Radiation Report

TPS7H4001-SP Single-Event Effects (SEE) Test Report

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this study was to characterize the single-event effects (SEE) performance due to heavy-ion irradiation of the TPS7H4001-SP. Heavy-ions with effective linear energy transferred (LET_{EFF}) of 49 to 75 MeV·cm^2/mg were used to irradiate 37 RHA devices in 92 experiments. Flux of ≈10^5 ions/cm^2·s and fluences of 8.1 × 10^5 to 2 × 10^7 ions/cm^2 per run were used. The devices were characterized over a variety of input voltages, loads, and LET_{EFF}. The results demonstrate that, when operated within its safe-operating-area (SOA), the TPS7H4001-SP is DSEE-free. SET characterization for V_{OUT} transients ≥ |3%| from the nominal output voltage (≈1 – V) and PWRGD are presented and discussed in this report. This report uses the QMLV TPS7H4001-SP device in a ceramic package. It is also applicable for the QMLP TPS7H4001-SP device in a plastic package which uses the same die as the QMLV device.

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1 Introduction

The TPS7H4001-SP is a space-grade, radiation hardened, 7-V, 18-A, synchronous buck, point-of-load (POL) converter, which has been optimized for small designs with high-efficiency operation and integration of the high-side and low-side power MOSFETs into a compact monolithic design. Further space saving is achieved through the use of the configurable switching frequency (0.1 MHz to 1 MHz), which can reduce the output filter lumped components and optimizing the power density (W/in^3). The device is offered in a thermally enhanced 34-pin ceramic, dual inline flat-pack package. General device information and test conditions are listed in Table 1-1. For more detailed technical specifications, user guides, and application notes, see the TPS7H4001-SP product page.

Table 1-1. Overview Information

DESCRIPTION[(1)]	DEVICE INFORMATION
TI Part Number	TPS7H4001-SP
Orderable Name	5962-1820501VXC
Device Function	Point-of-load (POL) switching regulator
Technology	250-nm linear BiCMOS
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University (15 MeV/nucleon)
Irradiation Temperature	25°C and 125°C (for SEL testing)

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2 Single-Events Effects (SEE)

The primary concern for the TPS7H4001-SP is the robustness against the destructive single event effects (DSEE). The principal destructive effects studied here are:

- Single-event latch-up (SEL)
- Single-event burn-out (SEB)
- Single-event gate rupture (SEGR)

The TPS7H4001-SP is DSEE-free when operated within the safe-operating-area (SOA). The SOA curve has been validated up to a LET_{EFF} = 75 MeV·cm^2/mg, using a total of 37 TPS7H4001-SP RHA qualified devices.

In mixed technologies such as the BiCMOS process used on the TPS7H4001-SP, the CMOS circuitry introduces a potential for SEL susceptibility. SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-substrate and n-well and n+ and p+ contacts) [1,2]. If formed, the parasitic bipolar structure creates a high-conductance path (creating a steady-state current that typically is orders-of-magnitude higher than the normal operating current) between power and ground that persists (is “latched”) until power is removed, the device is reset, or until the device is destroyed by the high-current state. When the TPS7H4001-SP is operated within its Safe-Operating-Area (SOA), as shown in Figure 7-1, the device is DSEE-free.

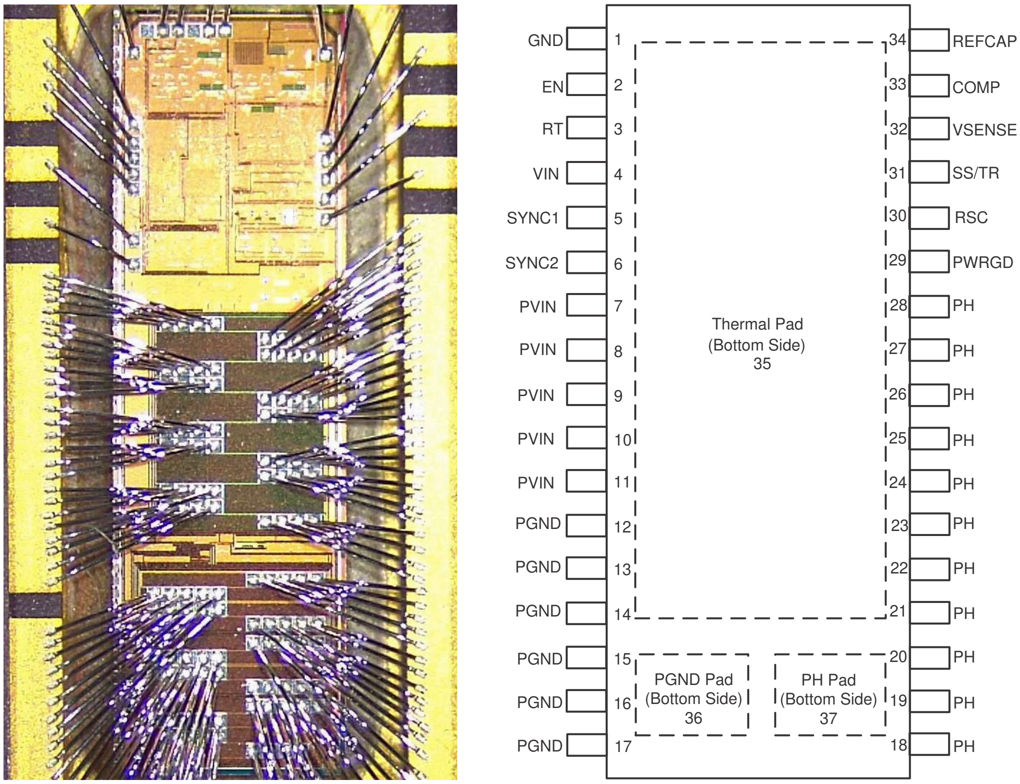
Since this device is designed to conduct large currents (up to 18 A) and withstand up to 7 V during the off state, the power LDMOS (P-type and N-Type, switching FETs) introduces a potential susceptibility for SEB and SEGR [3]. The TPS7H4001-SP was evaluated for destructive effects at die temperatures of 20°C and 60°C, under enabled (switching) and disabled modes. The device was evaluated at full load conditions and maximum voltage. Since it has been shown that the MOSFET is susceptible to burn-out decrement with temperature [4], the device was evaluated when operated under room temperature (RT) and with external cooling. The devices were cooled-down (or "chilled") by using VORTEC Tube (Model 611). The TPS7H4001-SP when operated within the SOA, as shown in Figure 7-1, is DSEE-free.

Under heavy-ions, the TPS7H4001-SP exhibits three transient modes that are fully recoverable without the need for external intervention. Characterized at room temperature and elevated temperature (125°C). The three observed transients are:

- A brief false PWRGD transient (referred to here as a $PWRGD_{SET}$) typically of 3 µs, indicating a non-stable output voltage even when the V_{OUT} voltage was properly regulated. PWRGD is an open drain digital flag that indicates the status of the output regulation. By design when the voltage is within a window of 9% of the reference the PWRGD becomes high Impedance (or open). However under heavy-ion this flag was being momentarily pulled down (activated), as an indication of a voltage regulation fault. This kind of SET can be filtered out by the use of an small R-C filter, as shown in Figure 8-5.
- A brief transient of the output voltage (referred to here as $VOUT_{SET}$). For the purpose of this report the transients were characterize for deviations ≥ |±3%| from the nominal output voltage of ≈1 V (±30 mV). These upsets typically have duration of 16 µs and 3.63% deviation from the nominal voltage. For more details, see Section 8.
- A soft-start power re-cycle, which results in the V_{OUT} dropping near zero volts and characterized by a recovery time governed by the soft-start (SS) capacitor. These variety of SETs are referred to here as SS_{SET}. It is important to notice that upsets of this kind were observed only at elevated temperatures (125°C). Not a single SS_{SET} was observed at room temperature or during the cool down testing (during the SEB testing).

3 Test Device and Evaluation Board Information

The TPS7H4001-SP is packaged in a 34-pin thermally-enhanced dual ceramic flat pack package (HKH) as shown in Figure 3-1. The TPS7H4001EVM-CVAL evaluation board was used to evaluate the performance and characteristics of the TPS7H4001-SP under heavy-ions. Board schematics are shown in Figure 3-3. Top view of the evaluation board used for radiation testing campaign is shown in Section 3.



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

Figure 3-1. Photograph of Delidded TPS7H4001-SP [Left] and a Pin-Out Diagram [Right]

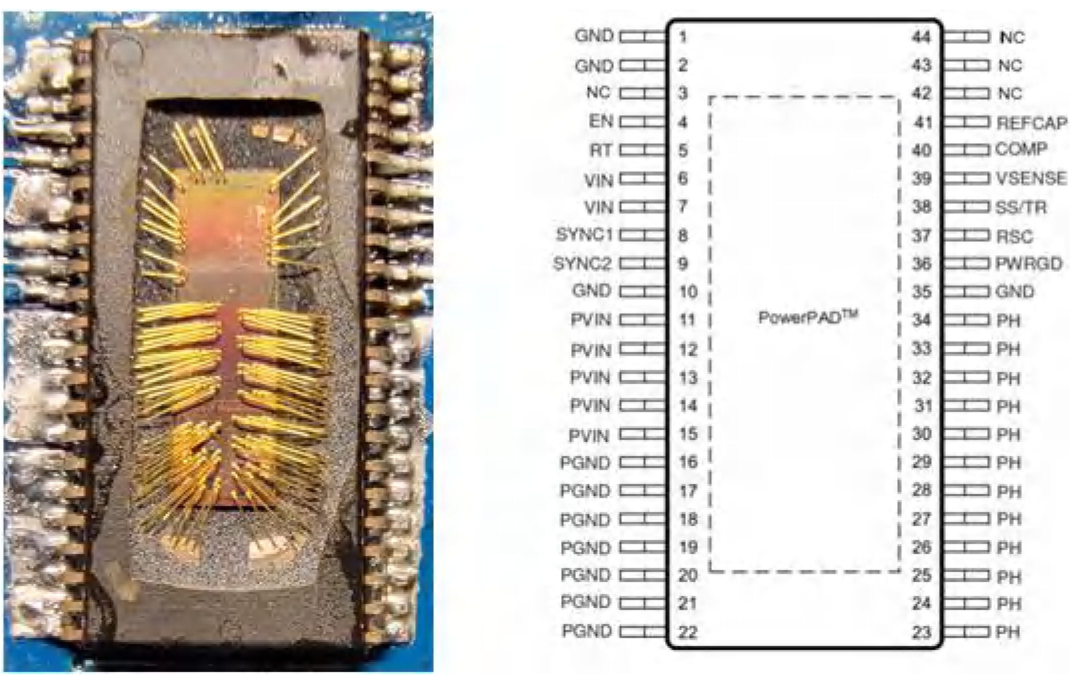


Figure 3-2. Photograph of the Delidded TPS7H4001-SP (SHP) [Left] and a Pin-Out Diagram [Right]

During some SET testing runs of the TPS7H4001-SP, the PWRGD filter was populated as indicated on the schematics. It is important to notice that the EVM ships with these components default as DNI. Transistor Q1 was removed for all the SEE test campaign.

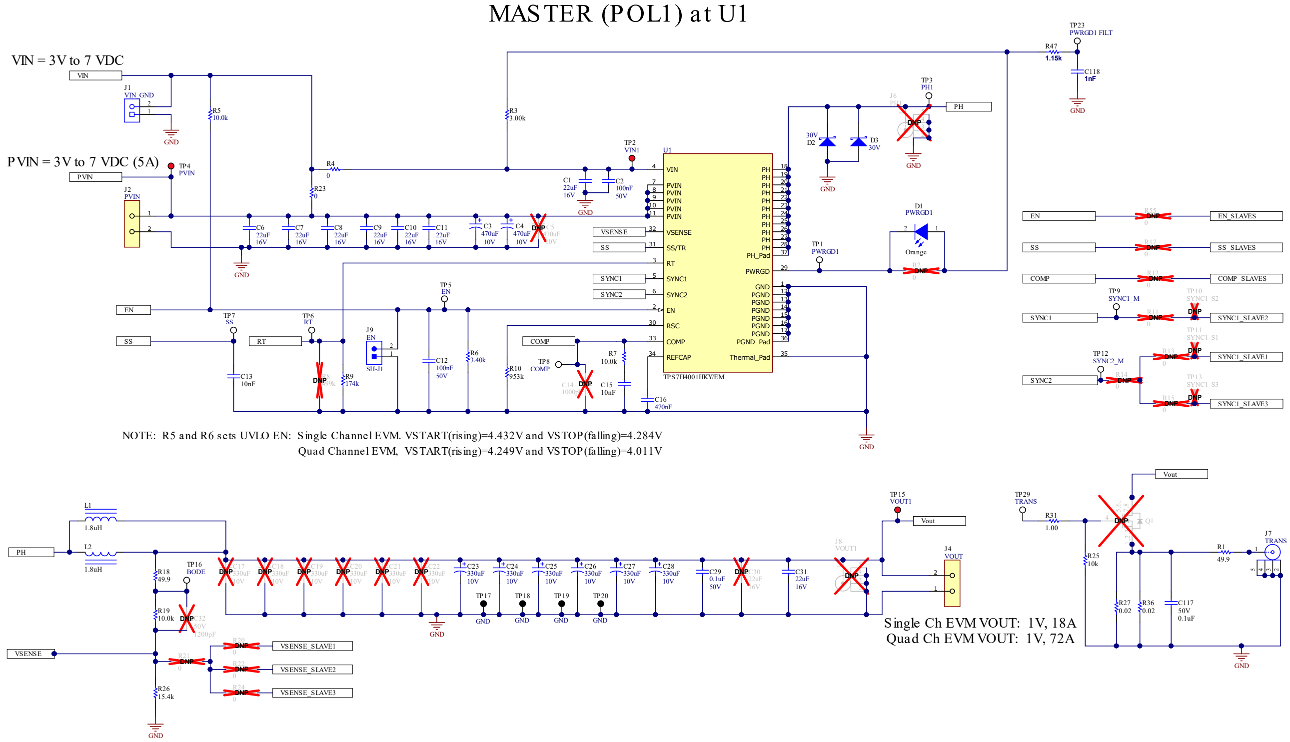


Figure 3-3. Schematic of the TPS7H4001EVM-CVAL Used During SEE Testing

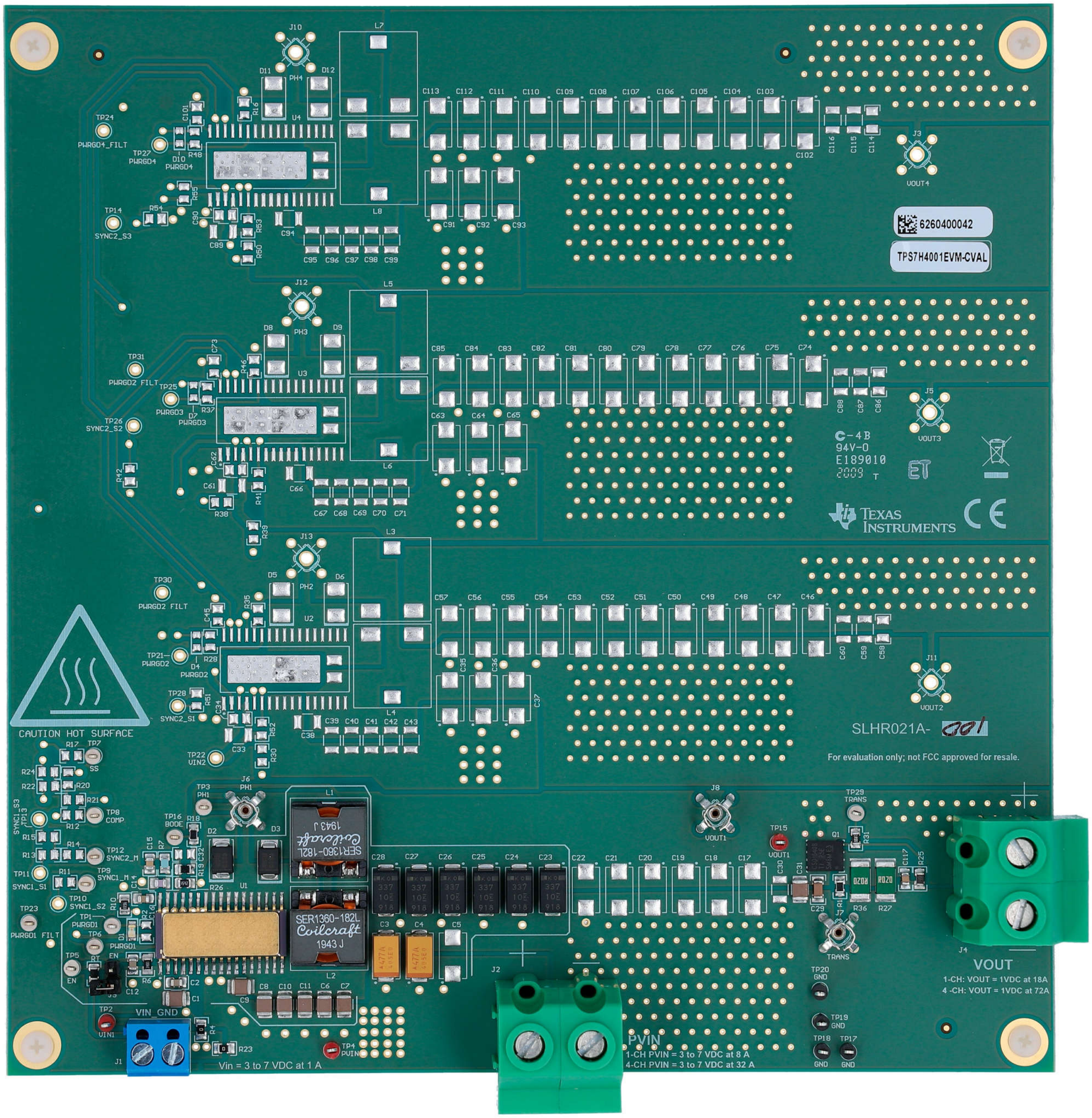


Figure 3-4. TPS7H4001EVM-CVAL Board (Top View)

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 [6], 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 flux of ≈ 10^5 ions/s·cm^2 were used to provide heavy-ion fluences of ≥10^7 ions/cm^2. For these experiments Silver (^{109}Ag) at angles of incidence of 0° and 25° were used for an LET_{EFF} of 49.3 and 54.8 MeV·cm^2/mg, respectively. Praseodymium (^{141}Pr) at angles of incidence of 0° and 27.3° were used for an LET_{EFF} of 66.37 and 74.95 MeV·cm^2/mg, respectively. Holmium (^{165}Ho), at angles of incidence of 0° were used for LET_{EFF} of 75.82 MeV·cm^2/mg. The ^{109}Ag, ^{141}Pr, and ^{165}Ho ions used had a total kinetic energy of 1.634, 2.114, and 2.474 GeV, in the vacuum (using the 15 MeV/amu), respectively.

The TPS7H4001-SP 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 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 ^{109}Ag and ^{141}Pr runs. For all the ^{165}Ho the distance was set to 30 mm.

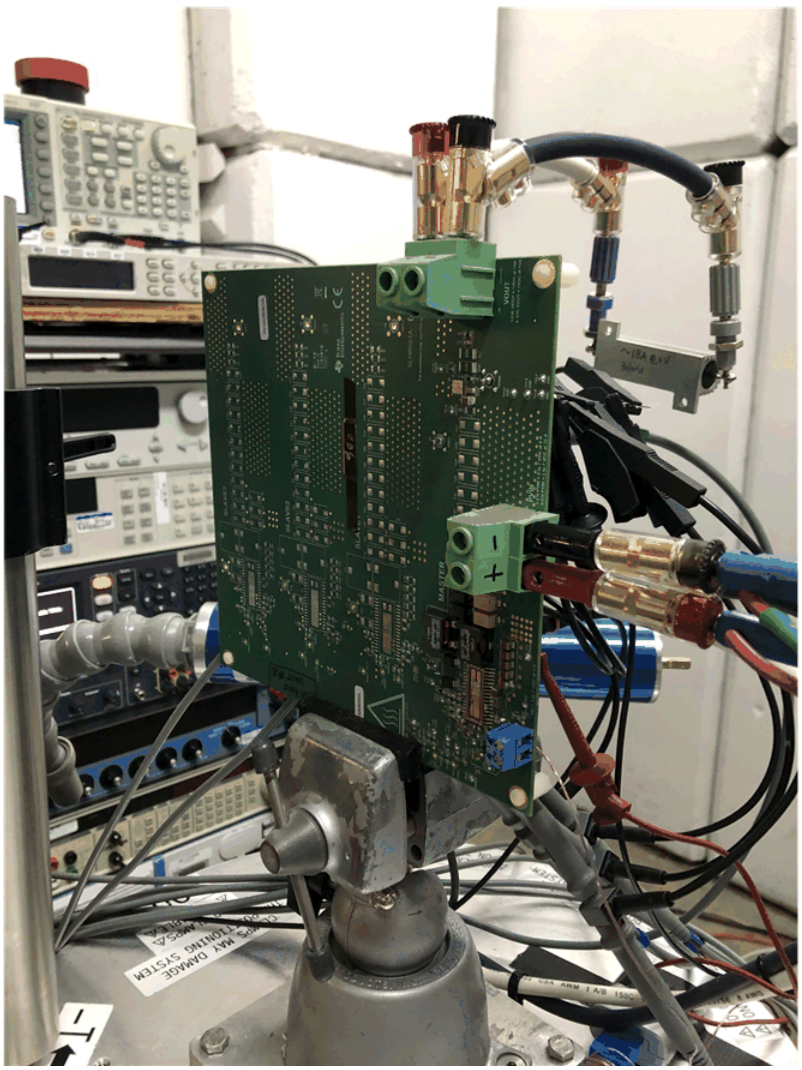


Figure 4-1. Photograph of the TPS7H4001-SP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port at the Texas A&M Cyclotron

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

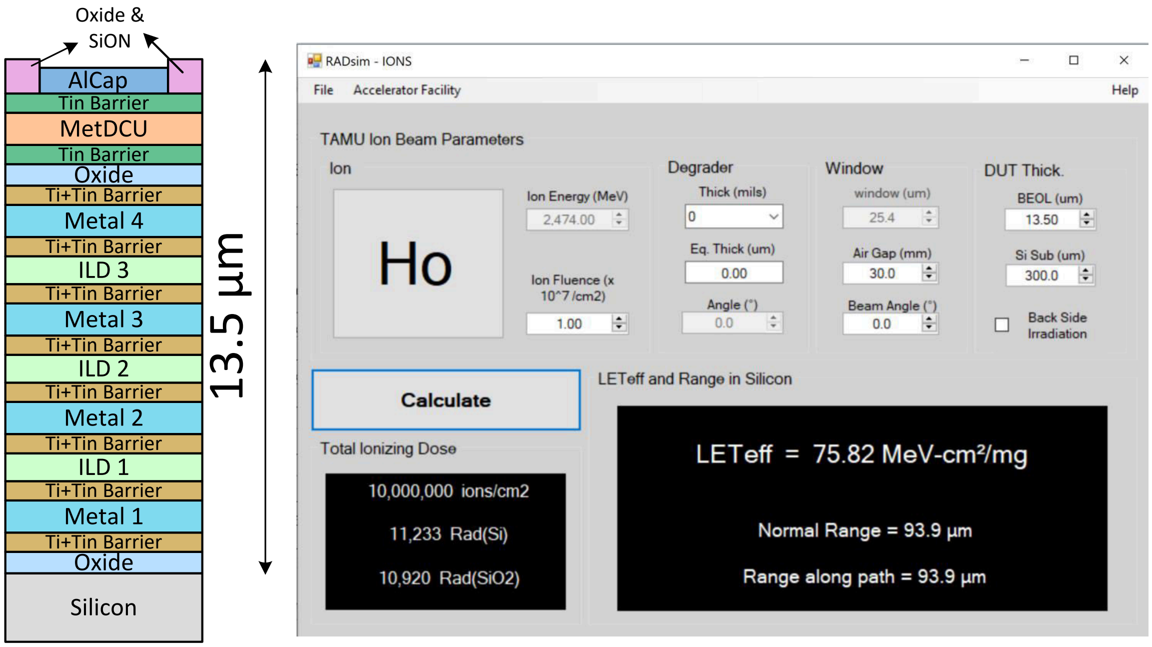


Figure 5-1. Generalized Cross Section of the BiCMOS Technology BEOL Stack on the TPS7H4001-SP [Left] and GUI of RADsim Application Used to Determine Key Ion Parameters [Right]

The TPS7H4001A-SP is fabricated in the TI Linear BiCMOS 250-nm process with a back-end-of-line (BEOL) stack consisting of four levels of standard thickness aluminum metal on a 0.6-µm pitch and damascene copper (Cu). The total stack height from the surface of the passivation to the silicon surface is 13.5 µm based on nominal layer thickness as shown in Figure 5-1. No polyimide or other coating was present; the uppermost layer was the nitride passivation layer (PON). Accounting for energy loss through the 1-mil thick Aramica beam port window, the 40-mm (30-mm for ^{165}Ho) air gap, and the BEOL stack over the TPS7H4001-SP, the effective LET (LET$_{EFF}$) at the surface of the silicon substrate, the depth, and the ion range was determined with the custom RADsim - IONS application (developed at Texas Instruments and based on the latest SRIM-2013 [7] models). The results are shown in Table 5-1. The stack was modeled as a homogeneous layer of silicon dioxide (valid since SiO2 and aluminum density are similar).

Table 5-1. LET$_{EFF}$, Depth, and Range in Silicon for the Heavy-Ions Used for the TPS7H4001-SP SEE Test Campaign

ION TYPE	Air Distance (mm)	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET$_{EFF}$ (MeV·cm^2 /mg)
^{109}Ag	40	0	84.1	84.1	49.3
^{109}Ag	40	25	75	82.7	54.8
^{141}Pr	40	0	89.4	89.4	66.37
^{141}Pr	40	27.3	77.9	87.7	74.95
^{165}Ho	30	0	93.9	93.9	75.82

6 Test Setup and Procedures

SEE testing was performed on a TPS7H4001-SP device mounted on a TPS7H4001SPEVM, 18-A, regulator evaluation module. Power was provided to the device by means of the PVIN input on the J2 connectors using the N6766A PS module mounted on a N6705 precision power supply in a 4-wire configuration. The P_{VIN} and V_{IN} were tied together using the R4 and R23 0-Ω resistors on the EVM. The device was loaded using a discrete power resistor of 55 mΩ dissipating 18 A (for most cases). For the case when the load was sweep to determine the load dependency on the DSEE a chroma electronic (model: 63630-80-80) load was used.

With the exception of the DPO digital oscilloscope, 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 test setup used for SEE characterization of the TPS7H4001-SP is illustrated in Figure 6-1 .Connections, limits and compliance used are shown in Table 6-1. The TPS7H4001-SP was tested at 3 different temperature conditions as described below:

1. T = 125°C used for all SEL testing. Temperature was achieved with the use of a convection heat gun aimed at the die.
2. T = 20 to 31°C (disable/enabled) used for SEB/SEG testing. Achieved by using a vortex tube aimed at the die.
3. Around 60°C (at 18 A, 7 V) for all SET characterization. Under this condition no external heat or cool element was used.

The die temperature was monitored during the testing using a K-Type thermocouple attached to the thermal pad vias (on the bottom side of the EVM) with thermal paste. The thermocouple was hold on place by using high temperature tape (kapton-tape). Die to thermocouple temperature was verified using a IR-camera, prior to the SEE test campaign.

Table 6-1. Equipment Set and Parameters Used for DSEE Testing the TPS7H4001-SP

Pin Name	Equipment Used	Capability (A)	Compliance (A)	Value Used (V)
P_{VIN}/V_{IN}	N6766A	15	10-15	5-7
Oscilloscope Card	NI-PXIe 5105	60MS/s	-	20Ms/s
Digital Phosphor Oscilloscope	Tektronix DPO7104C	40 GS/s	-	20MS/s - 2G S/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 TPS7H4001-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), or a device was damaged. The current on the P_{VIN} and V_{IN} (tied-together for all test) was monitored at all times.

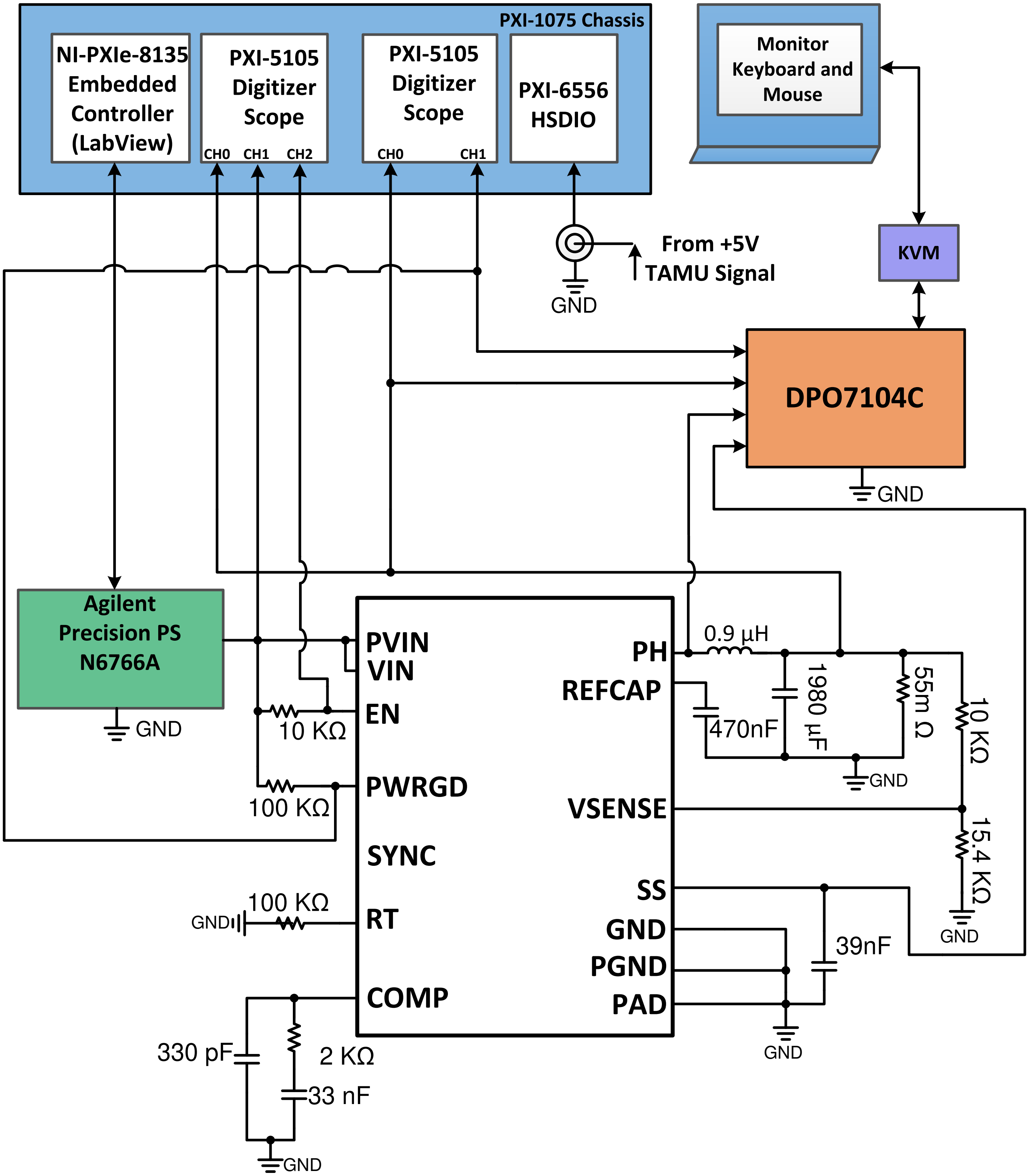


Figure 6-1. Block Diagram of the SEE Test Setup for the TPS7H4001-SP

7 Destructive Single-Event Effects (DSEE)

7.1 Safe-Operating-Area (SOA) Results

Many TPS7H4001-SP devices were characterized across voltage, load current, and LET_{EFF} by sweeping the variables. The purpose of this experiment was to determined the values at which destructive effects were observed, when controlling the variables. During the testing, only one variable was changed (sweep) at a time while the other remain constant at the maximum permissible values. The maximum values for each sweep variable is presented in Table 7-1. When collecting data for the DSEE of the TPS7H4001-SP, it was observed that the probability of damaging a device was greater at higher temperatures, consequently most of the DSEE data was collected at this temperature. During DSEE testing on runs 3, 11, 65, 67, and 69 the TPS7H4001-SP was tested for cross-conduction. Cross-conduction was tested by monitoring the phase to GND (low-side NMOS FET) and the PVIN to phase (high-side PMOS FET, by using a differential probe) and triggered using a AND digital trigger on the DPO7104C. The trigger V_{IH} (or logic 1) was specified as 500 mV. During the runs not a single upset was capture indicating that the TPS7H4001-SP did not suffer from cross-conduction upsets.

Notice that even when separate sections and chapter were created to present the SEL, SEB/SEGR, and SET in a more organized fashion, the DSEE terminology encapsulated all the device damage during the heavy-ion testing campaign regarding the temperature. This is valid since Flux of ≈10^5 ions/cm^2·s was used for all runs.

Table 7-1. Maximum Permissible Values for the Variables Sweep During the DSEE Testing

Variable Name	Maximum Value	Units
$P_{VIN} = V_{IN}$	7	V
Load current (I_{LOAD})	18	A
LET_{EFF}	75	MeV·cm^2/mg

For LET_{EFF} ≤ 75 MeV·cm^2/mg and load current of 18 A, the maximum permissible voltage to avoid DSEE is 6.4 V. Maximum voltage of 7 V can be achieved at LET≤ 75 MeV·cm^2/mg when the load current is decremented to ≤ 10 A. A visual representation of the SOA curve can be observed in Figure 7-1. The green area summarized the points were the TPS7H4001-SP can be operated at LET ≤ 75 MeV·cm^2/mg, without risk of damage. The red area represents the points where DSEE was observed, consequently the operating points must be avoided to reliably use TPS7H4001-SP.

DSEE failures were observed under the red area. The cross-section for these event is extremely small. During the SEE test campaign of the TPS7H4001-SP 17 units were damage from a total of 37. Table 7-2 shows the calculated upper-bound cross section when combining the fluences for all runs with same load,voltage and LET_{EFF}. The cross section values shown on the table calculated are calculated at 95% confidence interval (refer to SLVK047 for more details in the method used to calculate the upper bound cross section).

Table 7-2. DSEE Cross Section Table

Device Damage (#)	Total Units Tested (#)	Voltage (V)	Current (A)	LET_{EFF}(MeV·cm^2/mg)	Upper Bound Cross Section (cm^2/device)
1	3	7	18	49.3	1.79×10^{-7}
1	2	7	18	54.8	2.93×10^{-7}
0	4	5	18	66.37	9.22×10^{-8}
0	1	6.25	18	66.37	3.69×10^{-7}
0	1	6.4	18	66.37	3.69×10^{-7}
1	3	6.5	18	66.37	2.57×10^{-7}
0	1	6.6	18	66.37	3.71×10^{-7}
0	1	6.75	18	66.37	3.69×10^{-7}
0	1	6.8	18	66.37	3.69×10^{-7}
1	7	7	18	66.37	8.53×10^{-8}
0	3	5	18	74.95	6.15×10^{-8}
0	3	6	18	74.95	1.23×10^{-7}

Table 7-2. DSEE Cross Section Table (continued)

Device Damage (#)	Total Units Tested (#)	Voltage (V)	Current (A)	LET_{EFF} ($MeV \cdot cm^2/mg$)	Upper Bound Cross Section (cm^2/device)
0	2	6.25	18	74.95	1.84×10^{-7}
0	1	6.3	18	74.95	3.69×10^{-7}
0	1	6.375	18	74.95	3.7×10^{-7}
3	5	6.5	18	74.95	2.56×10^{-7}
0	1	6.7	18	74.95	3.69×10^{-7}
0	1	6.75	18	74.95	1.84×10^{-7}
0	1	7	9	74.95	3.7×10^{-7}
0	3	7	10	74.95	1.27×10^{-7}
1	2	7	11	74.95	4.57×10^{-7}
0	1	7	12	74.95	3.69×10^{-7}
1	1	7	13.5	74.95	7.13×10^{-7}
1	2	7	14	74.95	4.57×10^{-7}
0	1	7	16	74.95	3.69×10^{-7}
3	13	7	18	74.95	5.84×10^{-8}
0	1	5	18	75.82	1.84×10^{-7}
4	9	7	18	75.82	7.84×10^{-8}

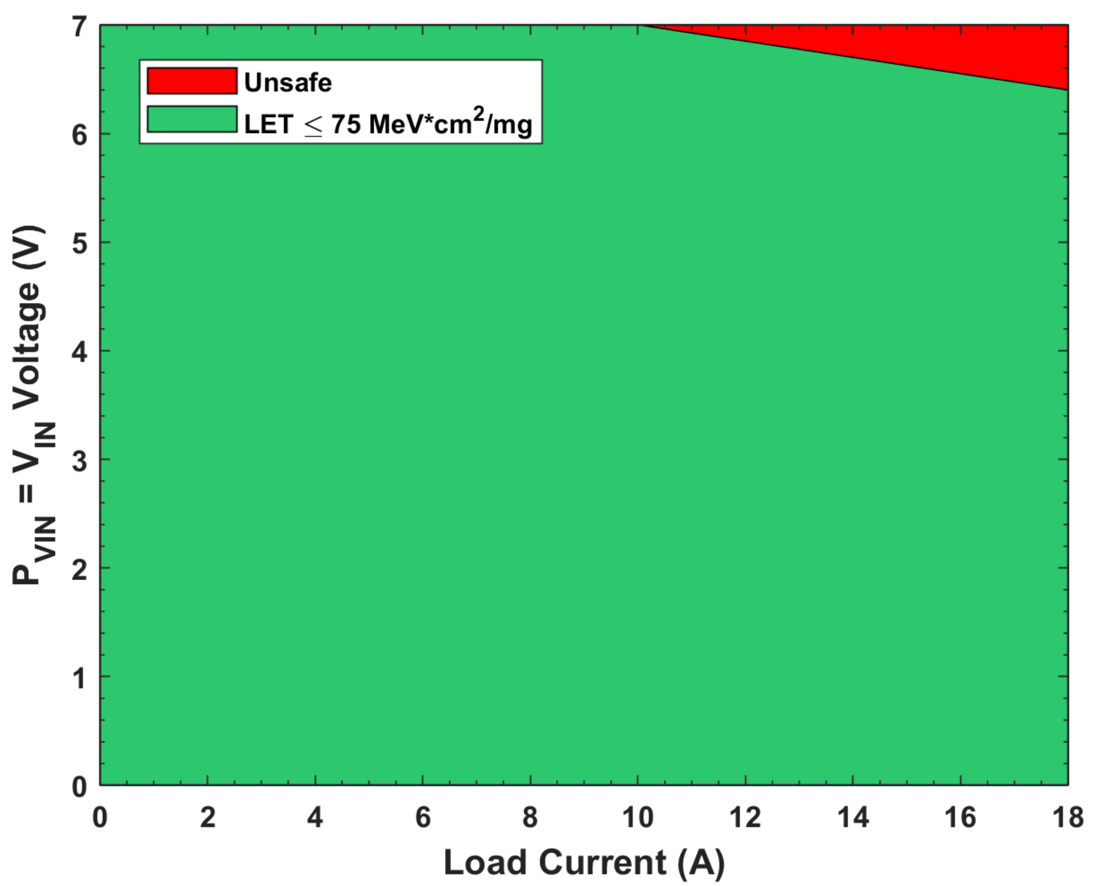


Figure 7-1. SOA Curve for the TPS7H4001-SP

7.2 Single Event Latch-Up (SEL) Results

SEL characterization was performed with forced hot air to maintain the die temperature at 125°C during the tests. A K-type thermocouple attached to the thermal pad vias (on the bottom side of the EVM) with thermal paste was used to monitored the temperature. The thermocouple was hold on place by using high temperature tape (kapton-tape). The thermocouple and die temperature were verified using a thermal IR camera, prior to the SEE test campaign.

The device was exposed to Silver (^{109}Ag), Praseodymium (^{141}Pr), and Holmium (^{165}Ho) ions. For ^{109}Ag angles of incidence of 0° and 25° were used for an LET_{EFF} of 49.3 and 54.8 MeV·cm^2/mg, respectively. ^{141}Pr at angles of incidence of 0° and 27.3° were used for an LET_{EFF} of 66.37 and 74.95 MeV·cm^2/mg, respectively. ^{165}Ho at angle of incidence of 0° was used for an LET_{EFF} of 75.82 MeV·cm^2/mg. For Silver and Praseodymium the air distance between the heavy-ion exit port and the DUT was set to 40-mm for all runs. In the case of Holmium the distance was set to 30-mm. Flux of ≈10^5 ions/cm^2·s and fluence of ≥ 10^7 ions/cm^2 per run were used for the SEL characterization. Run duration to achieve this fluence was approximately 2 minutes.

The SEL test condition and results are summarized in Table 7-3. The TPS7H4001-SP is DSEE-free when operated withing the green area under the SOA curve, presented in Figure 7-1. For more details on the DSEE cross section refer to Section 7.1.

Current vs time plot for run #3 (no damage) and run # 6 (damage) is shown in Figure 7-2 and Figure 7-3, respectively.

During the high-temperature characterization of the TPS7H4001-SP, the output voltage was monitored for transients –3% ≤ V_{OUT} ≤ 3% from the nominal voltage of ≈1 V (±30 mV), using the DPO7104C. Transients were observed at these conditions and in general the device behaved as described in Section 8, however a few upsets occurred where the output voltage dropped near zero with a long recovery time (≈2 ms). During this type of upset, the SS voltage dropped and initiate a restart cycle of the device. When this occurs, the recovery time is governed by the C_{SS} capacitor. For the case of the configuration used during the testing campaign of the TPS7H4001-SP the C_{SS} was set to 39 nF (≈2 ms).

Table 7-3. Summary of TPS7H4001-SP SEL Test Condition and Results

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2 / mg)	Flux (ions/ cm^2·s)	Fluence (ions/cm^2)	$P_{VIN} = V_{IN}$ (V)	Load (A)	Damage?
1	1	^{165}Ho	0	75.82	1.06E+05	1.00E+07	7	18	No
2	1	^{165}Ho	0	75.82	1.01E+05	1.00E+07	7	18	No
3	2	^{165}Ho	0	75.82	1.15E+05	1.00E+07	7	18	No
4	3	^{165}Ho	0	75.82	1.18E+05	2.61E+06	7	18	Yes
5	4	^{165}Ho	0	75.82	8.59E+04	9.99E+06	7	18	No
6	5	^{141}Pr	27.3	74.95	1.01E+05	4.15E+05	7	18	Yes
7	6	^{141}Pr	0	66.37	1.08E+05	5.25E+06	7	18	Yes
8	7	^{141}Pr	0	66.37	1.07E+05	9.96E+06	6.5	18	No
9	7	^{141}Pr	0	66.37	1.09E+05	1.00E+07	6.75	18	No
10	7	^{141}Pr	0	66.37	1.04E+05	1.00E+07	7	18	No
11	8	^{141}Pr	27.3	74.95	1.12E+05	4.34E+06	6.5	18	Yes
12	9	^{141}Pr	27.3	74.95	1.10E+05	9.96E+06	6	18	No
13	9	^{141}Pr	27.3	74.95	1.09E+05	1.00E+07	6.25	18	No
14	9	^{141}Pr	27.3	74.95	9.71E+04	1.00E+07	6.5	18	No
15	9	^{141}Pr	27.3	74.95	9.40E+04	1.00E+07	6.75	18	No
16	9	^{141}Pr	27.3	74.95	9.07E+04	9.99E+06	7	18	No
17	9	^{141}Pr	27.3	74.95	1.06E+05	1.00E+07	6.5	18	No
18	9	^{141}Pr	27.3	74.95	1.05E+05	9.99E+06	6.75	18	No

Table 7-3. Summary of TPS7H4001-SP SEL Test Condition and Results (continued)

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2 / mg)	Flux (ions/ cm^2·s)	Fluence (ions/cm^2)	$P_{VIN} = V_{IN}$ (V)	Load (A)	Damage?
19	9	^{141}Pr	27.3	74.95	1.11E+05	1.00E+07	7	18	No
20	10	^{141}Pr	27.3	74.95	1.03E+05	6.91E+06	7	18	Yes
21	11	^{141}Pr	27.3	74.95	9.75E+04	1.00E+07	6	18	No
22	11	^{141}Pr	27.3	74.95	1.01E+05	2.70E+06	6.5	18	Yes
23	12	^{141}Pr	27.3	74.95	1.04E+05	1.00E+07	6.25	18	No
24	12	^{141}Pr	27.3	74.95	9.84E+04	9.96E+06	6.375	18	No
25	12	^{141}Pr	27.3	74.95	9.58E+04	2.40E+06	6.5	18	Yes
26	13	^{141}Pr	0	66.37	1.08E+05	1.71E+06	6.5	18	Yes
27	14	^{141}Pr	0	66.37	1.06E+05	1.00E+07	6.25	18	No
28	14	^{141}Pr	0	66.37	1.10E+05	1.00E+07	6.4	18	No
29	14	^{141}Pr	0	66.37	1.08E+05	1.00E+07	6.5	18	No
30	14	^{141}Pr	0	66.37	1.13E+05	9.95E+06	6.6	18	No
31	14	^{141}Pr	0	66.37	1.11E+05	1.00E+07	6.8	18	No
32	14	^{141}Pr	0	66.37	1.13E+05	9.99E+06	7	18	No
33	15	^{141}Pr	27.3	74.95	1.15E+05	9.98E+06	7	9	No
34	15	^{141}Pr	27.3	74.95	1.22E+05	7.81E+06	7	13.5	Yes
35	16	^{141}Pr	27.3	74.95	1.13E+05	2.24E+06	7	11	Yes
36	17	^{141}Pr	27.3	74.95	1.06E+05	9.08E+06	7	10	No
37	17	^{141}Pr	27.3	74.95	9.97E+04	9.98E+06	7	10	No
38	17	^{141}Pr	27.3	74.95	9.87E+04	9.99E+06	7	11	No
39	17	^{141}Pr	27.3	74.95	9.82E+04	9.99E+06	7	12	No
40	17	^{141}Pr	27.3	74.95	1.02E+05	1.00E+07	7	14	No
41	17	^{141}Pr	27.3	74.95	1.02E+05	9.99E+06	7	16	No
42	17	^{141}Pr	27.3	74.95	1.04E+05	9.97E+06	7	18	No
43	18	^{141}Pr	27.3	74.95	1.01E+05	9.99E+06	7	10	No
44	18	^{141}Pr	27.3	74.95	1.10E+05	2.17E+06	7	14	Yes
45	19	^{109}Ag	0	49.3	1.19E+05	8.70E+06	7	18	No
46	19	^{109}Ag	0	49.3	1.09E+05	9.96E+06	7	18	No
47	19	^{109}Ag	25	54.8	1.15E+05	9.97E+06	7	18	No
48	20	^{141}Pr	27.3	74.95	1.28E+05	1.00E+07	6	18	No
49	20	^{141}Pr	27.3	74.95	1.21E+05	1.00E+07	6.3	18	No
50	20	^{141}Pr	27.3	74.95	1.16E+05	9.98E+06	6.5	18	No
51	20	^{141}Pr	27.3	74.95	1.13E+05	9.99E+06	6.7	18	No
52	20	^{141}Pr	27.3	74.95	1.12E+05	9.98E+06	7	18	No
53	20	^{141}Pr	27.3	74.95	1.16E+05	2.00E+07	7	18	No
54	20	^{141}Pr	27.3	74.95	1.05E+05	1.00E+07	7	18	No
55	21	^{109}Ag	25	54.8	9.31E+04	9.07E+06	7	18	Yes
56	22	^{109}Ag	0	49.3	1.02E+05	1.00E+07	7	18	No

Table 7-3. Summary of TPS7H4001-SP SEL Test Condition and Results (continued)

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2 / mg)	Flux (ions/cm^2·s)	Fluence (ions/cm^2)	$P_{VIN} = V_{IN}$ (V)	Load (A)	Damage?
57	23	^{109}Ag	0	49.3	1.01E+05	2.51E+06	7	18	Yes

$P_{VIN} = V_{IN}$ Current vs Time for Run #3

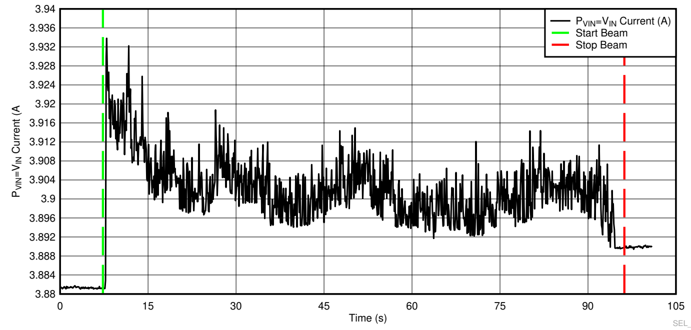


Figure 7-2. Typical Current vs Time Plot for a Non-destructive Run of the TPS7H4001-SP at T = 125°C

$P_{VIN} = V_{IN}$ Current vs Time for Run # 6

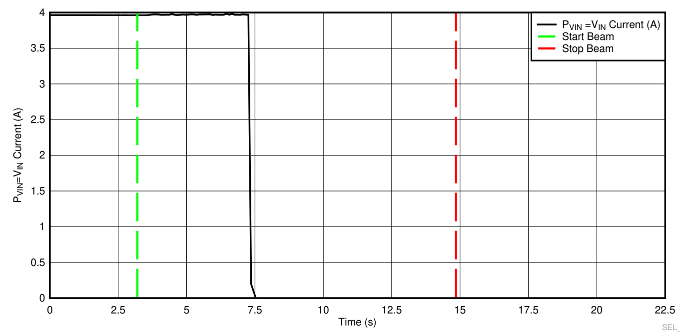


Figure 7-3. Typical Current vs Time Plot for a Destructive Run of the TPS7H4001-SP at T = 125°C

7.3 Single-Event-Burnout (SEB) and Single-Event-Gate-Rupture (SEGR) Results

SEB and SEGR data was collected at temperatures from 20 to 60°C, full load (18 A), $P_{VIN} = V_{IN}$ = 7 V (maximum recommended voltage), and $V_{OUT} \approx 1$ V at LET_{EFF} of 66.37to 75.82 MeV·cm^{2}mg. The device was tested under Enabled and Disabled Modes. The discrete power resistive load of 55 mΩ, was present at all times, even during the disabled testing. The load was connected to help identify if an momentary upset enabled the device. **During the disabled testing not a single unit was damaged, or an increment on current observed.** It has been shown that SEB/SEGR sensitivity decrements with higher temperatures and for that reason runs 59, 61, 63, and 69 the devices were cooled down by using a vortex tube aimed at the die.

The device was exposed to Praseodymium (^{141}Pr) and Holmium (^{165}Ho) ions. For ^{141}Pr angles of incidence of 0° and 27.3° were used for an LET_{EFF} of 66.37 and 74.95 MeV·cm^2/mg, respectively. ^{165}Ho at angle of incidence of 0° was used for an LET_{EFF} of 75.82 MeV·cm^2/mg. For Praseodymium the air distance between the heavy-ion exit port and the DUT was set to 40-mm. In the case of Holmium the distance was set to 30-mm. Flux of ≈10^5 ions/cm^2·s and fluence of ≥ 10^7 ions/cm^2 per run were used for the SEB/SEGR characterization. Run duration to achieve this fluence was approximately 2 minutes. Test conditions and results are summarized in Table 7-4.

The TPS7H4001-SP is DSEE free when operated withing the DSEE-free (green) area under the SOA curve presented in Figure 7-1. For more details on the DSEE cross section refer to Section 7.1.

Table 7-4. Summary of the TPS7H4001-SP SEB/SEGR Test Conditions and Results

All data discussed in this table was collected at 18-A load current.

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm2 / mg)	Flux (ions/cm2 ·s)	Fluence (ions/cm2)	P_{VIN}=V_{IN} (V)	Enabled	Damage?
58	1	^{165}Ho	0	75.82	1.11E+05	1.00E+07	7	Yes	No
59	1	^{165}Ho	0	75.82	1.10E+05	1.00E+07	7	No	No
60	5	^{165}Ho	0	75.82	9.38E+04	1.00E+07	7	Yes	No
61	5	^{165}Ho	0	75.82	9.88E+04	1.00E+07	7	No	No
62	6	^{165}Ho	0	75.82	9.43E+04	9.99E+06	7	Yes	No
63	6	^{165}Ho	0	75.82	1.09E+05	9.97E+06	7	No	No
64	10	^{141}Pr	0	66.37	1.20E+05	9.99E+06	7	Yes	No
65	11	^{141}Pr	27.3	74.95	1.05E+05	1.00E+07	7	Yes	No
66	12	^{141}Pr	27.3	74.95	1.42E+05	2.60E+06	7	Yes	Yes
67	13	^{141}Pr	27.3	74.95	9.66E+04	1.00E+07	7	Yes	No
68	14	^{141}Pr	27.3	74.95	1.05E+05	1.00E+07	7	Yes	No
69	15	^{141}Pr	27.3	74.95	1.14E+05	1.00E+07	7	Yes	No

8 Single-Event Transients (SET)

SET are defined as heavy-ion-induced transients upsets on the V_{OUT}, SS, and the PWRGD flag of the TPS7H4001-SP. SET testing was performed at room temperature (no external temperature control used), using Praseodymium (^{141}Pr) and Holmium (^{165}Ho) heavy-ions. For ^{141}Pr ion angles of incidence of 0° and 27.3° were used for an LET_{EFF} of 66.37 and 74.95 MeV·cm^2/mg, respectively. ^{165}Ho ion at angle of incidence of 0° was used for an LET_{EFF} of 75.82 MeV·cm^2/mg.

V_{OUT} SETs were characterize using a window trigger of ±3% (±30 mV) around the nominal output voltage (≈1 – V). The devices were characterize under P_{VIN} = V_{IN} = 5 and 7 V. The output load was set to 18 A for all runs by using a discrete power resistor of 55 mΩ. The DPO7104C was used for the characterization of the V_{OUT} transients. The output voltage was monitored by using the cold nose probe (J8). Sample rate of 20 MS/s and time of 200 µs/div (total of 2 ms) and 2 ms/div (total of 20 ms) were used during the characterization. For runs 80 and 90, the trigger signal used for the characterization was changed from V_{OUT} to soft start to validate the fact that at room temperature any SS_{SET} upset was observed. Even in the cases when the trigger signal was V_{OUT}, this kind of upset (SS_{SET}) can be identified since the voltage drops near zero and has a long transient recovery time. **It is important to note that no upset of this kind (SS_{SET}) was observed during the SET or the SEB/SEGR testing.** The vertical division of the DPO was optimized to minimize noise while having enough dynamic range to capture the upsets magnitude without saturation. The scope bandwidth was set to 20 MHz for all the data collection. The vertical division use during the SET characterization of the TPS7H4001-SP was between 10 and 20 mV/div. DC coupling with vertical offset and AC coupling was used as part of the data collection. Test conditions and results for the SET characterization of the TPS7H4001-SP are shown in Table 8-1 and Summary of the TPS7H4001-SP SET Test Conditions and Results at P_{VIN} = V_{IN} = 5 V.

It was observed that the numbers of upsets at V_{OUT} decrement with P_{VIN} = V_{IN} voltage for that reason the worst case (7 V) and typical rail voltage of 5 V were used for the characterization. All the observed upsets were positive on polarity. While most of the upsets were fast on the recovery time (between 10 µs to 22 µs), a total of 4 upsets with slow recovery time (in the milliseconds range) were observed. Transient time was calculated using the full-width-half-medium (FWHM) method. This method measure the time the output voltage takes pass by half of the maximum voltage for the given upset. The histogram of all recorded upsets is shown in Figure 8-1. A histogram of the normalized maximum voltage for all recorded upsets is shown on Figure 8-2. As can be observed most of the upsets are bounded between 3% and 5% with two upsets that have higher values than the typical or outlier. These upsets correlate with upsets that have long transient time. Time domain plots for typical V_{OUT} upsets are shown in Figure 8-3 and Figure 8-4, for the slow and fast transient time, respectively.

PWRGD SETs were characterized by monitoring the signal using the TP23 test point on the EVM. An edge-negative trigger with trigger value set to half the P_{VIN} = V_{IN} voltage was used for the characterization. For runs # 80-81 and #88-92, a low pass filter (R-C) was installed on the EVM to mitigate the SETs on the PWRGD signal. The resistor R47 was set to 1.15 kΩ while the capacitor C118 was set to 1 nF for the filter. As can be observed, the filter concept is a viable option since most of the $PWRGD_{SET}$ were filtered during this runs. A typical PWRGD SET is shown in Figure 8-5.

The upper-bound cross section at 95% confidence interval values is shown in Table 8-3 (see SLVK047 for more details in the method used to calculate the upper bound cross section).

Table 8-1. Summary of the TPS7H4001-SP SET Test Conditions and Results at P_{VIN} = V_{IN} = 5 V

At P_{VIN} = V_{IN} = 5 V, not a single unit was damaged.

During run # 80 the trigger signal was changed from V_{OUT} to SS

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2 / mg)	Flux (ions/cm^2 ·s)	Fluence (ions/cm^2)	-3% ≤ V_{OUT} ≤3% (from the Nominal Voltage)	PWRGD ≤ (V_{IN}/2)	$PWRGD_{FILTERED}$ ≤ (VIN/2)
70	11	^{141}Pr	0	66.37	1.13E+05	1.00E+07	0	23	Not Installed
71	13	^{141}Pr	0	66.37	1.01E+05	1.00E+07	0	17	
72	22	^{141}Pr	0	66.37	9.21E+04	1.00E+07	0	21	
73	23	^{141}Pr	0	66.37	9.39E+04	9.95E+06	0	23	
74	21	^{141}Pr	27.3	74.95	1.09E+05	9.98E+06	0	17	
75	21	^{141}Pr	27.3	74.95	8.86E+04	1.00E+07	0	32	
76	21	^{141}Pr	27.3	74.95	1.06E+05	9.98E+06	0	17	
77	21	^{141}Pr	27.3	74.95	1.31E+05	1.00E+07	0	19	
78	22	^{141}Pr	27.3	74.95	8.89E+04	1.00E+07	0	19	
79	23	^{141}Pr	27.3	74.95	9.73E+04	1.00E+07	0	21	
80	7	^{165}Ho	0	75.82	1.01E+05	1.01E+07	0$^{(Trigger=SS)}$	0	0
81	7	^{165}Ho	0	75.82	8.54E+04	9.95E+06	0	0	0

Table 8-2. Summary of the TPS7H4001-SP SET Test Conditions and Results at P_{VIN} = V_{IN} = 7 V

N/A in numbers of Upset on VOUT column, means the scope was not used for the specific run. N/A in the $PWRGD_{FILTERED}$ column means the low pass filter was not installed, during the run.

During run # 90 the trigger was changed from V_{OUT} to SS.

Run #	Unit #	Ion Type	Angle of Incidence (°)	LET_{EFF} (MeV·cm^2 /mg)	Flux (ions/cm^2 ·s)	Fluence (ions/cm^2)	Damage?	-3% ≤ V_{OUT} ≤3% (from the Nominal Voltage)	PWRGD ≤ (VIN/2)	$PWRGD_{FILTERED}$ ≤ (VIN/2)
82	13	^{141}Pr	0	66.37	9.75E+04	1.00E+07	No	3	7	N/A
83	22	^{141}Pr	0	66.37	1.06E+05	1.00E+07	No	8	4	N/A
84	23	^{141}Pr	0	66.37	9.34E+04	9.96E+06	No	9	7	N/A
85	21	^{141}Pr	27.3	74.95	1.45E+05	9.96E+06	No	33	6	N/A
86	22	^{141}Pr	27.3	74.95	1.03E+05	9.99E+06	No	21	3	N/A
87	23	^{141}Pr	27.3	74.95	9.46E+04	9.97E+06	No	37	1	N/A
88	1	^{165}Ho	0	75.82	1.15E+05	2.94E+06	Yes	N/A	1	0
89	7	^{165}Ho	0	75.82	1.12E+05	1.00E+07	No	39	6	1
90	7	^{165}Ho	0	75.82	1.11E+05	1.01E+07	No	0$^{(Trigger=SS)}$	1	0
91	8	^{165}Ho	0	75.82	1.11E+05	6.41E+06	Yes	31	4	1
92	9	^{165}Ho	0	75.82	8.59E+04	4.63E+06	Yes	23	0	0

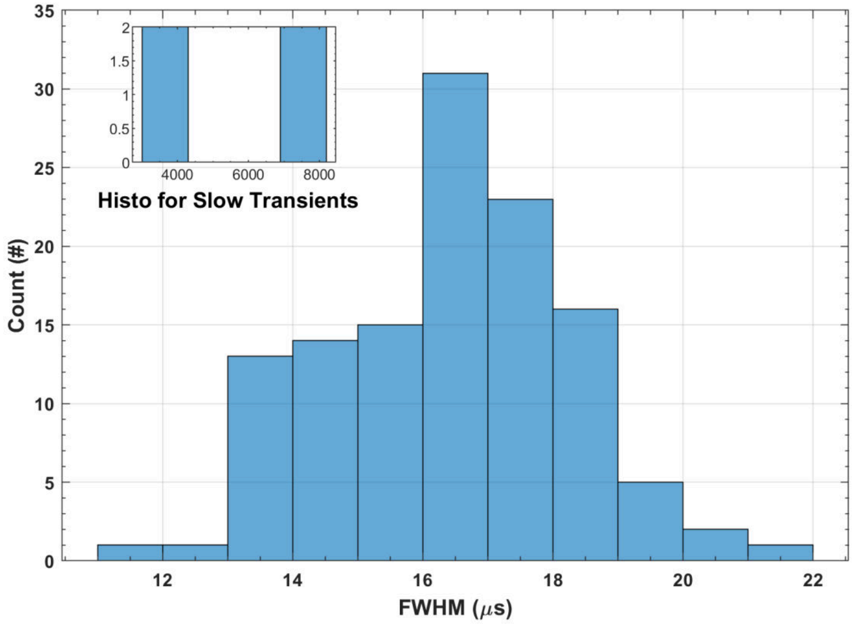


Figure 8-1. Histogram of the Transient Time for All Upset SETs

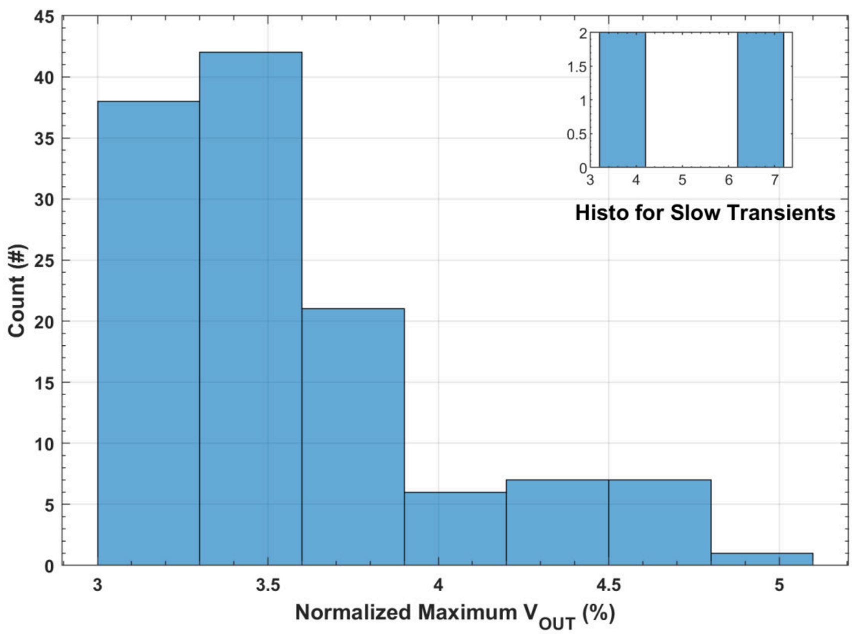


Figure 8-2. Histogram of the Normalized Maximum Voltage for All Observed SETs

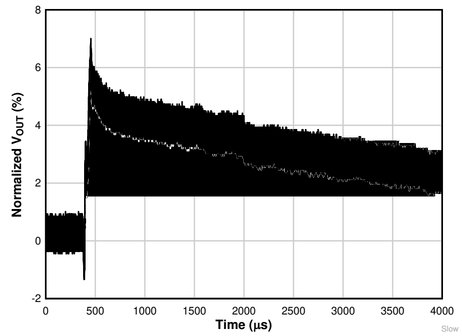


Figure 8-3. Long (Slow) Transient Time Upset on V_{OUT}

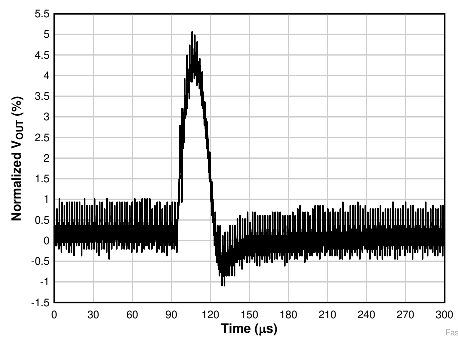


Figure 8-4. Typical (Fast) Upset on V_{OUT}

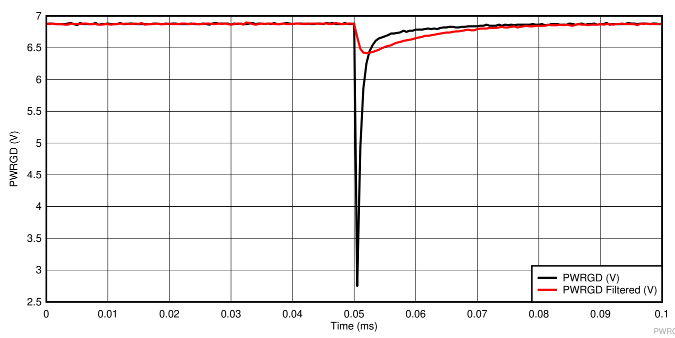


Figure 8-5. Typical PWRGD Upset With and Without Filtering

Table 8-3. Upper Bound Cross-Section for VOUT and PWRGD SETs

For this table, the runs for ^{141}Pr at Angle of Incidence of 27.3° and ^{165}Ho were combined (both considered as 75 MeV).

LET_{EFF} (MeV·cm^2/mg)	P_{VIN} = V_{IN} (V)	# of V_{OUT} ≥ |3%| Upsets	V_{OUT} Cross-Section (≥ |3%|) [cm^2/device]	# of PWRGD ≤ VIN / 2 Upsets	PWRGD Cross-Section (≤ VIN / 2) [cm^2/device]
66.37	5	0	9.21×10^{-8}	84	2.6×10^{-6}
75		0	5.27×10^{-8}	125	1.86×10^{-6}
66.37	7	20	1.03×10^{-6}	18	9.47×10^{-7}
75		184	4.17×10^{-6}	22	5.21×10^{-7}

9 Summary

The purpose of this report is to summarize the SEE data collected on RHA units of the TPS7H4001-SP. The data shows the TPS7H4001-SP is DSEE-free when operated within the safe area of the SOA curve. Also the SET characterization on the output voltage and the PWRGD signal is presented and discussed.

10 Total Ionizing Dose (TID) From SEE Experiments

The production TPS7H4001-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 ≈10 krad(Si) per 10^7 ions/cm^2 run. The cumulative TID exposure, for each device respectively, was always controlled to be less than 100 krad(Si). With the exception of the 17 units that were deliberately operated outside the SOA in an effort to capture the onset of DSEE, all 20/37 production RHA TPS7H4001-SP devices used in the studies described in this report stayed within specification and were fully-functional after the heavy-ion SEE testing was completed.

11 References

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12 Revision History

Changes from Revision A (November 2020) to Revision B (December 2021)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document [illegible]	1 / 6

Changes from Revision B (December 2021) to Revision C (May 2023)	Page
• Added text to *Abstract*	1
• Added *Photograph of the Delidded TPS7H4001-SP (SHP) [Left] and a Pin-Out Diagram [Right]*	6

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