FIRST NONDESTRUCTIVE MEASUREMENTS OF POWER MOSFET SINGLE EVENT BURNOUT CROSS SECTIONS

Dennis L. Oberg and Jerry L. Wert
Boeing Aerospace Company
Seattle, WA 98124-2499

ABSTRACT

A new technique to nondestructively measure single event burnout `cross sections for N-channel power MOSFETs is presented. Previous measurements of power MOSFET burnout susceptibility have been destructive and thus not conducive to providing statistically meaningful burnout probabilities. The nondestructive technique and data for various device types taken at several accelerators, including the LBL Bevalac, are documented. Several new phenomena are observed.

INTRODUCTION

Power MOSFETs have been increasingly utilized in many spacecraft systems [1]. It has recently been observed [2,3] that destructive burnout of these devices can be caused by single heavy ions, such as are found in cosmic rays.

Previous measurements of power MOSFET burnout susceptibility have been destructive. Devices were irradiated while the device drain-source voltage (V_{ds}) was increased until the device burned out. Thus, statistically meaningful data resulted in the destruction of many devices of each type, date code, and manufacturer for data at several values of V_{ds}, linear energy transfer (LET), and ion incident angle. An innovative current-pulse counting technique has been developed which, combined with current limiting, allows nondestructive measurement of power MOSFET burnout cross sections. For the first time, the current pulse structure has been seen (for both actual burnout and current limited cases). This may give insight into burnout mechanisms. Data have been acquired at several accelerators: the tandem Van de Graaff at the University of Washington's Nuclear Physics Laboratory, the 88-inch cyclotron at Lawrence Berkeley Laboratory (LBL) operated by the University of California, and the LBL Bevatron/Bevalac. A test system that interfaces to the Van de Graaff and the Bevalac is described.

It is shown that virtually the entire area of a power MOSFET chip is sensitive to burnout inducing ions. Evidence that charge collection may vary non-linearly over the track length is discussed.

TEST METHODOLOGY

CURRENT PULSE TECHNIQUE - We have developed a technique to observe nondestructive current pulses while avoiding device burnout. (As we shall demonstrate, these are pulses which would

NON-DESTRUCTIVE PULSE - Figure 2 shows a typical current pulse taken with 90 MeV incident chlorine ions at the Van de Graaff. This pulse was taken with a protection load resistor of 1k Ohm. The rise time for the pulse in figure 2 is seen to be approximately 20 ns, the peak current is about 0.6 A, and the total charge is about 40 nC. Clearly, this large value of current cannot be supplied through the 1K Ohm load resistor at 200 Volts. These pulses, therefore, must be caused by the discharge of the parasitic capacitance of the power MOSFET. The required value of capacitance to store this amount of charge is 200 pF. This is comparable to values listed in the data book [4]. The pulse amplitude is seen to be proportional to V_{ds}, as expected. We have prevented device burnout by current limiting. This demonstrates that the energy stored by the parasitic capacitance is not sufficient, by itself, to cause device failure. Voltage pulses similar in shape to those described above are observed at the gate of the power MOSFET in coincidence with the current pulse on the source. This gate signal is due primarily to coupling through the internal "Miller" capacitance. The resulting drain current also causes a voltage drop across the load resistor. The drain voltage recovers to the applied V_{ds} after approximately 1 μs.

BURNOUT PULSE - In figure 3, a destructive current pulse is depicted where the protection resistor has been shorted out. This is a drawing based on a composite of oscilloscope pictures taken at different sweep speeds. One can see the initial current pulse, similar in pulse width to that of a nondestructive pulse (also shown), but with a higher amplitude, followed by several smaller pulses. Noting the time scale change, a large long pulse, which is the actual "burnout", follows. This final pulse, of approximately 5000 nC, corresponds to more than 100 times the energy of a nondestructive pulse. The device was inspected after this pulse and found to be inoperative.

Using a laser test system [5], it was possible, in many cases, to protect a device from burnout, even though the load resistance was set to 0 Ohms. This was accomplished by applying a positive signal to the gate of the test device within approximately 400 ns after the laser pulse (i.e., prior to the actual "burnout" pulse, in figure 3). This gate signal turned the device on and reduced the effective V_{ds} below the burnout voltage threshold. Note that this is essentially what the protection resistor does in our circuit.

Proof of technique

TRUE BURNOUT - It is appreciated that proof is required to establish the correspondence of these current pulses with true burnout. An "informal" proof will be provided in the observation that a nondestructive current pulse occurs "if and only if" an actual burnout occurs (depending only on load impedance).

1) While the ion flux is held constant and the load resistor set to 1k Ohm, the device V_{ds} is set to produce a current pulse every few seconds, or for a specific fluence. Subsequently, the load resistor is set to 0 Ohms. (Since the device is turned off, no current flows and the value of V_{ds} is unchanged.) This will result in device burnout a few seconds after the irradiation starts. The

CROSS SECTION - Measured cross section data must also be independent of protection circuit parameters. Burnout cross section is here defined as the number of nondestructive current pulses divided by the fluence. This is then corrected for the cosine of the incident angle.

Cross section measurements were taken for several values of load resistor and DC drain current. (The drain current was varied by adjusting the gate voltage while V_{ds} was held constant.) These cross sections are all in agreement, within statistical errors (see figure 4).

TEST SYSTEM INDEPENDENCE - The concept of this nondestructive pulse counting technique has been shared with another group investigating the power MOSFET burnout problem [3]. They have used a slightly different circuit, but still based on the current-limiting, pulse-counting concept described here. The same conclusions were reached by this group. This technique has been successfully tested at several different accelerators. Another group at Boeing, who are using a laser to induce burnout in power MOSFETs, has also used this technique [5].

Test system

VAN DE GRAAFF TESTING - Most of the testing has been performed at the University of Washington's Nuclear Physics Laboratory, using their model FN tandem Van de Graaff accelerator. Figure 5 shows the test setup. Ions are accelerated up to approximately 120 MeV (depending on ion). The ions are scattered by a gold foil at the center of the scattering chamber in order to provide an easily monitored, uniform flux over the devices. The ion fluence, incident on the foil, is determined by integrating the beam current, collected by a Faraday cup. A ratio for conversion to ion flux, incident on the device, is determined by counting the ions in the Rutherford scattering peak with a surface barrier detector at the position of the device under test. Our portable test system (also in figure 5) is used to automatically control and measure the beam fluence, step V_{ds}, and count nondestructive current pulses. From this data the system calculates cross sections (as defined above). The test system sets the initial V_{ds} to the rated drain-source breakdown voltage (BV_{dss}) and then takes exposures for a predetermined time, fluence, or number of current pulses. The value of V_{ds} is then stepped down and exposures are taken until the current pulse (i.e., burnout) threshold is reached.

BEVALAC TESTING - Tests were conducted at the LBL Bevalac with 600MeV/amu Fe ions. A variable water column was used to reduce the energy and, thereby, set the LET to a desired value. The test setup is shown in figure 6. It is essentially a combined version of the hardware and software which has been used for previous power MOSFET testing and that which has been used for testing RAMs at the Bevalac [6,7]. The hardware communicates with the Bevalac/Biomed control computer with RS232 and TTL signals. The test system is able to read the dose directly from the Bevalac interface as well as set the water column. The beam may be temporarily interrupted at the end of the run. A stepping motor is used to automatically change the incident angle of the beam relative to the device. The software calculates the water column required for a actual circuit depends on the cross section, heavy ion spectrum, and actual circuit parameters, such as duty cycle, and load impedance.

IONS, ENERGIES, AND LETS USED - Most of the Van de Graaff data has been taken using approximately 90 MeV chlorine and iodine ions. Limited data has also been taken with 72 & 20 MeV oxygen, 54 & 10 MeV carbon, and 32 & 14 MeV lithium. The first measurements of power MOSFET burnout at cosmic ray energies were recently made at the LBL Bevalac. Iron ions at three values of LET (2, 8, & 12-15 MeV-cm^2/mg) were used in the data taking. Cyclotron data was taken with 200 MeV copper ions. The above LET values are summarized in table 1. Voltage threshold data Burnout cross section data for devices tested at all of the facilities is shown in figures 7 (IRF130) & 8 (2N6766). Data are shown in figure 9 for an IRF350.

VOLTAGE THRESHOLD DATA DISCUSSION - It can be seen, in figures 7 &8, that the maximum cross section, at 100% rated BV_{dss} , is close to the same for all of the ions. However, the voltage threshold for burnout is lower for the higher energy cyclotron data. The LET of the iodine ions is actually higher than the LET of the copper. This is one indication that the charge collection region extends deeper than the 15 μm range of the iodine ions. Distinctive features of the Bevalac data are the lower cross section at high values of V_{ds} and the apparently lower voltage threshold. This low value of cross section at full voltage cannot be presently explained. (Normalization error seems to be ruled out since cross section data taken on RAMs during the same run, with the same setup and ions, agree with data taken elsewhere.)

LET SCAN DATA - Data were taken at several LETs for a 2N6766 at a constant voltage of 200 V. The data for the highest energies for each ion are connected by the lines depicted in figure 10. It appears that the burnout threshold, for V_{ds} = 200 Volts, is near an LET of 1 MeV-cm^2/mg. The data for the 32 MeV lithium is seen to be much larger than expected from the general trend of the data, based on LET. This indicates that ionization by the primary ion may not be responsible for this cross section. Kinematic calculations have been done by us which show that the recoil of the silicon nucleus, due to the incident lithium ion, is likely responsible for this larger cross section. The maximum energy of the silicon recoil is larger for the higher incident energy lithium than for the lower incident energy. This larger energy deposition results in the larger cross section.

ANGULAR SCAN DATA - The calculation of system failure rates requires cross section data at varying voltages, angles, and LETs. It is seen, above, that the cross section decreases for lower voltages and lower LETs. It had been seen previously [3], that the same was true for increasing off-normal incident angles. This angular fall off could then be folded into the burnout rate calculations resulting in a lower failure rate than for anisotropic burnout sensitivity. Recent measurements call this into question (at least for short-range ions and voltages near 100% BV_{dss}). Data for two part types are displayed in figures 11 & 12. Here one sees the expected decrease in cross section as one progresses from normal to small off-normal angles; however, the cross section is seen to increase at

NON-CORRELATED BURNOUT SITE POSITION - It is well to note at this point, that the burnout site usually appears near a gate stripe on the die. See figure 13. The large fractional active area has led us to conclude that the "instigating" site (where the ion strikes) may occur nearly anywhere on the chip. Laser testing using a NdYAG laser [5] has since verified this. In these laser tests it has been demonstrated that the damaged sites can be located away from the actual laser beam spot.

BURNOUT SPOT - As further verification that true burnout is being observed, a failed device was examined under a microscope using an infrared viewer. Power was then applied to the device and the suspected burnout site was seen to glow, indicating the location of the short circuit.

Charge collection depth

SHORT DEPTH - Additional lower energy data for carbon and oxygen ions is also plotted in figure 10. This total set of data can be interpreted as providing "proof" that the charge collection depth is short, compared to the range of the ions; that is, the data is monotonic with LET (which would be valid for depths short compared to the ion range), rather than total energy (which would be valid for long depths). Additionally, a positive correlation between the charge deposition for various depths and the (monotonically increasing) cross section occurs only for a "depth" for charge collection of 5 µm or less. This is comparable to the depth of the "p-wells" of the power MOSFETs.

LONG DEPTH - The data from the Bevalac and cyclotron indicate that the range is much greater, possibly as large as 60 µm. The longer range and, hence, higher total energy deposition, may account for the lower voltage threshold.

DISCUSSION - A possible conclusion that might be drawn from the conflicting depth data is that charge collection may be more efficient in the "p-wells", while still extending through the substrate. This is also in accord with the angular effects we have seen; that is, for short range ions, a larger fraction of the total energy is deposited in the "p-wells", as compared with the deeper regions, as the incident angle is increased.

CONCLUSIONS

We have shown that one can accurately and nondestructively obtain useful single event burnout cross section data on power MOSFETs.

We have seen that the parasitic stored energy is not enough to cause device failure. Thus, protecting devices from burnout in space systems is possible if the load impedance is large enough. The required value of inductance to provide this impedance may be quite small. We have provided new details of the burnout current pulse structure. We have also presented data relating to the charge collection depth and angular effects together with our preliminary interpretation.

ACKNOWLEDGMENTS

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TABLE

Ion	**Energy**	**LET**	**Range**
	(MeV)	(MeV-cm^2/mg)	(µm)
I	90	30-40	15
Cl	90	16	25
O	72	4	63
O	20	7	14
C	54	2	75
C	10	4	11
Li	32	0.5	150
Li	14	1	45

FIGURE CAPTIONS - *(figures are not included in this file)*

Figure 1. Power MOSFET Test Circuit - This circuit diagram shows the current pulse detector as well as the current limiting load resistor. The capacitors provide de-coupling and the inductors keep fast signals in one circuit from false triggering the second.

Figure 2. Nondestructive Burnout Pulse - A non-burnout pulse is shown. (Maximum current is 0.6 Amperes.)

Figure 3. Destructive Burnout Pulse - A destructive burnout pulse is depicted (solid line). To show details, a computer scanned "montage" of oscilloscope pictures, taken at different sweep speeds, was used. (Maximum current is 5 Amperes.) The pulse from figure 2 is included at the same scale (smaller pulse).

Figure 4. Cross Section Dependence - The relative single event burnout cross section (i.e., number of counts for a constant fluence) was measured as a function of drain current (set by varying the gate voltage) and load resistance. Variations are within expected statistical variations (shown as an error bar).

Figure 5. Van de Graaff Test Setup - The test setup used at the UW Van de Graaff is depicted. See text for details.

Figure 6. Bevalac Test Setup - Bevalac setup showing variable water column, portable test system and interfaces to the Bevalac control computer.

Figure 7. Burnout Cross Sections for the IRF130 - Single event burnout cross section data from the Van de Graaff and LBL cyclotron (copper) for the IRF130 (BV_{dss} = 100 Volts). (Average of two parts). Bevalac iron data is also shown. See text for details.

Figure 8. Burnout Cross Sections for the 2N6766 -Single event burnout cross section data from the Van de Graaff and LBL cyclotron (copper) for the 2N6766 (BV_{dss} = 200 Volts). (Average of two parts). Bevalac iron data is also shown. See text for details.

Figure 9. Burnout Cross Sections for the IRF350 - Single event burnout cross sections for IRF350 (BV_{dss} = 400 Volts) using iodine and chlorine data from the Van de Graaff. (Average of two parts).

Figure 10. LET Scan for the 2N6766 - Single event burnout cross section versus LET for 2N6766 (BV_{dss} = 200 Volts). (Average of two parts). Data taken at the Van de Graaff, using various ions, as indicated. See text for details.

Figure 11. Angular Scan for the IRF240 - Angular scan of single event burnout cross section data for an IRF240 (BV_{dss} = 200 Volts) at several values of V_{ds} . Chlorine ions at 90 MeV. (Average of two parts).

Figure 12. Angular Scan for the IRF250 - Angular scan of single event burnout cross section data