Modeling and Simulation of Charge Generation Events Caused by Ion Irradiation in High Voltage Power Devices

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Abstract

In this paper, we present a model that describes the initial generation of charge due to the loss of kinetic energy of an ion penetrating into a semiconductor device. 2D simulations of a reverse biased power diode visualize the evolution of carrier densities and electric fields in the interior of the device as initiated by the ion. For the case of irradiation with 17MeV ^{12}C ions, the simulations agree well with recent experimental findings.

1 Introduction

Silicon semiconductor devices can fail when they are exposed to highly ionizing radiation like heavy ions or cosmic rays [1]. These so–called single event effects (SEE) occur in digital circuits [2], as well as in power devices [3]. As it is very difficult to perform measurements of the extremly fast processes occuring in the interior of the device, much effort has been spent in simulating the effects of a penetrating ion on the device behaviour, in particular regarding logic or low power devices like SRAM cells or low power MOSFETs. But only little work has been done on simulating the impacts of irradiation effects on high power devices.

In this paper, we present the numerical analysis of an ion irradiation experiment that was recently performed by *Maier et al.* [4]. A high power diode was irradiated by several types of ions. The charge generated by one single ion was measured in dependence on the applied bias. For a small reverse bias, the charge corresponds to the total absorption of the ion's kinetic energy. Applying a sufficiently high reverse bias, charge multiplication of up to four orders of magnitude sets on.

2 Modelling

For a detailed numerical analysis of the experimental processes and the visualization of the dynamical behaviour in the interior of the device, we developed a model that describes the initial generation of charge due to the loss of kinetic energy of an ion penetrating into the device. Additional terms

$$G_{ion}(\vec{x},t) = \frac{A}{2\pi a s}\cdot\frac{dE}{dz}\cdot\exp\left(-\frac{r^2}{2a^2}\right)\cdot\exp\left(-\frac{1}{2}\left(\frac{t-t_0}{s}\right)^2\right)$$

have to be added to the right hand sides of the carrier balance equations for electrons and holes, respectively. Here, *r* denotes the distance from the track of the ion and *t* the time. The energy loss function *dE/dz* was computed using the simulator TRIM (Transport of Ions in Matter) [5]. We obtain estimates of the radial (a=0.1μm) and temporal (s=1ps) Gaussian widths of the initial generation profile by solving the equation of motion of the ion within the device [6]. The initial generation rate is proportional to the kinetic energy *E* of the ion. Implementing the described model in the device simulator DESSIS [7] allowed us to perform numerical simulations of the ion irradiation experiment.

3 Simulation

We performed simulations of a p^+n–diode of 450μm length and a rated reverse blocking voltage of about 3.5kV. The junction is formed by a 1.5μm deep Gaussian p–diffusion in a lowly doped n–base. The width of the structure is 100μm about the plane of incidence of the ion. The diode was simulated without any external circuit, assuming an ideal voltage source. Therefore, the voltage was kept constant during the simulation. Fig. 1 shows the temporal and spatial evolution of the electric field in the plane of incidence, when a ^{12}C ion with a kinetic energy of 17MeV impinges perpendicularly from the anode side at z=0μm.

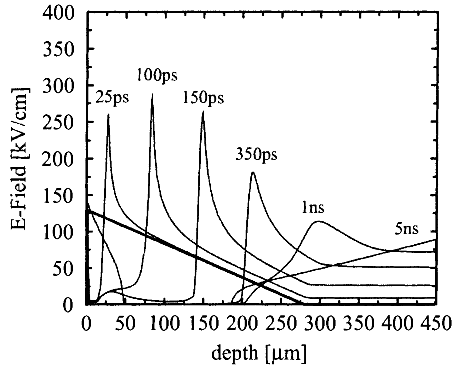

Fig. 1. Temporal and spatial evolution of the electric field in the plane of incidence for a reverse bias of 1800V.

After the ion impact, the generated electron/hole plasma distorts the initial triangular field and a steep field peak forms which starts propagating through the device. In the region left–sided of the peak plasma conditions occur. Here, the electric field is therefore nearly completely suppressed. For a reverse bias of 1800V, the field peak smoothes out while propagating towards the cathode contact (Fig. 1). The periode of a high electric field peak and a corresponding strong impact ionization is too short in order to enable the generation of a large amount of additional charge carriers. Therefore, the charge flowing out of the device corresponds to the total absorption of the kinetic energy of the ion.

A completely different situation occurs for a reverse bias of 2200V. Here, the initial electric field is already higher than that of the 1800V case in consequence of the higher reverse bias that has to be sustained. The steep field peak caused by the initial charge plasma injected by the ion is, accordingly, also higher. Finally, this leads to a field peak that propagates through the whole device with an undiminishing value of above 300kV/cm (see Fig. 2). It reaches the cathode contact after about 150ps.

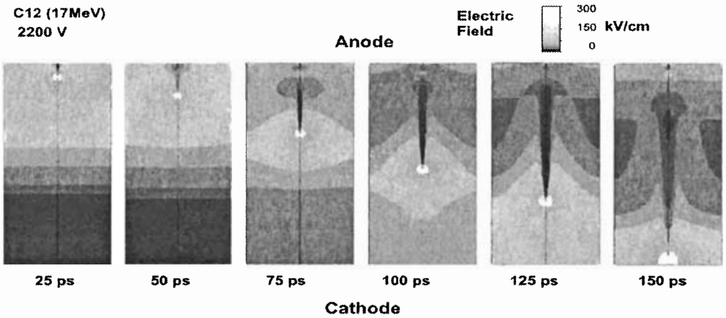

Fig. 2. 2D–plot of the propagating electric field peak for a reverse bias of 2200V.

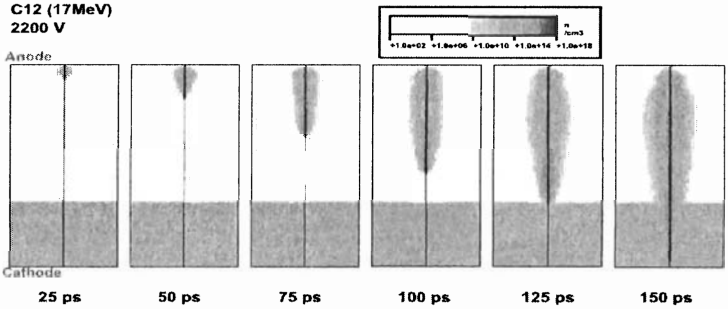

Fig. 3. 2D–plot of temporal and spatial evolution of the charge carrier density for a reverse bias of 2200V. A highly conductive filament has formed after 150ps.

Due to the corresponding strong avalanche multiplication caused by the high electric field the device is flooded with charge carriers along the whole plane of incidence. A highly conductive filament can form (see Fig. 3) which causes a short cut between anode and cathode after 150ps and, therefore, a high flow of current. As a consequence, charge can flow out of the device which is by serveral orders of magnitude higher than that in the absorption case.

4 Comparison between Simulation and Experiment

In Fig. 4 the simulated charge generated within the diode by one single ion is plotted and compared with the experimental findings of *Maier et al.* [5]. For the

17MeV ^{12}C ions simulation and experiment are in good agreement. The abrupt onset of charge multiplication of serveral orders of magnitude can be reproduced. But for the 270MeV ^{86}Kr ions the onset voltage is shifted towards higher voltages compared to the experiment. Here, the limitations of the 2D simulation become obvious. In 2D the field peak is not a real peak, but a field front. The third dimension in which the field can also be confined is missing. All in all, this leads to a lower peak value and, finally, to the shift of the onset of charge multiplication. The nature of the problem would require a full 3D simulation, but due to the limitions in computational resources available for us, this is not (yet) tractable.

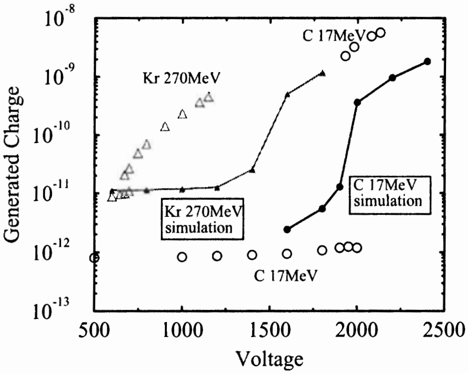

Fig. 4. Generated charge within the diode by one single ion. Comparison of experiment (symbols) and simulation (solid lines).

Even on the basis of 2D simulations, we were able to get a qualitative visualization of the intrinsic mechanisms of charge multiplication events occuring as consequence to the irradiation of high voltage devices by heavy ions. This knowledge about the physical processes in the interior of the device is indispensable for the design of new devices which are more resistant against cosmic rays.

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