# AN4021
# Application note

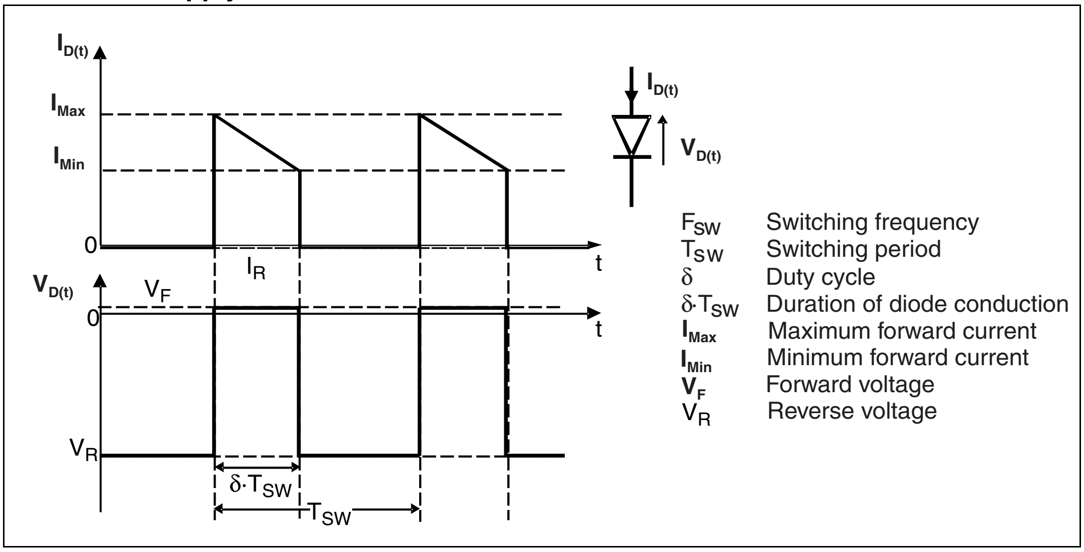
## Calculation of reverse losses in a power diode

## Introduction

This application note explains how to calculate reverse losses in a power diode by taking into account the impact of the junction temperature ($T_j$) as well as the reverse voltage $V_R$ on the leakage current.

The ideal current and voltage waveforms of an ultrafast diode in a power supply system during a switching cycle are illustrated *in Figure 1*.

**Figure 1. Ideal current and voltage waveforms of a diode in a switch mode power supply**




The reverse losses in a diode are the result of a reverse bias applied on the diode. They are due to the leakage current ($I_R$). This parameter ($I_R$) increases exponentially with the junction temperature. Most of time, the reverse losses are negligible for bipolar and silicon carbide diodes. For silicon Schottky structured diodes, these losses should be accurately estimated as they are the main origin of the thermal runaway risk phenomenon (*See AN1542*).

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# 1 Diode reverse characteristics

## 1.1 Junction temperature and reverse voltage dependence

The leakage current is an intrinsic parameter of the diode. In each ST Schottky and SiC diode datasheet, a curve of the leakage current (typical value) versus the reverse voltage and the junction temperature is provided (*Figure 2*).

Most of the time, the reverse losses are calculated using maximum values in order to consider the worst operating conditions for the diode in the application. The ratio between typical and maximum values can be obtained using the values given in the section “Static electrical characteristic” of the datasheet. (*Figure 3*)

**Figure 2. Reverse leakage current versus reverse voltage applied for the STPS20M100S (typical values)**

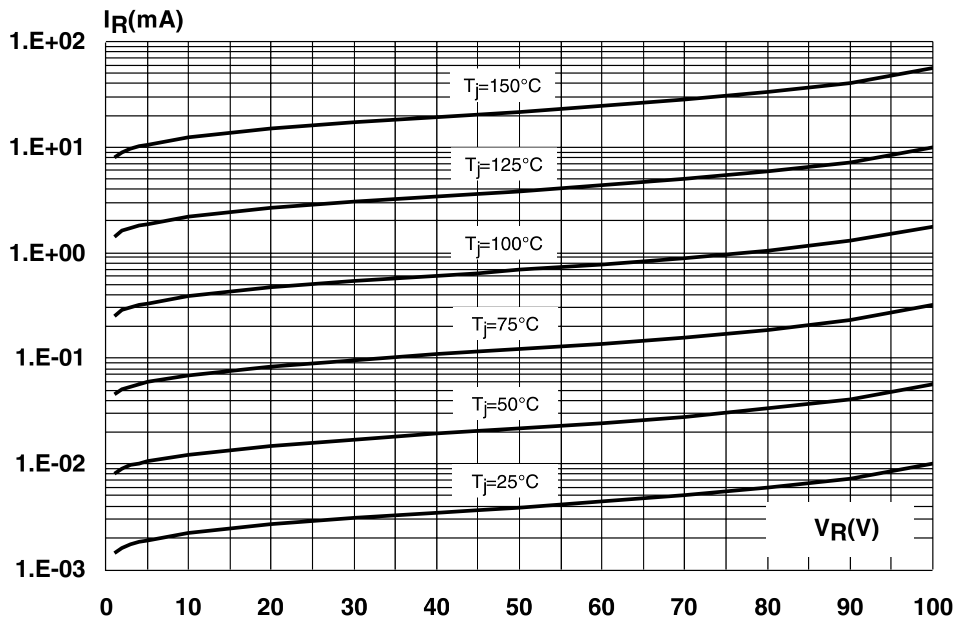



**Figure 3. Typical and maximum leakage current at the voltage rating of the diode ($V_{RRM}$) from the datasheet for the STPS20M100S**

| Symbol | Parameter | Test conditions | | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| $I_R$ | Reverse leakage current | $T_j$ = 25 °C | $V_R$ = 70 V | | 5 | | µA |
| | | $T_j$ = 125 °C | | | 5 | | mA |
| | | $T_j$ = 25 °C | $V_R$ = 100 V | | 10 | 40 | µA |
| | | $T_j$ = 125 °C | | | 10 | 40 | mA |

## 1.2 Diode reverse characteristics modeling: $I_R(V_R,T_j)$, “c” thermal coefficient

The parameter ($I_R$) increases by an exponential law with the junction temperature. Knowing a reference point $I_R(V_R,Tj_{Ref})$ and the value of the thermal coefficient “c”, one can easily calculate the leakage current at a given temperature $T_j$ using the following formula:

**Equation 1**

$$I_R(V_R,T_j) = I_R(V_R,T_{j\,Ref}) \cdot e^{c(T_j - T_{j\,Ref})}$$

Where $V_R$ is the reverse “plateau” voltage applied across the diode.

The “c” thermal coefficient represents the leakage current dependence with the junction temperature. Each diode has its own coefficient that can be calculated using two points as follows:

**Equation 2**

$$c = \frac{1}{T_{jRef2} - T_{jRef1}} \cdot \ln\left(\frac{I_R(V_R, T_{jRef2})}{I_R(V_R, T_{jRef1})}\right)$$

In each ST Datasheet, $Tj_{Ref1}$ & $T_{jRef2}$ are respectively 25°C and 125°C.

The “c” coefficient is independent of the reverse voltage $V_R$ applied across the diode.

# 2 Reverse losses: Basic equations

Reverse losses expression is the average dissipated power in the diode during the reverse biasing phase:

**Equation 3**

$$P_{REV}(T_j) = \frac{1}{T_{sw}} \int_0^{T_{sw}} V_R(t) \cdot I_R(V_R, T_j) \cdot dt$$

In case of a typical square waveform as illustrated on *Figure 1*, the reverse losses are equal to:

**Equation 4**

$$P_{REV}(T_j) = (1-d) \cdot V_R \cdot I_R(V_R, T_j)$$

Substitution of *Equation 1* into *Equation 4* yields

**Equation 5**

$$P_{REV}(T_j) = (1-d) \cdot V_R \cdot I_R(V_R, T_{jRef}) \cdot e^{c(T_j - T_{jRef})}$$

In some literature, it is possible to find the following expression:

**Equation 6**

$$P_{REV}(T_j) = P_{ref} \cdot e^{c \cdot (T_j - T_{jRef})}$$

With:

**Equation 7**

$$P_{ref} = (1-d) \cdot V_R \cdot I_R(V_R, T_{jRef})$$

# 3 An application example

Let us consider the example of a 45 W notebook adapter, using a flyback converter (*Figure 4*) working in continuous mode. The input voltage $V_{in}$ is 375 V and the output voltage $V_{out}$ is 14.5 V. The rectifier diode is a ST power Schottky STPS20M100S (20 A, 100 V). *Figure 5* shows the ideal waveforms of the diode. The duty-cycle of the transistor is: $\delta = 0.2$ and the transformer ratio is: m = 0.148.

Let us calculate the maximum reverse losses in the diode for this application.

**Figure 4. Flyback converter**

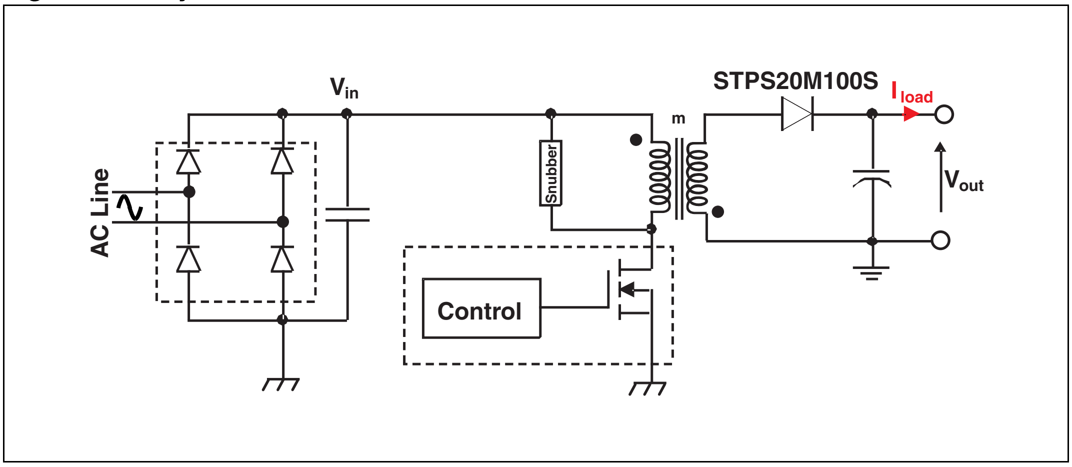
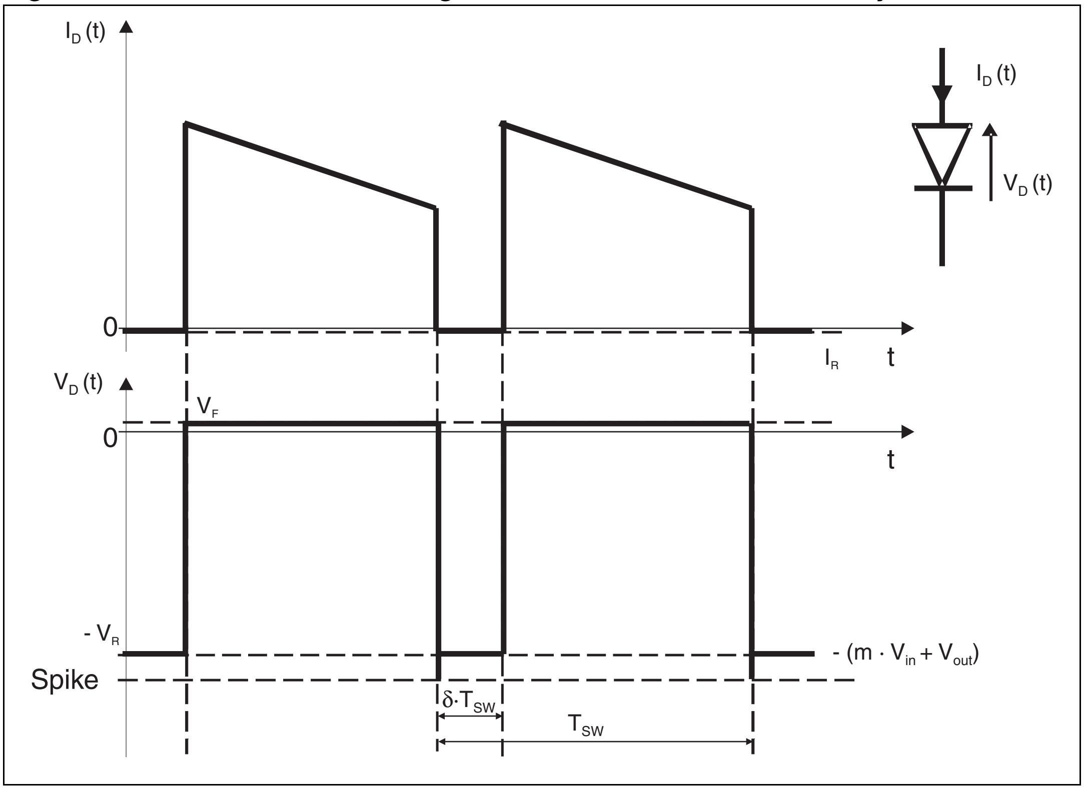



**Figure 5. Ideal current and voltage waveforms of the diode in the flyback converter**



### Step 1: Reverse voltage applied across the diode

When the transistor on the primary side of the transformer is on, the rectification diode is blocked with a reverse voltage equal to:

**Equation 8**

$$V_R = m \cdot V_{in} + Vout = 0.148 \cdot 375 + 14.5 = 70V$$

### Step 2: $I_R(V_R,T_{jRef})$ and thermal coefficient “c”:

The second step is to read the reference point value using the *Figure 2* given in each datasheet for the corresponding $V_R$. The reference temperature ($T_{jRef}$) considered is at a junction temperature of 125 °C.

In this example:

$I_{R(typ)}(V_R = 70\text{ V}, T_{jRef} = 125\text{ °C}) = 5\text{ mA}$ (typical value)

In order to consider the worst case for the power losses, we use the maximum values for the leakage current using the ratio given by the *Figure 3*.

**Equation 9**

$$\text{Ratio} = \frac{I_{R\,(max)}(100V, 125°C)}{I_{R\,(typ)}(100V, 125°C)} = \frac{40}{10} = 4$$

$I_{R(max)}(V_R = 70\text{ V}, T_{jRef} = 125\text{ °C}) = 5 \times 4 = 20\text{ mA}$

Using *Equation 2* and *Figure 2*, the coefficient “c” can be calculated:

**Equation 10**

$$c = \frac{1}{T_{jRef2} - T_{jRef1}} \cdot \ln\left(\frac{I_R(V_R, T_{jRef2})}{I_R(V_R, T_{jRef1})}\right) = \frac{1}{125-25} \cdot \ln\left(\frac{5 \cdot 10^{-3}}{5 \cdot 10^{-6}}\right) = 0.069°C^{-1}$$

### Step 3: Reverse losses expression:

From *Equation 5*, the maximum reverse losses expression is then:

**Equation 11**

$$P_{REV(max)}(T_j) = (1-d) \cdot V_R \cdot I_R(V_R, T_{jRef}) \cdot e^{c(T_j - T_{jRef})}$$

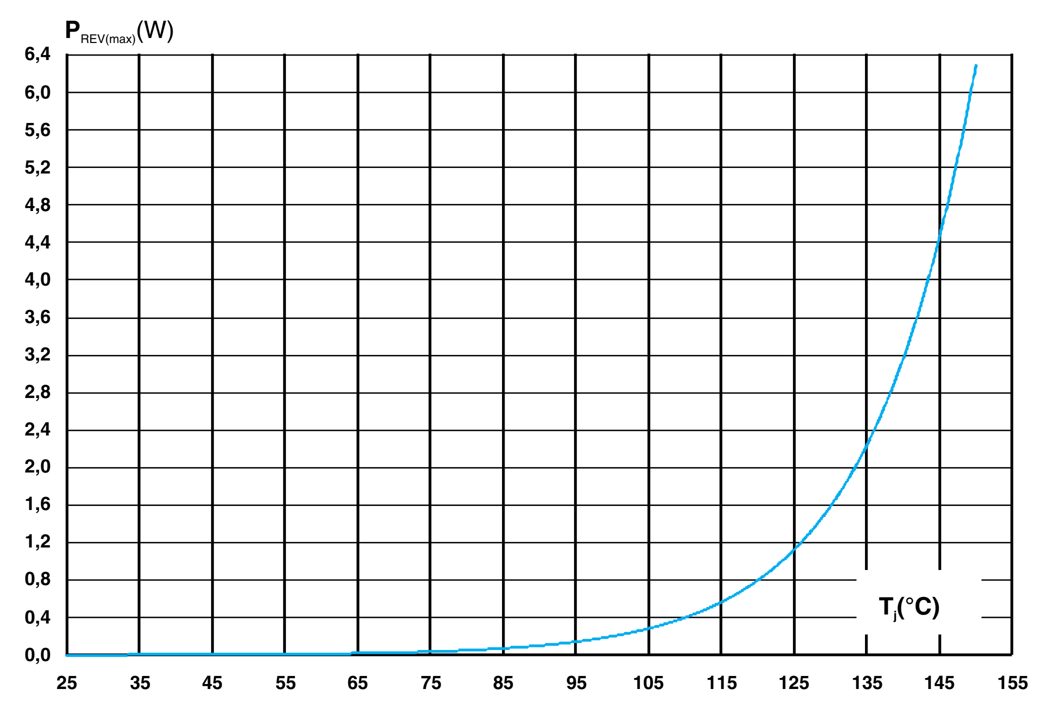
$$P_{REV\,(max)}(T_j) = (1-0.2) \cdot 70 \cdot 20 \cdot 10^{-3} \cdot E^{0.069(T_j - 125)}$$

with $T_{jRef} = 125$ °C

$$P_{REV(max)}(T_j) = 1.12 \cdot e^{0.069(T_j - 125)}$$

Finally, one can plot the evolution of reverse losses in the diode versus the junction temperature (*Figure 6*).

**Figure 6. Maximum reverse losses versus the junction temperature**




As shown on *Figure 6*, the reverse losses increase exponentially with the temperature.

For ST Bipolar diodes, the doping being platinum, the leakage current is very low resulting in negligible reverse losses.

For Schottky diode, there is a trade-off between the forward voltage drop and the reverse leakage current. In order to improve the efficiency of a Switch Mode Power Supply, a Schottky diode with a low forward voltage to the detriment of higher leakage current would be preferred.

In this case, the heat sink size will be larger in order to keep the junction temperature of the diode low enough and avoid a thermal runaway phenomenon. (Refer to the AN1542).

# 4 Revision history

Table 1. Document revision history

| Date | Revision | Changes |
|---|---|---|
| 26-Apr-2012 | 1 | Initial release. |