increases, is due to the fact that lifetime in the emitter layers grows with temperature faster than does the lifetime in the base of the structure ($\delta > \Delta$).

The contact resistance parameters (see equation (14)) were found to be $R_C(300) = 1.24 \times 10^{-4}$ Ω cm^2 and $\beta = 1.85$. It is noteworthy that these values are rather close to $R_C = 2.1 \times 10^{-4}$ Ω cm^2 and $\beta = 2.25$, obtained earlier for 6 kV 4H-SiC p^+–n diodes [14].

The *I–V* characteristics calculated using the values obtained for the parameters N_τ, δ, α, $R_C(300)$ and β well describe the experimental results across the entire temperature interval under study at current densities $j \leqslant 4000$ A cm^{-2}. At larger values of *j*, an essential difference is observed, as expected, between the calculated isothermal and experimental pulse *I–V* characteristics.

Figure 3 shows as an example the calculated isothermal (curve 1) and experimental pulse (curve 2) *j–V* characteristics at an ambient temperature of 352 K. As can be seen, curves 1 and 2 virtually coincide at $j \leqslant 4000$ A cm^{-2}. Just the same behaviour was been observed at all the temperatures.

Figure 4 shows calculated isothermal *j–V* characteristics for the same temperatures as those in figure 2(*b*). Comparing experimental (figure 2(*b*)) and calculated (figure 4) curves, we can conclude that the positions of the inversion points, which determine the regions of current stability [18], appreciably differ for the actual isothermal *j–V* curves and

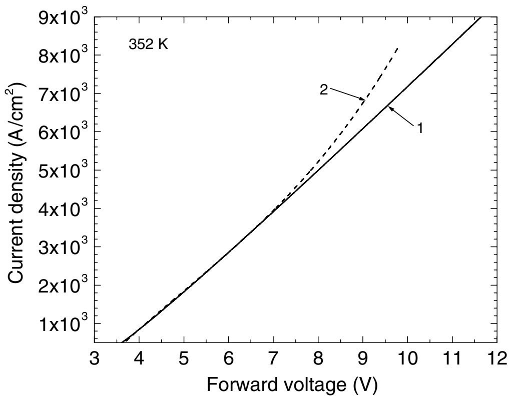

Figure 3. Calculated isothermal (curve 1) and experimental pulse (curve 2) forward j–V characteristics at 352 K.

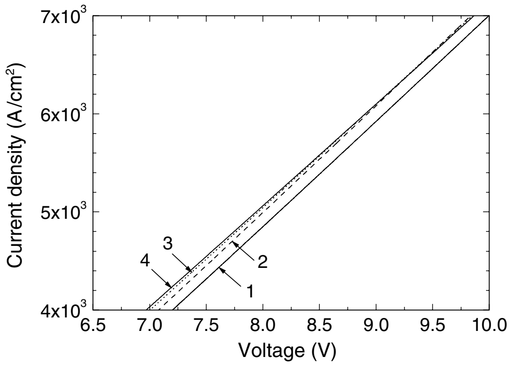

Figure 4. Calculated isothermal forward j–V characteristics of the diode under study at different ambient temperatures and high current densities (cf figure 2(b)). Temperature T (K): 1–292; 2–352; 3–421; 4–472.

the experimental pulse j–V characteristics. It can be seen that the isothermal characteristic at 292 K (curve 1, figure 4) has no points of intersection with the other curves, including the current density–voltage characteristic at 472 K (compare with figure 2(b)). The isothermal characteristics at the ambient temperatures $T = 352$, 421 and 472 K intersect virtually at the same point: $j \approx 6500$ A cm^{-2}.

It is noteworthy that the intersection of several I–V characteristics at approximately the same point ($j \approx 2500$ A cm^{-2}) in the temperature interval from 293 to 553 K was experimentally observed in [14] for a 6 kV ($W = 50$ μm) 4H-SiC diode.

Calculations show that, at high current densities and considerably higher temperatures, the run of the temperature dependence of current changes substantially (figure 5). The inversion points shift to considerably smaller current densities. At high current densities, the current decreases steadily and rather steeply as the temperature increases. The change in the nature of the temperature dependence of current can be explained as follows. As can be seen from the estimates made in section 2, the main contribution to the forward voltage drop across the diode, V, comes at room temperature from the terms V_L and V_{eh} (see equation (1)). Generally speaking, V_L can exhibit the following types of behaviour as the temperature becomes higher. It may both decrease, because of a rise in the lifetime, and increase due to a decrease in the mobility

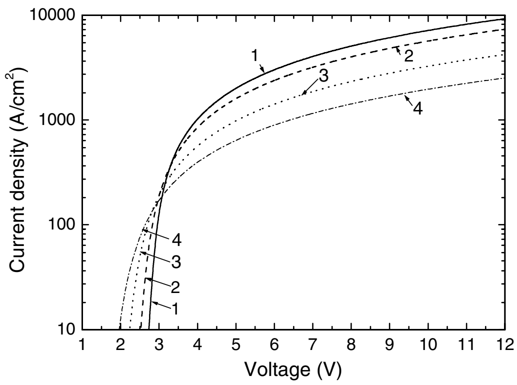

Figure 5. Calculated isothermal forward j–V characteristics at high ambient temperatures. Temperature T (K): 1–472; 2–600; 3–800; 4–1000.

at higher temperatures. Such a situation leads to complicated and non-monotonic temperature dependence of the current (at a given V).

In view of the fact that the EHS is caused by the Coulomb interaction, the temperature dependence of the constant Gp_0 was taken to be

$$(Gp_0)(T) = (Gp_0)(T_0)\left(\frac{T}{T_0}\right)^{\alpha}, \tag{16}$$

where $\alpha = 1.5$. Hence, the contribution from V_{eh} to V steadily decreases as the temperature grows, to become rather small at elevated temperatures. Meantime, the contribution to V from the contact resistance, V_c, which steadily grows with temperature, becomes highly important. If the temperature is high enough, just V_c determines the temperature dependence of the current at a given bias.

Tentative analysis shows that, under the self-heating conditions in the dc mode, a strong temperature dependence of the current can give rise to some interesting and practically important effects. As the bias increases, the temperature of the diode becomes higher, and a situation may occur in which current will *decrease*, rather than *increase*, with further rise in the bias (negative differential resistance of N-type). It is worth noting that a similar effect has been observed in n-Si semiconductor resistors in the dc mode (see, for example, [23]). Nucleation and motion of thermal domains, as well as the corresponding current instability, have been observed in the samples in such conditions. However, analysis of these effects is beyond the scope of this paper.

5. Conclusion

Pulse I–V characteristics have been measured in high-voltage (base width $W = 70$ μm) 4H-SiC rectifier diodes with a record-breaking high carrier lifetime τ of 3.7 μs at room temperature up to current densities of 8 kA cm^{-2} in the temperature range 292–472 K. It has been shown that, at so high current densities, the pulse I–V characteristics fail to simultaneously meet the two necessary requirements to be satisfied when measuring steady state isothermal I–V characteristics. On the one hand, the duration of the measuring pulse, t_0, should be long enough to provide a full modulation of the base resistance by non-equilibrium carriers ($t_0 \geqslant (2$–$3)\tau$). On the other hand, if the lifetime τ is long enough to provide a really deep base modulation ($W/L_a \leqslant$ (2–3)), the self heating of the diode during this measuring pulse is unacceptably large. A method for extraction of the true isothermal *I–V* characteristics from experimental results has been demonstrated for the example of high-voltage 4H-SiC rectifier p^+–n–n^+ diodes. The method is based on comparison of experimental pulse *I–V* characteristics with a physically adequate simulation. Calculations predict a very strong temperature dependence of the current at elevated ($T \geqslant 600$ K) ambient temperatures. Tentative estimates show that an N-type negative differential conductivity can be observed in forward *I–V* characteristics of 4H-SiC rectifier diodes in the dc mode.

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