International Rectifier

# Bi-directional FlipFET™ MOSFETs for Cell Phone Battery Protection Circuits

*As presented at PCIM 2001*

**Authors:** *Mark Pavier, *Hazel Schofield, *Tim Sammon, **Aram Arzumanyan, **Ritu Sodhi, **Dan Kinzer

* International Rectifier, Holland Road, Hurst Green, Surrey, RH8 9BB, UK
** International Rectifier, 233 Kansas St., El Segundo, CA, 90245 USA

## Abstract

A bi-directional chip scale power MOSFET device is introduced for use in cell phone battery protection circuits. This device utilises the monolithic integration of two common drain power MOSFETs and solder bump technology to produce an ultra low footprint solution. Battery protection MOSFET packaging technology is reviewed along with cell phone current requirements. Comparisons are drawn between the in circuit performance of the bi-directional device and an industry standard TSSOP8. Device related losses in relation to IC drive strategy and conclusions on the effects of Rdson and package volume on cell phone talk and standby times are presented.

## Introduction

Advances in battery chemistry technology have been one of the key enablers for smaller hand held portable devices. Over the past decade battery technologies have evolved from Nickel based chemistries, such as NiCd and NiMH, to lithium ion chemistries. Whilst lithium ion based chemistries ultimately offer increased gravimetric and volumetric energy densities over their Nickel counterparts, there are potential risks that need to be addressed when adopting Lithium based cells. For example, during overcharge of Lithium ion cells, lithium metal may build up on the cell electrodes. This lithium build-up readily oxidises in air, which is a strongly exothermic reaction and a potential fire risk. Similarly, over-discharge may cause irreparable damage to the cells. The key to preventing these effects occurring is to introduce protection circuitry into the battery pack. These circuits typically contain a control IC, battery protection MOSFETs, and a gas gauge IC to monitor the charge status of the battery pack or cell.

In this paper we examine battery protection MOSFET technologies and demonstrate a new Bi-directional N-channel FlipFET™ device specifically designed for use in battery protection circuits. Typical cell phone power consumption data are presented for talk time and standby mode operating conditions. This data is utilised to compare the in circuit performance of the bi-directional FlipFET™ device with an industry standard dual N-channel TSSOP8 device. In circuit efficiency data are presented along with conclusions on the effects of MOSFET losses on cell phone operating times.

## Battery protection circuits

A variety of circuit topologies exist for lithium ion cell and battery protection. For battery packs containing 2 or more cells these may consist of N or P-channel MOSFETs switching on the negative or positive rail of the battery output terminals respectively. For cell phones, where space is at a premium and typically only one Li-ion cell is used, N-channel switching topologies are more common. The reason for this being that N-channel power MOSFET devices typically have a higher channel mobility and therefore lower Rdson per unit area for a given blocking voltage. A typical cell phone Li-ion battery protection circuit schematic is shown in figure 1. The circuit consists of a protection IC, gas gauge IC and N-channel power MOSFET devices. Depending upon IC used, additional components may also be present such as a current sense resistor, fuse, and temperature sensing elements.

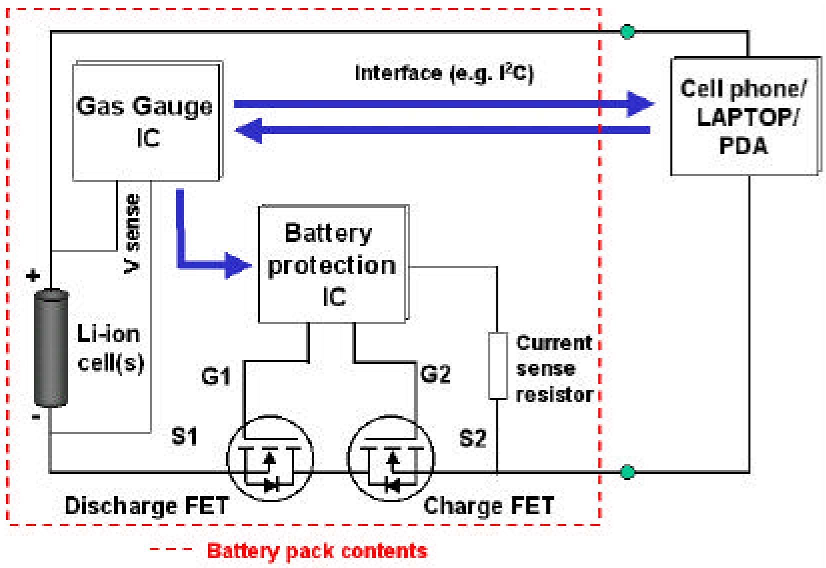


**Figure 1. Li-ion battery protection circuit schematic**

Where charge and discharge control are required the N-channel MOSFET's are normally connected in common drain configuration, as shown in figure 1. The MOSFET whose source is in direct contact to the cells output is referred to as the discharge FET. The FET with its source connected to the load is referred to as the charge FET*.

* Note this terminology also holds when P-channel positive rail switching is adopted.

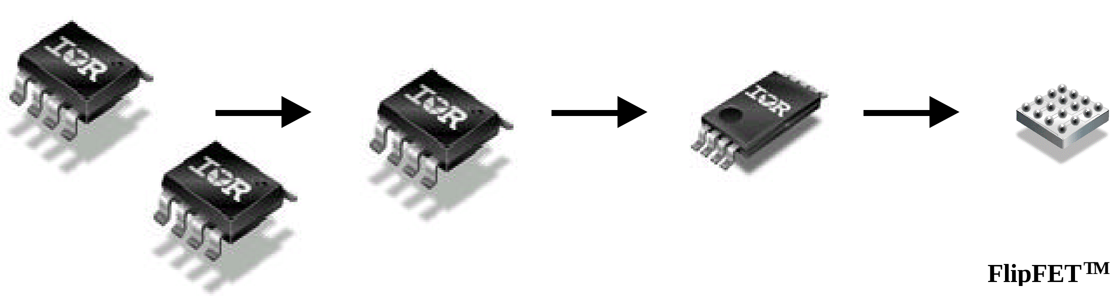
### Discharge mode

Under normal discharge operation the discharge FET is turned on (Vgs1 > Vgth). Whilst the charge FET's body diode is forward biased and able to conduct current during discharge, this FET is also turned on in order to reduce the voltage drop between cell output and load (Vgs2 > Vgth). A lithium ion cell will have a lower limit to which the cell voltage must not fall below to prevent damage to the cell. In most cases the IC will have a pre-set internal under-voltage reference. If the battery reaches this point the discharge FET (and charge FET) turn(s) off, effectively open circuiting the load.

### Charging mode

Lithium ion cells are typically charged using a constant current constant voltage strategy. During charge mode the load is replaced or paralleled with a charger. Under normal charge conditions the charge FET is turned on (Vgs2 > Vgth). The discharge FET's internal body diode will be conducting. In most cases the discharge FET will also be switched on to minimize the voltage drop between the charger and cell (Vgs1 > Vgth). As mentioned in the introduction, overcharge can also damage the cell. If the charge voltage increases past that of the IC's built in voltage reference, the charge FET and, if on, the discharge FET, will be turned off.

**Figure 2. Evolution of MOSFET devices for battery protection circuits**



**2 x Discrete SO-8** | **Dual die SO-8** | **Dual die TSSOP8** | **FlipFET™ New platform**

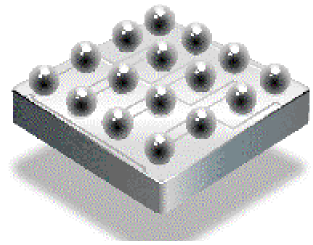


**Figure 3. The bi-directional FlipFET™ MOSFET**

The bi-directional FlipFET™ MOSFET consists of two common drain N-channel power MOSFETs monolithically combined on a single die. Solder bumping technology has been utilised to provide gate and source connections to each MOSFET device [3]. The drain connections are formed internally within the silicon epitaxial layer and substrate. A diagram showing the internal connectivity of the device is shown in figure 4.

**Choice of packaging for battery protection MOSFET devices**

The continuous reduction in power MOSFET cell pitch and improvements in cell technology has lead to silicon with lower specific on resistance. This has enabled designers to reduce the package sizes required for a given power requirement. This trend has been noted in the use of MOSFETs in battery protection circuits. Designers have gradually adopted dual die packages over discrete single die devices in packages such as the SO-8, and have now adopted smaller outline devices such as the TSSOP8. Figure 2 illustrates the trend that has been enabled by improved MOSFET silicon performance.

Whilst the trend in silicon improvement continues, package related losses are becoming more significant. So much so, that in high current designs it is now important to address both the package and silicon contributions to on resistance losses if one is to achieve more efficient devices [1]. Package related resistive losses in SOIC and TSSOP type packages come from the device leads (copper), die attach adhesive (silver loaded adhesive), and gold bond wires connected between die and leads. These can contribute several milli-Ohms to the device on resistance in dual die packages.

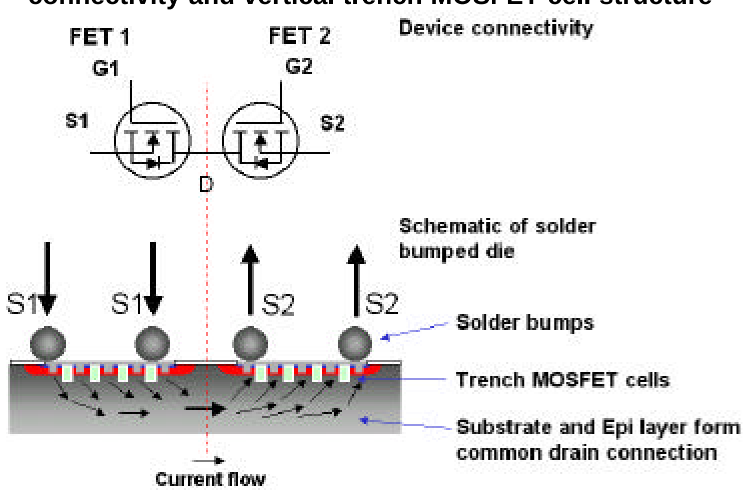
Package leads and encapsulation materials used in TSSOP and SOIC packages also add additional area, weight and volume to the active silicon. For example, in a dual die SO-8 type package the total silicon area will be in the region of 3 to 4 $mm^2$. The total area, or footprint, occupied by the SO-8 package on the circuit board is 30 $mm^2$. The ratio of silicon to footprint is only in the region of 10 to 15%.

In order to produce low $R_{dson}$, area efficient devices, clearly both package footprint and resistance losses due to interconnects must be reduced. This can be achieved using a combination on flip chip and solder bump technologies [2]. IR has previously adopted this technology for single device MOSFETs with significant improvements in die to footprint ratio [3]. Solder bump technology can now be utilised to produce common drain MOSFET devices for use in battery protection circuits.

## Bi-directional FlipFET™ MOSFET

With reference to figure 4 conventional current flow through the device is as follows: when both devices are on, current flows in through the bumps S1, between the MOSFET vertical trench cells into

**Figure 4. Schematic diagram showing dual N-channel MOSFET Bi-directional FlipFET™ connectivity and vertical trench MOSFET cell structure**

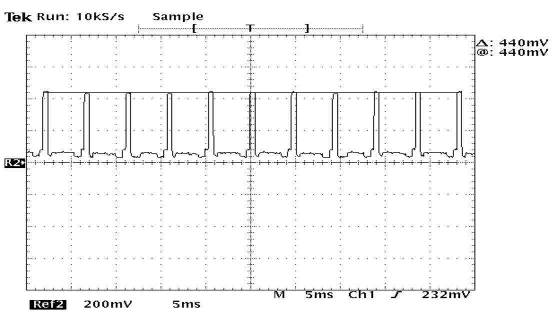


the silicon epi and substrate. Current then flows across the epi and substrate layer and back up through the trench MOSFET cells of device 2, and out of the die through solder bumps S2. Note it is assumed that the potential difference between S2 and S1 is positive, and Vgs1 and Vgs2 are driven on (i.e.Vgs1,Vgs2 >Vgsth). Alternatively if the polarity between S1 and S2 is reversed the device will conduct in the opposite direction. The device therefore exhibits true bi-directionality.

**Understanding cell phone power requirements**

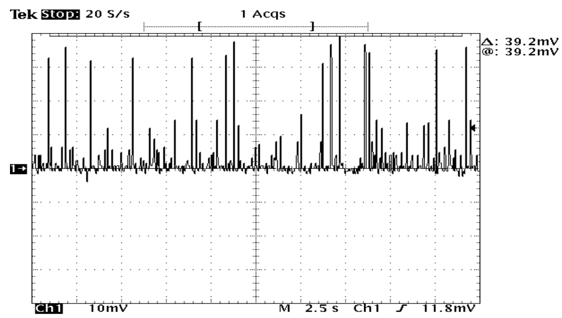
Prior to benchmarking the Bi-directional FlipFET™ device with an industry standard TSSOP8 device, a study on cellphone power requirements was performed. A series shunt resistor was inserted in the ground rail of a dual band cellphone battery operating in Europe. Current waveforms for various modes of operation were recorded using a digital storage oscilloscope. Current waveforms recorded during talk time and standby modes are shown below in figures 5 and 6 respectively.

**Figure 5. Standby mode current waveform**




Waveforms captured from the DSO were averaged to obtain the cellphone current consumption data shown in table 1. With reference to the two waveforms in figures 5 and 6 and table 1, it can be noted that there are significant differences in the phones current consumption during talk and standby modes of operation. During talk time there are periodic current pulses which peak in the region of 1.3A, whilst in standby mode, peak currents are typically in the region of a few hundred mA.

**Figure 6. Talk time current waveform for GSM for GSM cellphone (with network) cellphone**




The average current consumption in talk time is in the region of 370mA. In standby mode current consumption is dependent on whether a network is present or not. With a network present the average current consumption is approximately 13 mA. If the network is absent this current approximately doubles due to increased activity within the phones PA as a network is located.

**Table 1. Summary of dual band cellphone current requirements**

| Mode of operation | DC offset current [mA] | Waveform type | Average current [mA] |
|---|---|---|---|
| **Standby mode with network** | 6 | 10 to 100mA non-periodic pulses<br>20mA periodic pulses @ 217Hz | 13 |
| **Standby mode without network** | 6 | 10 to 100mA non-periodic pulses + 20mA periodic pulses @ 217Hz | 27 |
| **Talk time** | 225 | 1.1 to 1.3A periodic pulses 217Hz,<br>pulse duration 470us | 370 |

## Comparison of Bi-directional FlipFET™ and TSSOP8 in-circuit performance

Demonstration circuits were fabricated to compare the performance of the bi-directional FlipFET™ device and an industry standard TSSOP8 device. Images of the circuits are shown in figure 7. The circuits are based upon a Mitsumi 1491 reference circuit assembled on double sided polyimide flex.
To highlight the effects of Rdson on battery protection circuit efficiency, the two devices where selected to have significant differences in Rdson. Here a 30V TSSOP8 device is compared with a 20V bi-directional FlipFET™ device. The later has approximately half the Rdson of the TSSOP8 device.

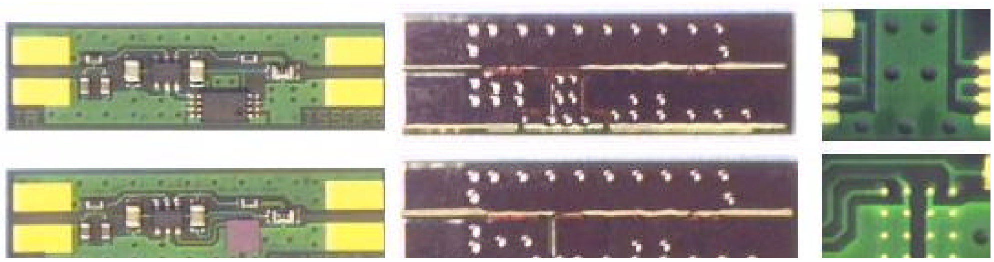
the MOSFETs source terminals, was measured across the two devices as a function of battery voltage under simulated talk and standby mode time conditions.

Examples of talk time Vss versus cell voltage plots are show in figure 8. The Vss of the bi-directional FlipFET™ is an order of magnitude lower than that of the TSSOP8 device. In both data sets the MOSFETs Vss increases with decreasing battery voltage. In the case of the TSSOP8 device the Vss increases more significantly as the battery voltage decreases below 3V. This is a consequence of the IC's linear gate drive with respect to the battery input voltage, and the higher

**Figure 7. Bi-directional FlipFET™ and TSSOP8 demonstration circuits**

**TSSOP8**

**Bi-directional FlipFET™**



**Top side** **Bottom side** **Footprint**

gate threshold voltage of the TSSOP8 device (Vgsth = 1.3V typical compared with 1V for the bi-directional device). In the case of the TSSOP8 device the MOSFETs therefore turn off earlier in the battery discharge cycle than those of the bi-directional device. To reduce

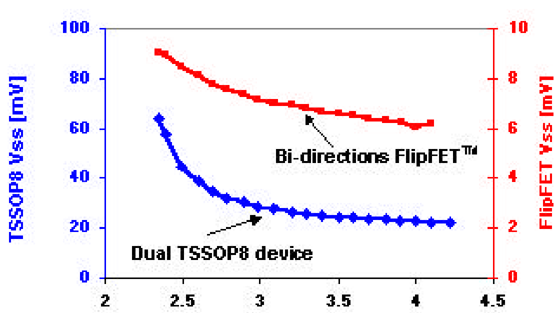
The in circuit efficiency of battery protection MOSFETs can be calculated using the relationship:

$$\text{Efficiency} = \frac{\Sigma\,[(\mathbf{V}c(I,t) - \mathbf{V}ss(I,Vc)) \times I(t)]}{\Sigma\,[\mathbf{I}(t) \times \mathbf{V}c(I,t)]},$$

where Vc(I,t) and I(t) are the cell voltage and current flowing though the MOSFETs respectively. Note that the latter is dependent on both current and time. Vss(I,Vc), the voltage dropped across

losses within the MOSFETs, the Vgth should be selected to ensure the MOSFET channels are fully enhanced over the cells discharge range. The lower gate threshold voltage of the Bi-directional FlipFET™ device is therefore better suited to this application.

**Figure 8. Vss vs. battery voltage for TSSOP8 and Bi-directional FlipFET™ MOSFET devices**




A comparison of the bi-directional FlipFET™ with the TSSOP8 device is shown in table 2. The bi-directional device occupies half the footprint and 70% of the height of the TSSOP 8 device. Whilst the bi-directional FlipFET™ device has only 60% the Rdson of the TSSOP 8 device, the in circuit efficiency is only improved marginally in talk time simulations. In standby mode simulations the effect is negligible with only 0.02% improvement. In terms of cell phone operating times these efficiency improvements equate to a few minutes extra operation at most.

International
IOR Rectifier

**Table 2. Comparison of Bi-directional FlipFET™ and dual TSSOP8 in circuit performance**

| Package: | 30V dual N TSSOP8 | 20V Bi-directional FlipFET™ | % Change |
|---|---|---|---|
| **Footprint [$mm^2$]:** | 19.8 | 9.7 | - 51 |
| **Height [um]:** | 1000um | 720 um | - 28 |
| **Rdson [mOhm] @ Vgs = 2.5V** | 72 | 30 | -58 |
| **Rdson [mOhm] @ Vgs = 4.5V** | 60 | 20 | -67 |
| **Talk time efficiency [%]:** | 99.31 | 99.82 | +0.5 |
| **Standby mode efficiency [%]:** | 99.98 | 99.99 | +0.02 (!) |
| **Talk/Standby times assuming extra volume for energy storage [Hrs]** | 65.6/2 Stby/talk | 70.2/2.2 Stby/talk | +7/+10 Stby/talk |

Significant improvements in cell phone talk and standby mode times come from utilising the extra circuit volume freed up by use of smaller packages to store extra energy. For example if the circuit height is reduced from that of the TSSOP8 to that of the FlipFET™ the improvement in talk time is typically in the region of an extra 10 minutes. In standby mode you can also expect improvements in the region of an extra 4.6 hours. Note that in these calculations it is assumed that the battery protection circuit is positioned on top of the battery pack.

**Conclusions**

An ultra low footprint chip scale packaged bi-directional power MOSFET for battery protection circuits has been demonstrated. A study into the effects of Rdson on battery circuit efficiency has shown that further reducing the power MOSFET Rdson does not significantly improve the battery protection circuit efficiency in this case. Significant improvements in cell phone talk and standby modes are gained from reducing protection circuit volume. This can be achieved by adopting bi-directional chip scale power MOSFET technologies.

**References**


[1] 'Power MOSFETs gain performance refinements', G. Bassak, EE Times. 11/03/99
[2] 'Flip chip technologies', J. Lau, Published by McGraw-Hill. 1995
[3] 'A new generation of Wafer Level Packaged HEXFET Devices', T.Sammon, H. Schofield, A. Arzumanyan, D. Kinzer. P-23 PCIM Europe 2000 Proceedings