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Article

Failure Estimates for SiC Power MOSFETs in Space Electronics

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Abstract: Silicon carbide (SiC) power metal-oxide-semiconductor field effect transistors (MOSFETs) are space-ready in terms of typical reliability measures. However, single event burnout (SEB) due to heavy-ion irradiation often occurs at voltages 50% or lower than specified breakdown. Failure rates in space are estimated for burnout of 1200 V devices based on the experimental data for burnout and the expected heavy-ion linear energy transfer (LET) spectrum in space.

Keywords: single event effects; heavy ions; silicon carbide; single-event burnout; power devices; power MOSFETs; reliability; failure rates

1. Introduction

Silicon carbide (SiC) has excellent properties for power device applications. In comparison to silicon, it has higher breakdown field and higher thermal conductivity. SiC devices are ideally suited to high voltage, high power-density power converter applications, both on Earth and in space. These devices, in comparison to silicon devices, have advantages in breakdown voltage (~10× Si), low on-resistance (~1/100 Si), high temperature operation (~3× Si) and high thermal conductivity (~10× Si) [1]. The typical terrestrial electrical reliability results for SiC power devices are excellent [2–6]. Advancements in the crystal quality of 4H-SiC substrates and epitaxial growth capabilities, improvements in 4H-SiC device gate oxides, and innovation in processing has yielded a significant commercial presence for SiC power metal-oxide-semiconductor field effect transistors (MOSFETs).

For spaceborne electronics, consideration must be given to the radiation response of a device. SiC power MOSFETs are affected by total ionizing dose (TID), but, typically, TID response is acceptable at a total dose <100 krad(Si), and, depending on the application, devices can be useful up to 300 krad(Si) [7]. However, the sensitivity of SiC power devices (both MOSFETs and diodes) to energetic heavy ions has been found to be higher than might be expected with both leakage current degradation and single event burnout being observed.

In this paper, we briefly discuss typical SiC power MOSFET reliability evaluations and the data for the degradation and burnout of 1200 V SiC power MOSFETs. Based on the available burnout versus linear energy transfer (LET) experimental data and an approximation of the heavy-ion integrated LET spectrum expected in space, we estimate the worst-case failure rate for SiC power MOSETs in several space orbits.

2. Brief Review of SiC Mosfet Electrical Reliability

Since their commercial introduction in about 2010, the reliability of SiC power MOSFETs has been carefully examined by a number of researchers [2–6]. Early on, it was expected that the weakest element in a 4H-SiC power MOSFET would be the MOS gate dielectric. However, improvements in materials and fabrication techniques have yielded reliable 4H-SiC gate oxides. A time dependent dielectric breakdown (TDDB) study of gate oxides in 4H-SiC showed that a 100-year lifetime at a temperature of 375 °C can be expected if the oxide electric field E_{ox} is lower than 3.9 MV/cm, suggesting that catastrophic failure of the gate oxide due to electrical stress is a manageable reliability issue for these devices [3]. High temperature tests on commercial devices from two sources indicated that the 1200 V SiC MOSFETs tested are capable of operating with junction temperatures over 250 °C for more than 500 h and an estimated 5×10^4 h at 150 °C.

Accelerated life high temperature reverse bias (HTRB) tests and time dependent dielectric breakdown (TDDB) tests of gate oxides in 4H-SiC have been carried out on 1200 V production devices [5,6]. This work estimated TDDB mean time to failure values (MTTF) of nearly 10^7 h in continuous operation with 20 V applied to the gate. The HTRB test lifetime extrapolation yields over 10^7 h at 960 V continuous operation and somewhat more than 10^5 h at 1200 V. Field failure data are less than 5 FIT (1 FIT = 1 failure per billion hours) [5]. These reliability assessments [5,6] of commercially available devices indicate mean device lifetimes of more than 1000 years under normal device operating conditions.

Consequently, in terms of electrical reliability tests, SiC power MOSFETs are well suited for applications requiring high voltage and high power-density. However, for spaceborne electronics, the natural space radiation environment must be factored into the reliability considerations. We also note that these devices are susceptible to burnout due to terrestrial neutrons and their terrestrial radiation reliability has been evaluated by Lichtenwalner et al. [6] and Akturk et al. [8].

3. Radiation Effects Data on 1200 V SiC Power MOSFET Devices

SiC power MOSFETs may undergo catastrophic single event burnout (SEB) when exposed to energetic heavy ions or protons [9–11]. Two types of single-event effects are observed when SiC power MOSFET devices are irradiated with heavy ions: degradation and catastrophic failure [10,11]. Figure 1 displays published single event burnout data from four different experiments examining SEB for 1200 V SiC power MOSFETs [9–11]. These 1200 V devices were manufactured by Wolfspeed (a CREE Company, Durham, NC, USA) [12]. There were differences in the on-resistance and current rating depending on the particular data set.

Note that, for LETs > 10 MeV-cm^2/mg, all devices fail at reverse voltages significantly below the device rated voltage of 1200 V. In addition to SEBs, permanent damage to the device is manifested as an increase in drain leakage with the higher LET ions, similar to that observed in SiC Schottky barrier diodes [13]. No leakage current increase was observed for LETs <5 MeV-cm^2/mg, including protons, before SEBs were observed. Witulski et al. [9] used technology computer-aided design (TCAD) simulations to demonstrate that turn-on of the parasitic bipolar transistor inherent in the SiC power MOSFET structure is part of the physical mechanism leading to catastrophic SEB failure in these devices. This is similar to what has been observed for SEB in silicon power MOSFETs.

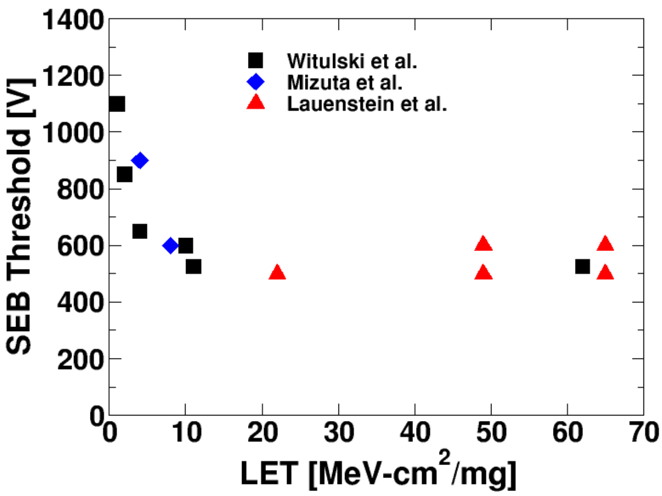

Figure 1. Experimental measurements of single event burnout (SEB) threshold voltage versus heavy-ion linear energy transfer (LET) for 1200 V SiC Power metal-oxide-semiconductor field effect transistors (MOSFETs). Data from [9–11].

4. Estimate of the Worst-Case Failure Rate for SiC Power MOSFETs in Space

Estimating the failure rate (FR), the failure in time or FIT rate, and the mean time between failures (MTBF), requires an estimate of the cross section for SEB failure and the flux of particles at an LET or higher that will cause this failure. Since SEB is a catastrophic failure, we use MTTF (mean time to failure) rather than MTBF. We will use a modification of the method proposed by Dashdondog et al. [14], based on worst-case assumptions. This method is similar to that of Titus et al. [15], as applied by Lauenstein et al. [16].

The 1200 V devices fail at approximately 500 V for any LET > 10 MeV-cm^2/mg. Thus, the cross section for SEB failure is assumed to have reached its saturation values for LET > 10 MeV-cm^2/mg. Since the bias boundary for SEB is almost constant for LET > 10 MeV-cm^2/mg, we will define SEB failure as operation at a reverse voltage greater than 500 V for any LET > 10 MeV-cm^2/mg. The failure rate (FR) under these conditions can be expressed as

$$\mathrm{FR} = \sigma \int \mathrm{Flux(LET)}\, \mathrm{dLET},$$

where σ is the saturated MOSFET SEB cross-section and the integral is evaluated over the ion flux as a function of LET. The integral is to be evaluated for LETs greater than 10 MeV-cm^2/mg (the cross section is assumed to be zero for LET values lower than the SEB threshold value). The value of this integral depends on the spacecraft mission or orbit and solar activity. To estimate the failure rate for SiC power MOSETs in space, we make some assumptions about the SEB cross-section and the integrated LET spectrum expected.

The devices tested by Witulski et al. [9] and represented by the data points in Figure 1 have a chip size of approximately 2 mm by 3 mm. Since the cross-section for SEB is not known from experiments, a simple approximation is made based on the chip area (6×10^{-2} cm^2). However, the entire chip is not sensitive. In addition, the time when the device is reverse biased is less than 100%. Taking the sensitive area as 50% of the die area and the duty-cycle to be 50%, this reduces the effective cross-section, independent of LET, to

$$\sigma = 1.5 \times 10^{-2}\ \mathrm{cm}^2.$$

For our estimates, we use LET distributions from Xapsos et al. [17] and from CREME96 [18] as shown in Figure 2. The Xapsos et al. spectrum is based on a probabilistic model of cumulative solar heavy ion spectra behind 100 mils of aluminum during a solar maximum time period. The potential impact of inelastic proton interactions is not considered. Only a very small fraction of the recoils from proton nuclear reactions have LETs > 10 MeV cm^2/mg and would most likely contribute a negligible amount to the failure rate [19,20].

The estimate here is based on the 99% confidence level curve, which Xapsos et al. consider as appropriate for use as a conservative design estimate of the single-event rate due to solar particles during solar max. The integral for LET greater than 10 MeV-cm^2/mg results in

$$\int \text{Flux(LET) dLET} = 10\ \text{cm}^{-2}\ \text{day}^{-1}.$$

This choice of effective cross section and of an integrated LET spectrum yields

$$\text{FR} = 6.25 \times 10^{-3}/\text{h and FIT} = 6.25 \times 10^{6}.$$

This FIT value leads to a mean time to failure (MTTF) of 160 h. This estimate, however, neglects a number of factors including possible angular effects.

SEB is most likely for an ion strike near normal to the top surface of the device. There is no published data on the angular effects in SiC power MOSFETs. If we assume that the device is sensitive to SEB for strikes $\pm 15^\circ$ to normal [21,22] and that in the spacecraft the environment is isotropic, only about 1/67 of the 4π steradian geometry is available for SEB. This leads would to a reduction in the calculated FIT by a factor of approximately 70. Even if we assume that the FIT is too high by a factor of 70, the MTTF is still on the order of 11,200 h or less than 1.5 years. This is a high FIT rate compared to that due to other reliability concerns. The range of FITs for most components is 100 to 1000, based on electrical reliability.

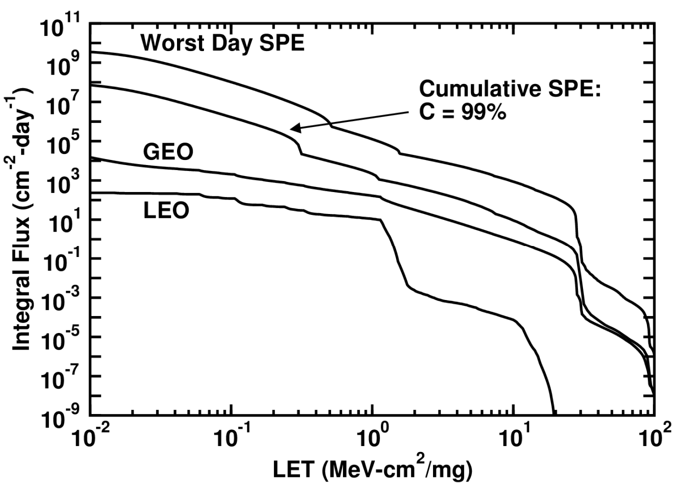

Figure 2. Worst day solar particle event (SPEW) from CREME96 [18]. GEO and LEO are solar minimum spectra from CREME96 [18]. Cumulative solar particle event spectra at the 99% confidence levels after Xapsos et al. [17]. Results for 100 mils aluminum shielding. GEO—geostationary orbit, often referred to as a geosynchronous equatorial orbit (GEO); LEO—low Earth orbit, common usage in discussing satellites.

If we consider the worst day solar particle spectrum as given by CREME96 [18], which is based on the 1989 event averaged over one day as determined from GOES–6 and –7 instrumentation, we obtain

$$\int \text{Flux(LET) dLET} = 10^{3}\ \text{cm}^{-2}\ \text{day}^{-1},$$

which yields

$$\text{FIT} = 6.25 \times 10^{8} \text{ and MTTF} = 1.6\ \text{h}.$$

Table 1 tabulates the integral evaluated for LET greater than 10 MeV-cm^2/mg behind 100 mils of aluminum shielding, the worst-case FIT and the MTTF for the episodic cases considered above and for two additional long-term average environments (GEO, LEO) as calculated using CREME96 [18].

Table 1. Value of integral LET spectra (Int.) and SiC MOSFET FIT and MTTF for several space scenarios. All results assume 100 mils of aluminum shielding.

Spectrum	Int. (no./cm^2-Day)	FIT (1 Per Billion Hours)	MTTF (Hours)
SPEW	1000	6.25×10^8	1.6
SPE	10	6.25×10^6	160
GEO	0.9	5.6×10^5	1786
LEO	1×10^{-4}	62.5	1.6×10^7

SPEW = worst day solar particle event (SPE) from CREME96; SPE = cumulative SPE at solar max., 99% confidence from Xapsos; GEO = geostationary Earth orbit during solar min. from CREME96; LEO = low Earth orbit during solar min. from CREME96.

As seen from the values in Table 1, the FIT and MTTF vary significantly with mission and solar activity. In low earth orbit with typical solar activity, the devices should operate for years. However, in a worst case solar event, the device may only last a few hours, if that long. Results given in the table are illustrated in Figure 3. In GEO, the devices are expected to fail in relatively short times. In low earth orbit with typical solar activity, the devices should operate for years. In LEO at a solar max, you might expect the time to failure to be reduced, but the ion flux will be modified by the earth's magnetosphere.

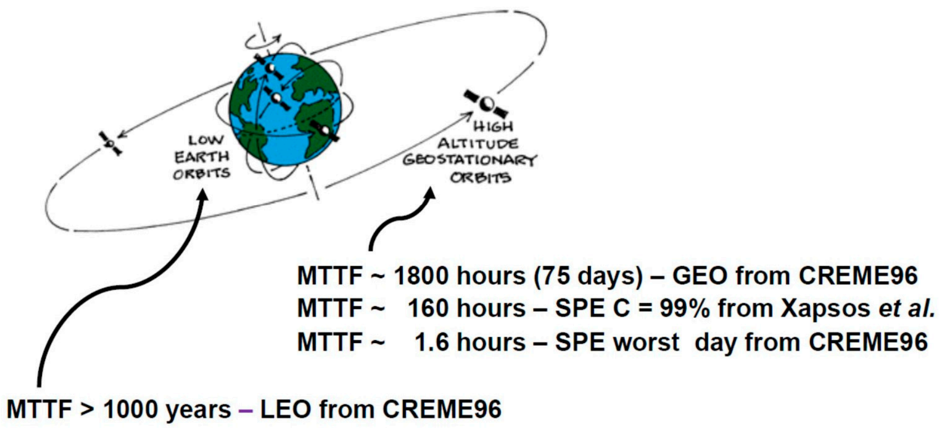

Figure 3. SEB failure rate for two potential orbits for a 1200 V SiC power MOSFET. Image from Department of Commerce, National Oceanic and Atmospheric Administration.

5. Discussion

In this work, we have considered 1200 V SiC MOSFET devices and estimated the failure rate in the space radiation environment for several different possible missions. Experimental results have demonstrated that these devices fail at approximately 500 V for any LET >10 MeV-cm^2/mg. We estimate the SEB failure rate based on a constant cross section for operation at a reverse voltage greater than 500 V for any LET > 10 MeV-cm^2/mg.

A number of assumptions have been made to arrive at the estimates given above in Table 1 and the uncertainty in these estimates for FIT and MTTF may be relatively large. Even so, regardless of the assumptions, it appears that SiC power MOSFETs have the potential for significant failure rates due to heavy ion radiation exposure in the space radiation environment.

There may be situations where size, weight, and power requirements justify the use of SiC power MOSFETs in space. The Orion multi-purpose crew vehicle (MPCV) was developed by NASA to send crews of up to six astronauts on missions through space that could last as long as six months. As a secondary mission, the craft will also be used as a backup vehicle for cargo and crewed missions to the International Space Station. In addition, 1200 V SiC power MOSFETs are being used for this system [23]; however, these devices are being used with the voltage significantly derated. Additionally, SiC power MOSFETs are in use for the NASA MMS (Magnetospheric Multiscale) spacecraft.

This worst-case analysis indicates that, at this time, thorough heavy ion testing of any commercially available SiC MOSFET component proposed for utilization in spaceborne electronic systems is needed. Currently, any use of 1200 V SiC MOSFETs would require significant de-rating. A 1200 V device should not be used at voltages above 500 V in any radiation environment with LETs > 10 LET >10 MeV-cm^2/mg.

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Conflicts of Interest: The authors declare no conflict of interest.

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