Transient Voltage Suppressors: Operation and Features

Introduction

Modern Transient Voltage Suppressors (TVS) or TVS diodes are the most commonly utilized protection components in data transmission systems due to their fast response time, low clamping voltage, and longevity. These solid state P-N junction devices are specifically designed to protect sensitive semiconductors from the damaging effects of transient overvoltages.

TVS diodes are parallel protection elements. Under normal operating conditions they are high-impedance, appearing as an open circuit to the protected component, although a small amount of leakage current is present. During a transient event, the TVS diode junction avalanches providing a low-impedance path for the transient current. Thus, the transient current is diverted away from the protected component and shunted through the TVS diode to ground. The voltage across the protected device is limited to the clamping voltage of the TVS. Once the transient has passed, the TVS returns into high-impedance state.

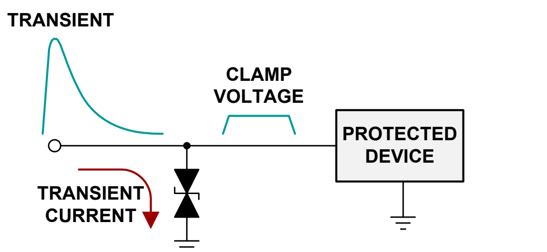

FIGURE 1. TVS SHUNTS PROTECTED DEVICE DURING TRANSIENTS

TVS diodes neither wear out nor degrade parametrically as long as they are operated within specified limits. This robustness along with fast response time and low clamping voltage make TVS diodes ideal for use as board level protectors for RS-485 bus nodes.

The electrical characteristics of TVS diodes are determined by factors such as junction area, doping concentration and substrate resistivity. Their power and surge capability are proportional to the junction area. TVS diodes are constructed with large cross sectional area junctions for absorbing high transient currents. While the I-V characteristic is similar to that of a Zener diode, TVS diodes are specifically designed, characterized and tested for transient suppression, unlike Zener diodes, which are designed and specified for voltage regulation.

TVS diodes are available in a wide range of device structures, operating voltages and junction capacitances. Legacy devices often present single TVS designs for unidirectional or bidirectional operation, with operating voltages from 5V to 440V and junction capacitance of up to 1000pF. Modern TVS designs range from single diodes to diode arrays, can operate down to 2.8V, and possess low junction capacitances of as little as 3pF, thus enabling the transient protection of every single bus node.

Unidirectional TVS Devices

The most basic TVS design is that of a unidirectional TVS diode, shown in Figure 2. Here the TVS diode is reverse-biased during a positive transient. The TVS acts in avalanche mode as the transient current I_1 flows. The spike is clamped at or below the maximum clamping voltage of the device.

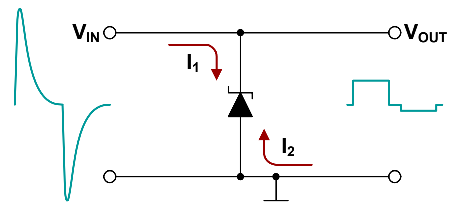

FIGURE 2. CLAMPING ACTION OF A UNIDIRECTIONAL TVS

During the negative transient, the TVS diode is forward-biased and the spike is clamped to one diode drop as the device conducts I_2 in the forward direction.

The V-I characteristic of a unidirectional TVS diode is shown in Figure 3. Because the TVS diode is reverse-biased for positive transient voltages, the V-I characteristic for this mode is drawn in the first quadrant of the diagram.

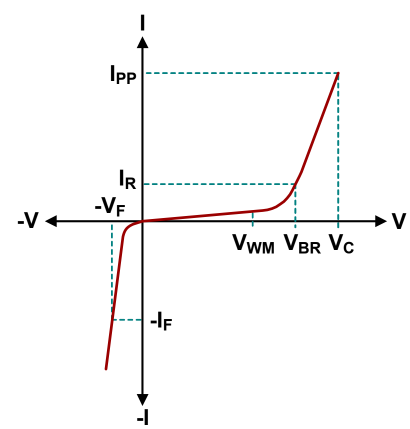

FIGURE 3. V-I CHARACTERISTIC OF A UNIDIRECTIONAL TVS

Here, V_{WM} is the TVS standoff voltage at which the device draws a leakage of maximum 1µA. Thus, V_{WM} is also the maximum possible line voltage of the application up to which the TVS operation does not impact the performance of the protected circuit. The breakdown voltage, V_{BR}, is the voltage where the TVS starts conducting and a TVS current of 1mA flows. V_C is the maximum TVS clamping voltage measured across the device during the application of a pulse current, I_{PP}, for a specified waveform, such as an 8/20µs or 10/1000µs transient pulse.

For negative transient voltages the TVS is forward biased. The V-I characteristic for this mode is therefore shown in the third quadrant. Here, V_F is the forward voltage measured across the device for a specified forward current, I_F.

Unidirectional TVS diodes are used across DC power and DC signal lines to protect CMOS components which are highly vulnerable to negative transient voltages below their ground (0V) reference level.

Bidirectional TVS Devices

A bidirectional TVS diode, shown in Figure 4, is reverse biased during both positive and negative transients. Thus, the TVS always acts in Avalanche mode as the transient currents I_1 or I_2 flow. Positive and negative transient voltages are clamped at or below the maximum clamping voltages of the device.

During the positive transient, D_1 conducts in the forward direction and D_2 is reverse biased conducting in avalanche mode. The action is reversed during the negative transient.

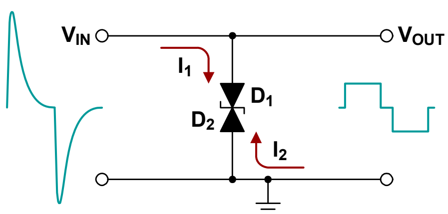

FIGURE 4. CLAMPING ACTION OF A BIDIRECTIONAL TVS

The V-I characteristic of most bidirectional TVS diodes is symmetrical as shown in Figure 5. Bidirectional TVS diodes are used to protect components with symmetric, positive and negative supply rails, and data lines operating over extended common-mode voltage ranges.

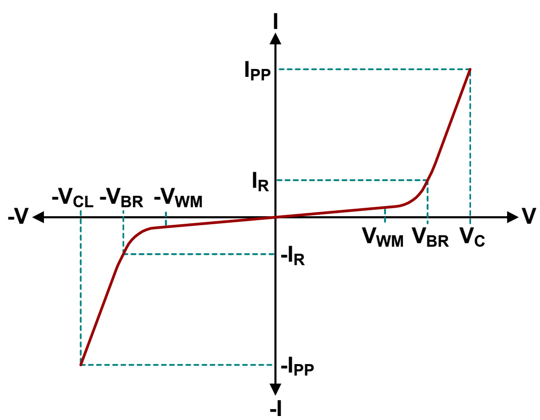

FIGURE 5. V-I CHARACTERISTIC OF A BIDIRECTIONAL TVS

TVS Peak Pulse Power vs Pulse Duration

The peak-pulse power ratings of integrated TVS devices designed for surge suppression ranges from 200W up to 15kW. Most of these devices are rated for the long 10/1000µs current waveform used in telecom applications. Surge tests applied to RS-485 networks however, utilize the much shorter 8/20µs pulse. Therefore, intuitively a TVS rated for a long pulse width should be able to tolerate significantly more power over a much shorter pulse width.

To easily convert the peak-pulse power level from one pulse width to another, TVS datasheets provide a pulse-power versus pulse-width characteristic. An example of a curve for a TVS rated at 200W for a 10/1000µs pulse is shown in Figure 6.

To determine the TVS peak power for an 8/20µs pulse, we start from the initial 200W power level at the 1000µs mark (A), and follow the power rating curve to the 20µs mark (B). Moving horizontally to the left axis yields the new peak pulse power of 0.95kW.

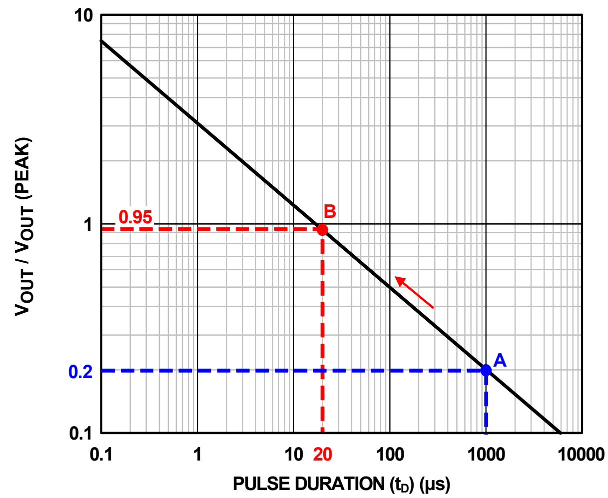

FIGURE 6. PEAK PULSE POWER vs PULSE DURATION

To determine the corresponding peak-pulse current, the new peak-pulse power is divided by the TVS peak clamping voltage, which, according to TVS manufacturers, can be assumed constant for all pulse durations.

The datasheet for the TVS in Figure 6 specifies its peak clamping voltage with 21.5V, thus yielding a peak pulse current of 200W/21.5V = 9.3A for the 10/1000µs waveform. For the much shorter 8/20µs waveform, the new peak pulse current is 950W/21.5V = 44.2A. These results are summarized in Table 1.

TABLE 1. DEVICE PARAMETERS OF 200W TVS, SMF13CA

PART NUMBER	PULSE DURATION, t_D (µs)	PEAK PULSE POWER P_{PP} (W)		MAX. CLAMPING VOLTAGE V_C AT I_{PP} (V)	PEAK PULSE CURRENT I_{PP} (A)	
		+25°C	+85°C		+25°C	+85°C
SMF13CA	10/1000	200	120	21.5	9.3	5.6
	8/20	950	570	21.5	44.2	26.5

TVS Power Derating vs Temperature

TVS datasheets specify peak pulse power ratings for an ambient temperature of T_A = +25°C. To prevent the TVS from thermal overload when operating at elevated temperatures, datasheets often provide a pulse-power derating versus temperature curve, shown in Figure 7. Thus, to operate the TVS in Table 1 at +85°C, its peak pulse power and current must be derated to 60% of the specified values at +25°C.

For the 10/1000µs pulse, the derated values are P_{PP-85} = 120W and I_{PP-85} = 5.6A, and for the 8/20µs pulse, P_{PP-85} = 570W and I_{PP-85} = 26.5A (see Table 1).

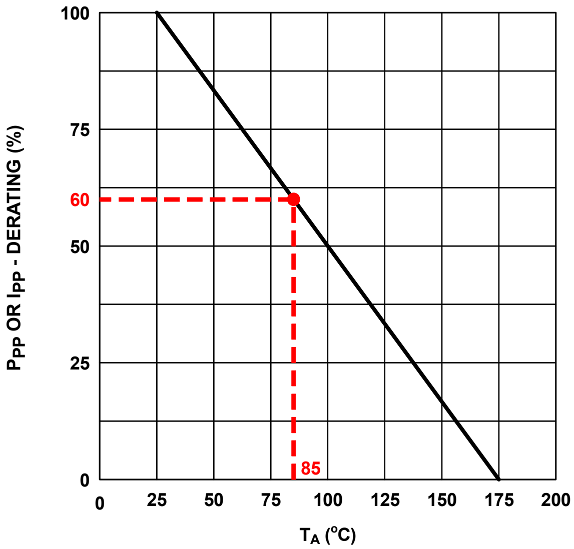

FIGURE 7. PEAK PULSE POWER DERATING vs TEMPERATURE

TVS Junction Capacitance

A TVS device has a junction capacitance resulting from mobile electrons and holes on opposite sides of the P-N junction and depletion layer. This is equivalent to parallel plates with an intervening dielectric layer of silicon in between, thus constituting a basic capacitor. Applying a reverse bias voltage widens the depletion region and decreases the capacitance as the bias voltage is increased.

Low voltage TVS devices with high dopant concentration have a narrow depletion region, producing higher capacitance values. Progressively higher voltage devices have exponentially decreasing levels of dopant and wider depletion regions with a corresponding reduction in capacitance. Figure 8 depicts capacitance versus breakdown voltage for unidirectional and bidirectional, 400W rated TVS devices of the low-cost SMAJ series. The bidirectional TVS diodes have two p-n junctions in series, thus further reducing capacitance.

Similar capacitance graphs for different power rated TVS devices vary proportionally to their rated Peak Pulse Power (P_{PP}). Thus, a 1000W TVS has typically 2.5 times the capacitance of a 400W device with the same standoff voltage rating.

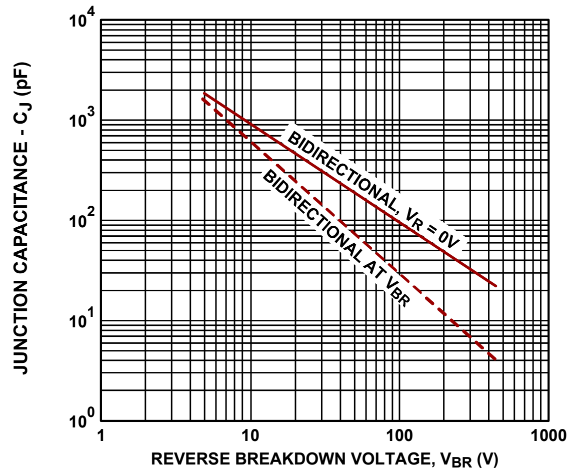

FIGURE 8. CAPACITANCE vs BREAKDOWN VOLTAGE

Typical values for capacitance versus reverse-bias voltage are shown in Figure 9 for five devices of various stand-off voltages, often found in RS-485 applications. Here the junction capacitance drops exponentially as bias voltage is increased since the depletion layer is widening as reverse bias is increased.

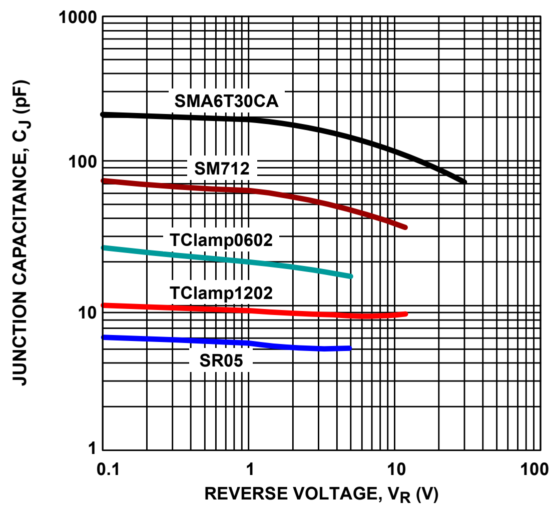

FIGURE 9. CAPACITANCE vs REVERSE BIAS VOLTAGE

At DC operating voltage and low frequencies, the capacitance of a TVS does not affect performance. At higher frequencies however, signal attenuation occurs.

For data transmission applications, such as RS-485, capacitive loading can be effectively reduced by using a low-capacitance rectifier diode in series and in opposite direction to the TVS, as shown in the left leg of the circuit in Figure 10A. With both diodes in series, the total capacitance of the left leg is reduced to the capacitance of the single rectifier diode.

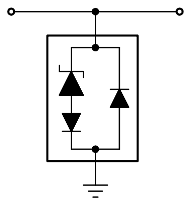

FIGURE 10A. UNIDIRECTIONAL TVS

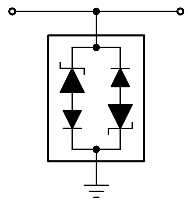

FIGURE 10B. BIDIRECTIONAL TVS

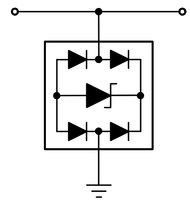

FIGURE 10C. BIDIRECTIONAL TVS ARRAY

FIGURE 10. LOW CAPACITANCE TVS CONFIGURATIONS

This combination however, only clamps positive transients, for negative transients the left leg remains high-impedance. To protect a data line from positive and negative transients, a second low capacitance diode is added in parallel, thus making the total device capacitance twice that of a single, low capacitance diode.

For symmetrical, bidirectional protection, two of the low capacitance TVS-diode combinations are integrated in an anti-parallel configuration, as shown in Figure 10B. Here the total TVS capacitance will also be twice that of an individual rectifier diode.

Because positive and negative signal or data pulses can affect the charging and discharging of the large capacitance of the avalanche TVS diode, modern TVS designs utilize low capacitance steering diodes in a full-wave rectifier bridge configuration to maintain the TVS capacitance charged and to inherently protect the diodes from either polarity of high voltage transients. The overall capacitance of this combination, shown in Figure 10C, has approximately the same value as that of the low-capacitance TVS in Figure 10A.

TVS Design Cautions

Application examples of transient protected RS-485 nodes often have the TVS diodes directly connected to the transceiver bus terminals. Depending on the transceiver type, standard or fault-protected transceiver, its internal ESD protection circuits might or might not interfere with the clamping action of the external TVS devices during a transient event.

Fault-protected or overvoltage protected (OVP) transceivers, such as Intersil's ISL3245xE and ISL3249xE families, have high stand-off voltages of $V_{I/O} = \pm60V$ and ESD trigger levels of $V_T = \pm70V$, which do not impact the operation of external TVS components.

Standard RS-485 transceivers however, have ESD trigger levels close to the TVS breakdown voltage, V_{BR}, thus making an interaction between ESD cells and TVS diodes inevitable.

ESD structures with Zener switching characteristics share the high transient current with the TVSs, while those with snap-back characteristics can actually turn the TVS diodes off, thus being forced to absorb the transient energy by themselves.

Since a surge transient has about 8 million times the energy of an ESD transient of the same peak pulse voltage, an ESD cell is at risk of damage by high surge currents, even when paralleled by an external TVS.

Figures 11 and 12 depict the interactions between a standard transceiver's internal ESD protection and an external TVS for positive transient voltages.

The ESD structure in Figure 11 has a Zener characteristic, similar to the one of the external TVS. Although both clamping structures share the surge current, the energy created within the ESD Zener is far beyond its absorption capability and the Zener burns out.

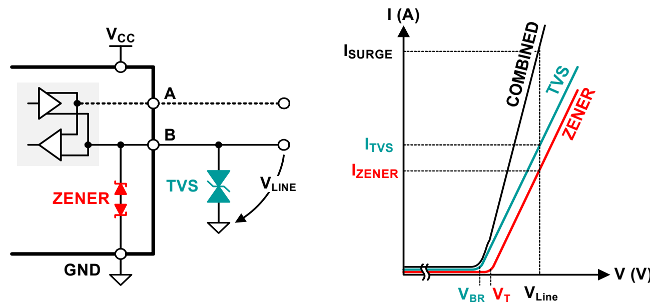

FIGURE 11. TRANSCEIVER DAMAGE DUE TO ZENER SHARING HIGH TRANSIENT CURRENT WITH TVS

The ESD structure in Figure 12 consists of a Silicon Controlled Rectifier (SCR) with snap-back characteristics.

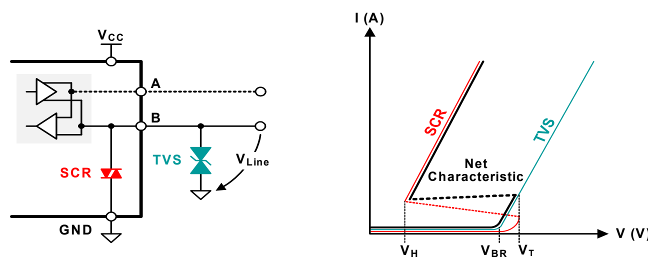

FIGURE 12. TRANSCEIVER DAMAGE DUE TO SCR SHUNTING TVS

Because the TVS breakdown (V_{BR}) is lower than the SCR trigger level (V_T) the TVS starts conducting first. Increasing current causes its clamping voltage, V_C, to rise until it reaches V_T. At this moment, the SCR snaps back to a clamping voltage, V_{SCR} that is below the TVS breakdown, thus turning the TVS off. Again, the energy created within the SCR is beyond its absorption capability and the SCR burns out.

Because of the unfavorable outcome for ESD structures, designers are strongly discouraged from connecting TVSs directly to the bus terminals of standard transceivers.

To design a robust transient protection scheme for RS-485 nodes, designers have two options to choose from:

1. Add current limiting components in series with the bus terminals of standard transceivers, which is discussed in application note AN1978 “Surge Protection for Intersil's Standard RS-485 Transceivers”.
2. Use Overvoltage Protected (OVP) transceivers with high stand-off capability, which tolerate high TVS voltages. This is discussed in application note AN1979 “Surge Protection Simplified with Intersil's Overvoltage Protected (OVP) Transceivers”.

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