Whitepaper

The science of thermal stability: Ensuring optimal performance in reverse-biased diodes

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Diodes are commonly used in rectifier and power conversion applications where they are required to operate as reverse bias. The self-heating, caused by the leakage current that occurs when a diode operates in reverse bias, critically impacts its ability to function safely. The boundary conditions within which a diode can safely operate are called the safe operating area (SOA). When using a diode in rectifier applications, the device must stay within its SOA with a sufficient safety margin to ensure robust and reliable operation. This is especially important in high-power density (and therefore high temperature) automotive applications where occupant safety is paramount.

This white paper examines the thermal stability of reverse-biased diodes and explores the concept of thermal runaway. It also demonstrates how to calculate the SOA of a diode before discussing the factors which influence the thermal limits of devices in rectifier applications, including technology and package types.

The diode as a thermal system

Apart from self-heating caused by leakage current, the thermal stability of a diode in reverse bias also depends on its ability to dissipate this heat via the thermal resistance of the system in which it operates. In thermal equilibrium, the junction temperature of a device can be described using the following equation, in which a fixed ambient temperature T_a is considered thermal 'ground':

$$T_j = R_{th(j\text{-}a)} \times P_{dissipated} + T_a$$

$R_{th(j-a)}$ is the thermal resistance between the junction and ambient environment, and $P_{dissipated}$ is the amount of power dissipated in the device. A steady state condition is arrived due to the two competing processes shown in Figure 1.

1. The capacity of the thermal system to dissipate heat through the thermal resistance (denoted by the petrol line).
2. The self-heating of the device generated by reverse leakage current (and potential switching losses), where the level of leakage current increases in line with junction temperature (denoted by the orange line).

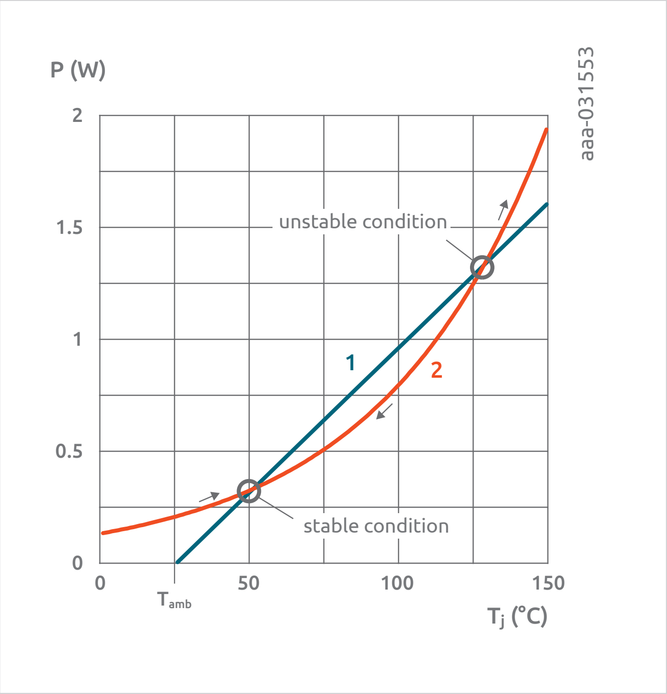

Figure 1. Steady-state thermal equilibrium operating condition

The petrol line (representing dissipated power) intersects the x-axis at the ambient temperature and then rises with a slope proportional to the system's thermal conductance ($1/R_{th}$). The generated power caused by the diode's leakage current (orange line) rises exponentially with increasing junction temperature. The coordinates of the point of intersections of the two curves are thermal equilibrium conditions. The first point of intersection corresponds to a stable thermal equilibrium for the system. Here, as long as the power generated through device self-heating is lower than that dissipated, the junction temperature will decrease and converge toward a thermally stable operating condition. However, if more power is generated than can be dissipated (the point of intersection in the graph representing an unstable condition), the device junction temperature will continue to increase, eventually becoming thermally unstable in a process referred to as 'thermal runaway'. As a result, the device will continue to draw more current until it fails due to thermal overstress.
Figure 2 shows an x-ray image of a device that has failed due to thermal runaway.

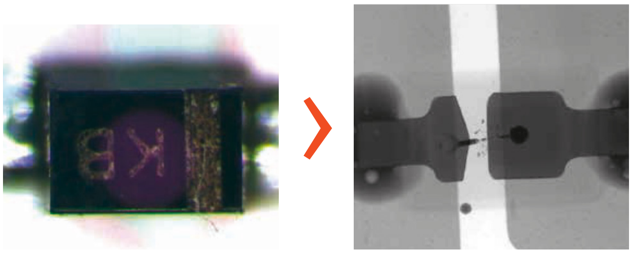

Figure 2. Device failure due to thermal runaway

Here, the damage was caused by the fusing current of the bond wire being exceeded. However, for a clip-bond packaged device, thermal overstress would destroy the semiconductor die. The apparent discolouration of the epoxy moulding compound demonstrates the high level of heating which occurred.

The system's safety margin is the temperature gap between stable and unstable conditions. As ambient temperature increases, the safety margin shrinks until the stable and unstable equilibrium conditions coincide (Figure 3) at the point where the conditions for thermal runaway are satisfied:

$$\frac{dP_{generated}}{dT} = \frac{1}{R_{th}}$$

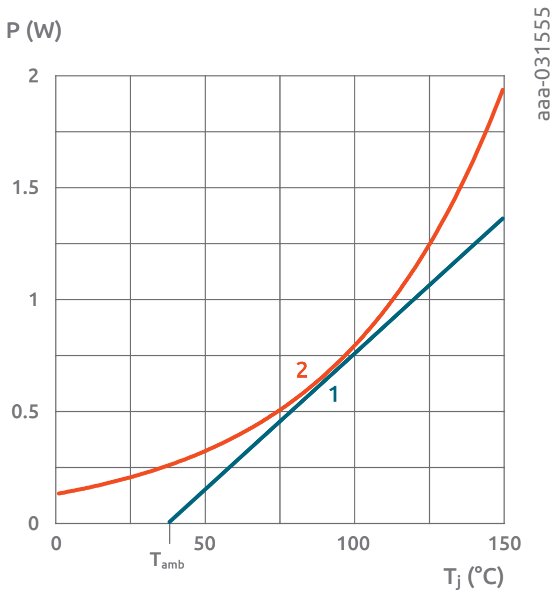

Figure 3. Continuously rising ambient temperature lowers the thermal safety margin and increases the risk of thermal runaway

The limits of the thermal runaway condition define the safe operating area of a diode in reverse bias. For a given reverse bias voltage, V_R, the corresponding leakage current, I_R, is measured over junction temperature. By applying the formula:

$$\frac{dP_{generated}}{dT} \times R_{th} \geq 1 \; (with \; P_{generated} = V_R \times I_R)$$

the temperature limit for thermal runaway can be calculated at each reverse bias point for a given thermal resistance (R_{th}). This equation is illustrated graphically in Figure 4, which shows the maximum thermally stable reverse voltage for a diode based on its junction temperature.

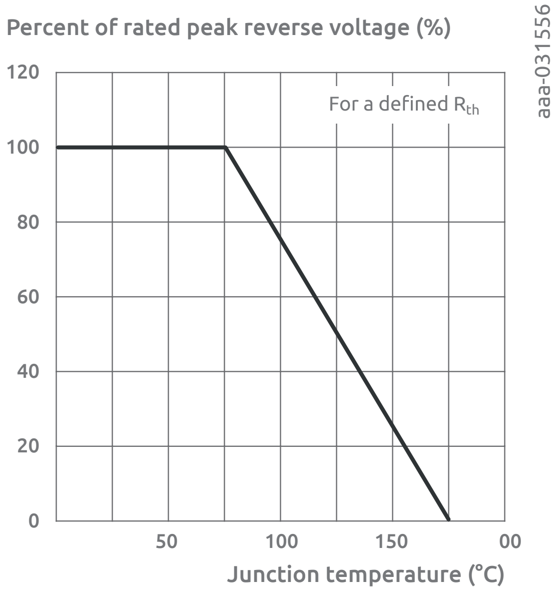

Figure 4. Relationship between maximum reverse voltage and junction temperature of a diode

In practice, the SOA graph is used as follows:
The required maximum reverse voltage determines the maximum junction temperature for a given application, where a product's $R_{th(j\text{-}a)}$ is known. The generated power can be calculated by taking into account the leakage current of the device at the given reverse voltage and junction temperature (as stated in the device datasheet). The maximum allowable ambient temperature can be easily calculated from:

$$T_{amb\_max} = T_{j\_max} - P_{dissipated} \times R_{th(j\text{-}a)}$$

How device technology affects SOA

A diode's SOA is strongly impacted by thermal resistance according to the following formula:

$$\frac{dP_{generated}}{dT} = \frac{1}{R_{th}}$$

Consequently, the SOA can be increased using packages with a low junction-to-solder-point thermal resistance $Rth_{(j\text{-}sp)}$ or PCBs and substrates with better thermal properties, e.g. ceramic PCBs. The semiconductor technology used to construct a diode also impacts its SOA, as the reverse leakage current is responsible for the generated power at a given bias point. When comparing the leakage current of different technologies, it is better to use the current density rather than the actual leakage current. This approach eliminates the impact of die size and enables a like-for-like comparison of different technologies. Figure 5 shows the relationship between leakage current density and junction temperature for five different diode technologies (at a reverse bias voltage of 100 V), including:

- 100 V low leakage current planar Schottky;
- 100 V low V_f planar Schottky;
- 200 V hyperfast recovery diode;
- 120 V SiGe (silicon germanium) diode
- 100 V Trench Schottky

This graph can be interpreted as follows:

- As expected, the low V_f Schottky diode (constructed with a low work function metal) exhibits the highest leakage current
- In contrast, the leakage current density of the low leakage planar Schottky device is two orders of magnitude lower, demonstrating the exponential impact of the barrier height on the leakage current
- The hyperfast recovery diode also has low leakage current density
- Interestingly, the leakage current density for the novel SiGe diode technology is the same as that of the hyperfast recovery diode
- The Trench Schottky technology exhibits a higher reverse leakage current density than the low leakage planar Schottky (due to its trench construction).

A decisive factor in determining the thermal stability of a diode in reverse bias is not the actual leakage current but the increase in the rate of leakage current over temperature. To help better understand this, Figure 6 shows the derivates of the graphs shown previously in Figure 5 with respect to temperature. The exponential nature of the reverse leakage current density over temperature means these derivative graphs are also exponential and, therefore, linear on a logarithmic scale. Nonetheless, the device order remains the same, with SiGe and hyperfast technologies showing the greatest potential for thermal stability, while the low V_f planar Schottky has the least.

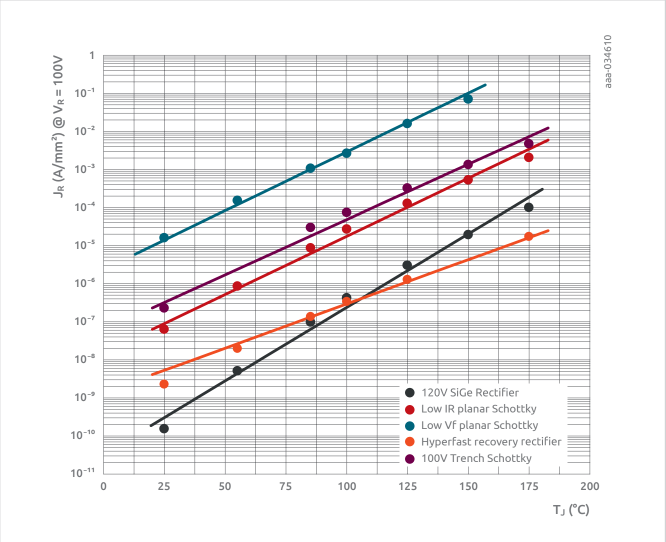

Figure 5. Leakage current density of five different rectifier technologies measured at 100 V

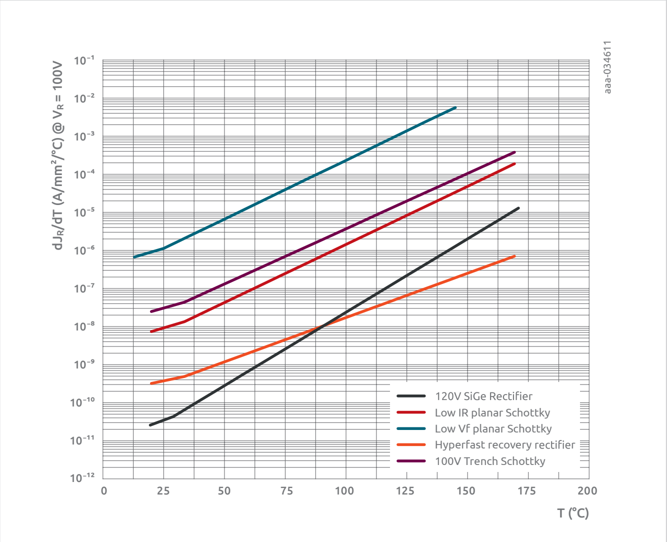

Figure 6. Derivative of leakage current density at 100 V reverse bias with respect to junction temperature

How package type affects SOA

When examining the influence of package type on the SOA of a diode constructed from a specified technology, it is again necessary to use normalized currents (to negate the effect of crystal sizes). Consequently, thermal resistance must also be normalized. For this purpose, the thermal resistance is normalized with respect to the footprint of the package. This approach allows a stability factor to be calculated for a given reverse bias voltage as follows:

$$\frac{dJ_R}{dT} \times V_R \times R_T$$

A system remains thermally stable if the value calculated using this equation is less than 1. Conversely, systems with values greater than 1 will eventually become thermally unstable. Figure 7 shows the stability limits for different technologies in SOT23 packaging. In this comparison, the $R_{th(j\text{-}a)}$ of a SOT23 on a standard footprint and a single-layer PCB has been normalized with respect to the recommended footprint area of SOT23. This states that for these operating conditions, a planar low V_f Schottky diode in 100 V reverse bias can only be operated up to a maximum junction temperature of 41 °C to prevent thermal runaway from occurring. On the other hand, the SiGe diode and the hyperfast recovery diode can support junction temperatures over 150 °C while maintaining thermal stability.

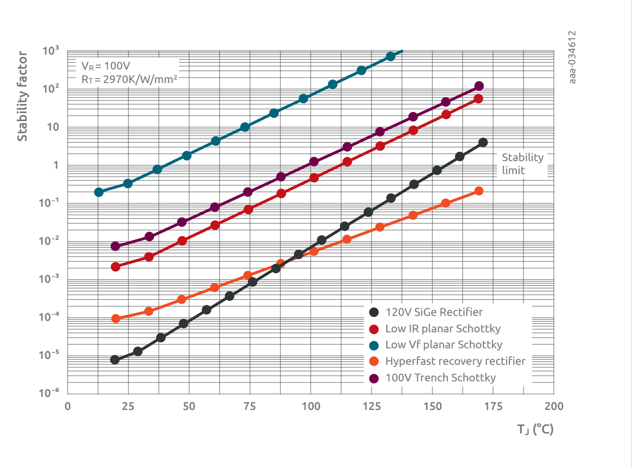

Figure 7. Stability factors for different technologies in SOT23 package at 100 V reverse voltage

Figure 8 shows the results of a similar exercise performed on a DFN1110D-3 (SOT8015) package. Here, the stability limit for the planar low V_f Schottky technology at 100 V reverse voltage is shifted upwards to Tj=62 °C. This result highlights the excellent thermal behaviour of the DFN package. Note that while the absolute value of its junction-to-ambient thermal resistance is larger than that of a SOT23 package, DFN has a much smaller footprint.

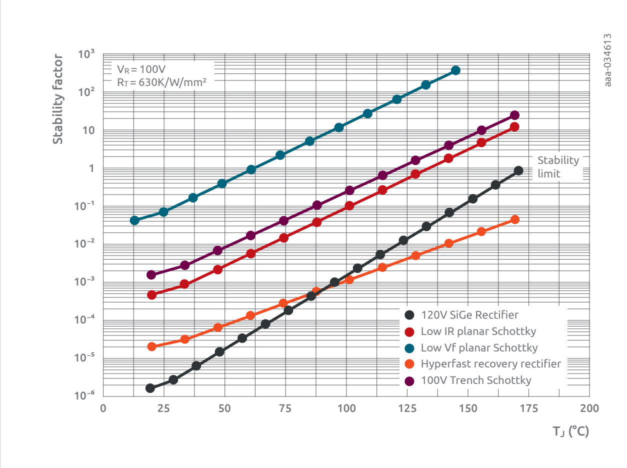

Figure 8. Stability factors for different technologies in DFN1110D-3 (SOT8015) package at 100 V

Conclusion

Diodes are commonly used in rectifier applications which require them to operate in reverse bias, where they are sensitive to temperature. Ensuring a diode operates in its SOA requires understanding its thermal behaviour. This white paper examines the thermal stability of reverse-biased diodes and explores the concept of thermal runaway. It also demonstrated how to calculate the SOA of a diode before discussing the factors which influence the thermal limits of devices in rectifier applications, including technology and package types. SiGe technology bridges the gap between hyperfast and Schottky diodes, showing a better trade-off between the leakage current (corresponding to SOA) and forward voltage drop. SiGe rectifiers show excellent robustness against surge currents which can occur in automotive applications.

About Nexperia

Headquartered in the Netherlands, Nexperia is a global semiconductor company with a rich European history and over 15,000 employees across Europe, Asia, and the United States. As a leading expert in the development and production of essential semiconductors, Nexperia's components enable the basic functionality of virtually every electronic design in the world – from automotive and industrial to mobile and consumer applications. The company serves a global customer base, shipping more than 100 billion products annually. These products are recognized as benchmarks in efficiency – in process, size, power, and performance. Nexperia's commitment to innovation, efficiency, sustainability, and stringent industry requirements are evident in its extensive IP portfolio, its expanding product range and its certification to IATF 16949, ISO 9001, ISO 14001 and ISO 45001 standards.

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