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3.3 kV IGBT and Diode Chipset Using Lifetime Control Techniques and Low-Efficiency Emitters

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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 3.3 kV. 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.

Keywords: Chipset for 3.3 kV, emitter efficiency variation, irradiated free-wheeling diode, two dimensional device simulation, Poisson equation.

1 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

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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 [15]. 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 [15]. 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.

2 Diode Concept

The introduction of fast power switches such as IGBTs or hard-driven GTOs results in switching transitions at high $\mathrm{d}i/\mathrm{d}t$ and $\mathrm{d}v/\mathrm{d}t$ 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. Furthermore, the temperature dependencies of the device properties are different if an irradiation or if an diffusion process is used for the control of carrier lifetime [14]. 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 3.3 kV CAL (Controlled Axial Lifetime) diode [7]. The applied irradiation types result in excellent device properties and a high dynamical ruggedness up to a $\mathrm{d}i/\ dt$ of 5500 A/μs at a DC link of 2200 V [13]. Figure 1(a) shows the forward voltage characteristics simulated and measured for a production sample with an active area of 0.91 cm^2 rated to 100 A. The temperature

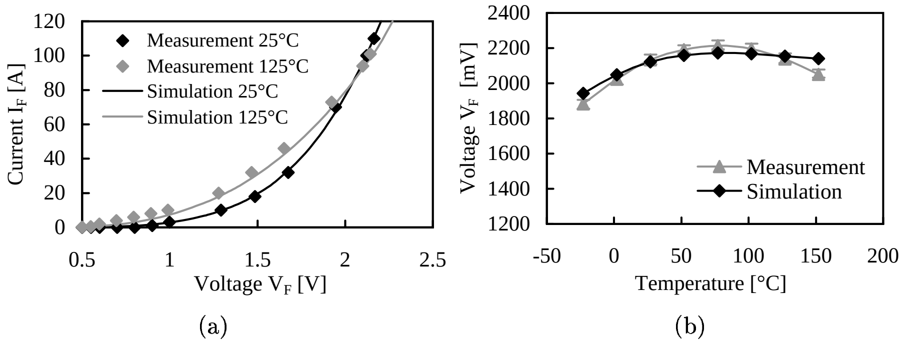

Fig. 1. (a) Forward voltage characteristics of the 3.3 kV diode. (b) Forward voltage vs. temperature of 3.3 kV diode ($J = 110$ A/cm^2).

dependence of the forward voltage on temperature at rated current is shown in Figure 1(b). At rated current, the forward voltage increases with temperature and the temperature coefficient is positive over a wide temperature range. This is important for the paralleling of devices in power modules. As shown in Figure 2, the reverse recovery behavior of the 3.3 kV diode appears to be soft, which avoids overvoltages as a result of a reverse current snap-of.

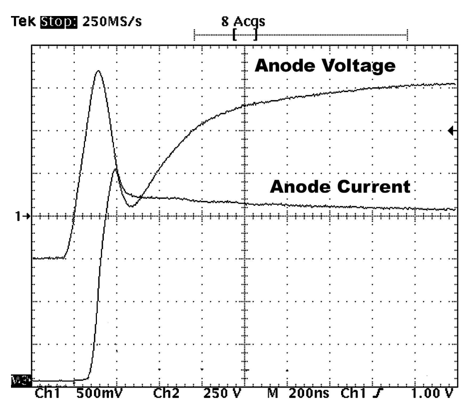

Fig. 2. Reverse recovery measurement at T=125°C, $V_R = 1800$ V, $J_F = 100$ A, di/dt=3.5 kA/μs (100 A/div, 250 V/div, 200 ns).

3 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. Fre-

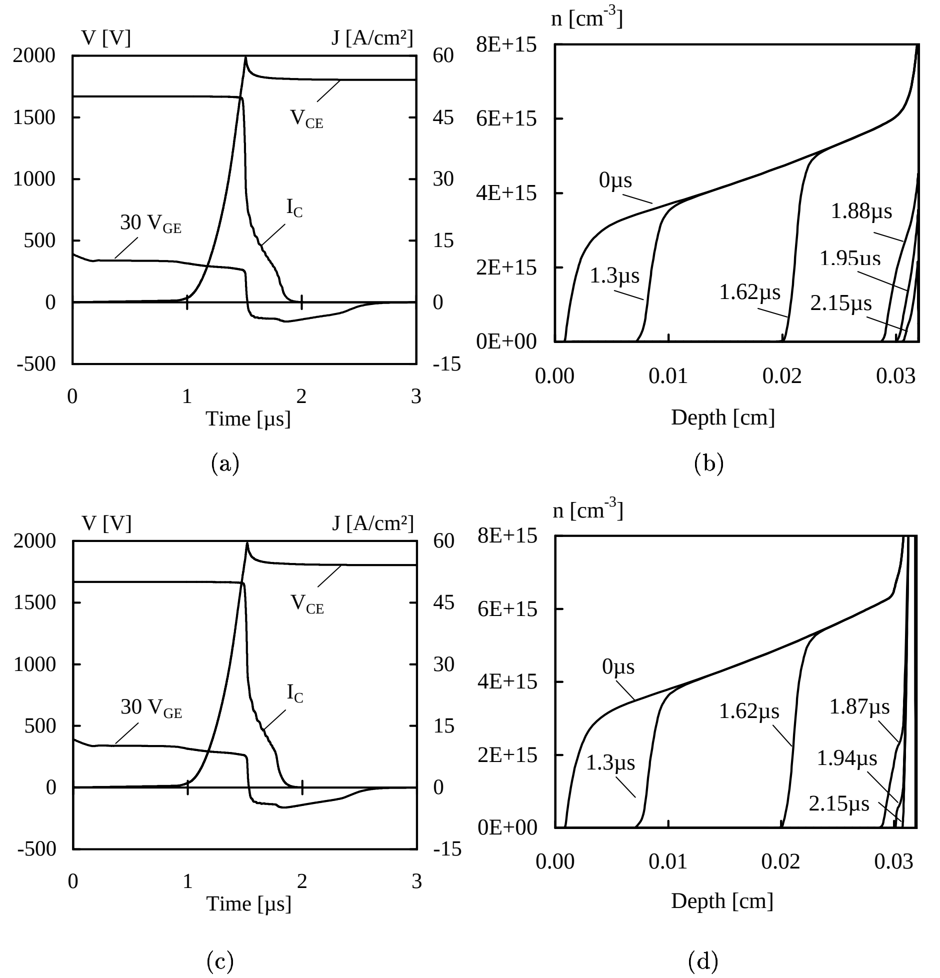

Fig. 3. (a) Simulation of IGBT turn-off (Type I, no lifetime control). (b) Electron distribution at turn-off in IGBT I. (c) Simulation of IGBT turn-off (Type II, lifetime control). (d) Electron distribution at turn-off in IGBT II.

quently, 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, 16].

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

Table 1. Backside Emitter Parameters

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

Table 2 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.

Table 2. Parameter Comparison of IGBT I and IGBT II
(JF=50 A/cm^2, A=1 cm^2, VR=1800 V, T=25°C)

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

Furthermore, the switching behavior has been characterized by means of device simulation. The turn-off waveforms of both devices are shown in Figures 3(a) and 3(c). 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 3(b) and 3(d)).

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.

4 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 6 A and 50 A at a current density of 50A/cm2 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 4(a). Figure 4(b) shows the dependence of the forward voltage on temperature at rated current density. The realized positive temperature coefficient is very usefull for an easy paralleling of chips inside a power module as commonly used. Table 3 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 2. The turn-on losses of the 50 A device are reduced by about

Table 3. Measured Parameters of manufactured IGBT I ($J_F = 50$ A/cm^2, $V_R = 1800$ V).

Type	T [°C]	$V_{CE_{sat}}$ [V]	E_{off} [mJ]	E_{on} [mJ]	f_{max} [kHz]
6A	25	2.90	2.9	7.3	2.7
	12	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

25% compared to the simulation results (Table 2) or even compared with the 6 A device (Table 3). 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 6 A 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 12 A.

The total losses (switching losses and on-state losses) at rated current density permit a relatively high maximum operation frequency fmax. According to practical reasons, the maximum operation frequency is defined for an approximate power dissipation of 300 W/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 85 A/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 5(a)

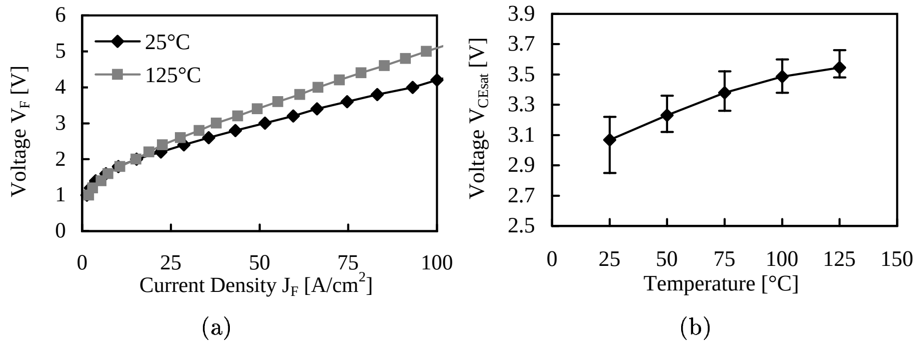

Fig. 4. (a) IGBT I forward voltage vs. current density. (b) IGBT I forward voltage vs. temperature ($J = 50$ A/cm2).

shows the turn-on of a 6 A PT IGBT at a voltage of 1800 V. The measurement was taken in a conventional double-pulse circuit in combination with a 12 A CAL diode, therefore the freewheeling diode is measured in low current condition which leads to higher turn-on losses as mentioned before. Figure 5(b) shows the measured turn-off waveforms of this device combination at a voltage of 1800 V and the rated current density of 50 A/cm^2.

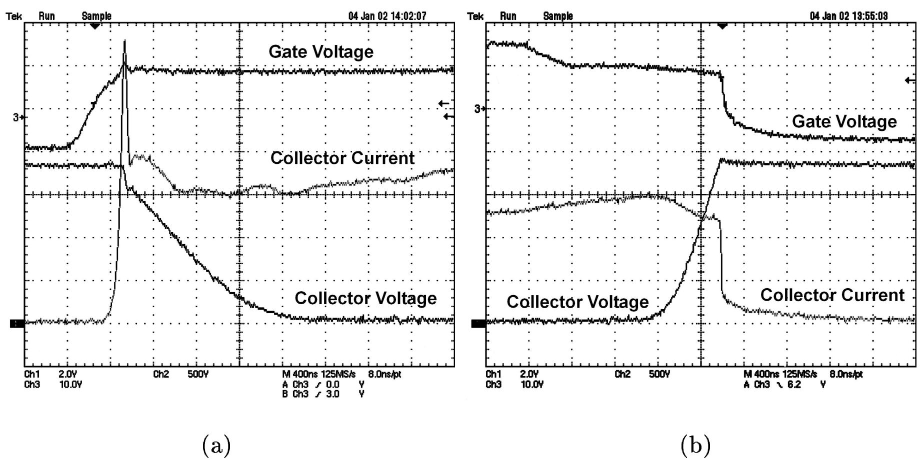

Fig. 5. (a) IGBT I turn-on at 125°C, V_R=1800 V, J_F=50 A/cm^2, $R_G = 300\ \Omega$ (I_C: 2 A/div, V_C: 500 V/div, V_G: 10 V, 400 ns). (b) IGBT I turn-off at 125°C, $V_R = 1800$ V, $J_F = 50$ A/cm^2, $R_G = 300\ \Omega$ (I_C: 2 A/div, V_C: 500 V/div, V_G: 10V, 400 ns).

5 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.

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