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# AND9893/D

# 650V SUPERFET® III Easy Drive, the optimized high voltage Super Junction MOSFETs for hard and Soft Switching Topologies

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**APPLICATION NOTE**

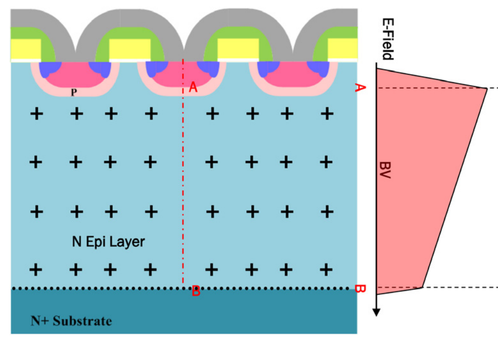
## INTRODUCTION

This application note describes the 4th generation Super Junction MOSFET from ON Semiconductor, called the SUPERFET III Easy Drive MOSFET. This technology is currently available with a 650V breakdown rating, $BV_{DSS}$. Major features of this technology are ease of use, lower EMI, and reduced voltage spikes during switching transients, along with excellent body diode ruggedness. The Easy Drive technology enables these features by integrating an optimized internal gate resistance along with optimized device capacitances. Therefore, this technology is suitable for both hard and soft switching topologies in various applications.

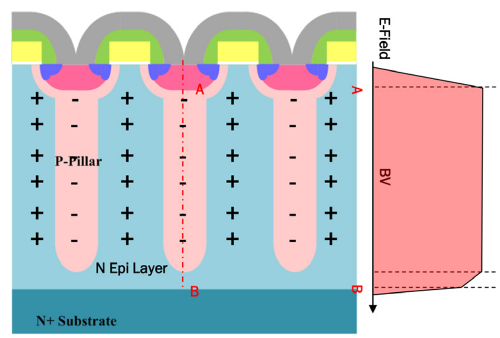
## SUPER JUNCTION MOSFET TECHNOLOGY

Super Junction MOSFET technology is often considered as the best silicon device technology available for optimizing low on−state resistance [$R_{DS(ON)}$] and [$R_{DS(ON)} \times Q_G$] figure of merit (FOM), where $Q_G$ is the device total gate charge. Super Junction technology has mostly replaced planar high voltage MOSFETs, and the [$R_{DS(ON)} \times Q_G$] FOM is generally considered the most important indicator of the MOSFET performance in Switched Mode Power Supplies (SMPS).

Figure 1 provides a comparison of the vertical structure and electric field profile of a planar MOSFET and a Super Junction MOSFET. The breakdown voltage ($BV_{DSS}$) of the planar MOSFET is determined by doping concentration and thickness of N Epi Layer. The slope of electric field distribution on N Epi Layer is proportional to the doping concentration. Therefore, thick and lightly doped epi is needed to support higher breakdown voltage. The major contribution to on−resistance of high−voltage MOSFET comes from the N Epi Layer: the on−resistance exponentially increases with the light doping and thick N Epi Layer for higher breakdown voltage. In high−voltage MOSFET technologies, the most remarkable achievement for on−resistance reduction is Super Junction technology shown in Figure 2. Super Junction technology has deep p−type pillar−like structure in the body in contrast to the well−like structure of conventional planar technology. The effect of the pillars is to confine the electric field in the lightly doped epi region. Thanks to this p−type pillar, the resistance of n−type epi can be dramatically reduced compared to the conventional planar technology, while maintaining same level of breakdown voltage. This new technology broke silicon limits in terms of on−resistance and achieves only one−fifth specific on−resistance per unit area compared to planar processes. This technology also achieved unique non−linear parasitic capacitance characteristics and therefore enabled reduced switching power losses.




**Planar MOSFET**




**Super−Junction MOSFET**

**Figure 1. Vertical Structure and Electric Field Profile of Power MOSFETs**



May, 2019 − Rev. 0

Publication Order Number:
AND9893/D

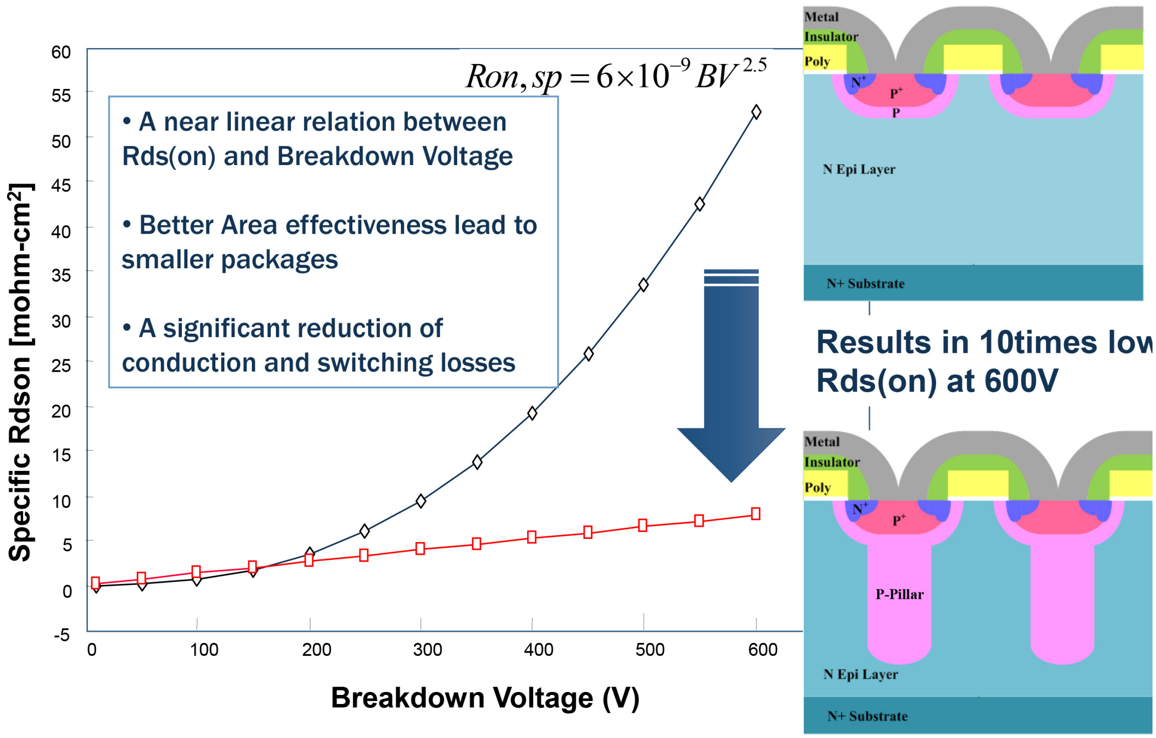



**Figure 2. Vertical Specific $R_{DS(ON)}$ of Planar MOSFET / Super Junction MOSFET as Function of Breakdown Voltage**

One undesirable feature of Super Junction technology is that it can create extremely fast transients during switching events. These transients can interact with parasitic circuit inductance and capacitance and generate very large voltage spikes and oscillations. Therefore, ON semiconductor has designed three SUPERFET III versions to help address various topologies and design requirements. As shown in Figure 3, the SUPERFET III series consists of FAST, Easy Drive, and FREFT version with optimized key parameters for target applications and topologies.

The Easy Drive version is targeted to produce slower switching transients that produce low EMI and low switching noise compared to the FAST design. However, the switching loss is balanced in order to achieve acceptable system efficiency in both hard and soft switching.

The FRFET version is optimized for soft switching topologies such as the Phased Shifted Full Bridge (PSFB) or LLC resonant topology that requires an improved reverse recovery behavior (more robust) body diode.

The FAST version offers the highest efficiency and highest power density in hard switching topologies by minimizing switching losses. While the FAST version optimizes switching losses, it often requires additional snubber circuitry or ferrite beads to control switching spikes and oscillations. Again, the FAST version is intended to be used for attaining highest possible efficiency in hard switching topologies, but careful attention is needed for soft switching topologies.

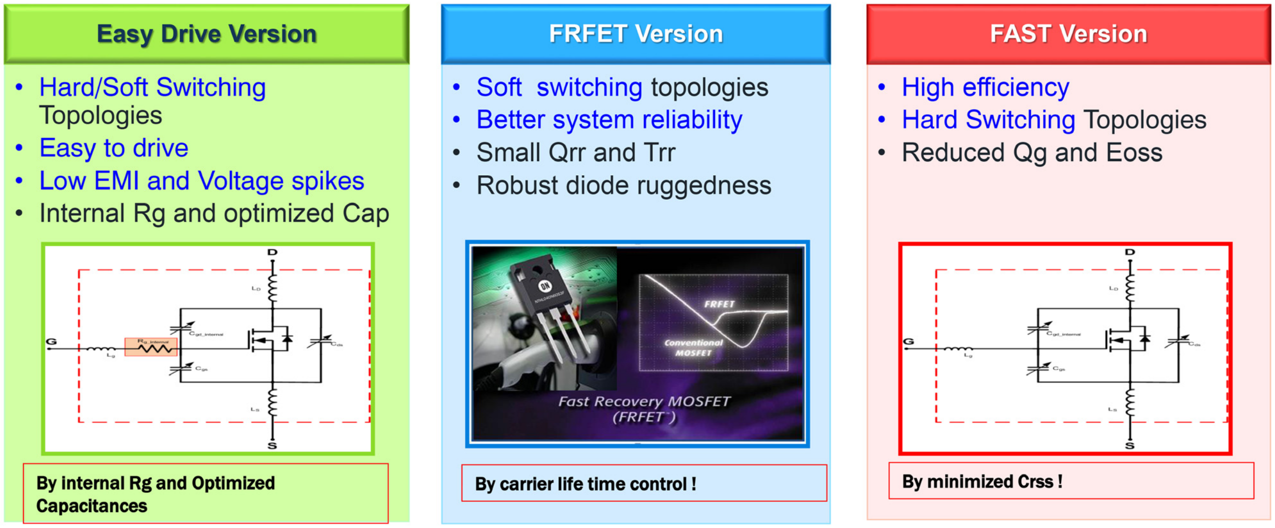



**Figure 3. Super Junction MOSFET Series for Optimized Performance for Each Topologies**

### ON Semiconductor's Super Junction MOSFET History

Table 1 is provided to show the evolution of Super Junction MOSFET technology at ON semiconductor. The first generation Super Junction MOSFET, the SUPERFET I MOSFET, was introduced in 2003 and surpassed the performance of the existing best−in−class planar MOSFET. In 2009, the second−generation SJ MOSFET, named SUPREMOS MOSFET was released by using a deep trench technology, which was the first technology of it's kind. The SUPREMOS achieved a much higher active cell density versus SUPERFET I. The 3$^{rd}$ generation technology, called SUPERFET II MOSFET, offers three product families: Easy Drive version, FRFET version and FAST version and was designed to address the expanding needs of the various off−line AC/DC markets. The 4th generation technology, called SUPERFET III was also designed to address the ever expanding needs of the various off−line AC/DC markets while improving upon power density and efficiency versus the SUPERFET II. The SUPERFET III Easy Drive, which reduces the typical area specific $R_{DS(ON)}$ reduced 45% than SUPREFET II technology, was released in 2015. This technology comes with an integrated gate resistor and optimized capacitance to achieve self−limiting di/dt and dv/dt characteristics. The SUPREFET III EASY R0 version was released for improved efficiency by removing internal gate resistance from SUPREFET III Easy Drive.

**Table 1. ON Semiconductor's Super Junction MOSFET Family and History**

| Product Family | Release | $BV_{DSS}$ | $V_{TH}$ | Characteristics | Internal $R_G$ | $Q_{RR}$ |
|---|---|---|---|---|---|---|
| SUPERFET I | 2003 | 600 V | 4.0 V | Ease of use<br>Good body diode ruggedness | Small | Large |
| SUPERFET I FRFET | 2005 | 600 V | 4.0 V | Fast recovery & robust body diode<br>For resonant converter / inverter topologies | Small | Small |
| SUPREMOS | 2009 | 600 V | 3.0 V | World first Deep Trench Technology<br>Fast switching speed | Small | Large |
| SUPREMOS FRFET | 2010 | 600 V | 4.0 V | Fast recovery & robust body diode<br>For resonant converter / inverter topologies | Small | Small |
| SUPERFET II FAST | 2011 | 600 V | 3.0 V | Maximized system efficiency<br>Fast switching speed, but reduced dv/dt | Small | Large |
| SUPERFET II Easy Drive | 2012 | 600 V | 3.0 V | Ease of use<br>Controlled di/dt and dv/dt at abnormal conditions | Large | Large |
| SUPERFET II FRFET | 2012 | 650 V | 4.0 V | Fast recovery & robust body diode<br>For resonant converter / inverter topologies | Small | Small |
| SUPERFET III Easy Drive | 2015 | 650 V | 3.5 V | Ease of use<br>Controlled di/dt and dv/dt at abnormal conditions | Large | Large |
| SUPERFET III Easy Drive R0 | 2017 | 650 V | 3.5 V | Optimized switching performance<br>Lower switching losses from SF3 Easy Drive | Small | Large |

### Target application and topologies

As mentioned, the SUPERFET III Easy Drive technology is optimized for both hard and soft switching topologies that are commonly used in server, telecom, computing, lighting, and charger applications. The Easy Drive technology can provide low switching noise, better EMI and increased reliability in many AC–DC SMPS applications, which often require high power density, high system efficiency and high reliability. One example is an AC–DC SMPS consisting of a Power Factor correction (PFC) and LLC resonant converter.

| Application | PFC | DC–DC |
|---|---|---|
| Server | Boost / Active bridge | LLC |
| Telecom | Boost / Active bridge | LLC |
| Computing | Boost | TTF / LLC |
| Consumer (TV) | Boost | LLC |
| Adaptor | Single stage flyback | |

The SUPERFET III Easy Drive MOSFETs can be used as a boost switch in the hard–switched PFC and also used in the primary side of a half–bridge or full–bridge LLC, which provides soft switching (zero voltage switching, ZVS) on the primary side MOSFETs.

### Easy Drive Features and Benefits

One of the main goals of the Easy Drive technology is to provide a well–balanced trade–off between switching losses and switching noise, which consists of voltage spikes and oscillations. The Easy drive technology aims to optimize the internal gate resistance and internal input/output capacitances of the MOSFET to tame switching transients, which will reduce voltage spikes and oscillations, but still provide low switching losses. As mentioned, the alternate technology to the Easy Drive is the FAST version. The FAST version optimizes switching losses to achieve highest efficiency, but it often requires additional snubber circuitry or ferrite beads to control switching spikes and oscillations. The FAST version is only introduced in this application note and not discussed in depth here.

One common issue with Super Junction technology is the high switching transients interact with parasitic package inductance and capacitance between MOSFET gate, drain, and source terminals. These parasitic elements often create underdamped resonant circuits that tend to large voltage and current oscillations, which can compromise EMI and device reliability.

- Excellent FOM [$R_{DS(ON)} \times Q_G$]
- Outstanding ease of use and low EMI
- $BV_{DSS}$ of 650 V at $T_j$ = 25°C, 700 V at $T_j$ = 150°C
- Robust body diode

SUPERFET III Easy Drive has very low $R_{DS(ON)}$ compared to previous generation, SUPERFET II technology.

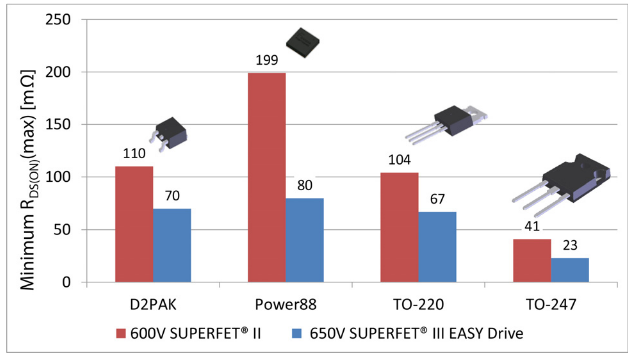



**Figure 4. Minimum $R_{DS(ON)}$ (Max.) in Different Packages of Power MOSFETs**

Simple way to damp oscillation is well known to put a gate resistor, you can easily understand damping effect of gate resistor is much effective if we put this internal gate resistance inside of the device, and embedded to gate pad, so the final goal of SUPERFET III Easy Drive is to make the device as much as possible independent of the parasitic coming from the device itself and from the PCB layout. Not only internal gate resistance, this technology has very optimized parasitic capacitances for ease of use and lower EMI and voltage spikes during switching transient. Thanks to robust body diode of this technology, it is suitable for not only hard switching but also soft switching topologies.

### Positioning of SUPERFET III Easy Drive

As shown in Figure 4. for previous generation SUPERFET II, 41 mΩ could fit for standard TO–247 package, now SUPERFET III Easy Drive can provide much lower $R_{DS(ON)}$, 23 mΩ in TO–247 package. Especially, $R_{DS(ON)}$ of SUPERFET III Easy Drive is reduced up to 50% in Power88 package compared to SUPERFET II technology. Therefore, SUPERFET III Easy Drive enable to reduce PCB area and easily design for higher power density. It is well suited for space–constrained applications such as telecom and server power systems by reducing device counts. As shown by this spider chart in Figure 5, spider chart plots the values of each categories, efficiency, FOM, $E_{OSS}$, EMI and body diode ruggedness, along a separate axis on scale of zero to five. In this spider chart, SUPERFET III Easy Drive improved $E_{OSS}$, $Q_G$ and Efficiency from SUPERFET II Easy Drive while gate oscillation trade–off is minimized. Also body diode ruggedness and gate oscillation is much better than competitor's FAST version. Overall performance of SUPERFET III Easy Drive is well balanced.

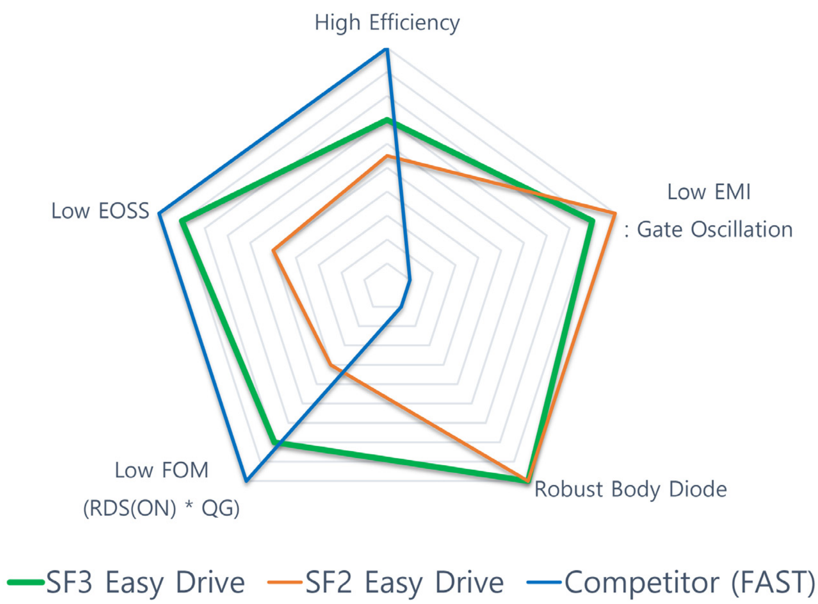



**Figure 5. Performance Comparisons SUPERFET III Easy Drive of Against Previous Generation and FAST Version on Spider Chart**

## SUPERFET III EASY DRIVE SERIES

### Integrated Gate Resistance

SUPERFET III Easy Drive enables optimized switching and low switching noise to achieve high efficiency and low EMI in applications due to optimized design. The high switching speed of Super Junction MOSFETs is reduces switching losses, but can have negative effects; such as increased EMI, gate oscillation, and high peak drain−source voltage in applications. A critical control parameter in gate−drive design is the external series gate resistor ($R_g$). This dampens the peak drain−source voltage and prevents gate ringing caused by lead inductance and parasitic capacitances of the power MOSFET. It also slows down the rate of rise of the voltage (dv/dt) and current (di/dt) during turn−on and turn−off switching transient.

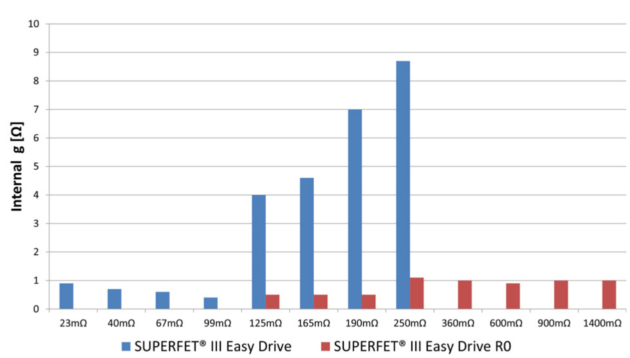



**Figure 6. Internal Gate Resistance ($R_G$) of SUPERFET III Easy Drive and R0 Version**

$R_g$ also affects the switching losses in MOSFETs. Controlling these losses is important as devices must achieve the highest efficiency in the target application. From an application standpoint, selecting the correct value for $R_g$ is very important. As shown in Figure 6, SUPERFET III Easy Drive employs an integrated gate resistance, which is not Equivalent Series Resistance (ESR), but is a gate resistor to reduce gate oscillation and control switching dv/dt and di/dt under high current conditions. The value of integrated gate resistance is optimized with gate charge for each products. SUPERFET III Easy Drive R0 version is available with minimized internal gate resistance in order to support applications, where higher system efficiency is more critical than ease of use. The Super Junction technology can dramatically reduce both on−resistance and parasitic capacitances, which usually are in trade−off. With smaller parasitic capacitances, the Super Junction MOSFETs have extremely fast switching characteristics and reduced switching losses. Naturally, this switching behavior occurs with greater dv/dt and di/dt that affect switching performance via parasitic components in devices and PCB. Combination of high dv/dt, di/dt with circuit and device parasitic components lead to gate oscillation or switching noise. The parasitic oscillation can cause gate−source breakdown, bad EMI, large switching losses, losing gate control, and can even lead to MOSFET failures. As show in Figure 7, SUPERFET III Easy Drive effectively reduces gate oscillation and noise during turn−off switching transient thanks to not only internal gate resistor and but also optimized parasitic capacitances.

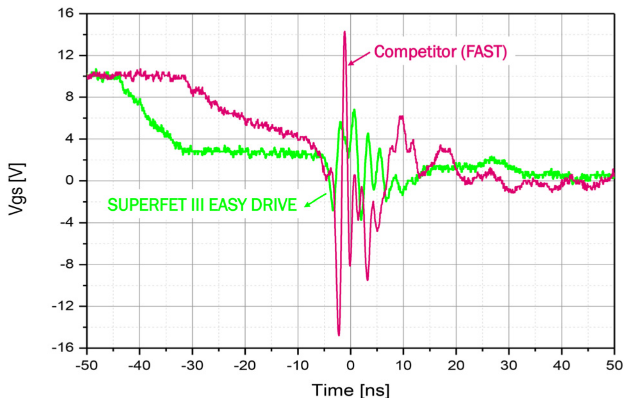



**Figure 7. Gate Oscillation During Turn−off Transient**

Advantage of SUPERFET III Easy Drive is the improved area specific $R_{DS(ON)}$ compared to previous generation. Thanks to reduced specific $R_{DS(ON)}$ of SUPERFET III Easy Drive, parasitic device capacitances of SUPERFET III Easy Drive, that effect to switching behavior, can be reduced. Table 2 shows the key parameter comparison. Reduced $E_{OSS}$ and gate charge, lowering switching and driving losses is advantages of SUPERFET III Easy Drive. It also reduces driving current capability. Figure 8 shows a total gate charge measurement of the SUPERFET III Easy Drive, SUPERFET II Easy Drive and competitor under same condition, $V_{DS}$=400 V, $V_{GS}$=10 V, and $I_D$=8.5 A. The total gate charge and miller plateau of SUPERFET III Easy Drive is less than half of the SUPERFET II Easy Drive and competitor.

### Electrical Characteristics Comparison

**Table 2. Key Parameter Comparison of ON Semiconductor's Super Junction MOSFET Family and Competitor**

| Generation / Product | FCP190N65S3 | FCP190N60E | Competitor A |
|---|---|---|---|
| **Specification** | SUPERFET III Easy Drive | SUPERFET II Easy Drive | |
| $BV_{DSS}$ at $T_J$=25°C | 650 V | 600 V | 600 V |
| $I_D$ | 17.0 A | 20.6A | 20.2 A |
| FOM [$R_{DS(ON)} \times Q_G$] | 6.1 Ω nC | 12.2 Ω·nC | 11.4 Ω ·nC |
| $R_{DS(ON)}$ Max. | 190 mΩ | 199 mΩ | 190 mΩ |
| $V_{GSS}$ | ±30 V | ±20 V | ±20 V |
| $Q_g$ @ $V_{dd}$=400 V, $I_D$=8.5 A, $V_{gs}$=10 V (Note 1) | 31 nC (Note 1) | 64 nC (Note 1) | 60 nC (Note 1) |
| Internal $R_g$ | 7 Ω | 5 Ω | 8.5 Ω |
| $E_{OSS}$ at 400 V | 3.6 μJ | 6.0 μJ | 5.2 μJ |
| Body Diode, $Q_{RR}$@ $I_D$=8.5 A, $V_{gs}$=10 V (Note 1) | 5.0 μC (Note 1) | 4.7 μC (Note 1) | 6.2 μC (Note 1) |
| Peak Diode Recovery dv/dt | 20 V/ns | 20 V/ns | 15 V/ns |
| MOSFET dv/dt | 100 V/ns | 100 V/ns | 50 V/ns |

1. Measured value under same condition

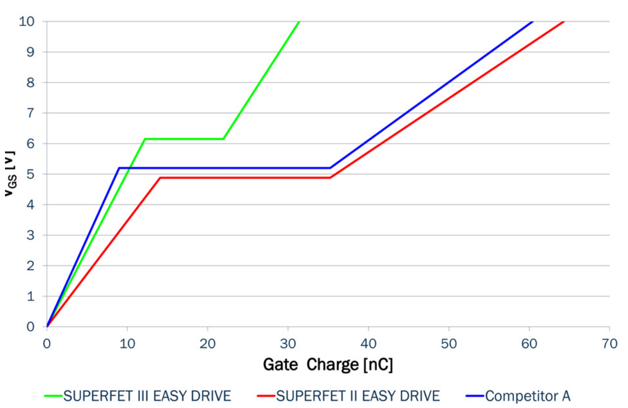



**Figure 8. Gate Charge ($Q_G$) Comparison @ $V_{dd}$ = 400 V, $I_D$ = 8.5 A, $V_{gs}$ = 10 V, 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and Competitor**

An output capacitance giving equivalent stored energy at the working voltage of power converter is the best alternative for these applications. In hard−switching applications, the MOSFET channel conducts higher current than load current during turn−on, because of the additional discharging current of output capacitance. Therefore, $E_{oss}$ of the MOSFET during turn−off is internally dissipated through the MOSFET channel during turn−on. The stored energy in output capacitance, $E_{oss}$ of the MOSFET, is very critical in hard−switching applications, such as power factor correction (PFC), especially at light loads, because it is fixed and independent of load. A SUPERFET III Easy Drive, FCP190N65S3, has approximately 40% and 31% less stored energy in output capacitance than SUPERFET II Easy Drive, FCP190N60E and competitor, respectively (for a typical switching power supply bulk capacitor voltage, 400 V), as shown in Figure 9. Potential failure of power

MOSFET may happen due to body diode reverse recovery in phase shifted full bridge or LLC resonant topologies.

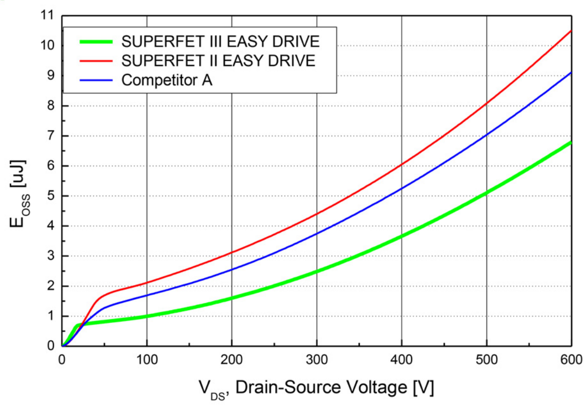



**Figure 9. Comparisons of $E_{OSS}$: 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and Competitor**

Even though voltage and current of Power MOSFETs are within safe operating area, some unexpected failures associated with shoot through current, reverse recovery dv/dt and breakdown dv/dt happened in various conditions, such as under light load, start−up, load transient or output short mode. Figure 10 shows body diode reverse−recovery ruggedness, comparing the 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and competitor. Both SUPERFET II and SUPERFET III Easy Drive showed robust body diode compared to the competitor. The reverse−recovery measurements show that competitor fails at a di/dt of 2700 A/μs and a dv/dt of 23 V/ns, where the SUPERFET III Easy Drive survives >3000 A/μs and 55 V/ns. This type of failure is observed in many resonant topologies. The failing devices destroy themselves during the reverse−recovery phase where the voltage is high and current and di/dt is still high. The SUPERFET III Easy Drive provide high dv/dt ruggedness of the body diode for higher system reliability in ZVS topologies.

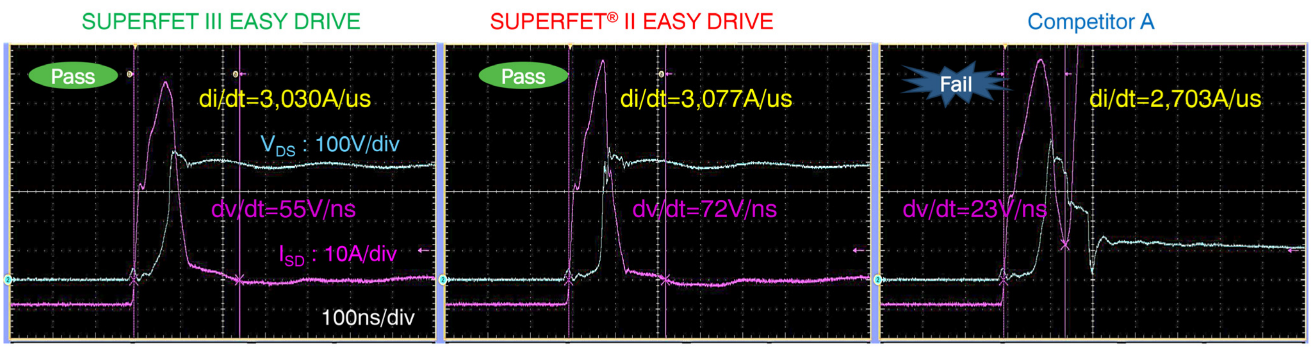



**Figure 10. Measured Body Diode Reverse−Recovery Ruggedness Waveforms Comparing SUPERFET III Easy Drive of Against Previous Generation and Competitor**

As shown in Figure 10, SUPERFET III Easy Drive shows very smooth drain−source voltage slop compared to previous generation and competitor during hard commutation of body diode. Smooth and lower dv/dt help to reduce displacement current which can trigger the parasitic BJT of MOSFET during reverse recovery operation of body diode.

### Switching Performance Comparison

Figure 11 and 12 show the measurement of $E_{OFF}$ and turn−off dv/dt comparisons for 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and competitor under $V_{DD}$=380 V, $V_{GS}$=10 V and $R_G$=4.7 Ω in various $I_D$ conditions. $E_{OFF}$ is 9% and 33% less for 650 V SUPERFET III Easy Drive compared to that of 600 V SUPERFET II Easy Drive and 600 V competitor under same condition. Even though turn−off switching loss of 650 V SUPERFET III Easy Drive show relatively much lower value of than 600 V SUPERFET II Easy Drive and 600 V competitor, turn−off dv/dt is much lower than SUPERFET II Easy Drive and similar to competitor at high current (6A~17A). Soft turn−off switching behavior of SUPERFET III Easy Drive provide more design margin in peak current condition such a stat−up, AC drop test for load transient conditions.

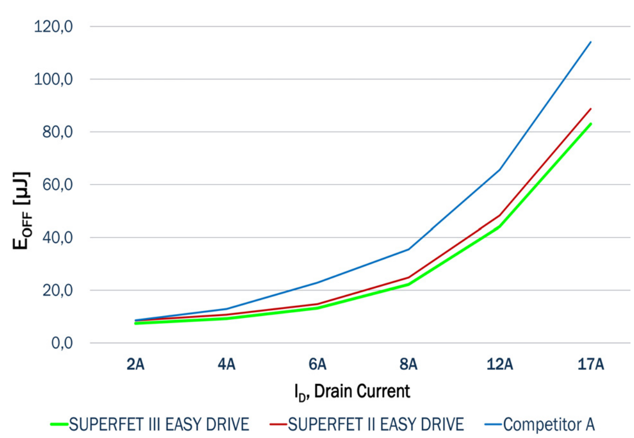



**Figure 11. Comparisons of Turn−off Switching Loss, $E_{OFF}$: 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and Competitor under $V_{DD}$=380 V, $V_{GS}$=10 V, $R_G$=4.7 Ω**

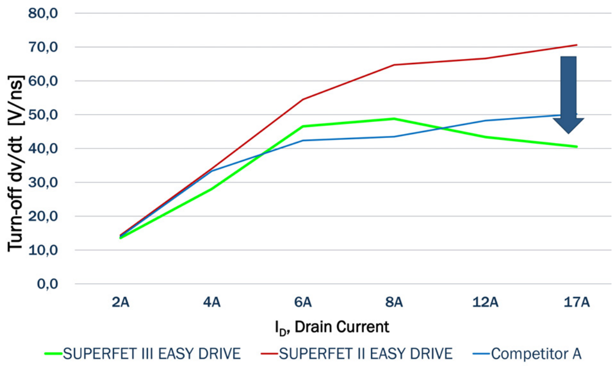



**Figure 12. Comparisons of Turn−off dv/dt: 190 mΩ SUPERFET III Easy Drive, SUPERFET II Easy Drive and Competitor under $V_{DD}$=380 V, $V_{GS}$ = 10 V, $R_G$ = 4.7 Ω**

### Efficiency Comparison in 460 W CCM PFC in Server Power Supply

As referring to the key parameter comparison, SUPERFET III Easy Drive has lower $E_{OSS}$, switching loss, smaller $Q_G$. 460 W server power supply is used to compare the efficiency of the SUPERFET III Easy Drive vs. SUPERFET II Easy Drive and competitor. Input voltage is 110 $V_{AC}$ and switching frequency is 65 kHz and gate resistor for turn−on is 10 Ω and turn−off is 5.1 Ω. The efficiency measurements are shown in Figure 13. SUPERFET III Easy Drive shows the best efficiency over the whole load range (0.1~0.16%).

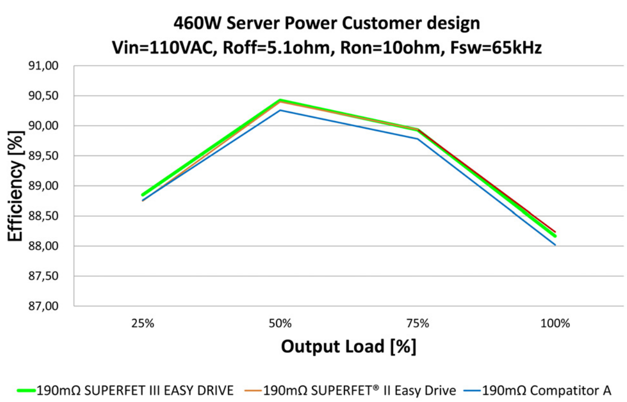



**Figure 13. Efficiency Comparisons between 190 m Ω SUPERFET III Easy Drive, SUPERFET II Easy Drive and Competitor in a 460 W Server power Customer Design**

### Efficiency Comparison in 3 kW Bridgeless PFC in Telecom Power Supply

Figure 14 shows the efficiency comparison for a 3 kW bridgeless PFC in telecom power supply with $V_{in}$=230 Vac, and switching and $F_{SW}$=90 kHz. SUPERFET III Easy Drive offer 0.13~0.29% efficiency benefits over whole load range thanks to lower $E_{OSS}$ and turn−off switching loss and conduction loss.

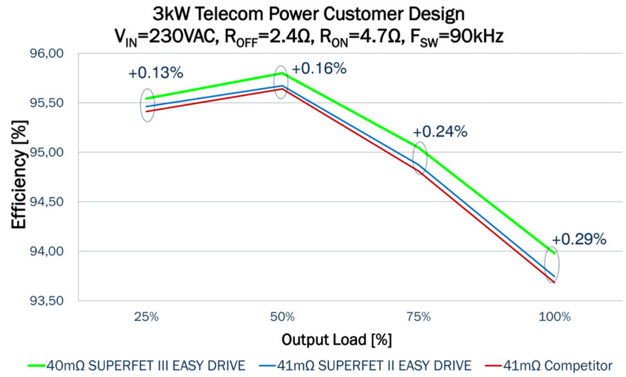



**Figure 14. Efficiency Comparisons between 40 mΩ SUPERFET III Easy Drive, 41 mΩ SUPERFET II Easy Drive and 41 mΩ Competitor in a 3 kW Telecom power Customer Design**

### SUPERFET III Easy Drive R0 Series

SUPERFET III Easy Drive has an integrated gate resistance in order to achieve reduce switching dv/dt and di/dt for better EMI and ease of use, but drawback of high $R_G$ value is reducing system efficiency. SUPERFET III Easy Drive R0 is developed to support applications need higher efficiency.

### Performance and benefits for SUPERFET III Easy Drive and Easy Drive R0 version

Table 3 shows performance trade−off between SUPERFET III Easy Drive and Easy Drive R0. In case of the 190 mΩ, SUPERFET III Easy Drive has 7 Ω and shows relatively lower turn−off dv/dt, but higher turn−off switching loss. To achieve maximum efficiency, we recommend to use very small external gate resistors for SUPERFET III Easy Drive. SUPERFET III Easy Drive R0 removes the internal gate resistance and offer lower switching losses for better system efficiency as shown in Figure 15 and 16.

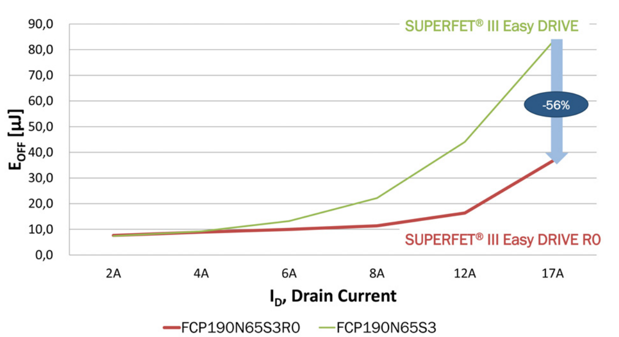



**Figure 15. Comparisons of Turn−off Switching Loss, $E_{OFF}$: 190 mΩ SUPERFET III Easy Drive, Easy Drive R0 under $V_{DD}$ = 380 V, $V_{GS}$ = 10 V, $R_G$ = 4.7 Ω**

The faster switching of the power MOSFETs enable higher power conversion efficiency. However, parasitic components in the devices and boards are involving switching characteristics more as the switching speed is getting faster.

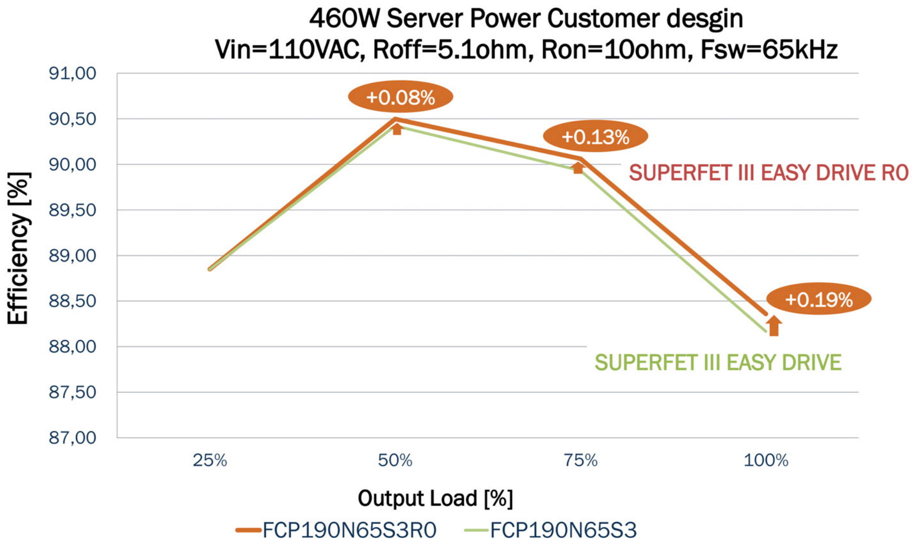



**Figure 16. Efficiency Comparisons between: 190 mΩ SUPERFET III Easy Drive, Easy Drive R0 in a 460 W Server Power Customer Design**

**Table 3. Performance Trade–off and Benefits Between SuperFET III Easy Drive and Easy Drive R0**

| | Easy Drive version | Easy Drive R0 version |
|---|---|---|
| Performance | Slow switching @Turn off<br>→Low peak Vds<br>→Low dv/dt and Gate Oscillation | Fast switching @Turn off<br>→Faster Switching<br>→Lower switching loss |
| Benefit | Better EMI | Better system efficiency |

| | Easy Drive version – FCP190N65S3 | Easy Drive R0 version – FCP190N65S3R0 |
|---|---|---|
| Internal Rg | 7 Ω | 0.5 Ω |

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