New Plasma Shaping Technology for Optimal High Voltage Diode Performance

A. Kopta, M. Rahimo, U. Schlapbach
ABB Switzerland Ltd, Semiconductors
Fabrikstrasse 3,
CH-5600 Lenzburg, Switzerland
Tel.: +41 / (0) – 58 586 12 54
Fax: +41 / (0) – 58 586 13 09
E-Mail: arnost.kopta@ch.abb.com
URL: http://www.abb.com/semiconductors

Keywords

«Free wheel diode (FWD)», «Reverse recovery», «Robustness», «Device Characterization», «Design»

Abstract

In this paper, a newly developed diode technology platform for 3.3 kV, 4.5 kV and 6.5 kV diodes for next generation high power IGBT modules will be presented. The new diode range offers low losses and soft recovery characteristics combined with a high reverse recovery safe operating area and superior surge current capability. The new diode technology employs a double local lifetime-control method using He^{++} irradiation to control the on-state electron-hole distribution on both the anode and cathode sides of the diode.

Introduction

The main challenge in the design of high voltage diodes for IGBT application is to ensure low losses combined with soft reverse recovery behavior. The high stray inductances encountered in these applications, together with design restrains mainly given by the need for a high immunity against cosmic ray induced failures have a strong impact on the diode performance. With the recent introduction of the next generation of high voltage IGBTs comprising significantly reduced losses [1], [2], the development of a new diode generation matching the performance of these IGBTs has become inevitable. Today, state of the art high voltage diode designs utilize technologies comprising either local lifetime control, or the usage of low concentration diffusion profiles to control the emitter efficiency of the anode and cathode emitters [3]-[8]. Recently, diodes employing structured cathode designs to improve the diode softness have been suggested [9], [10]. These diode technologies have a big potential in terms of reverse recovery softness and safe operating area. Nevertheless, they require additional backside processing and have to be further developed in order to reach their full potential.

In this paper we will present a newly developed technology utilizing a double local lifetime-control technique to optimize the on-state electron-hole plasma distribution in the diode. Thanks to the improved plasma distribution, the overall losses were reduced, while maintaining the soft recovery characteristics of the standard technology. This new diode technology will be referred to as SPT^+, where the abbreviation SPT stands for Soft Punch-Through, referring to the soft reverse recovery characteristics of the diode.

The advantages of the new diode as well as the motivation for the development work presented in this paper will now be explained based on a thermal simulation [12]. Fig. 1, shows the maximum output current as function of switching frequency of the new 3.3 kV / 1500 A HiPak module comprising 24 SPT^+ IGBTs and 12 anti-parallel diodes. The figure shows the module output current in inverter mode (black curve) as well as in rectifier mode for the standard SPT diode (blue curve) and the new SPT^+ diode (red curve). The standard SPT diode has too high total losses and would clearly limit the output current of the module in rectifier mode. At a switching frequency of 400 Hz, the output current would only be 1250 A as compared to the SPT$^+$ IGBT capability in inverter mode of nearly 1500 A. By using the new SPT$^+$ diode with lower total losses, the output current in rectifier mode can be increased to match the inverter mode performance over the entire frequency range. The objective of this work was to develop a new diode technology with the required loss reduction to match the capability of the SPT$^+$ IGBT. At the same time, the diode softness and ruggedness had to be at least as good as in the original technology to ensure that the new diode could be switched as fast as the old one. A lower di/dt capability would otherwise increase the IGBT turn-on losses, which would unwantedly decrease the output current in inverter mode and in this way limit the module performance.

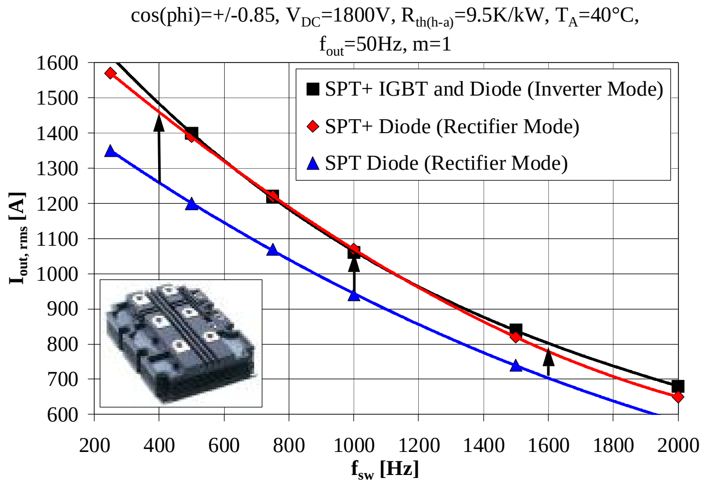

Fig. 1: Simulated output current as function of the switching frequency of the 3.3 kV / 1500 A SPT$^+$ HiPak module (24 IGBTs and 12 diodes).

SPT$^+$ Diode Technology

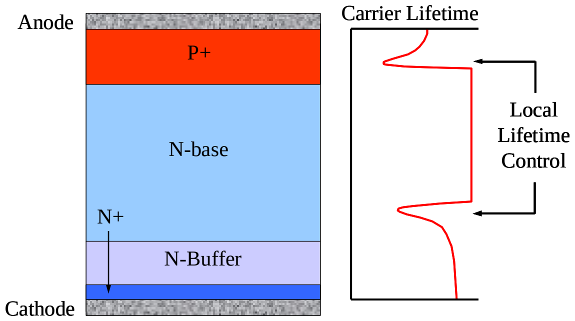

Fig. 2: SPT$^+$ diode cross-section and carrier lifetime profile.

In Fig. 2, a cross-section of the SPT$^+$ diode and the corresponding carrier lifetime profile can be seen. The SPT$^+$ diodes utilize the same silicon resistivity and thickness as well as anode and cathode diffusion profiles as the original SPT diodes. On the anode side, a high-doped P$^+$ emitter is used. The emitter efficiency is adjusted with a first He^{++} defect peak placed inside the P$^+$ diffusion profile. Both SPT and SPT$^+$ diodes have the same first (anode-sided) He^{++} peak and thus the same anode emitter efficiency. In order to control the plasma concentration in the N-base region and on the cathode side of the diode, the SPT$^+$ technology utilizes a second He^{++} peak, placed deeply inside the N-base from the cathode side. In this way, a double local lifetime profile as shown in the right part of Fig. 2 was achieved. With this approach, no additional homogenous lifetime control in the N-base as used in the SPT technology is necessary.

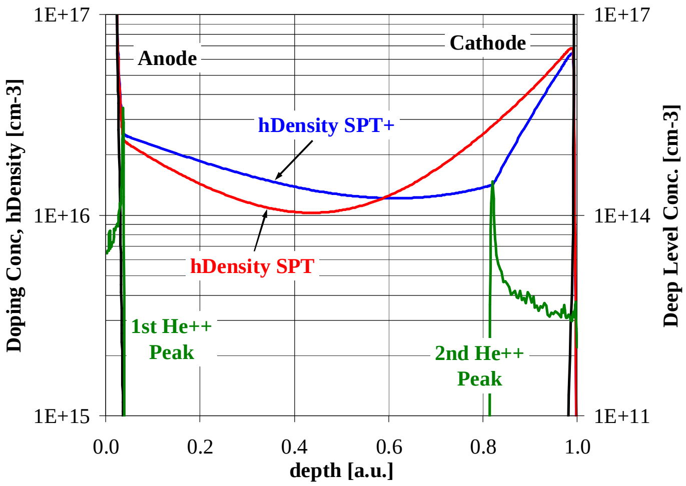

Fig. 3: Simulated on-state hole density in high voltage SPT and SPT$^+$ diodes.

In Fig. 3, a comparison of the simulated on-state plasma distribution between the SPT$^+$ and the standard SPT diode can be seen. Homogenous lifetime reduction in the N-base as employed in the SPT diode leads to a hammock shaped plasma distribution (red curve). The low plasma concentration in the middle part of the diode results in high conducting losses, whereas the high plasma concentration on the cathode side results in a long reverse recovery current tail and high recovery losses, without offering clear immunity against current snap-off under all conditions. In the SPT$^+$ diode, the more advanced irradiation scheme with a double He^{++} irradiation and no additional homogenous lifetime-control of the middle part of the N-base leads to an improved plasma distribution resulting in a shorter current tail and lower recovery losses. One of the big advantages of the SPT$^+$ technology is that the plasma concentration can be optimized by changing the depth and the concentration of the second He^{++} peak. In this way the best trade-off between losses and recovery softness can be achieved. In Fig. 4, the achieved reduction of the on-state losses as compared to the SPT technology for the entire voltage range can be seen.

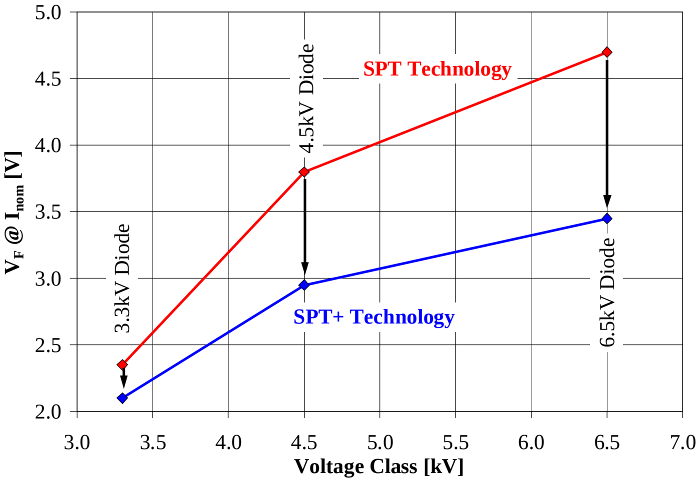

Fig. 4: Reduction of the on-state voltage drop achieved by the SPT$^+$ diode technology for 3.3 kV to 6.5 kV diodes.

Loss Reduction with Double He^{++} Irradiation

In this section, the impact of the double He^{++} irradiation on the diode losses and nominal switching behavior will be discussed based on 4.5 kV diode results. The equally important softness optimization will be discussed in the next section based on measurements done on 3.3 kV diodes.

In Fig. 5, the technology curve of the 4.5 kV SPT and SPT$^+$ diodes can be seen. Both diodes have an active area of 0.8 cm^2 and were characterized using the SPT$^+$ nominal current of 83 A, which corresponds to a current density of 105 A/cm^2. Under these conditions, the original SPT diode has an on-state voltage drop of 3.2 V and 255 mJ recovery losses. The final SPT$^+$ diode design has about 150 mV higher on-state voltage drop but only 155 mJ or 40% less recovery compared to the standard diode, which represents a significantly improved technology curve.

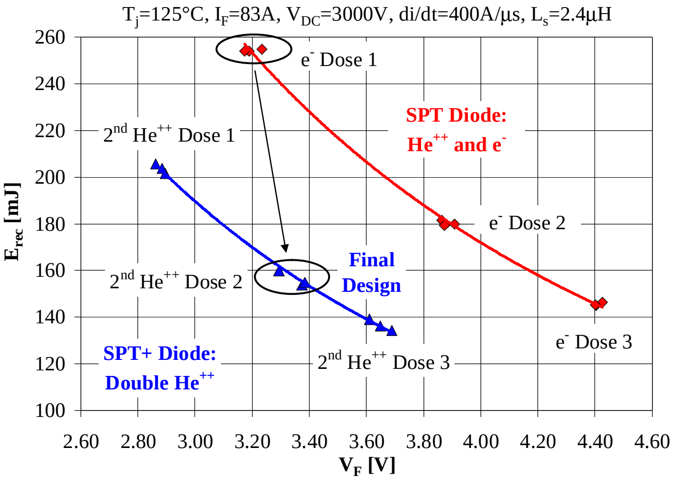

Fig. 5: Technology curve of the 4.5 kV SPT and SPT$^+$ diodes under nominal conditions. The different points on the two technology curves were in the case of the SPT diodes achieved by different electron irradiation doses, and in the SPT$^+$ diodes with different 2nd He^{++} peak doses.

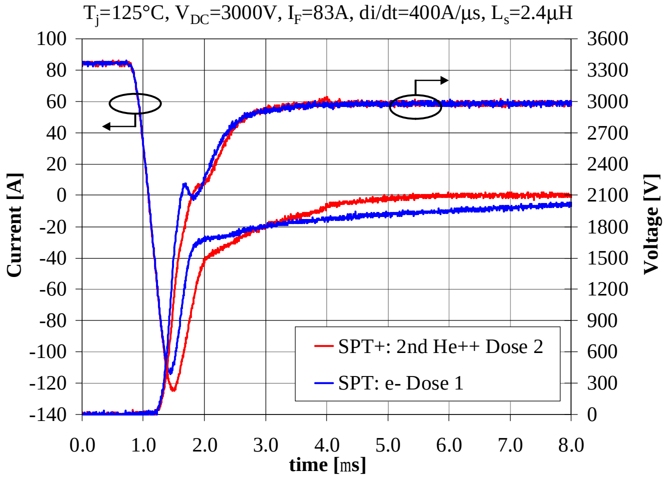

Fig. 6: 4.5 kV diode reverse recovery waveforms under nominal conditions.

In Fig. 6, the recovery waveforms measured under nominal conditions for these two diodes can be seen. The corresponding simulated on-state hole density can be seen in Fig. 3. The second He^{++} peak used in the SPT$^+$ diodes significantly reduces the plasma concentration on the cathode side, which reduces the recovery current tail and thereby the recovery losses. In spite of the fact that both diodes use the same He^{++} irradiation in the anode, due to the missing homogenous lifetime reduction, the SPT$^+$ diodes have a higher plasma concentration on the anode-side of the N-base. This causes the SPT$^+$ diode to have an increased peak current (I_{RR}), which can have negative effects on diode softness and SOA. On the other hand this also slows down the initial voltage rise during recovery (dV/dt), which reduces the stress on the electrical insulation in the driven motor. The plasma concentration in the middle of the N-base can be controlled by the depth and irradiation dose of the second He^{++} peak. In this way, the SPT^{+} diode can be optimized to get the best trade-off between losses and softness as will be discussed in the next section.

In Fig. 7, the on-state characteristics of the SPT^{+} diode are shown. The diode has a positive temperature coefficient of the on-state voltage drop (V_F) already well below the nominal current, which is necessary to ensure good parallel operation within the IGBT module. At rated current and 125 °C, the diode has a typical on-state voltage drop of 3.4 V, or 400 mV higher than at room temperature. Under the same conditions, the standard SPT diode only has a difference of 200 mV between the 125 °C and room temperature voltage drops.

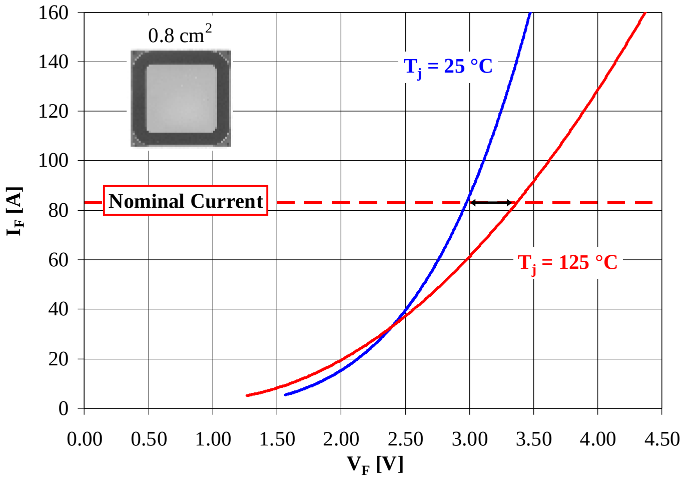

Fig. 7: 4.5 kV SPT^{+} diode on-state characteristics at room temperature and 125 °C.

Trade-off between Diode Losses and Softness

The reduction of the cathode-sided plasma concentration can be critical for the diode softness. The irradiation scheme in the SPT^{+} diodes had therefore to be thoroughly optimized in order to reach the desired characteristics. This optimization will now be discussed based on electrical results from the 3.3kV SPT and SPT^{+} diode. The double He^{++} technology will also be compared to standard SPT diodes, which were fabricated using thinner silicon as an alternative method to reduce losses.

In Fig. 8, the technology curve of the 3.3kV SPT and SPT^{+} diodes are shown. All diodes have an active area of 1.16 cm^2. The characterization was made using the nominal current of the SPT^{+} diodes, which is 125 A. This corresponds to a nominal current density of 108 A/cm^2. Two different versions of the SPT diode employing different silicon specifications were fabricated in order to investigate the impact on losses and softness. The standard version has the same silicon as was also used to make the SPT^{+} diodes. The second version utilizes a 5% thinner, higher resistivity material. The two materials were designed to have approximately the same cosmic ray failure rate. The thinner diode was irradiated with a slightly higher electron dose to have the same on-state voltage drop but lower recovery losses compared to the standard SPT diode version. As can be seen in Fig. 8, in spite of the thinner silicon the losses are, still considerably higher than by the SPT^{+} diodes.

The SPT^{+} diodes were irradiated using three different second He^{++} peak doses (D1 to D3) at two different peak depths. The depth of the second He^{++} peak defines the technology curve, placing devices with a shallow peak depth (green curve) on a slightly better technology curve than the ones utilizing a deeper peak position (blue curve). Together with the losses, the depth of the second peak also strongly determines the diode softness. As already mentioned, one of the most important preconditions for the new diode technology was that the reverse recovery had to be at least as soft as the one of the standard SPT diodes. This goal was achieved by the diode marked as the final design in Fig. 8 (He^{++} dose 1 and He^{++} depth 2).

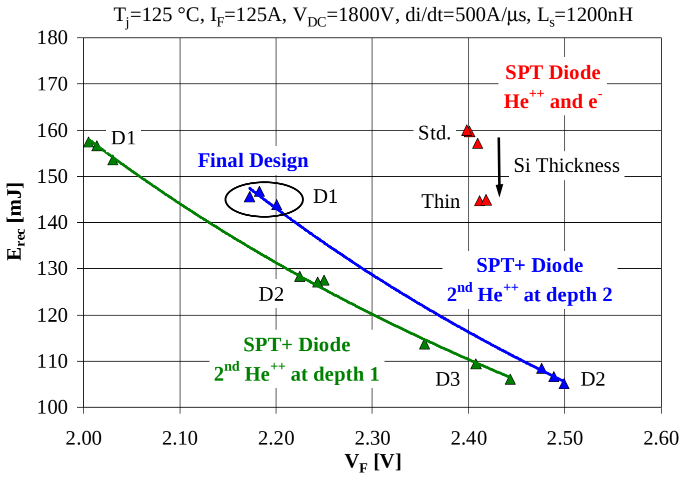

Fig. 8: 3.3 kV SPT and SPT$^+$ diode technology curves. The SPT diodes were made with two different silicon thicknesses. The SPT$^+$ diodes were made using two different second He^{++} peak depths and three different doses.

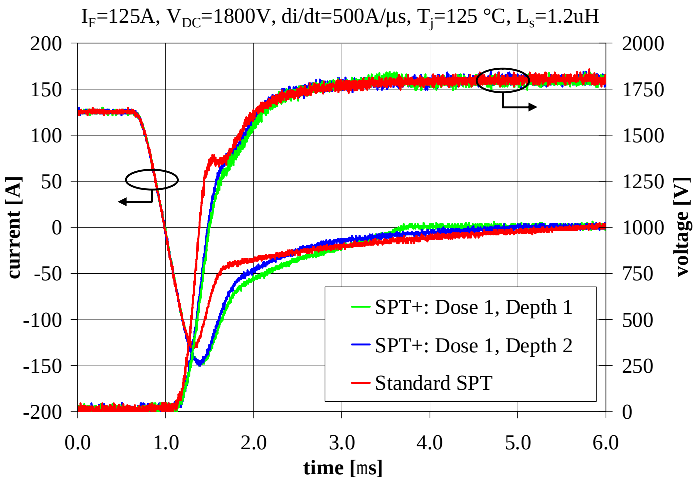

Fig. 9: 3.3 kV SPT and SPT$^+$ diode recovery waveforms under nominal conditions. The standard SPT diode as well as two SPT$^+$ diodes with different 2nd He^{++} peak depths, but the same doses are shown.

Fig. 9 shows the reverse recovery waveforms under nominal conditions for the standard SPT diode, as well as two SPT$^+$ diode versions with different second He^{++} peak depths. The SPT$^+$ diode with the final design uses He^{++} dose 1 and peak depth 2 as compare to the second shown version, which was made using the same dose but with a shallower peak position (He^{++} dose 1 and depth 1). Under the condition in Fig. 9, all three diodes show a smooth switching behavior. Fig. 10 shows the waveforms of a reverse recovery softness test. The test was done at 1/10 of the nominal current but still using the nominal DC-link voltage and stray inductance. The temperature was 125 °C, which was found to be the most critical condition in terms of softness for this diode technology. Fig. 10a shows the two SPT diodes with the standard and the thin silicon, and Fig. 10b shows the two SPT$^+$ diode versions with different second He^{++} peak depths. Already at these moderate conditions, the thin SPT diode shows a large overshoot voltage and subsequent oscillations. Although on a worse technology curve than the SPT$^+$ diodes, the thin SPT diode clearly has a snappier reverse recovery behavior.

The SPT^+ diode with the shallow second He^{++} peak position also shows a current snap-off, whereas the diode with the deep peak position recovers as softly as the original SPT diode. This shows that by choosing the parameters of the second He^{++} peak properly, the SPT^+ diode can be made as soft as when utilizing the traditional irradiation scheme of the standard SPT technology. Furthermore, it can be concluded that a long current tail is not always necessary to achieve a soft recovery behavior. The shape of the current tail given by the shape of the remaining plasma is much more decisive for the softness then the actual tail length.

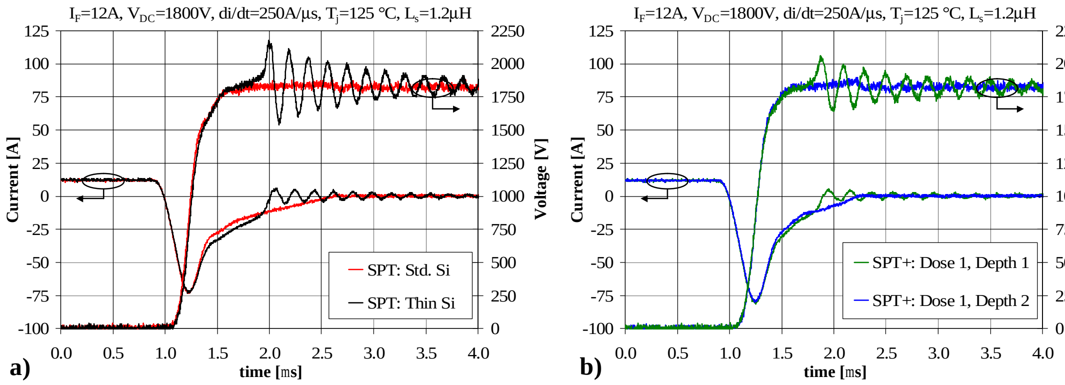

Fig. 10: 3.3 kV SPT and SPT^+ diode softness waveforms measured at 1/10 of the nominal forward current. Fig. 10a shows the standard and the thin SPT diode. Fig. 10b shows two SPT^+ diodes with the same second peak dose, but with two different peak depths (standard and shallow).

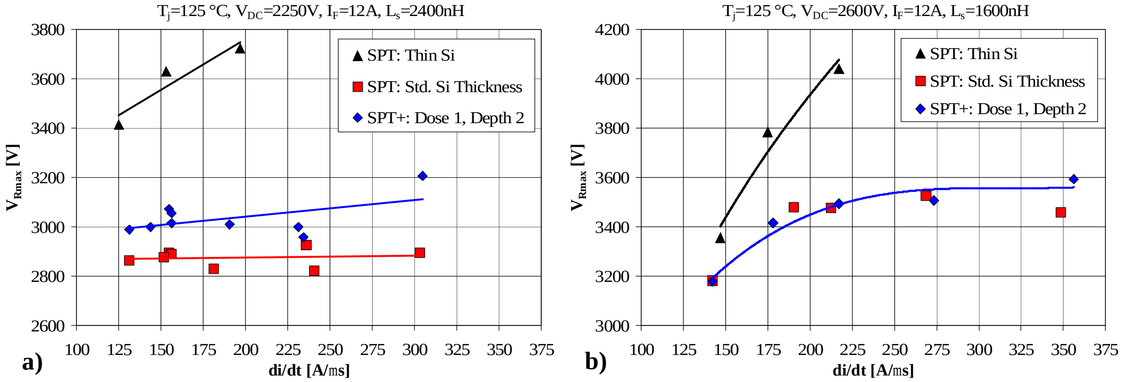

Fig. 11: 3.3 kV diode softness test at low forward current (I_F = 1/10 of I_{nom},) showing the reverse recovery overshoot voltage as function of the recovery di/dt. a) Moderately high DC-link voltage combined with a high stray inductance. V_{DC} = 2250 V, L_s = 2400 nH. b) Very high DC-link voltage and moderately high stray inductance. V_{DC} = 2600V, L_s = 1600 nH.

Fig. 11 shows the reverse recovery softness under more stressful conditions. In the two graphs, the peak voltage, which is a good indicator for the diode softness, has been plotted against the reverse recovery di/dt. The final SPT^+ diode design (dose 1, depth 2) as well as the standard and the thin SPT diode are shown. The tests were again done at 1/10 of the nominal current, but at higher stray-inductances and higher DC-link voltages than above. In Fig. 11a, the DC-link voltage was 2250 V and the stray-inductance was 2.4 µH, which is about twice the nominal stray inductance the diode encounters in typical applications. At high stray-inductance, the SPT^+ diode shows slightly more snappiness especially at high di/dt's compared to the standard SPT diode. The thin SPT diode performs as expected very poorly in these test, showing massive over-voltage peaks. In Fig. 11b, the diodes were tested using a lower stray inductance but at a higher DC-link voltage (V_{DC} = 2600 V, L_s = 1.6 µH). Under these conditions, the SPT^+ diode has the same softness as a standard SPT diode even up to very high di/dt values. This shows that the SPT^+ technology has good softness, comparable to the old SPT technology under all application relevant operating conditions. At extreme conditions, the lower plasma concentration on the cathode side can nonetheless lead to a more snappy behavior. The only alternative to otherwise reduce the diode losses is by thinning the silicon, which clearly yields a diode with unacceptable snap-off problems.

Reverse Recovery Ruggedness

The reverse recovery safe operating area (SOA) of the new SPT$^+$ technology was extensively investigated and compared to the standard SPT technology. The results will be discussed based measurements of the 4.5kV diodes. The SOA limit was measured using a high DC-link voltage and a high stray inductance (V_{DC} = 3600 V, L_s = 4 µH). The current was stepped up from 1/10 to 2 times the nominal value. After a successful pass, the reverse recovery di/dt was increased by lowering the gate-resistor value ($R_{g,on}$) of the switching IGBT until the diode failed. With this procedure it was ensured that the global SOA of the diode was found, including failures due to snappy recovery. In Fig. 12, the last pass reverse recovery waveforms of the SPT as well as the SPT$^+$ diode can be seen. Both diodes show an extremely rugged performance with a peak-power of 700 kW/cm^2 for the SPT$^+$ diode. This high recovery robustness was achieved thanks to the combination of a highly doped anode emitter, which prevents any reach-through effects and a carefully designed electron-hole plasma shape. In Fig. 13, the measurements using the next lower gate resistor values are shown. In this test, both diodes failed, but apparently for different reasons. The SPT$^+$ diode failed due to an over-voltage peak and a subsequent electric field distortion due to the low plasma concentration on the cathode side of the N-base [11]. In this failure mode, the destruction point is always located in the central part of the active diode area, whereas the SPT diodes always fail at the edge of the main active area junction. During on-state operation, significant electron-hole plasma is also stored in the area of the diode located vertically underneath the junction termination. During reverse recovery, the resulting current geometrically concentrates into the edge of the main junction, where it locally increases dynamic avalanche and heating. Due to the higher plasma concentration on the cathode side, this effect is much stronger in SPT diodes and limits the SOA capability of this diode technology. Obviously, the 4.5 kV SPT$^+$ diodes have the same SOA capability as the original SPT diodes. The failure mechanisms are in both cases connected to the remaining plasma at the cathode side. The SPT$^+$ diodes are destroyed because the plasma concentration is too low, while the SPT diodes fail due to a too high plasma concentration.

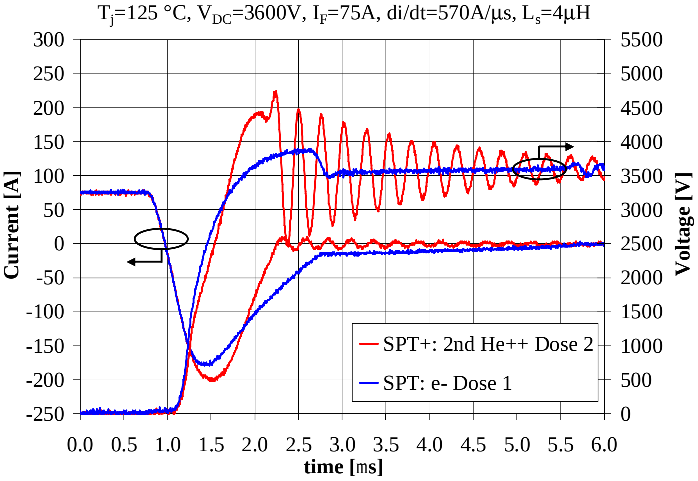

Fig. 12: 4.5 kV SPT and SPT$^+$ diode SOA-waveforms just before destruction. V_{DC} = 3600 V.

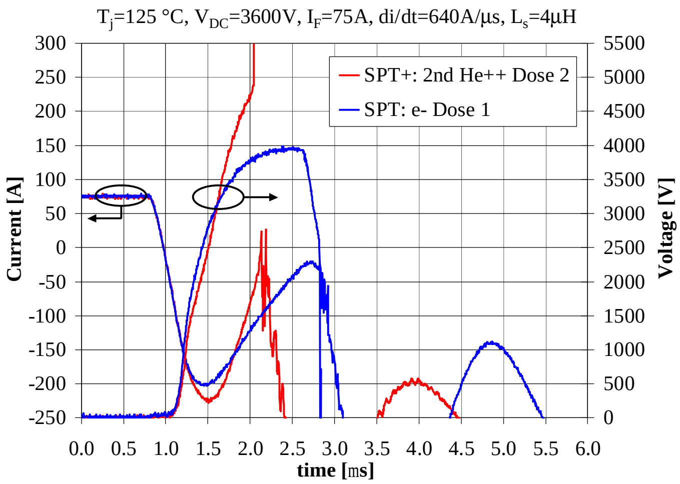

Fig. 13: 4.5 kV SPT and SPT$^+$ diode SOA-failures. Both diode fail under the same conditions, but for different reasons.

Surge Current Capability

In Fig. 16, the surge current waveforms of the 4.5 kV SPT$^+$ diode are shown. The measurements were made on module level, which means that 12 diodes with a total active area of 9.5 cm^2 were tested in parallel. The pulse duration was 10 ms in this test. The diodes reached a peak current of 12.4 kA, corresponding to an I^{2}t value of 830 kA^{2}s before failing. The achieved surge current capability is thereby very similar to the one of the standard SPT diodes. The different irradiation schemes do not have an influence on the capability. The high surge current capability is achieved thanks to the strongly doped and deeply diffused anode and cathode emitter profiles.

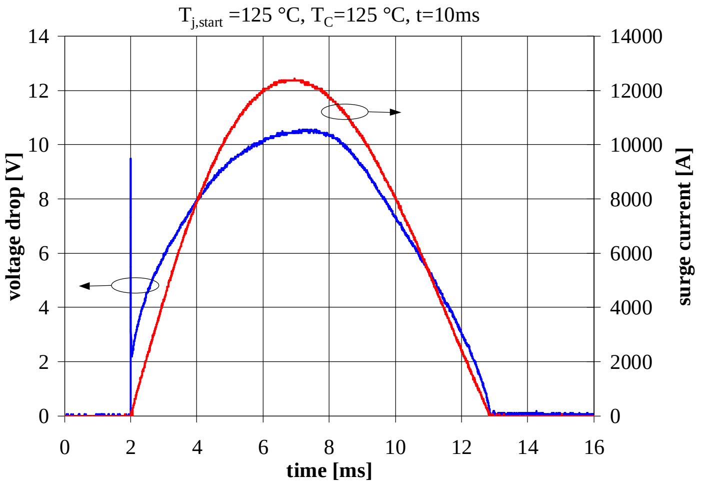

Fig. 14: Surge current waveforms of the 4.5 kV SPT$^+$ diode on module level. The I^{2}t value is 830 kA^{2}s.

Leakage Current

Lifetime control by He^{++} irradiation introduces deep levels into the silicon band-gap, which are known to increase the reverse leakage current of the diode. The leakage current has to be kept small in order to prevent thermal runaway during blocking at high temperatures. In the case of the SPT$^+$ diode, two He^{++} peaks were used, and therefore the leakage current also was an important parameter, which had to be optimized during the development work. Fig. 15 shows the probability plot of the leakage current of several hundred 3.3 kV SPT and SPT$^+$ diodes. The measurement was done at $T_j = 125$ °C and $V_R = 3300$ V. In spite of the additional He^{++} irradiation, the SPT$^+$ diodes do not show higher leakage currents than the standard SPT diodes. The reason for this is that the leakage currents are in both cases dominated by the He^{++} peak on the anode side due to its much higher implantation dose.

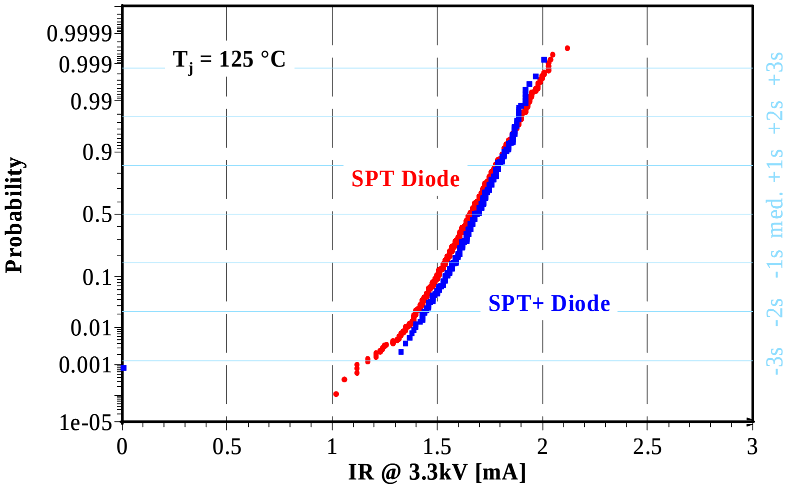

Fig. 15: Probability plot of the 3.3 kV diode leakage current at $T_j = 125$ °C and $V_R = 3300$ V.

Conclusion

In this paper, a newly developed high voltage diode technology for IGBT-modules was presented. The new diode technology uses a double-sided local lifetime control with He^{++} irradiation to adjust the on-state electron-hole plasma. The new diodes offer significantly reduced total losses combined with soft reverse recovery behavior and high ruggedness. The cathode sided He^{++} peak can be used to control the trade-off between diode losses and softness. In this way the diode characteristics can easily be adjusted according to the application requirements.

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