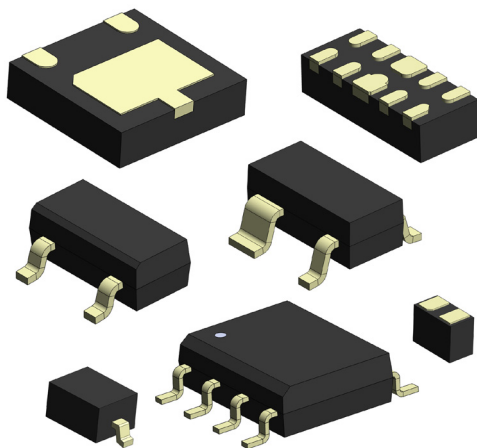# Eaton TVS Diode ESD Suppressors

TVS Diode

Introduction to overvoltage

Transient voltages and electrostatic discharge (ESD) are typical problems that impact the reliability and durability of electronic equipment. Transient voltage suppression (TVS) diodes provide surge protection to protect internal electronics from damage.

Electronic devices and equipment function optimally within a specified maximum working voltage, above which latent or catastrophic failures may occur in internal components. An overvoltage condition occurs when the supply voltage in electronic equipment exceeds its absolute maximum rated voltage. It can result from several sources, including lightning strikes, electrostatic discharge, insulation failure, arcing, or switching electromagnetic pulses (SEMPs). Particularly for electronic devices, ESD events can occur in normal product use and also in the manufacturing process, and it is crucial to protect against ESD threats.

The following are fundamental ratings and terminologies associated with Eaton TVS diode ESD suppressors:

Nominal reverse working voltage (V_{RWM}): Also referred to as reverse standoff voltage, V_{RWM} is the voltage at which the TVS diode draws minimal leakage current (typically a few microamperes) from the circuit. It is the maximum operating voltage of a TVS diode when it is "OFF."

Breakdown voltage (V_{BR}): This is the voltage at which avalanche breakdown occurs in a TVS diode, resulting in low impedance.

Reverse leakage current (I_R): The leakage current that flows through a TVS diode when it is reverse biased.

Clamping voltage (Vc): This is the voltage across a TVS diode at its peak pulse current (I_{pp}) rating. The clamping voltage of the TVS diode must be lower than the failure voltage of the circuit. The closer the clamping voltage is to the normal operating voltage, the more effective the protection.

Capacitance: A measure of stored charge, generally in picofarads (pF), between the input pin and another reference point (often ground/earth), typical with a 1 MHz signal.

Peak Current (I_{pp}): The difference between the maximum positive and maximum negative amplitudes of a current waveform.

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ESD fundamentals

Electrostatic discharge is a subtle part of our daily lives that creates challenging operating conditions for electronic devices and equipment. Electrostatic discharge occurs due to a sudden build-up of charges at the point of contact between two dissimilar materials or dielectric breakdown. Damage in electronic equipment due to ESD costs billions of dollars annually, resulting in higher manufacturing costs, downtime on machinery, and lost productivity. However, with adequate circuit protection, ESD strikes up to 30 kV can be suppressed with a high degree of reliability.

ESD failure modes for electronic components include soft and hard failures and failures due to latent defects. Soft failures due to ESD events are temporary failures, typically resulting in corruption of data and the device continues to function within the circuit. Hard failures result in permanent or catastrophic damage to components, necessitating replacement before the equipment functions normally again. A latent failure occurs when an ESD event has caused damage to a component, but it continues to function within the circuit with a significantly reduced operational life.
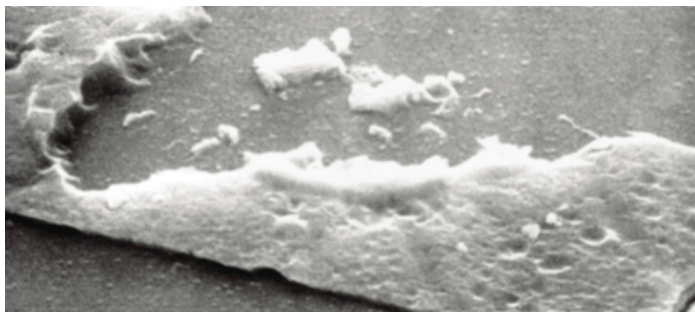

Figure 1: Latent damage in a circuit trace due to ESD.

Overvoltage threats requiring circuit protection

The main overvoltage threats to electrical equipment requiring circuit protection includes ESD from human contact, lightning transients, and electrically fast transients (EFT). All of these lead to excessive power dissipation that can damage electrical circuits. Internationally-recognized standards for overvoltage protection in electronic/electrical equipment include the IEC 61000-4-2, IEC 61000-4-4, and IEC 61000-4-5 provided by the International Electrotechnical Commission.

ESD due to human contact

While we may not notice, our bodies accumulate and discharge hundreds to thousands of volts on a daily basis. When a charged body part comes in contact with an electronic device, static electricity is discharged. For example, a human finger, after walking across carpeted floors and touching the USB port of a portable device in dry weather can discharge several kV of energy. ESD events of this kind can deliver up to 30 kV at 20% relative humidity, a very common threat capable of damaging sensitive electronic components such as ICs.

IEC 61000-4-2

IEC 61000-4-2 covers system-level ESD immunity, which applies to ESD caused by human contact. According to this standard, the typical ESD pulse waveform due to human contact can be seen in Figure 2.
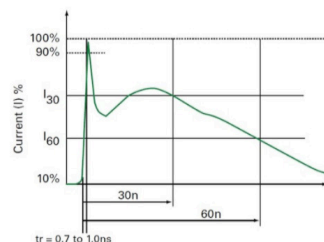

Figure 2: EFT pulse waveform IEC 61000-4-2.

As can be seen in the ESD pulse waveform in Figure 2, the rise time (tr) is very short (0.7 to 1 ns) with most of the energy dissipated within the first 30 ns, after which it decays rapidly. Thus, very fast-acting overvoltage protection is required for timely response to ESD events.

A test setup designed to simulate the ESD waveform consists of a 2 to 15 kV DC generator, two resistors with values of 10 MΩ and 300 Ω respectively, a 150 pF capacitor, and the electronic device under test (DUT).
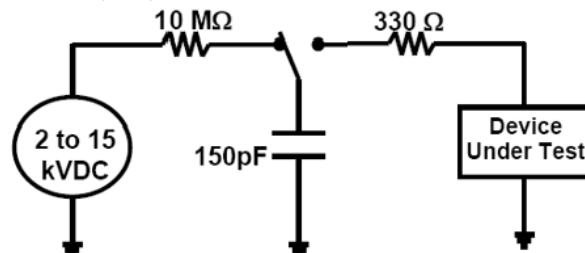

Figure 3: IEC 61000-4-2 ESD immunity test setup.

The DC voltage generator charges the 150 pF capacitor when the switch is connected to the 10 MΩ resistor and when the switch is connected to the opposite position, the capacitor discharges itself into the DUT. IEC 61000-4-2 specifies test voltages for system-level ESD immunity in various equipment for contact and air discharge as follows:

IEC 61000-4-2 level	Contact discharge	Air discharge
Level 1	2 kV	2 kV
Level 2	4 kV	4 kV
Level 3	6 kV	8 kV
Level 4	8 kV	15 kV

Table 1: IEC 61000-4-2 levels for air and contact discharge.

As seen in Table 1, Levels 1 to 4 shows increasing contact and air ESD ratings, with Level 4 being the highest in the standard. The most suitable choice of TVS diode will depend on the level of ESD protection required in a specific application. All of Eaton's TVS diodes have achieved a Level 4 minimum when tested to the IEC 61000-4-2 with many options available with even higher ESD withstand protection, providing up to 30 kV for both air and contact discharging.

Lightning-induced transients

Voltage transients due to lightning occur randomly, and are highly disastrous to electrical equipment where there is inadequate circuit protection, e.g., in communication systems and power lines. Lightning is a natural phenomenon that occurs when two regions of opposite polarity in the atmosphere briefly equalize, leading to surges containing up to 1 GJ of energy and up to 120 kV of surge voltage.

Direct and induced lightning current waveforms

The 10/350 and 8/20 µs current waveforms characterize direct and indirect lightning strikes, respectively, to find the level of protection in electronic equipment. ESD suppressors are not intended to protect against direct lightning strikes. However, lightning strikes can send transients throughout electrical distribution for long distances, up to 1 mile in some cases, and Eaton TVS Diode ESD suppressors can help protect against these surge events.
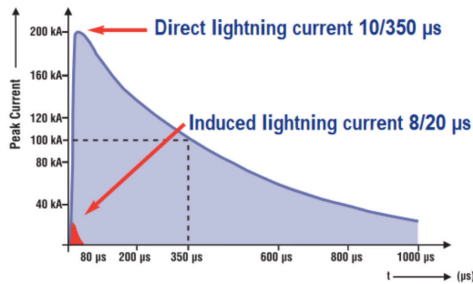

Figure 4: Current waveforms for direct and induced lightning.

IEC 61000-4-5

IEC 61000-4-5 is the IEC's standard for immunity against electrical surges such as those from lightning or switching of power systems. Lightning-induced transients can result from direct lightning on outdoor electrical circuits producing surge voltages, indirect lightning strikes inducing surge voltages in conductors, or lightning ground current flows. The purpose of the IEC 61000-4-5 standard is to produce a model that simulates lightning or power switching surge conditions and evaluate the level of immunity electrical/electronic equipment have against them. Placing a protection device, such as Eaton's TVS ESD suppressors directly at the inputs of the equipment can help protect against lightning-induced transients.

According to IEC 61000-4-5, a typical lightning voltage wave is as shown in Figure 5:
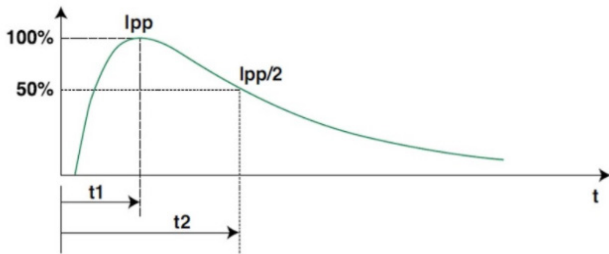

Figure 5: Lightning pulse waveforms per IEC 61000-4-5.

The IEC 61000-4-5 test setup consists of a high-voltage source (U), charging resistor (Rc), energy storage capacitor (Cc), impedance matching resistor (Rm), impulse duration shaping resistor (Rs), and rise time shaping inductor (Lt).
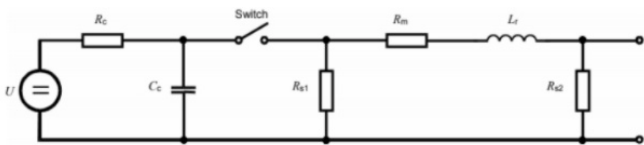

Figure 6: IEC 61000-4-5 test setup with a combination wave generator.

When the circuit is open, the HV source generates a 1.2 µs/50 µs voltage waveform while the current waveform in a short-circuit is 80/50 µs. The surge generator is referred to as a combination wave generator. The source impedance chosen ranges from 2 to 42 Ohms, depending on the nature of the electrical equipment requiring protection.

The IEC 61000-4-5 standard specifies test voltage levels for surge immunity in various classes of electrical/electronic equipment as follows:

IEC 61000-4-5 Surge Test Levels		
Class	Voltage level (kV)	Maximum peak current at 2 Ω (A)
1	0.5	250
2	1	500
3	2	1000
4	4	2000
X	Custom	Custom

Table 2: IEC 61000-4-5 test levels for electrical surge immunity.

Class 1: Partially protected environment.

Class 2: Electrical environment where the cables are well separated, even at short runs.

Class 3: Electrical environment where power and signal cables run in parallel.

Class 4: Electrical environment having interconnections run as outdoor cables along with power cables and the cables are used for both electronic and electric circuits.

Electrically-fast transients (EFT)

Electrically-fast transients occur due to the operation of inductive loads, such as heavy-duty motors, relays, and switching contactors in power distribution systems or resulting from utility providers switching in or out of their power factor correction equipment. For the purposes of this whitepaper, ESD suppression and induced lightning protection are the focus.

IEC 61000-4-4

The IEC 61000-4-4 standard covers protection for EFT. According to the standard, the typical lightning pulse waveform is as in Figure 7:
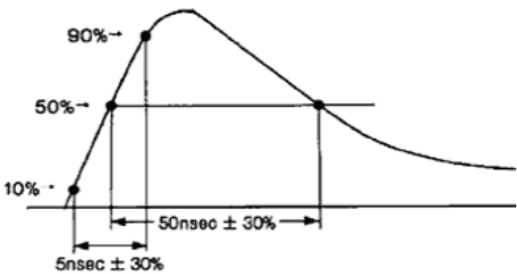

Figure 7: EFT pulse waveform IEC 61000-4-4.

Human body model ESD testing for electronic devices

The human body model (HBM) characterizes the susceptibility of electronic devices to damage due to ESD events equivalent to a human body part touching a device's port. The figure below shows an equivalent circuit for ESD discharged from the human body. It uses a 100 pF capacitor to discharge into a DUT via a 1500 Ohm resistor. The value of the resistor is selected to replicate human body resistances, usually between 50 and 5000 Ohms.
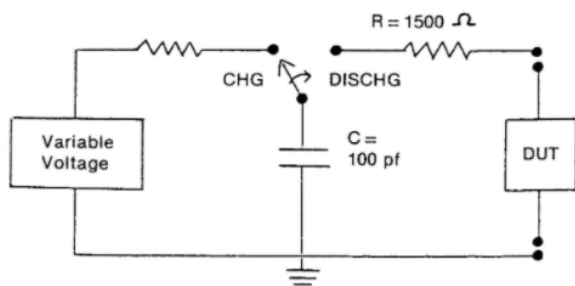
Figure 8: HBM equivalent circuit.

MIL-STD-883

A widely-used model for ESD immunity testing is the MIL-STD-883. It evaluates the effects of electrostatic discharge in military and aerospace hardware such as electronic equipment in cabins. A standard test setup consists of resistors (a suitable MΩ resistor and 1.5 kΩ resistors), a 100 pF capacitor, a HV supply, and the DUT.

According to JEDEC Solid State Association, ESD sensitivity classes for electronic/electrical equipment are as follows:

Classification	Successful ESD performance
Class 1	0V to 1999V
Class 2	2000V to 3999V
Class 3	4000V or greater

Table 3: ESD sensitivity classifications, MIL-STD-883 Method Number 3015.

How TVS diodes operate

Transient-voltage-suppression (TVS) diodes are solid-state overvoltage protection devices that work based on the diode avalanche breakdown principle when installed in parallel to the normal circuit. They are ideal for protecting internal components from short-duration (transient) and medium/high voltages and connected in parallel. When a TVS diode receives an instantaneous, high-energy shock between its terminals, it rapidly (on a nanosecond scale) enters into a low-impedance state (avalanche breakdown) to absorb the large current and clamp the voltage to a safe level. Thus, the diode protects downstream circuit elements from overvoltage by providing a low-impedance path through itself to shunt the excess current until the transient passes. However, within a safe operating voltage range, TVS diodes do not interfere with power or signal transmission through the equipment by maintaining a high impedance.

Eaton TVS Diode ESD Suppressors utilize silicon avalanche technology (see extra information at end of whitepaper) to provide reliable protection for electronics against damaging voltage transients, such as ESD strikes and lightning. They are ideal for overvoltage protection in I/O interfaces and high-speed digital and analog signal lines. They offer very low clamping voltages, high peak power, and high current dissipation, and nanosecond response times.

TVS diodes are available in industry footprints and custom sizes, with nominal reverse working voltages from 3.3 V to 70 V and diode capacitances down to 0.15 pF. The products meet 30 kV ESD withstand ratings and 2 kW of peak power dissipation on an 8/20 μs waveform without significant degradation. For the best surge protection, Eaton TVS diodes should be placed as close as possible to the point of entry, such as the I/O ports. Applications of Eaton TVS diodes include consumer, computing, power systems, medical, and industrial.

Voltage-current characteristics of TVS diodes

The voltage-current (V-I) characteristics of Eaton TVS diodes are similar to those of Zener diodes. However, while Zener diodes provide voltage regulation, Eaton's TVS diodes are strictly used for voltage protection.

Typical V-I properties of transient-voltage-suppression diodes are as shown in Figure 9:
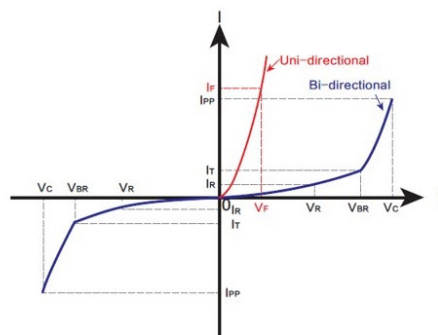

Figure 9: V-I curve for Eaton TVS diode ESD suppressors.

When connected in parallel to a circuit, Eaton's TVS diode theoretically shunts all the excess current through itself to ground. In practice, however, all TVS diodes offer a small internal resistance (known as a dynamic resistance) that causes a voltage drop across the protected device when the diode is in its conducting state, which is equivalent to the clamping voltage.

Eaton's TVS diode ESD suppressors can safeguard virtually all types of electronic equipment and devices. These products are unidirectional or bi-directional P-N junction devices with avalanche breakdown characteristics.

A common misconception about TVS diodes is that unidirectional types suppress positive overvoltages only while bi-directional diodes suppress both positive and negative overvoltages. However, this is not the case as the vast majority of unidirectional TVS diodes suppress voltages in both polarities. The actual difference is that unidirectional types have asymmetrical current-voltage (V-I) properties while bi-directional TVS diodes have symmetrical V-I properties.

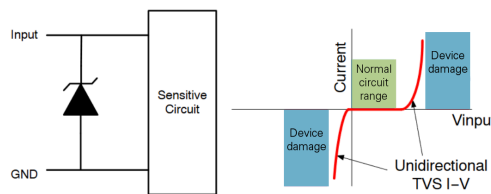Figures 10 and 11 below show overvoltage protection using both types of TVS diodes:

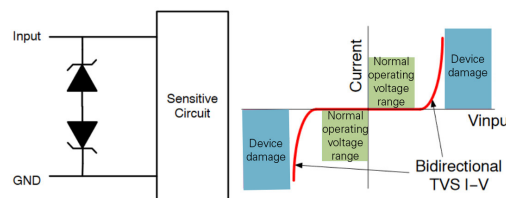**Figure 10:** Overvoltage protection using a unidirectional TVS device.

Figure 11: Overvoltage protection using a bi-idirectional TVS device.

Bidirectional TVS diodes are ideal for protecting electrical nodes having signals that are bi-directional or both above and below the ground voltage.

Eaton's reliable overvoltage protection

For over 100 years, Eaton has been at the forefront of cutting-edge design and development of circuit protection devices for the industrial, automotive, energy management, computing, medical, and consumer markets.

For more information on Eaton's overvoltage and overcurrent protection technology, check out our selection guide.

Eaton's Reliable Overvoltage Protection

Different doping processes are used to add trivalent ions (such as boron) and pentavalent ions (such as phosphorus) into the same intrinsic semiconductor (silicon or germanium) to form a P-region and an N-region on the original intrinsic semiconductor. Due to the high concentration of free electrons in the N region, they will spontaneously diffuse to the low concentration P region and recombine with the holes in the P region.

From the macroscopic view, it can also be seen that the holes in the P region diffuse to the N region, and the free electrons in the N region diffuse to the P region. The particles after diffusion recombine with each other, thus forming a space charge region (also called depletion layer) at the junction. The depletion layer forms an internal electric field from N region to P region. The internal electric field hinders the diffusion of free electrons and facilitates the drift of holes. With the increase of the internal electric field, the diffusion of free electrons is weakened, and the drift of holes is enhanced gradually. Finally, a dynamic equilibrium is achieved.
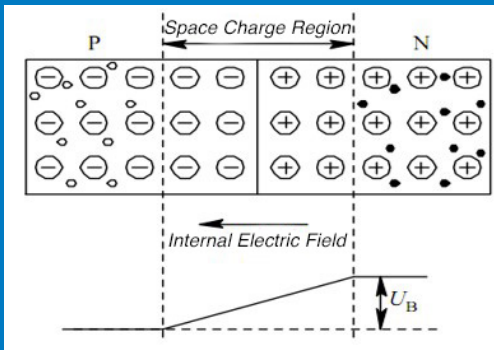

Figure 12: The doping process.

When the reverse voltage is applied to the PN junction, the PN junction is in the reverse bias, and the direction of the external electric field is the same as that of the internal electric field. As a result, the resistance of the internal electric field to the free electrons diffusion is enhanced, and the diffusion current is greatly reduced, as that of the internal electric field as shown in Figure 13 (Image A). At this time, the holes in the PN junction region form a drift current under the action of the internal electric field. However, due to the low holes concentration, it can be basically ignored. So the PN junction shows high resistance. In general, PN junction shows unidirectional conductivity.

When the forward voltage is applied to the PN junction, the PN junction is biased forward, and the direction of the external electric field is opposite to that of the internal electric field, which weakens the internal electric field. Therefore, the resistance of the internal electric field, as shown in Figure 13 (Image B) to the free electrons diffusion is weakened, and the diffusion current is increased. The diffusion current is much larger than the drift current, so the effect of drift current can be ignored, and the PN junction shows low resistance.
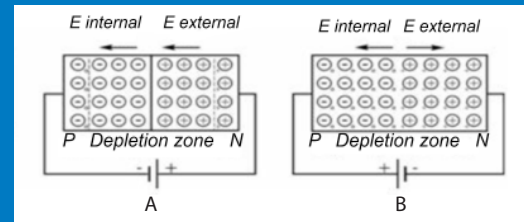

Figure 13: Reverse breakdown of the PN junction.

According to the mechanism, reverse breakdown can be divided into Zener breakdown and Avalanche breakdown:

In the case of high doping, because the width of the depletion layer is very small, a small reverse voltage can form a strong electric field in the depletion layer, which directly destroys the covalent bond, makes the valence electrons break away from the covalent bond, and produces electron-hole pairs, resulting in a sharp increase in the current. This breakdown is called Zener breakdown, also known as tunnel breakdown. Zener breakdown is temporary and can be recovered.

When the reverse voltage of the PN junction increases, the electric field in the space charge region increases. In this way, the electrons and holes passing through the space charge area will increase the energy obtained under the action of the electric field. The electrons and holes running in the crystalline structure will collide with the crystal atoms continuously. Through such collision, the valence electrons bound in the covalent bond can be collided out to produce free electron-hole pairs. Under the action of the electric field, the newly generated carriers collide with other valence electrons and produce new free electron and hole pairs. Such a chain reaction makes the number of carriers in the barrier layer avalanche increase, and the current flowing through the PN junction increases sharply. This collision ionization leads to the breakdown of the PN junction called avalanche breakdown, also known as electron avalanche phenomenon.

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