The Trade-Off between Surge-Current Capability and Reverse-Recovery Behaviour of High-Voltage Power Diodes

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Abstract

*This paper discusses the trade-off between surge-current capability on the one hand and reverse-recovery charge, ruggedness and softness of high-voltage diodes on the other hand. Diodes with a CIBH (*Controlled Injection of Backside Holes*) structure in front of the cathode and a highly doped p^+-region combine high surge-current capability with reverse-recovery ruggedness and softness. This can be further improved by embedding a SPEED (Self-adjusting p-Emitter Efficiency Diode) or an IDEE (Inverse injection Dependency of Emitter Efficiency) structure in front of the anode. The IDEE concept causes a decrease of the emitter efficiency at low current densities and an increase of the emitter efficiency at high current densities. This reduces the reverse-recovery charge and further increases the surge-current capability. It is shown that the recently introduced IDEE concept works more efficiently than the SPEED concept.*

Keywords: surge current, reverse recovery, High voltage diode, destruction, ruggedness, softness, losses.

INTRODUCTION

To ensure a soft and rugged reverse-recovery behaviour, the plasma in the n^--region should run out in front of the n^+-region. The presence of a cathode-side depletion layer at the time of plasma-layer exhaustion leads to a clash of both depletion layers and a resulting snappy switching behaviour [1]. Furthermore, cathode-side filaments, which are considered dangerous in terms of device destruction [2,3], can appear. An important measure concerning soft and rugged reverse recovery is the tailoring of the plasma distribution at the on-state (Fig. 1). A characteristic parameter to evaluate the plasma distribution can be given by the relation

$$\eta_{forw} = \frac{p_{c,forw}}{p_{a,forw}}, \qquad (1)$$

where $p_{c,forw}$ is the carrier density near the n^--n^+-junction and $p_{a,forw}$ is the carrier density near the p^+-n^--junction. According to Hall's theory, η_{forw} is smaller than 1 in a diode with ideal emitters due to the higher mobilities of electrons compared to holes. However, modern diode concepts invert the plasma distribution to achieve $\eta_{forw} > 1$ [4,5] (Fig. 1).

The surge-current capability of modern wire-bonded diodes is mainly determined by thermal stress caused by energy losses which lead to a melting of the metallization around the bondfeet [6,7]. To decrease the energy losses, the forward voltage drop at high currents should be low. This goal is achieved by a high plasma level in the whole n^--region. This demand conflicts with the optimisation of the reverse-recovery behaviour which requires a low $p_{a,forw}$ in the application-relevant current range. The trade-off can be improved by controlling η_{forw} by the forward current.

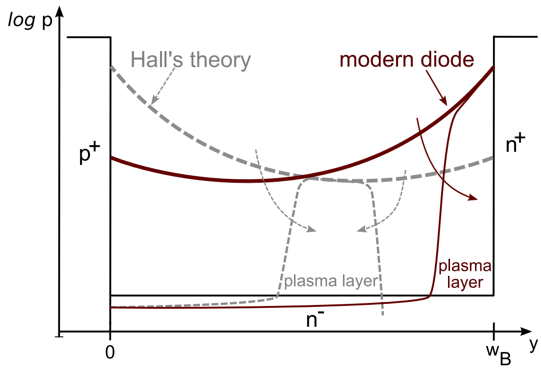

Fig. 1: Carrier distribution during on-state and shortly before exhaustion of the plasma layer (dashed lines: Hall's theory, continuous line: typical soft-recovery diode).

Fig. 2 schematically shows the forward characteristics and the plasma distributions of a reference diode with laterally homogeneous emitter regions and an optimised diode. Both diodes have the same conducting losses and almost the same turn-off losses at rated current. The optimised diode has a significant lower voltage drop for high current, leading to a higher surge-current capability. Such an optimised diode behaviour was achieved by implementing the Self-adjusted p Emitter Efficiency

Diode (SPEED) concept [8]. However, the plasma level in front of the p^+-region of the optimised diode is higher at twice the rated current $2 \cdot I_{Rated}$. For this reason the optimised diode tends to be snappy and not rugged if it is turned off from high current levels. A measurement on a non-optimized SPEED diode showed a lack of reverse-recovery ruggedness (Fig. 3).

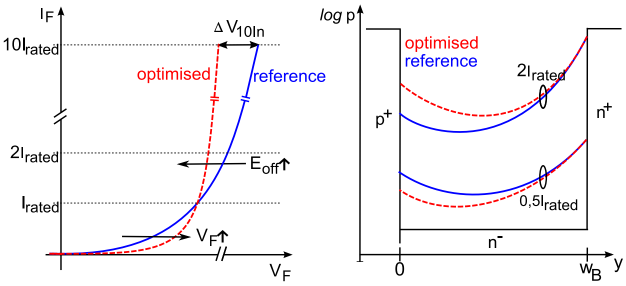

Fig. 2: Left: Schematic forward characteristic. Right: Schematic on-state charge carrier distribution.

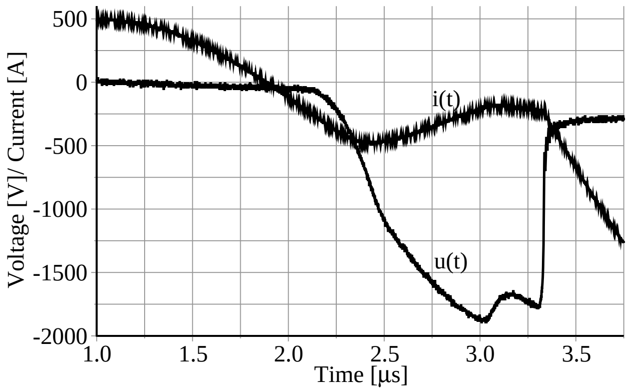

Fig. 3: Measured voltage and current transients during a destructive reverse recovery of a non-optimized SPEED diode.

In this work, we consider the SPEED concept and the recently introduced Inverse Injection Dependency of Emitter Efficiency (IDEE) concept [9], which both improve the trade-off between surge current capability and reverse-recovery behaviour. However, we first investigate how the implementation of a Controlled Injection of Backside Holes (CIBH) structure [10] guarantees soft and rugged reverse recovery and how this accounts for the improvement of surge current capability. All analyses have been done using the device simulator $\text{Sentaurus}_{\text{TCAD}}$ [11].

ANODE EMITTER CONCEPTS

The aim of CIBH structure introduced in 2006 was to improve diode reverse-recovery softness and ruggedness, which has been proven by device simulation and experiment [10]. Furthermore, a 25 % improvement of the trade-off between the forward voltage drop and the reverse-recovery losses has been achieved [12]. In this work, we want to investigate whether the CIBH concept still suppresses the appearance of a cathode-side depletion layer during reverse recovery if η_{forw} is higher than 1. If this would be the case, the trade-off between surge-current capability and reverse-recovery softness could easily be achieved by implementing a CIBH structure. We simulated three different diode structures with the same n^--region and the same n^+-region with a high emitter efficiency γ_C. The p^+-n^--n^+-diode (reference diode) consists of a p^+-region with a low emitter efficiency γ_A. The CIBH diode additionally has a CIBH structure in front of the cathode. In the third diode, the doping density of the anode-side emitter region has been increased by around one order of magnitude (CIBH diode with high p^+ doping). The simulation results (Figs. 4, 5) show that there is a cathode-side depletion layer in the reference diode at t = 1.875 µs.

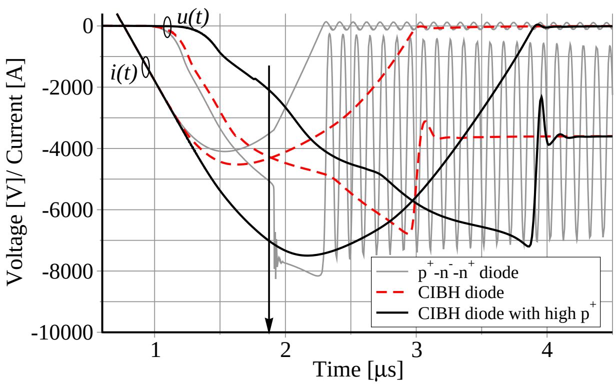

Fig. 4: Voltage and current waveforms during reverse recovery of a p^+-n^--n^+-diode, a CIBH diode and a CIBH diode with increased p^+-doping. All diodes have a breakdown capability of about 8 kV. (L_c = 4.7 µH, V_{dc} = 3600 V, $I_F = I_{rated}$ = 200 A).

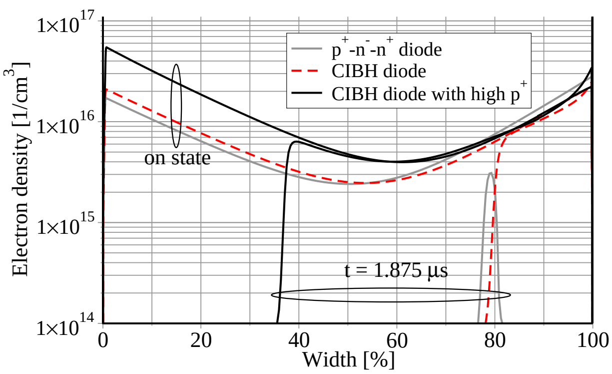

Fig. 5: Electron density at the onset and during reverse-recovery process (t = 1.875 µs) of a p^+-n^--n^+-diode, a CIBH diode and a CIBH diode with increased p^+-doping, Fig. 4.

Shortly after 1.875 µs, the plasma layer exhausts and the diode turns into the switching self-clamping mode (SSCM). After about 0.3 µs the diode leaves the SSCM with strong current and voltage oscillations. Contrary to this behaviour, the appearance of a cathode-side depletion layer is successfully prevented by the CIBH structure. This is the reason for the high reverse-recovery softness of CIBH diodes [10,12]. Although the value of η_{forw} in the CIBH diode with high p^+ doping is about 2.5, the implemented CIBH structure inhibits the appearance of a cathode-side depletion layer. Beside the excellent reverse-recovery behaviour, the surge-current capability of the CIBH diode with high p^+ doping is very high compared to the other diodes due to the increased plasma level. The simulations show that the improvement of the surge current capability is an additional potential of the CIBH concept. However, the reverse-recovery charge of the CIBH diode with high p^+ doping is very high, leading to strongly increased switching losses.

To overcome this disadvantage, an improved anode emitter can be implemented by means of the SPEED concept. This leads to low anode-side plasma levels at low and medium current densities and high plasma levels at high current densities, which occur during a surge-current event. Consequently, the anode-side emitter efficiency,

$$\gamma_A = \frac{j_p}{j_{total}} = 1 - \frac{j_n}{j_{total}}, \quad (2)$$

should increase with increasing forward current density. The SPEED structure consists of highly-doped p^+-areas within a low-doped p^--region (Fig. 6).

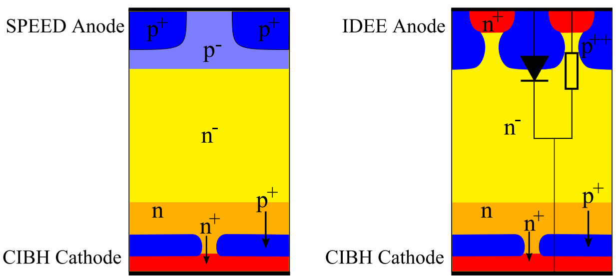

Fig. 6: Basic structure of the SPEED-CIBH diode and the IDEE-CIBH diode. The n-channels of the IDEE anode are narrow enough to shield the n^+-layer from the electric field.

The concept uses the fact that the amount of minority current density j_n will be higher if the doping density of the p-emitter region is lower. At low and medium current densities, the current is mainly flowing between the p^+-regions due to the higher junction barrier in the area of the p^+-regions leading to a low γ_A. At higher current densities, the voltage drop increases leading to a significant current flow through the p^+-regions. This current flow results in an increased plasma level.

The new IDEE structure has a highly-doped p^{++}-region which is interrupted by small n-channels (Fig. 6). At low current densities, the main part of the current flows as electron current (j_n) through the n-channels, leading to the desired low γ_A. The current through the p^{++}-regions is significantly lower because charge carriers have to cross the barrier of the p^{++}-n^- junction. However, this changes with increasing j_{total} because j_n is limited due to the resistance of the n-channels. The dependency of γ_A on the current density is successfully inverted, compared to a reference diode with a homogenous p^+-region (Fig. 7).

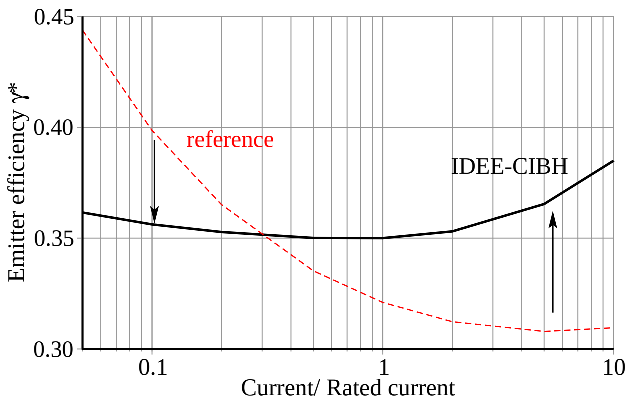

Fig. 7: Emitter efficiency γ* of the anode-side emitter depending on the forward current (simulated).

To compare the different diode structures, the carrier lifetimes of the diodes were adjusted in order to have the same forward voltage drop at rated current (62.5 A). The SPEED and the IDEE diode were combined with a CIBH concept, which does not influence the forward voltage drop. The forward characteristics of these diodes show reduced forward voltage drops at high current densities, which indicate already a higher surge-current capability compared to the reference diode (Fig. 8).

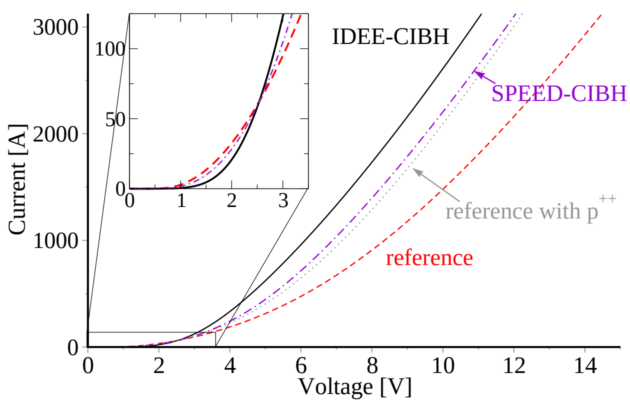

Fig. 8: Forward characteristic for high currents of several diodes. All diodes have a breakdown capability of about 5 kV. (simulation @ T = 400 K).

These results show a successful control of the emitter efficiency. IDEE concept works more efficiently than the SPEED concept, because there is no barrier like the p^{-}-n^{-} junction for the charge carriers.

REVERSE-RECOVERY DESTRUCTION CAUSED BY CATHODE-SIDE FILAMENTS

Diodes with a SPEED or an IDEE emitter concept have higher values of η_{forw} at high currents which promotes the appearance of a cathode-side depletion layer during reverse recovery at high forward currents. A cathode-side depletion layer is not only critical in terms of softness. If both the extension of the cathode-side depletion layer and the reverse current are high, current filaments will appear. Cathode-side filaments tend to be immobile or they only move with a relatively small velocity [2,13]. That leads to strong local heating and can cause diode destruction through thermal runaway [14]. Such a destruction mechanism is seen as the reason for the diode failure shown in Fig. 3.

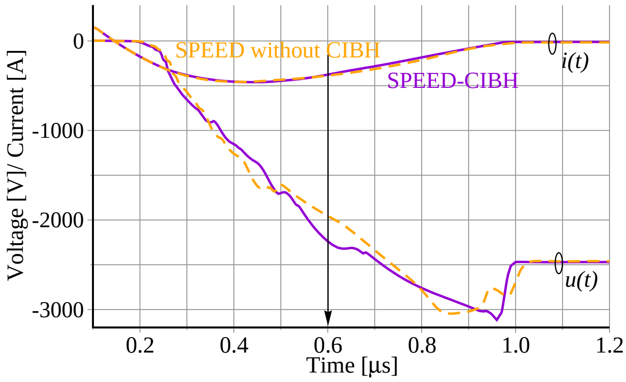

Fig. 9: Voltage and current waveforms during reverse recovery of the SPEED-CIBH diode and the SPEED diode without CIBH (L_c = 714 nH, V_{dc} = 2500 V, $I_F = 2.5 \cdot I_{rated}$ = 156.25 A, $T_{initial}$ = 400 K, R = 2.5 Ω).

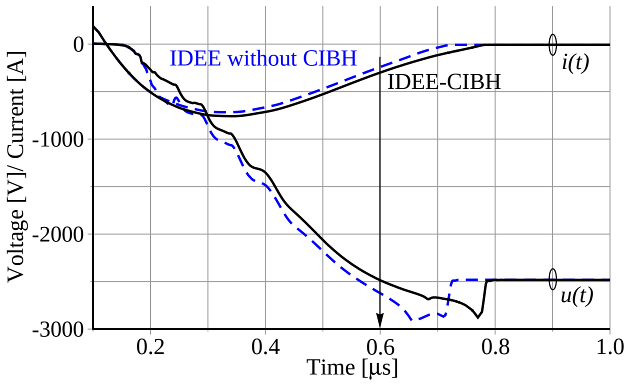

Fig. 10: Voltage and current during reverse recovery of the IDEE-CIBH diode and the IDEE diode without CIBH (L_c = 714 nH, V_{dc} = 2500 V, $I_F = 3 \cdot I_{rated}$ = 187.5 A, $T_{initial}$ = 400 K, R = 2 Ω).

To improve the safe operation area of diodes, the anode emitter structures were combined with a CIBH cathode structure. To demonstrate the effect of CIBH, electrothermal reverse-recovery simulations of the IDEE-diode and the SPEED-diode with and without a CIBH structure were performed. The simulation circuit consists of an ideal switch, a voltage and current source, a circuit inductance and an additional resistance which limits the transient overvoltage [2]. The initial current level was 2.5 times the rated current and 3 times the rated current, respectively.

The voltage and current waveforms (Figs. 9, 10) of the diodes with and without CIBH structure are similar. Figures 11 and 12 show the current density distribution of all diodes at 0.6 µs. The diodes without CIBH structure show a single immobile cathode-side filament. Current contraction into a single filament with a high current density is successfully suppressed in the diodes with CIBH structure by triggering multiple filaments at the positions of the p-islands with a respective maximum current density that is much smaller compared to the maximum current density in the cathode-side filament of the diode without CIBH structure.

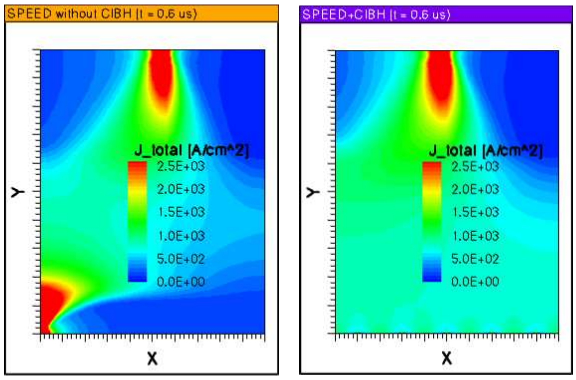

Fig. 11: Current density distribution in the SPEED diode without CIBH (left) and with CIBH (right) at 0.6 µs, Fig. 7.

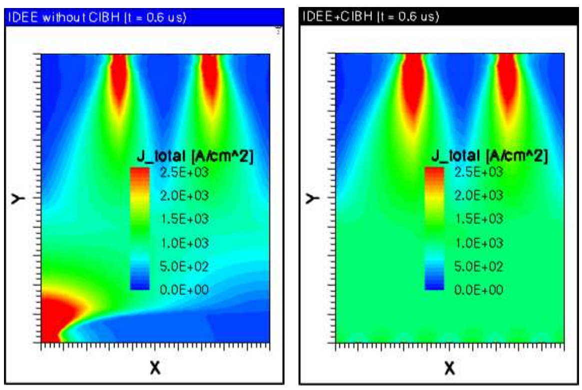

Fig. 12: Current density distribution in the IDEE diode without CIBH (left) and with CIBH (right) at 0.6 µs, Fig. 8.

INCREASED SURGE CURRENT CAPABILITY

To investigate the surge-current capability, electrothermal simulations with 10 ms half sine pulses were performed. Auger and Shockley-Read-Hall recombination, carrier-carrier scattering, doping-dependent, temperature-dependent and electric-field-dependent mobilities were included. Both emitter concepts, SPEED and IDEE, lead to a power loss reduction at high surge currents, indicating a significant improvement of the surge-current capability (Fig. 13). The 22-% reduction of IDEE-CIBH diode is higher than the 17-% reduction of the SPEED-CIBH diode. These results show the better emitter efficiency of the IDEE concept.

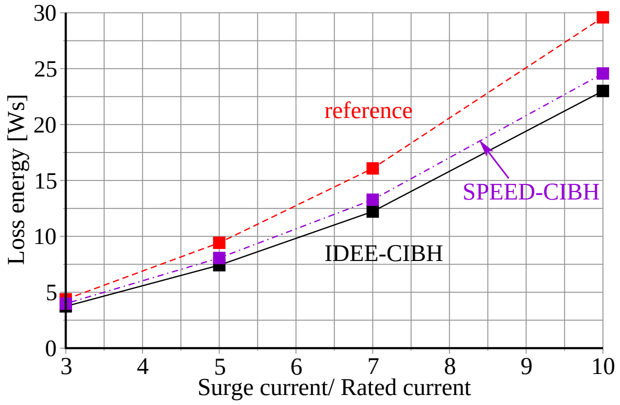

Fig. 13: Energy dissipation depending on surge current maximum (10 ms half sine pulses).

PEAKS IN THE ELECTRIC-FIELD STRENGTH IN THE SPEED STRUCTURE DURING REVERSE RECOVERY

The lateral p^--p^+ junction of the SPEED structure can lead to increased electric-field strength peaks during reverse recovery. If such electric-field strength peaks are very high, they limit the diode ruggedness. Three different SPEED variations were investigated numerically (Fig. 14). The first type has deep p^+-regions, so that the p^+-n^- junction has the same penetration depth as the p^--n^- junction. In the second SPEED structure, referred to as deep p^+ with VLD, the doping concentration of the p^+-regions decreases gradually in lateral direction. The third SPEED structure possesses shallow highly-doped p^+-regions. The area ratios p^+/p^- at the anode contact have been adjusted for all three SPEED structures in order to achieve the same on-state operating point as the reference diode (Fig. 8). Electrothermal simulations of the diode reverse recovery were performed by switching off the diodes from the rated current at a dc-link voltage of 2500 V. Due to the adjustment of the area ratio p^+/p^-, the stored charge carriers and the values of η_{forw} are similar in all three diodes, leading to nearly identical current and

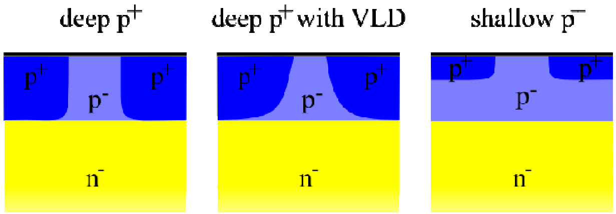

Fig. 14: Investigated SPEED variations (schematically).

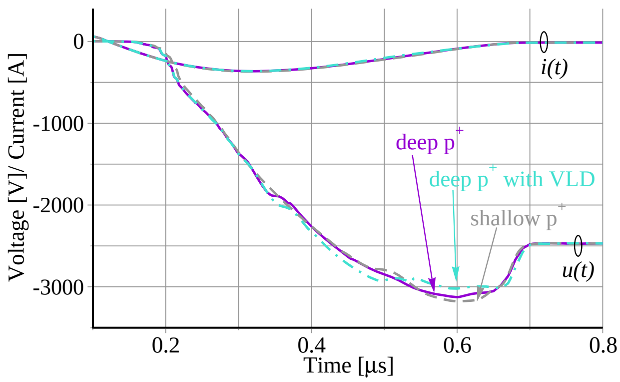

Fig. 15: Voltage and current during reverse recovery of diodes with different SPEED designs (L_c = 714 nH, V_{dc} = 2500 V, $I_F = 3\ I_{rated}$ = 187.5 A, $T_{initial}$ = 400 K, R = 2 Ω).

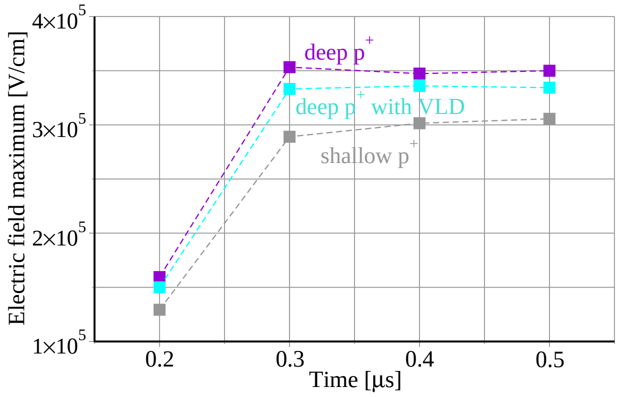

Fig. 16: Absolute value of the maximum electric-field strength in the anode emitter region for different SPEED designs and certain points in time.

voltage waveforms (Fig. 15). However, the analysis of the maximum electric-field strength peaks in the SPEED structures reveals significant differences (Fig. 16). The use of the deep p^+ with VLD structure reduces the peak values by around 6 %. The reduction could be further increased by an optimisation of the lateral doping variation. The on-state voltage drop of the SPEED with deep p^+ with VLD is about 0.2 V higher at the tenfold of the rated current, indicating a small reduction of the surge-current capability compared to the SPEED with deep p^+-regions. This could be modified by larger extensions of the VLD areas. The

SPEED with shallow p^+-regions shows the same small reduction of the surge-current capability, but in this case the reduction of the electric-field strength peaks during reverse recovery accounts for about 18 %. Therefore, the SPEED with shallow p^+-regions delivers the best compromise. The electric field peaks are located in the p^--regions. For that reason, lateral electric-field strength components do not influence the electric field peaks.

CONCLUSION

A significant improvement of the trade-off between surge-current capability and reverse-recovery characteristics has been presented for a CIBH-diode with a highly-doped p^+-region at the anode side. Simulations show the promising potential of the CIBH diode. A further improvement can be achieved by implementing anode emitter concepts, such as SPEED and IDEE, which modify the dependence of emitter-efficiency on current density. Both concepts contribute to a reduction of the reverse-recovery charge. The IDEE-CIBH diode delivers the best trade-off with a 22-% energy loss reduction during surge current. The CIBH structure prevents single cathode-side filaments which are supposed to be the reason for the measured low reverse-recovery ruggedness of SPEED diodes. Furthermore, an appropriate design of the SPEED structure with a low penetration depth of the p^+-region and/or VLD structures at the lateral p^+-p^- junctions are essential to avoid highly destructive electric-field strengths.

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