

## High Efficiency Power Switches

Nasser Kutkut - PowerDesigners, LLC - Madison, WI

The revolution and wide spread of switchmode power conversion technology is greatly attributed to the invention and rise of power semiconductor switching devices. These *powerful* switches gave designers the ability to precisely switch power on and off at ever increasing speeds allowing them to *process power* in a whole new way.

It all started with the mighty **Bipolar Junction Transistor (BJT)** in 1970, the first fully controllable and commercially viable power switch. BJTs gave rise to switchmode power conversion by late 1970s and made this class of converters a reality. Then came the **Metal Oxide Field Effect Transistor (MOSFET)** by the late 1970s, a new class of power devices that offered significant performance improvements compared to BJTs and extended the limits of power conversion technology as we know it today. In the 1980s, a new addition to the family of power devices was made with the invention of the **Insulated Gate Bipolar Transistor (IGBTs)**. The IGBT was built on the core MOSFET technology and extended MOSFET operation into high power applications.

### **Bipolar Junction Transistors (BJTs)**

A BJT is a current controlled device where the device is turned on and off by controlling the current into its base junction ( $I_B$ ). A base drive circuit is normally employed to achieve that (Fig. 1). When a BJT is turned on, a forward voltage drop is developed across the device terminals (collector-to-emitter), which gives rise to power loss (conduction loss) and thus heat loss while the device is conducting current. However, this voltage drop is relatively low and is easily tolerated by the external circuitry.

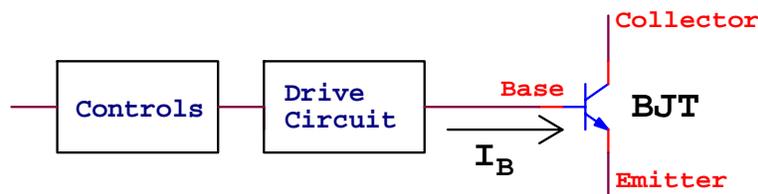


Fig. 1: The BJT with drive and control circuitry

Due to the relatively low forward voltage drop and consequently low conduction loss of BJTs, they have very high current handling capabilities and were used across the board in low to high power applications.

Although BJTs were the only real power transistors throughout the 1970's, they had considerable performance and control limitations, namely:

1. The drive circuitry was complex and quite sizeable since the base current require to turn-on and off the device is quite high.
2. BJTs have relatively slow switching characteristics limiting their maximum operating switching frequencies to the low kHz range.
3. The BJT is a negative temperature coefficient device, meaning that the device is liable for thermal runaway as the device temperature increases

The above limitations accelerated the pace of searching for a new power device and yielded to the development of the power MOSFET.

### **Metal Oxide Field Effect Transistors (MOSFETs)**

A MOSFET is a voltage controlled device where the device is turned on and off by controlling the voltage across the gate-source junction ( $V_{GS}$ ) (Fig. 2). Unlike BJTs, MOSFETs have high input impedances and thus require minimal gate currents to turn-on and off. This greatly simplifies the drive circuitry and reduces its cost. In addition, MOSFETs have very fast switching characteristics allowing them to operate into the MHz range.

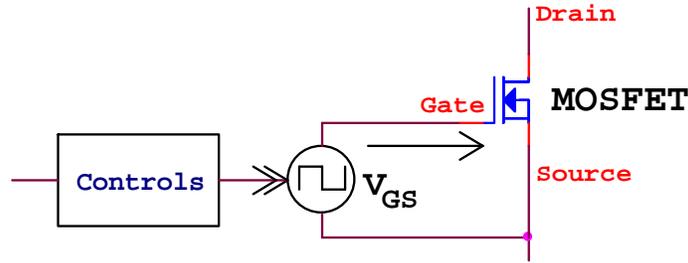


Fig. 2: The MOSFET with drive and control circuitry

When a MOSFET is turned on, it exhibits a resistive like behavior and will thus develop a forward voltage drop across its terminals (drain-to-source). Similar to BJTs, this gives rise to power and heat loss (conduction loss) in the device. Unlike BJTs, however, and since MOSFETs are merely resistors while switched on, they have a positive temperature coefficient thus stopping thermal runaway.

In general, MOSFETs extended the performance advantages of BJTs in terms of high-current handling capability while eliminating their drawbacks in terms of:

1. Ease of control: Simpler and lower cost drive circuitry.
2. Faster switching behavior: allowing operation into the MHz range. This resulted in the miniaturization of power converters as the size of the passive and filtering components was greatly reduced.
3. High current carrying capabilities: The positive temperature coefficient characteristics allow MOSFETs to be paralleled which further increases their current handling capability.

The above has led to MOSFETs becoming the devices of choice for power designers and to the elimination of BJTs in low to medium power applications.

Well it is all good to be true for MOSFETs. MOSFETs do have limitations, namely:

1. Relatively low breakdown voltages: The breakdown voltage limit of the metal oxide junction is limited to 1000-1200V. This has limited the use of power MOSFETs in high voltage applications.
2. High on-resistance especially at high breakdown voltages, which limits their current handling capabilities. The resistive like behavior of MOSFETs entails that the voltage drop increases with increasing currents (IR drop) as well as increasing temperatures (increased resistance). One way to alleviate the forward drop limitation is to parallel MOSFETs to reduce the equivalent resistance, similar to connecting resistors in parallel (Fig. 3). Just like resistors, the equivalent resistance of the parallel configuration is divided down by the number of parallel devices. This greatly reduces the conduction losses and increases the current carrying capability of power MOSFETs.

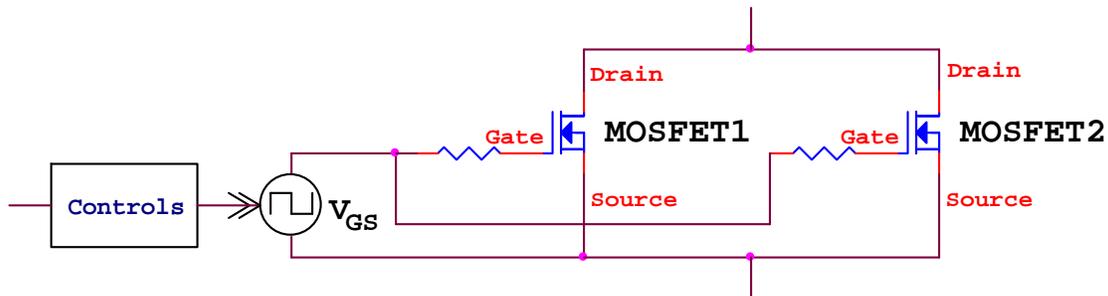


Fig. 3: Parallel connected MOSFETs for increased current handling capability and reduce conduction loss

## Insulated Gate Bipolar Transistors (IGBTs)

An IGBT is a “*combo*” device derived from the power MOSFET and BJT technologies. In fact, the IGBT is a “spinoff” from power MOSFETs invented to extend the performance limitations of power MOSFETs into high voltage and high power applications. It combines the low conduction loss of a BJT with the *relatively* high switching speed of a MOSFET.

The IGBT physical structure is a true representation of the “*combo*” technology the device incorporates having a MOSFET input stage and a BJT output stage (see Fig. 4).

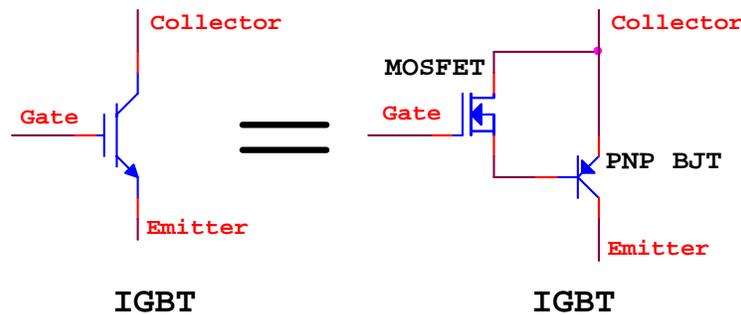


Fig. 4: IGBT symbol and equivalent internal structure showing the input MOSFET and the output BJT

Similar to power MOSFETs, the IGBTs are voltage controlled devices and have high input impedances thus requiring minimal gate drive circuitry. In addition, IGBTs can turn-on and off at speeds comparable to MOSFETs. Unlike MOSFETs, however, IGBTs exhibit forward voltage drops and current densities similar to BJTs while switching much faster. In addition, their breakdown voltages are much higher than MOSFETs with readily available devices having breakdown voltages in excess of 5000V.

In summary, the performance improvements of IGBTs over MOSFETs and BJTs are summarized below:

1. MOSFET input stage which entails high input impedance, minimal drive requirements, and simple and low cost drive circuitry
2. Fast switching behavior comparable MOSFETs
3. Low forward voltage drop resulting in lower conduction losses
4. High current carrying capabilities. Presently, IGBTs are available in current ratings in excess of 1000A.
5. High breakdown voltages approaching few thousand volts

The above performance improvements make IGBTs the devices of choice in high voltage and high power applications. Specifically, IGBTs are better suited for voltages in excess of 600V and for power levels in excess of 5-10kW.

Just like MOSFETs, it's too good to be true. And yes, IGBTs have their own limitations. Some of the major limitations of IGBTs include:

1. Lower switching speeds in comparison with MOSFETs. Although IGBTs switch faster than BJTs, they are relatively slower than MOSFETs. This is in part due to the tail current effect they exhibit when the device is turned off which may extend for few microseconds (see Fig. 5).
2. Higher switching losses compared to MOSFETs. Again, this is mainly due to the tail current effect, which increases switching losses and limits the maximum switching frequency (see Fig. 5).
3. Possibility of uncontrollable latch-up (stays-on) under overstress conditions (high  $dv/dt$  or  $di/dt$ )

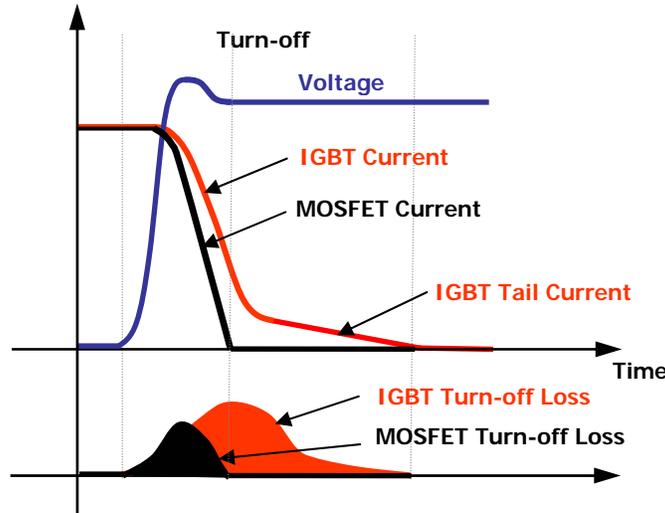


Fig. 5: MOSFET and IGBT turn-off behavior

**Comparison**

Table 1 below summarizes the main performance characteristics of BJTs, MOSFETs, and IGBTs. As shown in the table, BJTs performance is no longer favorable and their use is now limited to select applications, mainly at low switching frequencies and where the applications requirements are low. On the other hand, MOSFETs and IGBTs are now the devices of choice of almost all power designers.

Table 1: Charge Technology Comparison

<b>COMPARISON CRITERIA</b>	<b>BJTs</b>	<b>MOSFETs</b>	<b>IGBTs</b>
Drive Method	Current	Voltage	Voltage
Drive Circuit Complexity	High	Low	Low
Switching Speeds	Slow ( $\mu$ s)	Very Fast (ns)	Medium
Switching Frequencies	few kHz	Up to 1 MHz	< 50 kHz
Forward Voltage Drop	Low	Medium	Low
Current Carrying Capability	High	Medium	High
Breakdown Voltage	High	Medium (<1500V)	Very High (~5000V)

**Which Device is Better: a MOSFET or an IGBT**

Well, the magic answer is: **IT DEPENDS**. There isn't a clear line that can be easily drawn. The choice of a MOSFET versus an IGBT in a given application depends greatly on the application needs and requirements.

In developing a simple criteria to choose between MOSFETs and IGBTs in a given application, the switching frequency and the voltage withstand requirements can be used. Figure 6 shows the application range of MOSFETs and IGBTs based on the operational frequency and voltage requirements of a given application. It is clear that MOSFETs are still the "king of the hill" in low voltage (<300V) and low to medium power applications (<10kW). As the voltage requirements increase, IGBTs become more appealing. However, at higher switching frequencies, MOSFETs are still superior due to their faster switching speeds. Higher frequency operation of IGBTs is now feasible by employing soft switching power conversion techniques.

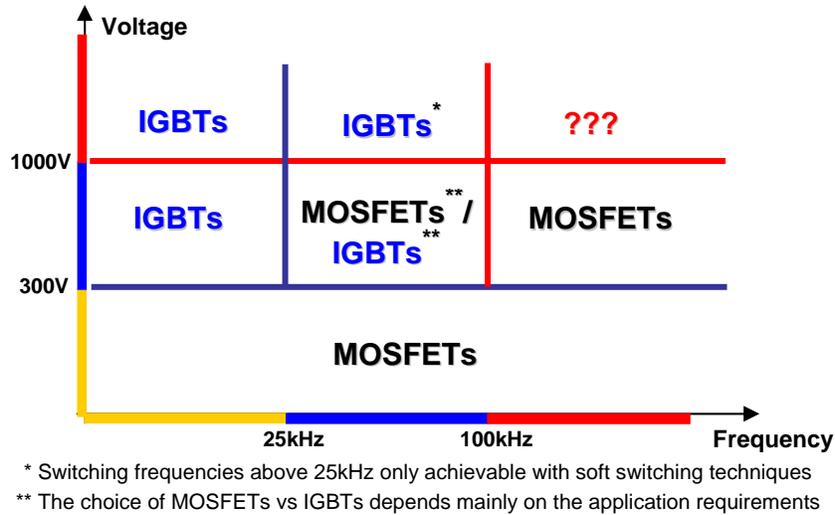


Fig. 6: MOSFETs and IGBTs Application Range

In summary, there has been euphoria and a push to claim IGBTs as a “*new*” technology while classifying MOSFETs as being a “*mature*” old technology. Many have been pushing the notion that IGBTs have significant performance improvements over MOSFETs and should be the device of choice in applications above 300V. This is far from true especially with continual innovations in MOSFET device and processing technologies that continue to push the limits of these devices into higher voltage and higher power applications.

**Selected References:**

- 1- “IGBT or MOSFET: Choose Wisely”, IR Tech Note.
- 2- “Fast High Speed TrenchStop IGBT and Duo Pack”, Infineon Application Note.