High Voltage SPT+ HiPak Modules Rated at 4500V

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Abstract

In this paper, the next generation 4.5kV HV-HiPak IGBT modules employing the newly developed SPT+ IGBT and diode technologies will be presented. The new modules have significantly lower conduction and switching losses while exhibiting higher SOA capability when compared to the previous generation. In this paper extensive results from the characterization of the new module and the 4.5kV SPT+ chip-set will be presented.

1. Introduction

Development trends in power electronic systems continue to demand power devices with continuously improving characteristics in terms of reduced losses, increased ruggedness and improved controllability. Following the introduction of the new generation of 1700V and 3300V SPT+ IGBT HiPak range [1], in this paper the next generation 4.5kV HV-HiPak IGBT modules employing SPT+ IGBTs and Diodes will be presented. The SPT+ IGBT platform has been designed to substantially reduce the total semiconductor losses while increasing the turn-off ruggedness above that of the current SPT technology. The SPT+ platform exploits an enhanced carrier profile through planar cell optimization, which is compatible with ABB's advanced and extremely rugged cell design. The new cell technology significantly increases the plasma concentration at the emitter, which reduces the on-state voltage drop without affecting the turn-off losses. Due to the combination of the enhanced cell design and the soft-punch-through (SPT) buffer concept, the SPT+ IGBT technology enables ABB to establish a new technology-curve benchmark for the 4500V voltage class. The on-state losses of the new 4.5kV IGBT exhibit approximately a 30% reduction as compared to the standard SPT device while keeping the same E_{off} value. The new 4.5kV HV-HiPak modules will provide high voltage system designers with enhanced current ratings and simplified cooling while further enhancing the recently acquired robustness of the SPT IGBTs.

2. The 4.5kV HV-HiPak module

The 4.5kV HV-HiPak module (fig. 1) is an industry-standard housing with the popular 190 x 140 mm footprint. It uses Aluminium Silicon Carbide (AlSiC) base-plate material for excellent thermal cycling capability as required in traction applications and Aluminium Nitride (AlN) isolation for low thermal resistance. The HV-HiPak version utilized for the 4.5kV voltage class is designed with an isolation capability of $10.2kV_{RMS}$.

Fig. 1: The 4.5kV HV-HiPak module comprising the newly developed SPT+ chip-set.

To achieve the high reliability required by its targeted applications (e.g. traction), the HV-HiPak module has been optimized for operation in harsh environments. This has been accomplished by designing the 4.5kV SPT+ chips to have smooth switching characteristics and rugged performance, qualities that are essential in the high-inductance environments of high voltage power electronic systems. The internal wiring and layout of the module were optimized in order to minimize oscillations and current imbalances between the chips. Finally, the whole design was qualified by standard reliability tests including HTRB (High Temperature Reverse Bias), HTGB (High Temperature Gate Bias), THB (Temperature Humidity Bias 85°C/85% relative humidity), APC (Active Power Cycling) and TC (Temperature Cycling).

3. 4.5kV SPT+ chip-set technology

3.1. SPT+ IGBT technology

The SPT+ IGBT platform was developed with the goal to substantially reduce the on-state losses while maintaining the low switching losses, smooth switching behavior and high turn-off ruggedness of the standard SPT (Soft-Punch-Through) IGBTs. This was achieved by combining an improved planar cell design with the already well-optimized vertical design utilized in the SPT technology. In fig. 2 a cross-section of the SPT+ IGBT can be seen. 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 [1], [4], [5], [6]. 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 (RBSOA) of the SPT+ cell could be increased even 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.

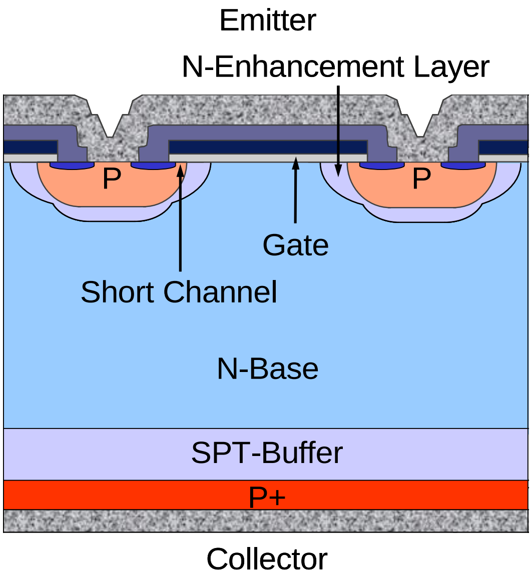

Fig. 2: SPT+ IGBT technology.

One of the most important requirements high voltage IGBTs have to fulfill is that they have to have high ruggedness against cosmic ray induced failures. The cosmic ray induced failure rate is determined by the shape of the electric field at the PN junction of the P-well, which in the SPT+ technology strongly depends on the shape and concentration of the N-enhancement layer. The cosmic ray ruggedness of the SPT+ cell was therefore extensively investigated and verified on the whole high voltage SPT+ range from 3.3kV up to 6.5kV class IGBTs. For an optimized N-enhancement layer and cell design, measurements show that the SPT+ IGBT does not have higher failure rates than the equivalent standard IGBT. In fig. 3, the measured cosmic ray failure rate of the 4.5kV SPT+ IGBT can be seen. The 4.5kV SPT+ IGBT has a failure rate of well below 1FIT at a DC-link voltage of 3000V.

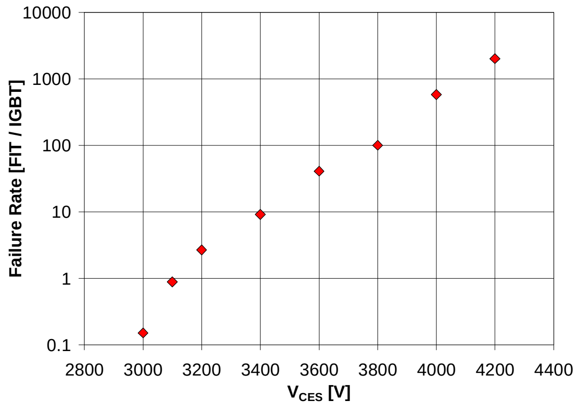

Fig. 3: 4.5kV SPT+ IGBT cosmic ray ruggedness measured at room temperature in a proton beam and scaled to sea level. 1FIT corresponds to 1 failure in 10^9 operating hours.

3.2. SPT+ diode technology

Fig. 4 shows a cross-section of the SPT+ diode. The new technology utilizes a double local lifetime-control technique to optimize the shape of the stored electron-hole plasma [7], [8]. Due to the improved plasma distribution, the overall losses could be reduced while maintaining the soft recovery characteristics of the standard SPT diode technology.

On the anode side, the SPT+ diode employs the same design as used in the standard SPT technology, utilizing a high-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, implanted deeply into the N-base from the cathode side is used. In this way, a double local lifetime profile as shown in fig 4 is achieved. With this approach, no additional homogenous lifetime control in the N-base is necessary. Due to the improved shape of the stored electron-hole plasma, a better trade-off between total diode losses and recovery softness was achieved.

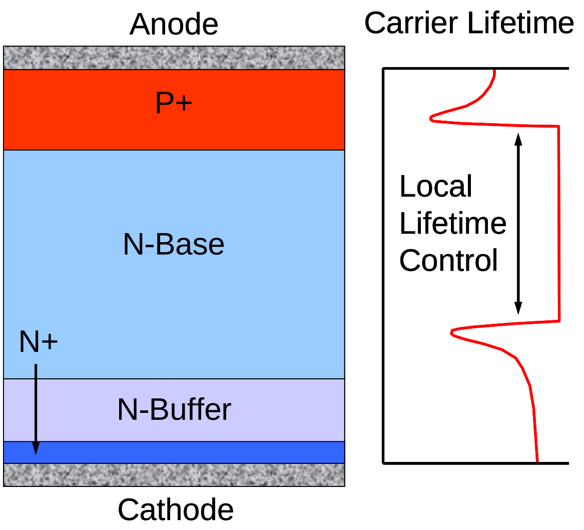

Fig. 4: SPT+ diode technology.

4. 4.5kV/1000A HV-HiPak electrical performance

To verify the performance of the 4.5kV SPT+ chips and the HV-HiPak module, extensive measurements were carried out. The results of this characterization will be presented in this section. The nominal rated current of the 4.5kV HV-HiPak module is 1000A, which corresponds to a current density of 50A/cm^2 for the IGBT and 100A/cm^2 for the diode. For dynamic measurements, the nominal DC-link voltage was 3000V, while SOA and softness measurements were carried out at 3600V.

4.1. Static characteristics

In fig 5, the on-state curves of the 4.5kV SPT+ IGBT can be seen. The typical on-state voltage drop ($V_{CE,on}$) at nominal current and T_j=125 °C is 3.65V. The SPT+ IGBT shows a positive temperature coefficient of $V_{CE,on}$, starting already at low currents, which enables a good current sharing capability between the individual chips in the module.

In fig 6, the on-state characteristics of the 4.5kV SPT+ diode are shown. Due to the advanced plasma shaping utilizing a double He++ irradiation, 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 3.4V.

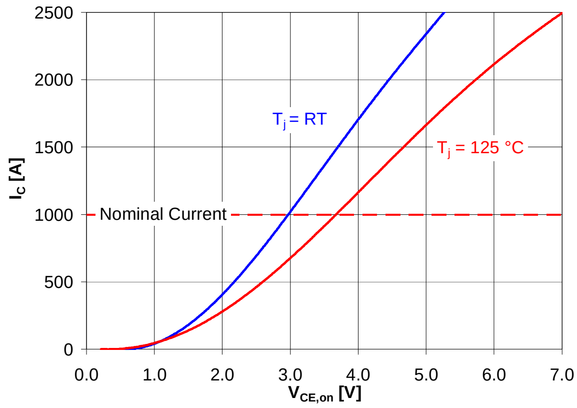

Fig. 5: Forward characteristics of the 4.5kV SPT+ IGBT.

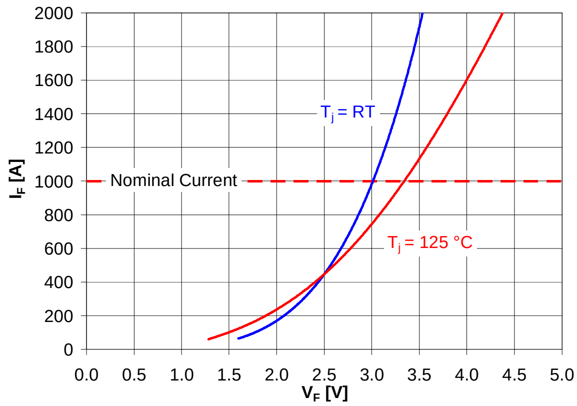

Fig. 6: Forward characteristics of the 4.5kV SPT+ diode.

4.2. Switching characteristics under nominal conditions

Fig. 7 shows the turn-off waveforms of the 4.5kV HiPak module measured under nominal conditions i.e. at 1000A and 3000V. Under these conditions, the fully integrated turn-off losses are 4.6J. The extremely rugged SPT+ cell enables the IGBT to be switched using a small gate-resistor, resulting in a fast voltage rise, which reduces the turn-off losses. In the shown test, the module was switched off using an $R_{g,off}$ of 2.7Ω, which results in a voltage rise of 3100V/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.

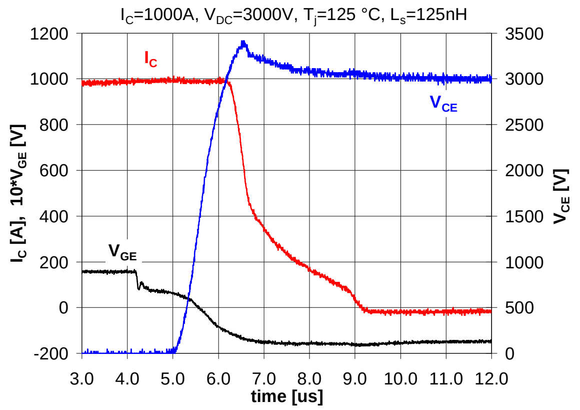

Fig. 7: 4.5kV SPT+ IGBT turn-off under nominal conditions measured on module level. E_{off}=4.6J.

Fig. 8 shows the turn-on waveforms under nominal conditions. The low input capacitance of the planar SPT+ cell allows a fast drop of the IGBT voltage during the turn-on transient. This, combined with the low-loss SPT+ diode brings the turn-on switching losses down to a typical value of 3.6J.

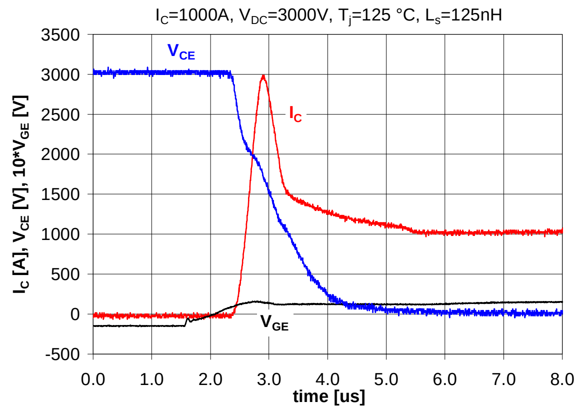

Fig. 8: 4.5kV SPT+ IGBT turn-on under nominal conditions measured on module level. E_{on}=3.6J.

In fig 9, the reverse recovery waveforms of the diode under nominal conditions are shown. 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 2.4J. 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. In the shown recovery test, the IGBT was turned on using a gate resistor ($R_{g,on}$) of 2.7Ω, which results in a diode di_F/dt of 7500A/µs.

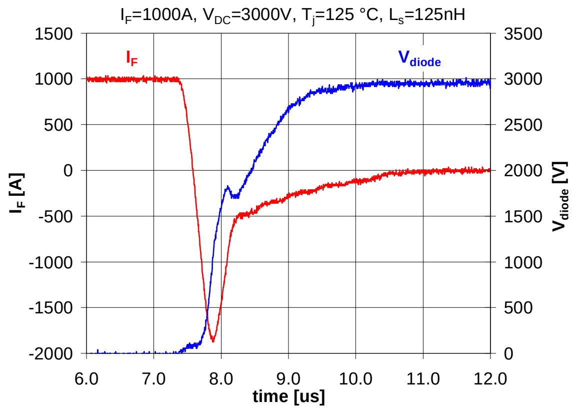

Fig. 9: 4.5kV SPT+ diode reverse recovery under nominal conditions measured on module level. E_{rec}=2.4J.

4.3. Trade-off curve and output current

In fig. 10 the trade-off curve between the IGBT on-state voltage drop and turn-off losses at nominal condition is shown. The different points on the technology curve correspond to SPT+ IGBTs with different anode emitter efficiencies. The anode emitter efficiency, together with the buffer design, determines the IGBT leakage current and short-circuit capability. The final point on the technology curve ($V_{CE,on}$ = 3.65V, E_{off} = 4.6J) was carefully selected based on the trade-off between leakage current, short-circuit capability and a good balance between switching and conduction losses. Fig. 11 shows the resulting output current as function of the switching frequency for the 4.5kV HV-HiPak module [9].

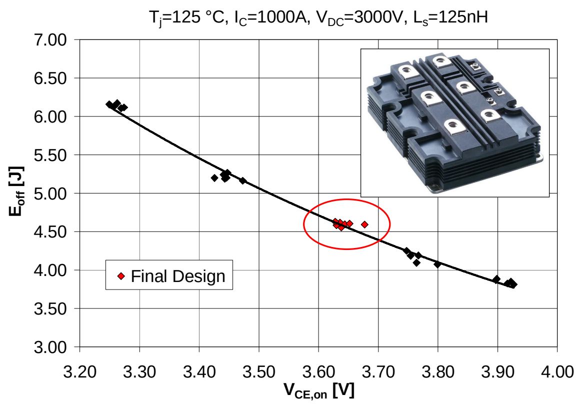

Fig. 10: 4.5kV SPT+ IGBT technology curve measured on module level.

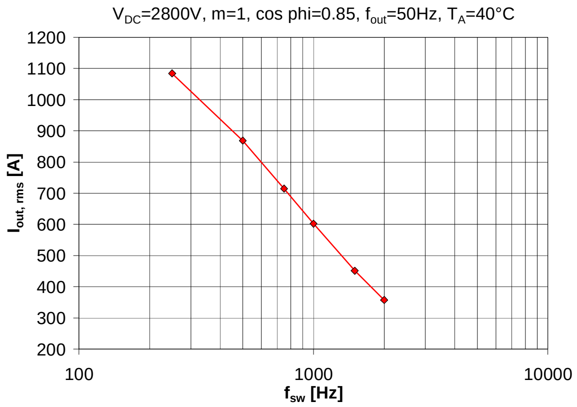

Fig. 11: 4.5kV HV-HiPak module output current as function of the switching frequency.

4.4. Turn-off and reverse recovery ruggedness

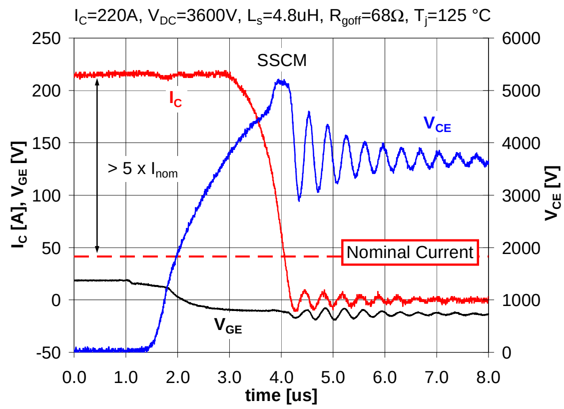

Fig. 12: 4.5kV SPT$^+$ IGBT turn-off under SOA conditions measured on chip level.

One of the main advantages of the new 4.5kV SPT$^+$ IGBT is its extremely high turn-off ruggedness, setting a new benchmark for this voltage class. Fig. 12 shows the single chip turn-off capability of the final 4.5kV SPT$^+$ IGBT-design employed in the HiPak module. In this test, a current of 220A, which corresponds to more than five times the nominal current, was turned off against a DC-link voltage of 3600V at a junction temperature of 125 °C. The stray inductance was 4.8uH, which corresponds to a module-level stray inductance of 200nH. No clamps or snubbers were used in this test. Thanks to the ruggedness of the SPT$^+$ cell, the IGBT is capable of sustaining a long period of strong dynamic avalanche. At t=3.8µs, the stored electron-hole plasma has been completely extracted and the IGBT enters into Switching Self-Clamping Mode (SSCM) [3]. In this operational mode, the current is purely supported by avalanche generation. The IGBT remains in SSCM until the energy stored in the stray inductance has been completely dissipated. A high SSCM ruggedness was obtained by optimizing the SPT buffer.

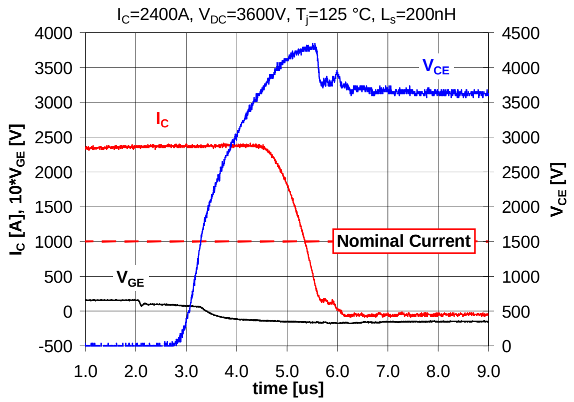

Fig. 13: 4.5kV SPT$^+$ IGBT turn-off under SOA conditions measured on module level.

Fig. 13 shows a turn-off waveform at module level, where a current of 2400A was switched against a DC-link voltage of 3600V. The test was conducted with a gate resistance of 2.7Ω, again without using any clamps or snubbers. This test shows that the 4.5kV SPT$^+$ IGBT also has an excellent SOA capability when paralleled in the HiPak module. This very harsh test has been implemented as the standard SOA test made during the final outgoing production-level module testing. This is to ensure a high quality and reliability of all shipped 4.5kV HV-HiPak modules.

Fig. 14 shows the corresponding production level test of the diode reverse recovery SOA.

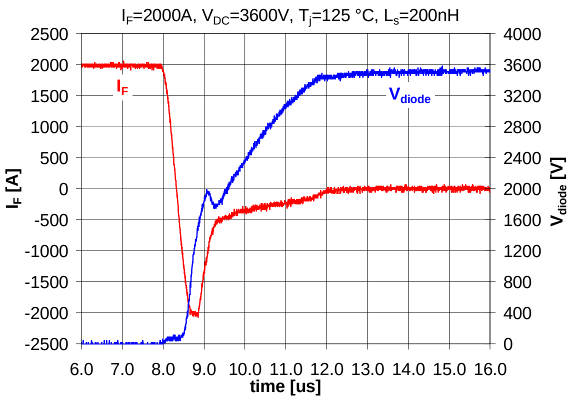

Fig. 14: 4.5kV SPT$^+$ diode reverse recovery under SOA conditions measured on module level.

4.5. Short-Circuit SOA

The short circuit waveforms of the 4.5kV HV-HiPak module can be seen in fig. 15. The IGBT was designed to withstand a short circuit at V_{GE}=15.0V for all DC-link voltages up to 3600V and junction temperatures between –40 °C and 125 °C.

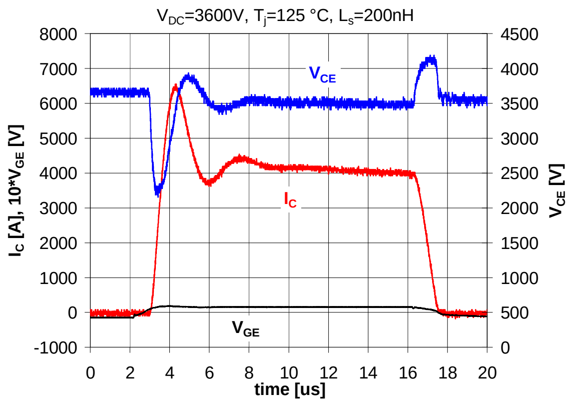

Fig. 15: 4.5kV SPT+ IGBT short-circuit characteristics measured on module level.

4.6. Surge current capability

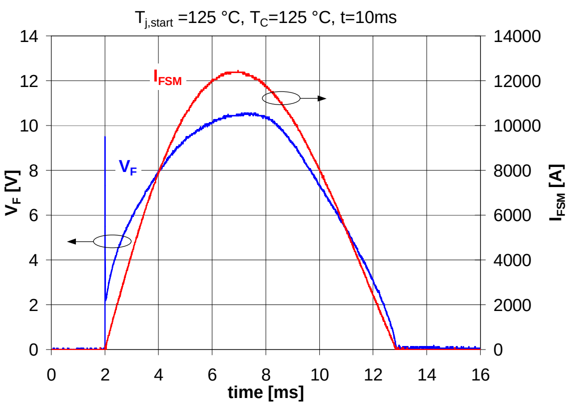

Fig. 16: 4.5kV SPT+ diode surge current waveforms on module level.

Finally, in fig. 16 the surge current waveforms of the 4.5kV SPT+ diode are shown. The measurements were made on module level, which means that 12 diodes with a total active area of 9.5cm^2 were tested in parallel. The pulse duration was 10ms in this test. The diodes reached a peak current of 12.4kA, corresponding to an I^2t value of 830kA^{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.

5. Conclusions

In this paper, the new 4.5kV/1000A HV-HiPak module employing SPT+ IGBTs and diodes was presented. The SPT+ technology offers an unmatched combination of low losses, high ruggedness and smooth switching behavior. The SPT+ IGBT technology significantly increases the plasma concentration at the emitter side, which strongly decreases the on-state voltage drop without affecting the turn-off losses. The SPT+ diode employs a double local lifetime control, which lowers the total losses without compromising the soft recovery behavior. The new 4.5kV HV-HiPak modules will provide high voltage system designers with enhanced current ratings and simplified cooling while further enhancing the recently acquired robustness of high voltage SPT IGBTs.

6. Literature

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