Destructive Single-Event Failures in Diodes

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Abstract**—**We examine single-event induced destructive failures in Schottky diodes. We first identified failures in DC-DC converters, and later confirmed their existence in independent diodes. The mechanism for failure along guard rings is also discussed.

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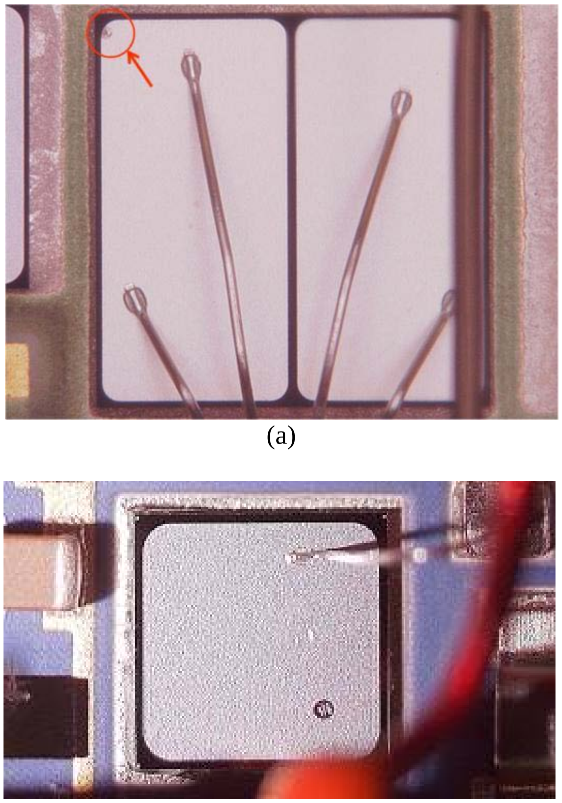
Introduction

In the 2012 Institute for Electrical and Electronics Engineers (IEEE) Nuclear and Space Radiation Effects Conference (NSREC) Radiation Effects Data Workshop (REDW) [1], O'Bryan, *et al.*, highlighted destructive single-event effects that were observed in DC-DC converters by two different manufacturers, International Rectifier (IR) [2] and Crane Aerospace [3]. In both cases, the failures were attributed to the shorting of the anode and the cathode of output diodes due to a heavy ion strike. Additional testing was completed by looking at the M3G280515T, the flight version (as opposed to the M3G2804R513R5T, which is an Engineering Test Unit [ETU]) of the IR DC-DC converter [4]. Both IR parts are triple output DC-DC converters with 28 V inputs. The flight version uses the same diodes as the ETU, but other components are replaced with radiation-hardened versions. Similarly, these parts were also susceptible to destructive single-event effects. The Crane DC-DC converters were the MTR28515, which is not a space-qualified part, but does come with total ionizing dose data. Like the IR parts, it is also a triple output converter with a 28 V input. Figures 1a and 1b show images of the damage to the output diodes [1] in the IR engineering unit and the Crane flight part, respectively. The failure in the IR part is along the guard ring, while the location of the failure in the diode used in the Crane converter is more centrally located.


(a)

(b)

Fig. 1. The small dots are the locations where the metal melted due to the single-event in the (a) M3G2804R513R5TEM engineering model and in the (b) MTR28515 [1].

Hundreds, if not thousands, of diodes are routinely flown on spacecraft, and generally are not considered to be susceptible to single-event effects. The implication of these diode failures could be catastrophic to scientific instruments, or even entire spacecraft, necessitating full understanding of the scope of the issue. In this paper, the diodes internal to the DC/DC converters previously tested were independently irradiated in order to identify and understand the failure mechanism and then calculate failure rates to determine the severity of the potential impact to NASA missions.

Test Facilities and Experimental Set-Up

Parts Tested

The diodes irradiated in this work are the ON Semiconductor MBR20200CT [5], which are a dual 200 V, 20 A Schottkey diodes. This part was used on the outputs of both IR DC/DC converters. A total of 45 MBR20200CT diodes were irradiated.

The diode in the Crane converter is manufactured to the specifications of their own Source Control Drawing (SCD), but they are the equivalent to the Sensitron SD125SB45A [6]. These diodes are 45 V, 15 A Schottkey rectifiers. These diodes are not only used in the MTR family of converters, but they are also used in the space-qualified equivalents, the SMTR line. 25 diodes were available for testing, but ultimately, only 4 were irradiated.

Test Facilities

The Sensitron diodes were tested at Lawrence Berkeley National Laboratory's (LBNL) 88" cyclotron using the 10 MeV/amu beam cocktail. The ON Semi diodes, however, were tested on multiple occasions at both LBNL and Texas A&M University's (TAMU) Radiation Effects Facility at the Cyclotron Institute. The ion beam cocktails used were the 10 MeV/amu tune at LBNL, and the 15 MeV/amu and 25 MeV/amu tunes at TAMU.

Test Set-Up

The experiments were conducted using the NASA GSFC high-voltage power MOSFET motherboard, which is pictured in Figure 2 with five of the MBR20200s mounted on daughter cards connected to the motherboard. This board was designed to enable testing of 6 parts without having to enter the cave and manually move cables or parts. In order to test the diodes, no gate connection was made, and the cathode was connected to the source test points on the board. Likewise, the anode of the diodes was connected to the drain locations. In the case of the MBR20200s, since they are dual diodes, the cathodes and anodes were simply shorted to each other.

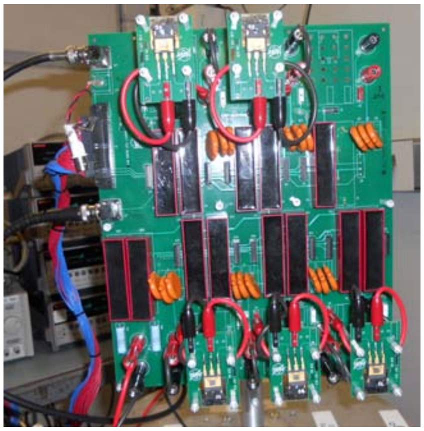


Fig. 2. High-voltage power MOSFET test board equipped with five MBR20200 mounted on daughtercards.

We used a Keithley 2410 SourceMeter for the anode and cathode voltages. A Data Acquisition unit (DAQ), the Agilent 34907A, was used to switch between the six parts in the chamber at a given time. There was also a 1 GHz mixed-signal oscilloscope, a Tektronix MSO5104, to capture any transients or other waveforms that might be seen on the output. A Keithley 2400 SourceMeter was also used to supply power to the relays on the motherboard. We controlled all the equipment using a personal computer and two LabView programs, one to capture and save the waveforms from the oscilloscope and one to supply the appropriate voltage to the diodes and run the post-irradiation tests.

Test Results

ON Semiconductor MBR20200CT

Previous work indicated that Schottky diode failures due to single-events [7] occur along the guard rings [8], which is where the MBR20200CT in the M3G2804R513R5TEM appear to fail as well. In [8], Ralston-Good shows that a short is formed between the guard ring and the n+ substrate of Schottky diodes when an ionizing radiation pulse is simulated. This short causes localized temperature rises from increased electric fields due to increased potential gradients over small areas. This increase in temperature causes the carrier concentration to increase exponentially, leading to a mesoplasma [9, 10] at the guard ring. A similar phenomenon could occur with the ion track from a heavy ion, shorting the guard ring and silicon substrate, leading to a mesoplasma at the guard ring.

The ON Semi diodes were tested on four different occasions. It was quickly determined that, independent of the IR DC-DC converters, the diodes are, in fact, susceptible to destructive SEEs. EEE-INST-002 states that all diodes should be derated to 75% of rated voltage, so in theory, these diodes could be used up to a voltage of 150 V. Figure 3 shows the last reverse voltage value at which the diode was biased before it suffered a destructive failure. The parts irradiated with 508 MeV V (here V is for Vanadium, rather than voltage) failed at voltages slightly greater than 150 V. The parts irradiated with 1032 MeV Kr, however, failed considerably below the 75% of rated voltage threshold. Fortunately, Kr is above the iron knee in the galactic cosmic ray linear energy transfer spectrum, so the abundance in space is lower, which will reduce the failure rate.

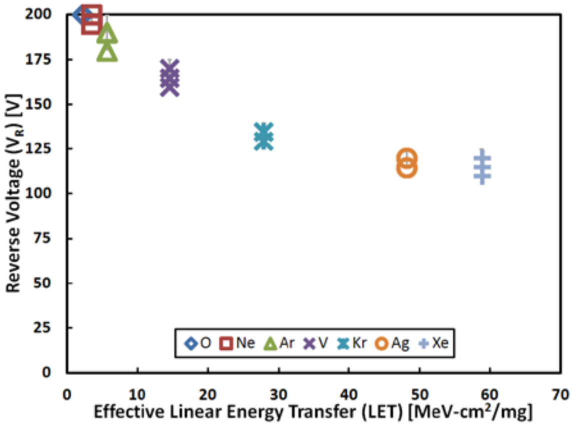


Fig. 3. The last voltage at which an ON Semiconductor MBR20200CT diode was irradiated without destructive failure. The error bars (many of which are smaller than the symbols) indicate the voltage at which the part did fail.

Additionally, the last passing voltage appears to bottom out around Ag, as it has roughly the same last passing and failure voltages as Xe. A similar phenomenon has been described by S. Liu, *et al.*, in power MOSFETs [11]. The authors showed that a minimum field must be applied for power MOSFETs to be susceptible to single-event burnout. Ordinarily, the minimum drain voltage required for failure decreases with increasing atomic mass or increasing ion LET; however, when below the minimum field required for burnout, heavier ions no longer fail at a lower voltage than their lighter counterparts. Instead, the minimum failure drain voltage reaches an asymptote, and remains constant even when irradiated with heavier ions. This appears to be occurring in the diodes as well.

All data presented to this point have been at normal incidence. Figure 4 shows the last passing reverse voltage as a function of effective LET. The angles investigated with Ag were 10° and 30°, while with Xe, the parts were irradiated at angles of 10°, 30°, 45°, and 60°. The 0° data in this figure are the Ag and Xe data included in Figure 3. Surprisingly, the last passing voltage does not improve with angle as quickly as might be expected. This is illustrated in Figure 5, where the last passing voltage is plotted as function of angle, rather than LET, for Ag and Xe. The data up to and including the 45° points follow the cosine law, as expected; however, the 60° points make the trend much more linear in appearance. This is likely due to the large charge collection volume inherent in diodes. Unlike CMOS, where the collection volume is limited solely to the channel, the collection volume is really the entire silicon cathode. As a result, the volume through which the ion track deposits charge does not decrease with the same severity at angle as it does through the small channels of MOSFETs.

While it is difficult to accurately calculate destructive SEE cross-sections due to the delays associated with stopping the beam after the error has occurred, Figure 6 shows the failure cross-section as a function of Linear Energy Transfer (LET). The data have a clear onset threshold; no failures were observed with 183 MeV O (LET = 2.19 MeV-cm^2/mg), but they did occur at 195 V and 200 V with 216 MeV Ne (LET = 3.49 MeV-cm^2/mg). The cross-section values associated with O are plotted as an upperbound by simply taking the inverse of the fluence at the last passing voltage, which was the rated voltage of the diode, 200 Vm because no failures were observed at this point.

Using the data from the cross-section curve, failure rates can be calculated for the diode. Table 1 shows the failures per device per day for a number of solar conditions in a near-Earth interplanetary/geosynchronous orbit behind 100 mils (2.54 mm) of Al shielding.

TABLE 1.
Near-Earth interplanetary/geosynchronous failure rates for the MBR20200CT based on a variety of solar conditions.

	Errors/device-day
Solar Min	1.66E-05
Solar Max	4.36E-06
Worst Week	9.26E-03
Worst Day	4.64E-02
Worst 5 Minutes	1.74E-01

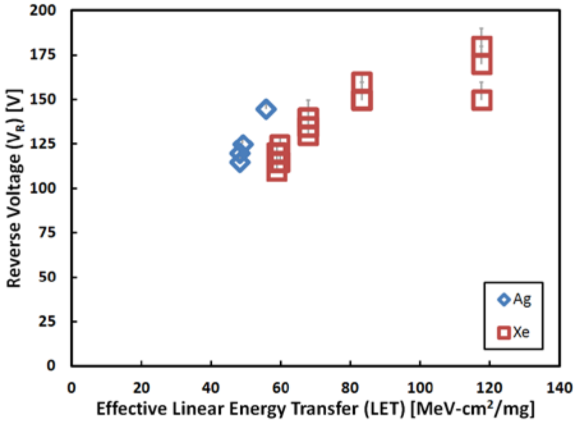


Fig. 4. The symbols indicate the last voltage at which an ON Semiconductor MBR20200CT diode passed. This figure only includes data from ions taken at angle. The 0° degree points are included as well and can also be found in Figure 3.

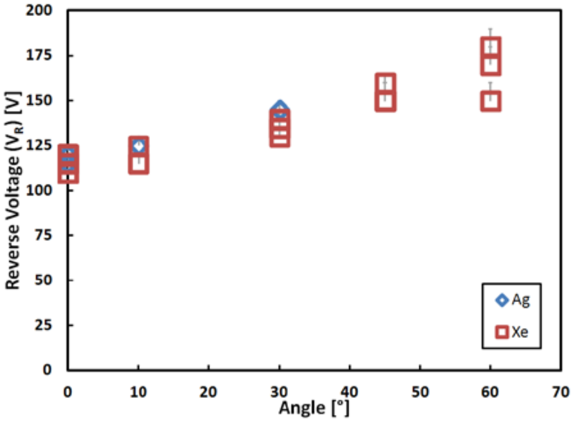


Fig. 5. Last passing reverse voltage as a function of angle for Ag and Xe irradiations of ON Semi MBR20200CT diodes. The charge collection volume does not change drastically with angle, hence, the last passing voltage also does not change quickly.

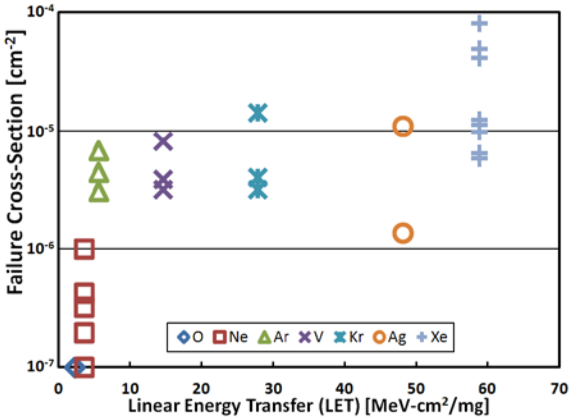


Fig. 6. Failure cross-section as a function of LET for the MBR20200CT diode.

These values were calculated using CRÈME-MC with an onset LET of 3.49 MeV-cm^2/mg and a saturated cross-section of 10^{-5} cm^{-2}, based roughly on the average of the Xe cross-section values as found in Figure 4. Based on the sheer number of diodes flying on a given spacecraft and the length of NASA missions, single-event-induced diode failures could become a serious issue.

Sensitron SD125SB45A

The Sensitron SD125SB45A 45 V Schottky diodes were irradiated with 1232 MeV Xe (LET = 58.8 MeV-cm^2/mg) at LBNL. No diodes failed during these irradiations. During the original MTR28515 experiments, the converters saw no destructive failures with TAMU's 1934 MeV Xe, which has an LET of 51.5 MeV-cm^2/mg after a 30 mm air gap. The failures only occurred in the converter when irradiated with 2714 MeV Ta (LET = 77.3 MeV-cm^2/mg, also with a 30 mm air gap), indicating that either the minimum LET threshold was not met, or possibly that something other than an SEE failure was observed in the diode in the converter, latent ESD damage for instance. Because the location of the failure, as indicated in Figure 1b, was not along the guard ring, like the MBR20200s, and the inability to destroy the diode independently, strengthens the argument that the failure in the MTR28515 may be due to something other than burnout in the diode. Interestingly though, the diodes tested by Titus et al., in [8] were 150 V and 45 V Schottky rectifiers from IR, and like in this work, the 45 V diode did not fail under high dose rate conditions, but the parts with higher voltage ratings did.

Conclusions

In this summary, we have shown that diodes are susceptible to destructive single-event effects, and that these failures occur along the guard ring. By determining the last passing voltages, a safe operating area can be derived. By derating off of those values, rather than by the rated voltage, like what is currently done with power MOSFETs, we can work to ensure the safety of future missions.

However, there are still open questions about these failures. Are they limited to a single manufacturer, a small number, or all of them? Is there a threshold rated voltage that must be exceeded to see these failures? With future work, we hope to answer these questions. In the full paper, laser results will also be presented to verify that failures only occur along the guard ring.

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