650 V SUPERFET® III FRFET® New Fast Reverse Recovery Super-Junction MOSFET for High Efficiency and Reliable EV Charging Applications

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APPLICATION NOTE

INTRODUCTION

The fast DC charging pole is rapidly expanding throughout the world. The fast chargers are required to make it possible to drive longer distances and overcome range limitation without spending several hours charging the battery [1]. The three−phase Vienna PFC and two−level full−bridge LLC resonant converter using 600~650 V super junction MOSFETs are typical topologies used for developing power modules for DC EV chargers. These topologies are popular for EV fast charging pole applications due to the high efficiency, reduced voltage stresses on semiconductor switches, and high power density. Historically, super junction MOSFETs have been used in resonant topologies such as the LLC, but the body diode reverse recovery performance of the super junction MOSFET is not attractive for many soft−switching topologies due to its body diode performance. As shown in Figure 1, the reverse recovery of conventional planar MOSFET is much softer than that of super−junction MOSFET. When considering similar circuit situations, a snappy body diode always generates higher voltage spikes and drain voltage slew rates (dV_{DS}/dt), which often results in device failure.

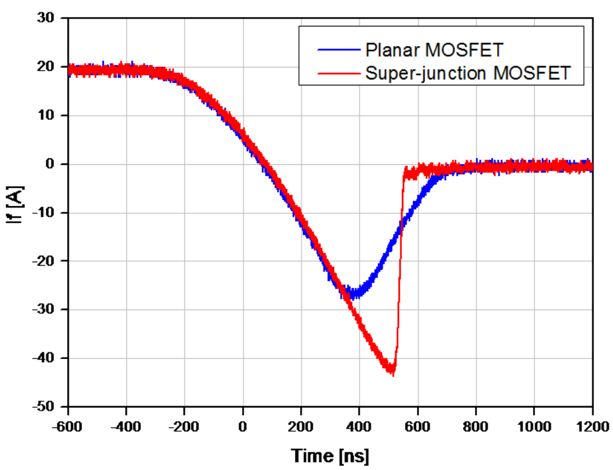


Figure 1. Reverse Recovery Behavior Comparison between Planar MOSFET and Super−junction MOSFET under V_{DD} = 400 V, di/dt = 100 A/μs, I_{SD} = 20 A

The soft body diode of the Planar MOSFET is suitable for resonant topologies. Furthermore, low reverse recovery charge (Q_{RR}) and robust body diode characteristics are correlated to increased reliability. However, low on−state resistance ($R_{DS(ON)}$) and stored energy in the output capacitance (E_{OSS}) of the MOSFET are critical parameters used to maximize efficiency in resonant converters. Therefore, the low $R_{DS(ON)}$ and E_{OSS} combined with the robust body diode of the fast recovery super−junction MOSFETs can effectively minimize resonant energy required to achieve soft switching without increasing the circulating energy and improve the system reliability. A fast recovery body diode Super Junction (SJ) MOSFET called, SUPERFET® III FRFET®, combines the best−in−class body diode performance with low dynamic resistance (R_{OSS}) and improved switching transients to optimize efficiency in resonant converters. In this application note, power MOSFET parameters of new fast recovery SJ MOSFETs are analyzed in the two−level full bridge LLC resonant converter used for EV fast DC charger, along and their impact on reliability.

650 V SUPERFET III FRFET

Target Application and Topologies

High voltage Super−Junction MOSFETs were developed to satisfy specific system requirements such as: improved system efficiency, reduced voltage spikes, high EMI performance, increased system reliability and cost effectiveness in several applications, as shown in Figure 2. SUPERFET III FRFET is optimized for soft switching topologies such as the Phased Shifted Full Bridge (PSFB) or LLC resonant topology that requires an improved reverse recovery body diode, especially for high performance applications such as Server / Telecom powers and EV charges.

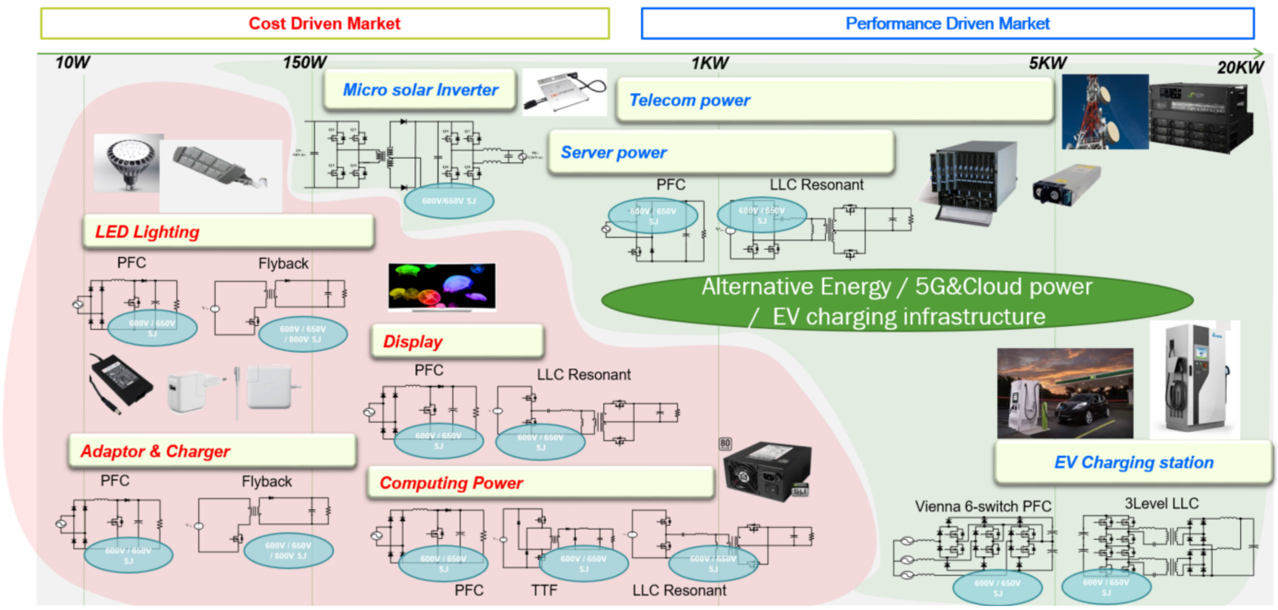


Figure 2. Target Application for 600 V ~ 800 V Super−Junction MOSFETs

Features and Benefits of 650 V SUPERFET III FRFET

Features	Benefits	Applications
• Best in Class body diode	• High System Reliability	• Server / Telecom
• Low switching noise	• Ease of use for fast design-in	• EV Charging Station
• Lower $R_{DS(ON)}$ / Same Packages	• High Power Density • Less paralleling MOSFETs	• Solar / UPS
• Lower FOM • $R_{DS(ON)\ max.} \times Q_{g\ typ.}$	• High System Efficiency	• LED lighting and computing
• 650V BV_{DSS}	• Improved Safety Margin	

The SUPERFET III FRFET technology can provide low $R_{DS(ON)}$ and the best−in−class body diode for lower conduction loss, and increased reliability in many AC−DC SMPS applications, which often require high power density, high system efficiency and high reliability.

Many optimizations have been achieved on the MOSFET body diode since more applications require the embedded body diode to perform as the critical component in the system. Lifetime control is a very effective solution used to reduce the reverse recovery charge and reverse recovery time of the body diode. However, there are some drawbacks due to the lifetime control processes. More lifetime control often results in the further increase of MOSFET on−resistance. This will add more power loss and is critical to the resonant converters. The SUPERFET III FRFET has been optimized to combine the lower $R_{DS(ON)}$ while dramatically improving body diode performance. The SUPERFET III FRFET reduced the Q_{RR} and T_{RR} by about 91% and 71% respectively, compared to those of EASY DRIVE as shown in Figure 3.

DUTs	Q_{rr} [uC]	T_{rr} [ns]	I_{rrm} [A]	Vds [V]
FCH023N65S3 (EASY DRIVE)	19.6	482.0	79.3	448.5
NTH027N65S3F (FRFET)	1.7 -91%	142.6 -71%	21.7 -73%	376.5 -72V

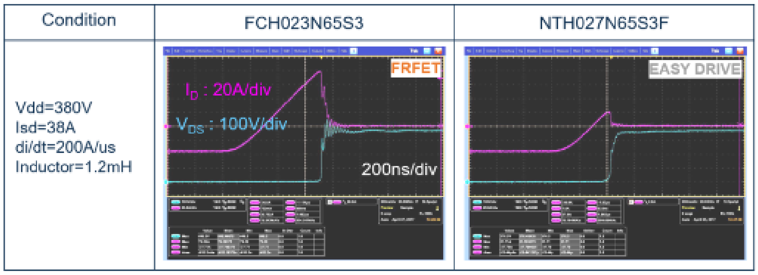


Figure 3. Body Diode Reverse Recovery Comparison between 650 V SUPERFET III FRFET vs EASY Drive under V_{DD} = 380 V, I_{SD} = 38 A, di/dt = 200 A/µs, T_j = 25°C

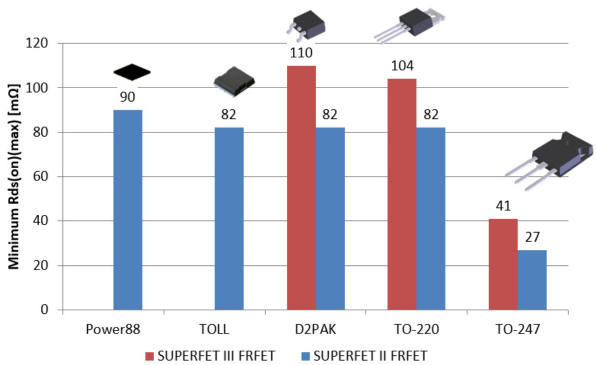


Figure 4. Minimum $R_{DS(ON)}$ (Max.) in different Packages of Power MOSFETs

As shown in Figure 4, the lowest possible maximum $R_{DS(ON)}$ of the SUPERFET III FRFET is 27 mΩ for TO−247 and 82 mΩ for TO−220 package. It is well suited for space−constrained applications such as fast EV charging systems by reducing the number of paralleled devices. Furthermore, the kelvin source SMD packages such as the Power88 and TOLL are available for space−constrained applications such as telecom and server power systems. The new SUPERFET III FRFET provides the best−in−class body diode performance such as the extremely small Q_{RR}, low voltage spikes, and best−in−class body diode ruggedness, while still providing ultra−low $R_{DS(ON)}$ and excellent switching performance. SUPERFET III FRFET achieved 45% lower $R_{DS(ON)}$ compared to previous generation with faster switching and the best−in class body diode performance. Table 1 provides other parameter improvements that truly benefit in resonant converters applications. As shown in Table 1, Both figures−of−merit (FOM's) , $[R_{DS(ON)} \times Q_G]$ and $[R_{DS(ON)} \times Q_{RR}]$ of SUPERFET III FRFET are dramatically reduced by 46% and 57% respectively, compared to the previous generation.

Table 1. CRITICAL SPECIFICATION COMPARISON UNDER SAME CONDITION

DUTs	BV_{DSS}	$R_{DS(ON)}$ max.	Q_g max.	T_{rr}	Q_{rr}
650 V / 33 mΩ SUPERFET III FRFET, NTHL033N65SHF	650 V	33 mΩ	182 nC	78 ns	1.4 µC
600 V / 41 mΩ SUPERFET II FRFET, FCH041N60F	600 V	41 mΩ	269 nC	103 ns	2.6 µC
600 V / 37 mΩ Fast Recovery SJ, Competitor A	600 V	37 mΩ	128 nC	82 ns	1.6 µC
600 V / 38 mΩ Fast Recovery SJ, Competitor B	600 V	38 mΩ	220 nC	103 ns	2.5 µC

The Power MOSFET devices used on the primary side of the LLC resonant converter must have a rugged body diode since there are a many hard commutation situations that can create very high MOSFET stress, especially during output short−circuit condition or start−up [2].

Figure 5 shows an LLC resonant converter during a short−circuit condition, where one of the primary side Power MOSFETs failed.

As shown in Figure 6, SUPERFET III FRFET shows the best−in−class body diode performance under the same test condition. The Q_{RR} of the SUPERFET III FRFET is reduced by 46%, 22%, and 44% respectively, compared to previous fast recovery SJ MOSFETs and competitors even though it has the lowest $R_{DS(ON)}$. Due to the the extremely low Q_{RR}, it shows the lowest voltage spikes during reverse recovery. The improved body diode of the SUPERFET III FRFET can effectively prevent device failure by reverse recovery dv/dt and static breakdown in resonant topologies under abnormal conditions. The output capacitance determines how much circuit inductance is required to enable ZVS conditions. SUPERFET III FRFET has approximately 25% less E_{OSS} at 400 V than previous generation. Therefore, lower C_{OSS} of SUPERFET III FRFET requires less resonant energy to achieve soft switching without increasing the circulating energy.

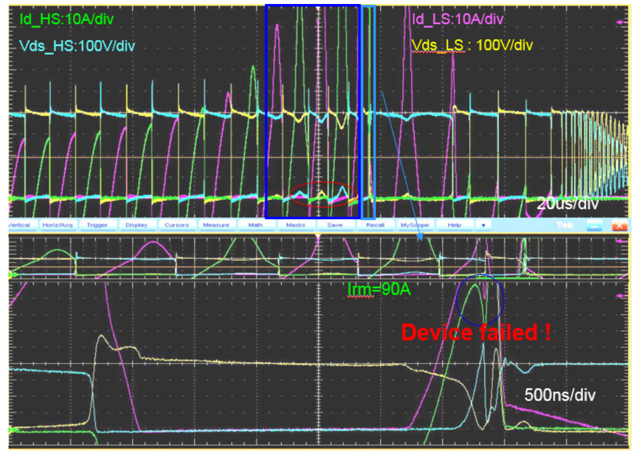
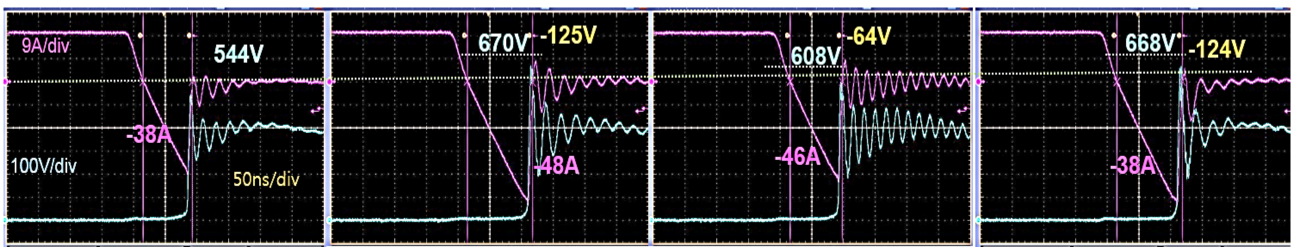


Figure 5. Waveforms of Power MOSFETs in LLC Resonant Converter at Short−Circuit Condition

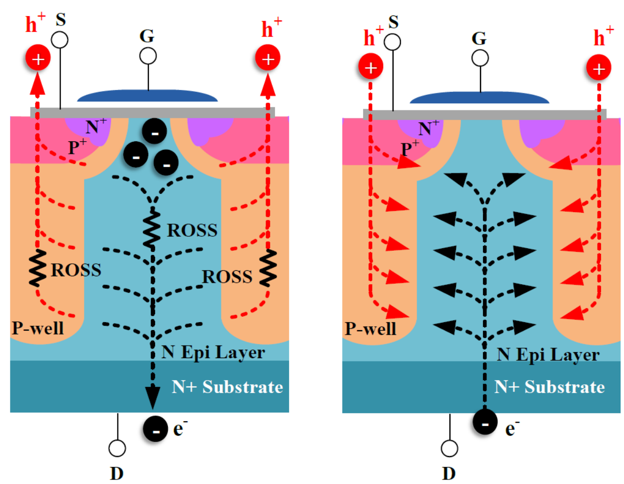


(a) 33 mΩ SUPERFET III FRFET **(b) 41 mΩ SUPERFET II FRFET** **(c) 37 mΩ Competitor A** **(d) 38 mΩ Competitor B**

Figure 6. Comparisons of Reverse Recovery Behavior of Fast Recovery SJ MOSFETs under I_{SD} = 20 A, di/dt = 800 A/µs, V_{DS} = 400 V

Dynamic R_{OSS} Loss in LLC Resonant Converters

Recently, the power loss from the hysteretic C_{OSS} behavior is analyzed in many papers [3]. Unexpected power losses associated with the latest SJ MOSFETs in ZVS topologies generated due to the hysteretic phenomenon of the output capacitance, C_{OSS}. This power losses related to C_{OSS} hysteresis is more critical when operating under high frequency soft switching conditions, especially in medium and light loads. Figure 7 describes the C_{OSS} charge and discharge parts, where the electron current (black dashed line) and hole current (red dashed line) and charge pockets (resistance) during charge and discharge of SJ MOSFET. Current flow of electron and holes originates charges between the N− epi and P−well pillars and must be removed through a highly resistive path. The resistance by this charge pocket (R_{OSS}) can be treated as a equivalent resistor during charging and discharging. This energy losses can be observed by the hysteresis loop area large signal C_{OSS} during charge−discharge cycle as shown in Figure 8. The energy loss related to the C_{OSS} hysteresis of the super−junction MOSFET depends on the design.



(a) C_{OSS} Charge **(b) C_{OSS} Discharge**

Figure 7. C_{OSS} Charge and Discharge of SJ MOSFET, Electron (e⁻) and hole (h⁺) Currents and Charge Pockets (Black and Red)

Figure 9 shows the resulting equivalent circuit of the MOSFET during C_{OSS} charging and discharging in the LLC resonant converter.

R_{OSS} results in a dynamic C_{OSS} loss for every switching cycle and increases the energy dissipated in the device [4]. This additional dynamic C_{OSS} of the super junction MOSFET is much higher than the planar MOSFET due to its epi pillar structure. This dynamic C_{OSS} loss is affected by device structure, die size, and switching dV_{DS}/dt.

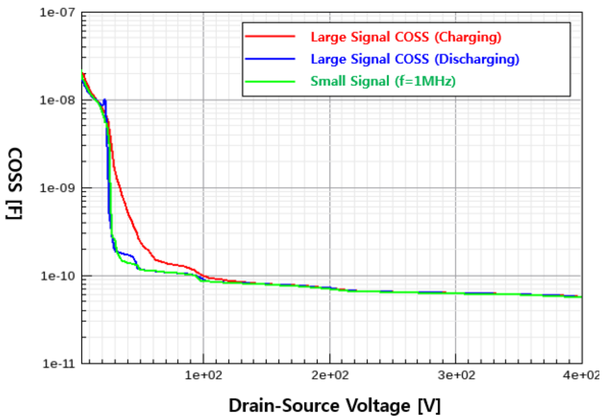


Figure 8. Comparison between Small Signal C_{OSS} (green line) and Large Signal C_{OSS}(red and blue lines)

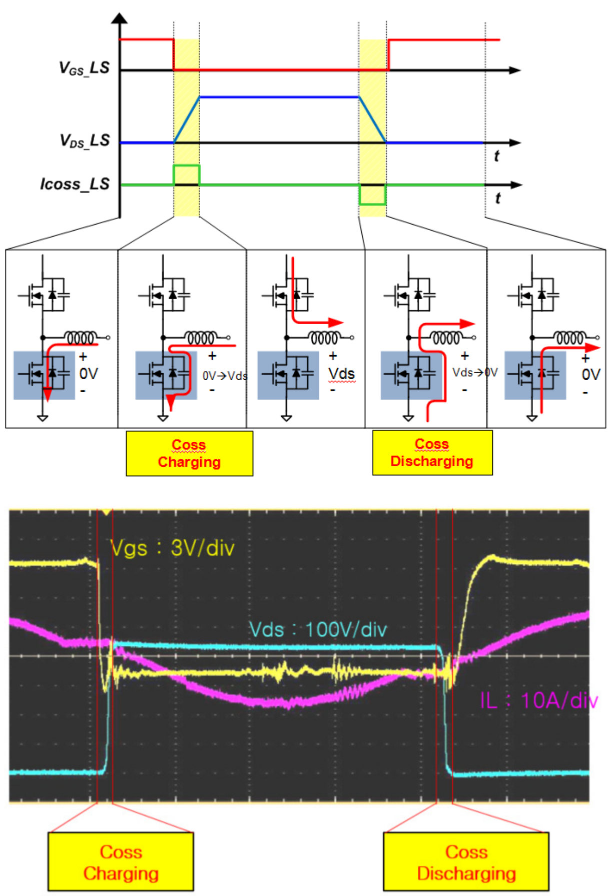


Figure 9. Equivalent Circuit of MOSFET during C_{OSS} Charging & Discharging in LLC Resonant Converter

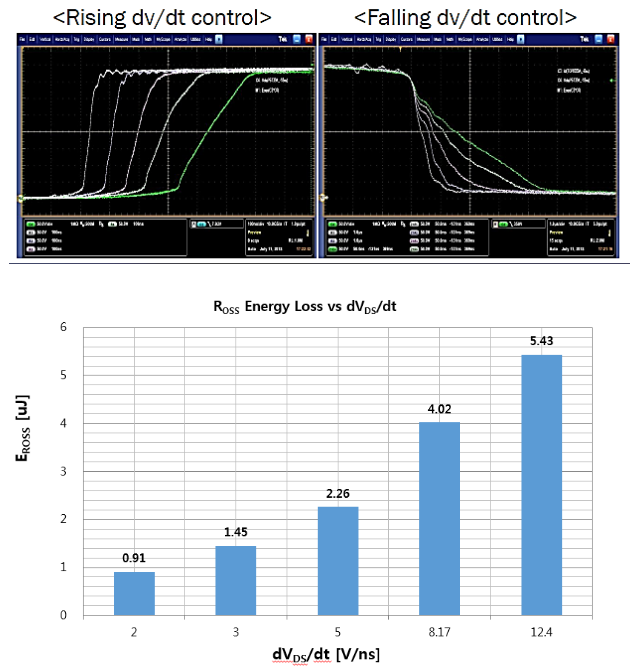


Figure 10. Energy Losses of SJ MOSFET during R_{OSS} Energy Loss vs Switching dv/dt during Charging and Discharging [0~400 V_{DS}]

Figure 10 shows energy losses of the super−junction MOSFET during charging and discharging of the C_{OSS} according to the switching dV_{DS}/dt. The energy loss from R_{OSS} is higher under a high dV_{DS}/dt condition, because of the higher displacement current generated by the high dV_{DS}/dt ($I^2 \cdot R_{OSS}$). As a results, the highly resistive path through R_{OSS} induces significant Joule heat for electrons and holes at N−epi and P−well pillars during the higher dV_{DS}/dt switching. SUPERFET III FRFET is optimized for lower C_{OSS} energy dissipation.

Performance Evaluation in 15 kW Fast EV Charging Module

The temperature and efficiency of the SUPERFET III FRFET is compared with the best competitor in a two−level LLC resonant converter of 15 kW fast EV charging module. Input voltage of the fast EV charging module is operated from a three−phase 380 VAC input with output voltage and current set to 750 V and 20 A, respectively. Total 8 pcs~16 pcs super junction MOSFETs (Q7~Q14) are used in the primary side of two−level full−bridge LLC resonant converter shown in Figure 11.

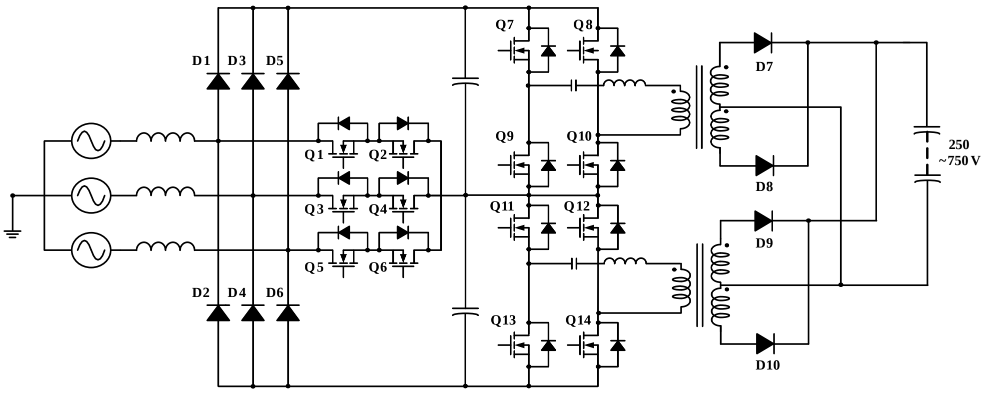
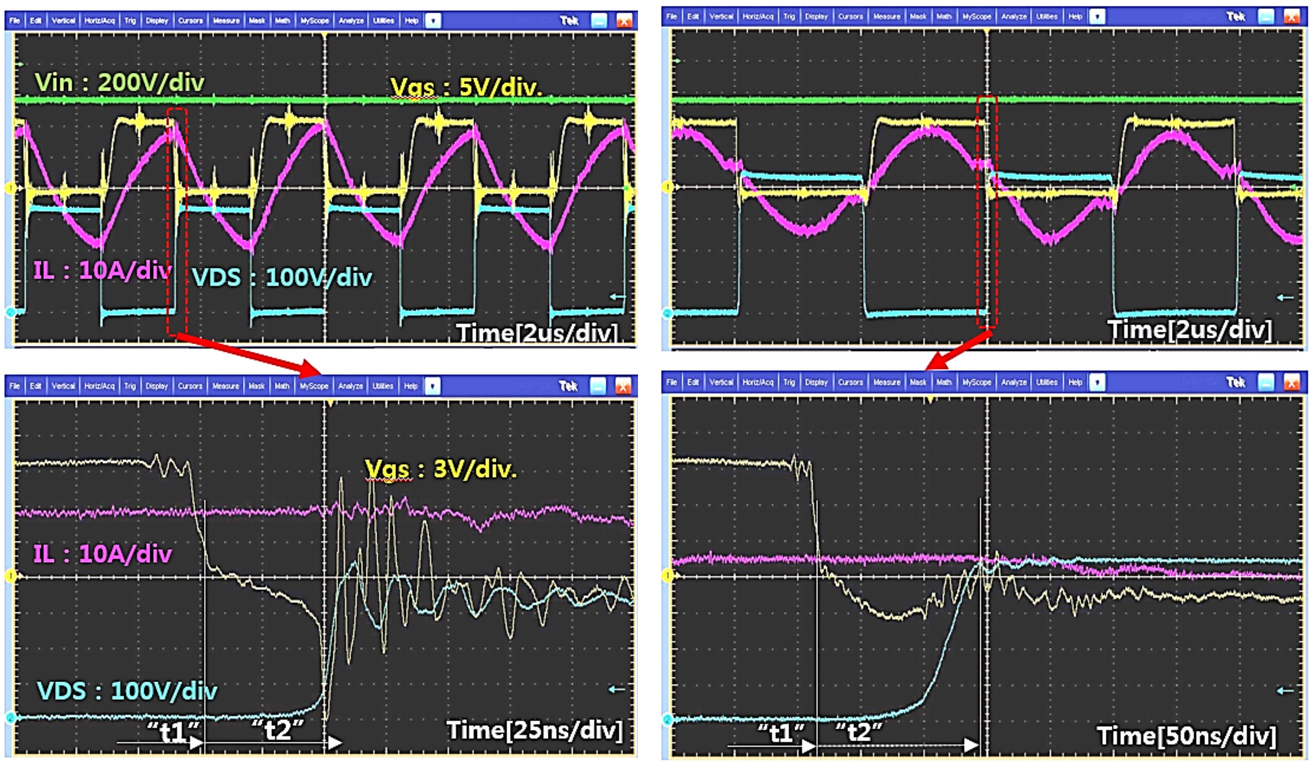


Figure 11. Power Stage of EV Charging Module : 3 phase Vienna PFC and Two Level Full−bridge LLC Resonant Converter



(a) P_{OUT} = 5 kW: 200 V / 25 A / 207 kHz, above resonant frequency (fs > fr)

(b) P_{OUT} = 15 kW: 750 V / 20 A / 127 kHz, below resonant frequency (fs < fr)

Figure 12. Operation Waveforms in 15 kW Two−level FB LLC of EV Charging Module

Output voltage range of the EV charging module is 200~750 V and depends on the battery voltage of EV cars. Figure 12 shows the operation waveforms of the power MOSFET. At light condition (5 kW, 200 V / 25 A), switching frequency (200 kHz) the dV_{DS}/dt during the turn−off transient is much higher than full load condition (15 kW, 750 V / 20 A, 127 kHz). The MOSFET channel is conducting during period “t1” and the MOSFET C_{OSS} is charged during period “t2” Figure 12 shows the operating waveforms in the 15 kW two−level FB LLC of the EV charging module under light and full load. Therefore, R_{OSS} loss of the primary side MOSFETs is much more critical due to higher switching frequency and dV_{DS}/dt under light load condition.

Especially, power loss of MOSFET is critical because there are many devices (8~16 pcs) used in the two−level FB LLC of the EV charging module. It is not only an issue of efficiency, but also of thermal management and reliability in this application. Power dissipation in the MOSFETs is highly dependent on on−resistances, R_{OSS}, gate charge, and body diode condition period as well as the switching frequency and operating temperature.

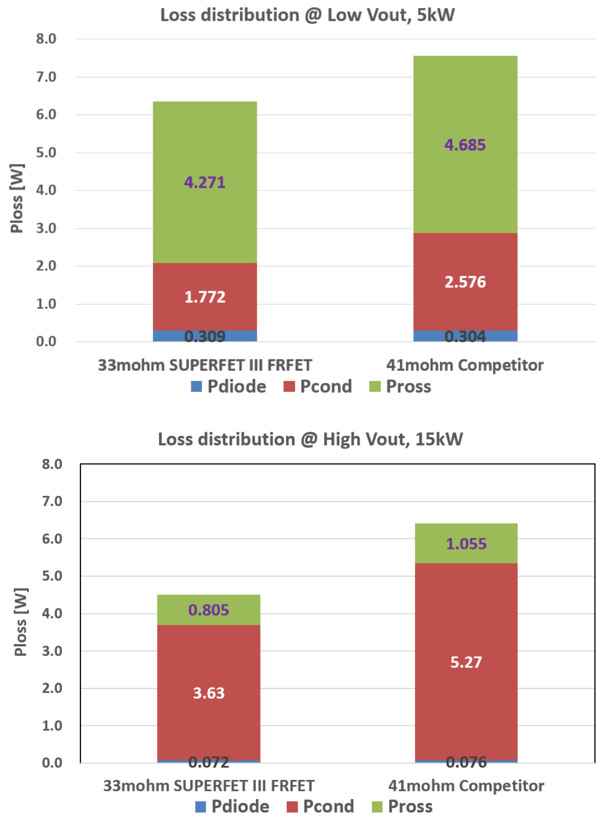


Figure 13. Power Loss Distribution under Light Load and Full Load in Two−level FB LLC of EV Charging Module

Figure 13 shows the power loss distribution of the MOSFETs in two−level FB LLC resonant converter of EV charging module under both light load and full load.

As shown in Figure 13, the R_{OSS} loss is a more critical loss for light load efficiency. These parasitic−related losses are a function of dV_{DS}/dt and the R_{OSS} of output capacitance of the MOSFET are proportional to the switching frequency. In order to increase system efficiency, R_{OSS} loss has to be reduced while using a low $R_{DS(ON)}$ device. Figure 13 shows power loss distribution under light load and full load in two−level FB LLC of EV charging module. Both R_{OSS} loss and $R_{DS(ON)}$ loss of 33 mΩ SuperFET III FRFET is reduced about 16% and 30% compared to 41 mΩ competitor respectively in light load and full load condition. Also total power losses of device in light load is higher than those in full load condition. Therefore case temperature of device is higher in light load condition in Figure 14. As shown in Figure 14, efficiency of SUPERFET III FRFET increases about 0.25%~0.27% and the operating temperature is reduced by 5.7°C to 9°C compared to the competitor at light and full load condition, respectively thanks to the reduced conduction loss and output capacitive loss because of lower $R_{DS(ON)}$ and R_{OSS}.

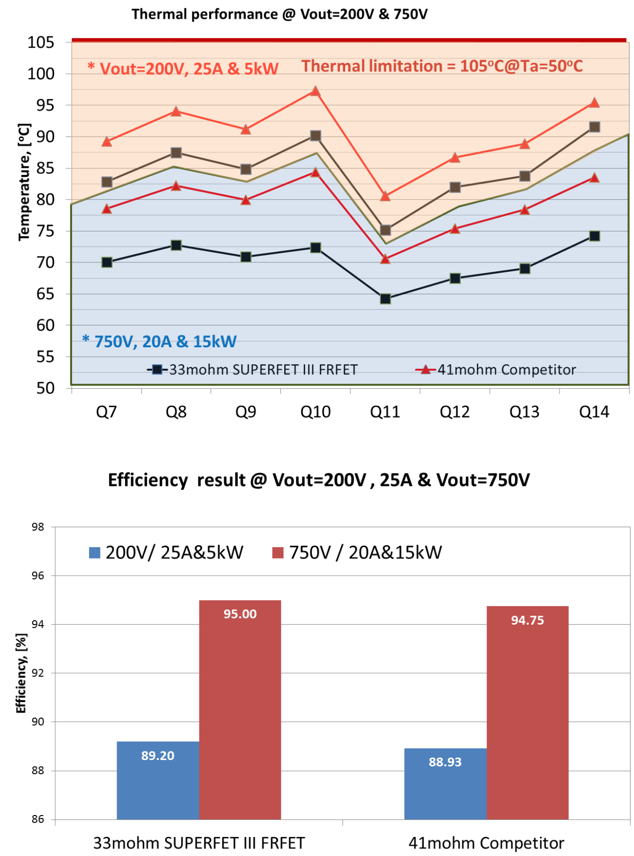


Figure 14. Thermal and Efficiency Comparison in Two−level FB LLC of 15 kW EV Charging Module

650 V SUPERFET III FRFET HF Series

There are two versions of the SUPERFET III FRFET, the F−version and HF−version. Table 2 shows the performance trade−off between the SUPERFET III FRFET F−version and HF−version that can be used as a customer's design requirements. The SUPERFET III FRFET HF−version is designed with very low R_{OSS} loss since it uses a slightly different pillar process than the F−version. It is developed to support applications that need higher efficiency for both hard and soft switching topologies. The SUPERFET III FRFET F−version shows relatively lower turn−off dv/dt for better EMI, but increases R_{OSS} loss compared to the HF−version. For better system efficiency, it is recommended to use the SUPERFET III FRFET HF version since it offers lower R_{OSS} and switching losses as shown in Figure 15 and 16. The trade−off is that the HF−version will switch faster with higher dv/dt compared to the F−version.

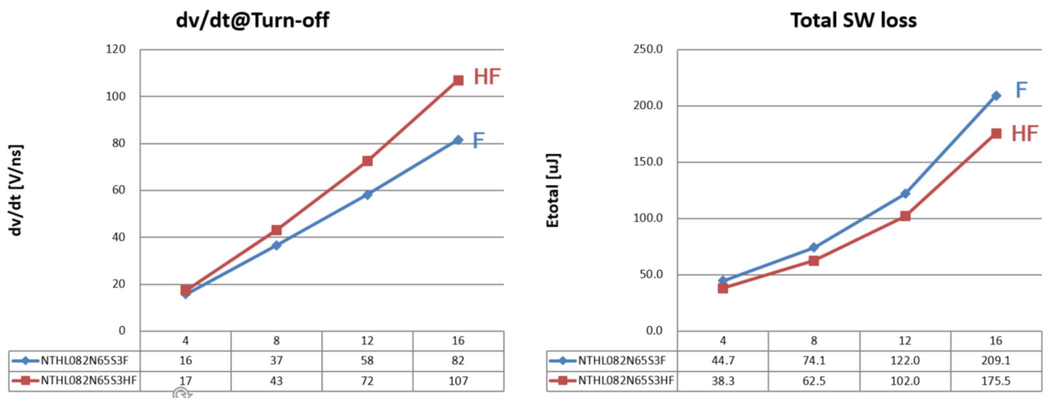


Figure 15. Comparisons of Turn−off Switching Characteristics: 82 mW SUPERFET III FRFET F and HF version under V_{DD} = 380 V, V_{GS} = 10 V, R_G = 4.7 Ω

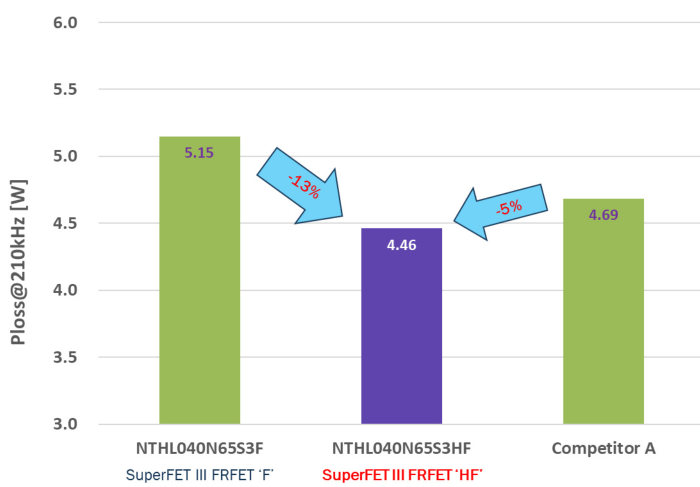


Figure 16. Power Loss Comparison: SUPERFET III FREFET F vs HF vs Competitor under in Two−level FB LLC of EV Charging Module

Table 2. PERFORMANCE TRADE−OFF AND BENEFITS BETWEEN SUPERFET III FRFET F VERSION AND HF VERSION

	FRFET F Version	FRFET HF Version
Performance	Slow switching @Turn off → Low peak Vds → Low dv/dt and Gate Oscillation	Fast switching @Turn off → lower R_{OSS} loss → Lower switching loss
Benefit	Better EMI	Better system efficiency

Conclusion

The latest SUPERFET III FRFET shows best in class body diode performance and low dynamic C_{OSS} loss. The SUPERFET III FRFET technology is designed to achieve better efficiency not only at the full load condition with low conduction loss, but also at the light load conditions by minimizing the R_{OSS} loss. The FRFET series can provide outstanding reliability performance in soft switching topologies. Due to the very low $A{\cdot}R_{DS(ON)}$ of the SUPERFET III FRFET, it is highly optimized for the two−level FB LLC resonant converter for high power fast EV charging applications.

• H: TO-247AB, HD: TO-247AD
• 4L : TO247-4L
• HF : High efficiency FRFETQ
• Z : Zener diode b/w Gate and Source

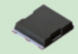
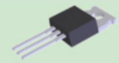
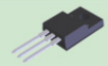
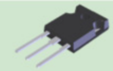
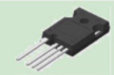
PKG	D2PAK	Power88	TOLL	TO-220	TO-220F	TO-247	TO-247-4L
RDS(on)							
27mΩ						NTH027N65S3F NTHL027N65S3HF	NTH4L027N65S3F
33mΩ						NTHL033N65S3HF	
40mΩ						NTHL040N65S3F NTHL040N65S3HF NTHLD040N65S3HF	NTH4L040N65S3F
50mΩ						NTHL050N65S3HF	
65mΩ						NTHL065N65S3F NTHL065N65S3HF	
82mΩ	NTB082N65S3F		NTBL082N65S3HF	NTP082N65S3F NTP082N65S3HF	NTPF082N65S3F	NTHL082N65S3F NTHL082N65S3HF	
90 / 95mΩ	NTB095N65S3HF	NTMT090N65S3HF		NTP095N65S3HF		NTHL095N65S3HF	
110mΩ	NTB110N65S3HF	NTMT110N65S3HF		NTP110N65S3HF	NTPF110N65S3HF	NTHL110N65S3F	
150mΩ	NTB150N65S3HF	NTMT150N65S3HF		NTP150N65S3HF	NTPF150N65S3HF		
190mΩ	NTB190N65S3HF	NTMT190N65S3HF		NTP190N65S3HF	NTPF190N65S3HF	NTHL190N65S3HF	

Figure 17. 650 V SUPERFET III FRFET MOSFET Lineup

Reference

[1] Ministry of Housing and Urban−Rural Development. (2015, Dec. 7). Notice on Enhancing the Planning and Construction Work of Electric Vehicle Charging Infrastructure. [Online]. SUPERFET Available: http://www.mohurd.gov.cn/wjfb/201601/t20160115_226326.html

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