First Observations of Power MOSFET Burnout with High Energy Neutrons

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Abstract

Single event burnout was seen in power MOSFETs exposed to high energy neutrons. Devices with rated voltage ≥ 400 volts exhibited burnout at substantially less than the rated voltage. Tests with high energy protons gave similar results. Burnout was also seen in limited tests with lower energy protons and neutrons. Correlations with heavy-ion data are discussed. Accelerator proton data gave favorable comparisons with burnout rates measured on the APEX spacecraft. Implications for burnout at lower altitudes are also discussed.

I. INTRODUCTION

A. Background

It is now well known that when heavy ions strike an n-channel power MOSFET, the energy deposited can lead to single event induced burnout (SEB). This destructive effect was first reported by Waskiewicz, et al., in 1986 [1]. Later, a nondestructive test technique was developed to allow measurement of SEB cross sections [2]. Since then, SEB and single event gate rupture (SEGR) have been extensively studied. See the review paper by Titus and Wheatley [3] for a comprehensive bibliography on this subject. Much of this SEB and SEGR data has been compiled and published [4].

Most SEB testing of n-channel MOSFETs has been conducted with ions having a linear energy transfer (LET) greater than 25 MeV-cm^2/mg. In the few cases where ions with LET less than 10 MeV-cm^2/mg were used, SEB was still measured. Data for a 200 V device, taken from our 1987 study [2], is displayed in figure 1 covering LETs ranging from 0.5 to 16 MeV-cm^2/mg. In addition, we recently performed an SEB test on a 500 V device using ions with LET values ranging from 5.5 to 36 MeV-cm^2/mg. The SEB cross section for this device is also shown in figure 1. The ions, energies, and LETs used for the 200 V device are given in [2]. Heavy ions from the Lawrence Berkeley Laboratory 88” cyclotron (table 1) were used for the 500 V device.

Tastet, et al., tested a similar 500V MOSFET with fluorine ions (LET = 4.3 MeV-cm^2/mg) [5], as well as with higher LET ions [6], and obtained similar results. At an LET of 4.3 MeV-cm^2/mg, the SEB cross section was ~10^{-5} cm^2. This is consistent with our test data. However, the authors report that they were not sure their devices were experiencing SEB with the fluorine ion beam but rather SEGR [5].

Table 1. Characteristics of particles described in the text. The first 5 entries are ions used at LBL.

Ion	**Energy**	**LET**	**Range**
Ne	90	5.5	54
Ar	180	14.3	47
Co	266	26.0	43
Kr	387	38.0	45
Xe	612	63.0	46
Li	14	1.0	45
Li	32	0.5	150
n	100	*~0.00001*	*(long)*
p	100	0.006	40,000
a	3 - 100	0.8 - 0.07	14 - 3470
Si	20	*(peak)* 15.0	8
Units⇨	*MeV*	*MeV-cm^2/mg*	*mm*

Since low LET ions can cause SEB, it is then possible for the recoils induced by high energy neutrons and protons to also cause SEB. We used neutrons with an energy spectrum extending up to 800 MeV to expose a variety of power MOSFETs. For devices with a voltage rating of 400 V, or greater, and operated at greater than 75% of rated voltage, SEB was observed with fluences of less than 10^8 n/cm^2.

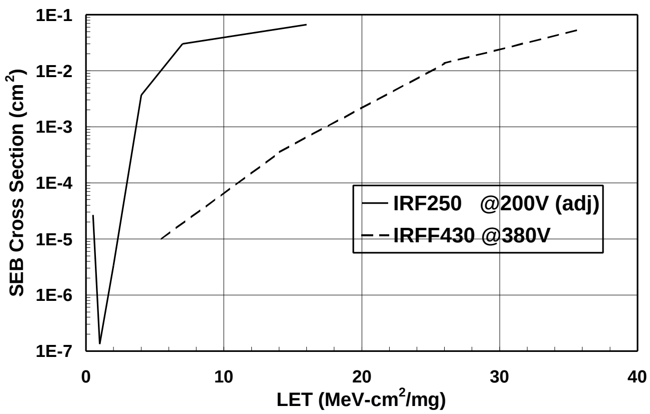

Figure 1. Comparison of SEB cross sections versus LET. The IRF250 data has been normalized by the appropriate factor (i.e., 0.14/0.42) to account for its larger die.

B. *Other proton and neutron tests*

Wasciewicz, et al., were the first to expose power MOSFETs to 50 and 150 MeV protons [7]. The devices they tested had rated voltages ranging from 60 to 200 V. In general, SEB was seen only at voltages greater than 90% of rated voltage. For the 200V IRF250 devices they tested, the average cross section was seen to be less than 10^{-10} cm^2. (As will be seen, this data is comparable to our measurements on the IR IRF250 power MOSFET devices.)

More recently, Wheatley, et al., looked at SEGR using a variety of heavy ions as well as protons [8]. For the devices they tested, SEGR occurred with ions having LETs down to 3.4 MeV-cm^2/mg but did not occur with protons.

In addition, power MOSFETs have been exposed to low energy neutrons [9], but only with 1 MeV equivalent neutrons. Such low energy neutrons are not capable of causing single event effects (SEE). Only neutrons of energy greater than about 5 MeV, the threshold for (n,p) and (n,α) reactions in silicon, are capable of inducing SEE because of the higher energy recoils produced in such reactions [10]. With the 1 MeV neutrons, for fluences of $>10^{14}$ n/cm^2, increases in the breakdown voltage were seen due to irradiation induced defects. This effect is not relevant for the low values of neutron fluence reported here.

On several occasions, integrated circuits have been exposed to high energy neutron beams and both single event upset [11] and single event latchup [12] were measured. In addition, charge collection measurements with high energy neutrons have been made in surface barrier detectors [13]. However, this paper marks the first study of power MOSFETs exposed to high energy neutrons.

II. Facilities Used for SEB Testing

A. *Weapons Neutron Research facility (Neutrons)*

Neutron induced single event effects data have often been recorded using psuedo-monoenergetic neutron sources [10]. However, to better simulate the environment at aircraft altitudes, we have used the Weapons Neutron Research (WNR) facility at the Los Alamos National Laboratory. This facility provides a neutron spectrum, extending up to 800 MeV, similar in shape to that found in the atmosphere, but approximately 3×10^5 times more intense than that found at 40,000 feet (12 km). The neutron spectrum for WNR is shown in figure 2. The dosimetry and other details are described elsewhere [11]. Test cards, containing up to 6 power MOSFETs each, were placed within the 7.5 cm diameter beam of the WNR facility beam. A total of 24 devices could be tested simultaneously.

B. *Harvard Cyclotron Laboratory (Protons)*

Proton induced single event effects have been recorded on numerous occasions [14], but the effects seen were almost always upset. Such data is of great importance for devices flown in space in low earth orbit due to the trapped proton radiation belts. The cyclotron laboratory at Harvard University (HCL) has often been used for such studies [15]. The first proton induced SEB data [7] was taken at the HCL. The cyclotron facility provides 160 MeV protons which can then be degraded to lower discrete energies by placing calibrated slugs of plastic and lead in front of the device [15]. In addition to monoenergetic beams, a modulator wheel has been used to simulate the energy spectrum seen in the proton belts [16].

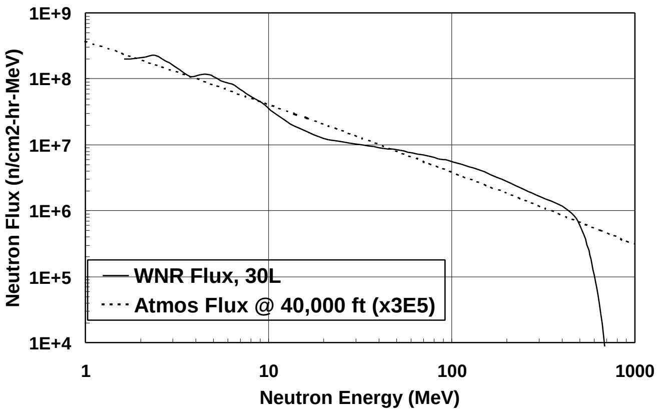

Figure 2. Neutron spectra at WNR and at 40,000 feet. The atmospheric flux has been multiplied by 3×10^5.

The test cards used at WNR were used to test a few power MOSFETs with 30 MeV, 73 MeV, and 148 MeV protons at HCL. Additional tests were done with the modulator wheel.

C. *BREL 14 MeV Neutron Generator (Neutrons)*

The Kaman Sciences A-711 neutron generator located at the Boeing Radiation Effects Laboratory (BREL) has previously been used for SEE testing [17]. This is a monoenergetic neutron source producing 14 MeV neutrons from a D-T reaction. We were the first to use this beam for SEB testing of power MOSFETs.

D. *LBL 88" Cyclotron*

Most of the heavy ion SEB data described in this paper was taken at the Lawrence Berkeley Laboratory 88" cyclotron. This facility has been used for single event effects testing for many years [18]. The ions and properties of the standard 4.5 MeV/amu "Aerospace Cocktail" are listed in table 1.

III. Neutron & Proton SEB Test Results

A. *Parts Tested*

Several types of power devices were tested. They are listed in table 2. All devices were power MOSFETs except for the Ixys 30N60 which is an insulated gate bipolar transistor (IGBT). In addition, only commercial, unhardened, devices were tested. The International Rectifier (IR) SEB data was, in general, representative of the other manufacturer's power MOSFET SEB data.

In order to compare the results from various SEB tests it should be noted that power MOSFETs are composed of an array of identical cells. Therefore, the main difference between device types of different drain-source resistance (but, the same manufacturer, process and voltage) is the number of cells and, hence, the area of the die. Such similar devices also have similar SEB voltage thresholds. The die area of the devices tested is given in table 2. Based on previous tests [7], we know that the heavy ion SEB cross section, as a function of LET, may reach an asymptotic value which is approximately 40% of the total die area (including the termination). Thus for this study, where necessary, we will compare device SEB characteristics by normalizing the SEB cross section by the die size.

Table 2. Parts Tested.

Part Type	Mfg.	Rated V_{ds}	Die Area
IRF150	IR[†]	100 V	0.42 cm^2
2N6798	IR	200 V	0.14 cm^2
IRF250	IR	200 V	0.42 cm^2
IRF360	IR	400 V	0.62 cm^2
IRFF430	IR	500 V	0.14 cm^2
IRF460	IR	500 V	0.62 cm^2
24N50	Ixys	500 V	~0.7 cm^2
IRF460	Ixys	500 V	~0.6 cm^2
0350N5	Supertex	500 V	~0.1 cm^2
30N60[‡]	Ixys	600 V	~0.2 cm^2

[†] *International Rectifier* [‡] *IGBT*

B. *Neutrons*

Except for the 100 volt power MOSFET, all of the devices tested exhibited SEB. The devices rated at 200 volts failed only near full rated voltage. The 400 volt and 500 volt rated power MOSFETs failed at V_{ds} values well below the rated voltage. The current pulses were similar in amplitude and duration to those seen previously in heavy ion tests [2] and were counted as described there.

Figure 3 shows the neutron-induced SEB cross section data for several different International Rectifier power MOSFETs that were tested. The SEB cross section for the 200 volt device we tested is comparable to the proton SEB cross section for the 200 volt part of Wasciewicz [7]. The higher voltage rated devices had rather large cross sections for SEB when operated at or near their rated voltage (e.g., the SEB cross section is within an order of magnitude of the SEU cross section of a 1Mb static RAM). For the 400 V and 500 V parts, SEB was seen at voltages that are much lower fractions of the rated voltage than the 200 V part.

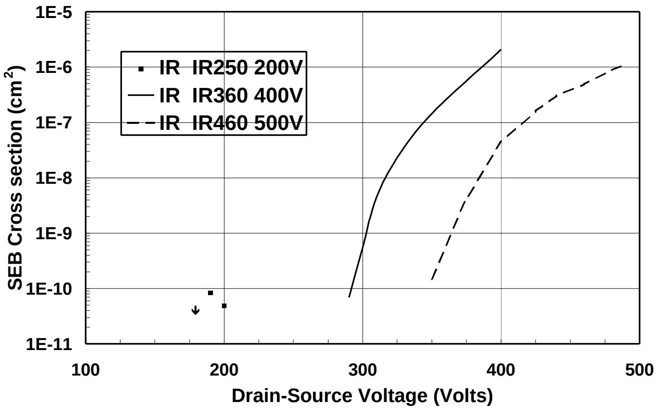

Figure 3. Neutron SEB cross sections for the IRF250, IRF360, and IRF460. The data were taken at WNR.

A comparison of SEB thresholds for neutrons and heavy ions is shown in table 3. In all cases the SEB voltage threshold for neutrons is higher than the threshold for heavy-ion induced SEB. In addition, the neutron SEB threshold voltage approaches the heavy-ion SEB voltage threshold as the rated voltage of the MOSFETs increases.

C. *Protons*

Proton induced SEB data is shown for an IR IRFP360 in figure 4. Data are shown for several proton energies as well as for the simulated trapped proton spectrum. It can be seen that the cross section data for the higher discrete proton energies is very similar to proton spectrum data. In addition, the cross section data taken with the proton spectrum is about the same as that taken with neutrons at WNR. The lower proton energy SEB cross sections are smaller, suggesting that the SEB observed is due primarily to the higher energy protons.

D. *14 MeV Neutrons*

Limited SEB testing was also carried out with 14 MeV neutrons and the results show (figure 4) that they can also induce SEB. As expected from the low energy proton data, the voltage threshold for SEB is higher and the cross section is lower than results with the higher energy neutrons and protons.

Table 3. Comparison of threshold voltages and cross sections for neutrons and heavy ions (cobalt ions at an LET of 26 MeV-cm^2/mg). The heavy ion SEB data is from reference [4].

Mfg.	Part Type	Rated Vds (V)	Heavy Ion Threshold (V)	WNR Neutron Threshold (V)	WNR Threshold % of Rated	Threshold Ratio Heavy Ion/ WNR
IR	IRF250	200	140	190	95%	74%
IR	IRF360	400	220	280	70%	79%
IR	IRF460	500	300	330	66%	91%

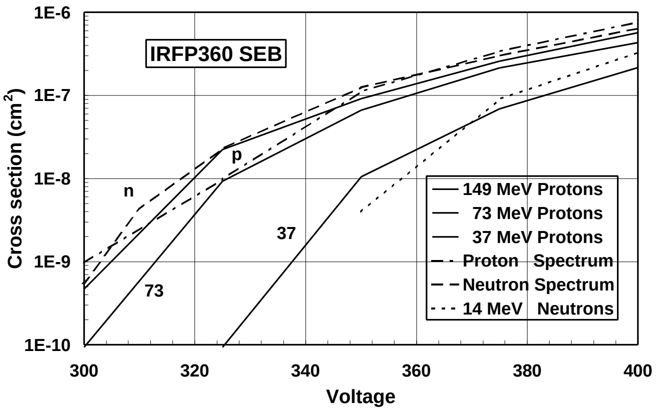

Figure 4. SEB data for an IR IRFP360. Proton and neutron data are shown. Note the similarity of the WNR data to the high energy proton data. Also note the 14 MeV neutron data compared to the lowest energy proton data.

The 14 MeV neutrons present an interesting case in terms of energy deposition. The highest energy recoil that can be produced by 14 MeV neutrons is approximately 3.5 MeV. Since it takes 3.3 eV to generate an electron-hole pair in silicon, this is equivalent to generating a total charge of 0.15 pC [17]. This is very low energy deposition by the recoil, but it should be noted that the dominant reaction also produces an alpha-particle of about 8 MeV, and its energy deposition may also be involved in initiating the SEB process.

E. Insulated Gate Bipolar Transistors

A limited number of tests of insulated gate bipolar transistors (IGBTs) were also conducted with protons and 14 MeV neutrons. Heavy ion results led us to believe that the SEB response would be similar to that of similarly rated power MOSFETs [4]. These 600V devices (Ixys IXGH30N60) were seen to have a heavy ion SEB threshold of 350V. Testing with HCL protons showed the threshold to be near 400V. (This is about what one would expect from the trend exhibited in table 3.) Testing with 14 MeV neutrons exhibited a response only at the rated voltage.

For both neutrons and protons, the resulting effect was device failure. Titus [3] notes that the internal capacitance of a power MOSFET could store enough energy to defeat the current-limiting resistor and destroy the device. As these IGBTs were high voltage, large die devices, this is a likely possibility. Additional heavy ion tests were conducted and device failure was also seen at these voltages. However, the current pulse waveform was clearly indicative of SEB. Tests at extreme gate-bias voltages, to enhance any SEGR response [19], did not change the failure threshold. Thus we conclude that the failure mechanism for this IGBT is SEB. (This is also a likely reason that Tastet, et al., thought they saw SEGR, rather than SEB, when testing at the high drain-source voltages required to induce SEB at low LET [5].)

IV. Comparison with Heavy Ions

In table 1, we have also indicated the energy deposition of high energy neutrons and protons as well as for silicon and α-recoils. The "LET" for a neutron is just the dose converted to LET units. We see that the LET for neutrons and protons is much less than that for the 32 MeV lithium ion used in the measurement of figure 1. The increase in SEB cross section for the 32 MeV lithium (lowest LET) ion may have been a first indication of the role of the recoil nucleus (figure 1).

It is not clear what mechanism is responsible for causing the neutron or proton induced SEB. The recoils from neutron and proton interactions with silicon have a limited amount of energy to deposit, generally about 20 MeV or roughly 1 pC. If we were to take an overly simplified approach, such as that of [20], and use the data from heavy ion induced SEB testing, we would find that an enormous amount of charge has to be deposited to induce SEB, about an order of magnitude larger than what the proton or neutron recoils can deposit. Thus the mechanism is more complicated than direct energy deposition. There must be some kind of multiplicative effect to enhance the energy deposited by the neutron, or proton, recoils.

A better approach is to look at the current induced avalanche (CIA) model of Wrobel for SEB [21]. In this two-step model, high current caused by the energy locally deposited by the heavy ion is followed by the creation of a much narrowed depletion region where the peak electric field increases. The peak electric field reaches a point at which it sustains avalanche multiplication which causes a regenerative feedback condition that leads to SEB. Thus, it is possible to view the breakdown as a two step process based on the fact that the proton/neutron interactions simultaneously produce both (high LET) recoils and (low LET) alpha particles. These two resultant particles combine to establish the high electric field condition. According to this model, the high LET recoil causes the high current which greatly narrows the depletion region, and about 2 ps later, a companion alpha particle reaches the narrowed junction where it deposits its energy. Using the equations for this model [21] and typical parametric values for a 500 V power MOSFET, (e.g., epi thickness of 40 µm, N_n concentration of about 5×10^{14} ions/cm^3, as given by formula 1 of reference 9) the narrowed depletion junction across which the alpha particle would deposit its energy is 2 to 3 µm. Since the alpha-particle will have already traversed a large fraction of its range, it will be near its peak LET of about 1 MeV-cm^2/mg, maximizing its energy deposition. Alternatively, a simpler model in which the energy deposited by the recoil is enhanced by a type of avalanching effect might be a possible explanation for the SEB.

The two-step model might be plausible since it accounts for larger energy deposition by the two particles and fits with the CIA model, but a preferred approach would be to work

Table 4. Comparison of device cross sections (from reference 13). The cross sections for the SRAM and DRAM are per bit and the µCtlr is per device . LET is in units of MeV-cm^2/mg.

Part	**Type**	**HI** s (cm^2 per bit) @LET=3	**HI** s (cm^2 per bit) @LET=5	**WNR** s (cm^2 per bit)	**Ratio** HI3/WNR	**Ratio** HI5/WNR
IMS1601	64K SRAM	3.0E-7	1.0E-6	4E-13	7.5E5	2.5E6
TMS44100	4M DRAM	4.5E-8	1.0E-7	1E-13	4.5E5	1.0E6
87C196	µCtlr	1.7E-4	6.0E-4	5E-10	3.4E5	1.2E6

with a 2-D modeling code such as Medici [22]. Simulations of the carrier distributions within a power MOSFET structure have been successfully modeled with this code [22] and correlate well with experimental results [22]. We would hope that the extensive evidence of proton/neutron induced SEB in MOSFETs shown in this study will encourage new simulation studies that incorporate the proton/neutron interaction with silicon. By this means, a better understanding of the mechanisms responsible for proton/neutron induced SEB will be achieved. Such modeling studies may clarify whether it is a one-step or two-step energy deposition by protons or neutrons that initiates the process leading to SEB.

As previously noted, integrated circuits have been tested for single event upset in both the WNR and heavy ion beams [11]. In table 4, we show the ratio of SEU cross section, per bit, from low LET heavy-ions to the SEU induced by WNR neutrons for the same parts. In figure 5 we plot heavy ion and WNR SEB cross sections for 500 V devices. The heavy-ion SEB cross section is approximately 4×10^5 times that for neutron induced SEB as measured in the WNR beam (after adjustment is made for the different die areas). This ratio is close to the comparable SEB ratio seen in table 4. In figure 5, we also see that the heavy-ion SEB cross section, at rated voltage, for a 500 V device is approximately 40% of the die area.

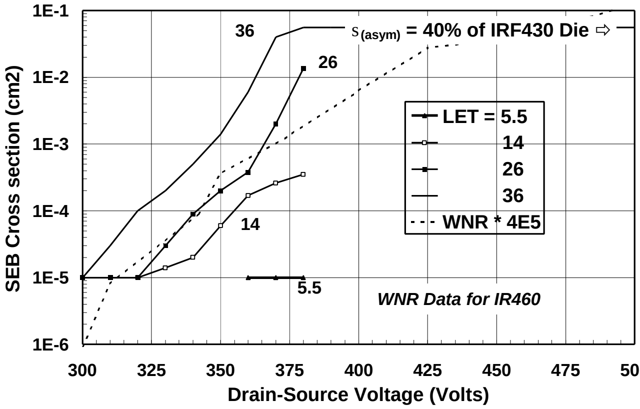

Figure 5. Comparison of heavy ion and neutron SEB cross sections versus V_{ds}. The WNR data for the IRF460 was first adjusted for die size (×0.23) and then multiplied by 4×10^5 to account for the heavy ion to neutron SEU ratio seen.

The SEU referred to is simply the result of the recoil nucleus depositing charge in the sensitive volume of the device. Ziegler [24] calculates the probability of producing a nuclear "hit" in 10 µm of silicon as 1/(4×10^4). He then gives the probability of making a "hit" in the active volume as 1/(1×10^6). This latter value is what we see for the ratio in the last column of table 4. In our charge collection work done at WNR [11], we calculated the BGR ("burst generation rate") for producing a recoil of various energies. Taking a value between that given for the 10 µm device and the 300 µm device we get a BGR of 3×10^{-15} cm^2/µm^3 at 10 MeV. This corresponds to a probability of producing a 10 MeV recoil of ~1/(3×10^5) in 10 µm.

Thus the 4×10^5 ratio is just the probability of a neutron or proton producing a "suitably" energetic recoil nucleus. If neutron or proton induced SEB is the result of a more complicated two-step process, it would not necessarily have the same ratio. Thus, more modeling is required to fully understand neutron SEB.

V. IMPLICATIONS FOR SYSTEMS

A. Introduction

Power MOSFETs used in systems are normally not used at their rated voltage. Instead they are usually derated by some factor. The Military Standard 975J (NASA) requires derating to no more than 75% of the rated voltage. Other applications may require more or less derating. It is well known that use in space often requires more derating to prevent heavy ion induced SEB or SEGR. It is not so well known that use in more benign environments may also require SEB prevention derating.

We will show, in the following sections, that our predicted SEB rates accurately reflect what is actually seen in space. Then we will predict the SEB rates at lower altitudes. Avionics systems are shown to be at potential risk due to the neutrons seen at high altitudes. We shall see that even ground level systems may be at risk from SEB in some high voltage devices.

B Spacecraft Observations

SEB in power MOSFETs has recently been observed in space [25]. Adolphsen, et al., have taken measurements of SEB versus voltage for several device types flown on the CRUX experiment on the APEX spacecraft [25]. Power MOSFETs, from the same lot as the CRUX flight parts, were provided to us for proton testing at HCL. The proton SEB data for the 200V parts is shown in figure 6. The SEB cross section data was used together with the AP8MIN [26] proton environment flux data to calculate the expected SEB rate for the APEX mission. This is presented in figure 7 along with the measured data from APEX.

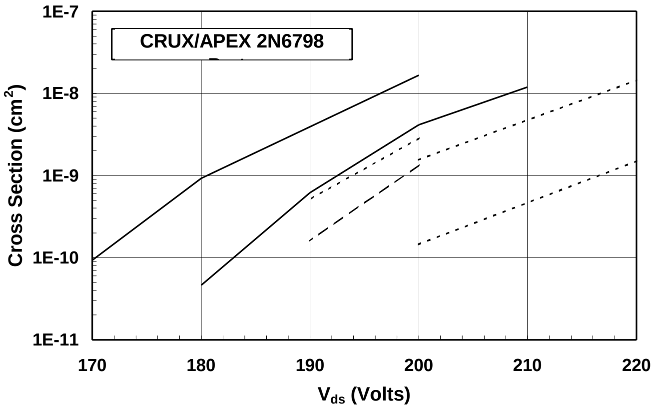

Figure 6. Proton SEB data taken at HCL. Data for 148 MeV protons (solid lines) and the simulated proton spectrum (broken lines) are shown.

Note that the ground test data for the 5 parts, shown in figure 6, indicates a large variation in SEB voltage threshold. Here we take the voltage threshold as that voltage where the SEB cross section is some constant small value (e.g., ~1×10^{-9} cm^2). The spread in threshold voltage seen is larger than usually seen for heavy ion SEB. This appears to be mainly due to part to part variation. In addition, there seems to be some shift due to the difference between the high energy and the spectrum data. However, the statistical variation in the random amount of energy deposited by the recoil nucleus may also be involved, but without a good model for the SEB effect it is hard to determine which parameter is most influenced by variations in the recoil energy deposition. The standard deviation of the voltage thresholds for the ground test parts is indicated in figure 7. We see that the calculated and observed rates agree to well within the standard deviation of the voltage threshold data. This excellent agreement of the flight data indicates that our other predictions should be accurate.

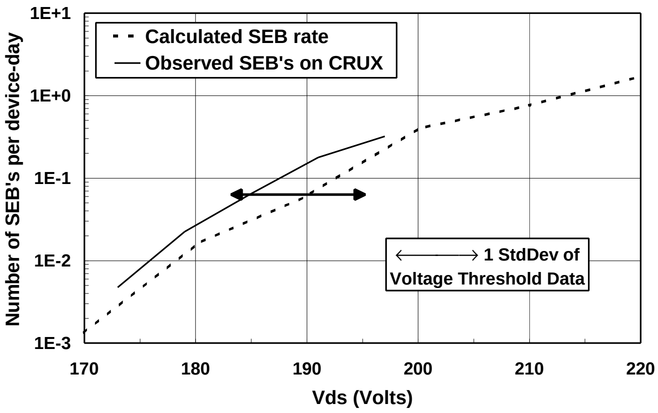

Figure 7. Proton SEB rates calculated from ground test data and observed on CRUX/APEX.

C. *Avionics Systems*

Since the WNR spectrum simulates the atmospheric neutron environment, it is of interest to see what the SEB rate would be in aircraft systems operating at 40,000 feet. Figure 8, shows the predicted SEB rate for various power MOSFETs as a function of voltage. (The SEB rate is just the cross section times the neutron flux at 40,000 feet.)

The higher rated devices clearly are at risk at voltages which are well below their maximum operating drain-source voltage. We know of no data indicating that SEB failures have occurred in avionics systems. There may be several reasons for this, foremost being the actual design of power supplies. Some power supply designs appear to be capable of absorbing sizable burnout pulses whereas other designs may not. (It should also be noted that most airplane power systems operate at 270 V.) Nevertheless, avionics power supply designers should be aware of this potential threat when utilizing power MOSFETs at high voltages.

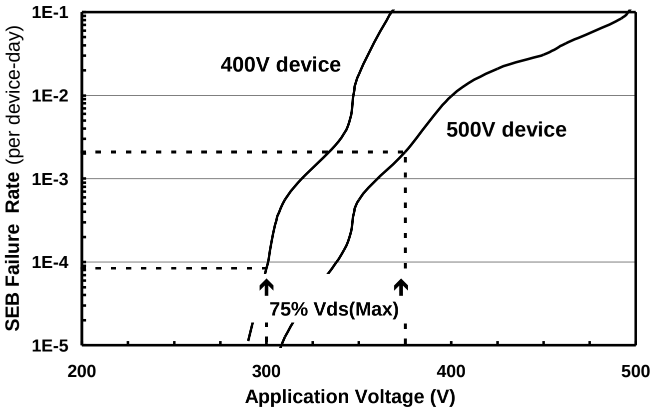

Figure 8. Expected neutron SEB rates at 40,000 feet. The data are calculated for the IR IRF360 and IRF460.

D. *Ground Level Systems*

Neutron-induced single event upset has been observed at ground level [27], where the neutron flux is approximately 1/300 of the flux at 40,000 feet. Thus, it is of interest to extrapolate our present findings to lower altitudes. We shall see that power MOSFETs, and other power devices, can experience failures at ground level.

From figure 8, the predicted failure rate for a IRF460 operated at 75% of its rated voltage is 2×10^{-3} per day at 40,000 ft. At ground level this would be 7×10^{-6} per day. Converting this rate to the measure used in reliability studies, FITs (failures in 10^9 hours), this corresponds to 330 FITs. Similarly, for an IRFP360 the failure rate would be ~12 FITs at 75% of its rated voltage, see figure 9. These values would increase to about 1400 and 140, respectively, for operation at 85%.

It should be noted that power MOSFET manufacturers perform reliability tests at high temperatures to accelerate the failure process (e.g., high temperature reverse bias tests). The failures seen in such testing are most likely unrelated to neutron induced SEB. However, the derived failure rates, for normal operating temperatures, are around 70 FITs [28,29]. Thus the failure rate which would be observed in use could be increased substantially by neutron induced SEB for devices rated at or above 500 volts unless additional derating is used.

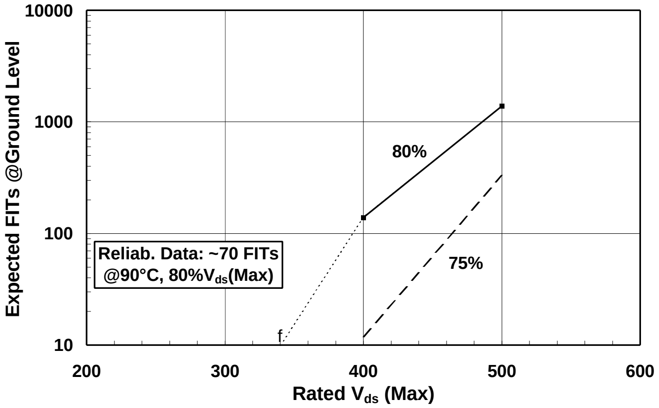

Figure 9. Expected power MOSFET failures, due to SEB, at ground level. {"FITs" are failures in 10^9 hours.)

Large, high voltage devices are of more concern. High voltage thyristors, used in the power converters of European railroads, have experienced failures [30]. In that reference, Kabza, et al., show a failure rate of 10^7 FITs (i.e., 10^{-2} failures per hour) for devices operated at ~4100 volts. They also determined that the failures depended on the applied voltage and that no failures were seen when the experiment was carried out when shielded in a salt mine. Ongoing work will determine if these failures can be correlated with atmospheric neutron exposure.

VI. CONCLUSIONS

Single event burnout in power MOSFETs caused by heavy ions has been a consideration for spacecraft designers for some time. We have shown that SEB failure can be induced by energetic neutrons and protons and can occur in situations where heavy ions are not present. Clearly, to avoid system failure, some aspects of the derating system used for space systems must be used in avionics applications. Ground level applications were also shown to be susceptible to SEB under certain conditions.

Postulations on the mechanism, relative to heavy ion effects, have been made. We have shown flight and ground test data for proton induced SEB. The excellent agreement of the calculated and observed SEB rates validates the accuracy of our predictions for other altitudes. The threshold voltages and cross sections due to neutron induced SEB in power MOSFET are such that further study is warranted.

VII. ACKNOWLEDGMENTS

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