J-K Lim, M. Bakowski

Final report – Study of Cosmic Ray Reliability (AP4)

Activity in project "Beyond Silicon – Reliability assessment of SiC MOSFET power semiconductor devices for heavy-hybrid and electric vehicles, part 2"
(Bortom kisel - utvärderingen av tillförlitligheten hos SiC MOSFET komponenter för tunga hybrid och el-fordon, del 2 (projektnr 42615-2)

Introduction

The reliability of power semiconductor devices is of high priority. This is basically based on the fact that the power devices are often used in critical/exposed applications. **Fig. 1** depicts a list of different reliability issues that ultimately lead to device failures. This project is dedicated to a special failure mechanism that is caused by cosmic rays. The main objective of the project is to establish a modelling procedure for the simulation of destructive failures by the numerical methods using TCAD (Technology Computer-Aided Design, thereafter TCAD). Overall goal is to be able to predict and determine the reliability of silicon carbide (thereafter, SiC) devices with respect to the exposure to cosmic rays depending on different device designs and voltage ratings.

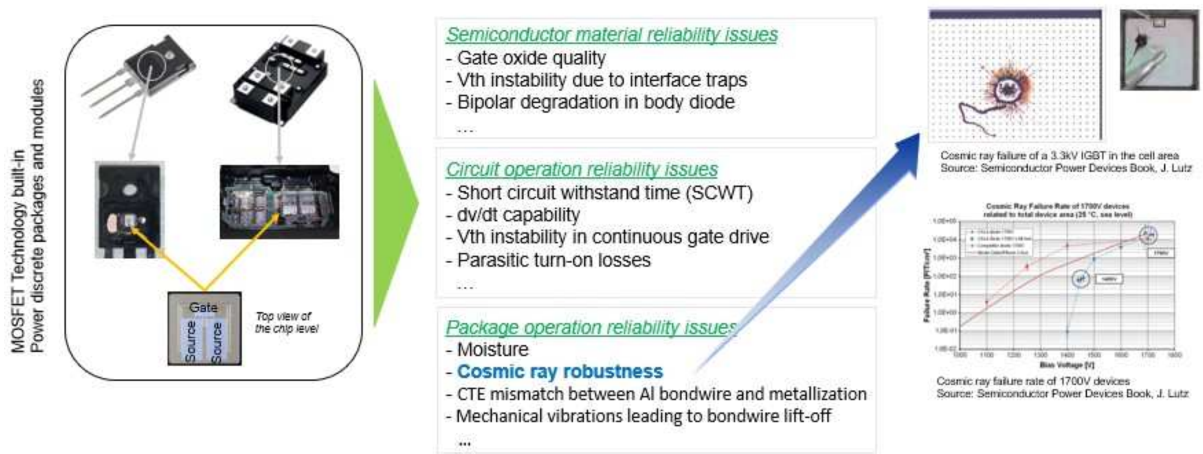

Fig. 1. Overview of reliability issues of power semiconductor devices on device, circuit and package level.

Background

Electronics is constantly exposed to the bombardment by high energy particles present in the cosmic rays reaching surface of the earth. Irradiation by high energy neutrons present in cosmic rays generates heavy charged particles in semiconductor materials by nuclear reactions. These particles generate in turn electron-hole pairs which in the presence of high electric field lead to dynamic avalanche or activation of parasitic device structures inherent to the typical power devices. In the case of the MOSFET it is the parasitic n-p-n transistor created by the emitter, p-body and drift region of the MOSFET. In the case of the IGBT it is the parasitic thyristor created by the cathode emitter, p-base, n-base and anode emitter of the IGBT. Activation of parasitic transistor or latch-up of the parasitic thyristor leads eventually to thermal run-away and destruction of the device due to excessive temperature.

Contradicting results are obtained experimentally depending on different device types and device designs. The introduction of SiC (Wide-Bang Gap, thereafter WBG) devices in applications means that 1.2 kV to 3.3 kV Si IGBT devices are being replaced by SiC MOSFETs with the same voltage rating. The physical failure mechanisms involved depend on the device types (MOSFET, IGBT, and rectifier), device design, device voltage rating and semiconductor materials. It becomes then important to evaluate the effect of cosmic rays on devices of different types made of different semiconductor material for the same application. Furthermore, the question of the relative cosmic ray robustness of SiC devices as compared to the Si ones has strategic importance considering prospects of implementation of SiC devices in power electronic applications. It is therefore of great importance to be able to model and predict robustness of devices to cosmic rays. Only then it is possible to compare devices and evaluate the influence of device design, voltage rating and semiconductor materials.

Very little is known about cosmic ray robustness of SiC devices. There are no Si MOSFETs with such high voltage ratings and response of SiC material to radiation is not sufficiently established. There are several factors talking in favour of SiC compared to Si, like the reduced size of the devices for the same current rating, smaller thickness of the drift region by almost one order of magnitude and much larger bandgap. The smaller chip size reduces the probability of being hit by the cosmic rays, thinner high voltage region reduces the volume available for possible generation of charge carriers and larger bandgap results in higher energy needed for generation of electron-hole pairs.

At the other hand the electric field strength is one order of magnitude higher compared to silicon. The few available experimental studies indicate higher possible reliability of SiC MOSFETs compared to Si IGBTs **[1]** and MOSFETs **[1, 2]**. Also, the recent experimental study focusing on the photovoltaic central inverters indicated higher possible reliability of SiC MOSFETs compared to Si IGBTs **[3]**.

The question is of great importance also for automotive applications and high-power energy conversion. The question of increased robustness of SiC devices is related to possibility of having smaller margins between the device rated voltage and voltage in the application. Normally it is necessary to lower the voltage in the application to 65% of the rated voltage in the case of Si devices due to cosmic ray reliability **[4]**. Necessity to use devices with much higher voltage rating than required results in higher device and system losses. Closing the gap between the rated voltage and voltage required by application facilitates then further gains in energy efficiency in addition to improved reliability.

The use of WBG and foremost SiC devices, enables compact smart energy conversion systems with high efficiency for many applications like automotive, photovoltaic inverters and high-power energy conversion. Compactness and efficiency of power electronics are both of special value for electric drivetrains in vehicles. Factors like improved service life, reduced weight, higher efficiency and reduced total cost of electric power train all contribute to speed up the electrification of vehicles and to commercial breakthrough for the WBG technologies.

Project purpose and goal

A long-term voltage stability of power devices is influenced by cosmic ray radiation leading to creation of excess carriers by generation of electron-hole pairs which induce a catastrophic breakdown by activating parasitic bipolar structures inherent to the device designs or by mechanism of dynamic avalanche. There are not many published reports on the subject of SiC device failures related to cosmic rays. There are few experimental data published and some limited data from device manufacturers. Experimental data indicate better reliability of SiC devices compared to silicon ones. It is however impossible to draw any certain conclusions from these results because interpretation of the results is strongly dependent of the type of the device that has been tested and on the choice of the silicon device used as reference.

In most of the applications (applications below 4 kV) bipolar silicon devices of the type IGBT (and bipolar diodes) are replaced by unipolar SiC devices of the type MOSFET (and Schottky diodes). It is thus necessary to carefully analyse electric field conditions and device physics of different device types and designs used in the experiments. Also, the knowledge about the difference between the breakdown voltage and the operational voltage is of crucial importance for the interpretation of the result. For these reasons, the numerical simulations and formulation of theoretical models are unavoidable. The issue of cosmic ray reliability modelling based on numerical simulations is the subject of this project.

This project is a first step of activities with the long-term objective of establishing the robustness of SiC devices with respect to the cosmic rays. The objective of this project is to set-up the simulation environment and establish modelling procedure in order to perform a wider study to determine robustness of SiC MOSFETs at different operation voltages for automotive and high-power conversion applications. In the future project experiments are planned involving Uppsala, The Svedberg Laboratory, to apply and test established modelling procedure on statistically representative sample of devices. To accelerate a broad introduction of new SiC technology, it is crucial to ascertain reliability of SiC

devices to be equal or higher than that of current Si devices. This is best done by increasing the understanding and modelling capability of the mechanisms controlling the device time of life and device failures in the field.
The specific goal of this project is to formulate and verify modelling procedure for catastrophic failures in the SiC power devices, caused by high energy particles present in cosmic radiation, in order to be able to reproduce the failure modes in the simulation environment. It is of great importance to clarify the sensitivity of SiC devices to cosmic rays considering one order of magnitude higher electric field in combination with one order of magnitude thinner drift region and much higher bandgap compared to silicon. The failures caused by cosmic radiation make it necessary to use devices with much higher rating voltage in applications in order to lower the internal electric field (so called derating) which results in increased losses in devices and systems.

The specific targets of our investigation into modelling of cosmic rays-induced failures are listed below;

a) to make a comparison between Si and SiC power MOSFETs under conditions of heavy ion-induced failures in a blocking state
b) to define safe operating conditions relevant to different voltage designs.
c) to evaluate sensitivity of linear energy transfers (LETs) with respect to operation voltages.

Furthermore, the numerically evaluated failure mechanisms should be experimentally verified under extended investigation.

The ultimate objective of the project is to verify the hypothesis of higher cosmic-ray reliability of SiC devices compared to the Si ones.

Device structures and models

To analyse the cosmic rays-induced failure mechanisms in the simulation, two types of commercial SiC MOSFET structures with different blocking voltage capabilities of 1.2 kV and 3.3kV are analysed by SEM (Scanning Electron Microscopy, thereafter SEM) and reproduced in device models as shown in **Fig. 2**. The two structures differ in the thickness of epitaxially grown drift layer which is 10 µm for 1.2 kV and 30 µm for 3.3 kV voltage device. From different drift thickness designs, we would expect that the MOSFET with a thicker drift thickness has a wider safe operation area under radiation exposure and thus higher immunity to cosmic ray induced failures, “Single-event burnout (SEB)”.

The simulation device models are calibrated with the measured static characteristics of the devices. The reproduced output and transfer characteristics are compared between the simulations and measurements including a temperature dependency as shown in **Fig. 3-6**. The reconstructed device structures are built into the TCAD models and used to emulate the real failure scenarios by simulations.

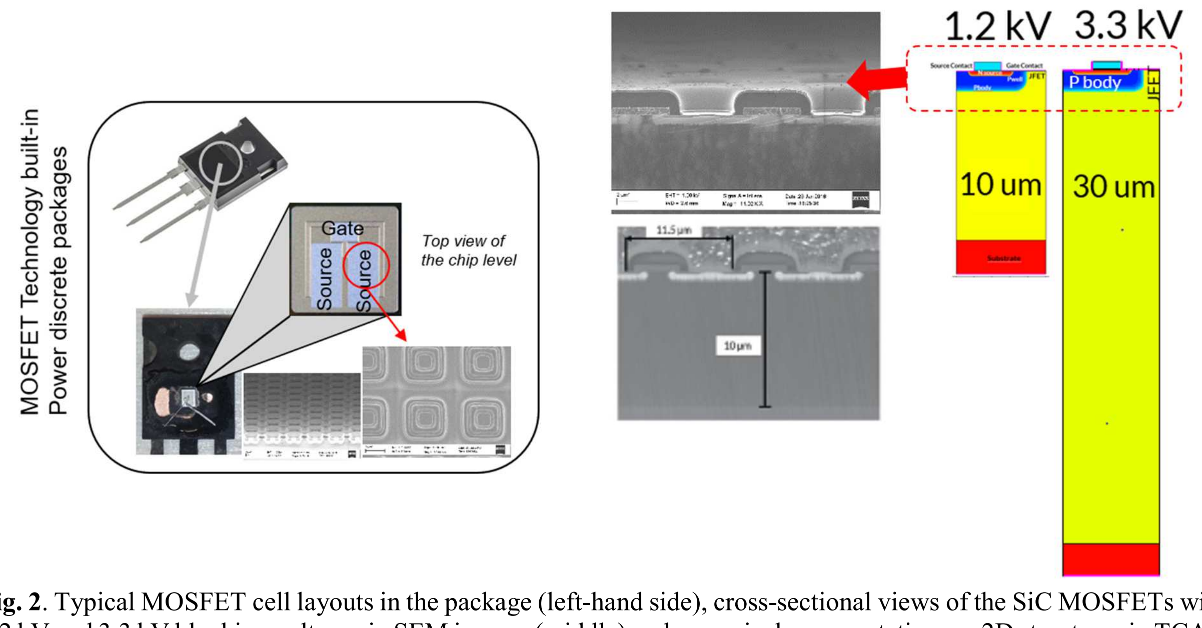

Fig. 2. Typical MOSFET cell layouts in the package (left-hand side), cross-sectional views of the SiC MOSFETs with 1.2 kV and 3.3 kV blocking voltages in SEM images (middle) and numerical representations as 2D structures in TCAD (right-hand side).

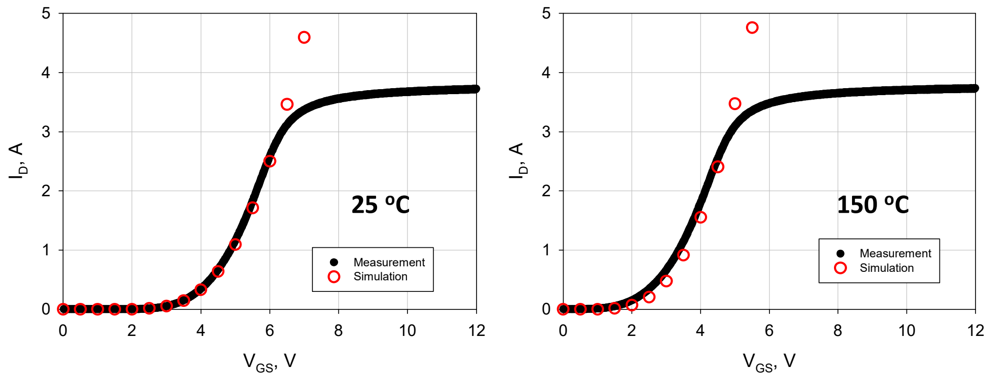

Fig. 3. 1.2 kV MOSFET, measured and simulated transfer characteristics at 25 °C and 150 °C

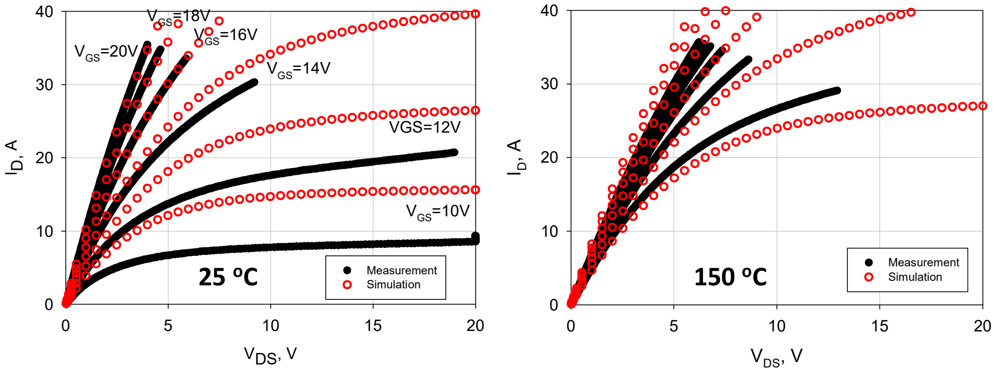

Fig. 4. 1.2 kV MOSFET, measured and simulated output characteristics at 25 °C and 150 °C

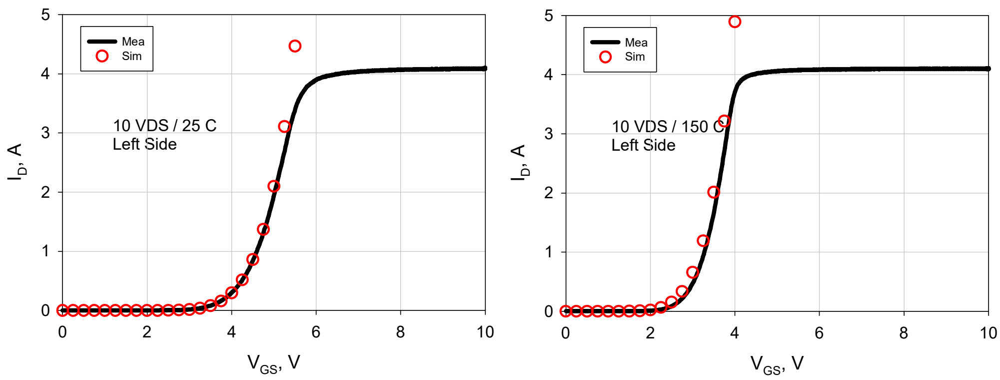

Fig. 5 3.3 kV MOSFET, measured and simulated transfer characteristics at 25 °C and 150 °C

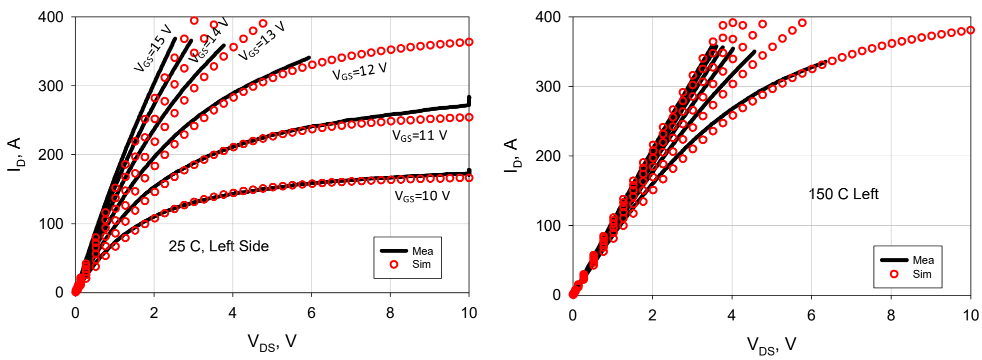

Fig. 6 3.3 kV MOSFET, measured and simulated output characteristics at 25 °C and 150 °C

Definition of heavy ion models

Energetic particle radiation models such as gamma radiation, alpha particles, and heavy ions are available in Sentaurus TCAD. When these high-energy particles penetrate a power device, they deposit their energy by electron-hole pair generations as shown in **Fig. 7**. It gives rise to an extremely high leakage current in a blocking state. Finally, as the process continues, the device loses voltage blocking capability. In the simulation, the half pitch of a unit cell of MOSFET is used in all the cases. The physical models with specific material parameters are included in the simulation structures and inner self-heating phenomenon is analysed with thermodynamics models as well.

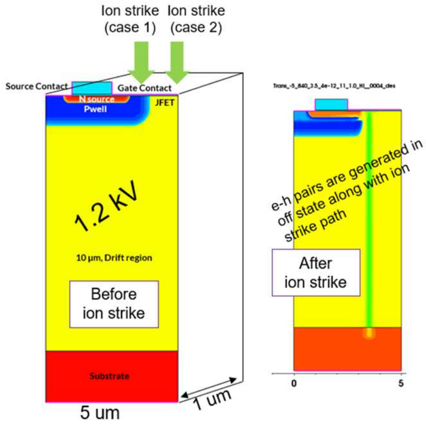

Fig. 7 Heavy ion penetrations in 1.2 kV SiC MOSFETs

Among the energetic particle radiation models, a heavy ion impinging process is introduced in this study as shown in **Fig. 8**. The generation rate of the electron-hole pairs caused by the heavy ion is computed by

$$G(l, w, t) = G_{LET}(l)R(w, l)T(t)$$

where $R(w, l)$ and $T(t)$ are the functions describing the spatial and temporal Gaussian distribution in the generation rate.

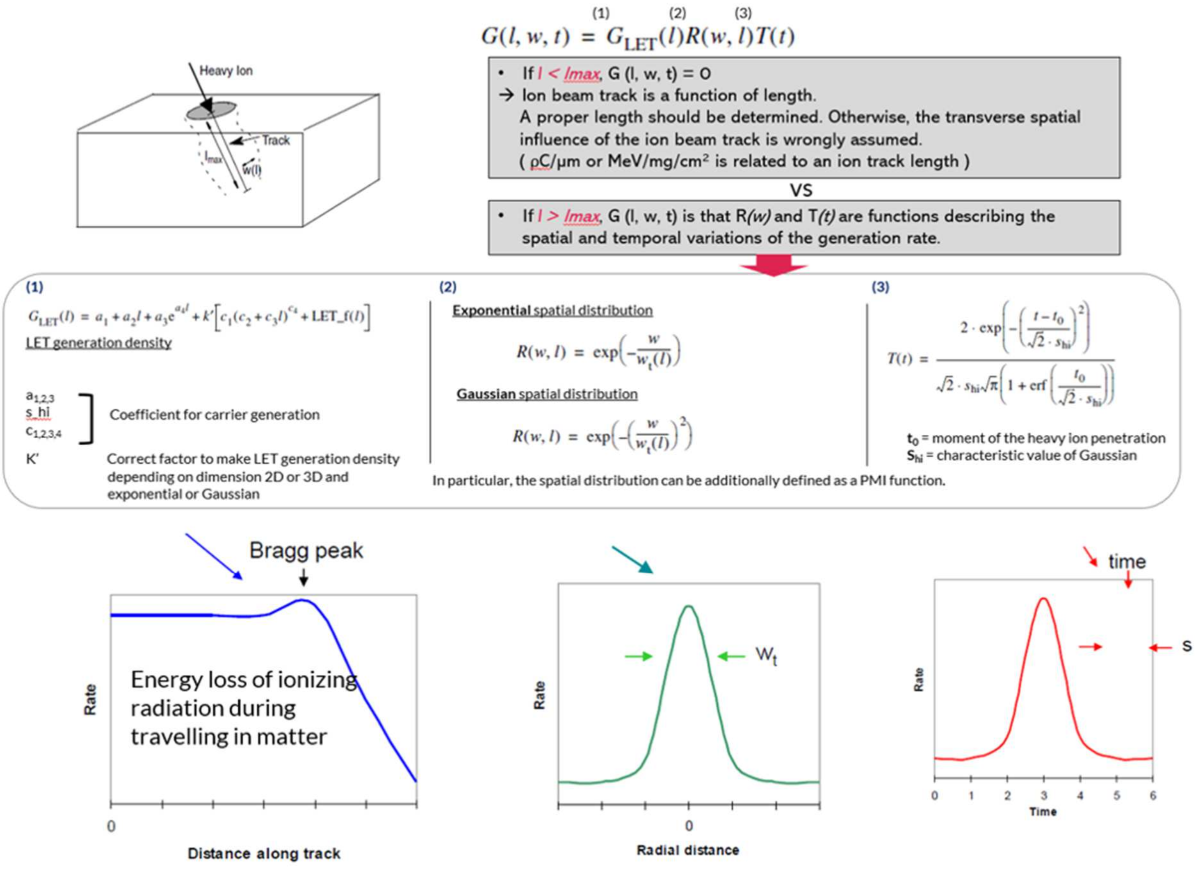

Fig. 8 Simple model for heavy ion impinging process in TCAD **[5,6]**

$G_{LET}(l)$ is the linear energy transfer (LET) generation density which is related to the LET of the ions. In the simulation, the LET is usually defined as the charge deposited per unit of track length and given in pC/µm different from the experiment unit expressed in MeV/mg/cm^2. The liner energy transfer (LET) ranges are converted with respect to SiC material mass (1 pC/µm = 151 MeV/mg/cm^2). Defined LET generation density, spatial Gaussian distribution, and time are defined and implemented in the device models and all parameters are summarized in the table below.

Table 1. Parameters for radiation models

Direction	Vertical
Location	Channel or JFET region
Peak charge deposition time	100 ps
Track length	Penetration of drift region
Track radius	0.05 µm
Characteristic value of Gaussian function, *T(t)*	2 ps
Spatial distribution	Gaussian
Unit	Pico Coulomb

The heavy ion track is initially set to penetrate the entire device. The track length is selected the same as drift region thickness, while the track radius is kept constant. The ion strikes are introduced in most sensitive regions, in a channel (carrier path) and a JFET region (high electric field). It should be noted that the simulation results are qualitative rather than quantitative. It is because the charge track generated by the incident ions corresponds to a sheet instead of a cylinder as shown in **Fig. 9**.

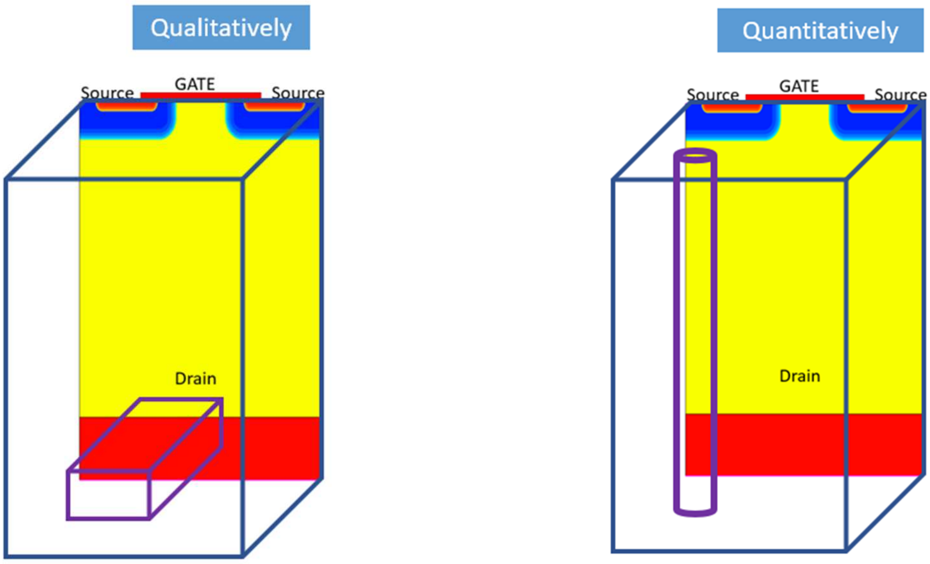

Fig. 9 Heavy ion strike in 2D and 3D structures.

Heavy ion-induced failure mechanisms

To evaluate the heavy ion-induced failures, we mainly observe the drain leakage current and electric field distribution before and after the ion strike at the blocking state as shown in **Fig. 10, 11, and 12**. The basic failure is well known as the single-event burnout (thereafter SEB). A heavy ion strike is introduced at a certain time with a duration time controlling e-h generation rates as shown in **Fig. 11** for the case of stopping range within the drift region. In general, for both limited and penetrating range, the streamer is formed **[7]**, with high electric field peaks at PN$^-$ and NN$^+$ junctions, as shown in **Fig. 12**. The drain enters a high carrier injection due to impact ionization increase at NN$^+$ junction (Kirk effect). Also, avalanche current regeneratively feeds a bipolar operation at PN$^-$ junction. Finally, we expect following failure modes as a result of the ion strike: i) the blocking voltage degradation due to the abruptly increased drain leakage current (SEB) and ii) increased current under SEB gives rise locally to extremely high device temperature exceeding melting temperature of Al bond-wire in the package.

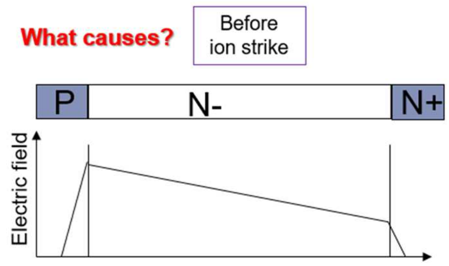

Fig. 10 Device keeps a blocking state before ion strike

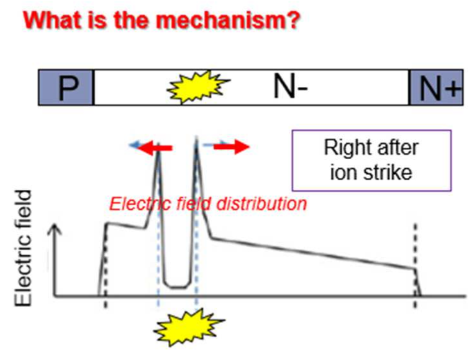

Fig. 11 As a result of the ion strike, impact ionization (e-h pairs generation) occurs at two locations within the drift region

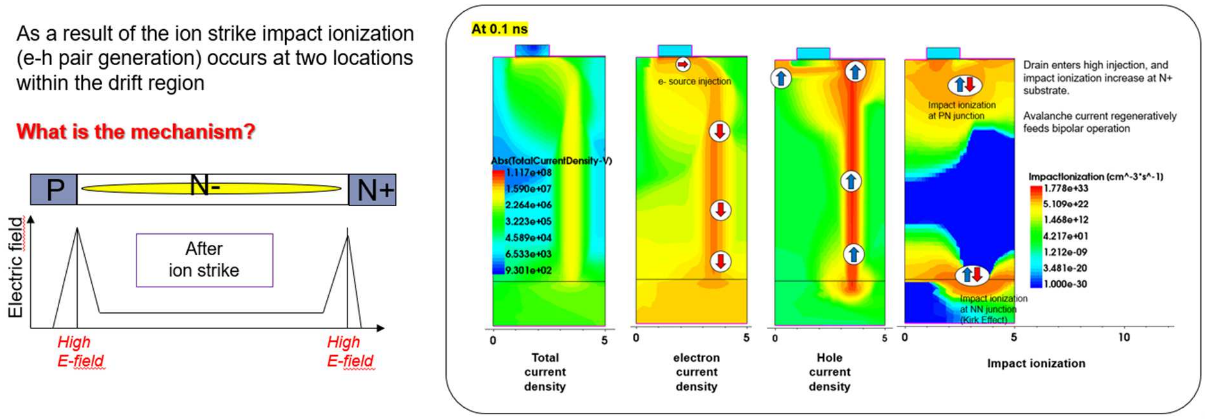

Fig. 12 Electric field forms peaks that run through the drift region of the device, forming a streamer **[7]** connecting PN^- and NN^+ junctions.

Results

To evaluate the SEB in power devices, the failure criterion is set to an increased drain leakage current at the blocking state. This dynamic current induced by the SEB leads to localized increase in lattice temperature that leads to localized damage of the p-n junctions. Finally, the device is malfunctional in the blocking state. A transient device simulation can describe SEB triggering leading to the electron-hole pairs generated along the track of recoil ions from PN^- and NN^+ junctions. The SEB threshold voltages are investigated with respect to the ratio of the rated voltage and the operation voltage. In order to assume the worst case, the LET is set to 1 µC/um corresponding to 151 MeV/mg/cm^2 and the most vulnerable position of the ion path is assumed to be in a channel region.

At first the SEB simulation is performed with Si MOSFET as a reference and to be compared with SiC MOSFET. The results are presented in **Fig. 13** and show clearly that the drain leakage current and the lattice temperature are extremely increased at fixed LET value of 2.0 µC/um and with the simulated device area of 5 um^2. At 100 ps after the ion strike, the drain current suddenly reaches to 0.15 A at 800 V. We assume that the initial drain current generation is related to the strike of the energetic heavy ions and then impact ionization generations are induced due to high electric field appeared at PN^- and NN^+ junctions. The current is impossible to clamp, and the device is finally burnt out., the maximum lattice temperature peaks over 1241 K (967 ºC), at this time, which is close to a melting point of the package. The other LET energies of 0.01 – 0.05 µC/um are insensitive to SEB behaviour under the same blocking voltage condition.

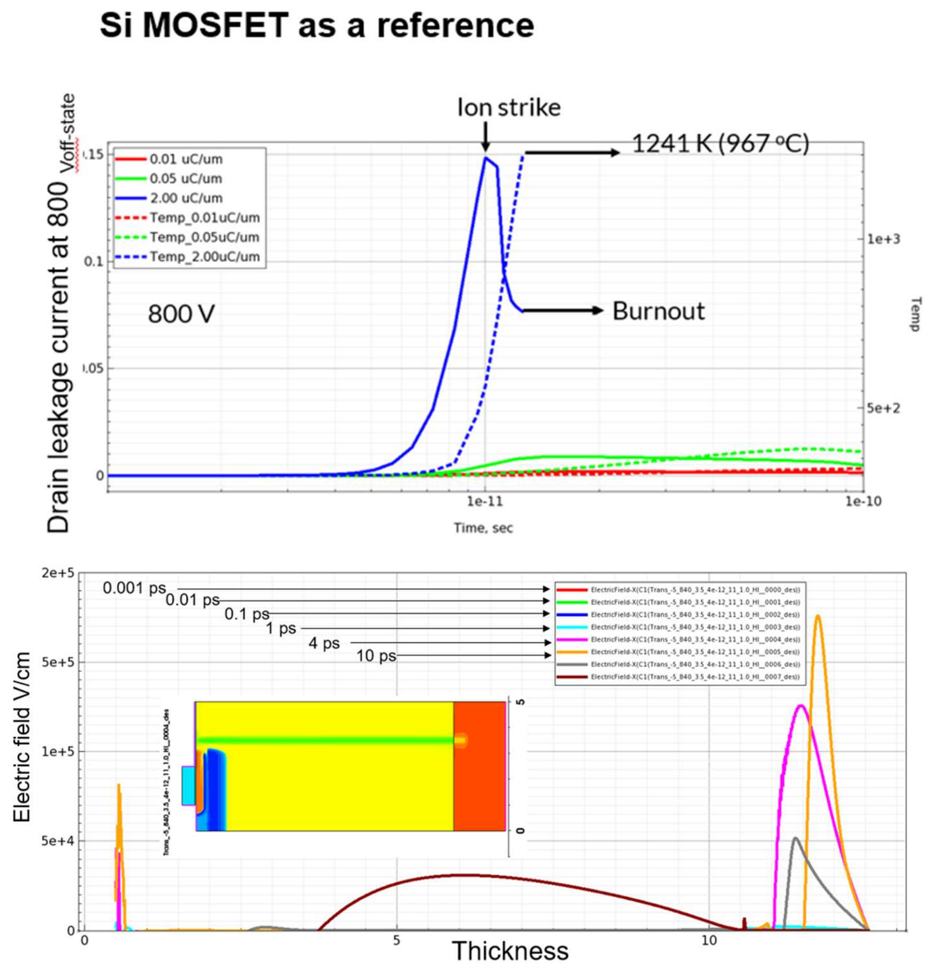

Fig. 13 Drain leakage current at blocking state of 800 V and electric field intensity at different times after ion strike with 2.0 μC/um in reference Si MOSFET.

On the other hand, it is hard to reach the SEB threshold with 1 μC/um corresponding to 151 MeV/mg/cm^2 in the 1.2 kV SiC MOSFET under 800 V and even maximum rated voltage as shown in **Fig. 14**.

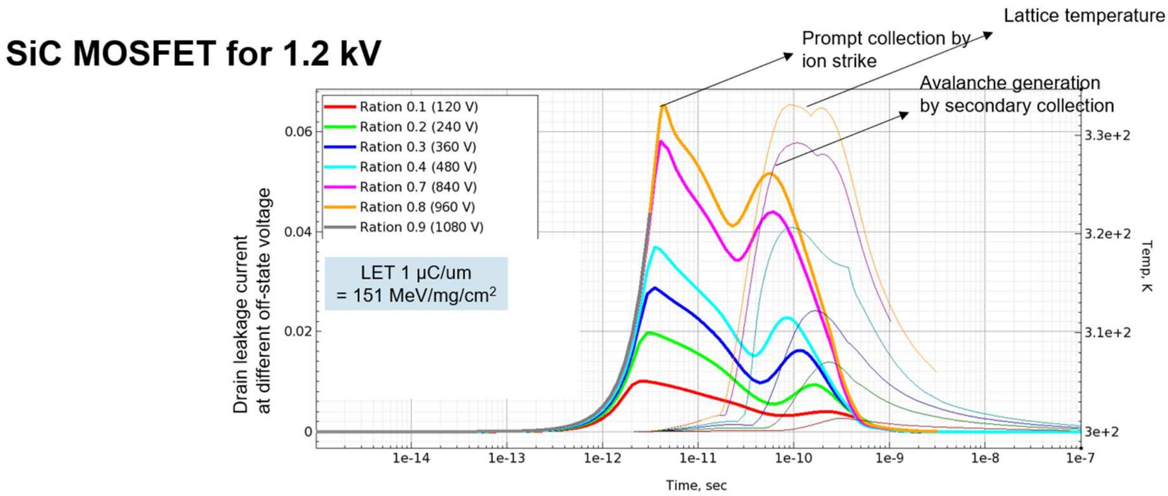

Fig. 14 Drain leakage current in the blocking state for different ratios of operational and rated voltage.

As can be seen in **Fig. 14**, the initial drain current generations are increased right after the ion strike and the currents are slightly decreased within 50 ps, similar to Si MOSFET. Then, the second avalanche-generation currents are observed but the peak currents are lower than the ones with the ion strike. After 1ns, the currents are completely recovered, and the lattice temperatures are also decreased. We clearly assume that SiC MOSFETs has the probability of ion-triggered avalanche much lower than Si MOSFETs. It is due to SiC material has a higher electric field capability (x 10 higher) than Si material. Therefore, the SEB threshold and SOA (safe operating area) are higher and wider, respectively, in the case of SiC power devices compared to Si MOSFETs with the same voltage rating.

In **Fig. 14** the evolution of the drain current as a function of a ratio of rated voltage and operational voltage is shown at the fixed LET. At the LET of 1 pC/µm, the avalanche currents are further increased with increased operation voltages. It means that the probability of the ion-triggered avalanche (impact ionizations) gets higher and is proportional to increased depletion width vertical to the substrate. The choice of the operation voltage is critical with respect to the SEB failure. SiC MOSFETs show much lower lattice temperatures during the same conditions much below levels required for the SEB failure.

Conclusions

Simulation of heavy ion-induced power device failures (called SEB) have been implemented in TCAD. The failure mechanisms are emulated as a transient current after the heavy ion strike in the blocking state in Si and SiC MOSFETs. In Si MOSFETs, the single-even burnout behaviour is observed under certain SEB threshold conditions defined by the operational voltage and the LET value. Failure mechanisms involve charge collection of the charge generated by the ion strike and impact ionization generations induced by highly increased electric fields. On the other hand, SiC MOSFETs are insensitive to equivalent SEB thresholds. This is most probably related to higher critical electric field of SiC material compared to Si.

In future investigations SiC MOSFETs with different allowable blocking capability should be studied to cover different SEB threshold ranges in terms of different LET values and drift region thicknesses. This type of the simulation failure study is of crucial importance to interpret the experimental results and to predict biasing conditions at which damages can be induced in the critical regimes of SiC power MOSFETs as a function of LET ranges of ion species.

In this study, we have confirmed by simulations that 1.2 kV SiC MOSFETs should have higher cosmic ray (SEB) reliability compared to the Si MOSFETs with the same voltage rating.

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