AN4789
Application note

Monolithic Schottky diode in ST F7 LV MOSFET technology: improving application performance

Introduction

Modern MOSFET technology is leading to higher performance in terms of Figure of Merit (FoM), and considerable improvement in overall device performance. When a Power MOSFET is used in bridge topologies and as synchronous rectifier in the secondary side of a power supply, body-drain diode features together with FoM become critical. The integration of a Schottky diode within the MOSFET structure improves device efficiency and switching-noise performance.

Contents

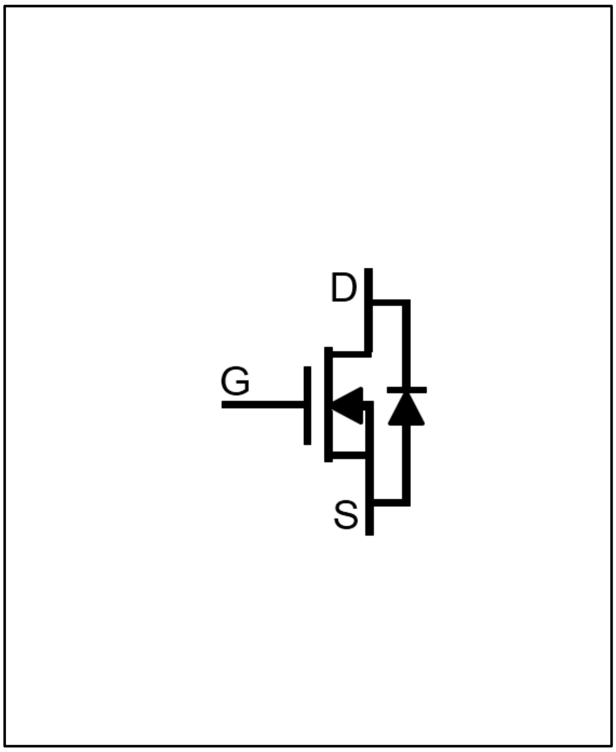
1 Description

Today, a large number of systems and applications can benefit from modern power MOSFET technologies, offering excellent overall performance both for static and dynamic electrical parameters. Specific drain-source on-state resistance ($R_{DS(on)}$ per transistor active area) has been gradually reduced in the latest MOSFET generations, allowing the use of power transistors with smaller die sizes without any negative impact on current capability and on-state losses. Smaller device die size and improved gate oxide structure reduce total gate charge (Q_g) with significant enhancement in device dynamic performance. Thus, MOSFET Figure of Merit (FoM = $R_{DS(on)} \cdot Q_g$) becomes lower and lower, allowing considerable efficiency gain in high switching frequency applications. However, especially in synchronous rectification and in bridge configuration, $R_{DS(on)}$ and Q_g are not the only important parameters for power MOSFETs. In fact, the dynamic behavior of the intrinsic body-drain diode also plays an important role in overall MOSFET performance. The forward voltage drop ($V_{F,diode}$) of the body-drain diode impacts device losses during freewheeling periods (the device is in an off-state and the current flows from the source to drain through the intrinsic diode); the reverse recovery charge (Q_{rr}) affects not only the device losses during the reverse recovery process but also the switching behavior, as the voltage spike across the MOSFET increases with Q_{rr}. So, low V_{FD} and Q_{rr} diodes, like Schottky diodes, can improve overall device performance especially when it mounted in bridge topologies or used as a synchronous rectifier, and in particular at high switching frequencies and for long diode conduction times. In this article, new 60 V ST MOSFETs with monolithic Schottky diode will be evaluated in SMPS and motor control environments, highlighting their benefit compared to standard devices.

2 Intrinsic MOSFET body-drain diode and Schottky features

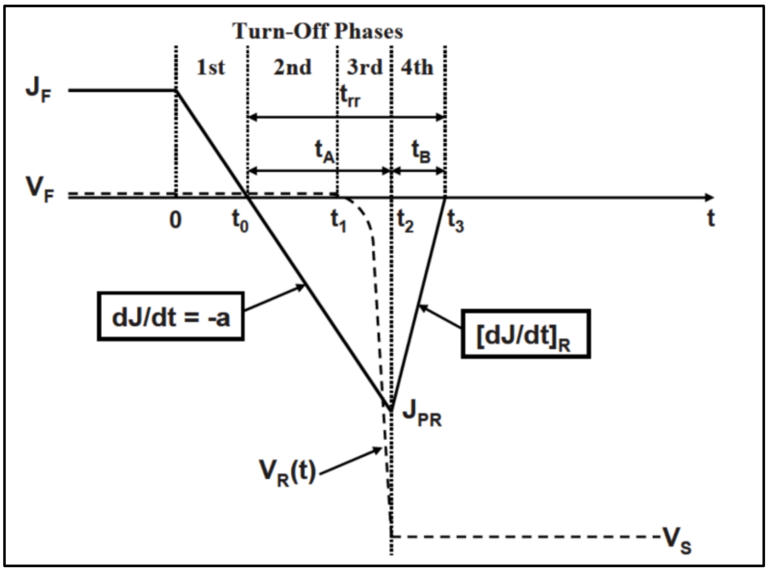
In *Figure 1*, the typical symbol for an N-channel power MOSFET is shown. The intrinsic body-drain diode is formed by the p-body and n-drift regions, and is shown in parallel to the MOSFET channel.

Figure 1: Symbol of a power MOSFET



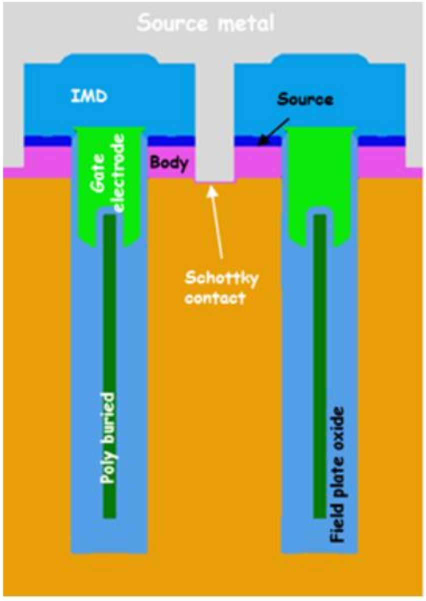
Once a power MOSFET is selected, the integral body diode is fixed by silicon characteristics and device design. As the intrinsic body diode is paralleled to the device channel, it is important to analyze its static and dynamic behavior, especially in applications where the body diode conducts. Thus, maximum blocking voltage and forward current have to be considered in reverse and forward bias, while when the diode turns-off after conducting, it is important to investigate the reverse recovery process (*Figure 2*). When the diode goes from forward to reverse bias, the current does not reduce to zero immediately, as the charge stored during the on-state must be removed. So at $t = t_0$, the diode commutation process starts and the current reduces with a constant and slope (-a), fixed only by the external inductances and the supply voltage. The diode is forward biased until t_1, while from t_1 to t_2 the voltage drop across the diode increases, reaching the supply voltage with the maximum reverse current at $t=t_2$. The time interval (t_3-t_0) is defined as the reverse recovery time (t_{rr}), while the area between the negative current and zero line is the reverse recovery charge (Q_{rr}).The current slope during t_B is linked mainly to device design and silicon characteristics.

Figure 2: Diode reverse recovery process



The classification of soft and snap recovery is based on the softness factor $S = \frac{t_B}{t_A}$: this parameter can be important in many applications. The higher the softness factor, the softer the recovery. In fact, if the t_B region is very short, the effect of quick current change with the circuit intrinsic inductances can produce undesired voltage overshoot and ringing. This voltage spike could exceed the device breakdown voltage. Moreover, EMI performance worsens. As shown in *Figure 2*, during diode recovery high currents and reverse voltage can produce instantaneous power dissipation, reducing system efficiency. In addition, in bridge topologies the maximum reverse recovery current of a low side device adds to the high side current, increasing its power dissipation up to the maximum ratings. In switching applications like bridge topologies, buck converters or synchronous rectification, the body diode is used as a freewheeling element: in these cases, reverse recovery charge (Q_{rr}) reduction can help to maximize system efficiency and limit possible voltage spike and switching noise at turn-off. One strategy to achieve this objective is the integration of a Schottky diode in the MOSFET structure (*Figure 3*). A Schottky diode is realized by an electrical contact between a thin film of metal and a semiconductor region. Because the current is mainly due to majority carriers, the Schottky diode has a lower stored charge and consequently can be switched from forward to reverse bias faster than a silicon device. An additional advantage is its lower forward voltage drop (≈ 0.3 V) than Si diodes, meaning that a Schottky diode has lower losses during the on state.

Figure 3: MOSFET structure with integrated Schottky diode

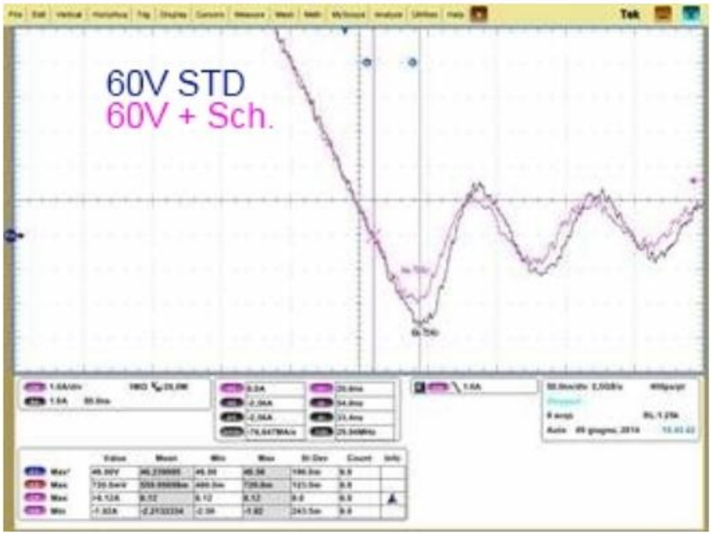


STMicroelectronics' new 60 V MOSFET with embedded Schottky diode represents the right device choice when Q_{rr} and $V_{F,diode}$ have to be optimized to enhance overall system performance. In *Table 1* and *Figure 4* the main electrical parameters and the reverse recovery waveforms of standard and integrated Schottky devices (same BV_{DSS} and die size) are shown.

Table 1: MOSFET parameters

Device	**BV @ 250 µA**	**$R_{DS(on)}$ @ 30 A**	**Q_{rr}**	**$V_{F,diode}$**
60 V MOS standard	>60 V	1.2 m Ω	100 nC	600 mV
60 V MOS with Schottky	>60 V	1.3 m Ω	90 nC	250 mV

Figure 4: Reverse recovery waveforms



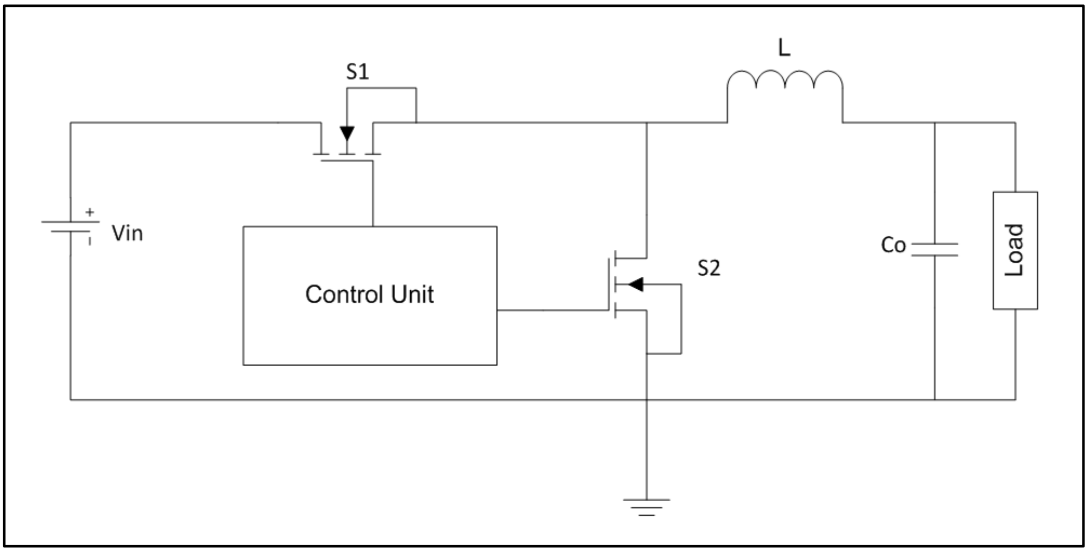
3 Benefits of monolithic Schottky diodes in power management environments

In this section, we evaluate the benefits of a monolithic Schottky diode in two different power converters: buck or step-down converters and LLC with secondary-side synchronous rectification. In each topology, a 60 V MOS with monolithic Schottky diode is compared to the standard device.

3.1 Step-down converter

In a synchronous buck converter (*Figure 5*), a power MOSFET with an integrated Schottky diode can be mounted as low side device (S2) to enhance overall converter performance.

Figure 5: Single-phase synchronous buck converter topology



In fact, low side body diode conduction losses ($P_{diode,cond}$) and reverse recovery losses (P_{Qrr}) are strictly related to diode forward voltage drop ($V_{F,diode}$) and its reverse recovery charge (Q_{rr}):

Equation 1

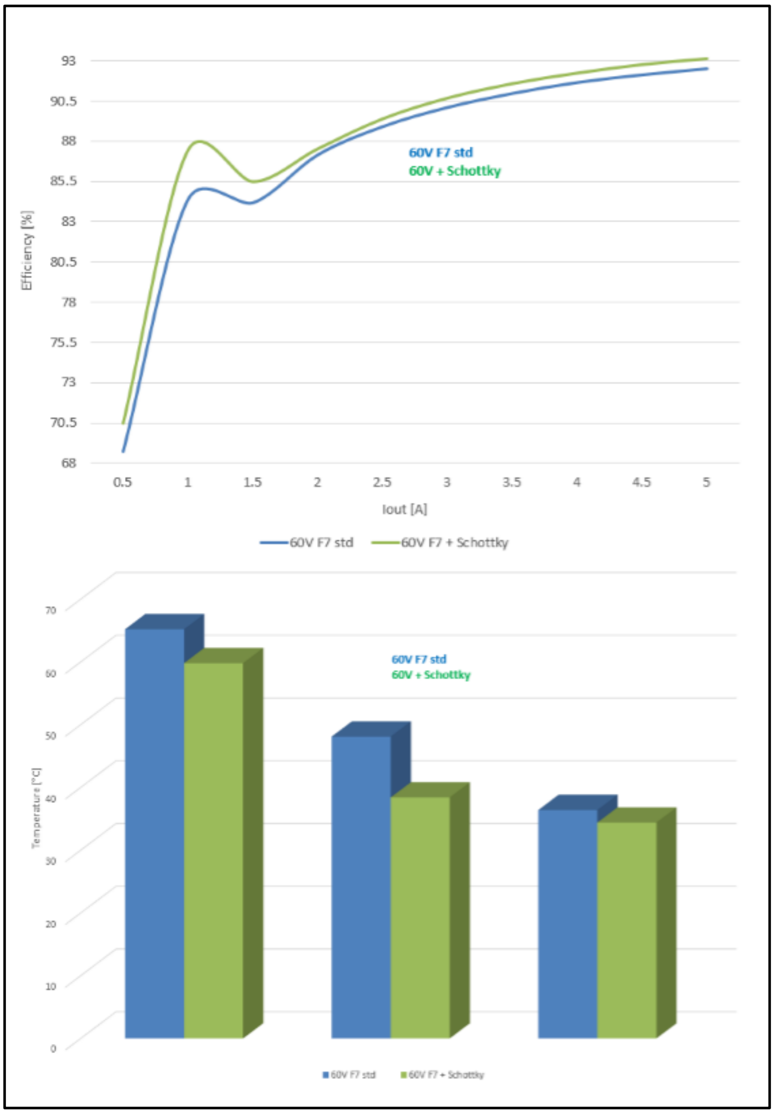
$$P_{diode,cond} = V_{F,diode} \cdot I_{OUT} \cdot f_{SW} \cdot t_{dead}$$

Equation 2

$$P_{Qrr} = Q_{rr} \cdot f_{SW} \cdot t_{dead}$$

As shown in Equations 1 and 2, these losses increase with the switching frequency, the converter input voltage and the output current. Moreover, the dead time, when both FETs are off and current flows in the low side body diode, seriously affects the diode conduction losses: with long dead times, low diode forward voltage drop helps to minimize its conduction losses, thereby increasing efficiency. In *Figure 6*, the efficiency and device temperatures in a 60 W, 48 V - 12 V, 250 kHz synchronous buck converter are reported.

Figure 6: Efficiency and thermal measurements

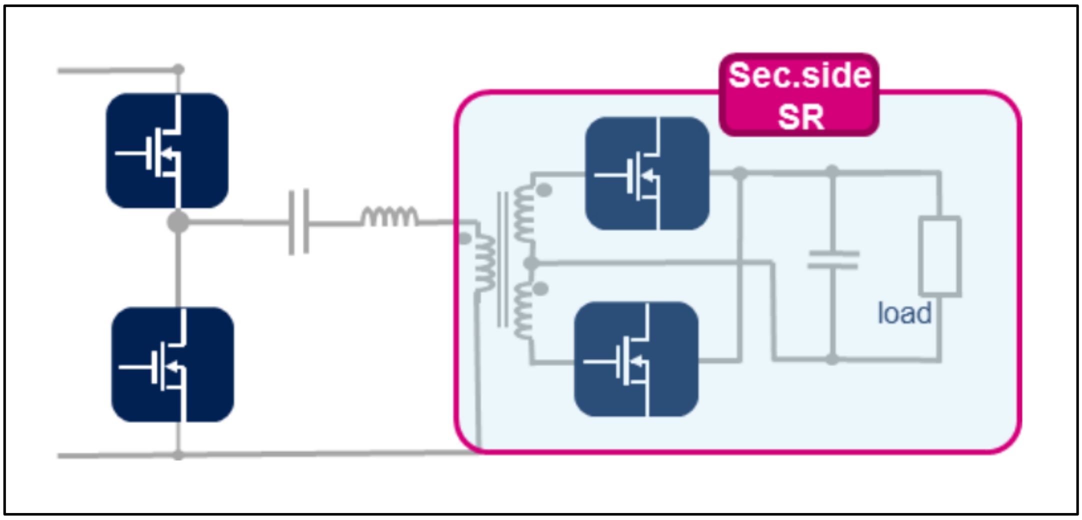


The 60 V plus Schottky device has higher efficiency in the entire current range and lower temperature. Efficiency gain is particularly evident at low currents as diode conduction time is larger to reduce gate driving losses and improve light load efficiency.

3.2 LLC converter

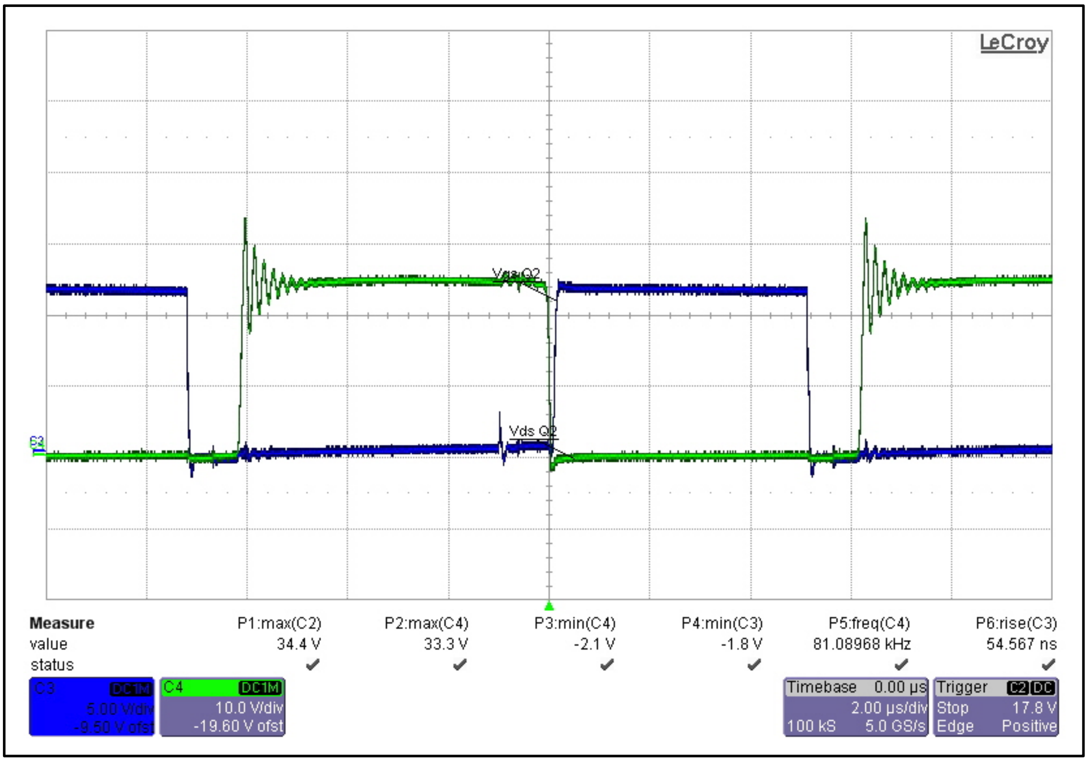
In isolated power converter environments, when the output power increases, the right choice of the secondary side synchronous rectifiers become crucial to guarantee good power capability and high overall efficiency. Power MOSFETs at secondary side must have $R_{DS(on)}$ as low as possible to reduce conduction losses, especially for high load currents. Together with low $R_{DS(on)}$, synchronous rectifiers should have optimized body diode behavior (in terms of Q_{rr} and $V_{F,diode}$) in order to reduce diode losses (reported in Equations 1 and 2, but also to minimize possible voltage spikes during turn-off transient. Typical switching frequencies for synchronous FETs are included between 80 - 130 kHz. In this case, as the switching frequency is quite low, the dead-time value (fixed by the controller driving the FETs) defines the advantage of using MOSFETs with an integrated Schottky diode as synchronous rectifiers. 60 V standard and Schottky integrated devices are compared in a 500 W digital power supply, made up of two power stages: power factor corrector and an LLC with synchronous rectification. The maximum output current is 42 A, while the switching frequency at full load is 80 kHz. In *Figure 7*, the simplified schematic of an LLC converter with synchronous rectification is shown.

Figure 7: LLC converter with synchronous rectification



The dead-time is around 1 µs, as shown in the steady state waveforms at full load (*Figure 8*).

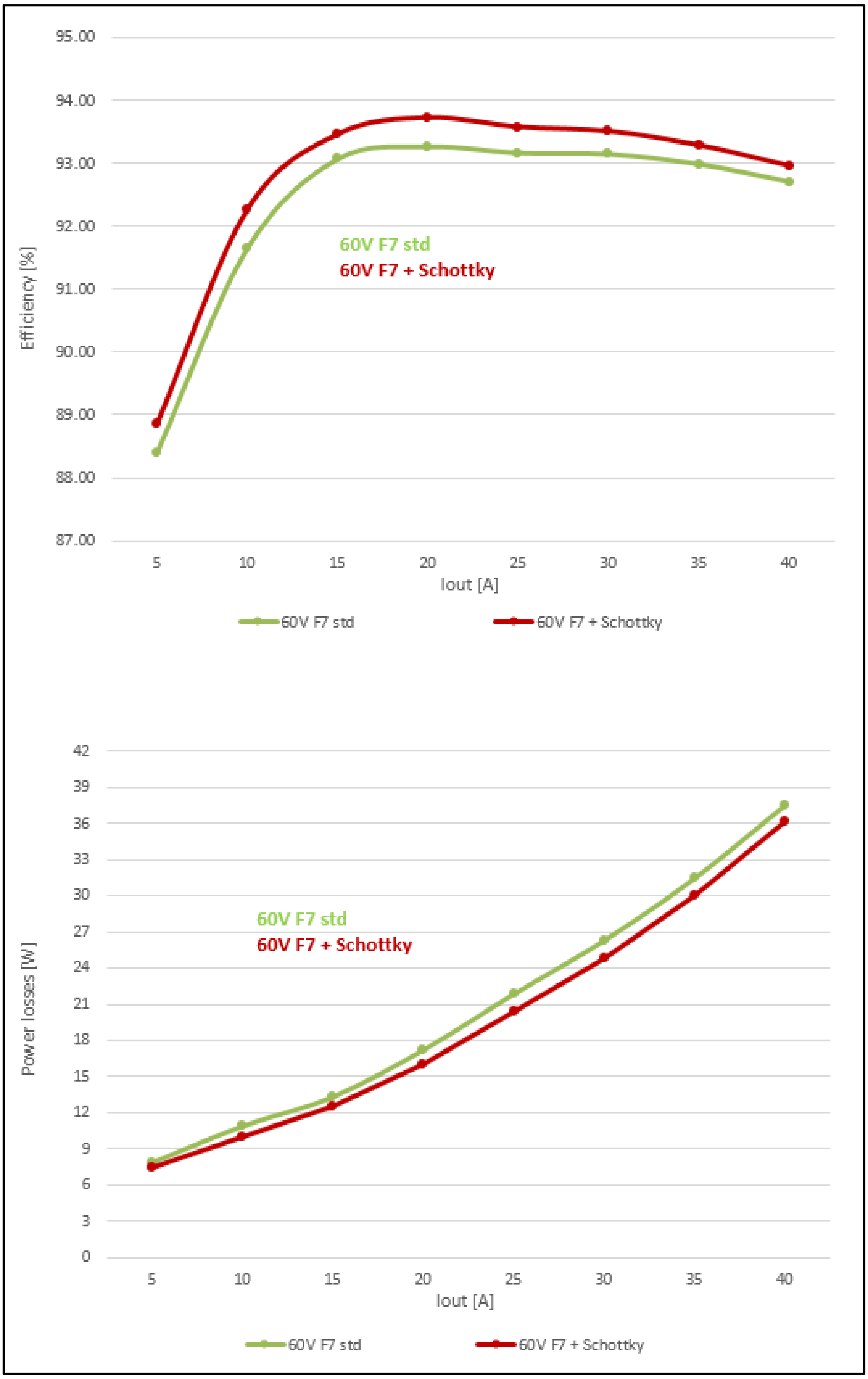
Figure 8: Synchronous FET waveforms at full load



Measure	P1:max(C2)	P2:max(C4)	P3:min(C4)	P4:min(C3)	P5:freq(C4)	P6:rise(C3)
value	34.4 V	33.3 V	-2.1 V	-1.8 V	81.08968 kHz	54.567 ns
status	✓	✓	✓	✓	✓	✓

For high values of dead-time, the benefits of an integrated Schottky diode are remarkable, as lower $V_{F,diode}$ and Q_{rr} minimize diode conduction and recovery losses, enhancing system performance. As shown in *Figure 9* (red tracks for embedded Schottky and green for standard FET), the 60 V device with integrated Schottky diode performs better than the standard one, with higher efficiency and lower power losses both at light and full load.

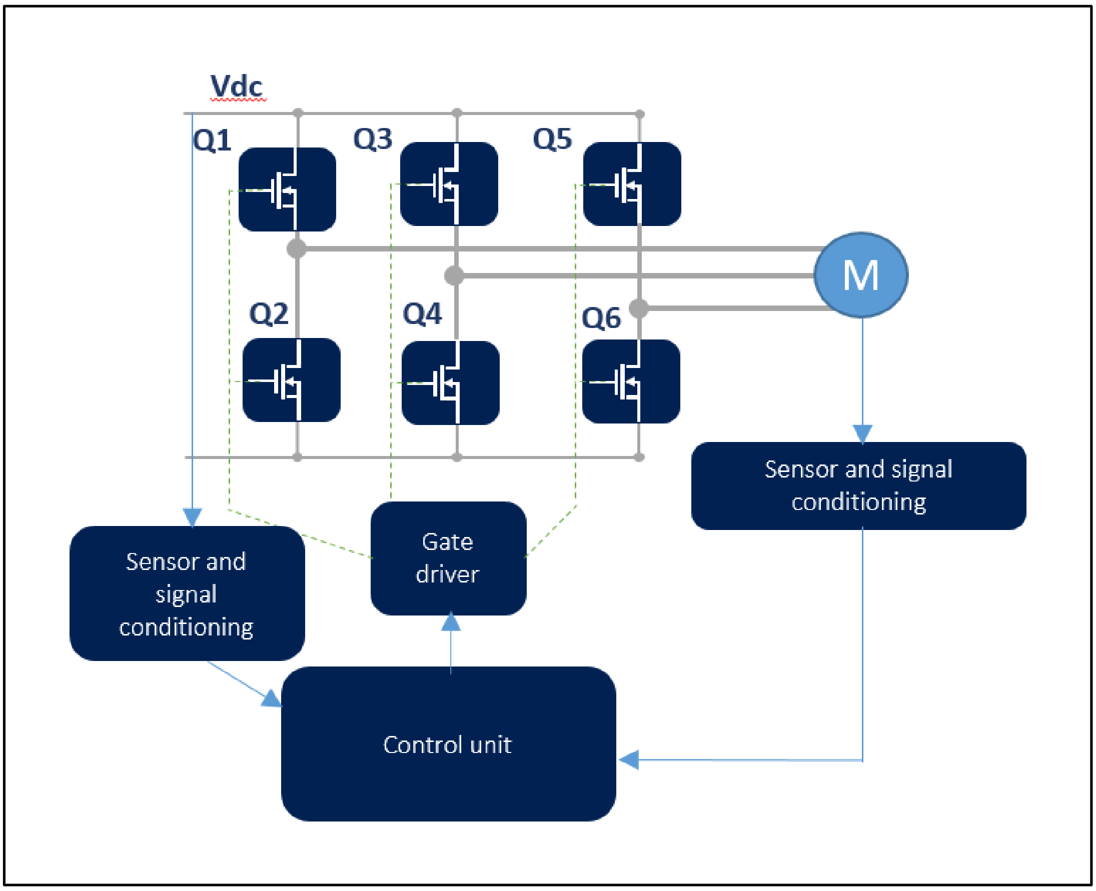
Figure 9: Efficiency and power loss curves in an LLC converter



4 Switching behavior improvement in bridge topologies

In bridge topologies, the reverse recovery process occurs at the end of the freewheeling period of the low side device (i.e. Q2 in *Figure 10*) before that the high side (i.e. Q1) starts conducting. The resulting recovery current adds to the high side current (as explained in *Section 2: "Intrinsic MOSFET body-drain diode and Schottky features"*). Together with the extra-current on the high side device, low side reverse recovery and its commutation from V_{ds} ≈ 0 V to V_{dc} can produce spurious bouncing on the low side gate-source voltage, due to induced charging of low side C_{iss} (input capacitance) via C_{rss} (Miller capacitance).

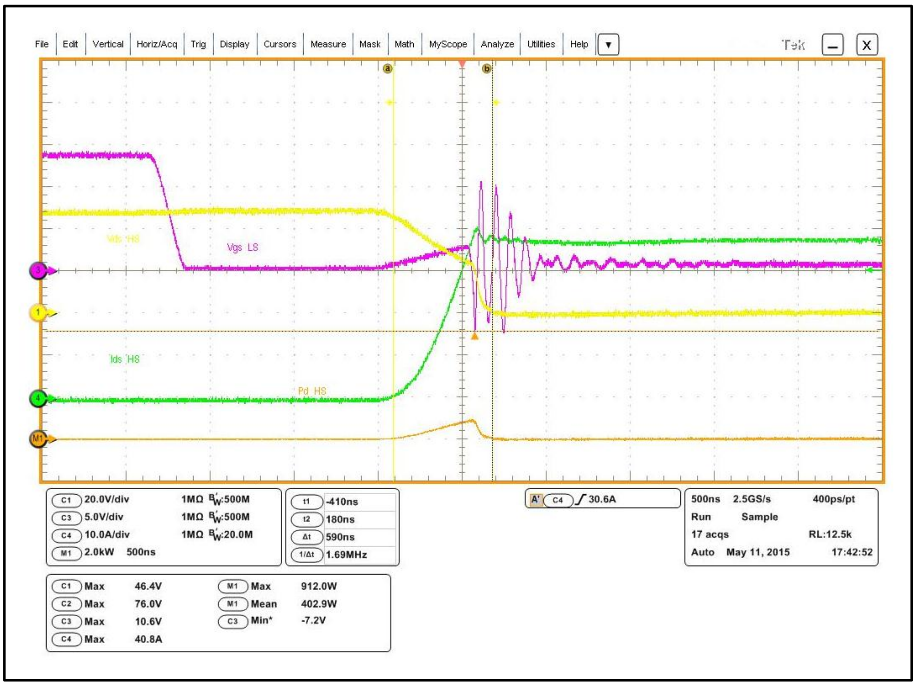
Figure 10: Full-bridge converter schematic



As a consequence, the induced voltage on the Q2 gate could turn on the device, worsening system robustness and efficiency. The low side device, in bridge configuration, should have soft commutation, without dangerous voltage spikes and high frequency ringing across the drain and source. This switching behavior can be achieved using a power MOSFET with integrated Schottky diode as low side devices. In fact, its lower reverse recovery charge (Q_{rr}) has a direct impact on the overshoot value. The higher the Q_{rr}, the higher the overshoot. Lower values for V_{ds} overshoot and ringing reduce the spurious voltage bouncing on the low side gate, limiting the potential risk for a shoot-through event. Furthermore, soft recovery enhances overall EMI performance, as the switching noise is reduced. In figures *11* and *12* the high side turn-on waveforms for standard and embedded Schottky devices are shown; considering the purple trace in *Figure 11* and green trace in

Figure 12 (LS gate-source voltage), it is shown that the device with the Schottky diode shows strong reduction of low side spurious bouncing.

Figure 11: Standard FET HS turn-on waveforms



C1 20.0V/div 1MΩ BW:500M
C3 5.0V/div 1MΩ BW:500M
C4 10.0A/div 1MΩ BW:20.0M
M1 2.0kW 500ns

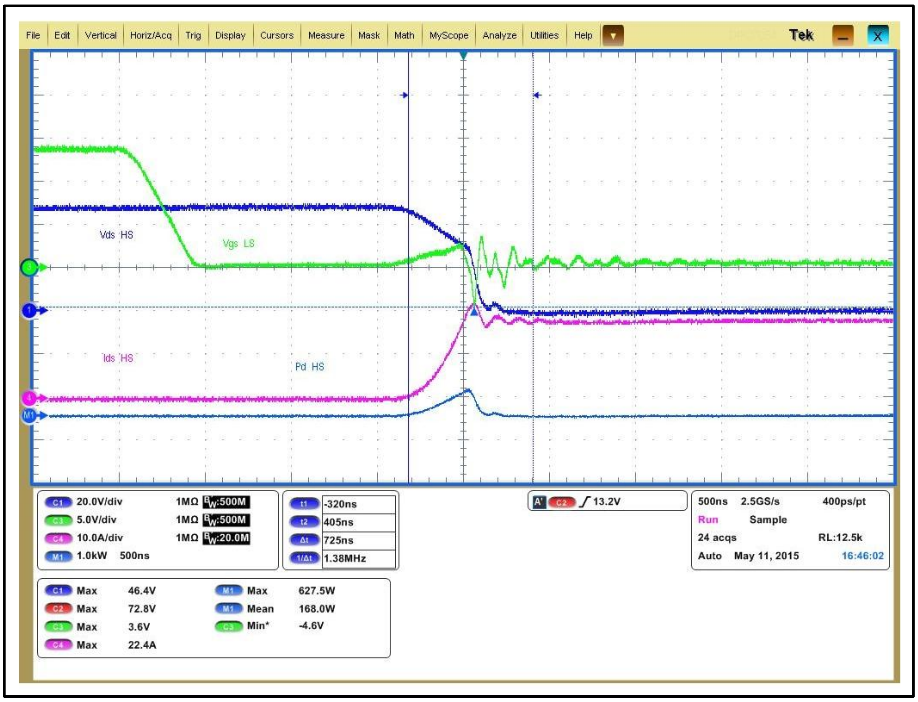
t1 -410ns
t2 180ns
Δt 590ns
1/Δt 1.69MHz

A' C4 ∫ 30.6A

500ns 2.5GS/s 400ps/pt
Run Sample
17 acqs RL:12.5k
Auto May 11, 2015 17:42:52

C1 Max 46.4V
C2 Max 76.0V
C3 Max 10.6V
C4 Max 40.8A
M1 Max 912.0W
M1 Mean 402.9W
C3 Min* -7.2V

Figure 12: Embedded Schottky FET HS turn-on waveforms



C1 20.0V/div 1MΩ BW:500M
C3 5.0V/div 1MΩ BW:500M
C4 10.0A/div 1MΩ BW:20.0M
M1 1.0kW 500ns

t1 -320ns
t2 405ns
Δt 725ns
1/Δt 1.38MHz

A' C2 ∫ 13.2V

500ns 2.5GS/s 400ps/pt
Run Sample
24 acqs RL:12.5k
Auto May 11, 2015 16:46:02

C1 Max 46.4V
C2 Max 72.8V
C3 Max 3.6V
C4 Max 22.4A
M1 Max 627.5W
M1 Mean 168.0W
C3 Min* -4.6V

5 Summary

In many applications (synchronous rectification for industrial and telecom SMPS, DC-AC inverter, motor drives), the right MOSFET must be selected not only considering $R_{DS(on)}$ and Q_g, but also evaluating the static and dynamic behavior of the intrinsic body-drain diode. STMicroelectronics' new 60 V “F7” power MOSFET with integrated Schottky diode ensures optimized performance for efficiency and commutation when a soft reverse recovery with low Q_{rr} is required. Furthermore, its low $V_{F,diode}$ value allows the achievement of higher efficiency when long freewheeling periods or dead-times are present in the application.

6 References

“*Fundamental of Power Semiconductor Devices*”, B.J.Baliga - 2008, Springer Science

7 Revision history

Table 2: Document revision history

Date	Version	Changes
17-Dec-2015	1	Initial release.

IMPORTANT NOTICE – PLEASE READ CAREFULLY

STMicroelectronics NV and its subsidiaries (“ST”) reserve the right to make changes, corrections, enhancements, modifications, and improvements to ST products and/or to this document at any time without notice. Purchasers should obtain the latest relevant information on ST products before placing orders. ST products are sold pursuant to ST’s terms and conditions of sale in place at the time of order acknowledgement.

Purchasers are solely responsible for the choice, selection, and use of ST products and ST assumes no liability for application assistance or the design of Purchasers’ products.

No license, express or implied, to any intellectual property right is granted by ST herein.

Resale of ST products with provisions different from the information set forth herein shall void any warranty granted by ST for such product.

ST and the ST logo are trademarks of ST. All other product or service names are the property of their respective owners.

Information in this document supersedes and replaces information previously supplied in any prior versions of this document.

© 2015 STMicroelectronics – All rights reserved