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Neutron-Induced Single Event Burnout in High Voltage Electronics

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Abstract

Energetic neutrons with an atmospheric neutron spectrum, which were demonstrated to induce single event burnout in power MOSFETs, have been shown to induce burnout in high voltage (>3000V) electronics when operated at voltages as low as 50% of rated voltage. The laboratory failure rates correlate well with field failure rates measured in Europe.

I. INTRODUCTION

Single event burnout (SEB) in power MOSFETs caused by heavy ions had been a well known destructive effect first observed in 1986 [1]. In most investigations of this effect, heavy ions with high LET (> 25 MeV-cm²/mg) had been used, but in a few cases, ions with LET < 10 MeV-cm²/mg had also been shown to induce the SEB effect [2]. This prompted a 1995 evaluation of the effect of high energy neutrons and protons on power MOSFETs [3], using the non-destructive test technique developed almost 10 years earlier [2]. The energetic neutrons and protons were shown to cause single event burnout in power MOSFETs [3].

A few years before this neutron test, European and Japanese manufacturers of high voltage semiconductors noticed that some of their devices were undergoing burnout failures in the field during normal operation of newly developed train engines [4,5]. These devices consisted of diodes and GTO (gate turn-off) thyristors which were rated at 4500V, and were normally operated at 50-60% of rated voltage. They were designed for terrestrial use of > 35 years, so when the failures first appeared in the field, they were very puzzling. Eventually, room temperature DC testing was carried out, which was very unconventional at the time, and during the long term high voltage DC stress tests, failures appeared as they had in the field. The failure mode was investigated in greater detail pursuing a variety of proposed causes [4]. A salt mine experiment convinced the investigators that the cause of the failures was cosmic rays. Testing the high voltage devices is more difficult than with power MOSFETs because when they fail, they cannot be tested non-destructively.

In the salt mine experiment, 18 diodes (4500V, 6.5 cm. diameter) from a single batch were DC-stress tested at 4000V in three locations at different altitudes (salt mine, top-floor laboratory and basement). The first phase was in a top-floor laboratory having only a tin roof above it which provided the baseline condition. Six failures were encountered over a period of about 700 device-hr. In the second phase the devices were tested in a salt mine about 500 ft below ground for about 7000 device-hr, and not a single failure resulted. In the third phase the devices were returned to the laboratory and 3 failures were recorded over about 300 device-hr, about the same failure rate as in phase 1. In the last phase, the diodes were relocated to a basement and two failures were recorded over 1000 device-hr, a significantly lower failure rate than in the laboratory. Thus the naturally occurring cosmic rays were identified as the cause of the burnouts, and shielding reduced the failure rate.

Similar experiments were carried out in Japan using GTOs with similar but more detailed results [5]. In this case decreasing failure rates were observed with the GTOs at 4300V for three controlled shielding configurations of 0, 1.7 ft and 6.7 ft of concrete. The decrease in failure rate with concrete thickness in the GTOs was very significant, and is very similar to the concrete shielding experiment carried out by Ziegler in testing SRAMs at Leadville, Colorado [6]. In Figure 1 we plot the reduction of the GTO and SRAM single event induced failure rates as a function of concrete thickness, along with theoretical curves for the attenuation of high energy neutrons in concrete [7]. The theoretical curves are based on neutron attenuation that is governed by a relaxation length, λ, such that the reduction is given by *exp* (-shield × density/ λ), and for the atmospheric neutron spectrum, $\lambda \sim 140$ gm/cm² [7]. From Fig. 1 it is clear that the induced single event failure

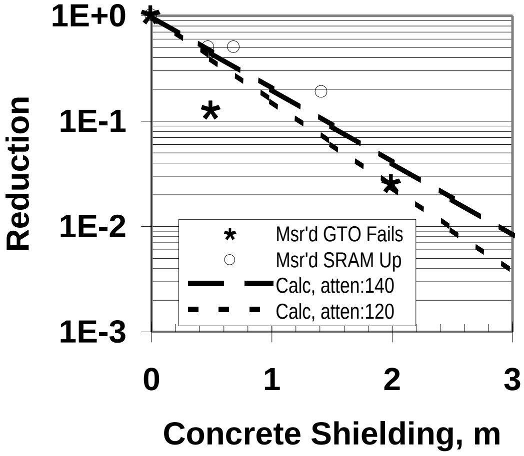

Figure 1 Reduction in Ground Level Single Event Effects in Devices Due to Concrete Shielding Attenuation of Neutrons

rates in the GTO and SRAM devices directly correlate with the atmospheric neutrons.

II. Power MOSFET Experience with Neutrons

We recently showed that energetic neutrons and protons can cause single event burnout (SEB) in power MOSFETs [3]. The energetic neutron beam was provided by the WNR (Weapons Neutron Research) facility at Los Alamos National Lab, which has the same energy spectrum as the atmospheric neutrons [3]. The proton beam was provided by the Harvard Cyclotron, and it was used in both the monoenergetic and simulated trapped spectrum modes. In general, 400V and 500V MOSFETs exhibited neutron-induced SEB when operated at voltages above 300V [3]. However, even 200V n-channel MOSFETs were made to undergo burnout by neutrons at voltages above 190V (IRF250), and by protons when operated at above voltages 170V (2N6798) [3]. The neutron and proton fluences needed to cause SEB varied, with the higher the operating voltage, the lower the required particle fluence. The measured neutron and proton SEB cross sections varied from about 1E-6 cm² (applicable to 400V parts operated at 400V) to 1E-10 cm² (200V parts at 200V or 400V parts operated at 300V). SEB could also be induced by 14 MeV neutrons from a D-T neutron generator in 400V and 500V MOSFETs.

New tests have been performed at the WNR on different power MOSFETs and the results are being reported here. The new devices that were tested for single event burnout are listed in Table 1. These new parts were selected mainly because they are higher voltage devices. The new 500V n-channel MOSFET by Motorola was selected because it is the n-channel counterpart of the one of the few high voltage p-channel MOSFETs that we could find. This 500V p-channel MOSFET was tested to investigate the possibility of gate rupture.

These tests were carried out to try to answer two questions, first is the effect really SEB, i.e., could it be single event gate rupture (SEGR), and second, how do higher voltage parts (i.e., rated at > 500V behave). To answer the first question, can high energy neutrons (i.e., >10 MeV) induce SEGR, we used an indirect approach. It is well known from heavy ion testing that p-channel power MOSFETs are immune from SEB, but they can undergo SEGR [9,10]. Thus, we tested two similar power MOSFETs, one a p-channel and one an n-channel in the WNR beam. Both are rated at 500V and were from the same vendor (in this case Motorola: n-channel was MTW20N50E and p-channel was MTP2P50E). The n-channel MOSFET exhibited burnout pulses at voltages below 400V, but the p-channel power MOSFET, operated normally even when the full rated voltage of 500V was applied. Subsequently, the MTP2P50E was tested with a Cf-252 source to simulate heavy ions. After absorbing a fission fragment fluence of ~2E7 p/cm² at 500V (LET of ~40 MeV-cm²/mg), the MTP2P50E still operated normally (negligible gate leakage current), although the drain current did increase from nil to 0.5 µA. Thus, the WNR testing of this p-channel MOSFET in the WNR indicating no SEGR is not conclusive as to whether neutrons can induce SEGR in MOSFETs. The p-channel MOSFET chosen for this demonstration was a 500V device, much higher than the highest rated p-channel devices previously tested for SEGR, which was 200V (four of nine 200V devices exhibited SEGR with heavy ions, and five did not up to 200V [10]). These nine p-channel MOSFETs were by three different vendors, none of which was Motorola. Thus the fact that the MTP2P50E did not undergo SEGR with heavy ions may either be unique to this part or vendor, or may be indicative of the behavior of the few higher voltage p-channel MOSFETs that are available. It runs counter to the increased SEGR sensitivity of n-channel MOSFETs that increases with rated voltage [11], but it also means that we cannot conclusively rule out SEGR by high energy neutrons, even though, due to the thinness of the gate and the lower LET of the neutron recoils compared to that of heavy ions, this might be expected.

Higher voltage n-channel MOSFETs were also tested. A number of these were tested using the WNR beam, and some of these were also tested using a beam of 14 MeV neutrons. In Figure 2 the SEB cross section from WNR irradiation for power MOSFETs and IGBTs rated at 500V and above are shown. Also included are the SEB cross sections for one of the 500V MOSFETs, the IRF460, that was previously tested [3]. In Figure 3, the SEB cross sections are plotted for the three high voltage power MOSFETs that were tested with both 14 MeV and WNR beam (1-800 MeV) neutrons. For the 400V device, the IRFP360, the SEB cross section, shows very similar behavior, as a function of applied voltage, for the two neutron beams. For the two 1000V devices, the APT1002 and IRFPG50, the behavior of the SEB cross sections as a function of voltage is quite different when using the WNR beam compared to the 14 MeV neutron beam.

Burnout pulses are seen at much lower voltages when the 1000V power MOSFETs were irradiated in the WNR beam compared to irradiation by 14 MeV neutrons. The higher energy WNR neutrons produce much more energetic reaction products in the silicon compared to those induced by the 14 MeV neutrons. Although the quantitative relationship between the drain-source voltage, V_{ds}, required to initiate SEB and the

Table 1 List of Parts Tested with WNR Beam and 14 MeV Neutrons

Part #	Mfg.	Rated V_{ds}, V	Type
MTW20N50E	Motorola	500	N chan. MOSFET
MTP2P50E	Motorola	500	P chan. MOSFET
APT1002RBN	APT	1000	N chan. MOSFET
IRFPG50	IR	1000	N chan. MOSFET
HGTG20N120E2	Harris	1200	IGBT
40HF160	IR	1600	Rectifier Diode
AR2009S44	Ansaldo	4400	Rectifier Diode

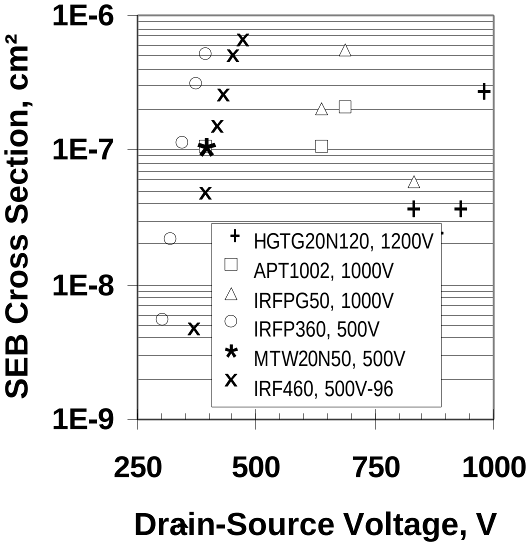

Figure 2 SEB Cross Section in MOSFETs and IGBT As a Function of Applied Voltage for WNR Neutron

energy deposited by the reaction products isn't clear, this phenomenon is consistent with burnout in power diodes, as will be discussed later.

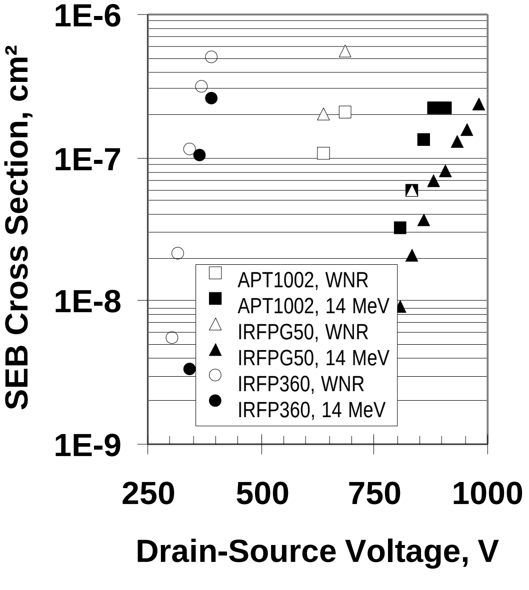

Figure 3 SEB Cross Section in MOSFETs As a Function of Applied Voltage for WNR and 14 MeV Neutrons

III. Burnout in High Voltage Electronics

In Europe, where high voltage devices are widely used for railroad applications, these devices are required to have failures rates of less than 100 FITs (FITs are failures in 10^9 device hours) at application voltages. This requires a reduction in the application voltage down to less than 50% of the device breakdown voltage. To assure that the 100 FIT number is met, manufacturers of high voltage devices for railroad applications have to supply data showing the dependence of the failure rate on voltage. This failure dependence on voltage is extremely strong. A 5% decrease in the operating voltage relative to the breakdown voltage can typically mean a decrease in the failure rate of a factor of 5.

The failure mechanism in high voltage devices is not understood in detail so there is no accurate way to derive a theoretical dependence of the failure rate on voltage. The failure is obviously coupled with a charge carrier multiplication event, as is also the case with power MOSFETs [3], and so it is directly tied to the electric field distribution in the device. eupec (European Power- Semiconductor and Electronics Company GmbH), a subsidiary of Siemens, specializes in the manufacture of high voltage devices for traction, power supply and similar applications. Eupec uses an empirical method to estimate the failure rates at low voltages, derived from a comparison of the voltage dependence of the hole ionization integral with the experimental failure dependence at higher voltages [12]. One important feature of the voltage dependence is that the failure rate data, at voltages high enough to allow measurements of burnout, indicated a linear dependence on a semilog plot. However, the ionization integral, when extrapolated to lower voltages, shows a fall-off at low voltages (see Figure 4).

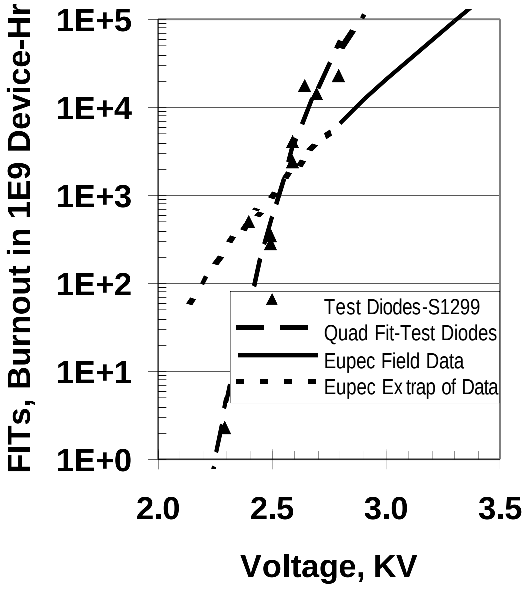

Figure 4 Burnout Failure Rate in Eupec D1461S Diodes from WNR Neutron Beam Measurements as Ground Level FITs

Once we learned of the power diode failures, we examined the European burnout data in high voltage diodes from the vantage point of our experience of inducing SEB in power MOSFETs with the WNR neutron beam. We found that we could predict the diode burnout rates within a factor of 10, just by applying the WNR SEB experience in power MOSFETs. For example, phase 1 of the salt mine experiment (6 failures in 700 device-hr) gave a failure rate equivalent to approximately 6E6 FITs which applies to the 6.5 cm diameter diode operated at 4000V. From the power MOSFET SEB data, it appears that the asymptotic heavy ion SEB cross section is ~ 50% of the total die area, i.e., one out every two heavy ions striking the MOSFET causes SEB, and that the neutron/proton induced SEB cross section is ~4E5 times smaller compared to the heavy ion cross section [3]. Assuming that these same factors apply to burnout in high voltage diodes, and using the high voltage diode data, (active area ~30 cm^2 so that 15 cm^2 is taken as the heavy ion burnout cross section, i.e., using 50% of the die area), the neutron-induced burnout cross section is calculated to be 3.8E-5 cm^2. The failure rate from cosmic ray neutrons on the ground would be this cross section multiplied by the ground level neutron flux, 20 n/cm^2-hr (> 10 MeV) [8], which leads to 7.5 E5 FITs, within a factor of 10 of the measured number of FITs. If every heavy ion was assumed to cause SEB, or a different ratio of the heavy ion/neutron SEB cross section was used, the agreement with the measured FITs would have been even better.

Furthermore, if we were to assume that the neutron SEB cross section is proportional to the active volume (active area × depletion depth), rather than the active area, then the agreement with the field failure data is greatly improved. That the SEB cross section is proportional to the active volume is reasonable because the energy deposition leading to SEB is from the neutron induced recoils, and the number of recoils is proportional to the active volume of silicon in which the recoils are generated. For the power MOSFETs, the depletion depth is about 50 µm, but for the diodes it is approximately 500 µm. Thus, based on the assumption of proportionality to volume, the SEB cross section would be ten time larger, 3.8 E-4 cm^2, leading to a 10 times larger number of FITs, 7.5 E6, in surprisingly good agreement with the field data.

Based on the proportionality of the SEB cross section to either the active area or active volume of the diodes, this approach of testing with the WNR beam appeared to be very promising. It provided a methodology for performing accelerated testing by irradiating the diodes with high energy neutrons having the same spectrum as the cosmic ray neutrons. This testing could be done quickly, especially compared to the previous direct method of experimentally determining the failure rate at voltages close to application voltages, which requires hundreds of devices to be operated over thousands of hours.

IV Neutron Testing of High Voltage Diodes

Based on the apparent good correlation between the observed diode failure rate and that derived from the power MOSFET testing at the WNR [3], eight Eupec high voltage diodes of one specific type were tested in the WNR neutron beam. These disk diodes, D1461S, rated at 4.5 kV, were from a single batch because the starting material has a strong influence on the failure rate. The diode consists of a deep n- region, about 500 µm thick, followed by a much thinner p+ region. The diodes were irradiated in the beam for fluences of ~6E7 n/cm^2 at a set voltage before the voltage was increased by about 100V and the irradiation continued. In most cases burnout was very abrupt (no incremental change in leakage current or precursor pulses), but in a few cases the leakage current increased by small intervals and small pulses were observed at lower voltages before the large burnout pulse was observed at the higher voltage. In Figure 4 we compare the failure rate, in FIT units, as measured in the WNR beam, and as observed from field measurements. [Our experimental number of FITs from the WNR test is equal to 2E10/FLU, where FLU is the WNR fluence of neutrons (>10 MeV) to cause a single burnout.] The field failure curve was measured down to 2.8 kV and extrapolated to lower voltages. It also was adjusted for the actual doping concentrations of the starting material. The WNR data are based on measurements in 8 devices. In the voltage region in which the field and WNR data overlap (2.8 kV) the agreement is within a factor of 3, which is considered to be very good when accounting for all of the uncertainties.

At 2.8 kV, the highest voltage used in the WNR test, the failure occurred in less than 5 seconds of beam exposure. Thus, to have tested the diodes at higher voltages in the beam we would have had to reduce the flux by a factor of 10-100. Such a reduction in intensity would have required prior arrangement with the Los Alamos staff, and so couldn't be done. At the low voltage end, one device, operated at 2.3 kV, was in the beam for 9 hours and didn't fail. Some of the WNR data points in Fig. 4 are based on the response of two devices, and some on just one part. At voltages < 2.6 kV the WNR data falls off much more rapidly than the extrapolated field failure curve, indicating that unless there are other cosmic ray particles in the field causing the failures, which is not true, the requirement for a failure of 100 FITs is fulfilled at voltages at least 200V higher than originally expected.

Four other types of diodes were tested in the WNR beam, two others from Eupec and two from other vendors. The results of these burnout tests are shown in Figure 5 in which we plot the SEB cross section on the y-axis, rather than the number of FITs, as in Fig. 4. Figure 5 contains the results of diode irradiations by the WNR beam, as well as by 14 MeV neutrons. The number of FITs is based on the number of hours in use on the ground through the correlation of the neutrons with E>10 MeV between cosmic ray neutrons on the ground and those in the WNR tests. Thus burnouts expressed as FITs applies only to the WNR beam, and can't be used for SEB induced by 14 MeV neutrons.

From WNR/14 MeV Tests As a Function of Applied Voltage

From Fig. 5 we observe that first, the few Eupec D1461S diodes from slightly different batches (series 1297 and 1298) that were tested exhibited burnout at voltages very similar to the comparable values for the series S1299 burnout data (also shown in Fig. 4 but in different units). Secondly, a single Eupec D921S diode (4.5 kV diode), which uses a different

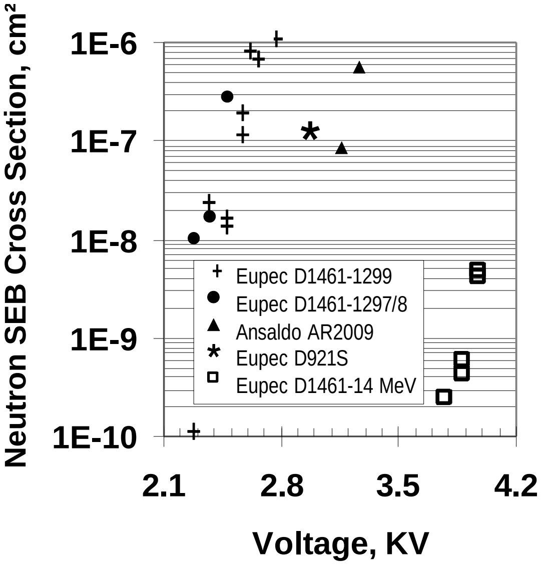

Figure 5 SEB Cross Section in High Voltage Diodes (4.5 kV)

design than the D1461S diodes, shows a notably higher voltage for burnout. Third, several 1600V 40HF160 rectifier diodes were exposed in the WNR beam and none exhibited burnout. These devices received fluences ranging from ~2-6 E8 n/cm², and all that were seen were very small amplitude noise-like pulses. Fourth, two 4400V rated AR2009 rectifier diodes by the Italian manufacturer Ansaldo were exposed in the beam, and their burnout cross section, as shown in Fig. 5, is quite similar to that of the Eupec D921S diode.

Eupec researchers have previously obtained field/extrapolated FIT curves for the two diode designs, D1461S (type I) and the D921S (type II) [12]. The FIT curves for the two diodes appear to be almost parallel, with the D921S requiring much higher voltage to induce burnout compared to the D1461S. Thus the D1461S FIT curve in [12], comparable to the field data curve in Figure 4, is offset and to the left of the curve for the D921S by about 600V for the same number of FITs. From Fig. 5 displaying our WNR data, we see that from the single data point for the D921S, the D921S requires about 500V more than the D1461S diodes to induce burnout for the same SEB cross section. Thus the relative susceptibility to burnout between the D1461S and D921S diodes obtained from field data and from our WNR measurements are in relatively good agreement, especially since we tested only one D921S diode in the WNR. The fact that the two Ansaldo diodes burned out at voltages and SEB cross sections similar to the Eupec D921S indicates that burnout is a generic effect, independent of vendor.

A few of the D1461S diodes were also exposed to the 14 MeV neutron beam. In this case, the voltage had to be increased by more than ~1500V, compared to the WNR tests, i.e., close to 4000V, before burnout could be induced. Fig. 5 also shows the resulting data points from these tests of the D1461S diodes in the beam of 14 MeV neutrons. This is even more pronounced than the difference in voltages leading to SEB from the irradiation of 1000V power MOSFETs in the two neutron beams.

VI Heavy Ion Testing of High Voltage Diodes

A limited amount of testing of the high voltage diodes was carried out with heavy ions [12]. Because the diodes have a thin metallic plate on both sides, beams of low Z ions were used that have ranges long enough to penetrate to the diode within the cover plates. Thus these heavy ion tests are not typical of the testing carried out on electronics intended for use in space; however, these high voltage diodes are intended for terrestrial applications only. The heavy ion tests were conducted with ^{12}C ions [at the VICKSI accelerator at the Hahn-Meitner-Institute (Berlin) and the Dynamitron at the University of Bochum] and alpha particles (VICKSI). D921S diodes were tested with the ^{12}C ions of different energies and burnout could be induced as the voltage was increased. Table 2 summarizes the voltages that induced burnout along with the irradiation orientation and ion energy [12]. As seen in Fig. 5, the diode experiences burnout when irradiated with high energy neutrons at voltages of 3000V and above. The ^{12}C fluences to induce burnout were in the range of 1E4-1E5 ion/cm². Results of the alpha irradiation of the D921S diodes are also included in Table 2.

Table 2 Results of ^{12}C and Alpha Irradiations of D921S Eupec Diodes Leading to Burnout

Ion	Energy, MeV*	Burnout Voltage, V	Beam Orientation
^{12}C	252	3000-3700	Normal (90° to face)
^{12}C	190	3600-4050	Normal (90° to face)
^{12}C	140	4000-4200	Normal (90° to face)
^{12}C	244	4100-4300	30° to face
^{12}C	128	4300-4800	30° to face
alpha	98†	2650-2850	N/A‡

* Energy of the ^{12}C entering the silicon
† Initial energy of the α, only 25 MeV is deposited in silicon
‡ Much higher α particle fluences were used, up to ~1E10 p/cm²

The conclusion drawn from these tests, based on an analysis of the range and LET of the ^{12}C ions [12] is that the decelerated ^{12}C ions did not cause the failure, but rather that the burnout mechanism is triggered only if the ^{12}C causes a nuclear reaction with the silicon. The 190 MeV energy was chosen so that these C ions would have a range that just exceeded the depletion depth of ~500 µm. Thus as these C ions slowed down in the Si, the LET increased significantly (at a point with 100 µm left, the LET had doubled, and with 10 µm left, the LET had increased by a factor of 5). In contrast, the 252 MeV C ions had such a long range (~900 µm) that their LET changed very little over the entire depletion region. Since the burnout response was similar for C ions of both energies, even though the LETs varied significantly, direct ionization could not be responsible for the burnout. Thus a C-Si reaction is required, and once it occurs, it appears to set off a self-supporting multiplication process, which depends on both the location of the reaction and the field conditions in the immediate surroundings [12].

VII Possible Mechanisms Involved in Burnout

As previously indicated, it is clear that a charge carrier multiplication event is involved in the burnout process, but we do not know the exact details. In our earlier examination of neutron-induced SEB in MOSFET [1], we found no model that could satisfactorily explain the effect. The best available model, the current induced avalanche (CIA) model proposed by Wrobel [13] provided useful insights and the bases for possible mechanisms, and to that extent, it was more relevant than the generic simulations that others had carried out with 2-D charge modeling codes. However, we had overlooked the work by Kuboyama and co-workers [14-16] which, based on characterizing the response of power MOSFETs to heavy ions through use of the new EPICS (energetic particle induced charge spectroscopy) technique, provides a model that we can use and adapt to explain SEB in both MOSFETs and high voltage diodes.

For power MOSFETs, the Kuboyama model shows that charge deposition proceeds in three stages in leading to burnout. These are shown in Fig. 6. When an ion strikes a power MOSFET operated at a specific V_{ds}, a first charge peak is registered due to the deposition of the direct charge of the ion. As V_{ds} is increased two effects are seen. Firstly, a second peak is seen which results from charge injected from the source electrode by the activated parasitic bipolar transistor [14]. According to this aspect of the model, the potential redistribution by the plasma column directly activates the parasitic bipolar transistor [14]. The increase in the voltage in the epi region, ΔV_P, determines the amount of injected current, and ΔV_P depends on V_{ds}, the LET of the ion and the penetration depth of the ion [14]. Secondly the charge at which the first peak occurs, is found to register at higher values of charge, and this is due to avalanche multiplication.

Finally the third stage is reached in which enough charge has been injected from the first two mechanisms that a charge threshold, Q_{th}, (roughly 1000 pC) has been reached such that any additional charge deposition, due to a further increase in V_{ds}, leads to a burnout pulse. This third stage at higher V_{ds} is a regenerative feedback process which results from the current increasing ΔV_P, followed by ΔV_P regeneratively increasing the current through charge injection. At low V_{ds} the charge injection occurs outside the ion track, and so is not regenerative, but at higher V_{ds}, the charge injection occurs at the inner core of the ion track and thus it becomes regenerative. This is the Kuboyama model.

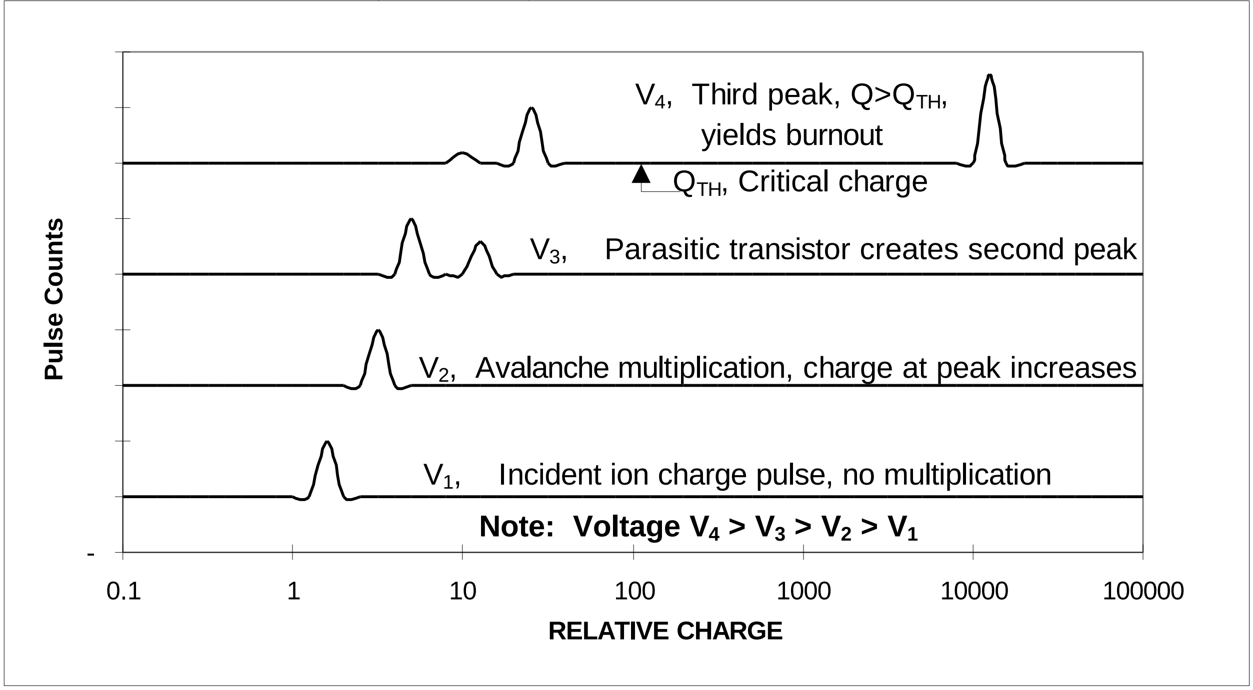

Figure 6 Simplified Representation of Kuboyama Model, Using Charge Deposition To Follow Development of Single Event Induced Burnout in Power MOSFETs

Kuboyama further noted that with high LET ions (Z > 30), the second peak is quite close to Q_{th}. However, lower Z ions such as C and Cl could also induce SEB when V_{ds} was high enough (for the IRF450, this was 300V), but in this case there is a broad signal (at least 2 orders of magnitude) between the second peak and Q_{th}. Kuboyama attributes this broad signal to reaction products from C-Si nuclear reactions that have high energy transfer rates, i.e. LETs [14]. This appears to be the same mechanism responsible for neutron induced SEB, i.e., energy deposited by the reaction products from nuclear reactions with the silicon. Kuboyama was able to further demonstrate quantitatively that nuclear reactions also play a role in heavy ion SEB [16]. Unfortunately because the energy deposition by the heavy ion leading to SEB includes both direct energy deposition by the ion, the main contributor, as well as deposition due to nuclear reaction products, Kuboyama's nuclear reaction SEB evaluations cannot be directly compared to our neutron induced SEB measurements.

Nevertheless, we can gain further insight into the factors involved from Kuboyama's studies on the Fuji Electric 500V 2SK725 MOSFET [16]. He indicates the nuclear cross section for inelastic scattering (probability of an interaction) with silicon is about 3 barns for a 3.5 GeV Xe ion, 1.3 barns for a 500 MeV Kr ion and about 0.2 barns for high energy neutrons. Thus the neutron inelastic cross section in Si is more than a factor of 10 lower than that for the Xe and Kr ions used by Kuboyama. Even more significantly, the range of the reaction products produced by the high Z ions and neutrons are drastically different, and as previously indicated, this range is an important factor in determining the activation of the parasitic bipolar transistor. Kuboyama showed this by comparing the ranges of recoils to the 50 µm depth of the active/over layer in the 2SK725. For the Xe-Si recoils, most have ranges that exceed this depth whereas a smaller fraction of the Kr-Si recoils exceed 50 µm [16]. Lower energy, lower Z ions that Kuboyama also used, such as 200 MeV Ni and 150 MeV Cl have many fewer recoils with such long ranges in Si, and high energy neutrons have no recoils with a 50 µm range. To compensate for the shorter range, the lower energy ions require higher Vds to induce SEB, 300V for the Cl, 280V for Ni, 210V for Kr and 95V for Xe. The higher the Vds the greater the avalanche multiplication. With strong avalanche multiplication, the number of electrons injected into the plasma column becomes larger than the decay rate in the plasma column, and the conductivity of the column increases with time [15]. This leads to SEB with a strong current flow.

In general terms, the Kuboyama model can be adapted to the burnout situation in a diode which is similar to that of the MOSFET except that there is no source region to inject additional electrons. We have pictured the perceived steps in the process of a high voltage diode being irradiated by an energetic particle in Figure 7, which we shall refer to as the Eupec model that is patterned after the Kuboyama model for MOSFET burnout in Fig. 6. With the diode at relatively low Vds, the first charge peak is registered due to deposition of charge directly from the incident ion. As Vds is increased low levels of avalanche multiplication are reached (<2) which give rise to a second peak. This peak occurs at a value of charge that is about 1000 times greater than that of the first, direct ion, peak. This second pulse must be generated by multiplication due to high local fields. In some devices the first peak disappears and every ion generates the pulse at very high charge which still remains nondestructive. Finally, as Vds is further increased, a single pulse destroys the diode due to its own capacitance.

Charge pulses similar to those shown in Fig. 7 have actually been measured during the ^{12}C testing of high voltage diodes [17], and the sequence is similar to that depicted in the figure. Following the Kuboyama model, for the high voltage diodes, it appears to be the recoils from nuclear reaction by light ions/neutrons with the Si that deposit the initial energy that is multiplied by the local fields leading to the second peak, and ultimately to destructive burnout.

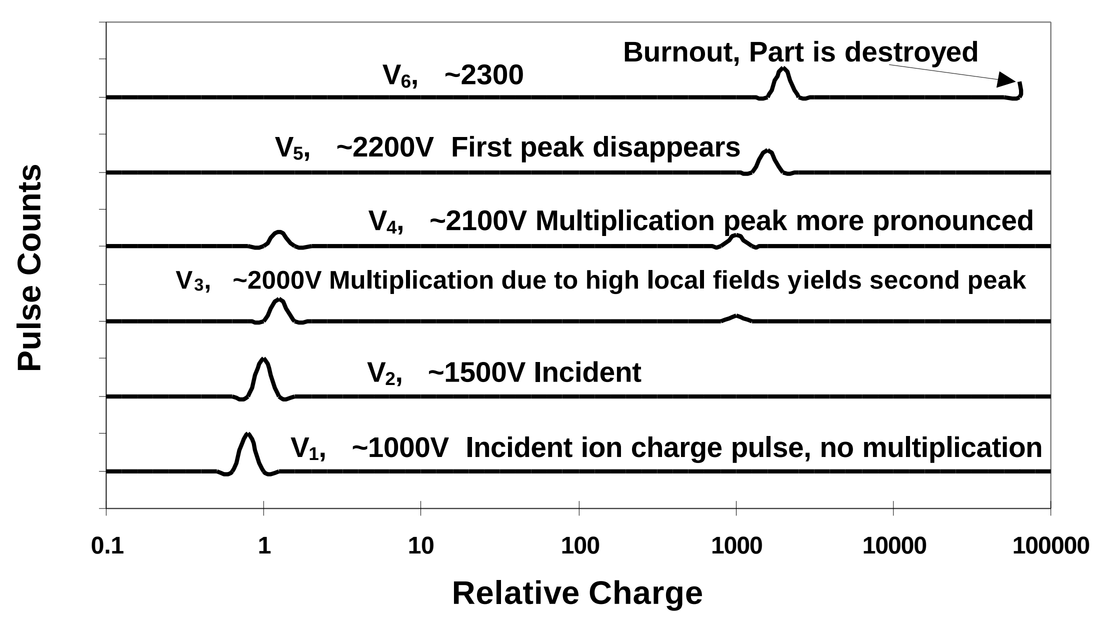

Figure 7 Simplified Representation of Results from eupec Tests in Which High Voltage Diodes Were Irradiated with 17 MeV Carbon Ions [12]

We looked at other possible explanations for the observed burnout that could be further quantified but couldn't find any. The effect known as "reach through" or "punch through", was initially considered by Boeing, although it had been rejected by the Europeans earlier [4]. In reach through, the dopant level is changing such that the electric field "reaches through" to the junction [18]. With the initial lightly doped n- region, the electric field is essentially constant, and the breakdown voltage is equal to the depth of the n- region, d, multiplied by the electric field ($V_B \sim E_B \times d$). As the dopant level in the n-region increases such that the depletion region just reaches to the end of the dopant region where the field is now 0, the breakdown voltage is approximately ~0.5 times $E_B \times d$. However, "reach through" cannot be the mechanism involved in the neutron-induced burnout because it would have to be via neutron reactions changing the dopant concentration, and the neutron fluences involved are many orders of magnitude too low to do this.

Another body of data that we looked at for applicability to the high voltage diode burnout situation is that of charge multiplication in silicon detectors [19,20]. Charged particles impinging on a silicon radiation detector are known to produce charge multiplication. In a recent study, a variety of charged particles from the U-400 cyclotron of the Flerov Laboratory of Nuclear Reactions (JINR, Dubna, Russia) were directed into silicon surface barrier detectors (SSBDs) [20]. Charge multiplication was observed for the higher LET ions [S (200 MeV) and above], but not for the lower LET ions (C, O, Ne and Mg, energies of 100-200 MeV). For the high LET ions, a second, multiplied peak, appears adjacent to the expected regular peak, and as the voltage across the SSBD is increased, the charge multiplication is increased [18]. In this case charge multiplication is defined as the offset between the multiplied and initial peaks. In addition, as the voltage across the SSBD increased, the charge multiplication increased, i.e., the multiplied peak appeared at an increasingly higher channel relative to the regular peak, as seen in the pulse traces [20].

Of particular interest to our diode burnout situation is the fact that not only did the multiplied peak appear at higher energies with increasing V, but that the size of the multiplied pulse, the area under the peak increased dramatically. In [20] pulse distributions are given that result from ^{34}S ions impinging on an SSBD at voltages ranging from 200-500V. The SSBD had a breakdown voltage of ~650V [21]. We have estimated the size of the initial and multiplied pulses (peak height × FWHM) for each of the four distributions [20]. At 200V, the number of multiplied pulses is very small compared to the initial peak pulse, but at 300V the two kinds of pulses are of approximately the same magnitude, and at 500V, the multiplied pulses appear 10 times more frequent than the initial peak pulse. The mechanism appears to be quite different from that observed by others with light ions near the breakdown voltage [19].

In [20] the charge multiplication, defined as the offset between the multiplied and regular peaks, is analyzed in terms of an avalanche multiplication model due to the dynamic focusing of the electric field by the plasma column created by the charged particle. The dynamic focusing model was developed previously [22] and it successfully explains the multiplication in terms of the relative offset between the initial and multiplied peaks. Unfortunately, to date, we have not been able to utilize this theoretical treatment to explain multiplication in terms of the ratio of the size of the initial and multiplied pulses.

VIII Conclusion

High voltage diodes were exposed to the WNR neutron beam and single event burnout failures were recorded. The measured failure rate correlates well with the diode burnout rate recorded in the field by the manufacturer. The results indicate that a derating of up to 50% is required for some types of high voltage diodes.

On a very basic level, the burnout mechanism in the high voltage diodes appears to be similar to that of SEB in power MOSFETs. The burnout appears to be an avalanche induced effect initiated by recoils from neutron interactions with the silicon, however there are also distinct differences between the behavior in the MOSFETs and in the high voltage diodes. We were able to use the Kuboyama model developed for heavy ion SEB in power MOSFETs to explain the steps involved in neutron-induced burnout in MOSFETs. Two stages of charge multiplication are involved, a non-burnout phase followed by burnout at higher voltages, and the multiplication is due to charge injected from the source electrode by the activated parasitic bipolar transistor. The simplified Eupec model adapts the Kuboyama approach to high voltage diodes and finds that with increasing voltage, the initial charge deposited by recoils is multiplied by local fields leading to a non-burnout multiplication peak. When the voltage is raised above a critical value, this leads to destructive burnout in the diodes. However, a much more detailed understanding of the multiplication effects will be required in order to be able to anticipate/predict the behavior of new designs of high voltage devices in the cosmic ray neutron environment.

Today, power electronics constitute a very large market world wide, about $5-6 billion, and approximately 30% of this is devoted to industrial applications. At present, very high voltage devices, those operating above 2000V, are not manufactured in the United States, although research efforts towards that goal are being carried out. One of the largest of these is the power electronics building block (PEBB) program sponsored by the US Navy to develop technology for distributing and controlling electrical power aboard Navy ships. One of the new device types produced by Harris Corp. for the PEBB program is the metal oxide silicon controlled thyristor (MCT). We have shown that neutrons can induced SEB in a variety of silicon power device technologies, e.g. MOSFETs, IGBTs, GTOs and diodes. Therefore, it is certainly possible that this new type of silicon device, the MCT, will also be susceptible to SEB. Thus, for applications above 2000V, WNR testing would be encouraged because SEB may be a concern due to the cosmic ray neutrons at ground and sea level.

There may be other future terrestrial power technology applications for which burnout induced by the cosmic ray neutrons may be important. One such example is that of an electrical car in which the battery system is designed to be operated at 400V. In this case, if a 600V power MOSFET were used, it would probably lead to burnout (based on Fig. 2), but if a 1000V MOSFET were used, burnout would be precluded, as shown in Fig. 2.

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