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Neutron Induced Single-Event Burnout in SiC Power Diode

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Abstract

Neutron induced single-event burnouts (SEBs) of silicon carbide (SiC) power diodes have been investigated by white-neutron irradiation experiments and transient device simulations. It was confirmed that a rapid increase in lattice temperature leads to the formation of a crown-shaped aluminum and cracks inside the device due to internal stress when the local lattice temperature reaches the sublimation temperature. SEB device simulation indicated that the peak lattice temperature is located in the vicinity of the n^-/n^+ boundary and p^+/n^- junction with high electric field strength. Moreover, the simulated peak lattice temperature corresponded to the positions of the observed destruction traces. From these facts, SEBs of SiC diodes can be characterized by lattice temperature increase up to the sublimation temperature because of the high heat generation density.

1. Introduction

Cosmic ray neutrons cause catastrophic failures in power semiconductor devices. Single event burnouts (SEBs) of insulated gate bipolar transistors (IGBTs) and silicon (Si) power diodes have been investigated by white-neutron irradiation experiments and transient device simulations. The following SEB triggering mechanism has been proposed [1-3]. Recoil ions created by nuclear spallation reactions between incident neutrons and Si nuclei generate electron-hole pairs along the ion track in the device. Transient device simulations have described the initial generated charge along the ion track during the reverse biased state. The dynamic current due to the electron-hole pairs increase the electron density in the vicinity of the n^-/n^+ boundary. The space charge effect of the carriers leads to an increase in the strength of the electric field at the n^-/n^+ boundary. Onset of impact ionization at the n^-/n^+ boundary can trigger an inherent parasitic transistor action. In contrast to IGBTs, diodes do not have an inherent parasitic transistor. The SEB failure mechanism of diodes is closely related to local secondary breakdown. Finally, the highly localized current results in thermal destruction. It was clarified that impact ionization at the n^-/n^+ boundary is a key point of the SEB triggering mechanism in power devices.

This paper investigates neutron induced SEBs of SiC power diodes by white-neutron irradiation experiments and transient device simulations. The dielectric breakdown field of SiC is about one digit greater than Si. Therefore, the drift region thickness of SiC power devices can be reduced to one-tenth of Si with the same breakdown voltage, and low-loss characteristics can be achieved. However, the peak value of the electric field strength is ten times larger than that of Si. Consequently, the heat generation density of a SiC power device is about two orders of magnitude higher than that of a Si power device. This high heat generation density leads to a rapid increase in the lattice temperature in the device. Simulation showed that the lattice temperature increase period of a SiC power diode is two orders of magnitude less than that of a Si power diode, because of the high heat generation density. The SiC power device eventually reaches the sublimation temperature and, consequently, device destruction occurs.

Moreover, it was confirmed by white-neutron irradiation experiments that the rapid increase in the lattice temperature leads to the formation of a crown-shaped aluminum. Then, as shown in Fig. 1, when the lattice reaches the sublimation temperature, cracks form inside the device due to internal stress. SEB device simulation indicated that the peak lattice temperature is located in the vicinity of the n^-/n^+ boundary and p^+/n^- junction with high electric field strength. The simulated peak lattice temperature corresponded to the positions of the destruction traces shown in the cross sectional view. From these facts, SEBs of SiC diodes can be characterized by lattice temperature increase up to the sublimation temperature because of the high heat generation density.

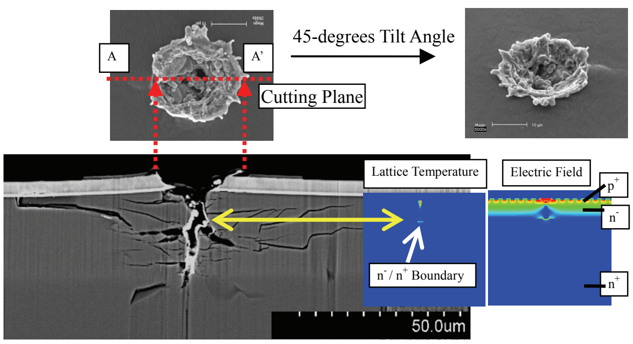

Fig. 1. Cross sectional scanning electron microscope (SEM) view of SEB destruction trace, simulated lattice temperature and electric field at time point 6 shown in Fig. 4.

2. SEB of SiC Power Diode Caused by White Neutron-Irradiation

White neutron-irradiation experiments were performed to investigate SEBs of power diodes. A voltage was applied between the cathode and anode during the white neutron irradiation. Figure 2 shows SEM views of the device surface after aluminum etching. Cracks reflecting the hexagonal crystal orientation of SiC were observed at the molybdenum surface. Carbon precipitation was formed at the center. Figure 3 shows SEM and stereomicroscope views after cutting 3μm from the device surface using a focused ion beam (FIB). The cracks that occurred inside the SiC device were formed by internal stress due to sublimation. The stereomicroscope view shows the interference of light between the crack planes, and the area has a radius of within about 80μm. These results show evidence that the inside of the SiC device has reached the sublimation temperature.

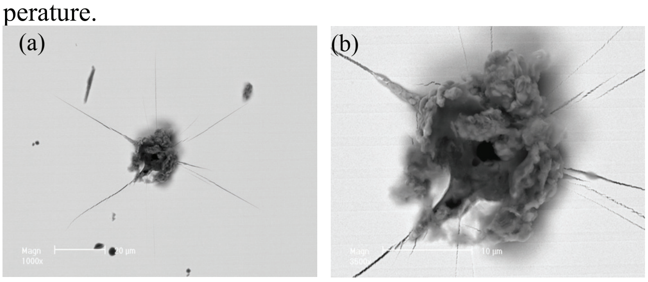

Fig. 2. SEM views of device surface after aluminum etching: (a) overall view and (b) magnified view.

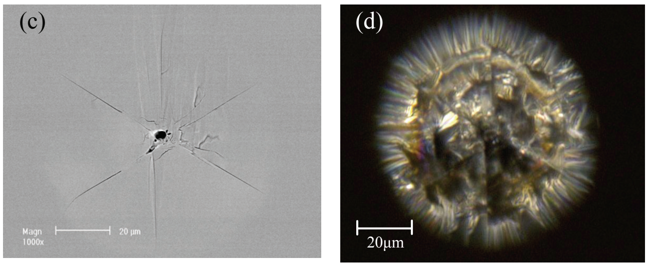

Fig. 3. 3μm cutting from device surface using FIB: (c) SEM view, and (d) stereomicroscope view.

3. Coupled Electro-Thermal Simulation of SEB

A coupled electro-thermal simulation of a SEB was performed. The maximum lattice temperature of SiC eventually reaches sublimation temperature. The lattice temperature-increase period of a SiC power diode is two orders of magnitude less than that of a Si power diode, because of the high heat generation density [1-3]. In addition, the aluminum surface temperature remains at room temperature due to the short-time event. The displacement current leads to a temporary decrease in SEB current at point 4.

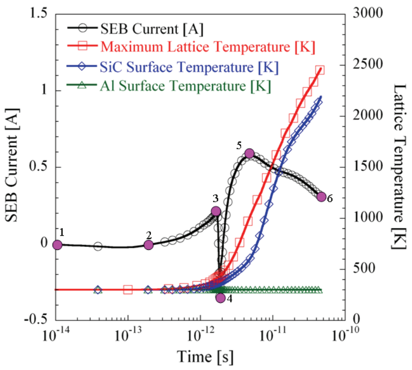

Fig. 4 Simulated SEB current (A) and temperature (K)

Figure 5 shows the electric field distribution along the ion track at the times shown in Fig. 4. The peak electric field shifts from the p^+/n^- junction to the n^-/n^+ boundary, because the electron density increases in the vicinity of the n^-/n^+ boundary. This indicates that double-sided impact ionization occurred as shown in Fig. 6. This double-sided impact ionization corresponds to diode secondary breakdown [3]. The electric field distribution is consistent with the lattice temperature distribution shown in Fig. 1. Furthermore, the temperature distribution shows evidence that the increase in the lattice temperature up to the sublimation temperature results in SEB of SiC power diodes.

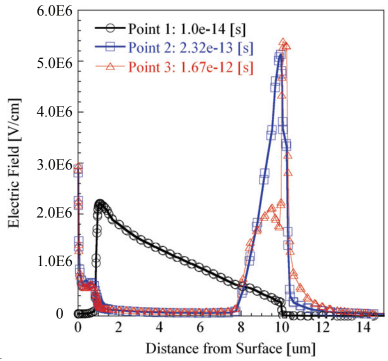

Fig. 5. Electric field distribution along ion track at the times shown in Fig. 4.

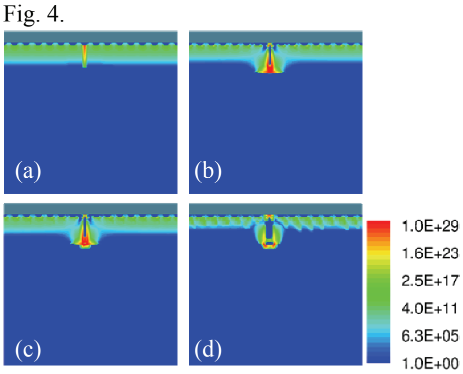

Fig.6. Impact ionization rate ($s^{-1}cm^{-3}$) at the times shown in Fig. 4: (a) point 1, (b) point 3, (c) point 4, and (d) point 5.

4. Conclusions

Neutron induced SEBs of SiC power diodes were investigated by white-neutron irradiation experiments and transient device simulations. It was confirmed that SiC power diode SEBs occur due to a rapid increase up to the sublimation temperature because of the high heat generation density. In addition, double-sided impact ionization occurs due to the space-charge effect in the same way as Si. Furthermore, the simulated peak lattice temperature agreed closely with the experiment results.

References

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