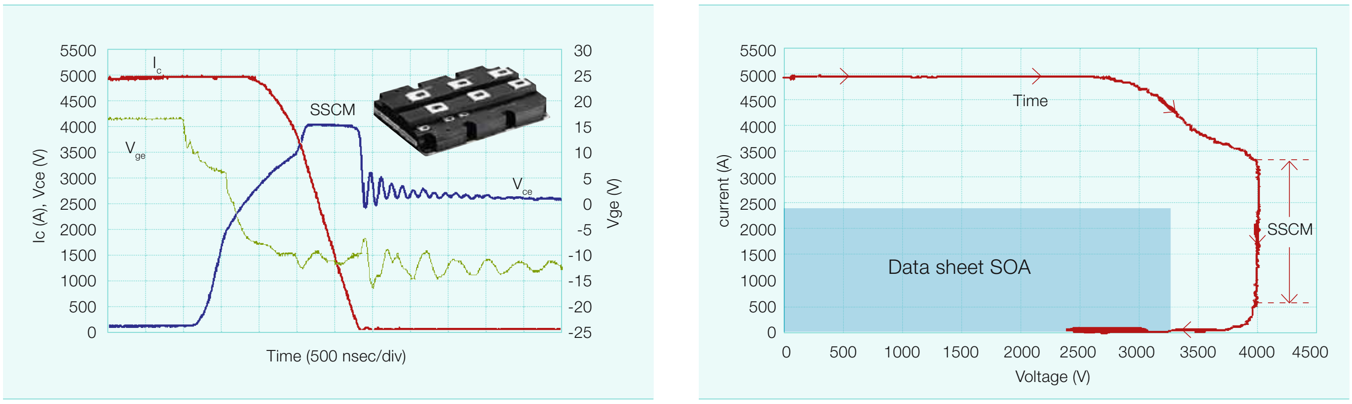
Switching to higher performance

The evolution of IGBT technology

Munaf Rahimo, Arnost Kopta

Two decades ago, a seemingly simple variant of the silicon power MOSFET began to change the power electronic landscape: the insulated-gate bipolar transistor (IGBT). This revolution has continued throughout the 1990s and into the new millennium. The IGBT presents interesting characteristics combining both MOS and bipolar structures with highly advantageous features for power system designers – mainly its low losses, its high input impedance permitting the use of comparatively small gate drivers, and its short-circuit withstand capability and robust turn-off performance. While the first commercially available IGBTs did not exceed blocking voltages above 600V, and currents of a few amperes, development trends focused on increasing the power handling capability. Today, high-voltage IGBTs and their counterpart diodes (with ratings of up to 6.5 kV) are being manufactured successfully for 3.6 kV DC-link applications. In addition, high-current IGBT modules with large numbers of chips in parallel are employed in many applications with current ratings of up to 3,600 A. The availability of such a wide range of current and voltage ratings has resulted in the utilization of the IGBT in many power electronic applications; these include traction, HVDC and industrial drives with the respective emphasis on the differing performance requirements of each type of application. In this article, the latest development trends in IGBT and diode design are presented. These have enabled these devices to make a considerable leap forwards in terms of performance. An outlook into future development trends, targeting further improvements in the IGBT and diode characteristics, is also looked into.

1 3.3 kV/1,200 A IGBT module RBSOA at 125 °C (V_{DC} = 2,600 V, I_C = 5,000 A, R_G = 1.5 Ω, L_S = 280 nH)


a RBSOA current and voltage waveforms

b I/V square RBSOA curve

The power electronics community upholds a long wish list of improvements targeted at the electrical performance of power semiconductor devices. Despite the fact that the IGBT offers the user a broad range of attractive electrical characteristics, improvements on these are continuously being demanded. Over the past years, the main development trend for power semiconductors was aimed at increasing the power density for a given targeted application. From the device viewpoint, the limitations are three fold:

- First the total losses in the device
- Second the safe operating area (SOA) boundaries
- And finally the maximum allowable junction temperature during operation

Moreover, a further limitation exists for the removal of the power dissipated in the device. However, this challenge remains a focus of package and system cooling developments. Recent power semiconductor developments at ABB were mainly aimed at tackling the first two limits, especially for high-voltage devices.

SPT: The SOA breakthrough

Trends for the development of IGBTs and diodes have always been aimed at obtaining a sufficiently large SOA as required by many power electronic systems operating under hard-switching conditions. Until recently, in order to overcome the insufficient ruggedness – especially for high voltage devices – system designers had no choice but to resign themselves to a number of operational limits to be able to attain the necessary switching capability. These measures included de-rating and the use of voltage clamps, snubbers and high gate resistances.

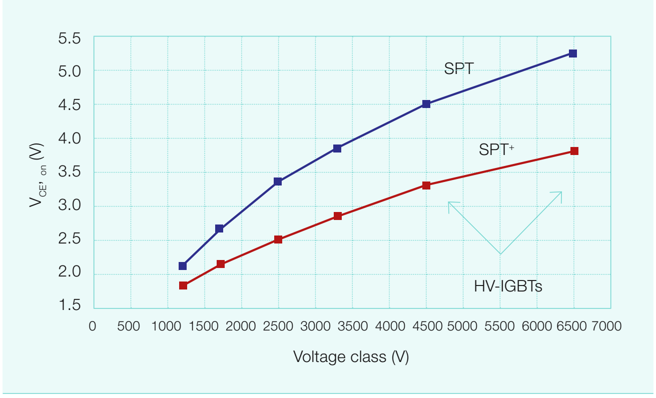
> The SPT+ technology not only offers significantly lower losses but also an increased SOA capability as compared to the standard technology.

It was the introduction of the soft-punch-through (SPT) concept featuring thinner silicon, combined with a highly-rugged planar cell-design platform, substantially increasing the cell latch-up immunity, that allowed lower losses to be achieved. The change also heralded a clear breakthrough in SOA limits. The new technology enabled the devices to withstand the critical and formerly unsustainable phase of dynamic avalanche and resulted in a remarkable increase of ruggedness. Thus, the high-voltage IGBTs were able to reach a new operational mode referred to as the switching-self-clamping-mode (SSCM) as the overshoot voltage reaches levels close to that of the static breakdown voltage. It was demonstrated that the IGBT could remarkably still withstand such conditions, leading to an ultimate square SOA behavior. This mode of operation can be seen in the 3.3 kV/1,200 A IGBT module RBSOA waveforms shown in 1a and the associated square SOA I/V curve in 1b. Similar improvements were also achieved for the short-circuit SOA capability of the IGBT and the reverse recovery SOA for the anti-parallel diode.

SPT+: Lower losses and larger SOA

The next milestone was the reduction of the total losses of the IGBT and diode without sacrificing the performance advantages mentioned above. The SPT+ IGBT platform was designed to substantially reduce on-state voltage while increasing the high turn-off ruggedness to above that of the SPT technology. ABB's SPT+ IGBT technology permitted the company to establish a new technology curve benchmark over the whole IGBT voltage range from 1,200 V to 6,500 V 2. The values for $V_{ce(sat)}$ are obtained at the same current densities and for similar turn-off losses

2 SPT+ IGBT on-state Vce(sat) reduction for voltage ratings up to 6,500 V



for each voltage class. In the following sections of this article, the new SPT+ IGBT and diode performance are explained and demonstrated with the example of a high-voltage 6.5 kV module.

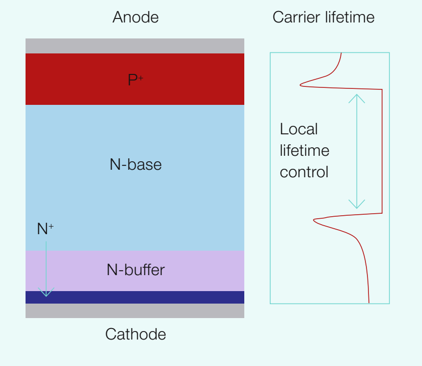
SPT+ IGBT and Diode technology

The advanced SPT+ IGBT performance was achieved by combining an improved planar cell design with the already well-optimized vertical structure utilized in the SPT technology. A cross-section of the SPT+ IGBT is shown in 3. The planar SPT+ technology employs an N-enhancement layer surrounding the P-well in the IGBT cell. The N-layer improves the carrier concentration on the cathode side of the IGBT, thus lowering the on-state voltage drop ($V_{CE,on}$) without significantly increasing the turn-off losses. A further reduction of $V_{CE,on}$ was achieved by reducing the channel resistance by shortening the lateral length of the MOS-channel. By optimizing the shape of the N-enhancement layer, the turn-off ruggedness SOA of the SPT+ cell could be increased beyond the level of the already very rugged standard SPT cell. In this way, the SPT+ technology not only offers significantly lower losses but also an increased SOA capability as compared to the standard technology.

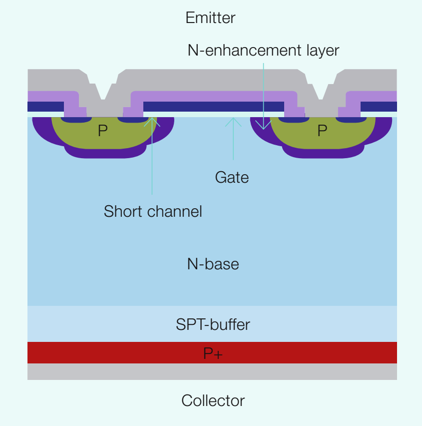
4 shows a cross-section of the SPT+ diode. The SPT+ diode technology utilizes a double local lifetime-control technique to optimize the shape of the stored charge. Due to the improved charge distribution, the overall losses could be reduced while maintaining the soft recovery characteristics of standard SPT diodes.

On the anode side, the SPT+ diode employs the same design as used in the standard SPT technology, utilizing a strongly-doped P+-emitter. The anode emitter efficiency is adjusted using a first He^{++} peak placed inside the P+-diffusion. In order to control the plasma concentration in the N-base region and on the cathode side of the diode, a second He^{++} peak is implanted deeply in the N-base from the cathode side. In this way, a double local lifetime profile is achieved as shown in 4. With this approach, no additional homogenous lifetime control in the N-base is necessary. A better trade-off between total diode losses and recovery softness was achieved due to the improved shape of the stored electron-hole plasma.

4 SPT+ diode technology

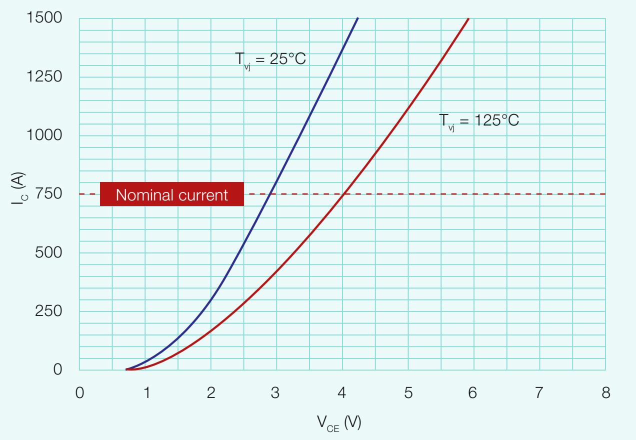


3 SPT+ IGBT technology

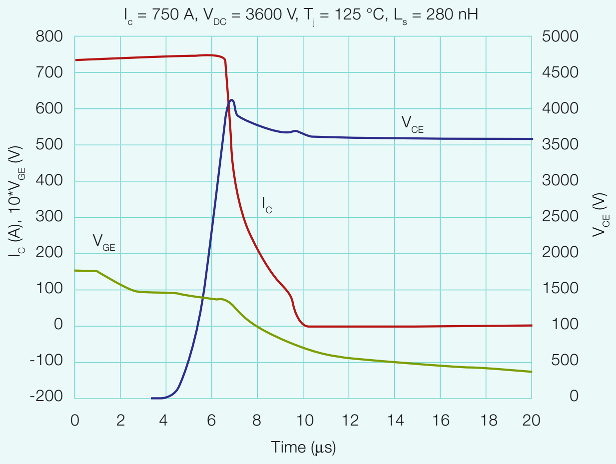


5 The 6.5 kV HV-HiPak module comprising the newly developed SPT+ chip-set

6 Forward characteristics of the 6.5 kV SPT+ IGBT (module level measurements)



7 6.5 kV SPT+ IGBT turn-off under nominal conditions measured at module level



The 6.5kV SPT+ HV-HiPak™ module

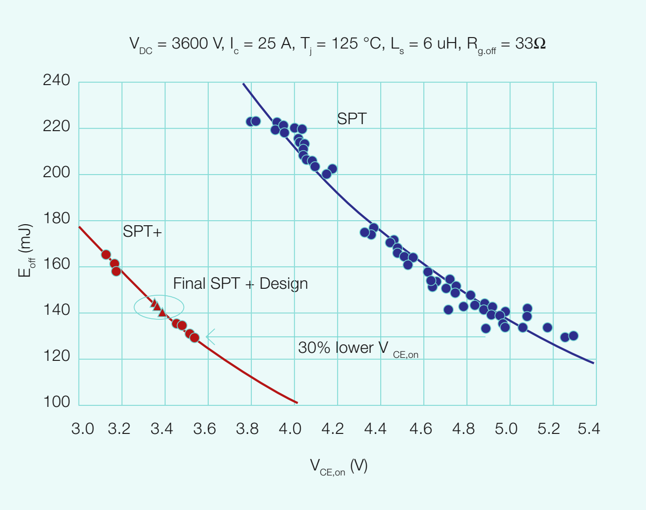
The on-state losses of the new 6.5kV SPT+ IGBT exhibit a reduction of approximately 30 percent when compared to the standard SPT device. This, in combination with the increased ruggedness of the SPT+ IGBT has enabled the current rating to be increased from 600A for the standard 6.5kV HiPak™ up to 750A for the new SPT+ version. The 6.5kV HV-HiPak module shown in 5 is an industry-standard housing with the popular 190 × 140mm footprint. It uses aluminum silicon carbide (AlSiC) baseplate material for excellent thermal cycling capability as required in traction applications and aluminum nitride (AlN) isolation for low thermal resistance. The HV-HiPak version utilized for the 6.5kV voltage class is designed with an isolation capability of 10.2kV$_{RMS}$.

To verify the performance of the 6.5kV SPT+ chips and the HV-HiPak module, extensive measurements were carried out. The results of this characterization are presented in this section. For the dynamic measurements, the nominal DC-link voltage was 3,600V, while SOA and softness measurements were carried out at 4,500V.

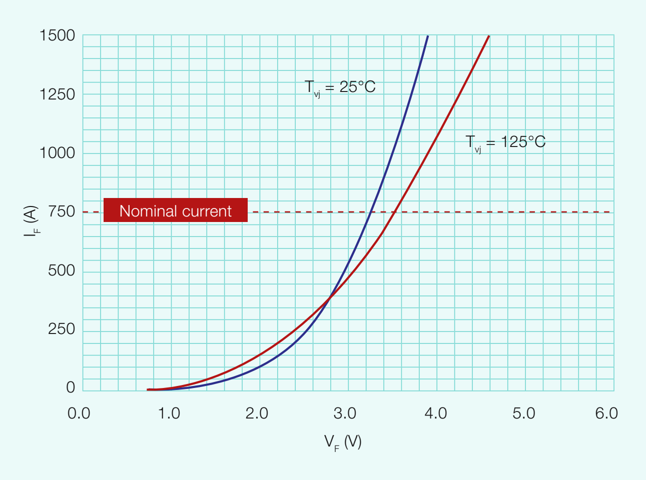
IGBT characteristics and losses

The on-state curves of the 6.5kV SPT+ IGBT are shown in 6. The typical on-state voltage drop ($V_{CE,on}$) at nominal current and T_j=125°C is 4.0V. The SPT+ IGBT shows a positive temperature coefficient of $V_{CE,on}$, already starting at low currents. This enables a good current sharing capability between the individual chips in the module.

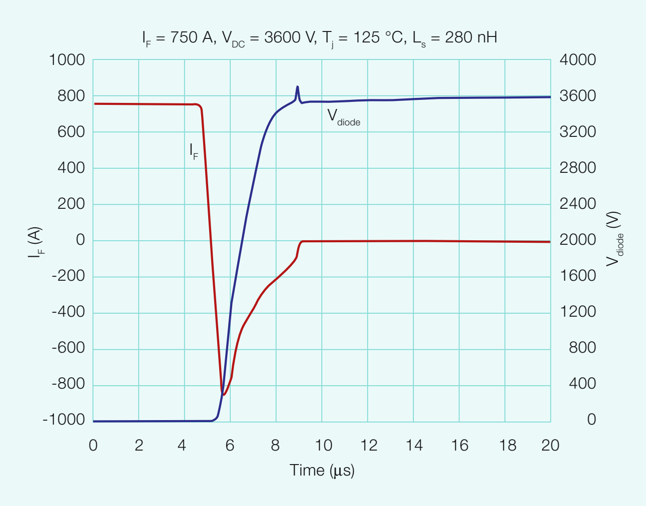
8 6.5kV SPT+ IGBT technology curve measured at chip level



9 Forward characteristics of the 6.5kV SPT+ diode (module level measurements)



10 6.5kV SPT+ diode reverse recovery under nominal conditions measured at module level, E_{rec}=2.8J



7 shows the turn-off waveforms of the 6.5kV HiPak module measured under nominal conditions ie, at 750A and 3,600V. Under these conditions, the fully integrated turn-off losses of the module amount to 5.2 J. The module was switched off using an external gate resistor ($R_{g,off}$) of 15Ω, which results in a voltage rise of 2,000V/µs. The optimized N-base region combined with the soft-punch-through (SPT) buffer allows the collector current to decay smoothly, ensuring a soft turn-off behavior without any disturbing voltage peaks or oscillations even at high DC-link voltages and stray inductances.

8 shows the trade-off curve between the IGBT on-state voltage drop and the turn-off losses for the SPT+ as well as that of the standard SPT IGBT measured at chip level. The different points on the technology curves correspond to IGBTs with different anode emitter efficiencies. The devices were measured at a collector current of 25A, which is the nominal current of the SPT IGBTs. The new SPT+ IGBT exhibits an approximately 30 percent lower on-state voltage drop ($V_{CE,on}$) for the same turn-off losses as compared to the standard SPT chip. The final point on the technology curve for the SPT+ IGBTs was carefully selected based on the trade-off between reverse leakage current and turn-off softness while maintaining a good balance between switching and conduction losses.

Diode characteristics and losses

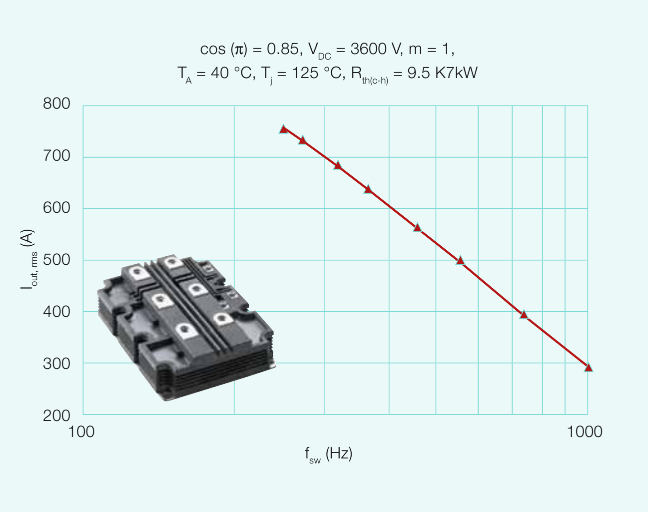
9 shows the on-state characteristics of the 6.5kV SPT+ diode. Due to the advanced plasma shaping utilizing a double He^{++} irradiation scheme, the diode has a strong positive temperature

coefficient of V_F already well below the nominal current. At rated current and 125 °C, the diode has a typical on-state voltage drop of 3.5 V.

10 shows the reverse recovery waveforms of the diode under nominal conditions. By carefully designing the cathode-sided He++ peak, a short, but still smoothly decaying current tail was achieved. Under nominal conditions, the diode recovery losses are 2.8 J. Thanks to the high ruggedness and soft recovery behavior, the diode can be switched with a high di_F/dt, which significantly reduces the IGBT turn-on losses.

> One of the main advantages of the new 6.5 kV SPT+ IGBT is its extremely high turn-off ruggedness, setting a new benchmark for this voltage class.

11 6.5 kV SPT+ HiPak module output current as function of the switching frequency



Module output current

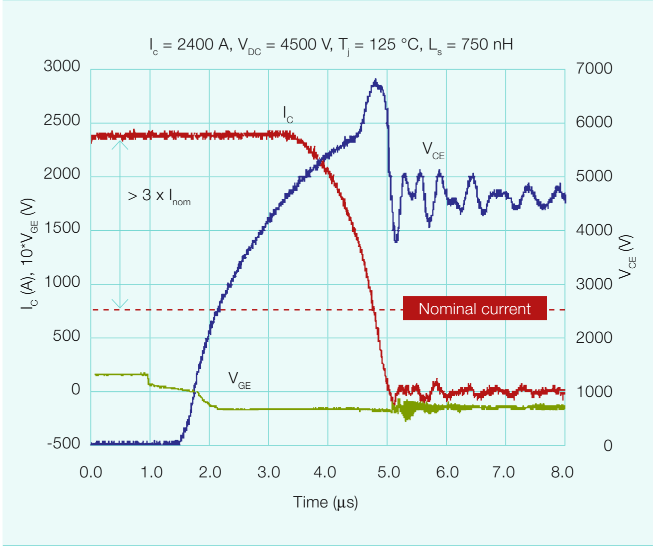
In order to evaluate the performance of the 6.5 kV SPT+ module under real application conditions, a thermal simulation was performed of the output current as function of the switching frequency. The results are shown in 11. The 6.5 kV SPT+ IGBTs have been optimized to operate in an application environment with high stray inductances utilizing low switching frequencies. In order to guarantee a smooth-switching behavior, the IGBT was designed using a relatively strong anode emitter efficiency. This increases the electron-hole concentration on the anode side of the N-base and assures a smoothly decaying current tail during turn-off at high stray inductances and DC-link voltages. This leads to a chip with low conduction losses and increased turn-off losses, which is ideal for low switching frequencies.

Turn-off and reverse-recovery

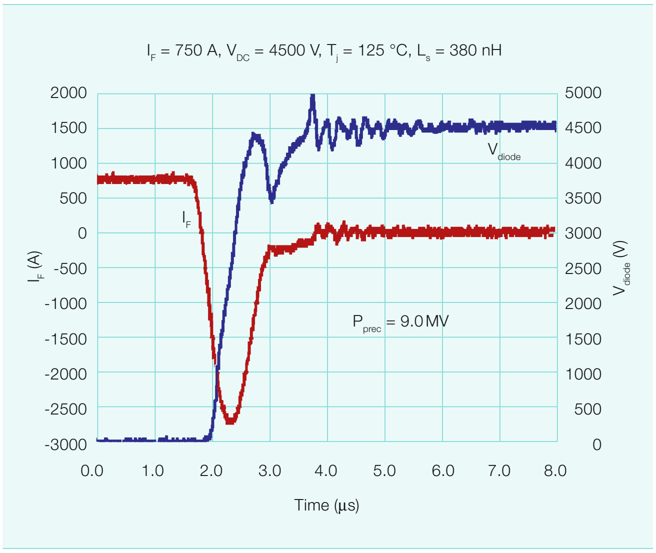
One of the main advantages of the new 6.5 kV SPT+ IGBT is its extremely high turn-off ruggedness, setting a new benchmark for this voltage class. 12 shows a turn-off waveform at module level, in which a current of 2,400 A – which corresponds to more than three times the nominal current – was switched-off against a DC-link voltage of 4,500 V at a junction temperature of 125 °C. The test was conducted with an external gate resistance of 1.0 Ω, without using any clamps or snubbers. The stray inductance in this test was 750 nH, which is more than double the value that can be expected in the targeted application environment, even under worst-case conditions.

Thanks to the ruggedness of the SPT+ cell, the IGBTs are capable of sustaining a long period of strong dynamic avalanche during the turn-off transient and so show an excellent SOA capability. In this test, the turn-off peak power reached a value of 11.7 MW. In standard production-level testing all modules are subjected to a turn-off SOA test with three times nominal current (2,250 A) where the modules are driven into dynamic avalanche. This very harsh test has been imple-

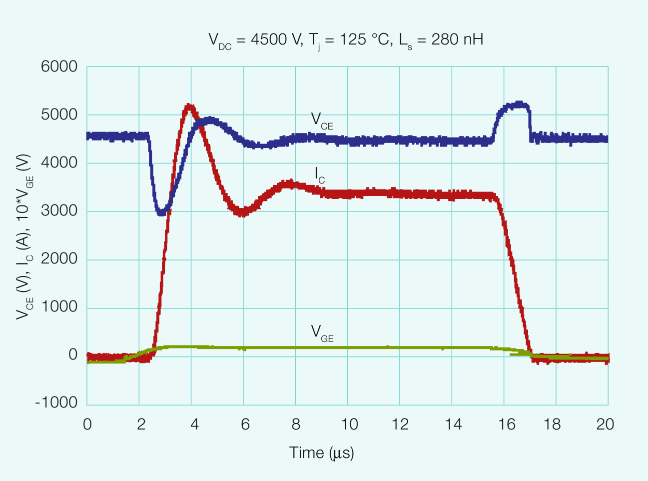
12 6.5 kV SPT+ IGBT turn-off under SOA conditions measured at module level, $P_{poff} = 11.7$ MW



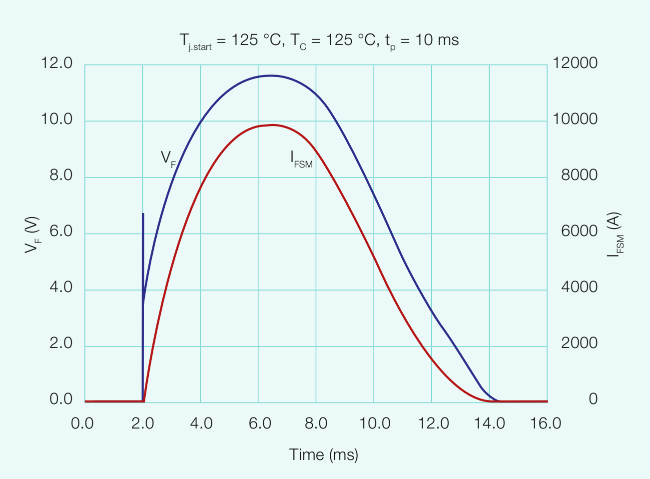
13 6.5 kV SPT+ diode reverse recovery under SOA conditions measured at module level.



14 6.5 kV SPT+ IGBT short-circuit characteristics measured at module level



15 6.5 kV SPT+ diode surge current waveforms at module level



mented in order to ensure a high quality and reliability of all shipped 6.5 kV HV-HiPak modules.

13 shows a diode reverse recovery SOA test at module level measured with a forward current of 750 A (nominal current) and a DC-link voltage of 4,500 V. Due to the IGBT turn-on characteristics, the diode peak power reaches its maximum value close to the nominal current and starts decreasing again for higher forward currents. The diode was switched using an external gate resistor ($R_{g,on}$) of 1.2 Ω reaching a switching speed of 7,000 A/us and a peak power of 9.0 MW.

Short-circuit SOA

The short circuit waveforms of the 6.5 kV SPT+ module can be seen in 14. The IGBT was carefully designed to withstand a short circuit at V_{GE} = 15.0 V for all DC-link voltages up to 4,500 V and junction temperatures between – 40 °C and 125 °C. The desired short-circuit ruggedness was achieved by optimizations of the SPT-buffer and the anode emitter efficiency.

Surge current capability

To verify the surge current capability of the 6.5 kV SPT+ diode, the HiPak module was subjected to 100 surge pulses with a magnitude of 9.9 kA and pulse duration of 10ms (I^2t = 523 kA^{2}s) as shown in 15. After the 100th pulse, the module was electrically re-tested to ensure that no degradation had taken place. In the subsequent destruction test the single pulse surge current capability was determined. The diodes reached a peak current of 12.3 kA, corresponding to an I^2t value of 705 kA^{2}s before failing. This excellent surge current capability was achieved thanks to a combination of the strongly doped P+-emitter and a low on-state voltage drop facilitated by the optimum plasma distribution shaped by the double He++ irradiation scheme.

> The most important enabler, namely the power handling capability (SOA) of devices, has risen to a level where IGBTs can theoretically be operated at currents that greatly exceed the ratings of modern systems.

Future trends

With the advancements of modern IGBT and diode structures, device designers are facing a growing challenge in finding ways to further improve IGBT performance using conventional plasma enhancement and silicon thickness reduction techniques. Today, more development effort is being aimed at reviving the reverse conducting IGBT (RC IGBT), which combines both the IGBT and diode in a single structure as means for providing higher power for a defined area (ie, module footprint). The potentials that could arise from such a technological step are great.

Furthermore, the maximum junction temperature is increasingly moving into the limelight of development interest. The fact that the most important enabler, namely the power handling capability (SOA) of devices, has risen to a level where IGBTs can theoretically be operated at currents that greatly exceed the ratings of modern systems, has further increased the pressure towards expanding the temperature range. Since the output power is proportional to the temperature difference (ΔT) between the chip junction and the cooling medium a higher allowable operating temperature of the semiconductor immediately increases the power density for a given device area. Hence, an increase by 25 °C enhances the rated power by 25 to 35 percent, depending on the cooling conditions.

For more on IGBTs, see "Performance-enhancing packaging" on page 9 of this issue of *ABB Review*.

Munaf Rahimo
Arnost Kopta
ABB Semiconductors
Lenzburg, Switzerland
munaf.rahimo@ch.abb.com
arnost.kopta@ch.abb.com