Radiation Report

TL7700-SEP Single-Event Effects (SEE)

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this study was to characterize the single-event effects (SEE) performance due to heavy-ion irradiation of the TL7700-SEP supply-voltage supervisor. Heavy-ions with an effective linear energy transferred (LET_{EFF}) of 20 to 48 MeV·cm^2/mg were used to irradiate the devices with fluences of 1×10^6 to 2×10^7 ions/cm^2. The results demonstrate that the TL7700-SEP is SEL-free up to LET_{EFF} = 43MeV·cm^2/mg at 125°C, and SEB-free up to 48MeV·cm^2/mg at 25°C. SET characterization at 20 and 48 MeV·cm^2 on the $\overline{\text{RESET}}$ output of the device are also presented and discussed.

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1 Trademarks

All trademarks are the property of their respective owners.

2 Overview

The TL7700-SEP is a bipolar integrated circuit designed for use as a reset controller in microcomputer and microprocessor systems. The SENSE voltage can be set to any value greater than 0.5 V using two external resistors. Circuit function is very stable with supply voltage in the 1.8-V to 40-V range. The TL7700-SEP device is designed for operation from –55°C to 125°C.

Additional technical details and documents can be found on the TL7700-SEP Product Page

Table 2-1. Overview Information

DESCRIPTION (1)	DEVICE INFORMATION
TI Part Number	TL7700-SEP
VID Number	V62/19602
Device Function	Radiation hardened supply-voltage supervisor in space enhanced plastic
Technology	JI1
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy Ion Fluence per Run	$1 \times 10^6 – 2 \times 10^7$ ions/cm^2
Irradiation Temperature	125°C (for SEL testing)
	25°C (for SEB and SET testing)

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3 SEE Mechanisms

The primary single-event effect (SEE) events of interest in the TL7700-SEP are single-event latch-up (SEL). From a risk/impact point-of-view, the occurrence of an SEL is potentially the most destructive SEE event and the biggest concern for space applications. The bipolar process JI1 was used for the TL7700-SEP. CMOS circuitry introduces a potential for SEL and SEB susceptibility. SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-sub and n-well and n+ and p+ contacts). The parasitic bipolar structure initiated by a single-event creates a high-conductance path (inducing a steady-state current that is typically orders-of-magnitude higher than the normal operating current) between power and ground that persists (is “latched”) until power is removed or until the device is destroyed by the high-current state. The TL7700-SEP exhibited no SEL with heavy-ions up to an LET_{EFF} of 43 MeV-cm^2/mg at a fluence of 10^7 ions/cm^2 and a chip temperature of 125°C.

To evaluate the SEL effects a bias voltage of 40 V on V_s supply voltage was used. Heavy ions with LET_{EFF} = 43 MeV·cm^2/mg were used to irradiate the devices. Flux of 10^5 ions/s-cm^2 and fluence of 10^7 ions/cm^2 were used during the exposure at 125°C temperature.

For SEB evaluation, a bias voltage of 40 V on V_s was used with ^{109}Ag providing a LET_{EFF} = 48 MeV·cm^2/mg to irradiate the device. Flux of 10^5 ions/s-cm^2 and fluence of 2 × 10^7 ions/cm^2 were used during the exposure.

Evaluaition of SET effects was performed at the minimum recommended bias voltage of 1.8 V on V_s as lower voltages are usually considered worst-case for SET effects. The heavy ion species ^{109}Ag was used to generate an LET_{EFF} = 48 MeV·cm^2/mg and ^{63}Cu was used for generate an LET_{EFF} = 20 MeV·cm^2/mg. The device was tested using both heavy ion species at a flux of 10^4 ions/s·cm^2 and fluence from 1 × 10^6 to 5 × 10^6 ions/cm^2.

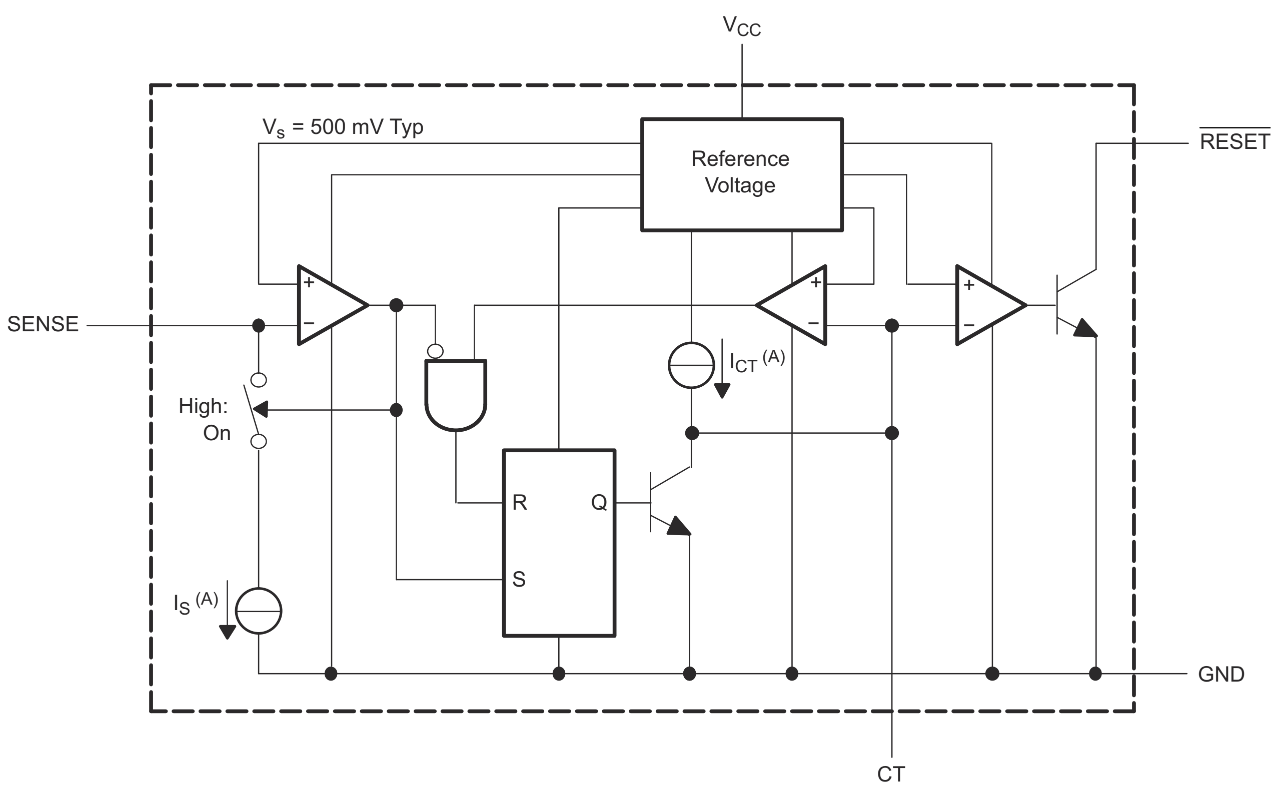

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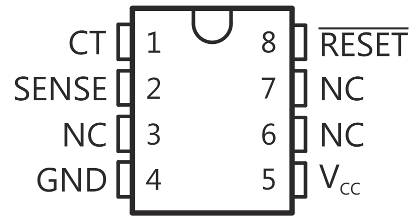
Figure 3-1. Functional Block Diagram of the TL7700-SEP

4 Test Device and Test Board Information

The TL7700-SEP is packaged in a 8-pin, TSSOP shown with pinout in Figure 4-1. The TL7700-SEP bias board used for the SEE characterization is shown in Figure 4-2 and bias diagram in Figure 4-3.



NC – No internal connection

The package was decapped to reveal the die face for all heavy ion testing.

Figure 4-1. TL7700-SEP Pinout Diagram

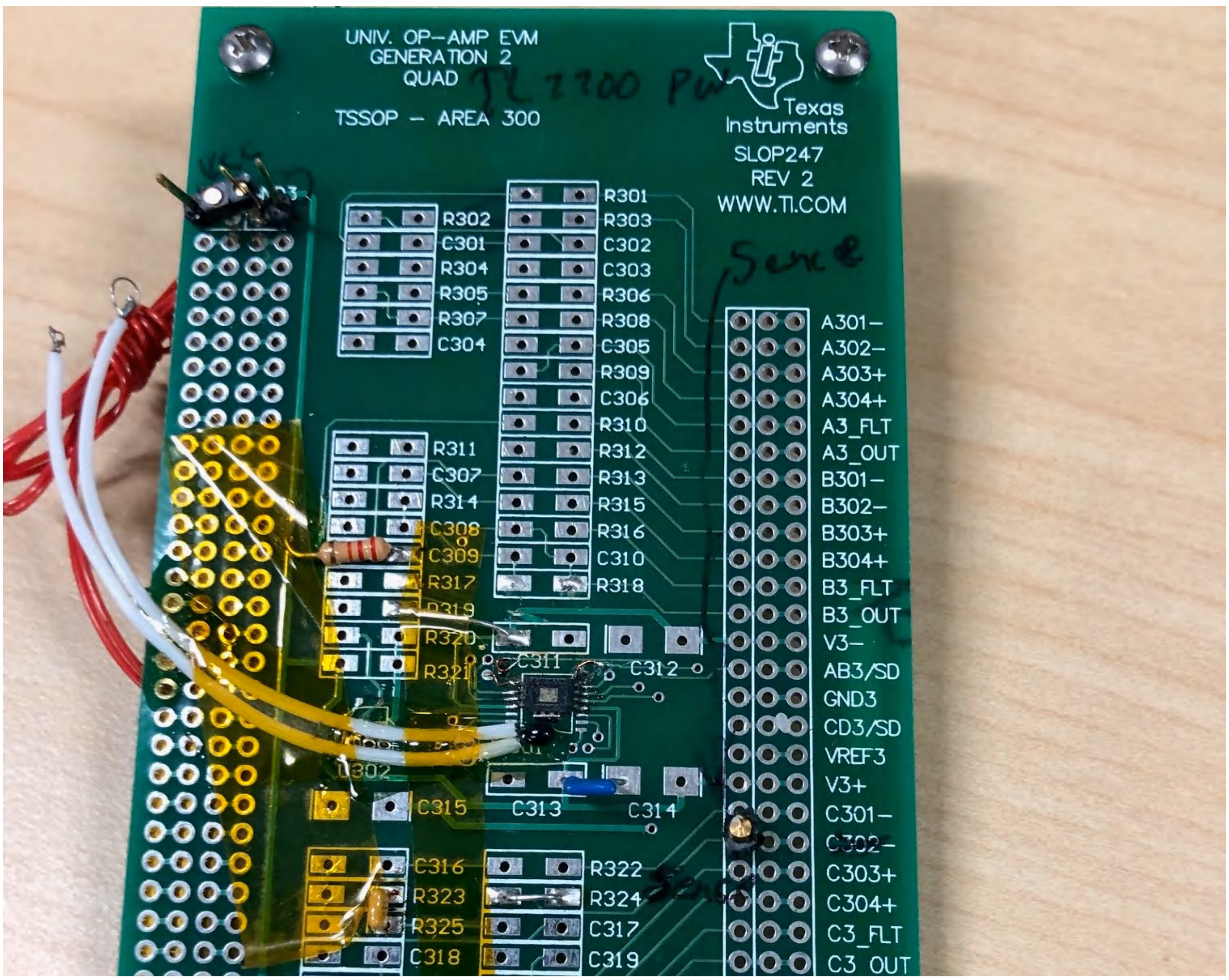


Figure 4-2. TL7700-SEP Bias Board Used for SEE Testing

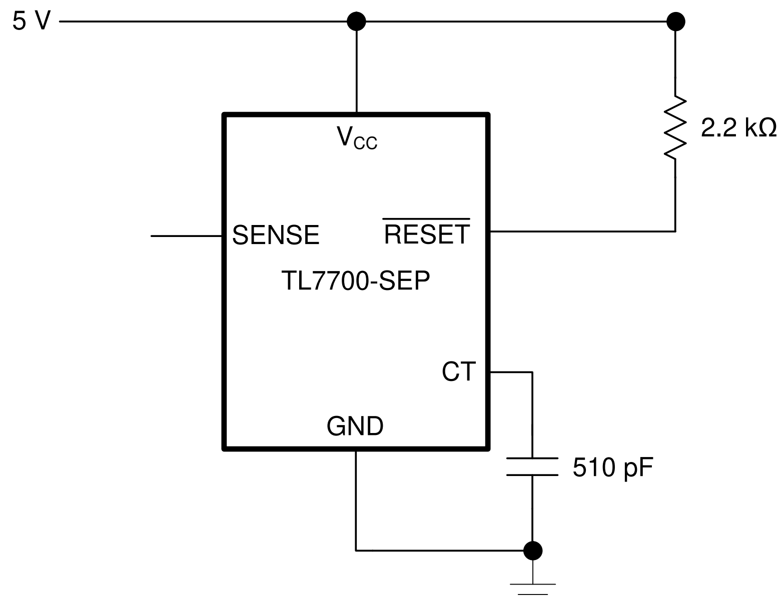


Figure 4-3. TL7700-SEP Bias Diagram

5 Irradiation Facility and Setup

The heavy ion species used for the SEE studies on this product were provided and delivered by the TAMU Cyclotron Radiation Effects Facility [3] using a superconducting cyclotron and advanced electron cyclotron resonance (ECR) ion source. Ion beams are delivered with high uniformity over a 1-in diameter circular cross sectional area for the in-air station. Uniformity is achieved by means of magnetic defocusing. The intensity of the beam is regulated over a broad range spanning several orders of magnitude. For the bulk of these studies, ion fluxes between 10^4 and 10^5 ions/s-cm^2 were used to provide heavy ion fluences between 10^6 and 10^7 ions/cm^2. For these experiments silver (Ag) and copper (Cu) ions were used. Ion beam uniformity for all tests was in the range of 91% to 99%.

The TL7700-SEP test board used for the experiments at the TAMU facility is shown in Figure 3. Although not visible in this photo, the beam port has a 1-mil Aramica (DuPont® Kevlar®) 1-in diameter window to allow in-air testing while maintaining the vacuum within the accelerator with only minor ion energy loss.

6 Depth, Range, and LET$_{EFF}$ Calculation

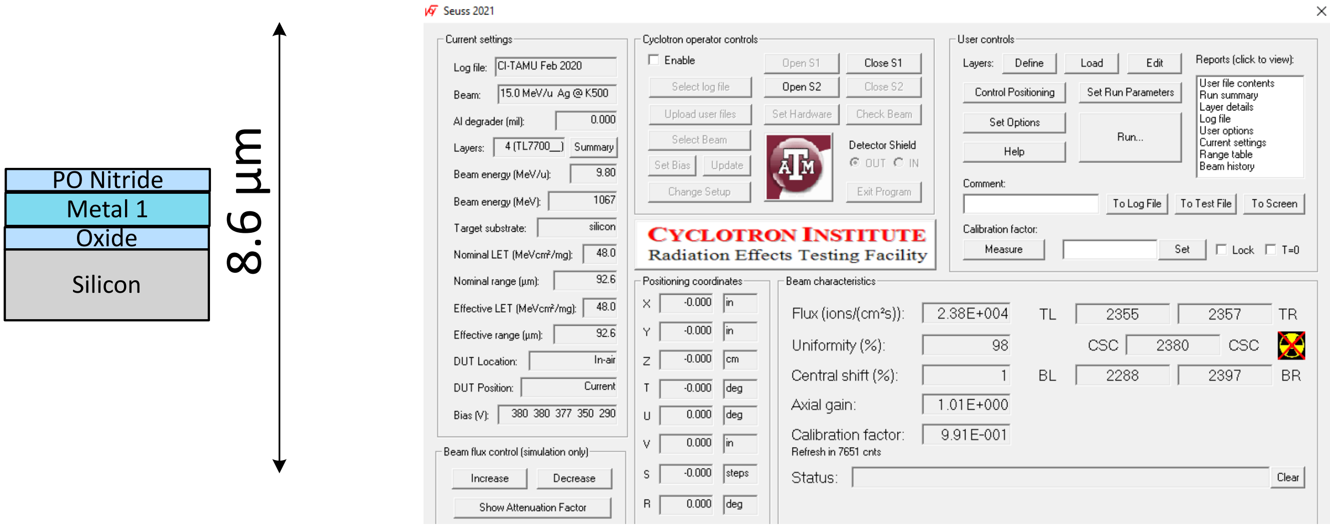


Figure 6-1. Generalized Cross Section of the JI1 Technology BEOL Stack on the TL7700-SEP [Left] and GUI of Seuss Application Used to Determine Key Ion Parameters [Right]

The TL7700-SEP is fabricated in the TI Linear JI1-Bipolar process with a back-end-of-line (BEOL) stack consisting of one level of standard thickness aluminum. The total stack height from the surface of the passivation to the silicon surface is 8.6µm based on nominal layer thickness as shown in Figure 6-1. No polyimide or other coating was present; the uppermost layer was the nitride passivation layer (PON). Effective LET (LET$_{EFF}$) at the surface of the silicon substrate, the depth, and the ion range was determined using TAMU's Seuss application shown in Figure 6-1. The Seuss software accounts for energy loss through the 1-mil thick Aramica beam port window, the 40-mm air gap, angle of incidence,and the BEOL stack over the TL7700-SEP. Results of the calculations perfomed by Seuss are shown in Table 6-1, and in the the LET$_{EFF}$ and Range plot in Figure 6-2.

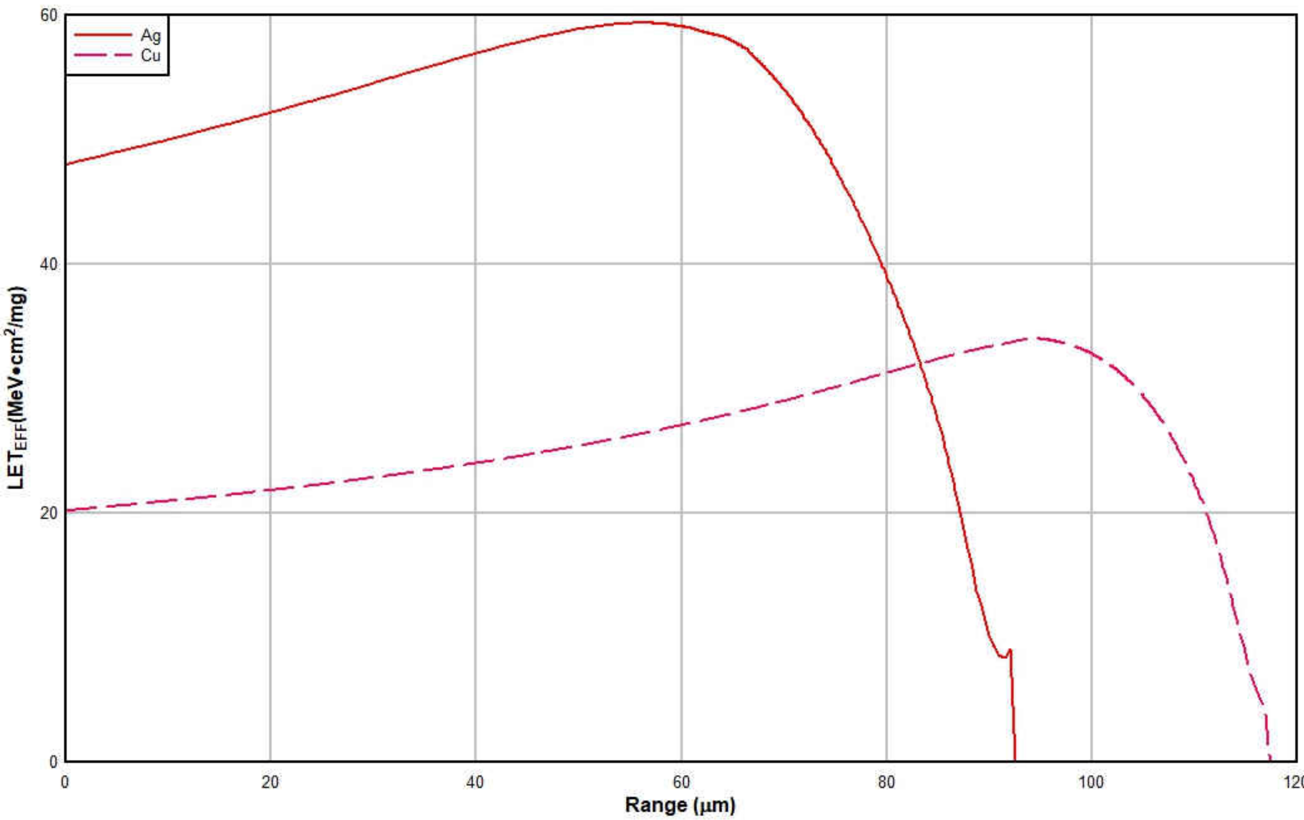


Figure 6-2. Plot of LET$_{EFF}$ and Range in TL7700-SEP for Ag and Cu

Table 6-1. Ion LET$_{EFF}$, Depth, and Range in Silicon

Ion Type	Air Distance (mm)	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET$_{EFF}$ (MeV·cm^2/mg)
^{109}Ag	40	0	92.6	92.6	48.47
^{63}Cu	40	0	117.4	117.4	20

7 Results

7.1 Single Event Latch-Up (SEL)

During SEL characterization, the device was heated using forced hot air, maintaining the IC temperature at 125°C. The temperature was monitored by means of a K-type thermocouple attached as close as possible to the IC. The species used for the SEL testing was a silver (^{109}Ag) ion with an angle-of-incidence of 0° for an LET_{EFF} = 43 MeV-cm^2/mg. The kinetic energy in the vacuum for this ion is 1.634 GeV (15-MeV/amu line). A flux of approximately 10^5 ions/cm^2-s and a fluence of approximately 10^7 ions were used for three runs. The V_s supply voltage is supplied externally on board at recommended maximum voltage setting of 40 V and the Vsense is set at 0.503 V. Run duration to achieve this fluence was approximately 2 minutes. No SEL events were observed during the run shown in Table 7-1. Figure 7-1 shows a plot of the current vs time.

7.1.1

Table 7-1. TL7700-SEP SEL Conditions Using ^{109}Ag at an Angle-of-Incidence of 0°

RUN #	DISTANCE (mm)	TEMPERATURE (°C)	ION	ANGLE	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	LET_{EFF} (MeV.cm^2/mg)
44	40	125	Ag	0°	1.00×10^5	1.00×10^7	43

No SEL events were observed, indicating that the TL7700-SEP is SEL-immune at LET_{EFF} = 43 MeV-cm^2/mg and T = 125°C. Using the MFTF method described in Appendix A , the upper-bound cross-section (using a 95% confidence level) is shown in Table 7-2.

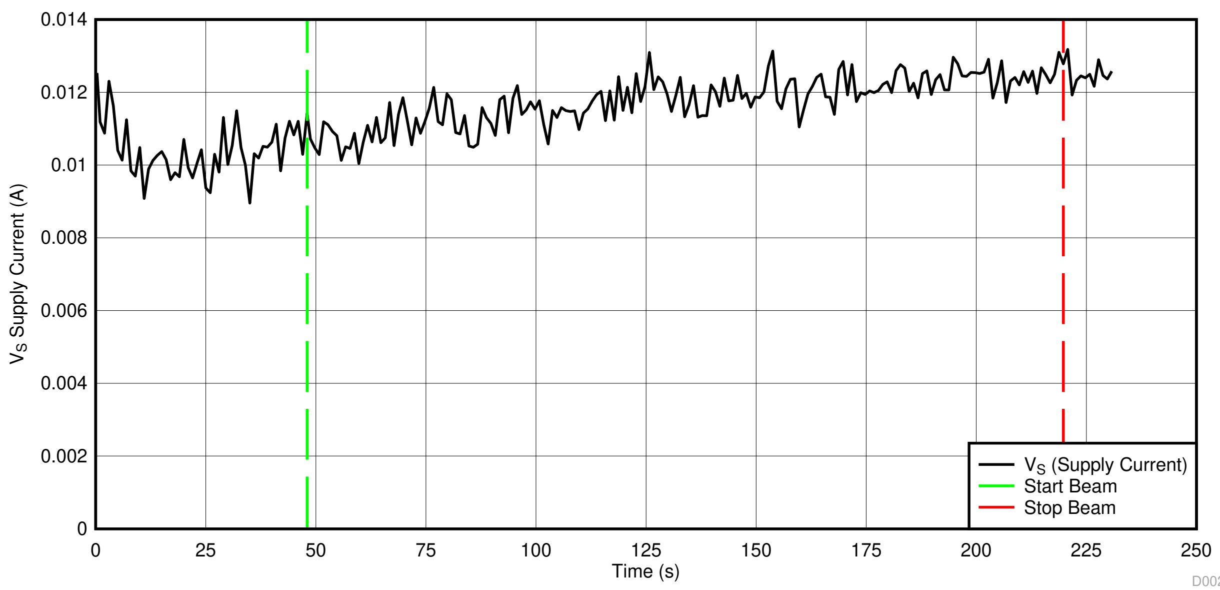


Figure 7-1. Current vs Time (I vs t) Data for V_s Current During SEL Run #44

Table 7-2. Upper Bound Cross Section for SEL

LET_{EFF} (MeV·cm^2/mg)	Total Fluence (# ions)	# of Events	Cross-Section [cm^2/device]
43	2.00×10^7	0	1.84×10^{-7}

7.2 Single-Event-Burnout (SEB)

The device was evaluated for SEB at the maximum recommended voltage of 40 V. The $\overline{\text{RESET}}$ output of the device was set to the logical low state by forcing a voltage below the 0.5 V reference of 0.45 V into the SENSE pin of the device. The species used for the SEB testing was a silver (^{109}Ag) ion with an angle-of-incidence of 0° for an LET_{EFF} = 48 MeV-cm^2/mg. A flux of approximately 10^5 ions/cm^2-s and a fluence of approximately 2×10^7 ions were used. During SEB testing, no abnormal behaviour was observed in the input current.

7.2.1

Table 7-3. TL7700-SEP SEB Conditions Using ^{109}Ag at an Angle-of-Incidence of 0°

RUN #	DISTANCE (mm)	TEMPERATURE (°C)	ION	ANGLE	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	LET_{EFF} (MeV·cm^2/mg)
7	40	25	Ag	0°	1.00×10^5	2.00×10^7	48.47

During SEB testing the $\overline{\text{RESET}}$ output was set to the logical low state, and the input current was monitored for increases that would indicate a momentary upset that changed the output state of the deivce. The device was not damaged in testing, and no increases in device input current current were observed over the period of approximately 200 seconds needed to reach the target fluence of 2×10^7 ions.

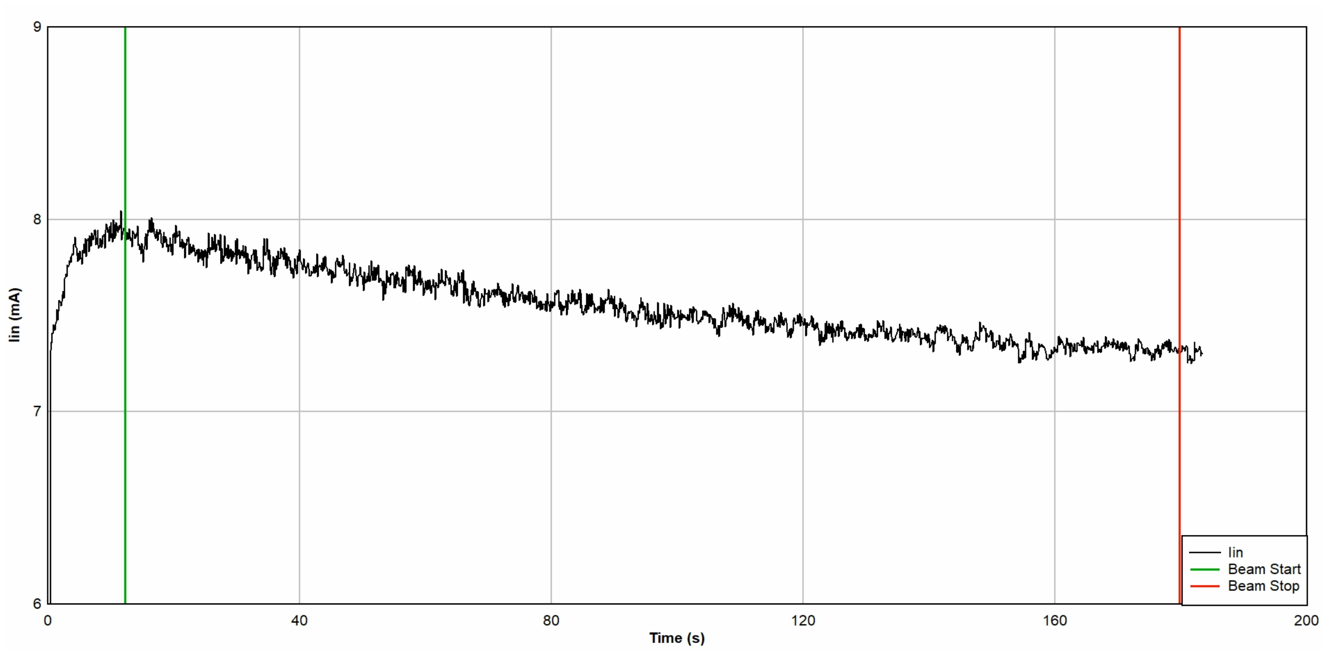


Figure 7-2. Current vs Time (I vs t) Data for V_S Current During SEB Run #7

Table 7-4. Upper Bound Cross Section for SEB

LET_{EFF} (MeV·cm^2/mg)	Total Fluence (# ions)	# of Events	Cross-Section [cm^2/device]
48.47	2.00×10^7	0	1.84×10^{-7}

7.3 Single-Event Transients (SET)

SETs are defined as heavy-ion-induced transients on the $\overline{\text{RESET}}$ of the TL7700-SEP. SET testing was performed at room temperature (no external temperature control used), using Silver (^{109}Ag) and Copper (^{63}Cu) heavy-ions. For both ions an angle of 0° for LET_{EFF} of 20 and 48 MeV·cm2 /mg, respectively. Two units underwent SET characterization, one was exposed to ^{109}Ag during two tests where the output was set to logical high, and two where the output was logical low. A second unit was used for one output high and one output low test while being exposed to ^{63}Cu. During tests where the output was high, transients were captured using a negative edge trigger at the enable low value of 1.05 V, for output low tests the rising enable value of 1.18 V was selected and a rising edge trigger was used to capture transients. The reason these values were selected was that in most cases the TL7700-SEP will be used to disable a point of load when the output voltage goes below a desired voltage that is considered problematic for the system in case. The device was evaluated for SET at the minimum recommended voltage of 1.8-V. Usually the minimum voltage is considered the worst-case condition for SET. Run duration needed to achieve fluences used in the six tests shown in Table 7-5 ranged from 10 seconds to 1 minute.

Transients consisted of a partial or full dropout of the voltage from the output of the device. These dropouts typically recovered quickly (less than 100µs) and had a maximum duration of approximately 140µs. The histogram of all recorded transients is shown on Figure 7-3. Time domain plots for typical transients are shown on Figure 7-4 and Figure 7-5, for the slow and fast transient time, respectively.

7.3.1

Table 7-5. TL7700-SEP SET Conditions Using ^{109}Ag and ^{63}Cu at an Angle-of-Incidence of 0°

RUN #	DISTANCE (mm)	TEMPERATURE (°C)	ION	ANGLE	FLUX (ions·cm²/mg)	FLUENCE (# ions)	LET_{EFF} (MeV·cm²/mg)	$\overline{RESET}$	Number of Transients (#)
1	40	25	Ag	0°	1.00E+04	1.00E+06	48.47	High	2054
2	40	25	Ag	0°	1.00E+04	3.00E+06	48.47	High	5788
3	40	25	Ag	0°	1.00E+04	1.00E+06	48.47	Low	1
4	40	25	Ag	0°	1.00E+04	5.00E+06	48.47	Low	0
5	40	25	Cu	0°	1.00E+04	1.00E+06	20	High	1771
6	40	25	Cu	0°	1.00E+04	1.00E+06	20	Low	0

During tests where the device's output was set to the logical high state, the number of captured transients scaled linearly with the fluence the device was exposed to. After post-processing it was observed that in some instances more than a single transient per record was present. In the cases that all the waveforms were not saved into memory the transient linearly scale by using the following formula:

$$\#\ of\ \ Upsets = \left(\frac{\#\ of\ \ Upsets\ \ After\ \ Post-Processing}{\#\ of\ \ Recorded\ \ Upsets}\right) \times Total\ \ Count\ \ of\ \ Triggers \tag{1}$$

For the case in which the output was set to the logical low state, only one transient was observed at LET_{EFF} ≈ 48 MeV·cm²/mg, this transient was observed at the beginning of the run.

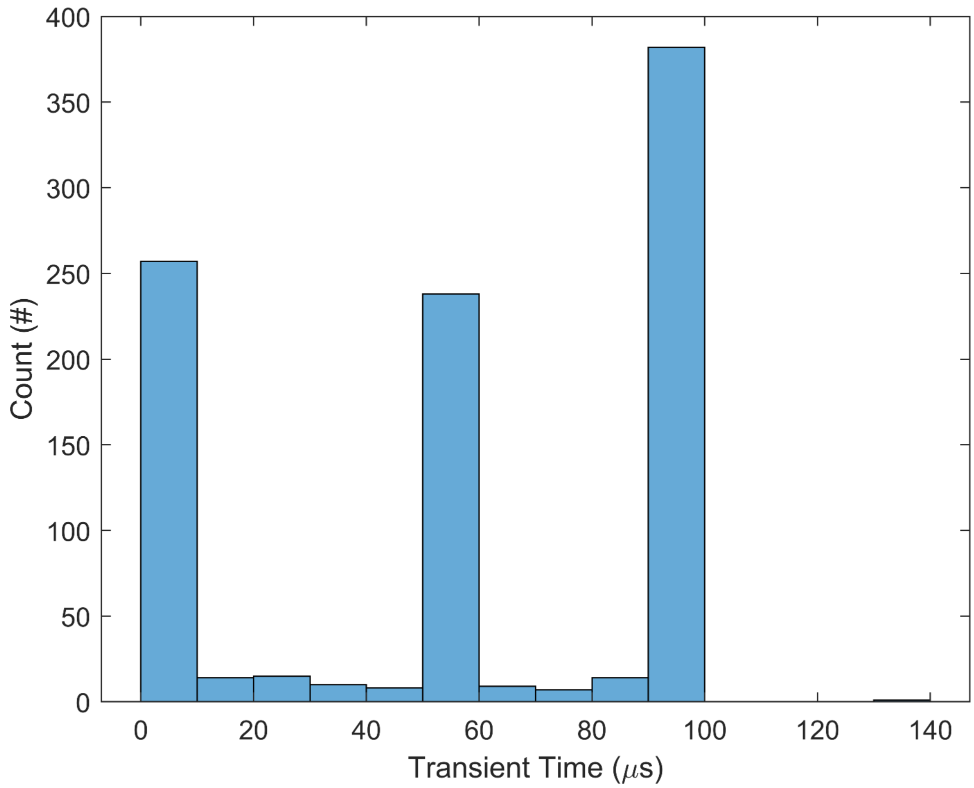


Figure 7-3. Histogram of the Transient Time for All SETs

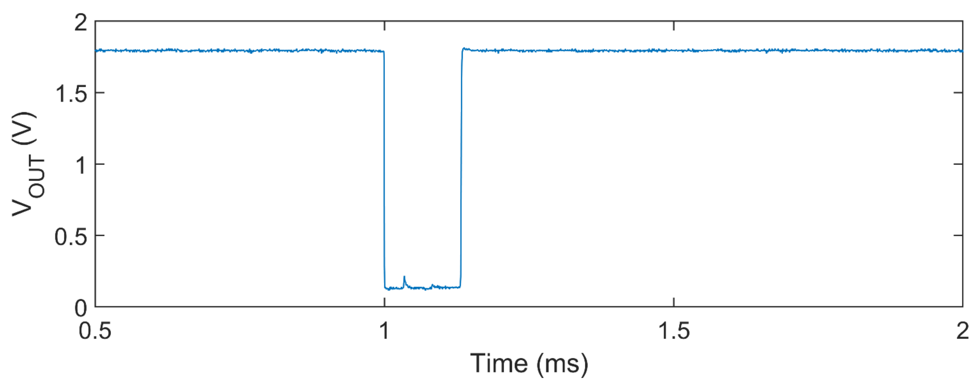


Figure 7-4. Long (Slow) Transient on $\overline{\text{RESET}}$

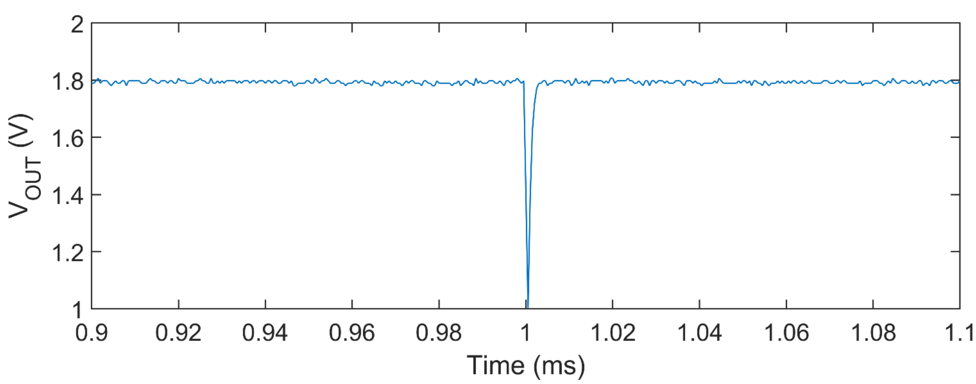


Figure 7-5. Short (Fast) Transient on $\overline{\text{RESET}}$

Table 7-6. Upper Bound Cross Section for $\overline{\text{RESET}}$ SETs

LET_{EFF} ($MeV \cdot cm^2/mg$)	$\overline{\text{RESET}}$	Total Fluence (# ions)	# of $\overline{\text{RESET}}$ Transients	$\overline{\text{RESET}}$ Cross-Section [cm^2/device]
48.47	High	4.00×10^6	7842	2.00×10^{-3}
	Low	6.00×10^6	1	9.29×10^{-7}
20	High	1.00×10^6	1771	1.86×10^{-3}
	Low	1.00×10^6	0	3.70×10^{-6}

8 Event Rate Calculations

Event rates were calculated for LEO (ISS) and GEO enviornments by combining CREME96 orbital integral flux estimations and simplified SEE cross-sections according to methods described in Heavy Ion Orbital Environment Single-Event Effects Estimations application report. We assume a minimmum sheilding configuration of 100 mils (2.54 mm) of aluminum, and "worst-week" solar activity (this is similar to a 99% upper bound for the enviornment). Using the 95% upper-bounds for the SET, SEL, and SEB. Event rate calculation for SEL and SEB is shown on table Table 8-1 and Table 8-2 respectively. **It is important to note that these numbers are for refrecnce since no SEL or SEB events were observed.**

Table 8-1. SEL Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} ($MeV \cdot cm^2/mg$)	CREME96 Integral FLUX ($/day/cm^2$)	σSAT (cm^2)	Event Rate (/ day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	43	4.56×10^{-4}	1.84×10^{-7}	1.178×10^{-10}	4.907×10^{-3}	2.326×10^{7}
GEO		1.497×10^{-3}		3.997×10^{-10}	1.665×10^{-2}	6.855×10^{6}

Table 8-2. SEB Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} ($MeV \cdot cm^2/mg$)	CREME96 Integral FLUX ($/day/cm^2$)	σSAT (cm^2)	Event Rate (/ day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	48.47	4.56×10^{-4}	1.84×10^{-7}	8.021×10^{-11}	3.342×10^{-3}	3.416×10^{7}
GEO		1.497×10^{-3}		2.624×10^{-10}	1.093×10^{-2}	1.044×10^{7}

Table 8-3. $\overline{\text{RESET}}$ Low SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} ($MeV \cdot cm^2/mg$)	CREME96 Integral FLUX ($/day/cm^2$)	σSAT (cm^2)	Event Rate (/ day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	20	4.56×10^{-4}	9.29×10^{-7}	4.788×10^{-6}	1.549×10^{2}	5.722×10^{2}
GEO		1.497×10^{-3}		3.719×10^{-5}	6.171×10^{3}	7.367×10^{1}

9 Summary

Radiation effects of TL7700-SEP radiation hardened supply-voltage supervisor in space enhanced plastic was studied. This device passed total dose rate of up to 20 krad(Si) and is latch-up and burn-out immune up to LET_{EFF} = 43 MeV-cm^2/mg and T = 125°C. SET characterization for the deice is also presented and discussed.

10 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (June 2022) to Revision A (August 2022) **Page**

A Confidence Interval Calculations

For conventional products where hundreds of failures are seen during a single exposure, one can determine the average failure rate of parts being tested in a heavy-ion beam as a function of fluence with high degree of certainty and reasonably tight standard deviation, and thus have a good deal of confidence that the calculated cross-section is accurate.

With radiation hardened parts however, determining the cross-section becomes more difficult since often few, or even, no failures are observed during an entire exposure. Determining the cross-section using an average failure rate with standard deviation is no longer a viable option, and the common practice of assuming a single error occurred at the conclusion of a null-result can end up in a greatly underestimated cross-section.

In cases where observed failures are rare or non-existent, the use of confidence intervals and the chi-squared distribution is indicated. The Chi-Squared distribution is particularly well-suited for the determination of a reliability level when the failures occur at a constant rate. In the case of SEE testing, where the ion events are random in time and position within the irradiation area, one expects a failure rate that is independent of time (presuming that parametric shifts induced by the total ionizing dose do not affect the failure rate), and thus the use of chi-squared statistical techniques is valid (since events are rare an exponential or Poisson distribution is usually used).

In a typical SEE experiment, the device-under-test (DUT) is exposed to a known, fixed fluence (ions/cm^2) while the DUT is monitored for failures. This is analogous to fixed-time reliability testing and, more specifically, time-terminated testing, where the reliability test is terminated after a fixed amount of time whether or not a failure has occurred (in the case of SEE tests fluence is substituted for time and hence it is a fixed fluence test [5]). Calculating a confidence interval specifically provides a range of values which is likely to contain the parameter of interest (the actual number of failures/fluence). Confidence intervals are constructed at a specific confidence level. For example, a 95% confidence level implies that if a given number of units were sampled numerous times and a confidence interval estimated for each test, the resulting set of confidence intervals would bracket the true population parameter in about 95% of the cases.

In order to estimate the cross-section from a null-result (no fails observed for a given fluence) with a confidence interval, we start with the standard reliability determination of lower-bound (minimum) mean-time-to-failure for fixed-time testing (an exponential distribution is assumed):

$$MTTF = \frac{2nT}{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}} \tag{2}$$

Where *MTTF* is the minimum (lower-bound) mean-time-to-failure, *n* is the number of units tested (presuming each unit is tested under identical conditions) and *T*, is the test time, and χ^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence level and where *d* is the degrees-of-freedom (the number of failures observed). With slight modification for our purposes we invert the inequality and substitute *F* (fluence) in the place of *T*:

$$MFTF = \frac{2nF}{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}} \tag{3}$$

Where now *MFTF* is mean-fluence-to-failure and *F* is the test fluence, and as before, χ^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence and where *d* is the degrees-of-freedom (the number of failures observed). The inverse relation between *MTTF* and failure rate is mirrored with the *MFTF*. Thus the upper-bound cross-section is obtained by inverting the *MFTF*:

$$\sigma = \frac{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}}{2nF} \tag{4}$$

Assume that all tests are terminated at a total fluence of 10^6 ions/cm^2. Also assume there are a number of devices with very different performances that are tested under identical conditions. Assume a 95% confidence level (σ = 0.05). Note that as *d* increases from 0 events to 100 events the actual confidence interval becomes smaller, indicating that the range of values of the true value of the population parameter (in this case the cross-section) is approaching the mean value + 1 standard deviation. This makes sense when one considers that as more events are observed the statistics are improved such that uncertainty in the actual device performance is reduced.

Table A-1. Experimental Example Calculation of MFTF and σ Using a 95% Confidence Interval

Degrees-of-Freedom (d)	2(d + 1)	χ^2 @ 95%	Calculated Cross Section (cm^2)		
			Upper-Bound @ 95% Confidence	Mean	Average + Standard Deviation
0	2	7.38	3.69E–06	0.00E+00	0.00E+00
1	4	11.14	5.57E–06	1.00E–06	2.00E–06
2	6	14.45	7.22E–06	2.00E–06	3.41E–06
3	8	17.53	8.77E–06	3.00E–06	4.73E–06
4	10	20.48	1.02E–05	4.00E–06	6.00E–06
5	12	23.34	1.17E–05	5.00E–06	7.24E–06
10	22	36.78	1.84E–05	1.00E–05	1.32E–05
50	102	131.84	6.59E–05	5.00E–05	5.71E–05
100	202	243.25	1.22E–04	1.00E–04	1.10E–04

B References

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