

DirectFET™ Power MOSFET Packaging Technology Enables Discrete Multiphase Converter Design Capable of up to 2MHz/phase Operation

Ralph Monteiro, Carl Blake and Jason Chiu
International Rectifier
233 Kansas Street, El Segundo, CA 90245

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Abstract

VRM designers have adopted multiphase topologies for several years now in order to meet the CPU transient response and high current requirements. As the requirements continue to increase, operating frequencies of over 1MHz/phase will not be uncommon. Operating power MOSFET devices at frequencies over 1MHz will pose significant challenges to established power electronic packages such as the DPAK and wirebonded SO-8 devices.

This paper describes the design and performance of a VRM designed using DirectFET™ MOSFETs designed to address this problem. The VRM demonstrated efficiencies above 80% at frequencies of up to 2 MHz/phase and 20A/phase.

I. INTRODUCTION

Next generation microprocessors operate at voltages approaching 1V and escalating frequencies. Current requirements are increasing rapidly, increasing the need for very fast transient response. Transient response has increased from 20A per microsecond to about 325A per microsecond since 1999, and is projected to grow to 400A per microsecond by next year. To address these challenges and shrink the large capacitor banks that would be required, buck converters must operate at frequencies in the 1-2MHz range. At such high frequencies switching losses become critical due to PCB trace inductance and power package parasitics. Various manufacturers have introduced new surface mount packages targeted at reducing package parasitics. One such package is the DirectFET MOSFET from International Rectifier. The unique construction of the DirectFET MOSFET power package offers improvements in both the package parasitics while enabling innovative thermal solutions that reduce footprint size and layout parasitics. This paper discusses the design of a high current VRM capable of operating at up to 2MHz/phase at over 80% efficiency using a discrete design. This has lead industry experts to believe that

only an integrated solution could ever reach such switching frequencies.

II. DIRECTFET MOSFET CONSTRUCTION

DirectFET packaging has a unique construction that provides breakthroughs in package parasitics and heat dissipation capabilities, dramatically increasing efficiency and current carrying capacity of the device.

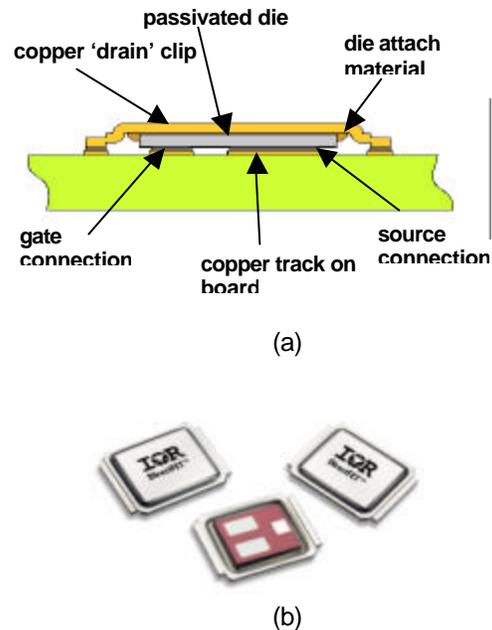


Fig. 1. DirectFET Packaging (a) Cross Section (b) Photograph showing bottom side of passivated die.

Figure 1 shows the DirectFET package applied to a MOSFET die. The silicon die is encapsulated into a copper housing. The bottom of the package consists of a die specifically designed with source and gate contact pads that can be soldered directly to the PCB. A proprietary passivation system on the silicon die isolates the gate and the source pads to prevent shorting and acts as a solder mask when the device

is mounted on the PCB. The passivation layer also protects the termination and gate structures from moisture and other contamination. The copper "can" forms the drain connection from the other side of the die to the board. This design eliminates the lead-frame and wire bonds, reducing die-free package resistance (DFPR) to a mere 0.1mOhm in an SO-8 footprint compared to 1.5 mOhm for the standard SO-8 package.

The large-area contacts combined with the copper housing significantly improve heat dissipation compared to a SOIC plastic molded package: the junction-to-PCB thermal resistance is reduced to 1°C/W, compared to 20°C/W for a standard SO-8 package. The copper 'can' provides a heat sink surface, improving top junction-to-case thermal resistance to 3°C/W compared to 18°C/W for a SO-8.

With the use of heatsinks and cooling air flow, the DirectFET package can dissipate more heat out of the top of the package, reducing junction temperature by up to 50°C compared to the SO-8 solution. Effective top-side cooling means that heat dissipated can be pulled away from the circuit board, increasing the currents that the device can safely carry. High top $R_{th(J-C)}$ explains why standard and derivative SO-8 packages are only used with single-side cooling through the PCB.

III. VRM DESIGN USING DIRECTFET MOSFETS

To demonstrate the benefits of this new packaging technology in a VRM design, a high current 4phase VRM was designed using DirectFET MOSFETs. The board is a 6-layer PCB using 4oz. Copper/layer. The 4-phase controller and the drivers used in the design are capable of operating at up to 2MHz/phase. To enable a small solution footprint, ceramic capacitors were used for both the input and output filter while the inductor is a 400nH high-current, small footprint coil (10mmX10mm).

The low profile of the DirectFET MOSFETs allows the converter design to be configured with the devices on the back of the board and a heat sink to be mounted on top of them while still staying within VRM 9.1 outline specifications. The heat sink is an aluminum finned heat sink measuring in 3.75in x 0.75in. It was attached on top of the DirectFET MOSFETs using an electrically isolating, heat conducting epoxy.

A single high side (IRF6604) and a single low side (IRF6607) DirectFET MOSFET are utilized per phase. To improve efficiency a chip scale packaged Scottky

diode (IR140CSP) was used in parallel with the synchronous FET. The low inductance of the DirectFET package and the chip scale packaged Scottky diode minimizes loop inductance and thus reduces body diode losses during MOSFET dead time. The design is capable of 120A (30A/phase) at high efficiency in a 3.8in x 1.1in footprint at room temperature and with 600LFM airflow. The specifications of the 30V DirectFET control and synchronous FET are shown in TABLE I. Note the high current capability (I_b) of both the devices which eliminates the need to parallel devices.

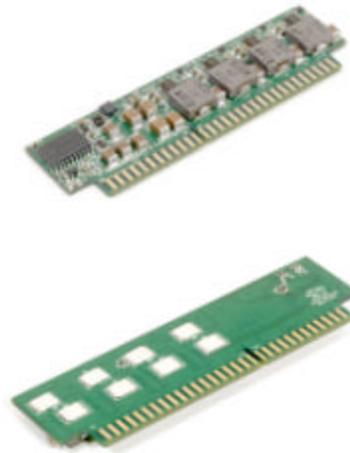


Figure 2. Images of front and rear sides of the 4-phase VRM board with DirectFET MOSFETs shown mounted on the rear side. The heat sink is not shown.

TABLE I: SPECIFICATIONS

Part #	$R_{DS(on)}$ mOhm @10V _{GS}	Q_G (nC)	Q_{GD} (nC)	Q_{GS} (nC)	I_b (A)
IRF6607	2.5	50	16	17	94*
IRF6604	9	17	6.3	5.1	49*

Note: All values typical
?? $T_{CASE} = 25^\circ C$

In-circuit efficiency measurements were made on the module at 500kHz using 600LFM airflow at room ambient. The module achieved 82% efficiency at 120A full load as shown in Figure 3. It is important to optimize gate drive voltage according to the frequency of operation. As can be seen in this case, a gate drive voltage of 7.5V_{GS} for 500kHz operation offers better efficiency at higher load currents than the 5V_{GS} gate drive.

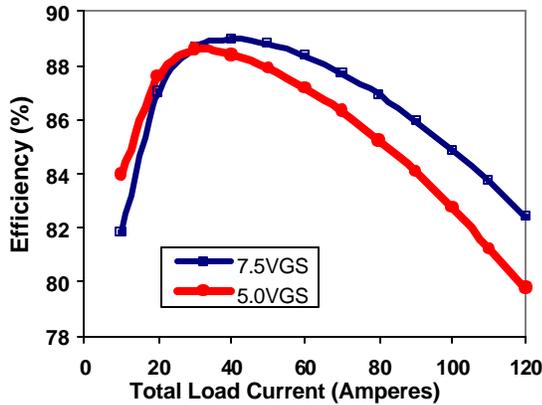


Figure 3. Efficiency at 500 kHz, 12V in, 1.7 Vout, in 1U type VRM using DirectFET MOSFETs with 4 oz copper PCB, 4 Phases with 600LFM airflow.

In order to test the performance of the board at 2MHz/phase, only two phases of the VRM were populated. Figure 4. shows the 2-phase VRM board.

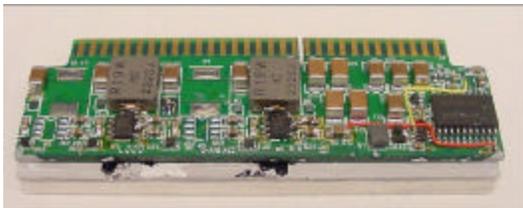


Figure 4. Image showing 2phase 1U VRM design including heatsink attached to underside of board

The efficiency of the 2-phase VRM board was measured in a wind tunnel with 400LFM airflow at 35°C ambient. The efficiency curve obtained is shown in figure 5. As can be seen the VRM achieves over 80% efficiency at up to 25A/phase.

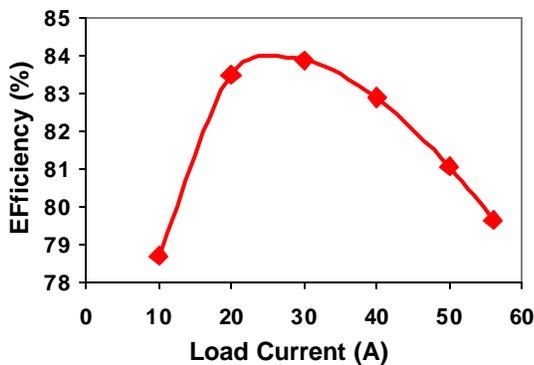


Figure 5. Wind tunnel efficiency measurement on the 2-Phase VRM using DirectFETs. Conditions: 400LFM at 35°C.

IV. IN-CIRCUIT EFFICIENCY COMPARISON OF DIRECTFET AND SO-8 DEVICES

In order to compare the performance of DirectFET MOSFETs versus the SO-8, two identical VRMs were built. One using SO-8s and the other using DirectFET MOSFETs. In both sets of devices tested the silicon technology and active areas were kept near identical. Both circuits containing SO-8 and DirectFET™ devices were cooled using a heatsink attached to the underside of circuit boards. In both circuits an airflow of 400LFM was directed onto the heatsinks during the recording of efficiency data.

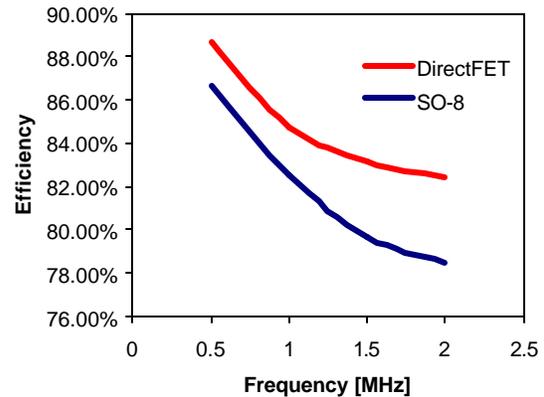


Figure 6. In circuit efficiency data versus frequency for SO-8 and DirectFET packaged silicon in 2-phase 1U VRM with 400LFM airflow switching 20A/phase.

Figure 6 shows the efficiency versus frequency curves of DirectFET™ and SO-8 devices operating in 2-phase, VRM circuits. The efficiency measurements were done at 20A/phase in both cases. The VRM circuits containing DirectFET™ packaged silicon show higher efficiencies than their SO-8 counterparts across the frequency spectrum measured. The difference in efficiency between the two circuits also increases with increasing frequency. This result reflects the reduced package parasitic losses in the DirectFET™ devices relative to those of the SO-8. It should be noted that the DirectFET™ packaged devices were also able to operate under higher load current conditions. For example at 1MHz the DirectFET™ VRM circuits were able to switch up to 30A /phase whilst maintaining a board temperature of less than 100C. SO-8 devices were only able to switch in the region of 20A/phase under identical operating conditions. The higher current handling capability of the DirectFET™ populated VRM circuits is attributable to the combination of lower package parasitics and the increased thermal performance of the DirectFET™ package.

V. COMPARISON OF SO-8 AND DIRECTFET VRM SWITCHING WAVEFORMS

In order to highlight the effect of package parasitics on switching performance, the switching waveforms of the VRM using SO-8 MOSFETs and that of the VRM using DirectFET MOSFETs were observed. Figure 7 shows a captured waveform of an SO-8 device switching 30 amps. A similar waveform captured from a DirectFET™ device switching 30 amps is shown in figure 8.

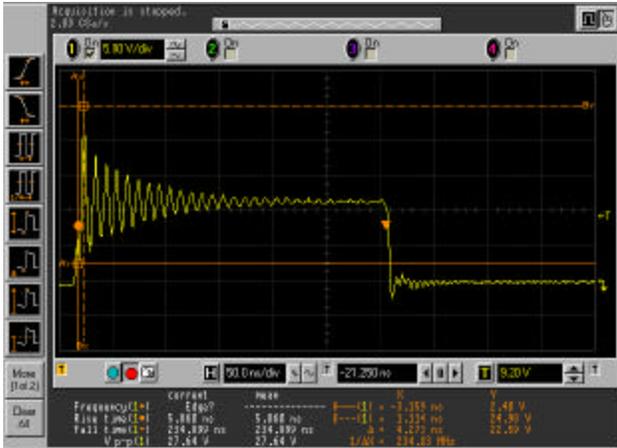


Figure 7. In circuit V_{ds} switching waveforms of SO-8 packaged device

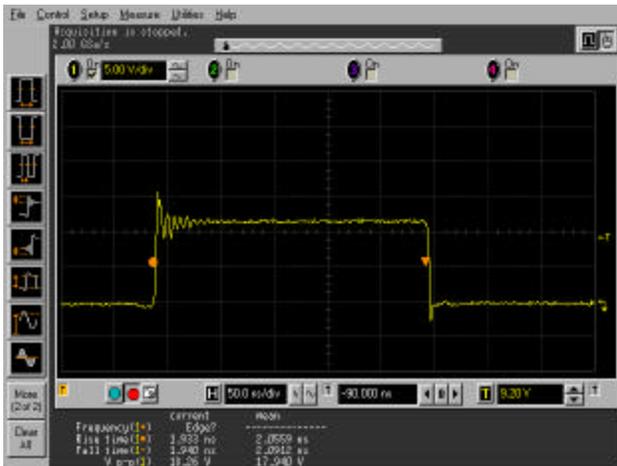


Figure 8. In circuit V_{ds} switching waveforms of DirectFET™ packaged device

Comparing the waveforms in figure 7 and 8 it can be concluded that the DirectFET™ device produces considerably lower peak ringing voltages in circuit than that of the SO-8 device. Since the silicon in both packages is of the same active area and technology, it can be concluded that the difference is purely due to package parasitics. The higher ring for the SO-8

package is due to the fact that the inductance is much higher.

VI. CONCLUSIONS

The VRM designed using DirectFET MOSFETs was shown to be capable of operating at up to 2MHz/phase. Operating VRMs at higher frequencies enables the processor transient requirements to be met with a fewer number of output capacitors, thus saving board space as well as solution cost.

There are several reasons for the success of DirectFET at high frequencies where other discrete packages would struggle. Besides the low package parasitics and thermal resistances, DirectFET MOSFETs offer the top side cooling which allows a much more compact design. This reduces PCB losses and contributes to the high efficiencies obtained at high operating frequencies.