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AN-9065
FRFET® in Synchronous Rectification

Introduction

A synchronous rectifier becomes essential building block for greater efficiency and higher power density in switching power supplies. It is popular in applications from high-end servers to laptop adapters. This application note shows potential failure modes of power MOSFETs and solutions for synchronous rectification in flyback topology. An enhanced FRFET®, power MOSFET with fast recovery body diode, provides higher reliability at the same performance.

Synchronous Rectifier Operation and Potential Failure Modes

Most of today's power MOSFETs have a vertical DMOS structure. In this structure, many parasitic elements exist, such as capacitances, bipolar junction transistor (BJT), and a diode. The inherent anti-parallel diode formed by drain-source P-N junction is sometimes called body diode. The body diode is fully functional as general rectifiers, but it does not perform as optimally as general rectifiers. It has a very long reverse recovery time and large reverse recovery charge. In spite of its limited performance, the body diode has been utilized as freewheeling diode because it can make simple circuit without adding system cost. Among many applications, a synchronous rectifier is a good example of actively utilizing body diode. It replaces the rectifier for better efficiency. Power losses can be lowered when the product of MOSFET's on-resistance and drain current is less than the diode forward voltage drop. Increasing power density and achieving higher energy efficiency are most challenging issues in power conversion today. The popular flyback topology is aligning with this trend. A flyback converter with a synchronous rectifier is shown in Figure 1.

Conduction periods of primary MOSFET and secondary MOSFET should not overlap to guarantee proper operation of the converter. A delay between primary MOSFET turn-on and secondary MOSFET turn-off, and vice versa, must be introduced to prevent simultaneous conduction of the MOSFETs. This delay results in current flow through body diode of the secondary MOSFET. Then the body diode is switched off when the primary MOSFET turns on. The switching process of the diode from on state to reverse blocking state is called reverse recovery. A device failure may happen during body diode reverse recovery. Another failure mode is breakdown dv/dt. It is a combination of breakdown and static dv/dt. A device undergoes avalanche current and displacement current at same time.

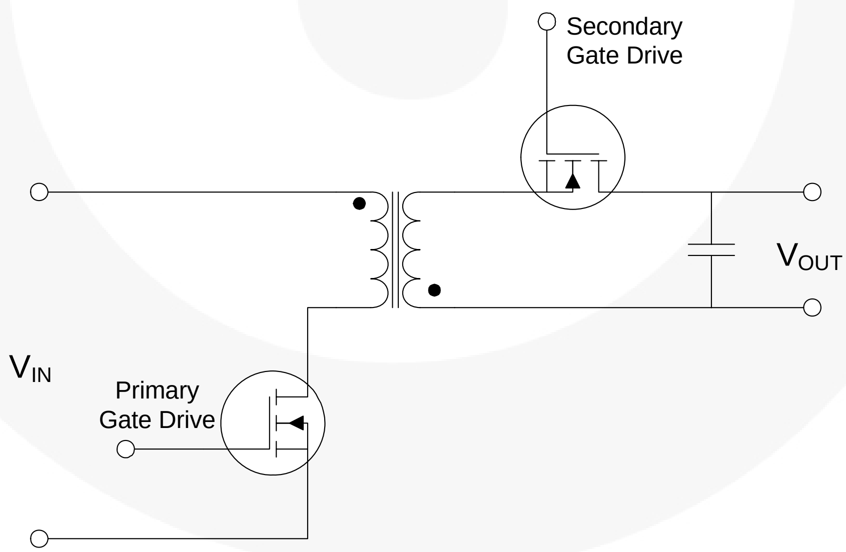

Figure 1. Flyback Converter with Synchronous Rectifier

Body Diode Reverse Recovery dv/dt

Figure 2 shows operational waveforms from a synchronous rectifier block of a flyback converter. The picture is enlarged to show the diode turn-off transition in detail. A gate bias is removed 1µs prior to trigger point. So, the body diode conducts in forward for a while. Diode current starts to decrease and become near zero at the trigger point. Even though the current level is not high, there is stored charge that should be removed to go back to reverse blocking state. The removal of the stored charge occurs via two phenomena; the flow of a large reverse current and recombination. A large reverse recovery current occurs in the diode during the process. This reverse recovery current flows through the body diode of MOSFET because the channel is already closed.

Some of reverse recovery current flows right underneath N+ source. As shown in Figure 3, there is a little resistance described as Rb. Basically, base and emitter of parasitic BJT are connected together by source metal. In practice, the small resistance works as base resistance. Therefore, parasitic BJT can be turned on when enough current flows through Rb. Once the parasitic BJT turns on, a hot spot is formed and more current flows through it due to negative temperature coefficient of the BJT. Finally, the device fails. If the P-N junction temperature is higher than room temperature before the process begins, it is easier to form a hot spot. So, current level and starting junction temperature are the most important factors for device failure.

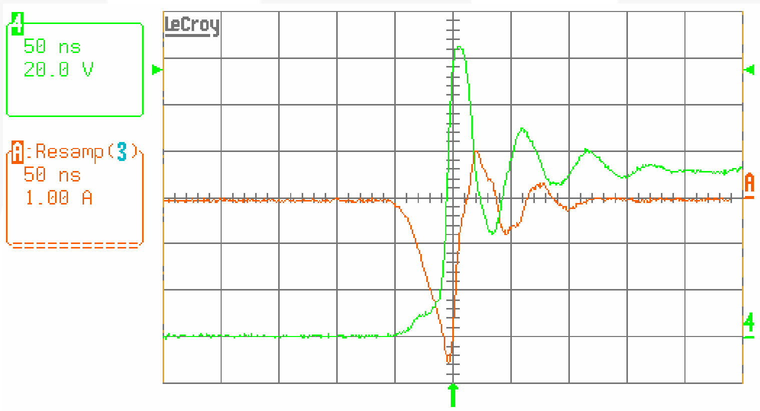

Figure 2. Voltage and Current Waveforms

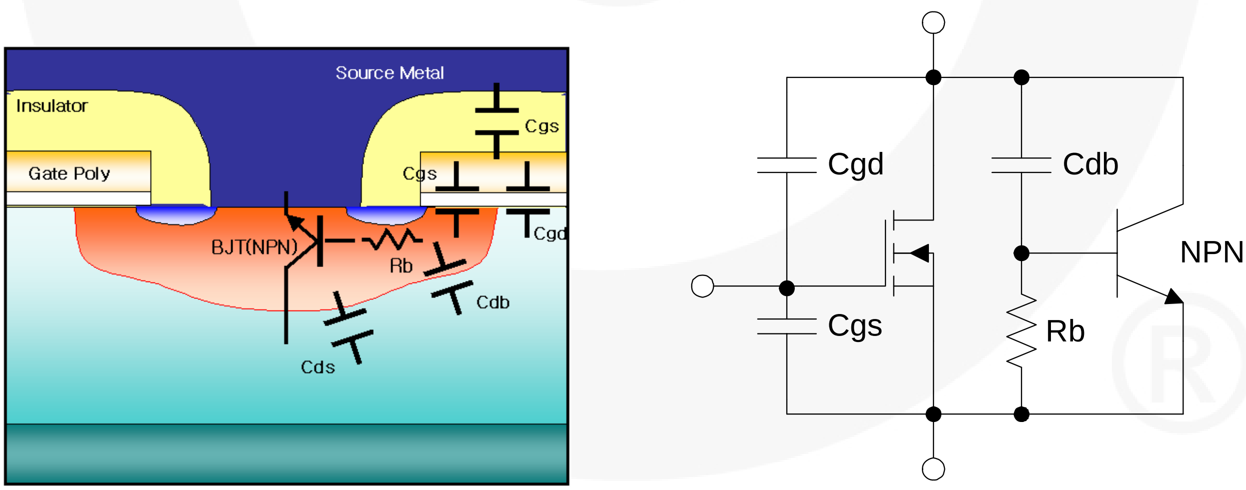

Figure 3. MOSFET Vertical Structure and Parasitic Elements and Equivalent Circuit

Major factors that affect peak reverse recovery current are forward current and di/dt. Figure 4 shows the increase of peak reverse recovery current according to the forward current level. The device under test (DUT) is the same as that in Figure 2. As shown in Figure 4, body diode conduction should be minimized to lower peak reverse recovery current. This is more critical with self-driven synchronous rectifier because its gate control is not precise compared to dedicated controllers. Sometimes, missing control signal occurs under abnormal conditions, such as shorted output terminals. Another factor is the switching speed of the primary MOSFET. Faster turn-on of the primary MOSFET causes higher rate of di/dt across the secondary synchronous rectification MOSFET. As the di/dt becomes bigger, peak reverse recovery current increases. This is critical design challenge because it is also related to switching power losses and EMI.

Breakdown dv/dt

In the case of extremely fast transition, drain-source voltage may exceed the maximum rating of a device during body diode reverse recovery process. For example, the maximum drain-source voltage in Figure 2 is over 120V even though the device is a 100V-rated MOSFET. Because of high voltage spike, the MOSFET enters breakdown mode and commutating current flows through P-N junction. It is the same mechanism as avalanche breakdown. In addition to this process, high dv/dt affects the failure point of the device. More displacement current is built up with greater dv/dt. The displacement current is added to avalanche current and device becomes more vulnerable to failure. Basically, the root cause of failure is parasitic BJT turn-on due to high current and temperature; but the primary cause is body diode reverse recovery or breakdown. Failure analysis shows unique burn marks caused by each failure mode. In practice, these two failure modes happen randomly.

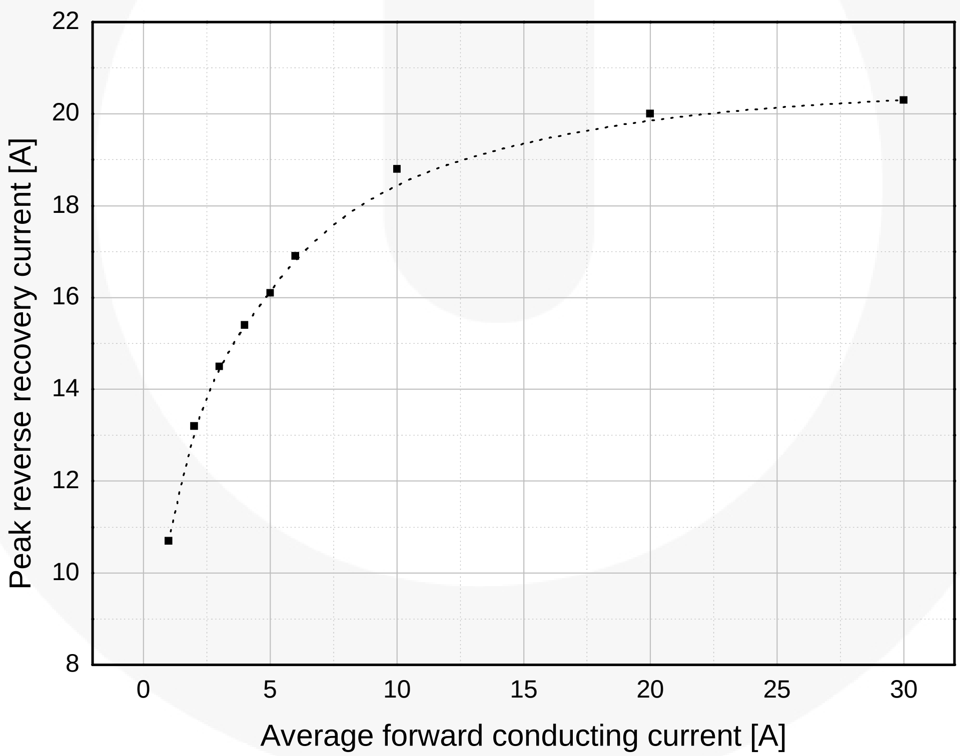

Figure 4. Peak Reverse Recovery Current vs. Forward Current at 400A/µs

Solutions

As more and more applications use an embedded body diode as the critical component in the system, many advances in body diode characteristics have been accomplished. Among them, gold or platinum diffusion and electron irradiation are known to be very effective solutions. These processes control the carrier lifetime to reduce reverse recovery charge and reverse recovery time. There are, however, drawbacks due to the processes. More lifetime control results in the further increase of MOSFET on-resistance. This adds more power loss and is critical to the synchronous rectifier. Another negative effect is the increase of drain-source leakage current. Usually, electron irradiation has fewer side effects and therefore is suitable for the synchronous rectification MOSFET because the on-resistance is most important parameter from performance point of view. Figure 5 shows an effect of electron irradiation process.

To avoid these problems, finding an optimum point is very important. Process parameters used for the device in Figure 5 are determined by considering both minimizing negative effects and fulfilling application requirements. This new MOSFET with fast recovery body diode, FRFET®, fits in synchronous rectifier perfectly. Its peak reverse recovery current has been reduced to the level that does not cause device failure, while maximum on-resistance does not change at all. It can also withstand more than double the current stress during breakdown dv/dt mode. With all of these improved characteristics, the FRFET® provides enhanced reliability in a synchronous rectifier.

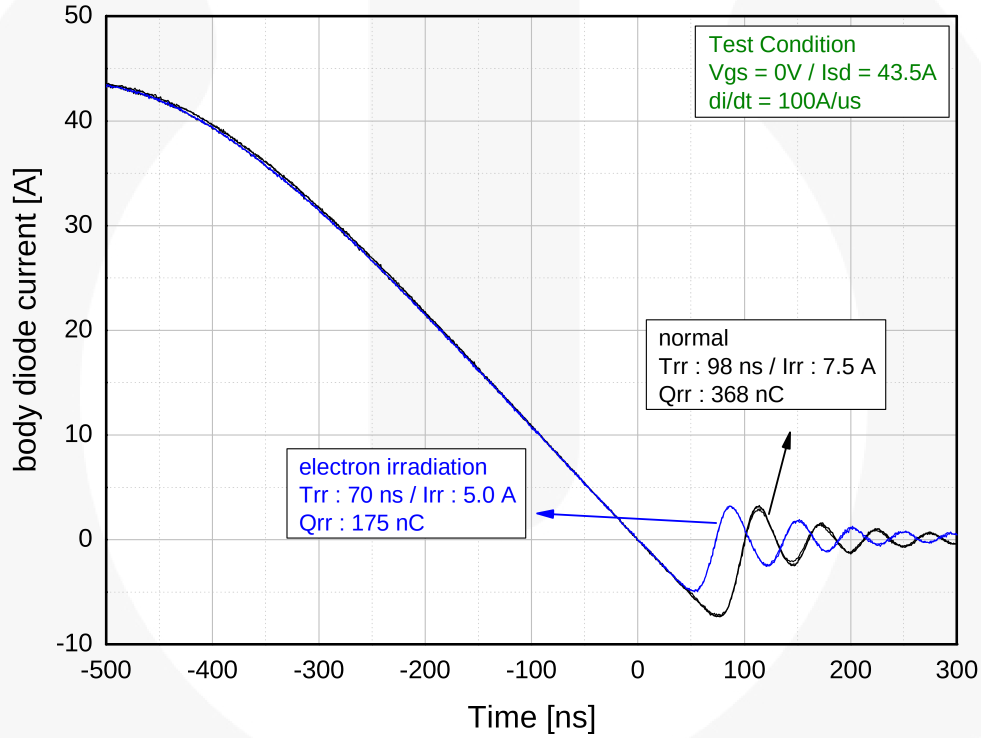

Figure 5. Reverse Recovery Waveforms

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