Radiation Report

TPS73801-SEP Single-Event Effects (SEE) Test Report

ABSTRACT

The effects of heavy-ion irradiation on the single-event effect performance of the TPS73801-SEP LDO regulator is summarized in this report. Heavy ions up to 43MeV-cm^2 / mg were used to irradiate production devices in 17 experiments with fluences of 10^7 ions / cm^2. The results show that the TPS73801-SEP is SEL and SEB free up to 43MeV-cm^2/mg across the full electrical specification with upper bound cross section on the 10^{-7} cm^2/device. SETs were characterized at V_{OUT} = 2.5V and 12V; and at V_{IN} = 5V and 15V, respectively. Exclusions greater than ±5% around the nominal voltages, were categorized as an upset. For the SET characterization, only seven upsets were observed on the 16 experiments (or runs) and were all at V_{OUT} = 2.5V. The upper bound cross section for the SETs is on the order of 10^{-8} cm^2 / device.

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1 Overview

The TPS73801-SEP is a radiation hardened, 1A, low dropout (LDO) regulator optimized for fast transient response. At a load of 1A, the device typically features 300mV of dropout. In addition to fast transient response, the LDO features low output noise, making the device designed for sensitive RF applications. Quiescent current is well controlled and does not rise in dropout. Additional features of the device are reverse battery and current protection, thermal shutdown, and current limiting. The device is offered in a plastic 6-pin DCQ (SOT-223) package.

General device information and test conditions are listed in Table 1-1. For more detailed technical specifications, EVM user guides, and application notes, please see the TPS73801-SEP product page

Table 1-1. Overview Information (1)

Generic Part Number	TPS73801-SEP
Part Number	TPS73801MDCQTPSEP and TPS73801MDCQPSEP
Device Function	Low Dropout (LDO) Voltage Regulator
Technology	JI1-Bipolar
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy-ion Fluence per Run	1×10^7 ions / cm^2
Irradiation Temperature	25°C and 125°C (for SEL testing)

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2 Single-Event Effects

The primary concerns for the TPS73801-SEP are its resilience against the destructive single event effects (DSEE): single event burnout (SEB) and single-event latch-up (SEL). A bipolar junction transistor can suffer SEB at voltages lower than the open circuit collector-emitter voltages (BV_{CEO}) (1) (2). The TPS73801-SEP was tested up to the recommended maximum input voltage. No current increment was seen demonstrating that the TPS73801-SEP is SEB-free across the full electrical specifications and up to 43MeV-cm^2 / mg with fluences of 10^7 ions / cm^2 and room temperature.

The TPS73801-SEP is a bipolar-only process; because of this the LDO is virtually SEL-free. However there is a remote possibility of SEL in non-vertical structures and for that reason the device was checked for SEL. The TPS73801-SEP did not show any SEL with heavy-ions up to 43MeV-cm^2 / mg and fluences of 10^7 ions / cm^2 and a die temperature of 125°C.

For power devices the power integrity is also a concern, stable outputs are mandatory and single event transients (SETs) must be bounded and have fast recovery time. The TPS73801-SEP was characterized for ±5% deviation from nominal voltage at V_{OUT} of 2.5V and 12V. Only 7 events that exceed the ±5% were observed on 16 experiments. The events were observed at V_{OUT} = 2.5V. Upper bound cross section using the MTBF method (shown in Appendix A) at 95% confidence interval is presented. Typical time domain transients plots are shown in Section 7. A histogram for the deviation from the nominal voltage on percentage is shown in Figure 7-1.

3 Test Device and Evaluation Board Information

The TPS73801-SEP used for the data collection presented on this report is packaged in a 6-pin SOT-223 (DCQ) as shown in Figure 3-1. The TPS73801-SEP DEM-SOT223LDO (compatible with most positive output LDOs in the SOT-223 board) was used to evaluate the performance and characteristics of the TPS73801-SEP. Top and bottom views of the evaluation board used for radiation testing are shown in Figure 3-2. Board schematics are shown on Figure 3-3. The Bill of Materials (BOM) used for this characterization was populated on DEM-SOT223LDO demonstration fixture. The input capacitor, output capacitors, and feedback divider resistors used to set Vout are shown in Table 3-1 and Table 3-2.

For more information about the evaluation board, see the DEM-SOT223LDO tool folder.

Note that the device shown in Figure 3-1 was decapped to reveal the die face for all heavy-ion testing.

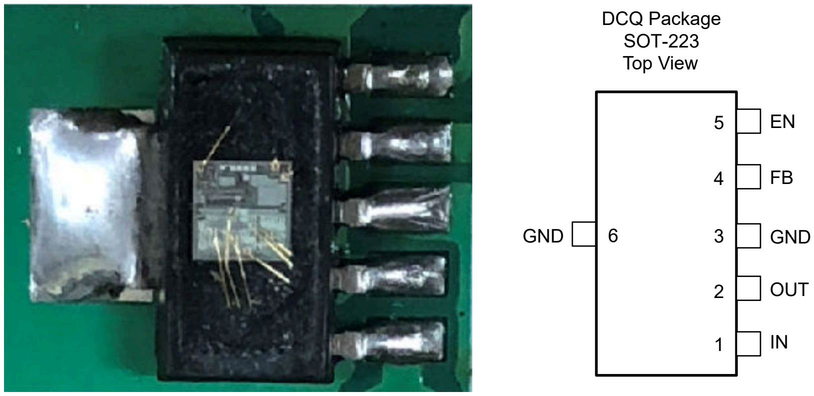

Figure 3-1. Photograph of Delidded TPS73801-SEP (Left) and Pinout Diagram (Right)

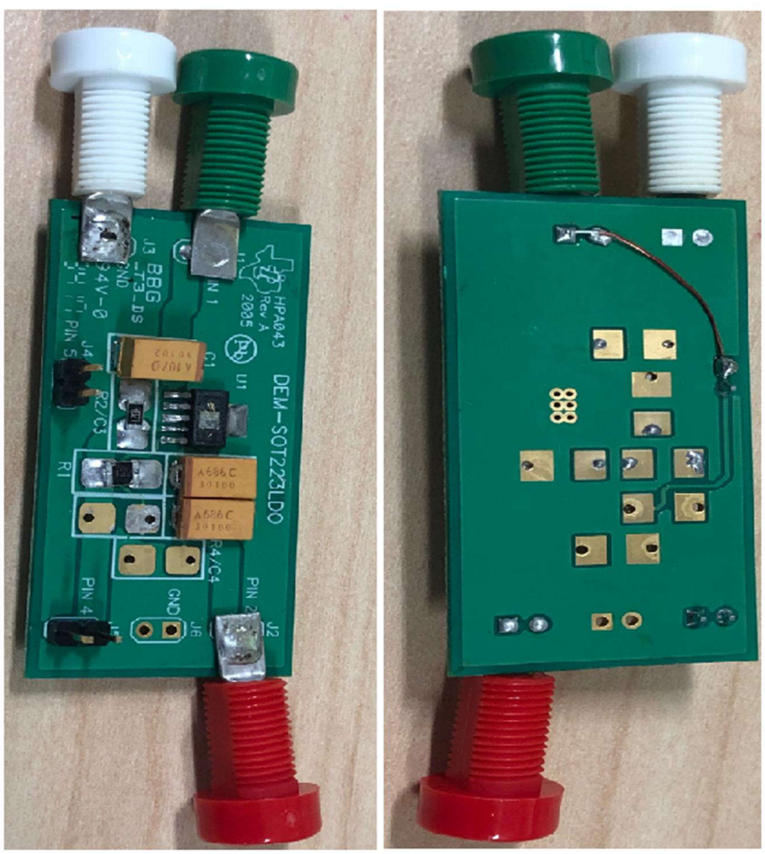

Figure 3-2. DEM-SOT223LDO Demonstration Fixture Board Top View (Left) and Bottom View (Right)

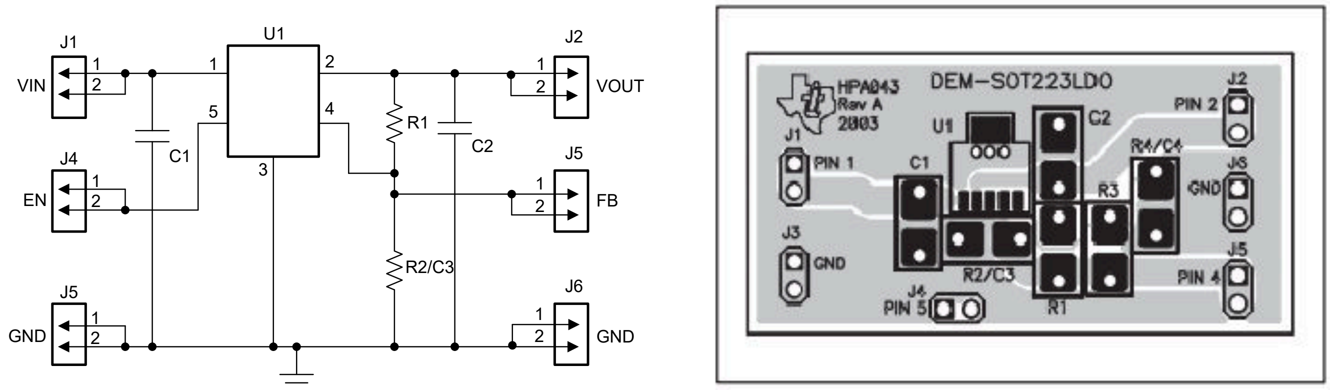

Figure 3-3. Schematic of the DEM−SOT223LDO Used During SEE Characterization

The input and output capacitors and resistive dividers for a particular output used for the heavy-ion characterization discussed in this report were populated on the board as listed in Table 3-1 and Table 3-2

Table 3-1. Input Capacitance BOM Used for SEE Characterization of the TPS73801-SEP

Quantity (Number)	Total (µF)	Part Number	Comment
1	85	T495X156M050ATE300 Populated	Populated 85µF Capacitor

Table 3-2. Output Capacitance and Resistors BOM Used for SEE Characterization of the TPS73801-SEP

Value (µF)	Quantity (Number)	Total (µF)	Resistor (kΩ)	Part Number	Comment
84.5	2	169	R1 4.33 (Vout 2.5V), 35.72 (Vout 12V), R2 4.021	C1210C104K5RACTU	Populated

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) and the 88-Inch Berkeley Accelerator Space Effects (BASE) Facility (4) (5) using a superconducting cyclotron and advanced electron cyclotron resonance (ECR) ion source. At the fluxes used, ion beams showed good flux stability and high irradiation uniformity over a 1in diameter circular cross sectional area for the in-air station (TAMU). 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 these studies ion fluxes of 10^5 ions / s-cm^2 were used to provide heavy-ion fluences up to 10^7 ions / cm^2.

For these experiments, Silver (^{47}Ag), Copper (^{29}Cu) ions were used. In some cases, angles were used to increment the LET_{EFF}. LET_{EFF} ranges from 28.9 to 43MeV-cm^2 / mg. Kinetic energy ranges from 1.25 to 2.47GeV in the vacuum. Ion beam uniformity for all tests were in the range of 90% to 99%.

The DEM-SOT223LDO Demonstration Fixture test board used for the experiments at the TAMU facility is shown in Figure 4-1. Although not visible in this photo, the beam port has a 1mil Aramica (DuPont® Kevlar®) 1in diameter window to allow 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 40mm for all runs.

Figure 4-1. Photograph of the TPS73801-SEP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Test Setup and Procedures

SEE testing was performed on a TPS73801-SEP device mounted on a DEM-SOT223LDO Demonstration Fixture. Power was provided to the device with the V_{IN} input on the J1 banana connectors using the N6702 precision power supply in a 4-wire configuration. The device was loaded using a chroma load on constant resistance (CR) mode.

The SEE events were monitored using a National Instruments (NI) PXie 5105 (60MS/s and 60MHz of bandwidth) digitizer module. The NI-PXIe Scope card was used to monitor V_{OUT} and V_{IN}. The trigger signal was V_{OUT} using an a window trigger set at ±5% from the nominal output voltage. All equipment was controlled and monitored using a custom-developed LabVIEW™ program (PXI-RadTest) running on a NI-PXIe-8135 Controller. A block diagram of the setup used for SEE testing of the TPS73801-SEP is shown in Figure 5-1. Limits and compliance used during the SEE characterization are shown in Table 5-1. In general, the TPS73801-SEP was tested at room temperature (no external heating applied) where the die temperature was approximately 25°C to 50°C under the load (0 to 1A) conditions used for the testing. A die temperature of 125°C was used for SEL testing and was achieved with a convection heat gun aimed at the die. The die temperature was monitored during the testing using a K-Type thermocouple attached to the heat slug vias of the EVM with thermal compound.

Table 5-1. Equipment Set and Parameters Used for SEE Testing of the TPS73801-SEP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
V_{IN}	Agilent N6702A (Channel 1)	5A	5A	2.5 to 20V
Oscilloscope card	HSDIO NI-PXIe 5105	60MS/s	—	20MS/s
Digital I/O	NI PXIe 6556	200MHz	—	50MHz

All boards used for SEE testing were fully checked for functionality and dry runs performed to verify 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 TPS73801-SEP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability was 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).

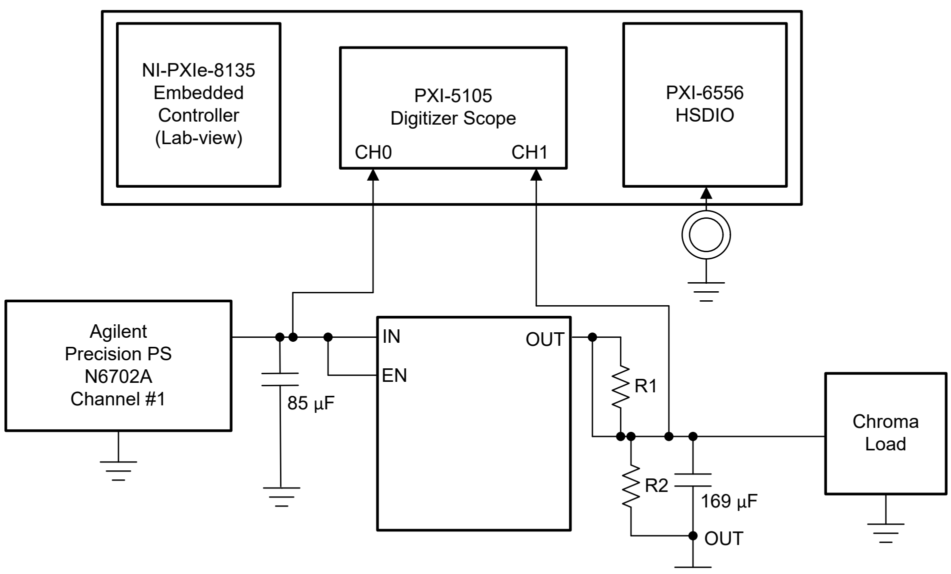

Figure 5-1. Block Diagram of the Test Setup Used for TPS73801-SEP SEE Characterization

During irradiation the PXIe-5101 scope card continuously monitored the V_{OUT} and V_{IN} of the TPS73801-SEP, and any deviation of ±5% of the nominal voltage triggering a capture.

During a trigger event, the digital scope card captured 40k samples (the card was continuously digitizing so when triggered, a predefined 20% of the samples that preceded the event were stored). The NI scope cards captured events lasting up to 2ms (40k samples at 20MS/s). In addition to monitoring the voltage levels of the scope cards (PXI), the current on the V_{IN} pin was also monitored during each test to monitor for any SEL event. No sudden increases in current were observed (outside of normal fluctuations) on any of the test runs indicated that no SEL events occurred.

6 Single-Event-Burnout (SEB) and Single-Event-Latch-up (SEL)

6.1 Single-Event-Burnout (SEB)

The TPS73801-SEP was tested for SEB at 50mA (load) and room temperature (RT). While the output voltage was held on regulation at 12V, the input voltage was set at 15V to test the LDO for any burnout. Data was collected at V_{IN} = 15, V_{OUT} = 12V and RT. Summary for SEB data collection and conditions is shown on Table 6-1.

Flux of 10^5 and fluences of 10^7 were used for the SEB characterization, using ^{47}Ag at incident. The distance between the exit port and the DUT was set to 40mm on all runs. *Not a single burnout was observed* while operating the TPS73801-SEP at input voltage of 15V. The cross section was calculated using the MTBF method described in Appendix A.

Table 6-1. Summary of the TPS73801-SEP SEB Conditions and Results

Run Number	Unit Number	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV × cm^2/ mg)	Flux (ions/ cm^2× s)	Fluence (Number of ions / cm^2)	Vin (V)	Vout (V)	Load (A)	SEB?	$\sigma_{PERCASE}$ (cm^2/ device)
1	1	Ag	0	43	1.00E+05	1.00E+07	15	2.5	50mA	No	2.31E-08

The SEB upper bound cross section is:

$\sigma_{SEB} \leq 2.31 \times 10^{-8}$ cm^2/ device at LET ≤ 43 MeV-cm^2/ mg, T = 25°C and 95% confidence.

6.2 Single-Event-Latch-up (SEL)

For the SEL characterization the LDO was heated up to 125°C using a forced hot air aimed at the die. Temperature was monitored using a K-type thermocouple attached to the SEP DEM-SOT223LDO DEM.^{47}Ag incident at 0 is used for the characterization. The distance between the heavy-ion exit port and the DUT was held constant at 40mm for all test. Flux of 10^5 and fluences up to 10^7 is used. SEL result is listed in Table 6-2. No SEL events was observed under any of the test runs. Upper bound cross section is calculated using the MTBF described on Appendix A.

$\sigma_{SEL} \leq 2.31 \times 10^{-8}$ cm^2/ device at LET ≤ 43MeV-cm^2/ mg, T = 125°C and 95% confidence.

Table 6-2. Summary of the TPS73801-SEP SEL Results [(1)]

Run Number	Unit Number	LET_{EFF} (MeV-cm^2/ mg)	Ion Type	Incident Angle (°)	Fluence (ions / cm^2)	Vin (V)	Vout (V)	Load (A)	SEL Events
17	4	43	Ag	0	10^7	5	1.2	0.020	0

(1) All data collected and discussed on this table was collected at T = 125°C.

7 SET Results

SETs were defined as heavy-ion-induced transients on the V_{OUT} of the TPS73801-SEP that were higher than ±5% of the nominal voltage. Characterization was conducted at output voltages of 2.5V and 12V. For each V_{OUT} load of 1A, 50mA was used.

Table 7-1 summarizes the test conditions of the TPS73801-SET characterization. Flux of 10^5 ions / cm^2-s and fluences up to 10^7 ions / cm^2 were used for the SET data collection. To capture the transients, window triggers with ±5% around the nominal voltage were used for all runs. Note that for each summary table, the last column represents the case by case upper bound cross section. However Table 7-3 summarizes the upper bound cross section by output voltage and LET when the events and fluence are combined. The cross sections were calculated using the MTBF method shown in Appendix A, at 95% confidence interval. Table 7-1 show the seven upsets on run number 10. As shown in Table 7-1, the SETs are bipolar transitions around the nominal voltage. A histogram showing the deviation from the nominal voltage (V_{OUT} = 2.5V) in percentage is shown in Figure 7-1.

Note that V_{OUT} = 2.5V is the worst case since the ±5% threshold is a smaller value when compared with the other (higher) output voltages used for the characterization. Transients have a longer duration at light load versus heavy loads. Time domain plots of the SETs are shown in Figure 7-2.

Table 7-1. Summary of the TPS73801-SEP SET for V_{IN} = 5V and V_{OUT} = 2.515V

Run Number	Unit Number	Load (A)	LET_{EFF} (MeV-cm^2 / mg)	Ion	Angle	Flux (Ions / cm^2 × s)	Fluence (Total Number of Ions)	Number of Events Less Than 5% of Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2 / device)
8	1	1	43	Ag	0	1.00E+05	1.00E+07	0	3.69E-07
9	1	.05	43	Ag	0	1.00E+05	1.00E+07	0	3.69E-07
10	1	.05	43	Ag	0	1.00E+05	1.00E+07	7	1.44E-06
19	1	1	29.9	Cu	45	1.00E+05	1.00E+07	0	3.69E-07
20	1	.05	29.9	Cu	45	1.00E+05	1.00E+07	0	3.69E-07
21	1	.05	29.9	Cu	45	1.05E+05	1.00E+07	0	3.69E-07
22	1	.05	20.1	Cu	0	1.05E+05	1.00E+07	0	3.69E-07
23	1	.05	20.1	Cu	0	1.05E+05	1.00E+07	0	3.69E-07
25	3	.05	20.1	Cu	0	1.05E+05	1.00E+07	0	3.69E-07
26	3	.05	20.1	Cu	0	1.05E+05	1.00E+07	0	3.69E-07
27	3	.05	20.1	Cu	0	1.05E+05	1.00E+07	0	3.69E-07

Table 7-2. Summary of the TPS73801-SEP SET for V_{IN} = 15V and V_{OUT} = 12V (1)

Run Number	Unit Number	Load (A)	LET_{EFF} (MeV-cm^2/mg)	Ion	Angle	Flux	Fluence	Number of Events > 5% of Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/ device)
15	2	.05	48.47	Ag	0	1.00E+05	1.00E+07	0	3.69E-07
16	2	1	48.47	Ag	0	1.00E+05	1.00E+07	0	3.69E-07
17	2	1	28.9	Cu	45	1.00E+07	1.00E+07	0	3.69E-07
18	2	.05	28.9	Cu	45	1.00E+05	1.00E+07	0	3.69E-07

(1) All runs presented on this table were using unit #2.

Table 7-3. Combined Upper Bound Cross Section for the TPS73801-SEP SETs

Vin (V)	Vout (V)	Load (A)	LET_{EFF} (MeV × cm^2/mg)	Fluence (Number of ions / cm^2)	Total Number of Events	$\sigma_{COMBINED}$ (cm^2)
15	12	0 to 1	43	2.00E+07	0	1.84E-07
5	2.5	0 to 1	43	3.00E+07	7	4.81E-07
5	2.5	0 to 1	28.9	3.00E+07	0	1.23E-07
5	2.5	0 to 1	20.1	5.00E+07	0	7.38E-08

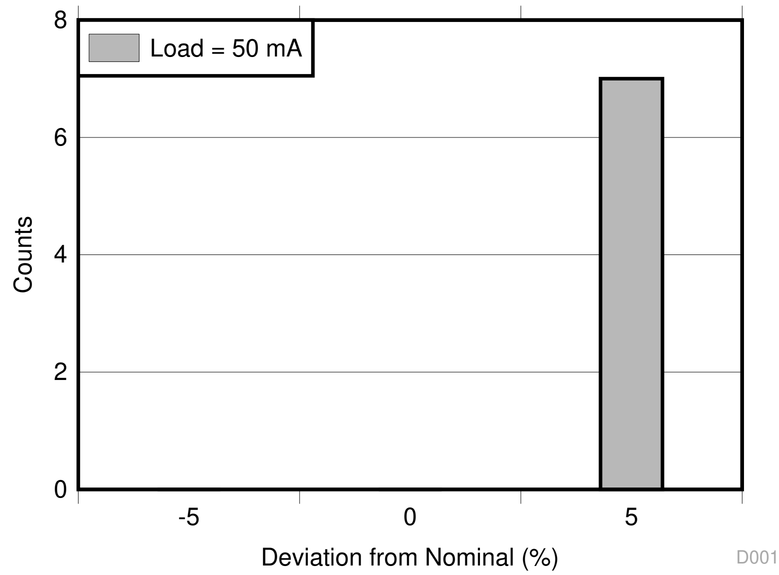

Figure 7-1. Histogram of the Deviation from Nominal Voltage for the SETs

Figure 7-1 is based on the seven upsets greater than ±5% of nominal V_{OUT} = 2.5V.

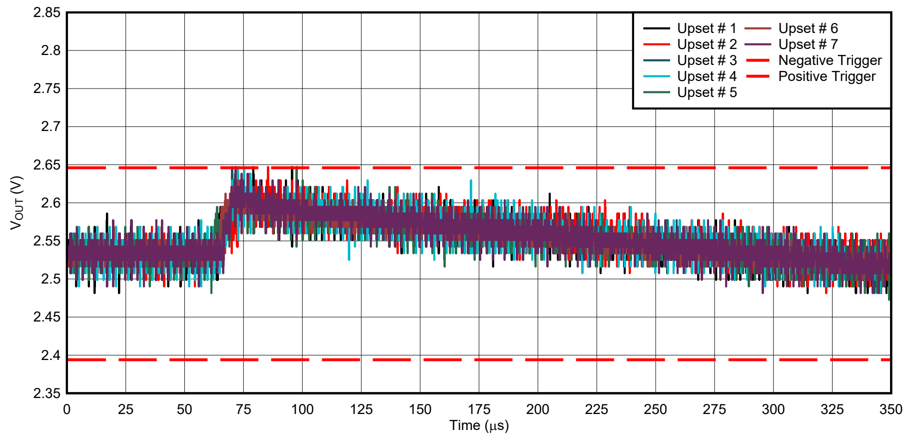

Figure 7-2. Transient Events on VOUT

8 Summary

The purpose of this report is summarize the SEE of the TPS73801-SEP under heavy ions. The data shows that the TPS73801-SEP is SEB and SEL free across the full electrical specifications and up to 43MeV-cm^2/ mg with fluence of 10^7 ions / cm^2. No SEL or SEB was observed, and the cross section for the SEL and SEB is shown to be on the order of 10^{-8} cm^2 / device. See Section 6 for more details.

SETs were characterized at different output voltages and across the full load of the TPS73801-SEP. Only seven transients higher than 5% were observed on 16 runs. Those transients were all observed at V_{OUT} = 2.5V. Worst case for SETs deviations is observed at lower output voltages, and worst case transients response time are observed at light loads. The SET cross section is shown to be on the order of 10^{-8} cm^2/ device.

A Confidence Interval Calculations

For conventional products where hundreds of failures are seen during a single exposure, a user 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 as a result, have 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 an 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 designed 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) (11). 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 approximately 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):

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

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 x^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*:

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

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 – 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. As a result, the upper-bound cross section is obtained by inverting the MFTF:

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

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 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. As more events are observed, the statistics are improved so that uncertainty in the actual device performance is reduced.

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

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

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C Revision History

Changes from Revision * (January 2019) to Revision A (March 2024) **Page**

- Added Figure 7-2 to Section 7 10

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