Radiation Report

TMP461-SP Single-Event Effects (SEE) Radiation Test Report

ABSTRACT

The purpose of this study was to characterize the effects of heavy-ion irradiation on the single-event effect (SEE) performance of the TMP461-SP Remote and Local Digital Temperature Sensor. Heavy ions with an LET_{EFF} of 76 MeV-cm^2/mg were used to irradiate the devices with a fluence of 1 × 10^7 ions/cm^2. The results demonstrate that the TMP461-SP is SEL-free up to LET_{EFF} = 76.18 MeV-cm^2/mg at 125°C, and dynamic SET cross section is presented.

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1 Overview

The TMP461-SP device is a radiation-hardened, high-accuracy, low-power remote temperature sensor monitor with a built-in local temperature sensor. The remote temperature sensors are typically low-cost discrete NPN or PNP transistors, or substrate thermal transistors or diodes that are integral parts of microprocessors, analog-to-digital converters (ADC), digital-to-analog converters (DAC), microcontrollers, or field-programmable gate arrays (FPGA). Temperature is represented as a 12-bit digital code for both local and remote sensors, giving a resolution of 0.0625°C. The two-wire serial interface accepts the SMBus communication protocol with up to nine different pin-programmable addresses.

Table 1-1 lists general device information and test conditions. For more detailed technical specifications, user-guides, and application notes, see http://www.ti.com/product/TMP461-SP/technicaldocuments.

Table 1-1. Overview Information

DESCRIPTION	DEVICE INFORMATION (1)
TI Part Number	TMP461-SP
SMD Number	5962-1721801VXC
Device Function	Remote and Local Digital Temperature Sensor
Technology	LBC8LV
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy Ion Fluence per Run	1×10^6 – 1×10^7 ions/cm^2
Irradiation Temperature	25°C and 125°C (for SEL Testing)

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2 SEE Mechanisms

The primary SEE events of interest in the TMP461-SP are single-event latch-up (SEL), single-event burn-out (SEB), and single-event transient (SET). From a risk and impact point-of-view, the occurrence of an SEL and SEB is potentially the most destructive SEE event and the biggest concern for space applications. In mixed technologies such as the LBC8LV process used for the TMP461-SP, the 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 (and is *latched*) until power is removed or until the device is destroyed by the high-current state. The process modifications applied for SEL-mitigation were sufficient as the TMP461-SP exhibited no SEL with heavy ions up to an LET_{EFF} of 76.18 MeV-cm^2/mg at a fluence of 10^7 ions/cm^2 and a chip temperature of 125°C.

This study was performed to evaluate the cross section and transient effects with a bias voltage of 3.6V and 2.5V. To capture different SET signature events, the trigger was set with ±2° variance. Heavy ions with LET_{EFF} 65.65 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 room temperature. The output temperature data was processed and analyzed.

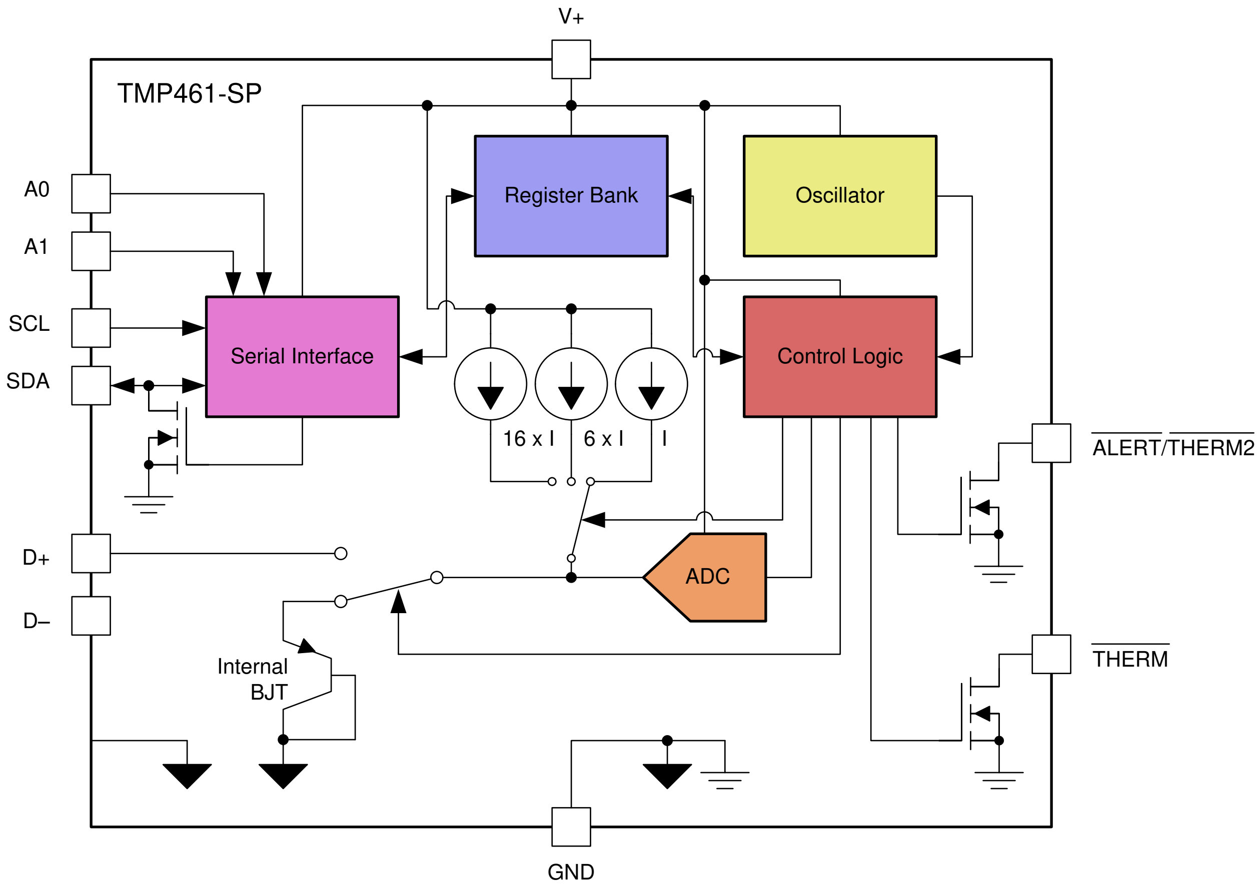
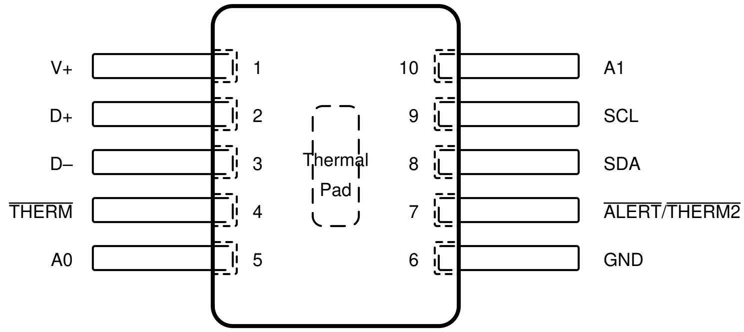


Figure 2-1. Functional Block Diagram of the TMP461-SP

3 Test Device and Test Board Information

The TMP461-SP is packaged in a 10-pin, thermally-enhanced, dual ceramic flat pack package (CFP) shown with pinout in Figure 3-1. The TMP461 evaluation board used for the SEE characterization is shown in Figure 3-2 and schematics are shown in Figure 3-3.



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

Figure 3-1. TMP461-SP HKU (CFP, 10) Pinout Diagram

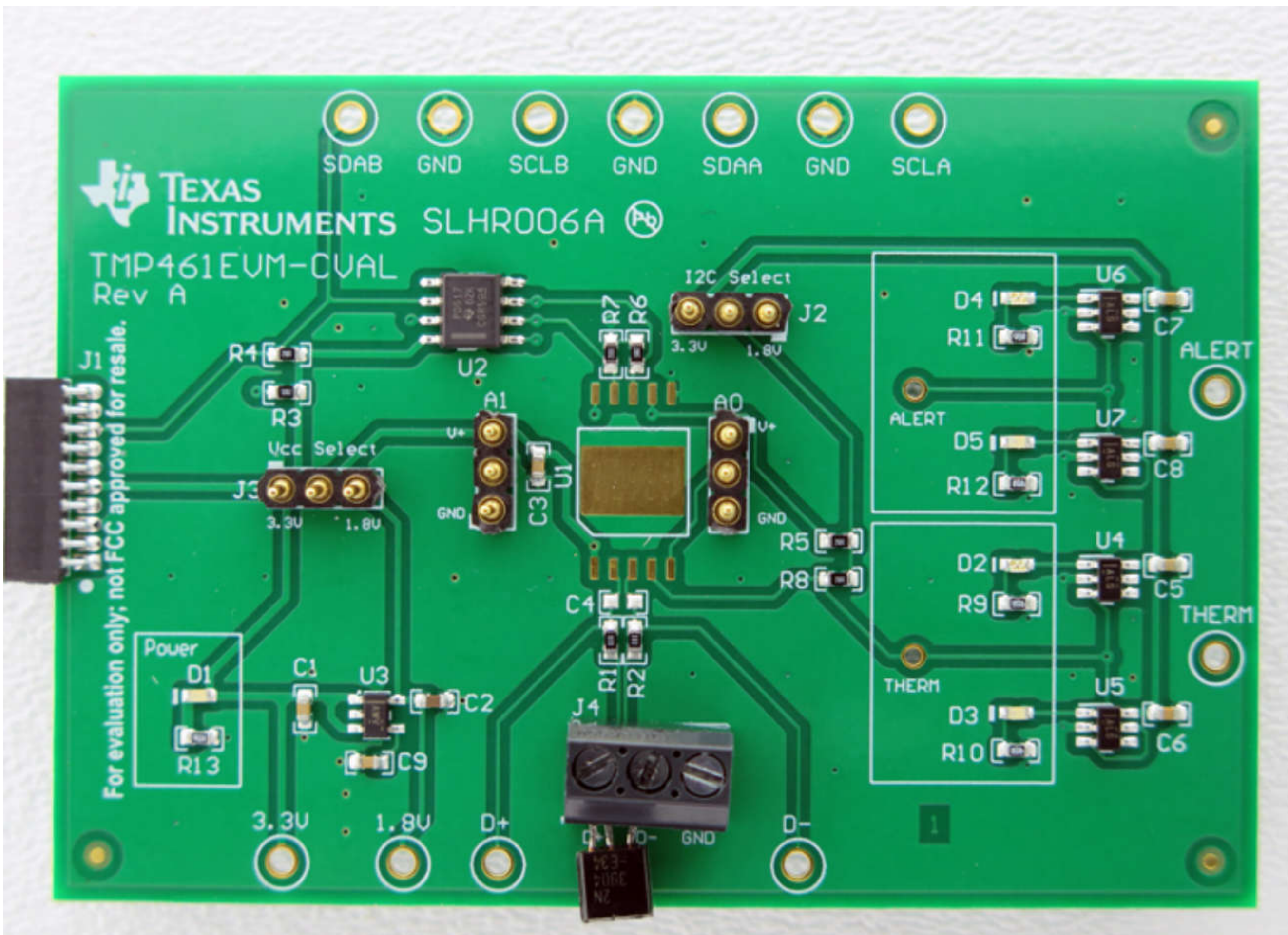


Figure 3-2. TMP461EVM-CVAL Temperature Sensor Evaluation Module Board

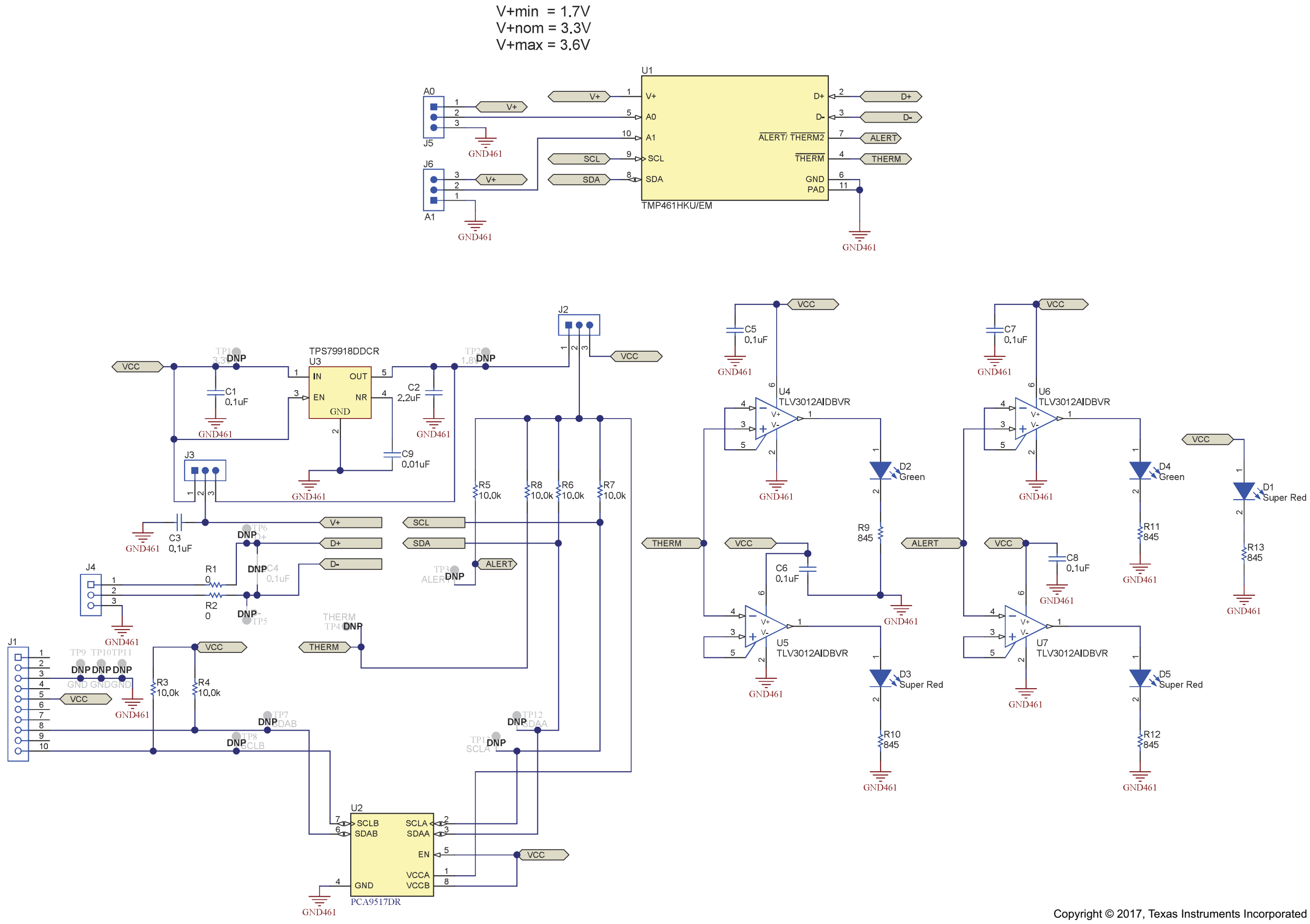


Figure 3-3. Schematic of TMP461EVM-CVAL Evaluation Board Used to Perform the SEE

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. 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 Praseodymium (Pr) ions were used. Ion beam uniformity for all tests was in the range of 91% to 98%. Figure 4-1 shows the test boards as it was used for exposure at the TAMU facility. The 1-mil Aramica window allows in-air testing while maintaining the vacuum within the accelerator with only minor ion energy loss. The air space between the device and the ion beam port window was maintained at 40 mm for all runs. For more information on the effective LET range and depth for the experiments, see Table 4-1.

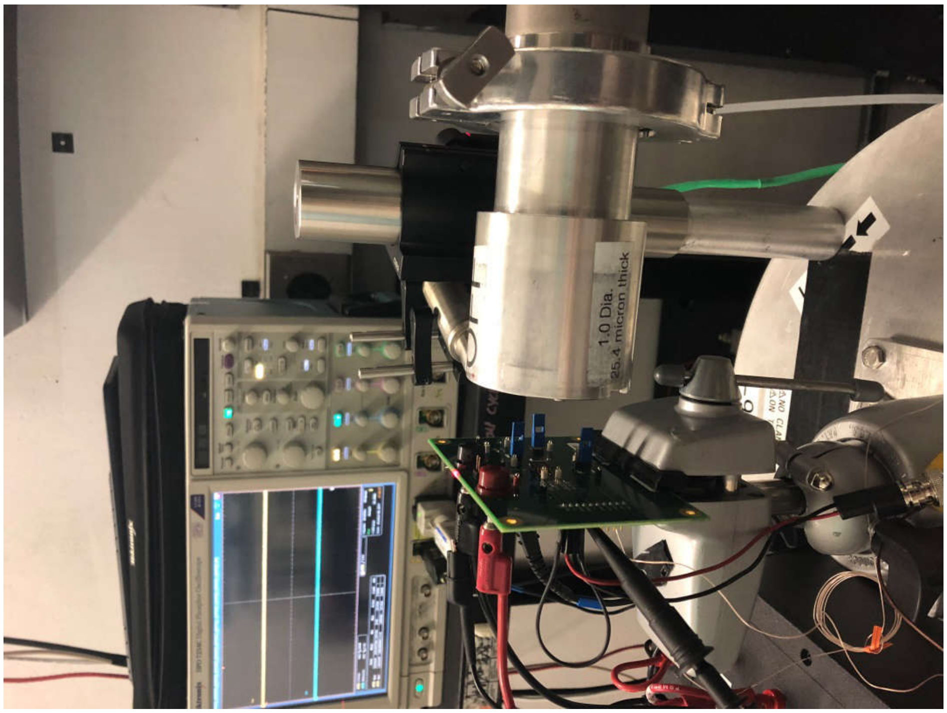


Figure 4-1. Evaluation Board Mounted in Front of Heavy Ion Beam Exit Port at the TAMU Accelerator Facility With a 40-mm Air Gap

Table 4-1. Ion Used for SEE Characterization and Effective LET_{EFF}

ION TYPE	ANGLE OF INCIDENCE	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	LET_{EFF} (MeV-cm^2/mg)	NOTES
Pr	25°	1.00E+05	1.00E+07	76.18	No Latch-Up
Pr	25°	1.00E+05	1.00E+07	76.18	No Latch-Up
Pr	0°	1.00E+05	1.00E+07	65.65	No Latch-Up
Pr	0°	1.00E+05	1.00E+07	65.65	No Latch-Up

5 Results

5.1 SEL Results

During SEL characterization, the device was heated using forced hot air, maintaining the die temperature at 125°C. The temperature was monitored by means of a K-type thermocouple attached as close as possible to the die. The species used for the SEL testing was a Praseodymium (^{59}Pr) ion with angle of incidence at 0° and 25° for an LET_{EFF} = 76.18 MeV-cm^2/mg and 65.65 MeV-cm^2/mg. The kinetic energy in the vacuum for this ion is 0.885 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 all seven runs. The VCC voltage was set to the recommended maximum at 3.6V. Run duration to achieve this fluence was approximately two minutes. No SEL events were observed during all four runs shown in Table 5-1. Figure 5-1 shows a plot of the current versus time.

Table 5-1. TMP461-SP SEL Conditions Using ^{59}Pr With Angle-of-Incidence = 0° and 25°

RUN #	DISTANCE (mm)	TEMPERATURE (°C)	ION	ANGLE	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	LET_{EFF} (MeV.cm^2/mg)
23	40	125	Pr	25°	1.00E+05	1.00E+07	76.18
24	40	125	Pr	25°	1.00E+05	1.00E+07	76.18
25	40	125	Pr	0°	1.00E+05	1.00E+07	65.65
26	40	125	Pr	0°	1.00E+05	1.00E+07	65.65

No SEL events were observed, indicating that the TMP461-SP is SEL-immune at LET_{EFF} = 76.18 MeV-cm^2/mg and T = 125°C. Using the *MFTF* method described in Appendix A and combining (or summing) the fluences of the seven runs (4×10^7), the upper-bound cross-section (using a 95% confidence level) is calculated as:

$\sigma SEL \leq 1.84 \times 10^{-7}$ cm^2 for LET_{EFF} = 76.18 MeV-cm^2/mg and T = 125°C.

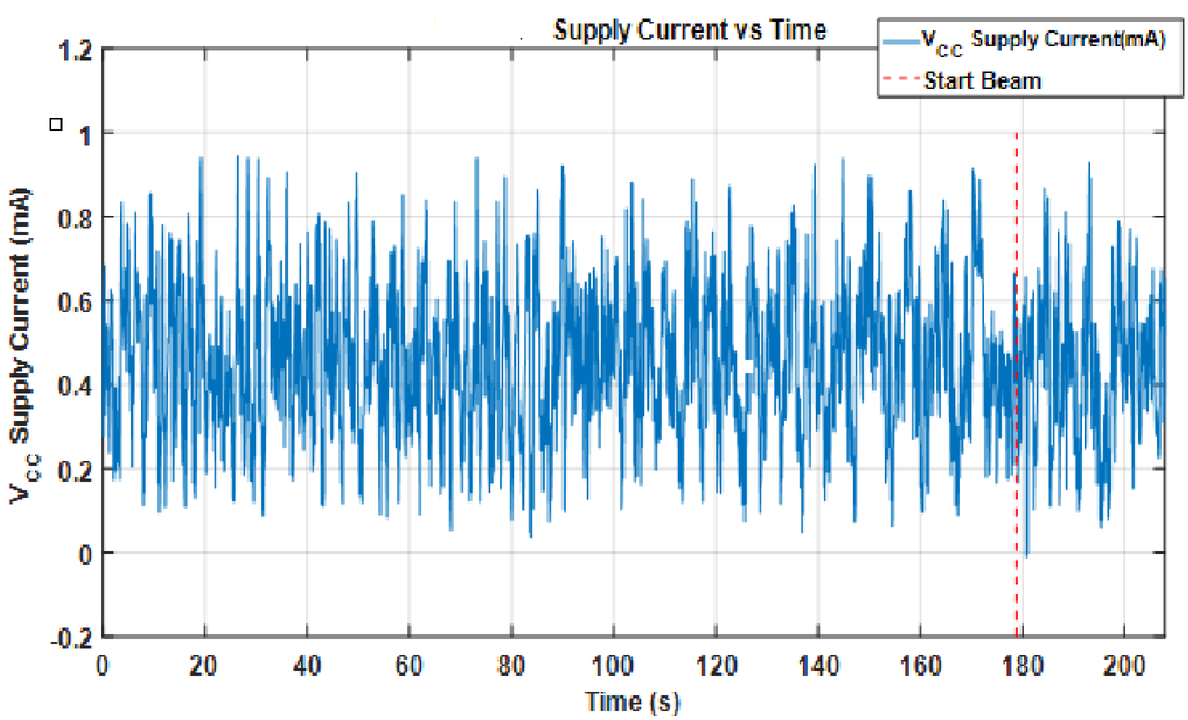


Figure 5-1. Current versus Time (I vs t) Data for VCC Supply Current During SEL Run #23

5.2 SET Results

A study was performed to evaluate the cross section and transient effects with a bias voltage of 3.3V. To capture different SET signatures events, the triggers was set with ±2.0°C variance. Initial temperature readings were recorded for the local channel and each remote channel. All device registers were read in 350 ms intervals and the current temperature readings were compared with the initial readings to record all events that exceeded ±2.0°C. To ensure that previous transients were not affecting subsequent register reads, a device reset was issued between each measurement. The TMP461-SP device supports reset using the two-wire general-call address 00h (0000 0000b). The TMP461-SP device acknowledges the general-call address and responds to the second byte. If the second byte is 06h (0000 0110b), the TMP461-SP device executes a software reset. This software reset restores the power-on reset state to all TMP461-SP registers and aborts any conversion in progress. The cross section plot shown below highlights when the TMP461 was in extended mode and issued a I2C two-wire general-call reset before every temperature read. Extended mode can be set up through the I2C TMP461-SP registers to broaden the temperature range of the output results.

Heavy ions with LET_{EFF} 65.65 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 room temperature. The output temperature data was processed and analyzed. SET events were observed, the upper-bound cross-section (using a 95% confidence level) is calculated as:

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

σSEL ≤ 2.1 × 10^{-6} cm^2 for LET_{EFF} = 65.65 MeV-cm^2/mg and T = 25°C at 3.6V.

σSEL ≤ 2.1 × 10^{-6} cm^2 for LET_{EFF} = 65.65 MeV-cm^2/mg and T = 25°C at 2.5V.

Table 5-2. Summary of TMP461-SP SET Results

RUN #	DIE TEMP (°C)	UNIT #	DISTANCE (mm)	ION TYPE	ANGLE OF INCIDENCE (°)	LET_{EFF} (MeV·cm²/mg)	FLUX (ions·cm²/mg)	FLUENCE (# of ions)	V+ (V)	# of EVENTS	COMMENTS
26	25	1	40	Ag	0	48	1.00E+04	1.00E+06	3.3	324	Extended mode with no resets
28	25	1	40	Ag	0	48	1.00E+04	2.00E+06	3.3	26	Extended with resets
29	25	1	40	Ag	0	48	1.00E+04	2.00E+06	3.3	116	Extended with no resets
30	25	1	40	Ag	0	48	1.00E+04	2.00E+06		676	Nonextended with no resets
32	25	1	40	Ag	30	56.36	1.00E+04	2.00E+06	3.3	643	Extended mode with no resets
34	25	1	40	Ag	30	56.36	1.00E+04	2.00E+06	3.3	28	Nonextended mode with no resets
35	25	1	40	Ag	30	56.36	1.00E+04	2.00E+06	3.3	33	Extended mode with resets
36	25	1	40	Ag	30	56.36	1.00E+04	2.00E+06	3,3	34	Nonextended mode with resets
38	25	1	40	Ho	0	76	1.00E+04	2.00E+06	3.3	368	Extended mode with no resets
39	25	1	40	Ho	0	76	1.00E+04	2.00E+06	3.3	575	Nonextended mode with no resets
40	25	1	40	Ho	0	76	1.00E+04	2.00E+06	3.3	41	Extended mode with resets
41	25	1	40	Ho	0	76	1.00E+04	2.00E+06	3.3	48	Nonextended mode with resets
44	25	1	40	Ar	0	8.7	1.00E+04	2.00E+06	3.3	22	Extended with no resets
45	25	1	40	Ar	0	8.7	1.00E+04	2.00E+06	3.3	20	Nonextended with no resets

Table 5-2. Summary of TMP461-SP SET Results (continued)

RUN #	DIE TEMP (°C)	UNIT #	DISTANCE (mm)	ION TYPE	ANGLE OF INCIDENCE (°)	LET_{EFF} (MeV·cm²/mg)	FLUX (ions·cm²/mg)	FLUENCE (# of ions)	V+ (V)	# of EVENTS	COMMENTS
46	25	1	40	Ar	0	8.7	1.00E+04	2.00E+06	3.3	24	Extended with resets
47	25	1	40	Ar	0	8.7	1.00E+04	2.00E+06	3.3	22	Nonextended with resets

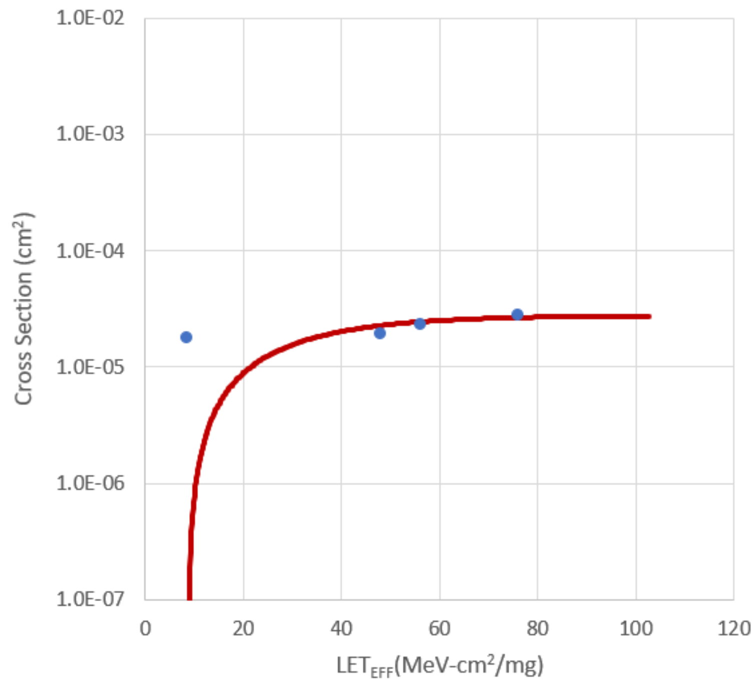


Figure 5-2. Cross Section versus LET

5.3 Event Rate Calculations

Event rates were calculated for LEO (ISS) and GEO environments by combining CREME96 orbital integral flux estimations. The error rate was calculated using the upper bound cross section calculated as discussed in Appendix A and the integral flux at approximately LET_{EFF} = 48 MeV·cm^2/mg for LEO (ISS) and GEO. A minimum shielding of 100 mils (2.54 mm) of aluminum and *Worst Week* solar activity was assumed. *Worst Week* is similar to 99% upper bound for the environment.

Table 5-3. SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

ORBIT TYPE	ONSET LET_{EFF} (MeV·cm^2/mg)	CREME96 INTEGRAL FLUX (/day·cm^2)	σ SAT (cm²)	EVENT RATE (/DAY)	EVENT RATE (FIT)	MTBE (YEARS)
LEO (ISS)	8.7000	5.38E-01	2.78E-05	8.27E-06	3.44E+02	3.31E+02
GEO		4.54E-02		6.50E-05	2.71E+03	4.21E+01

6 Summary

Radiation effects of remote and local digital temperature sensor TMP461-SP was studied. This device is latch-up immune up to 76.18 MeV. The SET study was done by monitoring the temperature readout using the MSP430 device and monitoring the temperature readout and logging the values using a GUI for each run. Importantly, there were no transients observed up to rail voltage.

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 (because 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, 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)
- *T*, is the test time
- χ^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence level
- *d* is the degrees-of-freedom (the number of failures observed)

With slight modification for this example, 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:

- *MFTF* is mean-fluence-to-failure

- *F* is the test fluence
- χ^2 is the chi-square distribution evaluated at 100(1 – α / 2) confidence
- *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 [1]

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

(1) Using a 95% confidence interval for several different observed results (d = 0, 1, 2,…100 observed events during fixed-fluence tests) assuming 10^6 ions/cm^2 for each test. Note that as the number of observed events increases the confidence interval approaches the mean.

B References

1. M. Shoga and D. Binder, "Theory of Single Event Latchup in Complementary Metal-Oxide Semiconductor Integrated Circuits", *IEEE Trans. Nucl. Sci., Vol. 33(6)*, Dec. 1986, pp. 1714-1717.
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9 Revision History

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

Changes from Revision D (November 2023) to Revision E (February 2026)	Page
• Added content to Section 5.2	7

Changes from Revision C (September 2023) to Revision D (November 2023)	Page
• Changed Table 5-2	7
• Changed Figure 5-2	7
• Changed Table 5-3	9

Changes from Revision B (January 2021) to Revision C (September 2023)	Page
• Changed document title from: Single-Event Effects Test Report for TMP461-SP High-Accuracy Remote and Local to: TMP461-SP Single-Event Effects (SEE) Radiation Test Report	1
• Added content to Section 5.2	7

Changes from Revision A (February 2020) to Revision B (January 2021)	Page
• Updated the numbering format for tables, figures and cross-references throughout the document	1