AN3358
Application note

Turbo2 600 V diodes: optimized solutions for PFC and other applications

Introduction

In a switched mode power supply, there are a great number of electronic functions where 600 V ultrafast diodes are used. Each diode has a specific function. In one application a parameter can be critical but secondary in another.

A rectifier manufacturer who wants to propose an optimized solution for each function needs to develop several families with different trade-offs (mainly between the forward voltage V_F and reverse recovery charge Q_{rr}).

STMicroelectronics' Turbo2 600 V ultrafast diodes offer three different families in order to offer an optimal solution for each application.

After some general information about this new technology, a discussion of the PFC application, working in continuous mode, transition mode and fixed-off-time, is presented. In the case of continuous mode operation, hard switching and soft switching conditions are considered. Some other conventional functions are also touched upon.

Contents

1 General information

1.1 Technology information

The Turbo2 families are manufactured using simple rules to insure high quality and reliability. These diodes are planar structures on epitaxial layers. The wafers are thus subjected to reduced mechanical stress for planar diodes compared to mesa ones.

The use of epitaxial layers makes the V_F/t_{rr} trade-off independent of the wafer thickness, the contrary of homogenous diodes. These properties make the manufacturing of large diameter wafers possible. So the wafers benefit from state-of-the-art technology on recent equipment.

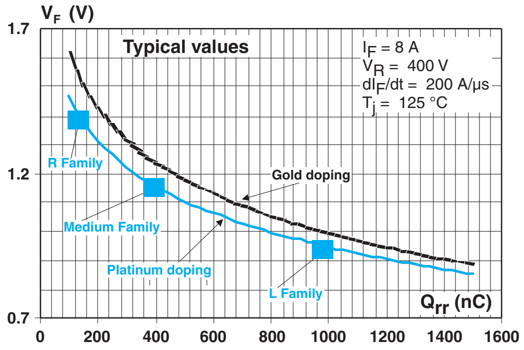
Epitaxial diodes, which present good drift area thickness, are particularly suitable for diodes up to 600 V and exhibit a significantly superior V_F/t_{rr} trade-off. The lifetime control of the carriers for the Turbo2 diodes is obtained through platinum (P_t) doping. P_t doping is required for high junction temperature applications because it results in low reverse current at elevated temperature and, in this way, presents a low thermal runaway risk.

1.2 V_F, Q_{rr} trade-off for the three families

The three families are: STTHxxR06 (R stands for rapid with low Q_{rr}), STTHxx06 (medium V_F and Q_{rr}), and STTHxxL06 (Low forward voltage).

Figure 1 shows where a trade-off occurs in three operational areas. A technology using gold doping is also shown.

Figure 1. V_F - Q_{rr} trade-off for an 8 A diode

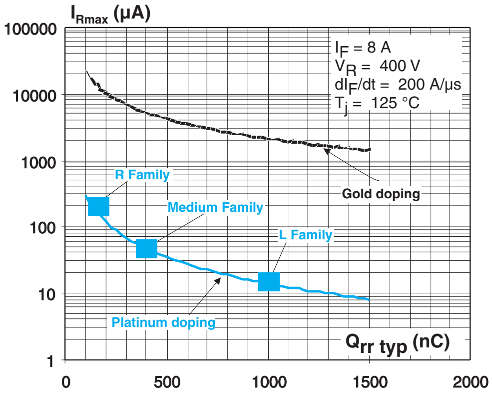


1.3 Platinum doping and low leakage current

Figure 2 shows the trade-off between leakage current I_R and Q_{rr} in several operational areas. The faster the diode, the higher the I_R is. This rule is true for both gold and platinum doping. For the same Q_{rr}, I_R is approximately 100 times lower with platinum doping. The corresponding “R” family with gold doping would have a high maximum leakage current (18 mA at 125 °C and 400 V). As shown later in this Application note, with such a leakage current thermal instability can be reached for operating junction temperatures higher than 125 °C in a conventional application.

It will also be shown that I_R is also a critical parameter for diodes in axial and SMD packages.

Figure 2. I_R - Q_{rr} trade-off in several operational areas for an 8 A diode

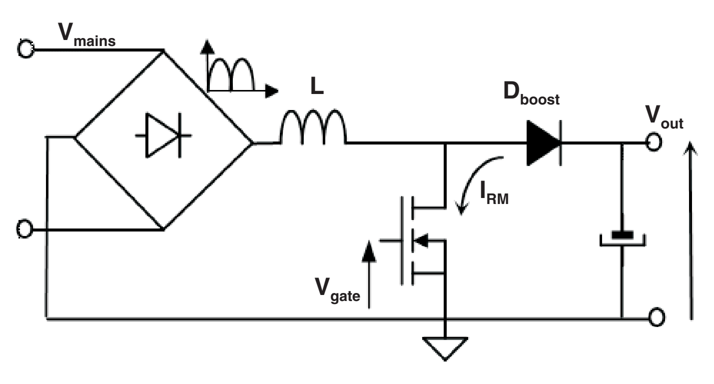


2 Main applications of 600 V ultrafast diodes

This section discusses the trade-offs in a common application. Boost power factor corrector (PFC) will be widely covered since it is a major application. A typical PFC circuit is shown in *Figure 3.*

2.1 Power factor corrector applications

Figure 3. Boost power factor corrector circuit



2.1.1 Boost diode in PFC working in continuous mode

Hard switching conditions

PFC applications are mainly designed in continuous mode when the power is greater than 200 W.

In such an application, it is well known that the greatest losses due to the diode are the switching losses in the transistor (P_{ontr}) when it turns on. The reverse recovery current (I_{RM}) of the boost diode flows into the MOSFET (*Figure 3*). Consequently, the best choice in most cases is the “R” family.

Switching losses due to I_{RM} depend mainly on two parameters: the operating junction temperature T_j and the mains voltage V_{mains}.

Figure 4 and *Figure 5* show that the switching losses for STTH8R06 quickly increase when T_j increases and when V_{mains} decreases. These curves are drawn with a software tool realized by these authors.

If the PFC only works on 240 V mains, with a low operating junction temperature, switching losses will be less critical and the best trade-off could be the intermediate trade-off: STTHxx06.

However, most PFCs are designed to work in a wide mains voltage range (85 V-264 V) with an operating junction temperature (in the worst case) close to 100 °C. The “R” family will be the family usually recommended.

Figure 4. Switching losses versus T_j at turn off of the diode

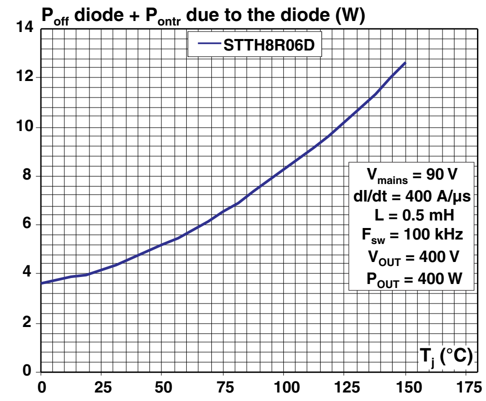
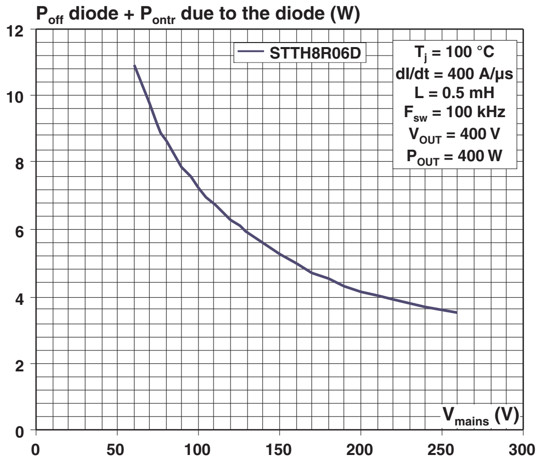


Figure 5. Switching losses versus V_{mains} at turn off of the diode



T_{jmax} before thermal runaway

The maximum junction temperature T_{jmax} before thermal runaway can be calculated using *Equation 1*, *Equation 2* then *Equation 3*.

Equation 1

$$\delta = 1 - \frac{2\, V_{\text{mains peak}}}{\pi\, V_{OUT}}$$

Equation 2

$$I_R(V_{OUT}, T_{jmax}) = \frac{1}{V_{OUT} \cdot \delta \cdot c\, R_{th(j\text{-}a)}}$$

Equation 3

$$T_{jmax} = 125 + \frac{1}{c} \cdot \log_e\left(\frac{I_R(V_{OUT,}\ T_{jmax})}{I_{Rmax}(V_{OUT,}\ 125\ °C)}\right)$$

Where:

- δ is the average duty cycle of the blocking time of the diode given by *Equation 3*.
- V_{OUT} is the output voltage.
- c is a constant with units of $°C^{-1}$. Each diode has its own “c” coefficient depending on the technology of the diode and the reverse voltage V_R applied. It can be determined from *Equation 3* for two values of leakage current corresponding to application reverse voltage V_{out}, for example: $I_R(V_{out}, 100\ °C)$ and $I_R(V_{out}, 125\ °C)$.
- $R_{th(j\text{-}a)}$ is the thermal resistance between junction and ambient (heatsink + diode).

With the following conditions:

$V_{OUT} = 400$ V, $c \approx 0.055\ °C^{-1}$ (for the “R” family)

$V_{mains} = 85$ V, $\delta = 0.8$, $R_{th(j\text{-}a)} = 10$ °C/W

Figure 2 gives $I_{Rmax(400\ V,\ 125\ °C)} = 215$ µA for an 8 A “R” family diode and 17 mA for the equivalent diode in gold doping.

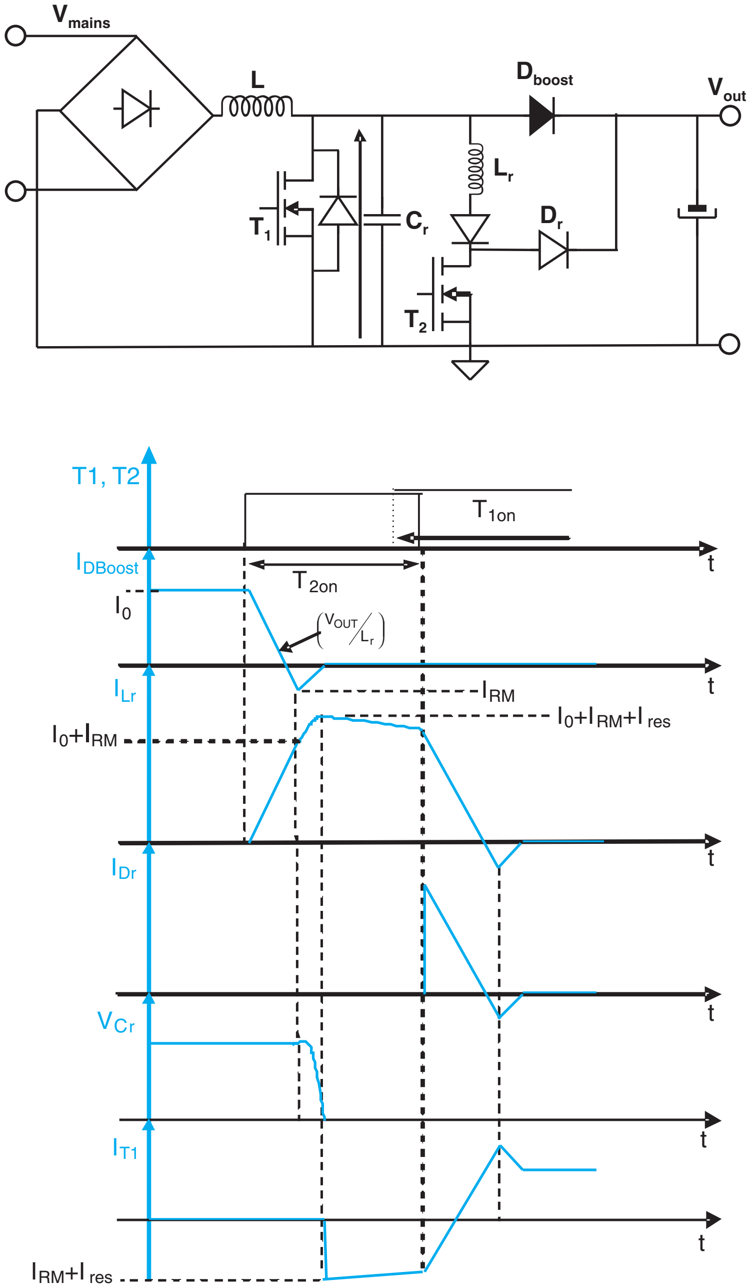
Equation 2 and *Equation 3* give $T_{jmax} = 184$ °C for Turbo2 and 104 °C for the equivalent diode in gold doping.

Soft switching condition

Designers can use a number of techniques to turn on the MOSFET in soft switching conditions and reduce the switching losses due to I_{RM}.

Figure 6 and *Figure 7* show two solutions, widely used with the associated waveforms during switching time. In the non-dissipative circuit *Figure 6*, the smaller transistor T2 turns on before the main one T1. The dI/dt when D_{boost} turns off is controlled by L_r ($dI/dt = V_{out}/L_r$), and T1 turns on at zero current. Consequently, the switching-on losses will be close to zero. With this circuit, the reverse recovery current of the boost diode is less critical. The best choice, following the application conditions (switching frequency, L_r…) will be “the intermediate” or the “L” trade-off.

Figure 6. Non-dissipative soft switching solution

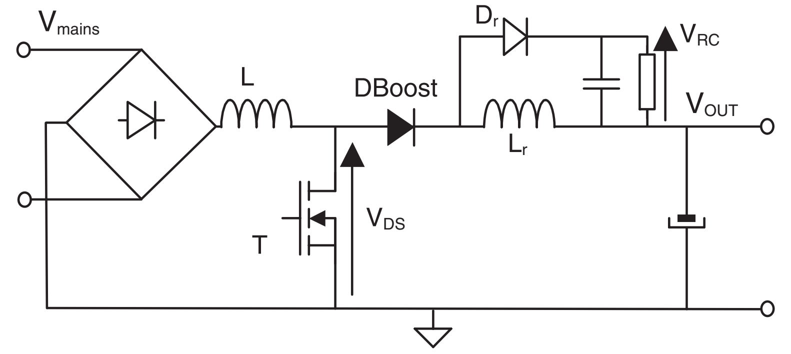


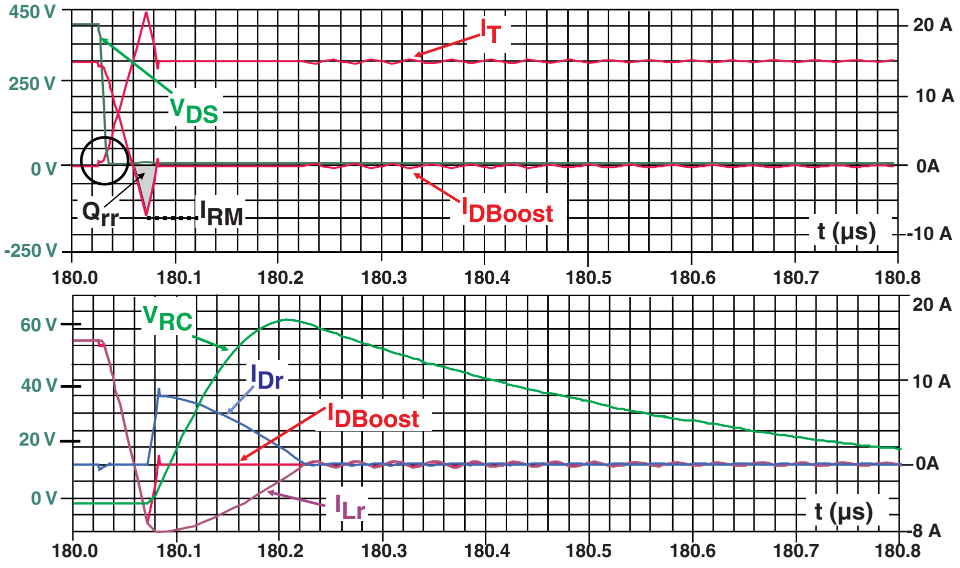
The topology shown in *Figure 7* is more simple but more dissipative than that in *Figure 6*.

The waveforms in *Figure 7* show the MOSFET turning on at zero current, thus reducing the switching losses. When the diode turns off, the L_r inductor is charged with the reverse recovery current of the boost diode. This energy will be dissipated in the resistor.

The higher I_{RM} is the higher the losses in the resistor are. In this application I_{RM} is more critical than in the previous one. The best choice for the boost diode trade-off will be “R” or medium family depending on the application conditions.

Figure 7. Dissipative soft switching solution





Another very interesting alternative soft switching solution is described in the application note AN3276, “ST solution for efficiency improvement in PFC applications, back current circuit (BC2)”. AN3276 presents a patented soft switching circuit from STMicroelectronics offering performance similar to that of SiC Schottky diodes.

2.1.2 Boost diode in PFC working in transition mode

The transition mode (TM) is widely used for low power PFC (<200 W). The particularity of this control mode working between continuous and transition mode is a simple control and a few external components. This control mode results in variable frequency operation and a constant on time of the MOSFET.

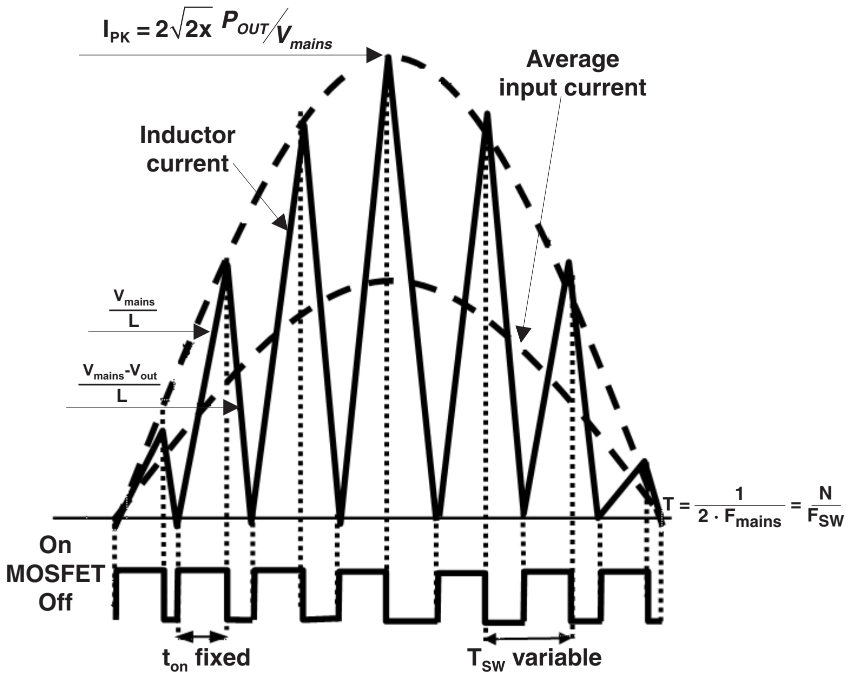
Consequently, the current flowing through the Boost inductor is triangular (*Figure 8*). It increases through the MOSFET following the slope defined by V_{mains}/L, and decreases through the diode following a low dI/dt given in Equation 4.

Equation 4

$$\frac{dI}{dt} = \frac{V_{mains} - V_{OUT}}{L}$$

In this case dI/dt may have a value up to 0, the necessary condition for the next cycle.

Figure 8. Inductor current waveform and MOSFET timing



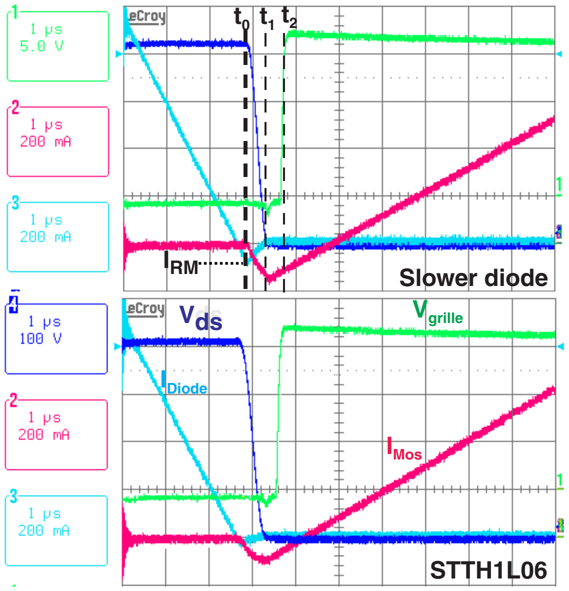
The ZCD circuit (zero current detection) turns on the MOSFET at zero current, avoiding high switching losses in the MOSFET due to the recovery charge of the diode.

Unlike the continuous mode, the Q_{rr} of the diode it is not the key parameter any more. In the transition mode, the main losses of the diode are due to the forward voltage. It is then possible to optimize the V_F parameter to the detriment of Q_{rr}, due to the low dI/dt_{off} of the diode (<1 A/µs) fixed by the inductor.

Nevertheless, an accurate study at switch-off of the diode shows that the Q_{rr} parameter cannot be indefinitely relaxed. *Figure 9* highlights this phase when the current of the diode reaches 0, and shows that this time is composed of 3 phases:

- **Phase 1 [t0,t1]**: The diode is open. There is a resonant circuit between the equivalent capacitance (C_{ds} MOS + C_j diode) and the boost inductance, which has as its initial condition the I_{RM} of the diode.
- **Phase 2 [t1,t2]**: V_{DS} reaches 0 and the body diode of the MOSFET enters in conduction and the current linearly increases through the V_F of the body diode.
- **Phase 3 at t2**: The ZCD circuit turns the MOSFET on and the current continues to linearly rise through the $R_{DS(on)}$.

Figure 9. Switch-off comparison between STTH1L06 and a slower diode



It can be observed that the dead time (t0,t2) increases with the I_{RM} of the diode. This time a negative current flows through the power MOSFET and is the source of additional losses. This duration depends on the slope (versus V_{mains}, L) and also on the I_{RM} of the diode (the initial condition of phase 1). During this time there is no power transferred to the load. In this way, with a very slow diode, the sum of the losses due to high I_{RM} cannot be negligible compared to these of the conduction losses. Therefore, there is a limit for Q_{rr}. This limit appears for the full range PFC at 110 V. In this condition the current in the power MOSFET takes more time to reach 0 (maximum dead time).

The maximum Q_{rr} of the “L” family has been optimized taking these considerations into account.

According to the application conditions (P_{out}, V_{mains}, dI/dt_{max}, F_{sw}, T_j), the medium trade-off could be also considered. The optimum choice between low forward voltage trade-off (STTHxxL06) and the medium trade-off (STTHxx06) could be determined by efficiency measurement.

In transition mode a diode with a small current rating is used. It is generally a small package (axial or SMD packages) with high thermal resistances. Consequently, the junction temperature of the diode, which is mainly fixed by the conduction losses, can be high. *Equation 2* in *Section 2.1* shows that the thermal resistance is a critical parameter for the thermal runaway limit. *Table 1* compares the thermal runaway limit between Turbo2 and a gold-doped diode working in a transition mode PFC in the following conditions:

$R_{th(j-a)}$ = 75 °C/W, c ≈ 0.072 $°C^{-1}$, V_{OUT} = 400 V, V_{mains} = 85 V, δ = 0.808

Table 1. T_{jmax} comparison between Turbo2 and gold doping diode

	STTH3L06	Gold Doping
I_{Rmax} 125 °C, 400 V	15 µA	1.5 mA
T_{jmax} before thermal runaway limit is reached.	176 °C	112 °C

This comparison shows that gold-doped diodes are limited in high temperature. There is no thermal runaway risk when Turbo2 uses platinum doping. For all these reasons, in most cases, the “L” family is recommended for the PFC application working in transition mode.

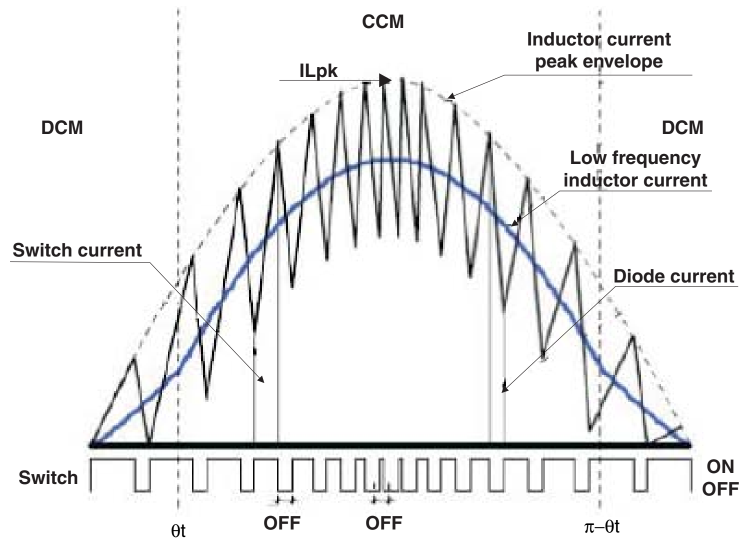
2.1.3 Boost diode working in fixed-off-time (FOT) PFC

In this third PFC operating mode, instead of maintaining the on-time fixed, such as TM PFC, the T_{off} is kept constant and the T_{on} is free to be changed in order to modulate the power drained from the source according to the load.

This modulation method, is described in the Application note AN1792, “Design of fixed-off-time controller PFC pre-regulators with L6562”.

As shown in *Figure 10* in FOT mode, the PFC works in DCM and CCM modes along the line semi period.

Figure 10. Inductor, switch and diode currents in a CCM FOT-controlled PFC stage

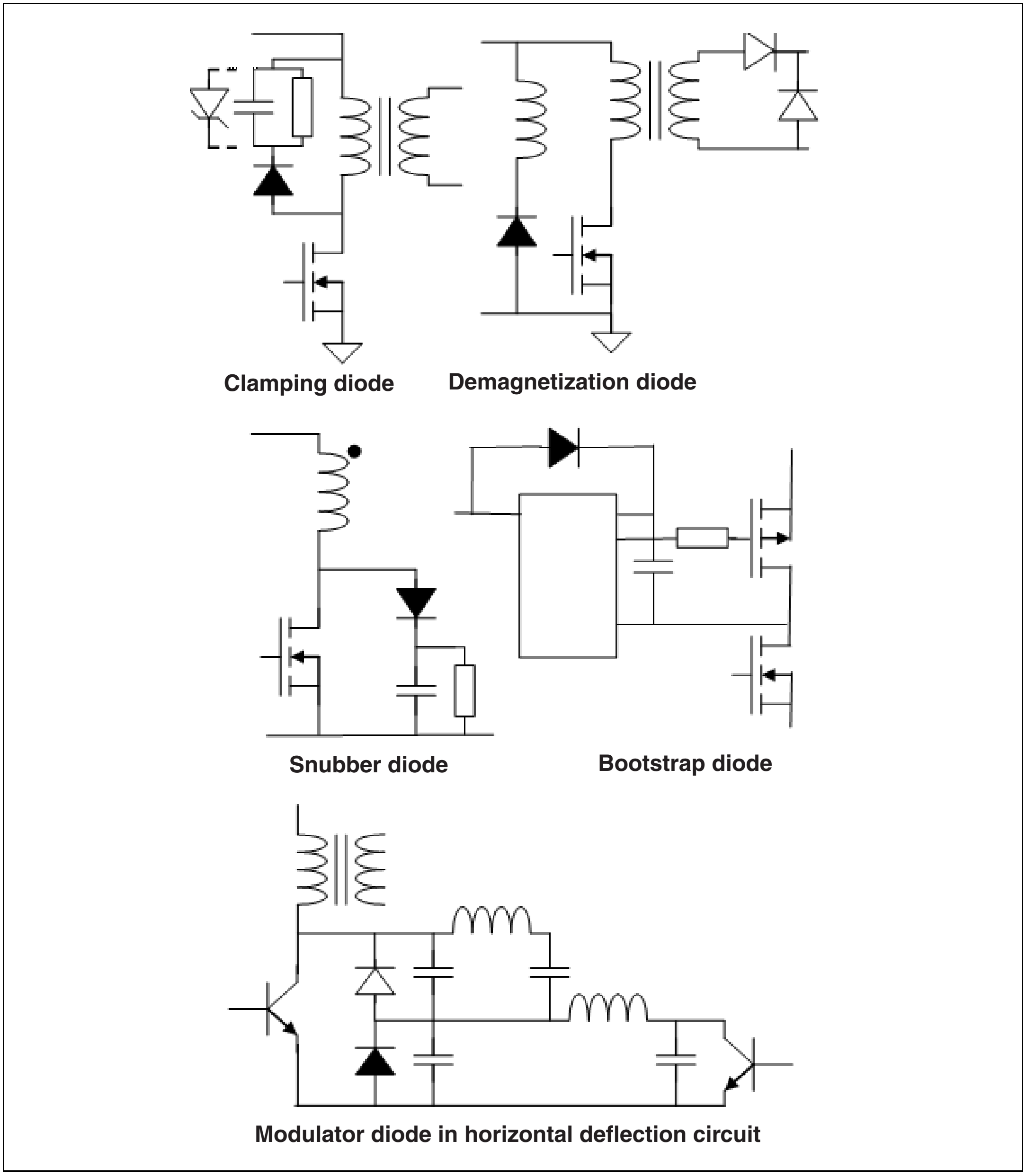


In this operating mode, according to the application conditions the optimal diode will be the medium trade-off (V_F/Q_{RR}) or the rapid trade-off (“R” family). The designer should make some measurements of efficiency to confirm the good trade-off diode in its application.

2.2 Other applications

There are numerous other electronic functions, where 600 V ultrafast diodes are used. For example, rectification, demagnetization, snubber, bootstrapping, clamping, or East-West correction in a horizontal deflection circuit for TV or monitor (*Figure 11*).

Figure 11. Traditional applications of 600 V ultrafast diodes



Clamping diode

Demagnetization diode

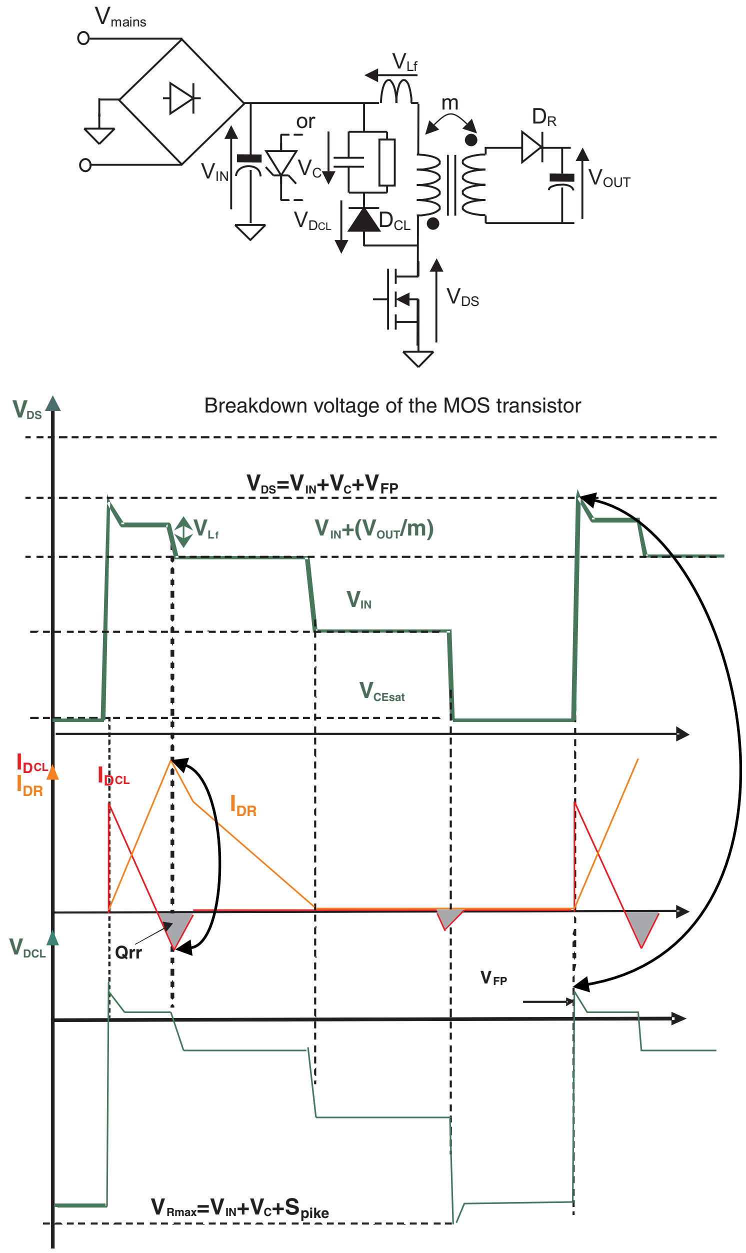
Snubber diode

Bootstrap diode

Modulator diode in horizontal deflection circuit

It is not possible in this document to analyze each function in detail. We will focus on the clamping function used in flyback converters. The function of the clamping circuit is to protect the MOSFET against the overvoltage due to the energy in the leakage inductance of the transformer. The associated waveforms are represented in *Figure 12.*

Figure 12. 600 V ultrafast diode waveforms in clamping function



When the MOSFET turns off, the inductive circuit opens and an overvoltage V_{Lf} appears in addition to the voltage across the primary inductor V_{OUT}/m. The effect of this overvoltage turns on the clamping diode. Thus, the drain voltage is equal to $V_{DS} = V_{IN} + V_C + V_{FP}$.

V_{FP} is the peak forward voltage across the 600 V diode. V_C is a DC voltage realized either by an RC circuit in parallel or by a clamping diode such as a Transil™.

The first key parameter of the diode is V_{FP}. V_{DS} has to be lower than the breakdown voltage of the MOSFET. If V_{FP} is too high the designer may be obliged to choose a higher voltage MOSFET (for example 800 V instead of 600 V).

To avoid thermal runaway problems a low value of leakage current is necessary as the diode is normally a 1 A device in an SMD or axial package. A low I_R will also contribute to the reduction of consumption in stand-by mode. The forward voltage is not a critical parameter because the diode conducts about ten nanoseconds every switching period.

When the clamping voltage is made with a Transil, it is generally better to use an ultrafast type diode. When an RC solution is used, the capacitance is discharged through the reverse recovery current of the diode, thus reducing the losses in the resistor.

The Turbo2 technology, which allows low leakage current and low peak forward voltage, is well suited for this application. The best trade-off with a Transil, will be the “R” or the medium family. With an RC solution the choice will generally be between the “L” and the “medium” families.

TM: Transil is a trademark of STMicroelectronics

3 Conclusion

This Application note presents the main applications of the 600 V ultrafast diodes. These applications are numerous, each requiring a slightly different trade-off among the diode parameters. In order to propose an optimized solution for each one, three trade-offs are proposed by STMicroelectronics. There are some general rules to define the right trade-off. For example, the “R” family for PFC working in continuous mode and hard switching condition and the “L” family for PFC working in transition mode. However, there are also applications for which a deeper study will be necessary.

An important benefit of the platinum doping implemented in the Turbo2 technology resides in the use of the diodes at high junction temperature without thermal runaway risk in normal prescribed condition of use (<175 °C).

4 References

[1] ST Application note AN628, “Designing a high power factor switching preregulator with the l4981 continuous mode”

[2] PCIM, Nuremburg, 2000 “New solution to optimize diode recovery in PFC boost converter”, B. Rivet.

[3] ST Application note AN667, “Designing a high power factor switching preregulator with the l6560 transition mode”

[4] ST Application note AN966, “Enhanced transition mode power factor corrector”

[5] ST Application note AN1792, “Design of fixed-off-time controller PFC preregulator with the L6562”

[6] ST Application note AN3276, “ST solution for efficiency improvement in PFC applications, back current circuit (BC^2)”

5 Revision history

Table 2. Document revision history

Date	Revision	Changes
14- Sep-2011	1	First issue

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