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Latest Technology PT IGBTs vs. Power MOSFETs

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Abstract

This paper compares the switching and conduction loss performance of the latest generation of punch-through (PT) IGBTs with power MOSFETs. Also included is a brief overview of the PT IGBT structure. Benefits due to the unique striped, metal gate of Power MOS 7® IGBTs are enumerated, as well as some differences in characteristics between PT IGBTs and power MOSFETs. These IGBTs provide a lower cost alternative to high voltage power MOSFETs under many conditions, sometimes with superior performance.

Introduction

With the combination of an easily driven MOS gate and low conduction loss, the IGBT is the device of choice for high current and high voltage applications. Now with the latest generation of PT IGBTs, the tradeoff between switching and conduction losses is balanced so that IGBTs encroach upon the high frequency, high efficiency domain of power MOSFETs. In fact, the industry trend is for IGBTs to replace power MOSFETs in switch mode power supply (SMPS) applications if the voltage is above about 300 Volts.

This trend is made possible by a significant improvement in switching speed with the latest generation of PT IGBTs while retaining the low conduction loss that is characteristic of IGBTs. In most cases, circuit designers who use these latest technology IGBTs can significantly reduce costs with little, if any sacrifice in efficiency.

This paper gives an overview of PT IGBT technology, compares features and benefits with power MOSFETs, and shows performance improvements in various high frequency, high voltage SMPS applications.

PT IGBT Structure

A PT IGBT is basically an N-channel power MOSFET constructed on a p-type substrate [1], as illustrated by the generic IGBT cross section in Figure 1.

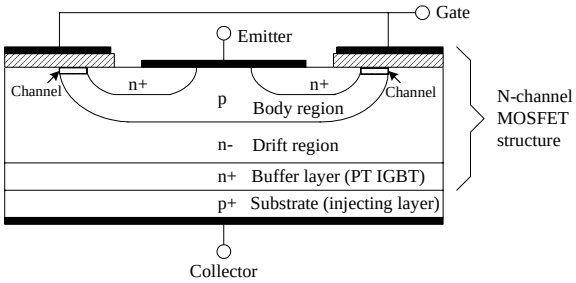

Figure 1 PT IGBT Cross Section

In an IGBT, the reverse current through the MOSFET intrinsic body diode is blocked. This leads to a simple equivalent circuit model for an IGBT, which is simply a diode in series with the drain of an N-channel power MOSFET, as shown in Figure 2. The blocking capability of this series diode is typically only about 15 to 30 Volts. A separate diode must be connected anti-parallel to the IGBT if reverse current flow or

protection from reverse voltage is required as in a bridge circuit, which will be discussed.

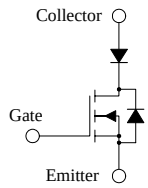

Figure 2 Simple IGBT Equivalent Circuit

Looking at Figure 2, it would seem that the on-state voltage across the IGBT would be one diode voltage drop higher than for the N-channel power MOSFET by itself. It is true in fact that the on-state voltage across an IGBT is always at least one diode voltage drop. However, compared to a conventional high voltage power MOSFET of the same die size and similar voltage rating, an IGBT has significantly lower on-state voltage.

The reason for this is that a MOSFET is a majority carrier only device, meaning that only electrons flow; current is unipolar. In an IGBT, the flow of electrons through the channel and drift region draws positive carriers, called holes, into the drift region toward the emitter. Therefore current flow in an IGBT is composed of both electrons and holes; current is bipolar.

This injection of holes (minority carriers) significantly reduces the effective resistance to current flow in the drift region. Stated otherwise, hole injection increases the conductivity, or the conductivity is modulated. The resulting reduction in on-state voltage is the main advantage of IGBTs over conventional high voltage power MOSFETs.

IGBTs trade lower on-state voltage for slower switching speed at turn-off. The reason for this is during turn-off the electron flow can be stopped rather abruptly by reducing the gate-emitter voltage below the gate threshold voltage, just as with a power MOSFET. However, holes are left in the drift and body regions, and there is no terminal connection to facilitate removing them. The only ways to remove these minority carriers are by sweep-out, which depends on the voltage across the device, and by internal recombination. A tail current exists until recombination is complete, and this tail current has historically been the major drawback of IGBTs.

Because of the high injection efficiency of the p+ layer, an n+ buffer layer (shown in Figure 1) is used to control the transconductance (gain) of the device by limiting the number of holes that are injected into the drift region in the first place. Since minority carrier lifetime in the buffer layer is much lower than in the drift region, the buffer layer also absorbs trapped holes during turn-off.

In addition to the n+ buffer layer, the tail current in a PT IGBT is controlled by limiting the amount of time that a minority carrier dwells before being recombined. This is called minority carrier lifetime control. An electron irradiation process during manufacturing creates recombination sites throughout the silicon, which greatly reduces minority carrier lifetime and hence the tail current. Holes are quickly recombined, even with no voltage across the device as in soft switching. The tradeoffs with lifetime control are an increase in on-state voltage, called $V_{CE(on)}$, and slightly higher leakage current at high temperature.

Switching Speed

Turn-on characteristics of an IGBT are very similar to a power MOSFET. Turn-off differs though because of the tail current. Thus the turn-off switching energy in a hard switched clamped inductive circuit gives an indication of the switching speed and tail current characteristic of an IGBT. Figure 3 depicts the tradeoff between turn-off switching energy E_{off} and $V_{CE(on)}$.

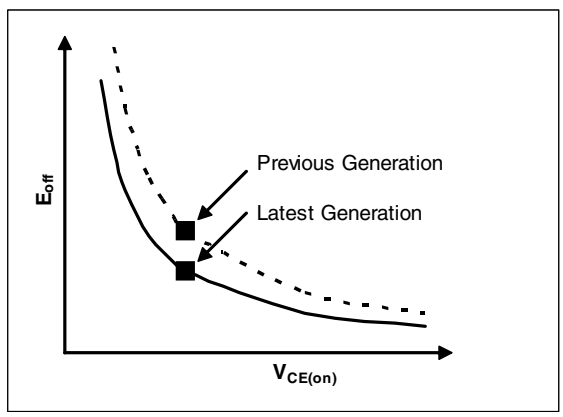

Figure 3 Turn-Off Energy vs. $V_{CE(on)}$

Within any technology, in order to reduce conduction loss, switching energy must increase, and vice versa. Only technology improvements can yield both lower conduction and lower switching losses. Figure 3 shows two technology curves, the dashed curve depicting the performance of previous generation IGBTs, and the solid curve depicting the performance and tradeoff point of the latest generation of PT IGBTs, such as the Power MOS 7® IGBTs from Advanced Power Technology. By utilizing the latest PT IGBT technology, switching energy has been reduced by 30% to 50% without significantly increasing $V_{CE(on)}$,

resulting in a high performance IGBT optimized for high voltage SMPS applications.

Usable Frequency versus Current

A useful way to compare the performance of different devices is to graph usable frequency versus current. What makes this so valuable is that it incorporates not only conduction loss, but also switching loss as well as thermal resistance. It also makes it easy to compare the performance of different types of devices, like IGBTs and power MOSFETs.

Beginning with the fundamental relationships:

$$P_{diss} = P_{cond} + P_{switch} = \frac{T_J - T_C}{R_{\theta JC}}, \; P_{cond} = I_C \cdot V_{CE(on)} @ I_C,$$

and $P_{switch} = (E_{on} + E_{off}) \cdot f_{switch}$, the maximum switching frequency is derived as [1]:

$$F_{max} = \min(f_{max1}, f_{max2})$$

$$f_{max1} = \frac{0.05}{t_{d(on)} + t_{d(off)} + t_r + t_f}, \; f_{max2} = \frac{P_{diss} - P_{cond}}{E_{on} + E_{off}}$$

It is f_{max1}, a percent of switching time limitation that limits the frequency at low current; f_{max2}, a thermal limitation, limits the frequency otherwise. The f_{max1} pulse width limitation rule favors small devices with their small capacitances and shorter delay times. In this case, the estimated time spent switching (the sum of delay, rise, and fall times) is no more than 5% of the total switching period. A different pulse width limit rule may be used, but it does make sense to limit the time spent switching to some percentage of the total switching period so the die has time to cool between switching transients. Above a certain current, the frequency is limited by heat dissipation due to switching and conduction losses (f_{max2}) rather than a pulse width limitation (f_{max1}).

Lower losses as well as lower thermal resistance $R_{\theta JC}$ result in higher maximum frequency. In general, a device that is thermally capable of the highest switching frequency is the most efficient device.

Figure 4 shows usable frequency versus current curves for three devices: a PT IGBT and two power MOSFETs. All three are the latest technology devices from Advanced Power Technology.

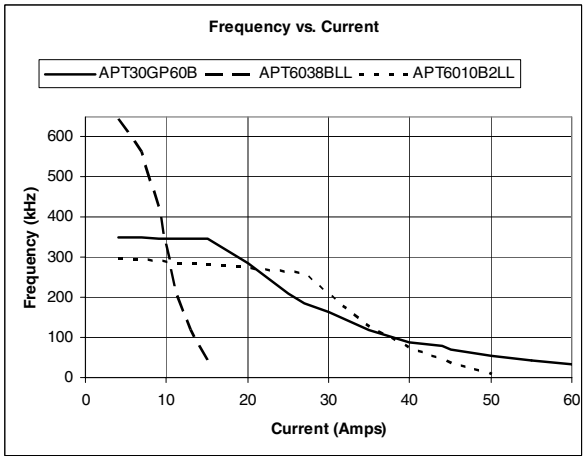

Figure 4 Usable Frequency vs. Current

The APT30GP60B is a 600 Volt Power MOS 7® IGBT rated at I_{C2} = 49 Amps in a TO-247 package. The APT6038BLL and APT6010B2LL are 600 Volt Power MOS 7® MOSFETs rated at I_D = 17 and 54 Amps respectively. The APT6038BLL is in a TO-247 package, and the APT6010B2LL is in a T-MAX™ package (TO-247 without a hole).

The test conditions for Figure 4 are: hard inductive switching, 400 V, T_J = 125 °C, T_C = 75 °C, 50% duty cycle, and 5 Ω total gate resistance (the equivalent gate resistance for each part is very small because of the metal gate and is therefore ignored). For each device, a 15 Amp, 600 Volt ultra-fast recovery diode was used as the clamp (freewheeling) diode. The test circuit is representative of boost, buck, or other clamped inductive switching circuit topologies.

The APT30GP60B and the APT6038BLL have the same die size, and the APT6010B2LL is approximately three times larger in area. Device cost depends on die area, so the device with the smallest die size that meets an application's requirements is generally the least expensive choice.

Suppose we want to switch 8 Amps at 200 kHz. By looking at Figure 4, it is clear that the APT6038BLL is the best part since it can switch at a much higher frequency than the other parts. Note that this is because of the f_{max1} pulse width limitation, which is what limits the usable frequency of the APT6010B2LL and the APT30GP60B below about 27 and 15 Amps respectively.

Now suppose we want to switch 20 Amps at 200 kHz. Either the APT30GP60B or the APT6010B2LL will work, but the APT30GP60B IGBT is about one third the cost of the APT6010B2LL because of its smaller

die size. The APT6038BLL is completely out of the running. Above 37 Amps the IGBT wins, even though its die size is smaller; its junction temperature would be lower than that of the MOSFET at a given frequency. This goes against conventional wisdom, which says that a MOSFET is always more efficient than an IGBT, and that higher efficiency means higher cost.

The curves in Figure 4 warrant a few more comments. First, note that the I_D rating of the APT6038BLL is 17 Amps, but in this application, this part can't handle more than about 10 Amps. Under different conditions though, such as lower duty cycle, it could handle its "rated current". Rated currents do not necessarily tell you how much current a device can handle in an application because they are based on continuous conduction loss (no switching loss) with the case held at a certain temperature. Basically they tell you the relative size and conduction loss of the device.

Second, a convenient comparison to note is that the I_D rating of the APT6010B2LL (continuous conduction with the case at 25 °C) is similar to the I_{C2} rating of the APT30GP60B (continuous conduction with the case at 110 °C), 54 and 49 Amps respectively. These two current ratings are similar, and the performance of each device is also similar. Both are capable of 200 kHz operation at about half their current ratings. So matching up the MOSFET I_D rating to the IGBT I_{C2} rating is a quick way to make initial comparisons between power MOSFETs and Power MOS 7® IGBTs.

Third, an IGBT has higher current density, which equates to lower on-state voltage and enables using a smaller die at the same power level as a high voltage power MOSFET. Due to dramatically increased on-resistance with increasing breakdown voltage ratings, power MOSFETs rated at or above about 300 Volts have lower current densities than IGBTs. This is why a PT IGBT with a 600 Volt rating can replace a MOSFET rated at around 400 Volts or higher. The smaller IGBT die size results in a higher thermal resistance than a power MOSFET, but the junction temperature is not higher due to lower losses. Remember, thermal resistance is accounted for in the usable frequency versus current curves.

Finally, different devices are best under different operating conditions. At high frequency and relatively low current, a MOSFET is usually the best choice (or you could use a smaller size PT IGBT). At high current, an IGBT is the best choice because conduction loss increases very modestly with increasing current, whereas the conduction loss of a power MOSFET is proportional to the current squared. At most frequency or current ranges, more than one device type might work well, so there is often more than one right answer. However, the latest generation PT IGBT will usually be the least expensive option. This very important point is the reason behind an emerging trend to replace power MOSFETs with IGBTs in high voltage, high frequency power supplies.

Gate Design and Drive

Power MOS 7® IGBTs are unique in that they are designed to switch extremely fast, and they incorporate a proprietary, striped layout metal gate design. The result is extremely low internal equivalent gate resistance (EGR), a fraction of an Ohm; much lower than poly-silicon gate devices. Low EGR enables faster switching and consequently lower switching losses. The striped, metal gate structure also results in extremely uniform and fast excitation of the gate, minimizing hot spots during switching transients and improving reliability. Finally, a striped gate structure is more tolerant of defects inevitably induced during the manufacturing process, which improves ruggedness and reliability, especially at high current or high temperature.

The gate drive requirements for these IGBTs are very similar to MOSFETs. When replacing a power MOSFET with a Power MOS 7® IGBT in a high frequency application, the same gate drive voltage may be used, even if it's only 10 Volts. However, a 12 to 15 Volt gate is recommended for both power MOSFETs and IGBTs to minimize the turn-on switching loss.

Just as for power MOSFETs, a negative voltage gate drive is not necessary for turn-off. Although initial turn-off may be sped up, a negative gate drive does not affect the IGBT tail current. The main reason for using a negative gate drive is to achieve the ultimate in switching speed while preventing dv/dt induced turn-on in a bridge topology.

Ways to avoid dv/dt induced turn-on through device design are:

- Maximize the ratio of C_{ies} over C_{res}, since these form a capacitive voltage divider at the gate.
- Minimize the equivalent gate resistance (EGR).
- Increase the gate threshold voltage.

The Power MOS 7® series of IGBTs addresses each of these with an industry leading figure of merit $V_{GE(th)} \times C_{ies} / C_{res}$, extremely low EGR due to the metal gate, and a 3 Volt minimum gate threshold voltage (4.5 Volt typical at 25 °C). In fact, this figure of merit is as good

or better than the industry leading Power MOS 7® series of power MOSFETs from Advanced Power Technology.

Temperature Effects

Turn-on switching speed and loss for both power MOSFETs and IGBTs are practically unaffected by temperature. Reverse recovery current in a diode however increases with temperature, which increases the turn-on loss in hard switched applications. Turn-off speed of power MOSFETs is also virtually unaffected by temperature, but IGBT turn-off speed degrades and switching loss consequently increases with increasing temperature. However, switching loss is low to begin with due to minority carrier lifetime control in Power MOS 7® IGBTs keeping the tail current quite short.

All IGBTs initially have a negative $V_{CE(on)}$ temperature coefficient (TC) that transitions to a positive TC as collector current increases from zero. The sign and magnitude of the $V_{CE(on)}$ TC can be determined by the slope of a graph of $V_{CE(on)}$ versus temperature at a fixed current. Figure 5 shows the APT65GP60B2 $V_{CE(on)}$ versus temperature for three currents.

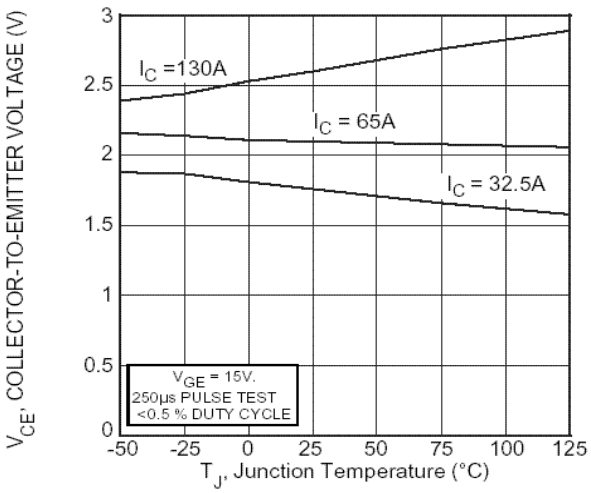

Figure 5 $V_{CE(on)}$ TC for APT65GP60B2

At 32.5 Amps, the slope is negative, corresponding to a negative $V_{CE(on)}$ TC. At 65 Amps, the slope and hence $V_{CE(on)}$ TC is almost zero. The TC crossover point for this device is at about 75 Amps, which can be seen in the output characteristics graph (not shown here). At 130 Amps, the APT65GP60B2 has a *positive* $V_{CE(on)}$ TC. The temperature coefficient has been carefully balanced by design, facilitating paralleling this device.

A negative TC is desirable because $V_{CE(on)}$ decreases slightly with increasing temperature, reducing conduction loss. Conventional power MOSFETs have a strong positive $R_{DS(on)}$ TC; conduction loss more than doubles when going from 25 °C to 125 °C operation. A positive temperature coefficient is desirable for paralleling because of inherent thermal stability, but it is not necessary as long as there is good heat sharing between devices [2], [3].

Performance in SMPS Circuits

Hard Switched Boost Converter

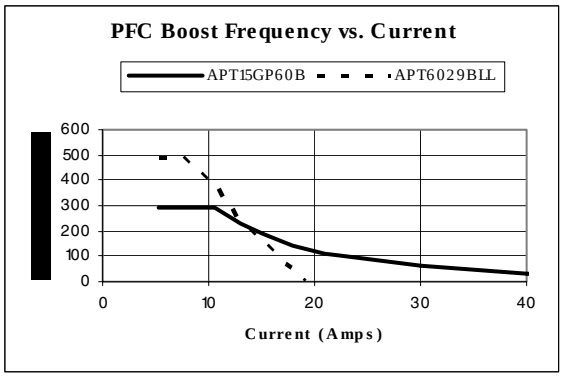

Figure 6 PFC Boost Frequency vs. Current

Figure 6 compares the maximum operating frequency versus current of an APT15GP60B IGBT (I_{C2} = 27 Amps) with an APT6029BLL MOSFET (I_D = 21 Amps). The test conditions are the same as for Figure 4: hard inductive switching, 400 V, T_J = 125 °C, T_C = 75 °C, 50% duty cycle, and 5 Ω total gate resistance. The same 15 Amp, 600 Volt output diode was used for each part. Each part can operate at 200 kHz, 14 Amps. At higher current, the IGBT is the better choice since its operating frequency is higher than for the MOSFET. The IGBT is also smaller than the MOSFET and consequently lower cost. Below 14 Amps, the MOSFET can operate at higher frequency than the IGBT, meaning that the MOSFET would be more efficient.

Phase Shift Bridge

Figure 7 shows the maximum operating frequency of the same type of parts as in Figure 6, except the IGBT is an APT15GP60BDF1 – a Combi part that incorporates an ultra-fast recovery diode anti-parallel to the IGBT. The APT6029BFLL is a FREDFET instead of a MOSFET, meaning it is a MOSFET with a fast body diode characteristic suitable for bridge applications.

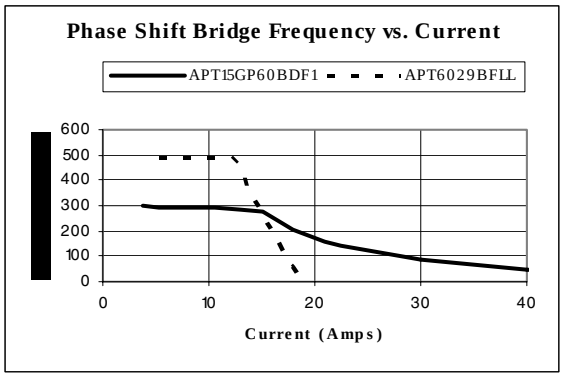

Figure 7 Phase Shift Bridge Frequency vs. Current

This phase shift bridge circuit has zero-voltage turn-on, and turn-off is considered to be hard switched. You can see that the frequency versus current curves have simply shifted to higher current compared to the hard switched boost converter of Figure 6. In particular, notice that the IGBT curve has shifted farther than the MOSFET curve. This is because the IGBT has much lower conduction loss than a MOSFET. The majority of MOSFET losses are due to conduction loss when operating above about 13 Amps. By comparison at 15 Amps, the APT6029BFLL has about 75 Watts conduction loss and the APT15GP60BDF1 has about 14 Watts conduction loss. Switching loss dominates the IGBT losses up to about 40 Amps. Above 40 Amps, IGBT conduction loss is higher than switching loss.

When operating below about 300 kHz, the IGBT takes more advantage of the benefits of soft turn-on in the phase shift bridge, i.e., the increase in its maximum operating current is greater than for the MOSFET. The same would be true if turn-off was soft switched. Even with no voltage across it, internal recombination due to minority carrier lifetime control in the PT IGBT ensures that a tail current won't drag on when the voltage across the device climbs. Low switching losses due to soft switching are complemented by the low conduction loss of the IGBT, regardless of whether switching is soft turn-on or soft turn-off, or both. Thus the Power MOS 7® IGBTs are well suited for soft as well as hard switching applications.

Another important point is that the performance of the diode in the IGBT Combi part is far superior to the FREDFET body diode, even though the FREDFET body diode is processed to significantly improve its recovery speed compared to a standard MOSFET body diode. This is because the area of the FREDFET body diode is much larger than the Combi diode, and such a large diode area is not required. The larger area of the FREDFET body diode results in much higher reverse recovery charge and current and consequently longer diode commutation time and higher conduction losses.

Conclusion

Combining significantly improved switching speed, low conduction loss, and universal soft switching compatibility with the all important factor of lower cost, the latest generation of PT IGBTs is truly capable of replacing MOSFETS in high frequency SMPS applications. Although high voltage power MOSFETs will have a place in the power electronics industry for the foreseeable future, the trend is for IGBTs to take their place.

[1] J. Dodge, J. Hess; "IGBT Tutorial", Application Note APT0201, Advanced Power Technology

[2] J. Dodge; "Parallel Connection of Power Electronic Devices", Application Note APT0202, Advanced Power Technology

[3] "Application Characterization of IGBTs", Application Note INT990, International Rectifier