

MicroNote 134

Zeners and Transient Voltage Suppressors: Can Either Device Be Used For The Same Applications?

By Kent Walters

This MicroNote will review the differences of zeners and transient voltage suppressors (TVSs) for a better understanding of each device and examine whether there are any applications where they can be combined without serious compromise.

Background History

Zener and TVS semiconductor components have been available for many years. Zener diodes were the first offered for those applications requiring a shunt (parallel) voltage regulator starting in the early 1960s. The first generation of silicon p-n junction TVS devices, specifically designed for transient voltage protection, followed about ten years later. The TVS devices were also located in front of the load to be protected and primarily served as a shunt path to ground for high surge currents that were generated upstream in the circuit by high-voltage transients such as inductive switching, induced lightning, and electro-static discharge (ESD) events.

Both of these zener and TVS semiconductor diode product families primarily use the avalanche breakdown voltage properties of a silicon p-n junction for their important features. In that respect, the TVS diode is also sometimes called an “ABD” or avalanche breakdown diode. Originally the term zener in semiconductor physics applied only to a lower voltage reverse breakdown mechanism (typically below 5 V) involving field emission or tunneling with relatively high dynamic impedance features as further described herein. This was named after the initial founder Dr. Clarence Zener for the lower voltage breakdown mechanism in the late 1950s. However, the zener name now applies to virtually all voltage regulator diodes, including those using avalanche breakdown up to many hundreds of volts that provide much lower dynamic impedance qualities (lower change in voltage with increasing current).

Design

Zeners and TVSs are similar in silicon p-n junction diode structures. Both are driven into reverse breakdown for either regulating or clamping voltage features. However, there can still be notable differences in design and how well they perform for each described application. This may include how their p-n junctions are fabricated to assure uniformity, what size p-n junction area is provided, how they may be bonded to adjacent packaging materials for thermal management, and how they are electrically tested or screened for these two product applications. Despite those possible differences, the manufacturing methods can still be similar. Some examples can also be physically the same including diode package but electrically screened for different parametric features.

The short term peak pulse power (P_{PP}) rating for a TVS is primarily determined by the active p-n junction area (silicon die size) to distribute surge current over a broader area and avoid excessively high-current densities or hot spots. The higher the P_{PP} , the larger the active p-n junction area must be. This same design feature also reduces thermal impedance ($R_{\theta JX}$) in degrees centigrade per watt at very short transient heating times to help minimize p-n junction heating at very high power levels. This can also be dependent on the bond qualities to the active TVS die element and immediate surrounding material.

NOTE: The thermal time-constant for heat escaping from the silicon die to adjacent internal packaging materials is approximately 0.5 ms for most designs. Further details on heat flow distance versus elapsed time may be found in MIL-STD-750 Test Method 3101.5 and the figure in Appendix A.

As P_{PP} ratings are increased for TVSs, so does the cost with the amount of silicon required as well as a larger package size. In some examples, higher P_{PP} ratings for TVSs can be achieved by stacking multiple p-n junctions (die) in series where the short heating power can be distributed across more individual silicon die when applied with correct overall design features. Sometimes this is also achieved by various module designs involving many discrete packaged TVS devices internally.

Higher dc power ratings for zeners requiring continuous heat dissipation also need lower thermal resistance junction to case ($R_{\theta JC}$), as well as junction to ambient ($R_{\theta JA}$), in how well it is mounted. As a result, the external mounting (heat sinking) also becomes important for higher dc power levels particularly those rated above a few watts. These features are less critical to die size and more dependent on the package it is placed. This also includes how well the package is mounted or heat sunk for removing the continuous heat generated particularly for higher power levels. For 10 W or higher, packages can often involve larger metal packages such as DO-4, DO-5, TO-3, or similar designs. In these examples, stacking die in series is not advantageous, because it would be more difficult to remove heat out of the individual silicon die elements where the heat path becomes longer and inefficient to dissipate heat from the package.

Similar considerations must also be given to specialized TVSs involving much longer transients, such as 50 ms transients or longer, as exemplified by MIL-STD-704 for protecting other electronics from abnormal voltages in aircraft, as well as MIL-STD-1275 for military vehicles involving “load-dump” applications. This can often involve further packaging cost for greater internal heat sinking near active p-n junctions.

The thermal management involving external heat sinking for continuous power is normally not needed on most TVSs for short transients, since the event is concluded well before the heat can pass beyond the active p-n junction region where it would then require further dissipation or heat sinking to the surrounding ambient. However, this can also still be a concern for repetitive surges with high duty factors and cumulative heating effects, as described in [MicroNote 133](#).

Most TVS applications only involve “random recurring transients” where the device has cooled before the next transient. This is also how most TVSs are specified in their P_{PP} ratings. This may typically be 15 to 20 seconds or longer between any recurring transient events. Most of the military applicable detail specifications in MIL-PRF-19500 for TVS devices state a minimum of one minute between recurring transients.

Electrical Testing Zeners

Despite having good design practices for both zener and TVS products, one of the significant differences between the two is how they are electrically tested, or 100% screened. This is also reflected in military upgrade screening requirements for JANTX, JANTXV, and JANS when comparing zeners and TVSs.

For zeners, the parametric features primarily included for 100% screening are those that ensure good voltage regulation at a test current (I_{ZT}) that is 25% or less of the dc power rating of the zener. As a result of the fixed power rating in a particular product series, the specified I_{ZT} will decline as zener voltage (V_Z) increases.

The majority of zener products typically range from 3.3 V to 200 V. However, some may extend below or above these values. Each nominal zener voltage is offered in $\pm 5\%$ tolerances. They can also be provided in wider 10% tolerances, as well as much tighter 2% and 1% tolerances. In addition to the V_Z testing, the device is also screened for dynamic impedance (Z_{dT}), which is a measure of how well the device can regulate voltage or how minimal the voltage change will be with a change in the test current. This is usually achieved by applying a 10% modulation of the test current (I_{ZT}) and then measuring the change in voltage at 60 Hz or 1000 Hz. The quotient of the voltage and current change is the dynamic impedance for a maximum specified limit in ohms.

There can also be a second dynamic impedance test similarly performed with a 10% modulation of a much lower nominal current value (I_{zk}) near what is called the knee region, which is closer to the onset of voltage regulation where avalanche breakdown begins. This also provides a further indication of how well the device regulates voltage at lower operating currents when the dynamic impedance parameter is identified as Z_{zk} .

Another method of determining voltage regulation qualities is measuring how small the voltage change will be over a broad change in current. This is simply achieved by testing for a maximum allowed voltage change between two specified test currents.

The reverse leakage current (I_R) is also tested where it is most often specified at 75% of the V_z . However, there are exceptions to this for lower voltage devices where the I_R test is done at a lower percentage of V_z . The I_R is an important test for device integrity and long-term reliability. Also the forward voltage (V_F) is typically specified at higher currents in the low-voltage-conduction direction.

Although a square-wave surge current rating at 8.3 ms is often specified or rated by design in the zener direction, it is not usually a 100% screening requirement, nor does it include any specific maximum voltage requirement during surge as would be required for TVS devices with a specified maximum clamping voltage (V_C). Unlike TVSs, it is very unusual for zeners to be offered as bidirectional devices.

For further information on zeners, the JEDEC Solid State Technology Association offers JESD211 entitled, "Zener and Voltage Regulator Diode Rating Verification and Characterization Testing."

Electrical Testing TVSs

When further comparing TVSs for electrical parameters compared to zeners, similar features may be called by different names. For example, TVSs are also tested for reverse leakage current—or what is called standby current (I_D)—at the working peak voltage, or standoff voltage (V_{WM}), that is typically 80% or 90% of the specified minimum breakdown voltage ($V_{BR(MIN)}$). This is somewhat higher compared to zeners at 75%. The breakdown voltage (V_{BR}) is usually tested at relatively low power and fixed current for most TVS products, such as 1 mA to 10 mA. However, it may also vary similarly to how zeners are tested for V_z in avalanche breakdown features at higher power levels, depending on the original JEDEC registration. In those examples for higher test currents, it is primarily used only as a reference test current condition for $V_{BR(MIN)}$, and the maximum is not specified. The TVS devices do not include dynamic impedance testing, since they are not used as a voltage regulator at lower currents.

In some TVS product families, both the minimum and maximum breakdown voltage ($V_{BR(MIN)}$ and $V_{BR(MAX)}$) are specified similar to a zener, whereas other examples may only specify $V_{BR(MIN)}$. That is because TVS products are not a voltage regulator, and the maximum voltage feature is only a concern during the transient event that drives the TVS device significantly into avalanche breakdown where a maximum clamping voltage (V_C) is specified. In that respect, TVSs are only "idling" in normal operation at the specified V_{WM} voltage or less, with very low standby current (I_D) below the avalanche breakdown region. They are only driven into their avalanche breakdown region when an infrequent (random recurring), higher transient voltage occurs. During that brief moment, they will clamp the voltage and conduct a large amount of current through the device as a shunt path (typically to ground) to protect a downstream sensitive load.

For that important electrical feature during surge, the maximum clamping voltage (V_C) is specified at a very high peak pulse current (I_{PP}) for a specified wave form. The most often used wave form is at 10/1000 μ s (i.e., 10 μ s rise and 1000 μ s fall time to the 50% decay point). However, it can also include 8/20 μ s or other waveforms such as 0.1/6.4 μ s, 6.4/69 μ s, 40/120 μ s, or 50/500 μ s as found in the RTCA DO-160 aviation spec requirements.

The maximum rated V_C is approximately 45% higher than the $V_{BR(MIN)}$, or a ratio of 1.45 for most TVS products, except for lower voltage TVSs that may approach 1.55 with their higher dynamic impedance effects from field emission or tunneling as earlier described. This ratio of V_C/V_{BR} is also known as the clamping factor. In the example of bidirectional TVS devices, this I_D , V_{BR} , and surge testing for V_C is done in both directions. For unidirectional TVS devices, a maximum forward surge voltage requirement (V_{FS}) may also be included.

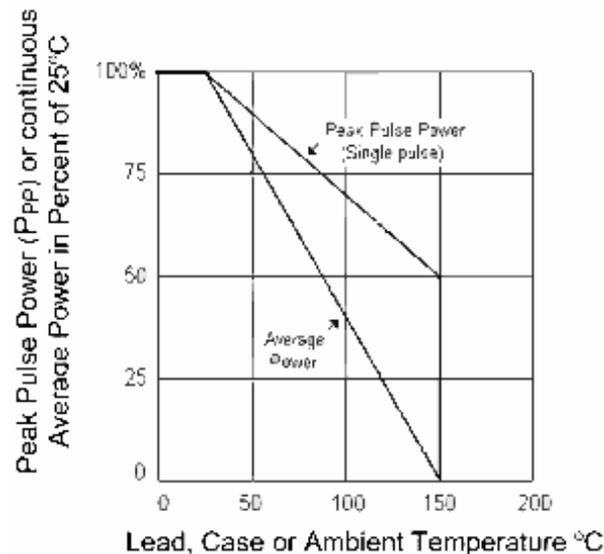
There is another voltage comparison described for TVSs that is identified as voltage clamping ratio. This compares the clamping voltage to working peak voltage (V_C/V_{WM}). Neither the clamping factor nor the voltage clamping ratio is directly shown on TVS datasheets. Nevertheless, they can still provide a better understanding of voltage ratios and what to expect in protection limits during a transient with reference to either V_{BR} or the V_{WM} of the TVS. The voltage clamping ratio of V_C/V_{WM} can be of further importance to the design engineer. This ratio or added voltage margin (above and beyond the normal operating voltage for clamping protection) is sometimes referred to as the additional “voltage overhead” needed in an application. This ratio is typically a value of 1.60 or more with respect to V_{WM} depending on where the

V_{WM} value was specified—either at 80% or 90% of the $V_{BR(MIN)}$ —on the TVS datasheet. It can also be further influenced by low voltage TVSs, where these ratios are higher similar to what is observed in dynamic impedance for lower voltage zeners as earlier described. Nevertheless, this type of clamping ratios for silicon p-n junction TVSs are significantly lower than metal oxide varistors (MOV) technologies.

The mathematical product of the maximum specified V_C and I_{PP} ($V_C \times I_{PP}$) is the peak pulse power (P_{PP}) rating of the TVS device. Similar to zeners, the specified maximum peak pulse current (I_{PP}) will decline as the voltage selection of the TVS devices increase since the rated P_{PP} remains fixed within a TVS product datasheet. For TVSs, the rated power is primarily with reference to the transient surge power where very high P_{PP} can be achieved for a typical TVS device design with little or no external heat sinking, given the typical “random recurring” 10/1000 μ s transient threat (or shorter) will conclude before the heat escapes from the TVS package. That is not the case for high-duty-factor repetitive surges, as described in [MicroNote 133](#), where appropriate package design and heat sinking should also be considered similar to high power zeners where dc power is the primary concern.

The P_{PP} derating curves with temperature for TVS devices are now generally being shown in a different manner than zeners in newer TVS datasheets in the industry. This difference is primarily reflecting the actual higher p-n junction temperatures during a transient where the projected slope of linear derating would intersect those higher temperatures (typically 250 °C to 275 °C). This method of derating P_{PP} is achieved for “random recurring” transients where the device is allowed to cool before the next event. However, these TVS derating curves are also shown to abruptly go to zero power at the maximum rated temperature (lead or case) of the TVS package materials such as 150 °C for plastic and 175 °C for glass, ceramic, or metal packages. Zeners are derated in the conventional manner with a linear decline to zero at the maximum rated package temperature when operating with continuous power. See [Figure 1](#) (see [page 4](#)) for comparisons of these different derating methods.

Figure 1: Power Derating Differences



Combining Both TVS and Zener Features

With these described differences in design and test features between TVS and zener devices, the question still remains if they can be combined in an acceptable manner. As suggested earlier, there will be compromises where overall performance will be less than optimum for generating a single product with both qualities for continuous voltage regulation as well as transient voltage protection. Those options will be examined as well as some unique applications already doing this to a limited extent for reducing “voltage overhead” as earlier described.

The primary tradeoff is the thermal management or derating features that must be considered in these combined dual roles. If a TVS device is also used as a zener for continuous voltage regulation, the device would then be operating with sustained power dissipation where internal p-n junction temperatures are driven well above ambient from its own thermal resistance junction to ambient $R_{\theta JA}$. That type of operating condition will reduce P_{PP} capabilities as shown in the temperature-derating curves found in most TVS datasheets. This additional derating for a dual purpose role would go beyond other TVS derating considerations often directed at elevated ambient operating temperatures. If the dc power is low or is not applied continuously with a low duty factor, that scenario for the zener portion in this dual role may not result in any significant temperature increase, and very little derating may apply (beyond any other elevated ambient temperature considerations). Nevertheless, such example diode combinations should be further tested for both TVS and zener parametric requirements to ensure proper operation for a dual-role application.

Similarly if a zener is also used as a TVS, it may not be an optimum design for required peak pulse power (P_{PP}) and peak pulse current (I_{PP}) for the applicable transient waveform threats. Also it would not be 100% surge tested to verify clamping voltage (V_C) features. Nevertheless, a zener could be further tested in those respects for specific applications, particularly if the thermal derating features are also considered for both applications, and the zener was otherwise adequate in design size for the needed P_{PP} and I_{PP} requirements. After the P_{PP} capability is determined at a specific pulse width, for example 10/1000 μs or shorter, the overall graphical display of P_{PP} versus pulse width can often easily be determined. This is typically a linear relationship where the slope is virtually the same on a log-log plot as seen for all TVS products, such that the P_{PP} increases by one decade for every two decades that the pulse width is decreased. The only thing that primarily changes for different TVS products is the absolute position of this curve on the ordinate axis for P_{PP} . This has also been historically recognized as a Wunsch-Bell Curve for different waveform impulses in the vicinity of 1 ms or less for most silicon p-n junction devices (including zeners). More on this subject can be found in [MicroNote 104](#) and [MicroNote 120](#).

The normal surge current rating for zeners is provided at 8.3 ms with a square wave. Unfortunately, the described Wunsch-Bell curve cannot be accurately positioned with that one reference point, because it is beyond the 1 ms range where the curve is otherwise linear on a log-log plot. Beyond 1 ms, the P_{PP} starts to flatten depending on package design, and eventually approaches continuous (dc) power after many seconds where the device capabilities are also subject to external mounting (heat sinking) variables. That is also why most TVS device are rarely characterized beyond 1 ms unless they are designed for that purpose. Fortunately, most transient threats are well below 1 ms in duration.

In some very stringent TVS voltage applications, design engineers must deal with very tight “voltage overhead” requirements between the continuous operating voltage and maximum required V_C for downstream circuit protection. In those examples, with well controlled voltage or load-line conditions, the TVS device is allowed to be continuously operated in voltage very near to or slightly into its V_{BR} region, similar to a zener regulator, rather than at 80 to 90% of the $V_{BR(MIN)}$ for the rated working peak voltage V_{WM} .

Instead of operating in a normal preferred “standby” mode with very low leakage currents at V_{WM} (as most TVS applications specify), this scenario would include some level of continuous applied power as a result of current flowing in avalanche breakdown, similar to a zener. That may also increase the V_{BR} to a slightly higher value due to the self-heating effects and positive temperature coefficient of the breakdown voltage identified as $\alpha_{V(BR)}$ on many TVS datasheets where voltage increases with temperature. This can also eventually limit the dc current (and power) through the TVS if the applied continuous operating source voltage (V_s) is only slightly above the V_{BR} where the source resistance (R_s) also becomes a factor in a self-limiting mode of operation.

In this scenario, the limited current is described by the equation: $I = (V_s - V_{BR})/R_s$, where the V_{BR} approaches the value of V_s as the TVS device p-n junction temperature increases and current starts to approach zero in this equation. It does not quite achieve that value, because the current in this equation (as well as power and self-heating) are diminished as V_{BR} increases. This mode of operation will apply when V_s is slightly greater in value than V_{BR} when trying to continuously operate a TVS near its breakdown voltage at lower currents similar to a zener. If V_s is less than V_{BR} , then the TVS is again in its low leakage region (below breakdown voltage) as normally desired. It can remain in either of these operating modes, where V_s is in the same vicinity as V_{BR} with low applied power, until a high power transient voltage occurs when the TVS will be briefly driven into its clamping mode at high surge currents, as expected. The high surge currents (I_{PP}) can be calculated as shown in MicroNote 125.

The temperature coefficient of TVS devices ($\alpha_{V(BR)}$) is typically 0.04 %/°C to 0.11 %/°C in the 6 V–200 V range for V_{BR} , as also described in MicroNote 203 for zener temperature coefficients (α_{VZ}). For example, if we assume an $\alpha_{V(BR)}$ value of 0.10%/°C for a 50 V TVS device, and we observe that the V_{BR} has increased by 5% as a result of operating continuously into its breakdown region (similar to a zener) due to the operating supply voltage (V_s) being just above the V_{BR} value, that type of operation will equate to a 50 °C junction temperature rise of the TVS. With that temperature rise, the P_{PP} must be derated accordingly as previously described as part of the compromises of trying to operate it as both a zener and TVS. Nevertheless some applications with tight “overhead voltage” requirements may still utilize this feature since the clamping factor (V_c/V_{BR}) is much lower than the voltage clamping ratio (V_c/V_{WM}) of a TVS.

Note: The $\alpha_{V(BR)}$ for the TVS will affect both the low current V_{BR} and the high current V_c in the same manner. It is also this same relationship that primarily causes the V_c to increase well above V_{BR} during a transient due to significant p-n junction heating during the short high-current transient event. A smaller portion of that voltage increase is due to parasitic resistance (R_S) effects and Ohm’s Law within the TVS component at the typical 10/1000 μ s surge ratings. The R_S value is also found in SPICE modeling, as described in MicroNote 010 on the Microsemi web site.

Another method of reducing the effective V_c for sensitive applications, that requires minimal “voltage overhead” with reference to the normal rated V_{WM} operating voltage, is to oversize the TVS beyond what would be expected with a defined transient threat in terms of P_{PP} and waveform, so that the device is not driven to its maximum rated V_c . This is also described in MicroNote 108.

Summary

Zeners and TVSs have different design considerations and are also tested differently for their primary operating features. As a result, selecting for overall optimum performance and thermal management requires careful consideration. Only under judiciously chosen operating conditions can they be combined with careful consideration and accompanied by special device testing. Those special product features can also be provided by Microsemi on an SCD basis.

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