Radiation Report

Single-Event Effects Test Report of the TRF0206-SP 6.5-GHz Differential Amplifier

ABSTRACT

The effect of heavy-ion irradiation on the single-event effects performance of the TRF0206-SP high-performance, differential amplifier is summarized in this report. Heavy-ions with an LET_{EFF} up to 82.1 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 TRF0206-SP is SEL-free up to LET_{EFF} = 82.1 MeV-cm^2/mg and 125°C, and the cross section for the SET is discussed.

Table of Contents

1 Overview....3
2 Single-Event Effects....3
3 Test Device and Evaluation Board Information....4
4 Irradiation Facility and Setup....5
5 Depth, Range, and LET_{EFF} Calculation....6
6 Test Set-Up and Procedures....6
7 Single-Event Latch-up (SEL) Results....8
8 Single-Event Transients (SET) Results....9
9 Event Rate Calculations....11
10 Summary....11
A Total Ionizing Dose from SEE Experiments....11
B Confidence Interval Calculations....11
C Orbital Environment Estimations....13
D References....15
E Revision History....15

List of Figures

Figure 3-1. TRF0206-SP Radiation Board....4
Figure 3-2. TRF0206-SP Radiation board Schematic for SEE Testing....4
Figure 4-1. TRF0206-SP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port....5
Figure 5-1. GUI of RADsim Application Used to Determine Key Ion Parameters....6
Figure 6-1. Block Diagram of the Test Setup Used for the TRF0206-SP Mounted on an EVM....8
Figure 7-1. Temperature Versus Time Data for VDD During SEL Run #2 on the TRF0206-SP....9
Figure 7-2. Current Versus Time Data for VDD During SEL Run #2 on the TRF0206-SP....9
Figure 8-1. Cross Section and Weibull-Fit for the DC Test on OUTP....10
Figure 8-2. Cross Section and Weibull-Fit for the DC Test on OUTM....10
Figure C-1. Integral Particle Flux vs LET_{EFF}....14
Figure C-2. Device Cross-Section vs LET_{EFF}....14

List of Tables

Table 1-1. Overview Information....3
Table 5-1. LET_{EFF}, Depth and Range for the Ions Used for SEE Characterization of the TRF0206-SP....6
Table 6-1. Equipment Set Up and Parameters Used for the SEL Testing the TRF0206-SP....7
Table 7-1. Summary of TRF0206-SP SEL Results (1)....8
Table 8-1. Summary of the TRF0206-SP DC Tests....10
Table 8-2. Weibull-FIT Parameters for DC Test....10
Table 9-1. SET Event Rate Calculations for Worst-Week LEO and GEO Orbits....11

Table B-1. Experimental Example Calculation of Mean-Fluence-to-Failure (MFTF) and σ Using a 95% Confidence Interval [(1)] 13

Trademarks

LabView™ is a trademark of National Instruments Corporation.

DuPont® and Kevlar® are registered trademarks of E.I. du Pont de Nemours and Company.

All trademarks are the property of their respective owners.

1 Overview

The TRF0206-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). The TRF0206-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 TRF0206-SP offers a 6.5-GHz 3-dB 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/TRF0206-SP.

Table 1-1. Overview Information

Description	Device Information
TI Part Number	TRF0206-SP
SMD Number	5962-2122001VXC
Device Function	Differential Amplifier
Technology	SiGe-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 TRF0206-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 TRF0206-SP is low, SEB is not a concern.

The TRF0206-SP was characterized for SEL events. In mixed technologies, such as the SiGe-BiCMOS process used for the TRF0206-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 TRF0206-SP exhibited no SEL with heavy-ions of up to LET_{EFF} = 82.1 MeV-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 TRF0206-SP SET performance was characterized up to LET_{EFF} = 74.92 MeV-cm^2/mg. The device was characterized for SET at supply voltage of 3.3 V under DC input conditions. Test conditions and results are discussed in Section 8.

3 Test Device and Evaluation Board Information

The TRF0206-SP is packaged in a 12-pin, thermally-enhanced, leadless ceramic chip carrier package (LCCC) as shown in Figure 3-1. The TRF0206-SP Radiation Board was used to evaluate the single-events-effects (SEE) of the TRF0206-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 3-2. For more technical information about the TRF0206-SP, see https://www.ti.com/product/TRF0206-SP/technicaldocuments.

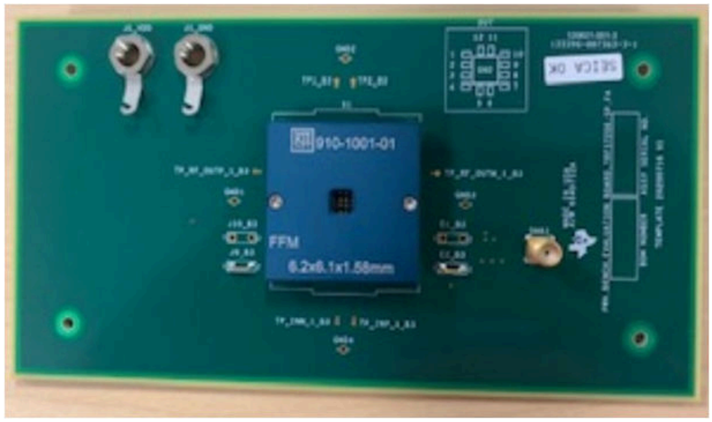


Figure 3-1. TRF0206-SP Radiation Board

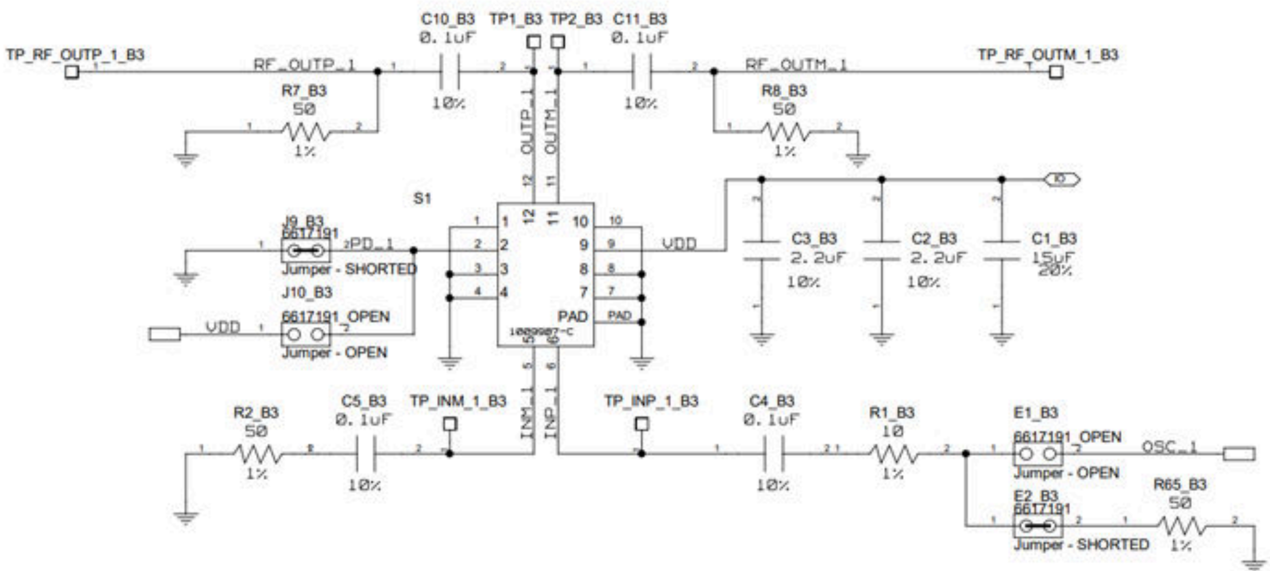


Figure 3-2. TRF0206-SP Radiation board Schematic for SEE Testing

4 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. 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/s-cm^2 were used to provide a heavy-ion fluences between 10^6 and 10^7 ions/cm^2.

For these experiments Holmium (^{165}Ho), Praseodymium (^{141}Pr), Silver (^{108}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 ^{141}Pr, ^{84}Kr and ^{63}Cu ions used had a total kinetic energy of 2114, 1259, and 944 MeV in the vacuum, (15-MeV/amu line) respectively. Ion beam uniformity for all tests was in the range of 88 to 97%.

Figure 4-1 shows the TRF0206-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®), 1-in diameter to allow in-air testing while maintaining the vacuum in the accelerator with only minor ion energy losses. The air space between the DUT and beam exit port the 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.

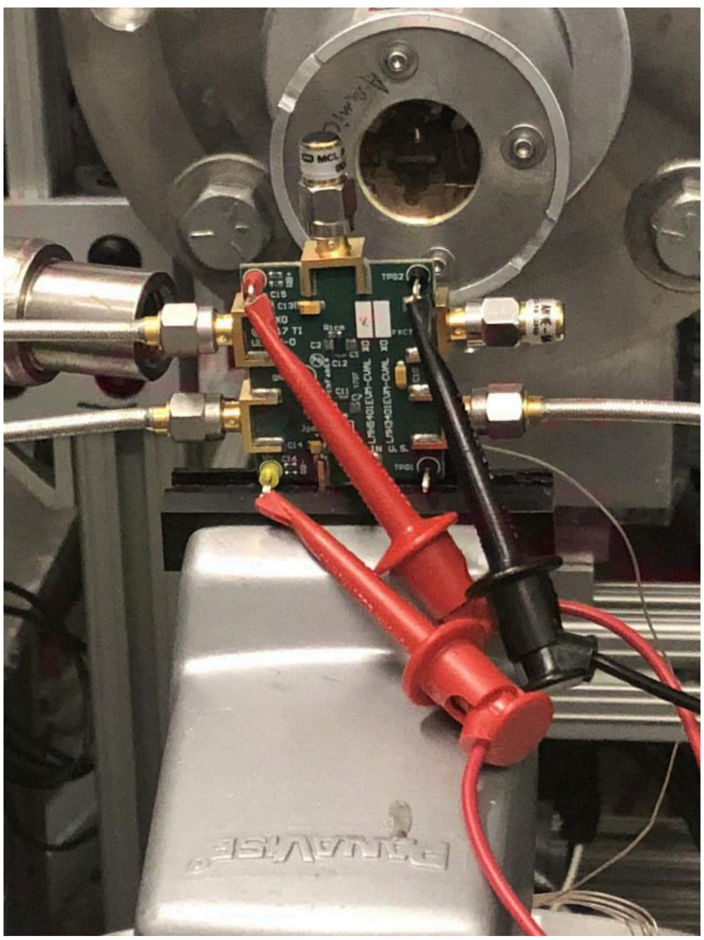


Figure 4-1. TRF0206-SP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Depth, Range, and LET_{EFF} Calculation

The TRF0206-SP is fabricated in the TI SiGe-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 backgrinded 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 [4] 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.

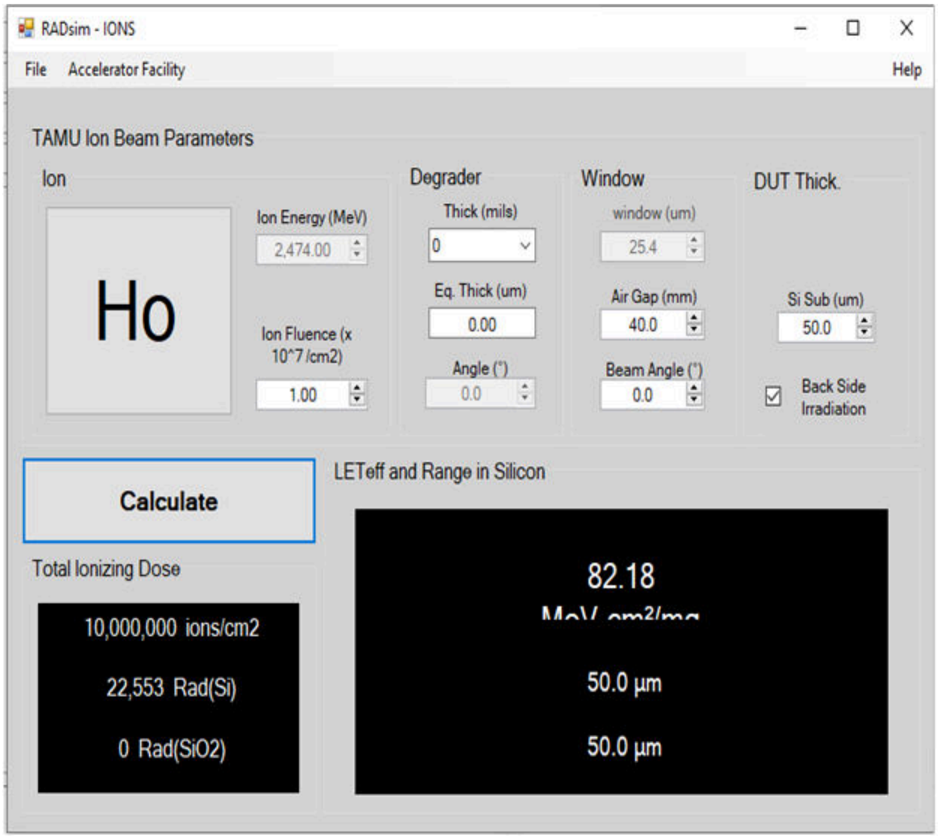


Figure 5-1. GUI of RADsim Application Used to Determine Key Ion Parameters

Table 5-1. LET_{EFF}, Depth and Range for the Ions Used for SEE Characterization of the TRF0206-SP

Ion Type	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET_{EFF} (MeV-cm²/mg)	Distance (mm)
Cu	0	50	50	24.54	40
Kr	0	50	50	36.1	40
Ag	0	50	50	57.73	40
Ag	30	50	57.7	67.95	40
Pr	0	50	50	70.60	40
Pr	20	50	53.2	74.92	40
Ho	0	50	50	82.18	40

6 Test Set-Up and Procedures

SEE testing was performed on a TRF0206-SP device mounted on a EVM. The device was provided power through the VDD (3.3 V) and GND inputs using the N6702 precision power supply. The TRF0206-SP was evaluated with a DC input condition provided on the IN+ input. The INM pin is terminated on a 50-Ω termination in the EVM. The PD pin (J9) was connected to GND to keep the chip enabled.

The devices was evaluated in differential (DE) output modes. SETs where monitored using a DPO7254C Digital Phosphor Oscilloscope (4 ch, 2.5-GHz BW and 40-GS/s Sample Rate).

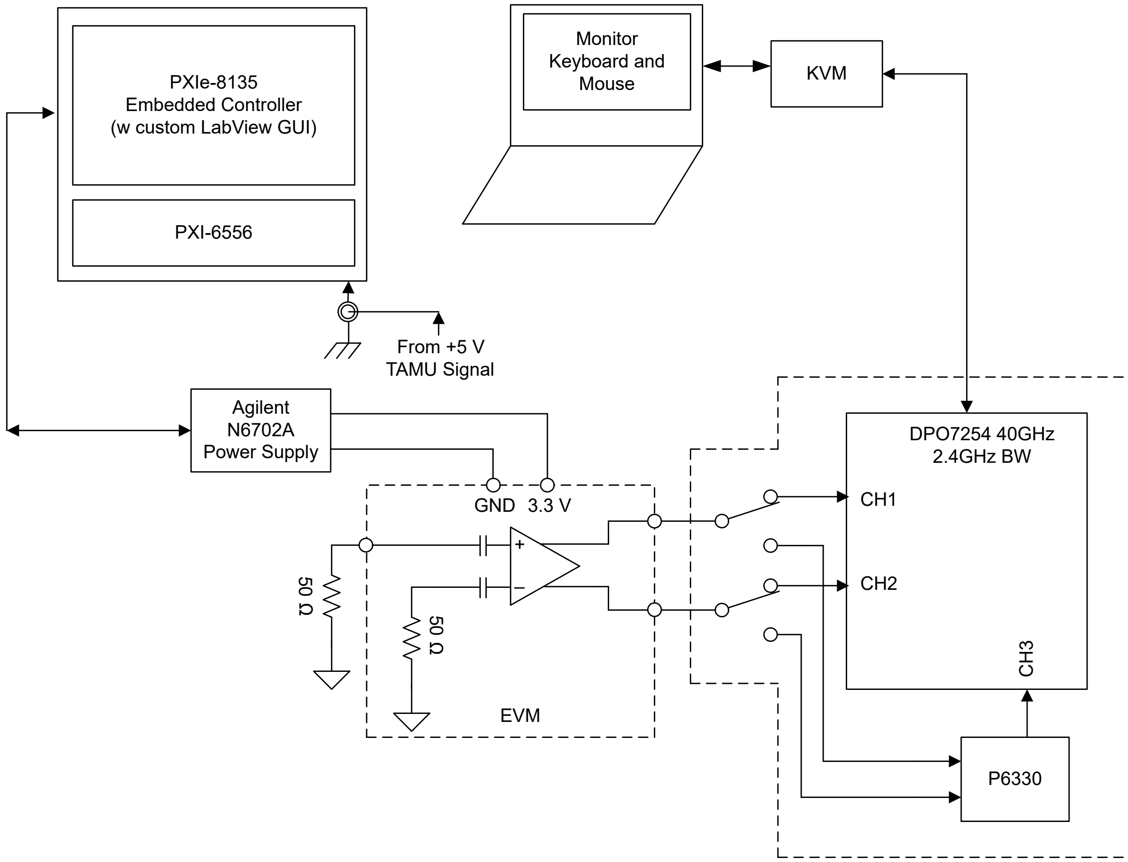
In SE mode, the outputs of the TRF0206-SP was monitored on the scope. In the DE mode, the outputs were monitored using a P6330 High Speed probe (BW > 3 GHz). The DPO was used to monitor the output voltage and capture any SET that exceed the limits set for the window trigger. The scope has a 3.2-µs update rate under the conditions used when collecting data (Fast-Frame mode). The update rate represents the amount of time to re-arm the scope trigger after an upset.

The power supply (PS) was controlled and monitored using a custom-develop LabView™ program (PXI-RadTest) running on a NI-PXIe-8135 controller. The DPO7254C was controlled using it front-panel interface. The DPO was left in the cave at all times, to minimize the probe cable length. A KVM extender was used to control and view the DPO from the control room at TAMU. A block diagram of the setup used for SEE testing the TRF0206-SP is shown in Figure 6-1. Equipment settings and compliances used during the characterization are provided 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 by using a K-type thermocouple attached as close as possible to the die.

Table 6-1. Equipment Set Up and Parameters Used for the SEL Testing the TRF0206-SP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
VDD	Keysight Power Supply N6702A	5 A	5 A	+3.45 V
OUTP and OUTM	Tektronix Oscilloscope DPO7104C	40 GS/s	—	20 GS/s
OUTP and OUTM	Tektronix Diff probe P6330	BW > 3 GHz	—	2.4 GHz (DPO BW)

All boards used for SEL 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 TRF0206-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).



The SPDT connections shown in the block diagram was not physically present at any time, rather is used to represent the SE and DE connections using one block diagram.

Figure 6-1. Block Diagram of the Test Setup Used for the TRF0206-SP Mounted on an EVM

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° for an effective LET of 82.1 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 3.4 V.

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 TRF0206-SP is SEL-immune at T = 125°C and LET = 82.1 MeV-cm^2/mg.

Table 7-1. Summary of TRF0206-SP SEL Results (1)

Run #	Unit #	Test Type	Temp (°C)	Ion Type	LET_{EFF} (MeV-cm^2/mg)	Fluence (ions/cm^2)	VDD (V)	Uniformity	Results
1	1	SEL	125	Ho	82.1	1.0×10^7	3.4	92 %	Pass
2	1	SEL	125	Ho	82.1	1.0×10^7	3.4	92 %	Pass
35	2	SEL	125	Ho	82.1	1.0×10^7	3.4	96 %	Pass
36	2	SEL	125	Ho	82.1	1.0×10^7	3.4	96 %	Pass
37	2	SEL	125	Ho	82.1	1.0×10^7	3.4	96 %	Pass
38	3	SEL	125	Ho	82.1	1.0×10^7	3.4	95 %	Pass

Table 7-1. Summary of TRF0206-SP SEL Results [1] (continued)

Run #	Unit #	Test Type	Temp (°C)	Ion Type	LET_{EFF} (MeV-cm^2/mg)	Fluence (ions/cm^2)	VDD (V)	Uniformity	Results
39	3	SEL	125	Ho	82.1	1.0×10^7	3.4	95 %	Pass

(1) SEL results with T = 125°C and LET_{EFF} = 82.1 MeV-cm^2/mg

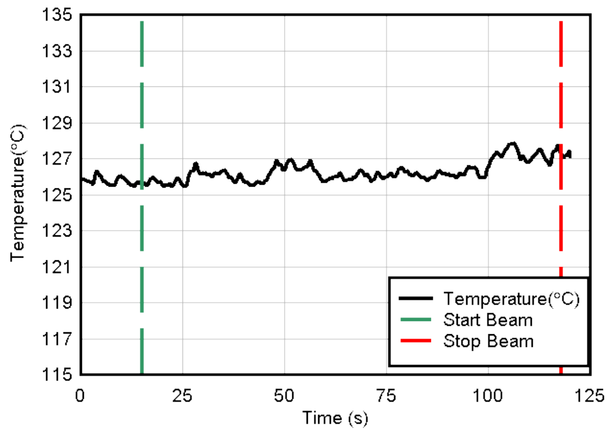


Figure 7-1. Temperature Versus Time Data for VDD During SEL Run #2 on the TRF0206-SP

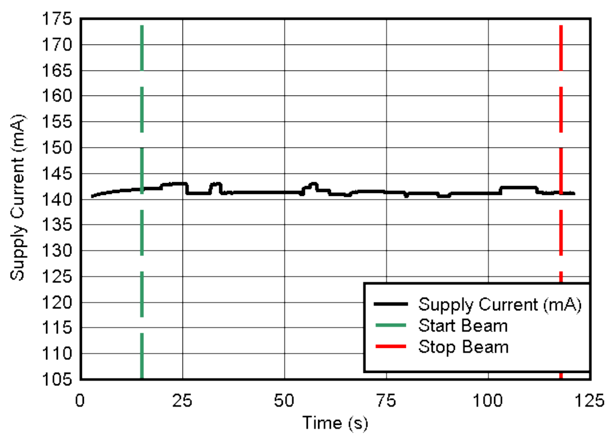


Figure 7-2. Current Versus Time Data for VDD During SEL Run #2 on the TRF0206-SP

8 Single-Event Transients (SET) Results

The TRF0206-SP was characterized for SETs from 9.75to 74.92 MeV-cm^2/mg (Table 5-1 provides more information) at 3.2 V supply voltage. The device was tested at room temperature for all SETs runs. TRF0206-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 static (DC) inputs. The SETs discussed on this report were defined as output voltages excursion that exceed a window trigger set on the DPO7104C. Outputs of the TRF0206-SP were monitored under both conditions each leg of the differential outputs was terminated at 50 Ω in the EVM. Test conditions used during the testing are provided in Table 8-1. Positive and negative upsets excursions were observed under DC test. For each upset the maximum, minimum and transient recovery time was recorded. Weibull-Fit and cross section for the DC tests are shown in Figure 8-1 and Figure 8-2 respectively. The Weibull equation used for the fit is shown in Equation 1, and parameters are provided in Table 8-2. To calculate the cross section values at the different supply voltages 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. The $\sigma_{PERCASE}$ cross section presented on the summary tables, was calculated using the MTBF method at 95%

confidence. When observing the upsets, both outputs legs (inverting and non-inverting) track each other for most of the time. Since both legs track each other differentially the upset is cancelled.

Table 8-1. Summary of the TRF0206-SP DC Tests

Run #	Unit #	Test Type	Temp (ºC)	Ion Type	LET_{EFF} ($MeV \cdot cm^2/mg$)	Flux (ions/ $cm^2 \cdot s$)	Fluence (ions/cm^2)	Uniformity 6	Trigger Value	# Events (OUTP)	# Events (OUTM)
1	3	SET	25	Ar	9.75	1.07E+05	1.00E+07	91 %	LL = –60 mV; UL = 60 mV	52	56
2	3	SET	25	Cu	24.54	1.22E+05	1.00E+07	90 %	LL = –60 mV; UL = 60 mV	59	58
3	3	SET	25	Cu	24.54	1.17E+05	1.00E+07	88 %	LL = –30 mV; UL = 30 mV	88	97
4	3	SET	25	Cu	24.54	1.24E+05	1.00E+07	90 %	LL = –10 mV; UL = 10 mV	99	94
5	3	SET	25	Kr	36.1	1.23E+05	1.00E+07	93 %	LL = –10 mV; UL = 10 mV	84	96
6	3	SET	25	Ag	57.74	1.15E+05	1.00E+07	83 %	LL = –10 mV; UL = 10 mV	96	96
7	3	SET	25	Ag	67.95	9.08E+04	1.00E+07	83 %	LL = –10 mV; UL = 10 mV	234	234
8	3	SET	25	Pr	70.6	1.08E+05	1.00E+07	97 %	LL = –10 mV; UL = 10 mV	115	112
9	3	SET	25	Pr	74.92	1.18E+05	1.00E+07	97 %	LL = –10 mV; UL = 10 mV	143	143
10	3	SET	25	Ar	9.75	1.38E+05	1.00E+07	88 %	LL = –60 mV; UL = 60 mV	47	48
11	3	SET	25	Ar	9.75	1.24E+05	1.00E+07	89 %	LL = –100 mV; UL = 100 mV	18	18
12	3	SET	25	Ar	9.75	1.79E+05	1.00E+07	92 %	LL = –120 mV; UL = 120 mV	6	6

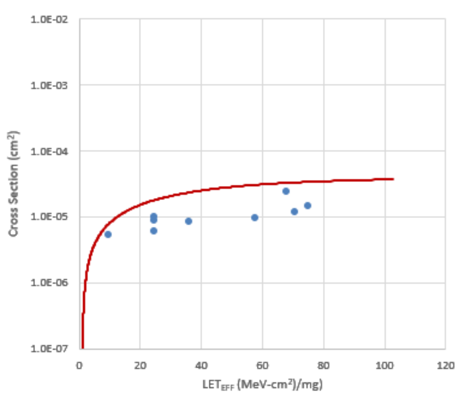


Figure 8-1. Cross Section and Weibull-Fit for the DC Test on OUTP

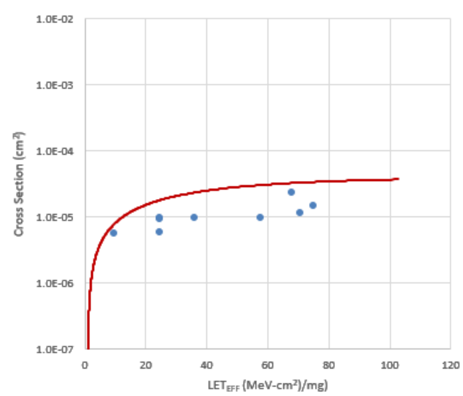


Figure 8-2. Cross Section and Weibull-Fit for the DC Test on OUTM

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

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

Parameter	OUTP	OUTM
Onset ($MeV\text{-}cm^2/mg$)	1.00	1.00
σ_{SAT} (cm^2)	0.00004	0.00004
W	40	40

Table 8-2. Weibull-FIT Parameters for DC Test (continued)

Parameter	OUTP	OUTM
s	1	1

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 *Appendix C* . We assume a minimum shielding configuration of 100 mils (2.54 mm) 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 DC at supply voltage of 3.3 V the event-rates of the TRF0206-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·cm^2/mg)	CREME96 Integral Flux (/day·cm^2)	σ_{SAT} (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	1.0000		4.00×10^{-5}	5.90×10^{-05}	$2.46 \times 10^{+03}$	46.4
GEO				5.17×10^{-04}	$2.15 \times 10^{+04}$	5.30

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 TRF0206-SP 6.5-GHz, Low Noise, Low Power, Fully-Differential Amplifier. Extensive SEE testing with heavy-ions having LET_{EFF} from 9.75 to 82.1 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 TRF0206-SP is SEL-free up to LET_{EFF} = 82.1 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 TRF0206-SP in two harshly conservative space environments.

A Total Ionizing Dose from SEE Experiments

The production TRF0206-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 ≅ 1 krad(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 100 krad(Si). The two production TRF0206-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 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)

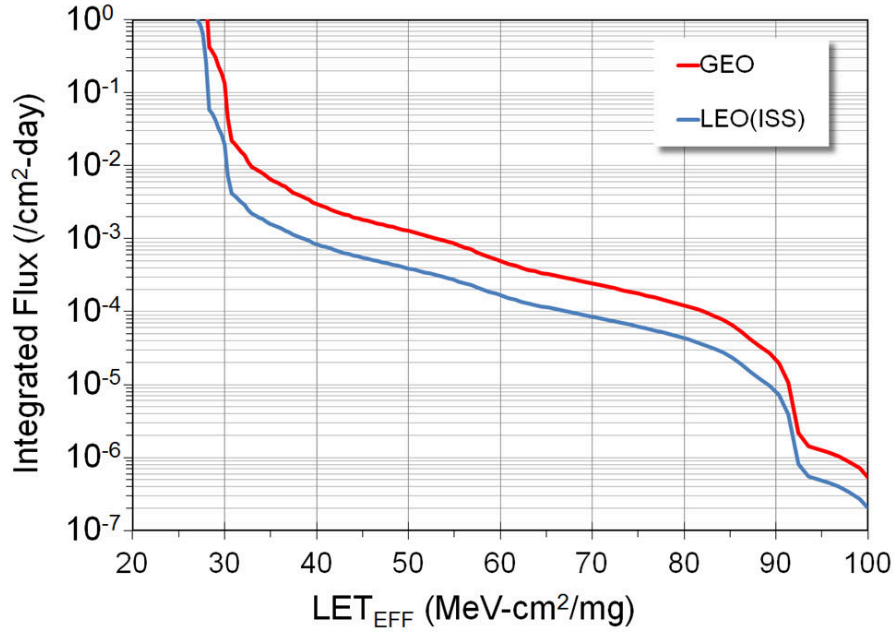
Degrees-of-Freedom (d)	2(d + 1)	χ^2 at 95%	Calculated Cross-Section (cm^2)		
			Upper-Bound at 95% Confidence	Mean	Average + Standard Deviation
0	2	7.38	3.69E–06	0.00E+00	0.00E+00
1	4	11.14	5.57E–06	1.00E–06	2.00E–06
2	6	14.45	7.22E–06	2.00E–06	3.41E–06
3	8	17.53	8.77E–06	3.00E–06	4.73E–06
4	10	20.48	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.

C Orbital Environment Estimations

To calculate on-orbit SEE event rates, one needs both the device SEE cross-section and the flux of particles encountered in a particular orbit. Device SEE cross-sections are usually determined experimentally while flux of particles in orbit is calculated using various codes. For the purpose of generating some event rates, a Low-Earth Orbit (LEO) and a Geostationary-Earth Orbit (GEO) were calculated using CREME96. CREME96 code, short for Cosmic Ray Effects on Micro-Electronics is a suite of programs [6] [7] that enable estimation of the radiation environment in near-Earth orbits. CREME96 is one several tools available in the aerospace industry to provide accurate space environment calculations. Over the years since its introduction, the CREME models have been compared with on-orbit data and demonstrated their accuracy. In particular, CREME96 incorporates realistic *worst-case* solar particle event models, where fluxes can increase by several orders-of-magnitude over short periods of time.

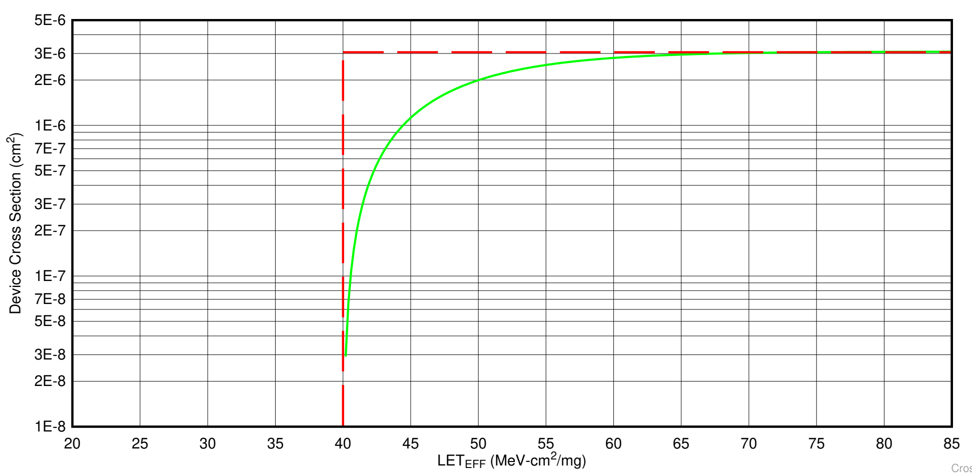
For the purposes of generating conservative event rates, the worst-week model (based on the biggest solar event lasting a week in the last 45 years) was selected, which has been equated to a 99%-confidence level worst-case event [8] [9]. The integrated flux includes protons to heavy ions from solar and galactic sources. A minimal shielding configuration is assumed at 100 mils (2.54 mm) of aluminum. Two orbital environments were estimated, that of the International Space Station (ISS), which is LEO, and the GEO environment. Figure C-1 shows the integrated flux (from high LET to low) for these two environments.



LEO(ISS) (blue) and a GEO (red) environment as calculated by CREME96 assuming worst-week and 100 mils (2.54 mm) of aluminum shielding.

Figure C-1. Integral Particle Flux vs LET$_{EFF}$

Using this data, we can extract integral particle fluxes for any arbitrary LET of interest. To simplify the calculation of event rates we assume that all cross-section curves are square – meaning that below the onset LET the cross-section is identically zero while above the onset LET the cross-section is uniformly equal to the saturation cross-section. Figure C-2 shows the approximation, with the green curve being the actual Weibull fit to the data with the *square* approximation shown as the red-dashed line. This allows us to calculate event rates with a single multiplication, the event rate becoming simply the product of the integral flux at the onset LET, and the saturation cross-section. Obviously this leads to an over-estimation of the event rate since the area under the square approximation is larger than the actual cross-section curve – but for the purposes of calculating upper-bound event rate estimates, this modification avoids the need to do the integral over the flux and cross-section curves.



Weibull Fit (green) is *simplified* with the use of a square approximation (red dashed line).

Figure C-2. Device Cross-Section vs LET$_{EFF}$

To demonstrate how the event rates in this report were calculated, assume that we wish to calculate an event rate for a GEO orbit for the device whose cross-section is shown in Figure C-2. Using the red curve in Figure C-1 and the onset LET value obtained from Figure C-2 (≅ 40 MeV-cm^2/mg) we find the GEO integral flux to be ≅ 2.97

× 10^{-3} ions/cm^2-day. The event rate is the product of the integral flux and the saturation cross-section in Figure C-2 (≅ 3.09 × 10^{-6} cm^2):

$$GEO\ Event\ Rate = \left(2.97 \times 10^{-3} \frac{ions}{cm^2 \times day}\right) \times \left(3.09 \times 10^{-6}\ cm^2\right) = 9.17 \times 10^{-9} \frac{events}{day} \quad (5)$$

$$GEO\ Event\ Rate = 3.82 \times 10^{-10} \frac{events}{hr} = 0.382\ FIT \quad (6)$$

$$MTBF = 298901\ Years! \quad (7)$$

D References

1. M. Shoga and D. Binder, “Theory of Single Event Latchup in Complementary Metal-Oxide Semiconductor ICs”, IEEE Trans. Nucl. Sci,, 33(6), Dec. 1986, pp. 1714-1717.
2. G. Bruguier and J.M. Palau, “Single particle-induced latchup”, IEEE Trans. Nucl. Sci, Vol. 43(2), Mar. 1996, pp. 522-532.
3. TAMU Radiation Effects Facility website. http://cyclotron.tamu.edu/ref/
4. “The Stopping and Range of Ions in Matter” (SRIM) software simulation tools website. http://www.srim.org/index.htm#SRIMMENU
5. D. Kececioglu, “Reliability and Life Testing Handbook”, Vol. 1, PTR Prentice Hall, New Jersey,1993, pp. 186-193.
6. https://creme.isde.vanderbilt.edu/CREME-MC
7. A. J. Tylka, et al., "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code", IEEE Trans. Nucl. Sci., 44(6), 1997, pp. 2150-2160.
8. A. J. Tylka, W. F. Dietrich, and P. R. Bobery, “Probability distributions of high-energy solar-heavy-ion fluxes from IMP-8: 1973-1996”, IEEE Trans. on Nucl. Sci., 44(6), Dec. 1997, pp. 2140 – 2149.
9. A. J. Tylka, J. H. Adams, P. R. Boberg, et al.,“CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code”, Trans. on Nucl. Sci, 44(6), Dec. 1997, pp. 2150 – 2160.

15 Revision History

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

Changes from Revision * (December 2022) to Revision A (August 2024)	**Page**
• Added Temperature Versus Time plot and Supply Current Versus Time Plot for SEL test................................	8

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265