Experimental and simulation studies of radiation-induced single event burnout in SiC-based power MOSFETs

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Abstract
The single event burnout (SEB) effects of SiC power MOSFET are investigated by irradiations. An SEB is observed when drain biased above 400 V for $^{181}$Ta ion irradiation. The failure analysis shows a melting “hole” near the gate region due to the thermal runaway. Based on TCAD simulations, the impact ionization and parasitic bipolar are the key factors to trigger SEB in SiC MOSFET. Unlike the impact ionization, the turning on of the parasitic bipolar is not necessary for an SEB. But it will significantly reduce the threshold of SEB. Except for SEB, another permanent damage mode is also observed, which is manifested as the increase of leakage current and the abnormal of the output characteristics. This damage may be related to the latent track produced by heavy ion according to the failure analysis. The SEBs are observed for proton irradiations. The maximum LET value of the proton-induced secondary ions can reach 13.9 MeV cm$^2$/mg for 100 MeV proton. The simulations imply that most of the secondary ions can contribute to SEB. The biggest discrepancy from heavy ion irradiation is that no leakage current increases and output characteristics degradations are observed for the device without SEB after proton irradiation.

1 INTRODUCTION

Silicon carbide (SiC) is attractive for power device application due to the high breakdown electric field and higher thermal conductivity [1–3]. Compared with silicon, the breakdown electric field strength and thermal conductivity of SiC are increased by about ten times and three times respectively, which makes it very suitable for manufacturing high power devices. In order to achieve the same voltage capacity, the thickness of power devices based on SiC materials can be smaller than that of silicon-based devices. The SiC power MOSFETs can achieve a higher breakdown voltage with the same on-resistance.

However, SiC power MOSFETs is still sensitive to ion irradiation in space applications, similar as its silicon counterparts [4, 5]. Several works reported the increase of device leakage current before failure under the heavy ion irradiation [6, 7]. SiC power MOSFETs may also undergo catastrophic SEB above a certain gate and/or drain bias when exposed to energetic heavy ions [8–10]. Based on these phenomena, Li et al. [11] tried to re-evaluate the safe operation area (SOA) of SiC MOSFETs into safe zone, leakage increasing zone, and breakdown zone under heavy ion irradiation. Even though the heavy ion induced SEB of SiC MOSFETs are reported, the physics mechanisms of SEB remain to be explored. It was clarified that impact ionization is a key point of the SEB triggering mechanism in SiC power devices [12]. The previous works also proves that the turning on of parasitic bipolar transistor in the SiC power MOSFET structure leads to catastrophic SEB by TCAD simulations [13, 14], but the lattice heating effect is not considered. The SEB destruction ultimately came from the thermal damage caused by the highly localized current [15, 16]. So the lattice temperature distributions during the SEB is crucial important to understand the SEB.
mechanisms. Furthermore, few works focused on the single event effects of SiC MOSFETs caused by protons. Mizuta et al. had conducted proton irradiation for SiC power MOSFETs and SEB was observed for 70 MeV proton [17], but the mechanism of proton single event effect was not explained in details.

In this paper, the radiation-induced SEBs are investigated by heavy-ion and proton irradiation. Both the gate and drain leakage current are monitored during irradiation to distinguish the different damage modes of SiC MOSFETs. Failure analysis is conducted for the device with SEB. Both the destruction morphology and region are identified. The SEB mechanisms are investigated by TCAD simulation with considering the lattice heating effect. Moreover, the information of secondary ions produced by proton nuclear reaction are obtained. The secondary ions which may contribute to the SEB are determined.

2 | EXPERIMENTAL DETAILS

All the devices used in our experiment are SiC n-channel MOSFETs (C2M0080120D, 1200 V, 80 mΩ) from CREE Inc. The scanning electron microscopy (SEM) cross-section diagram of the device is shown in Figure 1. Heavy-ion irradiations were conducted at the Heavy Ion Research Facility in Lanzhou (HIRFL), using \(^{181}\)Ta ions with an initial energy of 2443.5 MeV. The devices were de-capsulation before heavy ion irradiation to assure the Ta ion can reach the active region of the device. The \(I-V\) characteristics of the devices were tested after de-capsulation to verify the function of the devices. The \(^{181}\)Ta beam irradiations were performed in air with heavy-ions passing through a vacuum/air transition foil. A flux detector was placed in the beam line before the DUTs to monitor the real-time beam flux. The ion linear energy transfer (LET) value in the DUTs was 81.3 MeV cm\(^{-2}\)/mg. The range of ions in the SiC device is 98.5 µm based on the calculation of SRIM [18]. Proton irradiations were conducted at Northwest Institute of Nuclear Technology. The chosen proton energies were 60 and 100 MeV. During heavy-ion and proton irradiations, the test boards were mounted on a two-dimension-movement platform and only one sample was irradiated at one time. The ion beam was at normal incidence. The devices were OFF biased during irradiation, i.e. drain terminal biased at a positive high voltage, source and gate grounded. Both the leakage currents at drain and gate were real-time monitored by the Keithley 2400 and 2410 Source-Meter, respectively. After irradiation, the \(I-V\) characteristics of the devices without SEB were tested by Keysight B1505 power semiconductor parameter analyser.
FIGURE 3  Failure analysis of SiC MOSFET with SEB after $^{181}$Ta ion irradiation. Irradiation bias voltage: $V_{gs} = 0$ V and $V_{ds} = 400$ V. (a) OBIRCH analysis of the de-capsulated device. The light spot represents the damage region. (b) SEM image of the damage region after stripping metal layer.

FIGURE 4  Time evolution of drain and gate leakage currents for SiC MOSFET during $^{181}$Ta ion irradiation. The ion flux is $1000 \text{ cm}^{-2} \text{s}^{-1}$. No SEB occurs during irradiation. (a) Irradiation bias voltage: $V_{gs} = 0$ V and $V_{ds} = 200$ V. (b) Irradiation bias voltage: $V_{gs} = 0$ V and $V_{ds} = 300$ V.

FIGURE 5  Output characteristics before and after $^{181}$Ta ion irradiation for the device without SEB. Irradiation bias voltage: $V_{gs} = 0$ V and $V_{ds} = 300$ V. Output characteristics of the device become abnormal after irradiation, as shown in Figure 5. It seems that heavy-ions introduce latent permanent damage at the gate region. As a result, the gate of the device loses control of channel current. This phenomenon is shown more clearly in Figure 6. The light spots which represent the damage regions are distributed across the entire device surface during the OBIRCH analysis. Each light spot may correspond to one leakage path introduced by one heavy ion. No light spot is observed for the device without irradiation. It proves that the spots are indeed caused by the heavy ion irradiation. As $2443.5$ MeV Ta ion penetrating through the active area of SiC MOSFET, it will interact with the extra-nuclear electrons of target atoms and deposit energy. When the energy deposition is greater than a certain threshold, the material around the ion track can even melt, and then cool rapidly and solidify. Since the recrystallization rate is less than the solidification rate of material, a high concentration of complex defects and defects are leaved after the rapid quenching. Then localized defect clusters will form along the ion path. That is to say the latent track with amorphous structure is generated.
The high electronic energy loss of 2443.5 MeV Ta ions can induce latent tracks in the active area of SiC MOSFET, which are leakage channels and made of defect clusters along ion paths. This can also explain the observed leakage increase during heavy ion irradiation.

It is interesting to note that the SEB is not always observed even though the drain bias is high enough during the Ta ion irradiation. Figure 7 shows the time evolution of drain and gate leakage currents for SiC MOSFET during $^{181}$Ta ions irradiations with low flux of 1000 cm$^{-2}$ s$^{-1}$ under the relatively high drain biases. The drain current suddenly increases of two orders of magnitudes at 9 s and then linear increases to 3.1 mA at $1.55 \times 10^5$ cm$^{-2}$ influence when the device is biased at $V_{ds} = 400$ V. It continues to increase when the ion beam is shut down, only the growth rate has slowed down. This is neither a typical SEB nor a latent track damage observed under the low bias irradiation. Although an abrupt increase of drain current occurs, the leakage current is not directly increase to the limited current of the Source-Meter as the typical SEB in Figure 2. Then the failure is characterized as persistent increase of drain leakage current which is similar as the latent track damage. These leakage current increases might be attributable to the cumulative damage at drain-body junction [$^{17}$]. The same situation is observed when the device is biased at $V_{ds} = 500$ V with low flux irradiation, as shown in Figure 7(b). The only difference is that the drain leakage current is growing faster. The failure analysis of this device is shown in Figure 8. The failure point is located at the gate region. An excess material occurs near the gate, which is recognized to be oxide using energy dispersive spectrometer (EDS), as shown in Figure 8(b). Simultaneously a crack is observed at the gate. The gate is cut out using focused ion beam (FIB) along the dot line. Figure 8(c) shows the cross-sectional SEM image at the FIB location. It implies that part of the gate material has melted. The excess part observed along the gate in Figure 8(b) is associated with the motion of molten gate from within the device to the surface. This is not a typical SEB signature, but it indicates that a local high temperature region is produced near gate during irradiation.

3.2 | Proton-induced SEB in SiC MOSFETs

Figure 9(a) illustrates the time evolution of drain leakage currents for SiC MOSFET during 100 MeV proton irradiations. Unlike heavy ion irradiation, no leakage current increase is observed for protons irradiation before SEBs occurred. The
FIGURE 7  Time evolution of drain and gate leakage currents for SiC MOSFET during $^{181}$Ta ion irradiation. The ion flux is 1000 cm$^{-2}$ s$^{-1}$. (a) Irradiation bias voltages: $V_{gs} = 0$ V and $V_{ds} = 400$ V. (b) Irradiation bias voltages: $V_{gs} = 0$ V and $V_{ds} = 500$ V.

drain leakage current even decrease as the total influence increase. When SEB occurs, the drain current abruptly increases to 21 mA and then limited by the Source-Meter. The observed SEB onset bias data are given in Figure 9(b). Three devices are tested under each bias condition. If no SEB is observed for all the devices when the proton fluence is up to $1 \times 10^{10}$ cm$^{-2}$, then assuming that SEB will not occur at this bias condition. The onset voltages for SEB failure are 925 and 1000 V for 100 and 60 MeV proton irradiation, respectively. Figure 10(a) shows the optical microscope image of a device with SEB after de-capsulation. Even the electrode surface exhibits damage due to SEB. It indicates that the Al surface temperature exceeds its melting point. The SEM image of the damage region after striping metal layer is shown in Figure 10(b). It reflects the occurrence of melt-solidification at the surface within the damage region due to the highly localized SEB current. A crack is observed under the damage region deep into the SiC substrate using FIB.

The high energy proton causes SEB by indirect ionization. When a proton strikes into an SiC MOSFET, the secondary ions produced in the proton-nucleus reaction will create electron-hole pairs along its tracks, then may lead to SEB. The information of proton-induced secondary ions in SiC MOSFET are obtained by PHITS [21] simulations. Figure 11(a) shows the types and yields of secondary particles produced by 100 MeV proton. The number of He, C, and Si ions dominates in all the secondary products. Even though the energy of He ion is larger than the other secondary ions (the largest energy can reach 50 MeV), the LET value of He ion is small due to the small atomic weight, as shown in Figure 11(b). So it can merely contribute to SEB. The maximum LET value of the secondary ions can reach 13.9 MeV-cm$^2$/mg (1 keV/$\mu$m in SiC = $3.03 \times 10^{-3}$ MeV-cm$^2$/mg). The previous works prove that the threshold LET value to induce an SEB is about 2 MeV-cm$^2$/mg when drain biased at 925 V [19]. It can be concluded that most of the secondary ions except for He may contribute to the SEB induced by 100 MeV proton.

It is different from the heavy ion irradiation, no output characteristics degradations are observed before and after proton irradiation for the device without SEB, as shown in Figure 12. It implies that proton would not cause the permanent damage of the SiC MOSFET unless there is an SEB.

3.3 TCAD simulations

To verify the SEB mechanisms in SiC power MOSFET, two-dimensional simulations are performed using the Sentaurus TCAD tools [22]. The simulated device structure is generated using the information from the published literature and reverse engineering. The models used in the SEB simulations include conventional drift-diffusion model for transport, the Shockley Read Hall model and Auger model for generation-recombination, Doping Dependence model, High Field Saturation model and Enormal model for mobility. Apart from these essential physics models, the incomplete ionization and anisotropy of SiC material are also taken into account. In addition, the anisotropic impact ionization model is employed to simulate the breakdown behaviours. Thermal equations (lattice heating) are also considered for this study. During the simulation, the heavy ions are incident vertically from the top of the OFF biased device. The incident position of heavy ion is source/body region (2.5 $\mu$m apart from the middle of the SiC MOSFET), which corresponds to the most sensitive region to cause a SEB [19]. The heavy ion strike occurs 100 ps after the transient simulation begins, giving the device simulation enough time to achieve steady state. The track length of the heavy ion is $20 \mu$m which can pass through the entire drift layer and the Gaussian track radius is 50 nm. The LET values of the heavy ion and the drain voltages are varied during the simulations. The LET is defined as the charge deposited per unit of track length and given in pC/$\mu$m in the simulation. It can be transfer to MeV/mg/cm$^2$ by: $1$pC/$\mu$m (SiC) = 151 MeV/mg/cm$^2$ for SiC device.
FIGURE 8  Failure analysis of a SiC MOSFET after $^{181}$Ta ion irradiation with low flux. Irradiation bias voltage: $V_{gs} = 0$ V and $V_{ds} = 400$ V. (a) OBIRCH analysis of the de-capsulated device. (b) SEM image of the damage region after striping metal layer. (c) SEM image at the FIB location.

Figure 13 shows the heavy ion induced drain current density and maximum lattice temperature as a function of time for SiC MOSFET with and without impact ionization model turned on. The drain current is sharply increase and remains at a high level after heavy ion striking in with impact ionization model activated. The maximum lattice temperature increases from 300 to 3690 K at $10^{-8}$ s with the increase of drain current. It means the occurrence of SEB. The sublimation temperature of SiC material is about 2973 K. The maximum lattice temperature inside the SiC device reaches the sublimation temperature at about 1.1 ns after the ion striking in, which would result in thermal damage in the device. Figure 14 shows the simulated lattice temperature distribution in the SiC MOSFET after the ion striking in. Figure 14(a)–(d) correspond to the point A, B, C and D in Figure 13, respectively. The increase of lattice temperature first appears at the n-drift/n+ drain region along the heavy ion track. At 250 ps after striking, lattice temperature increase occurs at the source region. The lattice temperature at the n-/n+ region reaches 1100 K at the same time. It is worth to note that the maximum lattice temperature point transfer from the n-/n+ region to the source region at 900 ps. At this time the maximum lattice temperature at source region is over 2000 K, while the maximum lattice temperature near n-/n+ region is about 1600 K. This is related to the collection of high density carriers produced by impact ionization in source region. It can be predicted that the source region is the earliest burnout area in SEB.

The radiation induced drain current gradually decays after the strike and cannot stay at the high level with impact ionization model inactivated. It is indicative of no burnout. Simultaneously, the lattice temperature reaches maximum of 595 K at about 1.9 ns after striking and then gradually decrease, as shown in Figure 13. It proves that impact ionization is the necessary condition for SEB. Figure 15 shows the simulated lattice temperature distribution in the SiC MOSFET after the ion striking in with impact ionization model turning off. Figure 15(a)–(d) correspond to the points A', B', C' and D' in Figure 13, respectively. The maximum lattice temperature region distributes near the n-/n+ junction during the whole process.

As heavy ion striking in, electron-hole pairs are generated along the track. Then the electrons and holes are collected...
FIGURE 9 (a) Time evolution of drain leakage currents for SiC MOSFET during 100 MeV proton irradiation. Irradiation bias voltage: Vgs = 0 V and Vds = 950 V. (b) SEB failure threshold for different energy proton irradiation. “x” represents SEB occurs and “+” represents no SEB is observed. Three devices are tested under each bias condition.

As the minority carriers traveling a certain distance in the space charge region, they will acquire enough energy to generate impact ionization and create more electron-hole pairs. At this time, the emitter current is multiplied by the impact ionization mechanism and form drain current (i.e. collector current of the parasitic transistor). It can be expressed as,

\[ I_D = M I_E \]

(4)

where \( M \) is the avalanche multiplication factor. For a high voltage p+/n junction, \( M \) is proportional to the reverse bias voltage (here is the drain voltage) and is given by [23],

\[ M = \frac{1}{1 - (V_D/BV)^6} \]

(5)

where \( BV \) is the breakdown voltage. Simultaneously, the hole produced during the impact ionization process will drift to the body region and maintain the voltage drop between source and body, which is expressed as,

\[ V'_{drop} = (M - 1) I'_R R_{PB} = (M - 1) I_0 e^{(V_{drop}' - V_b)/kT} R_{PB} \]

(6)

If \( V'_{drop} > V_b \), then positive feedback mechanisms are built up. The large currents will lead to thermal runaway and burnout.

It can be seen from Equations (1) and (5) that LET values of heavy ion and drain bias voltage are the primary factors related to the SEB. The radiation induced hole current \( I_{PR} \) depends on LET and it determines the initial turn on of the parasitic transistor. The drain voltage affects the strength of the avalanche multiplication, because the impact ionization coefficients are exponentially related to the electric field. The electric field profile as a function of time after ion striking for SiC MOSFETs with and without SEB are presented in Figure 16. The displacements of the electric field peak from p-body/n-drift junction to n-drift/n-drain junction are observed for all the devices with and without SEB. This phenomenon is due to the Kirk effect induced by the injection of large concentrations of electrons into the n-drift region and the build-up of the negative space charge zone [13, 24]. The electric field returns to its original state after 9900 ps in Figure 16(a). The low LET value cannot turn on the parasitic bipolar transistor, causing the failure of the positive feedback establishment. The excess carriers will be gradually extracted out of the device with time, then the Kirk effect disappears. This is also proved by the results in Figure 17(a). The radiation-induced holes are accumulated in body region and result in the potential increase in body region. But the body potential is lower than the source potential during the whole process, which implies that the parasitic transistor is turning off.
FIGURE 10  Failure analysis of an SiC MOSFET with SEB after 100 MeV proton irradiation. Irradiation bias voltage: $V_g = 0$ V and $V_d = 950$ V. (a) Optical microscope image of the device after de-capsulation. (b) SEM image of the damage region after striping metal layer.

FIGURE 11  Information of secondary ions produced by the nuclear reaction of 100 MeV proton. (a) Types and yields of secondary ions. (b) LET distributions of the secondary ions.

FIGURE 12  Output characteristics before and after proton irradiation for the device without SEB.

FIGURE 13  Simulation of drain current density and maximum lattice temperature as a function of time in the SiC MOSFET after the heavy ion striking in. Bias condition during simulation: $V_d = 500$ V, $V_g = 0$ V. LET = 0.35 pC/µm. Filled scatter lines: the impact ionization model is activated. Unfilled scatter lines: the impact ionization model is inactivated.
A stable high electric field is built up at the n-drift/n-drain junction for the device with SEB, as shown in Figure 16(b). The peak value of electric field at p-body/n-drift junction is 1.1 MV/cm before irradiation. The electric field peak drift to the n-drift/n-drain junction and can reach a maximum of 3.0 MV/cm after ion striking. The impact ionization will then mainly happen at the n-drift/n-drain junction and the higher electric field allows the establishment of a strong ionization rate to maintain the turning on of bipolar transistor. This is consistent with the result in Figure 17(b), the body potential become larger than the source potential after 250 ps, and the bipolar is turning on. Even both the drain voltage and the LET value of heavy ion are high enough, the high electric field at n-drift/n-drain junction cannot hold on and the bipolar remains turning off if the impact ionization model is inactive during the simulation, as shown in Figures 16(c) and 17(c). The drain current will die out, leaving the device unharmed. It is also interesting to note that the peak value of electric field in gate oxide can reach 10.6 MV/cm at 10 ps for ion with \( \text{LET} = 0.35 \text{ pC}/\mu\text{m} \), as shown in Figure 16(b). It is almost equal to the oxide breakdown field (≈12–15 MV/cm), which implies that a gate rupture may happen.

In another simulation, a MOSFET structure without source region is constructed, as shown in Figure 18(a). So there is no parasitic bipolar structure in this device. The comparisons of the simulated drain current density as a function of time for this structure without source region and the regular SiC MOSFET after heavy ion striking in are shown in Figure 18(b). During simulations, the impact ionization model is activated and both the SiC MOSFET and the device without source are biased at \( V_{ds} = 500 \text{ V} \). When the LET value of heavy ion is 0.07 pC/\( \mu\)m,
FIGURE 15  Simulation of lattice temperature in the SiC MOSFET before and after the heavy ion striking in. The impact ionization model is turning off during simulation. Bias condition during simulation: $V_{ds} = 500$ V, $V_{gs} = 0$ V. (a) 10 ps, (b) 100 ps, (c) 250 ps and (d) 900 ps after the ion striking in. They correspond to the $A'$, $B'$, $C'$ and $D'$ point in Figure 13.
SEB occurs for the SiC MOSFET and no SEB occurs for the device without source. The SEB does not happen until the LET value of heavy ion reaching 0.21 pC/µm. It implies that a SEB can still happen if only considering impact ionization and excluding the effect of parasitic bipolar. The turning on of the parasitic bipolar is not necessary for an SEB. But the turning on of parasitic bipolar is a key factor for the SEB in SiC MOSFET.

4 | CONCLUSION

The radiation-induced SEBs are investigated for SiC power MOSFETs. The onset voltage of SEB is \( V_{do} = 400 \text{ V} \) (OFF bias with \( V_{gs} = 0 \text{ V} \)) under Ta ion irradiation with LET = 81.3 MeV·cm²/mg. The damage region is identified by OBIRCH and
FIGURE 18  (a) An SiC MOSFET structure without source region. (b) Simulation of drain current density as a function of time for the regular SiC MOSFET and MOSFET without source after the heavy ion striking in SEM for the device with SEB. A melting “hole” is observed near the gate region due to the thermal runaway in SEB. Except for SEB, the high LET heavy ion can also lead to other permanent damage. It is manifested as the increase of gate/drain leakage currents and the abnormal output characteristics for SiC MOSFET after irradiation. This is explained by the cumulative damage of the latent tracks.

The impact ionization and turning on of parasitic bipolar are the key factors to trigger SEB in SiC MOSFET according to TCAD simulations. The LET value of the heavy ion determines the initial turn on of the parasitic transistor and the drain voltage affects the strength of the avalanche multiplication. So only if the heavy ion LET value and drain bias voltage are both enough high, the SEB can occur. Unlike the impact ionization, the turning on of the parasitic bipolar is not necessary for an SEB, which is proved by the simulations. But it will significantly reduce the threshold of SEB and make the SEB easier to happen. The radiation induced maximum lattice temperature is located at the n-drift/n+ drain region along the heavy ion track at first, then transfer to the source region during SEB. It seems that the source region is the earliest damage area in SEB.

For proton irradiation, the SEBs are observed due to the indirect ionization. The onset threshold voltages for SEB failure are 925 and 1000 V for 100 and 60 MeV proton irradiation, respectively. It is proved that most of the secondary ions may contribute to the SEB. Unlike heavy ion irradiation, the leakage current does not increase, but decrease as the total influence increase during proton irradiation.

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