A new Diode Structure with Inverse Injection Dependency of Emitter Efficiency (IDEE)

Roman Baburske, Josef Lutz
Chemnitz University of Technology
Chair of Power Electronics and EMC
Chemnitz, Germany
Email: Roman.Baburske@etit.tu-chemnitz.de
Josef.Lutz@etit.tu-chemnitz.de

Hans-Joachim Schulze, Hans Peter Felsl
Infineon Technologies AG
Neubiberg, Germany

Ralf Siemieniec
Infineon Technologies Austria AG
Villach, Austria

***Abstract*—In this paper, a new diode structure with Inverse injection Dependency of Emitter Efficiency (IDEE) concept is presented which has been investigated by device simulation. The IDEE concept in combination with a Controlled Injection of Backside Holes (CIBH) cathode structure improves substantially the trade-off between surge current capability, turn-off losses and turn-off ruggedness. The IDEE diode is characterized by an anode-side highly doped p^+-region, which is interrupted by n-doped channels. In contrast to conventional emitters, the IDEE anode region provides a low emitter efficiency at low currents and a high emitter efficiency at high currents. This feature leads to a reduced anode side plasma density and improved reverse recovery at low current densities; on the other hand the diode's surge current capability is significantly enhanced.**

I. Introduction

The ability to withstand high surge current pulses in the forward direction is of great importance for diodes in high power applications. Additionally, diode reverse recovery is an essential process in converters, since fast IGBTs are used. More must be done to ensure a rugged recovery even from a high forward current. Both the surge current capability and the reverse recovery ruggedness are usually increased by a high n^+-region emitter efficiency. To improve reverse-recovery softness and ruggedness, conventional diodes with p-doping controlled emitters (reference) provide a low charge carrier plasma level in front of the anode-side p^+-region to ensure a fast expansion of the anode-side space-charge region during turn-off. However, this measure also reduces the plasma level at very high currents and limits the surge current capability. This paper introduces a new diode concept which improves the trade-off between surge-current capability and diode reverse recovery ruggedness.

II. IDEE-Principle

The emitter efficiency of a diffused homogenous anode-side p^+-region is given by

$$\gamma_A = \frac{j_p}{j_{total}}, \qquad (1)$$

where j_p is the injected hole current density. For such emitters, γ_A strongly decreases with increasing current density, because more recombination takes place in the p^+-region. However, a low γ_A is desired at low and medium current levels to achieve low values of I_{RRM} and soft-recovery, and a high γ_A is desirable at high current levels, at which surge current events take place. If j_p in Eq. 1 is replaced by $j_{total} - j_n$, γ_A can be expressed by

$$\gamma_A = 1 - \frac{j_n}{j_{total}}. \qquad (2)$$

It can be seen that limiting j_n with increasing j_{total} leads to an inversion of the current dependency of the emitter efficiency. This can be achieved by implementing the new Inverse Injection Dependency of Emitter Efficiency (IDEE) concept, Fig. 1.

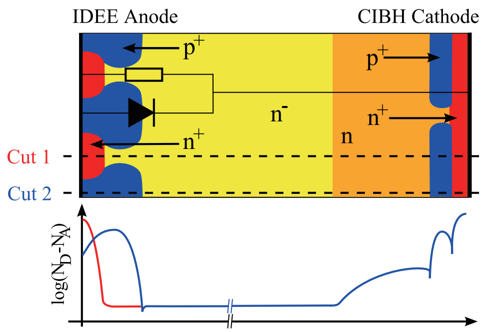

Fig. 1. Cross section of the IDEE-CIBH diode structure.

The very high doped p^{++}-region is interrupted by n-doped channels. At the metal-contact, there are n^+ doped regions to realize ohmic contacts. Furthermore, the diode shown possesses a CIBH-cathode structure which is important for reverse recovery ruggedness, but does not influence the diode in the forward state. Fig. 2 shows the simulated forward characteristics for high currents of the IDEE-CIBH diode and a reference diode with a homogeneously doped p^+-region. The lifetimes of the simulated 3.3-kV IDEE-CIBH diode were adjusted in order to have the same forward voltage drop at the rated current (62.5 A). Both diodes have the same n^--region dimensions. The forward voltage drop is increased in the IDEE-CIBH diode at low currents indicating a lower density of free charges in front of the p^+-region and a low emitter efficiency. However, the forward voltage drop decreases for high currents because of a high level of free

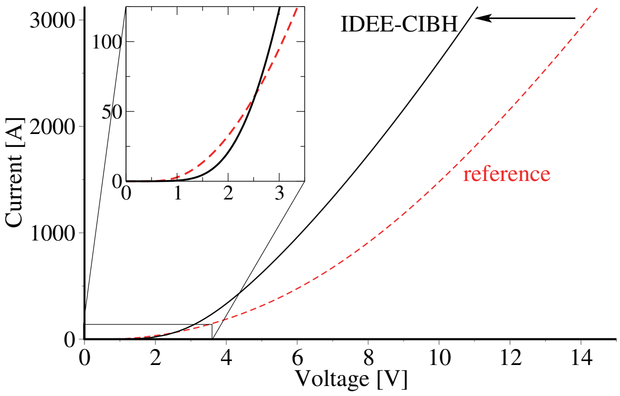

Fig. 2. Forward characteristic for high currents of the IDEE-CIBH diode and the diode with p-doping controlled emitter (reference) (T = 400 K).

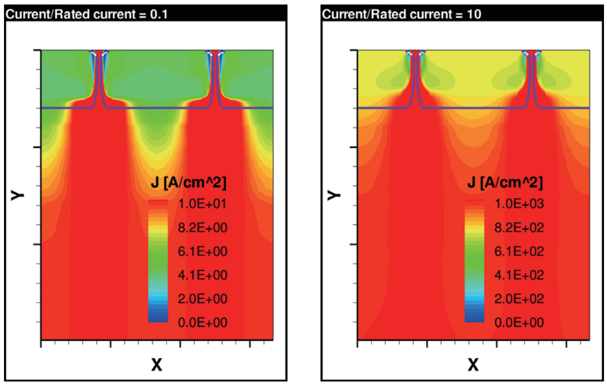

Fig. 4. Current density distribution at the anode-side of the IDEE-CIBH diode at j = 10 j_{rated} (left) and j = 0.1 j_{rated} (right) (top: anode, bottom: cathode).

charge carriers and a high emitter efficiency. The dependency of the emitter efficiency on the current has been extracted from the simulation results, as shown in Fig. 3. The new IDEE-CIBH diode shows the desired inverted dependency with low values of γ_A at low currents and high values at high currents, whereas the conventional p-doping controlled diode shows the typical strong decay of γ_A with increasing currents. The electron density j_n in Eq. 2 is given by

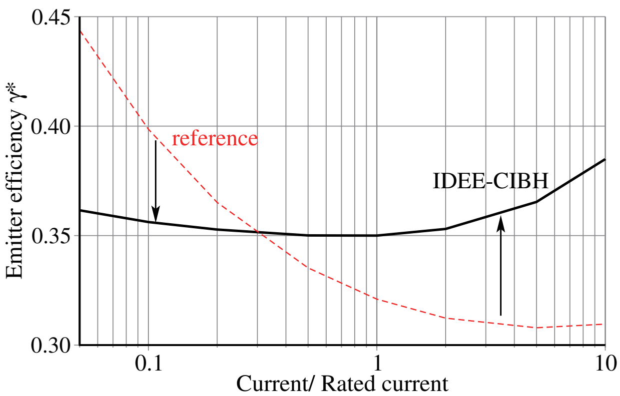

Fig. 3. Emitter efficiency γ^* of the anode-side emitter depending on forward current.

$$j_n = \frac{V_{j,pn}}{R_{ch} \cdot A_{ch}}, \tag{3}$$

where $V_{j,pn}$ is the voltage drop across the p^{++}-n^{-}-junction, R_{ch} denotes the n-channel resistance and A_{ch} is the n-channel area. At low currents, the current through the p^{++}-regions is significantly lower, because charge carriers have to cross an additional barrier, the p^{++}-n^{-}-junction. Nearly the whole current is flowing as j_n through the n-channels. However, this changes with increasing j_{total}, because j_n is limited due to the resistance of the n-channels. Whereas, only 38 % of the current flows through the p^{++}-regions at $I = 0.1\ I_{rated}$, this current part accounts for 75 % of the current at I = 10 I_{rated}, as shown in Fig. 4. The fact that the majority of the current flows through the p^{++}-regions leads to an increase of γ_A and to the desired high plasma level in front of the IDEE-structure. The reason for the still higher j in the n-channels at I = 10 I_{rated} (Fig. 4, right) is due to a decrease of R_{ch} caused by a higher density of free charges.

The IDEE concept is more effective than SPEED [1] and MPS [2] concepts, where charge carriers have to overcome an additional barrier, either a p-n^{-}-junction or a schottky barrier. In contrast to the SPEED-structure, the distance between the p^{+} areas is significantly smaller. As a result the electric field is shielded by lateral components in the area of the n-channels, and the new diode provides the same breakdown voltage as the reference diode, Fig. 5.

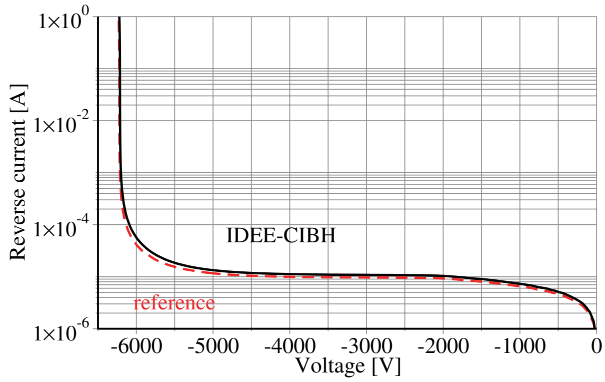

Fig. 5. Reverse characteristic of IDEE-CIBH diode and the reference diode (T = 300 K).

III. Improvement of Surge Current Capability

The significantly reduced forward voltage at high currents compared to a p-doping controlled emitter diode (reference) already indicates an improvement of the surge current capability, as seen in Fig. 2. To further investigate the surge current capability, electro-thermal simulations with 10 ms half sine pulses have been performed with Sentaurus_{TCAD} [3]. Auger and Shockley-Read-Hall recombination, carrier-carrier scattering, doping-dependent, temperature-dependent and electric-field-dependent mobilities were included. The charge-carrier lifetimes were homogeneously distributed over the middle region of the diode. Fig. 6 shows the simulated

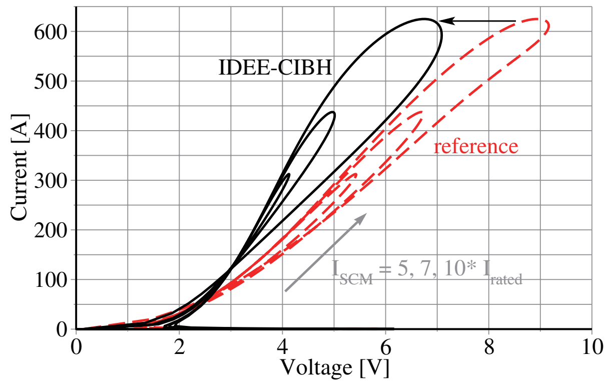

Fig. 6. Surge current behavior during a 10 ms half sine pulse with variation of the maximum current.

surge current behavior in the V-I coordinate system. The curves are located near the static forward characteristic for increasing currents. The thermal heating causes a decrease of the carrier mobilities provoking higher voltage drops at decreasing currents. A destruction of modern power diodes during surge current is typically caused by strong heating due to high currents and high forward voltage drops [4], [5]. The temperature peaks around the bondfoot contact areas leading to melted metallization around the bondfeet [5]. The IDEE-CIBH diode shows an energy loss reduction of around 22 % at high surge currents, indicating a significant improvement of the surge current capability, as shown in Fig. 7. Both diodes

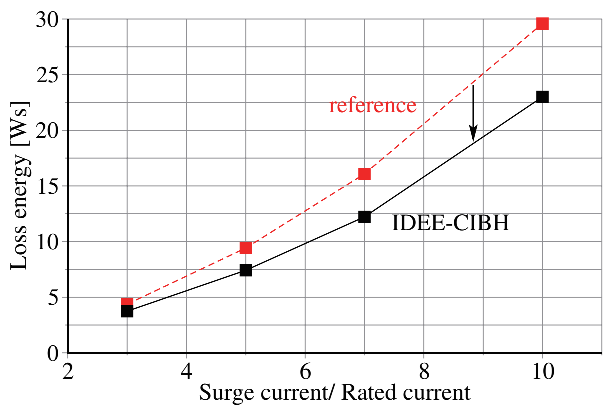

Fig. 7. Energy losses depending on surge current maximum (10 ms half sine pulses).

could be further optimized by a thicker metallization and a larger bondfoot contact area [5].

IV. High Reverse Recovery Ruggedness

Due to the adjustment of the carrier lifetimes, turning-off the rated current leads to a similar E_{off}. To ensure a soft reverse-recovery, the plasma layer should remain in front of the n^+-region. Furthermore, the ruggedness can be limited by the occurrence of current filaments in the depletion regions during reverse-recovery, due to a modification of the shape of the electric field by avalanche-generated charge carriers. This behavior is connected with a branch of negative differential resistance (NDR) in the characteristic of the depletion layer [6], [7]. Anode-side filaments move laterally because of a strong plasma extraction in the vicinity of the filament and the resulting increased expansion of the anode-side depletion layer. As the voltage drop across the depletion layer is the same at every point, the peak of the electric field strength decreases in the vicinity of the filament; the filament is extinguished at that position and a new filament appears at an adjacent position where the width of the depletion layer is lower [6]. The heat-source that is the anode-side filament moves, preventing strong local heating and the consequent diode destruction. However, the cathode-side filament behaves different. It styss fixed. The width of the depletion layer shrinks in the vicinity of a cathode-side filament due to the velocity saturation of the electrons and holes in the high-field region [8], [9]. Therefore the peak of the electric field remains in the center of the filament and the filament can only move through thermal effects. The thermal movement depends strongly on the temperature gradient and is generally significantly slower [10]. Furthermore, the immobility of the cathode-side filament inhibits the onset of multiple filaments leading to an extremely high current density in the filament which triggers a rapid diode destruction with a point shaped failure. To avoid such destructive behavior and to achieve a soft recovery, the forward carrier distribution should be asymmetrical with a lower plasma level in front of the p^+-region. However, the IDEE-concept already lifts the charge carrier density at the anode-side at I_{rated}, as shown in Fig. 8. The situation becomes even more critical when turning off

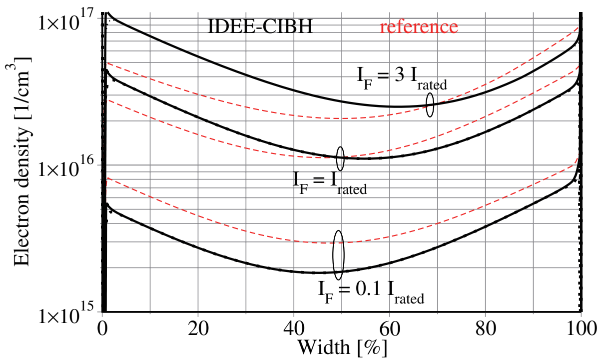

Fig. 8. Electron density distribution during on-state for I_F = 0.1, 1, 2 I_{rated}.

from higher currents. For that reason, a CIBH-structure [11] was implemented at the cathode side.

For the electro-thermal simulation of the reverse-recovery behavior, the avalanche coefficients of Valdinoci et al. [12] were used. In addition to the silicon layer, a solder layer (150 μm thick) and a copper layer (300 μm thick) were added at the cathode side. The temperature at the bottom of the copper layer was fixed at 400 K. The IDEE diode was simulated with and without the CIBH-structure. The simulated voltage and current curves are similar, Fig. 9. The current curve indicates a small increase of the reverse-recovery charge due to the injection of backside holes. This implies a slightly higher reverse-recovery time. The current density distribution

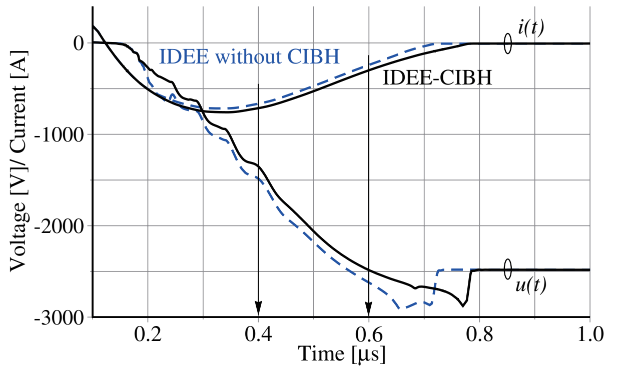

Fig. 9. Voltage and current during turn-off of IDEE diode and IDEE diode without CIBH (L_c = 70 nH, V_{dc} = 2500 V, I_F = 187.5 A = 3 I_{rated}, $T_{initial}$ = 400 K, R = 2).

in the IDEE diode without CIBH, as seen in Fig. 10, shows a cathode-side filament at $x = 0$ μs which indicates the possible destruction by the described mechanism. The onset of a single

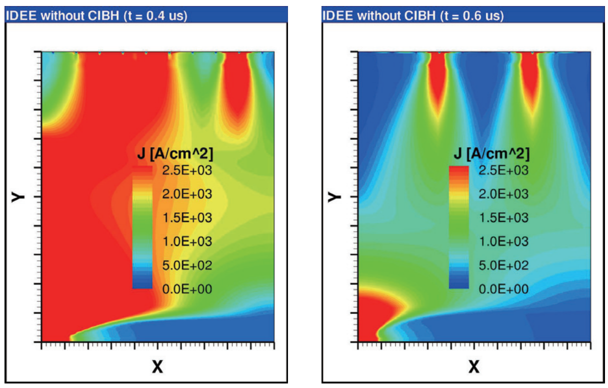

Fig. 10. Current density distribution in the IDEE diode without CIBH at 0.4 us (left) and 0.6 us (right), Fig. 8 (top: anode, bottom: cathode).

cathode-side filament is successfully suppressed by the CIBH concept, Fig. 11. The additional avalanche region between the

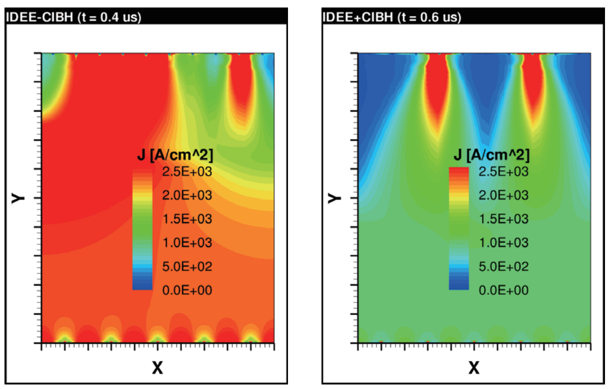

Fig. 11. Current density distribution in the IDEE-CIBH diode at 0.4 us (left) and 0.6 us (right), Fig. 8 (top: anode, bottom: cathode).

p-islands and the n^+-region provokes multiple filaments which are homogeneously distributed over the active area. The diode current is no longer flowing through one single filament, but divides into several parts. This behavior counteracts strong local heating and destruction.

To ensure reverse recovery ruggedness of an IDEE diode without CIBH, the efficiency of the anode emitter region had to be reduced, for example by decreasing the doping of the p^{++}-regions. However, this measure would reduce the surge current capability. A huge improvement in surge current capability while keeping the reverse-recovery ruggedness can only be achieved by implementing both structures, the IDEE structure in front of the anode and the CIBH structure in front of the cathode.

V. Conclusion

A new emitter structure called IDEE has been introduced and investigated by numerical device simulation. This structure consists of a highly doped p^{++}-region which is interrupted by n-channels. By implementing the IDEE structure, the dependency of the emitter efficiency on the forward current can be inverted. This allows a diode design with a lower voltage drop at high currents ensuring high surge current capability. It has been shown that the trade-off between surge current capability and reverse-recovery ruggedness can be optimised, if the new IDEE structure is combined with the common CIBH structure. Such a diode with the same forward voltage drop at the rated current reveals a 22 % energy loss reduction during the surge current.

References

[1] H. Schlangenotto, J. Serafin, F. Sawitzki, and H. Mauder, "Improved recovery of fast power diodes with self-adjusting p emitter efficiency," *IEE Electron Device Lett.*, vol. 10, no. 7, pp. 322–324, Jul. 1989.

[2] B. Baliga, "Analysis of a high-voltage merged p-i-n/Schottky (MPS) rectifier," *Electron Device Letters, IEEE*, vol. 8, no. 9, pp. 407–409, Sep 1987.

[3] (2007) Advanced tcad manual. Synopsys Inc. Mountain View, CA. [Online]. Available: http://www.synopsys.com

[4] T. Hunger, O. Schilling, and F. Wolter, "Numerical and experimental study on surge current limitations of wire-bonded power diodes," in *Proc. PCIM*, May 2007.

[5] B. Heinze, R. Baburske, J. Lutz, and H.-J. Schulze, "Effects of metallisation and bondfeets in 3.3kv free-wheeling diodes at surge current conditions," in *Proc. of ISPS*, Prague, Czech Republic, Aug. 2008, pp. 223–228.

[6] J. Oetjen, R. Jungblut, U. Kuhlmann, J. Arkenau, and R. Sittig, "Current filamentation in bipolar power devices during dynamic avalanche breakdown," *Solid-State Electronics*, vol. 44, no. 1, pp. 117–123, 2000.

[7] R. Baburske, J. Lutz, and B. Heinze, "Effects of Negative Differential Resistance in High Power Devices and some Relations in DMOS Structures," in *IRPS*, Anaheim, Californien, USA, May. 2010.

[8] R. Baburske, B. Heinze, F.-J. Niedernostheide, J. Lutz, and D. Silber, "On the formation of stationary destructive cathode-side filaments in p^+-n^--n^+ diodes," in *Proc. ISPSD*, Barcelona, Spain, Jun. 2009, pp. 41–44.

[9] R. Baburske, B. Heinze, J. Lutz, and F.-J. Niedernostheide, "Charge-carrier plasma dynamics during the reverse-recovery period of p^+-n^--n^+ diodes," *IEEE Trans. Electron Devices*, vol. 55, no. 8, pp. 2164–2172, Aug. 2008.

[10] F. J. Niedernostheide, F. Falck, H.-J. Schulze, and U. Kellner-Werdehausen, "Influence of joule heating on current filaments induced by avalanche injection," *IEE Proc.-Circuits Devices Syst.*, vol. 153, no. 1, pp. 3–10, 2006.

[11] M. Chen, J. Lutz, M. Domeij, H. P. Felsl, and H. J. Schulze, "A novel diode structure with controlled injection of backside holes (CIBH)," in *Proc. ISPSD*, Naples, June 2006, pp. 9–12.

[12] M. Valdinoci, D. Ventura, M. Vecchi, M. Rudan, G. Baccarani, F. Illien, A. Stricker, and L. Zullino, "Impact-ionization in silicon at large operating temperature," in *Proc. SISPAD*, Kyoto, 1999, pp. 27–30.