Coupled Electro-Thermal Simulations of Single Event Burnout in Power Diodes

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***Abstract*—Power diodes may undergo destructive failures when they are struck by high-energy particles during the off state (high reverse-bias voltage). This paper describes the failure mechanism using a coupled electro-thermal model. The specific case of a 3500-V diode is considered and it is shown that the temperatures reached when high voltages are applied are sufficient to cause damage to the constituent materials of the diode. The voltages at which failure occurs (e.g., 2700 V for a 17-MeV carbon ion) are consistent with previously reported data. The simulation results indicate that the catastrophic failures result from local heating caused by avalanche multiplication of ion-generated carriers.**

***Index Terms*—Avalanche multiplication, coupled electro-thermal simulations, single event burnout (SEB).**

I. Introduction

COSMIC rays can cause catastrophic failure in power devices due to single event burnout (SEB), caused by localized breakdown in the bulk of the device. Since the discovery of this destructive phenomenon in power MOSFETs by Waskiewicz *et al.* in 1986 [1], much work has been done to identify the responsible failure mechanisms. For power MOSFETs, the failure is attributed to the turn-on of a parasitic transistor when a high-energy ion strikes the device in the OFF state. The incident ion generates electron-hole pairs along its path; as the charges are separated by the electric field, a current is produced. When the charge flows to ground via the body, the voltage drop in the body resistance may turn on the parasitic bipolar transistor. Avalanche-generated holes returning from the base-collector region are the key to sustaining a regenerative feedback process that can induce second breakdown, which may lead to physical destruction of the device as shown in Fig. 1 [2].

The vulnerability of power diodes to catastrophic failures was first reported in 1994 by Kabza *et al.* [3] and Zeller [4]. Their efforts were focused on failure rates as a function of the applied voltage. This work did not provide a physical explanation of the failure mechanism. Later studies showed that the direct energy deposition from a high-energy particle crossing the device is insufficient to cause burnout failure [5], [6]. It was suggested that a particle-induced nuclear excitation can lead to local field sufficient for impact ionization.

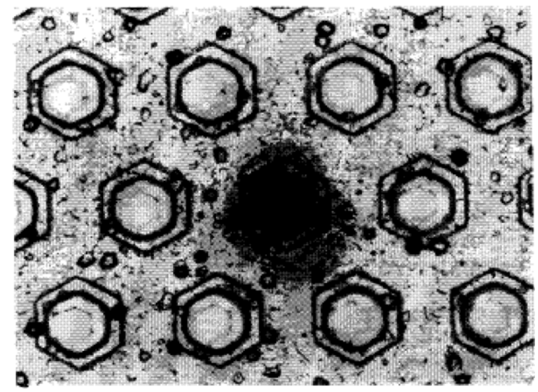

Fig. 1. Optical image of SEB in a power MOSFET (IRF150), after Stassinopoulos *et al.* [2] (© 2000 IEEE).

Avalanche multiplication was proposed as one of the key mechanisms responsible for triggering SEB events in diodes and experiments were used to investigate the processes leading to charge multiplication using nondestructive measurements [7]–[9]. The generated charge data for Kr, Si, and C ions are summarized in Fig. 2 as a function of the applied voltage [7]. The vertical lines represent the threshold voltage of the multiplication process. This steep transition illustrates the sensitive dependence of generated charge on applied voltage.

The SEB mechanism is different for diodes than for bipolar transistors or power MOSFETs because of the absence of bipolar gain [10]. A general model of the failure mechanism in diodes suggests that ion-generated charge is multiplied by avalanching, resulting in a very high current while a high reverse-bias voltage is applied. It has been suggested that the resulting high power density may lead to thermal breakdown of the device [3], [11].

The SEB models of power diodes published to date do not attempt to describe the entire burnout process, including the eventual failure due to thermal effects. In particular, the maximum temperature reached during a single event has not been quantified to ascertain if Joule heating can produce sufficiently high temperatures to cause physical damage. Inclusion of these effects is required to obtain more detailed understanding of the mechanisms responsible for SEB, particularly in power diodes. In this paper, we identify through nonisothermal simulations the physical mechanisms responsible for SEB in diodes. Thermal effects are modeled by incorporating the thermal diffusion equation, and by including temperature-dependent electrical models. The results demonstrate that the maximum temperature that occurs during catastrophic single events is nearly 1500 K, which

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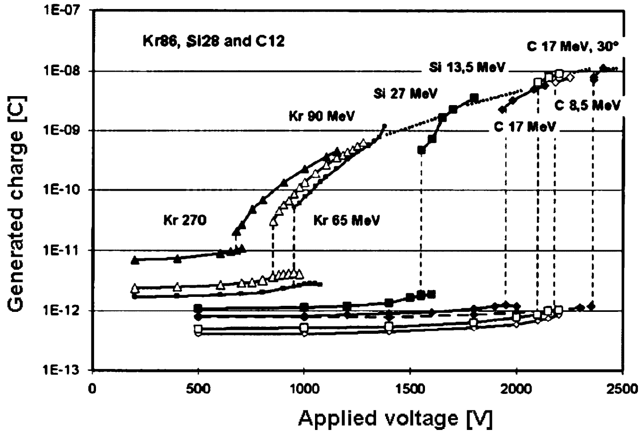

Fig. 2. Summary of results on avalanche multiplication in 4 kV diodes under ion irradiation. Different ions and different energies are presented, reprinted from Maier *et al.* [7] (© 1998 Elsevier).

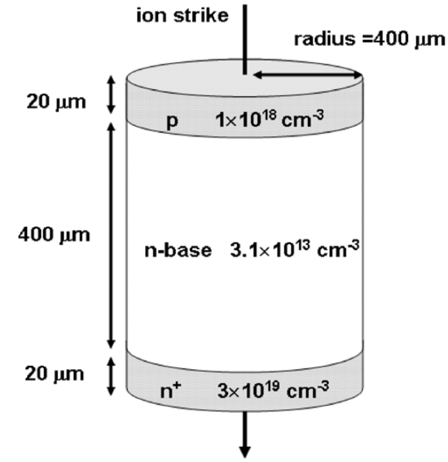

Fig. 3. Power diode structure showing the doping concentrations and the device dimensions.

suggests that thermal mechanisms are responsible for the diode failure.

II. Electro-Thermal Model

The temperature rise resulting from an ion strike is very important in describing the burnout failure process in power devices. Previous simulation attempts to model SEB in power devices assumed a constant lattice temperature [5], [12]–[14] and consequently did not determine if the temperature reached a level sufficient to cause physical damage. In this work, we conducted the simulations using a coupled electro-thermal model implemented in the device simulator DESSIS-ISE [15]. A high-voltage diode with cylindrical geometry was utilized for the simulations.

The electrical characteristics were obtained by solving Poisson's equation, along with the continuity equations for both electrons and holes. A mobility model that accounts for lattice scattering and doping dependence was used along with the velocity saturation model for high electric fields. The Shockley–Read–Hall model was used to describe generation-recombination processes, and the Auger recombination model was included in heavily doped regions. The impact ionization model is very important in describing ion-induced breakdown and the parameters used in the simulations were based on [16]. Ion-induced charge deposition is modeled with a temporally and spatially localized carrier generation rate [17]. The deposited charge was added to the generation-recombination terms in the carrier continuity equation.

Strike-induced charge, combined with charge multiplication due to avalanching, can result in sufficiently large current to generate high local temperatures. In some cases, the temperature may rise above the melting temperatures of the constituent materials of the diode (Al, Si, etc.), resulting in damage. This poses the need for a coupled electro-thermal model that can adequately simulate the burnout mechanism in power devices [11]. Non-constant lattice temperatures were simulated by adding the thermal diffusion equation to the electrical models [18].

Most electrical properties of semiconductor devices are temperature dependent. Therefore, the influence of lattice heating on device characteristics is crucial. As temperature increases, lattice scattering increases. As a result, the mobility decreases, and in turn the current density becomes lower. Jacoboni *et al.* reported that for a 100°C increase in silicon, mobility decreases by 20% [19]. Moreover, at high electric fields, increasing temperature limits the carrier saturation velocity. Also, avalanche-generated charge decreases as temperature increases due to the decrease of impact ionization rates at high temperatures. This occurs because of the increase of lattice scattering as temperature increases, which leads to reduced mean free path. In addition, as temperature increases, the effective intrinsic concentration increases.

III. Simulations of SEB in Power Diodes

A. Diode Structure

A power diode with a breakdown voltage of 3500 V was simulated in our study. This diode was chosen to allow direct comparison to the experimental data of [7]. A very lightly doped 400 μm n-base (3.1×10^{13} cm^{-3}) is confined by two highly doped regions: n (3×10^{19} cm^{-3}) and p (1×10^{18} cm-3), as shown in Fig. 3. A cylindrically symmetric simulation structure with a 400 μm radius was used. The strike was coincident with the symmetry axis. The size of the device was determined to assure no edge interactions with either ion-generated carriers or diffusing thermal energy. The density of the ion-induced charge was obtained from the linear energy transfer (LET) of each strike by assuming a 3.6 eV ionization energy for electron-hole pairs. The radial distribution of excess charge was expressed as a Gaussian distribution with a characteristic length of 0.02 μm. The temporal distribution of charge also was modeled as a Gaussian function with its peak at 5 ps and a standard deviation of 0.2 ps.

Initial simulations were conducted to explore the effects of nonconstant lattice temperature and to show the important role of the impact ionization model. The simulation was performed under reverse bias (high blocking voltage) because the energetic ion does not induce failure when the device is forward biased. In the simulations described here, the device was irradiated with 17 MeV carbon ions (LET $=$ 4 MeV-cm^2/mg) when a 2700 V reverse bias was applied.

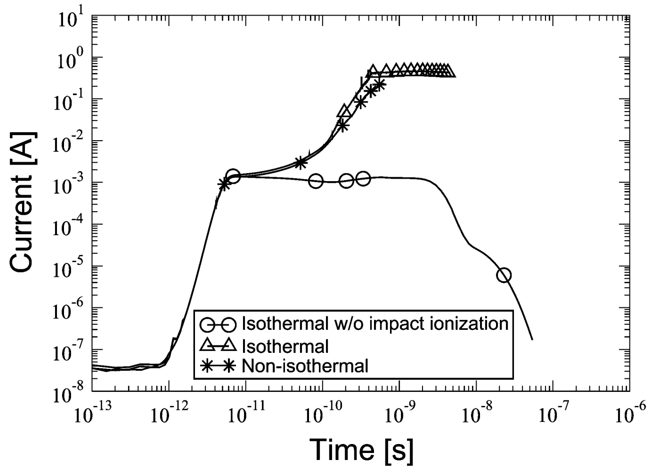

Fig. 4. Comparisons between the electrical characteristics for different models: isothermal, isothermal without impact ionization and nonisothermal simulations.

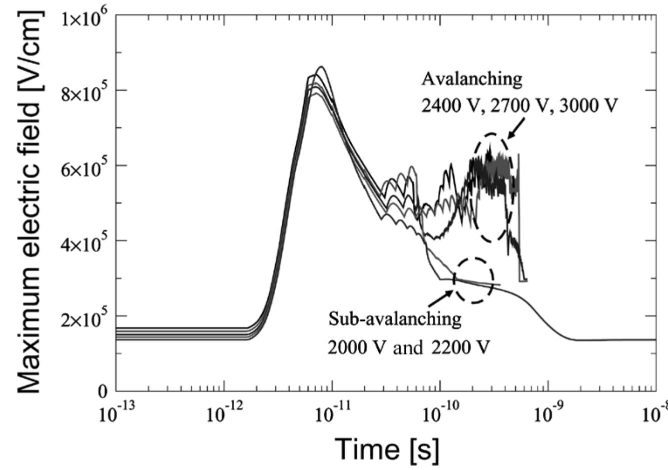

Fig. 5. Simulation of the transient maximum electric field along the ion track.

Fig. 4 shows the currents for three cases: isothermal model, isothermal model without impact ionization, and nonisothermal model. The transient simulation shows two peaks of the output current. The first peak is a result of the ion-induced charge collected from the depletion region; thus, its collection is very quick. As can been seen in this figure, the current is mostly caused by avalanche multiplication, which is represented by a second peak that occurs at about 4×10^{-10} s. For the isothermal simulations without the impact ionization model, the total current corresponds to the deposited charge. The current of the nonisothermal model is less than that of the isothermal model due to the decrease of avalanche generated charge as temperature increases [20]. Next, we investigate the charge multiplication using isothermal simulations. Then, we explain the SEB mechanism by including self-heating effects using nonisothermal simulations.

B. Charge Amplification Using Isothermal Simulations

We used the isothermal model to reproduce the carbon-ion results in [7], since that measurement was nondestructive, which limited heating. This approach was used to obtain simulation results that can be compared to the collected charge data shown in Fig. 2. Using only the nonisothermal simulation, it was not possible to obtain complete current waveforms after reaching high temperatures.

The occurrence of SEB is highly dependent on the applied voltage. Beyond a specific voltage, the impact ionization process is triggered, resulting in more charge due to avalanche multiplication. This is defined as an avalanching event. On the other hand, sub-avalanching events occur at low voltages where the collected charge corresponds only to the ion-induced charge.

Our assessment of the threshold voltage of avalanching is based on the transient maximum electric field as shown in Fig. 5 For applied voltages of 2400 V, 2700 V, and 3000 V, the maximum electric field exhibits an increase after about 6×10^{-11} s, caused by avalanche multiplication. The maximum electric field in the case of sub-avalanching events (2000 V and 2200 V) diminishes before triggering significant avalanche multiplication.

In Fig. 6, we show the simulated output currents for two different voltages: 2000 V (sub-avalanching) and 2700 V

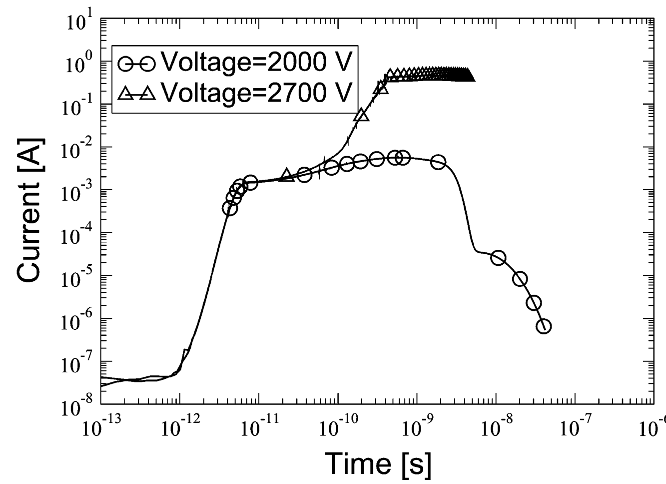

Fig. 6. Output currents during an ion strike for applied voltages of 2000 V and 2700 V.

(avalanching). High current is observed for the 2700 V case, compared to the 2000 V case, indicating the occurrence of significant impact ionization. This can be understood by looking at the spatial profiles of the electric field and the electron density for the two voltages as functions of time. When 2000 V is applied, a high electric field spike exists at the end of the ion track at 20 ps, as shown in Fig. 7(a). With time, this electric field diminishes and the required electric field for triggering the avalanche multiplication cannot be sustained, as mentioned previously. The electron density in this case [Fig. 7(b)] cannot support a current path between the anode and the cathode.

Entirely different behavior is observed when 2700 V is applied. Fig. 8(a) and (b) shows the temporal movement of the electric field peaks and the corresponding spreading of the electron density. The electric field peak increases as it moves through the device, which increases the impact ionization rates, adding more charge to the plasma. This sets up a positive feedback mechanism by increasing the electric field, which opposes the diffusing charge. This feedback mechanism is sustained until the electron density (in the 2700 V case, for example) becomes large throughout the distance between the anode and the cathode, causing a short circuit. This explains the steady state of the output current after about 500 ps, which is shown in Fig. 6. The peak of the electric field moves from the

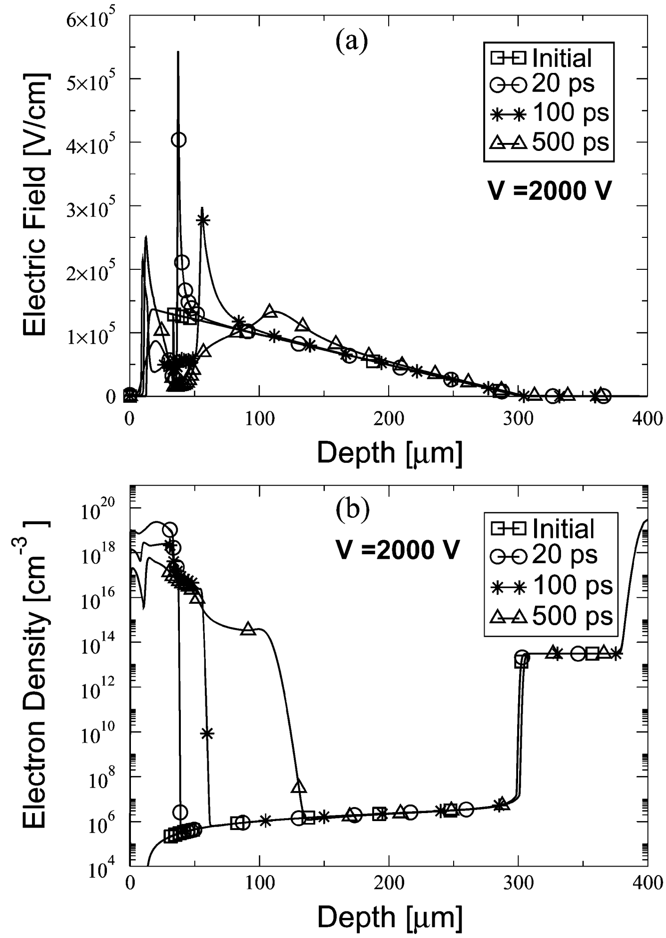

Fig. 7. Spatial and temporal evolution of (a) the electric field and (b) the electron density for an applied voltage of 2000 V.

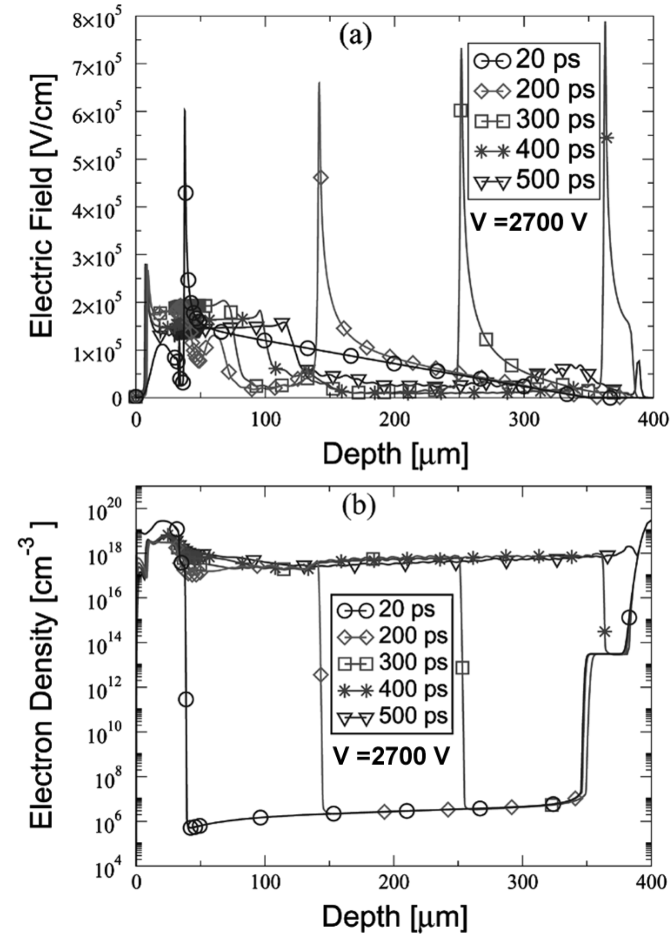

Fig. 8. Spatial and temporal evolution of (a) the electric field and (b) the electron density for an applied voltage of 2700 V.

pn junction to the nn^+ junction. This mechanism is similar to the process leading to second breakdown of power diodes when high voltage pulses are applied [21], [22]. The failure due to second breakdown is triggered by the onset of impact ionization at the nn^+ junction, which is analogous to the movement of the electric-field peak shown in Fig. 8(a).

Fig. 9 demonstrates qualitative agreement between the collected charge of our simulation results and the experimental results reported by Maier *et al.* [7]. About two to three orders of magnitude more charge is collected for the cases when 2400 V or 2700 V is applied, in comparison to the 2000 V case. Note that the collected charge obtained for the 2400 V and 2700 V simulations would have been even higher, but the simulations had to be terminated before the current decreased all the way to zero because of limitations on computing time. The high amount of charge due to the avalanche multiplication process has been associated with the onset of SEB [7], [12], but this has not been related directly to the actual failure mechanism. In the next section, we use coupled electro-thermal simulations to determine the maximum temperature reached during the SEB event and relate the failure mechanism to thermal processes.

C. Nonisothermal Simulations of SEB in Diodes

To investigate the role of thermal effects in device failure, nonisothermal simulations were conducted for different applied voltages with a 17 MeV C ion strike. Fig. 10 shows the transient current response as the voltage increases. As described previously, higher currents are obtained at high voltages (2700 V, 3000 V, and 3500 V) due to avalanching, in contrast to low voltages (500 V, 1000 V, and 2000 V). The behaviors of the electric field and the electron density in nonisothermal simulations are analogous to those plots belong to the isothermal simulations

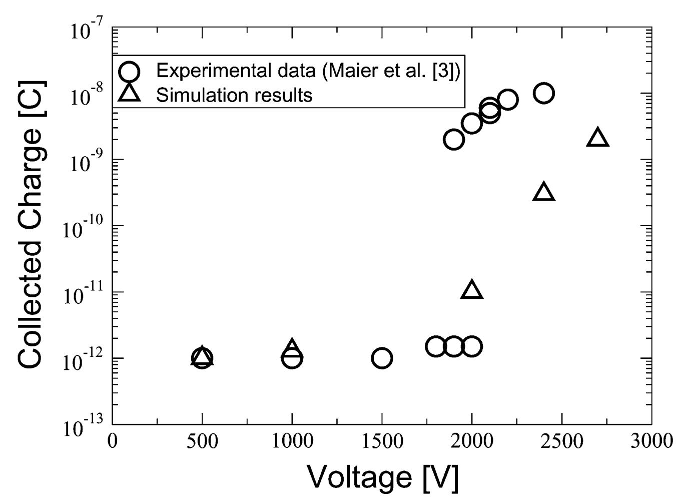

Fig. 9. Collected charge obtained by simulation in comparison to experimental data.

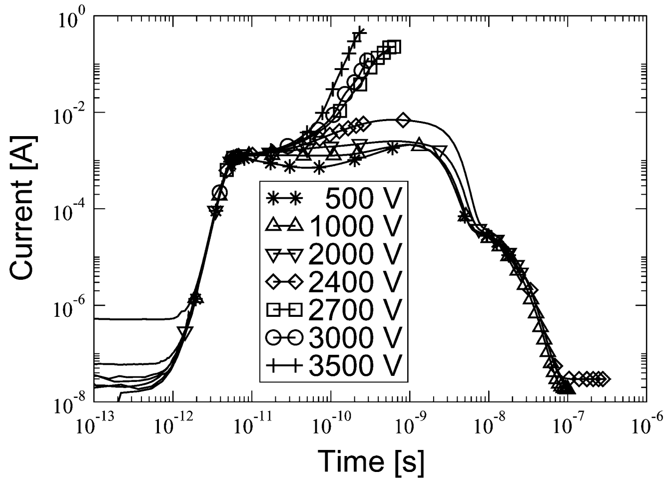

Fig. 10. Nonisothermal simulated output currents at applied voltages of 500 V, 1000 V, 2000 V, 2400 V, 2700 V, 3000 V, and 3500 V.

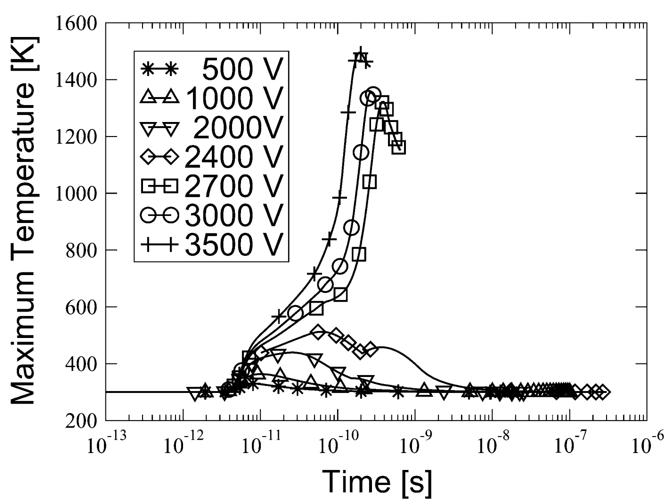

Fig. 11. Simulation of maximum temperature as a function of time for applied voltages of 500 V, 1000 V, 2000 V, 2400 V, 2700 V, 3000 V, and 3500 V.

shown in Figs. 7 and 8. With the inclusion of thermal effects, self-heating due to an ion strike was simulated. Fig. 11 shows the temporal maximum temperature for the previous voltages. For the case of 1000 V, for example, the energy deposited by Joule heating was able to dissipate by diffusion before damaging the device. In this case, the temperature increases only up to 334 K. In this sub-avalanching region, the initial deposited charge does not cause high heat generation because of the small value of the product of the current density and electric field. Therefore, this case is nondestructive and does not lead to SEB of the diode.

On the other hand, when 2700 V is applied, the maximum local temperature reaches the range in which materials used in the diode, e.g., aluminum (933 K) and silicon (1680 K), may melt or otherwise be damaged. These high temperatures are observed when significant avalanching occurs. The lattice temperature reaches its maximum in about 2×10^{-10} s. The high temperature is a result of the large amount of avalanche-generated charge.

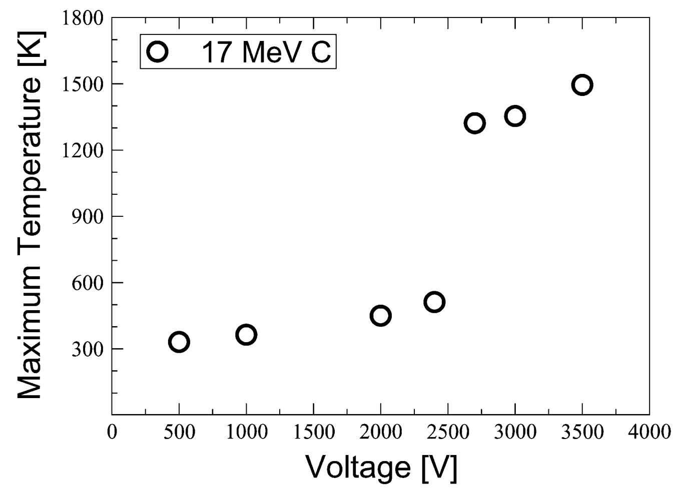

Fig. 12. Simulation of maximum temperature as a function of the applied voltage.

The results presented in Fig. 5 suggest that there is significant avalanche multiplication when 2400 V is applied, but the nonisothermal simulations showed that the maximum temperature in this case was not high enough to lead to SEB. This is because the temperature increase (to about 500 K) during the ion strike led to a decrease of the impact ionization rate. This shows the importance of the inclusion of thermal effects in order to understand and analyze the SEB phenomenon.

The temperature rise compounds the Joule heating through coupling to electrical effects as shown in Fig. 12, which plots the maximum temperature vs. the applied voltage. The maximum temperature increases rapidly once avalanching occurs. It was shown above that the applied voltage has to exceed approximately 2700 V in this diode before the Joule heating is sufficient to cause physical damage. This agrees well with experimental data reported by Maier *et al.* [7].

The temperature rise is extremely localized. In fact, the hot spot extends only 0.2 μm in the radial direction away from the strike (center line). However, the heating occurs in a region that is approximately 14 μm long in the lightly doped region at the junction. The localization results because of the relatively long diffusion times for thermal transport compared to the characteristic times for strike-induced charge deposition, electron drift, and recombination. Therefore, most of the Joule heating occurs in an extremely localized region.

IV. Conclusion

Nonisothermal simulations were used to analyze the electrical and thermal effects of SEB on a power diode. Thermal effects are essential in describing the failure mechanism and predicting whether failure will occur. The particular diode considered in this work failed at high applied voltages ($\geq$ 2700 V) when it was exposed to 17 MeV C ions. The failure mechanism is triggered by avalanching. The actual failure criterion was identified as the occurrence of local temperatures near the melting temperature of the constituent materials of the diode. These high temperatures are responsible for causing permanent damage in the device. Inclusion of the thermal effects provides physical understanding of the mechanisms responsible for SEB in power diodes.

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