Single-Event Effects Test Report of the LMT01-SP Temperature Sensor

ABSTRACT

The purpose of this study was to characterize the effects of heavy-ion irradiation on the single-event effect (SEE) performance of the LMT01-SP Digital Temperature Sensor. Heavy ions with an $\mathrm{LET_{EFF}}$ of 93.98 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 LMT01-SP is SEL-free up to $\mathrm{LET_{EFF}}$ = 93.98 MeV-cm^2/mg at 125°C, and dynamic SET cross section is presented.

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1 Overview

The LMT01-SP device is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse count current loop interface, being released for space applications. The LMT01-SP digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability, while minimizing software overhead. TI’s LMT01-SP device achieves a maximum ±3°C accuracy with very fine resolution (0.0625°C) without system calibration or hardware and software compensation. The LMT01-SP’s pulse count interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01-SP’s integrated EMI suppression and simple 2-pin architecture makes it suitable for onboard and off board temperature sensing in a noisy environment. The LMT01-SP device can be easily converted into a two-wire temperature probe with a wire length up to two meters.

Table 1 lists general device information and test conditions. For more detailed technical specifications, user-guides, and application notes, see www.ti.com/product/LMT01-SP/technicaldocuments.

Table 1. Overview Information(1)

DESCRIPTION	DEVICE INFORMATION
TI Part Number	LMT01-SP
SMD Number	5962R1821301VXC
Device Function	Digital Temperature Sensor
Technology	CMOS7
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy Ion Fluence per Run	1×10^7 ions/cm^2
Irradiation Temperature	125°C

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2 SEE Mechanisms

The primary SEE events of interest in the LMT01-SP are single-event latch-up (SEL), single-event burn-out (SEB) and single-event transient (SET). From a risk/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. The CMOS circuitry present in the CMOS7 process used for the LMT01-SP 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 process modifications applied for SEL-mitigation were sufficient as the LMT01-SP exhibited no SEL with heavy ions up to an LET_{EFF} of 93.98 MeV-cm^2/mg at a fluence of 10^7 ions/cm^2 and a chip temperature of 125°C.

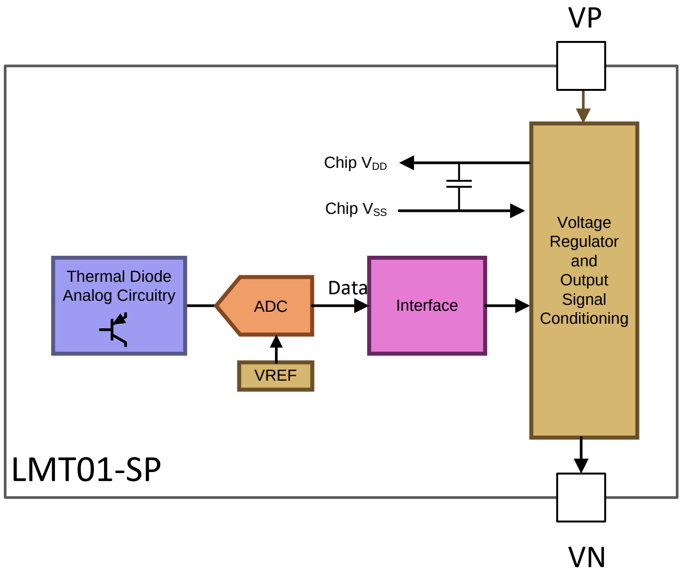

Figure 1. Functional Block Diagram of the LMT01-SP

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3 Test Device and Test Board Information

The LMT01-SP is packaged in a 2-pin ceramic package. For the SEL characterization, a simple breakout board was used to provide access to the device pins with the maximum 5.5 V applied between the pins for biasing.

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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 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 of 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 95% to 96%. Figure 2 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, please refer to Table 2.

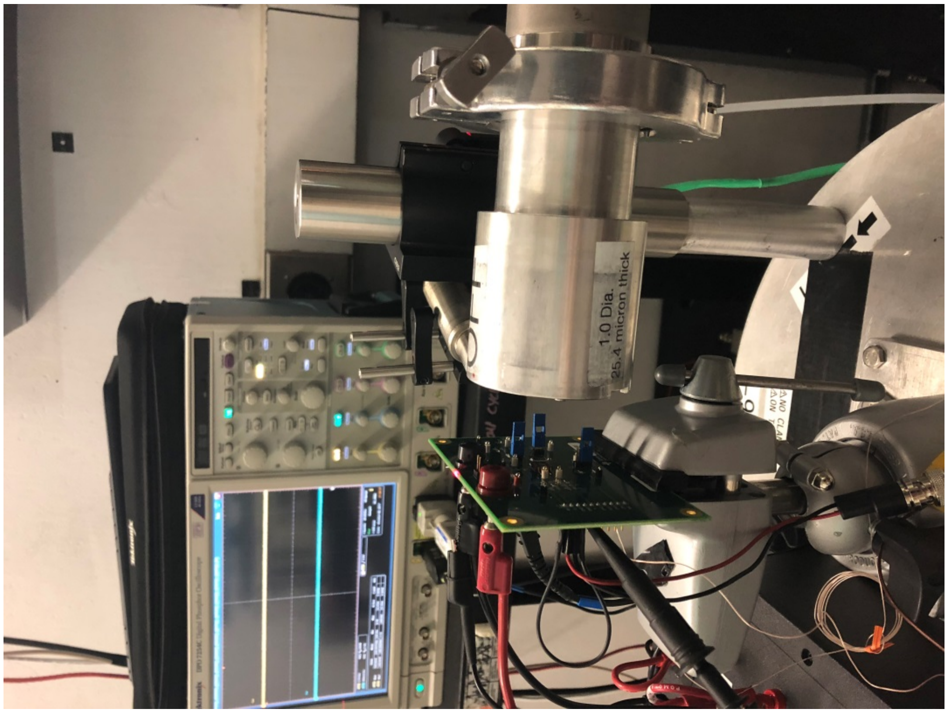

Figure 2. Sample Figure of Evaluation Board Mounted in Front of Heavy Ion Beam Exit Port at the TAMU Accelerator Facility With a 40-mm Air Gap

Table 2. 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	45°	1.03e+05	9.76E+05	93.98	No Latch-Up
Pr	45°	9.95E+04	1.00E+07	93.98	No Latch-Up
Pr	45°	9.71E+04	9.99E+06	93.98	No Latch-Up

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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 45° for an LET_{EFF} = 93.98 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 5.5 V. Run duration to achieve this fluence was approximately 2 minutes. No SEL events were observed during all four runs shown in Table 3. Figure 3 shows a plot of the current vs time.

Table 3. LMT01-SP SEL Conditions Using ^{59}Pr With Angle-of-Incidence = 45°

RUN #	DISTANCE (mm)	TEMPERATURE (°C)	ION	ANGLE	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	LET_{EFF} (MeV·cm^2/mg)
41	40	125	Pr	45°	1.03E+05	9.76E+05	93.98
42	40	125	Pr	45°	9.95E+04	1.00E+07	93.98
43	40	125	Pr	45°	9.71E+04	9.99E+06	93.98

No SEL events were observed, indicating that theLMT01-SP is SEL-immune at LET_{EFF} = 93.98 MeV-cm^2/mg and T = 125°C. Using the *MFTF* method described in Appendix A and combining (or summing) the fluences of the three runs, the upper-bound cross-section (using a 95% confidence level) is calculated as:

$\sigma\text{SEL} \leq 1.76 \times 10^{-7}$ cm^2 for LET_{EFF} = 93.98MeV-cm^2/mg and T = 125°C.

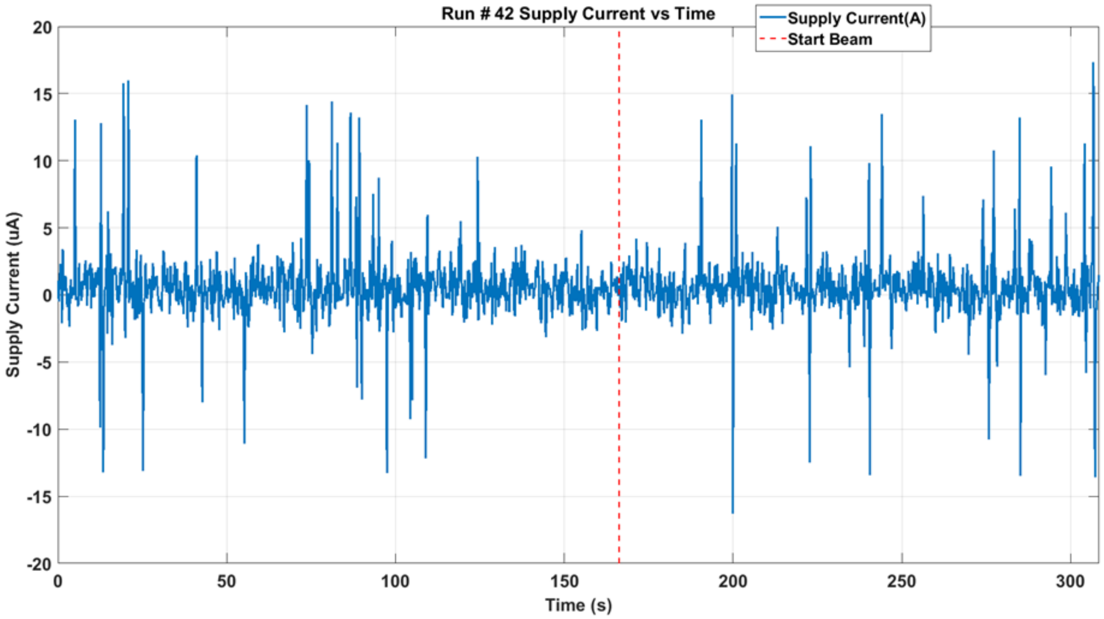

Figure 3. Current vs Time (I vs t) Data for VCC Supply Current During SEL Run #42

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6 Summary

Radiation effects of digital temperature sensor LMT01-SP was studied. This device is latch-up immune up to 93.98 MeV. Additional SET data collection is planned.

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Appendix 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):

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

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*:

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

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*:

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

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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 ($\sigma = 0.05$). 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 4. 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.

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(3) TAMU Radiation Effects Facility website. http://cyclotron.tamu.edu/ref/

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