AN90015

Reverse bias Safe Operating Area (SOA) of rectifiers

Rev. 1.0 — 20 May 2020 application note

Document information

Information	Content
Keywords	Safe Operating Area (SOA), rectifiers, thermal runaway, thermal equilibrium, SiGe rectifier
Abstract	This application note explains what is the thermal runaway of a rectifier, demontrates the calculation of the SOA and describes the main factors influencing the thermal limits of a rectifier.

1. Introduction

Operating a rectifier within its safe operating area (SOA) with a sufficient safety margin is crucial for a robust design, especially at the high ambient temperatures seen in high-power density or high-temperature automotive applications . This application note explains what is the thermal runaway of a rectifier, demontrates the calculation of the SOA and describes the main factors influencing the thermal limits of a rectifier.

2. Rectifier as a thermal system – thermal runaway

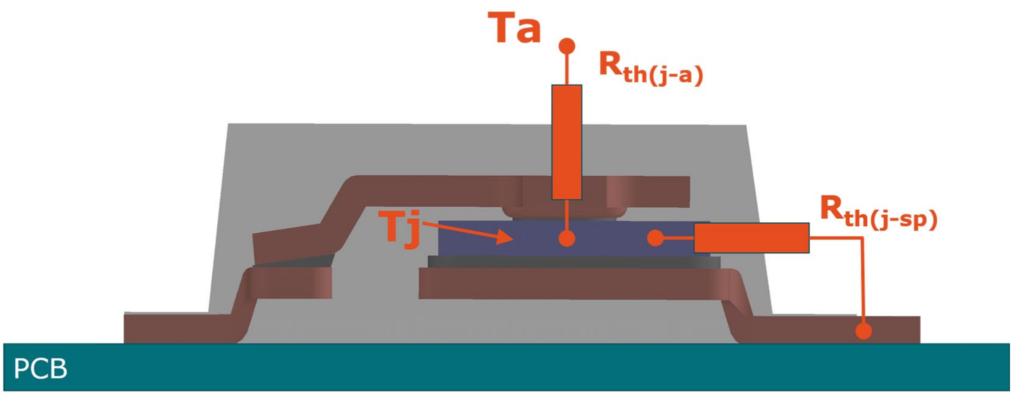


Fig. 1. Definition of thermal resistances in a clip-bond package

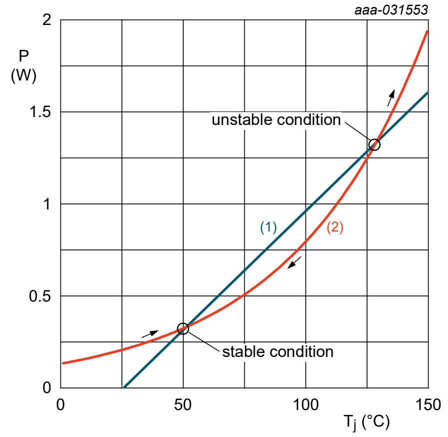
The thermal stability of a rectifier in reverse direction is determined by the interaction of its leakage current which causes self-heating, and the capability of the rectifier to dissipate this heat through the thermal resistance in the system. In thermal equilibrium, the junction temperature of the device can be described as follows with a fixed ambient temperature T_{amb} as thermal ground:

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

where $R_{th(j\text{-}a)}$ is the thermal resistance between junction and ambient and $P_{dissipated}$ is the amount of dissipated power in the device.

The equilibrium condition as illustrated in Fig. 2 is the outcome of two parallel processes:

1. The capability of the thermal system to dissipate heat through the thermal resistance (graph (1))
2. The self heating of the rectifier ($P_{generated}$) caused by its own reverse leakage current (graph (2)) and by possible switching losses, with increasing leakage current over the junction temperature



(1) dissipated power

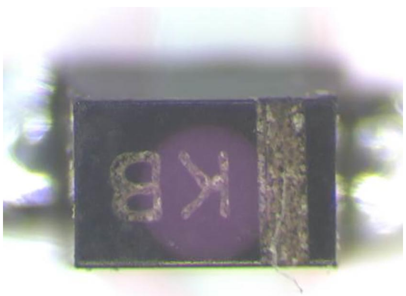
(2) generated power (self-heating)

values of x and y axes are exemplary

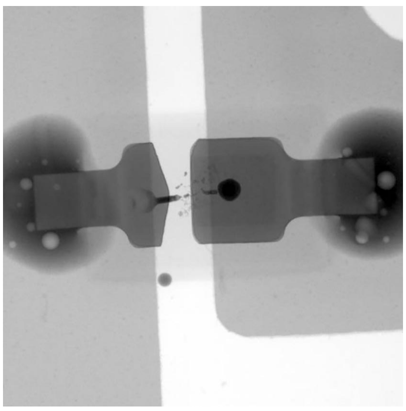
Fig. 2. Thermal equilibrium: the intersections of the graphs are the coordinates for an equilibrium condition

As shown in Fig. 2, the curve representing the dissipated power intersects the x-axis at ambient temperature and then rises with a slope which is proportional to the thermal conductance ($1/R_{th}$) of the system. As the leakage current increases exponentially over temperature, the generated power caused by the leakage current of the diode increases exponentially when the junction temperature increases. The intersections of the two graphs give the coordinates for an equilibrium condition. The first intersection corresponds to the stable operation of the system (stable condition). As long as the generated power through self-heating is smaller than the dissipated power, the junction temperature of the device decreases and, in thermal equilibrium, converges toward a stable condition. This model also explains the heating-up of the device when the system is switched on, as the junction temperature converges to the stable condition (arrow pointing to the stable condition in Fig. 2).

However, if more power is generated than dissipated (intersection representing unstable condition) the junction temperature increases until the device eventually becomes thermally unstable. This is termed 'thermal runaway'. The device will draw more and more current until it fails completely due to thermal overstress. Fig. 3 shows an x-ray picture of a device which has failed due to thermal runaway. In this case, the fusing current of the wire bond has been exceeded. In the case of clip-bond packages, the die itself would be destroyed by thermal overstress. The discoloration of the epoxy molding compound testifies to the high heat experienced by the device.



a. Epoxy molding compound discolored through the heat

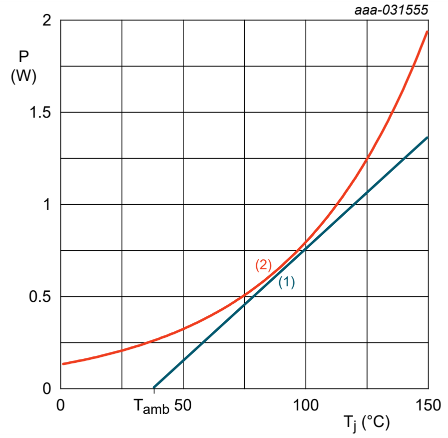


b. X-ray: fusing current of the wire bond has been exceeded

Fig. 3. Failed device due to thermal runaway

The temperature gap between stable and unstable operation is the safety margin of the system. As shown in Fig. 4, with an increase of ambient temperature, this safety margin shrinks until the stable and the unstable conditions coincide.

This is obviously the case when the condition $\frac{\Delta P_{generated}}{\Delta T} > \frac{1}{R_{th}}$ occurs.



(1) dissipated power

(2) generated power

Fig. 4. Thermal runaway: no stable condition

3. SOA of a rectifier in reverse direction

The limits given by the thermal runaway condition define the Safe Operating Area (SOA) of a rectifier in reverse direction. For each reverse bias voltage V_R, the corresponding leakage current I_R is measured over junction temperature by applying the formula:

$$\frac{\Delta P_{generated}}{\Delta T} \times R_{th} \geq 1 \text{ (with } P_{generated} = V_R \times I_R\text{)}$$

The temperature limit for thermal runaway can be calculated for each reverse bias point for a given R_{th}. The graph resulting from this calculation shows the maximum thermally stable reverse voltage for a rectifier based on its junction temperature (Fig. 5). For a given R_{th}, the derating curve defines the maximum reverse voltage the rectifier can withstand before going into thermal runaway.

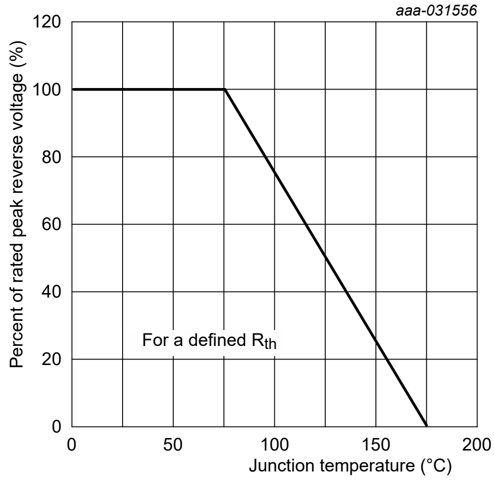


Fig. 5. Maximum reverse voltage as a function of junction temperature

In practice, the SOA graph in Fig. 5 is used as follows:

for a given application with known $R_{th(j-a)}$ of the product, the requested maximum reverse voltage defines the maximum junction temperature according to this graph.

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 given in the rectifier datasheet. Finally, the maximum allowable ambient temperature can be calculated:

$$T_{amb(max)} = T_{j(max)} - P_{generated} \times R_{th(j-a)}$$

4. Main factors influencing the SOA of a rectifier

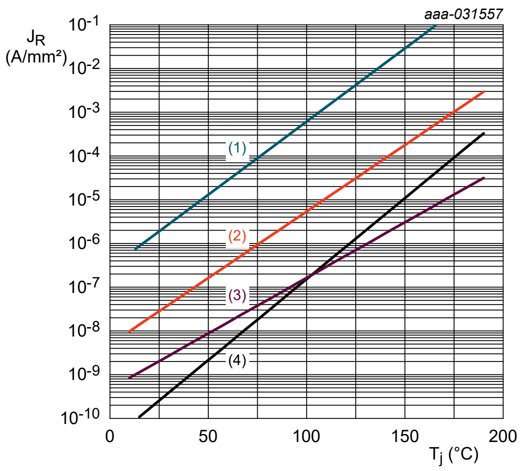
As described in Section 3 and according to the formula $\frac{\Delta P_{generated}}{\Delta T} \geq \frac{1}{R_{th}}$, the thermal resistance of the system has a strong impact on the SOA of a rectifier. As a result, the SOA of a rectifier can be extended by using products in packages with a low junction-to-solder-point thermal resistance $R_{th(j\text{-}sp)}$, and/or by using Printed-Circuit Boards (PCB) or substrates with improved thermal properties, e.g. ceramic PCBs.

The impact of the chosen rectifier technology on the SOA is another important aspect, because the generated power is caused by the reverse leakage current of the rectifier at a given bias point. In order to compare the leakage current of different technologies, it makes sense to use the leakage current density rather the leakage current itself (see Fig. 6). This method eliminates the impact of the die size. The graphs in Fig. 6 show the behavior of the leakage current density of four different products depending on the junction temperature.

The chosen products are as follows:

- 100 V Schottky rectifier with a barrier height (φ_B) of 805 meV
- 100 V Schottky rectifier with a barrier height of 665 meV
- 200 V hyperfast recovery rectifier
- Nexperia's novel 120 V Silicon Germanium (SiGe) rectifier

The leakage current is measured at V_R = 60 V, with a margin of more than 40 V until the breakdown voltage, therefore the leakage current is barely affected by the breakdown. In a first approximation, the leakage current at this bias point is mainly dominated by the intrinsic leakage rather than by effects at the cell termination.



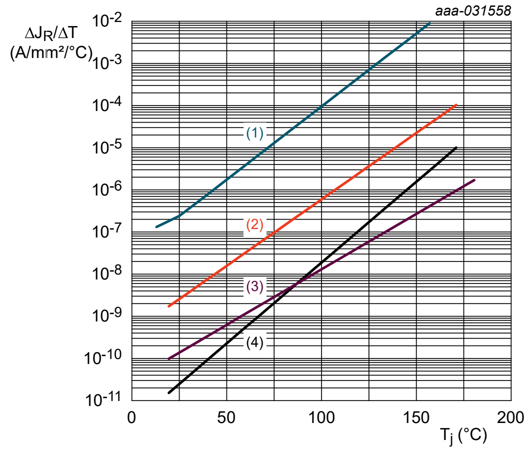
V_R = 60 V
(1) 100 V Schottky rectifier; φ_B = 665 meV
(2) 100 V Schottky rectifier; φ_B = 805 meV
(3) 200 V hyperfast recovery rectifier
(4) 120 V SiGe rectifier

Fig. 6. Leakage current density as function of temperature: comparing SiGe rectifier to Schottky rectifiers with two different barrier heights and a hyperfast recovery rectifier

The highest leakage current density is observed for the Schottky rectifier with the low barrier height. Leakage current density decreases by two orders of magnitude if the barrier height is increased from 665 meV to 805 meV. The lowest reverse current density is achieved by the hyperfast recovery rectifier (an even lower leakage current can be expected for recovery rectifiers with standard switching speeds, not shown in this comparison). Interestingly, the leakage current density for the novel SiGe rectifier technology is at the same level as for the hyperfast recovery rectifier.

The decisive factor in determining the thermal stability of the rectifier in reverse direction is the increase rate of the leakage current over temperature. Therefore the graphs in Fig. 6 have been differentiated with respect to temperature, resulting in Fig. 7.

Due to the exponential progress of the reverse leakage current density over the temperature, its derivative is also exponential and therefore linear on a logarithmic scale. Taking into account the well-known trade-off between the reverse leakage current and the forward voltage drop of a rectifier, SiGe rectifiers represent the best compromise in terms of thermal stability (leakage current) and the efficiency (forward voltage drop).



V_R = 60 V

(1) 100 V Schottky rectifier; φ_B = 665 meV

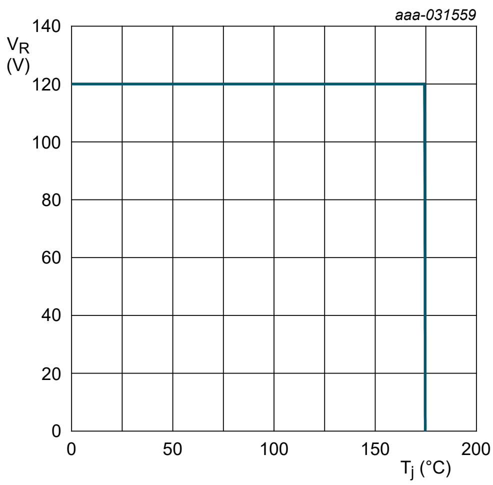
(2) 100 V Schottky rectifier; φ_B = 805 meV

(3) 200 V hyperfast recovery rectifier

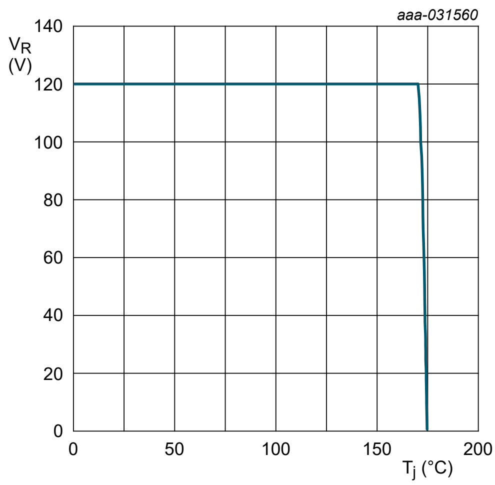
(4) 120 V SiGe rectifier

Fig. 7. Derivative leakage current density as function of temperature: comparing SiGe rectifier to Schottky rectifiers with two different barrier heights and a hyperfast recovery rectifier

As an example, the resulting SOA for Nexperia SiGe rectifier PMEG120G20ELR is illustrated in Fig. 8 for two different thermal resistances: optimal PCB with R_{th} = 18 K/W and standard footprint with R_{th} = 220 K/W. Even on the standard footprint, the SiGe rectifier can provide its full maximum reverse voltage up to almost 175 °C junction temperature, without going into thermal runaway.



a. Optimal PCB with R_{th} = 18 K/W



b. Standard footprint with R_{th} = 220 K/W

Fig. 8. PMEG120G20ELR: Derated maximum reverse voltage as a function of junction temperature; typical values

5. Summary

The consideration of the safe operating area of the rectifier in high-temperature applications is crucial for a robust design. The condition for thermal runaway is fulfilled if the term $\frac{\Delta P_{generated}}{\Delta T} \geq \frac{1}{R_{th}}$ is met. Apart from the thermal resistance of the system, the applied rectifier technology contributes to the thermal stability of the device. Nexperia's novel SiGe rectifiers demonstrate excellent thermal stability up to almost the maximum junction temperature.

6. Revision history

Table 1. Revision history

Revision number	Date	Description
1.0	2020-05-20	Initial version

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List of Tables

List of Figures

Contents

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Date of release: 20 May 2020