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An investigation into the impact of LET on the Single Event Burnout (SEB) sensitivity of a 3.3 kV PiN diode

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HIGHLIGHTS

- Single Event Burnout (SEB) in a PiN diode through simulation was studied.
- The correlation between the ion's LET and threshold voltage of SEB (V_{SEB}) was investigated.
- The Linear Energy Transfer (LET) of the ions was determined using SRIM.
- The electrical properties of the device due to irradiation were analyzed using the Silvaco TCAD tool.
- Ions with higher LET values can cause burnout at a lower VSEB level, increasing the device's sensitivity to SEB.

ABSTRACT

High-voltage semiconductor devices are vulnerable to Single Event Burnout (SEB) as a result of interactions with Galactic Cosmic Rays (GCR). SEB is a permanent failure triggered by the passage of a single particle during the turn-off state of the device. This paper investigates SEB in a PiN diode induced by various ions in space through simulation. The Linear Energy Transfer (LET) of the ions studied was determined using SRIM. Additionally, the electrical properties of the device due to irradiation were analyzed using the Silvaco TCAD tool. The key indicator of SEB occurrence is the threshold voltage of SEB (V_{SEB}). Therefore, the correlation between the ion's LET and V_{SEB} was investigated. The results indicate that the most sensitive region is in the middle of the device, and SEB is caused by avalanche multiplication of ion-generated carriers. It was also observed that the V_{SEB} decreased from 3200 V to 2100 V; as the LET increased from 0.19 to 58 MeV.cm^2.mg^{-1} for He and Ta, respectively. Consequently, ions with higher LET values can cause the device to burnout at a lower V_{SEB} level, increasing the devices sensitivity to SEB.

KEYWORDS

Single Event Burnout (SEB)
Linear Energy Transfer (LET)
PiN diode
Silvaco TCAD
SRIM
Threshold Voltage of SEB

HISTORY

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1 Introduction

Modern space technology has developed over the last few decades, leading to a continuous increase in power demand for space platforms. The power systems of future space platforms must be able to operate reliably in space for more than 30 years without the need for maintenance (Gollapudi and Omura, 2021). In 2016, NASA identified high-power electric propulsion as the first priority for future space technologies. These technologies utilize high-power devices that are expected to function in space environments for decades (Khurelbaatar et al., 2023).

High-power semiconductor devices are essential in modern spacecraft and propulsion systems. However, the performance of these devices may be degraded by space radiation. In space, there are charged ions with energy levels up to 10^{20} eV (Soelkner et al., 2004). The interaction of electronic devices with ionizing radiation may affect their performance, potentially leading to failure. The reliability of these systems is crucial due to the high costs associated with space applications. When electronic devices are exposed to radiation, they may lose their correct performance due to cumulative or Single Event Effects (SEEs). Cumulative effects are gradual and occur throughout the lifetime of the devices in a radiation environment. These effects can be classified as Total Ionizing Dose (TID) and Displacement Damage (DD). On the other hand, SEEs are stochastic events that disrupt the behavior of electronic devices or systems due to the impact of a single ionizing particle. SEEs are further divided into soft errors and hard errors. Single Event Burnout (SEB) is a destructive form of SEE (a hard error) that can damage power

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devices exposed to radiation. SEB is a widely recognized problem for space applications. It occurs in high-voltage devices when they are in the OFF-state. SEB was first observed in power MOSFETs in 1986 (Waskiewicz et al., 1986). However, subsequent reports indicate that power diodes may also be susceptible to this phenomenon from heavy ion strikes (Kabza et al., 1994). In recent years, numerous studies have been conducted to understand SEB mechanisms and develop hardening approaches for various power devices to minimize their vulnerability to radiation (Soelkner et al., 2004; Fei et al., 2020; Lu et al., 2020; Pocaterra and Ciappa, 2023; Srivastava et al., 2023).

The investigations showed that as the applied voltage of electronic devices increases, the probability of failure and malfunctions due to SEB increases because of interactions with galactic charged particles in space (Patel, 2004; Reinhardt et al., 1998). The key parameter for the SEB sensitivity of the device is the threshold voltage (V_{SEB}), which is related to the devices ability to resist SEB (Wu et al., 2023). Scheick et al. point out that the V_{SEB} may be much lower than the breakdown voltage (V_{BD}) of the device and it could vary under irradiation from different ions (Scheick, 2014). According to experimental results from Martinez et al. for p-GaN gate HEMT, V_{SEB} would likely have be lower for heavier ions (Martinez et al., 2018).

Obtaining SEB data through tests for semiconductor devices is an expensive, challenging and time-consuming task, due to the destructive nature of the test. However, simulation tools provide an opportunity to investigate the behavior of the device under irradiation. Silvaco TCAD is one of such tools that is based on finite-element methods for solving the equations.

In this paper, simulations were performed using Silvaco TCAD to understand the electrical properties of a PiN diode during irradiation. The PiN diode is considered due to the presence of a P-i-N structure in all high voltage semiconductor devices. For this purpose, the sensitive injection position and the V_{SEB} of each ion were conducted, and then the correlation between different values of LET and V_{SEB} was studied.

2 Materials and methods

The PiN diode with a voltage breakdown (V_{BD}) of 3.3 kV is used in this study. Simulations were performed using the Victory module of the Silvaco TCAD tool to analyze the device behavior under irradiation by various ions. This tool is based on finite-element methods and solves Poisson's and carrier continuity partial differential equations for the device. Key models employed in the simulation include the Shockley-Read-Hall (SRH) recombination model, the Auger recombination model, the impact ionization model, and the electric-field dependent model. Doping levels and dimensions used in the PiN diode simulations are outlined in Table 1. As particles traverse through the material, they deposit some or all of their energy through direct or indirect ionization, creating a column of electron-hole pairs along their path. According to the Bethe-Bloch equation, the LET value initially increases with energy and, then decreases after reaching a peak value (Grimes et al., 2017).

To understand the relationship between V_{SEB} and LET, several ions with relatively high flux in space were selected. The ions studied in this work, include He, O, Ne, Si, Fe, Cu, Br, Kr, and Ta. To ensure consistency among the ions studied in this work, it was assumed that all of them would pass entirely through the device. Therefore, the energy and LET in the silicon were calculated using SRIM for the same range of ions. Subsequently, electrical simulations were conducted to identify the most sensitive region in the device and to observe the impact of heavy ion strikes on the PiN diode's behavior. The V_{SEB} at a specific LET value could be determined by gradually increasing the cathode voltage and monitoring the transient current. The results will be presented in the following section.

Table 1: The parameters used in the diode simulation.

Region	Length (μm)	Doping (cm^{-3})
n^+	20	1×10^{18}
(i-layer) n^-	300	3×10^{13}
P^+	20	1×10^{18}

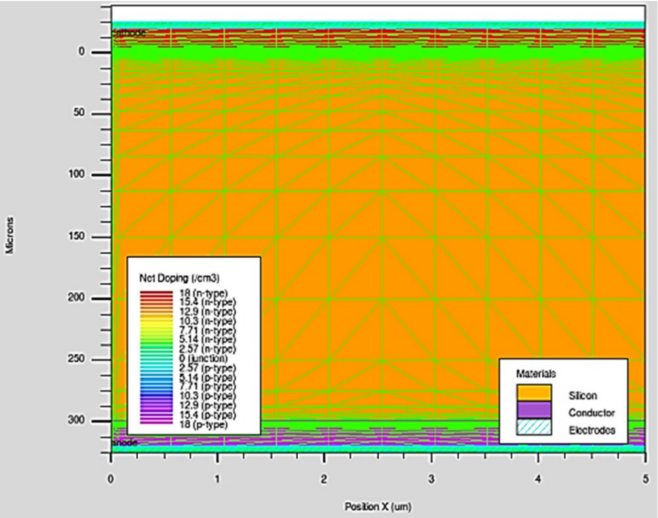
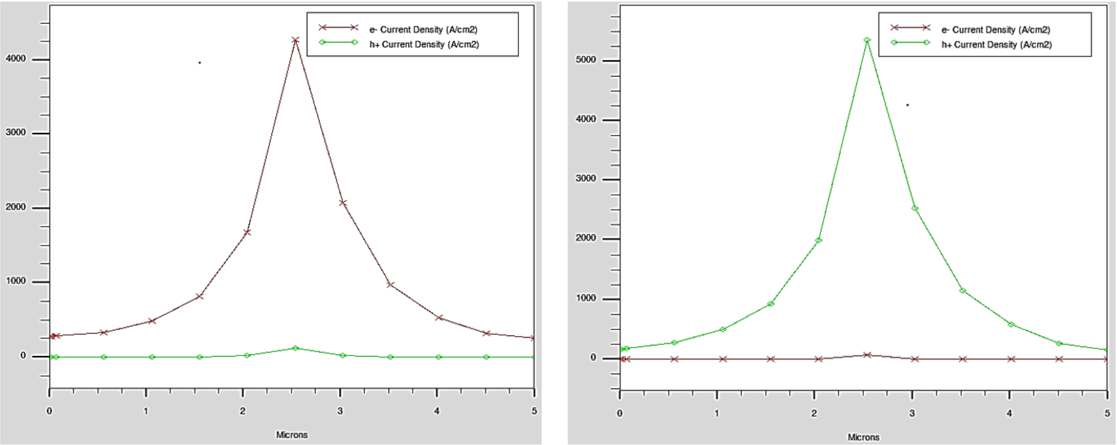


Figure 1: The simulated structure of PiN diode using Sivaco TCAD tool.

3 Results and discussion

The simulated 2D diode structure is depicted in Fig. 1. The colour changes are due to the variation of doping value in different layers of the device. As depicted in this figure, the n^+ and p^+ regions are distinguished in red and violet, respectively. When ions strike the device, electron-hole pairs are generated. Due to the electric field, the strike-induced electron-hole pairs separate. Electrons move towards the cathode, while holes move towards the anode. The current density of electrons and holes around the cathode and anode after the incidence into the PiN diode is illustrated in Figs. 2-a and 2-b.



(a) (b)

Figure 2: The current density of the generated electron and holes around the (a) cathode and (b) anode after ion strike. The strike location is in $x = 2.5$ μm.

In order to investigate the most sensitive region, ions with different values of LET were struck into the various locations on the PiN diode. The most sensitive region is defined by the minimum LET value that triggers SEB. Figure 3 illustrates the minimum LET required to cause SEB in the device at different positions. The results indicate that the most sensitive region is located in the middle of the device, where the device is most likely to burnout when the ion with lower LET strikes on it.

The transient behavior of the cathode current in the device after an ion strike is illustrated in Fig. 4. This figure shows the ion strike with two values of LET=13.6 MeV.cm^2.mg^{-1} and LET=27.2 MeV.cm^2.mg^{-1}. According to the simulation results, the current pulse after the ion strike for LET=13.6 MeV.cm^2.mg^{-1} falls back to zero and the device recovers. Therefore, no SEB has occurred. However, for LET=27.2 MeV.cm^2.mg^{-1}, the current increases significantly, resulting in device burnout. The occurrence of SEB is attributed to the presence of a strong electric field after the particle strike and the multiplication of ion-generated carriers.

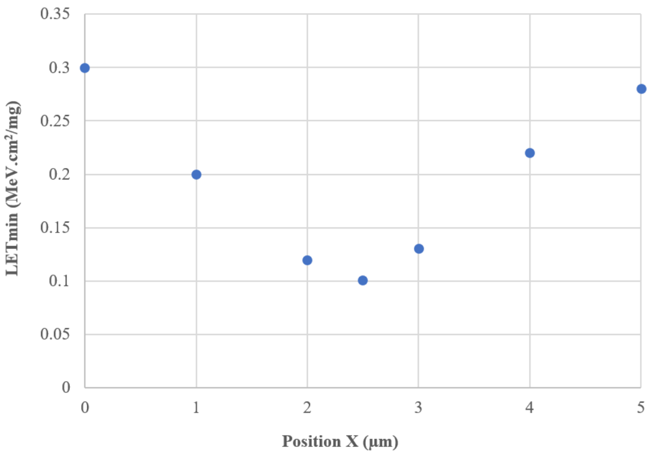


Figure 3: The sensitivity of different positions in the PiN diode.

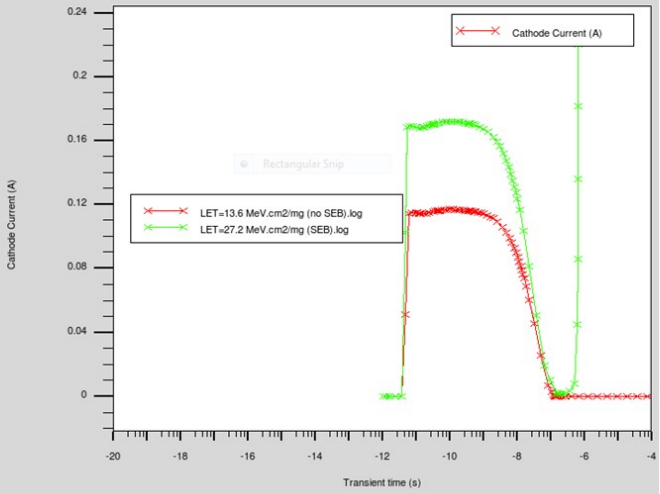


Figure 4: Cathode transient current as a result of ion strike with two values of LET. LET= 13.6 MeV.cm^2.mg^{-1} and LET=27.2 MeV.cm^2.mg^{-1}.

In order to investigate the correlation between V_{SEB} and LET, the transient current for different biases below the breakdown voltage has been simulated by irradiating of the ions in the middle of the device, which is the most sensitive region. The results are shown in Table 2, indicating that the V_{SEB} is different under irradiation of different values of LET. As shown in Table 2, the V_{SEB} of He, Cu, and Ta ions obtained 3200 V, 2500 V, and 2100 V, respectively. The results show that the V_{SEB} decreases with an increase in LET value. This was expected due to the higher energy deposition in the device and more carrier generation resulting from higher LET values, leading to more multiplication.

Therefore, the ion with a higher LET value possesses a lower V_{SEB}. This means that the sensitivity of the device to the occurrence of SEB increases when ions with higher LET strike it. A similar result has recently been obtained for GaN HEMT power devices (Wu et al., 2023).

Table 2: Relationship of VSEB and LET value of different ions.

Ion	Range	Energy (GeV)	LET in Silicon ($\mathrm{MeV.cm^2.mg^{-1}}$)	VSEB (V)
Ta	Whole the device	4.7	58	2100
Kr	Whole the device	2	19.5	2450
Br	Whole the device	1.8	18.7	2480
Cu	Whole the device	1.4	13.6	2500
Fe	Whole the device	1.2	11.4	2600
Si	Whole the device	0.5	4.4	2800
Ne	Whole the device	0.3	2.5	3000
O	Whole the device	0.25	1.8	3100
He	Whole the device	0.025	0.19	3200

4 Conclusions

In this work, a simulation study on the SEB induced in a PiN diode has been conducted to investigate the impact of LET value on the SEB sensitivity of the device. To understand the relationship between the ions LET and the SEB threshold voltage (V_{SEB}), SRIM was used to determine the LET of the studied ions in the silicon. The transient behavior of the device was then analyzed using Silvaco TCAD tool. The results indicate that the PiN diode is most sensitive to ions injected in the middle of the device. SEB is caused by avalanche multiplication of ion-generated carriers. Additionally, it was also observed that the V_{SEB} decreases from 3200 V for He to 2100 V for Ta, when the LET increased from 0.19 to 58 $\mathrm{MeV.cm^2.mg^{-1}}$. Consequently, ions with higher LET values can cause the device to burnout at lower voltages and make it more sensitive to SEB.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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