Modeling of the Cosmic Radiation-Induced Failure Mechanism in High Power Devices

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ABSTRACT

Ion irradiation experiments provide valuable insight into the failure mechanism caused by cosmic radiation in power devices. After penetrating into the semiconductor, ions lose their kinetic energy in the vicinity of the surface. Applying sufficiently high reverse voltage, an incident ion induces a high electric field peak at the anode side of a power device which, by impact ionization, generates a highly conductive filament, while it propagates towards the cathode. In contrast with such experiments, natural cosmic rays may cause a nuclear reaction anywhere within the volume of a device, through which recoil ions can be produced. In this case, two electric field peaks form and propagate in opposite direction, respectively. This process represents the basic mechanism leading to cosmic radiation-induced failures of power devices.

Keywords: semiconductor power devices, modeling, cosmic radiation, device failure, streamer

1 Introduction

About ten years ago, it had been recognized that, even at sea level, semiconductor power devices can be destroyed by the action of cosmic radiation. Since then, a number of experimental and theoretical investigations have been performed to understand this phenomenon. A widely accepted model of the failure mechanism assumes that highly ionizing recoil ions are produced by a nuclear reaction between an incident energetic neutron and a silicon nucleus of the substrate material of the device. The ions are able to generate a highly localized burst of charge which, by impact ionization, is amplified in regions with high electric field as they exist in reverse-biased power devices. Eventually, this may lead to the thermal breakdown of the device. In order to achieve a more robust device design with enhanced hardness against cosmic radiation, a detailed knowledge of the physical mechanism leading to failure is indispensable. As the processes initiated by an incident neutron are ultra-fast, it is extremely difficult to investigate the transient physical effects in the interior of a power device by experiments. Therefore, we have been working on a simulation model which is able to explain and to visualize the cosmic radiation-induced failure mechanism in a detailed and quantitative manner.

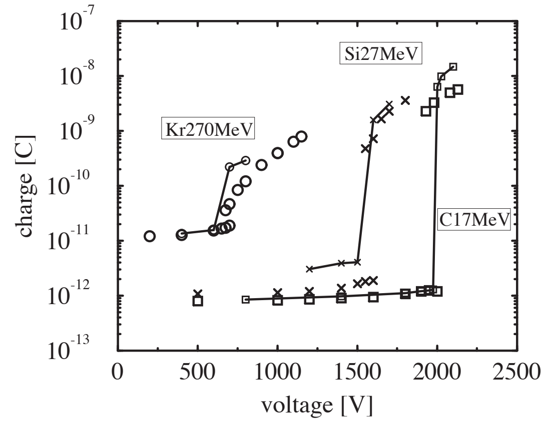

Figure 1: Charge generated in the interior of a NPT-diode by incident ^{86}Kr (270 MeV), ^{28}Si (27 MeV), and ^{12}C (17 MeV) ions. Shown are calculated results (solid line) in comparison with experimental data (symbols).

2 Modeling of Ion Irradiation

Ion irradiation experiments have proven to provide valuable insight into the physical processes which lead to device failure [1], [2]. We modeled an experiment in which a non-punch-through (NPT) diode with a volume breakdown voltage of 4 kV was irradiated with different species of ions from ^{12}C to ^{86}Kr and kinetic energies ranging from 8.5 MeV to 270 MeV [3]. Fig. 1 shows the charge that is generated by one single ion in the interior of the NPT-diode as a function of the applied reverse bias. The ions penetrate into the diode at the anode side, where the pn-junction is located about 1.5 μm below the surface [2].

For small reverse voltage, the charge flowing out of the device corresponds to the amount of charge generated by the total absorption of the kinetic energy of the ion. Therefore, the charge remains nearly constant in this voltage range. The energy dissipated by the incident ion generates a highly localized charge plasma of electrons and holes that disturbs the stationary triangular electric field inside the diode. The electrically neutral plasma pushes the electric field out of the anode region.

NSTI-Nanotech 2005, www.nsti.org, ISBN 0-9767985-2-2 Vol. 3, 2005

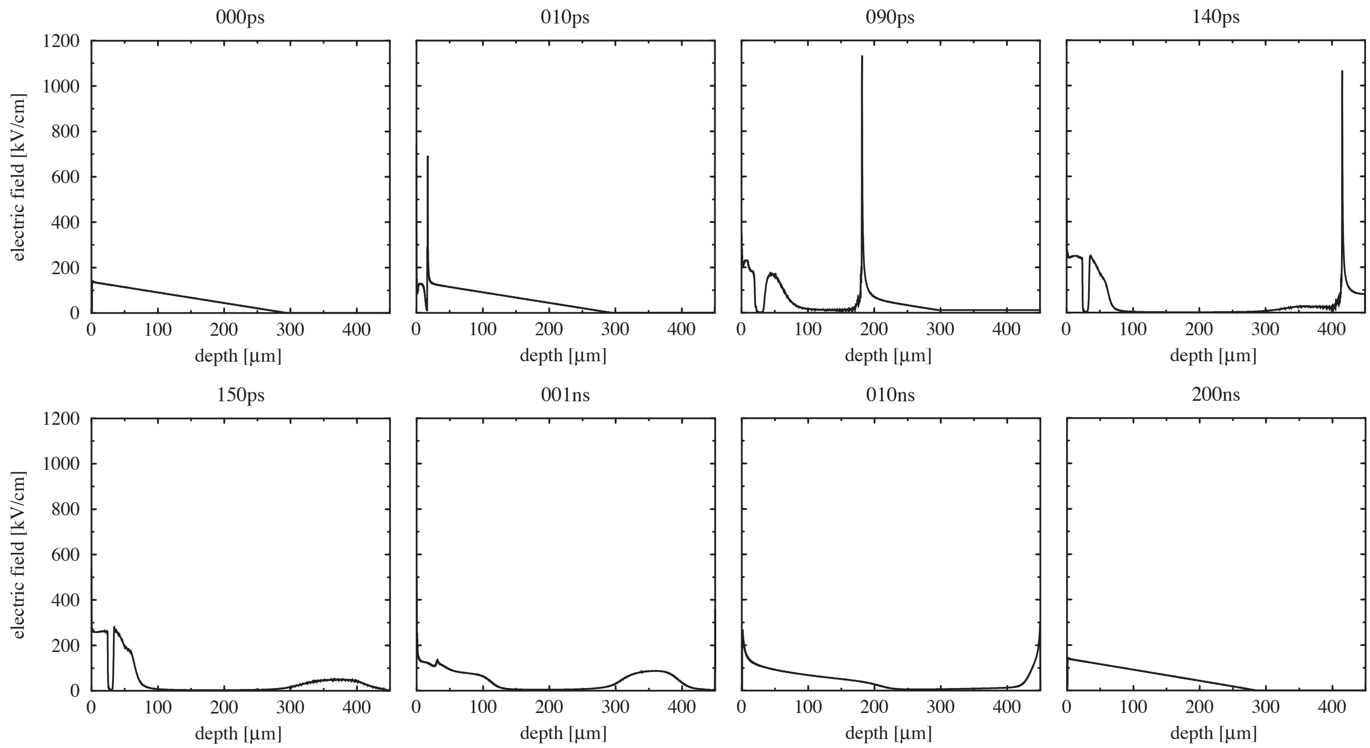

Figure 2: Spatial and temporal distribution of the electric field along the axis of symmetry of a NPT-diode induced by an incident ^{12}C ion with a kinetic energy of 17 MeV penetrating into the device at $z = 0$.

As a consequence, a field peak develops at the front of the plasma. For small voltages, the charge carriers start diffusing out of the plasma region and the concentration gets lower. Accordingly, the field peak also decreases. The period during which the electric field peak exists is too short for the generation of a perceptible amount of additional charge carriers by impact ionization.

Applying sufficiently high reverse voltage, a completely different process is observed. Beyond a certain threshold voltage V_{th} massive charge multiplication up to four orders of magnitude sets on. This is effected by the occurrence of a so-called streamer, which is a phenomenon well-known from gas discharges [4]. Due to the higher stationary electric field, the peak value of the ion-induced field is also higher compared to the non-multiplication event described above. Now a stable state can develop in which the field peak travels within 150 ps through the entire device from the anode to the cathode side (see fig. 2). The field peak is not driven by the transport of carriers but by the continuous generation of charge at the plasma front. This explains its extremely high velocity which exceeds the high-field saturation velocity of electrons and holes by about one order of magnitde. A strong impact ionization builds up and supports a highly conductive plasma filament that constitutes a short between anode and cathode with very high current density. After the electric field peak has reached the cathode contact it disappears. In the sequel, diffusion perpendicular to the plasma filament becomes the dominant process and, therefore, the carrier concentration decreases again. After 200 ns the stationary triangular field is completely recovered.

In the vicinity of the threshold voltage V_{th}, it depends on the details of each single ion trajectory whether or not multiplication occurs. Therefore, at the same voltage both multiplication and non-multiplication events are observed in the experiment (see fig. 1). Increasing the reverse voltage beyond V_{th} leads to an increasing probability for multiplication events. As the simulation model assumes cylindrical symmetry, it is restricted to straight ion paths parallel to the axis of symmetry. Consequently, it is not possible to obtain different events at the same voltage.

Despite the high amount of charge, multiplication events are in principle non-destructive. However, with increasing reverse voltage the small probability that a multiplication event may lead to device failure also increases in case of ion irradiation.

Our simulation model assumes carrier transport by drift and diffusion coupled to Poisson's equation as implemented in the device simulator TeSCA [5]. To keep the computational expense affordable, thermal effects are not taken into account. The carrier generation rates include additional terms which describe the initial depo-

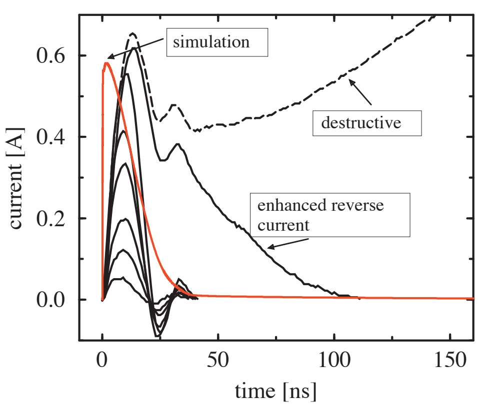

Figure 3: Measured current transients induced by an incident ^{12}C-ion and a simulated current pulse for a voltage of 2000 V.

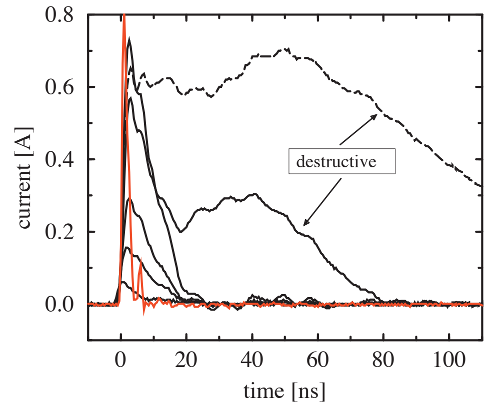

Figure 4: Measured current transients induced by 180 MeV protons in the NPT-diode at a reverse bias of 1750 V.

sition of charge in space and time based on the energy loss distribution of the penetrating ion as reported in [6]. The energy loss function, in turn, is calculated using the simulator TRIM [7]. Furthermore, it was necessary to revalidate the impact ionization coefficients for very high electric fields with reference to proper experimental data. The excellent agreement between our model and the experimental results as depicted in fig. 1 proves its validity for different species of ions and kinetic energies. The model is applicable to different types of NPT and punch-through (PT) diodes [2] as well as to IGBTs [8].

Fig. 3 shows measured current transients of reversible events resulting from incident ^{12}C-ions with a kinetic energy of 17 MeV for applied voltages between 1955 V and 2010 V. A detailed description of the measurement setup and the external circuit can be found in [9]. The peak currents vary between 50 mA and 650 mA. Additionally, two pulses leading to a damage of the device are included in fig. 3. One causes a permanent increase of the reverse current of about 20 μA, the other one a full destruction of the device. The destructive pulses have a peak current comparable to the reversible ones, but their pulse length is much longer.

The shape of the simulated pulse corresponds quite well to the measured transients. The peak current is within the values obtained by experiment and the length is only slightly larger. The rise time of the simulated pulse is extremely short. The measured rise times are limited by the temporal resolution of the equipment and the parasitics within the circuit.

The length of all non-destructive pulses is equal with a value of about 30 ns. It is difficult to measure the exact pulse length because the end of the pulse signal is disturbed by reflections in the connecting cables. The pulse length is very sensitive to the structure of the device, but not to the applied reverse bias or to the external circuit. It is essentially determined by the transit time of the holes which, after generation at the cathode side, travel to the anode.

3 Failure Initiated by Cosmic Radiation

As the flux density of cosmic radiation is relatively small at sea level, tests need to be performed by the use of particle accelerators. For this work, we used the 180 MeV proton source at the TSL in Uppsala, Sweden. For kinetic energies above 50 MeV, there is no difference between the action of protons and neutrons with respect to the initiation of the failure mechanism. In the nuclear reaction between a penetrating nucleon and a silicon nucleus of the semiconductor substrate material all species of recoil ions ranging from ^{1}H to ^{29}P can be produced [10].

Fig. 4 shows the measured current transients resulting from 180 MeV protons penetrating into the above-mentioned NPT-diode with a reverse bias of 1750 V. The occurrence of multiplication events already at a reverse bias of 1750 V indicates that the average kinetic energy of the recoil ions after a nucleon-induced reaction is higher than that employed in the ion irradiation experiment discussed above. The majority of the measured pulses is non-destructive. But also two events leading to the damage of the device are depicted which are characterized by significantly longer pulses. The different pulse shapes reflect the statistical nature of the parameters of the initial inelastic nuclear reaction, such as, the location of the nuclear event within the device, the species of produced recoil ion, and its kinetic energy. In contrast to that, for the ^{12}C-ion-induced pulses only the peak currents differ (see fig. 3).

Penetrating ions deposite their kinetic energy in the vicinity of the semiconductor surface. Therefore, one single electric field peak forms at the anode and propagates towards the cathode as shown in fig. 2. In contrast,

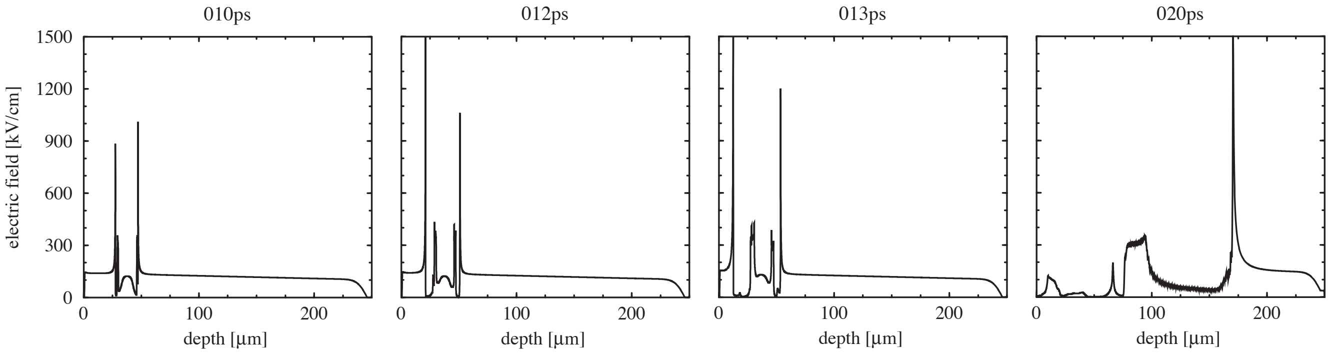

Figure 5: Spatial and temporal distribution of the electric field along the axis of symmetry of a PT-diode induced by a recoil ^{12}C ion with a kinetic energy of 17 MeV that was produced by a nuclear reaction in a depth of $z = 30\,\mu$m.

a nuclear reaction induced by an incident nucleon may occur anywhere in the interior of the device. We simulated this situation assuming a recoil ^{12}C-ion with a kinetic energy of 17 MeV produced in a depth of 30 μm below the surface of a PT-diode. A ^{12}C-ion with 17 MeV will be stopped in silicon within 16 μm. The generated charge plasma now causes two steep electric field peaks, one at the front side of the plasma region at $z = 46\,\mu$m, the other one at the backside at $z = 30\,\mu$m. The two peaks start propagating in opposite direction, respectively, as it is shown in fig. 5. After 15 ps the first peak has reached the anode and disappears. The second peak needs 25 ps to reach the cathode contact. The strong impact ionization at the field peak causes a highly conductive filament between anode and cathode. This constitutes the basic physical failure mechanism which, depending on the specific parameters of the initial reaction between intruding nucleon and silicon nucleus, can lead to the destruction of a power device.

The simultaneous presence of extremely high electric fields, high carrier densities, and very steep gradients, occurring in ultra-fast transient processes, makes it tremendously difficult to achieve a numerically stable simulation even in the case of one single field peak. With two field peaks we find that, by the inherent coupling through Poisson's equation, the peaks form a pair acting in combination. Therefore each numerical perturbation affecting one peak immediately transfers to the other one and, thus, worsens the overall stability and accuracy. Nevertheless, our investigations clearly show that the basic configuration with two electric field peaks propagating in opposite directions is qualitatively correct and can be described and explained within the framework of the commonly used drift-diffusion model.

4 Conclusion

We developed a physical model and performed computer simulations which explain and visualize the processes that lead to the self-sustained amplification of an initial charge deposition generated by a high energetic ion inside a semiconductor power device. A steep field peak propagating from the anode to the cathode builds up a highly conductive filament which may short the device. The excellent agreement between our simulations and ion irradiation experiments demonstrates the validity and accuracy of the model.

By natural cosmic radiation, recoil ions can be produced anywhere within the device volume in consequence of a radiation-induced nuclear reaction. This causes a process, in which two steep electric field peaks can form, each propagating in opposite direction towards the respective contact. The resulting current filament can eventually cause the total destruction of the device.

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