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Short Communication

Fast switch-off of high voltage 4H–SiC npn bipolar junction transistor from deep saturation regime

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Abstract

It has been demonstrated experimentally that the switch-off time of a high-voltage power (1.8 kV, 3.8 A) 4H–SiC bipolar junction transistor in the deep-saturation mode can be decreased from 200 to 25 ns by using an appropriate switch-off base signal. In such conditions, the switch-off time in the common-emitter configuration can be shorter than the switch-on time.

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Keywords: Silicon carbide; Bipolar junction transistor; Fast switch-off

1. Introduction

In recent years, considerable progress has been made in developing power 4H–SiC-based bipolar devices: diodes, bipolar junction transistors (BJTs), and thyristors [1–3]. Static and transient characteristics of power (1.8 kV, 3.8 A) 4H–SiC npn BJTs with current gain \( b \) of about 30 at room temperature have been studied recently [4,5].

In all bipolar devices, the switch-off process is, as a rule, the slowest transient process limiting the highest achievable operation frequency. For power switching BJTs the problem of the switch-off time is especially important because the switch-on time becomes shorter, and switch-off time, by contrast, longer with increasing saturation level [4,6].

In this paper, we report for the first time on a strong decrease in the switch-off time of high voltage 4H–SiC npn BJTs in the deep saturation mode.

2. Experimental

1.8 kV, 3.8 A 4H–SiC BJTs were fabricated by Cree Inc., with a 20-\( \mu \)m-thick n' -collector layer doped to \( 2.5 \times 10^{15} \) cm\(^{-3} \), 1-\( \mu \)m p-base layer doped to \( 2.5 \times 10^{17} \) cm\(^{-3} \), and 0.75-\( \mu \)m n' -emitter layer. The p'-contact regions were formed in the base by aluminum implantation. The collector junction was terminated with a junction termination extension formed by boron implantation. The emitter-base configuration of 1 \times 1.4 mm\(^2 \) devices had inter-digitized “overlayer” geometry, with base finger pitch of 23 \( \mu \)m and emitter finger width of 12 \( \mu \)m. The total length of the emitter fingers was 6 cm (total emitter area \( S_E = 7.2 \times 10^{-2} \) cm\(^2 \), total collector area \( S_C = 1.4 \times 10^{-2} \) cm\(^2 \)). The base current gain \( \beta \) measured in the active mode at base current \( I_B = 1 \) A was equal to 20. For more details see Refs. [2,5].

The BJT was turned on in the common-emitter (CE) configuration by applying a long positive gate pulse. The characteristic BJT switch-on times were studied thoroughly in Ref [4]. The BJT was turned off by switching off the gate pulse or, alternatively, by applying a negative base current pulse.

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3. Results and discussion

The BJT switch off was studied in the deep saturation mode at base current $I_b = 1 \text{ A}$, collector bias $V_0 = 250 \text{ V}$, and collector load resistance $R_L = 50 \Omega$. The saturation parameter $N = (\beta I_b - I_{C_{\text{sat}}})/I_{C_{\text{sat}}}$ [6], where $I_b$ is the input base current, and $I_{C_{\text{sat}}} \approx V_0/R_L$ is the saturated collector current. Hence, $N \approx 3$ for the given $I_b$, $V_0$, and $R_L$. It is noteworthy that the collector current density in this regime is $700 \text{ A/cm}^2$.

Curve 1 in Fig. 1a shows the decay of the base current during the conventional switch-off process. The total time of the base current drop is equal to 35 ns. The time dependence of the collector current $I_C$, which corresponds to this mode is represented by curve 1 in Fig. 1b. It is seen that the total time of the collector current drop is 200 ns.

As shown in Ref. [4], the total rise time of the collector current in the CE configuration in the active mode, which is equal to 130 ns, is defined by the $\beta C_{\text{CB}} R_L$ product, where $C_{\text{CB}}$ is the effective collector–base capacitance. With $N$ increasing, the total rise time of the collector current decreases, to become only 50 ns at $N = 4$ [3]. Hence, just the time of the collector current drop defines the limiting operation frequency.

The switch-off time, $\Delta t_{\text{off}}$, can be made shorter by applying a negative base pulse in the switch-off process (curve 2 in Fig. 1a and b). For the case shown in Fig. 1 ($I_b = 1 \text{ A}$, $I_C = 5 \text{ A}$, $N = 3$), the minimum $\Delta t_{\text{off}} = 25 \text{ ns}$ is reached at $I_b^* \approx 0.7 \text{ A}$. The time dependence of the base current (curve 2 in Fig. 1a) is virtually not affected by the collector bias $V_0$ and this dependence has just the same form across the whole range of $V_0$ variation, from 0 to 250 V.

The time dependence of the base current in the switch-off process (curve 2 in Fig. 1a) is qualitatively similar to that of the current waveform in measurements of the reverse current recovery for p–n junctions [7,8]. Minority carriers (electrons) are removed from the base by the negative base current. It is very interesting to note that the collector current becomes zero when a considerable charge of non-equilibrium electrons and holes exists in the base. Comparison of curve 2 in Fig. 1a and b readily shows that a noticeable base current is observed approximately 120 ns after the break of the collector current.

It is noteworthy that the drastic shortening of the switch-off time leads to a remarkable decrease in energy loss per switching cycle and an increase in the maximum operation frequency of switching power SiC BJTs.

4. Conclusion

The switch-off time of a power high-voltage (1.8 kV, 3.8 A) 4H–SiC BJT in the deep saturation mode can be decreased from 200 to 25 ns by applying an appropriate switch-off base signal. In such conditions, the switch-off time in the CE configuration is shorter than the switch-on time. The decrease in the switch-off time makes it possible to diminish remarkably the energy loss per switching cycle and results in higher possible maximum operation frequency of switching.

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