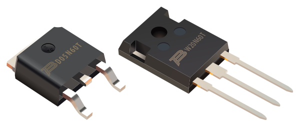
IGBT vs. MOSFET – Determining the Most Efficient Power Switching Solution

WHITE PAPER



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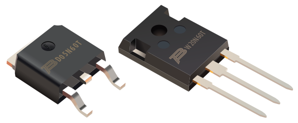
INTRODUCTION

Electronic devices are finding their way into a growing variety of products. Whether the product is portable or stationary, most electronic devices have a requirement to convert electrical energy (or switch) from one form to another, and to do it efficiently. Power electronics are incorporated for this purpose, and suppliers have developed a rich selection of switching devices from which to choose for any given application. The trend for today's power electronics is to use semiconductor switching devices to rectify, switch and control voltage and current.

As the choices among diode, thyristor, metal oxide semiconductor field-effect transistor (MOSFET) and integrated-gate bipolar transistor (IGBT) solutions expand, it is important to understand how to differentiate among them. Examining a few of the most popular technologies in semiconductor switching devices provides a foundation on which to determine the optimum choice for a given design.

This paper outlines the structure, key features and main operational differences in the three switching technologies available, and provides several application examples where these devices are typically specified. It will also provide an introduction to the new IGBT components provided by Bourns that have been designed for high voltage, high power switching applications including the switching of high currents in high voltage systems.

IGBT vs. MOSFET – Determining the Most Efficient Power Switching Solution



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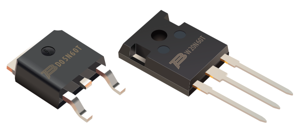
WHY SOMETHING NEW IS NECESSARY

A shifting climate toward using cleaner forms of energy is driving an expanding awareness of energy usage at many levels, and this can begin at the component level for power switching efficiency. While nowhere near comprising the full scope of applications, several of the applications listed below employ semiconductor switching devices to operate more efficiently.

- From small home motors to large industrial and automotive motors
- Uninterruptible power supply (UPS) inverters changing DC to 50/60 Hz
- Motor drives and switching in home appliances (e.g., refrigeration compressor, induction cooking surfaces, air conditioning fans and heaters as a relay replacement)
- Generating high power pulses in high energy physics
- Power conversion in AC to AC and AC to DC systems
- Controlling current flow in induction heating systems for cooking and industrial applications
- High power Class D audio amplifiers
- Welding H-bridge inverters

Such applications typically operate at high voltage and high power. Power electronics switching devices that have been suitable solutions in the past may not quite achieve the more stringent specifications required today to deliver a reliable and efficient system.



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THE BIG THREE

Three technologies that warrant exploration are the bipolar junction transistor (BJT), MOSFET and IGBT. All have three main connections to the outside: a collector, an emitter and a base in the BJT; a gate, source, and drain in the MOSFET; and a collector, gate, and emitter in the IGBT. The biggest difference at a fundamental level is how these semiconductor devices are driven. A BJT is driven by current, whereas the MOSFET and IGBT are voltage driven. This is an important distinction to keep in mind throughout this paper.

BJTs

A simple way to think of the BJT is as two diodes back to back in either a PN to NP or NP to PN configuration, thereby forming a PNP junction or NPN junction. The BJT becomes a three-terminal semiconductor device with the first layer as the emitter, the middle of the three layers as the base, and the third layer as the collector.

Figure 1 shows the BJT in its most common configuration, which is as a common emitter. Here, the emitter is tied to ground and the output is taken from between the collector and emitter. A common emitter configuration in a BJT offers a medium input impedance, high output impedance, medium current and voltage gain, and very high power gain. The current equation in this configuration is $i_E = i_C + i_B$ such that the current into and out of the device is equal. Small changes in base current result in large changes of current at the collector. These small changes in the base current control the circuit.

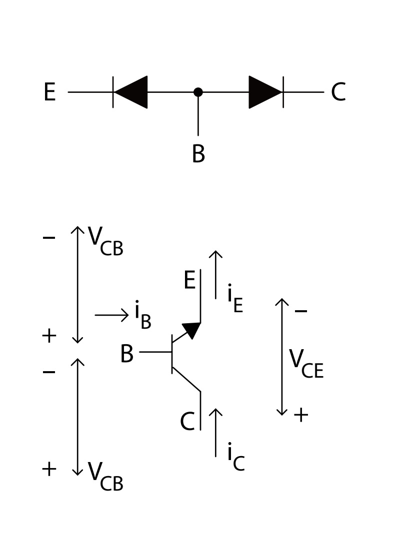
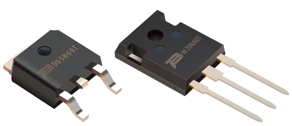


Figure 1. | *BJT Common Emitter*



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THE BIG THREE (Continued)

MOSFETs

MOSFETs historically have gotten the most attention from designers among the appropriate transistors. Similar to the BJT, a MOSFET can either be n-channel or p-channel. The n-channel MOSFET is popular in applications such as AC/DC power supplies, DC-DC converters and inverter equipment. The p-channel MOSFET is more often incorporated in load switches, high-side switches and other similar applications. Some benefits of the MOSFET over the BJT include a high input impedance, small reverse transfer capacitance, low gate power consumption, wide safe operating region and easy driving. MOSFETs became more widely incorporated compared to the BJT in the last 20+ years due to their smaller size and faster switching capabilities.

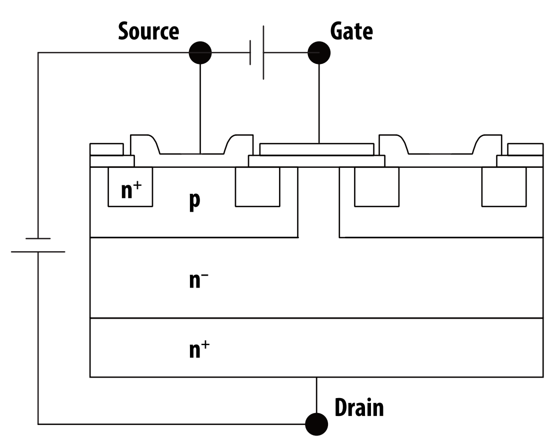
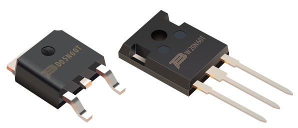


Figure 2. | *A Cross Section of the MOSFET*

A cross section of the MOSFET, shown in Figure 2, reveals a slightly more complicated structure than the BJT. Operation is different due to the voltage driven aspect. A voltage, V_{ds}, is applied between the drain and source with positive drain polarity, and a voltage, V_{gs}, is applied between gate and source with positive gate polarity. When the applied voltage causes electrons to be attracted to the p-type layer under the gate insulator film, an inversion layer is formed. Specifically, part of the p-type layer is turned into an n-type region. Formation of this inversion layer presents an n-layer path from the drain to the source of the MOSFET. It operates at a low resistance because of this path. The applied V_{ds} determines the drain current, as does the load. However, the scope of where MOSFETs can be used is limited by the voltage levels specified in certain applications, especially when high current is present in high voltage applications.



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THE BIG THREE (Continued)

IGBTs

An IGBT combines the strengths of the BJT and MOSFET into a single device. The input is essentially a voltage controlled MOSFET gate with high input impedance. The output stage of the BJT portion of the design offers very high power gain and output current flow. The most common IGBT styles are punch-through (PT) and non-punch-through (NPT). More recently, developers have introduced technology enhancements such as field-stop (FS), trench gates and integrated diodes, also known as FRDs, to provide forward and reverse bias operation in the same package.

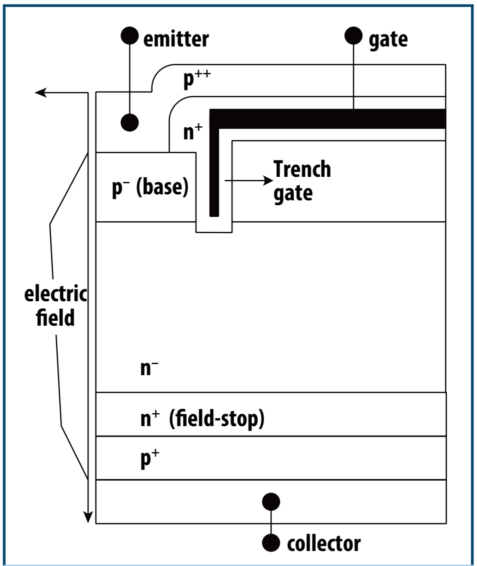


Figure 3. | *A Cross Section of an FS Trench Gate IGBT*

Figure 3 shows the cross section of an FS trench gate IGBT. The IGBT operates similarly to the MOSFET where the R_{be} value (see Figure 4) is set so that the IGBT does not turn on. Applying the 'ON' signal to the gate of the n-channel MOSFET introduces a conduction state. Current then flows from the emitter to the base of the PNP transistor at the second stage of the IGBT. The base current reduces the 'ON' resistance of the MOSFET.

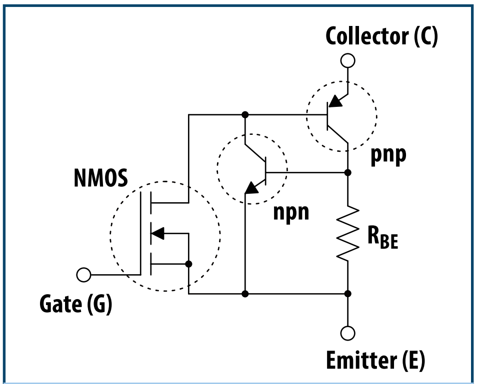
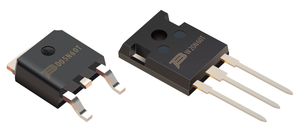


Figure 4. | *Internal equivalent circuit of an IGBT*

The operation of an IGBT is very similar to that of a MOSFET. Applying a positive voltage from the emitter to the gate terminal causes electrons to flow toward the gate terminal. Once the voltage reaches or exceeds the threshold voltage, electrons will flow toward the gate to form a conductive channel that allows current to flow from the collector to the emitter. As electrons flow from the emitter to the collector, positive ions from the substrate are attracted to the drift region toward the emitter.

The IGBT is often used in easy driving, soft switching circuit applications such as home appliances and induction heating that have voltage ranges of 600 to 1800 V or in hard-switching applications such as general inverters with a voltage of 600 V. In the former, IGBTs provide the advantage of low switching losses, and in the latter, IGBTs provide required high breakdown capacity.



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THE BIG THREE (Continued)

Features	BJT	MOSFET	IGBT
Drive Method	Current	Voltage	Voltage
Drive Circuit	Complex	Simple	Simple
Input Impedance	Low	High	High
Drive Power	High	Low	LOW
Switching Speed	Slow (µs)	Fast (ns)	Middle
Operating Frequency	Low	Fast	Middle
S.O.A.	Narrow	Wide	Wide
Saturation Voltage	Low	High	Low

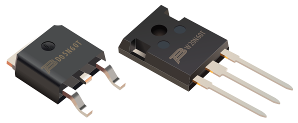
IT COMES DOWN TO MOSFET VS. IGBT

Numerous trade-offs are often considered among the three semiconductor switching devices, and MOSFETs and IGBTs generally come out as winners in support of high voltage and high current designs. The IGBT is considered to be the optimal combination of the benefits of a MOSFET gate and BJT current output, yet there are areas where the MOSFET prevails. Namely, since the IGBT is a minority carrier device, the movement of electrons in the bipolar portion creates a tail current that slows the device turn 'OFF' speed. This limits the IGBT's switching frequency and makes power MOSFETs the better choice in high frequency applications. MOSFET switching frequency is limited by the travel of electrons across the drift region and the time required to charge the input gate and Miller capacitances.

The IGBT has advantages over the power MOSFET and BJT. It has a very low 'ON'-state voltage drop and better current density in the 'ON' state. This allows for a smaller die size with the possibility of more economical manufacturing costs. Driving IGBTs is simple and requires low power. It is easier to control the IGBT voltage-driven input in high voltage and high current applications when compared to the current controlled BJT. The conduction, forward blocking and reverse blocking capabilities of the IGBT are superior to the BJT.

The FS structure of an IGBT has a high temperature V_{ce_sat} that makes it easier to balance the collector current even when operating in parallel. The V_{ce_sat} characteristic means there is a voltage drop when the collector current flows in the forward direction. The MOSFET's small voltage drop has an advantage in low current applications, whereas the IGBT is better than the MOSFET in high current applications. Low voltage MOSFETs have a much lower 'ON' resistance than IGBTs. These factors make MOSFETs ideal for switching power supplies and other applications that operate at about 100 kHz and at low current density. Conversely, IGBTs are superior solutions in AC drives that operate under 20 kHz with high current density. It is easier to drive the IGBT at lower operating frequencies since the input capacitance is approximately 1/10 of that of a MOSFET with similar ratings. Along with these operational differences is the element of efficiency.

IGBT vs. MOSFET – Determining the Most Efficient Power Switching Solution



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HEAT AND POWER

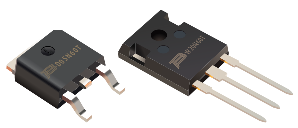
The forward characteristic of the MOSFET is strongly dependent on temperature, which creates divergent IGBT and MOSFET performance with increasing temperature. Power MOSFETs have junction temperature limitations and close attention should be paid to the maximum junction temperature specified in the data sheet. MOSFETs generally require a heat sink nearby in order to dissipate heat. This introduces added expense, and requires extra board space and additional design components, even when representing the heat sink as a network of thermal resistors and capacitors.

IGBTs are much more efficient thermally and do not require heat sinks. However, IGBTs can be damaged by extended power pulses and heat transfer conditions. If a hot spot is formed by excessive current concentration in the gate area, the cells within and surrounding the hot spot could lose gate control, turn on the BJT and eventually destroy the device.

ENERGY AND EFFICIENCY

The configuration of an IGBT has evolved and improved with trench gate field-stop (TGFS) technology. Implanting a back emitter and field-stop in the IGBT allows for better control of the dynamic behavior. The V_{ce_sat} and E_{off} trade-off curve is also enhanced with the trench structure. It allows for a thinner die, and thus a higher cell density. This results in improved performance with lower conduction and switching loss, greatly increased robustness, and significantly reduced thermal resistance. Thermal impedance is a long standing limitation of MOSFETs.

The IGBT has superior efficiency and reduced audible noise. It can be optimized for both low conduction and low switching loss. Most of the loss in an IGBT is from switching loss, which is far less than what is observed in the MOSFET. In an IGBT, turn 'ON' energy, E_{on}, is a contributor, though the turn 'OFF' energy, E_{off}, dominates. If a diode is present in the IGBT, then its switching losses also must be accounted for in the total energy loss.



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PUTTING IGBTs TO WORK

While there may be some similarities in design with any of the three components discussed, it is time to examine a few designs that feature the IGBT for power switching. The following applications were chosen to showcase an IGBT's high-voltage and high-current characteristics.

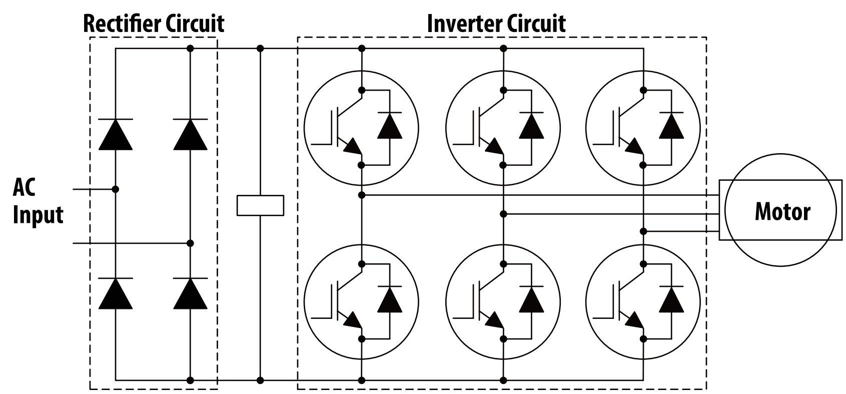


Figure 5. | *Motor Drive Circuit*

Figure 4 is a motor drive circuit. Here, the IGBT switches the inverter circuit, which performs DC to AC conversion in order to drive the motor. Using IGBTs in appliance, industrial, and automotive motors helps enhance their efficiency.

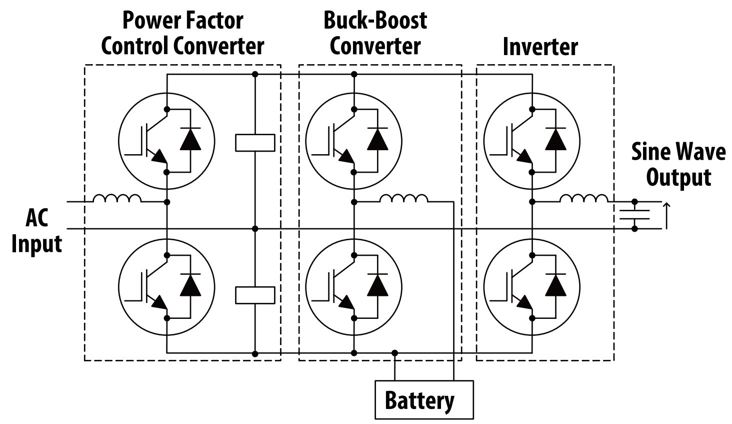
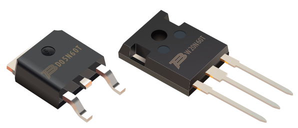


Figure 6. | *UPS Circuit*

A UPS circuit is shown in Figure 5. IGBTs are used often in midsize to large capacity UPS models. This application operates with several kVA or higher, and the IGBT contributes to improved efficiency and space-savings in the overall UPS unit.



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PUTTING IGBTs TO WORK (Continued)

Figure 6 includes two diagrams of an induction heating circuit. In one, the induction heating relies on LC resonance to achieve zero-voltage switching. In the other, it relies on LC resonance for zero-current switching. Both cases strive to reduce switching loss. These inductive heating applications have a high resonance voltage or high resonance current, respectively, which makes IGBTs ideal for switching. The two circuits are examples of what could be found in an induction cooker, induction rice cooker or microwave oven.

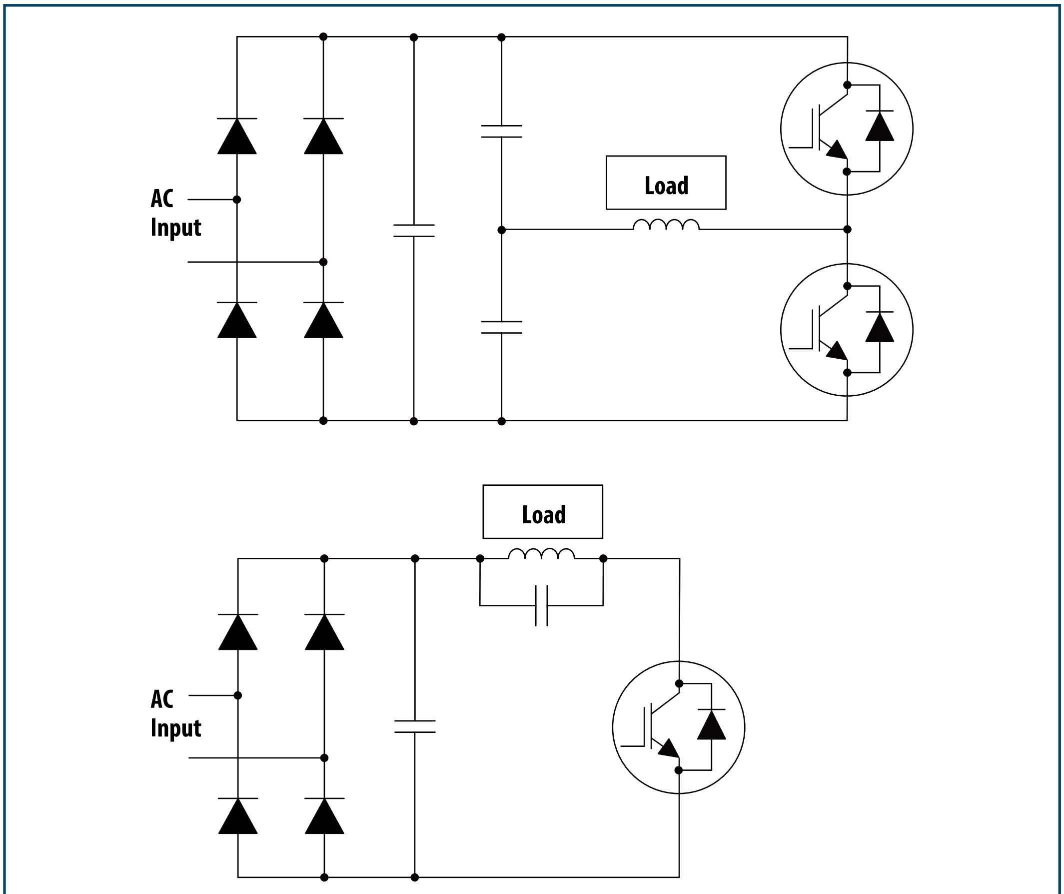
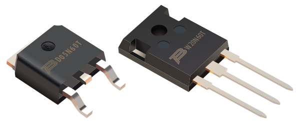


Figure 7. | *Induction Heating Circuit*

IGBT vs. MOSFET – Determining the Most Efficient Power Switching Solution



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RULES OF THUMB

Having compared and seen what is inside the various semiconductor switching devices, a few general rules of thumb can be helpful to summarize the differences.

Fundamentally, an IGBT is preferred for breakdown voltages greater than 400 V, and a MOSFET is preferred for breakdown voltages less than 250 V.

MOSFETs provide superior performance in higher frequency applications.

IGBTs offer improved performance compared to MOSFETs in the following ways:

- Ability to withstand overloads
- Parallel current capability
- Smoother turn 'OFF' and turn 'ON' waveforms
- Reduced EMI
- Lower 'ON'-state conduction loss and switching losses
- Lower thermal impedance
- Minimal snubber, if any is required at all

When selecting an IGBT for an application, it is the robustness, thermal capacity, switching frequency, and diode performance that must be considered closely. There will be efficiency tradeoffs based on the application since device parameters will introduce unique power loss contributions.

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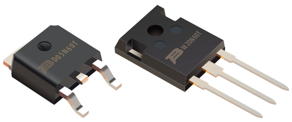

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CONCLUSION

As shown in this paper, an IGBT has many advantages compared to other power switching components including the usual choice of a MOSFET. In most applications with a supply voltage over 300 V, using IGBTs with their inherent lower voltage drop will increase the efficiency, in particular when operating at high temperatures. This reduces the heat sink requirements and eases the thermal design. The thermal impedance is reduced in IGBTs since the semiconductor current path is shorter and has a higher current density.

IGBTs are particularly well-suited for high voltage and high current systems using frequencies around 100 kHz or below. This is because the IGBT has lower switching losses and lower conduction losses than similarly rated MOSFETs. Overload durability is improved and smaller or no snubbers are required in IGBT applications. The waveforms during IGBT switching are softer, resulting in lower EMI from the application.

IGBT technology is mature and proven, and it has tremendous future potential. IGBT losses are dominated by conduction loss, but they can perform reasonably well with a marginally high V_{ce_sat} and drastically lower E_{off}.

As a leader in developing component technologies, Bourns' new trench gate field-stop technology-based IGBTs are designed to deliver enhanced application efficiencies. Each application is different and may require design tradeoffs; that is why it is helpful to have a better understanding of the differences among the three main semiconductor power switching devices. This knowledge allows designers to select the power electronics component best suited to meet the specifications for a given application.

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