ISSUE: October 2020

Avoiding Thermal Runaway In Schottkys Is Key To More Reliable And Efficient Designs

by Jos van Loo, Taiwan Semiconductor Europe, Zorneding, Germany and Kevin Parmenter, Taiwan Semiconductor America, Chandler, Ariz.

Schottky diodes are used more and more in applications where there is a combination of high ambient temperatures and higher voltages present. Typical examples would be longer LED strings in lighting applications and 48-V automotive systems. This means it is time to revisit thermal runaway on Schottky diodes. By better understanding how the maximum T_j of a Schottky diode is defined and why thermal runaway happens, design engineers will be able to build more efficient and more reliable products.

In this article, we begin by explaining the different interpretations and uses of maximum junction temperature, and the physical attributes of Schottkys that determine this rating on the datasheet. Next, we look at the factors that lead to thermal runaway and describe its two forms—static and dynamic. We will then discuss the importance of reliability testing, mainly the HTRB (high temperature reverse bias) test and thermal modeling in avoiding thermal runaway.

Since a device's thermal ratings are key to assessing vulnerability to thermal runaway, we will discuss these ratings in the context of second sourcing, explaining what you need to know to compare different models from different vendors. Finally, we will describe the differences between planar and trench technology, and package characteristics in terms of their impact on thermal runaway.

Much of this discussion revolves around a Schottky rectifier's forward voltage (V_f) and leakage current (I_r) specifications, how they influence thermal performance, junction temperatures, reliability, efficiency, and aspects of Schottky device structure that influence these two specifications.

Maximum Junction Temperature

The maximum junction temperature T_j of a Schottky rectifier can be interpreted and used in four different ways:

- determining the current rating
- setting up reliability testing
- calculating long-term reliability
- preventing thermal runaway.

What is unique to Schottky diodes is that because the maximum junction temperature is dependent on the PCB layout, the end application dynamic conditions can be prime causes of thermal runaway.

Rating Conventions

The definition of T_{jmax} of a Schottky diode is linked to the barrier material (Fig. 1) used to manufacture the product. Usually they are grouped in 150°C or 175°C rated products. The T_{jmax} is the first and best indicator of the leakage current you can expect. When second sourcing a Schottky diode, after comparing the breakdown voltage and the V_f spec, the next step is to compare the maximum T_j.

Many different barrier materials exist in the industry. These are mainly platinum based with different quantities of silicide "mixed in" to create different alloys that give various barrier heights. In theory they could be called 145°C, 155°C or 170°C products. These are then grouped by rating convention into 150°/175°C rated products. Each barrier material has a unique V_f/I_r value for a given die size. Designers should not assume however that different suppliers always use the same barrier material for a given T_{jmax}, and actual testing in the circuit is necessary to compare two diodes.

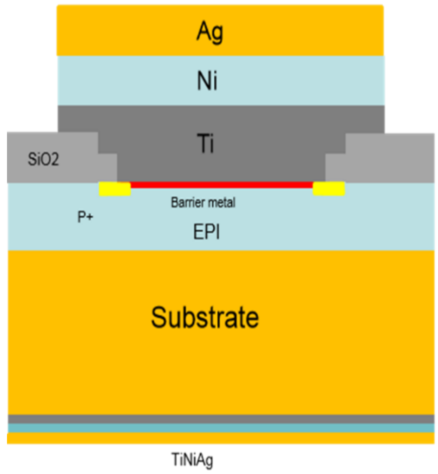

Fig. 1. Location of barrier materials in a planar Schottky device structure.

In general, in a planar device the V_f depends on the composition and height (thickness) of the barrier material, the die size and the resistivity of the EPI (which is linked to the breakdown voltage).

Thermal Runaway

The formula $dP_{tot}/dT_j < 1/R_{thj-a}$ for the definition of T_{jmax} shows that the T_{jmax} of a Schottky is dependent on the test board or application. So, in the case of a Schottky diode, a higher T_{jmax} does not necessarily mean a more reliable product or better quality.

In most applications, efficiency is a key factor and the V_f of a T_j = 150°C rated product is better than a T_j = 175°C rated product for the same die size. Only in circuits with a very high T_a (automotive or down hole instrumentation are examples) and/or very high voltages, is a higher T_j needed. The formula shows what the thermal runaway point is for each diode/application combination. *It will never be the same for two different products, so specific individual component testing is needed.*

One should also distinguish between static and dynamic thermal runaway. Dynamic thermal runaway happens when a Schottky diode is switched from the on to the off state. When the reverse power losses become dominant thermal runaway can happen. The V_f has a negative temperature coefficient that keeps the system stable with increased currents and temperatures. The leakage current I_r has a positive temperature coefficient resulting in potential positive feedback. So, if a device is switched from on to off at a higher temperature and the reverse losses are higher than the forward losses, the junction temperature may drift upward resulting in thermal runaway.

This may happen in fast switching applications such as switching power supplies, LED drivers or even in a dc operation like in a photovoltaic junction box. So, designers using a 150°C T_j rated barrier material and seeing I_r currents of several milliamps and blocking voltages of 80 V or higher should seriously consider going to a lower leakage, higher-temperature barrier material (usually with a V_f penalty).

Fig. 2 depicts a typical example of a power dissipation versus junction temperature curve for a Schottky diode. This curve is taken from the IEC 62979 norm for PV junction boxes and indicates the various conditions in the PV application which could cause thermal runaway. However, this curve is generalized—it applies to rectifiers of any rating and applies broadly to other applications.

In Fig. 2, a certain forward loss F1 or F2 occurs in a diode, depending on the forward current through the diode. This line intersects with the thermal resistance curve to determine the junction temperature. The forward losses of the diode decrease linearly due to the negative temperature coefficient. Plotted against these curves are the exponentially growing reverse losses (R). The intersection points will determine whether thermal runaway happens or not. If the reverse losses are higher at a given T_j than the forward losses, there is instability.

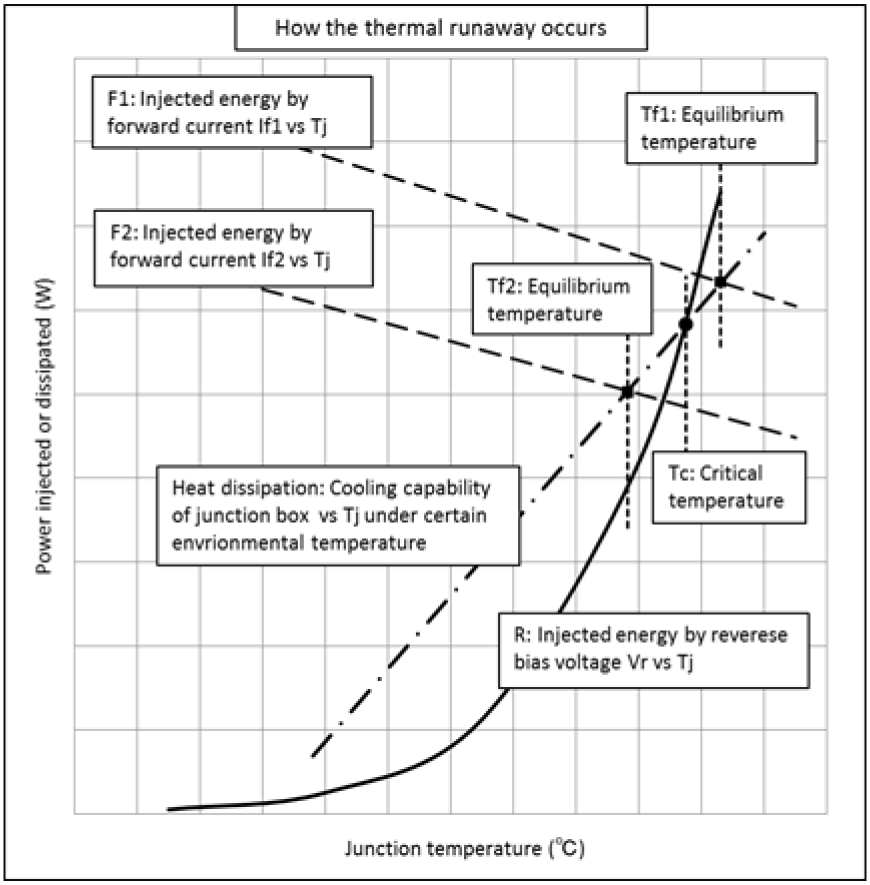

Fig. 2. Thermal runaway graphs per IEC 62979.

Static thermal runaway happens when the device is purely reverse biased, like in an HTRB (high temperature reverse bias) test performed as part of the qualification testing of the semiconductor devices (Fig. 3). The ambient temperature is increased until the maximum T_j is reached considering reverse losses.
$T_j = T_a + P_d*R_{thj-a}$. At some stage thermal runaway will occur.

When evaluating an HTRB test plan, the T_a temperature needs to be adjusted to reach the correct maximum T_j of the datasheet specification based upon the thermal resistance, so the devices are being stress tested rather than inducing destructive failures. This is the domain of the device test engineer.

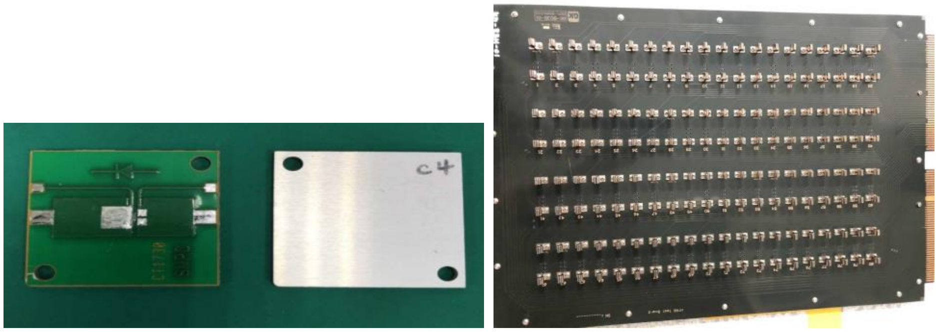

Fig. 3. Typical pictures of HTRB test boards.

From the perspective of the circuit designer this is purely theoretical, yet it is useful for designers to understand how parts are tested and qualified. In practical circuits a Schottky diode would never be used this way. In the case of static thermal runaway, the situation implies a very high ambient temperature. In the case of dynamic thermal runaway, the root cause is very high-power dissipation and blocking voltage.

Reliability

The purpose of the HTRB test is to detect manufacturing and/or device defects—like contamination, mechanical damage, etc.—not to measure thermal runaway. An incorrect barrier height is a serious defect, usually detected via an HTRB test. However, these manufacturing defects also result in thermal runaway.

For rectifiers and TVS diode devices, designers rightly assume that a T_j of 175°C is better than a T_j of 150°C and that the higher the T_{jmax}, the better the reliability. This argument does not necessarily apply in the same way for a Schottky diode. The difference in T_j may be just a difference in the thermal runaway point of a barrier material.

Schottky rectifiers are quite sensitive to moisture. So, when it comes to reliability testing, moisture stress tests such as an 85-85 test (85°C at 85% relative humidity) and HTRB are quite important. In many applications, Schottky diodes are some of the hottest components on the PCB (Fig. 4).

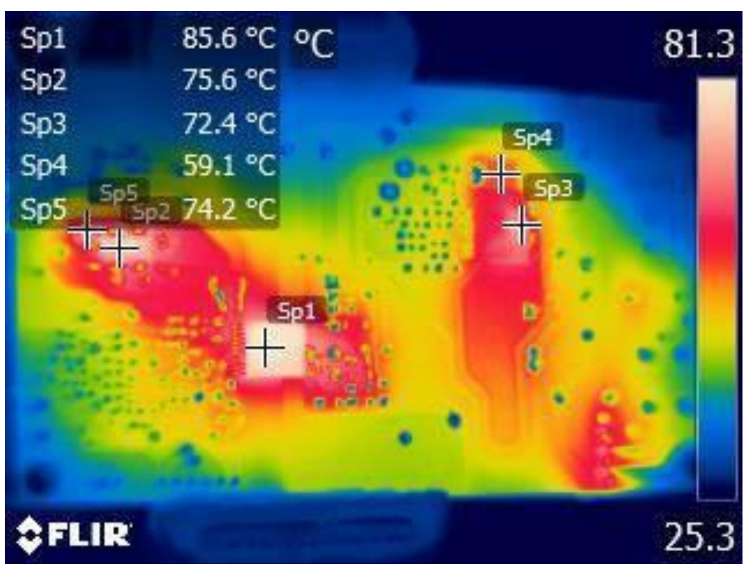

Fig. 4. IR camera measurements are the easiest way to judge and compare the efficiency of Schottky rectifiers and critical to evaluating their reliability. (Image taken from Power Integrations DER 750 Design Engineering Report for a 42-V/42-W LED driver at 90-Vac input.)

This thermal image (Fig. 4) of a power converter application shows that the Schottky diode is one of the hottest components on the PCB. That implies that there are a lot of temperature/power cycles with a very high delta T_j.

The Coffin-Manson Mechanical Crack Growth Model [1] has been used successfully to model crack growth in solder and other metals due to repeated temperature cycling as equipment is turned on and off in its end use application. This model takes the form

$$Nf = A \cdot f^{-\alpha} \cdot \Delta T^{-\beta} \cdot G(T_{max})$$

where Nf is the number of cycles to fail, f is the cycling frequency, ΔT is the temperature range during a cycle and $G(T_{max})$ is an Arrhenius[2] term evaluated at the maximum temperature reached in each cycle.

Typical values for the cycling frequency exponent α and the temperature range exponent β are around -1/3 and 2, respectively (note that reducing the cycling frequency reduces the number of cycles to failure).
The ΔH activation energy term in $G(T_{max})$ is around 1.25.

From this discussion, it becomes clear that it is in the designer's interest to have as low a delta T_j in their design as possible. This is mainly achieved by lowering the thermal resistance and choosing a Schottky device with a barrier material with a lower barrier height or a lower V_f. The factors that contribute to low thermal resistance will be discussed further in the current rating/package design section.

Second Sourcing

Like standard rectifiers, the current rating of a Schottky diode can be influenced by specsmanship. Often the R_{thj-a} in a Schottky's derating curve and the point at which the derating starts is expressed empirically. For example, the same diode shown in Fig. 5 can have a 2x current rating under different thermal circumstances. This can be avoided if the vendor uses case temperature T_c on the x-axis and specifies the R_{thj-c} as a fixed value in the datasheet. This is done for most SMD parts.

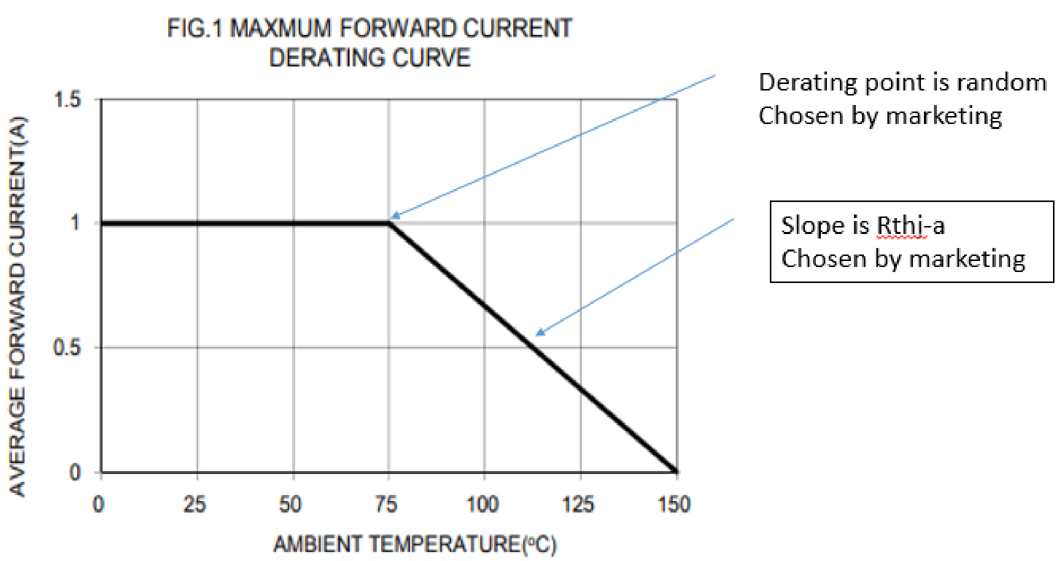

Fig. 5. Derating curve of a Schottky diode.

But designers should also be careful when the derating graphs do use the T_c on the x-axis, rather than T_a. In most designs the thermal resistance consists of two parts: the thermal resistance junction-to-case/lead and the thermal resistance case/lead-to-ambient. Unless the products are heatsinked (or have very good convection cooling), the latter part of the thermal resistance is the major contributor (75% plus). Derating using T_c then becomes meaningless.

Also, keep in mind that the concept of the infinite heatsink is purely theoretical—it has no practical application. In addition, it must be understood that the only parameter the semiconductor device manufacturer can control is the resistance from junction to case and/or leads. It is up to the designer to keep the junction temperature of the device as low as possible in the end application.

As Schottky diodes are mainly used in pulsed environments with a certain duty cycle, such as SMPS applications, the typical V_f curves are the better ones to compare (Fig. 6). With a Schottky diode, the typical V_f curves are also dependent on the barrier material used and the technology (trench or planar) so these curves do not necessarily allow you to compare apples to apples (die sizes). Compare the V_f at the highest pulsed repetitive current in your circuit and average die temperature expected to get the best indication of how switching diodes might influence your power conversion efficiency.

One can also get an immediate understanding of the T_j for a given V_f for the part used and can compare curves at 100°C or 125°C with other products on a level playing field.

Thus, using current rating alone to second source Schottky diodes can lead to practical applications problems.

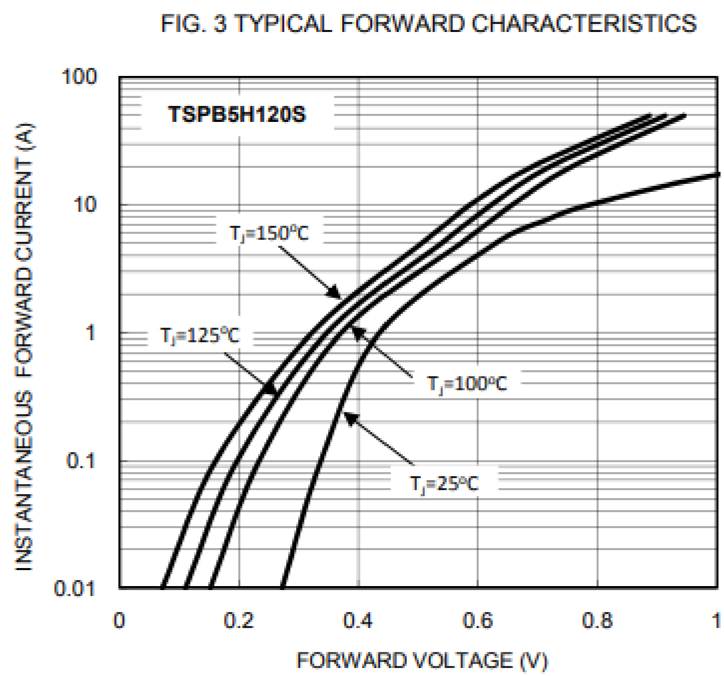

Fig. 6. V_f curves for the TSPB5H120S, a 120-V Schottky in an SMPC 4.0 package.

The main difference when second-sourcing Schottky diodes versus other diode types is that the leakage current losses can no longer be ignored and need to be compared in detail, both on the datasheet and through testing. For Schottky diodes, the P_d in the $T_j = T_a + P_d*R_{thj-a}$ equation consists of two components: $P_d = V_f*i_f + I_r*V_{br}$. The leakage current losses depend on the voltage applied, the temperature, the barrier material used and the die size. In the case where an 80-V reverse voltage is applied, a 5-mA leakage current can cause significant losses.

Reverse losses can be important, and as the voltage increases the chances of thermal runaway also increases. Compare the I_r curves at higher temperatures (Fig. 7). But realize that making I_r curves for hundreds of datasheets at high temperatures can be a tedious job. As a result, there may be datasheet errors. Compare the leakage currents measured in your actual circuit at your maximum temperature.

Understand that there may be outliers and that five samples in the lab could be insufficient. Design with enough margin that with a CpK shift of 3 sigma, for example, you will still have a functional circuit. The I_r maximum values in the datasheets are an indication but may be impractical or misleading for your design.

FIG. 6 TYPICAL REVERSE CHARACTERISTICS

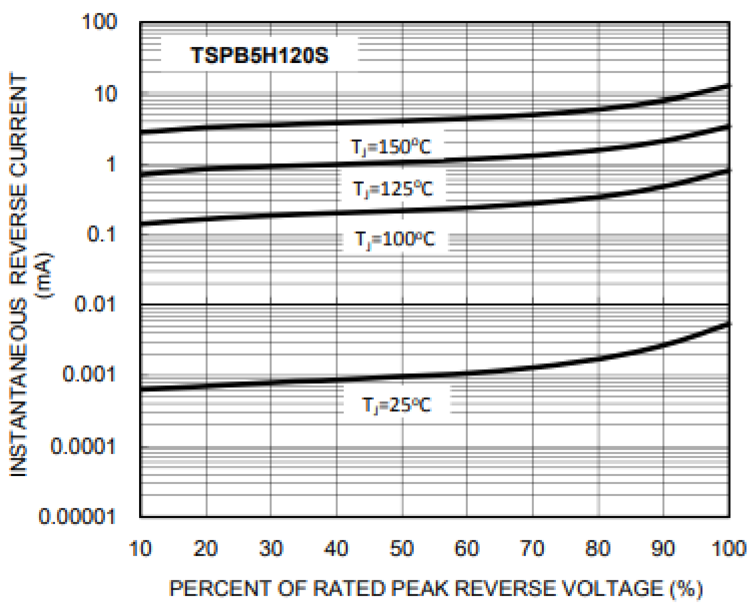

Fig. 7. Leakage current of the TSPB5H120S, a 120-V Schottky in an SMPC 4.0 package.

In contemplating reverse losses designers are encouraged to take the path of conservative design, especially when the Schottky diode is not heatsinked. An example of a conservative design would be to limit the temperature on the PCB to 90°C or 95°C at the product's expected maximum ambient temperature. Checking this with an IR camera is always recommended. If something is running hot in the lab at 25°C or so, it will not get better when it's operating in an ambient of 40°C or 70°C in the field. A 20% derating on voltage is also a good idea.

The T_j can sometimes also be used to make lifetime calculations using FIT data and the well-known and often used Arrhenius equation.[2] But if the main losses in the intended application are in forward direction, then it needs to be noted that a design with a T_j of 149°C is not that much better than a design with a T_j of 151°C for a 150°C rated product. The FIT data maybe just a little bit lower but neither design will offer zero defects. This gives insight and perspective to the concept of maximum T_j.

In recent years, most new Schottky products that have been released have a unique die source per part name. This was not the case in the past, when there was a so-called "prime bin" process, and products that did not meet the original specification were downgraded. As an example, a 40-V part was sold as 30 V, 60 V as 50 V, 100 V as 90 V and so forth.

Note that the V_f rating of a Schottky diode is very dependent on the breakdown voltage. So, if a product has the same V_f specification as another part, but a different voltage, then the higher-voltage part is the prime bin. PAT testing, which uses statistical methods to assure parts meet the specifications, should eliminate reliability concerns about the lower voltage parts. This information, which can be requested from the Schottky supplier, may help you when faced with a supply chain issue.[3]

A Schottky diode has a major influence on the efficiency of your circuit so it should always be considered carefully and measured. The EMI performance will be different in circuit and obviously needs to be retested. If your product was tested and qualified—certified for EMI-RFI-EMC—and you replace the part with something else, non-compliance issues can occur. A comparison of the capacitance curves is a good start. However, applying pre-compliance EMC test methods and looking at the ringing waveforms across the device with an oscilloscope should be employed before and after changing parts.

Planar And Trench Technology

Trench Schottky diodes are a very different technology than planar diodes (Fig. 8). They have a better (lower) V_f for a given die size or a lower I_r for a given V_f (versus a planar diode). Their capacitance is usually higher, which may increase losses but also reduce EMI. In addition, they have a different temperature coefficient.

Mixing planar and trench Schottky diodes makes cross referencing more complicated. The advantages of a trench Schottky become clearer at higher voltages. They result in V_f specifications at 120 V+ that planar products cannot meet.

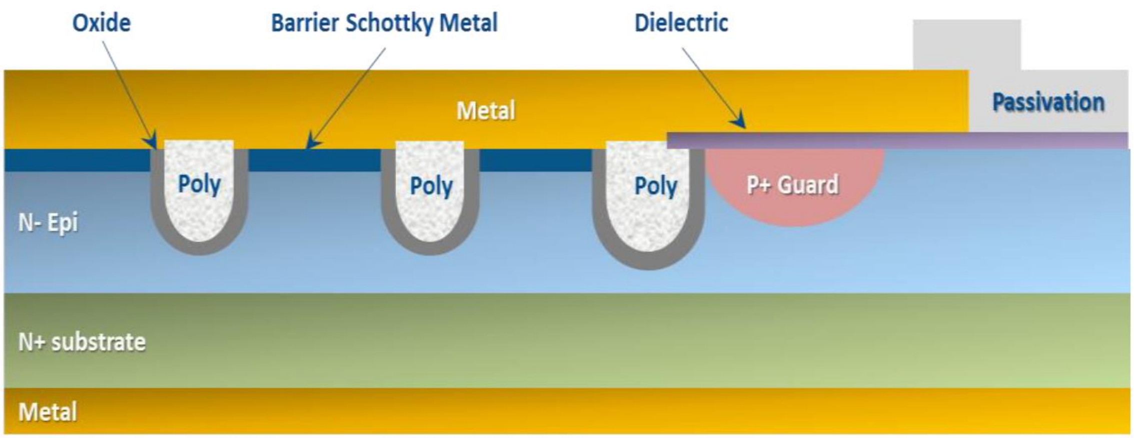

Fig. 8. The trench Schottky structure.

Packaging

From a static thermal runaway perspective, some packages are worse than others. The SMC package is one of the worst when it comes to static thermal runaway. It can handle very big die, which leads to large leakage currents and reverse losses, yet it also suffers from a poor heat conduction path. With a larger R_{thj-l} thermal resistance inherent in the long leads within the package, it results in a larger delta T_j. This combined with the recommended soldering pad layouts (which can be quite small) leaves you with the worst conditions for static thermal runaway possible in this package.

Many Schottky diodes are available with a T_j rating of 125°C. If the cause of the T_j rating is static thermal runaway during an HTRB test due to a low barrier height, then the designer should take this into account. If the application runs at a lower ambient temperature and there is no risk of thermal runaway, good and reliable designs can be achieved with Schottky diodes rated at 125°C.

Packages with exposed pads help Schottky rectifier technology the most. When reducing packages sizes, one needs to distinguish between applications where transient thermal impedance (surges) are the most critical and those where steady-state power dissipation is more critical.

Usually TVS diodes and standard rectifiers used in ac-dc conversion at lower power are driven by transient thermal impedance demands. The existing die can be put in a smaller package while keeping the surge performance needed without issues. This is different with Schottky diodes. In most applications there is significant continuous power dissipation thus, thermal resistance is critical. As the thermal resistance is mainly determined by the size of the solder pads and the PCB used (number of layers, copper thickness thermal vias etc.) the use of smaller packages is more limited, although the reduced height can be of interest.

The exception are the new packages with exposed pads. Their reduced R_{thj-l} gives a meaningful contribution in the reduction of the junction temperature when keeping the PCB temperature limited to 90°C or 95°C. This can be best visualized by looking at the construction of the package as illustrated in Fig. 9.

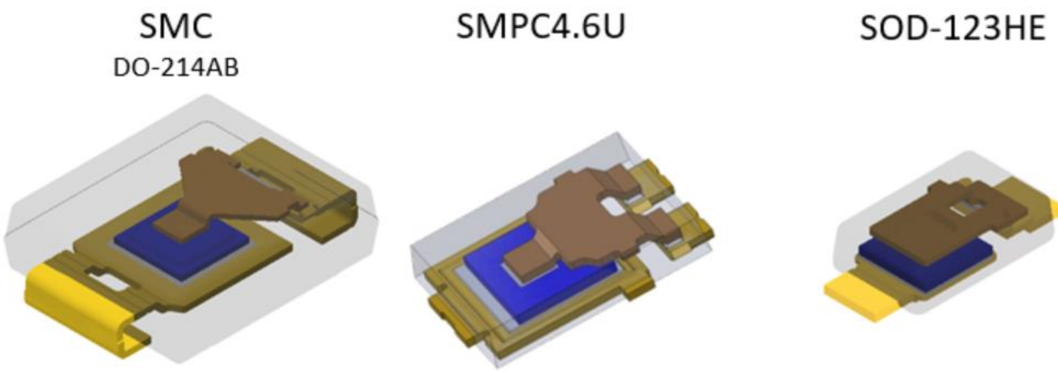

Fig. 9. Drawing of typical Schottky packages.

Every mm of lead length adds to the thermal resistance R_{thj-l}. Therefore, if you look at the SMC package as an example, the distance the heat must travel to the PCB is quite long. In contrast, packages such as the SOD123HE and SMPC4.6U which have lower thermal resistances, are ideally suited to Schottky and Trench Schottky technology. Keeping component and PCB temperatures below 90°C to 95°C is critical for meeting UL and other safety agency certifications for your power design.

Conclusion

Every designer should evaluate whether or not thermal runaway is a potential problem in their design. If it is not, Schottky diodes rated at a lower T_j of 150°C may not only produce more efficiency but also a more reliable design and lower operating temperatures. When the possibility of thermal runaway exists, it is necessary to perform a careful analysis of the device in the intended application. It cannot be assumed that two different diodes will behave in a similar way.

Special care needs to be taken when second sourcing Schottky rectifiers in this case using not only datasheet comparisons, but also in-circuit electrical and thermal measurements. The latter should include thermal IR imaging of the PCB under worst-case conditions. As always, it is encouraged and recommended that you utilize your Schottky rectifier supplier's field applications engineering team to help answer questions in the actual application and use case conditions.

References

1. "The Coffin-Manson Mechanical Crack Growth Model," explained in the Engineering Statistics Handbook, found under "Other Models".
2. "Arrhenius" model, explained in the Engineering Statistics Handbook.
3. "A Guide To Second Sourcing Rectifiers" by Jos van Loo and Kevin Parmenter, How2Power Today, January 2020.

About The Authors

Jos van Loo is a technical expert on power semiconductors with more than 30 years' experience. In his role as technical support engineer at Taiwan Semiconductor Europe, Jos consults with customers on rectifiers, MOSFETs and power management ICs.

Kevin Parmenter is an IEEE Senior Member and has over 20 years of experience in the electronics and semiconductor industry. Kevin is currently director of Field Applications Engineering North America for Taiwan Semiconductor. Previously he was vice president of applications engineering in the U.S.A. for Excelsys, an Advanced Energy company; director of Advanced Technical Marketing for Digital Power Products at Exar; and led global product applications engineering and new product definition for Freescale Semiconductors AMPD - Analog, Mixed Signal and Power Division. Prior to that, Kevin worked for Fairchild Semiconductor in the Americas as senior director of field applications engineering and held various technical and management positions with increasing responsibility at ON Semiconductor and in the Motorola Semiconductor Products Sector. He holds a BSEE and BS in Business Administration.

For further reading on designing with rectifiers, see the How2Power Design Guide, and locate the Component category and select "Diodes and Rectifiers."