Comparison of SEB Cross-section between Spallation Neutron and Mono-energetic Proton for SiC MOSFETs

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Abstract

The radiation-induced single event burnout (SEB) is observed for SiC MOSFETs by conducting proton and spallation neutron irradiation. Proton irradiation at different energies indicates that the SEB cross-section increases with the increase of proton energy. Under different bias voltages, the SEB cross-section of protons with energies of 100 MeV and above will exceed that of spallation neutrons. The atmospheric neutron SEB failure rates of SiC MOSFETs are calculated based on the proton-induced and neutron-induced SEB cross-sections, respectively. The failure rates calculated by the two different methods are consistent, with the error between the two results being less than 49%. The information of the secondary ions produced by spallation neutron and proton is obtained through Monte Carlo simulations. The simulation results imply that the SEB caused by protons and spallation neutrons is strongly correlated with the ionizing energy deposition of their secondary ions from nuclear reactions. As the proton energy increases, the number of secondary ion products with sufficient energy deposition to induce SEB increases. The magnitude of the SEB cross-sections for spallation neutrons and protons also depends on the number of secondary particles that deposit energy above the threshold energy.

Full Text

Comparison of SEB Cross-Section Between Spallation Neutron and Mono-Energetic Proton for SiC MOSFETs

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Abstract: Radiation-induced single-event burnout (SEB) in SiC MOSFETs is investigated through proton and spallation neutron irradiation experiments. Proton irradiation at various energies demonstrates that the SEB cross-section increases with proton energy. Under different bias voltages, the SEB cross-section for protons with energies of 100 MeV and above exceeds that of spallation neutrons. Atmospheric neutron SEB failure rates for SiC MOSFETs are calculated using both proton-induced and neutron-induced SEB cross-sections. The failure rates obtained from the two methods show good consistency, with a maximum discrepancy of less than 49%.

Secondary ion information produced by spallation neutrons and protons is obtained through Monte Carlo simulations. The results indicate that SEB caused by protons and spallation neutrons is strongly correlated with the ionizing energy deposition of secondary ions from nuclear reactions. As proton energy increases, the number of secondary ion products with sufficient energy deposition to induce SEB increases. The magnitude of SEB cross-sections for spallation neutrons and protons also depends on the number of secondary particles that deposit energy above the threshold.

Keywords: Atmospheric neutron failure rate, SiC MOSFET, single-event burnout, spallation neutron

1. Introduction

The advantages of SiC power MOSFETs, including high efficiency, high voltage tolerance, and low loss, have enabled their widespread adoption in applications such as new energy vehicles, charging stations, and photovoltaic systems [1],[2]. However, power devices used in terrestrial environments face reliability risks from atmospheric neutrons. Previous studies have demonstrated that power electronic devices are vulnerable to terrestrial cosmic radiation [3]-[5], and SiC MOSFETs exhibit similar reliability concerns. Numerous studies have reported destructive single-event burnout (SEB) failures induced by atmospheric neutrons [6]-[10], making atmospheric neutron-induced SEB one of the most serious reliability issues for SiC MOSFETs in terrestrial applications [11]. Consequently, evaluating the failure rate caused by atmospheric neutrons is essential to meet the high reliability requirements of SiC MOSFETs in power applications.

The most effective approach for estimating atmospheric neutron failure rates is accelerated irradiation testing. The JEDEC JEP151 standard recommends two types of nucleon beams for accelerated testing of power devices: mono-energetic protons and spallation neutrons [12]. Spallation neutrons are an ideal radiation source because their energy spectrum closely approximates that of natural atmospheric neutrons. When mono-energetic protons are employed for accelerated testing, the energy should be at least 150 MeV. However, due to spectral differences, a mono-energetic proton beam of at least 150 MeV cannot accurately represent the effects of the low-energy portion of the natural atmospheric spectrum, potentially leading to overestimation of device failure rates from terrestrial atmospheric neutrons. The JEDEC JESD89A standard has indicated that atmospheric neutron-induced soft errors in SRAM can be derived from Weibull fits to mono-energetic proton SEU cross-section data [13],[14]. Similarly, Weibull fitting curves of SEB cross-sections for protons at different energies might be used to assess the atmospheric neutron failure rate of power devices, though this method has not been experimentally verified and its applicability to power devices remains uncertain.

This paper presents irradiation tests on SiC MOSFETs using spallation neutrons and mono-energetic protons at various energies. The differences in SEB cross-sections between spallation neutrons and protons of different energies are compared, and atmospheric neutron SEB failure rates are calculated based on accelerated test results from both radiation sources. Finally, secondary ion characteristics obtained through Monte Carlo simulation are used to explain the observed differences in SEB cross-sections between spallation neutrons and protons.

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2. Experimental Details

Commercially available SiC n-channel power MOSFETs C3M0065090D (900 V, 36 A, 65 mΩ) from CREE Inc. were used as experimental samples. Since high-energy protons and neutrons can penetrate packaging materials, the samples were irradiated from the front side without package removal. Proton irradiations at 40-100 MeV were conducted at the Northwest Institute of Nuclear Technology, with a flux of 1$×10^{8}$ p/cm^2/s for 40 MeV protons and 2$×10^{7}$ p/cm^2/s for other energies. The 200 MeV and 300 MeV proton irradiations were performed at the Space Environment Simulation and Research Infrastructure (SESRI) at Harbin Institute of Technology, with an average proton flux of 5$×10^{6}$ p/cm^2/s.

During proton irradiations, test boards were mounted on a two-dimensional movement platform, with only one sample irradiated at a time, as shown in Figure 1: see original paper. The proton beam area of 2 cm × 2 cm covered the active area of the device. The device under test (DUT) was aligned to the center of the proton beam using a laser, with the beam at normal incidence. Devices were biased in the OFF state during irradiation, with the drain terminal at a positive high voltage and the source and gate grounded. The drain terminal was biased using a Keithley 2290 high-voltage power supply, as shown in Figure 1: see original paper. The drain current was monitored in real time using a Keithley DMM7510 multimeter, which has an internal resistance of 10 MΩ in series with the DUT. This internal resistance limits the monitored current when the DUT experiences burnout. Irradiation experiments were conducted at various operating voltages, with three samples tested at each voltage.

Neutron irradiations were performed using the Atmospheric Neutron Irradiation Spectrometer (ANIS) at the China Spallation Neutron Source (CSNS). The energy spectrum of this spallation neutron source is presented in our previous works [15],[16]. The maximum neutron energy exceeds 1 GeV, and the neutron flux at the sample location with energies above 10 MeV is 6.17\$×10ˆ{5}\$ n/cm^2/s. The test setup for spallation neutron irradiation was identical to that described in [16]. Neutron irradiation experiments were also conducted at various operating voltages, with ten samples tested at each voltage. The beam was at normal incidence with an area of 10 cm × 6 cm, allowing all ten samples to be irradiated simultaneously. Irradiation at a specific voltage was completed when all devices failed or when the total neutron fluence (>10 MeV) reached 9\$×10ˆ{9}\$ n/cm^2.

3. Results and Discussions

A. SEB Cross-Section and Failure Rate Calculations Under Different Radiation Sources

[Figure 2: see original paper] shows the real-time monitored currents during proton irradiation when the SiC MOSFET is biased at 750 V. A proton pulse is incident on the device every 12 s, accompanied by a transient current pulse. An SEB event occurs when the total proton fluence reaches 7.28\$×10$^{\{8\}/cm}$\{2\}\$, manifested as an abrupt increase in drain current. The SEB damage regions in the SiC MOSFET are located using Emission Microscope (EMMI) testing, with the emission region indicating the damage location, as shown in [Figure 3: see original paper]. The damage regions are randomly distributed, and the SEM image in [Figure 3: see original paper] reveals that material has melted due to thermal runaway during SEB. Similar SEB phenomena were observed under spallation neutron irradiation [15].

SEB cross-sections corresponding to different drain bias voltages under mono-energetic proton irradiation for the 900 V SiC MOSFETs are calculated using:

$$\sigma_{SEB}(V_{bias}, E_p) = \frac{r}{\phi_{proton}}$$

where E_p is the proton energy, V_{bias} is the drain bias voltage during irradiation, r is the total number of failures under irradiation at V_{bias}, and ϕ_{proton} is the sum of the proton fluence for each irradiated device. The calculated SEB cross-section results are shown in . The relationship between SEB cross-section and proton energy can be obtained by fitting the data with a four-parameter Weibull distribution:

$$\sigma_{SEB}(V_{bias}, E_p) = \sigma_0 \left(1 - \exp\left\{-\left[\frac{E_p - E_0}{W}\right]^S\right\}\right)$$

where σ_0 is the saturation SEB cross-section, E_0 is the threshold proton energy below which the SEB cross-section is considered zero, and W and S are fitting parameters. The Weibull fitting parameters for different drain biases are shown in .

Similarly, the SEB cross-sections as a function of drain bias for SiC MOSFETs can be calculated from the spallation neutron experimental results:

$$\sigma_{SEB}(V_{bias}) = \frac{r}{\phi_{neutron}}$$

where $\phi_{neutron}$ is the sum of the neutron fluence with energy >10 MeV for each irradiated device. Since spallation neutrons have a continuous energy spectrum, the SEB cross-section obtained in the experiment represents the average cross-section caused by neutrons of different energies.

[Figure 4: see original paper] compares the SEB cross-sections between mono-energetic protons and spallation neutrons under different drain biases for SiC MOSFETs. The proton-induced SEB cross-section increases with both drain bias and proton energy. SEB is only observed for proton irradiation with energies of 60 MeV and above when the drain bias is below 850 V. At a drain bias of 700 V, the SEB cross-section increases from 5.02\$×10^{-11}\$ cm^2 to 5.12\$×10^{-10}\$ cm^2 as proton energy increases from 60 MeV to 300 MeV. At a drain bias of 850 V, the SEB cross-section increases from 7.86\$×10^{-12}\$ cm^2 to 7.37\$×10^{-9}\$ cm^2 as proton energy increases from 40 MeV to 300 MeV. The average SEB cross-section caused by spallation neutrons also increases with drain bias. Notably, when proton energy exceeds 100 MeV, the corresponding SEB cross-section surpasses the average SEB cross-section caused by spallation neutrons at bias voltages of 700–850 V. This indicates that using the proton SEB cross-section at a single energy point above 100 MeV instead of the average spallation neutron cross-section would overestimate the failure rate of this SiC device.

Combining the Weibull fitting curve of mono-energetic proton SEB cross-section data with atmospheric neutron spectrum data, the atmospheric neutron-induced SEB failure rate of the SiC MOSFET can be calculated using:

$$\lambda_{SEB,proton} = \int_{E_{min}}^{E_{max}} \frac{d\Phi_n(E_n)}{dE_n} \sigma_{SEB}(E_n, V_{bias}) dE_n$$

where $d\Phi_n(E_n)/dE_n$ is the differential neutron flux at New York sea level, as shown in [Figure 5: see original paper], and E_{max} and E_{min} are the upper and lower limits of neutron energy. The calculated SEB failure rates for operation at sea level in New York are shown in . The atmospheric neutron-induced SEB rates increase with applied drain bias, reaching approximately 2.73 FIT at $V_{ds} = 700$ V and 52.0 FIT at $V_{ds} = 850$ V.

The SEB failure rates of SiC MOSFETs are also calculated based on the spallation neutron SEB cross-section [12]:

$$\lambda_{SEB,neutron} = \sigma_{SEB,neutron}(V_{bias}) \times \Phi_n$$

where $\Phi_n = 13$ n/cm^2/h is the natural atmospheric neutron flux with energy >10 MeV at New York sea level. The SEB failure rate calculated from the spallation neutron experiment ($\lambda_{SEB,neutron}$) is consistent with that calculated from the proton cross-section ($\lambda_{SEB,proton}$), with a maximum error of approximately 49.0%, as shown in .

B. Comparison of Secondary Ion Characteristics Generated by Proton and Neutron

Since both neutrons and protons induce SEB through secondary ions generated by nuclear reactions, the different SEB cross-sections between mono-energetic protons and spallation neutrons can be analyzed by comparing their secondary ion products. The secondary ion products of mono-energetic protons and spallation neutrons in SiC MOSFETs are obtained using PHITS calculations [17],[18]. The calculation setup is identical to that in our previous work [15]. A sensitive volume (SV) is defined in the simulation structure, and information about secondary ions generated by nuclear reactions that enter the SV is recorded, as only the energy deposited by secondary ions in the SV contributes to SEB. According to [19], the sensitive volume for triggering SEB is near the n-drift/n+ drain junction for short-range secondary ions. Therefore, an SV with dimensions of 2.5 m × 4 m × 20 m is defined near the n-drift/n+ drain junction of the SiC MOSFET in the PHITS simulation. Mono-energetic neutrons and spallation neutrons are incident vertically from the top of the simulation structure. The incident proton energies are set to 40 MeV, 60 MeV, 100 MeV, 200 MeV, and 300 MeV. The energy spectrum of the incident spallation neutrons is similar to that in [Figure 5: see original paper]. The total number of incident particles is 5$×10^{8}$ for each radiation source.

Figure 6: see original paper shows the number of secondary ions produced by 300 MeV protons and spallation neutrons. The secondary ion products cover all ions from H to Si. The total number of secondary ions produced by spallation neutrons is higher than that produced by 300 MeV protons, particularly for secondary C, Mg, Al, and Si ions. The maximum energy of secondary ions (excluding secondary protons) produced by 300 MeV protons and spallation neutrons can reach 185 MeV and 139 MeV, respectively. However, 95.2% of secondary ions produced by spallation neutrons have energies below 10 MeV, compared to 82.2% for 300 MeV protons.

Secondary ions primarily induce SEB through ionizing energy deposition. [Figure 7: see original paper] shows the variation of ionizing energy loss with energy for different secondary ions in the range of 0.1 MeV to 200 MeV, calculated using SRIM code [20]. For energies below approximately 10 MeV, the ionization energy loss of most secondary ions increases with energy. Due to low ionization energy loss, secondary ions with low energy are unlikely to induce SEB. When considering only secondary ions with energies above 2 MeV, the number of secondary ion products from 300 MeV protons exceeds that from spallation neutrons, as shown in Figure 6: see original paper, indicating that 300 MeV protons are more likely to induce SEB in SiC MOSFETs. This explains why SiC devices exhibit higher SEB cross-sections under 300 MeV proton irradiation.

Figure 8: see original paper shows the deposited energies of different secondary ions in the SV of the SiC MOSFET for 300 MeV protons. The deposited ionizing energies in the SV range from 10^{-5} to 15.7 MeV. A threshold energy of 2.4 MeV is defined in this work based on previous heavy ion experimental data for SiC MOSFETs [21],[22], assuming that SEB occurs when the ionizing energy deposition in the SV exceeds this threshold. In the range of 10^{-5} to 0.6 MeV, the total deposited energy in the SV primarily comes from direct ionization of incident protons (H ions). Since the energy deposition in the SV for most protons is below 1 MeV, it is unlikely to trigger SEB. For energy depositions exceeding 2.4 MeV, relatively high numbers of He, C, N, O, Ne, and Mg ions are observed, implying that these ions are the major contributors to SEB. For secondary ion products of spallation neutrons, He, C, and Mg ions are the most abundant among ions with energy deposition exceeding 2.4 MeV, as shown in Figure 8: see original paper, making these ions more likely to cause SEB.

Figure 8: see original paper shows the number of secondary ions produced by protons at different energies and spallation neutrons as a function of deposited energy in the SV. For protons with energies of 60 MeV, 100 MeV, 200 MeV, and 300 MeV, the numbers of secondary ions with energy deposition exceeding 2.4 MeV are 7.26\$$\times 10^{\{-7\}/source, 9.16\times 10}\{-7\}/source, 1.02\times 10^{\{-6\}/source, and 1.18\times 10}\{-6\}/source, respectively. Higherprotonenergiesgeneratemoresecondaryionsthroughnuclearreactions, meanin$
$energyprotonsaremorelikelytocauseSEB, consistentwiththeexperimentalresultsin[Figure4 :$
$seeoriginalpaper]. Meanwhile, thenumberofsecondaryionswithenergydepositionexceeding2.4MeVforspallat$
7}\$/source, which is lower than that for 60 MeV protons. When the drain bias is close to the rated voltage, the threshold energy is relatively low (2.4 MeV), and the SEB cross-section for spallation neutrons is lower than that for 60 MeV protons, as observed at $V_{bias} = 850$ V in [Figure 4: see original paper].

It is worth noting that the threshold energy increases as drain bias decreases. If the threshold energy is increased to 6.4 MeV, the numbers of secondary ions with energy deposition exceeding the threshold are 1.80\$$\times 10^{\{-8\}/source, 5.40\times 10}\{-8\}/source, 1.26\times 10^{\{-7\}/source, 1.64\times 10}\{-7\}/source, and 3.00\times 10$^\{-8\}\$/source for 60–300 MeV protons and spallation neutrons, respectively. In this case, the SEB cross-section for spallation neutrons is larger than that for 60 MeV protons but smaller than that for 100 MeV protons, corresponding to the situation at

$V_{bias} = 700$ V.

4. Conclusion

The SEB induced by mono-energetic protons and spallation neutrons in SiC MOSFETs is investigated. SEB phenomena are observed during both proton and spallation neutron irradiation. The proton-induced SEB cross-section increases with drain bias and proton energy, becoming higher than that of spallation neutrons when proton energy exceeds 100 MeV. Atmospheric neutron SEB failure rates at New York sea level are calculated based on accelerated irradiation test results using both mono-energetic protons and spallation neutrons. The failure rates are calculated to be 2.73-52.0 FIT for $V_{ds} = 700$–850 V using proton experimental results at four distinct energy levels, and 1.47-26.5 FIT for $V_{ds} = 700$–850 V based on spallation neutron results. The maximum error between the failure rates calculated by the two methods is 49%, indicating that both methods can be employed to assess the atmospheric neutron failure rate of SiC MOSFETs.

The characteristics of secondary ions generated by protons at different energies and spallation neutrons are compared using PHITS simulations. The results indicate that SEB caused by protons and neutrons is strongly correlated with the ionizing energy deposition of secondary ions from nuclear reactions. As proton energy increases, the number of secondary ion products with sufficient energy deposition to induce SEB also increases, leading to higher SEB cross-sections for higher-energy protons. When the SiC MOSFET is biased near its rated voltage, the number of secondary ion products from 60 MeV protons capable of inducing SEB exceeds that from spallation neutrons, resulting in a lower SEB cross-section for spallation neutrons compared to 60 MeV protons. As the device bias voltage decreases, the energy deposition required to induce SEB increases, and the number of secondary ion products from 60 MeV protons sufficient to induce SEB becomes lower than that from spallation neutrons, making the average SEB cross-section of spallation neutrons higher than that of 60 MeV protons.

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Figure Captions

[Figure 1: see original paper] (a) Test board and sample installation. (b) Test setup for proton irradiation.

[Figure 2: see original paper] Current monitored during proton irradiation for 900 V SiC MOSFETs. Bias condition during irradiation: $V_{ds} = 750$ V.

[Figure 3: see original paper] Damage location and morphology of SiC MOSFETs after irradiation. (a) 200 MeV proton irradiation. (b) 300 MeV proton irradiation.

[Figure 4: see original paper] SEB cross-sections as a function of proton energies under different drain biases for SiC power MOSFETs. The solid line shows the Weibull fits of SEB cross-sections as a function of proton energies. The dashed line shows the average SEB cross-section of the spallation neutron source under different drain biases.

[Figure 5: see original paper] Atmospheric neutron spectrum at New York sea level.

[Figure 6: see original paper] (a) Number of all secondary ions produced by 300 MeV protons and spallation neutrons. (b) Number of secondary ions with energy above 2 MeV produced by protons and spallation neutrons.

[Figure 7: see original paper] Ionizing energy loss of different secondary ions as a function of energy.

[Figure 8: see original paper] (a) Deposited energies of different ions in SiC device for 300 MeV protons. (b) Deposited energies of different secondary ions in SiC device for spallation neutrons. (c) Number of secondary ions produced by protons with different energies and spallation neutrons as a function of deposited energy in SiC device.

Table Captions

SEB cross-sections corresponding to different drain voltages under mono-energetic proton and spallation neutron irradiation.

Weibull fitting parameters corresponding to different drain biases.

Comparisons of SEB failure rates obtained by mono-energetic proton and spallation neutron irradiation under different drain voltages.

Note: Figure translations are in progress. See original paper for figures.