APT

Technology to the Next Power

Application Note APT0408
IGBT Technical Overview

Distinguishing Features
Application Tips

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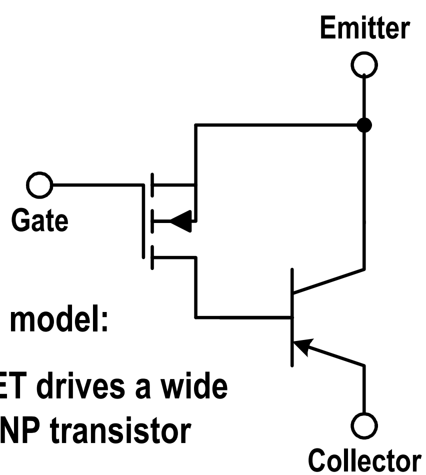
29 November 2004

What is an IGBT?

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

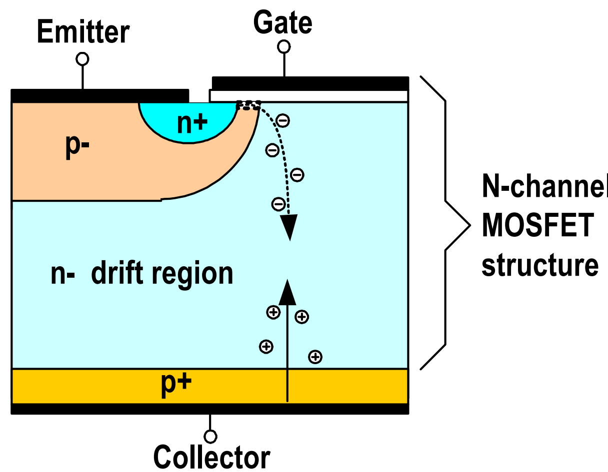
- *MOSFET*
  - A *voltage-controlled gate* **that turns the device both on and off**
- *Bipolar Transistor*
  - *Bipolar current* **– much lower resistance than a MOSFET**
  - *Tail current* **at turn-off**
  - *Blocked reverse current*



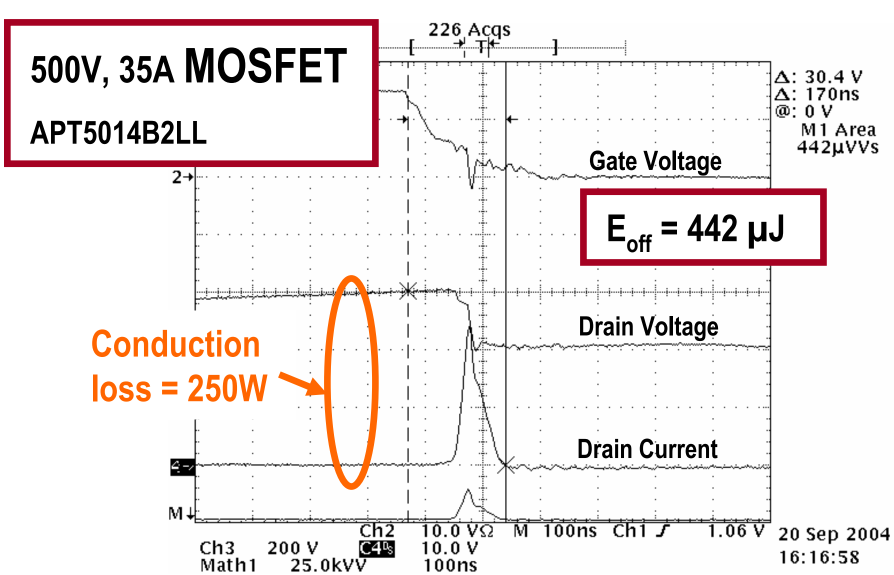
Simple model:

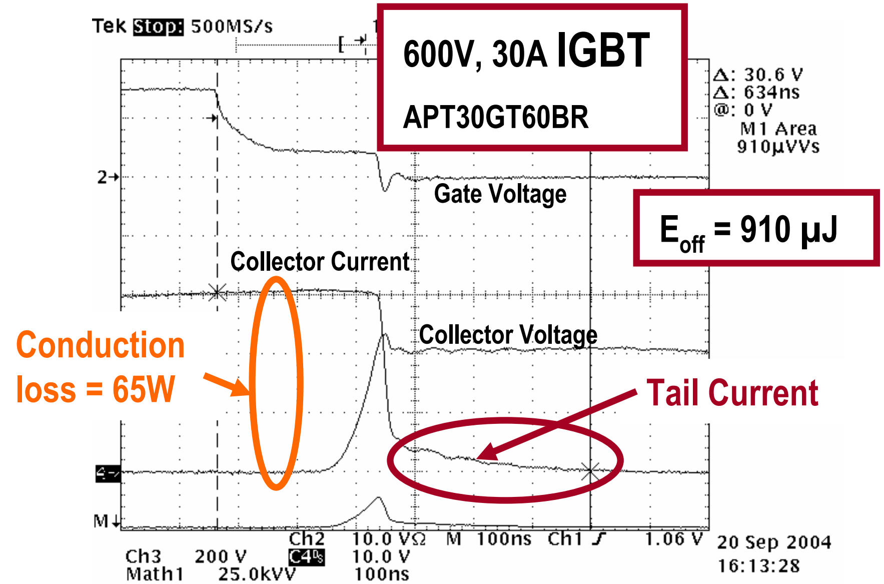
MOSFET drives a wide base PNP transistor

IGBT Cross Section



Tradeoff: Conduction vs. Switching Loss





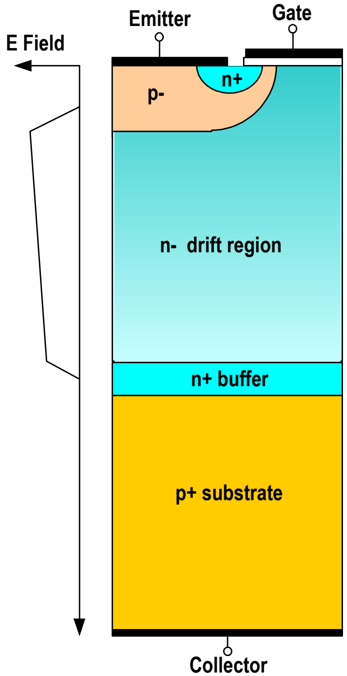
Test conditions: 400V, 30A, 125°C,
R_G = 10Ω, V_{GG} = 15V
hard switched,
no snubber

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

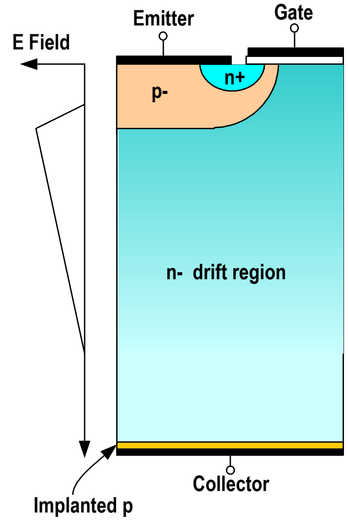
	PT	NPT	Field Stop
Switching Loss	**Low** Short tail current Significant increase in E_{off} with temperature	**Medium** Long, low amplitude tail current Moderate increase in E_{off} with temperature	**Low** Short tail current Moderate increase in E_{off} with temperature
Conduction Loss	**Low** Flat 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



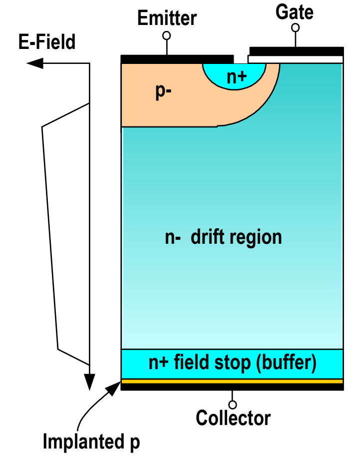
Punch-Through (PT)

- 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

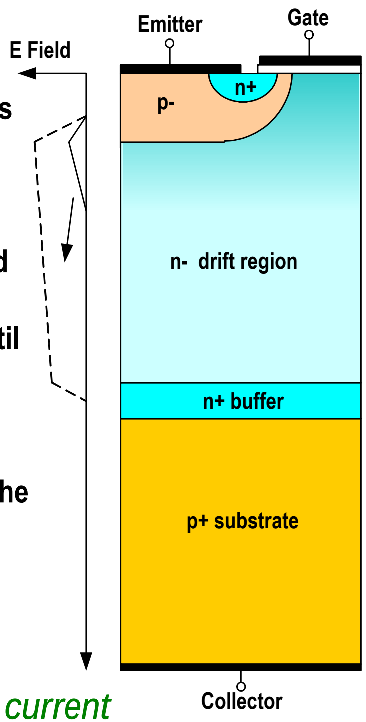


Field Stop

- 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

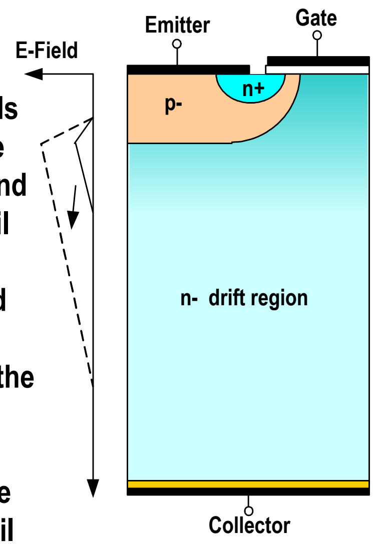
E-field expands as carriers are recombined (some carriers near the E-field boundary are swept out) until full voltage is supported and the E-field terminates in the buffer region.



PT

- *Short tail current*
  - 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

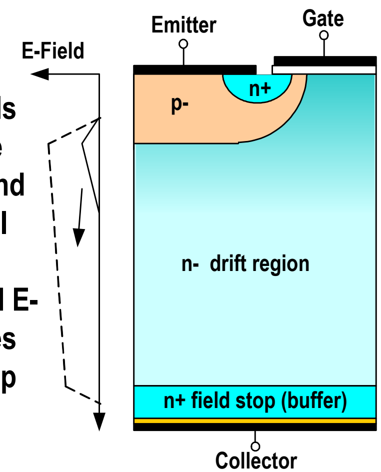
E-field expands as carriers are recombined and swept out until full voltage is supported and the E-field terminates in the drift region. Some carriers remain outside the E-field until either swept out or recombined.



NPT

- *Long, low amplitude tail current*
  - 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

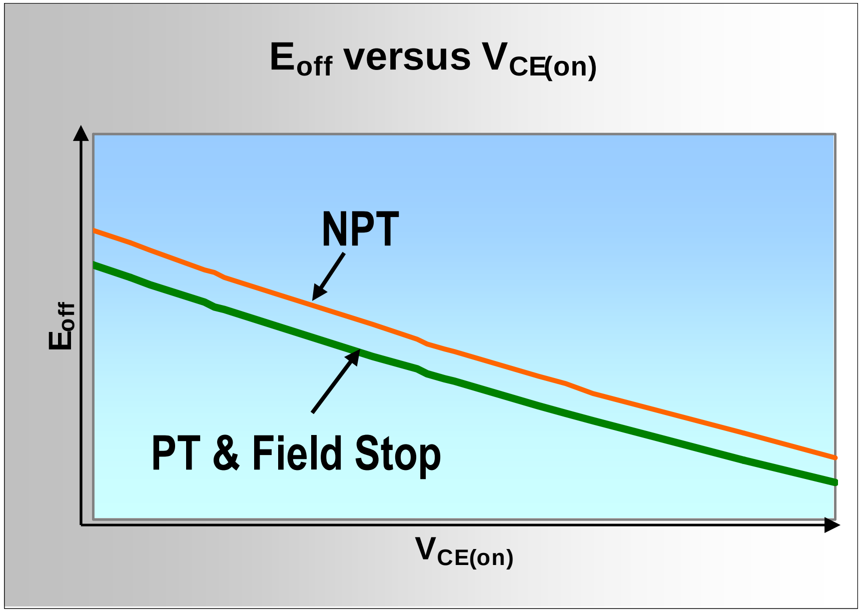
E-field expands as carriers are recombined and swept out until full voltage is supported and E-field terminates in the field stop region.



Field Stop

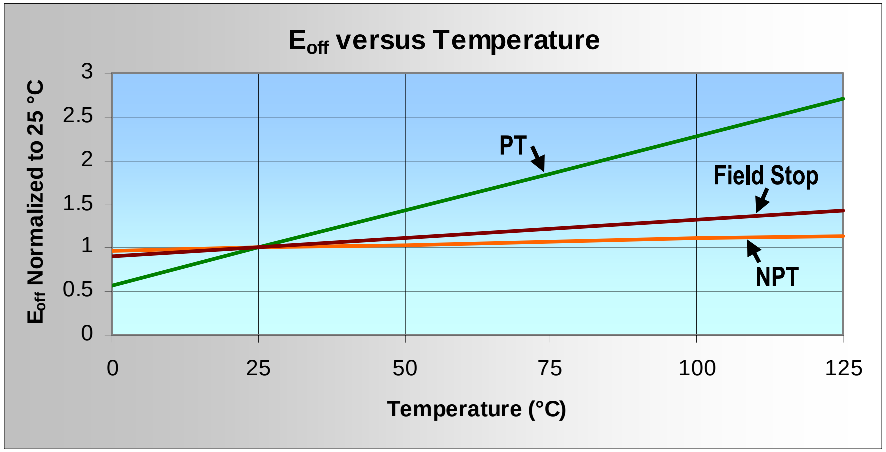
- *Short tail current*
  - Have higher carrier injection than NPT and hence sometimes use minority carrier lifetime control (less amount than PT)
  - Electric field extends across drift region, eliminating long, low amplitude tail current

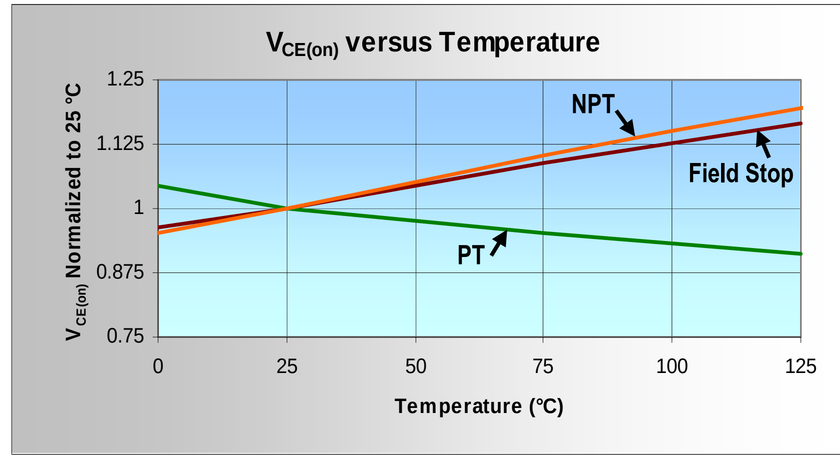
Conduction versus Switching Loss



- 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*

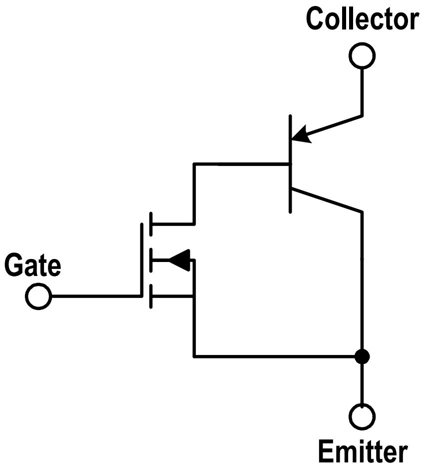
- Sorting is required for good current sharing
  - Recommend sort $V_{CE(on)}$ at nominal test current to within 0.1V
  - Part-to-part variation in $V_{CE(on)}$ is wider because of
    - p+ substrate and epi
    - Minority carrier lifetime control
- Negative temperature coefficient of $V_{CE(on)}$ (secondary 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)



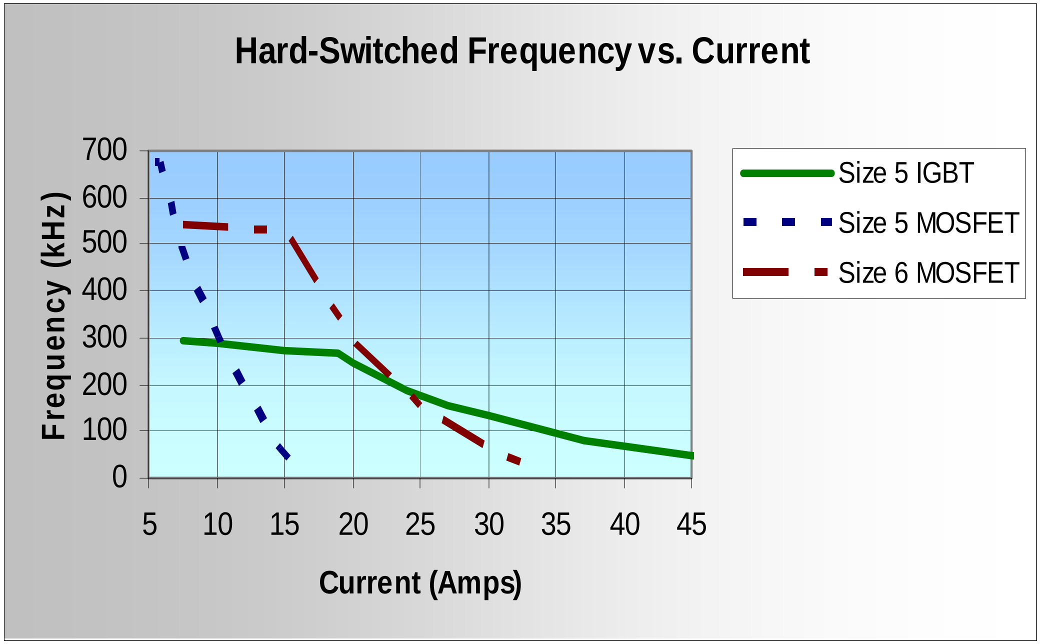
Usable Frequency and Current

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 ≥ MOSFET I_D rating



Example:

600V PT IGBT vs. 500V MOSFETs

Same ultrafast diode clamp in each case

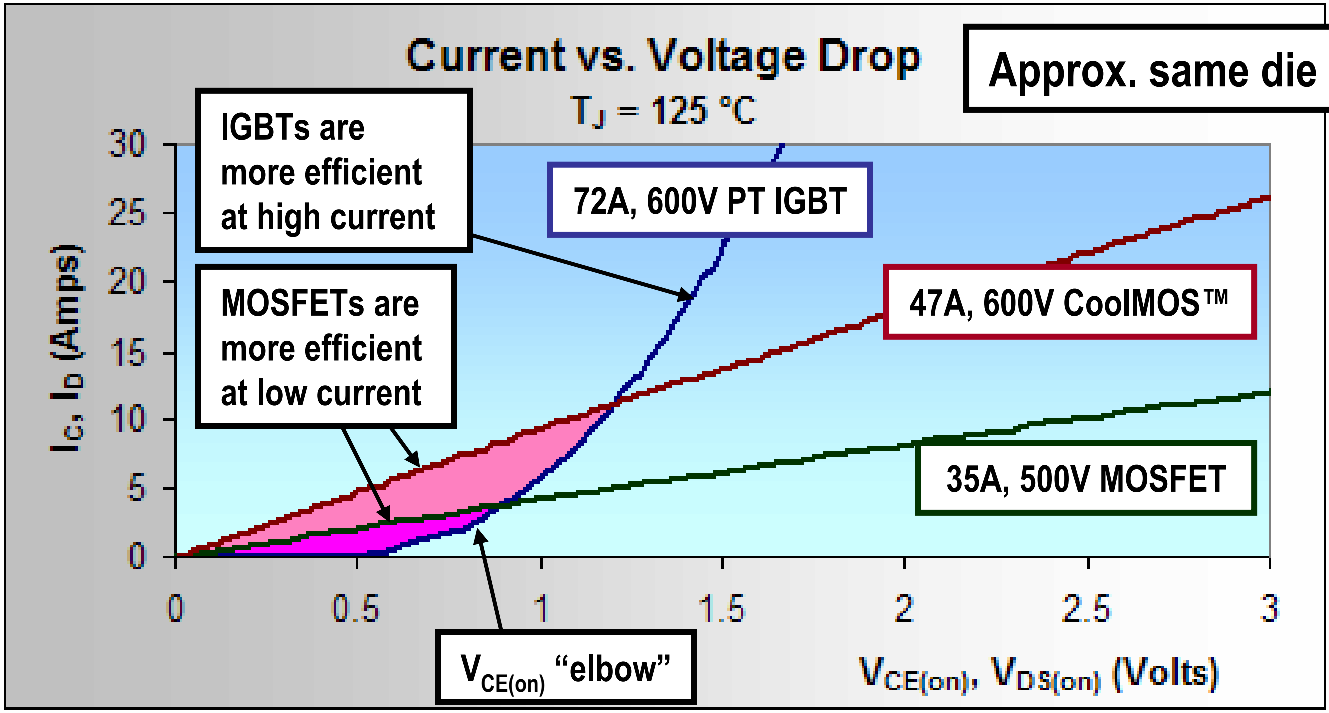
$$F_{max} = \min(f_{max1}, f_{max2})$$

$$f_{max1} = \frac{0.05}{t_{d(on)} + t_r + t_{d(off)} + t_f}$$

$$f_{max2} = \frac{P_{diss} - P_{cond}}{E_{on2} + E_{off}}$$

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

Operation at Low Current



Side note

Implications for PFC:

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

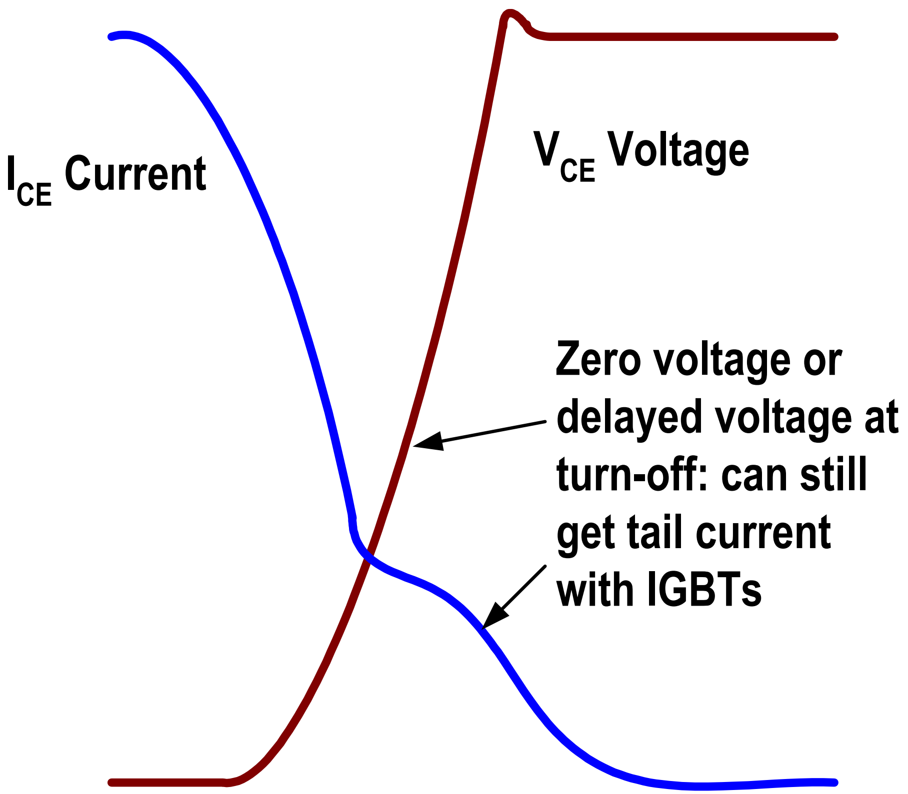
- Low current near zero-crossings favors MOSFETs
- Higher turn-off switching loss of IGBT
- Possible incompatibility with turn-off snubbers if used with IGBT

- **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**

"COOLMOS" comprise a new family of transistors developed by Infineon Technologies AG. "COOLMOS" is a trademark of Infineon Technologies AG

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)



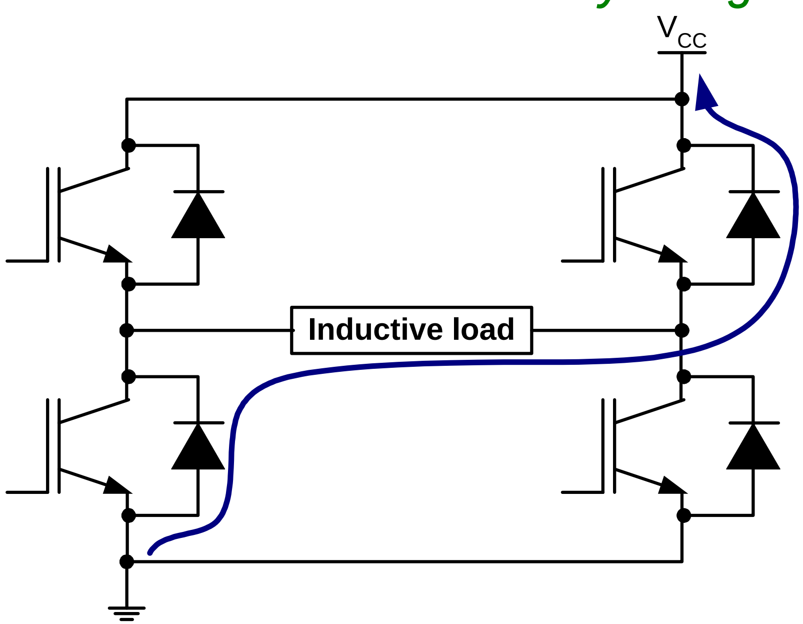
Applications Requiring Anti-Parallel Diode

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**

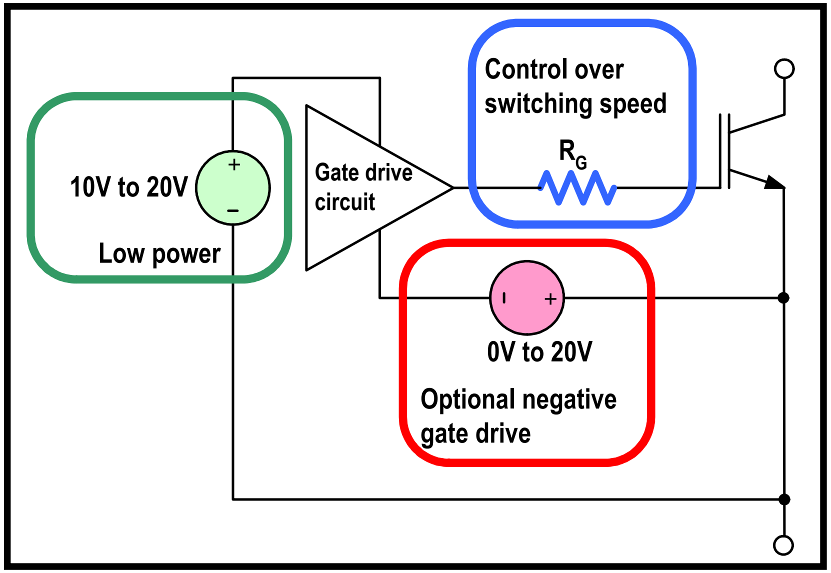


Side note:

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