Optimizing the Ultra-Fast POWERplanar™ Rectifier Diode for Switching Power Supplies

National Semiconductor
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INTRODUCTION

A key device in all high voltage AC-DC power supplies is the ultrafast, reverse recovery rectifier diode. These diodes (D1 and D2 in *Figure 1*) not only play a major role in power supply efficiency but also can be major contributors to circuit electromagnetic interference (EMI) and even cause transistor failure if they are not selected correctly. One would assume that by now, this rectifier diode should approximate the behavior of an ideal switch, i.e., zero on-state voltage, no reverse leakage current and instanteous turn-on. At first glance, the design of this single pn-junction device would appear to be quite straight forward but a review of the device equations reveals that many compromises must be made to optimize its performance. An understanding of these tradeoffs will allow the circuit designer to select the most appropriate rectifier diode.

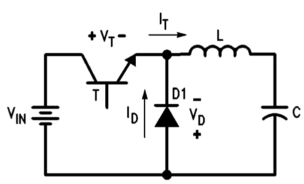

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FIGURE 1a. Buck Regulator to Step-Down Input Voltage V_{IN}

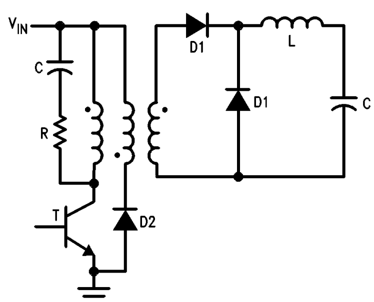

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FIGURE 1b. Forward Converter

Consider how the non-ideal behavior of rectifier D2 affects the circuit performance of the buck regulator in *Figure 1a*. The solid lines in *Figure 2a* depict the switching behavior of the transistor switch and rectifier in comparison to the waveforms (dashed lines) that represent an ideal rectifier. There are four differences between the two cases:

1. The most significant difference is that the peak collector current of the transistor switch (I_T in *Figure 2a*) at the end of turn-on (time t_2) has been increased by the magnitude of the peak reverse recovery current of the rectifier ($I_{R(REC)}$). Correspondingly, the peak power dissipation within the transistor has increased from P_T to P_T as shown in *Figure 2c*.
2. The maximum transistor voltage V_T at turn-off (t_4–t_6 in *Figure 2a*) has been increased by the dynamic voltage drop of the rectifier during turn-on. Since buck regulators generally run at low voltages, this increase has a minimal effect. However, it is more significant in the forward converter circuit of *Figure 1b* and in bridge circuits operating from high bus voltages where the voltage margins cannot be as generous.
3. Since the rectifier is not ideal, its power dissipation consists of the following components:
   a. Conduction loss (V_F x I_F) during the on-time.
   b. Turn-off loss during time t_2–t_3 and turn-on loss during time t_5–t_6 *(Figure 2d)*.
   c. Reverse blocking loss (V_R x I_R) during period t_3–t_5.
4. The rectifier regains its reverse blocking capability at time t_2. A "snappy" rectifier that quickly turns off $I_{R(REC)}$ will contribute much more EMI than a "soft", fast recovery rectifier.

A better transistor switch will intensify rather than improve the shortcomings of the fast recovery rectifier, so it is necessary to consider more fully the conduction and switching behavior of the rectifier diode.

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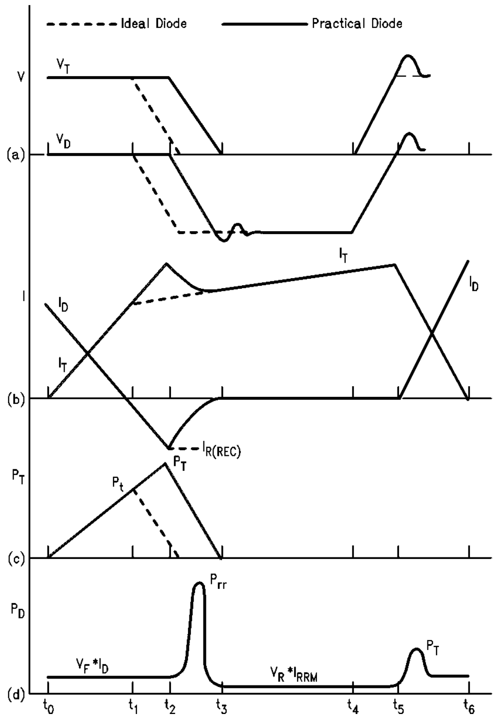

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FIGURE 2. Transistor and Rectifier Voltage and Current Waveforms for the Buck Regulator in *Figure 1a*

a) Transistor and Rectifier Voltage Waveforms
b) Transistor and Rectifier Current Waveforms
c) Transistor Power Dissipation
d) Rectifier Power Dissipation

POWER LOSSES IN THE ULTRA-FAST RECTIFIER DIODE

Consider the idealized rectifier current and voltage waveforms in *Figure 3* for a 50 kHz buck regulator. Power dissipation within the rectifier for a 50% duty factor is:

$$P = P(\text{conduction}) + P(\text{blocking}) + P(\text{reverse recovery})$$

$$P = \frac{1}{2}(V_F I_F + V_R I_R) + V_{RM} I_{R(REC)} t_b f$$

Typical values for a 200V, 8A rectifier are:

$f = 50$ kHz	$I_R = 1$ mA
$V_F = 0.9$V	$t_B = 25$ ns (assuming $t_b = t_{rr}/2$)
$I_F = 8$A	$V_R = 50$V
$I_{R(REC)} = 2.0$A	$V_{RM} = 200$V

$$P = \frac{1}{2}[(8A)\ (0.9V) + (50V)\ (1\ mA)]$$
$$+ (200V)\ (2A)\ (25\ ns)\ (50\ kHz)$$

$$P = 3.6W + 0.025W + 0.5W = 4.125W$$

CONDUCTION LOSSES

DC conduction or on-state losses occur whenever the rectifier is conducting forward current and consists simply of the integration of I_F x V_F during the on-time. Literature has dealt extensively with the computation of V_F for many different rectifier structures (Reference 1). The National Semiconductor POWERplanar™ line of fast recovery diodes are planar passivated, P + N − N+ epitaxial type, for which a cross-sectional view can be found in *Figure 4*. It can be shown that V_F is inversely proportional to minority carrier lifetime and directly proportional to epitaxial thickness (Wi in *Figure 4*).

Figure 5 plots theoretical curves of normalized V_F vs minority carrier lifetimes for rectifiers with 250V and 500V avalanche voltage breakdown. Since t_{rr} is approximately equal to minority carrier lifetime, it is apparent that high current pn-junction rectifiers are limited to 20 ns–50 ns reverse recovery times because V_F dramatically increases for minority carrier lifetimes less than these. It is also apparent that the V_F curves have a broad minima around 10 ns–30 ns so that another reason to select this value of minority carrier lifetime is that V_F becomes independent of small changes in minority carrier lifetime due to manufacturing tolerances.

It is immediately obvious that the key to maximizing current through the rectifier is to minimize V_F. However at 200 kHz, reverse recovery losses will quadruple to 4W, so that increasing attention must be paid to this parameter as operating frequency is raised.

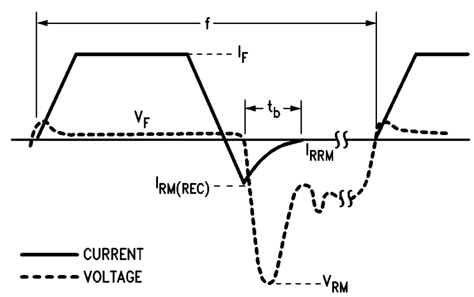

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FIGURE 3. Representative Current and Voltage Waveforms for the Rectifier in the Buck Regulator Found in *Figure 1a*

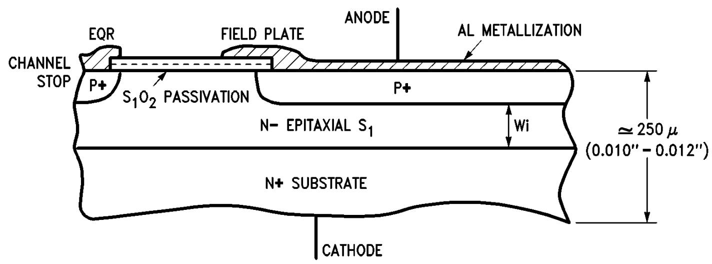

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FIGURE 4. Cross-Sectional View of a POWERplanar™ P + N − N+, Fast Recovery Rectifier

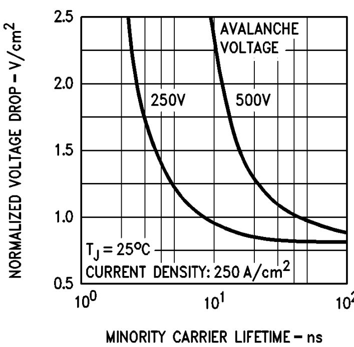

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FIGURE 5. Normalized V_F for 250V and 500V Rated Rectifiers as a Function of Minority Carrier Lifetime

REVERSE BLOCKING LOSSES

Planar passivation techniques have reduced surface leakage currents (I_R) to a negligible amount so that the principle reverse leakage current is recombination current in the space charge region. Some of the many methods to control minority carrier lifetimes are electron or neutron irradiation and gold or platinum diffusion, each with its own advantages and disadvantages. For 200V, ultrafast recovery rectifiers, gold diffusion still represents the best compromise between speed, V_F, I_R and ''soft'' recovery.

A drawback to gold diffusion is its relatively high reverse leakage current. It should be pointed out that the reliability of the gold-diffused product is the same as other rectifiers (all other factors being equal), since this leakage current is a bulk and not a surface phenomenon. *Figure 6* illustrates the dependency of recombination current on junction temperature and minority carrier lifetime, which is inversely proportional to the amount of gold in the depletion region. Experimental leakage test results have been plotted in *Figure 6* for the National Semiconductor 8A and 16A series of rectifiers (FRP820 and FRP1620 respectively) at 100°C, 125°C and 150°C. These points indicate that the low current injection level lifetime ranges from 20 ns–30 ns and is relatively independent of T_J. Since reliability design guidelines specify that the rectifiers be operated at one-half their voltage rating and 25°C–50°C below their maximum junction temperature, the expected leakage currents in well designed power supplies will run less than 1 mA.

REVERSE RECOVERY LOSSES

All pn-junction rectifiers, operating in the forward direction, store charge in the form of excess minority carriers. The amount of stored charge is proportional to the magnitude of the forward current. The process by which a rectifier diode is brought out of conduction and returned to its block state is called commutation. *Figure 7* shows an expanded view of current commutation, also called reverse recovery. Starting at time t_0, the rectifier is switched from its forward conducting state at a specified current ramp rate ($-dI_F/d_t$). The current ramp rate will be determined by the external circuit (E/L) or the turn-on time of a transistor switch. During the time t_1-t_2, the store charge within the rectifier is able to supply more current than the circuit requires, so that the rectifier behaves like a short circuit. Stored charge is depleted both by the reverse recovery current and recombination within the rectifier. Eventually the stored charge dwindles to the point that a depletion region around the junction starts to grow, allowing the rectifier to regain its reverse blocking voltage capability (t_2). From a circuit-design standpoint, the most important parameters are the peak reverse recovery current and ''S'', the softness factor. A ''snappy'' rectifier will produce a large amplitude voltage transient and contribute significantly to electro-magnetic interference. *Figure 8* illustrates the actual reverse recovery of two rectifier diodes. The peak voltage of the snappy rectifier is 175V compared to 142V peak for the FRP820, the higher voltage resulting from both the higher $I_{R(REC)}$ and the fact that the reverse recovery current decays to zero in a shorter time.

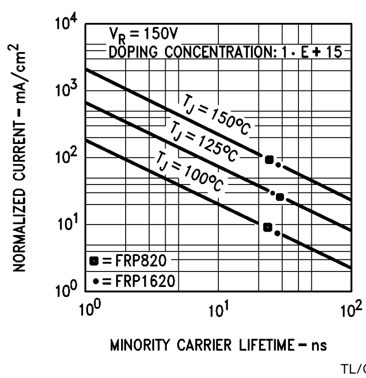

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FIGURE 6. Regeneration Current for Gold-Doped, P + N − N+ Rectifier Diodes

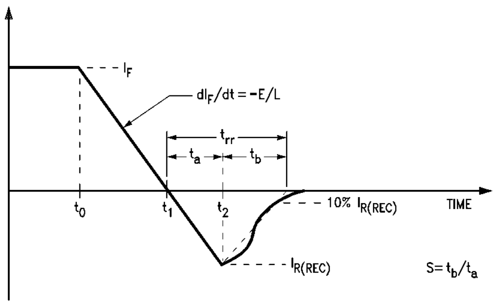

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FIGURE 7. Expanded View of Current Commutation in a Rectifier Diode

The relative snappiness of a rectifier may be defined quantitatively by dividing the reverse recovery time t_{rr} into two subperiods, t_a and t_b, as shown in *Figure 7*. The softness factor "S" is simply the ratio t_b/t_a. A rectifier with a low value S factor will be more likely to produce dangerous voltage transients, but it will also dissipate less reverse recovery energy than a high S factor rectifier. A reasonable compromise between these two conflicting constraints would be to design a rectifier with $S = 1$ ($t_a = t_b$). The S factors of the FRP820 rectifier and the competitive device in *Figure 8* are 0.55 and 0.31 respectively.

Only recently has it become possible to model the ramp recovery in p-i-n rectifiers (References 2, 3) and the following equations have proved useful in predicting reverse recovery parameters.

$$t_{rr} = \frac{Wi\sqrt{\tau/Da}}{8}$$

$$S = \frac{Wi}{4\sqrt{Da\tau}}$$

$$I_{R(REC)} = \left(\frac{dI_F}{dt}\right)\tau\left(1 + \frac{Wi}{8\sqrt{Da\tau}}\right) - 1$$

$$Q_{R(REC)} = 0.5\,\tau^2\left(\frac{dI_F}{dt}\right)$$

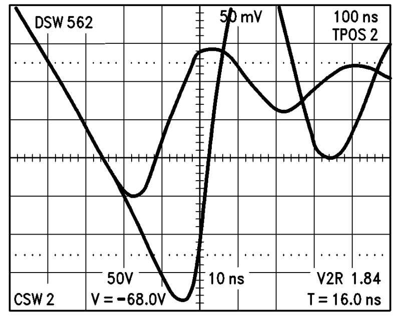
where:

τ = minority carrier lifetime

Wi = epitaxial thickness

Da = ambipolar diffusion constant

The blocking voltage rating of the rectifier primarily determines Wi; but for a given Wi, note that a short minority lifetime not only decreases $I_{R(REC)}$ but happily increases S. These two key parameters are plotted as a function of minority carrier lifetime in *Figure 9* for $dI_F/dt = 100\ A/\mu s$ and $T_J = 25°C$. As has been noted before, the minority carrier lifetime had been targetted for 20 ns–30 ns to minimize V_F and this choice has resulted in a typical value of $S = 0.65$ and $I_{R(REC)} = 1.5A$.



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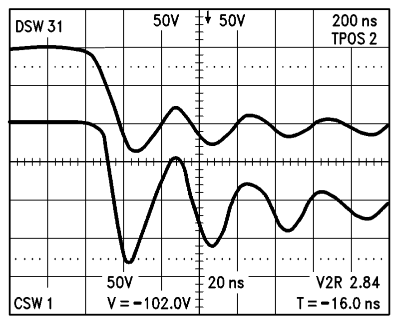
Test Conditions:

$T_j = 25°C$	I = 0.5 A/DIV
$I_F = 8A$	T = 10 ns/DIV
$dI_F/dt = 100\ A/\mu S$	



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Test Conditions:

$T_j = 25°C$	I = 50 VA/DIV
$I_F = 8A$	T = 10 ns/DIV
$dI_F/dt = 100\ A/\mu s$	

FIGURE 8. Comparison of Reverse Recovery of the FRP820 Series Rectifier to a Snappy Rectifier

REVERSE RECOVERY CHARACTERIZATION

Figures 10–13 plot $Q_{R(REC)}$, $I_{R(REC)}$, t_{rr} and S versus dI_F/dt for the FRP1600 series of rectifiers and typical use conditions of $I_F = 16A$ and $V_R = 200V$ and for two different junction temperatures of 25°C and 125°C. Theory not only predicts, but it has also been experimentally verified, that these parameters are relatively independent of I_F so only one value of the latter suffices. Any three of the four *Figures 10–13* completely specifies the reverse recovery behavior of the rectifier. Since S and T_{rr} vary the least over the plotting dI_F/dt range, it is convenient to formulate reverse recovery energy loss P in microwatts in terms of the circuit parameters V_R and dI_F/dt:

$$P = \frac{V_R\left(\frac{dI_F}{dt}\right)f}{2S}\left(\frac{St_{rr}}{1 + S}\right)^2 10^{-3}\ (\mu W)$$

where:

V_R = peak reverse voltage

dI_F/dt = ramp rate ($A/\mu s$)

f = operating frequency (kHz)

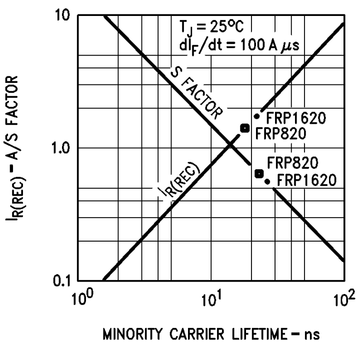

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FIGURE 9. Theoretical Plots of $I_{R(REC)}$ and S vs Minority Carrier Lifetime

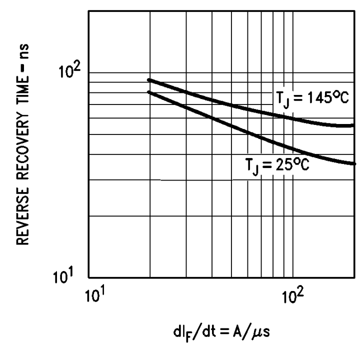

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FIGURE 12. Reverse Recovery Time of the FRM/FRP1600 Series Rectifier Diodes

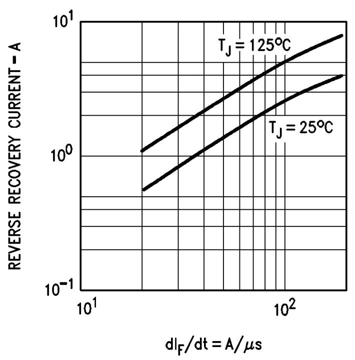

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FIGURE 10. Reverse Recovery Current for the FRM/FRP1620 Series Rectifiers

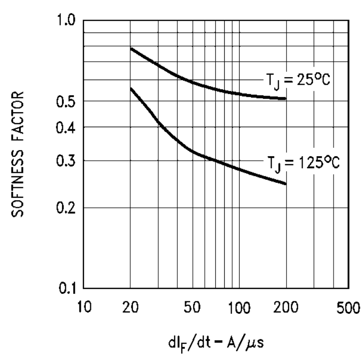

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FIGURE 13. Softness Factor S for the FRM/FRP1600 Series Rectifier Diodes

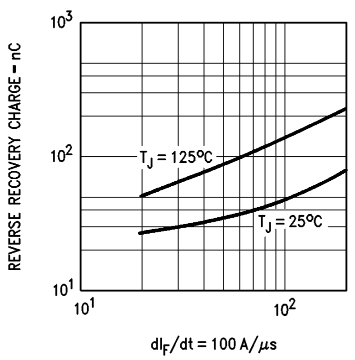

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FIGURE 11. Reverse Recovery Charge for the FRM/FRP1600 Series Rectifier Diodes

Example: Calculate the reverse recovery power loss for the FRP1620 rectifier running at:

$I_F = 16A$ $\quad V_R = 100V$

$dI_F/dt = 100\ A/\mu s$ $\quad T_J = 125°C$

$f = 75\ kHz$

From *Figures 12* and *13* $t_{rr} = 56$ ns and $S = 0.29$. Substituting these values in the above equation:

$$P = \frac{(100V)\ (100\ A/\mu s)(75\ kHz)}{(2)(0.29)} \left[\frac{(0.29)(56\ ns)}{1 + 0.29}\right]^2 10^{-3}\ \mu W$$

$P = 0.205W$

There are may ways to shape the reverse recovery voltage spike. The most simple and still most popular is the RC snubber circuit connected across the primary of the transformer in *Figure 1b*. This serves the dual purpose of suppressing voltage ringing and EMI due to the switching action of both the transistor and rectifier. William McMurray has shown how to design an RC snubber to minimize voltage transients and/or dV/dt ramps just due to the diode reverse recovery current (Reference 4) and also how to design snubbers to minimize transistor power dissipation (Reference 5). But to date, because the RC snubber plays a major role in reducing EMI, its design tends to be empirical rather than theoretical.

CONCLUSION

This application note has pointed out the major considerations in designing an ultrafast reverse recovery rectifier and shown that the control of minority carrier lifetime is the key in arriving at an optimum device. Because the diode contributes to EMI, its reverse recovery behavior must be carefully controlled and characterized in order to guarantee similar performance from lot to lot.

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