A Numerical "a-posteriori" – Method to Calculate Local Self-Heating in Power Devices After the Impact of a Cosmic Particle

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Abstract—**In the early 1990s the cosmic radiation had been identified as a cause for spontaneous failures in silicon high power devices. Within the past twenty years, experimental investigations and numerical analyses of the failure mechanisms have been published [1,2]. So Kaindl et al. found that the formation of a highly conductive plasma channel, a so-called streamer, is the first stage of thermal destruction after the impact of a cosmic particle [2,3]. However, a comprehensive physical understanding of the consecutive processes, which lead from the impact to the thermal breakdown of the device, was still missing, and self-consistent computer simulations of the temperature distribution inside the device were not yet practicable. We set up and validated an easy and effective model which couples the electrical energy domain with the thermal energy domain to gain a detailed understanding of the failure mechanisms. The proposed simulation model allows us to achieve a predictive failure and robustness analysis.**

Keywords: Silicon power devices, cosmic radiation, electro-thermal coupling, "a-posteriori"-method

I. INTRODUCTION

A nuclear reaction of a cosmic neutron with a nucleus of the silicon lattice inside a reverse-biased power device is the most frequent triggering event for cosmic radiadion-induced failure. As a result, the silicon nucleus decays in several light-weight ions with kinetic energies between 10 and 100 MeV, which are decelerated in the space charge region. They lose their kinetic energy by generating electron-hole-pairs forming a highly localized plasma channel whith a length of about 10 to 50 µm and a width of some 10 nm. The carrier density in the electrically neutral plasma channel is several orders of magnitude higher than the doping concentration; as a consequence, the local electric field breaks down. But at the rim of the plasma filament, there is a strongly localized charge imbalance that leads to a high electric field peak. Impact ionization in the vicinity of this field peak generates more and more carriers so that the length of the plasma channel is continuously growing. Once a critical blocking voltage is exceeded, the device runs into a stable state were the field peak rushes through the whole device within a period of about 100 ps. This phenomenon is called streamer; the result is a highly conductive, highly concentrated plasma channel which short-circuits the device from the anode to the cathode side. After the formation of the plasma channel, where carrier generation is the predominant physical mechanism, the carrier diffusion dominates the electrical behavior of the device. Because of the lateral diffusion the carrier density in the channel decreases, carriers are pulled and extracted by the contacts, and the device returns to its initial static blocking state after about 20 ns. During this processes a very high current density together with sharp electric field peaks in vicinity to the contacts (see Fig. 2) cause a local temperature increase by Joule heating. The temperature eventually exceeds the melting point of silicon (about 1700 K [4]), and the device can be destroyed by a highly localized melting hotspot.

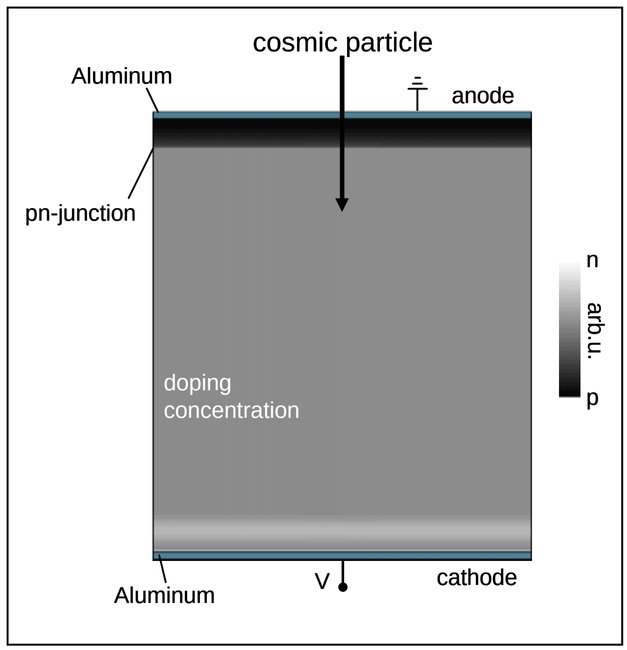

Figure 1. Schematic structure of a typical pin-diode.

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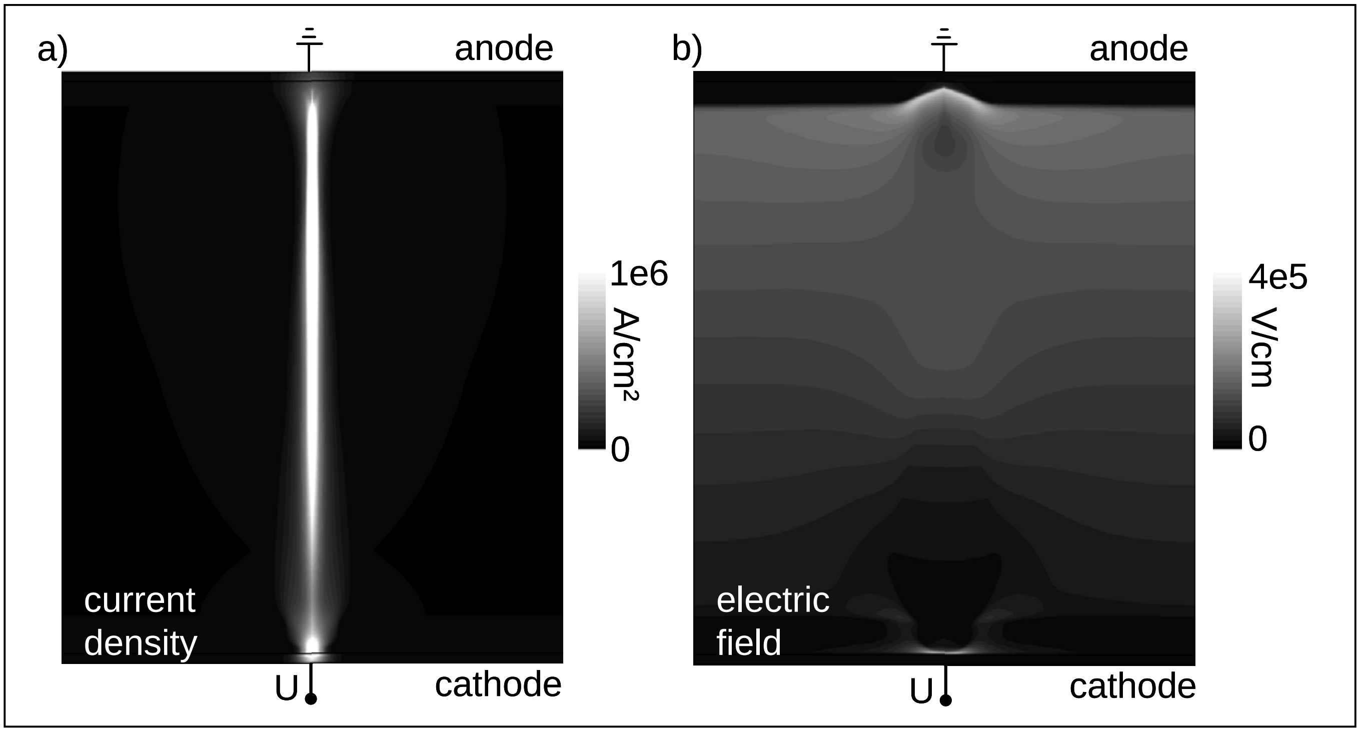

Figure 2. Simulated spatial distribution of the electrical current density (a) and the corresponding spatial distribution of the magnitude of the electric field (b) 1 ns after the impact of a cosmic particle.

In the following we present a 3D electro-thermal simulation method, which allows us to calculate both the electrical and the thermal behavior simultaneously. The model is validated by comparison with experimental data obtained from ion and nucleon irradiation measurements [5,12].

II. Simulation Model

A. Structure and Simulation Domain

The test structure for our simulations is a high power pin-diode. The doping profile and the simulation domain are schematically shown in Fig. 1. A low n-doped base zone is supplemented with a highly p-doped region at the anode side and a highly n-doped region at the cathode side. Aluminum layers at the contacts mimic the heat capacitances of the real contact metallization. A positive potential U applied at the cathode sets the diode in its blocking state. In order to cope with the three-dimensionality of the phenomena under investigation, we use an axialsymmetric simulation technique where the cosmic particle penetrates the device along the symmetry axis. At the contacts we apply Ohmic boundary conditions for the electrical potential and the carrier densities and floating boundary conditions for the temperature.

Considering the high speed and the strong localization of the streamer effect, a spatial discretization down to 20 nm and a temporal discretization down to 100 fs is necessary for the numerical solution of the partial differential equations.

B. Electrical Models

Our transient simulations are based on the widely used drift-diffusion transport model, with the physical parameters for mobilities, impact ionization etc. kept fixed at room temperature [6,7,8,9]. The parameters for the Chynoweth impact ionization model [8] were calibrated with reference to the results of ion irradiation measurements. The experimental data are in good accordance with the results obtained from our isothermal simulations with respect to the total charge generated in the device after the impact of an ion [5].

C. "A-Posteriori" - Method for Temperature Calculation

Joule heating is the predominant physical mechanism that causes a local temperature rise, when a high current density and a high electric field exist simultaneously. The local temperature distribution is then (approximately) described by the heat diffusion equation

$$\frac{\partial\left(c_L T\right)}{\partial t} - \operatorname{div}\left(\kappa \operatorname{grad} T\right) = \vec{j} \cdot \vec{E}, \qquad (1)$$

where T denotes the temperature, κ the thermal conductivity, c_L the heat capacity, $\vec{j}$ the electrical current density, and $\vec{E}$ the electric field. The most critical areas for thermal destruction are spots where the product of electric field and electrical current density attains its maximum. In the case considered, this is in the close vicinity to the cathode metallization (cf. Fig. 2).

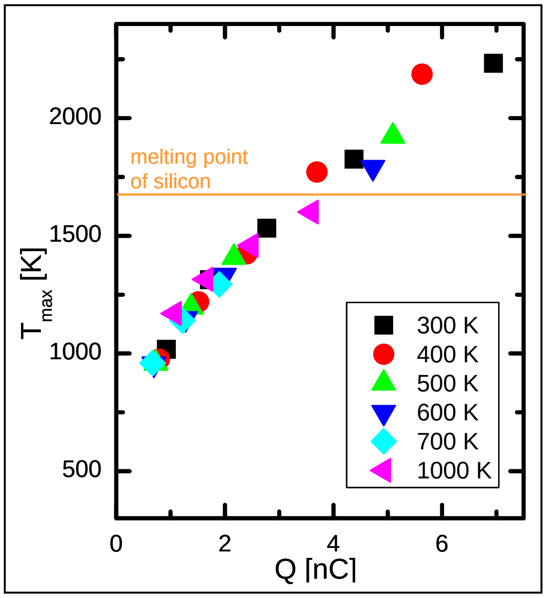

Figure 3. Maximum simulated temperature T_{max} at the hotspot in vicinity to the cathode as function of the total generated charge Q after the impact of a cosmic particle for different threshold temperatures (see text).

The thermal energy domain is coupled to the electrical domain by the temperature dependence of mobility and impact ionization (among others). In [5] we proposed an electro-thermally self-consistent simulation method to describe the coupling of electrical und thermal phenomena in the weakly doped base zone. This method fails at the hotspot near the cathode for the following reason: The electric field strength at this peak is limited by the impact ionization, which shows a strong temperature dependence in a way that the impact ionization rate decreases with increasing temperature. But a decreasing impact ionization rate inside the hotspot leads to an increase of the electric field which, in turn, causes an increase of Joule heating according to (1). This self-energizing effect amplifies every inaccuracy in the temperature dependence of the impact ionization coefficients in an exponential manner. One of the most reliable physical models covering a high temperature range up to 800 K has been set up by Reggiani et al. [10]. The temperature dependence is described by polynomials in temperature up to the tenth order. But the extrapolation of this model to temperatures higher than 800 K leads to erroneous results and divergent temperature. Together with the fact that the computational expense of an electro-thermally self-consistent calculation is about one week, direct electrothermal coupling turns out to be ineffective and yields unreliable results. A much faster calculation method with a much better approximation of the real spatial temperature distribution is achieved by using the "a-posteriori-method": After each time step of a transient isothermal electrical simulation, the local temperature distribution is calculated by solving the heat diffusion equation (1) where the heat generation term $\vec{j} \cdot \vec{E}$ is taken from the previous simulation step. This approach relies on the basic assumption that the temperature-dependence of the electrical transport model has only a

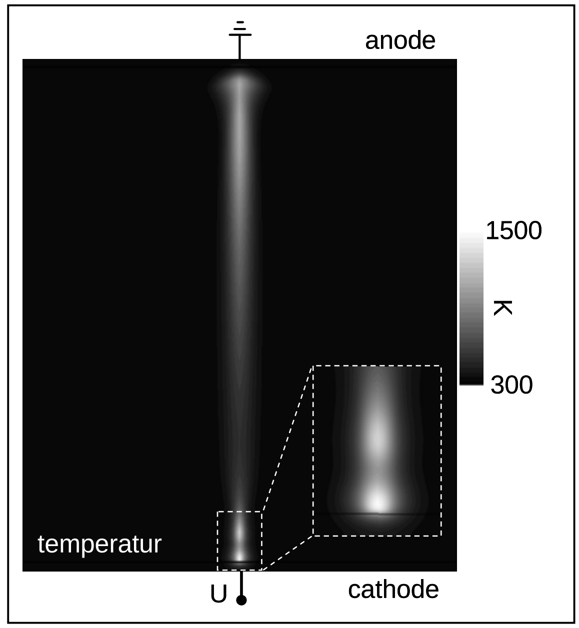

Figure 4. Simulated spatial distribution of the a-posteriori calculated temperature 20 ns after the impact of a cosmic particle.

minor effect on the resulting peak temperature. The plausibility of this assumption was corroborated by test simulations, where the correct temperature-dependence of the physical models was self-consistently included up to a certain threshold temperature, which was varied from 300 K (isothermal simulation) up to 1000 K (higher than the range of validity of the models used). We found that taking the exact temperature dependence into account would shift the maximum peak slightly up to the melting point of silicon (about 1700 K). This is demonstarted in Fig. 3. The maximum temperature in the hotspot in the vicinity of the cathode is plotted as a function of the total generated charge after the impact of a cosmic particle. The different symbols denote test simulations with different threshold temperatures, up to which the correct temperature dependence of the electrical parameters is used. We recognize that below the melting point of silicon all symbols share a common curve, with deviations in the range of about 10 percent.

The decoupled calculation of the temperature after each time step of an electrical simulation is not supported by the commercial simulation tools availabe to us. That is why we had to implement this feature as an add-on. The equation which is solved after each time step t_n for the present temperature distribution T_n is

$$T_n = T_{n-1} + \frac{\kappa}{c_L} \Delta T_{n-1} \cdot (t_n - t_{n-1}) + \frac{1}{c_L} \vec{j} \cdot \vec{E} \cdot (t_n - t_{n-1}) \quad (2)$$

where Δ is the Laplacian and constant thermal material properties κ and c_L are assumed. The updated temperature distribution is the result of the temperature at the last time step, the heat diffusion and the Joule heating. In this way the solution of the parabolic differential equation (1) is approximated by a first order numerical procedure, the Euler method [11]. The very short time steps of the isothermal

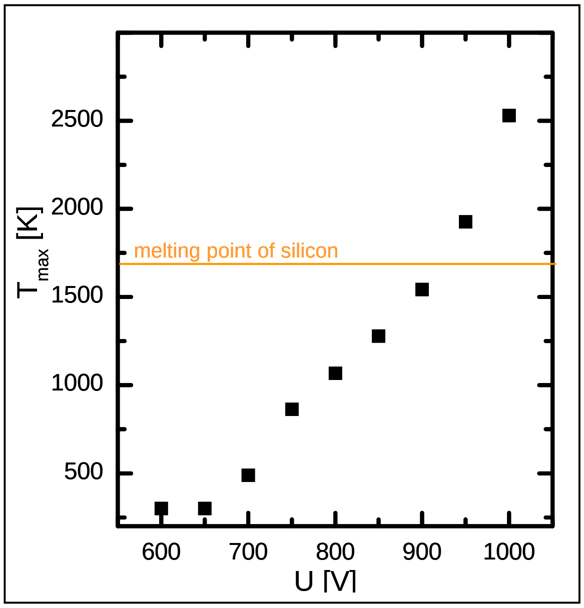

Figure 5. Maximum simulated temperature T_{max} at the hotspot in vicinity to the cathode after the impact of a cosmic particle as a function of the applied blocking voltage.

electrical simulation (down to 100 fs) guarantee the quality of this approximation. The a-posteriori calculation method allows us to calculate the local heating of a silicon power device after the impact of a cosmic particle with satisfactory accuracy. Typical simulation times are three days, which is much faster than the electro-thermally self-consistent simulation.

III. Simulation Results

Fig. 4 shows the spatial distribution of the a-posteriori calculated temperature 20 ns after the impact of a cosmic particle. At this time the temperature attains its maximum, before a significant heat flow sets on and cools down the sample. The hotspot in the vicinity of the cathode can be easily identified as the point of maximum temperature. The device runs into thermal destruction, when the maximum temperature at this point exceeds the melting point of silicon. The maximum peak temperature strongly depends on the blocking voltage applied to the terminals at the time of the particle impact. This is shown in Fig. 5, where the maxium temperature is plotted versus the blocking voltage. In our test structure, the melting point of silicon is exceeded between 900 V and 950 V. This conforms very well with irradiation measurements, where the device goes into destructive failure in a voltage range around 950 V. The applicability of our model for evaluating the robustness of different diode designs could successfully be demonstrated. It showed that predictive simulations are feasible to improve the hardness against cosmic radiation [12].

IV. Conclusion

Improving and optimizing the robustness of power devices against cosmic radiation must be based on a deep physical understanding of the failure mechanisms. Because of the nature of this fast and strongly localized phenomena, the experimental diagnostical capabilities are limited. We set up an electro-thermal simulation model which allows us to get a detailed view inside the microscopic phenomena that happen in a power device after the impact of a cosmic particle. The self-consistent coupling of the electrical and the thermal energy domain was replaced by an easy and effective a-posteriori method. In this way the local temperature distribution can be calculated with the required accuracy together with the advantages of an isothermal simulation. The results were validated with respect to irradiation experiments. It showed that our model provides a reliable basis for predictive failure analysis.

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