Application-Specific MOSFETs

Sampat Shekhawat, Bob Brockway, and BongJoo Choi

Abstract: MOSFETs, like other power devices, are making major direction changes and taking distinct bifurcated approaches. The first is innovations to improve the silicon and process technologies to overcome the limitations of the current technologies and the other is packaging these devices. These MOSFETs target multiple markets; including DC/DC, offline AC/DC, motion control, uninterruptible power supply (UPS), solar inverter, welding, steel cutting, switched-mode power supply (SMPS), solar/wind power, Electric Vehicle (EV) battery chargers, etc. The demand for electricity is increasing and, at the same time, the cost of power generation is also going up. There is increasing pressure on utility companies from government agencies to reduce harmful gas emissions. This is forcing equipment designers to increase efficiency and performance. Government agencies are setting up minimum efficiency requirements. This forces device designers to create application-specific MOSFETs with unique topology variations. In all these topologies, device parameters play a vital role in improving circuit efficiency and performance. Fairchild Semiconductor provides application-specific MOSFETs for various applications, as discussed in the following sections.

I. INTRODUCTION

Thyristor and Bipolar Junction Transistors (BJT) were the only power switches until the MOSFET was introduced in the late 1970s. The BJT is a current-controlled device; whereas the MOSFET is a voltage-controlled device. In the 1980s, the IGBT was introduced, which is also a voltage-controlled device. The MOSFET is a positive-temperature-coefficient device, whereas the IGBT may or may not be a positive-temperature-coefficient device. The MOSFET is a majority carrier device, making it ideal for high-frequency applications. Inverters, which change DC to AC electricity, can be operated at ultrasonic frequencies to avoid audible noise. The MOSFET also has high avalanche capability compared to the IGBT. Operating frequency is important in choosing a MOSFET. The IGBT has a lower clamping capability compared to the equivalent MOSFET. DC bus voltage at the inverter input, power rating, power topology, and frequency of operation must be considered when choosing between an IGBT and a MOSFET. An IGBT is generally used for 200V and above applications; whereas the MOSFET can be used in applications from 20V to 1000V. While Fairchild has 300V IGBTs, the MOSFET switching frequency is much higher than that of an IGBT. Newer MOSFETs have lower conduction loss and switching loss and are replacing IGBTs in medium-voltage applications up to 600V. Engineers who design Alternate energy power systems, UPS, Switched-Mode Power Supply (SMPS), and other industrial systems are continuously trying to improve the efficiency at light and full load, power density, reliability and dynamic performance of these systems. Wind power is among the fastest growing sources of energy generation and an application example is the wind mill flap control; in which large numbers of MOSFETs are used. Application-specific MOSFETs help achieve these improvements by catering to the different application requirements.

Other near-future applications that will require new and specific MOSFET solutions include easily installed EV charging systems for the home garage and business parking lots. These EV-charging systems will be operated by both PV solar systems and the utility grid. Wall-mounted EV-charging stations must be fast charging. Photo Voltaic (PV) battery charging stations will become important for telecom power too.

Three-phase motor drive and UPS inverters need the same types of MOSFETs, but PV solar inverters might need different MOSFETs, such as UltraFET MOSFETs and regular body diode MOSFETs. In recent years, there have been massive investments in PV solar generation. Most of the growth was initiated by residential solar projects; however, larger commercial projects are now surfacing. Events like the price of poly-silicon dropping from $400/Kg in 2007 to $70/Kg in 2009 enable tremendous market growth.

The grid-tie inverter, which is becoming popular, is a special inverter that converts DC to AC electricity and feeds into an existing utility (electrical) grid. The DC source can be generated by renewable sources, such as small or large wind mills or PV solar panels. This inverter is also known as a “grid interactive” or "synchronous" inverter. Grid-tie inverters only operate when they are tied to the grid. The inverters available on the market today are designed with different topologies, depending on the design trade-offs required. Standalone inverters are designed differently to supply power at unity, lagging, or leading power factor.

Market demand for PV solar systems already exists for the following reasons:

1. Solar can help to reduce high peak power cost
2. It can eliminate the volatility of fuel costs
3. Solar adds more power to the utility grid
4. Can be promoted as "green" energy

The US administration has established a goal of generating 80% of the nation's electricity from green energy sources. The reasons listed above, coupled with the US administration goal, have made PV solar solutions a growing market. This results in a growing demand for MOSFETs. If MOSFETs in different topologies are optimized, the end product solution is able to achieve significant improvements in efficiency.

High switching frequency applications require the reduction of parasitic capacitances of the MOSFET at the expense of R_{DSON}. Low-frequency applications, however, require the reduction of R_{DSON} as the highest priority. MOSFET body diode recovery is not important for single-ended applications, but becomes very important for double-ended applications because they require low t_{RR}, Q_{RR}, and softer body diode recovery. In soft-switched double-ended applications, these requirements are crucial to reliability. In hard-switched applications; as the operating voltage increases, turn-on and turn-off loss increases. To reduce turn-off loss, C_{RSS} and C_{OSS} are optimized against R_{DSON}.

MOSFETs support ZVS (Zero Voltage Switching) and ZCS (Zero Current Switching) topologies; whereas IGBTs support only ZCS topologies. Generally, IGBTs are used for high-current and low-frequency switching; whereas MOSFETs are used for low-current and high-frequency switching. Mixed Mode simulation tools can be used to design application-specific MOSFETs. Advances in silicon and trench technology have reduced on-resistance (R_{DSON}) and other dynamic parasitic capacitances; while improving body diode recovery of the MOSFETs. Package technology also plays a role in these application-specific MOSFETS.

II. INVERTER SYSTEMS

DC-to-AC inverters are widely used for motor drive, UPS and green energy systems. In general, high-voltage and high-power systems use IGBTs; but for LV, MV, and HV (12V to 400V input DC bus), MOSFETs are generally used. MOSFETs have gained popularity in high-frequency DC-to-AC inverters for solar inverters, UPS inverters, and motor drive inverters. In some applications for DC bus voltage greater than 400V, HV MOSFETs are being used for low-power applications. MOSFETs have an intrinsic body diode with very poor switching characteristics, which generally contributes high turn-on loss in the complimentary MOSFET of the inverter leg. In single-switch or single-ended applications, such as PFC or forward or flyback converters, the body diode is not forward biased and its presence can be ignored. The low carrier frequency inverter is burdened by size, weight, and cost of the additional output filter. The advantage of the high carrier frequency inverter is a smaller and lower-cost low-pass filter design. MOSFETs are a perfect fit for these inverter applications because they can operate at higher switching frequencies. This reduces Radio-Frequency Interference (RFI) because the switching frequency current component circulates within the inverter and output-filter, thereby eliminating the flow outside.

MOSFET Requirements for Inverter Applications

1. The specific on resistance (R_{SP}) should be low to reduce conduction loss. The device-to-device R_{DSON} variation should be less, which serves two purposes: a) DC component at the inverter output is less and this R_{DSON} can be used for current sensing to control abnormal conditions (mostly in low voltage inverters); and b) The low R_{SP} reduces the die size for the same R_{DSON}, which results in reduced cost.
2. The Unclamped Inductive Switching (UIS) should be acceptable when die size is reduced. The MOSFET cell structure should be designed with good UIS and should not be compromised too much. Generally, modern trench MOSFETs have good UIS for the same die size compared to planar MOSFET. Thin die reduces thermal resistance (R_{thJC}). In this case, lower Figure Of Merit (FOM) can be expressed as:

$$R_{SP} \times R_{thJC} / UIS \qquad (1)$$

3. Good Safe Operating Area (SOA) and lower transconductance.
4. Marginally low gate-to-drain capacitance, C_{GD}, (Miller charge), but low C_{GD}/C_{GS} ratio is needed. The moderately high C_{GD} helps reduce EMI. Very low C_{GD} increases dv/dt and, hence, EMI. The low C_{GD}/C_{GS} ratio reduces the chance of shoot-through. These inverters do not operate at high frequency, so some increase in gate ESR can be allowed. Since these inverters operate at medium frequency, some higher C_{GD} and C_{GS} may be allowed.
5. Lower C_{OSS} to reduce switching loss, even though the operating frequency is relatively low in this application. Some increase in C_{OSS} may be acceptable.
6. Sudden changes in C_{OSS} and C_{GD} during switching can cause gate oscillations with high overshoot, which can damage the gate over time. In this case; high source-to-drain dv/dt can become a problem.
7. High gate threshold voltage (V_{TH}) for better noise immunity and better paralleling of MOSFETs. V_{TH} should be more than 3V.
8. Body diode recovery: Softer and faster body diode with low reverse-recovery charge (Q_{RR}) and low reverse recovery time (t_{RR}) is needed. At the same time, softness factor S (Tb/Ta) should be greater than one (1). This reduces diode recovery, dv/dt, and shoot-through likelihood in the inverter. Snappy body diodes can cause shoot-through and high voltage spike problems.
9. In some cases, high (I_{DM}) pulsed-drain-current capability is needed to provide high (I_{SC}) short-circuit current immunity, high output filter charging current, and high motor starting current.
10. Controlled turn-on and turn-off, dv/dt, and di/dt of the MOSFET to control EMI.
11. Reduced common-source inductance by using more wire bonds on the die.

This paper discusses the characteristics of the fast-body diode MOSFET. In this technology, the life time of the body diode is killed, thereby reducing t_{RR} and Q_{RR}, which yields a MOSFET with a body diode similar to an epitaxial diode. This fast-body diode property makes this MOSFET an excellent choice for high-frequency inverters for various applications, including solar inverters. In the case of the inverter leg, the diode is forced to conduct in the forward direction by reactive current which makes its properties more important. A regular MOSFET's body diode generally has a long reverse recovery time and high Q_{RR}. If this body diode is forced to conduct when the load current is commutated from the diode to the complementary MOSFET in the inverter leg; a large current is drawn from the power supply for the whole duration of t_{RR}. This increases the power dissipation in the MOSFETs and reduces the efficiency. Efficiency is very important, especially in the case of solar inverters. A snappy body diode can also introduce a momentary shoot-through condition; e.g. when it recovers with high dv/dt, displacement current in the Miller capacitance can charge the gate above V_{TH} while the complimentary MOSFET is trying to turn-on. This may cause a momentary short circuit across the bus voltage, increasing power dissipation and causing MOSFET failure. To avoid this, an external SiC or regular silicon diode is connected in anti-parallel with the MOSFET. Since the MOSFET body diode has a low forward voltage, a Schottky diode must be connected in series with the MOSFET. In addition, an anti-parallel SiC must be connected across this MOSFET and Schottky diode combination *(see Fig. 1)*. When the MOSFET is reversed biased, the external SiC diode conducts and the series-connected Schottky diode does not allow the MOSFET body diode to conduct. This type of arrangement has become very popular in solar inverters to improve efficiency, but adds cost.

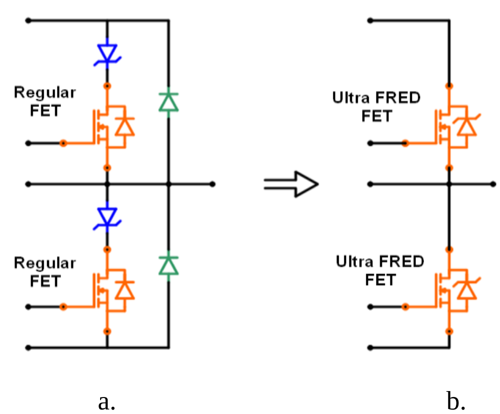

Fig. 1. Ultra FRFET® Replaces Deactivated Regular FET Body Diode in Inverter Leg

Fairchild Semiconductor's UniFET™ II with FRFET® is a high-voltage MOSFET technology power device that fits the applications listed above. The UniFET™ II die size is reduced as a result of reduced R_{SP} compared to UniFET, which also helps improve body diode recovery. There are two versions available: F-type, FRFET with moderately good body diode, and U-type, FRFET with the lowest Q_{RR} and t_{RR} on the market. The U type can eliminate SiC and Schottky diodes in the inverter leg, while achieving the same efficiency and reducing cost. Fig. 4 shows the efficiency comparison of the U-type FRFET, standard MOSFET configuration (as shown in Fig. 1b) and the SiC configuration (as shown in Fig. 1a). Fig. 2 shows diode recovery comparison between the FRFET U-type UniFET II and regular UniFET II. In this case, Q_{RR} has been reduced from 3100 nC to 260 nC and diode switching loss is drastically reduced.

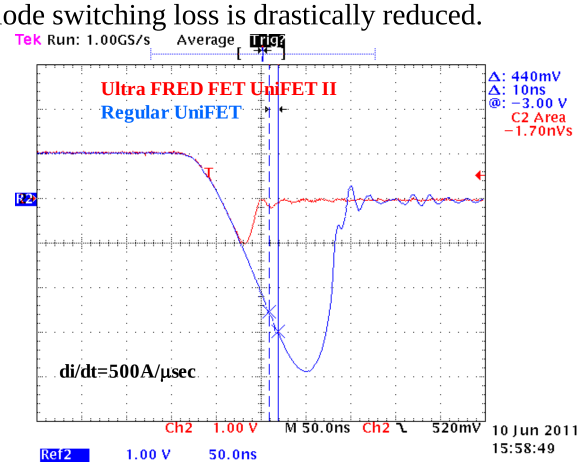

Fig. 2. **Body Diode Recovery Comparison of UniFET™ II Ultra FRFET and Regular UniFET™ II**

Fig. 3 shows how much turn-on loss can be reduced using the U-type FRFET; about 75% compared to the standard UniFET II MOSFET. Turn-on propagation delay, current, and voltage ringing are reduced and the conduction loss of the series Schottky diode is eliminated. The UniFET II also has lower C_{OSS} compared to UniFET, so switching loss is reduced.

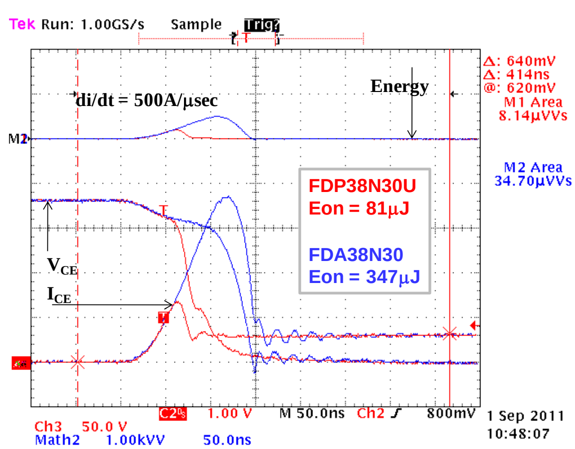

Fig. 3. **Turn-On Comparison of Standard MOSFET and FRFET® U-Type UniFET™ of Same Die Size**

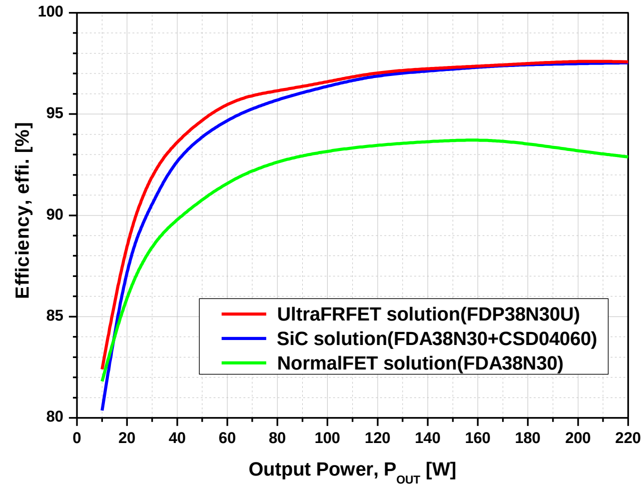

Fig. 4. **Efficiency of U-Type FRFET® in Solar Inverter vs. Standard MOSFET and SiC solution (SiC Diode as FWD)**

III. BATTERY-POWERED OFFLINE UPS INVERTERS

In medium-voltage applications, Fairchild's PT3, PT5, and PT7 MOSFET technologies are attractive solutions for this type of inverter.

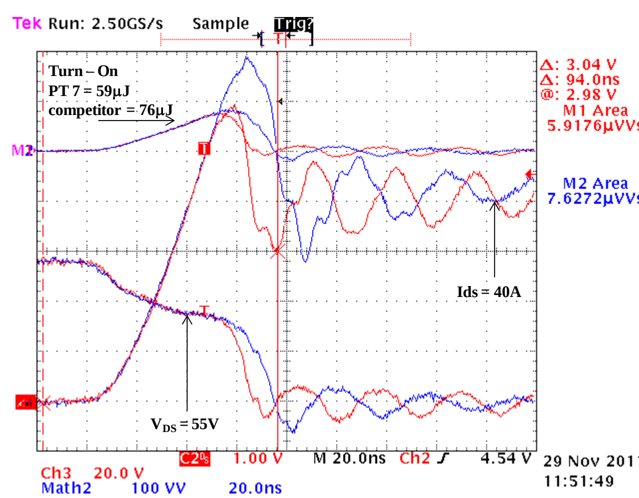

Fig. 5. **PT7 and Competition's best 80V MOSFET at Turn-On**

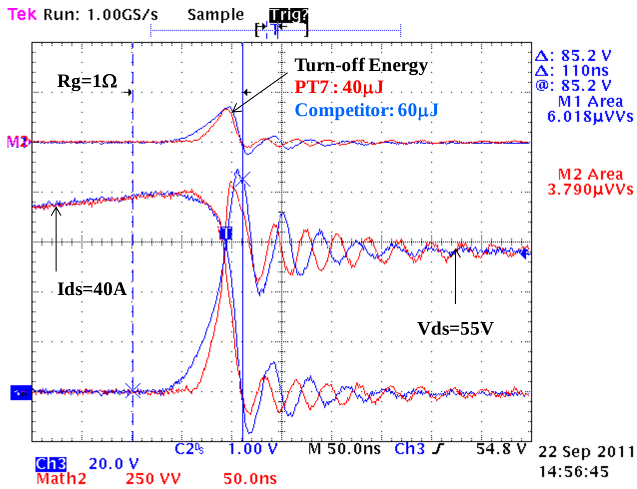

Fig. 6. PT7 and Competition's best 80V MOSFET at Turn-Off

Fig. 5 and Fig. 6 show Fairchild's PT7 MOSFET technology switching performance in an inverter application using the FDP023N08. It has about 30% lower turn-off energy when compared to the best MOSFET available on the market, as shown in Fig. 6. At the same time, turn-on loss is about 20% lower compared to same MOSFET, as shown in Fig. 5. The body diode has lower t_{RR} and Q_{RR}. Per Table 1, low Q_{GD}/Q_{GS} ratio improves inverter reliability. This MOSFET technology supports offline UPS inverters.

IV. SMPS MARKET

The Switched-Mode Power Supply (SMPS) industry is experiencing revolutionary developments in increased power density, efficiency, and reliability due to improved power circuit topologies and concepts combined with improved low-loss power devices. Phase-Shifted, Pulse Width Modulated, Zero-Voltage-Switched, Full-Bridge (PS-PWM-FB-ZVS) and LLC resonant converter topologies utilizing FRFET as power switches achieve these goals. LLC resonant converter is generally used for lower-power applications and PS-PWM-FB-ZVS for higher-power applications.

These topologies have the following advantages:

- Reduced switching loss
- Reduced EMI
- Reduced MOSFET stress compared to quasi-resonant topologies
- Reduced heat sink size and transformer size due to increased switching frequency, which increases power density

MOSFETs Requirements for Phase-Shifted-Full Bridge PWM-ZVS Converter and LLC Resonant Converter Applications:

1. Fast and soft body diode MOSFET with lower t_{RR} and Q_{RR} and optimized softness. This increases dv/dt and di/dt immunity and lowers the diode voltage spike and increases reliability.
2. Low Q_{GD} and Q_{GD} to Q_{GS} ratio. At light-load, hard switching occurs and high CGD*dv/dt could cause shoot-through.
3. Low and distributed internal ESR of the gate is good for ZVS turn-off and uneven current distribution during turn-off and turn-on.
4. Low C_{OSS} extends ZVS switching at light load. At light load, where ZVS switching changes to hard switching, low C_{OSS} reduces hard switching losses.
5. This topology is operated at high frequency, which requires an optimized, low-C_{ISS} MOSFET.

FRFET® UniFET™ II and SupreMOS® are recommended for the above applications. Regular MOSFET body diode can cause failure. For example: SupreMOS FRFET (FCH47N60NF) is suitable for this topology because both t_{RR} and Q_{RR} have been improved. In addition, the snappy diode, which can cause failure, has been improved.

V. OFFLINE AC/DC

Traditionally, the AC source is rectified into a large capacitor filter and current is drawn from the source in narrow high-amplitude pulses; this stage forms the front end of the SMPS. The high-amplitude current pulses produce harmonics that can cause severe interference with other equipment and reduce the maximum power that can be drawn. Distorted line voltage causes overheating of capacitors, dielectric stress, and over-voltage in insulation. Distorted line current increases distribution losses and reduces available power. Utilizing power factor correction ensures compliance with regulatory specifications, reduces component failure due to the stresses mentioned above, and improves device efficiency by increasing the maximum power that can be drawn from the source.

Power factor correction refers to the process by which the input is made to look more like a resistor. This is desirable because the resistor has a unity power factor, compared to the typical SMPS power factor values of 0.6 to 0.7. This allows the power distribution system to operate at maximum efficiency.

Power Factor Control Boost Switch Requirements

1. Low Q_{GD} x R_{SP} Figure Of Merit (FOM). Q_{GD} and C_{GD} are known to affect switching speed. Low C_{GD} and Q_{GD} reduces switching loss. Low R_{SP} reduces conduction loss.
2. Low C_{OSS} reduces turn-off loss for hard switching and ZVS switching.
3. Low C_{ISS} reduces gate drive power since PFC is generally operated at a frequency above 100KHz.
4. Immunity to high dv/dt capability for reliable operation.
5. High gate threshold voltage (V_{THGS}) (3 ~ 5 V) helps if MOSFET paralleling is required and provides immunity against re-applied dv/dt condition.
6. Sudden changes in parasitic capacitances of the MOSFETs during dynamic switching can cause gate oscillations that increase the gate voltage. This can affect the long-term reliability.
7. Gate ESR is important because high ESR can increase turn-off loss, especially in ZVS topologies.

For this application, UniFET™, UniFET™ II, regular SuperFET®, and SupreMOS® MOSFETs are recommended. The FCH76N60N is one of the lowest $R_{DS(ON)}$ super junction MOSFETs in a TO-247 package on the market. Design engineers can increase efficiency and power density by using SupreMOS technology. FCP190N60 is the latest addition to the SuperFET II family of MOSFETs. R_{SP} has been improved by one third compared to the SuperFET I, making it ideal for offline AC-DC applications.

Secondary-Side Synchronous Rectification:

Synchronous rectification is also known as “active” rectification, where the diode is replaced by a MOSFET. It is used to improve the rectification efficiency. Typically, the voltage drop in the diode can vary between 0.7 V and 1.5 V, causing high power loss in the diode. In low-voltage DC/DC converters, this voltage drop is very significant, causing a drop in efficiency. Sometimes Schottky rectifiers are used instead of silicon diodes; however, as voltage is increased, its forward-voltage drop also increases. In low-voltage converters, Schottky rectification does not provide enough efficiency, so these applications need synchronous rectification.

R_{SP} of modern MOSFETs has been reduced significantly and the dynamic parameters of the MOSFETs have been optimized. When the diode is replaced by these actively controlled MOSFETs, synchronous rectification can be active. Today’s MOSFETs can have a couple of milliohms of on-resistance and the voltage drop across the MOSFET can be significantly reduced, even at high currents. This increases efficiency significantly compared to diode rectification. Synchronous rectification is not hard switching; it has a zero-voltage transition in the steady state. During turn-on and turn-off, the MOSFET body diode conducts, which makes the voltage drop across the MOSFET negative and causes C_{ISS} to increase. Because of this soft switching, the gate plateau goes to zero, effectively reducing gate charge..

Below are some of the main requirements for synchronous rectification.

1. Low R_{SP}.
2. Low dynamic parasitic capacitances. This reduces gate drive power since synchronous rectification circuits generally operate at high frequency.
3. Low Q_{RR} and C_{OSS} reduce reverse current, which can be a problem when this topology operates at high switching frequencies. At high switching frequencies, this reverse current acts as a high leakage current.
4. Low t_{RR}, Q_{RR}, and soft body diode are needed to avoid momentary shoot-through and reduce switching losses. Turn-on is zero voltage switching. After the MOSFET channel turns off, the body diode again conducts. When the voltage on the secondary reverses, this body diode recovers, increasing the risk of shoot-through. A snappy diode may need a snubber circuit across each MOSFET.
5. Low Q_{GD}/Q_{GS} ratio.

TABLE 1. COMPARISON OF PT7 VS. BEST COMPETITOR

	C_{ISS} (pF)	C_{OSS} (pF)	C_{RSS} (pF)	Q_{GS} (nC)	Q_{GD} (nC)	Q_{GD}/Q_{GS} (RATIO)	BV_{DSS} (V)
PT7	10600	3300	176	53	22	0.42	80
COMPETITOR	11600	4210	296	46	27	0.59	80

Table 1 illustrates the performance differences between PT7 technology and a leading competitor. R_{SP}, C_{OSS}, C_{RSS}, and Q_{GD}/Q_{GS} ratio are all lower with Fairchild’s PT7 technology. PT7 MOSFETs are recommended for secondary-side active rectification. The PT7 die size is about 30% smaller for the same $R_{DS(ON)}$, which also reduces R_{SP} by 30%, so conduction loss can be reduced in synchronous rectification.

VI. ACTIVE OR-ING

The OR-ing device in its simplest form is a diode. It is a necessary evil that protects its input power source when it becomes faulty by not allowing current to flow into the power source. OR-ing diodes allow current to flow only in one direction. They are used to isolate redundant power sources so failure of one source does not affect the entire system. Eliminating a single point of failure allow the system to keep running with the remaining redundant power source(s). Accomplishing this isolation has problems, however. Once this OR-ing diode is inserted into the current path, extra power loss occurs and efficiency decreases. This power loss causes the OR-ing diode to generate heat, which requires the addition of a heat sink, which reduces the power density of the system. When the diode is turned-off, its reverse recovery becomes an issue; the diode has to be soft. To overcome some of these problems, Schottky diodes have been used. An important difference between these diodes and p-n diodes is the reduced forward voltage drop and negligible reverse recovery. Normal silicon diodes have a voltage drop between 0.7 and 1.7 V; a Schottky diode forward voltage drop is between 0.2 to 0.55 V. While system conduction loss is reduced when a Schottky diode is used as the OR-ing diode, a Schottky diode has high leakage current; which results in conduction loss. The loss is lower than silicon diode.

An alternate solution to this problem is to replace the Schottky diode with a power MOSFET. This introduces an extra MOSFET gate driver with added complexity. The MOSFET R_{DSON} has to be very low so the voltage drop across this MOSFET is much lower than the forward voltage drop of the Schottky diode. This can be called active OR-ing. Modern low-voltage MOSFET R_{DSON} is very low; it can achieve as low as a couple of milliohms even in TO-220 or D^2 packages. Fairchild’s FDS7650 in a PQFN56 package can get less than 1 milliohm for a 30 V MOSFET. When the OR-ing MOSFET is on, it can allow the current to flow in either direction. In the case of a fault, redundant power sources supply heavy current so the OR-ing MOSFET has to be turned-off quickly. Fairchild’s PT7 technology MOSFETs are also suitable for this application. This technology has the lowest R_{SP} in the market, making it excellent for this application.

