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Self-heating and destruction of high-voltage 4H-SiC rectifier diodes under a single short current surge pulse

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ABSTRACT

Self-heating of high-voltage (6 kV class) 4H-SiC rectifier p^+–n–n^+ diodes under the action of a single 20 μs forward current surge pulse has been studied experimentally up to current densities $j \approx 100$ kA/cm^2. The diode parameters are stable after a single surge pulse with current density $j \approx 60$ kA/cm^2, although the estimated temperature of the diode at the end of this pulse is ~1650 K. After several pulses of this amplitude or after subjecting the diode to pulses with higher current density, the diode degrades. The degradation is manifested in an irreversible decrease of the differential resistance of the diode under a high forward bias. Even a single 20 μs pulse with peak current density $j \approx 100$ kA/cm^2 leads to total destruction of the device.

1. Introduction

In recent years, silicon carbide (SiC) has demonstrated its great potentialities as a base material for high-power, high-temperature, and high-frequency devices. In particular, a considerable progress has been made in design and development of high-voltage SiC rectifier p–i–n diodes. These diodes exhibit a combination of very high blocking voltages (up to 20 kV), very fast switching, high working temperatures (up to 800 K), and low forward voltage drops at high and ultrahigh current densities [1–3].

The ability to withstand current surges is one of the most important requirements to p–i–n rectifier diodes [4,5]. Such surge currents appear rather frequently due to short circuits or high-power electromagnetic discharges.

It is necessary to distinguish between three characteristic types of current surges [6]. The first limiting case of an "infinitely long" pulse corresponds to self-heating in the dc mode. The operation of high-voltage 4H-SiC rectifier diodes in the dc surge mode was analyzed in detail theoretically and experimentally in Ref. [6]. It was demonstrated that the overload characteristics of the diode in this mode are mainly determined by the substrate thickness, diameter of the diode structure, and thermal characteristics of the heat-sink. With an "ideal" semi-infinite copper heat-sink characteristic of SiC power diodes with a substrate thickness of 350 μm and diode diameter of 400 μm, the irreversible degradation of the structures was observed at current densities of about 1700 A/cm^2.

Intermediate case corresponds to so-called "long" surge pulse. This pulse is usually given as a surge current rating for a specified pulse (a 60 or 50 Hz half cycle sine wave or a 8–10 ms rectangular pulse) [4,7,8]. In this mode the heat released in the active region of the diode has enough time to reach the heat-sink. These surge current ratings for SiC diodes can be as high as 6000–9000 A/cm^2 even for the structures with relatively thick (300–350 μm) substrate and relatively small diameter (400 μm) [4,8].

The opposite limiting case of a "short" pulse corresponds to a very short current pulse width t_0, during which heat does not have enough time to reach the heat-sink. Energy rating is often defined using "industry standard", such as 8/20 μs pulse, i.e. the pulse with 8 μs rise time and 20 μs fall time. At the same time, rectangular current pulses with a characteristic pulse duration $t_0 \approx 20$–50 μs are not infrequently used to characterize the ability of the diodes to withstand short pulse current surge. Use of a rectangular pulse makes it possible, on the one hand, to extract all necessary information about the overloading capacity of the structures, and, on the other hand, to simplify the physical analysis of this mode.

In this study, the self-heating of high-voltage (6 kV class) 4H-SiC rectifier diodes under the action of a single 20 μs current

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surge pulse was studied experimentally up to current densities $j \approx 100$ kA/cm^2.

2. Experimental

The device structures investigated here were 4H-SiC p^+–n–n^+ diodes manufactured by CREE, Inc. Diodes 400 μm in diameter were fabricated on 350 μm n-type substrates with a doping level of 5×10^{19} cm^{-3}. The voltage-blocking n-base, W, was 70 μm thick and had an effective donor doping concentration $N = N_d - N_a = 2 \times 10^{14}$ cm^{-3}. A cross-section of the diode is shown schematically in Fig. 1. The diodes were intended just for forward-biased measurements and were not terminated. The carrier lifetime τ in the n-base was measured using the open circuit voltage decay (OCVD) technique to be 3.7 μs at room temperature [9].

As shown in Ref. [10], the *real isothermal current–voltage (I–U) characteristics* of high-voltage SiC diodes cannot, *in principle*, be measured experimentally if the lifetime of nonequilibrium carriers is long enough for effective modulation of the base resistance. In such cases, isothermal *I–U* characteristics should be "reconstructed" from experimental pulsed current–voltage curves in terms of an adequate analytical or numerical model. A procedure of this kind, performed for high-voltage 4H-SiC rectifier diodes in Ref. [10], was used in the present study.

Forward 20 μs pulses with amplitudes of up to 460 V were applied to the diodes in question, connected in series with a silicon IGBT switch and precision power load resistors $R_l = 4.6\ \Omega$ (or 2.4 Ω, depending on the maximum reached current value) at time intervals of 5 min to provide the total cooling of the sample between the pulses. The rise time τ_0 of the pulses was about 0.3 μs: $U(t) = U_{max}[1 - \exp(-t/\tau_0)]$ with $\tau_0 = 0.3$ μs. Four identical diodes were tested in this regime.

3. Experimental results

Fig. 2a and b shows the time dependences of the current flowing through one of the diodes under study at different amplitudes U_{max} and a load resistance $R_l = 4.6\ \Omega$.

It is noteworthy that the current density $j \approx 61.4$ kA/cm^2 corresponds to the current $I = 76.7$ A (Fig. 2b). It will be demonstrated in the next Section that the energy $A = IU_0t_0$ released in the base of the diode at $U_{max} = 430$ V (Fig. 2b) corresponds to an overheating ΔT of about 1350 K (which, in turn, corresponds to a working temperature of the diode equal to ~1650 K). In spite of this circumstance, no degradation was observed on applying a single 20 μs pulse of such huge amplitude (under forward bias). Applying for the second time pulses with amplitudes from $U_{max} = 19.85$ V to $U_{max} = 231$ V

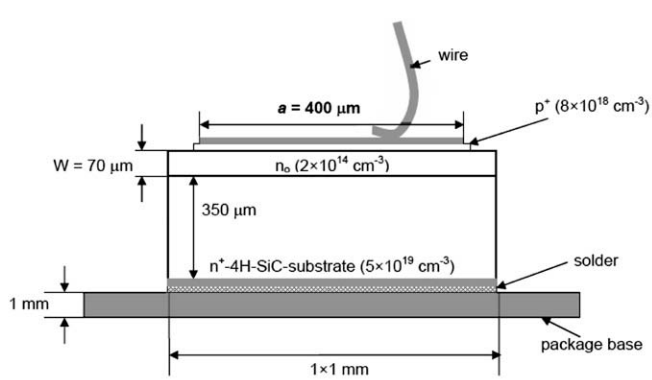

Fig. 1. Schematic cross-sectional view of a high-voltage (6 kV class) 4H-SiC rectifier p^+–n–n^+ diode.

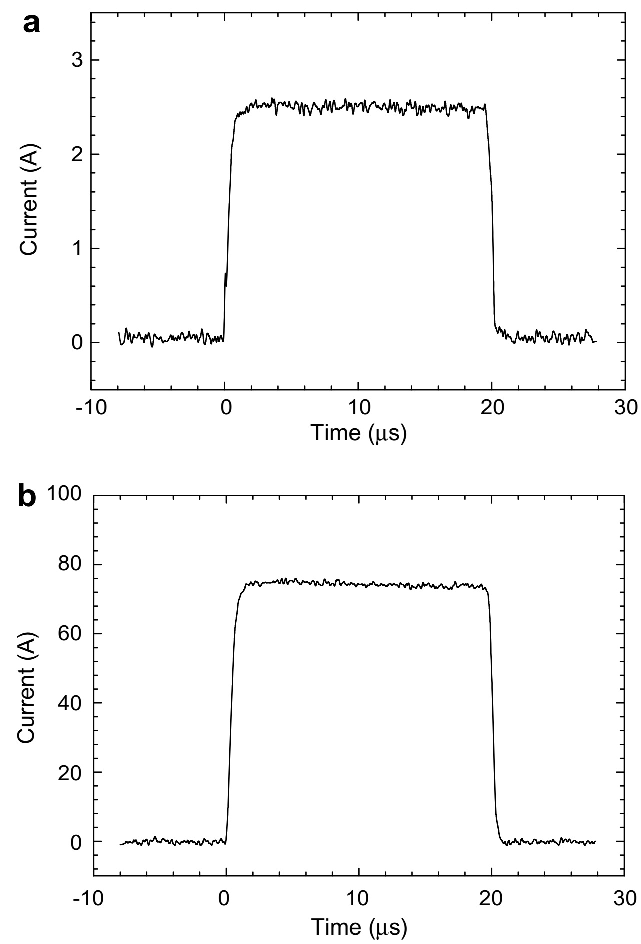

Fig. 2. Time dependences of the current flowing through one of the diodes under study at different amplitudes U_{max} and a load resistance $R_l = 4.6\ \Omega$. $U_{max}(V)$: a – 19.85; b – 430. These experimental conditions correspond to the currents flowing through the diode I (A): a – 2.58; b – 76.7 and forward voltages applied to the diode U_d (V): a – 6.65; b – 68.4. The difference between U_d and $[U_{max} - I \times R_l]$ is the voltage drop on the silicon IGBT, U_i, measured in separate experiments.

we made sure that the current pulse amplitudes and forward voltages were the same as those in the first set of measurements. Results obtained in the first and second experimental sets were qualitative similar for all samples. Scatter is shown in Fig. 3.

However, on applying a pulse with amplitude $U_{max} = 430$ V for the second time, we could reveal signs of degradation: at the same U_{max}, the current *increases* from 76.7 to 86.7 A, and the forward voltage U_d *decreases* from 68.4 to 51.1 V.

After that, we reduced the load resistance from $R_l = 4.6\ \Omega$ to $R_l = 2.4\ \Omega$ and performed a third set of measurements. At comparatively small currents ($I \leqslant 40$ A), the experimental results virtually coincided with those obtained in the first set of measurements. However, with U_{max} increasing further, the results obtained become fundamentally different. Besides, a very large scatter in the results was observed with different samples.

It should be emphasized that the current pulse shapes ($I(t)$ dependences) were virtually rectangular during the third set of measurements, just as in the first (see Fig. 2) and second sets. This circumstance allows us to represent the results obtained in a convenient form of the so-called "dynamic *I–U* characteristic" (Fig. 3).

Strictly speaking, the concept of the *I–U* characteristic cannot be applied to time-dependent problems, because this characteristic is of essentially steady-state nature. If, however, the current (and, accordingly, the voltage applied) varies rather weakly during the