Radiation Report

TRF0208-SP, Near-DC to 11GHz, Fully Differential RF Amplifier Single-Event Effects (SEE) Radiation Report

ABSTRACT

The effect of heavy-ion irradiation on the single-event effects performance of the radiation-hardness-assured (RHA) TRF0208-SP is summarized in this report. Heavy-ions with an LET_{EFF} up to 81.6 MeV-cm^2/mg were used to irradiate two production devices in multiple runs. Flux up to 10^5 ions/cm^2-s and fluences up to 10^7 ions/cm^2 at temperatures of 25°C (SET) and 125°C (SEL), were used for the characterization. Results demonstrate that the TRF0208-SP is SEL-free up to LET_{EFF} = 81.6 MeV-cm^2/mg and 125°C, and the cross section for the SET is discussed.

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1 Overview

The TRF0208-SP is a very high-performance, differential amplifier optimized for radio frequency (RF) or intermediate frequency (IF) applications. The device is ideal for a single-ended-to-differential (SE-DE) conversion when driving an analog-to-digital converter (ADC) such as the high performance ADC12DJ5200-SP and RF transceivers such as AFE7950-SP. The TRF0208-SP generates very low 2nd and 3rd order distortion when converting from SE to DE, making it an ideal replacement for high performance balun. The device incorporates a shutdown option. The TRF0208-SP offers a 11GHz 3dB bandwidth. Table 1-1 lists the general device information and test conditions.

For more detailed technical specifications, user's guides, and application notes visit: https://www.ti.com/product/TRF0208-SP.

Table 1-1. Overview Information

Description	Device Information
TI Part Number	TRF0208-SP
SMD Number	5962R2420201PXE
Device Function	Differential Amplifier
Technology	BiCMOS
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy-Ion Fluence per Run	10^6 (SET) – 10^7 (for SEL and SET) ions/cm^2
Irradiation Temperature	25°C and 125°C (for SEL testing)

2 Single-Event Effects

The primary concern for the TRF0208-SP are its resilience against the destructive single-event effects (DSEE), such as single-event latch-up (SEL) and single-event-burnout (SEB). Since the operating voltage of TRF0208-SP is relatively low, 3.3V, SEB is not a concern.

The TRF0208-SP was characterized for SEL events. In mixed technologies, such as the SiGe-BiCMOS process used for the TRF0208-SP, the presence of the CMOS circuitry introduces a potential SEL 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-substrate and n-well and n+ and p+ contacts) [1] [2]. If formed, the parasitic bipolar structure creates a high-conductance path (creating a steady-state current that is 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 TRF0208-SP exhibited no SEL with heavy-ions of up to LET_{EFF} = 81.6MeV-cm^2/mg at fluences in excess of 10^7 ions/cm^2 and a die temperature of 125°C.

Another concern on high reliability and performance applications is the single-events-transient (SET) characteristic of the device. The TRF0208-SP SET performance was characterized up to LET_{EFF} = 81.6 MeV-cm^2/mg. The device was characterized for SET at supply voltage of 3.3V under DC input conditions. Test conditions and results are discussed in Section 8.

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3 Test Device and Evaluation Board Information

The TRF0208-SP is packaged in a 12-pin RPV, WQFN - Flip Chip RLF (WQFN-FCRLF, 12) package as shown in Figure 3-1. The TRF0208SP-EVM evaluation board (EVM) was used to evaluate the single-events-effects (SEE) of the TRF0208-SP. Top view of the evaluation board used for the radiation testing are shown in Figure 3-1. Schematic of the evaluation board used for radiation testing is shown in Figure 3-3. For more technical information about the TRF0208-SP, see https://www.ti.com/product/TRF0208-SP/technicaldocuments.

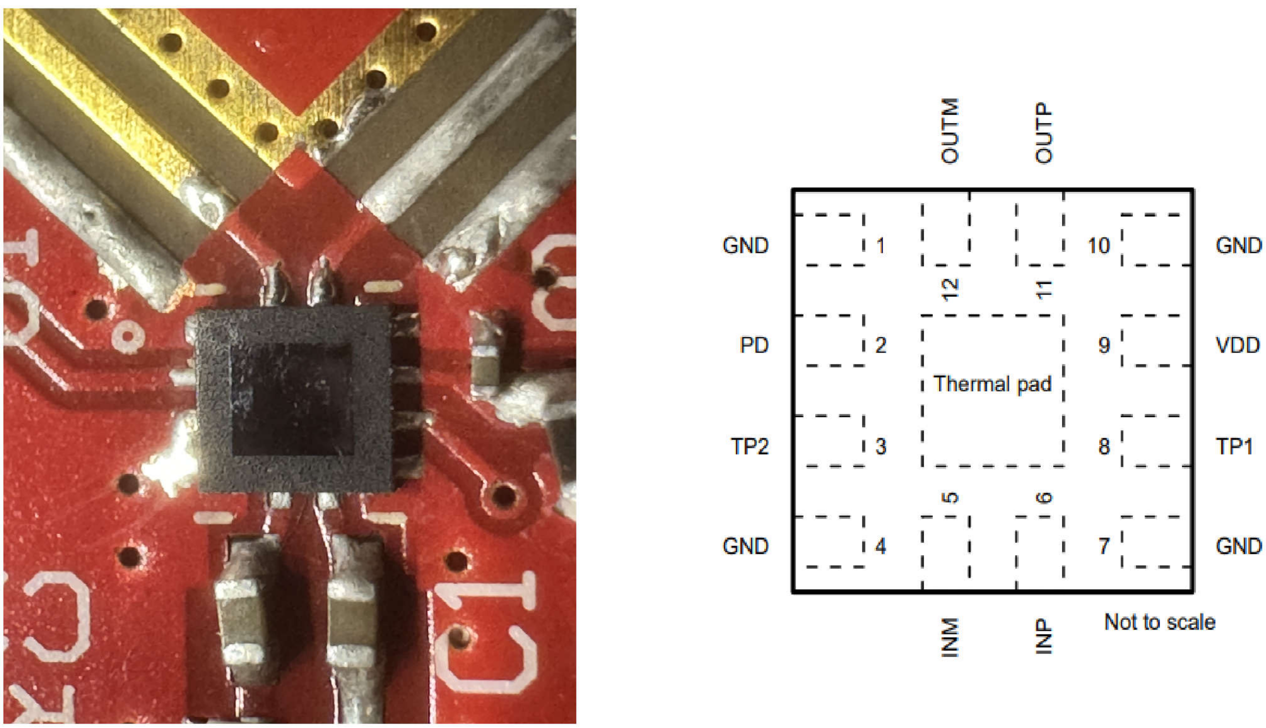

Figure 3-1. Decapped TRF0208-SP (Left) and Device Pin Out (Right)

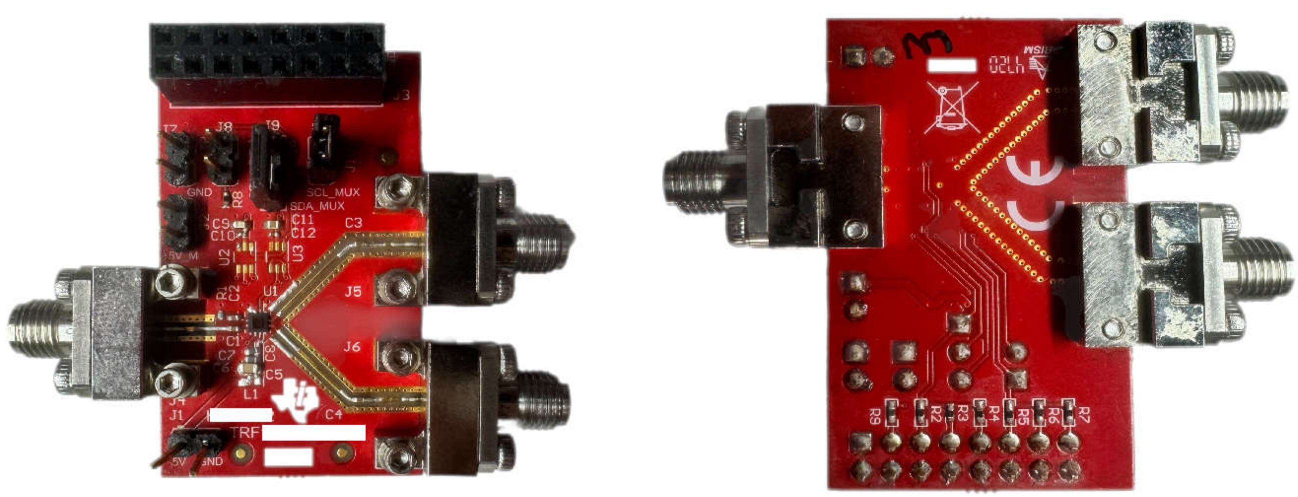

Figure 3-2. TRF0208SP-EVM Board Top View (Left) and Bottom View (Right)

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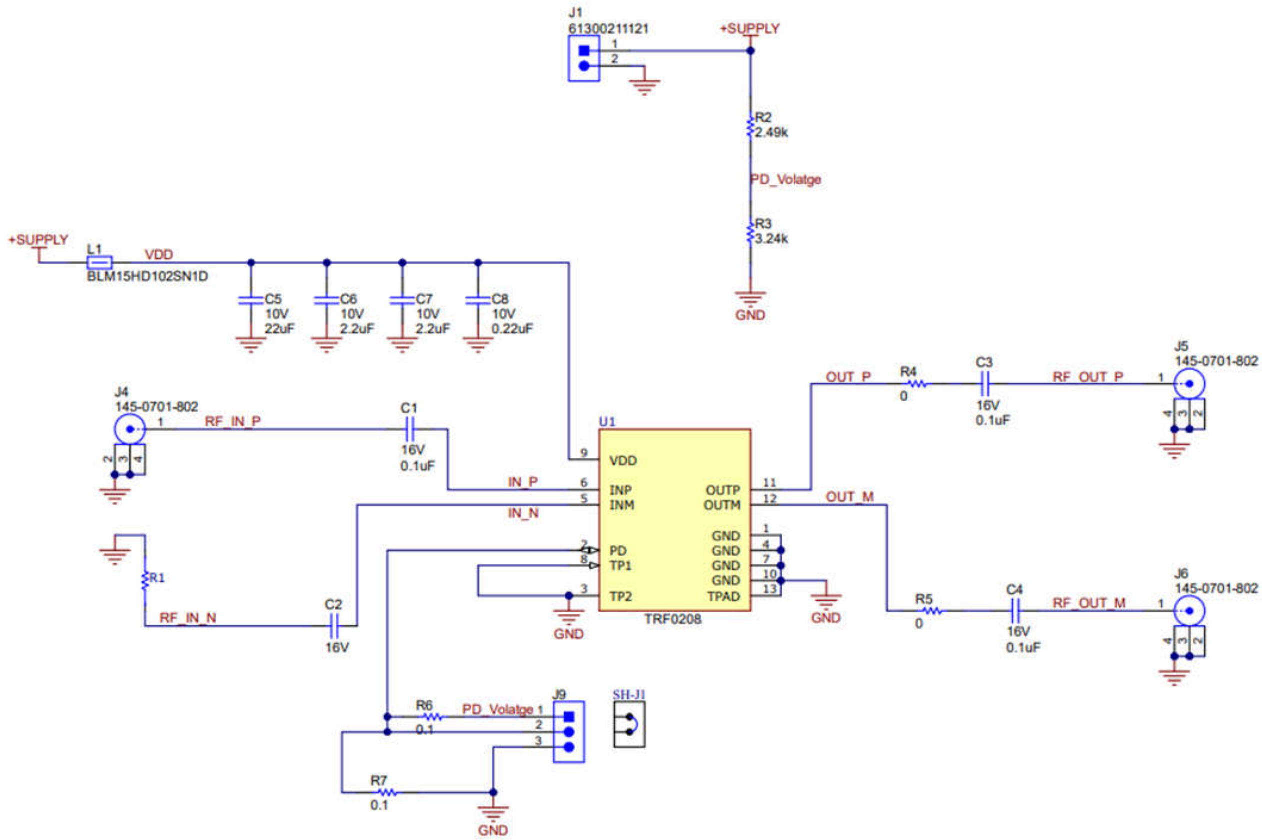

Figure 3-3. TRF0208-SP Evaluation Board Schematic for SEE Testing

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4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by the Texas A&M University (TAMU) Cyclotron Radiation Effects Facility [4], using a superconducting cyclotron and advanced electron cyclotron resonance (ECR) ion source. At the fluxes used, ion beams had good flux stability and high-irradiation uniformity over a 1-in diameter circular cross-sectional area for the in-air station. Uniformity is achieved by means of magnetic defocusing. The flux 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/cm^2-s were used to provide a heavy-ion fluences between 10^6 and 10^7 ions/cm^2.

For these experiments Holmium (^{165}Ho), Silver (^{107}Ag), Krypton (^{84}Kr), Copper (^{63}Cu) and Argon (^{40}Ar) were used. Angles were used to increment the LET_{EFF}, details are provided in Section 5. The ^{84}Kr and ^{63}Cu ions used had a total kinetic energy of 1259 and 944MeV in the vacuum, (15MeV/amu line) respectively. Ion beam uniformity for all tests was in the range of 88 to 97%.

Figure 4-1 shows the TRF0208-SP mounted on the EVM board in front of the beam exit port, as in the heavy-ion characterization. The beam port has a 1-mil Aramica (Kevlar®), 1in diameter to allow in-air testing while maintaining the vacuum in the accelerator with only minor ion energy losses. The air space between the device-under-test (DUT) and the beam exit port was set to 40 mm.

The data recorded in this report was based on finalized EVM boards with optimized component values that follow data sheet recommendations.

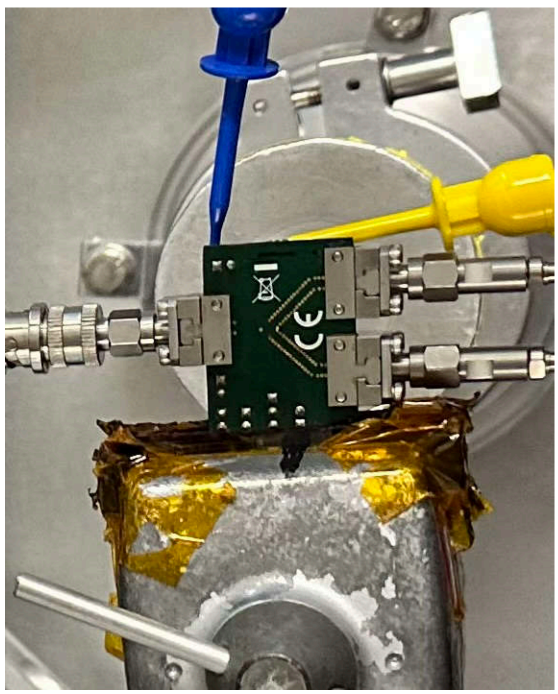

Figure 4-1. TRF0208-SP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

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5 Depth, Range, and LET_{EFF} Calculation

The TRF0208-SP is fabricated in the TI BiCMOS process and the die is packaged as a flip chip. The decapped unit exposes the silicon substrate directly when packaged in the flip-chip configuration. The units used were background to 50 microns, for proper ion penetration. The effective LET (LET_{EFF}), depth and range was determined with the custom RADsim - IONS application (developed at Texas Instruments and based on the latest SRIM2013 [5] models). The applications accounts for energy loss through the 1-mil thick Aramica (DuPont® Kevlar®) beam port window and the air gap between the DUT and the heavy-ion exit port (40 mm). An image of the RADsim - IONS is shown in Figure 5-1 and the ions details are provided in Table 5-1.

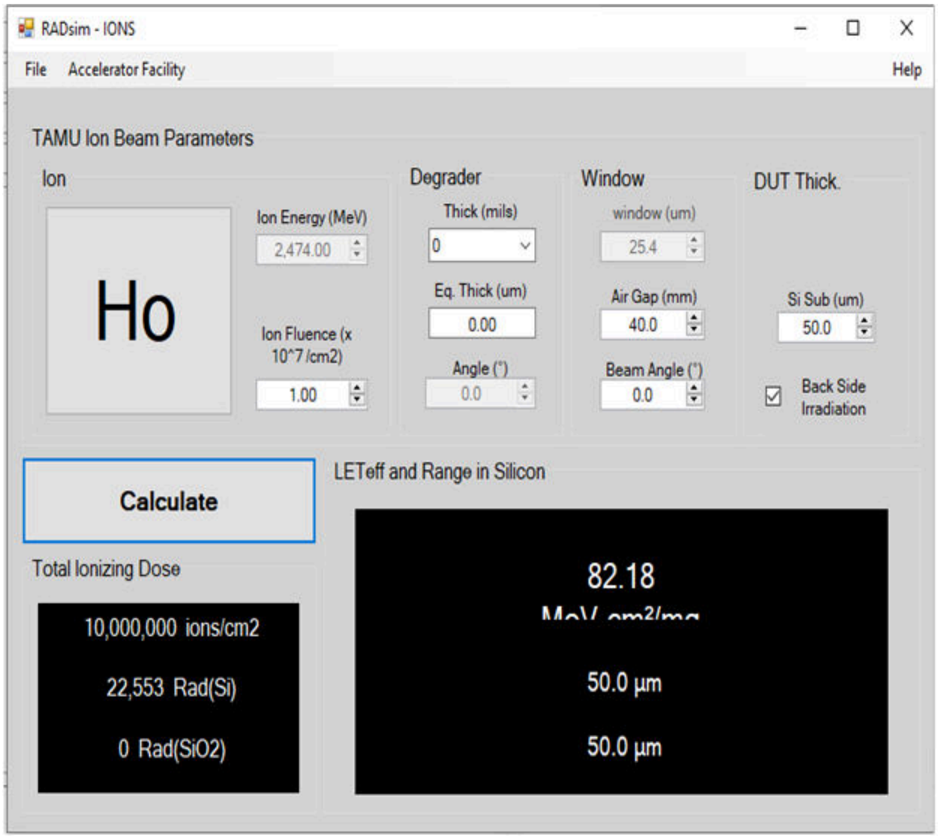

Figure 5-1. GUI of RADsim Application Used to Determine Key Ion Parameters

Table 5-1. LET_{EFF}, Depth and Range for the Ions Used for SEE Characterization of the TRF0208-SP

Ion Type	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET_{EFF} (MeV-cm²/mg)	Distance (mm)
Ar	0	50	50	9.62	40
Cu	0	50	50	24.54	40
Kr	0	50	50	36.1	40
Ag	0	50	50	57.73	40
Ho	0	50	50	81.6	40

6 Test Set-Up and Procedures

SEE testing was performed on a TRF0208-SP device mounted on a TRF0208SP-EVM. The device was provided power through J1 input (+SUPPLY = +3.45V and GND) using the PXIe-4139 precision power supply in a 4-wire configuration. The TRF0208-SP was evaluated with AC input signal provided on the INP input (J4). For the AC test, the input was driven onto the INP pin (J4) with R&S SME03 signal generator (capable of providing a 3GHz signal) using a high speed coaxial cable. Input frequency was set to 100MHz (most used), 500MHz, and 1GHz, the input amplitude was set in such way that the output was set to $800mV_{P-P}$. Also during all time the PD pin (J9 jumper) was connected to GND.

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The device was evaluated in differential mode. SETs where monitored using a Mixed Signal Oscilloscope, MSO58B (8 Channel, 1GHz, 6.25GS/s, 62.5M record length). The differential output of the TRF0208-SP is converted to single ended by using an Hyperlabs HL9402 balun and was monitored.

The power supply (PS) was controlled and monitored using a custom-developed LabView™ program (PXI-RadTest) running on a NI-PXIe-8135 controller. The R&S SME03 was controlled via the GPIB bus, using the stand alone LabView™ drivers. The MSO58B was controlled using its front-panel interface. The MSO was left in the cave at all times, to minimize the probe cable length. A keyboard, video, and mouse (KVM) extender was used to control and view the MSO from the control room at TAMU. A block diagram of the setup used for SEE testing the TRF0208-SP is illustrated in Figure 6-1. Equipment settings and compliances used during the characterization are shown in Table 6-1. For the SEL testing the device was heated using a convection heat gun aimed at the die. The junction temperature was monitored using a thermal camera at the Radiation facility.

Table 6-1. Equipment Setup and Parameters Used for SEE Testing the TRF0208-SP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
VDD (J1)	NI PXIe-4139	5A	5A	3.3V, 3.45V, 3.7V
INP (J4)	R&S SME03	5KHz-3GHz	—	100MHz, 500MHz, 1GHz
OUTP (J6) and OUTM (J5)	Tektronix MSO58B	6.25GS/S	—	6.25GS/s

All boards used for SEE testing were fully checked for functionality and dry runs performed to ensure that the test system was stable under all bias and load conditions prior to being taken to the TAMU facility. During the heavy-ion testing, the LabView™ control program powered up the TRF0208-SP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability had been confirmed, the beam shutter was opened to expose the device to the heavy-ion beam. The shutter remained open until the target fluence was achieved (determined by external detectors and counters).

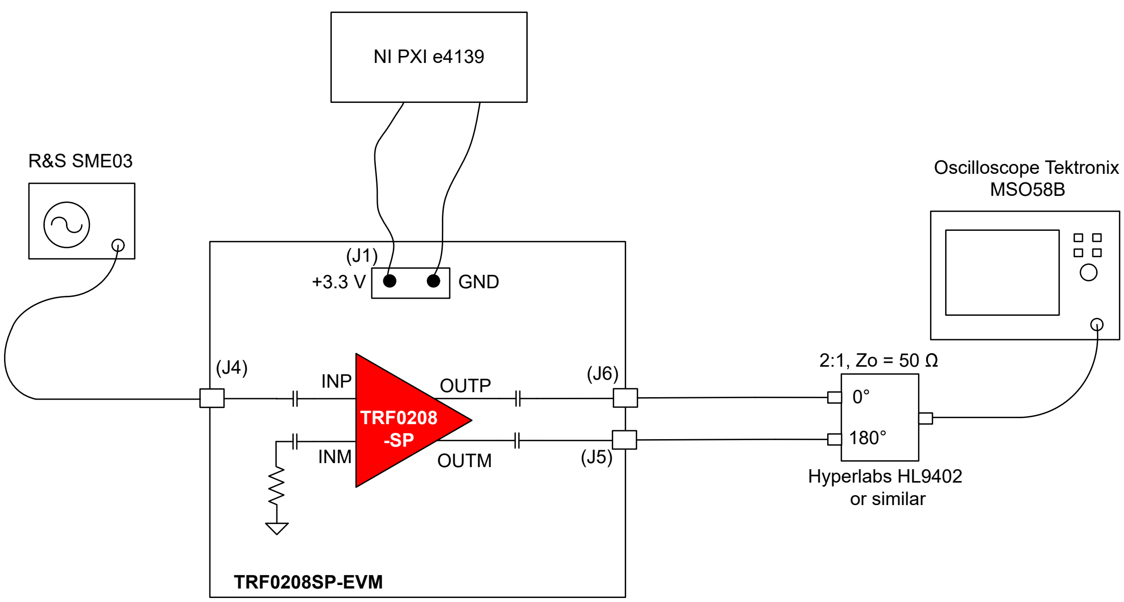

Figure 6-1. Block Diagram of the Test Setup Used for the TRF0208-SP Mounted on an EVM

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7 Single-Event Latch-up (SEL) Results

All SEL characterizations were performed with forced hot air to maintain the die temperature at 125°C during the tests. The device was exposed to a Holmium (Ho) heavy-ion beam incident on the die surface at 0° incident angle for an effective LET of 81.6 MeV-cm^2/mg. A flux of 10^5 ions/cm^2-s and fluence of 10^7 ions/cm^2 per run was used in all runs. The device was powered with voltage of 3.45V in most runs. In few runs device was tested at absolute maximum supply voltage of +3.7V. During all runs the device was actively amplifying a single ended input signal at 100 MHz. Both differential outputs were independently terminated (SE) to 50 Ω .

Time duration to achieve this fluence was approximately 2 minutes. The SEL results and conditions are provided in Table 7-1. All the runs passed, indicating that the TRF0208-SP is SEL-immune at a die-exposed temperature of T = 125°C and LET = 81.6 MeV-cm^2/mg.

Table 7-1. Summary of TRF0208-SP SEL Results (1)

Run #	Unit #	Test Type	Die-Exposed Temp. (°C)	Ion Type	LET_{EFF} (MeV-cm^2/mg)	Fluence (ions/cm^2)	VDD (V)	Uniformity	Results
1	1	SEL	125	Ho	81.6	1.0×10^7	3.45	92 %	Pass
2	1	SEL	125	Ho	81.6	2.0×10^7	3.7	92 %	Pass
3	2	SEL	125	Ho	81.6	1.0×10^7	3.45	96 %	Pass
4	2	SEL	125	Ho	81.6	2.0×10^7	3.7	96 %	Pass
5	2	SEL	125	Ho	81.6	2.0×10^7	3.45	96 %	Pass
6	3	SEL	125	Ho	81.6	1.0×10^7	3.45	95 %	Pass
7	3	SEL	125	Ho	81.6	2.0×10^7	3.7	95 %	Pass

(1) SEL results with T = 125°C and LET_{EFF} = 81.6 MeV-cm^2/mg

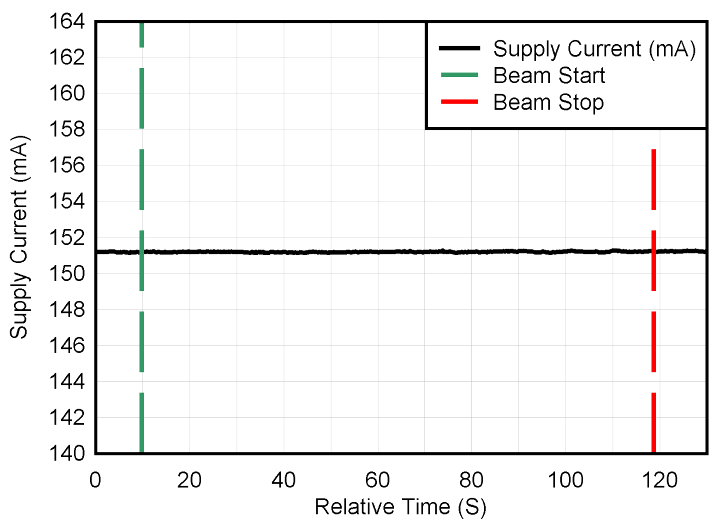

Figure 7-1. Supply Current versus Time Data for SEL Run #2 for the TRF0208-SP

8 Single-Event Transients (SET) Results

The TRF0208-SP was characterized for SETs from 9.62 to 81.6 MeV-cm^2/mg (Table 5-1 provides more information) at 3.3V supply voltage. The device was tested at room temperature for all SETs runs. TRF0208-SP devices were thinned for proper heavy-ion penetration into the active circuits. Average flux of 10^5 ions/cm^2-s and fluences of 10^7 ions/cm^2 per run were used during the heavy ion characterization. The devices were tested under AC inputs. The SETs discussed on this report were defined as output voltages excursion that exceed a window trigger set on the MSO58B. Outputs of the TRF0208-SP were converted to SE using HL9402 balun and monitored. Test conditions used during the testing are provided in Table 8-1. Positive and negative upsets excursions were observed under AC test. For each upset the maximum, minimum, and transient recovery time were recorded. All upsets are recovered under 10ns. Weibull-Fit and cross section for the AC tests are shown

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in Figure 8-1 . The Weibull equation used for the fit is shown below, and parameters are provided in Table 8-2. To calculate the cross section values the total number of upsets (or transients) and the fluences where combined (add together) by LET_{EFF} to calculate the upper bound cross section (as discussed in Appendix B) at 95% confidence interval. Worst case AC upset for each leg is shown in Figure 8-2. Though not observed during the testing, it is important to note that an SET event may result in output going up to saturation voltage.

Table 8-1. Summary of the TRF0208-SP AC Tests at V_{DD} = 3.3V

Run #	Unit #	Test Type	Die-Exposed Temp. (°C)	Ion Type	LETEFF (MeV·cm²/mg)	Average Flux (ions·cm²/mg)	Fluence (# of ions)	Uniformity	Trigger Value	#Events
1	4	SET	25	Ho (165)	81.6	1E+05	1E+07	96	UL = +20mV LL = –20mV	86
2	4	SET	25	Ho (165)	81.6	1E+05	1E+07	95	UL = +20mV LL = –20mV	76
3	4	SET	25	Ho (165)	81.6	10000	1E+07	93	UL = +20mV LL = –20mV	97
4	4	SET	25	Ho (165)	81.6	1E+05	1E+07	97	UL = +20mV LL = –20mV	91
5	4	SET	25	Ag (109)	56.1	1E+05	1E+07	95	UL = +20mV LL = –20mV	82
6	4	SET	25	Ag (109)	56.1	97690	9999000	96	UL = +20mV LL = –20mV	86
7	4	SET	25	Kr (84)	35.2	1E+05	9957000	95	UL = +20mV LL = –20mV	35
8	4	SET	25	Kr (84)	35.2	50830	9998000	95	UL = +20mV LL = –20mV	48
9	4	SET	25	Cu (63)	24	99340	1E+07	95	UL = +20mV LL = –20mV	10
10	4	SET	25	Cu (63)	24	50330	9880000	95	UL = +20mV LL = –20mV	6
11	4	SET	25	Ar (40)	9.62	57140	1E+07	94	UL = +20mV LL = –20mV	0
12	4	SET	25	Ar (40)	9.62	1E+05	1E+07	89	UL = +20mV LL = –20mV	0

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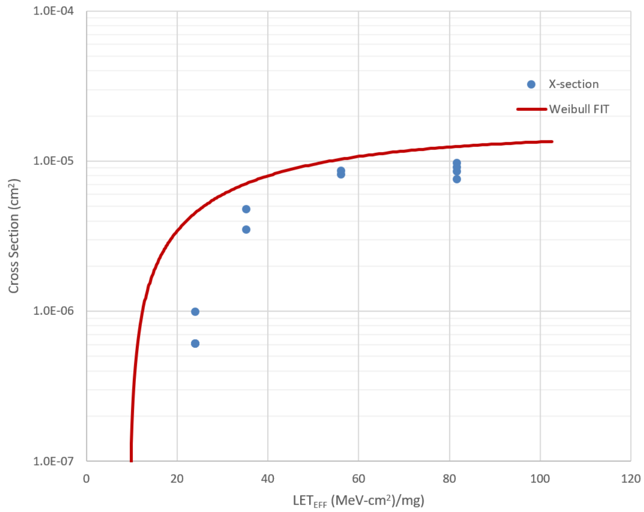

Figure 8-1. Cross Section and Weibull-Fit for the SET on OUT differential

$$\sigma = \sigma_{SAT} \times \left(1 - e^{-\left(\frac{LET - Onset}{W}\right)^{S}}\right) \quad (1)$$

Table 8-2. Weibull-FIT Parameters for DC Test

Parameter	Value
Onset (MeV-cm^2/mg)	9.62
σ_{SAT} (cm^2)	1.5× 10^{-5}
W	40
s	1

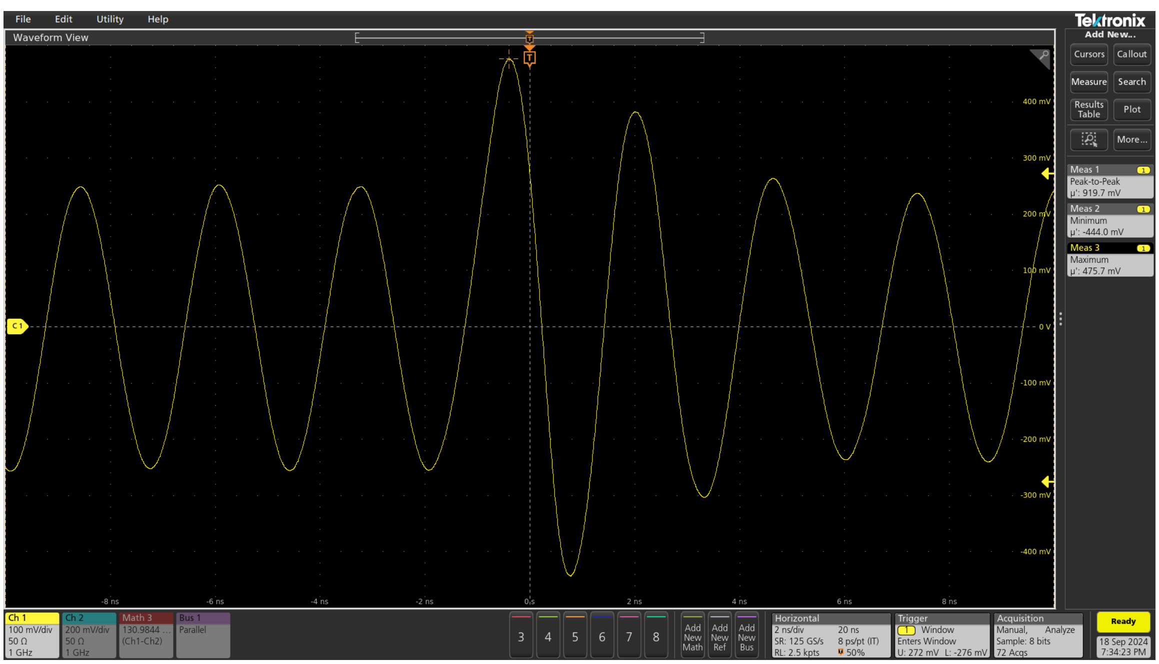

Figure 8-2. Worst Case Upset in AC Test When Monitoring Differential Output of the TRF0208-SP

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9 Event Rate Calculations

Event rates were calculated for LEO (ISS) and GEO environments 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*. We assume a minimum shielding configuration of 100 mils (2.54mm) of aluminum, and *worst-week* solar activity (this is similar to a 99% upper bound for the environment) is assumed. Using the 95% upper-bounds for the SEL, SET at supply voltage of 3.3V the event-rates of the TRF0208-SP are provided in Table 9-1.

Table 9-1. SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET ($MeV \cdot cm^2/mg$)	CREME96 Integral Flux ($/day \cdot cm^2$)	σ_{SAT} (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	9.62	36.4	1.5×10^{-5}	3.1×10^{-06}	129.042	884.565
GEO		301		2.43×10^{-05}	1012.67	112.727

10 Summary

The purpose of this study was to characterize the effect of heavy-ion irradiation on the single-event effect (SEE) performance of the TRF0208-SP 11GHz, fully differential, ADC driver RF amplifier. Extensive SEE testing with heavy-ions having LET_{EFF} from 9.62 to 81.6 MeV-cm^2/mg were conducted with heavy-ion fluences ranging from 10^6 to 10^7 ions/cm^2 per run. The SEE results demonstrated that the TRF0208-SP is SEL-free up to LET_{EFF} = 81.6 MeV-cm^2/mg. Also the SET cross sections are discussed under static input conditions. CREME96-based worst-week event-rate calculations for LEO (ISS) and GEO orbits clearly demonstrate the robustness of the TRF0208-SP in two harshly conservative space environments.

A Total Ionizing Dose from SEE Experiments

The production TRF0208-SP POL is rated to a total ionizing dose (TID) of 100 krad(Si). In the course of the SEE testing, the heavy-ion exposures delivered ≅ 1krad(Si) per 10^6 ions/cm^2 run. The cumulative TID exposure for each device respectively, over all runs they each underwent, was determined to be greater than 100krad(Si). The two production TRF0208-SP devices used in the studies described in this report stayed within specification and were fully-functional after the heavy-ion SEE testing was completed.

B 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

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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.

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):

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

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 x^2 is the chi-square distribution evaluated at 100 (1 – σ / 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*:

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

Where now *MFTF* is mean-fluence-to-failure and *F* is the test fluence, and as before, x^2 is the chi-square distribution evaluated at 100 (1 – σ / 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:

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

Let's assume that all tests are terminated at a total fluence of 10^6 ions/cm^2. Let's also assume that we have 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 B-1. Experimental Example Calculation of Mean-Fluence-to-Failure (MFTF) and σ Using a 95% Confidence Interval (1)

Degrees-of-Freedom (d)	2(d + 1)	χ^2 at 95%	Calculated Cross-Section (cm^2)		
			Upper-Bound at 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

(1) Using a 99% confidence for several different observed results (d = 0, 1, 2, and 3 observed events during fixed-fluence tests) on four identical devices and test conditions.

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