Ultra-fast Recovery Diodes Meet Requirements for High Frequency Operation and Power Ratings in SMPS Applications

Introduction

The switched-mode power supply market has shown an interesting trend in recent years, mainly driven by a new demand in PCs and Telecom applications. The implementation of new circuit topologies and a tremendous increase in switching frequency to meet new limits, have been the driving factors in the development of new semiconductor components.

Ultra-fast rectifiers are today playing a key role in these new topologies and in the trend of increased frequency of operation. International Rectifier has recently introduced a new series of Ultra-fast recovery diodes aimed specifically at the 12/24/48V SMPS output stage. This series extends IR's current product range of Ultra-fast recovery diodes with industry standard part number products (MUR series).

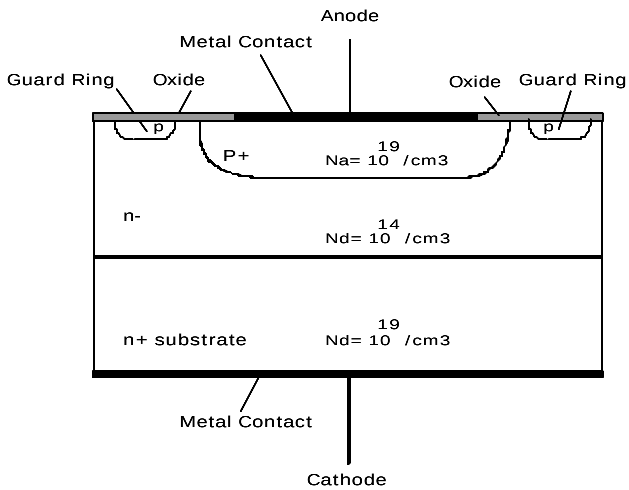
The new product series has been developed to meet today's requirement of high frequency operation and power ratings, using a technology platform flexible enough to match the performance improvement curve of the market requirements in the years to come.

Structure of Rectifier Diodes

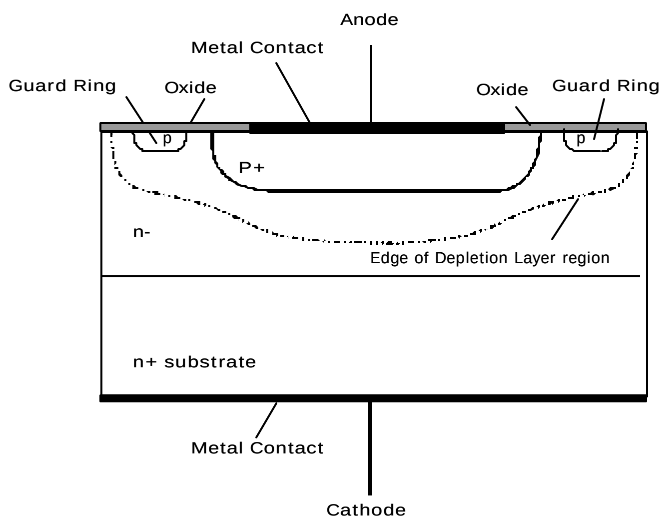
Almost all of the power semiconductor diodes manufactured today are made up around the same type of Pin structure. This basic structure allows semiconductor manufacturers to offer the widest range of performances and characteristics, such as blocking voltage capability, forward voltage drop and switching speed, by means of the control of a few key elements:

- Die Size
- Die Thickness
- Field Termination Structure
- Base Width
- Doping Level
- Recombination Lifetime Control

While the first two elements have a clear and direct affect on diode performance, the latter have influence over the characteristic of the diode's region (base) that separates the highly doped P and N regions, and that controls the dynamic (switching) and static (on-state) performances of the device.

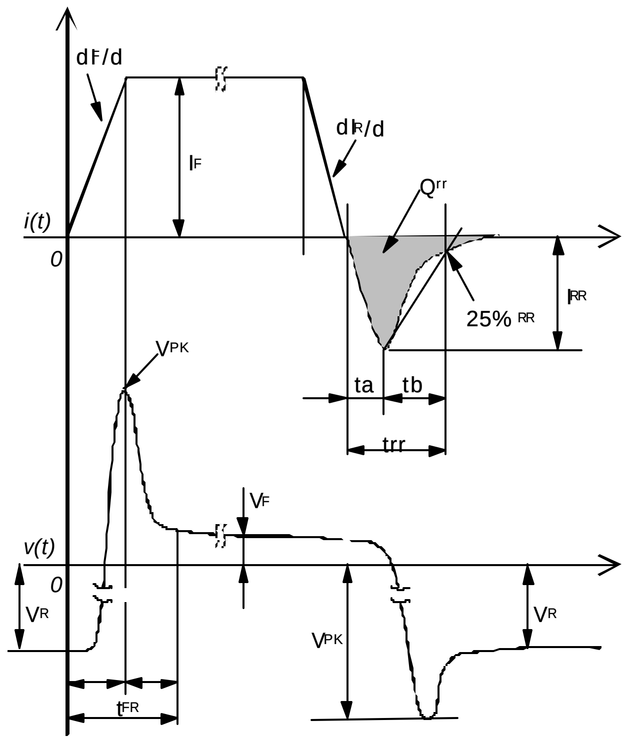


The n- region in the above illustration has the function to absorb the depletion layer created at the moment of the reverse polarization (reverse bias) of the PN junction. Therefore the dimension of this region will determine the blocking voltage characteristics. To help in visualizing this effect, the following illustration shows the situation during the diode the reverse polarization. The presence of P+ rings help to substantially improve the blocking voltage capabilities (reducing the intensity of the electrical field and lowering the gradient along the depletion borderline).



The thickness of the n- region adds a significant resistance to the forward current during the conduction of the diode, thus increasing the on-state power dissipation due to the increased forward voltage drop as well as the switching characteristic of the diode. To overcome this problem, the preferred solution is obtained with very high injection efficiency and a very “thin” base (the n- region physical dimension), achievable using epitaxial wafers. In fact, a rectifier requires a certain time before, from a status of conduction, it can physically block in the reverse direction and vice versa.

The following diagram illustrates the typical voltage-current waveforms for a diode driven by currents with a specified rate of rise during turn-on and a specified rate of fall during turn-off.



The first effect happens during the turn-on of the diode under a high value of current. This overshoot arises from the existence of the n- region, more resistive than the n+. During continuous conduction, the resistance of this region is reduced by the injection of the minority carriers. However, during high-speed turn-on, the current may raise much faster then the diffusion of the minority carriers injected from the junction. A high voltage drop develops across the n- region for the time the minority carriers can diffuse in the region and reduce the resistance. The level of the voltage overshoot is strictly related to the resistivity and thickness of the n- region. Therefore, the n- region is again designed to minimize its resistance within the constraints to achieve the target blocking voltage values.

An elevated forward voltage overshoot in the diode can be a serious problem in power circuits because this voltage may appear across a switching device (MOSFET or transistor) used in the circuits and exceed its breakdown voltage. The internal stray inductance can also cause an increase of the overshoot.

The second effect is the reverse recovery during the transition from the conduction state to the blocking state. This is due to the excess of carriers stored in the base that must be removed before the diode will be able to block the voltage, and this requires a finite time proportional to the "volume" of the region and the presence of recombination centers.

The removal of the stored charge occurs by means of two phenomena: (1) the flow of a large reverse current, followed by (2) the recombination effect.

Once the carriers are removed by the combined action of recombination and sweep-out by negative diode current, the depletion layer acquires a substantial amount of space charge from the reverse-bias voltage and expands into the drift region from both ends (junctions), thus the diode is able to block the reverse voltage. As long as an excess of carriers are at the end of the drift region, the p+n- and n+n- junctions must be forward biased. Thus the voltage will be little changed from its conduction value (or to be correct, reduced by the voltage drop caused by the reverse current and the ohmic contacts).

However, once the excess of carriers is no longer present at the end of ta, the junction becomes reverse biased. At this point, the diode voltage goes negative with a rate of change dV_R/dt proportional to dI_{REC}/dt.

As a further consequence, if the reverse recovery dI_{REC}/dt is large, the peak reverse voltage is also high, causing failures when exceeding the blocking voltage capability. Moreover a high level of dV_R/dt generates a noise immunity problem as well, because of the emission of a radio frequency.

These and many other factors limit the optimization of diode performance. Therefore, a different technological approach is required to overcome and minimize the trade-off of the characteristics with the variation of one element vs. the others. Low on-state voltage, faster switching times and larger breakdown voltages may not in fact co-exist easily without proper design and an advanced manufacturing technique.

For sure the most utilized technology in controlling the design and performances of fast recovery power diodes is by the means of so-called epitaxial wafers. This technology, applied for power diodes since the late '70s, allows the growth of a highly controlled (in thickness and resistivity) n layer on the original silicon substrate. In fact, the epitaxial wafer allows the best trade-off for the parameters specifically for the so-called Ultra-fast recovery category of power diode. However, to achieve the shorter recovery time and lower stored charge required by the increased switching frequency rectification, a substantial reduction of and improved control over the lifetime of the carriers is also required.

Lifetime Control

A reduction in the lifetime control can be obtained by the introduction of recombination centers into the n- region. Two fundamental processing methods have been developed to control lifetime in power devices:

- Using thermal diffusion of gold or platinum
- Bombarding the silicon wafer with high energy particles (electron irradiation, proton or alpha particles)

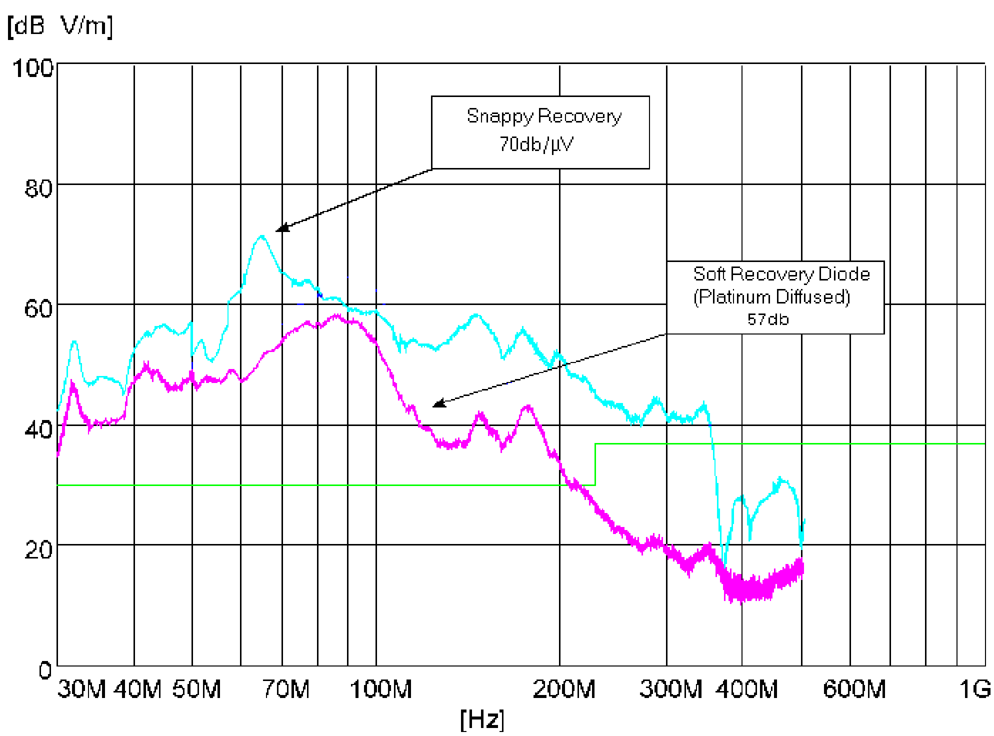
IR currently uses both these methods for the processing of its fast and Ultra-fast recovery diode series.

Several differences in results and process control exist among the different technologies that are related to the type and positioning of the recombination centers created in the n-region. In fact, the introduction of recombination centers also leads to an undesirable increase in leakage current. For equal forward conduction characteristics, the leakage current of electron-irradiated and platinum-doped devices are much lower than for the gold-doped devices, with the platinum process having the lowest absolute level.

Similarly, because gold and platinum diffusion produces the larger range in resistivity of the n- region (gold the largest) the worsening of the V_F is also smaller than when using electron irradiation technology. Electron irradiated parts also tend to have snappier recovery characteristics while using gold and platinum diffusion, and the diodes show much softer recovery.

Recovery softness is particularly important. In fact, when the slope of the recovery (tb portion) is very fast, it will generate significant radiated and conducted noise. The induced over-voltage may also cause damage to the diode or the switching element if the breakdown is exceeded.

The following illustration shows a typical impact on the EMI generated by different devices having levels of softness drastically different.



The softness is related to the quantity of charges left in the n- region after the full spread of the depletion zone in blocking mode. To sustain the demand of the current of the external stray inductance, allowing the current to return to zero in a smoother way, the charge left in the n- region must not be too low.

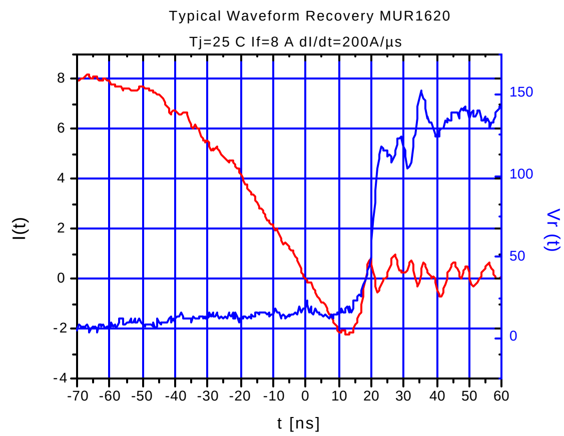
Of course, by keeping tb at the minimum, the losses in the diode might be reduced. However, as the above picture clearly shows, a much higher noise level is generated that requires additional cost in snubbers and filtering to maintain under the standard limit.

The New Ultra-fast Series

The new IR Ultra-fast recovery diode series (200-400V) adopts platinum diffusion in order to overcome the limitation of gold diffusion and the electron irradiation technology. With this approach, the best trade off for leakage current, forward voltage drop and reverse recovery, has been achieved with a maximum operating junction temperature of 175°C and a reverse recovery time as low as 15-20ns.

The graph at the right shows a typical switching characteristic at full rated current (8-amp) and 200A/µs of International Rectifier MUR1620 Ultra-fast recovery diode.

The reverse recovery time is 18ns and the peak reverse recovery current only 2A.
The controlled tb (6ns) portion generates almost no overvoltage spikes, while the total Q_{rr} is only approximately 20nC.



With this type of performance, the maximum allowable switching frequency for this Ultra-fast diode family would be up to 500-750kHz. This assumption is verified by the diode loss calculation used for the IR MUR1620 operating in a typical output rectification in a forward converter. Let's assume a current load of 8A @ 60% duty cycle, with a switching di/dt of 200A/µs and an over-voltage of 100V with the diode operating at the maximum junction temperature.

The contributions of conduction, switching and reverse to the overall power dissipation are as follows:

$P_d = I_F \times V_F \times$ Duty Cycle

from the datasheet V-I curve V_F at 8A, 175°C is 0.73V

$P_d = 8 \times 0.73 \times .60 = 3.50W$

$P_{rec} = 0.5 \times t_b \times V_R \times I_{REC} \times f$

from the datasheet $I_{rec} = 5.2A$ and $t_b = 18ns$ @ 200A/µs and $T_J = 175°$

then for a operating frequency of 750Khz

$P_{rec} = 0.5 \times 5.2 \times x100 \times 18e^{-9} \times 750e^{3} = 3.51W$

The losses in the off-state can be expressed as

$P_R = I_R \times V_R \times (1-D)$

At 100V and T_J = 175°C, the maximum leakage current is 200µA, therefore

$P_R = 200e^{-6} \times 100 \times 0.4 = 0.08W$

Then the total power dissipated is

$P_{TOT} = P_d + P_{REC} + P_R = 7.018W$

With this maximum power loss, assuming an Rth_{J-A} of 15°C/W, the diode can operate safely up to an ambient temperature of 70°C.

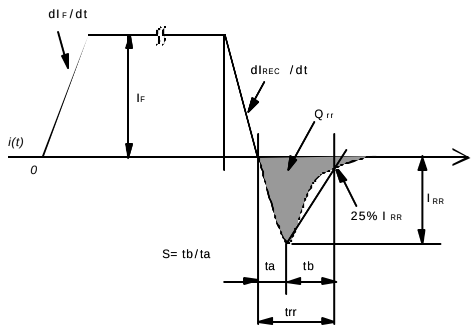
Appendix 1

A useful quantitative description of the relationships that link the reverse recovery parameters is easily obtained assuming the following simplification in the modeling of the reverse recovery characteristic:

$$S = \frac{t_b}{t_a}$$

$$t_{RR} = t_a + t_b$$

$$Q_{RR} \approx \frac{1}{2} I_{RR} \cdot t_{RR}$$



Based on these assumptions we may express the reverse recovery current as:

$$I_{RR} = \frac{dI_{REC}}{dt} t_a$$

Therefore we can rewrite the reverse recovery current expression in this way:

$$I_{RR} = \frac{dI_{REC}}{dt} t_{RR} \frac{1}{S+1}$$

and the Q_{RR} as follows:

$$Q_{RR} = \frac{1}{2} \cdot \frac{dI_{REC}}{dt} \cdot \frac{t^2{}_{RR}}{(S+1)}$$

at this point solving this for the t_{RR}

$$t_{RR} = \sqrt{\frac{2 \cdot Q_{RR} \cdot (S+1)}{\frac{dI_{REC}}{dt}}}$$

and then the expression for the current will be

$$I_{RR} = \sqrt{\frac{2 \cdot Q_{RR} \cdot (dI_{REC}/dt)}{S+1}}$$

from now on, changing the solution variables for all parameters can be obtained, and the following table summarizes the mathematical relationships.

Reverse Recovery Parameter Conversion table

t_{rr}	Q_{rr}	$I_{REC} = \frac{2 \cdot Q_{RR}}{t_{RR}}$	$S = \frac{t^2{}_{RR}}{2 \cdot Q_{RR}} \cdot \frac{dI_F}{dt} - 1$
t_{rr}	I_{rr}	$Q_{RR} = \frac{I_{REC} \cdot t_{RR}}{2}$	$S = \frac{t_{RR}}{I_{RR}} \cdot \frac{dI_F}{dt} - 1$
I_{rr}	Q_{rr}	$t_{RR} = \frac{Q_{REC} \cdot 2}{I_{REC}}$	$t_{RR} = \frac{Q_{REC} \cdot 2}{I_{REC}}$
t_{rr}	S	$I_{REC} = \frac{t_{RR}}{(S+1)} \cdot \frac{dI_F}{dt}$	$Q_{RR} = \frac{t^2{}_{RR}}{2 \cdot (S+1)} \cdot \frac{dI_F}{dt}$
I_{rr}	S	$Q_{RR} = \frac{I^2{}_{REC} \cdot (S+1)}{2 \cdot \frac{dI_F}{dt}}$	$t_{RR} = \frac{I_{REC} \cdot (S+1)}{\frac{dI_F}{dt}}$
Q_{rr}	S	$I_{REC} = \sqrt{\frac{2 \cdot Q_{RR}}{(S+1)} \cdot \frac{dI_F}{dt}}$	$t_{RR} = \sqrt{\frac{2 \cdot Q_{RR} \cdot (S+1)}{\frac{dI_F}{dt}}}$