Observation of Single-Event Burnout During Inductive Switching

Leif Scheick, *Member IEEE*, Greg Allen, *Member IEEE*, Larry Edmonds, Rembrandt Schaefer, and Rob Menke

***Abstract*— A power MOSFET demonstrated destructive Single-Event Effect (SEE) during ion irradiation in a switching circuit. Further investigation showed that the inductive load causing a spike in the drain-to-source voltage (VDS) that exceeded the manufacturer's rating for several nanoseconds was enough to allow SEB. These results indicate that SEB may occur in a very short window and flyback is critical for disciplined power supply design.**

***Index Terms*—Single Event Effect, MOSFET, Gate Rupture, Burnout, Flyback**

I. Introduction

Power MOSFETs have long been known to experience both Single-Event Gate Rupture (SEGR) [1-6] and Single-Event Burnout (SEB) from heavy ions [7],[8]. These are pictorially shown in Fig. 1. Since both SEB and SEGR occur when the drain-to-source voltage (VDS) is above a threshold value, the approach typically used in space has been to reduce VDS to below the SEE threshold voltage, which is a process called derating. SEB events have been observed in space due to protons when VDS has exceeded the threshold [9-11]. SEE in MOSFETs is very complex and depends on many test and environmental factors [12].

In many power supply applications like a boost or buck converter, the inductance in the local circuit will cause a spike on the drain on the MOSFET which is called flyback. The magnitude and duration of the spike depends on several aspects of the circuit, but it can be a nanosecond to microseconds. In many cases, the load current of a power supply may increase the flyback magnitude and may exceed the safe operating area (SOA) of the MOSFET. In some proposed mitigation approaches to managing this risk, the short duration of the overstress period is considered enough to mitigate a possible SEE. Despite continuing evidence that SEGR/SEB occur on a nanosecond scale [13-14], a short overstress window would prohibit an event and would also reduce the cross-section enough to minimize risk.

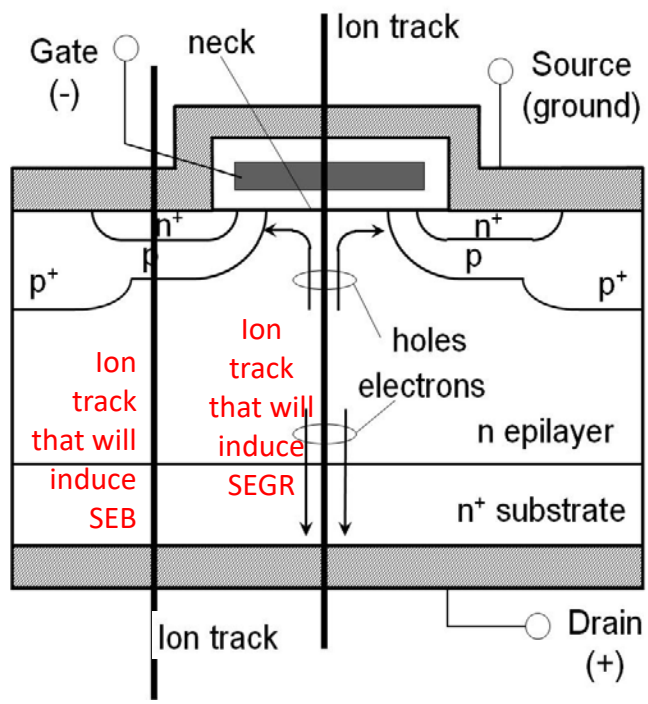


Fig. 1. 2D cross-section of a vertical Power MOSFET during an ion strike to the SEB (left ion track) and SEGR sensitive sites (right ion track). Proton and neutrons have also induced SEB.

Manuscript received July 14, 2017. The research in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Copyright 2017 California Institute of Technology. Government sponsorship acknowledged.

L. Z. Scheick is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (telephone: 818-354-3272, e-mail: leif.z.scheick@jpl.nasa.gov).

G. R. Allen is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (telephone: 818- 393-7558, e-mail: grallen@jpl.nasa.gov).

L. D. Edmonds is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (telephone: 818- 720-6660, e-mail: larry.edmonds@jpl.nasa.gov).

R, Schaefer is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (telephone: 818-393-2708, e-mail: Rembrant.Shaefer@jpl.nasa.gov).

R. Menke is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (telephone: 818393-7780, e-mail: Robert.Menke@jpl.nasa.gov).

The test discussed here was performed to show that an overstress on the order of nanoseconds of a MOSFET is enough to allow an SEGR or SEB to occur. To do this, a test circuit was designed such that the overshoot in the drain-to-source voltage was caused by inductive load. This was accomplished by testing in situ on the inductive load circuit. To test this vulnerability, SEE tests have been performed on MOSFETs installed in a circuit that was similar to a flight circuit. This type of testing would reveal which of the two failure modes was possible and determine the likelihood for power supply failure from either SEE type. This paper documents the test results.

II. Test Procedure

Eighteen high reliability and SEE hardened MOSFETs were chosen as part-to-part variation would be minimized. The Device Under Test (DUT) is a 250 V Hi-Rel Single N-Channel hardened (against SEE) MOSFET. This device is assured by the manufacturer to be SEE free up to 250 V when the gate-to-source voltage is zero volts. Fig. 2 shows the circuit that was tested. The gate was switched between 0 V to 5 V. The independent variable for the test was the load current, which changed the peak-to-peak voltage (Vpp) at the drain. The measured quantities of interest are Vpp at which the device fails in the beam, the fluence of ions to failure, and residual electrical parameters of the failed MOSFETs. DUT bias was actively monitored during testing as described below.

A. *Electrical measurements:*

The drain-to-source voltage was measured as a function of load current. The VDS was measured at the drain pin of the MOSFET with a 50 ohm Tektronix scope probe. Fig. 3 through Fig. 5 show example pre-rad scope captures under different loading conditions. The period of the test circuit is approximately 15 µs. Fig. 3 shows the "low-load" condition that has a spike in the V_{DS} smaller than the rated voltage of the device. Fig. 4 shows a "nominal load" condition that has the spike in the V_{DS} that goes above the device rating. Fig. 5 shows a V_{DS} spike with 200 ns per division time scale. Note the V_{DS} spike is above the 250 V rating for approximately 50 ns. This results in the DUT being out-of-spec for approximately 0.33% of a period.

It is important to note that in Fig. 5 the MOSFET does not operate in avalanche mode. MOSFETs have intrinsic reverse voltage from drain-to-source that is typically denoted BVD_{SS}. If that voltage is exceeded, high electric fields in the reverse biased P-N junction yield electron-hole pairs resulting in increased current in the drain. If avalanche mode were occurring in this device, the oscilloscope display in this case would be a clamped V_{DS} (which is not seen in Fig. 3), instead of the observed spike. The manufacture lists the minimum BVDss as 250 V in the datasheet while the actual BVDss is higher than that. This explains why the drain-to-source voltage on the DUT exceeds 250 V but does not exhibit avalanche mode operation.

B. *Test Sequence:*

Heavy ions testing was performed at the Texas A&M Radiation Effect Facility. A load current (which results in a a VDS) and test ion were selected and the device was irradiated to 10^7 ions/cm^2 or until device failure was seen. Until a cross-section was established with a given ion and load, a relatively low flux (10^3 ions/cm^2/s) was chosen. If no failure was observed after accumulating some fluence, the flux was gradually increased to 10^5 ions/cm^2/s during the run. If the device survived, the load current, and thus V_{DS} peak-to-peak, was increased and the test was repeated. This sequence was continued until device failure. In most cases two parts were tested in each ion condition to verify a SEB or SEGR. Fig. 6 shows the relation between load current and V_{DS} peak-to-peak.

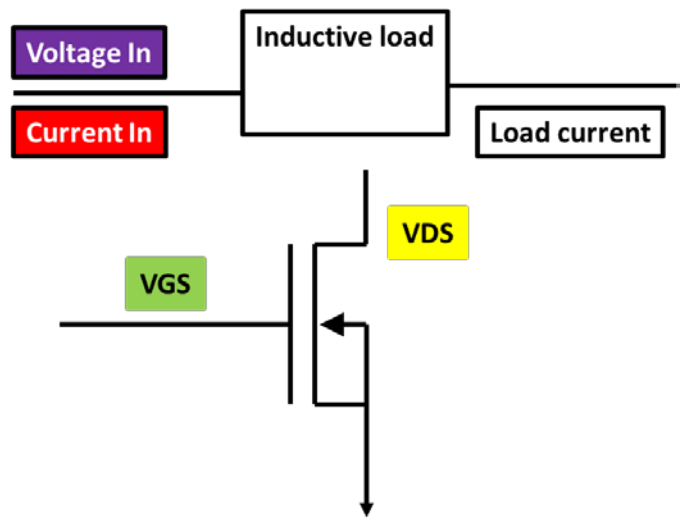


Fig. 2. Simplified test circuit. The load current was varied with an electronic load and the drain-to-source voltage, the input current, the gate-to-source voltage, and the input voltage to the test circuit were measured.

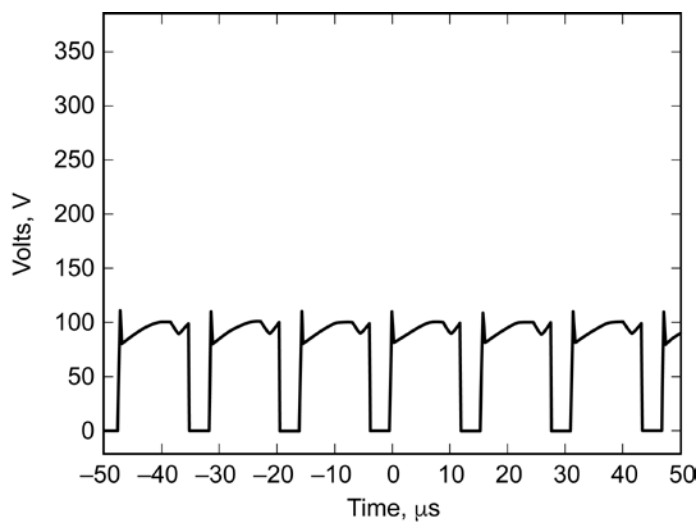


Fig. 3. The drain to source voltage on the MOSFET in the test circuit. The circuit load current is low, so the fly back from the inductor was low.

Protons testing was performed at the at Tri-University Meson Facility. The procedure was identical for protons except fluxes from 10^7 ions/cm^2/s to 10^8 ions/cm^2/s were chosen and

10^{11} ions/cm^2 as the target fluence. The proton energies were 20 MeV, 25 MeV, 45 MeV, and 105 MeV.

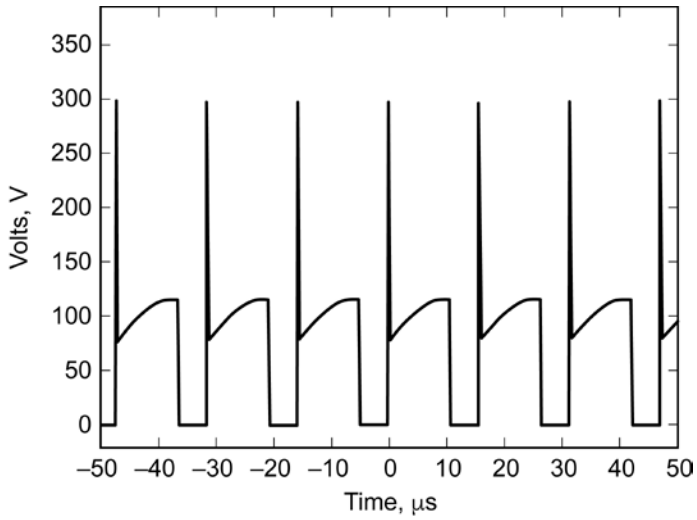
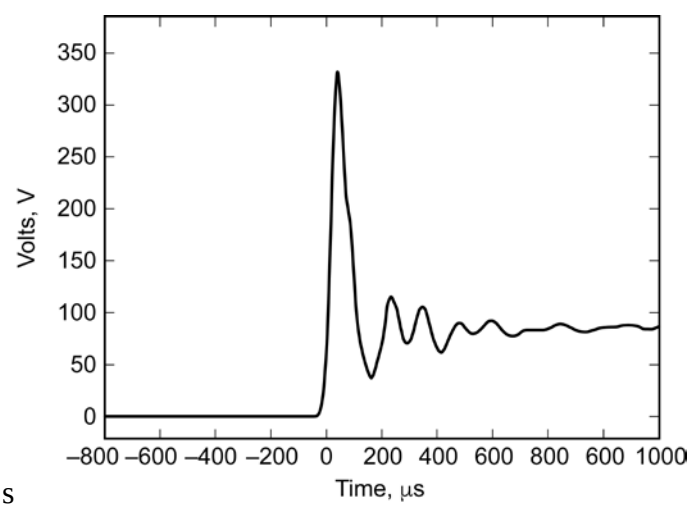


Fig. 4. "Nominal load" mode. In this condition, V_{DS} is at 300 V pk-pk. .



s

Fig. 5. Zoomed-in version of "Nominal Load" mode where V_{DS} at 334V pk-pk. .

III. RESULTS

All 18 DUTs exhibited catastrophic SEE, which resulted in circuit failure. Failure in all cases was prompt and irreversible. Fig. 7 shows scope captures of failure events induced by copper ions, and those from protons are shown in Fig. 8. The heavy ion results are shown in Fig. 9. Fig. 9 shows the cross-section as a function of V_{DS} and LET for heavy ions at TAMU and Fig. 10 shows the proton data at TRIUMF. Fig. 9 shows a typical cross-section with large error bars from fluence to failure measurements. Considering the low counting statistics and part-to-part variation, the wide variance in cross-section should not be surprising.

Once V_{DS} exceeds the threshold voltage, the cross-section as a function of Vds pk-pk voltage for SEB is roughly the area of the sensitive region multiplied by the fraction of time that V_{DS} exceeds the holding voltage (0.33% in this case). The cross-section at a given V_{DS}, LET combination (or V_{DS}, Energy) is the number of SEE divided by total fluence under failure conditions. Also of note, the resulting failure voltage varied only between 275 V and 305 V for the devices, which is between 110% and 122% of the rated voltage. This is well outside of the rated voltage of the device. Since the DUTs failed in the proton beam in a similar fashion to the heavy ions, SEB is the more likely failure mechanism. SEB and SEGR have been observed with protons and neutrons [9-11], [13] but is believed to be less likely for SEGR than for SEB. Considering that no SEE were seen when VDS < 300 V, the cross-section is expected be solely from overstress.

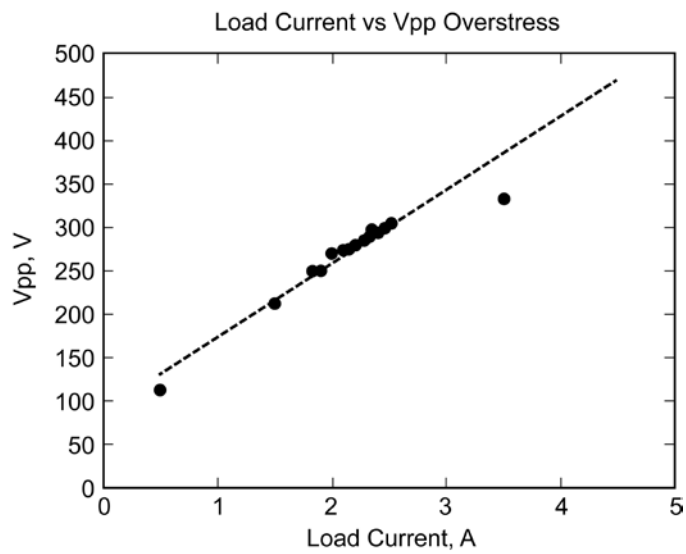


Fig. 6. Peak-to-peak V_{DS} as a function of load current for the test circuit.

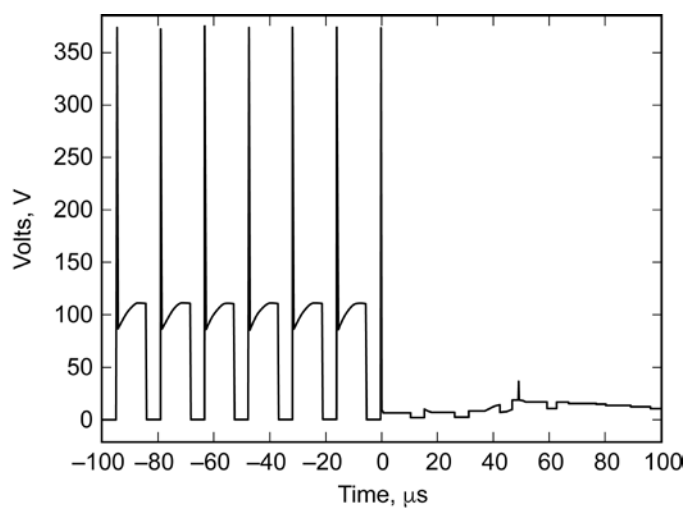


Fig. 7. Capture of a failure in the copper beam. The failure occurred during the inductive spike.

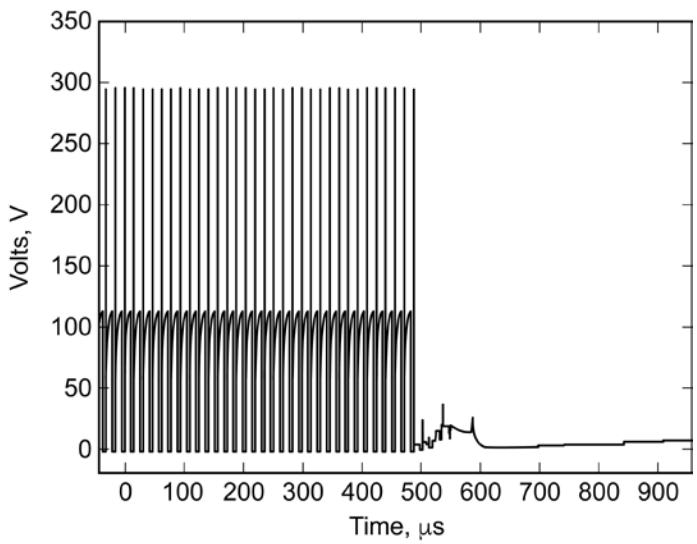


Fig. 8. Capture of a failure in the proton beam.

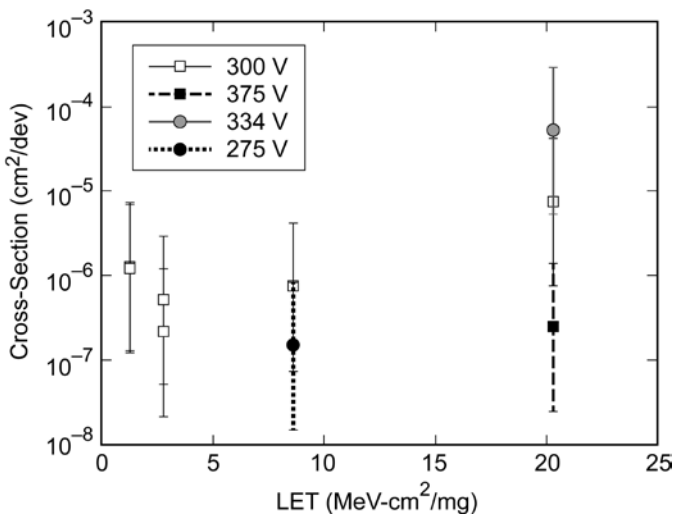


Fig. 9. Cross-section results for heavy ions. Error bars are 95% Poisson confidence.

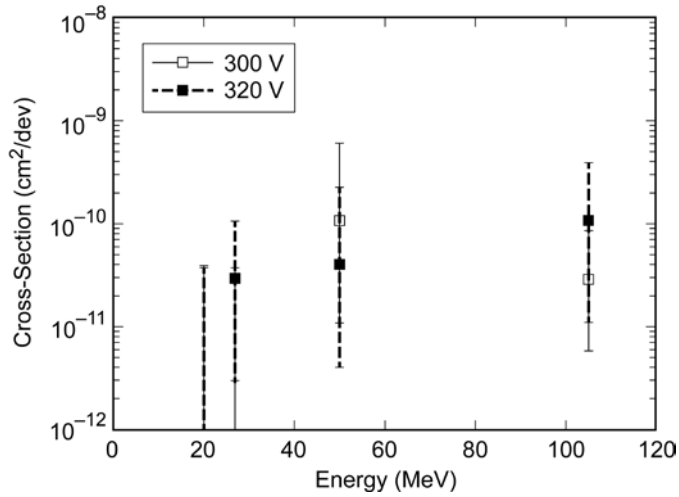


Fig. 10. Cross-section results for protons. Error bars are 95% Poisson confidence.

IV- DISCUSSION

SEB is the more likely failure mode, since protons were seen to induce the destructive SEE during our testing. SEGR have been observed with protons [13], however the effects seem to be small increases in leakage. Upon inspection of failed die with heavy ions (Fig. 11) and protons (Fig. 12), the failure site for both is indicative of SEB [3].

The cross-sections observed during testing include the approximate 0.33% overstress percentage of the test circuit period. This means that the cross-section estimated from the testing will be 0.33% of the cross-section that would be observed if the device were tested with a static voltage (above threshold.) The typical SEB cross-sections for power MOSFETs of this size are typically 10^{-3} to 10^{-1} cm^2 depending on VDS for heavy ions and 10^{-10} to 10^{-9} cm^2 for protons, so the measured cross-sections are commensurate with a proton hitting the device during the over stress spike. However, a particle may damage a device during non-overstress periods of the test circuit operation and then the overstress causes the device to fail. This scenario is considered much less likely due to the lower drain-to-source voltage when the gate-to-source voltage is close to 0 V; this voltage is ~100 V which is considered very low risk for latent damage. Regardless, the circuit test shows that the test circuit conditions result in data that predict a good probability of failure in the DUT. Another assumption of the approach is constantly operating in the same mode as during the test and at a constant load current. Since the cross-section will increase with increasing load current, we expect the rate will increase in this case. Likewise, if the power supply is not always on, the rate will drop. The neutron environment in a proton rich environment is also not considered. Secondary particles from proton and galactic cosmic ray induced nuclear reaction will produce these neutrons and will drive the rate up [8], [13]. Considering the sensitivity of the DUT in the test circuit, any radiation environment presents a threat to a MOSFET in a VDS application above the voltage at which SEE occurs.

V Conclusion

The conjecture that a short period where the drain-to-source voltage exceeds the SOA would be enough to mitigate an SEB or SEGR is disproven. The overstress period of tens of nanoseconds allowed for a destructive SEE to occur. The DUT showed destructive SEB under proton or heavy ion irradiation when operating in the power supply application with voltage stresses that exceed the manufacturer's rating (>250V). No tested device was seen to experience SEB when biased and irradiated at less than the manufacturers rating of 250 V. The energy threshold for proton induced SEB is roughly 20 MeV. Heavy ions with the lowest LET tested, 1.3 MeV-cm^2/mg, have also been observed to induce SEB during test. Further testing is planned to reduce the overstress period to determine if there is a period short enough to mitigate the SEE.

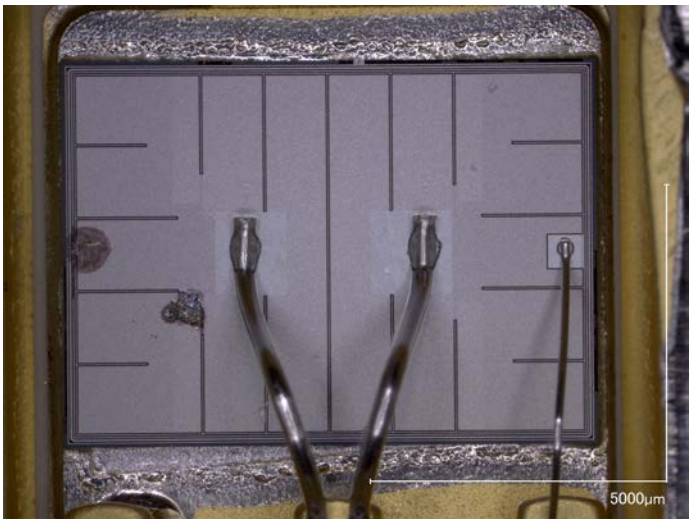


Fig. 11. Picture of a device that failed with heavy ions.

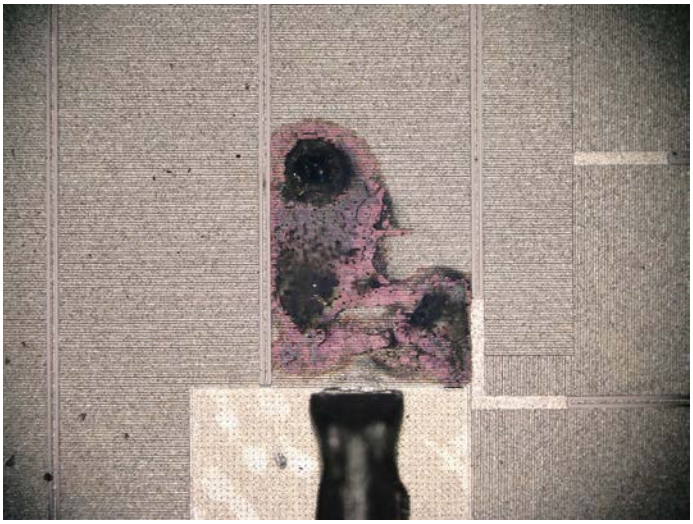


Fig. 12. Picture of a device that failed with protons.

References

[1] T. A. Fischer, "Heavy-ion-induced gate rupture in power MOSFETS," IEEE Trans. Nucl. Sci., vol. 34, pp. 1786–1791, Dec. 1987

[2] J. L. Titus and C. F. Wheatley, "Experimental studies of single-event gate rupture and burnout in vertical power MOSFETs," in *IEEE Transactions on Nuclear Science*, vol. 43, no. 2, pp. 533-545, Apr 1996.

[3] J. L. Titus, "An Updated Perspective of Single Event Gate Rupture and Single Event Burnout in Power MOSFETs," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 1912-1928, June 2013.

[4] T. H. Wheatley, C. F. Wheatley and J. L. Titus, "Early lethal SEGR failures of VDMOSFETs considering nonuniformity in the rad-hard device distribution," in *IEEE Transactions on Nuclear Science*, vol. 48, no. 6, pp. 2217-2221, Dec 2001.

[5] J. L. Titus *et al*., "Prediction of early lethal SEGR failures of VDMOSFETs for commercial space systems'," in *IEEE Transactions on Nuclear Science*, vol. 46, no. 6, pp. 1640-1651, Dec. 1999.

[6] J. L. Titus and C. F. Wheatley, "Proton-induced dielectric breakdown of power MOSFETs," in *IEEE Transactions on Nuclear Science*, vol. 45, no. 6, pp. 2891-2897, Dec 1998.

[7] A. E. Waskiewicz, J. W. Groninger, V. H. Strahan and D. M. Long, "Burnout of Power MOS Transistors with Heavy Ions of Californium-252," in *IEEE Transactions on Nuclear Science*, vol. 33, no. 6, pp. 1710-1713, Dec. 1986.

[8] D. L. Oberg and J. L. Wert, "First Nondestructive Measurements of Power MOSFET Single Event Burnout Cross-sections," in *IEEE Transactions on Nuclear Science*, vol. 34, no. 6, pp. 1736-1741, Dec. 1987.

[9] J. W. Adolphsen, J. L. Barth and G. B. Gee, "First observation of proton induced power MOSFET burnout in space: the CRUX experiment on APEX," in *IEEE Transactions on Nuclear Science*, vol. 43, no. 6, pp. 2921-2926, Dec 1996

[10] E. Normand, J. L. Wert, D. L. Oberg, P. R. Majewski, P. Voss and S. A. Wender, "Neutron-induced single event burnout in high voltage electronics," in *IEEE Transactions on Nuclear Science*, vol. 44, no. 6, pp. 2358-2366, Dec 1997.

[11] E. W. Cascio, K. J. Riley, J. McCormack and R. Flanagan, "Single Event Effects in Power MOSFETs Due to the Secondary Neutron Environment in a Proton Therapy Center," in *IEEE Transactions on Nuclear Science*, vol. 59, no. 6, pp. 3154-3159, Dec. 2012.

[12] V. Ferlet-Cavrois et al., "Influence of Beam Conditions and Energy for SEE Testing," *IEEE Transactions on Nuclear Science*, vol. 59, no. 4, pp. 1149-1160, Aug. 2012

[13] J. L. Titus, Yen-Sheng Su, M. W. Savage, R. V. Mickevicius and C. F. Wheatley, "Simulation study of single-event gate rupture using radiation-hardened stripe cell power MOSFET structures," in IEEE Transactions on Nuclear Science, vol. 50, no. 6, pp. 2256-2264, Dec. 2003.

[14] C. K. Maiti and T. P. Dash, "Simulation of single-event upset in power MOSFETs," 2017 Devices for Integrated Circuit (DevIC), Kalyani, 2017, pp. 25-29.

[15] A. Hands *et al*., "Single Event Effects in Power MOSFETs Due to Atmospheric and Thermal Neutrons," in *IEEE Transactions on Nuclear Science*, vol. 58, no. 6, pp. 2687-2694, Dec. 2011.