Catastrophic SEE on High-Voltage Power MOSFETs

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Abstract

SEE tests of high-voltage power MOSFETs from several manufacturers indicate long-range ions are worst case scenario for inducing SEGR/SEB. In situ measurements show SET in oxide can trigger SEGR and in epitaxial can elicit SEB.

Heavy ion irradiation of high-voltage power MOSFETs with long range ions (> 123μm in silicon) was performed using 14, 19, 22, 24, 28, and 39 MeV-cm^2/mg ions. Long range ions are more effective at inducing single event gate rupture (SEGR) than are short range ions. Prior to catastrophic failure some DUTs exhibited unusual electrical characteristics: 1. Increase in gate, drain and source current with increased V_{DS}, while V_{GS} was held constant. 2. Electrical breakdown at a lower V_{DS} value then expected. 3. All devices tested demonstrated high current single event transients (SET) (current spikes) at voltages significantly lower than the voltage at which the devices failed. 4. SEGR was observed for all but three DUTs, whose failure mode was single event burnout (SEB). Data from several different parts are presented.

I. INTRODUCTION

High-voltage power MOSFETs have not been widely used in past space missions. However, there is a current and increasing interest with in NASA for utilizing them in future missions. Radiation testing and evaluation of MOSFETs with high voltage rating (500V or greater) possess a new technical challenge, which test engineers must address. There is limited information available in the literature regarding the performance of high-voltage power MOSFETs in radiation environments. In this paper, SEGR and SEB results from a variety of high voltage power MOSFETs (550V to 1000V) manufactured by Fairchild, Advance Power Technology, and International Rectifier are presented.

II. DEVICE DESCRIPTION

All of the power MOSFETs tested were N-channel enhancement mode with gate-to-source (V_{GS}) voltage ratings of ± 20V with the exception of the Advanced Power Technology devices which have a voltage rating of ± 30V volts. Table 1 lists key properties of the MOSFETs used in this experiment. Epitaxial depth and doping levels were determined by spreading resistance measurements, conducted by Solecon Laboratories Incorporated using the four-point probe measurement technique.

Table 1: Manufacturer information for the power MOSFETs used in this experiment.

Part #	Mfr	V_{GS} Rating (volts)	Date code	Depth (μm)	Doping (ions/cm^3)	Uncertainty ±
IRHY7G30CMSE	IR	± 20	0048	100 113	~1x10^{18} ~1x10^{19}	36.5% 36.5%
IRFMG40	IR	± 20	9366*	100	~1x10^{18}	36.5%
IRHY7434CSE	IR	± 20	TBD	TBD	TBD	TBD
RFP4N100	Fairchild	± 20	TBD	125	~2x10^{18}	36.5%
APT10088HVR	APT	± 30	0218	TBD	TBD	TBD
APT1004RCN	APT	± 30	0042	100	~2x10^{18}	36.5%

*split into two groups: flight and non-flight.

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Of the six power MOSFET types used in this experiment only two are radiation hardened, they are the IRHY7G30CMSE and the IRHY7434CSE. The IRHY7G30CMSE devices that were tested came from the same wafer lot (B9003) and same date code 0048, with the exception of engineering samples I and II. The engineering samples were from different design development phases, which included variations in guard rings, doping concentration and epitaxial depth. The radiation hardened IRHY7434CSE has been used in previous space applications. This device was an unscreened and packaged TO-254 Bosch 550V power MOSFET. The IRFMG40 test batch was split into two groups, flight and non-flight. The flight group was designated as such based on additional screening performed on them by the manufacturer. The non-flight group was not screened. The Advanced Power Technology MOSFETs used were the APT1004RCN and the APT10088HVR, which are both 1000V power MOSFETs packaged in a TO-257 configuration. The only visible difference between these two devices is the die area, which is 4 times greater for the APT10088HVR than for the APT1004RCN. The Fairchild RFP4N100 power MOSFET was packaged in a plastic TO-220 configuration.

III. Experimental Details

SEGR and SEB are two types of catastrophic events that destroy a power MOSFET following the passage of an energetic heavy ion [1,2]. SEGR destroys the ability of the gate to regulate the current flow from the source to the drain by permanently damaging the insulator (SiO_2). SEB effectively shorts out the source to the drain. SEGR and SEB were defined as points on the V_{DS}, V_{GS} plane where the current (gate, drain, or source) exceeded 1µA during or following irradiation exposure under reverse bias conditions.

The test devices were all continuously monitored for leakage currents through the gate, source and drain. Prior to each irradiation, the DUT was measured with V_{GS} = specification maximum (–20V or –30V) and V_{DS} = 0V followed by V_{DS} = specification maximum (1000V) and V_{GS} = 0V. If the devices were still operational, the voltage was stepped up and the device was irradiated again. All DUTs were biased and measured with a Hewlett-Packard HP4142B high voltage module connected to a personal computer (PC) via a general purpose instrument bus (GPIB). Non-destructive electrical breakdown measurements were conducted on all DUTs using a Tektronix curve tracer type 576 prior to irradiation. Standard deviation was determined for each sample population and is listed in Table 2.

Table 2: Non-destructive electrical breakdown results.

Part # or sample population	Average breakdown (volts)	Standard Deviation (volts)
IRFMG40 (non-flight group)	1124.44	± 6.16
IRFMG40 (flight group)	1132.35	± 23.86
IRHY7G30CMSE	1310.00	± 89.44
IRHY7G30CMSE (Engineering Sample I)	1217.50	± 180.07
IRHY7G30CMSE (Engineering Sample II)	1021.25	± 44.54
IRHY7434CSE	615.26	± 25.25
RFP4N100	1099.29	± 60.85
APT1004RCN	1119.00	± 15.95
APT10088HVR	1109.60	± 19.89

Biasing conditions during irradiation was performed in any one of two gate-to-source (V_{GS}) voltages, i.e., –2V and –10V. A –20V gate-to-source was utilized to characterize the IRFMG40 non-flight group. The drain-to-source (V_{DS}) voltage was incremented in steps of 25 volts until SEGR and or SEB occurred. No stiffening capacitance or current limiting resistor was present between device and supply voltage. At each voltage step, the DUT was irradiated with a minimum fluence of $5x10^5$ particles/cm^2 and a flux of about $4x10^4$ particles/cm^2 per second.

All tests were performed at the Texas A&M Cyclotron facility with ions having 25MeV/AMU or higher in order to penetrate and exit the epitaxial region of each power MOSFET. Multiple values of Linear Energy Transfer (LET) values for krypton (^{78}Kr) were obtained by using attenuators to reduce the beam energy. Xenon (^{129}Xe) with an LET of 39.6 MeV-cm^2/mg was also used in this experiment. Table 3 lists the ions used in this experiment along with their corresponding range in silicon.

Table 3: List of ions used.

Ion	Energy (MeV)	Range in silicon (μm)	Incident LET(MeV cm^2/mg)
^{78}Kr	3120	601	14.2
^{78}Kr	1950*	320	19.0
^{78}Kr	2098*	197	24.0
^{78}Kr	948*	123	28.0
^{129}Xe	3197	254	39.6
^{79}Br	305**	33	39.8
^{127}I	343**	39	60.0

*Beam energy degraded by using attenuator.
**Beam used by IR to test IRHY7G30CMSE at BNL.

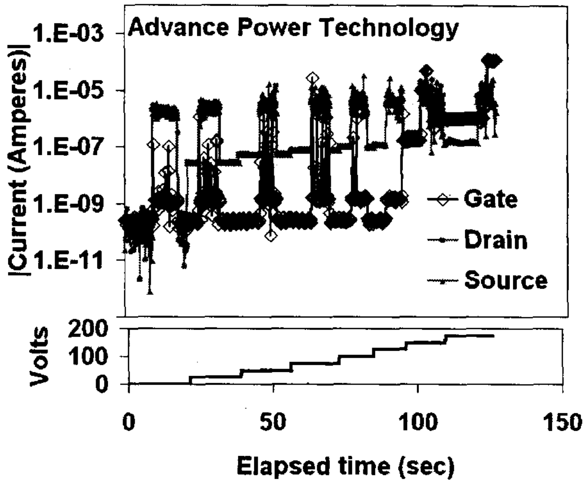
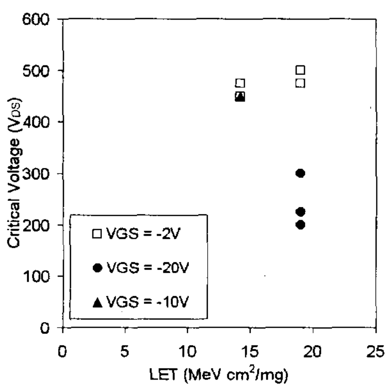


Figure 1: In situ DUT current measurement.

IV. TEST RESULTS

Figure 1 shows a typical strip chart captured during irradiation of a power MOSFET. The primary y-axis represents the current induced by the applied voltage and by the current generated by the electrons and holes, which were produced by the interactions of the traversing heavy ion (transient current spikes) with the active region of the MOSFET. The secondary y-axis represents the applied drain-to-source voltage. The x-axis represents the elapsed time of irradiation. The data shown on Figure 1 indicates that the DUT failed due to gate rupture (SEGR). Current from the gate flowed to the drain as well as to the source. Note the SETs that occur in the oxide at VDS values well below the eventual catastrophic failure.



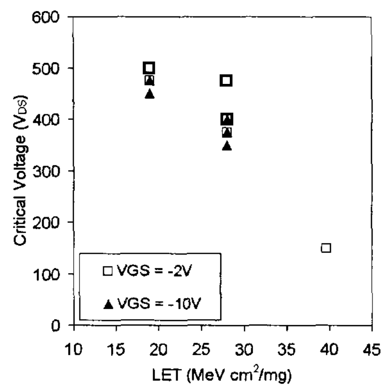


Figure 2: Radiation response of the IRFMG40 non-flight (left) and flight group (right) power MOSFET.

Figure 2 represents the radiation response of the IRFMG40 power MOSFET. The non-flight group (left graph) was biased with a gate-to-source bias of –2V, –10V, and –20V. The flight group (right graph) was biased with V_{GS} of –2 and –10V. All failures were due to gate rupture. At relatively low LET values both groups failed well below the expected electrical breakdown values (by ~40%), as shown in Table 2. At an LET of 39.6 MeV-cm^2/mg, the flight group DUTs failed at a V_{DS} of 125V with a V_{GS} of –2V. The variability of failure for this device for a given bias condition and LET was between 50V and 125V, V_{DS}.

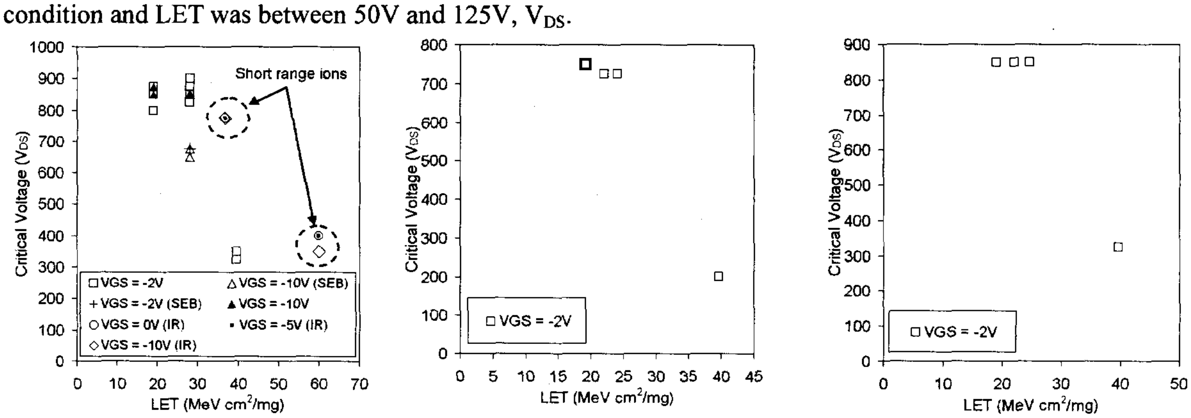


Figure 3: Radiation response of the IRHY7G30CMSE (left), engineering sample I (center) and II (right).

Figure 3 contains 3 graphs which represent the radiation response of the IRHY7G30CMSE and the two engineering samples I and II, respectively. Figure 3 (left) is a composite of two data sets, one is from the data set that we acquired during our radiation experiments and the other is the radiation experiment(s) reported by the manufacturer. Table 3 lists the ions that the manufacturer used. Two large dashed circles show the manufacturer's data. From spreading resistance measurements it is known that the epitaxial region of these devices ranges from 100μm to 113μm depending on which design phase the DUT comes from. The two data sets overlap at an LET of 39MeV-cm^2/mg. At this same LET value regardless of the bias conditions (0V, -5V, -10V), the short range ions do not elicit a failure until a V_{DS} of 775V. However, when long range ions are used with the same LET, failure is induced at a V_{DS} of 300V. In this same graph, failure points are labeled by a V_{GS} voltage followed by nothing or (SEB) or (IR), which represent SEGR failure, SEB failure or International Rectifier data with an unknown type of failure (SEGR or SEB). SEB was only found to occur with this device type at an LET of 28MeV-cm^2/mg. The variability of failure for this device for a given bias condition and LET was between 50V to 125V. At relatively low LET values all three MOSFET groups failed below the expected electrical breakdown values by 70%, 62%, and 83%, respectively; corresponding derated values (relative to 1000V) are 10%, 25% and 15%, respectively. Based on these test results IR has begun to modify and upgrade the IRHY7G30CMSE.

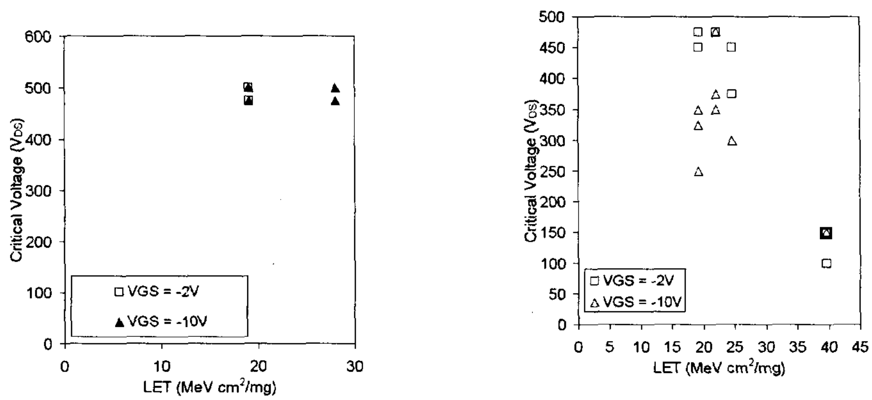
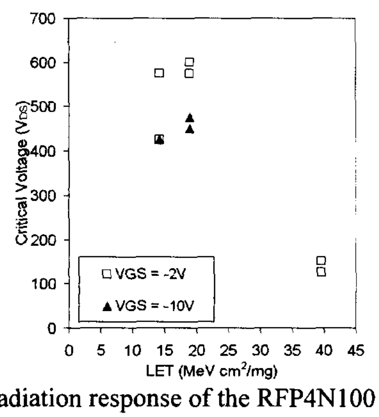


Figure 4: Radiation response of the APT1004RCN (left) and APT10088HVR (right).

Figure 4 represents the radiation response of the APT1004RCN (left graph) and APT10088HVR (right graph) by Advance Power Technology. At relatively low LET values, both of these devices failed at lower than expected electrical breakdown values by 45% and 43%, respectively. The variability in failure range from 25V to 125V for the APT10088HVR for a given LET and bias condition. At an LET of 39.6MeV-cm^2/mg, the device failed at a V_{DS} of 100V and a V_{GS} of –2V.



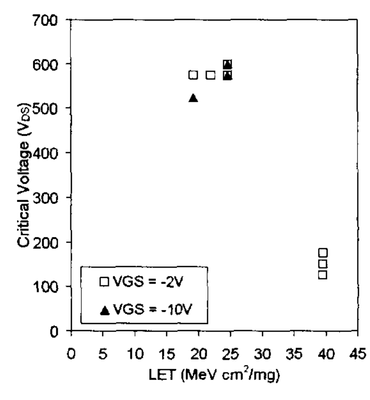


Figure 5: Radiation response of the RFP4N100 by Fairchild. Figure 6: Radiation response of the IRHY7434.

Figure 5 shows the radiation response of the RFP4N100 power MOSFET by Fairchild. At relatively low LET values, the device failed below the expected electrical breakdown value by 52%. The variability in failure ranged from 50V to 200V, V_{DS}. Figure 6 displays the radiation response of the IRHY7434, which is the only other radiation hardened 550V power MOSFET tested. At relatively low LET values, the device failed above the rated voltage (550V), but only slightly less than the expected electrical breakdown value of 615.25V ± 25.25V. The variability in failure is as high as 50V.

V. SUMMARY

Computer simulation and experiments have shown that when energetic heavy ions deposit energy near the Si/SiO_2 interface, a transient electric field is produced that is sensitive to the epitaxial doping, biasing conditions and ion track length [3]. Our current test results are in agreement with those previous results. Long range ions (ones that fully penetrate and exit the epi region) yield the worst case scenario for catastrophic failure. The SETs observed in the oxide are dependent on V_{DS}, but in the epi region they are not. In this study we found that DUTs with similar epi depth and doping concentration have similar radiation responses, i.e., IRFMG40 and APT1004RCN, even though both of these devices have different V_{GS} rating, ± 20V and ± 30V, respectively. SEGR was found to occur in all but three DUTs. Those three DUTs failed due to SEB for a particular manufacturer and a specific LET. The full paper will have additional strip charts generated from other in situ measurements, which show partial oxide ruptures (<1 μA) and transient current spikes (>1 μA with no SEGR) and the three DUT which failed due to SEB.

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