Reliability Concerns for Flying SiC Power MOSFETs in Space[§]

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Abstract: SiC power MOSFETs are space-ready in terms of typical reliability measures. However, single event burnout (SEB) often occurs at voltages 50% or lower than specified breakdown. Data illustrating burnout for 1200 V devices is reviewed and the space reliability of SiC MOSFETs is discussed.

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 (~10x Si), low on-resistance (~1/100 Si), high temperature operation (~3x Si) and high thermal conductivity (~10x Si) [1]. The typical terrestrial reliability results for SiC power devices are excellent [2-5] and device reliability continues to improve due to advancements in the quality of SiC substrates and epitaxial growth capabilities, and improvements in device processing.

For spaceborne electronics, consideration must be given to the radiation response of a device. SiC power MOSFETs are affected by TID (total ionizing dose) [6]; but in general, TID response is acceptable at a total dose < 100 krad, and dependent on the application can be used up to 300 krad. However, the sensitivity of SiC power devices (MOSFETs and diodes) to exposure 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 provide an overview of SiC power MOSFET evaluations for typical reliability tests and present data of the degradation and burnout of 1200 V SiC power MOSFETs. A conservative estimate of the failure rate for SiC power MOSETs is provided, based on the available burnout versus LET data and an approximation of the integrated LET spectrum expected in space.

SiC Power MOSFET Device Electrical Reliability

The reliability of SiC power MOSFETs has been carefully examined by a number of researchers. Early-on, it was expected that the weakest element in a 4H-SiC power MOSFET would be the MOS gate. However, subsequently, 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 has shown that a

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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 is not a reliability issue for these devices [3].

Accelerated life high temperature reverse bias (HTRB) testing has been carried out on 1200 V production devices [4]. This work extracted mean time between failure values (MTBF) of more than 10^7 hours at 960 V continuous operation and almost 10^6 at 1200 V. Field failure data is less than 5 FIT (failure rate of 1 per billion hours) [4].

Consequently, SiC power MOSFET electrical-reliability tests indicate these devices are well suited for high voltage, high power-density power converter applications in spaceborne electronics.

Radiation Effects Data on 1200 V SiC Power MOSFET Devices

SiC power MOSFETs may undergo catastrophic SEB when exposed to energetic heavy ions or protons [7 - 9]. Two types of single-event effects are observed when heavy ion testing SiC power MOSFET devices: degradation and catastrophic failure [8,9]. Figure 1 displays published single event burnout data from three different experiments for 1200 V SiC power MOSFETs [7 – 9].

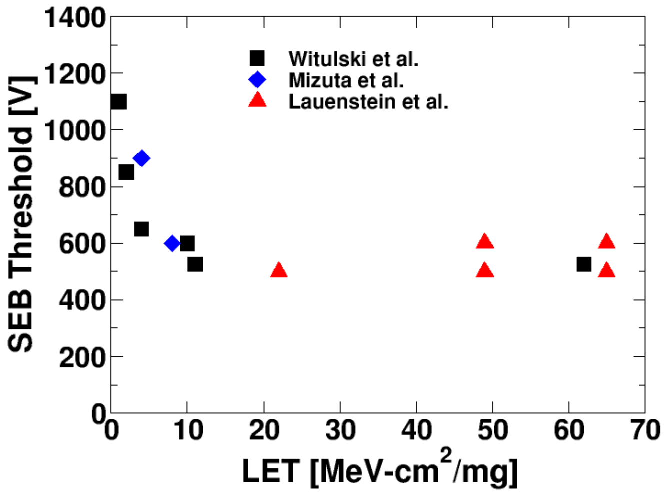

Figure 1: Experimental measurements of SEB threshold voltage versus heavy-ion LET for 1200 V SiC Power MOSFETs.

Note that all devices fail at reverse voltages significantly below the device rated voltage of 1200 V. In addition to SEBs, permanent damage is manifested as an increase in drain leakage current with higher LET ions, similar to that observed in SiC Schottky barrier diodes [10]. No leakage current increase was observed for lower LET ions, including protons, before SEBs were observed. Witulski *et al.* [7] have used 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.

Estimate of the Failure Rate for SiC Power MOSFETs in Space

Estimating the failure rate (FR), the failure in time or FIT (failure rate of 1 per billion hours), and the mean time between failures (MTBF), require an estimate of the cross section for SEB failure and the flux of particles at an LET or higher that will cause this failure. We will use a modification of the method proposed by E. Dashdondog *et al.* [11], based on worst-case assumptions.

The 1200 V devices fail at approximately 500 V for any LET > 10 MeV-cm^2/mg. Thus the cross section for SEB failure has 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) can be expressed as

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

where σ is the MOSFET SEB cross-section. The integral is evaluated for all LETs greater than 10 MeV-cm^2/mg using the LET distribution of Xapsos *et al*., based on a probabilistic model of cumulative solar heavy ion spectra behind 100 mils of aluminum [Figure 6 in ref 12]. The estimate here is based on the 99% confidence level curve, which is appropriate for a conservative estimate of the single-event rate due to solar particles.

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

The devices tested by Witulski *et al.* [7] have chip size of approximately 2 mm by 3 mm. If the cross-section for SEB is the chip area, then the cross-section is approximately 6 x 10^{-2} cm^2. However, the entire chip is not sensitive. Also, the time when the device is reverse biased is less than 100%. Taking the sensitive area as 0.5 of the die area and the duty-cycle to be 50%, this reduces the effective cross-section, independent of LET, to

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

Because SEB is a destructive effect in these experiments, the SEB cross-section could also be estimated as the inverse of the fluence at which SEB occurred [13]. Using this measure would result in a cross section 4 to 5 times smaller than the estimate based on the die and would result in a highly variable estimate since SEB occurs at different fluences in different experiments.

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

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

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. A FIT at this level leads to a mean time between failures (MTBF) of 160 hours. This estimate, however, neglects a number of factors including possible angular effects. Even if we assume that the FIT is off by a factor of 100, the MTBF is still on the order of 16000 hours or less than two years. If only the galactic cosmic ray component in the work of Xapsos *et al.* [12] is considered, the MTBF is approximately 670 hours. Regardless of assumption, it appears that SiC power MOSFETs have the potential for high failure rate due to heavy ion radiation exposure in space.

Conclusions

This worst case analysis would indicate that, at this time, thorough heavy ion testing of any SiC MOSFET component proposed for utilization in spaceborne electronics would be advisable. Currently, any use of 1200 V SiC MOSFETs would require significant de-rating and use under 500 V. Work is underway to more fully understand the SEB failure of SiC devices and to explore techniques for achieving more survivable devices.

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References

1. J-M. Lauenstein, M. C. Casey, K. A. LaBel, S. Ikpe. A. D. Topper, and E.P. Wilcox, Single Event Effects in Silicon Carbide Power Devices," NASA Electronic Parts and Packaging Program (NEPP) Electronics Technology Workshop (ETW). June 2015.
2. B. Ryu, B. Hull, S. Dhar, L. Cheng, Q Zhang, J. Richmond, M. Das, A. Agarwal, J. Palmour, A. Lelis, B. Geil, and C. Scozzie,"Performance, Reliability, and Robustness of 4H-SiC Power DMOSFETs," Materials Sci. Forum, vol. 645-648, pp. 969-974, 2010.
3. L.C. Yu, G.T. Dunne, K.S. Matocha, K.P. Cheung, J.S. Suehle, and K. Sheng, "Reliability Issues of SiC MOSFETs: A Technology for High-Temperature Environments," IEEE Trans. Dev. Matl. Rel., vol. 10, pp. 418-426, 210.
4. D.A. Gajewski, B.Hull, D.J. Lichtenwalner, S-H. Ryu, E. Bonelli, H. Mustain, G. Wang, S.T. Allen and J. W. Palmour, "SiC Power Device Reliability," Proc. 2016 IEEE Intl. Integrated Rel. Workshop (IIRW), pp. 29-34, 2016.
5. D. Grider *et al.,* "Recent Advances in 900 to 10 kV SiC MOSFET Technology," NASA Electronic Parts and Packaging Program (NEPP) Electronics Technology Workshop (ETW), June 2016.
6. A. Akturk, J. M. McGarrity, S. Potbhare, and N. Goldsman, "Radiation Effects in Commercial 1200 V 24 A Silicon Carbide Power MOSFETs," IEEE Trans. Nucl. Sci., vol. 59, pp. 3258–3264, 2012.
7. A.F. Witulski, D.R. Ball, K.F. Galloway, A. Javanainen, J-M. Lauenstein, A.L. Sternberg, and R.D. Schrimpf, "Analysis of SEB Physics in SiC Power MOSFETs," Presented at RADECS 2017 and submitted for publication to IEEE TNS.
8. J-M. Lauenstein, M. C. Casey, A. D. Topper, E. P. Wilcox, A. M. Phan, and K. A. LaBel, "Silicon Carbide Power Device Performance Under Heavy-Ion Irradiation," presented at IEEE Nuclear and Space Radiation Effects Conf., July 2015 and NASA Report GSFC-E-DAA-TN25023 (2015).
9. E. Mizuta, S. Kuboyama, H. Abe, Y. Iwata, T. Tamura, and A. S. Device, "Investigation of Single-Event Damages on Silicon Carbide (SiC) Power MOSFETs," IEEE Trans Nucl. Sci., vol. 61, pp. 1924–1928, 2014.
10. A. Javanainen *et al.*, "Heavy Ion Induced Degradation in SiC Schottky Diodes: Bias and Energy Deposition Dependence," IEEE Trans. Nucl. Sci., vol. 64, no. 1, pp. 415–420, 2017.
11. E. Dashhdondog, S. Harada, Y. Shiba, and I. Omura, "Failure rate calculation method for high power devices in space applications at low earth orbit," Microelectronics Reliability, vol. 84, pp. 502-506, 2016.
12. M.A. Xapsos *et al.,* "Model for Cumulative Solar Heavy Ion Energy and Linear Energy Transfer Spectra," IEEE Trans. Nucl. Sci., vol. 54, no. 6, pp. 1985- 1989, 2007.
13. I. Mouret, P. Calvel, M. Allenspach, J. L. Titus, C. F. Wheatley, K. A. LaBel, M.-C. Calvet, R. D. Schrimpf, and K. F. Galloway, "Measurement of a Cross-Section for Single-Event Gate Rupture in Power MOSFET's," IEEE Electron Dev. Lett., vol. 17, no. 4, pp. 163-165, 1996.