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Estimating Terrestrial Neutron-Induced SEB Cross Sections and FIT Rates for High-Voltage SiC Power MOSFETs

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Abstract—Cross sections and failure in time rates for neutron-induced single-event burnout (SEB) are estimated for SiC power MOSFETs using a method based on combining results from heavy ion SEB experimental data, 3-D TCAD prediction of sensitive volumes, and Monte Carlo radiation transport simulations of secondary particle production. The results agree well with experimental data and are useful in understanding the mechanisms for neutron-induced SEB data.

Index Terms—Cross section, failure in time (FIT), heavy ion, Monte Carlo, MOSFET, Monte Carlo radiative energy deposition (MRED), neutron, power, silicon carbide (SiC), single-event burnout (SEB).

I. INTRODUCTION

SILICON carbide (SiC) has excellent properties for use in power device applications. In comparison to silicon, it has higher breakdown field and thermal conductivity. SiC devices are ideally suited to high voltage, high-power density power converter applications, both at ground level and in space. However, SiC power MOSFETs have been found to be susceptible to heavy-ion irradiation. Additionally, SiC power MOSFETs may experience single-event burnout (SEB) at ground level due to terrestrial neutrons [1]–[8].

Silicon power MOSFETs are also susceptible to neutron-induced SEB [9]–[12]. SEB in silicon devices has been linked

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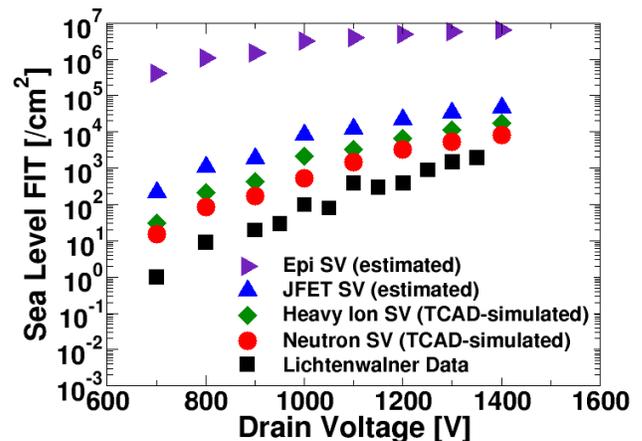


Fig. 1. Experimentally determined voltage-dependent neutron-induced SEB FIT for SiC power MOSFETs, after Lichtenwalner *et al.* [8], compared to simulated FIT based on basic mechanisms and Monte Carlo techniques developed in this paper.

to the parasitic bipolar junction transistor, which is an integral part of the device structure [13]. Some success has been achieved in simulating SEB in SiC power MOSFETs by assuming that the parasitic bipolar junction transistor in this device structure also has a major role in SEB [14].

There are limited data available for terrestrial neutron SEB of SiC power MOSFETs. Asai *et al.* [4] published cross-section data for Wolfspeed 1200-V SiC power MOSFETs from an experiment designed to replicate the terrestrial neutron spectrum. Similar cross sections have been reported by Rashed *et al.* [3]. Lichtenwalner *et al.* [8] have published sea-level failure in time (FIT) rate data, black data points shown in Fig. 1, for Wolfspeed 1200-V SiC power MOSFETs. Obtaining the SEB cross section and FIT rate experimentally is particularly challenging due to the destructive nature of SEB, requiring significant resources in both hardware and test facility beam access. Although nondestructive techniques, such as using a resistor on the drain node, exist for silicon power MOSFETs, these same techniques may not be applicable to SiC power devices [15].

Even more challenging is modeling neutron SEB, which requires the definition of the sensitive volume (SV) in the

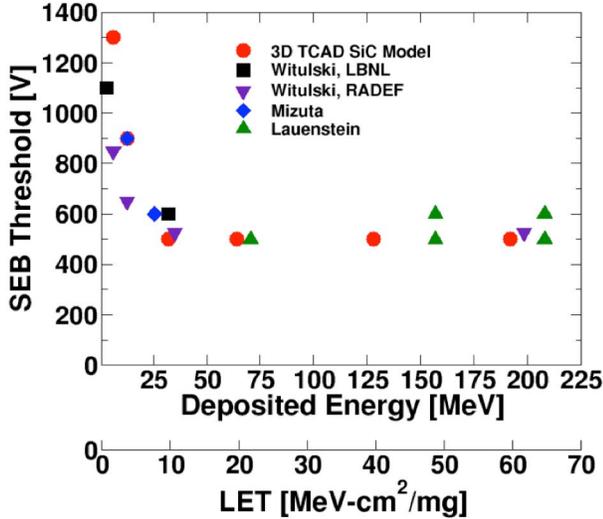


Fig. 2. SEB threshold bias voltage for 1200-V SiC power MOSFETs versus deposited energy, comparing heavy ion data [14], [18], [19] and 3-D TCAD simulation results. The second x -axis represents the LET corresponding to each value of deposited energy in the epi region.

device and selection of the secondary particles from an ensemble of neutron-induced nuclear reactions. These reactions may deposit enough energy in the SV to initiate SEB, implying that a criterion must be determined for whether or not an SEB has actually occurred. Currently, there is no model available to estimate neutron-induced SEB cross sections and FIT rates in SiC power MOSFETs.

In this paper, a modeling method is proposed to estimate SEB cross sections and FIT rates for the terrestrial neutron environments for SiC power MOSFETs. Although this paper is applied to a specific environment and technology, the methodology developed is applicable to other neutron environments for a wide range of power devices. Heavy ion data are used to determine a threshold energy required for SEB at a given bias. A 3-D TCAD model of the SiC MOSFET and heavy ion simulations are used to estimate the SV and to identify the range and energy of particles necessary for initiating SEB. Simulations using the radiation transport tool called Monte Carlo radiative energy deposition (MRED) [16], [17] are used to identify secondary particles from neutron-induced nuclear reactions in the SiC target which deposit energy that exceeds a threshold energy criterion in a defined SV. Analysis of the MRED simulations is used to generate the SEB cross section and to calculate the sea-level FIT rate, which is compared to data [8] (see red data points in Fig. 1).

II. HEAVY ION DATA

Heavy ion data for SiC MOSFETs from Wolfspeed, the C2M0080120D (1200 V, 80 m Ω), showing SEB threshold as a function of deposited energy in the 10- μ m-thick lightly doped epi region are given in Fig. 2 [14], [18], [19]. The second scale on the x -axis in Fig. 2 displays the linear energy transfer (LET). Converting heavy ion LET to energy deposited in the epi region provides a methodology for interpreting MRED simulation results in Section V. The conversion from

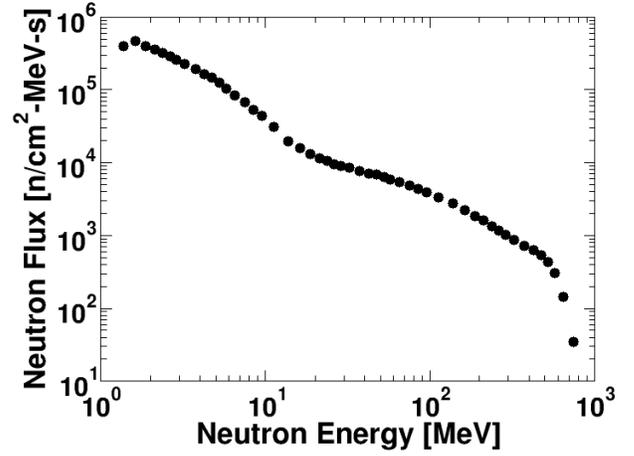


Fig. 3. Neutron spectrum from LANL [20] that closely matches the terrestrial neutron spectrum and is used for MRED simulations.

LET to deposited energy is accomplished by scaling the LET using path length through the epi region (10 μ m) and the mass of SiC (3.21 g/cm³). The deposited energy required to produce SEB ranges from 3 MeV at 1100 V to 25 MeV at 500 V, corresponding to an LET range of 1–10 MeV \cdot cm²/mg.

III. MRED SIMULATIONS

In order to better understand the distribution of recoil products from nuclear reactions produced when SiC is exposed to neutrons, a target with a cross-sectional area of 2 mm \times 3 mm (the size of the die) with a depth of 30 μ m was used for initial MRED radiation-transport simulations. The structure also has a 1- μ m tungsten overlayer to provide a reasonable representation of back end of line (BEOL) materials (the actual BEOL is not known). The neutron environment matched that of the Los Alamos National Laboratory (LANL) spallation neutron source, whose energy distribution closely matches that of terrestrial neutrons [20], [21]. The distribution of the terrestrial neutron spectrum as a function of energy is shown in Fig. 3. An event-weighting technique defined in [17] allowed the high-energy, low flux portion of the spectrum to be analyzed accurately.

As discussed earlier, the SiC power MOSFETs' threshold energy deposition for SEB depends on device bias. MRED simulations were run for the entire 2 mm \times 3 mm \times 30 μ m block of SiC to establish the likelihood of secondary particles depositing energy sufficient to cause SEB. In Fig. 4, the range and LET of secondary particles generated in the SiC by incoming neutrons are shown. For this illustration, only secondary particles with an LET greater than 1 MeV \cdot cm²/mg are recorded. This limit was defined based on the lowest recorded heavy ion LET that caused SEB (see Fig. 2). The range of LET values that are presented extends from an LET of 1 MeV \cdot cm²/mg up to an LET of almost 15 MeV \cdot cm²/mg. Based on heavy ion data, this range of LET values is well within the range required for SEB. Further analysis of the simulation results shown in Fig. 4 indicates that many of these secondary particles have a much shorter range than the heavy ions from LBNL and RADIATION EFFECTS FACILITY at University

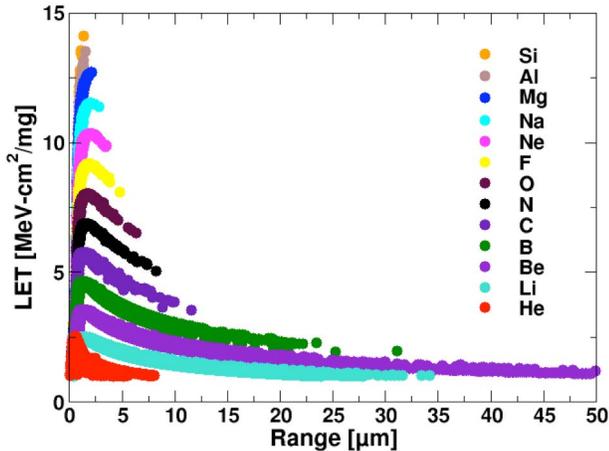


Fig. 4. Secondary particles (showing range and LET) generated from neutron environment and entering the primary SV as calculated by MRED.

TABLE I
PARAMETERS USED IN TCAD SIMULATIONS

Parameter	Value
4H-SiC	Bandgap=3.26 eV
N-Epi Doping/Depth	10^{15} cm^{-3} , 10 μm
Body Doping/Depth	10^{19} cm^{-3} , 1 μm
N+ Drain Doping	10^{19} cm^{-3}
Ion Track Radius/Length	50 nm, 15 μm
Impact Ionization Model	Anisotropic Avalanche

of Jyvaskyla. Out of 55 000 simulated secondary events, 80% of them had a range of 5 μm or less, and 65% have a range of 2 μm or less. This is a key takeaway and is important for determining the volume inside the SiC power MOSFET that is sensitive to neutron-induced SEB, as discussed in Section V.

IV. LONG-RANGE ION-INDUCED SEB SENSITIVE VOLUME

A 3-D TCAD model of a 1200-V SiC power MOSFET (Fig. 5) was developed in the Synopsys Sentaurus suite of TCAD tools [22], based on information from the published literature, with details of the simulations found in [14]. The device has an epi thickness of 10 μm , with doping in the mid- 10^{15} cm^{-3} range. Additional parameters are listed in Table I. These devices have a striped cell topology and are considered to be uniform in the third dimension. 3-D TCAD heavy-ion simulations were used to map out the most sensitive ion entry points in the device (normal incidence was assumed) [14] to develop a sensitive area. The 3-D TCAD simulation results for the most sensitive strike location are compared to heavy ion data [14], [18], [19] in Fig. 2, and the simulated heavy ions have a range consistent with the heavy ions in the beam, which is significantly longer than the thickness of the epi region. An event was classified as an SEB when the parasitic bipolar transistor turned on and the drain current entered a high state from which there is no recovery.

The sensitive area study in [14] has been extended in this paper by varying the ion strike entry location over the surface

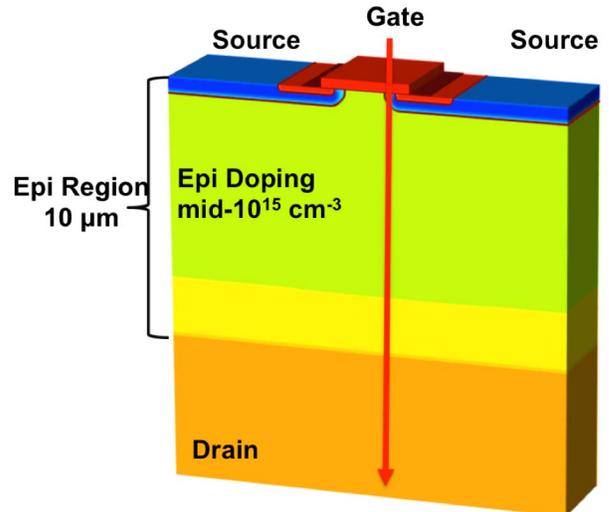


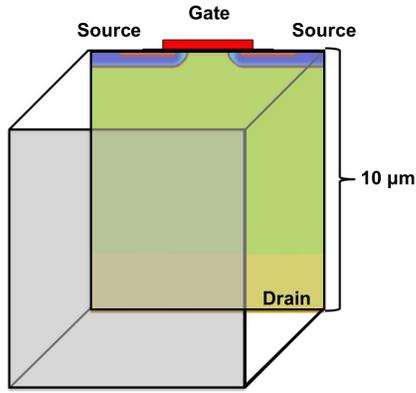
Fig. 5. 3-D TCAD model of a 1200-V SiC power MOSFET showing device structure (epi doping/depth). Also shown is a long-range ion track in a channel strike location.

of the device along the axis parallel to the striped gate. By including the third dimension, an SV model can be fully developed, and the MOSFET channel region was determined to be the most sensitive. In Fig. 5, the solid red line indicates a hit to the channel of the MOSFET. The heavy ions simulated in this paper have ranges that are significantly longer than the thickness of the 10- μm epi region. The SV developed using heavy ion simulations is a region that encompasses the width of the channel and the thickness of the epi region. The SV for long-range ion-induced SEB is shown in Fig. 6, and each gate metallization stripe has two SVs, one for each channel region.

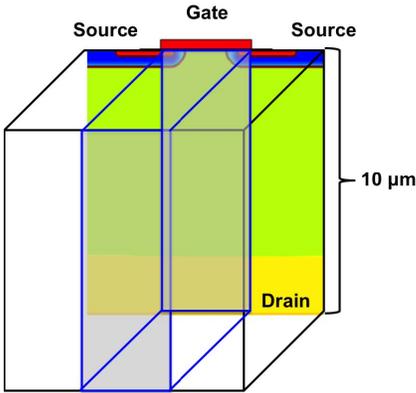
This refined SV greatly limits the region of charge deposition when compared to more traditional estimates, which include a very conservative estimate for SV to encompass the entire epi region, and a less conservative for SV that encompasses the JFET region of a power MOSFET. These SVs are also shown in Fig. 6. The conservative estimates are useful because they can be defined using feature sizes from the devices.

V. NEUTRON-INDUCED SEB SENSITIVE VOLUME

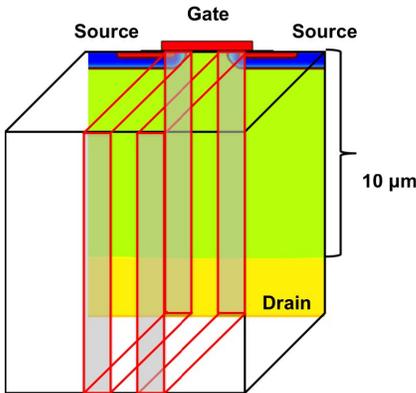
An ion passing through a semiconductor device deposits energy directly by generating electron-hole pairs. A neutron, however, will pass through a semiconductor device without directly generating charge. As shown in Fig. 4, there are also instances where a neutron may react with the semiconductor lattice and generate secondary charged reaction products. It was noted above that out of 55 000 MRED-simulated neutron-induced secondary events, 80% of the particles had a range of 5 μm or less, and 65% of the particles had a range of 2 μm or less. Consequently, most neutron-induced secondary particles have a range that is significantly shorter than the 10- μm epi thickness. Modeling and simulating neutron-induced SEB are more challenging than the same process for heavy ions due to the random nature and shorter range of the secondary particle generation. Developing an SV model



(a)



(b)



(c)

Fig. 6. Sensitive volume models in SiC power MOSFET can be estimated by (a) epi region, (b) JFET region, and (c) 3-D TCAD simulations showing two SVs per gate metallization region, each centered under the MOSFET channel.

that is more closely aligned with these secondary particles is more appropriate than using the SV model developed for long-range ions. This is examined in more detail using 3-D TCAD simulations by considering charge deposition along a track with a limited length of $2 \mu\text{m}$.

The heavy ion SEB threshold from earlier work [14] is given as a function of total energy deposited in the epi region (as shown in Fig. 2). Data show that the device will experience SEB for a heavy ion if the energy deposited exceeds the

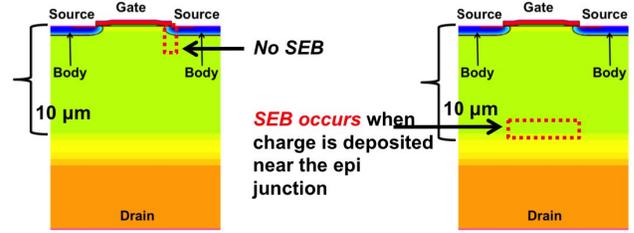


Fig. 7. Sensitive volume analysis using 3-D TCAD simulations to move the region of deposited charge throughout the device.

TABLE II

DEPOSITED ENERGY ESTIMATED FROM HEAVY ION DATA AS A FUNCTION OF BIAS (FROM FIG. 2). THE CORRESPONDING MRED-SIMULATED CROSS SECTION [FROM FIG. 10(B)] AND CALCULATED FIT RATE [(USING (1))] ARE GIVEN FOR THE TCAD-ESTIMATED SENSITIVE VOLUME FOR THE NEUTRON-INDUCED SECONDARY CASE

Bias [V]	Deposited Energy [MeV] <i>Estimated from heavy ion data Fig. 2</i>	Cross-Section [cm^2] <i>Simulated from MRED Fig. 10 (b)</i>	FIT [cm^2] <i>Calculated using Eqn. 1</i>
900	6.4	6×10^{-10}	1.2×10^2
1000	3.8	4×10^{-9}	8×10^2
1100	3.2	6.5×10^{-9}	1.3×10^3
1200	2.4	1.3×10^{-8}	2.6×10^3
1300	1.8	2.5×10^{-8}	5×10^3
1400	1.4	4×10^{-8}	8×10^3

threshold energy for SEB at a given bias, which is summarized in Table II. This paper assumes that the threshold energy for SEB is equivalent for neutron-generated reaction products and for heavy ions. For example, at 900 V, 6.4 MeV of deposited energy in the SV (with a path length of $10 \mu\text{m}$) results in a heavy ion-induced SEB (heavy ion data in Fig. 2). In this paper, we assume that at 900 V, neutron-induced energy deposition greater than or equal to 6.4 MeV in the SV will also result in SEB. However, the SV now has a path length of $<5 \mu\text{m}$ that corresponds to a neutron-induced secondary particle range, rather than the full $10\text{-}\mu\text{m}$ path length associated with a heavy ion. This is the basis of the sensitive-volume approximation used in most single-event rate-prediction tools.

3-D TCAD simulations were run and the size and location of the SV for charge deposition were varied. Fig. 7 shows two examples, one being a small region of charge deposition at the source/body and body/epi junctions, with the result being that SEB does not occur. In the other example, the charge is deposited in a small region at the epi/drain junction, which does result in SEB. The simulated drain currents for these two cases are shown in Fig. 8, along with the simulated drain current for an ion strike passing through the epi region. The ion strike generates a sharp peak current, followed by a runaway current event. However, charge deposited in a small volume

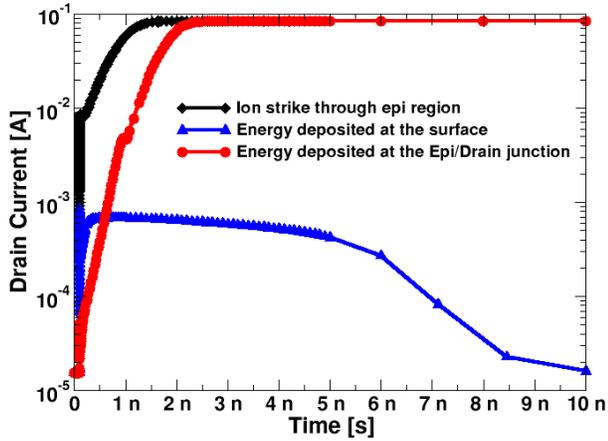


Fig. 8. 3-D TCAD simulations comparing an ion that deposits charge uniformly through the epi region (Fig. 5) to the equivalent amount of charge being deposited in two smaller volumes (Fig. 7).

at the surface of the device results in a transient that lasts approximately 10 ns followed by recovery. The last example shows charge deposited at the epi/drain junction resulting in a runaway current event that is much slower to evolve compared to the ion strike, but ultimately results in the parasitic BJT turn-on, and the positive feedback loop with impact ionization is completed. This is covered in more detail in [14]. However, the key takeaway is that charge needs to be deposited at the epi/drain junction in order to initiate impact ionization, whether it is from a long-range ion or a neutron-induced secondary particle.

These results show that simply generating the threshold energy inside the epi layer does not guarantee that neutron-induced SEB will occur. The actual location of the SV, and the region of charge deposition, is extremely important. The SV dimensions that were estimated from TCAD are a $4 \mu\text{m}$ wide $\times 2 \mu\text{m}$ tall region with the third dimension extending the length of the device along the stripe, as shown in Fig. 9. This SV is based on two observations obtained from the TCAD simulations: 1) the area under the channel and neck regions is the most sensitive and 2) charge generated near the epi/substrate junction is more likely to produce SEB than charge generated nearer to the surface. This effect is consistent with the prior work on single-event gate rupture showing that the region of charge deposition can influence device response [23]. Although the failure mechanism considered here (SEB) is different, both mechanisms are triggered by rearrangement of the potential in the epi region.

VI. CALCULATING CROSS SECTION AND FIT

The energy threshold SEB criterion and SV dimensions discussed in Section V and shown in Figs. 6 and 9 are used as filters in MRED [16], [17] simulations. Fig. 10(a) shows a histogram of the counts per fluence generated by MRED as a function of deposited energy within each of the SVs from secondary particles. The cross section versus energy deposited in each of the four SVs is shown in Fig. 10(b). This plot clearly shows how the dimensions of the SV influence the

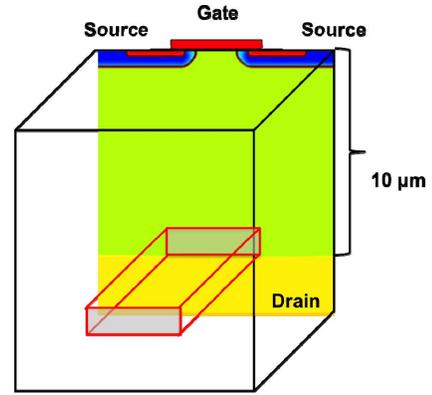


Fig. 9. Sensitive volume model for neutron-induced SEB in a SiC power MOSFET with one SV per gate metallization, centered under the channels and neck region at the epi/drain junction.

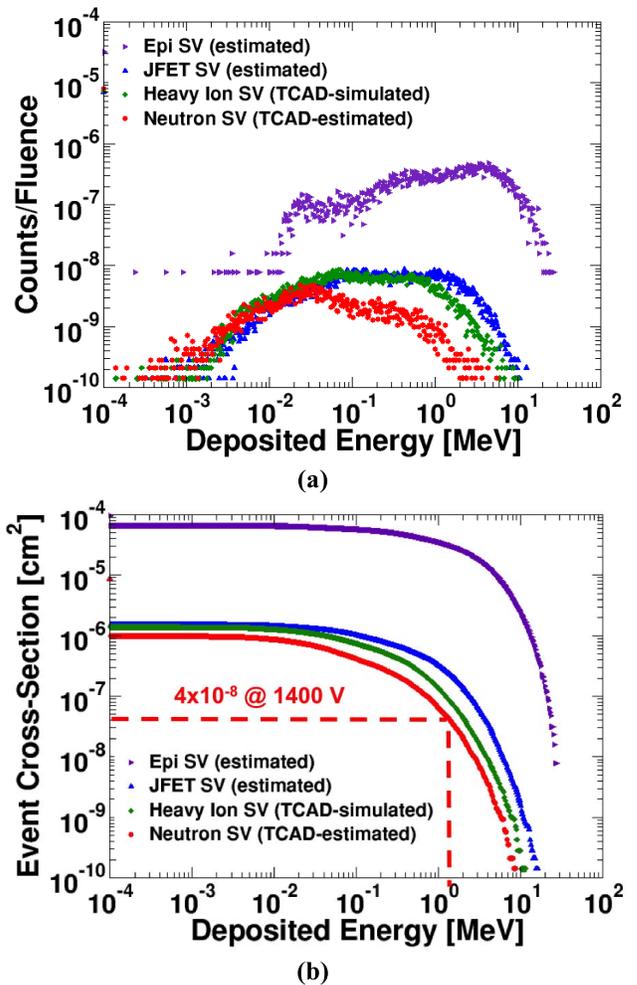


Fig. 10. (a) Secondary particle counts normalized to the fluence. (b) Reverse integral cross section for an SV that is defined using 3-D TCAD simulations for a neutron-induced SEB.

probability of a neutron-induced secondary depositing charge in that particular volume. For the conservative estimate using the epi layer as the SV, the event cross section is two orders of magnitude higher than using the estimate of the SV as the JFET region. As the SV is further refined, the event cross

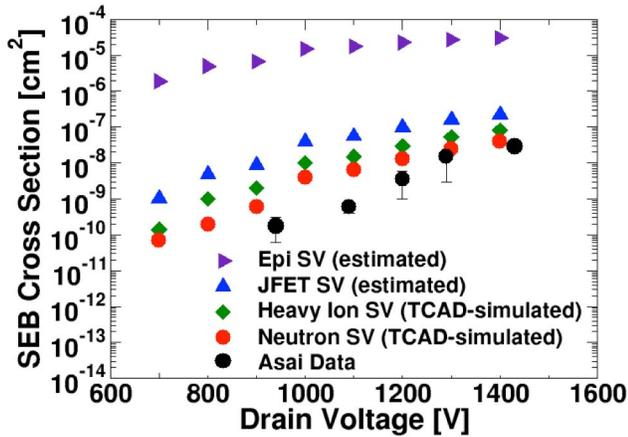


Fig. 11. Voltage-dependent neutron-induced SEB cross section for SiC Power MOSFETs, after Asai *et al.* [4], compared to the method for simulating cross section based on basic mechanisms and Monte Carlo techniques developed in this paper.

section continues to decrease. In Fig. 10(b), the event cross section is shown as a function of deposited energy, and a specific example is highlighted. At 1.4 MeV of deposited energy, the event cross section is $4 \times 10^{-8} \text{ cm}^2$ for the case using the TCAD-estimated SV for the neutron-induced secondary case. Heavy ion data suggest that SEB occurs for 1.4 MeV of deposited energy at a device bias of 1400 V.

In this way, the cross section can be mapped to the drain voltage required for SEB with the assumption that the threshold energy for SEB is equivalent for neutron-generated reaction products and for heavy ions. The simulation results presented in Table II for cross section as a function of bias are shown in Fig. 11 and compared to the previously published data [4].

Event cross section can be converted to FIT at a given bias by the following equation:

$$\text{FIT}/\text{cm}^2 = \frac{\sigma * \text{Neutron Flux} * 10^9 \text{ hours}}{\text{Die Area}[\text{cm}^2]} \quad (1)$$

with the sea-level neutron flux defined in [20]. The values for calculated FIT using the TCAD-estimated SV for the neutron-induced secondary case are also summarized in Table II. The calculated FITs are compared to the previously published data [8] in Fig. 1, showing better agreement for SVs estimated by TCAD than SVs described using device geometric dimensions. This model provides a reasonable method for estimating SEB cross section and calculating FIT rates; however, there are limitations. This paper has assumed that there is a single SV responsible for neutron-induced SEB, but the very nature of neutron-induced secondary particles (with such a wide range of energy deposition and range profiles) suggests that the single model method is still conservative when compared to data. A model that incorporates multiple SVs and coincidence of charge deposition may provide higher fidelity.

VII. CONCLUSION

In this paper, a modeling method is proposed to estimate SEB cross section and calculate FIT rates in a terrestrial

neutron environment for SiC power MOSFETs. Although this paper is applied to a specific environment and technology, the methodology developed is applicable to other neutron environments for a wide range of power devices.

Monte Carlo simulation techniques are used to generate a spectrum of secondary particles from the interaction of cosmic-ray generated terrestrial neutrons with SiC at sea level. These results, combined with analysis of existing heavy-ion SEB data for SiC power MOSFETs at low LET and calculation of SVs from TCAD, are used to estimate the SEB cross section and calculate FIT rates. These results agree reasonably well with available experimental data on terrestrial neutron-induced SEB. This approach can be applied to explore cross sections and FIT for power MOSFET SEB due to neutrons in both ground level and aerospace applications.

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