

Technology to the Next Power

Application Note APT0408 IGBT Technical Overview

Distinguishing Features Application Tips

Jonathan Dodge, P.E.
Applications Engineering Manager
Advanced Power Technology

29 November 2004

What is an IGBT?

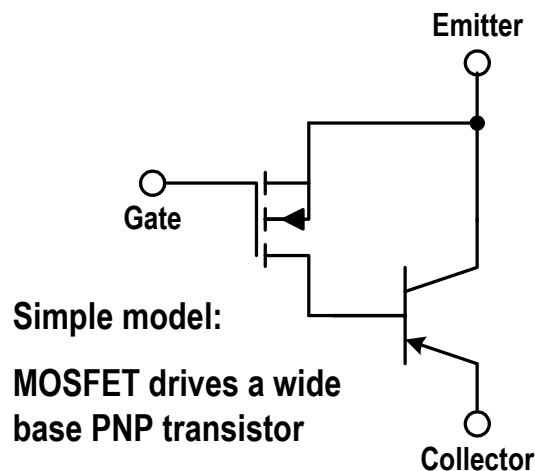
An IGBT is like a *MOSFET* and a *bipolar junction transistor* combined:

♣ *MOSFET*

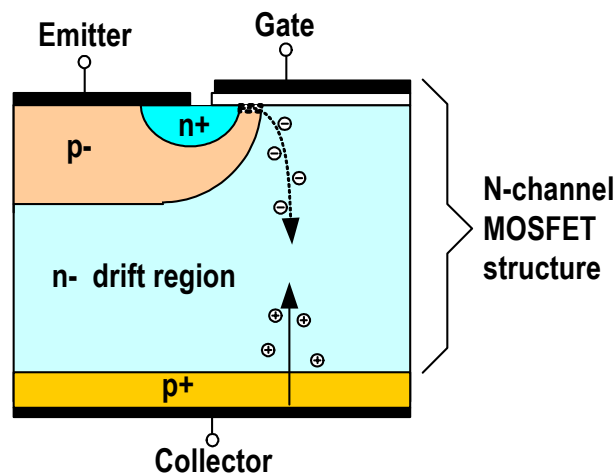
- A *voltage-controlled gate* that turns the device both on and off

♣ *Bipolar Transistor*

- *Bipolar current* – much lower resistance than a MOSFET
- *Tail current* at turn-off
- *Blocked reverse current*



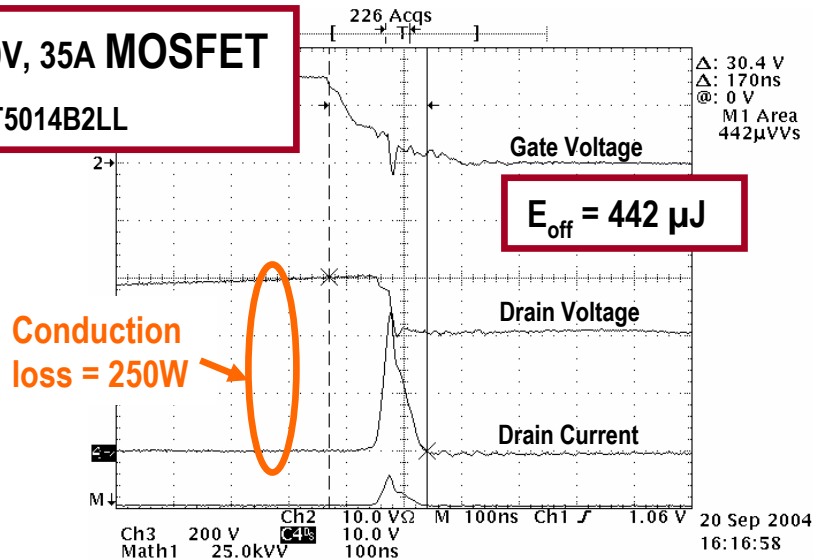
IGBT Cross Section



Tradeoff: Conduction vs. Switching Loss

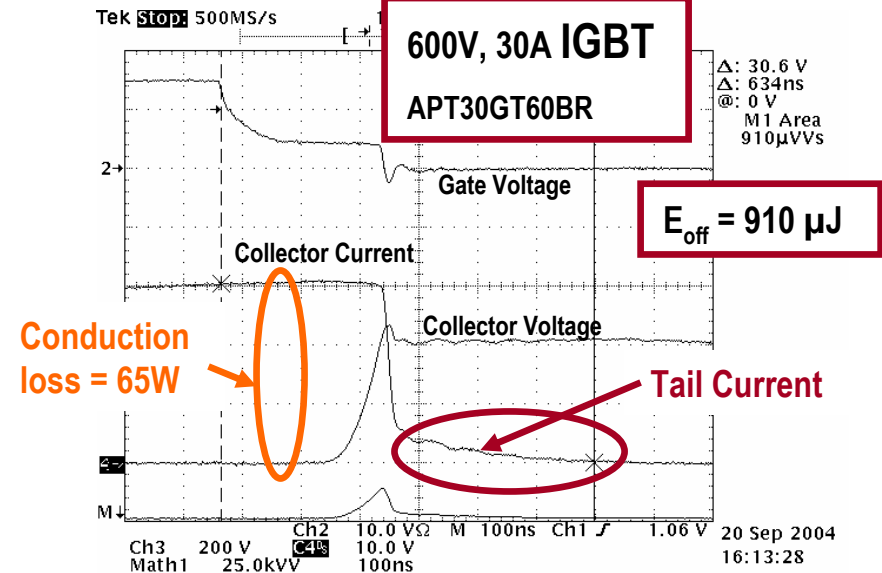
500V, 35A MOSFET

APT5014B2LL



600V, 30A IGBT

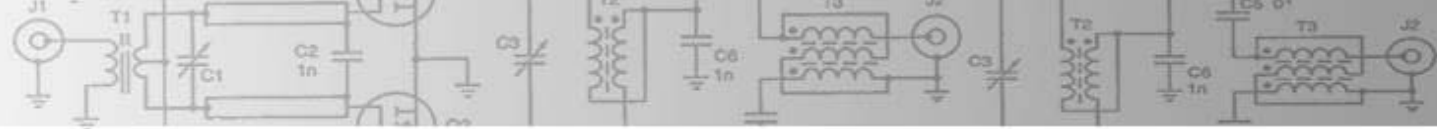
APT30GT60BR



- ♣ Low IGBT conduction loss due to bipolar current
- ♣ IGBT has higher switching loss due to tail current at turn-off

Test conditions: 400V, 30A, 125°C,
 $R_G = 10\Omega$, $V_{GG} = 15V$
hard switched,
no snubber

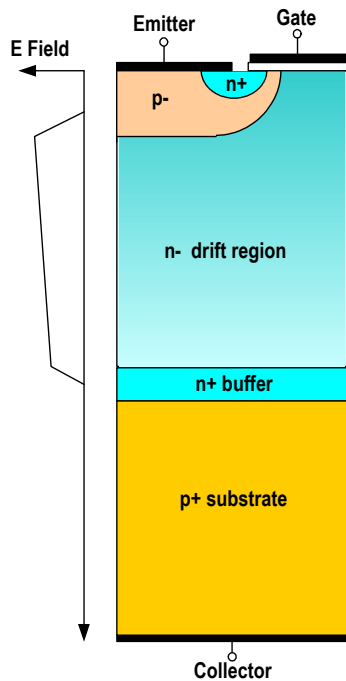
- Increases turn-off switching loss E_{off}
- Caused by minority carriers
 - At turn-off must be removed by internal recombination and sweep-out
 - Minority carrier lifetime control is sometimes used to accelerate internal recombination



IGBT Technology Capability Summary

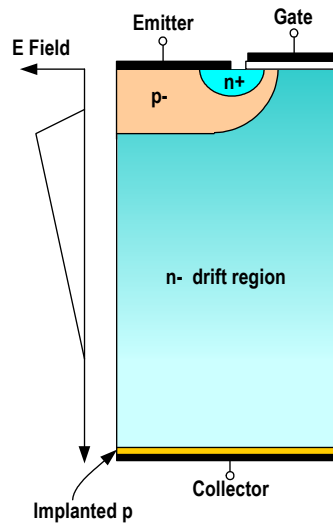
	PT	NPT	Field Stop
Switching Loss	Low Short tail current Significant increase in E_{off} with temperature	Medium Long, low amplitude tail current Moderate increase in E_{off} with temperature	Low Short tail current Moderate increase in E_{off} with temperature
Conduction Loss	Low Flat to slight decrease with temperature	Medium Increases with temperature	Low Increases with temperature
Paralleling	Difficult Must sort on $V_{CE(on)}$ Must share heat	Easy Optional sorting Recommend share heat	Easy Optional sorting Recommend share heat
Short Circuit Rated	Limited High gain	Yes	Yes

Construction



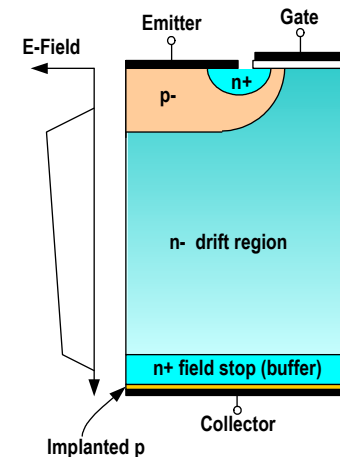
Punch-Through (PT)

- ♣ p+ substrate and epi
 - Heavy minority carrier injection
 - Requires minority carrier lifetime control
- ♣ Thin drift region lowers $V_{CE(on)}$
- ♣ Electric field “punches through” drift region to buffer layer



Non-Punch-Through (NPT)

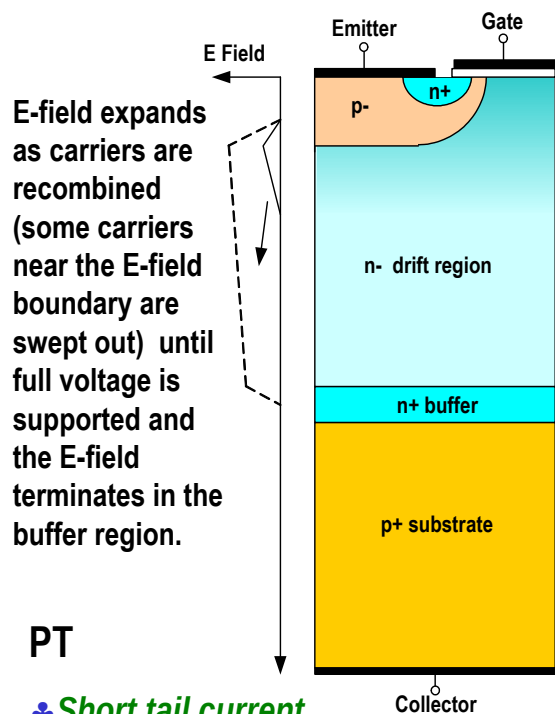
- ♣ Implanted p injector
 - Tightly controlled process
 - Controlled minority carrier injection
- ♣ No epi (lower cost)
- ♣ Typically no lifetime control
- ♣ Electric field does not punch through drift region



Field Stop

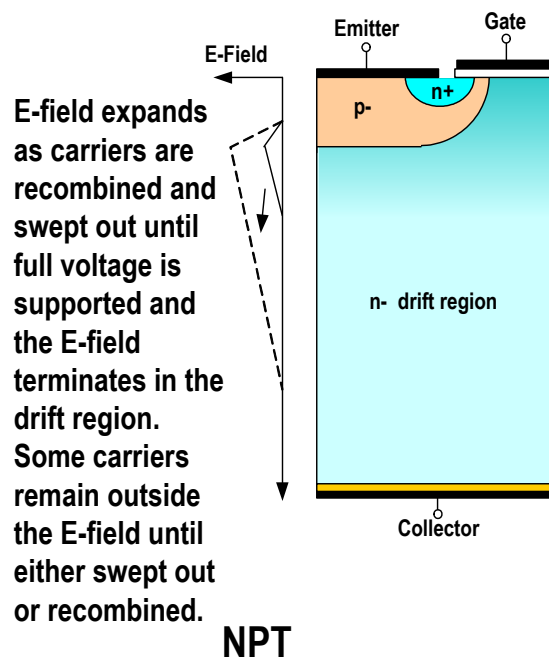
- ♣ Implanted p injector
 - Tightly controlled process
 - Controlled minority carrier injection
- ♣ No epi (lower cost)
- ♣ Thin drift region lowers $V_{CE(on)}$
- ♣ May use lifetime control
- ♣ Field stop (buffer) layer terminates electric field

Switching Speed

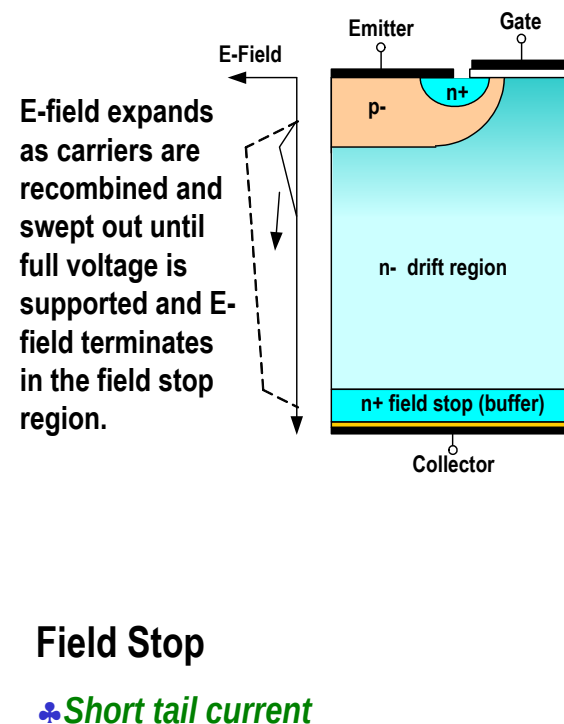


- Turn-off speed is determined largely by minority carrier lifetime control (sets recombination rate)
- Electric field extends across drift region, eliminating long, low amplitude tail current

❖ **More temperature sensitive** due to larger number of minority carriers

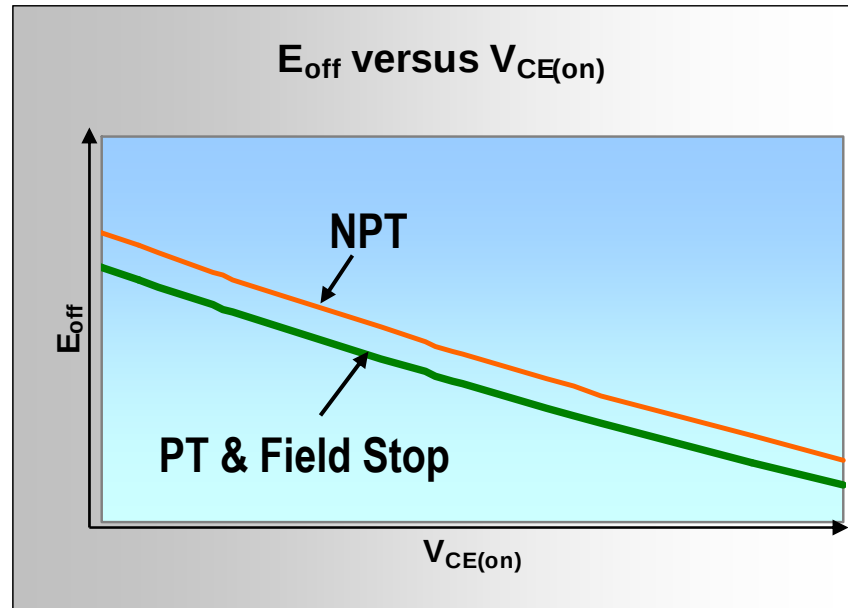


- Long minority carrier lifetime
- Electric field terminates within drift region
- Minority carriers not in presence of electric field diffuse into electric field
- Sweep-out of these carriers causes the long, low amplitude tail current

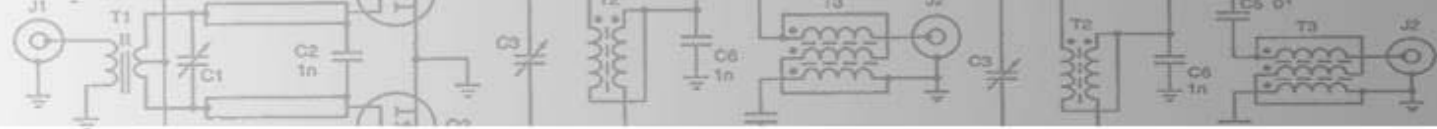


- Have higher carrier injection than NPT and hence sometimes use minority carrier lifetime control (less amount than PT)
- Electric field extends across drift region, eliminating long, low amplitude tail current

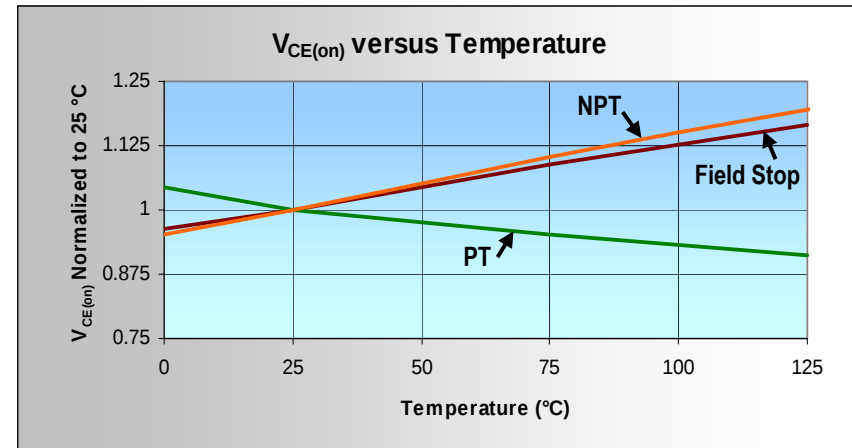
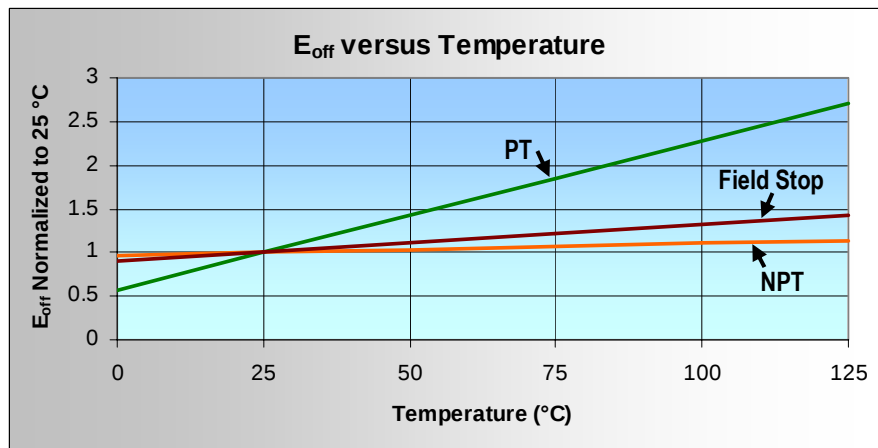
Conduction versus Switching Loss



- ♣ By design, E_{off} (switching loss) can be decreased by increasing $V_{CE(on)}$ (conduction loss)
- ♣ Conversely, $V_{CE(on)}$ can be decreased by increasing E_{off}
- ♣ E_{off} versus $V_{CE(on)}$ forms a technology curve
 - Both E_{off} and $V_{CE(on)}$ must be considered together when comparing IGBTs
 - The better the technology, the closer the curve is to the origin



$V_{CE(on)}$ and E_{off} versus Temperature



- ❖ $V_{CE(on)}$ and E_{off} are both temperature dependent
 - Slope of $V_{CE(on)}$ versus temperature is the temperature coefficient
 - Minority carrier lifetime increases with temperature
- ❖ PT
 - E_{off} increases significantly with temperature because of the large number of minority carriers
 - $V_{CE(on)}$ decreases slightly at operating current, also because of the large number of minority carriers
- ❖ NPT and Field Stop
 - E_{off} increases moderately with temperature because a moderate number of minority carriers are injected
 - $V_{CE(on)}$ increases because there are fewer minority carriers to overcome silicon resistance, which increases with temperature
- ❖ One IGBT type might perform better than another type at room temperature but worse at higher temperature

Paralleling

PT IGBTs are more **difficult**

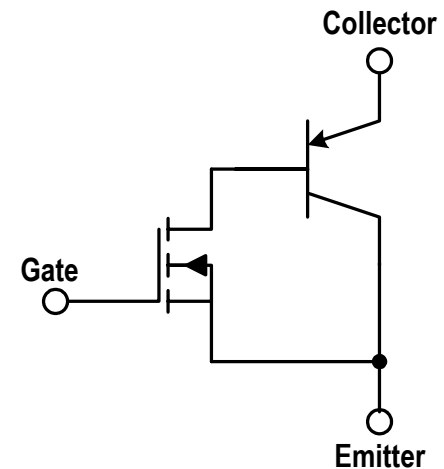
- ♣ Sorting is required for good current sharing
 - Recommend sort $V_{CE(on)}$ at nominal test current to within 0.1V
 - Part-to-part variation in $V_{CE(on)}$ is wider because of
 - p+ substrate and epi
 - Minority carrier lifetime control
- ♣ Negative temperature coefficient of $V_{CE(on)}$ (secondary issue)
 - PT IGBTs can be paralleled if *sorted* and they *share heat*
 - Can avoid paralleling by using single large die size PT IGBT

NPT and Field Stop IGBTs are **easy**

- ♣ Good current sharing due to narrow part-to-part distribution of $V_{CE(on)}$
 - Tight parameter distribution simplifies or eliminates sorting requirement
- ♣ Positive temperature coefficient of $V_{CE(on)}$
 - Inherent thermal stability
- ♣ Parallel similar to MOSFETs

Avalanche Capability

- ♣ All types of IGBTs can survive avalanche
 - Not all IGBTs have avalanche capability though
 - Depends on specific IGBT design
- ♣ More limited than MOSFETs due to:
 - Smaller die size for same power level
 - Higher gain at avalanche point due to PNP structure
- ♣ Reverse avalanche at about 25V for PT and many NPT and Field Stop
 - Some devices have high reverse avalanche capability, some don't; usually not specified
 - NPT can theoretically block similar voltage in both polarities but reverse breakdown voltage is usually much smaller (except for specialty devices)



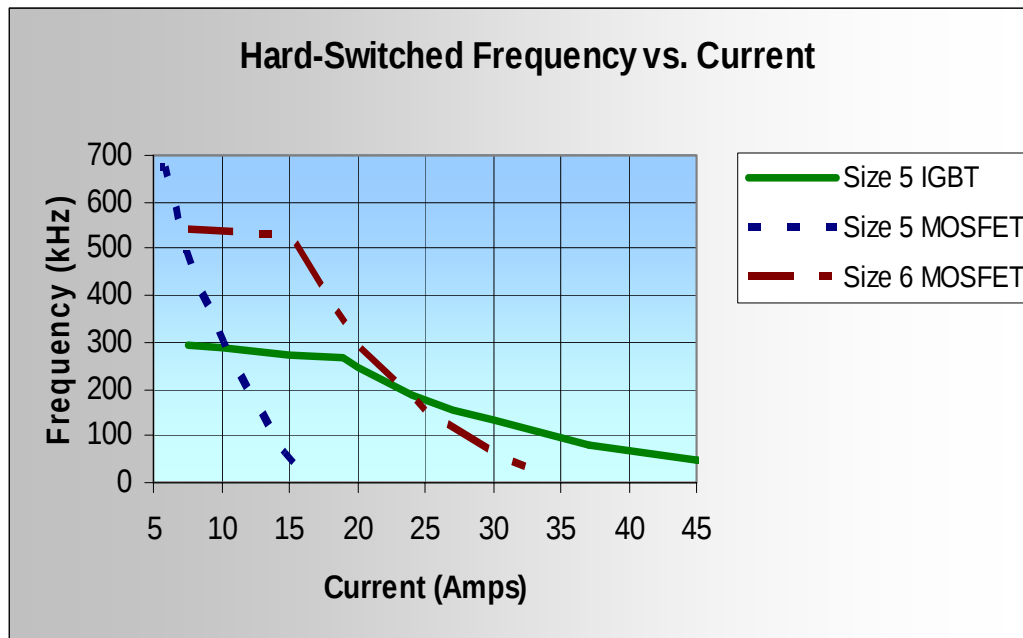
Usable Frequency and Current

IGBTs are best at

- ✦ Low to medium frequency – Up to about 150 kHz for 600V IGBT, 100kHz for 900V IGBT, 50kHz for 1200V IGBT, hard switched
- ✦ High current – more than 25% of current rating
- ✦ High voltage – more than 200V applied voltage

Smaller IGBT replaces MOSFET

- ✦ When replacing MOSFETs, match up current ratings such that IGBT I_{C2} rating $\geq$ MOSFET I_D rating



Example:

600V PT IGBT vs. 500V MOSFETs

Same ultrafast diode clamp in each case

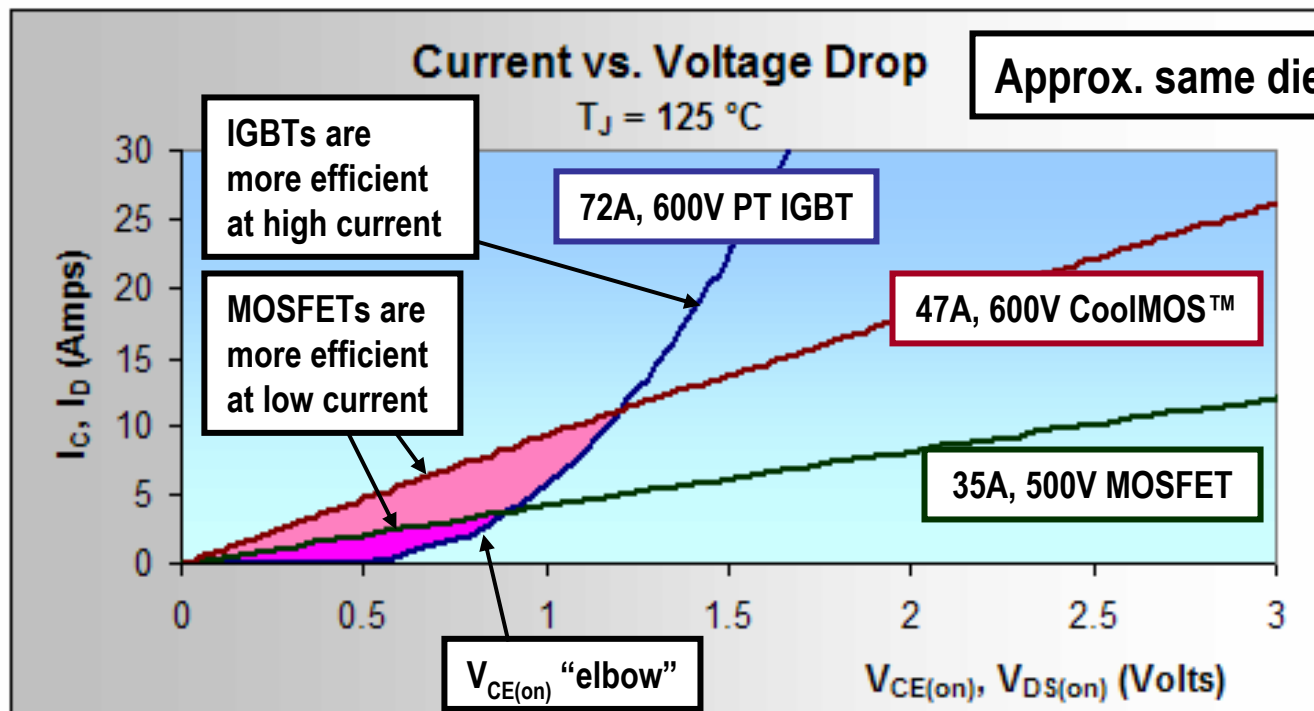
$$F_{\max} = \min(f_{\max 1}, f_{\max 2})$$

$$f_{\max 1} = \frac{0.05}{t_{d(\text{on})} + t_r + t_{d(\text{off})} + t_f}$$

$$f_{\max 2} = \frac{P_{\text{diss}} - P_{\text{cond}}}{E_{\text{on2}} + E_{\text{off}}}$$

$$P_{\text{diss}} = \frac{T_J - T_C}{R_{\theta JC}}$$

Operation at Low Current



Approx. same die size devices

Side note Implications for PFC:

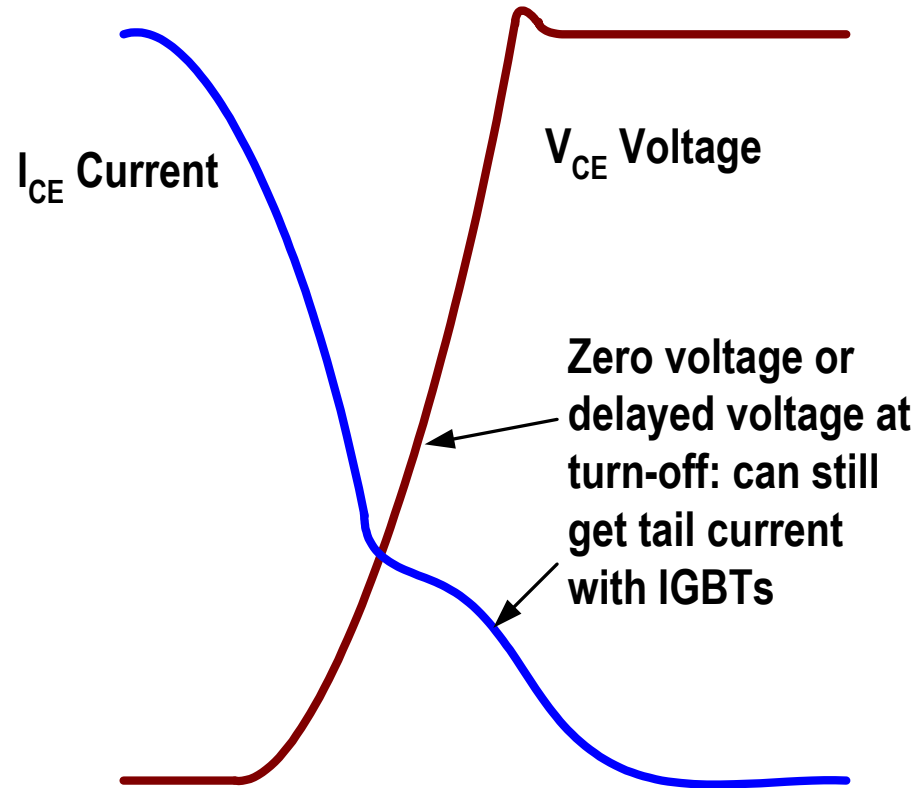
IGBTs beat MOSFETs only at high power & hard switched (above ~2kW) because:

- ♣ Low current near zero-crossings favors MOSFETs
- ♣ Higher turn-off switching loss of IGBT
- ♣ Possible incompatibility with turn-off snubbers if used with IGBT

- ♣ At low current, an IGBT has a $V_{CE(on)}$ "elbow": $V_{CE(on)}$ is never less than a diode voltage drop because of the second p-n junction in an IGBT
- ♣ MOSFETs have lowest conduction loss at low current

Snubbers and Soft Switching

- ♣ Soft switching can be zero-voltage, zero-current, or a combination of the two
- ♣ IGBT turn-on is like a MOSFET
 - Zero-voltage and zero-current both work well at turn-on
 - Reduced voltage and/or current also work well
- ♣ IGBT turn-off is like a bipolar
 - Zero-current works with IGBTs because there are no stored minority carriers
 - With zero-voltage or reduced voltage, a tail current can appear as collector-emitter voltage rises
 - There is less tail current impact if significant minority carrier lifetime control is used (as with a fast PT IGBT)



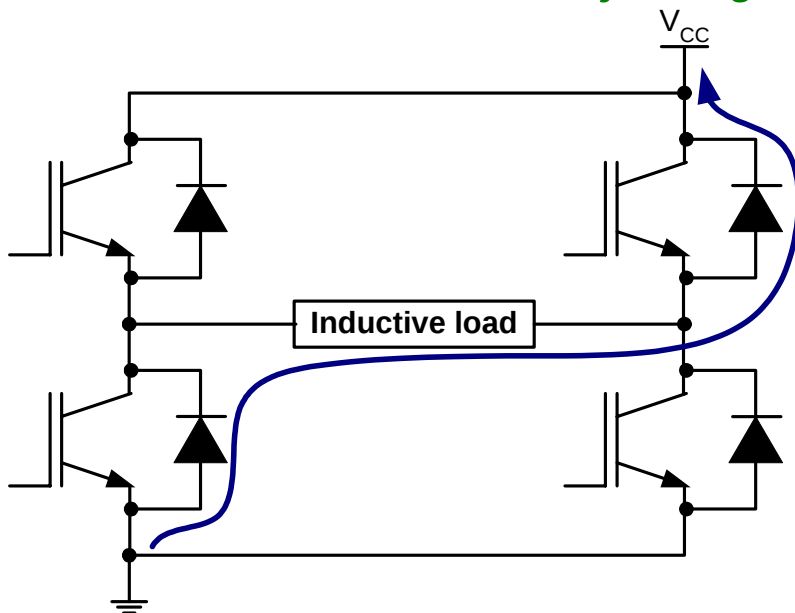
Applications Requiring Anti-Parallel Diode

Some applications require an anti-parallel diode to:

- ♣ Carry load current (freewheeling diode)
- ♣ Protect the switch

Combi products package an optimized diode with the IGBT

- ♣ *Much lower recovery charge* than MOSFET/FREDFET body diode

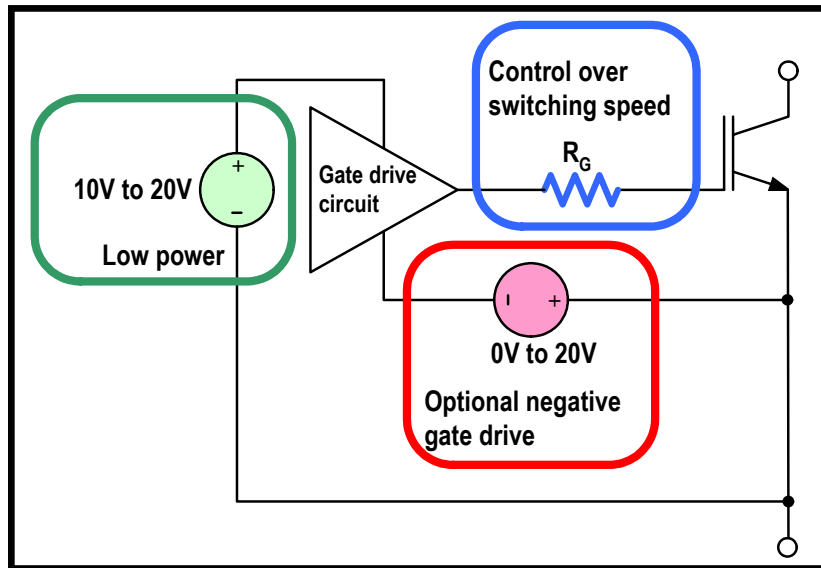


Side note:

IGBT Combis designed for SMPS have a diode current rating that is usually less than IGBT current rating because:

- ♣ Lower duty factor for the diode is common in SMPS applications
- ♣ Lower switching loss in the diode itself; less heat is generated in the diode than in the IGBT

IGBT Gate Drive



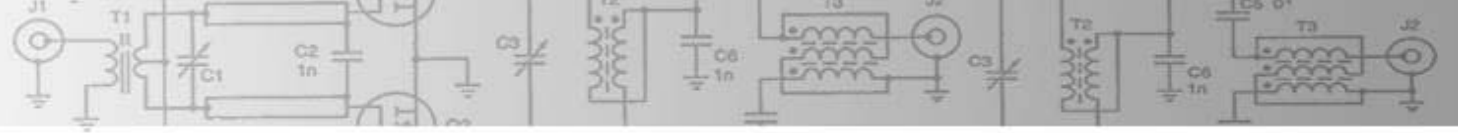
Side note:

Desat method of over-current detection is more effective with NPT and Field Stop IGBTs due to

- ♣ Lower gain
- ♣ Positive $V_{CE(on)}$ temperature coefficient

It is difficult to get desat to work with PT IGBTs

- ♣ Switching speed (rise and fall times) controlled by gate resistance, like a MOSFET
- ♣ **Positive-only gate drive OK, but...**
 - Negative gate drive is recommended for noise immunity in bridge and high power applications
 - Negative gate drive has no effect on tail current
- ♣ Drive voltage range is 15 to 18 Volts typically (often 15V minimum, 20V maximum):
 - IGBTs have higher gain than high voltage MOSFETs, therefore benefit more from higher gate drive voltage (lower turn-on loss, slightly lower conduction loss)
 - Some MOSFETs have a lower threshold voltage range than IGBTs
- ♣ IGBTs often have lower capacitance due to smaller die size – require less gate drive current than MOSFETs



Choosing an IGBT

- ♣ Field stop will replace NPT over time
 - Field Stop can be used where NPT is used
 - Field Stop is considered NPT because it has no epi, even though the electric field punches through drift region. It is really a PT IGBT with no epi.
 - Field Stop is sometimes simply called NPT, so you don't always know it is really Field Stop
- ♣ When paralleling, NPT and Field Stop are usually used
 - As switching speed approaches that of a MOSFET, Field Stop will be attractive for most massive paralleled applications
- ♣ Short Circuit Capable (motor drive):
 - High speed PT IGBTs are not short circuit rated although some low speed PT IGBTs are
 - NPT and Field Stop are short circuit capable
- ♣ For a given switching speed, PT IGBTs have a conduction loss advantage at operating temperature
- ♣ NPT and Field Stop can be lower cost