Application Report
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TVS Surge Protection in High-Temperature Environments

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ABSTRACT

To ensure reliability during events like power switching, hot plugs, lightning, and various other fault situations, systems must account for surge protection; however, most common surge-protection TVS diodes have significant variation over temperatures that is rarely accounted for. This variation can lead to failures in released products that were not seen in lab testing; to minimize these failures, TVS diode performance must be understood and accounted for. This report examines the temperature variation in conventional SMA and SMB type TVS diodes and compares them to the *TI Flat-Clamp* surge protection, and then shows laboratory testing in a real-world system that highlights the improved high-temperature performance of the TI Flat-Clamp devices.

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1 Introduction

It is essential to have robust protection for systems in environments where lightning strikes, switching of power systems, load changes, or hot pluggable interfaces are present. The most common approach for surge protection is to use transient voltage suppressor (TVS) diodes to clamp fault voltages to a safe level at the input to the system.

However, it is not easy or straightforward to choose the best diode for a system, especially in high-temperature environments. Usually TVS diodes have high clamping voltages, wide temperature variation, and significant performance degradation over their operating temperature range. To make matters more difficult, TVS diode data sheets rarely discuss or specify their performance at any temperature but 25°C, leaving the system designer to either guess or run time consuming tests to verify their system is protected over their operating temperature range.

TI has designed a new clamp technology to protect against transient surge events that helps to ensure robust protection against a wide temperature range. TI`s Flat-Clamp technology provides a solution to dissipate surge transients while simultaneously providing a precise, flat-clamping voltage across –40°C to 125°C which minimizes residual voltage to the protected system.

The surge-protection capabilities of this new technology are tested and evaluated in this application note and compared to a traditional TVS device. During the tests, a surge pulse is introduced to a system which is protected by each type of protection device and the results are compared to show that the TI Flat-Clamp device provides better protection for interfaces in harsh environments.

2 Surge Protection Considerations

2.1 TVS Diodes Specifications

In noisy environments, engineers design their systems to pass the IEC 61000-4-5 standard for system-level surge immunity which defines the test setup and procedures for surge immunity testing. Compared to ESD events, which are covered by the IEC 61000-4-2 standard, surge events (which usually occur during power system switching transients or lightning discharge scenarios) have 200 times longer pulse durations and much higher energy.

For details about the IEC electromagnetic compatibility (EMC) standards and related testing, see *IEC 61000-4-x Tests for TI's Protection Devices* .

Protection against surge transients is typically done by a TVS diode on the input of the interface. Designers must work around the limitations and constraints imposed by their TVS protection stage to ensure reliable operation and protection. The TVS breakdown voltage, V_{BR}, defines the applied voltage where the TVS begins to conduct current. During a fault event, the TVS diode will shunt significant amounts of current to ground up to the maximum TVS pulse current of I_{PP}, causing the voltage across the device to increase above V_{BR} due to the intrinsic dynamic resistance (R_{DYN}) of the diodes. This additional voltage must be considered when protecting your system. The voltage which is seen by downstream devices during a surge event is V_{CLAMP} and is calculated using Equation 1.

$$V_{CLAMP} = V_{BR} + I_{PP} * R_{DYN} \tag{1}$$

For the most reliable operation, the maximum V_{CLAMP} of a TVS diode should be below the absolute maximum rating of the downstream device. Any condition violating the absolute maximum ratings results in a risk of damaging the component.

These defined voltage levels are illustrated in Figure 1:

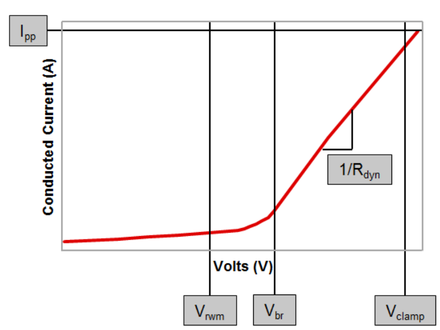

Figure 1. Stand-off, Break Down and Clamp Voltage

The R_{DYN} of conventional TVS diodes is generally high, producing a V_{CLAMP} significantly above V_{BR}. To ensure a robust system, designers must use components tolerant to the high V_{CLAMP} voltages or find TVS diodes with much lower R_{DYN}. Both solutions have problems; the first results in bigger and more expensive system components and the latter results in TVS diodes with higher leakage, capacitance, footprints, and cost.

2.1.1 Process and Temperature Variation

In addition, over process and temperature, V_{BR} and V_{CLAMP} vary significantly. Process variation is usually specified in device data sheets, while temperature variation can usually be calculated based on Equation 2. However, when αT, the thermal coefficient, is not determined in the data sheet, temperature variation cannot be calculated.

$$V_{BR@Tj} = V_{BR@25°C} \times (1 + \alpha T \times (T_j - 25)) \quad (2)$$

Figure 2 illustrates the shift in the I/V curve over process and junction temperature (T_j) for the SMAJ33A TVS diode. The green region below V_{RWM} is the region used for nominal system input voltages. The red region illustrates margin that is required by the system for robust protection during a surge event. In this region, the system cannot nominally operate; however, it must be tolerant to these voltages. The dashed vertical purple line is the maximum voltage the protected system could detect during a surge event.

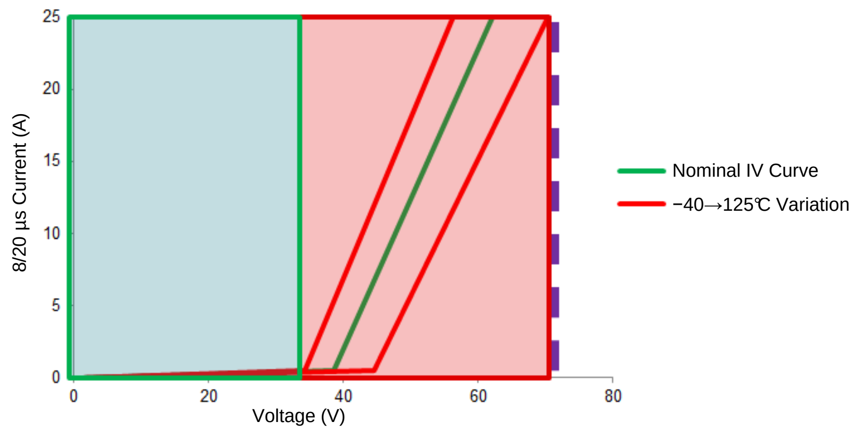

Figure 2. Process and Temperature Variation on SMAJ33A

The SMAJ33A nominal I-V curve is represented by the green curve with a V_{BR} of 39 V and a V_{CLAMP} of 60 V. The red curves illustrate the maximum I/V curve spread over process and temperature. As illustrated in Figure 2, at 125°C V_{CLAMP} extends to nearly 70 V while at –40°C V_{BR} drops to 34 V. Accommodating these shifts requires designing in extra margin to the system, increasing cost and complexity even further from nominal TVS operation.

2.1.2 Temperature Derating

In addition to the deviation in V_{BR} and V_{CLAMP}, TVS diodes often suffer from severe temperature derating in their surge performance. The IEC 61000-4-5 surge standard requires testing only at 25°C, but in reality, surge events occur with the same probability at higher temperatures as at room temperature. Figure 3 shows the temperature derating of the Littelfuse® SMAJ33A. The maximum dissipated current at 25°C is 33 A; however, the device current dissipation derates significantly over temperature until at 125°C the dissipation level drops to 6.6 A.

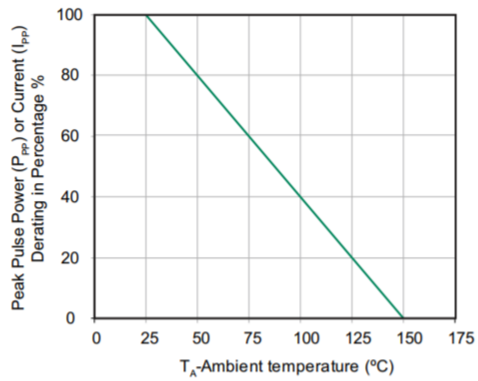

Figure 3. Littelfuse® SMAJ33A Series Temperature Derating

Table 1. SMAJ33A Temperature Derating Table

Temperature	MAX I_{PP} Dissipation
25°C	33 A
75°C	19.8 A
105°C	13.2 A
125°C	6.6 A

This is one reason why a system that passes IEC testing at room temperature can still see field failures. System designers must take into account their protection stages derating over temperature.

2.2 TI's Flat-Clamp Technology

To attempt to simplify protection stage design, TI has developed Flat-Clamp technology that offers much improved performance in harsh environments. The Flat-Clamp technology offers a solution for designers who need precise, reliable clamping performance even under rough environmental conditions. Figure 4 shows the functional block diagram of the technology. The primary difference between TI's Flat-Clamp technology compared to conventional TVS diodes is that in Flat-Clamp devices, the surge current is clamped by an active FET with a feedback loop (as shown in Figure 4) rather than clamped by a passive diode.

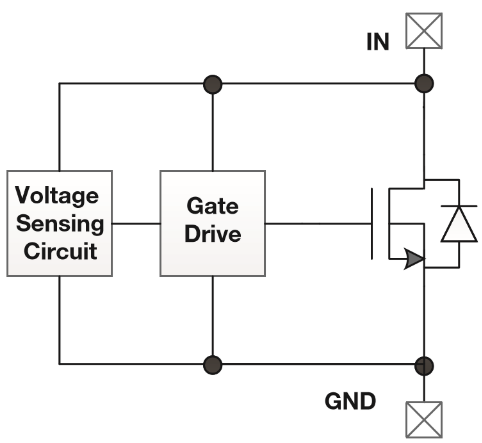

Figure 4. Functional Block Diagram of the Flat-Clamp Technology

This improved topology allows for significantly lower R_{DYN}, and therefore V_{CLAMP}, than conventional TVS diodes. Figure 5 shows clamping waveforms at 30 A, compared between a conventional TVS diode (SMF33A and TI`s TVS3300 Flat-Clamp diode.)

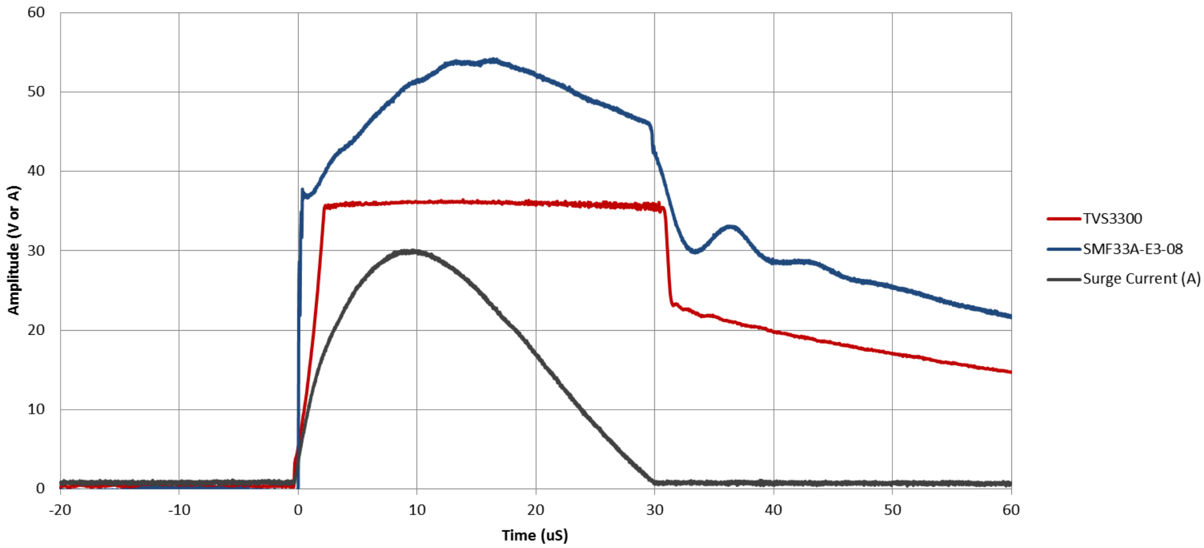

Figure 5. 8/20 µs Surge Clamping Waveform of Flat-Clamp Diode vs. Conventional TVS Diode

In addition, over temperature the R_{DYN} of the Flat-Clamp device has minimal variation compared to conventional R_{DYN} of the TVS, which helps to improve design reliability and simplify system design.

For more detail on the Flat-Clamp family operation and system advantages, see TI's *Flat-Clamp surge protection technology for efficient system protection* .

3 System Surge Protection Example

In this section, an example of a real world situation is highlighted where the TI Flat-Clamp device improves system robustness.

In this example, input protection is needed for a TPS7A4901 Low Dropout Voltage Regulator in a 4–20 mA loop input design. The equipment operates in an environment where the temperature can reach 85°C and according to the IEC 61131-2 standard for industrial PLCs, the equipment must survive a ±1-kV surge pulse through a 42-Ω impedance (the waveform is defined by IEC 61000-4-5), generating close to 24 A of surge current. The TPS7A4901 is a positive linear regulator with an input voltage range of 3–35 V and an absolute maximum applied voltage to the IN pin of 36 V.

To ensure reliability, it is best to ensure that the clamping voltage stays as close to the 36 V absolute maximum input voltage of the low dropout (LDO) as possible. Because the event is a short transient, a voltage slightly above the absolute maximum is unlikely to harm the system; however, a clamping voltage significantly above the absolute maximum input voltage will cause failures even with the short transient length. Satisfying this condition during a fault event can be simple at 25°C, but, as the temperature increases, the I-V curve of a conventional TVS device will shift higher, increasing V_{CLAMP} and leading to reliability problems. The diode will also derate, lowering its ability to dissipate fault energy.

3.1 TVS Diode Specifications

TVS manufacturers specify characteristics like I_{PP} or V_{CLAMP} in the data sheet at room temperature; however, there is rarely information about higher temperature operation. For example, the SMAJ33A data sheet varies by vendor, but generally only specifies the data sheet at T_A = 25°C with rarely any indication of the performance as the temperature rises. An experienced designer will have an understanding of how the parameters can be expected to shift, but an inexperienced designer can easily overlook that a shift will occur. Even an experienced designer must estimate, often leading to over-designed systems.

In contrast, TI's Flat-Clamp devices specify performance over the operating temperature range of the device. Designers can confidently predict the clamping performance of the device even at high temperature, leading to more efficient system design.

In this example, the performance between the TI TVS3300 and a competitor SMAJ33A is compared, an industry standard device for this type of application. Because the SMAJ33A does not have performance specified over temperature, testing is required to ensure robustness.

3.2 Test Setup

The test setup is a modified TPS7A4901EVM which is adjusted by adding an external protection diode as shown in Figure 6, where U2 is the TPS7A49 LDO and the input TVS diode is highlighted. The input TVS is tested with both a SMAJ33A TVS diode and a TVS3300 to compare the performance during a fault event.

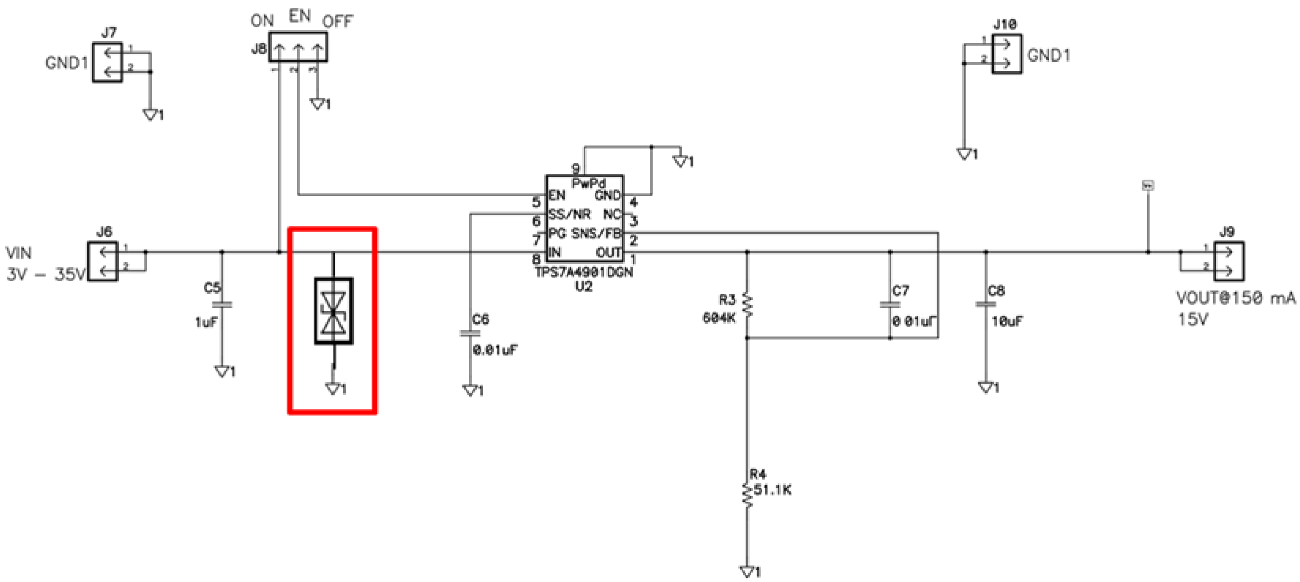

Figure 6. Modified TPS7A4901DGN EVM Schematic

Figure 7 shows the SMAJ33A with a footprint area of 13 mm^2 and Figure 8 shows the TI TVS3300 (on an adapter board) with a footprint of 1.2 mm^2. These adapter boards are designed to enable testing of the WCSP or SON packages on existing industry standard SMA or SMB footprints, for ease of evaluation without a new PCB layout. The diode and TVS3300 adapter board are soldered on top of the 1-µF input capacitors of the TPS7A49. Other than the TVS, the two boards are identical.

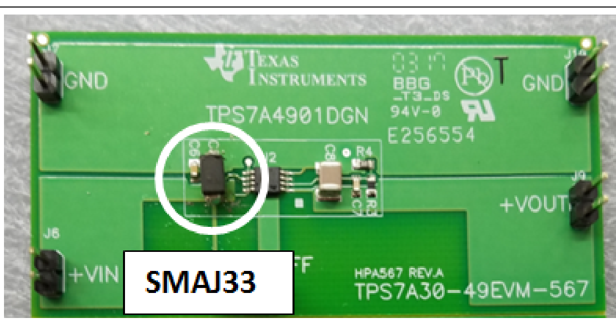

Figure 7. TPS7A4901DGN with SMAJ33A on the Input Voltage Line

Figure 8. TPS7A4901DGN with TVS3300 on the Input Voltage Line

The overall test setup is shown in Figure 9, where the design under test (DUT) in question is the modified TPS7A49EVM.

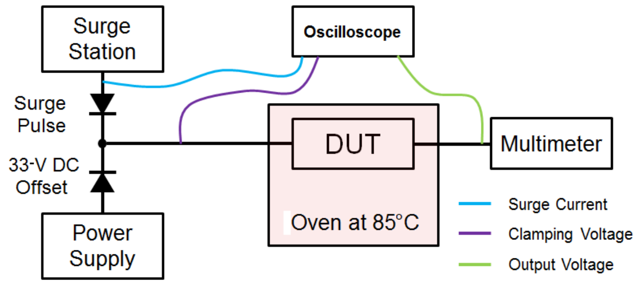

Figure 9. Test Setup Block Diagram

The DUT is heated under a thermal stream to 85ºC to simulate the high-temperature operating region. A DC offset voltage is applied to the TPS7A49 input to simulate standard operating conditions and a surge generator is used to generate the IEC 61000-4-5 surge pulse. An oscilloscope is used to measure the input current of the surge pulse, the clamping voltage, and the TPS7A49 output voltage. For redundancy, a multimeter is used to monitor the output voltage of the LDO.

3.3 Test Results

The DUT is placed in a 85ºC environment and exposed to surge events of increasing energy until a failure occurs. Figure 10 shows that, when protected with the SMAJ33A, the TPS7A49 breaks during a test of 8.38-A surge current and a V_{CLAMP} of 42.16 V. This is well below the required 24 A of surge immunity, showing that at this temperature range, the SMAJ33A cannot protect effectively, despite the data sheet nominal specifications. The failure occurs because the SMAJ33A high R_{DYN} causes poor regulation of the voltage during the surge, causing a rise to 42 V which is significantly above the 36 V absolute maximum of the TPS7A49 device.

However, during the same surge with the TVS3300, the V_{CLAMP} is 37.2 V and no harm is seen to the TPS7A49. This waveform is shown in Figure 11. Because this voltage is very close to the maximum input voltage rating of the TPS7A49 and the duration of the transient is short, there is no damage to the TPS7A49. In the waveforms, the blue curve is the current caused by the surge event, the purple curve is the voltage measured at the TPS7A49 input, and the green curve is the TPS7A49 output voltage.

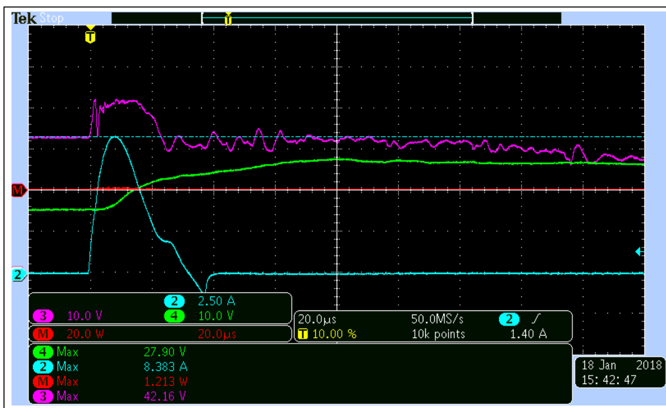

Figure 10. SMAJ33A Protection at 8.38 A at 85°C

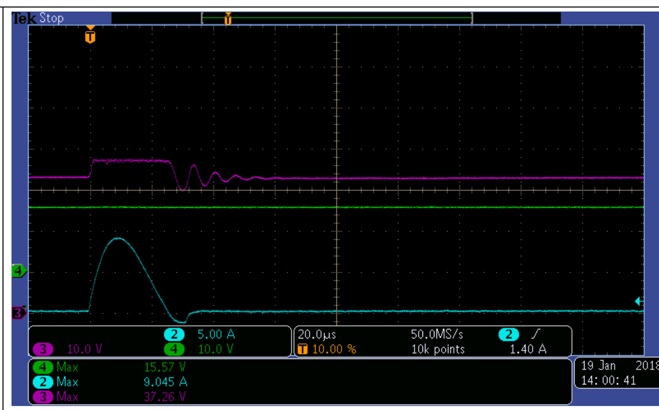

Figure 11. TVS3300 From TI Protection at 9 A at 85°C

By continuing to increase the output of the surge generator, it is found that the TVS3300 enables protection of up to four times more surge current than the SMAJ33A. Figure 12 shows the TVS3300 protecting at the required 24 A of surge current, and Figure 13 shows the final passing level of the TVS3300 at 33.7 A. These results show that the TVS3300 provides significant margin to pass the required surge test, even in high-temperature environments. In addition, there is no shift in the TPS7A49 output voltage during the surge event, showing that the TVS3300 can enable protection without disruption to normal system operation.

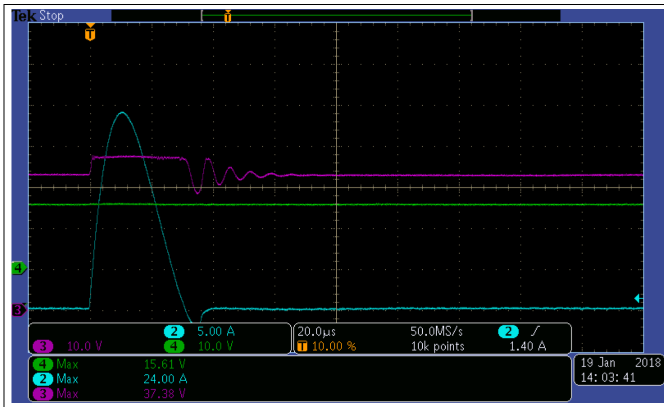

Figure 12. TVS3300 Clamping Waveform at 24 A at 85ºC

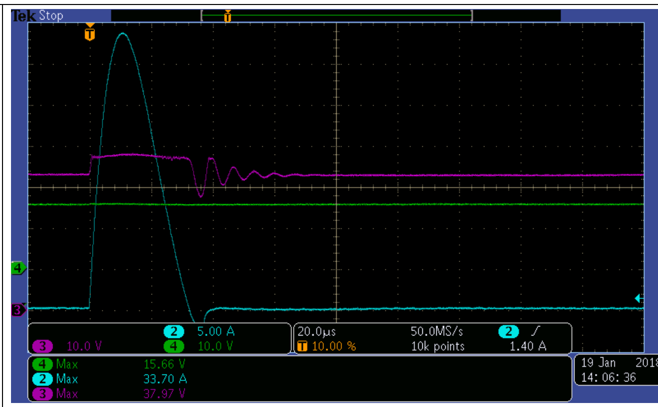

Figure 13. TVS3300 Clamping Waveform at Last Passing Current at 85ºC

It is clear that the Flat-Clamp TVS3300 provides more robust protection for the input to this piece of equipment than conventional TVS diodes. The very low R_{DYN} of the TVS3300 enables using the 36-V absolute maximum LDO. If a traditional TVS diode is used, the selected TPS7A49 device must be swapped with a device that is rated for 60 V or higher input tolerance, increasing cost and complexity of the design.

4 Summary

Unlike conventional TVS diodes, the TI Flat-Clamp devices enable robust protection in high-temperature, harsh EMC environments. Conventional TVS diodes have poor, difficult-to-predict performance at higher temperatures and can lead to system failures that are not seen during lab testing. For proper input protection design with conventional TVS diodes, additional margin and time-consuming lab characterization is required. However, TI Flat-Clamp diodes guarantee minimal performance shift over temperature and provide an easy solution for designers to ensure long system lifetimes.

TI offers several voltage options in the Flat-Clamp family as shown in Table 2

Table 2. TI Unidirectional Flat-Clamp Devices

Device	V_{rwm}	V_{clamp} at I_{pp}	I_{pp} (8/20 µs)	V_{rwm} leakage (nA)	Package Options	Polarity
TVS0500	5	9.2	43	0.07	SON	Unidirectional
TVS1400	14	18.4	43	2	SON	Unidirectional
TVS1800	18	22.8	40	0.5	SON	Unidirectional
TVS2200	22	27.7	40	3.2	SON	Unidirectional
TVS2700	27	32.5	40	1.7	SON	Unidirectional
TVS3300	33	38	35	19	WCSP, SON	Unidirectional

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