Hard Commutation of Power MOSFET

OptiMOS^{TM} FD 200V/250V

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1   Introduction

The modest advancement in the development of trench field-plate power MOSFETs in the last decades has allowed more and more applications and systems to benefit from the advantage of fast switching and high power density. The breakdown voltage has evolved from sub 20V to 250V for state-of-the-art trench field-plate Power MOSFETs.

In the 200V to 250V medium voltage range, up until now, Infineon has been offering industry leading OptiMOS™ 3 devices with the lowest figure of merit ($R_{DS(on)}$ x Q_g). They not only provide the lowest $R_{DS(on)}$ for highest efficiency, but also low gate charge for ultra-fast switching in high frequency applications.

As the breakdown voltage increases, the device undertakes more stress in a different dimension. While the voltage rating goes up, the current rating often goes down. This is the consequence of power limiting and is the most common and obvious thing for the designer to take into account. However, a very important trait of a Power MOSFET, which is often overlooked, is the hard commutation ruggedness of the body diode. This is crucial to system reliability. In a system where hard commutation occurs, body diode weakness can be catastrophic if the limit of this intrinsic device is exceeded. Designers should pay special attention in the design process, more specifically in the device selection stage, to ensure a reliable system.

This application note discusses the importance of hard commutation ruggedness of Power MOSFETs and introduces the new OptiMOS™ FD (Fast Diode) product family. These devices come with improved ruggedness with the body diodes against difficult hard commutation conditions. The application note explains how the better switching behavior of OptiMOS™ FD devices improves system reliability and performance.

2   Description of Hard Commutation

Commutation in this context refers to the switching behavior of a Power MOSFET. To commutate means to stop the current flow in the body diode of a MOSFET. The main advantage of a Power MOSFET is its high commutation speed when compared to other power semiconductor devices, such as IGBTs and Thyristors [3]. A trench field-plate MOSFET, a special structure of MOSFET, offers the lowest $R_{DS(on)}$ per area and all the advantages of a MOSFET. It is currently suitable for applications requiring up to 250V breakdown voltage.

The following discusses the reverse recovery process of the body diode, commutation types and definitions, hard commutation test setup, and the key parameter of this subject - reverse recovery charge.

2.1   Body Diode and Reverse Recovery
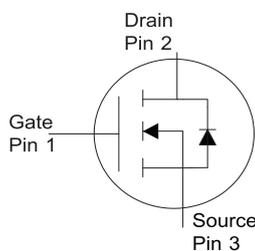
Figure 2.1: Symbol of a Power MOSFET

Figure 2.1 is the typical symbol used to represent a MOSFET. The diode in parallel with the channel of the device is called "body diode". Every MOSFET has a body diode and it is an intrinsic by-product of a MOSFET formed by the PN junction in its physical construction. Once a MOSFET is chosen for a design, the body diode that comes with it is also fixed. Therefore, a reliable system requires careful selection of the MOSFETs with robust body diodes to fulfill the requirement of the application.

Application Note
Hard Commutation of Power MOSFET

In switching converters, body diodes are common instruments used to provide the freewheeling capability at no extra component cost. It is an advantage in this case where no external diode is required. However, body diodes come with the same physical limitations as discrete diodes, such as maximum current rating and maximum blocking voltage, etc. One of the most important but often neglected limitations of body diodes is the undesired reverse recovery behavior. Reverse recovery occurs when the diode switches off while carrying a positive forward current as shown in Figure 2.2, where the voltage and current waveforms illustrate the turn-on and turn-off transitions of a diode.
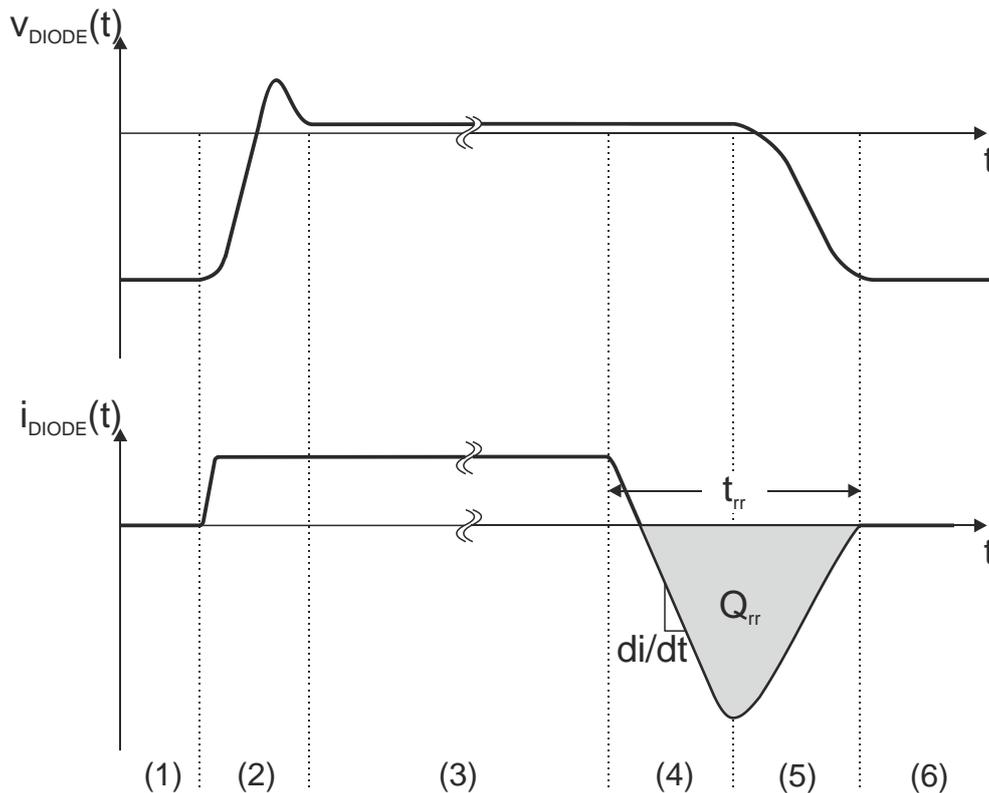
Figure 2.2: Operation of a diode [1]

The following explains each state of the diode operation in Figure 2.2.

At interval (1), the diode is in the off state.

1. The diode starts to turn on in interval (2). At the end of the turn-on process, the diode becomes forward biased.

2. The reverse recovery charge accumulates and is stored while the forward biased diode carries a positive current (3).

3. At the start of the turn-off interval (4), the current rolls off to zero then reverses direction. During the negative current, the reverse recovery charge stored in the device recombines.

4. In (5), the turn-off process finishes and in (6) the diode is off again.

This recombination process takes time (t_{rr}) and yields additional power loss. The shaded area in the diagram indicates the reverse recovery charge (Q_{rr}) - the key device parameter for hard commutation ruggedness.

2.2   Types of Commutation

There are two ways a Power MOSFET can be commutated – hard commutation and soft commutation.

Hard commutation of a MOSFET, in short, refers to the condition where the body diode of a MOSFET experiences reverse recovery, i.e. the body diode turns off while there is still forward current flowing through or accumulated reverse recovery charge. This type of commutation is the focus of this document.

On the other hand, soft commutation refers to commutating a MOSFET where reverse recovery of the body diode is avoided. This is common in soft switching converter topologies which deliberately enforce switching at zero current. As mentioned earlier, reverse recovery condition only occurs during turn-off transition as in the diagram, where both the forward current and diode voltage are positive. In theory, reverse recovery does not occur for zero-current switching. While soft switching is also an interesting topic and could potentially eliminate the concern for the hard commutation issue completely, it is out of scope here and will not be discussed further in this document.

2.3   Hard Commutation Explained in an Example Circuit

In a practical half-bridge application, a low side FET is used for synchronous rectification (SR) instead of a diode to minimize the conduction loss [2]. The channel of the SR FET conducts during the off state of the top side FET. Figure 2.3 is the schematic of Infineon's half-bridge hard commutation test setup. In this setup, the low side FET is tied to the ground. This forces the rectifier current to freewheel entirely through the body diode instead of flowing through the channel. Examination of the body diode by itself is made possible.
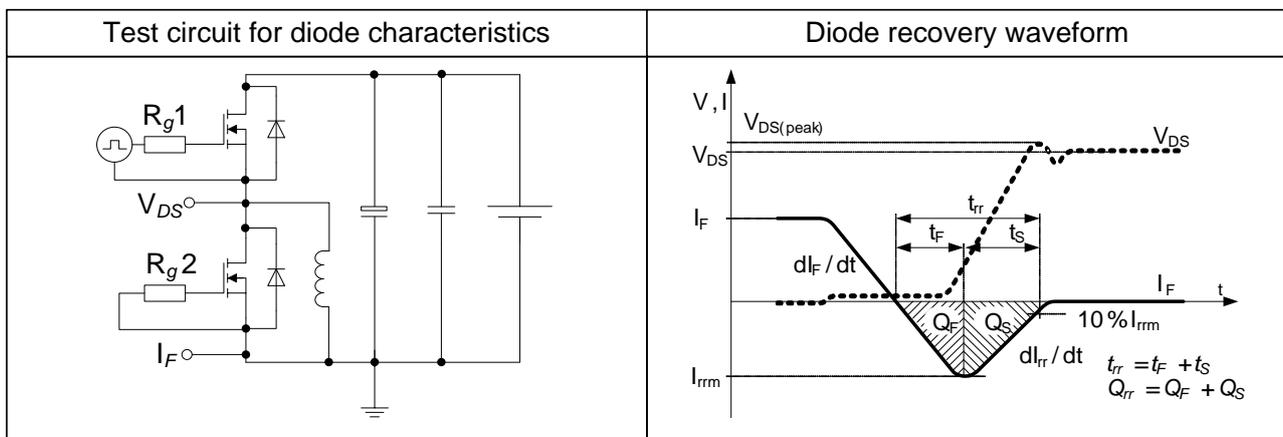
Figure 2.3: Infineon's hard commutation test circuit and diode recovery waveform

On the right are the diode voltage and current waveforms during the turn-off transition. The diode is initially forward biased carrying a positive forward current. As soon as the gate-source signal (V_{GS}) goes high to turn on the top side control FET, the body diode turn-off process of the low side FET is initiated. The diode current rolls off at a constant slope (*di/dt*) to zero and then reverses the direction. The negative current, also known as reverse recovery current (I_{rr}), finally reaches the negative peak (I_{rrm}) and then goes back up to zero. The reverse recovery process completes at this moment, and the body diode returns to its blocking state.

2.4 Reverse Recovery Charge (Q$_{rr}$)

Q$_{rr}$ and T$_{rr}$ specified in Infineon's OptiMOS™ datasheet are obtained using the characterization setup in Figure 2.3. Infineon follows JEDEC standard. T$_{rr}$ is measured as illustrated, and Q$_{rr}$ can be calculated by integrating the shaded area under the negative current curve in the diagram. It can also be approximated by the area of the shaded triangle as in equation (1).

$$Q_{rr} = 0.5 \cdot I_{rrm} \cdot t_{rr} \tag{1}$$

Note: In reality, the shaded triangular area contains both Q$_{rr}$ and Q$_{oss}$. Q$_{oss}$ is the charge in C$_{oss}$. It is difficult to distinguish which portion Q$_{rr}$ is and which portion Q$_{oss}$ is because there is no physical indication when Q$_{rr}$ recombination process completes. Q$_{oss}$ is more or less constant at different V$_{DS}$, so a more accurate estimation of the total Q$_{rr}$ is the area of the shaded triangle minus the Q$_{oss}$ specified in the datasheet. In the case where device enters avalanche, a way to estimate Q$_{rr}$ plus Q$_{oss}$ excluding avalanche energy is to integrate the area under the curve till the peak of V$_{DS}$ is reached.

2.4.1 Problem Caused by Q$_{rr}$ - Overshoot

In the half-bridge configuration, when the body diode is in reverse recovery, the direction of the body diode current flow is the same as the top side FET, thus a shoot through occurs. This behavior results in overshoot, which

- puts the device into avalanche and may degrade the device over time.
- or requires extra snubber circuitry to comply with the de-rating requirement of the application (commonly 80% de-rating), resulting in extra bill-of-material cost and additional design step for snubber tuning.

V$_{DS(peak)}$ in Figure 2.3 above denotes overshoot.

2.4.2 Q$_{rr}$ Dependency

As described previously, the waste of reverse recovery, Q$_{rr}$, causes overshoot, which potentially leads to device failure. The higher the Q$_{rr}$, the higher the overshoot. In other words, a device with lower Q$_{rr}$ is less susceptible to a rough hard commutation. Therefore, Q$_{rr}$ is a good indicator for a device's hard commutation ruggedness.

Since Q$_{rr}$ is undesirable yet unavoidable in many cases, it is important to understand the factors that influence reverse recovery behavior and Q$_{rr}$. The following illustrates the relationship between Q$_{rr}$ and its factors.
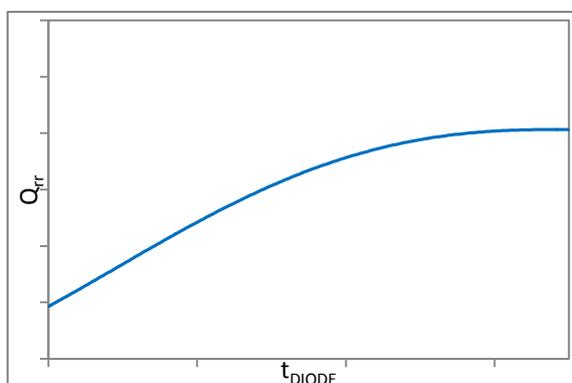

Reverse recovery charge accumulates over time. At a fixed diode conduction current and *di/dt*, Q$_{rr}$ accumulates in the MOSFET during body diode conduction. The longer the body diode conduction time, the more charge is accumulated until it saturates.

Figure 2.4: Q$_{rr}$ vs t$_{DIODE}$ (fixed I$_{DIODE}$ and *di/dt*)
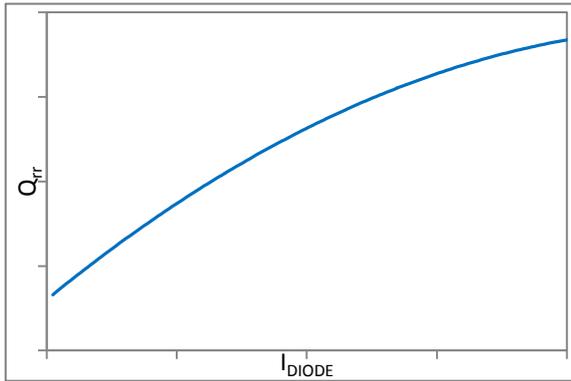
With di/dt fixed, the higher the body diode conduction current, the higher the stored Q_{rr} in the device.

Figure 2.5: Q_{rr} vs I_{DIODE} (fixed *di/dt* and t_{DIODE})
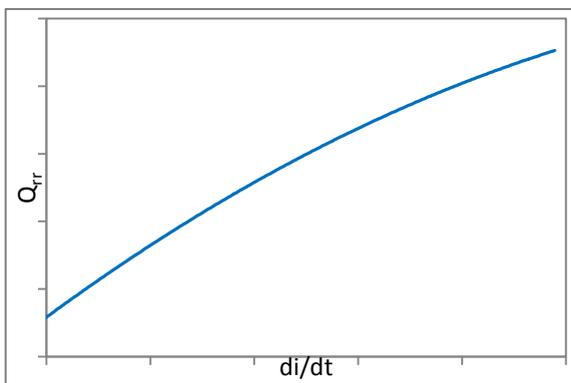
The saturated Q_{rr} also scales with how quickly the current changes. The higher the current slope (di/dt), the higher the Q_{rr}. In other words, if the commutation loop is designed well with very low inductance to allow fast switching, it is inevitable for the MOSFET to experience higher accumulated Q_{rr}.

Figure 2.6: Q_{rr} vs *di/dt* (fixed I_{DIODE} and t_{DIODE})

2.5   Solution to improve system reliability

Section 2.4.1 lists the factors which Q_{rr} depends on. It suggests that by changing the application condition, such as lowering the body diode conduction time, the diode forward current, and the hard commutation current slope, Q_{rr} can be minimized. However, it is easier said than done.

- Body diode conduction usually happens during dead time; therefore, it can be reduced by minimizing the dead time. However, there is always a limit how low the dead time could go down to.
- Diode conduction current is often set by the chosen topology, and changing topology is normally not desired.
- Current slope (*di/dt*) is related to the parasitic inductance of the commutation loop. First, it would require a redesign of the PCB to improve Q_{rr}. Second, a low *di/dt* means large parasitic inductance, which usually contradicts to a good PCB layout for high frequency application.

Alternatively, a better method to improve reverse recovery behavior is to reduce Q_{rr} in the device level. This allows Q_{rr} reduction regardless of the application condition. Illustratively, the three Q_{rr}-to-factor curves in section 2.4.2 would be brought downwards.

The next section introduces Infineon's new OptiMOS™ FD devices, optimized for hard commutation ruggedness, and demonstrates how its device level Q_{rr} reduction improves system reliability and performance.

3 Infineon's New Hard Commutation Optimized OptiMOS™

The newest offerings from Infineon, OptiMOS™ FD (Fast Diode) 200V/250V, offers the best reverse recovery behavior in the industry. These products provide Q_{rr} optimized solution for power system designers striving for highest standards of efficiency and reliability.

The new OptiMOS™ FD product family brings updates to the previous generation OptiMOS™ 3 200V/250V devices (already with the best figures of merit) by upgrading with the new hard commutation optimized body diode (Fast Diode).

3.1 Advantage

The new OptiMOS™ products in each voltage class offer various advantages, including

- fastest reverse recovery
- lowest reverse recovery charge
- minimized overshoot for hard switching topologies
- improved hard commutation ruggedness

These advantages all come without compromising the best in class figure of merit, $R_{DS(on)}$ x Q_g.

3.2 Measurement Results

This section highlights the key improvement of OptiMOS™ FD comparing to the OptiMOS™ 3 equivalent parts in a laboratory environment.

3.2.1 40% Q_{rr} and 20% I_{rrm} Reduction

In Figure 3.1, the diode current waveforms during body diode turning off for both OptiMOS™ FD and OptiMOS™ 3 are presented.
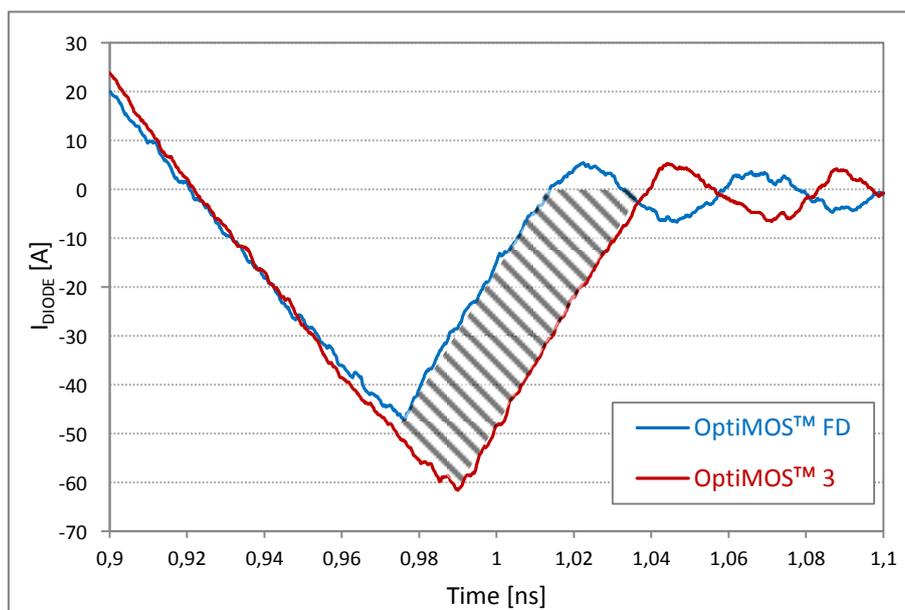

Figure 3.1: Experimental waveforms of reverse recovery current

These are the experimental results using the half-bridge hard commutation test circuit as shown in Figure 2.3. This waveform comparison showcases the main benefit of the new OptiMOS™ FD device. The shaded area illustrates the Q_{rr} reduction for the new OptiMOS™ FD device. An impressive, more than 40%, Q_{rr} reduction compared to the previous generation OptiMOS™ 3 device was achieved.

20% lower in peak reverse recovery current (I_{rrm}) was also observed. This reduces the energy quadratically when the device enters avalanche during reverse recovery.

In addition, Q_{rr} measurements (Figure 3.2: against three Q_{rr} factors in section 2.4.2 are compared between OptiMOS™ FD and OptiMOS™ 3 200V devices. OptiMOS™ FD results are obviously better in all application conditions. At some conditions, the improvement is even up to 60%.
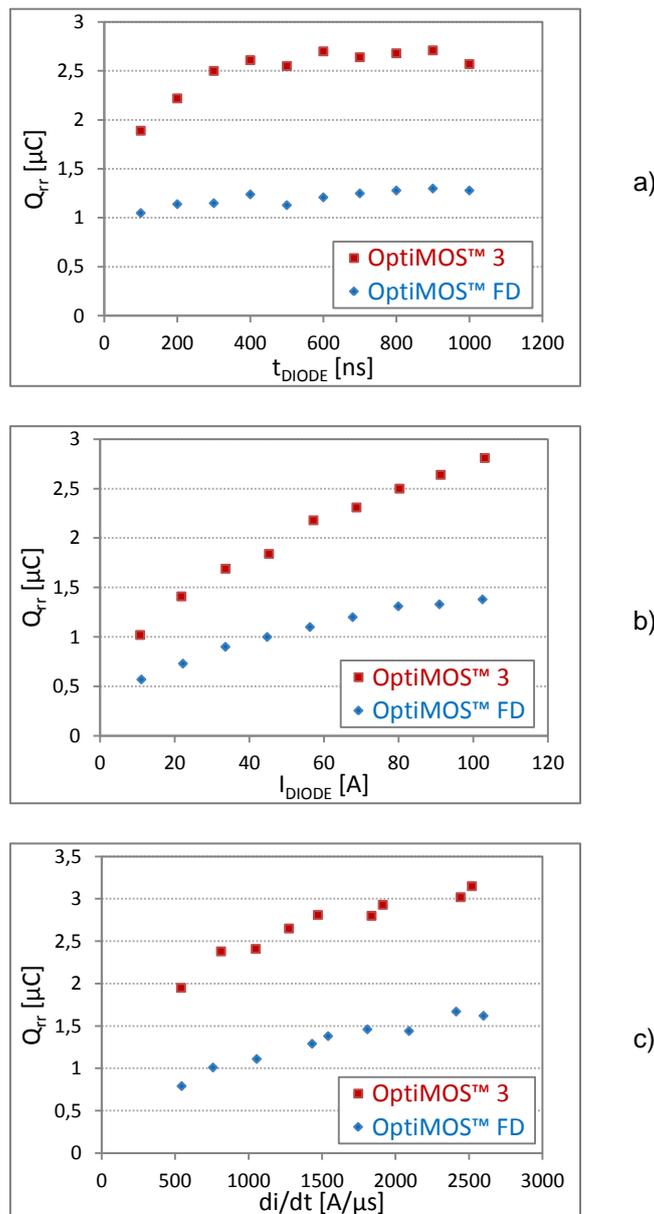

Figure 3.2: Q_{rr} Measurements (a) Q_{rr} vs t_{DIODE} @I_{DIODE}=100A and di/dt=1000A/µs; (b) Q_{rr} vs I_{DIODE} @di/dt=1500A/µs and t_{DIODE}=300ns; (c) Q_{rr} vs di/dt @I_{DIODE}=100A and t_{DIODE}=300ns.

Note: Q_{rr} numbers displayed in this section uses the Q_{rr} definition where avalanche occurs as described in the note in 0, integrating the area under the reverse recovery diode current up to $V_{DS(peak)}$.

3.2.2 Efficiency Boost

Q_{rr} is wasted energy, and it translates into power loss. 40% lower Q_{rr} leads to a significant reduction in power loss. On Infineon's 2kW ZVS full bridge phase-shifted (ZVS FBPS) DC-DC converter demo board (Figure 3.3), the secondary side synchronous rectifier (SR) stage MOSFETs are hard commutated; therefore, it is suitable to use this platform to examine the benefit of the new OptiMOS™ FD devices to the performance of the system. The SR stage on this demo board uses center tap configuration and has two parallel devices in each branch.
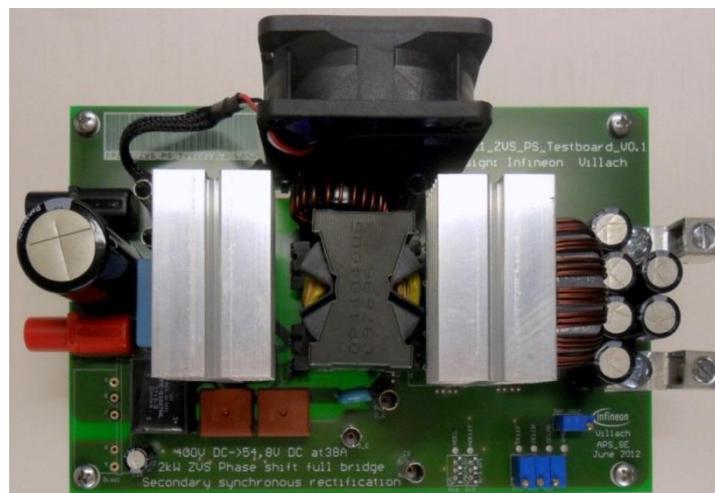

Figure 3.3: Infineon's 2kW ZVS full bridge phase-shifted DC-DC converter

The efficiency of the demo board with original optimized SR parts (OptiMOS™ 3 200V Best-in-Class devices) was first measured. Then the original SR devices were replaced by the new OptiMOS™ FD 200V devices. 4 SR devices (2 in each SR branch) in total were replaced. Efficiency readings for both measurements are given in Figure 3.4.
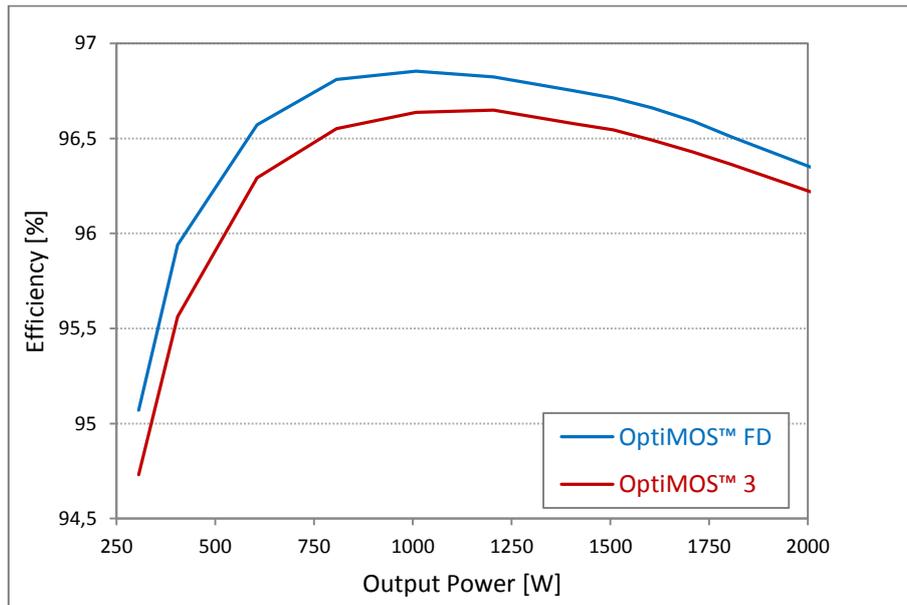
Figure 3.4: Efficiency comparison between OptiMOS™ FD and OptiMOS™ 3

Figure 3.4 demonstrates that by simply swapping the SR devices from previous generation OptiMOS™ 3 devices to the newest generation OptiMOS™ FD devices, significant overall efficiency boosts of up to 0.35% and 0.5%, respectively for 200V and 250V devices, were achieved.

3.3   Application

The main applications which can take advantage of the Fast Diode include, but not limited to,

- telecom
- industrial power supplies
- motor drives (for 48-110V systems)
- DC-AC inverter
- Class D audio amplifiers, etc.

4   Conclusion

In this document, the importance of hard commutation ruggedness and the factors which influence reverse recovery behavior are explained. Body diode hard commutation ruggedness is essential to system reliability. Q_{rr} is the key parameter to improve body diode ruggedness because it causes overshoot and puts the device into avalanche. In order to reduce Q_{rr}, the three factors of Q_{rr} – body diode conduction time, forward diode current, and diode turn-off current slope – can be minimized in the application. However, the best way is to reduce Q_{rr} at the device level. Systems where devices are hard commutated become more robust under all application conditions when devices with lower Q_{rr} are used.

Infineon's new OptiMOS™ FD 200V/250V are introduced. The experimental result shows Q_{rr} reduction of 40% to 60% when compared to the previous generation OptiMOS™ 3 devices. The performance of the system in terms of efficiency also improved significantly due to lowered Q_{rr}. Applications utilizing hard commutated 200V/250V Power MOSFETs can benefit tremendously from Infineon's new innovation.

5 Reference

[1] Erickson, R., Maksimovic, D., Fundamentals of Power Electronics, 2nd ed., Springer, 31 Jan. 2001

[2] Polenov, D., et al., "The Influence of Turn-Off Dead Time on the Reverse-Recovery Behaviour of Synchronous Rectifiers in Automotive DC/DC-Converters," EPE, 2009, pp.1-8

[3] Wikipedia contributors. "Power MOSFET." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 15 Apr. 2013. Web. 29 Apr. 2013