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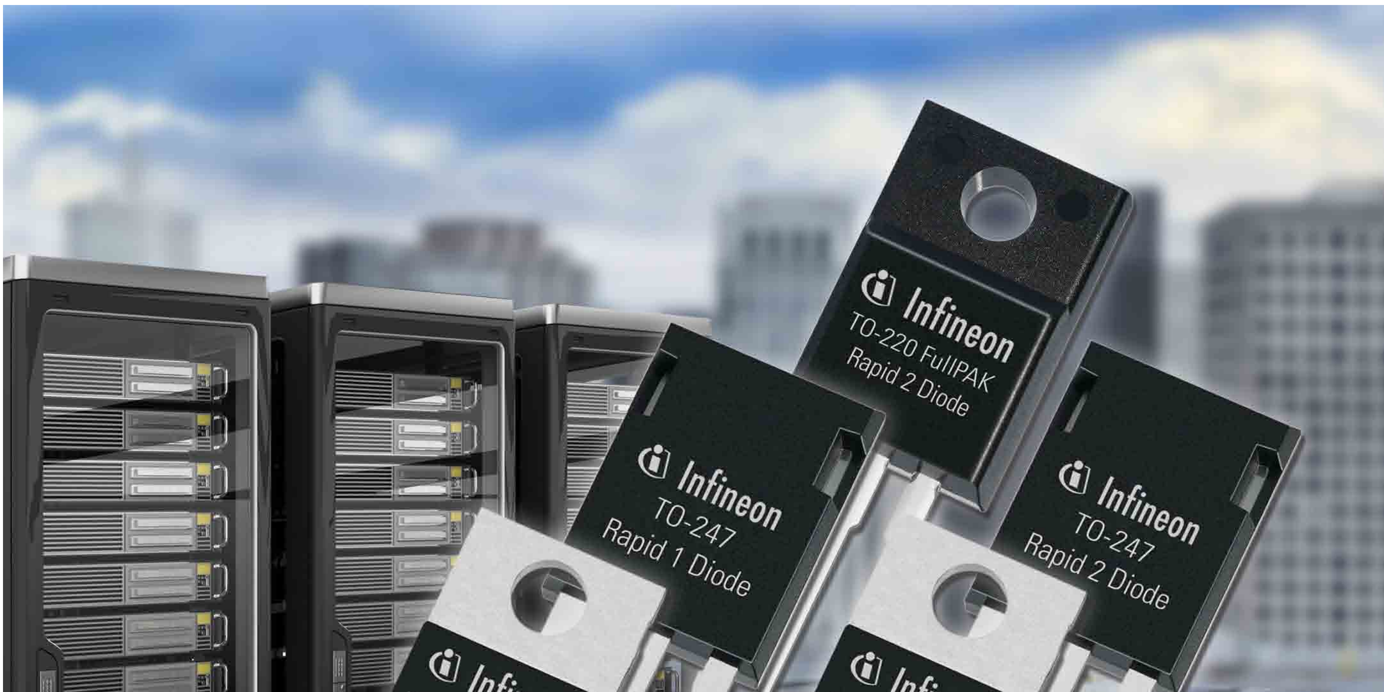
Power Systems Design: Empowering Global Innovation



Special Report: Powering Industrial Applications (pg31)

Diode choice impacts power system performance

It is important to use an optimized power device for any given application

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Power devices such as IGBTs and diodes are widely used in power electronics. Many applications use diodes as the PFC boost diode, free-wheeling diode, rectification on primary and secondary side, fast rectifiers for example in battery chargers. Generally, IGBTs have high switching losses due to the current tail which limits the switching frequency operation. Active power factor correction (PFC) circuits are widely used as a front end to meet these standards. Most active PFC circuit designs use boost topology in Continuous Conduction Mode (CCM) for high power applications. A boost diode is required in PFC circuits. An optimized diode is needed to meet high efficiency standards as well as high power density.

To achieve high efficiency with low EMI, it is a must to use an optimized power device for a specific application. For example, Infineon's Rapid 1 diode, with 1.35V temperature-stable forward voltage, is optimized for applications switching up to the 40kHz typically found in Home Appliance, Solar inverter and Welding machines. While Infineon's Rapid 2 diode, with short reverse recovery time, is optimized for applications switching between 40kHz to 100kHz, typical for a Boost PFC in Consumer SMPS. Application tests show lower conduction and switching losses, a soft reverse recovery and stable temperature behavior.

Rapid 1 or Rapid 2?

Different applications require different types of diodes. Diodes with low V_f are optimized for applications operating with low switching frequency while with low Q_{rr} and t_{rr} are optimized for applications operating with high switching frequency. As a result of applications needing diodes specially tuned for high or low speed switching, Infineon has developed the Rapid 1 and Rapid 2 diode families. Rapid 1 is V_f tuned to ensure lowest conduction losses and thus focus on application switching up to 40kHz. Meanwhile, for applications switching beyond 40kHz, the Rapid 2 has been developed to have a t_{rr} <20ns, ensuring that switching losses are kept to a minimum.

P-i-N diodes are categorized via a trade-off curve of V_f versus Q_{rr}/t_{rr} to either have low V_f with high Q_{rr} and t_{rr} or high V_f with low Q_{rr} and t_{rr}. Rapid 1 is a low V_f diode while Rapid 2 is a low Q_{rr} and t_{rr} diode. Static (low V_f) and dynamic (low t_{rr}) performance of a P-i-N diode are determined by the plasma of excess charge carriers injected into the drift region of the diode. This plasma modulates the conductivity of the diode, but needs to be removed from the device before a voltage can be supported. Higher plasma concentration results in better conductivity, i.e. lower V_f can be achieved, but a tradeoff exists meaning more charge is present and this takes time to remove. This high charge concentration results in a high Q_{rr}. Plasma level during the conduction state of a P-i-N diode is determined by the thickness of the drift layer, ambipolar carrier lifetime in the drift zone and it's variation over depth and injection efficiency of the anode or cathode. Commonly, plasma engineering is done by reducing the ambipolar lifetime, which has the drawback of a strong temperature coefficient (higher plasma at elevated temperature resulting in negative temperature coefficient of V_f and strong increase of losses at high temperature) plus providing additional generation levels in the bandgap which leads to high reverse leakage current levels at higher temperatures.

Rapid 1 for Low Switching Frequency Applications

High power applications need high power semiconductors and devices. IGBTs are commonly used as power switches while diodes are used for rectification and free-wheeling operations. Due to its current tail, IGBT is best operated at low switching frequency. So generally, low switching frequency operation is used at very high output power systems. Low conduction loss devices are essential on low switching frequency designs. Rapid 1 with low Vf is suitable for low switching frequency and high output power applications even at increased junction temperatures.

Rapid 1 advancement in thin wafer technology helps to maintain a stable Vf over temperature. A 30A/650V rated Rapid 1 diode is tested against two 30A/600V low Vf competitor diodes commonly found especially in the Asian solar market. The Rapid 1 exhibits an 18mV Vf difference from 25°C to 100°C in junction temperature (Tj), which when compared to the competitor diodes, offers more stability of temperature-dependent

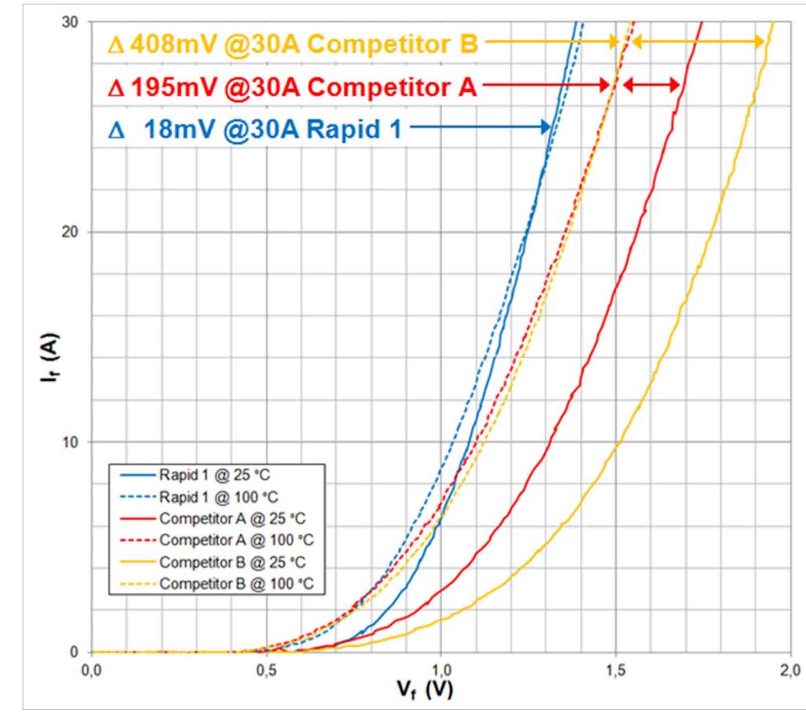

Figure 1: Diode Forward Voltage vs. Forward Current over Temperature

Vf compared to Competitor A (195mV) and Competitor B (408mV). Rapid 1 has also low Vf (1.406V) compared to competitor A (1.550V) and competitor B (1.542V). **(See Figure 1)**

Now we check the Vf-Qrr trade-off of these diodes to see how it affects overall performance. A double pulse test fixture is used to see how the diode will affect the power switch turn-on losses (EON). **(See Table 1)**

Rapid 2 for PFC Applications

The two modes of PFC operation are the Discontinuous Current Mode (DCM) and Continuous Current Mode (CCM). At DCM, the power switch turns-on while the inductor current is zero thus the boost diode has no forward current before the power switch turns-on. Hence, diodes with fast reverse recovery times are not needed. At CCM, the boost diode is conducting forward current before power switch turn-on. When the power switch turns-on, the

	V_f (V)	I_{RRM} (A)	Q_{rr} (nC)	$E_{on(switch)}$ (mj)
Rapid 1	1.406	14.99	861.2	1.019
Competitor A	1.550	19.22	712.7	1.016
Competitor B	1.542	22.74	772.3	1.019

Table 1: Diode and $E_{on(switch)}$ Test Result. I_D=30A, T_j=100°C

boost diode will be in transition from conducting to blocking state. This transition or reverse recovery time should be as fast as possible, since high current and voltage are present at this point, therefore high power losses. To have a fast reverse recovery time, boost diodes should have a low Q_{rr}.

Rapid 2 with low Q_{rr} reduce the power switch E_{ON}. With soft recovery characteristics it also reduces the EMI generated during boost diode recovery. To validate this, a hard-switched CCM boost PFC circuit with an output power capability of 800W is used as a test platform. The test platform input voltage can be varied from 110 V_{AC} to 220V_{AC} and the output voltage (V_{OUT}) of the PFC is 400V_{DC}. Tests were done in a 25oC ambient temperature. The waveforms shown in figure 3 show an 8A/650V rated Rapid 2 boost diode reverse recovery time compared with some 8A/600V low Q_{rr} version competitors. As shown the boost diode is conducting forward current (I_F). After 20ns, the diode starts to divert the forward current to the power switch by turning-on the power switch. After 6ns, all boost diode forward current has been diverted to the power switch. This time duration is t_r. After t_r, the boost diode undergoes reverse current conduction at rate of dif/dt. Minority carriers have to be removed from the boost diode before a reverse voltage can be supported. Reverse current conduction starts after t_r then

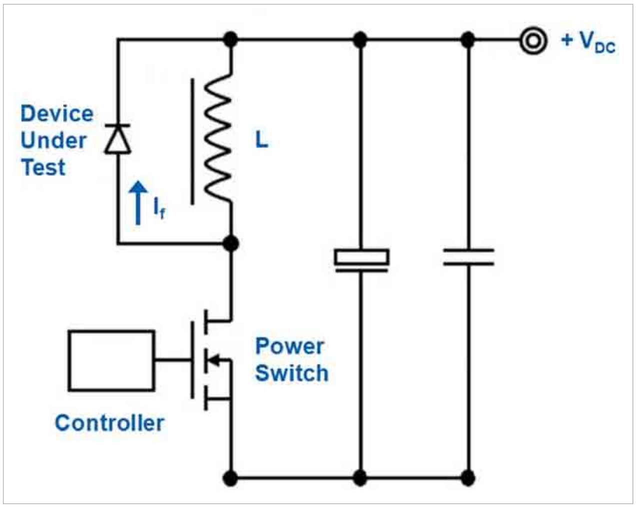

Figure 2: Boost Diode Reverse Recovery Waveforms and Test Circuit

peaks down to a maximum reverse current (I_{RRM}) then returns back to zero. (**See Figure 2**)

I_{RRM} affects the E_{ON} of the power switch since I_{RRM} is reflected as the current peak during the power switch turn-off to turn-on transition. Hence, I_{RRM} needs to be as low as possible to minimize power switch E_{ON}. Moreover, the t_{rr} (i.e. $t_a + t_b$) should be as short as possible to minimize the duration of E_{ON}. Attention is given to the softness recovery of the boost diode where t_b is longer in duration than t_a. The softness ratio (i.e. $S = t_b / t_a$) should always be greater than one. Less than this, the boost diode is said to be snappy in recovery. A snappy recovery may results in higher power dissipation across the boost diode during t_b.

Rapid 2 combines low I_{RRM} and t_a to have the lowest measured E_{ON} of the power switches and therefore offer higher efficiency and lower T_j of the power switch while maintaining a high S factor than the competitors. (**See Table 2**)

	I_{RRM} (A)	t_a (ns)	t_b (ns)	t_{rr} (ns)	Q_{rr} (nC)	S	$E_{on(switch)}$ (μj)
Rapid 2	13.46	7.8	11.2	19.0	127.9	1.4	51,1
Competitor C	14.74	9.0	6.4	15.4	113.5	0.7	55,1
Competitor D	15.38	9.9	12.2	22.1	169.9	1.2	58,5
where:	measured	measured	measured	$= t_a + t_b$	$= t_{rr} \cdot I_{RRM} \cdot 0.5$	$= t_b / t_a$	measured

Table 2: Reverse Recovery and $E_{on(switch)}$ Test Result

Rapid 2 has the best combination of low Q_{rr} and high softness ratio (S). In a PFC efficiency comparison at 115V_{AC} and 230V_{AC} input voltage over the entire load range in a 25°C ambient, in a good compromise between V_f and Q_{rr}, Rapid 2 shows a better efficiency from light to mid load while maintaining good efficiency at full load. Rapid 1 and 2 ruggedness is further increased by having a DC blocking voltage of 650V, i.e. 50V higher capability than the competitors, while having a soft recovery characteristic.

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