

Single Event Effects in 3.3 kV 4H-SiC MOSFETs Due to MeV Ion Impact

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Abstract. In this work, MeV alpha particles generated from an accelerator are used to study single event breakdown (SEB) in 4H-SiC MOSFET samples, rated at 3.3 kV. The samples are exposed to bursts of alpha particles under reverse bias conditions to investigate the SEB sensitivity to ion energy and reverse bias. The energies of alpha particles are chosen to reach different depths in the drift region of the MOSFET devices, and also to penetrate the whole drift region. Forward and reverse characteristics are measured after each exposure, as long as no failures occur, to ensure that the device performance is maintained. The measurements show that no significant effects are observed on the drain-source leakage current, while minor effects on gate behavior can be seen as a function of accumulated fluence. Furthermore, SEB can only be triggered with a reverse bias larger than, or equal to 3 kV. A standard MOSFET cell with a similar rated voltage is also simulated in Sentaurus TCAD to study these effects, using two different models for the incident ion-induced ionization: the Alpha Particle and the Heavy Ion model. Simulations show that the Alpha Particle model cannot induce any device failures even with a 3.5 kV reverse bias, while it is possible to trigger a failure by the Heavy Ion model, where the ionization can be selected. Carrier plasma and internal electric field distributions of the two models are plotted and compared, showing that device failures triggered by a heavy ion are related to the hole injection at epi-substrate interface, in which linear energy transfer (LET) of the particle plays an important role.

Introduction

It has been shown that terrestrial neutrons and energetic heavy ions in space can affect the reliability of SiC MOSFETs by increasing the leakage current and also induce unrecoverable device failures [1, 2] known as a single event burnout (SEB), occurring under reverse bias conditions. Energetic neutrons interact mainly via elastic scattering with target nuclei, which causes displaced Si and C ions to dissipate their kinetic energy in dense ionization tracks in the semiconductor. Highly energetic ions that penetrate devices will also dissipate their kinetic energy, forming more continuous tracks with intense electron-hole pair generation, sometimes described as linear energy transfer, LET. The mechanisms behind single event burnouts are complicated and have not been fully understood, but the mechanisms considered for SEBs of SiC MOSFETs include a combination of the dense ionization in the track and impact ionizations due to a high electric field in the drift region of the reverse biased devices. This may lead to an avalanche current and generate a positive feedback loop. Impact ionization may happen in all semiconductor devices, where high fields cause multiplication of carriers that may contribute to an avalanche breakdown. A MOSFET, which includes a parasitic bipolar junction transistor (BJT) consisting of the source, p-base and the low-doped drift region, is especially prone to experience a SEB since the leakage current from the avalanche process is amplified and the parasitic BJT is activated by extrinsic carriers flooding into p-base from the ion track [3, 4, 5].

In this work, we aim to further investigate the mechanisms of SEBs by exposing 4H-SiC MOSFET chips to very low fluence of MeV alpha particles from an accelerator. The energy of the alpha particles can be controlled and this possibility is used to investigate the combined effect of reaching different

depths and using different reverse bias. Experimental results so far show that it is not possible to trigger SEB for lower energy alpha particle with less penetration depth, even for voltages very close to the actual breakdown, occurring around 4 kV. However, for alpha particles with higher energies SEB may occur already at 3 kV. To understand these findings, a cell of similar design as the tested MOSFETs is modelled in Sentaurus TCAD, using two available models for generating the ionized track, the Alpha Particle model and the Heavy Ion model, which yields 5-6 times higher LET. The simulation results show that it is not possible to trigger SEBs with the Alpha Particle model due to the relatively low LET, while simulations with heavier ions and higher energies can easily cause enough ionization to initiate the SEB in the computer. The reasons for the failure of the Alpha Particle model to reproduce the experimental results will be discussed.

Experimental Methodology

Engineering samples of SiC MOSFET modules with a rated voltage of 3300 V are used in the experiments, and the breakdown voltage measured before experiments is around 4 kV. The lid of the module is removed before the module is placed in the irradiation chamber so the bare chip is exposed directly to the beam. Each module contains only one chip. The module is then connected via electrical vacuum feedthroughs to a 5 kV curve tracer from IWATSU to bias the device and record the characteristics before and after exposures. The mono-energetic alpha particle beam is provided by a tandem accelerator and the typical beam spot is about 1 mm². The beam is electrostatically scanned in horizontal and vertical directions to produce an irradiated area of about 4×4 cm², ensuring that the chip will be fully covered by a homogeneous fluence. A mechanical shutter is used to deliver typically a dose of 3×10^8 cm⁻² during a 1 s long “shot”, giving an average areal coverage of just a few alpha particles per cell. The measurements are carried out for specific alpha particle energies, probing different depths of the device, under increasing reverse bias to see the effect of the internal field. Typical device characteristics are measured both before and after each shot to monitor any gradual device degradation, but when a SEB occurs, it is immediately detected as a fatal event for the MOSFET. The experiments are carried out at room temperature.

The projected ranges of alpha particles as a function of their energy, including a 4 µm thick aluminum layer on top of the SiC, is calculated from SRIM [6] and shown in Fig. 1. Considered a several µm thick metal contact, the peak of the electric field at reverse bias is estimated to be at a depth of about 10 µm. The total drift region of these MOSFETs is around 30 µm.

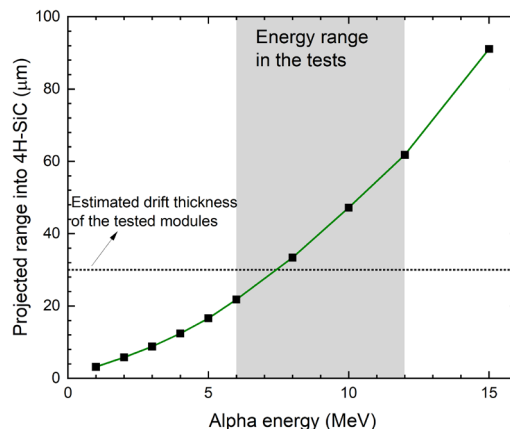


Fig. 1. The projected range of alpha particles in SiC, including a 4 µm thick aluminum contact layer. Only alpha particles above 10 MeV will penetrate the whole drift layer.

TCAD Modelling

A standard MOSFET cell with a similar voltage class [7] is modelled in Sentaurus TCAD and Table 1 gives dimensions and doping concentrations used in the modelling. The MOSFET cell is simulated at various reverse bias voltages and two different radiation models are included in the

simulations: Alpha Particle model that is designed particularly for alpha particle (He ion) irradiation and the Heavy Ion model [8]. The main difference between these two models is that the Alpha Particle model includes the enhanced ionization, the Bragg peak, at the end of the particle track since it models the physics of only alpha particles, while the Heavy Ion model gives less details, but enables simulations of random tracks and heavy ions with substantially higher LET. The default parameters of the Alpha model in Sentaurus are for silicon, and these are replaced by values for SiC according to [9]. The alpha particles in the simulations have an energy of either 6 or 10 MeV and uses SRIM data for the ionization. In the Heavy Ion model, a particle with a LET of 0.05 pC/ μm forms a 28 μm long cylindrical track, with a Gaussian radial distribution having an average radius of 70 nm. Other relevant physical models in the TCAD simulations are incomplete ionization, Arora mobility model, doping-dependent lifetime model (Scharfetter relation) and Hatakeyama avalanche model [8]. The time at which the generation rate reaches its peak value after the ion strike is set to 2 ps as a time margin for both models. The incident particle is always coming through the source region to mimic the most critical condition for SEB [2]. All the simulations are running at room temperature (300 K) and no heating of the device is included.

Table 1. MOSFET modelling parameters

Region	Thickness (μm)	Doping concentration (cm^{-3})
Source	0.2	10^{19}
Base	0.8	2×10^{17}
Drift	30	5×10^{15}
Substrate	1	8×10^{18}

Experimental Results

In the experiments, the tested module is always measured with gate and source shorted. Figure 2 shows the measured reverse IV characteristics under increasing reverse biases up till 3 kV after 6 MeV alpha particle irradiations. No SEB is observed during the experiments and neither can any leakage degradation be found after irradiations (Fig. 2a). Increasing alpha particle fluence has also insignificant effect on the leakage current, indicating that relatively few point defects, or generation centers, are introduced in the drift region (Fig. 2b).

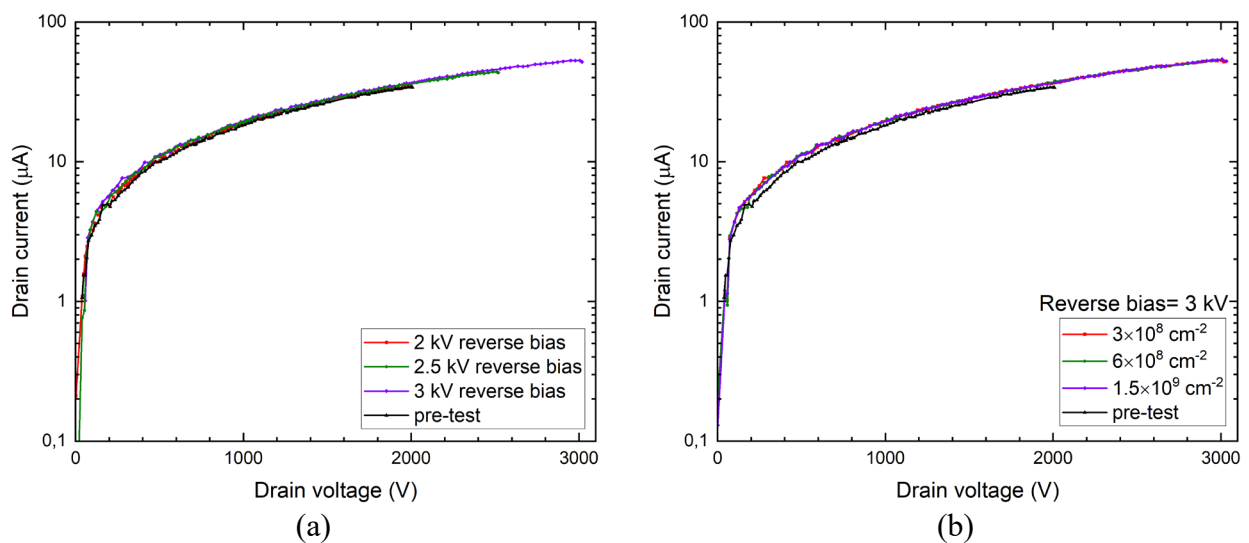


Fig. 2. Reverse characteristics of the tested module after irradiation with 6 MeV alpha particles. In (a), the reverse IV is shown for different reverse bias during the alpha particle exposure and in (b), the IV is shown with the accumulated fluence after exposure at 3 kV as a parameter.

Figure 3 shows two other typical characteristics of the MOSFETs, gate threshold voltage, V_{th} , and on-state drain-source resistance, $R_{ds(on)}$, after irradiation by 6 MeV alpha particles at various biasing. The exposure time is 1 s. The V_{th} is measured at 4.7 mA and on-state resistance $R_{ds(on)}$ is measured at 12 A with a gate voltage V_{gs} equal to 17 V. A slight decrease in V_{th} and increase in $R_{ds(on)}$ are found with increasing dose, which is probably due to the charge accumulation at the SiC-oxide interface, changing the trapping processes. These changes are not considered to significantly affect the device operation.

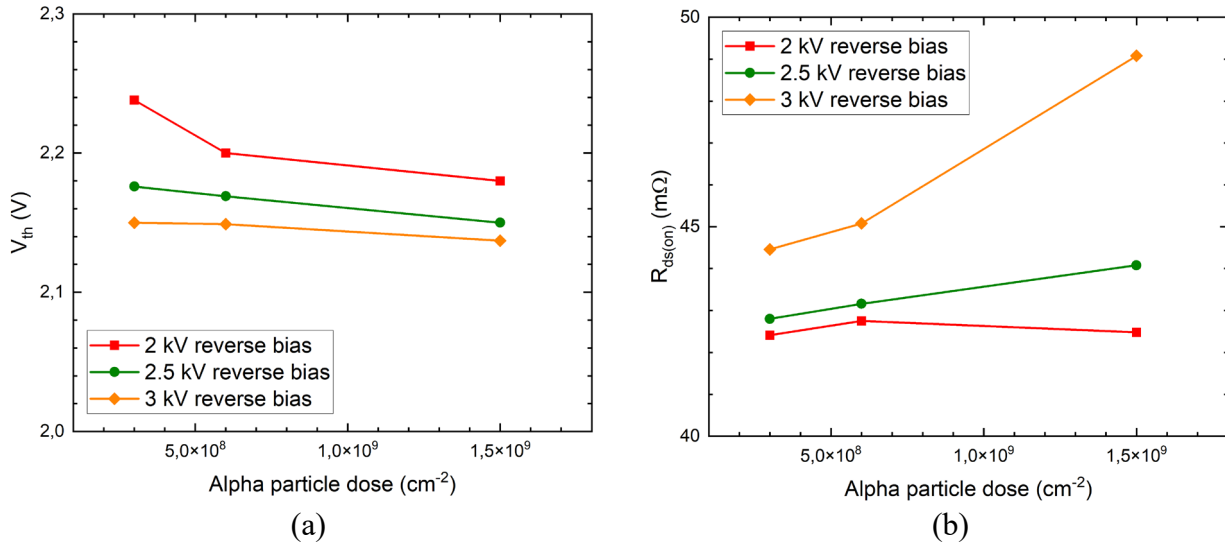


Fig. 3. Measured threshold voltage (a) and on-state resistance (b) from chip irradiated with 6 MeV alpha particles at different reverse bias. Minor changes can be seen, which are probably related to induced charges in the oxide or SiC/oxide interface.

For a given alpha particle energy, the reverse bias is increased until device failures are found. Here, SEB occurred at 6 and 10 MeV alpha particle irradiations under a bias of 3.5 and 3 kV, respectively. The SEBs could be repeated with new modules and the failure occurred each time for the same voltage level and alpha energy. Increasing the alpha particle fluence in each shot does not help to trigger the device failure, which indicates that the particle energy is a more crucial parameter. Figure 4 shows the relationship between alpha particle energy and the minimum reverse bias that triggers the device failures. It shows that a reverse bias of about 90% of maximum reverse voltage is required to induce device failures for 6 MeV alphas with stopping range close to the epi-substrate interface. For 10 MeV alphas, that reach deeper into the substrate, breakdown occurs at 75% of the maximum reverse bias.

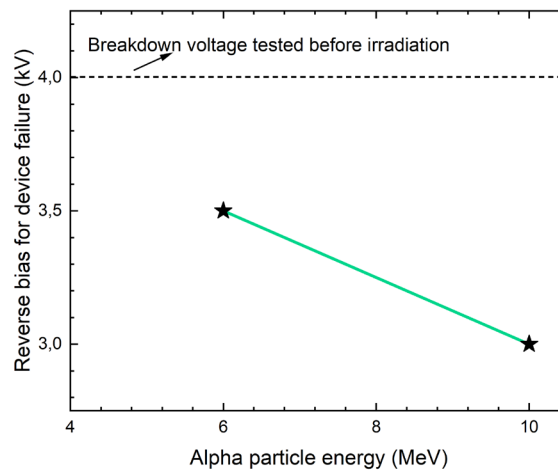


Fig. 4. The required reverse bias obtained from measurements to trigger device failures for alpha particles with different energies. The device cannot be destroyed by alpha particle exposure at these irradiation conditions with a reverse bias under 3 kV.

Discussions

Despite that several device failures are observed in measurements, no SEBs can be triggered in simulations with the Alpha Particle model, even with a reverse bias of 3.5 kV. Figure 5 plots the simulated drain current under a reverse bias of 3.5 kV within a nanosecond range. A single alpha particle can generate a local drift current with a current density reaching 10^4 A/cm², which will start to decrease slowly about 100 ps after the incident ion has passed. Simulations also show that the possibility of SEBs of SiC MOSFETs is not so sensitive to the energy of incident alpha particles, at least between 6-10 MeV range (red and green curves). However, SEBs are found when switching to the Heavy Ion model (yellow dashed curve). A heavy ion with an LET of 0.05 pC/ μ m with a track length of 28 μ m is able to cause a second, sharper increase in leakage after the plateau which eventually lead to a catastrophic breakdown.

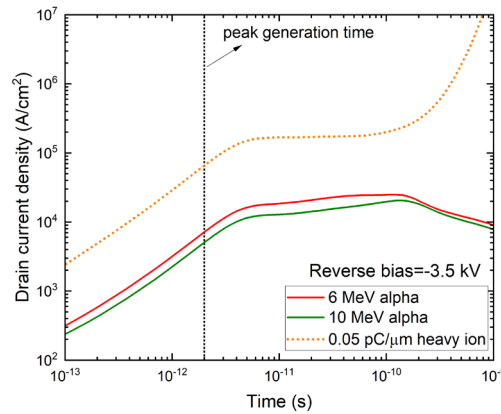


Fig. 5. Simulated transient leakage current plots under 3.5 kV bias. The peak generation time for all the particles is 2 ps (black dotted line). The heavy ion with a higher LET generates a sharp increase in current after the plateau and causes a breakdown.

The time-dependent electron distributions induced by different particles are shown in Fig. 6 for the Alpha Particle model (Fig. 6a and b) and for the Heavy Ion model (Fig. 6c and d). The excess charges generated by a 10 MeV alpha particle nearly diminish in 1 ns, while the amount of charge generated by the heavy ion is far more and also lead to a substantial current increase after 1000 ps following the irradiation.

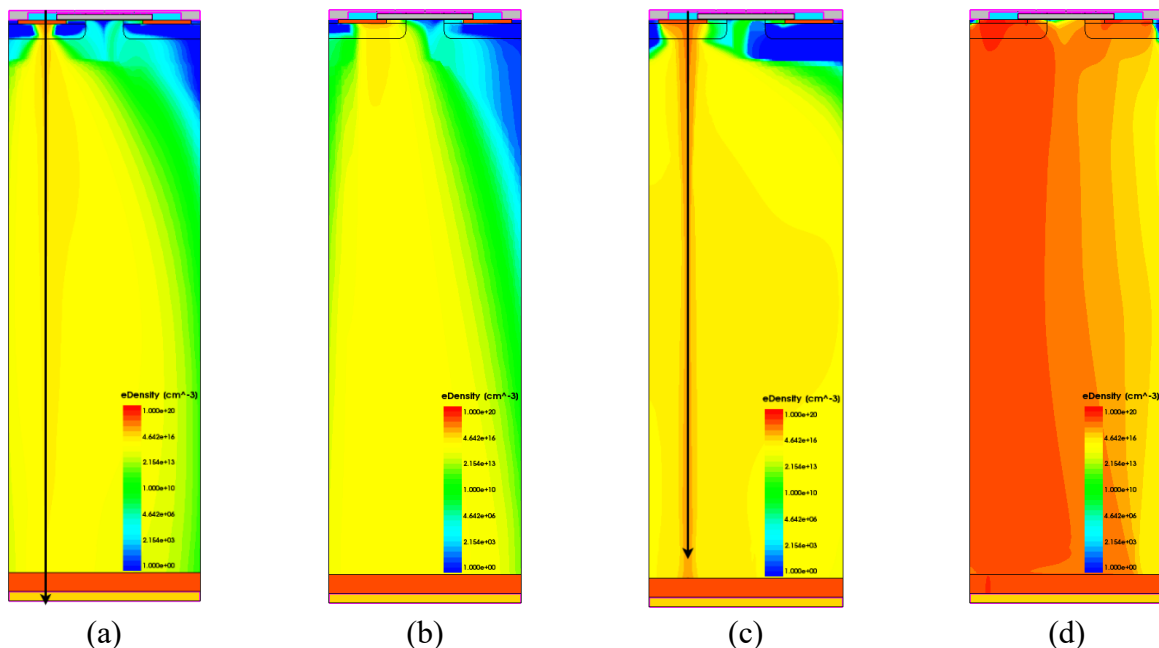


Fig. 6. Simulated electron densities of a 10 MeV alpha particle (a and b) and a heavy ion with a LET of 0.05 pC/ μ m (c and d), both captured at about 100 and 1000 ps after peak generation time. The tracks are shown with black arrows. All the plots have the same color scale.

The simulations also show that the SEB process is related to a redistribution of the internal electric field and Figure 7 shows the field distributions captured at different times from the two different radiation, Alpha Particle model in Fig. 7a and the Heavy Ion model in Fig. 7b. Particularly in the heavy ion simulations, the field peak starts to shift from the pn-junction under the gate towards the epi-substrate interface approximately 10 ps after the peak carrier generation time of the incident ion and excessive amounts of holes are injected into the substrate due to the field peaks. This is similar to what was reported in Ref. [10], where the field inside a bipolar transistor is reversed due to increasing collector current, following by the second breakdown at the epi-substrate interface.

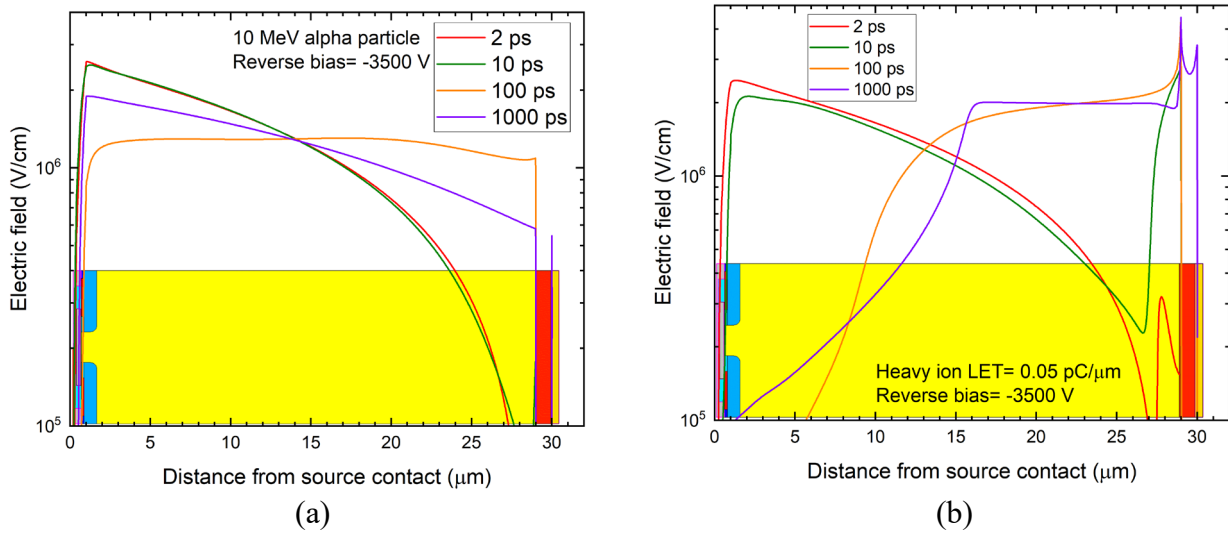


Fig. 7. Simulated electric field distributions by activating alpha particle (a) and heavy ion model (b). The development of a sharp field peak, which supports the avalanche process is found in heavy ion simulations. A simulated MOSFET model is used to show the location.

The injected hole plasma and localized high current density near the epi-substrate interface are shown in Fig. 8. The hole injection only occurs when the particle LET is high enough to reverse the electric field distribution and create field peaks at the epi-substrate interface. This demonstrates why no SEBs can be triggered by the alpha particles with low LET.

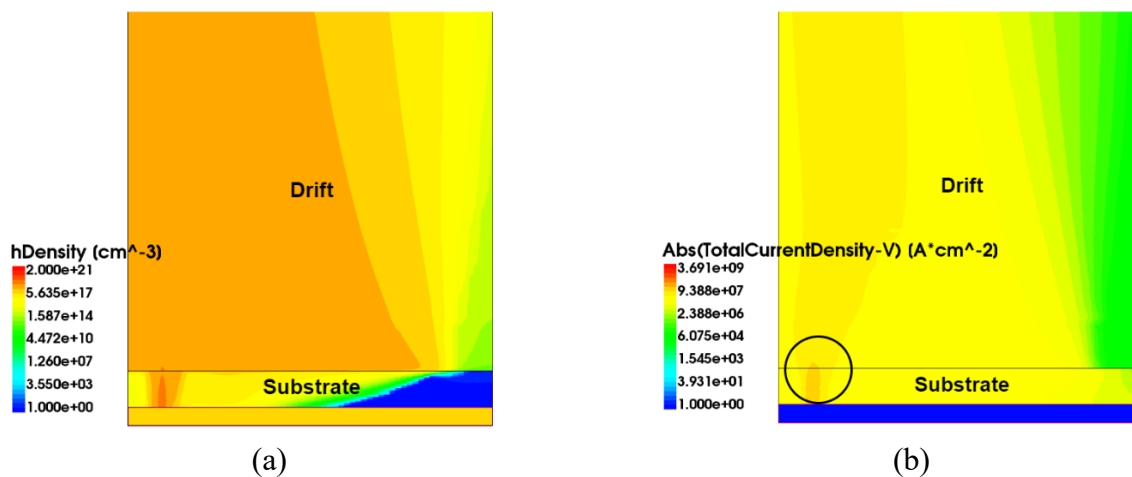


Fig. 8. Simulated localized hole density (a) and current density (b) at epi-substrate interface, showing how hole injection happens when the particle has a sufficient high LET.

Summary

MeV alpha particles with different energies and doses are used to trigger device failures of 3.3 kV rated SiC MOSFET samples. No significant leakage current or output degradation is found after irradiation at increasing alpha particle fluence in this relatively low fluence range. Experiments also show that no failure can be induced by 6 MeV alphas unless the applied bias is reaching 90% of maximum reverse voltage. Device failures are also be triggered by 10 MeV alphas, but at a lower reverse bias (75% of maximum reverse bias). Simulation results, on the other hand, show that no SEB can be found with Alpha Particle model activated, but a sharp increase in leakage current can be triggered by the Heavy Ion model with an LET that is roughly 5-6 times higher than 6 MeV simulated alpha particles. The ion with sufficiently high LET redistributes the internal electric field, shifts field peaks to the epi-substrate interface and causes the hole injection to accelerate the avalanche process.

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