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Short-circuit Capability of SiC Power MOSFETs

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Abstract

The short-circuit capability of Si power devices, defined in terms of a critical energy density, is the product of the heat capacity in the heat generation region and the rise in temperature. However, for SiC power devices, the heat generation region is significantly smaller than that for Si power devices, because the drift-region thickness is about 10 times less in SiC power devices. Therefore, formulae used for Si devices are not directly applicable to SiC devices.

In this study, analytical formulae are derived for the short-circuit capability of a SiC power device, and its ambient-temperature dependence, based on the thermal diffusion equation. The calculated results are found to be in good agreement with those of direct measurements.

1. Introduction

The dielectric breakdown field for SiC is about one order of magnitude higher than that for Si. Consequently, the drift-region thickness in SiC power MOSFETs can be reduced by about ten times, and the same breakdown voltage can be achieved, leading to low-loss characteristics. However, this results in higher thermal energy densities in SiC power devices. Moreover, increases in ambient temperature can reduce the short-circuit capability of such devices, defined in terms of a critical energy density. It is therefore important to clarify the factors that influence the short-circuit capability of SiC power devices, and also the effect of the ambient temperature.

Various short-circuit failure modes have been reported for Si power devices. One is a short circuit that occurs within a certain time after turning off the gate, and is caused by an increase in the leakage current in the forward-blocking state due to intrinsic carrier generation. Based on a theoretical analysis of the short-circuit capability of such devices, and the effect of ambient temperature [1], analytical formulae were derived, involving the product of the heat capacity in the heat generation region and the temperature increase. However, since for SiC power devices, the heat generation region is considerably smaller, these formulae are not directly applicable.

In the present study, analytical formulae for the short-circuit capability of SiC power devices and its ambient-temperature dependence are derived based on the thermal diffusion equation. The results obtained using these formulae are compared to those from measurements of actual devices.

2. Theoretical Analysis of Short-circuit Capability of SiC Power MOSFETs

As shown in Fig. 1, the intrinsic carrier concentration in Si begins to increase exponentially at a temperature of about 650 K, but this does not occur until about 1500 K for SiC. Since the melting point of Al is 933 K, this is lower than the temperature where thermal runaway occurs in SiC, and Al electrodes would thus be expected to melt before this takes place.

Figure 2 shows the ambient temperature dependence of the short-circuit energy density for SiC, determined by TCAD device simulation and experimental measurements. The short-circuit energy density is simulated based on two different failure criteria. The first is full thermal runaway, and the second is melting of the Al electrodes. The second criterion is seen is seen to yield good agreement with the measured short-circuit energy density. In addition, it has been reported that local temperatures can exceed the melting point of Al during failure [2]. Therefore, the critical temperature for short-circuit failure was taken to be 933 K in the present study.

An analytical formulae for the short-circuit capability of SiC is now derived based on the thermal diffusion equation during the short-circuit period, which expresses the temperature (T) as a function of position ($\mathbf{r}$) and time (t) as

$$\frac{\partial T(\mathbf{r},t)}{\partial t} - D_{\mathrm{SiC}}\nabla^2 T(\mathbf{r},t) = \frac{P_0}{\rho \cdot C_p \cdot \Delta} , \qquad (1)$$

where D_{SiC} (2.21 cm^2/s) is the thermal diffusivity of SiC, P_0 [W] is the power expressed as the product of the voltage and the current, ρ (3.21 g/cm^3) is the mass density, C_p (0.67 J/gK) is the heat capacity, and Δ [cm^3] is the Joule heating volume. The active region is taken to have a rectangular cross section with a width a and a height b, and the drift region thickness is c. The solution of Eq. (1) is

$$T(\mathbf{r},t) = T_0 + \frac{P_0}{\rho C_p \Delta}\int_0^t \mathrm{d}\tau \frac{1}{2}\left[\mathrm{erf}\left(\frac{a/2+x}{\sqrt{4D_{\mathrm{SiC}}\tau}}\right) + \mathrm{erf}\left(\frac{a/2-x}{\sqrt{4D_{\mathrm{SiC}}\tau}}\right)\right]$$
$$\times \frac{1}{2}\left[\mathrm{erf}\left(\frac{b/2+y}{\sqrt{4D_{\mathrm{SiC}}\tau}}\right) + \mathrm{erf}\left(\frac{b/2-y}{\sqrt{4D_{\mathrm{SiC}}\tau}}\right)\right]$$
$$\times \frac{1}{2}\left[\mathrm{erf}\left(\frac{c/2+z}{\sqrt{4D_{\mathrm{SiC}}\tau}}\right) + \mathrm{erf}\left(\frac{c/2-z}{\sqrt{4D_{\mathrm{Si}}C\tau}}\right)\right] . \qquad (2)$$

The temperature at the center of the Joule heating region is given by

$$T(\mathbf{0},t) = T_A + \frac{P_0}{\rho C_p \Delta}\int_0^t d\tau \left[\mathrm{erf}\left(\frac{a}{4\sqrt{D_{SiC}\tau}}\right)\right] \times \left[\mathrm{erf}\left(\frac{b}{4\sqrt{D_{SiC}\tau}}\right)\right]\cdot\left[\mathrm{erf}\left(\frac{c}{4\sqrt{D_{SiC}\tau}}\right)\right]. \quad (3)$$

Here, t_C is defined as $c^2/4\pi D_{SiC}$, and has a value of 36 ns when c is 10 μm. The experimentally determined short-circuit period (t_{sc}) for an actual SiC MOSFET was 8μs, as shown in Fig. 3, which is significantly larger than t_C.

The error function erf (x) can be approximated by

$$\mathrm{erf}(x) \approx \frac{2x}{\sqrt{\pi}} \quad \left(x \le \sqrt{\pi}/2\right). \qquad \approx 1 \quad \left(x \ge \sqrt{\pi}/2\right). \quad (4)$$

Equation (3) can then be simplified, and the short-circuit energy density can be expressed as

$$E_{SC}\left(\mathrm{J/cm^2}\right) = A\cdot\rho\cdot C_p\cdot c\cdot\left(T_C - T_A\right). \qquad A \equiv \frac{1}{2}\cdot\sqrt{\frac{t_{SC}}{t_C}}\cdot\frac{1}{1-\frac{1}{2}\sqrt{\frac{t_C}{t_{SC}}}}. \quad (5)$$

Here, T_A (K) is the ambient temperature.

The ambient temperature dependence of E_{SC} is expressed as

$$\frac{\partial E_{SC}}{\partial T_A} = -A\cdot\rho\cdot C_p\cdot c. \quad (6)$$

The coefficient A has a value of 7.7 when c is 10 μm and t_{SC} is 8 μs. From Eq. (5), E_{SC} is 10.57 $\mathrm{J/cm^2}$ for an ambient temperature of 300 K, which is in good agreement with the measured value of 10.03 $\mathrm{J/cm^2}$ shown in Fig. 2. From Eq.(6), the ambient temperature dependence of E_{SC} is calculated to be -0.0166 $\mathrm{J/(cm^2{\cdot}K)}$, which is similar to the value of -0.0184 $\mathrm{J/(cm^2{\cdot}K)}$ determined from the slope of the measured data in Fig. 2.

The above results confirm the validity of Eqs. (5) and (6) for SiC power devices, which differ from the equations for Si with regard to the dimensionless coefficient A.

3. Conclusions

Analytical formulae were derived for the short-circuit capability of SiC power devices, and its ambient temperature dependence. The values calculated using the proposed formulae were found to be in good agreement with measured values. It can therefore be concluded that the short-circuit capability of SiC power devices can be explained in terms of the thermal characteristics of the material.

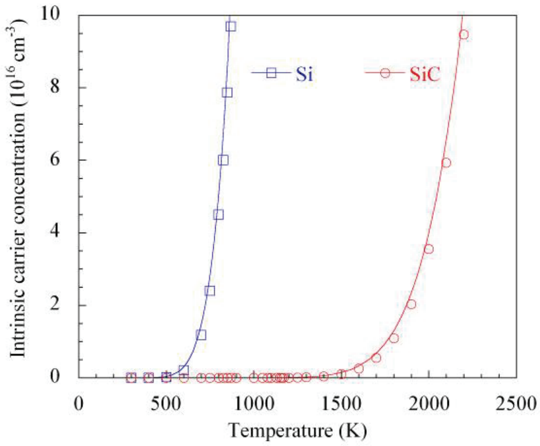

Fig. 1. Temperature dependence of intrinsic carrier concentration.

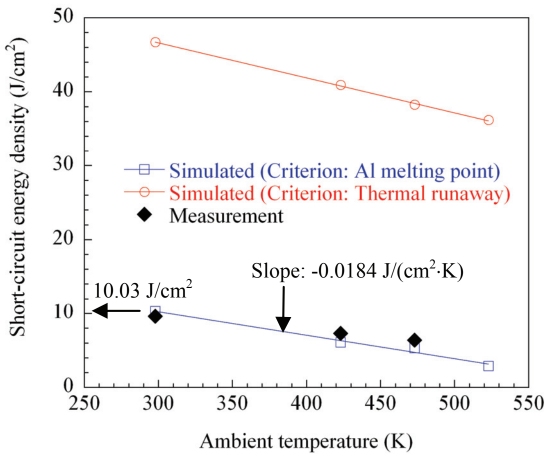

Fig. 2. Ambient temperature dependence of short-circuit energy density.

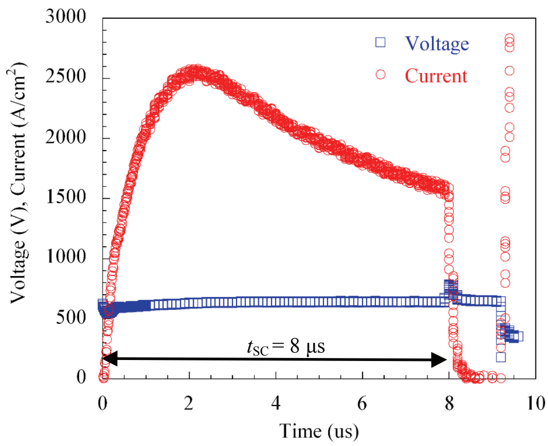

Fig. 3. Measured short-circuit waveform for a SiC power MOSFET at room temperature.

References

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