Functional Interrupts and Destructive Failures from Single Event Effect Testing of Point-Of-Load Devices

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35-word Abstract: We show examples of single event functional interrupt and destructive failure in modern POL devices. The increasing complexity and diversity of the design and process introduce hard SEE modes that are triggered by various mechanisms.

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I. INTRODUCTION

Power management has become increasingly important in modern integrated circuit (IC) designs. The power architectures in modern ICs are designed around microprocessors, Application-Specific-Integrated-Circuits (ASIC), or Field-Programmable-Gate-Arrays (FPGA). The supply voltage of these devices has continued to shrink (1.5 V for current generation), to keep pace with Moore's Law. However the current requirement has not decreased in the same fashion. As a result, the increasing power dissipation has created challenges for efficient power distribution. Efficient power management is particularly important in satellite and flight systems, where the limited board space complicates heat dissipation means. Flight systems necessarily had to adopt a distributed power system, where point-of-load (POL) devices are placed in close proximity to each load [1]–[2]. The distributed architecture reduces power losses and improves system efficiency [1]. The developments have prompted product innovations and advances in POL devices (e.g. linear regulators, switching regulators, and DC/DC converters).

The radiation susceptibility of POL devices has remained an important consideration for system hardness assurance. Voltage regulators are often designed with bipolar or BiCMOS technologies, due to the high current drive and fast switching requirements. The bipolar processes are vulnerable to enhanced low dose rate sensitivity (ELDRS), a challenging hardness assurance issue for bipolar ICs [3]–[4]. These circuit types are also susceptible to single event effects (SEE), with single event transients (SET) the most commonly dealt issue [5]–[6]. Most applications will require output capacitive filtering elements to suppress single ion-induced voltage glitches. Fortunately most circuit designs ordinarily already include several stages of capacitive filtering that are sufficient to handle the majority of the smaller SETs.

The most pertinent issue for radiation hardness assurance is destructive SEE. Single event latchup (SEL) is a common concern for many of today's state-of-the-art microelectronics. CMOS processes are generally much more susceptible to SEL than most bipolar processes. The POL devices that are designed with bipolar processes will be relatively less prone to SEL than other device types. However bipolar circuits can be susceptible to single event burnout (SEB) and single event dielectric rupture (SEDR). Moreover, many of today's POL devices incorporate hybrid designs with exotic technologies, which increase the vulnerability to various types of destructive SEEs. Some switching regulator designs employ several different types of technologies, including bipolar, CMOS, and/or BiCMOS processes with integrated power MOSFETs. The power MOSFETs are particularly vulnerable to SEB and single event gate rupture (SEGR), both of which are destructive and non-recoverable [7]–[9]. We show examples of such destructive failures in a state-of-the-art commercial switching regulator.

Furthermore, POL devices can be susceptible to rail-to-rail output dropouts, which are essentially a form of functional interrupt. In some cases, the dropouts require power cycling to recover operation. These events can disrupt system functionality. We will show that different upset modes can trigger the functional interrupts in different devices.

The reduction in size and increase in power output has introduced heat dissipation challenges, which can become problematic during heavy-ion beam testing. We will also discuss the details of these testing challenges, and how they can impact irradiation testing.

II. EXPERIMENTAL

A. *Device under study*

We show results for linear voltage regulators, switching regulators, and DC/DC converters from various manufacturers. Table I shows the part information featured in this paper, including the part number, manufacturer, device type, and process technology. We plan to include additional part types in the full paper.

Table I
Part description

Part Number	**Vendor**	**Type**	**Technology**
MSK5059RH	M.S. Kennedy	Buck regulator	Bipolar
L5973D	S.T. Microelectronics	Buck regulator	CMOS/Bipolar/LDMOS

B. *Irradiation facility*

We performed heavy ion and laser irradiation through several test campaigns. The heavy ion tests were carried out at the Texas A&M University Cyclotron Facility (TAMU) and the Lawrence Berkeley National Laboratory (LBNL) Accelerator Space Effects (BASE) facility. The irradiations at TAMU were performed with 15 MeV/amu heavy ions in air. The irradiations at LBNL were performed with a cocktail of 10 MeV/amu heavy ions in vacuum. No beam degraders were used during the tests.

The pulsed-laser irradiation was conducted at the Naval Research Laboratory (NRL) using a dye laser.

III. RESULTS

A. *MSK5059RH*

We evaluated the MSK5059RH buck regulator through several test campaigns with heavy ion and pulsed-laser irradiation. We observed an output dropout event during the initial heavy ion test at TAMU. Two parts were irradiated with identical electrical and radiation test conditions. We observed the dropout in one part. Figure 1 shows the supply current as a function of irradiation time, during three runs with Au at 45^o, and device settings of V_{in} = 7 V, V_{out} = 3.3 V, and I_{out} = 1.5 A. During the first run, the input supply current showed degradation in a step fashion, decreasing from approximately 1.18 A to 0.9 A, followed by a bigger decrease to 0.75 A. The output voltage degraded from 3.3 V to 2 V accordingly.

Finally the input supply current decreased to approximately 0.006 A, and the output dropped to 0 V. The device recovered normal operations after a power cycle. We observed similar behaviors during the following runs. The device failed to regulate with V_{in} = 10 V and I_{out} = 1.5 A, following the third run, indicating functional degradation.

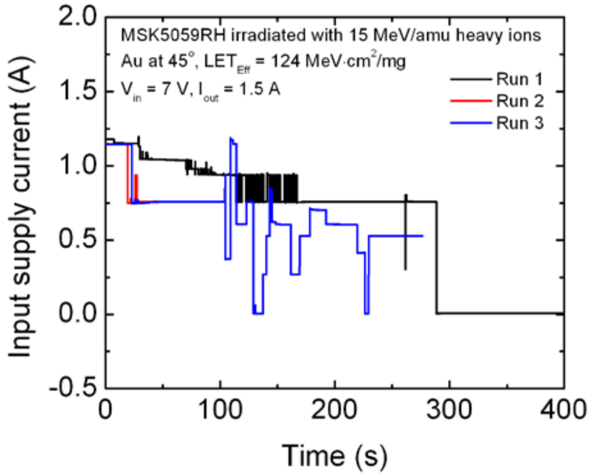

Figure 1. Input supply current as a function of irradiation time for the MSK5059RH, irradiated with Au at 45^o for LET_{eff} = 124 MeV·cm^2/mg, V_{in} = 7 V, V_{out} = 3.3 V, and I_{out} = 1.5 V. The traces show results from 3 irradiation runs in succession.

In addition to the heavy-ion and laser irradiations, Linear Technology and M.S. Kennedy also investigated the dropout phenomenon during a separate heavy ion test at LBNL. They also observed output dropout phenomenon. However the part showed destructive failure following the dropout. They found that the dropout and destructive failure correlated with the part temperature. The cooling mechanism inside the vacuum irradiation chamber was kept inactive during the initial irradiation. The case temperature of the part that showed failure had increased to approximately 58^{o}C prior to failure. The elevated temperature caused the thermal conductive compound to reach its melting temperature. The vacuum environment inhibited heat dissipation without the thermal compound. Consequently, the junction temperature exceeded the specification limit, leading to part failure. They repeated the irradiation on another part, while maintaining the cooling plate at 5^{o}C during irradiation. The case temperature remained at approximately 23^{o}C throughout the test. They did not observe dropout nor destructive failure for that part.

In addition to the heavy ion irradiations, we used a pulsed-laser to further investigate the locations of the sensitive regions. We found that scanning across one particular die location resulted in output dropouts, for V_{in} = 5 V, V_{out} = 3.3 V, and I_{out} = 0.2 to 4 A. Figure 2 shows the input current as a function of time. The output dropped out and recovered with a regular frequency on the same order as the laser pulse. We determined that the energy threshold was between 55 and 110 pJ. These laser energy values correspond to LETs of approximately 165 to 330 MeV·cm^2/mg, based on empirical data from previous tests [10].

We examined a microphotograph of the IC layout (not shown here due to vendor confidentiality), and determined that the sensitive location is occupied by a junction capacitor, which lies across the collector-base region of an NPN transistor in the band gap reference. The photocurrent from the pulsed-laser is amplified through the NPN transistor gain, thereby disrupting the reference loop.

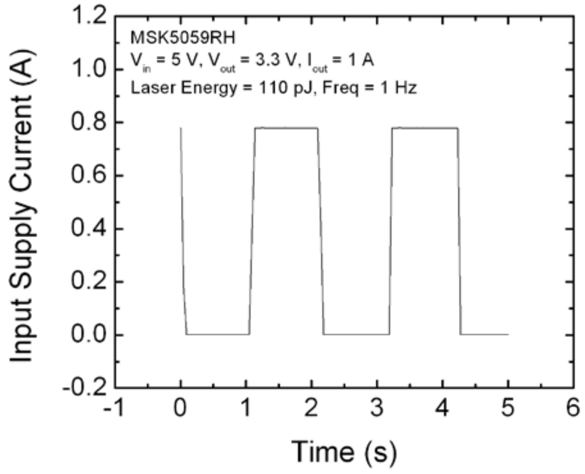

Figure 2. Input supply current as a function of irradiation time for the MSK5059RH, irradiated with pulsed-laser, for energy of 110 pJ, V_{in} = 5 V, V_{out} = 3.3 V, and I_{out} = 1 V.

B. L5973D

The L5973D buck regulator is manufactured with commercial CMOS and bipolar processes, with integrated laterally diffused power MOSFET (LDMOS). We irradiated two parts with 15 MeV/amu heavy-ions at TAMU. The device settings were V_{in} = 12 and 25 V, V_{out} = 3.3 V and I_{out} = 1.6 A. The majority of the events were rail-to-rail output voltage dropouts. The dropout duration varied from approximately 10 ms to over 800 ms. The events are self recoverable. The worst case dropouts exceeded the oscilloscope setting of 0.8 s, as shown in Figure 3. The event cross section at LET = 17.2 MeV·cm^2/mg is approximately 1.5×10^{-6} cm^2. Further tests are required to determine the saturation cross section LET and threshold LET.

We also observed destructive failures. Figures 4 and 5 show the input current and output voltage, respectively, for irradiation with Ar at 0^o and 60^o, with LET = 8.6 and 17.2 MeV·cm^2/mg. The device settings were V_{in} = 25 V, and I_{out} = 1.6 A. Both destructive events occurred when we initially increased the input voltage to 25 V from 16 V. The first event occurred for 60^o tilt angle. The input current spiked sharply to approximately 1 A before the device power was shut off. The output voltage increased to approximately 6 V, decreased to 2 V, then dropped to 0 V, within approximately 60 ms. The second destructive event occurred for 0^o tilt angle. The input current showed an initial decrease to approximately 50 mA. The output voltage fluctuated from 3.3 V to 0 V, before dropping out completely.

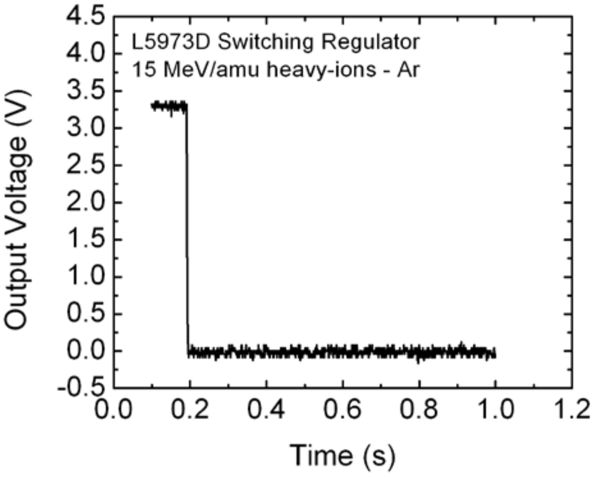

Figure 3. Output voltage as a function of time for the L5973D, irradiated with Ar, for V_{in} = 12 V and I_{out} = 1.6 A.

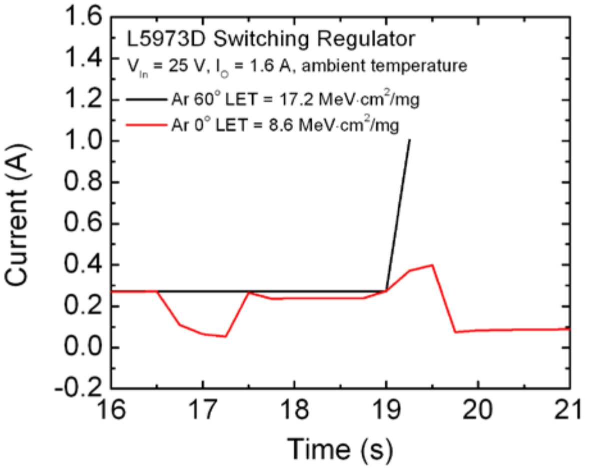

Figure 4. Input current vs. time during destructive events for the L5973D, irradiated with Ar at 0^o and 60^o, for V_{in} = 25 V and I_{out} = 1.6 A.

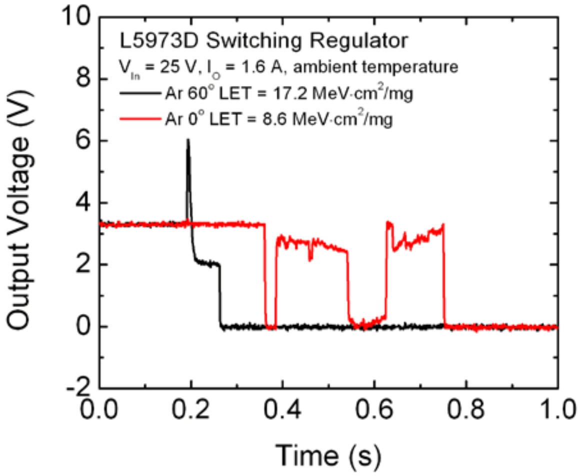

Figure 5. Output voltage vs. time during destructive events for the L5973D, irradiated with Ar at 0^o and 60^o, for V_{in} = 25 V and I_{out} = 1.6 A.

IV. DISCUSSION

A. *Self-Recoverable Functional Interrupt*

Although we observed several types of functional interrupts, some of the events were affected by temperature and/or TID-induced parametric degradation. Therefore, we distinguish those events from the classical SEE-induced examples.

We first discuss the laser test results for the MSK5059RH. The fact that the voltage dropouts from laser irradiation were relatively insensitive to the output load is contrary to the heavy ion test results, where the functional interrupt only occurred for higher output loads (1.5 and 4 A). Also, the dropouts from laser irradiation did not require power cycling to recover, unlike the dropouts from the heavy ion tests. The output recovered as soon as the laser was removed from the sensitive location. The different characteristics suggest that the degradation mechanism from the laser test is likely different from either of the heavy ion tests. The laser energy threshold was between 55 to 110 pJ, which is approximately equivalent to LETs of 165 to 330 MeV·cm^2/mg, according to NRL [10]. These values are much higher than the effective LETs used during the heavy ion test campaigns. This may explain why we did not observe these event types during the heavy ion tests.

The LET threshold is also much higher than the requirement for destructive SEE in most NASA missions – typically > 75 MeV·cm^2/mg. The particle flux is extremely low at such high LET. For example, the worst 5 minute average heavy ion flux for ions with LET > 100 MeV·cm^2/mg is less than 1×10^{-10} cm^2/sec, in a sun-synchronous polar orbit, during a solar particle event. Nonetheless, it is important to understand the mechanism, since a similar event can occur with a lower LET threshold in a different technology.

The switching regulator designs often employ current limit functions, to protect the device from over current conditions. A heavy ion strike can produce an internal current/voltage pulse, which could activate the built-in safety features and cause a temporary functional interrupt. The L5973D includes several such features, which may have prompted the voltage dropouts. There are two current limiting circuits that control the current flow through the power switch. The pulse by pulse current limit will force the power switch off, when the current reaches the internal threshold. And the frequency shifter reduces the switching frequency to lower the duty cycle. The inhibit function will set the device to standby mode, when the inhibit pin exceeds 2.2 V. However the current will be reduced to less than 100 μA during standby mode. In our case, the input current is approximately 0.017 A during the dropouts. Aside from these protection circuits, we have already shown in the MSK5059RH, that a strike on a sensitive node in the reference circuitry can disable the output. Furthermore, the pulse width modulator (PWM) is typically a sensitive component in switching regulators. Strikes on the PWM can cause missing pulses and/or phase shifts, which can produce voltage glitches. However, rail-to-rail dropouts are unlikely. We believe that the dropouts in the L5973D most likely originate from heavy ion strikes in the reference loop circuitry and/or the internal current limit circuitry. The duration of these dropouts can be problematic for many applications.

B. Non-Self-Recoverable Function Interrupt

We also observed more severe output dropouts that required power cycling to recover functionality. We believe that the event shown in Figure 1 is caused by heavy-ion dose deposition and/or device self-heating.

The part had accumulated approximately 120 krad(Si) prior to the dropout event. The total dose from heavy ion irradiation differs significantly from ^{60}Co, due to its highly non-uniform distribution and much higher recombination efficiency [11]. In fact, the calculated dose does not account for recombination at all. Therefore the given TID value is conservative. Micro-dose effects are known to cause threshold voltage shifts in some deep micron CMOS devices. However micro-dose effects are unlikely to significantly impact the gain degradation and/or leakage current in the given bipolar technology.

It is more probable that elevated temperature caused the output dropout. Although we did not observe destructive failure from the initial heavy ion test in TAMU, the part eventually showed functional degradation following the third dropout event, indicating possible internal physical damage from over-heating. We further discuss the destructive failure associated with the MSK5059RH below.

C. Destructive failure from device self-heating

The destructive failure of the MSK5059RH from the heavy ion test at LBNL is clearly brought on by device self-heating. The part did not have means of heat dissipation once the thermal compound dissolved, causing the temperature to increase above 58^{o}C. The part did not show destructive failure from the initial heavy ion test at TAMU, since the ambient air facilitated sufficient heat dissipation preventing thermal runaway. The temperature effect is also consistent with the output load dependence, since the power dissipation increases with increasing output load. Therefore we only observed the destructive events at relatively high output loading conditions.

The effect of elevated temperature reveals a challenge for SEE testing of the latest generation of POL devices, which are required to drive high current and low voltage loads. The high power conditions necessitate appropriate heat dissipation. Test board designs can become complicated, with consideration for the low noise requirement for SET characterization, and the flexibility of adjustable temperature control for SEL testing. The results shown here illustrate that insufficient heat dissipation can lead to destructive failure during SEE testing.

D. Destructive failure from integrated power MOSFET

The destructive events for the L5973D may be caused by SEL, SEB, and/or SEGR, since the device contains CMOS and LDMOS processes.

The input supply terminal is directly connected to the drain of the LDMOS. The input current signatures indicate that the failure either originated from the power MOSFET, in which case the mechanism is SEB and/or SEGR, or that a current surge from a SEL propagated to the power MOSFET, leading to destructive failure. SEL is a localized phenomenon. So the SEL current would need to propagate through several stages of circuitry to reach the power MOSFET. We believe that SEGR and/or SEB of the LDMOS are more probable.

A SEGR will either short the gate-to-source junction, resulting in a low device input current, or short the gate-to-drain junction, resulting in an initially high input current. The event from the 60^{o} irradiation, which showed a high current signature, is consistent with a SEGR that shorted the gate-and-drain junctions. The event from the 0^{o} irradiation can be caused by a SEGR of either type. Although the input current decreased initially, the time scale between the current readings (taken from the power supply) is on the order of 250 ms. Therefore we may not be able to capture an initial current spike from a SEGR, which can occur within picoseconds. The 0^{o} incident event is also consistent with a SEGR shorting the gate and source junctions, producing a low drain to source current.

The events may also be caused by SEB. Both SEB and SEGR are sensitive to the incident angle of the ion strike, with increased sensitivity for normal incidence strikes. The angular sensitivity of SEGR is more prominent than SEB. However, recent studies have found that the SEGR susceptibility depends on the atomic number of the ion specie, where the sensitivity is higher for heavier ions [7]. So the vulnerability of SEB increases relative to SEGR, for irradiations with lighter elements such as Ar. It is difficult to distinguish the two failure modes from the electrical signatures. We are currently performing destructive analysis to better understand the failure mechanisms.

The relatively low LET threshold (8.6 MeV·cm^2/mg) of the destructive event illustrates the challenge of designing radiation tolerant devices, while maintaining cutting edge performance specifications.

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