Bipolar transistors or MOSFETs?
Making the right choice of power switch

Abstract
The choice of technology for a power switch is not always clear cut. Whilst MOSFETs have become the default choice for many designers, bipolar transistors have many useful attributes which can be used beneficially in certain applications. Understanding the technological and parametric differences between MOSFETs and bipolar transistors is key to making the right choice for a given application.

Introduction

Over the last few years MOSFETs have become the default choice of power switch among power management circuit designers. They have benefited from much technology investment, often from equipment made available from obsolete DRAM fabs. They have enjoyed a high-tech image in the market place, have been widely promoted in colleges and universities, and have enjoyed much publicity in the electronics press.

Over the same period bipolar transistors have come to be considered as ‘old technology’. And yet, away from the spotlight, bipolar transistors have also continued to be developed, and in some applications can be a better choice of power switch than MOSFETs.

Device Characteristics

Given the preponderance of publicity in favor of MOSFETs it is easy to get the impression that MOSFETs are better in all respects than bipolar transistors. Comparing typical device datasheets it is apparent that they offer different characteristics which, if understood, can be exploited to maximize system efficiency and performance. A brief discussion of the significant characteristics is therefore presented, followed by some example applications where bipolar transistors can be advantageously employed.

On-state Resistance and Blocking Voltage

In recent years Trench MOSFETs have been developed, which removed the lateral current flow in the channel region in planar DMOS devices and eased the current concentration between neighboring cells (the so-called J-FET effect). On-resistances have been dramatically cut, particularly in the low-voltage range. Nevertheless current flow is concentrated in narrow channel regions and in low voltage devices the resultant channel resistance dominates the device on-resistance. Consequently, recent developments in low voltage MOSFET technology have sought to increase channel density by reducing lateral geometries. Higher voltage MOSFETs (which continue to use planar structures) also suffer from the high resistance of the lightly doped drain region, and according to theory on-resistance typically increases with breakdown voltage according to the relationship

$$\mathbf{R_{DS(on)} \propto BV^{2.6}}$$

Super-junction MOSFETs, which use a vertical resurf technique to reduce the resistance of the drain region, have been developed but these are prohibitively expensive for most applications.

Over the same period bipolar transistors have developed too and given appropriate drive conditions have matched or bettered MOSFETs in terms of die area specific on-state resistance (see figure 1). By careful optimization of process and chip layout, voltage biasing and current flow (conducted by carriers of both polarities) is evenly distributed across the chip area, leading to better silicon utilization. Furthermore, when a bipolar transistor is operated as a saturated switch the collector base junction becomes forward biased and results in minority carrier injection into the resistive collector region as the collector-emitter voltage collapses to its $V_{CE(sat)}$ value. This injection of minority carriers causes a corresponding increase in the majority carrier concentration in order to maintain charge neutrality, thereby significantly reducing the series resistance of the collector. No such conductivity modulation mechanism is present in MOSFETs and from this derives one of the bipolar transistor's advantages.

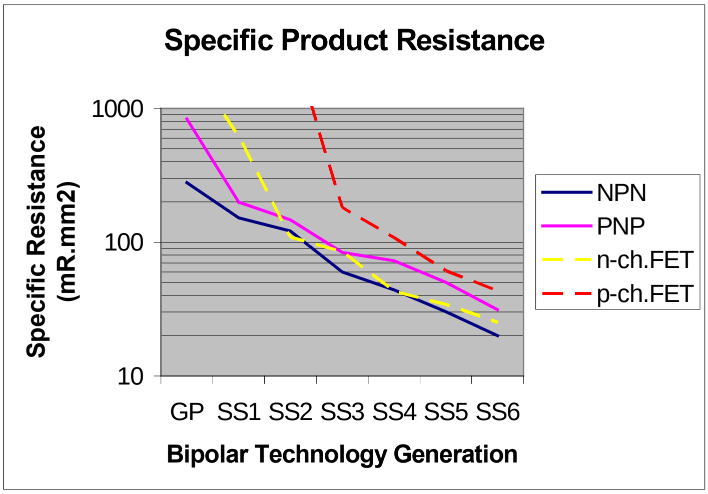

Figure 1. Specific on-resistance (20V devices)

Comparing the relationship between BV and $R_{CE(sat)}$ for Zetex' Gen3 range we find

$$\mathbf{R_{CE(sat)} \propto BV^2}$$

and this is demonstrated by the straight line plot in figure 2.

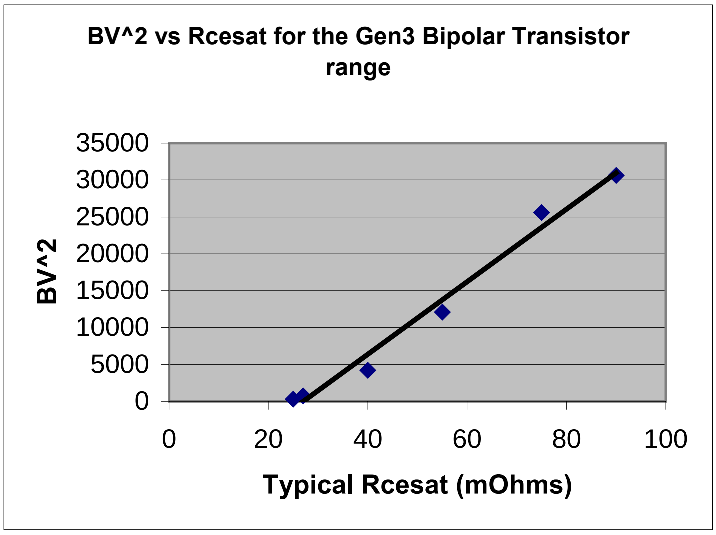

Figure 2. Breakdown voltage verses $R_{CE(sat)}$ for the Zetex Gen3 transistor series.

The effect of these different exponential values is to increase the specific area resistance advantage that the bipolar transistor has over MOSFETs at low voltages, as breakdown voltage increases. For example the FMMT459 450$V_{(CEO)}$ SOT23 packaged NPN transistor has a current capability of 150mA and a typical $R_{CE(sat)}$ of just 1.4Ω. In contrast similarly voltage-rated MOSFETs have such high specific on-resistance and poor current capability that they are only available in larger die sizes requiring packages such as DPAK or TO220.

A further attribute of bipolar transistors is the ability to block voltage in two directions, specified as a BV_{EBO} or BV_{ECO} characteristic. Provided they are high enough this ability can eliminate the need for a series diode or back-to-back pair of MOSFETs with their attendant forward losses, where bi-directionality is required.

Current Capability

An important factor in determining the current capability of a power switch is how the resistance varies with temperature. In this respect bipolar transistors are generally better than MOSFETs because whilst both share the detrimental effects of lattice scattering on carrier mobility, the gain of the bipolar transistor rises with temperature, thereby reducing the V_{BE} component of $V_{CE(sat)}$. Consequently the rise in $R_{CE(sat)}$ is the net effect of these two mechanisms and generally half that of the MOSFET. This leads to cooler running at high current densities and/or higher continuous currents per die area.

Drive Current, Voltage and Power

The drive requirements are arguably where the technologies differ most. When comparing performance and suitability of bipolar transistors and MOSFETs one has to be careful what conditions are specified. For example, bipolar transistors require sufficient base current to achieve the lowest $R_{CE(sat)}$ values, and when calculating power losses the base drive loss must be taken into account. High gain devices have been developed to minimize these losses.

Bipolar transistors require less than 1 volt to fully turn on, which combined with better temperature stability can be useful in low voltage applications, for instance when driven from a single battery cell.

MOSFETs require gate current only to charge and discharge the gate capacitance so under dc drive conditions the drive current is negligible. However, the gate drive voltage is critical to achieve the lowest $R_{DS(on)}$, and resistance dramatically increases as drive voltage approaches the gate threshold voltage.

Consequently, in the comparison of specific resistance shown in Figure 1 the highest practical values of drive current and voltage were chosen to give the fairest comparison.

Switching Speed

MOSFETs, being majority carrier devices, can switch very quickly (100's of kHz to over a MHz) given a sufficiently high current drive circuit. It is in this very application of driving power MOSFETs that bipolar transistors have been most beneficially used, exploiting their speed when operated in the linear region. However, when operated in the saturation region bipolar power transistors require the supply and removal of stored charge during each switching cycle, resulting in extended turn-off delay times. This has an impact on the practical switching speed of a saturated switch but which has been extended to several hundred kHz by the use of various circuit techniques to either operate the device on the knee of saturation or to actively remove the stored charge.

ESD Sensitivity

MOSFETs are inherently sensitive to ESD because of their thin gate dielectric. Electro-static charge delivered to the gate causes the voltage across the thin dielectric to rise according to its gate capacitance which, if it exceeds the dielectric rupture voltage, results in catastrophic failure. With good assembly housekeeping the potential for failure can be minimized but it always remains a risk. Bipolar transistors are inherently rugged and have no difficulty passing the human body model test.

Price

Whist the cost per silicon area for MOSFETs is generally higher than that for bipolar transistors due to the use of more complex processes employed and more process stages, the gap has closed over the years. Many of the factors discussed here impact the total cost of the circuit and it is by playing to the bipolar transistor's strengths and utilizing its unique attributes that they can be most cost effectively used.

A summary of the key parametric differences of the discussed technologies is presented in Table 1:

Characteristic	Bipolar Transistor	MOSFET
'On' resistance	Excellent - down to half that of the best MOSFET, depending on drive current available.	Good at full enhancement Moderate at low gate drive
Blocking Voltage	Bi-directional blocking capability. BV_{CES} , BV_{CEV} or BV_{CBO} may be appropriate for some applications.	Mono-directional, may require a series Schottky diode or back-to-back MOSFET pair in some applications.
Pulse Current	High	Moderate
Drive Voltage	Less than 1 V	1.8V to 10V, depending on the optimization.
Temperature stability	Excellent: V_{BE}: approx. 2mV per ºC $R_{CE(sat)}$ approx. 0.4% per ºC	Moderate: Vth: approx. 4 – 6mV per ºC $R_{DS(on)}$ approx. 0.6% per ºC
Drive Power	Moderate	DC: excellent; High frequency: moderate
Speed	Linear switch: Very fast Saturated switch: Moderate	Fast
ESD sensitivity	Very rugged	Sensitive
Price per area of silicon	Comparable	Comparable

Table 1. Parametric differences between MOSFETs and bipolar transistors

Applications Example 1: MOSFET gate driving

Power MOSFETs are often presented as voltage driven devices and as such may be mistakenly expected to be driven from any signal source, irrespective of current capability. This may be an acceptable assumption when driving in DC or very low frequency switching applications where fast edge speeds are not important, but increasingly power MOSFETs are used in switching circuits of hundreds of kHz to 2MHz and in these circumstances the gate charge requirements are a major consideration. The charge necessary to fully enhance a power MOSFET derives from its gate-source and gate-drain capacitances and is delivered via an external resistor. The gate voltage follows a characteristic RC time constant which (within EMI constraints) has to be short enough to traverse the linear region without incurring excessive switching losses in the power MOSFET.

The average gate current during the switching event can be calculated thus:

$$I_G = Q/t,$$

where

I_G is the average gate current
Q is the total gate charge ($Q_{GS} + Q_{GD}$)
t is the switching transient time (t_{ON} or t_{OFF})

For example a typical 100V, 35mΩ DPAK MOSFET requires approximately 50nC. If it was required to switch in 20ns a gate current of 2.5 Amps is required.

There are many potential solutions to provide gate drive for power MOSFETs, including dedicated IC drivers, standard logic ICs, discrete MOSFETs and bipolar transistors. The selection criteria for gate driving usually include

Switching speed (hence current capability)
Cost
Current gain
Size

Bipolar transistors are eminently suitable for this function as they exhibit fast switching in linear mode, have high pulse current capability, high current density, hence small size and cost.

One of the most popular and cost effective drive circuits is a bipolar, non-inverting totem-pole type driver as shown in figure 3 below:

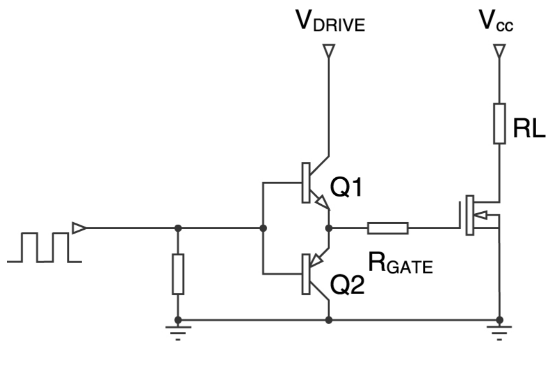

Figure 3. Totem Pole driver stage for power MOSFET

If in the above example the power MOSFET was required to switch at a frequency of 1MHz and driven to 5Vgs the power dissipation in each driver transistor can be calculated, worst case (assuming Rg = 0), as approximately

$$\begin{aligned} P_d &= ((V_{drive} * I * t * f) \div 2) + (V_{BE} * (I_C \div h_{FE}) * \text{Duty Cycle}) \\ &= ((5 * 2.5 * 2E^{-8} * 1E^{6}) \div 2) + (0.8 * 8.3\,E^{-3} * 2E^{-8} * 1E^{6}) \\ &= 125.1\text{mW} \end{aligned}$$

Assuming the base current is supplied from V_{drive} the losses per transistor are approximately

$$\begin{aligned} P_d &= ((V_{drive} * I * t * f) \div 2) + (V_{drive} * (I_C \div h_{FE}) * 2E^{-8} * 1E^{6}) * \text{Duty Cycle}) \\ &= ((5 * 2.5 * 2E^{-8} * 1E^{6}) \div 2) + ((5 * 8.3\,E^{-3} * 2E^{-8} * 1E^{6}) * 0.02) \\ &= 125.8\text{mW} \end{aligned}$$

With these power losses it is clear that bipolar transistors packaged in small surface mount packages are suitable, preferably co-packaged as complimentary dual devices. Some example transistors suitable for gate driving are shown in Table 2:

Device	Type	Package	BV_{CEO} (V)	I_C (A)	I_{CM} (A)	$h_{FE\ (typ)}$
Singles						
FMMTL618	NPN	SOT23	20	1.25	4	450
FMMTL718	PNP	SOT23	20	-1.0	-2	450
FMMT617	NPN	SOT23	15	3.0	12	450
FMMT717	PNP	SOT23	-12	-2.5	-10	450
FMMT491	NPN	SOT23	60	1.0	2	200
FMMT591	PNP	SOT23	-60	-1.0	-2	200
ZXT1M322	NPN	2x2mm MLP 3-L	15	4.5	15	450
ZXTAM322	PNP	2x2mm MLP 3-L	-12	-4.0	-12	450
ZXT3M322	NPN	2x2mm MLP 3-L	50	4.0	6	450
ZXTCM322	PNP	2x2mm MLP 3-L	-40	-3.0	-4.0	450
Duals						
ZXTD6717E6	NPN/PNP dual	SOT23-6	15 -12	1.5 -1.25	5 -3	300 300
ZXTDA1M832	NPN/PNP dual	3x2mm MLP 8-L	15 -12	4.5 -4.0	15 -12	300 300
ZXTD4591E6	NPN/PNP dual	SOT23-6	60 -60	1.0 -1.0	2 -2	200 200
ZXTDE4M832	NPN/PNP dual	3x2mm MLP 8-L	80 -70	3.5 -2.5	5 -3	450 450

Table 2. Example transistors suitable for gate driving

Applications example 2: Battery charging using Linear Chargers
Portable applications such as cell phones are becoming increasingly complex with more and more features designed into every generation. Lithium ion batteries have become the preferred choice for many of these applications due to their smaller size and extended battery life, but place tougher demands on controlling the charging cycle.

Figure 4. shows a typical charging cycle for a carbon electrode lithium ion battery.

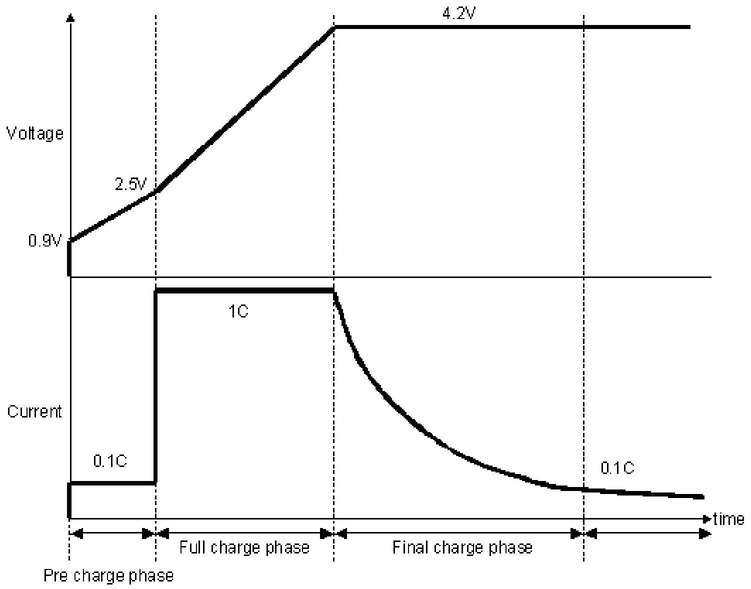

Figure 4. Charging cycle for a carbon electrode lithium ion battery

As shown the charge cycle is split into four phases:

i) Pre-charge
This phase is for recharging deeply discharged cells by topping up the charge in the battery so that normal charging can take place without damage. Charging current is typically set to 0.1C while the battery's deep cell discharge voltage reaches its cut-off voltage threshold.
ii) Full charge
Once the cut-off voltage threshold is reached constant current charging at 1C begins until the battery reaches its upper voltage threshold. This charging phase only takes a short time when compared to the battery’s charging cycle.
iii) Final charge
The start of the constant voltage charging phase is determined when the battery voltage reaches its upper voltage threshold. The battery voltage is maintained at its upper voltage threshold while the charging current decays exponentially from 1C to 0.1C, as a consequence of an increase in the internal resistance of the battery. The final charge phase takes the majority of time during the battery’s charging cycle and thus most of the power dissipated in the pass element is during this phase.
iv) Top up charge
In the top up charge phase, trickle charging is employed to maximize battery capacity. The battery voltage is maintained at its upper voltage threshold and charging current set to 0.1C for a fixed time period.

Linear Charging

Linear chargers are simple in design, small, and emit no EMI making them suitable for low noise environments. They use an external pass element to drop the voltage from the input supply to the battery voltage thus power dissipation is high (on-state resistance is not an issue here). A bipolar PNP transistor is advantageous in this application because of its bi-directional blocking capability, whereas a MOSFET requires a series Schottky diode to prevent current flowing from the battery to the supply, through its body diode. In this example a NCP1800 linear charger from OnSemi combined with a Zetex ZXT13P12DE6 bipolar transistor were used. A supply voltage of 5V, a base current of 20mA and base-emitter voltage of 0.8V were assumed. Figure 5. shows a typical linear charger circuit diagram.

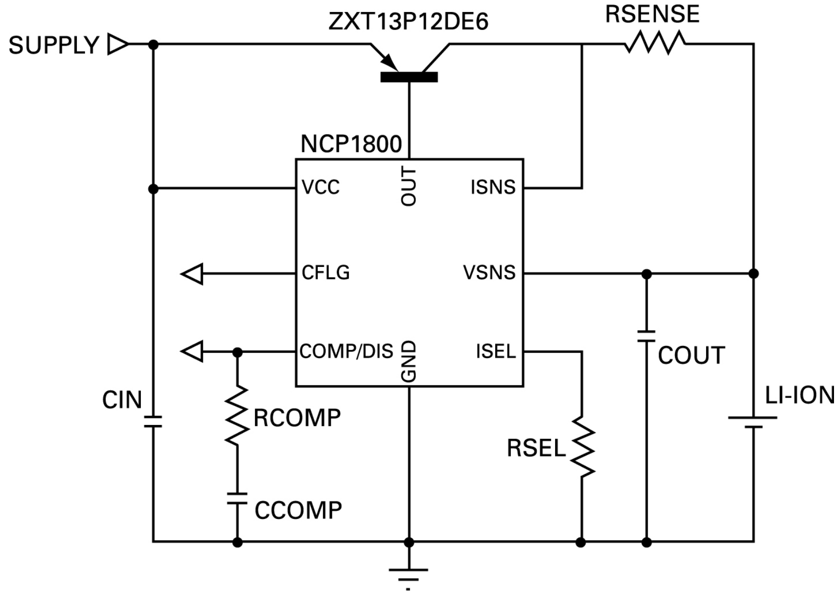

Figure 5. A typical linear charger circuit diagram.

The losses break down into their component parts, given in the formulae below:

$Pd_{(IC)} = V_{CC} \times I_{SUPPLY}$ (W)

$Pd_{(SENSE)} = I_{CHG}^2 \times R_{SENSE}$ (W)

$Pd_{(BASE)} = V_{BE(ON)} \times I_B$ (W)

$Pd_{(CE)} = I_{CHG} \times (V_{IN} - V_{DCD} - V_{SENSE})$ (W)

where $V_{SENSE} = I_{CHG} \times R_{SENSE}$ (V)

$Pd_{(TOTAL)} = Pd_{(SENSE)} + Pd_{(BASE)} + Pd_{(CE)}$ (W)

From these formulae we can model, show in graphical format, and identify the key parameters for the specification of the discrete element.

The charts below show the losses for each charging phase of the lithium ion battery.

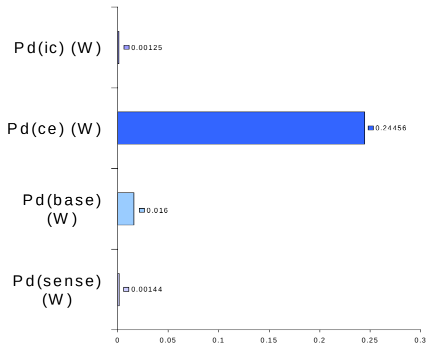

Figure 6. Pre charge phase

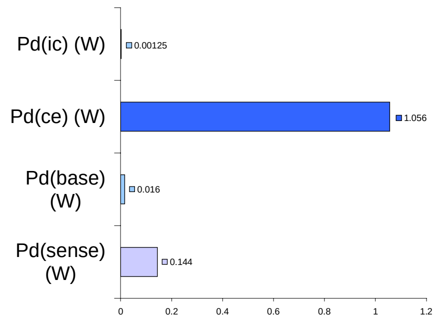

Figure 7. Full charge phase

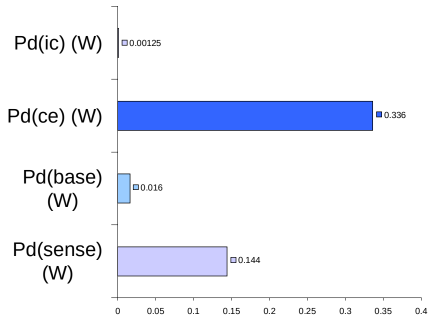

Figure 8. Final charge phase

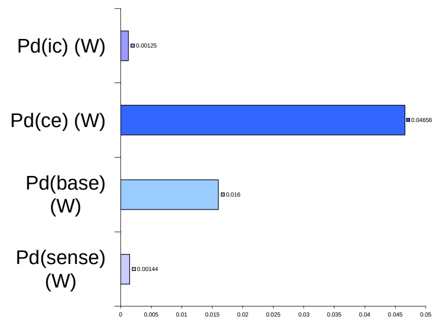

Figure 9. Top up charge phase

As can be seen above the on-state loss of the pass element dominates the power dissipated during all phases of the battery charging cycle. The final charge phase is most significant because it represents the bulk of the charging time during the whole cycle. Therefore the key parameters to consider in the selection of the pass element are package dissipation and cost. In this application bipolar transistors offer a cost advantage over MOSFETs because of their current capability per die area and their bi-directional blocking capability means that there is no requirement for a series Schottky diode.

Table 3 shows a selection of Zetex transistors which are suitable for linear charging lithium ion batteries.

Part number	V_{CEO} (V)	I_C (A)	h_{FE} @ I_C/V_{CE}	Package	Pd (W)
FMMT717	15	2.5	180min @ 2.5A/2V	SOT23	0.625
ZXT13P12DE6	12	4	200min @ 4A/2V	SOT23-6	1.1
ZXT13P20DE6	20	3.5	200min @ 3.5A/2V	SOT23-6	1.1
FZT788B	15	3	300min @ 2A/2V	SOT223	2.0
FZT1147A	12	5	250min @ 4A/2V	SOT223	2.5
FZT968	12	6	200min @ 5A/2V	SOT223	3.0

Table 3. Example transistors suitable for linear charging lithium ion batteries.

Applications Example 3: Resonant converter for CCFL backlight applications

LCD displays have become the dominant display technology over the last few years. Their user applications range from mobile phones, to digital still and video cameras, to PDAs, to laptop computers and LCD TVs. Each display consists of a display matrix and a backlight module, usually consisting of a light diffuser behind which is a lamp. Lamp technologies have also developed but still the most common type is the Cold Cathode Fluorescent Lamp (CCFL) which comes in various shapes, sizes and powers to suit the type of application. The backlight module is a significant power user for battery portable applications so the design is highly efficient and cost sensitive. There are two basic circuit topologies for driving the lamps:

a) resonant converter, using a bipolar transistor half-bridge (so-called Royer circuit), or
b) IC controller plus MOSFET half-bridge.

Resonant converter circuits have been popular for backlight applications for many years and many different variations on the circuit have been used, both MOSFET and bipolar, with and without external control. The circuit appears simple, and therein lies its cost advantage over IC controller/MOSFET solutions, but there are complex component interactions. With careful optimization of component values efficiencies of greater than 90% can be achieved. A simplified circuit is shown in Figure 10:

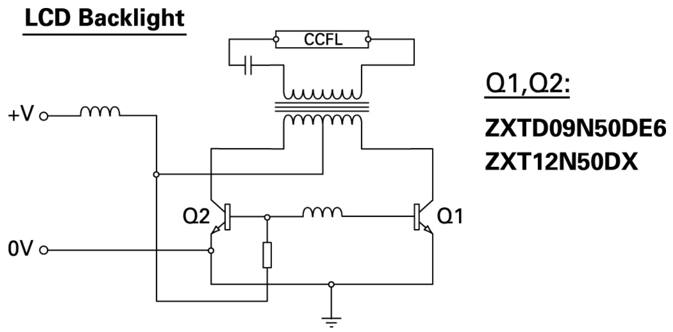

Figure 10. Simplified resonant converter circuit

During operation base current is supplied by the feedback winding and is set by base resistor values. The supply inductor and primary capacitor ensure that the circuit runs sinusoidally between 25kHz and 120kHz which is conveniently within the operating frequency range for bipolar transistors and minimizes RFI whilst providing adequate drive to the lamp. The important power switch selection characteristics are voltage rating, on-state resistance and (for bipolar transistors) gain.

Voltage Rating

The circuit requires transistor Q1 to a block voltage equal to π times the supply voltage whilst Q2 is driven into saturation, and vice versa. The superior silicon utilization of the bipolar transistor is further enhanced because when a transistor is blocking voltage it is also emitter-base reverse biased. This allows the use of the BV_{CEV}, BV_{CBO} or BV_{CES} characteristic, thus allowing a lower BV_{CEO} rated device with a lower on-state resistance than its MOSFET equivalent.

The BV_{EBO} rating of the transistor also comes under consideration. The transistor base is driven negative each cycle so circuit designers have to configure the transformer windings so as not to exceed the voltage rating. A high BV_{EBO} rating gives the designer more flexibility and is possible without detriment to the on-state resistance.

On-state Resistance

Analysis of the circuit shows that approximately two-thirds of the power losses derive from on-state losses and one third from switching losses. In most cases the transformer design determines the switching losses and sets the shape of the current and voltage waveforms. The on-state resistance determines the on-state losses, and here the bipolar transistor has an advantage over the MOSFET, as explained above.

Gain

On the one hand high gain results in lower saturation voltages and so is desirable. However high gain can result longer storage times and therefore increased switching losses. A compromise has to be reached and a desirable factor is to have a narrow gain band allowing the designer to optimize the circuit.

Finally, size (especially package height) is also an important parameter in applications such as mobile phones, digital still and video cameras and PDAs. The better silicon area utilization of bipolar technologies offers an inherent advantage over MOSFETs.

An alternative resonant converter circuit type is shown in Figure 11, where the control IC provides PWM dimming control via the low-side MOSFET switch (Q3) at 200Hz, soft start to minimize switching losses and protection for the bipolar transistors (Q1 and Q2) via lamp zero-current monitoring.

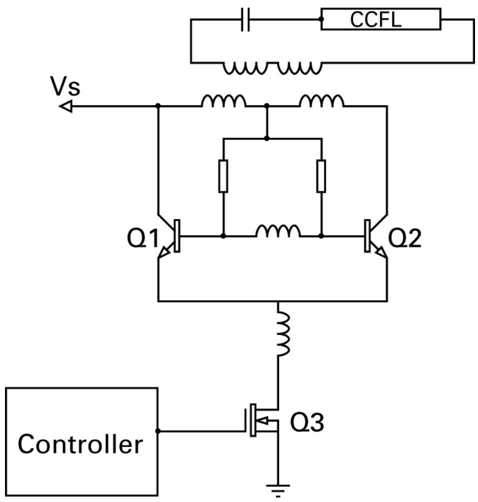

Figure 11. Resonant converter circuit with control IC

A selection of transistors suitable for use in resonant converter applications is shown in Table 4.

Device	BV_{CBO} / BV_{CES} (V)	BV_{EBO} (V)	$R_{CE(sat)}$ (mΩ)	I_C (A)	h_{FE} (min)	Package
Singles						
FMMT618	20	5	52	2.5	300	SOT23
FMMT619	50	5	75	2.0	300	SOT23
ZXTBM322	40	7.5	47	4.5	300	2x2mm MLP 3-L
ZXT13N15DE6	40	7.5	29	5.0	300	SOT23-6
ZXT13N20DE6	50	7.5	38	4.5	300	SOT23-6
FZT1048A	50	5	50	5.0	300	SOT223
FZT1049A	80	5	50	5.0	300	SOT223
ZXTCM322	100	7.5	68	4.0	300	2x2mm MLP 3-L
Duals						
ZXT10N20DE6	20	5	52	4.0	300	SOT23-6
ZXTDBM832	40	7.5	47	4.5	300	3x2mm MLP 8-L
ZDT619	50	5	75	2	300	SM-8
ZDT1048	50	5	50	5.0	300	SM-8
ZXTDCM832	100	7.5	47	4.5	300	3x2mm MLP 8-L

Table 4. Example transistors suitable for resonant converter applications.

Applications Overview

As demonstrated in the above examples, the unique characteristics of bipolar transistors can be exploited in many different applications. These and other examples are summarized in table 5 below.

Application	Circuit Requirements	Useful Bipolar Characteristics
Power MOSFET gate driving	Source/sink current Fast switching speed High pulse current High current gain Low cost (cf. MOSFET or IC drivers) Small size	NPN/PNP complementary pairs, fast switching in linear mode, high pulse current capability, h_{FE} 300 min. high current density/small chip, MLP, SOT323, SOT23, SOT23-6.
Linear Mode Battery Charging	P-Type switch Voltage drop, Vsupply to Vbatt Bi-directional voltage blocking Low cost (cf. MOSFET+Schottky) High gain Small size	PNP type Low package thermal resistance bi-directional voltage blocking high current density, h_{FE} 300 min MLP, SOT323, SOT23, SOT23-6
Current limited wall adapter, and Pulsed Mode Battery Charging	P-Type switch Low on-state losses High gain Low cost (cf. P-ch. MOSFET) Small size	PNP type Low $R_{CE(sat)}$ h_{FE} 300 min. Low specific $R_{CE(sat)}$/small chip MLP, SOT323, SOT23, SOT23-6
Resonant Converters (Royer type)	Voltage blocking > π x Vsupply Bi-directional voltage blocking Low on-state losses Low temperature rise Low cost (cf. IC + MOSFETs) Small size	$BV_{CER}/_{S}/_{V}$ characteristic, bi-directional voltage blocking, Low $R_{CE(sat)}$ Low package thermal resistance Low specific $R_{CE(sat)}$/small chip MLP, SOT223
Piezo Driving	H-bridge configuration Hi-voltage switching for max. deflection Low cost (cf. MOSFETs) Small size	NPN and PNP types BV_{ceo} up to 450V Low specific $R_{CE(sat}$ /small chip SOT23, SOT223, SM8
Motor Driving	Pull-up, pull-down and bridges High gain (IC controller driven) Low on-state losses 20 to 50kHz PWM frequency Inductive switching Low cost (cf. MOSFET+Schottky) Small size	NPN and PNP types h_{FE} 300 min. $R_{CE(sat)}$ < 100mΩ Low switching losses Excellent reverse gain reduces commutation losses MLP, SOT89, SOT223

Table 5. Applications for bipolar transistors

Conclusion

The choice of technology for a power switch is not always clear cut. Whilst MOSFETs have become the default choice for many designers bipolar transistors have many useful attributes which can be used beneficially in certain applications. Understanding the technological and parametric differences between MOSFETs and bipolar transistors is key to making the right choice for a given application. Bipolar transistors continue to be developed to optimize performance in these applications and will give real benefits in terms of circuit function, performance or cost for many years to come.

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