

Rectifier Reverse Switching Performance

Basic rectifier diode features were described in MicroNote 301. These included average forward current I_O , working peak reverse voltage V_{RWM} , reverse current I_R , breakdown voltage $V_{(BR)}$, forward voltage V_F , forward current I_F , and forward surge current I_{FSM} . For many low frequency applications, these parameters are adequate in selecting rectifiers.

As switching speeds or frequency of operation increase well beyond 400 Hz, rectifiers can become inefficient or notably handicapped to a variety of applications unless designed and selected with added performance features. This is most often given in terms of *reverse recovery time* t_{rr} . Applications may include switched mode power supplies or others requiring high speed rectifier response. In these examples, rectifiers are often expected to respond as ideal switches or "one-way-current-flow valves" to meet functional circuit requirements when subjected to forward and reverse voltage environments. High speed rectifiers best approach this ideal by minimizing switching energy losses and heat that can otherwise be generated in other circuit components and in switching rectifiers themselves. In other applications needing fast

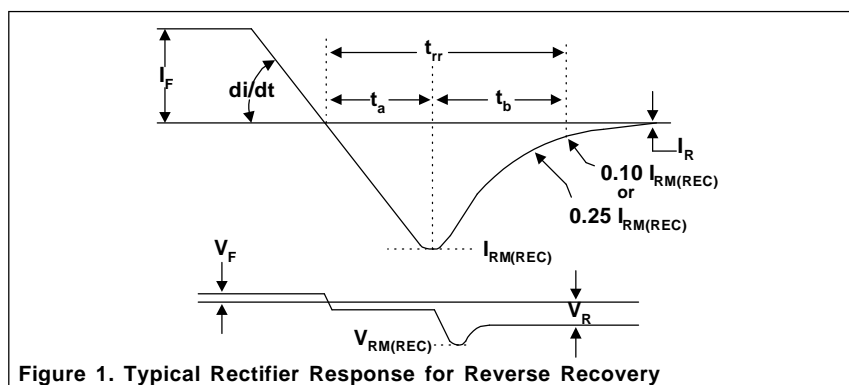
responding "catch" diodes, they also serve as protective voltage clamps in parallel to sensitive components such as MOSFETs and IGBTs. In such applications, good forward recovery characteristics in t_{fr} and V_{FRM} may also be needed.

The industry generally identifies a rectifier as "fast" if it is rated with reverse recovery of 500 ns or less ($\approx 1/10$ that of standard rectifiers). If further improved to 100 ns or less, it is often termed "ultrafast". Low current small signal diodes with 10-100 volt V_{RWM} are in the t_{rr} range of 0.75 to 5 ns. Medium to high current ultrafast rectifiers are available in a range of 15 to 60 ns as voltage rating is increased from 50 to 800 volt V_{RWM} operation. Rectifiers with voltages of 1000 to 1500 volts are also available in the range of 100 ns.

The reverse recovery time of a rectifier can best be understood by viewing the rate of decreasing current in the forward conducting direction and how quickly thereafter it effectively stops current flow. When switched in this manner, the typical current flow and voltage response of a

rectifier is shown in Figure 1. When forward current is switched or ramped down at some high rate of di/dt to zero in Figure 1, current flow does *not* simply come to an ideal stop. Instead the current briefly reverses its flow and continues until a peak overshoot occurs. It will then diminish thereafter to near zero (I_R). During the brief reverse current flow, the anticipated high reverse blocking voltage across the rectifier does *not* start appearing until the reverse current peak occurs. This delay can also significantly affect the switching energy in other components that must still support voltage when rectifier current is reversed.

As in most semiconductor components, voltage response is *current driven*. In rectifiers, voltage versus time is dependent on how long it takes for stored charge in forward current injected minority carriers near the pn junction to be swept out or *recovered* as current flow is reversed. In Figure 1, this process eventually peaks in charge removal rate or the *peak reverse recovery current* $I_{RM(REC)}$ before a depletion region forms and the rectifier begins supporting reverse voltage.



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Only after this peak occurs will reverse current diminish in the latter portion of switching. The overall time these semiconductor events occur to switch off current flow in the rectifier is represented by *reverse recovery time* t_{rr} .

In lower current applications, the reverse current overshoot for charge recovery is often limited by the circuit or test method used rather than the diode itself. When test limited in this manner, it is then simply identified as *reverse current* I_{RM} as shown in Figure 2. This is an important distinction from $I_{RM(REC)}$ since I_{RM} is *not* a diode dependent feature.

In either case, *recovered charge* Q_{RR} may be approximated by *area* under the reverse current-time curve. This Q_{RR} also represents energy that must be dissipated with reverse voltage in the power switching side of the circuit. In Figure 1 where it appears triangular and the apex is at $I_{RM(REC)}$, recovered charge Q_{RR} can be approximated by the expression:

$$Q_{RR} \simeq (1/2) t_{rr} I_{RM(REC)}$$

When I_{RM} is limited by application or test circuit, it will extend t_{rr} somewhat to recover the charge Q_{RR} . It is also apparent that high forward operating currents (I_O) injecting greater stored charge will

require longer reverse recovery time to switch. If I_O and V_F conduction losses result in *higher operating temperature*, this will also effectively increase t_{rr} , $I_{RM(REC)}$, and *switching losses*. Both suggest rectifiers should be conservatively chosen in I_O ratings versus application including any noted I_F difference in t_{rr} test characterization.

The reverse recovery time t_{rr} is comprised of two time intervals t_a and t_b when rectifiers respond with their own peak reverse recovery current $I_{RM(REC)}$ as shown in Figure 1. The t_a begins at the moment forward current has been ramped down from I_F where it intersects the zero current axis, and concludes at the rectifier $I_{RM(REC)}$ peak response point.

This t_a region is primarily dictated by *rectifier component design* in how quickly the $I_{RM(REC)}$ peak can be achieved with minority carrier lifetime control. During this t_a portion of switching, other circuit components may be subjected to fast rise time voltage-current where the rectifier has *not* yet begun to support reverse voltage. As switching rates (di/dt) increase, these other components must absorb corresponding greater switching energy and heating. As operating frequency increases, this can be excessive at high duty factors.

The latter part of reverse recovery time is t_b . It begins at $I_{RM(REC)}$

peak and ends where reverse current decays to a *specified level* (see Figure 1). In low to medium current “soft recovery” rectifiers, it is often where i_R diminishes to 10-25% of the specified peak I_{RM} test value. On higher rated current rectifiers, reverse recovery may also be specified to end at an intercept point on the zero-current axis after drawing a straight line from the $I_{RM(REC)}$ point to 0.25 $I_{RM(REC)}$ on the recovery curve. This line is then extended to the termination point on the zero-axis. For rectifiers with “abrupt recovery” or oscillatory *ring-off*, it is where reverse current again crosses the zero axis. These examples are in Figure 3.

The t_b region in reverse recovery is influenced by rectifier design *and circuit interaction*. It is this switching region where the rectifier is now supporting significant reverse voltage while reverse current is still diminishing. During this brief time, voltage and reverse current switching energy are now primarily absorbed by the rectifier. This can also generate notable rectifier *heating* if t_b is excessively long, particularly if repeated at high frequency.

From the combined effects of both t_a and t_b for reverse recovery time, it is apparent that minimal values of t_{rr} are needed to reduce switching energy stresses to other components as well as the rectifier diode itself in higher speed applications. Since t_b (and I_{RM}) are also influenced by the circuit, it is important to specify test requirements for t_{rr} that reasonably approximate actual operating conditions including forward current, di/dt , and temperature.

The latest industry standards for measuring reverse recovery time are found in JEDEC Standard JESD41 which is virtually identical

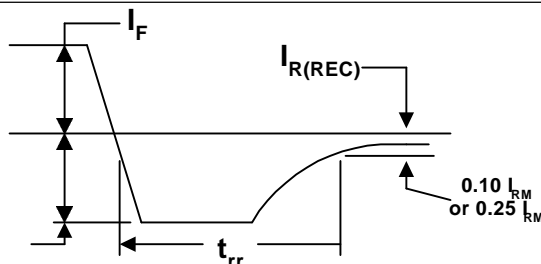


Figure 2. Circuit Limited I_{RM}

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to MIL-STD-750, Method 4031. Each has four different test conditions of various product operating ranges in forward current, di/dt , and t_{rr} . This includes test criteria for small signal diodes on up to large power rectifiers. The classification of *soft and abrupt recovery rectifiers* is another reverse recovery feature that can be important in many applications. It has previously been identified in the industry as *Recovery Softness Factor* where $RSF = t_b/t_a$. The higher the value in RSF, the softer the recovery. This is observed where reverse current decreases more slowly and smoothly in the t_b region to its steady state value (I_R) compared to the initial t_a region. In contrast, abrupt rectifiers exhibit a reverse current waveform that quickly cross the zero axis and often oscillate or ring off as in Figure 3. This can also result in excessive rf noise.

Newer JEDEC and international IEC standards will soon be recognizing soft and abrupt features with Reverse Recovery Softness Factor **RRSF** which is defined as the absolute value in ratio of di/dt slope in the t_a region divided by *greatest magnitude* of di/dt slope in the t_b region. Reasons for this become apparent when considering practical applications. If the t_b region is very short and abrupt, the effect of *rapid current change* with other circuit *loop inductance* can produce undesired transient voltages. If this Ldi/dt effect in the t_b region is high compared to the t_a region, it can result in an undesired reverse voltage peak that meets or exceeds the "buss line" voltage V_R

and reverse breakdown voltage $V_{(BR)}$ of the rectifier as well. Should this occur, the greater peak voltage $V_{RM(REC)}$ can be shown as in Figure 1. It may also display a voltage oscillation before settling to V_R for abrupt "ring off" examples. Similar to the t_b region, this $V_{RM(REC)}$ is influenced by circuit interaction (loop inductance). It can also be damaging to the rectifier, particularly if not rated in adequate $V_{(BR)}$ or peak reverse avalanche energy. A frequent way of minimizing excessive transient reverse voltages is by adding *snubbers* to the circuit. Nevertheless if the rectifier is sufficiently fast and not abrupt, snubbers can be downsized or eliminated.

Applications using fast or ultrafast rectifiers often specify soft recovery (greater RSF). However this also has limits. If a rectifier is excessively soft with high RSF, parasitic heating of the rectifier occurs from long t_b regions in reverse current-voltage effects.

To avoid abrupt recovery, some RSF requirements can also be misleading or incomplete. Since the t_b region and its di/dt response are influenced by circuit interaction as well as device design, the RSF

(or RRSF) using one specific test condition cannot adequately characterize these features for *various* operating conditions. It can also be observed when increasing the switching rate to greater magnitude di/dt that it results in higher absolute $I_{RM(REC)}$. This may also result in *more abrupt* diode response characteristics depending on circuit interaction. Therefore great care must be taken *if* the circuit is sensitive to abrupt recovery characteristics versus rectifier ratings or test condition specifications.

In conclusion, judicious rectifier selection with conservative circuit design is particularly important as switching speeds are increased. For lower switching losses, rectifiers should be selected with minimal recovery times and adequate current ratings for lower optimum operating temperatures. Also the reverse recovery time test conditions versus application must be considered along with circuit interface effects. For variable operating conditions and design margins at high speeds, this may also require circuits using snubbers

