Low-Loss IGBTs for Sub-2.5kW Inverter Applications

Better trade-off between device electrical performance and ruggedness

New depletion-stop trench IGBT technology combines low switching losses with the traditional IGBT advantage of low conduction loss for applications such as voltage domestic- and industrial-motor drives in the 2-30 kHz range.

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<IGBTs have traditionally addressed applications requiring high-voltage and -current ratings and relatively slow switching frequencies. When the switching frequency is low, the inherently low conduction losses resulting from the device's low VCE(on) (collector-to-emitter saturation voltage), which derive from the IGBT's minority carrier operation, outweigh the traditionally poor switching performance, enabling high overall operating efficiency. Mains-voltage applications such as energy-saving variable-speed motor drives can benefit from IGBTs' low on-state losses, which are lower than the corresponding losses in a power MOSFET. However, hard-switching designs operating at frequencies from 2-30kHz require improvements to the traditional IGBT's switching performance.

IGBT loss mechanisms

The latest-generation IGBTs, which benefit from depletion-stop trench technology, address the requirement for low conduction and switching losses, and carry up to 60% more RMS current than the previous generation of devices. This results in smaller discrete IGBTs and IGBT modules, and enables designers to reduce heat sink size significantly.

Switching losses in IGBTs result from the slow dispersal of holes in the drift region after the gate-emitter voltage falls below the threshold voltage to turn the device off. Either the holes recombine or a voltage gradient sweeps them out. Until this process completes, the IGBT exhibits a tail current, which slows the switching speed and increases switching losses. The PT (punch through) IGBT introduced a buffer layer adjacent to the drift region to quickly absorb remaining holes during turn off and, thereby, eliminate the excessive tail current. However, this enhanced switching performance is at the expense of higher VCE(on). In addition, PT IGBTs do not display the short-circuit-withstand capability most motor-control applications require.

Depletion-stop trench IGBTs

This lost conduction performance can be regained by adopting a trench structure to increase channel density compared to the traditional planar IGBT structure. Other factors that enhance VCE(on) performance include enhanced accumulation-layer injection and elimination of the parasitic JFET resistance inherent in the planar IGBT structure. Introducing a low-dose field-stop layer to the trench IGBT enhances the trade off between VCE(on) and switching loss still further, due to a reduction in the n-base thickness.

The depletion-stop trench technology now enters the next evolutionary stage in this progress toward low IGBT conduction and switching losses. The new depletion-stop layer allows further thinning of the n-base as well as a higher transistor gain and switching speed. In addition, the optimised device displays highly efficient anode properties, enabling enhanced control over minority carrier injection and a lower tail current at turn-off, delivering a further reduction in turn-off losses.

This new thin wafer, depletion-stop trench IGBT technology offers improved efficiency while maintaining the smooth turn-off characteristics and robust SOA (safe operating area) that hard-switching applications demand. VCE(on) and ETS (total switching energy) are both considerably lower than for planar PT and NPT type IGBTs. This combination of low saturation voltage and low total switching energy reduces power dissipation and improve current handling in applications operating at switching frequencies up to 30kHz. These devices also provide higher power density and reduce heatsink dimensions. Some applications can entirely eliminate the heatsink.

A schematic of the depletion-stop trench IGBT device shows emitter N+ regions adjacent to the trench (Figure 1). The fabrication process grows an oxide layer on the trench walls and then deposits polysilicon, filling the trench volume. The base contact and channel form through a P-base diffusion and a heavy P+ implant, respectively. The deep trench extends below the P-base junction to form a gate-bias-induced channel between N+ emitter and N- drift region. The P+ region in the backside of the wafer enhances anode efficiency. The combination of this device construction and the trench structure's high channel density produces a high carrier density in the drift region and a low forward voltage drop.

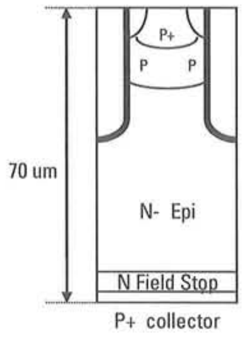

Figure 1: Schematic cross-section of the depletion-stop trench IGBT

In terms of forward voltage, switching energy, and RMS current versus frequency characteristics, trench IGBT devices offer improved performance compared to planar IGBTs. The depletion-stop trench IGBT devices clearly show lower conduction and switching-energy losses, leading to greater efficiency in inverter applications operating at high switching frequencies.

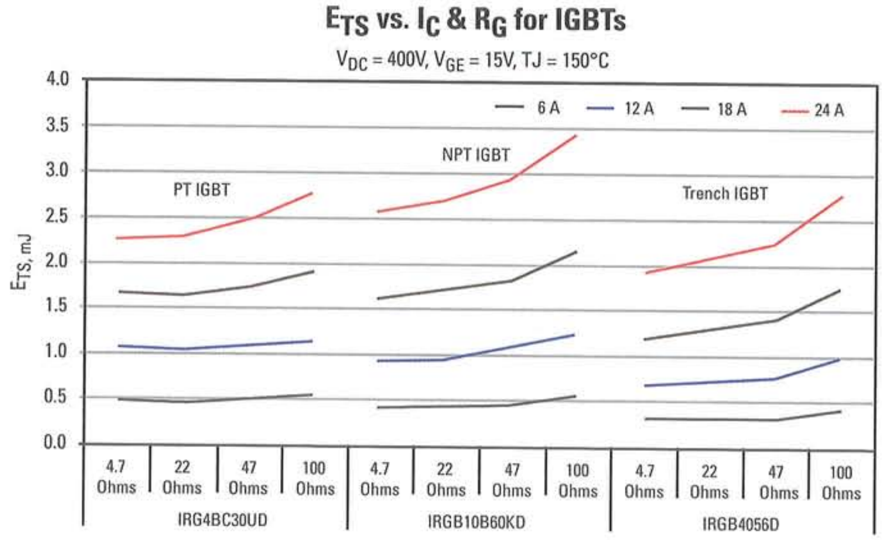

Figure 4: Switching energy characteristics of various IGBT technologies

Reduced stress for enhanced reliability
Further benefits of the depletion-stop trench IGBT include a number of features that provide more-robust performance in motion-control applications. One example is the IGBT's smooth turn-off characteristics under short-circuit conditions, which reduce voltage spikes and stress on the IGBT.

Another benefit is the absence of gate over charging during short-circuits. This can occur in older IGBT structures, leading to an over-current spike that stresses the device and impairs the reliability of the inverter. The trench IGBT's square RBSOA characteristic also enhances robustness by allowing safe switching under severe overload. This, along with high peak turn-OFF capability and good short-circuit rating, will allow more robust and reliable inverters suitable for a wide variety of applications.

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International Rectifier has developed the depletion-stop trench technology with the aim of maximising IGBT switching performance for appliance- and industrial-drive applications. The device designs optimise carrier lifetime in the drift region, as well as carrier lifetime and doping concentration in the depletion-stop region near the anode. Leakage current and device breakdown voltage both increase with decreasing lifetime in the drift region.

In addition, IR uses a 70-micron-thick wafer, which permits lightly doping the anode. This helps to reduce the total stored charge thereby improving the device's switching performance, especially at higher temperatures.

Optimising the construction, geometry, and doping in this way leads to lower VCE(on) and lower switching losses than the previous PT and NPT IGBT devices. In practical applications, depletion-stop trench IGBTs reduce losses and deliver up to 60% more RMS current than previous generation devices. For a given current, these devices require roughly 50% smaller heat sinks. The technology is suitable both for discrete IGBTs and for emerging families of smart power modules that combine driver circuitry with 600V IGBTs to simplify appliance-motor-control design. Depletion-stop trench IGBT technology enables a typical size reduction of 25% for such integrated modules.

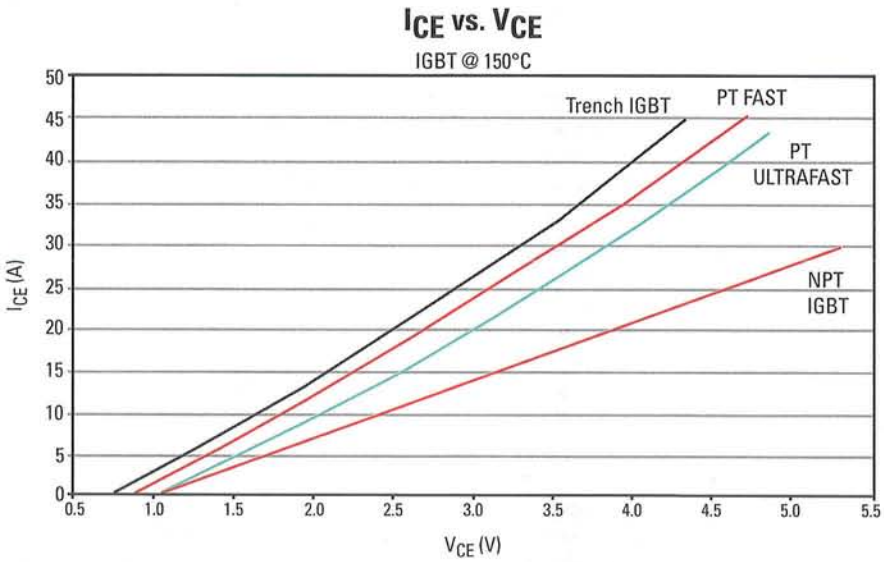

Figure 3: Forward voltage characteristics of various IGBT technologies

First silicon

International Rectifier has fabricated a 600V depletion-stop trench IGBT with a typical threshold voltage of 5.25V and typical VCE(on) of 1.6V. Figure 2 shows the typical depletion-stop trench-IGBT switching waveforms for turn-on and turn-off. In addition to lower losses, the diagram also highlights the much smoother turn-off waveform, smaller tail current at turn-off, and lower turn-off voltage spike for the depletion-stop trench IGBT, leading to reduced EMI. As a result, depletion-stop trench IGBT technology delivers a better trade-off between device electrical performance and ruggedness.

Performance comparison

The new 600V trench IGBT offers lower VCE(on) than previous generation PT and NPT devices, resulting in lower conduction losses (Figure 3). A comparison of switching characteristics again shows that the depletion-stop IGBT operates with smaller losses than previous generation devices (Figure 4).

Designers wishing to take advantage of the new IGBTs need not change their gate-drive circuits because the threshold and maximum gate voltages for these devices are in the same range as for PT and NPT devices. The trench IGBT also has lower total gate charge, shorter propagation delays, and shorter turn-on and turn-off transition times. Thus no modification is needed to the controller's dead-time or minimum-pulse-width settings.

Faster switching brings the risk of spurious turn on of an inverter's low-side device, which fast dV/dt transients can cause. Spurious turn on can result in shoot-through currents that may impair inverter reliability and lead to early failure. However, depletion-stop trench IGBTs display a high ratio of gate-to-emitter capacitance (CGE) to reverse transfer capacitance (CRES), which provides immunity to high dV/dt induced spurious turn-on. This ensures robust performance even at high dV/dt switching conditions.

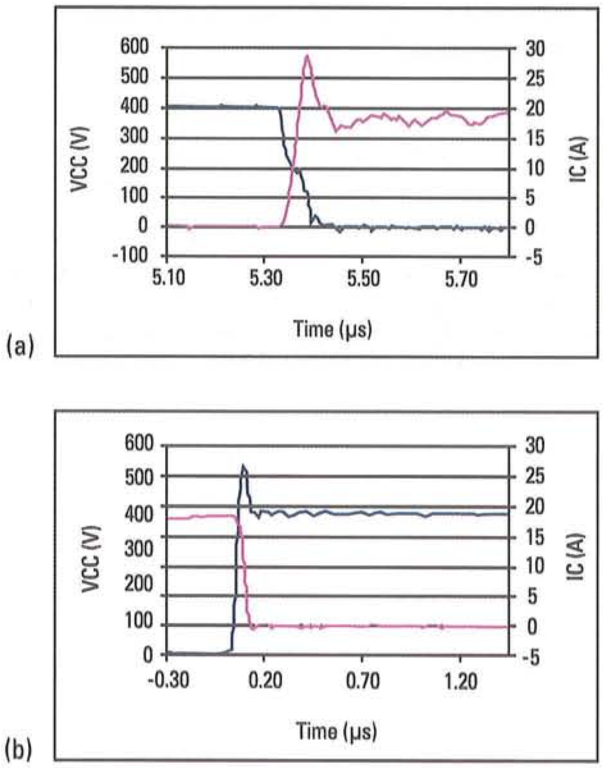

Figure 2: Typical switching waveforms (a) Turn-On and (b) Turn-Off (VCC=400V; IC=18A; L=200μH; RG=22W; TC=25°C)