TPS7A4501-SP Single-Event Effects Test Report

ABSTRACT

The effects of heavy-ion irradiation on the single-event effect performance of the TPS7A4501-SP LDO regulator has been summarized on this report. Heavy ions ranging from 27.3 to 99.3 MeV-cm^2/mg were used to irradiate production devices in 100 experiments with fluences ranging from 10^6 to 10^7 ions/cm^2. The results show that the TPS7A4501-SP is SEL and SEB free up to 91.9 MeV-cm^2/mg across the full electrical specification with upper bound cross section on the 10^{-7} cm^2/device. No SEL or SEB was observed on any of the 23 runs. SETs were characterized at V_{OUT} = 1.8, 2.5, 3.3 and 12 V at V_{IN} = 2.5, 3.3, 5 and 15 V, respectively. Exclusions greater than ±5% around the nominal voltages, were categorized as an upset. Only 18 upsets were observed on the 77 experiments (or runs) for the SET characterization and they were all at V_{OUT}=1.8-V. The upper bound cross section for the SETs is on the order of 10^{-6} cm^2/device.

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1 Overview

The TPS7A4501-SP is a space-grade, radiation hardened, up to 20-V, 1.5-A low dropout (LDO) regulator optimized for fast transient response. At a load of 1.5 A the device typically has 450 mV of dropout. In addition to fast transient response, the LDO has very-low output noise, making it ideal for sensitive RF applications. Quiescent current is well controlled and does not rise in drop-out. Some features of this device are: reverse battery and current protection, thermal shutdown and current limiting. The device is offered in a 10-pin CFP (U) for the QMLV version and in a thermally enhanced CFP (HKU) package for the RHA version.

General device information and test conditions are listed in Table 1. For more detailed technical specifications, EVM user-guides, and application notes please go to:

www.ti.com/product/TPS7A4501-SP

Table 1. Overview Information(1)

Generic Part Number	TPS7A4501-SP
Part Number	5962R1222403VXC
Device Function	Low Dropout (LDO) Voltage Regulator
Technology	JI1
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University and Lawrence Berkeley 88-Inch Cyclotron, University of California at Berkeley
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 Single-Event Effects

The primary concerns for the TPS7A4501-SP are its resilience against the destructive single event effects (DSEE): single event burnout (SEB) and single-event latch-up (SEL). BJT can suffer SEB at voltages lower than the open circuit collector-emitter voltages (BV_{CEO}) [1][2]. The TPS7A4501-SP was tested up to the recommended maximum input voltage. Not a single unit shown a current increment demonstrating that the TPS7A4501-SP is SEB-free across the full electrical specifications and up to 91.21 MeV-cm^2/mg at fluences of 10^7 ions/cm^2 and room temperature.

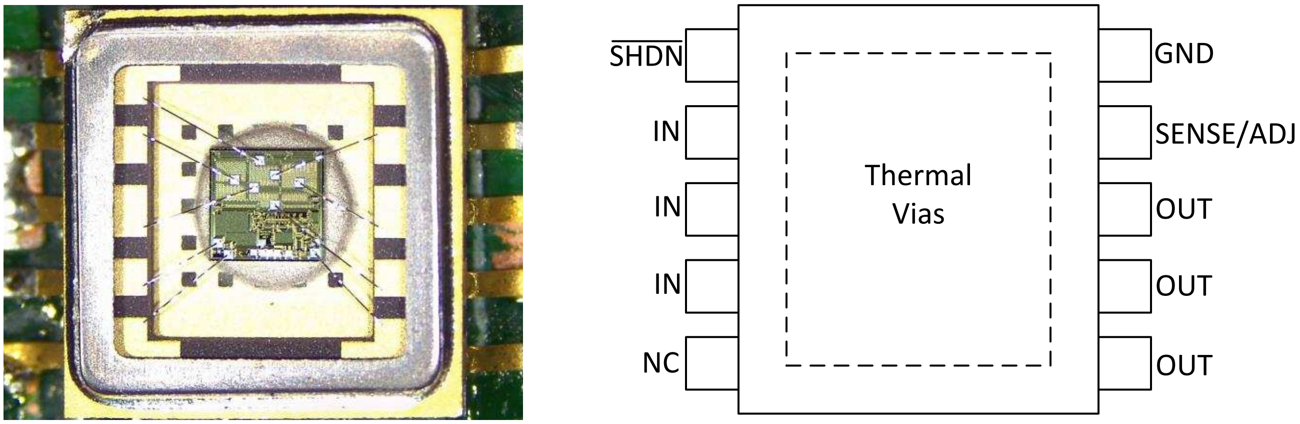
The TPS7A4501A-SP is a bipolar-only process; because of this the LDO is virtually SEL-free. However there does exist a remote possibility of SEL in non-vertical structures and for that reason the device was checked for SEL. The TPS7A4501-SP does not showed any SEL with heavy-ions up to 99.21 MeV-cm^2/mg 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) should be bounded and have fast recovery time. The TPS7A4501A-SP was characterize for ±5% deviation from nominal voltage at V_{OUT} of 1.8, 2.5, 3.3 and 15 V. Only 18 upsets that exceed the ±5% were observed on 77 experiments. The upsets were observed at V_{OUT} = 1.8 V. Upper bound cross section using the MTBF method (described in Appendix B) at 95% confidence interval is presented. Typical time domain transients plots are presented and discussed in Section 8. Histograms for the deviation from the nominal voltage on percentage (Figure 9) and response time (Figure 10) are presented.

3 Test Device and Evaluation Board Information

The TPS7A4501A-SP used for the data collection presented on this report is packaged in a 10-pin thermally-enhanced dual ceramic flat pack package (HKU) as show in Figure 1. The TPS7A4501EVM-CVAL evaluation board was used to evaluate the performance and characteristics of the TPS7A4501-SP. Top and bottom views of the evaluation board used for radiation testing are shown in Figure 2. Board schematics are shown on Figure 3. **The original TPS7A4501EVM-CVAL Bill of Material (BOM) was modified for the characterization.** The changes were made on the input and output capacitors, Table 2 and Table 3 shows the capacitor set used for the characterization discussed on this report. The tables identify the capacitors as Out of Box (OOB) or Extra. OOB are the capacitors that are already included on the TPS7A4501EVM-CVAL when ordered from the web. Extra are the capacitors that were added to increment the input/output capacitor bank.

For more information about the evaluation board please go to: www.ti.com/tool/tps7a4501evm-cval



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

Figure 1. Photograph of De-lidded TPS7A4501-SP [Left] and Pinout Diagram [Right]

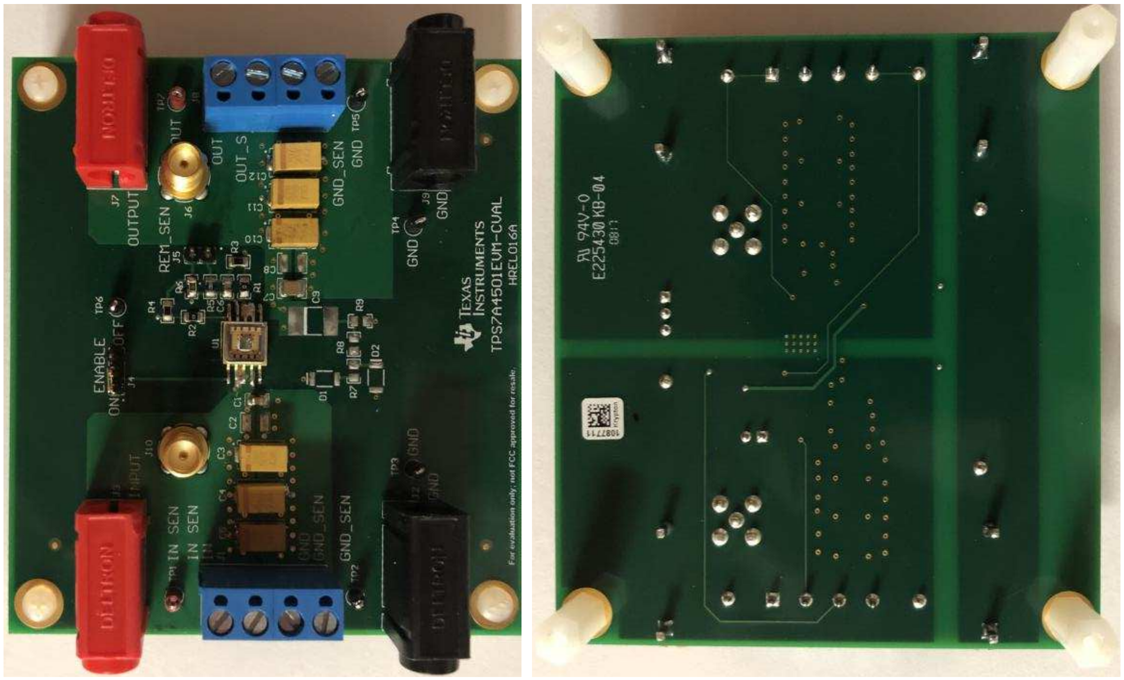
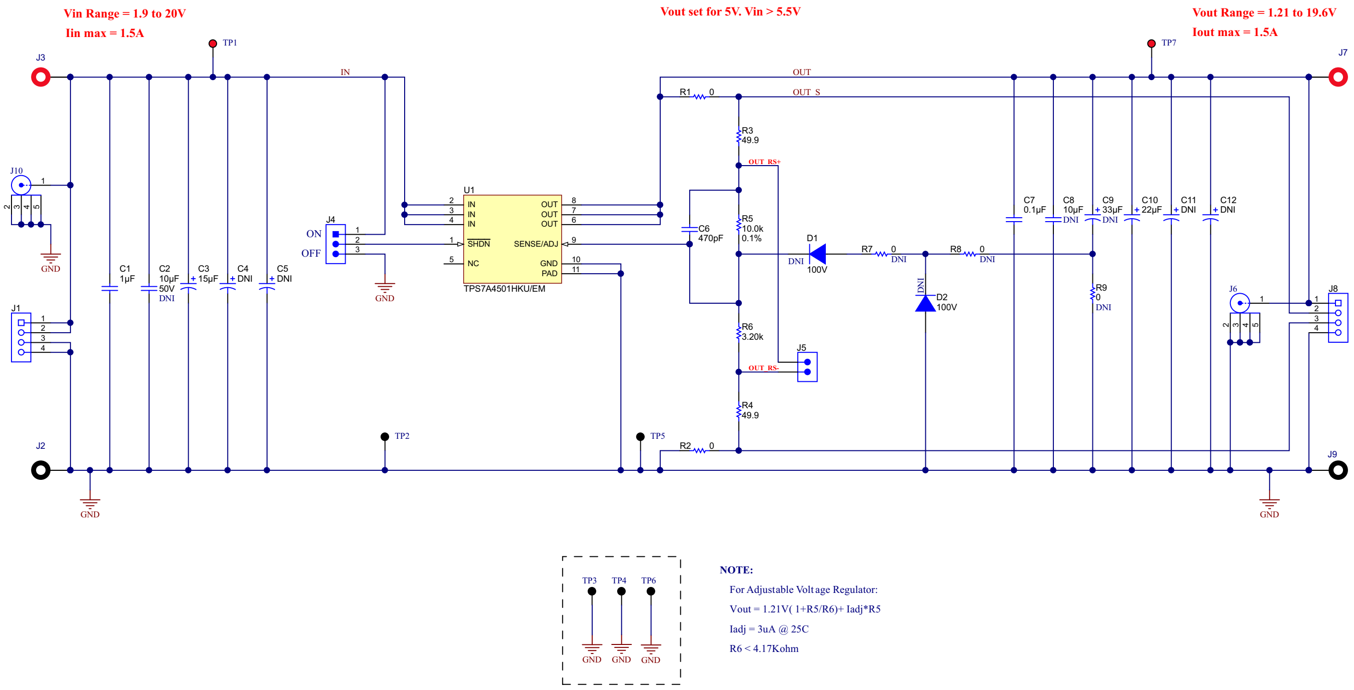


Figure 2. TPS7A4501EVM-CVAL Board Top-View [Left] and Bottom-View [Right]



NOTE: **The input and output capacitors used for the heavy-ion characterization discussed in this report were modified as shown in Table 2 and Table 3.**

Figure 3. Schematic of the TPS7A4501EVM-CVAL Used During SEE Characterization

Table 2. Input Capacitance BOM Used for SEE Characterization of the TPS7A4501-SP

Value (µF)	Quantity (#)	Total (µF)	Part #	Comment
15	1	15	T495X156M050ATE300	OOB
1	1	1	08055C105KAT2A	OOB
47	1	47	T498X476K035ATE500	Extra
22	1	22	T495D226K035ATE26	Extra
			Total (µF)	**85**

Table 3. Output Capacitance BOM Used for SEE Characterization of the TPS7A4501-SP

Value (µF)	Quantity (#)	Total (µF)	Part #	Comment
22	1	22	C1210C104K5RACTU	OOB
0.1	1	0.1	T495D226K025ATE200	OOB
100	1	100	T491X107K025AT	Extra
47	1	47	T498X476K035ATE500	Extra
			Total (µF)	**169.1**

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 had good flux stability and high irradiation uniformity over a 1-in 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 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, Krypton (^{84}Kr), Praseodymium (^{141}Pr), Homium (^{165}Ho) Gold (^{197}Au) and Xenon (^{132}Xe) ions were used. On some cases angles were used to increment the LET$_{EFF}$. LET$_{EFF}$ ranges from 27.2 to 99.29 MeV-cm^2/mg. Kinetic energy ranges from 1.25 to 2.47 GeV in the vaccuum. Ion beam uniformity for all test was in the range of 90% to 99%.

The TPS7A4501EVM-CVAL test board used for the experiments at the TAMU facility is shown in Figure 4. Although not visible in this photo, the beam port has a 1-mil Aramica (DuPont® Kevlar®) 1-in 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 40 mm for all runs.

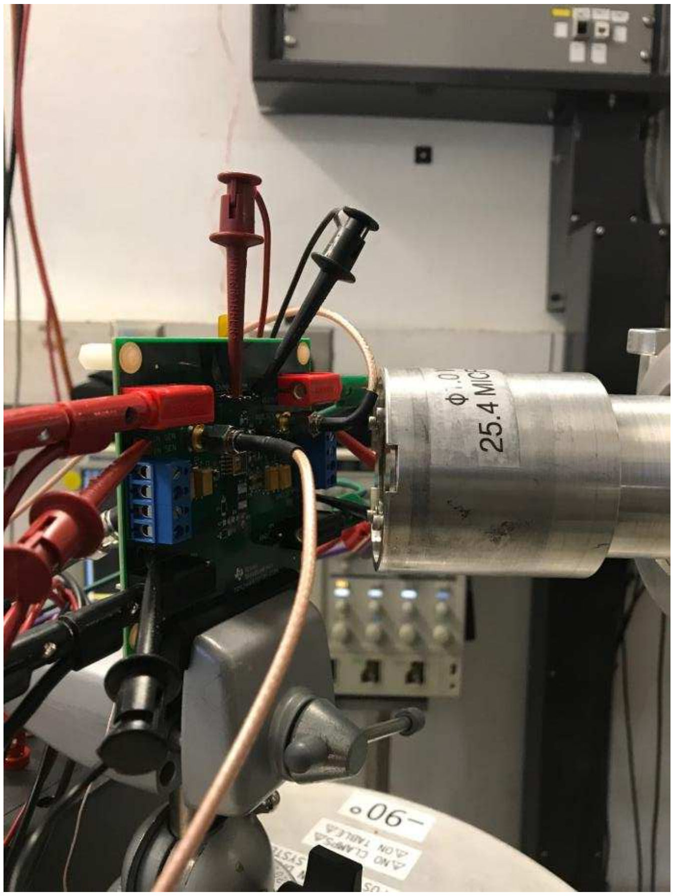
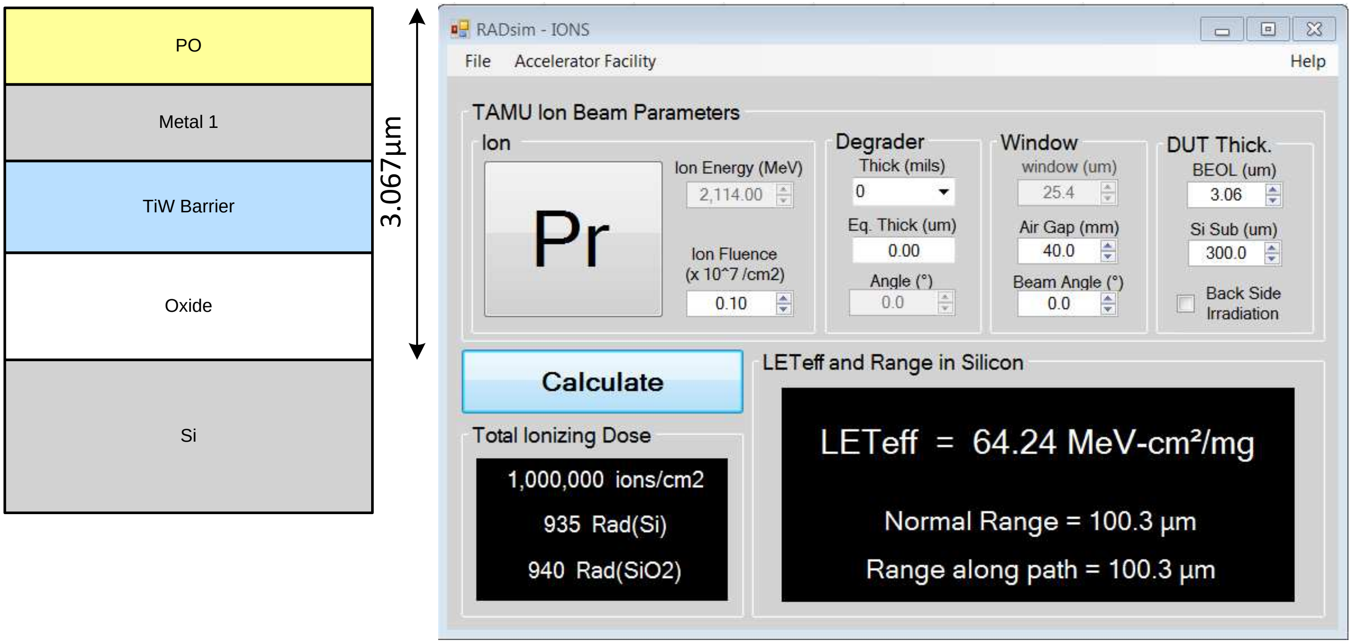


Figure 4. Photograph of the TPS7A4501-SP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Depth, Range and LET$_{EFF}$ Calculation



TAMU Ion Beam Parameters

Ion: Pr

Ion Energy (MeV): 2,114.00

Ion Fluence (x 10^7 /cm2): 0.10

Degrader: Thick (mils): 0; Eq. Thick (um): 0.00; Angle (°): 0.0

Window: window (um): 25.4; Air Gap (mm): 40.0; Beam Angle (°): 0.0

DUT Thick.: BEOL (um): 3.06; Si Sub (um): 300.0; ☐ Back Side Irradiation

Total Ionizing Dose

1,000,000 ions/cm2

935 Rad(Si)

940 Rad(SiO2)

LETeff and Range in Silicon

LETeff = 64.24 MeV-cm²/mg

Normal Range = 100.3 µm

Range along path = 100.3 µm

Figure 5. Generalized Cross Section of the JI1 Technology BEOL Stack on the TPS7A4501-SP [Left] and GUI of RADsim Application Used to Determine Key Ion Parameter [Right]

The TPS7A4501-SP is fabricated in the Texas Instruments Linear JI1 process with a back-end-of-line(BEOL) stack consisting of one level of standard thickness aluminum metal. Since LET for any given ion is largely a function of the material density through which the ion is traveling, and since the density of aluminum (2.70 g/cm^3) and silicon oxide (2.65 g/cm^3) are similar, the stack is modeled as a homogenous layer of silicon dioxide. The thickness from the surface of the passivation to the silicon surface is 3.067 µm (based on nominal thickness layer) as shown in Figure 5.

The left side of the image in Figure 5 shows a generalized JI1 technology BEOL stack on the TPS7A4501-SP cross section. The right side of the image shows the GUI of the RADsim-IONS (based on SRIM [6]) applications used to determine key ion parameters as: LET$_{EFF}$, depth and range for a given ion type, energy, stack, and facility. The applications are preset for TAMU and Berkeley ions cocktail. When the application is set for TAMU, it accounts for the 1-mil thick Aramica (DuPont™ KEVLAR®) and the distance from the DUT (in this case 40 mm). Table 4 shows the results for the ions used for the purpose of the TPS7A4501-SP SEE characterization.

Table 4. LET$_{EFF}$ Depth and Range for the Ions Used for SEE Characterization of the TPS7A4501-SP

Ion Type	Angle of Incidence	Depth in Silicon (µm)	Range in Silicon (µm)	LET$_{EFF}$(MeV-cm^2/mg)	Facility
Kr	0	146	146	27.28	TAMU
Kr	30	98.4	113.6	34.90	TAMU
Kr	45	102.4	144.8	38.72	TAMU
Pr	0	100.3	100.3	64.24	TAMU
Pr	30	86.5	99.9	74.29	TAMU
Pr	45	70	99	91.22	TAMU
Au	0	104.5	104.5	85.94	TAMU
Ho	0	96.8	96.8	75.17	TAMU
Ho	20	90.8	96.6	80.04	TAMU
Ho	25	87.4	95.6	83.02	TAMU
Ho	35	78.7	96.1	91.96	TAMU
Ho	45	67.5	95.5	106.73	TAMU

Table 4. LET$_{EFF}$ Depth and Range for the Ions Used for SEE Characterization of the TPS7A4501-SP (continued)

Ion Type	Angle of Incidence	Depth in Silicon (μm)	Range in Silicon (μm)	LET$_{EFF}$(MeV-cm^2/mg)	Facility
Xe	0	85.7	85.7	60.53	Berkeley
Xe	40	65	84.8	79.39	Berkeley

6 Test Setup and Procedures

SEE testing was performed on a TPS7A4501-SP device mounted on a TPS7A4501EVM-CVAL. Power was provided to the device by means of the V_{IN} input on the J3 and J2 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 (60 MS/s and 60 MHz 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 TPS7A4501-SP is illustrated in Figure 6. Limits and compliance used during the SEE characterization are shown in Table 5. In general, the TPS7A4501A-SP was tested at room temperature (no external heating applied) where the die temperature was usually ≈ 25°C to 50°C under the load (0-1.5 A) 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. Equipment Set and Parameters Used for SEE Testing of the TPS7A4501-SP

PIN NAME	EQUIPMENT USED	CAPABILITY	COMPLIANCE	RANGE OF VALUES USED
V_{IN}	Agilent N6702A (Ch # 1)	5 A	5 A	2.5 to 20 V
Oscilloscope card	HSDIO NI-PXIe 5105	60 MS/s	—	20 MS/s
Digital I/O	NI PXIe 6556	200 MHz	—	50 MHz

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 TPS7A4501-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).

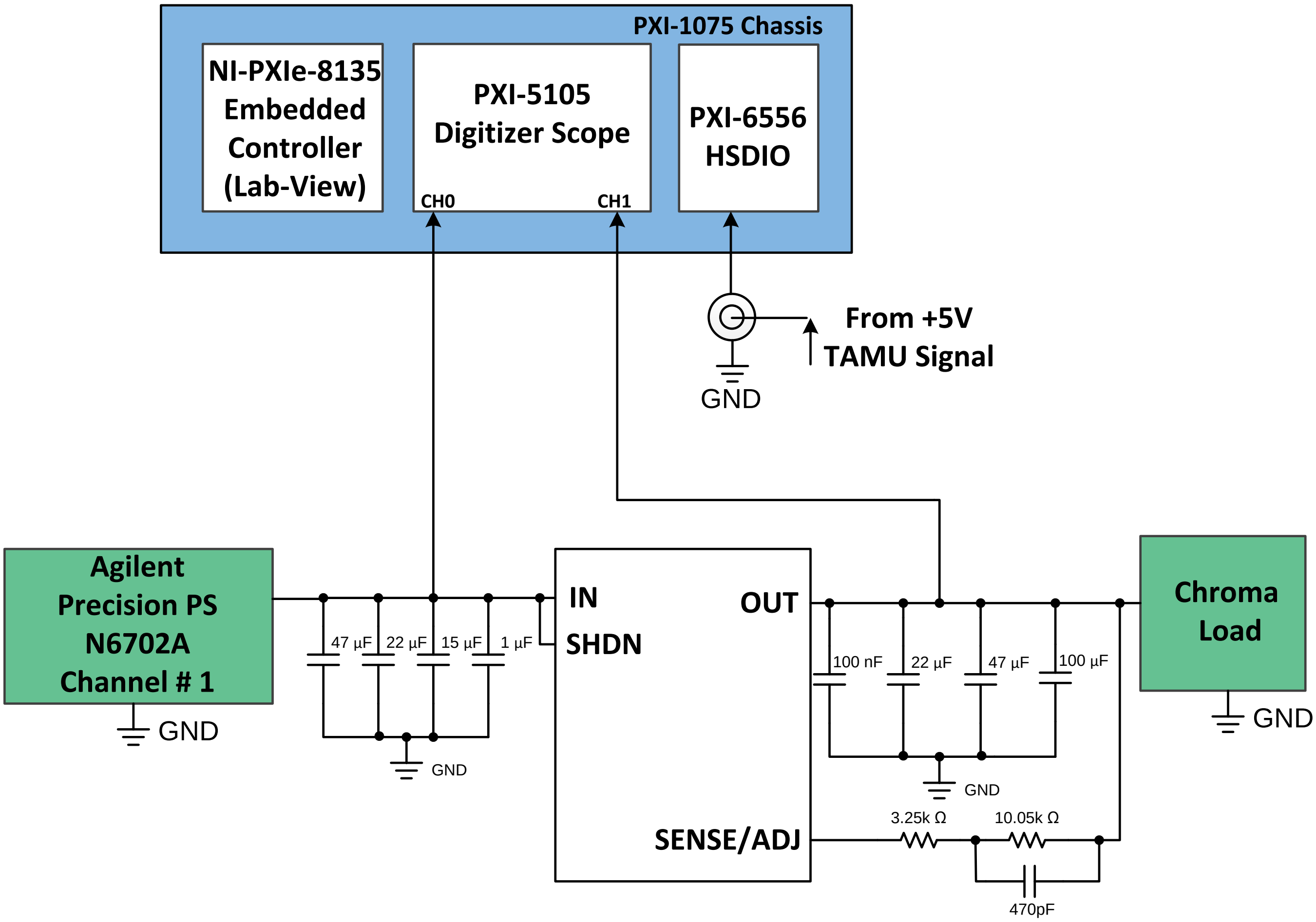


Figure 6. Block Diagram of the Test Setup Used for TPS7A4501-SP SEE Characterization

During irradiation the PXIe-5101 scope card continuously monitored the V_{OUT} and V_{IN} of the TPS7A4501-SP, and any deviation of ±5% of the nominal voltage triggering a capture.

During a trigger event, the digital scope card would capture 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 2 ms (40k samples at 20 MS/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.

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

7.1 Single-Event-Burnout (SEB)

The TPS7A4501-SP was tested for SEB at 10mA (load) and room temperature (RT). While the output voltage was held on regulation at 1.2 -V the input voltage was set to the recommended maximum input voltage of 20 V to test the LDO for any burnout. The output voltage was decreased to the minimum output voltage of the TPS7A4501-SP to maximize the voltage stress across the pass element of the LDO. Also data was collected at V_{IN} = 15, V_{OUT} = 12 V and RT. Summary for SEB data collection and conditions is shown on Table 6. The last column shows the cross section in a case by case scenario. However data was combined (fluences added together) to calculate the combined cross section. Results are shown on Table 7.

Flux of 10^5 and fluences of 10^7 were used for the SEB characterization, using ^{197}Au at incident and ^{141}Pr (TAMU) at 0°, 25° and 45° angle of incidence. The distance between the exit port and the DUT was set to 40 mm on all runs. Please refer to Table 4 for the LET_{EFF} values. *Not a single burnout was observed* while operating the TPS7A4501-SP at equal or below the maximum recommended input voltage of 20 V. The cross section was calculated using the MTBF method described in Appendix B.

Table 6. Summary of the TPS7A4501-SP SEB Conditions and Results

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2/mg)	Flux (ions/cm^2·s)	Fluence (#ions/cm^2)	Vin (V)	Vout (V)	Load (A)	SEB?	$\sigma_{PERCASE}$ (cm^2/device)
1	1	Au	0	85.94	1.00E+05	1.00E+07	20	1.2	10m	No	3.69E-07
2	1	Au	0	85.94	1.00E+05	1.00E+07	22	1.2	10m	No	3.69E-07
3	1	Au	0	85.94	1.00E+05	1.00E+07	26	1.2	10m	No	3.69E-07
4	2	Pr	0	64.64	1.08E+05	9.96E+06	15	12	0.00	No	3.70E-07
5	2	Pr	45	91.21	1.01E+05	1.03E+07	15	12	0.00	No	3.58E-07
6	3	Pr	0	64.64	9.75E+04	1.06E+07	15	12	0.50	No	3.47E-07
7	3	Pr	45	91.21	1.03E+05	1.00E+07	15	12	0.50	No	3.68E-07
8	3	Pr	45	91.21	1.04E+05	1.00E+07	15	12	0.50	No	3.69E-07
9	3	Pr	0	64.64	1.00E+05	1.00E+07	15	12	1.00	No	3.68E-07
10	3	Pr	45	91.21	1.02E+05	1.00E+07	15	12	1.00	No	3.69E-07
11	3	Pr	45	91.21	1.04E+05	9.97E+06	15	12	1.00	No	3.70E-07
12	2	Pr	0	64.64	1.10E+05	9.97E+06	15	12	1.50	No	3.70E-07
13	3	Pr	0	64.64	1.01E+05	9.99E+06	15	12	1.50	No	3.69E-07
14	2	Pr	30	74.29	1.06E+05	9.98E+06	15	12	1.50	No	3.70E-07
15	2	Pr	30	74.29	1.07E+05	9.97E+06	15	12	1.50	No	3.70E-07
16	3	Pr	45	91.21	1.04E+05	1.00E+07	15	12	1.50	No	3.68E-07

Table 7. Combined Upper Bound Cross Section for the TPS7A4501-SP SEB

Vin (V)	Vout (V)	Load (A)	LET_{EFF} (MeV·cm^2/mg)	Fluence (#ions/cm^2)	$\sigma_{COMBINED}$ (cm^2/device)
20	1.2	10m	85.9	3.00E+07	1.23E-07
15	12	0 - 1.5	64.24	5.06E+07	7.29E-08
15	12	0-1.5	74.24	1.99E+07	1.85E-07
15	12	1-1.5	91.21	6.03E+07	6.12E-08

Using the maxima from the combined upper bound cross section on Table 7, the SEB upper bound cross section is:

$\sigma_{SEB} \leq 1.85 \times 10^{-7}$ cm^2/device at LET ≤ 91.96 MeV-cm^2/mg, T = 25°C and 95% confidence.

7.2 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 thermal pad of the EVM. ^{165}Ho incident at 0, 20.5 and 35° and ^{141}Pr incident at 45° were used for the characterization (please refer to Table 4 for $\mathrm{LET_{EFF}}$). The distance between the heavy-ion exit port and the DUT was held constant at 40 mm for all test. Flux of 10^5 and fluences of 10^7 were used for all tests. SEL results are summarized on Table 8. No SEL events was observed under any of the test runs. Upper bound cross section is calculated using the MTBF described on Appendix B.

$\sigma_{SEL} \leq 3.69 \times 10^{-7}$ cm^2/device at LET ≤ 91.96 MeV-cm^2/mg, T = 125°C and 95% confidence.

Table 8. Summary of the TPS7A4501-SP SEL Results(1)

Run #	Unit #	$\mathrm{LET_{EFF}}$ (MeV-cm^2/mg)	Ion Type	Incident Angle (°)	Fluence (ions/cm^2)	Vin (V)	Vout (V)	Load (A)	SEL Events
17	4	83.02	Ho	25	$1o^7$	5	1.2	0.020	0
18	4	83.02	Ho	25	$1o^7$	7	1.2	0.020	0
19	5	91.96	Ho	35	$1o^7$	20	17.8	0	0
20	5	91.96	Ho	35	$1o^7$	20	17.8	0	0
21	6	91.22	Pr	45	$1o^7$	17	10	0.840	0
22	6	91.22	Pr	45	$1o^7$	17	10	.760	0
23	7	91.22	Pr	45	$1o^7$	5	1.2	0.830	0

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

8 SET Results

SETs were defined as heavy-ion-induced transients on the V_{OUT} of the TPS7A4501-SP that were higher than ±5% of the nominal voltage. Characterization was conducted at output voltages of: 1.8, 2.5, 3.3, and 12 V. Also for each V_{OUT} load of 20, 500,1000 and 1500 mA were used.

Table 9 to Table 12 summarize the test conditions of the TPS7A4501-SET characterization. Flux of ≥ 10^4 ions/cm^2-s and fluences of ≥ 10^6 ions/cm^2 were used for the SET data collection. To capture the transients, window triggers with ±5% around the nominal voltage was used for all runs. Notice that for each summary table, the last column represent the case by case upper bound cross section. However Table 13 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 described in Appendix B, at 95% confidence interval. Figure 7 show the 2 upsets on run # 76 and Figure 8 shows 2 of the 14 SETs on run # 84. As can be observed in Figure 8, the SETs are bipolar transitions around the nominal voltage. A histogram showing the deviation from the nominal voltage (V_{OUT} = 1.8 V) in percentage is presented in Figure 9. Notice that V_{OUT} = 1.8 V is the worst case since the ±5% margin is lower when compared with the other output voltages used for the characterization. Transients have a longer duration at light load vs heavy loads, this can be observed in the time domain plots of the SETs linked previously, and also in Figure 10.

Table 9. Summary of the TPS7A4501-SP SET for V_{IN} = 15 V and V_{OUT} = 12 V

Run #	Unit #	Load (A)	LET$_{EFF}$ (MeV-cm^2/mg)	Ion	Angle	Flux (Ions/cm^2·s)	Fluence (Total # of Ions)	# Events > 5% of Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/device)
24	8	0	64.24	Pr	0	1.16E+04	9.99E+05	0	3.69E-06
25	9	0	64.24	Pr	0	1.16E+04	9.96E+05	0	3.70E-06
26	8	0	74.29	Pr	30	1.07E+05	2.29E+06	0	1.61E-06
27	8	0	74.29	Pr	30	1.11E+04	3.20E+05	0	1.15E-05
28	8	0	74.29	Pr	30	1.10E+04	1.75E+06	0	2.11E-06
29	8	0	74.29	Pr	30	1.08E+04	9.99E+05	0	3.69E-06
30	8	0	74.29	Pr	30	1.07E+04	1.00E+06	0	3.69E-06
31	8	0	91.22	Pr	45	1.07E+04	1.00E+06	0	3.69E-06
32	9	0.5	64.24	Pr	0	1.15E+04	1.00E+06	0	3.68E-06
33	8	0.5	74.29	Pr	30	1.05E+05	1.87E+06	0	1.98E-06
34	8	0.5	74.29	Pr	30	1.10E+04	9.97E+05	0	3.70E-06
35	8	0.5	74.29	Pr	30	1.08E+04	9.98E+05	0	3.70E-06
36	8	0.5	74.29	Pr	30	1.11E+04	1.00E+06	0	3.69E-06
37	8	0.5	91.22	Pr	45	1.10E+04	1.00E+06	0	3.68E-06
38	8	0.5	91.22	Pr	45	1.02E+04	6.68E+04	0	5.53E-05
39	8	0.5	91.22	Pr	45	1.05E+04	9.98E+05	0	3.70E-06
40	8	0.5	91.22	Pr	45	1.04E+04	1.00E+06	0	3.68E-06
41	9	0.5	91.22	Pr	45	1.21E+04	9.98E+05	0	3.70E-06
42	9	0.5	91.22	Pr	45	1.23E+04	1.00E+06	0	3.69E-06
43	9	0.5	91.22	Pr	45	1.20E+04	1.00E+06	0	3.68E-06
44	9	0.5	91.22	Pr	45	1.17E+04	9.98E+05	0	3.70E-06
45	8	1	74.29	Pr	30	1.12E+04	9.99E+05	0	3.69E-06
46	8	1	74.29	Pr	30	1.08E+04	1.00E+06	0	3.69E-06
47	8	1	91.22	Pr	45	1.08E+04	1.00E+06	0	3.69E-06
48	8	1.5	64.24	Pr	0	1.14E+04	9.97E+05	0	3.70E-06
49	8	1.5	74.29	Pr	30	1.10E+04	9.98E+05	0	3.70E-06
50	8	1.5	74.29	Pr	30	1.11E+04	1.00E+06	0	3.69E-06
51	8	1.5	74.29	Pr	30	1.12E+04	1.00E+06	0	3.69E-06
52	8	1.5	74.29	Pr	30	1.07E+04	9.97E+05	0	3.70E-06
53	8	1.5	91.22	Pr	45	1.11E+04	1.00E+06	0	3.69E-06

Table 10. Summary of the TPS7A4501-SP SET for V_{IN} = 5 V and V_{OUT} = 3.3 V(1)

Run #	Load (A)	LET_{EFF} (MeV-cm^2/mg)	Ion	Angle	Flux	Fluence	# Events > 5% of Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/device)
54	5.5m	38.72	Kr	45	1.00E+04	1.00E+06	0	3.69E-06
55	5.5m	38.72	Kr	45	1.00E+04	1.00E+06	0	3.69E-06
56	5.5m	38.72	Kr	45	1.00E+04	2.00E+06	0	1.84E-06
57	5.5m	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
58	0.5	38.72	Kr	45	1.00E+04	2.00E+06	0	1.84E-06
59	0.5	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
60	1	38.72	Kr	45	1.00E+04	2.00E+06	0	1.84E-06
61	1	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
62	1.5	38.72	Kr	45	1.00E+04	2.00E+06	0	1.84E-06

(1) All Runs presented on this table were using unit # 10.

Table 11. Summary of the TPS7A4501-SP SET for V_{IN} = 5 V and V_{OUT} = 2.5 V(1)

Run #	Load (A)	LET_{EFF} (MeV-cm^2/mg)	Ion	Angle	Flux	Fluence	# Events > 5% of Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/device)
63	5.5m	38.72	Kr	45	1.00E+04	1.00E+06	0	3.69E-06
64	5.5m	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
65	5.5m	27.28	Kr	0	1.00E+04	5.00E+06	0	7.38E-07
66	500m	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
67	500m	27.28	Kr	0	1.00E+04	5.00E+06	0	7.38E-07
68	1	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
69	1	27.28	Kr	0	1.00E+04	5.00E+06	0	7.38E-07
70	1.5	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
71	1.5	27.28	Kr	0	1.00E+04	5.00E+06	0	7.38E-07

(1) All Runs presented on this table were using unit # 11.

Table 12. Summary of the TPS7A4501-SP SET for V_{IN} = 2.5 V and V_{OUT} = 1.8 V

Run #	Unit #	Load (A)	LET_{EFF} (MeV-cm^2/mg)	Ion	Angle	Flux	Fluence	# Events > 5% Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/device)
72	12	5.5m	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
73	12	5.5m	34.90	Kr	30	1.00E+04	5.00E+06	0	7.38E-07
74	12	5.5m	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
75	12	5.5m	34.90	Kr	30	1.00E+04	1.00E+06	0	3.69E-06
76	12	5.5m	64.24	Pr	0	1.00E+04	1.00E+06	2	7.22E-06
77	12	0.5	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
78	12	0.5	34.90	Kr	30	1.00E+04	5.00E+06	0	7.38E-07
79	12	0.5	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
80	12	0.5	64.24	Pr	0	1.00E+04	1.00E+06	0	3.69E-06
81	12	1	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07
82	12	1	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
83	12	1	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
84	12	1	64.24	Pr	0	1.00E+04	1.00E+06	16	2.6E-05
85	12	1.5	38.72	Kr	45	1.00E+04	5.00E+06	0	7.38E-07

Table 12. Summary of the TPS7A4501-SP SET for V_{IN} = 2.5 V and V_{OUT} = 1.8 V (continued)

Run #	Unit #	Load (A)	LET_{EFF} (MeV-cm^2/mg)	Ion	Angle	Flux	Fluence	# Events > 5% Nominal V_{OUT}	$\sigma_{PERCASE}$ (cm^2/device)
86	12	1.5	34.90	Kr	30	1.00E+04	2.00E+06	0	1.84E-06
87	12	1.5	64.24	Pr	0	1.00E+04	1.00E+06	0	3.69E-06
88	12	1.5	64.24	Pr	0	1.00E+04	1.00E+06	0	3.69E-06
89	13	5.5m	60.53	Xe	0	1.54E+04	1.00E+06	0	3.69E-06
90	13	0.5	60.53	Xe	0	1.50E+04	6.85E+05	0	5.39E-06
91	13	0.5	60.53	Xe	0	1.54E+04	1.00E+06	0	3.69E-06
92	13	1	60.53	Xe	0	1.57E+04	1.01E+06	0	3.65E-06
93	13	1	60.53	Xe	0	1.56E+04	1.01E+06	0	3.65E-06
94	13	1	60.53	Xe	0	1.56E+04	1.01E+06	0	3.65E-06
95	13	1.5	60.53	Xe	0	1.57E+04	1.01E+06	0	3.65E-06
96	13	1.5	60.53	Xe	0	1.58E+04	1.01E+06	0	3.65E-06
97	13	5.5m	79.39	Xe	40	1.10E+04	1.21E+06	0	3.05E-06
98	13	0.5	79.39	Xe	40	1.13E+04	1.06E+06	0	3.48E-06
99	13	1	79.39	Xe	40	1.13E+04	1.01E+06	0	3.65E-06
100	13	1.5	79.39	Xe	40	1.12E+04	1.01E+06	0	3.65E-06

Table 13. Combined Upper Bound Cross Section for the TPS7A4501-SP SETs

Vin (V)	Vout (V)	Load (A)	LET_{EFF} (MeV·cm^2/mg)	Fluence (#ions/cm^2)	Total # of Events	$\sigma_{COMBINED}$ (cm^2)
15	12	0 to 1.5	64.24	4.00E+06	0	9.22E-07
15	12	0 to 1.5	74.29	1.72E+07	0	2.14E-07
15	12	0 to 1.5	91.22	1.01E+07	0	3.65E-07
5	3.3	0 to 1.5	34.9	6.00E+06	0	6.15E-07
5	3.3	0 to 1.5	42.86	1.00E+07	0	3.69E-07
5	2.5	0 to 1.5	30.18	2.00E+07	0	1.84E-07
5	2.5	0 to 1.5	42.86	2.10E+07	0	1.76E-07
2.5	1.8	0 to 1.5	34.9	2.10E+07	0	1.76E-07
2.5	1.8	0 to 1.5	42.86	2.00E+07	0	1.84E-07
2.5	1.8	0 to 1.5	60.53	7.74E+06	0	4.77E-07
2.5	1.8	0 to 1.5	64.24	5.00E+06	18	5.69E-06
2.5	1.8	0 to 1.5	79.39	4.29E+06	0	8.60E-07

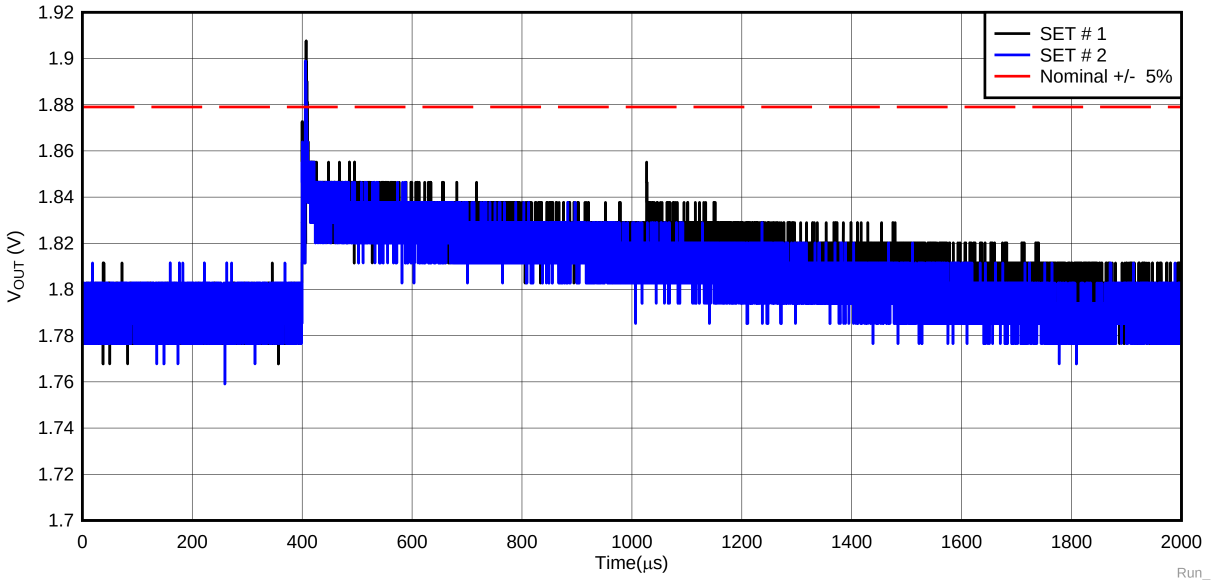


Figure 7. Time Domain SETs on Run # 76, Where V_{OUT} = 1.8 V and Load = 5.5 mA

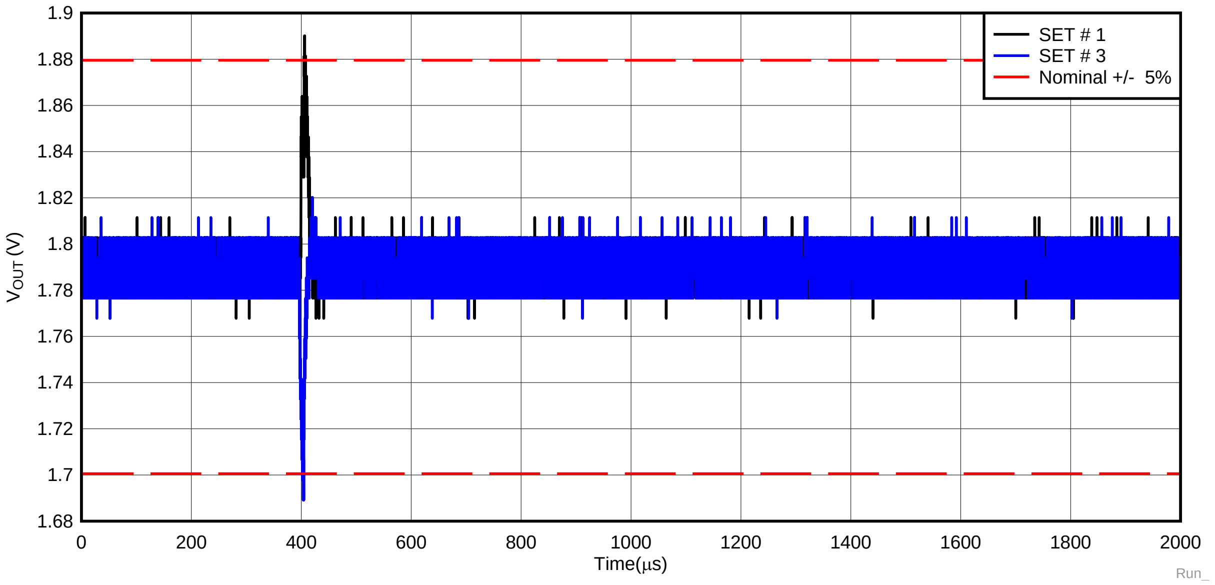
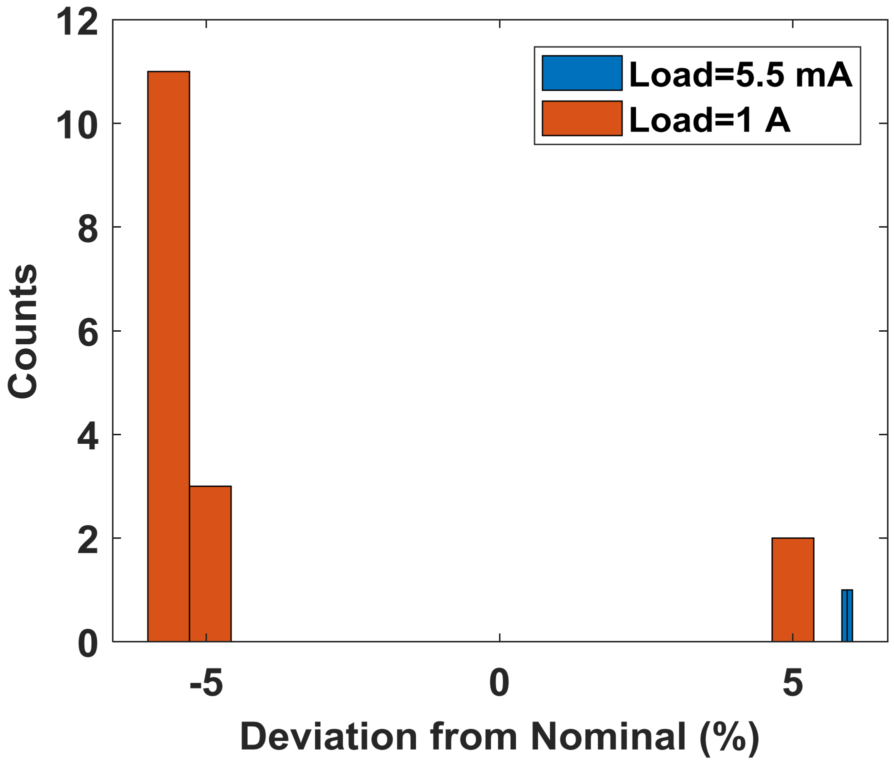
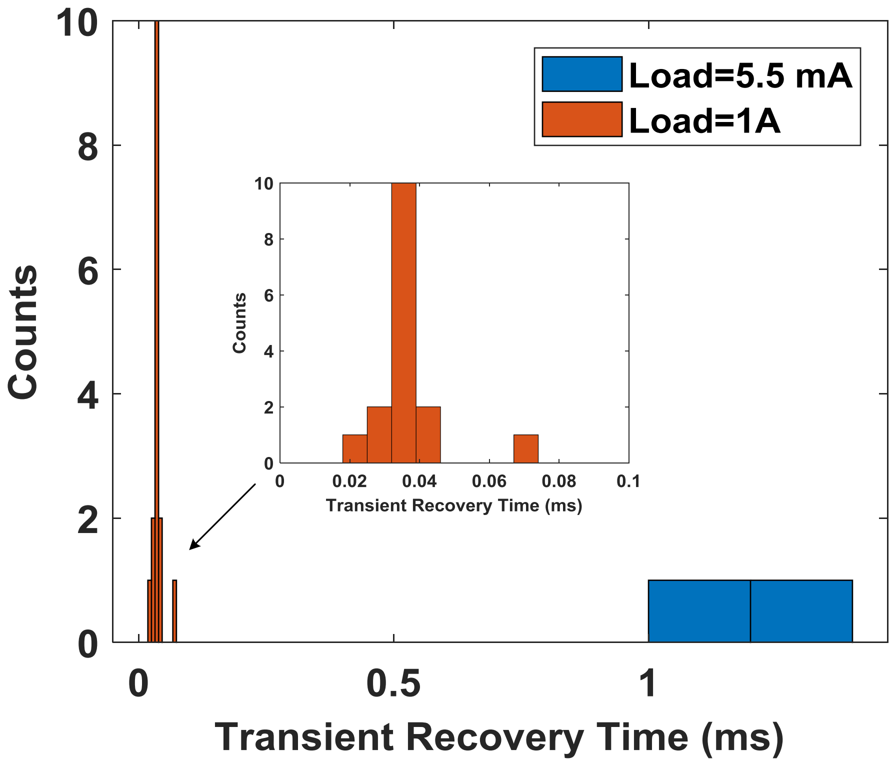


Figure 8. Time Domain SETs on Run # 84, Where V_{OUT} = 1.8 V and Load = 1 A



The histogram is based on the 18 upsets > ±5% of nominal V_{OUT} = 1.8 V.

Figure 9. Histogram of the Deviation from Nominal Voltage for the SETs



The histogram is based on the 18 upsets > ±5% of nominal V_{OUT} = 1.8 V.

Figure 10. Histogram of the Transient Time for the SETs

9 Summary

The purpose of this report is summarize the SEE of the TPS7A4501-SP under heavy ions. The data shows that the TPS7A4501-SP is SEB and SEL free across the full electrical specifications and up to 91.1 MeV-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^{-7} cm^2/device (please refer to Section 7 for more details). SETs were characterized at different output voltages and across the full load of the TPS7A4501-SP. Only 18 transients higher than 5% were observed on 77 runs. Those transients were all observed at V_{OUT} = 1.8 V. Worst case for SETs deviations is observed at low output voltages, and worst case transients response time are observed at light loads. SET cross section is shown to be on the order of 10^{-6} cm^2/device.

Total Ionizing Dose From SEE Experiments

The production TPS7A4501-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 and ≈ 10 krad(Si) per 10^7 ions/cm^2 run. The cumulative TID exposure for each device , over all runs they each underwent, was determined to be between 8.4 krad(Si) to 181 krad(Si). All qualified production devices used in the studies described in this report stayed within specification and were fully-functional after the heavy-ion SEE testing was completed.

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) [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 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):

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

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 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*:

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

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. Thus the upper-bound cross section is obtained by inverting the MFTF:

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

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 14. 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 @ 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 for several different observed results (d = 0, 1, 2...100 observed events during fixed-fluence tests) assuming 10^6 ion/cm^2 for each test.

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