Technology to the Next Power

Application Note APT0408
IGBT Technical Overview

Distinguishing Features
Application Tips

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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*

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**IGBT Cross Section**

- Emitter
- Collector
- Gate
- N-channel MOSFET structure
- Simple model: MOSFET drives a wide base PNP transistor
Tradeoff: Conduction vs. Switching Loss

♣ 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 $E_{\text{off}}$
  - 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

500V, 35A MOSFET
APT5014B2LL

600V, 30A IGBT
APT30GT60BR

Conduction loss = 250W

Conduction loss = 65W

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

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


Construction

Punch-Through (PT)
- Implant 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
- Thin drift region lowers $V_{CE(on)}$
- Electric field “punches through” drift region to buffer layer

Non-Punch-Through (NPT)
- Implant 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
- Implant 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

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

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 $\geq$ MOSFET $I_D$ rating

Example:

600V PT IGBT vs. 500V MOSFETs

Same ultrafast diode clamp in each case

- $F_{\text{max}} = \min(f_{\text{max}1}, f_{\text{max}2})$
- $f_{\text{max}1} = \frac{0.05}{t_{\text{on}} + t_r + t_{\text{off}} + t_f}$
- $f_{\text{max}2} = \frac{P_{\text{diss}} - P_{\text{cond}}}{E_{\text{on}2} + E_{\text{off}}}$
- $P_{\text{diss}} = \frac{T_f - T_C}{R_{\text{JC}}}$
Operation at Low Current

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

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

"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