PT-IGBT and Freewheeling Diode for 3.3kV using Lifetime Control Techniques and Low-Efficiency Emitters

Mario Netzel, Ralf Lerner, Ralf Siemieniec, Josef Lutz

Abstract— **The adjustment of emitter efficiency by variation of doping profiles or application of lifetime control techniques such as irradiation of electrons and helium are two generally recognized concepts for the improvement of power device characteristics. In this work both concepts were studied by use of device simulation for the development of an IGBT and freewheeling diode chipset for 3.3kV. Simulations were performed using an extended recombination model and recombination center data taken from measurements at different irradiated devices. Finally, this lead to the manufacturing of an IGBT using low-emitter efficiency and an irradiated freewheeling diode. The experimental results are in good accordance with the previously performed simulations and give evidence of the capabilities of present device simulation tools.**

I. Introduction

This paper presents the behavior as well as the most important static and dynamic parameters of a 3.3kV PT IGBT and freewheeling diode based on extensive numerical simulation and experiments. The experimental data were taken from engineering samples of IGBTs and FWDs, which are developed and optimized using the results of two-dimensional device simulations.

The used 2D device simulator TeSCA [4] solves the Poisson equation and the electron and hole current continuity equations which have been extended for the consideration of deep traps [14]. This is necessary as irradiation processes generate a number of recombination centers with different energy levels in the band gap of Silicon. The simulation parameters of the radiation-induced recombination centers have been determined in previous work and allow reliable simulations of irradiated devices [14].

The newly implemented recombination model also considers arbitrary recombination center profiles. For the description of these profiles it is possible to make use of different distribution functions.

II. Diode Concept

The introduction of fast power switches such as IGBTs or hard-driven GTOs results in switching transitions at high di/dt and dv/dt values. This finally lead to the development of improved designs for fast freewheeling diodes to prevent limitations of the whole system's overall performance. It is well known that the most efficient concept for an improved diode performance is the control of on-state excess carrier distribution in the device. This is usually attained by either varying the doping profile for a reduced emitter efficiency or by introducing lifetime profiles [6], [12]. Lifetime control is realized by irradiation of electrons, protons or helium or by doping of gold or platinum. Since irradiation processes are carried out after the high temperature processes and show a far better reproducibility, this lifetime control technique is the prefered one.

Devices subjected to irradiation with helium ions in combination with electron irradiation show a soft-recovery behavior as well as the best trade-off between static and dynamic losses in this voltage range [8].

Thus, for the freewheeling diode preference was given to the usage of a helium and electron irradiated 3.3kV CAL (Controlled Axial Lifetime) diode [7]. The applied irradiation types result in excellent device properties and a high dynamical rugged-

Mario Netzel and Ralf Siemieniec are with the Department of Solid-State Electronics at the Technische Universitaet Ilmenau, Germany; Ralf Lerner is with the X-FAB Foundries AG Erfurt, Germany; Josef Lutz is with the Faculty of Electrical Engineering and Information Technology at the Technische Universitaet Chemnitz, Germany

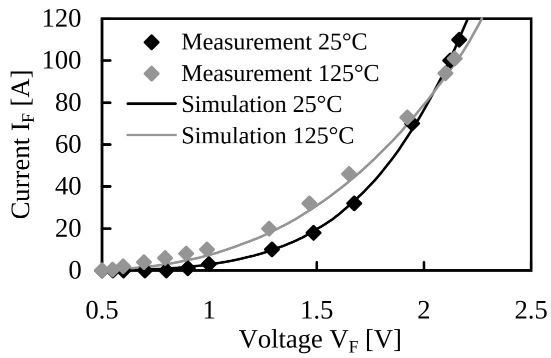

Fig. 1

Forward voltage characteristics of the 3.3kV diode

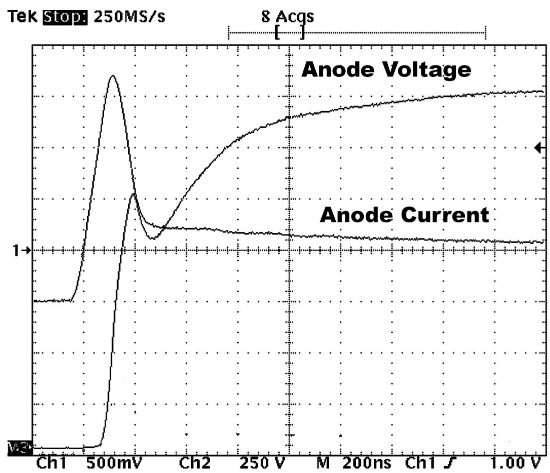

Fig. 2

Reverse recovery measurement at T=125°C, V_R=1800V, J_F=100A, di/dt=3.5kA/μs (100A/div, 250V/div, 200ns)

TABLE I
BACKSIDE EMITTER PARAMETERS

	Buffer Doping Peak	Buffer Depth	Emitter Doping Peak	Emitter Depth	Recombination Center Peak Position
I	$2 \cdot 10^{15} cm^{-3}$	$25 \mu m$	$6 \cdot 10^{16} cm^{-3}$	$0.2 \mu m$	-
II	$1 \cdot 10^{17} cm^{-3}$	$15 \mu m$	$5 \cdot 10^{18} cm^{-3}$	$1.0 \mu m$	$17 \mu m$

ness up to a di/dt of $5500A/\mu s$ at a DC link of 2200V [13]. Figure 1 shows the forward voltage characteristics simulated and measured for a production sample with an active area of $0.91cm^2$ rated to 100A. At rated current, the forward voltage increases with temperature. This is important for paralleling of devices in power modules. As shown in figure 2 the reverse recovery behavior of the 3.3kV diode appears to be soft, which avoids overvoltages as a result of a reverse current snap-of.

III. IGBT CONCEPT

For high-voltage IGBTs various device concepts are known. There are NPT- and PT-concepts, IGBTs with trench cells or cells with a planar gate. Frequently, local lifetime control by means of irradiation techniques is used for device optimization. Recently, the so-called field stop (FS) concept, which does not need carrier lifetime control, was applied to high-voltage IGBTs [1], [2], [3], [5], [9], [10], [15].

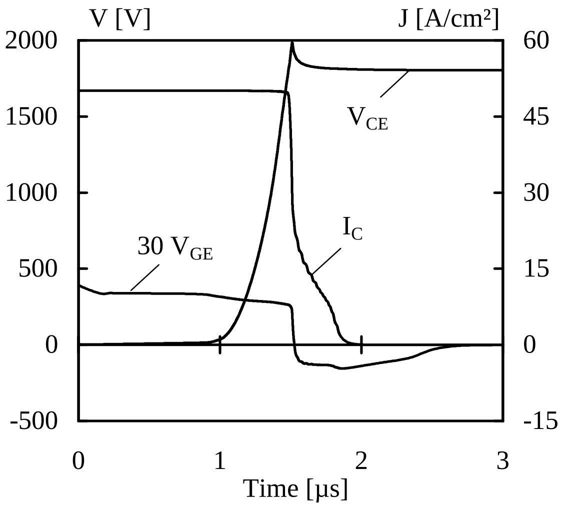

Fig. 3
SIMULATION OF IGBT TURN-OFF (TYPE I, NO LIFETIME CONTROL)

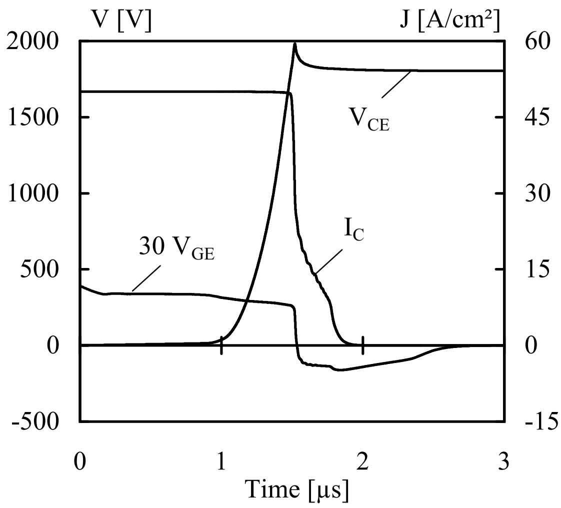

Fig. 5
SIMULATION OF IGBT TURN-OFF (TYPE II, LIFETIME CONTROL)

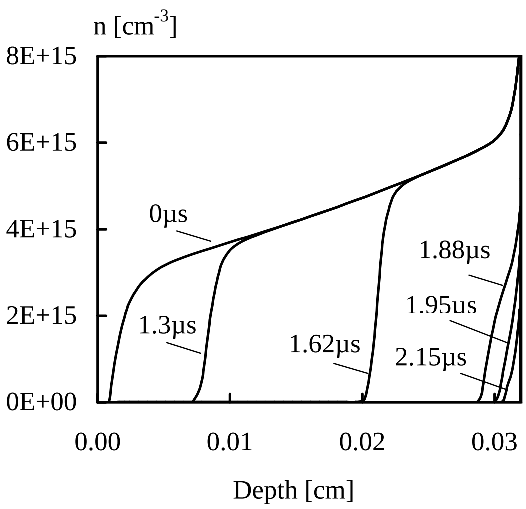

Fig. 4
ELECTRON DISTRIBUTION AT TURN-OFF IN IGBT I

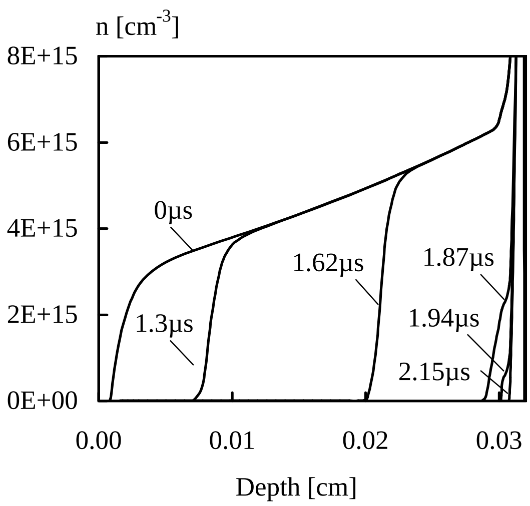

Fig. 6
ELECTRON DISTRIBUTION AT TURN-OFF IN IGBT II

TABLE II
PARAMETER COMPARISON OF IGBT I AND IGBT II (J_F=50A/cm^2, A=1cm^2, V_R=1800V, T=25°C)

	V_{CEsat} [V]	E_{off} [mJ]	E_{on} [mJ]
1	2.8	25.7	74
2	2.8	25.9	72

For the IGBT investigated in this work, a PT concept with a planar gate cell and large carrier lifetimes is used. While the planar gate cell has been optimized in previous work [11], properties of suitable backside emitter structures are investigated. Concerning the emitter design, two different emitter types are examined by use of device simulation:

1. low-doped buffer and low-efficiency emitter
2. medium doped-buffer, high-efficiency emitter and local lifetime control

Table I gives an overview about the typical parameters of the two different backside emitter structures.

Table II shows simulation results for the IGBTs I and II, which were designed to have equal forward voltage drops. Under the selected conditions, the radiated device shows no improvement in trade-off between static and dynamic losses compared to the non-radiated one.

Furthermore, the switching behavior has been characterized by means of device simulation. The turn-off waveforms of both devices are shown in figures 3 and 5. Comparing the turn-off of the different devices leads to no remarkable differences. Thus, there are no advantages or disadvantages concerning problems related to voltage overshoots or EMC. The tail current is comparably short for both devices as well.

When examining carrier distributions in the different devices at turn-off, no substantial differences could be found (figures 4 and 6).

Therefore, we prefered the concept of a low-doped buffer and a low-efficiency emitter for manufacturing of the engineering samples. Moreover, this approach offers an easy control of the trade-off between forward voltage drop and switching losses as another advantage. Very similar to NPT IGBTs this is realizable by only modifying the implantation dose for the p-emitter formation.

TABLE III
MEASURED PARAMETERS OF MANUFACTURED IGBT I (J_F=50A/cm^2, V_R=1800V)

Type	T [°C]	V_{CEsat} [V]	E_{off} [mJ]	E_{on} [mJ]	f_{max} [kHz]
6A	25	2.90	2.9	7.3	2.7
	125	3.38	3.7	8.6	2.1
50A	25	2.95	22.5	46.6	3.3
	125	3.52	28.3	55.4	2.5

IV. EXPERIMENTAL RESULTS

For the creation of a diffused low-doped buffer in combination with the usual process flow of NPT IGBTs without any additional thin-wafer steps, an adapted technology was developed. The manufactured engineering samples were designed for a rated current of 6A and 50A at a current density of 50A/cm^2 each. The combination of the diffused low-doped buffer with a low-doped emitter results in a positive temperature coefficient of the forward voltage over the whole current range as shown in figure 7. The realized positive temperature coefficient is very usefull for an easy paralleling of chips inside a power module as commonly used. Figure 8 shows the dependence of the forward voltage on temperature at rated current density. Table III contains the switching losses for this samples. The measured forward voltage drops and turn-off losses are in good accordance with the simulation results shown in table II. The turn-on losses of the 50A device are reduced by about 25% compared to the simulation results (table II) or even compared with the 6A device (table III). In case of the simulations these deviations were caused by the use of a non-radiated freewheeling diode since the development of the radiated freewheeling diode has not been completed at this time. In case of the 6A IGBT (which has been designed for development and characterization purposes only), the deviations result from the use of a freewheeling diode designed for a current of 12A.

The total losses (switching losses and on-state losses) at rated current density permit a relatively high maximum operation

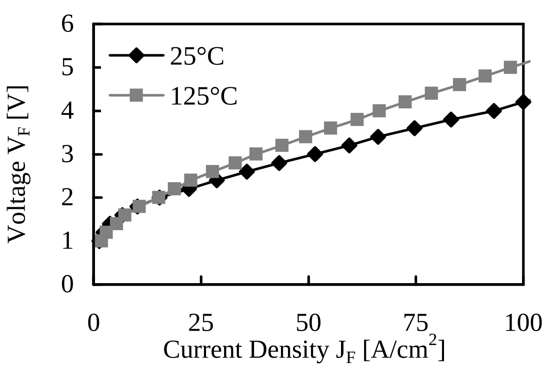

Fig. 7
IGBT I FORWARD VOLTAGE VS. CURRENT DENSITY

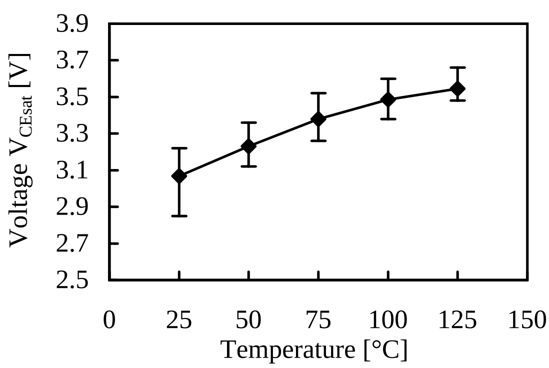

Fig. 8
IGBT I FORWARD VOLTAGE VS. TEMPERATURE (J= 50 A/CM^2)

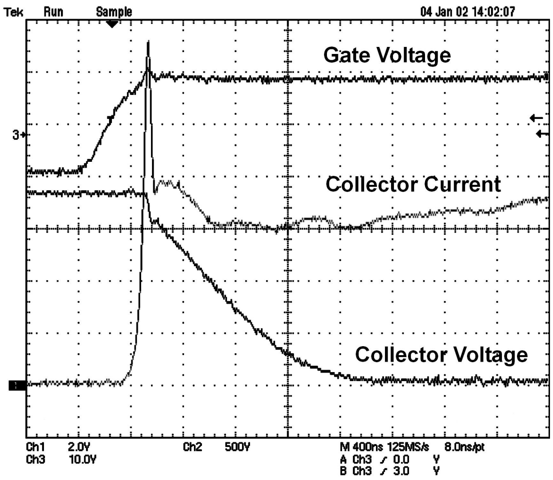

Fig. 9

IGBT I TURN-ON AT 125°C, V_R=1800V, J_F=50A/CM^2, R_G=300Ω

($I_C : 2A/div, V_C : 500V/div, V_G : 10V$, $400ns$)

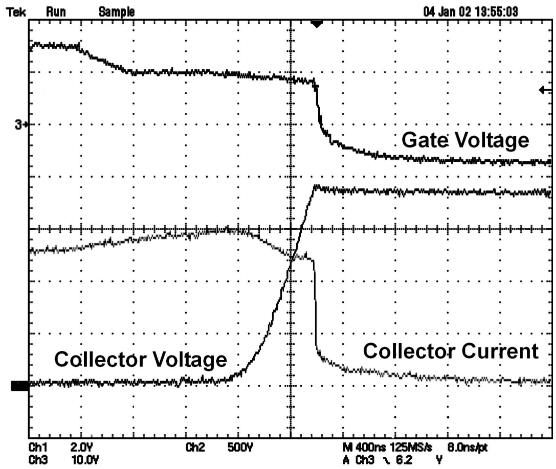

Fig. 10

IGBT I TURN-OFF AT 125°C, V_R=1800V, J_F=50A/CM^2, R_G=300Ω

($I_C : 2A/div, V_C : 500V/div, V_G : 10V$, $400ns$)

frequency f_{max}. According to practical reasons, the maximum operation frequency is defined for an approximate power dissipation of $300W/cm^2$ at a duty cycle of 1:1. If a lower frequency is used, it is possible to operate the IGBT at higher current densities up to $85A/cm^2$ which results in a reduced chip size. Of course this maximum frequency is a somewhat theoretical value since thermal resistances and cooling conditions have not been considered.

Figure 9 shows the turn-on of a 6A PT IGBT at a voltage of 1800V. The measurement was taken in a conventional double-pulse circuit in combination with a 12A CAL diode, therefore the freewheeling diode is measured in low current condition which leads to higher turn-on losses as mentioned before. Figure 10 shows the measured turn-off waveforms of this device combination at a voltage of 1800V and the rated current density of $50A/cm^2$.

V. CONCLUSION

Considering the preliminary results, the developed PT IGBT structure with a diffused lowed-doped buffer and a low-efficiency emitter combined with a radiated freewheeling diode shows potential to compete with radiated IGBTs.

The forward voltage drop as well as the switching losses are similar or lower compared with data published in other research papers or in data sheets. Furthermore, the temperature coefficient of the IGBT forward voltage drop is positive over the complete current range.

For the manufacturing of this IGBT type, an adapted process technology was developed which allows the use of a usual NPT process without any additional thin wafer steps.

ACKNOWLEDGEMENTS

This work is supported by grants of the Thuringia Ministry of Science, Research and Arts. The authors wish to thank the scientists from the Weierstrass Institute for Applied Analysis and Stochastics in Berlin, especially Dr. Nürnberg, Dr. Stefan and Prof. Gajewski, who developed the device simulator TeSCA.

REFERENCES

[1] F. Bauer, U. Thiemann, and T. Stockmeier. Design Considerations and Characteristics of Rugged Punchtrough (PT) IGBTs with 4.5kV Blocking Capability. In *Proc. ISPSD*, pages 327–330, 1996.

[2] J. G. Bauer, F. Auerbach, and A. Porst. 6.5kV-Modules Using IGBTs with Field Stop Technology. In *Proc. ISPSD*, pages 70–74, 2001.

[3] H. Brunner, M. Hierholzer, and T. Laska. Progress in Development of the 3.5kV High Voltage IGBT / Diode Chipset and Module Applications. In *Proc. ISPSD*, pages 225–228, 1997.

[4] H. Gajewski, B. Heinemann, and H. Langmach. *TeSCA-Handbuch*. Weierstrass-Institut für Mathematik, 1991.

[5] M. Kitagawa, I. Omura, and S. Hasegawa. 4500 V Injection Enhanced Insulated Gate Bipolar Transistor (IEGT) Operating in a Mode Similar to a Thyristor. In *IEDM Tech. Dig.*, pages 679–682, 1993.

[6] J. Lutz. Axial Recombination Center Technology for Freewheeling Diodes. In *Proc. EPE*, pages 1502–1506, 1997.

[7] J. Lutz. *Freilaufdioden für schnell schaltende Leistungsbauelemente*. Verlag ISLE, Dissertation TU Ilmenau, 2000.

[8] J. Lutz, E. Schimanek, and J. Nascimento. A new intelligent integrated Power Module with improved Freewheeling diode. In *Proc. PCIM*, 1999.

[9] K. Mochizuki, K. Ishii, and M. Takeda. Examination of Punch-Through IGBT (PT-IGBT) for High Voltage and High Current Application. In *Proc. ISPSD*, pages 237–240, 1997.

[10] M. Mori, H. Kobayashi, and T. Saiki. 3.3kV Punchthrough IGBT with Low Loss and Fast Switching. In *Proc. ISPSD*, pages 229–232, 1997.

[11] M. Netzel. *Analyse, Entwurf und Optimierung von diskreten vertikalen IGBT-Strukturen*. Verlag ISLE, Dissertation TU Ilmenau, 1999.

[12] A. Porst, F. Auerbach, and H. Brunner. Improvement of the Diode Characteristics Using Emitter-Controlled Principles (Emcon-Diode). In *Proc. ISPSD*, pages 213–216, 1997.

[13] U. Scheuermann and J. Lutz. High Voltage Power Module with Extended Reliability. In *Proc. EPE*, 1999.

[14] R. Siemieniec, W. Südkamp, and J. Lutz. Determination of Parameters of Radiation Induced Traps in Silicon. *Solid-State Electronics*, 2002. accepted for publication.

[15] T. Takahashi, A. Uenishi, and S. Kusunoki. A Design Concept for the Low Turn-Off Loss 4.5kV Trench IGBT. In *Proc. ISPSD*, pages 51–54, 1998.