Design with low-barrier Schottky diodes

About this document

Scope and purpose

This application note explores the implications of using low-barrier Schottky diodes. A simple mathematical toolbox was developed to facilitate the leakage current and junction temperature calculations from readily available data. The importance of self-heating due to leakage current was then evaluated for both static (high temperature reverse bias/HTRB-like) and dynamic (converter use) cases. Based on this analysis, design recommendations are summarised in the last part of this document.

Intended audience

Designers of power electronic equipment

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1 Schottky diode self-heating

The demand for more efficient power conversion has brought about significant advances in power devices. Schottky diodes have been also optimized to reduce losses, by reducing the major contributor to the loss budget – the conduction losses. This optimisation targets reducing the Schottky barrier height, which directly translates into reduced forward voltage V_F. This however is inextricably associated with increased leakage current, making these devices more sensitive to thermal runaway when operating at elevated junction temperatures and voltages.

This application note develops a practical toolbox for evaluating the thermal runaway conditions starting from data available in the datasheet. It then explores the corner cases of usage and concludes with design recommendations.

1.1 Junction temperature and leakage and conduction losses

The leakage current I_R flows from the cathode to the anode of the diode when the latter is reverse biased and exponentially depends on the junction temperature T_J:

$$I_R = I_{REF} e^{C_T (T_J - T_{REF})} \quad \text{(Eq. 1)}$$

where I_{REF} is the leakage current at a junction temperature T_{REF}, here 25°C for a given bias voltage. This can be obtained from the datasheet, see **Figure 1**.

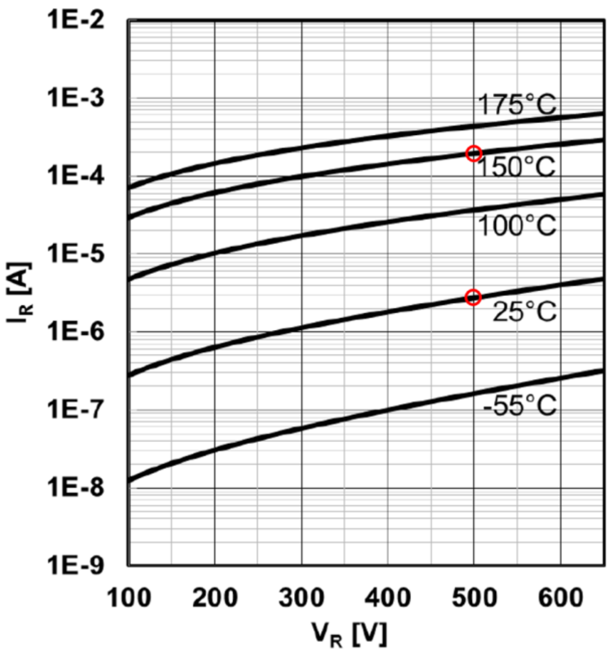

Figure 1 Datasheet plot of leakage current vs. reverse voltage

The temperature sensitivity coefficient C_T can be derived (Eq. 2) from the datasheet semi-log graph that relates the leakage current to the reverse voltage, parametrised for a range of junction temperatures (Figure 1).

$$C_T = \frac{1}{T_{REF2} - T_{REF1}} \ln\left(\frac{I_R @ T_{REF2}}{I_R @ T_{REF1}}\right) \quad [K^{-1}] \quad \text{(Eq. 2)}$$

where I_{REF1} is the leakage current taken for the junction temperature at T_{REF1}, with a second pair (I_{REF2}; T_{REF2}) taken at the same bias voltage V_R at a lower temperature. An example datapoint pair (150°C/200 µA; 25°C/3 µA at

500 V) is indicated in Figure 1 for the device IDDD20G65C6 [1] with the red dots. This data pair results in a temperature sensitivity coefficient of $C_T = 0.034\ K^{-1}$.

The junction temperature will depend on the thermal resistance R_{TH_JA}, the ambient temperature T_{AMB} and the diode losses according to Eq. 3:

$$T_J = R_{TH\_JA}(V_R I_R + P_{COND}) + T_{AMB} \qquad \text{(Eq. 3)}$$

where $V_R{*}I_R$ is the losses attributed to leakage (diode off-state) and P_{COND} is the losses associated with conduction (diode on-state).

Substituting Eq. 3 into Eq. 1 results in the expression relating the leakage current to the thermal and electrical/loss operating point of the diode:

$$I_R = I_{REF} e^{C_T[T_{AMB} - T_{REF} + R_{TH\_JA}(V_R I_R + P_{COND})]} \qquad \text{(Eq. 4)}$$

The off-state voltage V_R has a rather linear effect on the leakage current and is fairly independent of the thermal operating point – the lines in Figure 1 are parallel for each temperature point. We can also add the effect of increasing off-state voltage by multiplying Eq. 4 with a dedicated term:

$$C_V = 1 + a_V(V_R - V_{REF}) \qquad \text{(Eq. 4a)}$$

A linear curve fit to any of the curves in Figure 1 will yield a leakage current sensitivity of $a_V = 5.6$ nA/V. This investigation henceforth assumes $V_{REF} = 500$ V and the term in (Eq. 4a) equals one. Should the reverse bias voltage be different from 500 V, the term (Eq. 4a) should be integrated into the coefficient α in (Eq. 6a).

Rearranging to separate conduction from leakage losses:

$$I_R = I_{REF} e^{C_T[T_{AMB} - T_{REF} + R_{TH\_JA} P_{COND}]} e^{C_T V_R I_R R_{TH\_JA}} \qquad \text{(Eq. 5)}$$

The first term in (Eq. 5) indicates that the leakage current exponentially increases with conduction losses, scaled through the thermal impedance junction-to-ambient. The second term expresses a similar relationship; however, the losses here are dependent on the leakage current itself – a thermal runaway point therefore exists through the positive feedback in a loop "leakage current-loss-junction temperature". Such runaway could only be interrupted by zeroing the only externally accessible variable, V_R – this however is impractical in most power electronic circuits.

Increasing junction temperature thus causes exponentially increasing leakage current (Eq. 5) leading to increased losses in the diode off-state. These losses in turn cause further increase in leakage current, until an equilibrium is reached between the losses generated by leakage current and the capacity to transfer this heat to the ambient. The highest junction temperature from this point of view is thus very sensitive to the efficiency with which one can cool the diode die. Note that the thermal runaway, being dependent on the temperature within the die volume with a thermal constant up to about 100 µs, can occur rather quickly.

Eq. 5 can be rewritten in the form:

$$I_R = \alpha e^{\beta I_R} \qquad \text{(Eq. 6)}$$

with coefficients

$$\left| \begin{aligned} \alpha &= I_{REF} e^{C_T[T_{AMB} - T_{REF} + R_{TH\_JA} P_{COND}]} \\ \beta &= C_T V_R R_{TH\_JA} \end{aligned} \right. \qquad \text{(Eq. 6a)}$$

Eq. 6 is a transcendental equation with respect to the leakage current and unfortunately has no obvious closed-form solution other than:

$$I_R = -\frac{W_0(-\alpha\beta)}{\beta} \qquad \text{(Eq. 7)}$$

where W_0 is the Lambert function of order zero. A number of software packages have the function built-in, but in the interest of accessibility, it can be approximated with good precision for the purposes of this analysis with the first dozen or so terms in the Taylor expansion ($x = -\alpha\beta$) as shown below:

$$W_0(x) = \sum_{n=1}^{\infty} \frac{(-n)^{n-1}}{n!} x^n \qquad \text{(Eq. 8)}$$

Calculating the effects of the leakage current for Schottky diodes would follow quite closely the flow developed above. Use the data (Figure 1) from the diode datasheet to obtain values for the reference current I_{REF} and (Eq. 2) for C_T. Plug in the environmental variables (ambient T_{AMB} and reference T_{REF} temperatures, thermal impedance R_{TH_JA}) and operating-point variables (bus voltage V_R, conduction loss P_{COND}) in (Eq. 6). Resolve for the leakage current using (Eq. 7) or (Eq. 8). Use (Eq. 3) to calculate the junction temperature.

1.2 Static self-heating and HTRB tests

Eq. 4 (and its solution, Eq. 8) permits us to explore the design space for the Schottky diode for all relevant circumstances. One corner case is conditions without conduction losses ($P_{COND} = 0$), similar to those of the HTRB test. This test seeks to identify the robustness of the diode against thermal runaway under static conditions.

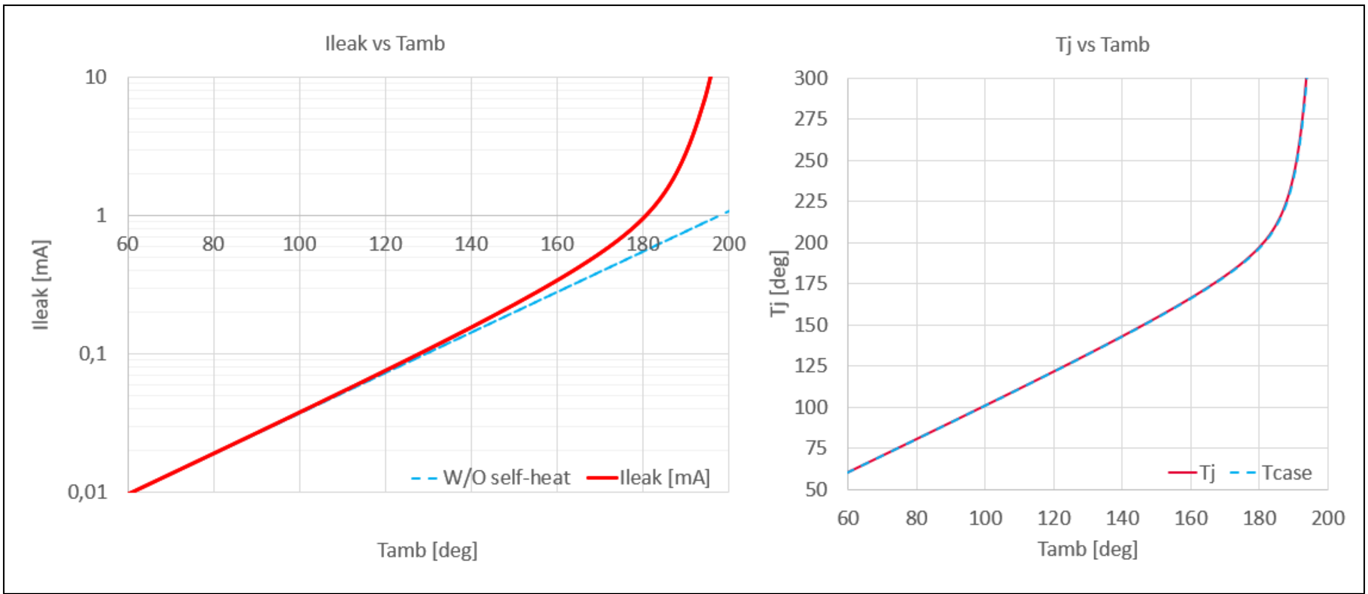

Figure 2 Evolution of leakage current and junction temperature with ambient temperature

A thermal runaway due to leakage current only is demonstrated in **Figure 2**. The left plot represents the leakage current for a thermal resistance of R_{TH_JA} = 35 K/W (device only cooled by the PCB). The broken line indicates the case where no self-heating due to leakage current is considered. Compare to this the solid line, where a runaway effect is discernible starting from an ambient temperature somewhat above 180°C. Formally, a runaway process occurs when the derivative of the function I_{LEAK} vs. T_{AMB} is above one, where small increments of T_{AMB} of only few degrees result in ever larger increases of both junction temperature and leakage current. For the curves above, this occurs consistently for junction temperatures above 250°C, assuming that such elevated temperatures do not compromise device integrity and thus (Eq. 5) is still valid. This fact does not endorse operation close to or above the maximum junction temperature; on the contrary, it demonstrates how thermally unstable the system is and calls for incorporating ample margins into the converter design.

Figure 2 also demonstrates the importance of ensuring a proper thermal interface even for static tests such as HTRB, holding the case temperature at a prescribed level in particular. Such tests should also include considerations such as inter-component heating and the means of imparting the ambient temperature to the devices in the test setup.

1.3 Dynamic self-heating

This section explores the case where both conduction and leakage current losses are present – as in a power converter. Depending on the operating point of the converter and the exact current waveforms, there is a relation between the conduction and leakage losses associated with the duty ratio of the active switch. In the analysis below (Eq. 7) is generalised by considering the losses when averaged over a switching cycle.

Figure 3 shows the diode junction temperature (left) and the repartition between leakage and conduction losses (right) for an ambient temperature T_{AMB} = 45°C. The dotted lines represent an "ideal" case with rather efficient cooling of R_{TH_JA} = 10 K/W. The dashed line represents an "end-of-life" case whereby the heatsink is underutilised – for example due to converter misplacement or an end-of-life condition with deteriorated TIM – where R_{TH_JA} = 15 K/W. The solid lines are obtained for R_{TH_JA} = 10 K/W, but the bus voltage has been increased by 10 percent. Also, the leakage current I_{REF} has been increased five times – notice that a ten-fold parameter variation is quite common for all Schottky diode types, industry-wide. This would be representative of a corner case that combines a surge condition on the converter voltage bus with unfavourable diode parameter variation.

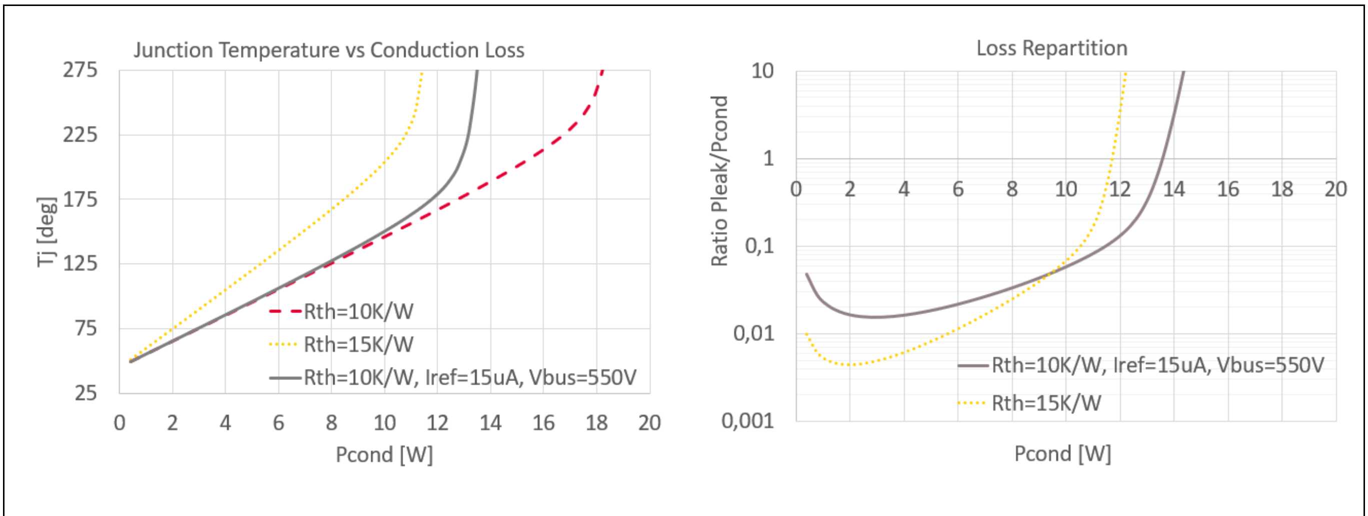

Figure 3 Junction temperature and loss repartition for operational range of conduction losses

Initially, the junction temperature follows quite closely the conduction loss increase. However, shortly after T_J = 175°C, the curves become much steeper – indicative of a thermal runaway, as demonstrated previously. The difference between the ideal case and the corner case is rather small. This indicates that the Schottky diode is fairly robust to reasonable variations about the converter operating point, provided it is operated sufficiently below the maximum junction temperature. The "end-of-life" case however brings the usable conduction losses to almost half of what the converter imposes on the diode at the moment of commissioning.

The fact that the thermal runaway is a highly unstable process is demonstrated with the curves on the right: the positive feedback effect commences when the losses attributed to leakage current are less than 10 percent of the conduction losses. Notice that nominal operation tolerates a leakage loss around 1 percent of the diode losses. The spacing between the two conditions is relatively narrow and is characteristic for all Schottky diodes, whether Si or SiC, that have been optimised for low forward voltage drop.

2 Summary and recommendations

Schottky diodes are known to have larger leakage currents than comparable voltage class PIN diodes. Nevertheless, they offer considerable advantages on a converter level by avoiding reverse recovery and switching losses whereby the resulting designs have smaller EMI, passives and heat management components. Further loss reductions can be seen in the latest generations of Si and SiC Schottky diodes that manage to reduce the Schottky barrier, but this comes with elevated leakage currents.

It is therefore wise to incorporate into the converter design the considerations of the losses associated with diode leakage current. A practical toolbox was developed in this document. Having explored the thermal runaway effect prevalent in low-barrier Schottky diodes, the following design recommendations can be formulated:

- Adopt a progressively conservative approach when utilising Schottky diodes with smaller forward voltages – include the leakage current losses in the loss calculation routine for the Schottky diode.
- Understand that there are device outliers and increase further operational margins to reduce early mortality – operate with a margin of 25°C below T_{MAX} for example – considering transient converter operation as well.
- Factor into the design environmental deterioration (of the thermal interface in particular) to extend operational lifetime. Depending on the adopted cooling solution (convection/forced-air/liquid) the effectiveness of heat extraction from the device junction can decrease by 50 percent or significantly more.

References

[1] Infineon Technologies AG: *CoolSiC™ Schottky diode (IDDD20G65C6)*; **Available online**

Revision history

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