Effects of Radiation on Commercial Power Devices

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Abstract-**The effect of various commercial power devices are presented. The devices have proved to be very fragile to single event effects, with some of the devices actually succumbing to catastrophic SEE with protons.**

Index terms—IGBT; BJT; switch; transistor; radiation, protons, heavy ions

I. Introduction

Many space applications are demanding more power and higher voltages. Unfortunately, the technology behind high blocking voltages in discrete devices is susceptible to radiation effects. The large feature sizes and low doped regions of silicon are the underlying liable areas of these devices to radiation. Many applications used is space require the devices to be in states that increase the susceptibility of power devices to radiation effects, such as no or low bias.

Most power solutions for design approaches in space employee the vertical power MOSFET, but these devices present limitations and trade challenges to NASA applications that require high speed or very large power or current applications. Other power devices can be applied in situation that power MOSFETs fall short. Integrated Gated Bipolar Transistors (IGBTs) are often used to offset the input leakage of bipolar power transistors. Due to its complexity, the IGBT exhibits several failure modes due to radiation [1]-[4]. Power bipolar transistors also are options for space power applications, since they offer high speed, but also have shown several radiation liabilities [5], [6] as well as the usual radiation effects that bipolar devices exhibit. Applications with silicon controlled rectifiers (SCRs), or thyristor, have been applied to radiation environments and testing [7].

The work presents the results from various testing of discrete power devices including IGBTs, power bipolar devices, and SCRs. Single event testing was done with heavy ions and protons and focused on the static blocking of voltages with the failure modes similar, if not the same as, SEB and SEGR in MOSFETs. TID and DDD testing was done with protons and gamma radiation.

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II. Procedure And Setup

The test devices selected for radiation testing were power bipolar transistors, IGBT (Isolated Gate Bipolar Transistor), and SCR (Silicon Controlled Rectifier), which were purchased from various manufacturers. Table I lists the device used in this study. All of the selected power switches are vertically deep structure devices, which required the use of long-range ions. Thus, all of the selected devices were irradiated using heavy ions that were acquired at the Texas A&M Cyclotron Facility. In addition to heavy ion irradiation the power MOSFETs were also exposed to gamma-rays and protons. The gamma-rays were acquired from JPL's gamma-ray facility, which is a cobalt irradiator. A subset of the power MOSFETs were irradiated with 63MeV protons, which were acquired at UC Davis Cyclotron Facility.

To test for single event effects, the heavy ion and proton irradiations were performed under the following procedure. For heavy ions, the test procedure involved maintaining fixed fluence steps of $1x10^5$ ions/cm^2 with a flux of $1x10^4$ ions per second/cm^2. The proton irradiation occurred in $2x10^{13}$ cm^{-2} steps. For both, the gate-to-source voltage (Vgs) (or gate-to-emitter (Vge)) was held constant under a reversed biased condition. Following the irradiation, if the device under test (DUT) was still functional, the drain-to-source voltage (Vds) (or collector-to-emitter (Vce)) was increased by a ΔV (20 volts) and irradiated once more. This process was continued until the device failed, e.g., Ig > 1µA or Id > 1µA or Is > 1µA. The failure point is an arbitrary cutoff that has been extensively used in the radiation literature and so it was adopted here. During all heavy ion irradiation, the power MOSFETs were biased using an HP4142 Modular DC source monitor. The HP4142 was controlled a personal computer via a general-purpose instrument bus (GPIB).

A. IGBT test specifics

The IGBT that was selected for radiation testing was a device that was populated with four sets of devices, e.g., four BJTs and four MOSFETs. An IGBT is comprised of a BJT connected to a MOSFET driver. Thus, there were four IGBTs connected in series per each FF150R12KE3G. In order to test the radiation response of the IGBT, each component that made up an IGBT had to be isolated. Isolation was accomplished by

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disconnecting wires that connected each of the four IGBTs in series. Each DUT was then electrically isolated from each other by physically disconnecting the electrical contacts. In order to establish that each IGBT was fully functional following the decapsulation process, each IGBT that made up a FF150R12KE3G was electrically tested. Any damaged IGBT was tagged and discarded from the test matrix.

The ion beam selected was xenon with an LET of 40.4 MeV cm^2/mg at an energy of 15MeV/amu. An LET of 50.0 MeV cm^2/mg was also achieved through the use of degraders that were placed upstream of the DUT. The particle flux was $1x10^4$ ions/cm^2 per seconds and the fluence $1x10^5$ ions/cm^2.

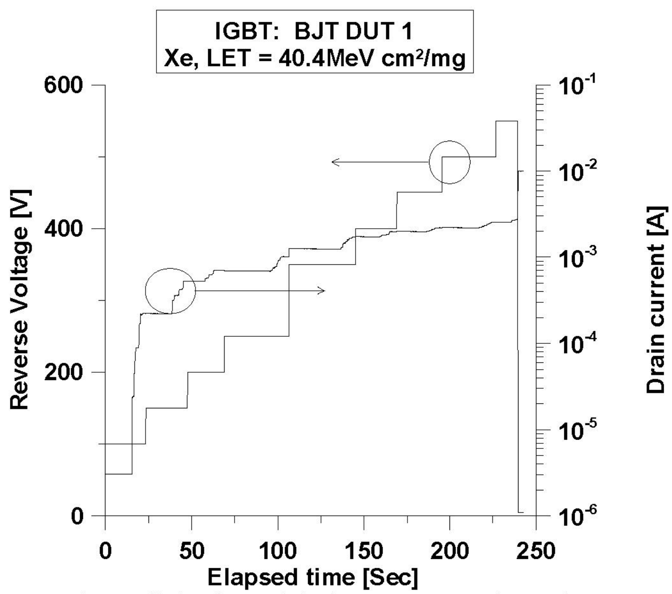

Fig. 1. Strip chart of device response to heavy ions.

B. SCR test specific

The SCR that was selected for radiation testing were packaged in a stud case style TO-209AC configuration. But in order to perform heavy ion irradiation, the die had to be exposed. Following the package removal all SCRs were electrically tested. Damaged SCRs were discarded from the test matrix.

The selected ions that were used to test the radiation response of the SCRs were gold (Au) with an energy of 2817 MeV, silver (Ag) with an energy of 1634 MeV, and argon (Ar) with an energy of 599 MeV. The LET and range in silicon for the various ions used were as follows: gold was 81.2 MeV cm^2/mg and a range in silicon of 148µm, silver 38.5 MeV cm^2/mg and a range of 156µm, and argon with an LET of 7.7 MeV cm^2/mg and a range of 229µm.

The gate contact is located at the center of the die and has a diameter of ~5mm. The cathode contact is located on the same side where the gate is located and its diameter is roughly the entire size of the die. This side of the die was referred to as the top of the die. On the opposite side of the gate and cathode contact is the anode. The entire back plane of the SCR is the anode. A special test fixture was designed for the irradiation of the SCR. Care was taken to ensure that most if not the entire die was exposed to the ion beam. The test fixture was also used to perform all electrical characterizations of the SCR.

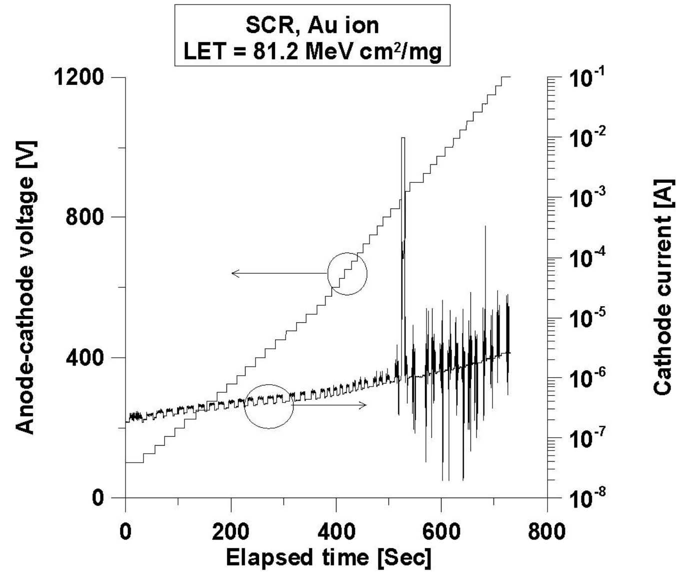

Fig. 2. Radiation response of the SCR DUT1 to gold ions. Shown in the Fig. are single event transients and a latch-up condition.

III. RESULTS

A. IGBT – Heavy Ions

Fig. 1 represents the radiation response of the BJT component in IGBT DUT1. The device was irradiated with xenon ions that had an incident LET value of 40.4 MeV cm^2/mg. The initial emitter-to-cathode voltage was set at 100 volts, at that voltage the cathode current exceeded the adopted failure criteria of 1µA. However, the high leakage current, Ice, that is observed in the Fig. can be attributed to photon-induced current. The overhead lights in the target chamber could not be turned off during the irradiation. Under the failure criteria, DUT1 failed at a voltage of 100 volts for an LET of 40.4 MeV cm^2/mg.

Table II shows the results of all IGBT radiation experiments conducted on each component. At an LET of 40.4 MeV cm^2/mg, the data shows that the BJT is very sensitive to single event effects. The MOSFET driver, on the other hand, failed at an emitter-to-cathode voltages of 1040 and 1100 volts, respectively. When an LET of 50 MeV cm^2/mg was utilized, no failures were observed for the BJT. This result is surprising. Additional testing should be undertaken in order to ascertain the validity of this result. The MOSFET driver was also irradiated with an LET of 50 MeV cm^2/mg and the results indicate that the MOSFET is very susceptible to SEGR at this LET value. The device failed with an emitter-to-cathode voltage of 40 volts. Again, additional radiation experiments are recommended in order to validate this result. These data indicated that range is definitely an issue for these devices.

B. IGBT – Protons

Four decapsulated Eupec FF150R12KE3G IGBT samples were irradiated in vacuum, using a very small beam size that allowed irradiation of only one MOSFET or BJT from one of the 4 IGBTs in a given sample. Pre-irradiation IGBT array leakage current ranged from 1 to 7 μA. For two samples, one BJT was irradiated while biasing only its corresponding IGBT and monitoring the IGBT's leakage. Both BJTs shorted out within the first second of irradiation, reaching leakage currents of 10 mA (the limit of the HP4142 power supply) and losing voltage (voltages dropped from 1000V to under 10V). Because the failures were reached in a time period shorter than our smallest measurement interval, we can state only that failure occurred at a fluence < 1.5 x 10^{11} p/cm^2). No recovery was observed upon stopping the beam, or following power cycling. The same behavior was observed for the additional two samples that were irradiated in vacuum, for which one MOSFET was irradiated while biasing only its corresponding IGBT.

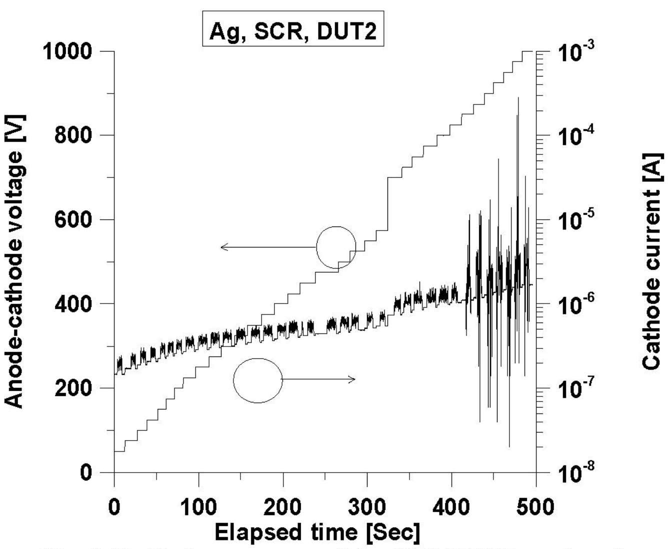

Fig. 3. Radiation response of the SCR DUT2 to silver ions. Shown in the Fig. are single event transients.

Table I. Devices tested in this study.

Man.	Part type	Part #	Blocking voltage	Cur. rating	Tested with
Eupec	TT121N12KOF	SCR	1200V	120A	Proton
IR	STO83S12PFK0	SCR	1200V	85A	Proton HI
Eupec	FF150R12KE3G	IGBT	1200V	150A	Proton HI

The results for the 2 virgin devices that were irradiated in air were inconsistent. The beam size was large enough so that one entire IGBT (out of the four per device) could be irradiated. Pre-irradiation leakage of the IGBT under test ranged from 0.2 to 0.7 μA. For one device, immediate failure was observed (at a fluence < 1.7 x 10^{10} p/cm^2). The other device shorted out at a fluence of 3.28 x 10^{13} p/cm^2. It was noted following irradiation that the virgin device that failed immediately was irradiated without certain packaging screws that partially cover the active regions. The presence of these screws in the virgin device that failed at 3.28 x 10^{13} p/cm^2 could have been shielding that device somewhat. As with the decapsulated samples, no recovery was observed following irradiation or power cycling.

C. SCR – Heavy ions

Table III shows the results of all radiation experiments conducted on the Silicon Controlled Rectifiers. The selected SCR is a device that is rated for 1200 volt. Thus, the highest voltage used was 1200 volts. Column 5 shows the anode-to-cathode voltage at which the cathode current exceeded the 1μA criteria. Column 6 displays information observed in the data for each DUT, transients or latch-ups.

Table II: Results of all IGBT irradiations.

IGBT #	Component tested	LET MeV cm^2/mg	last pass Vec (V)	Failure Vec (V)
DUT1	BJT	40.4	N/A	100
DUT4	BJT	40.4	N/A	100
DUT5	BJT	50	1100	no failure
DUT3	MOSFET	40.4	1020	1040
DUT2	MOSFET	40.4	1090	1100
DUT7	MOSFET	50	20	40

Fig. 2 shows the response of the SCR DUT1 for Au irradiation. At the anode-to-cathode voltage of 875 volts a latch-up was observed. The latch-up was negated via the cycling of power. Fig. 3 shows the radiation response of DUT2 to silver ions. No latch-ups were observed under this test condition. Multiple single event transients were observed starting at 850 volts. No permanent damage was noticed following all irradiations.

Table III: Radiation results for all tested SCRs (STO83S).

SCR #	Ion	LET (MeV cm^2/mg)	Last pass Vrev (V)	Failure point Vrev (V)	Comments:
DUT1	Au	81.2	875	900	Latch-up at 875V
DUT2	Ag	38.5	750	775	Multiple transients
DUT3	Ar	7.7	925	950	Multiple transients

D. SCR – Protons

The typical pre-irradiation forward off-state current of our TT121N12KOF samples was approximately 2.5 μA. This value exceeded 1 mA very rapidly during irradiation, within the first second of irradiation (the smallest time increment used for our measurements). This time period corresponded to a fluence of 1.7 x 10^{10} p/cm^2.

Fig. 4 shows the 63.3-MeV proton irradiation response of a representative Eupec SCR sample. The failure criterion of 10 mA was reached at an average fluence of 4.6 x 10^{12} p/cm^2 for the five delidded SCRs. As stated above, this device is a dual

SCR. Two samples had both of their SCRs irradiated (one at a time). The failure point was earlier for SCRs that were the second per sample to be irradiated (possibly due to beam scatter during the irradiation of the first SCR). The average failure point for the "first" SCRs was 6.2 x 10^{12} p/cm^2, and the average failure point for the "second" SCRs was 2 x 10^{12} p/cm^2.

Two virgin samples were also irradiated (on only one SCR per sample), and the average failure point was 3.4 x 10^{13} p/cm^2, an order of magnitude higher than for the delidded samples. Fig. 4 shows the forward off-state current response to 63.3-MeV protons of a virgin Eupec SCR.

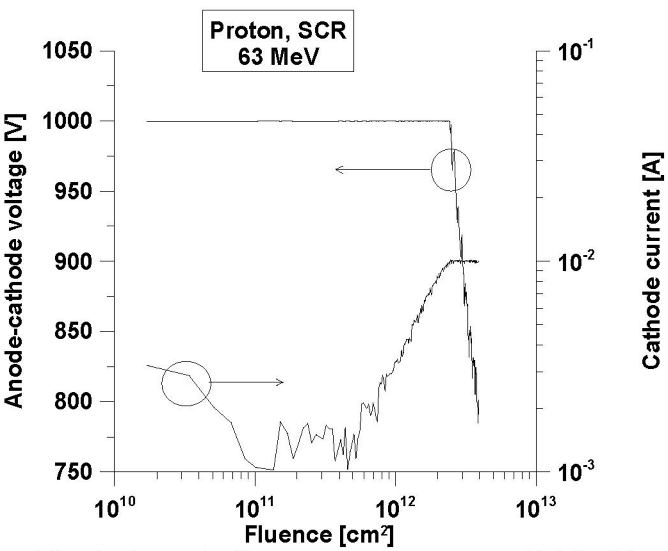

Fig. 4. Forward off-state current response to 63.3-MeV protons. The DUT is a virgin Eupec TT121N12KOF SCR, biased at 1000V.

Only one of the five irradiated IR STO83S12PFK0 SCR samples was irradiated while decapsulated from its packaging. The pre-irradiation off-state leakage current, while biased at 1000V, was approximately 2.5 µA. The 10 mA failure criterion was reached at a fluence of 9.07 x 10^{12} p/cm^2. After the beam was turned off (and the DUT was still under bias), the leakage current remained at the limit of the power supply, and the voltage dropped, until leveling off at 572V. This behavior is presented in Fig. 5. After a subsequent 10-minute period with no bias, the leakage current had dropped to < 0.2 mA. The DUT was monitored for an additional seven minutes under bias, and the leakage current dropped to 0.08 mA by the end of that interval.

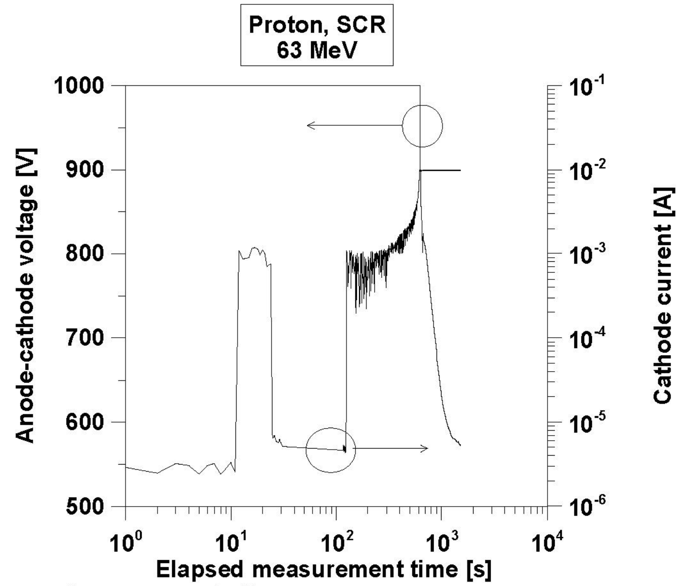

Fig. 5. Forward off-state current response to 63.3-MeV protons. The DUT is a decapsulated IR STO83S12PFK0 SCR, biased at 1000V.

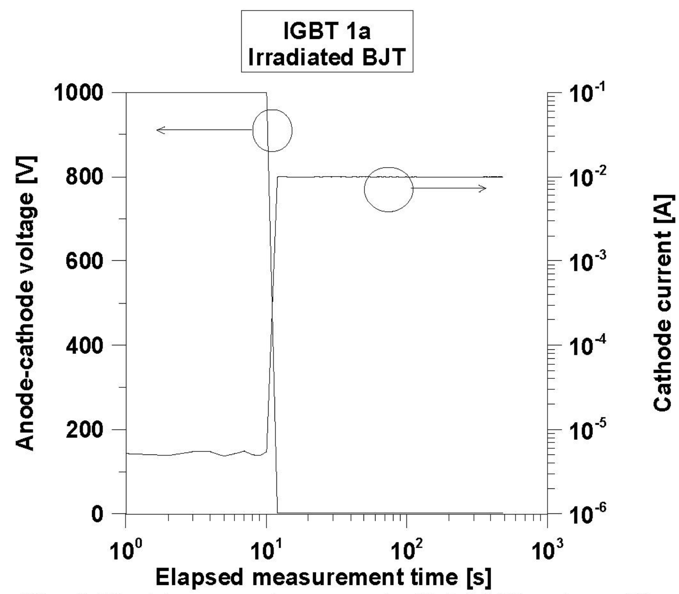

Fig. 6. Blocking current response to 63.3-MeV protons. The DUT is a BJT within a Eupec FF150R12KE3G IGBT; biased with 1000V, the gate off, and zero potential between the gate and emitter. The drop of VCE and railing of ICE is indicative of an SEE.

Since power cycling was necessary for annealing to begin, once the 10 mA current limit had been reached, it is reasonable to say that the mechanism is a type of latch-up condition that is reached gradually, as a function of fluence. However, it is interesting to note that the beam was lost during the irradiation of the decapsulated device. During the interval that the beam was off and the DUT was still biased, current recovery (lessening) was observed. This implies that dual mechanisms that are fluence dependent may be at play for the STO83S12PFK0.

The average pre-irradiation leakage current for the four virgin samples (irradiated with packaging intact) was 2.2 μA. The mean failure point for the four virgin devices was 3.6 x 10^{13} p/cm^2, with a standard deviation of 2.45 x 10^{12} p/cm^2. Limited post-irradiation characterization was performed on the virgin devices, but some recovery was seen following power cycling in these devices as well (with leakage current dropping to a few milliamps after 2-5 minutes). Fig. 6 shows the proton irradiation response of a representative virgin device.

For two samples, one BJT was irradiated while biasing only its corresponding IGBT and monitoring the IGBT's leakage. Both BJTs shorted out within the first second of irradiation, reaching leakage currents of 10 mA (the limit of the HP4142 power supply) and losing voltage (voltages dropped from 1000V to under 10V). Because the failures were reached in a time period shorter than our smallest measurement interval, we can state only that failure occurred at a fluence < 1.5 x 10^{11} p/cm^2). No recovery was observed upon stopping the beam, or following power cycling. The same behavior was observed for the additional two samples that were irradiated in vacuum, for which one MOSFET was irradiated while biasing only its corresponding IGBT.

IV. Conclusions

Not surprisingly, commercial off the shelf discrete power devices are vulnerable to radiation effects. With the large features, light doping, and extreme electric fields, the radiation damage mechanisms, like charge collection and displacement damage, are extremely prominent.

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