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Field Shielded Anode (FSA) Concept Enabling Higher Temperature Operation of Fast Recovery Diodes

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***Abstract*— In this paper, we introduce the Field Shielded Anode (FSA) concept that enables higher temperature operation of fast recovery diodes with planar junction termination. Conventional diodes utilizing local lifetime control principles show excellent dynamic properties at the expense of a higher leakage current, which is generated during reverse blocking when the space charge region penetrates into the zone containing the radiation defects. In contrast to this, the FSA concept spatially separates the space charge region from the zone with the radiation defects. The ruggedness of conventional diodes can be exceeded with the new FSA concept, while the leakage current is reduced by a factor of ~4. This was achieved using a special junction extension introduced between the active area and the guard-ring termination. The design parameters and their influence on the softness and the safe-operating area are presented.**

I. INTRODUCTION

Fast recovery diodes are used in modern power converters. With continuously improved performances of switches such as the IGBT, the diode needs to follow in order to not become the limiting factor. The utilization of the chips in traction and drive applications requires high ruggedness, good surge-current capability, reverse recovery softness and low-loss operation. There are two main concepts of high power free-wheeling diodes established for applications, which require blocking voltages in the range of 1.2kV to 6.5kV and current ratings of 50A to 300A per chip. While the first one is based on the emitter-controlled principle [1], the second one utilizes local control of the axial carrier-lifetime to tailor the dynamic properties [2]. Both concepts have their inherent advantages and drawbacks. We will focus here on the principle of local carrier lifetime control. This concept is commonly implemented by an ion-irradiated anode to reduce the peak recovery current and the switching losses and provide soft reverse recovery. In addition, this is combined with an electron or ion irradiation to reduce the plasma in the n-base region in order to limit the reverse recovery losses under normal operation condition and dynamic avalanche under harsh switching transients to ensure a high safe operating area (SOA) performance [3]. Nevertheless, the localized point defects generated by the irradiations are a source of leakage current, when subjected to a space charge region of a reverse biased anode p-n junction. This effect is more pronounced for hydrogen or alpha-particle irradiated diodes compared to electron irradiated ones. The strong spatial localization of the defects from ion irradiation and the high defect introduction rate of the deep levels, which increases with the particle's size, are responsible for an increased leakage current. In this paper, we present the FSA concept, which eliminates the impact of these effects on the leakage current by locating the radiation defects outside the space charge region without sacrificing on any other parameters.

II. FIELD-SHIELDED-ANODE (FSA) CONCEPT

A conventional diode with locally incorporated deep levels to utilize local lifetime control is shown in Fig. 1. In this case the electric field evolving during reverse blocking is penetrating into the zone of radiation defects already at very low reverse voltages. This generates a high leakage current and limits the thermal stability of the chip.

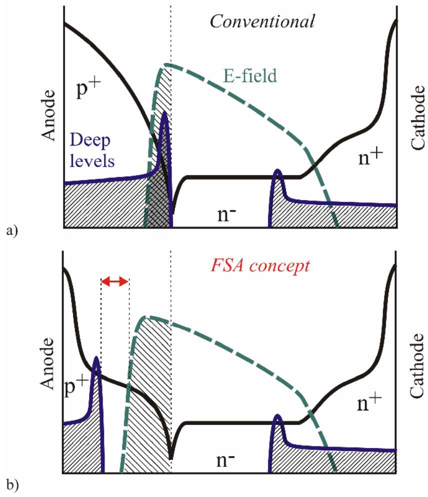

Figure 1. Schematic drawing (not to scale) of the cross-sections of two fast recovery diodes. a) The conventional diode has a single deep diffused anode-profile. b) Field shielded anode design separates the deep levels from the space charge region.

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Introducing a low-doped p-buffer region which acts as a Field-Shielding Anode (FSA) overcomes this issue inherently, because the space charge region is spatially separated from the zone of irradiation defects Fig. 1b. This kind of profile has been previously applied for large area discrete diodes [4]. However, their doping profile is much deeper and normally combined with a beveled angle junction termination, which can not be applied to the diode chips used here. Therefore, in the case of the chip-diodes, the doping profile has to comply with the requirements of a planar junction termination, consisting either of a guard-ring structure or a junction termination extension. Hence, the deeper part of the anode p-type layer is limited below 30 µm, while the doping concentration is increased to maintain the reverse blocking capability. Since the increase of the doping concentration can deteriorate the softness of reverse recovery, a careful optimization of the doping profile is of primary importance

III. EXPERIMENTAL

TABLE I. TABLE OF DIODES USED IN THE PAPER

Table Head	**FSA diodes**			**Conventional diode**
	A	***B***	***C***	***D***
FSA dose (a. u.)	150%	100%	50%	
$V_{breakdown}$ (V)	4100	4100	4000	4000
V_F (V) @ I_F = 125A	2.1	2.1	2.1	2.05
I_R (mA) V_R =3.3kV, T_j = 125°C	~0.6	~0.6	~0.7	~2

A conventional diode and three FSA-diodes variants have been used for this study. The FSA-diodes differ in the ion-implantation dose of the buffer anode implantation named FSA-dose according to Tab. I. The conventional diode "D" also differs in the position of the defect peak of the ion irradiation, which is situated within the p-n junction Fig. 1. The measured spreading resistance profiles of these diodes are shown in Fig. 2. Although the FSA-diode variants differ in the depth of the p-n junction (referred to as "buffer"-anode), the blocking voltage is not affected. It is more important to note the different levels of the p-buffer. In addition the surface concentration is of the same level as for the convention diode.

A. *Static parameters – leakage current*

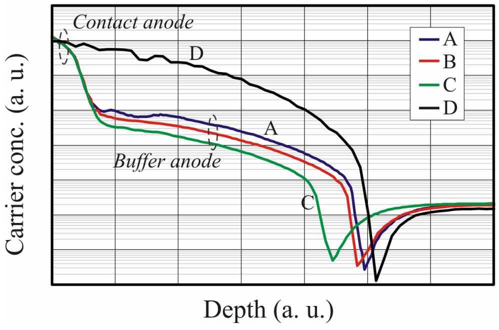

Figure 2. The anode doping profiles of the diodes under study.

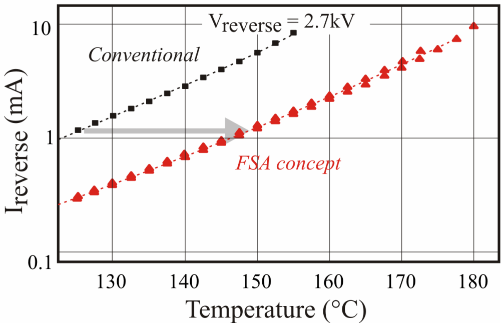

Figure 3. Leakage current scaling with temperature for the conventional and the FSA diode (type "B").

It has been shown in Tab. I that both the forward voltage drop V_F and the blocking voltage $V_{breakdown}$ of the diode match the performance of the conventional diode. However, the superior static blocking behavior is fully maintained at elevated temperatures and reflects the advantage of the FSA-concept, as illustrated in Fig. 3. The arrow highlights the fact that the leakage current of the conventional diode at 125°C is equal to that of the FSA concept at 150°C. In addition, the FSA-diode offers stable reverse blocking even beyond a junction-temperature of 170°C.

The comparison of leakage currents between the devices A, B and C in Tab. I show that the leakage current can increase when the concentration of the anode buffer doping and junction depth decreases down to the level of diode "C". Consequently, diode "C" sets a lower limit on the buffer characteristic that should be designed to fully support the field before penetrating into the zone of irradiation defects.

B. *Dynamic parameters – softness*

An important performance parameter for a diode is the capability to switch-off low currents without oscillations over the whole temperature range, in particular at high DC-link voltages and under the influence of a high stray-inductance. This phenomenon is referred to as "softness". Fig. 4 shows the switching of the diodes "A" and "C" at a high DC-link voltage from an ON-state current which is one ninth of the nominal current and with a stray inductance which is double as high as for the rated IGBT module employing such chips. Diode "A" exhibits a reverse recovery maximum current I_{RM} in the range of 95A. During the subsequent tail-current phase the current snaps off at around I_F = -25A resulting in a high dI/dt causing a voltage overshoot up to 4.5kV. In contrast to the behavior of diode "A", diode "C" shows a 20% lower I_{RM} as a result of a lower concentration of the ON-state plasma at the anode side of the n-base. During the following tail-current phase, the charge-carriers are extracted without a current snap-off and the maximum detected reverse bias overshoot voltage is limited to 3.1kV. In Fig. 4, the maximum amplitude of the generated voltage oscillations during reverse recovery is indicated by the grey bars for the four different diodes and considered as an indicator of the softness. It reflects the sensitive dependence of the softness and hence the maximum reverse recovery peak on the buffer-anode doping concentration and therefore on the associated emitter efficiency buffer-doping of the FSA-diodes. As a rule of thumb - the lower the buffer doping concentration the softer is the diode. This is a consequence of the purely emitter controlled mode of the low current operation. Diode “C” is in this setup matching the performance of the conventional (reference) diode “D”. In contrast to the low current regime, the highly doped “contact” anode and the radiation defects of the local lifetime control determine the plasma levels at the anode side for higher current levels Fig. 1.

In summary it can be concluded that the required softness can be tuned by the doping-level of the deep buffer implant resulting in a tradeoff between the static reverse blocking behavior and the reverse recovery softness.

C. *Dynamic parameters – safe operating area*

The FSA-diode and in particular the buffer anode profile was discussed so far in the vertical direction only. However, a reliable diode operation under fast reverse recovery requires also a laterally optimized doping profile to ensure excellent dynamic properties like softness and high robustness. The latter requires the introduction of a junction extension in between the active area and the guard-ring termination Fig. 5a. This region resembles that of a resistive zone introduced previously [5]. However the junction extension utilized herein is formed by smaller guard rings having a laterally overlapping buffer doping while the high contact doping remains separated. A crucial parameter is the junction extension width.

Fig. 5b shows the dependence of the maximum (last pass) commutating d*I*/d*t* during diode turn-off. This graph confirms the necessity of the modified junction extension, because an early device failure is observed for a small width of the junction extension. For wider junction extension regions the device failure is located in the active area identifying that the full potential of the diode is utilized while exceeding the performance of the conventional diode.

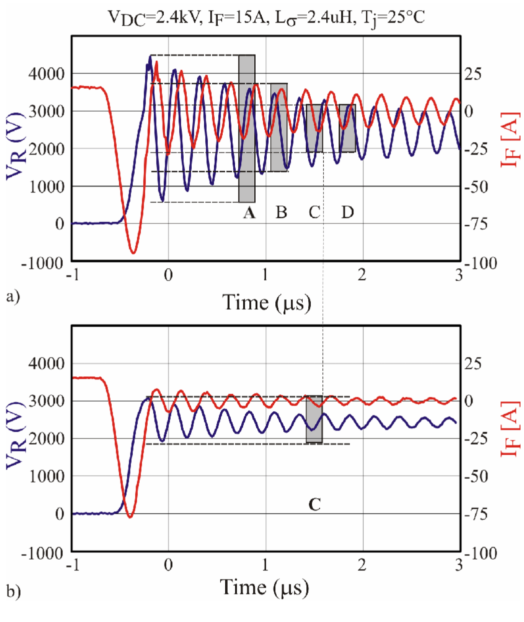

Figure 4. Reverse recovery waveforms for the FSA-diodes. a) Diode “A”. b) Diode “C”.

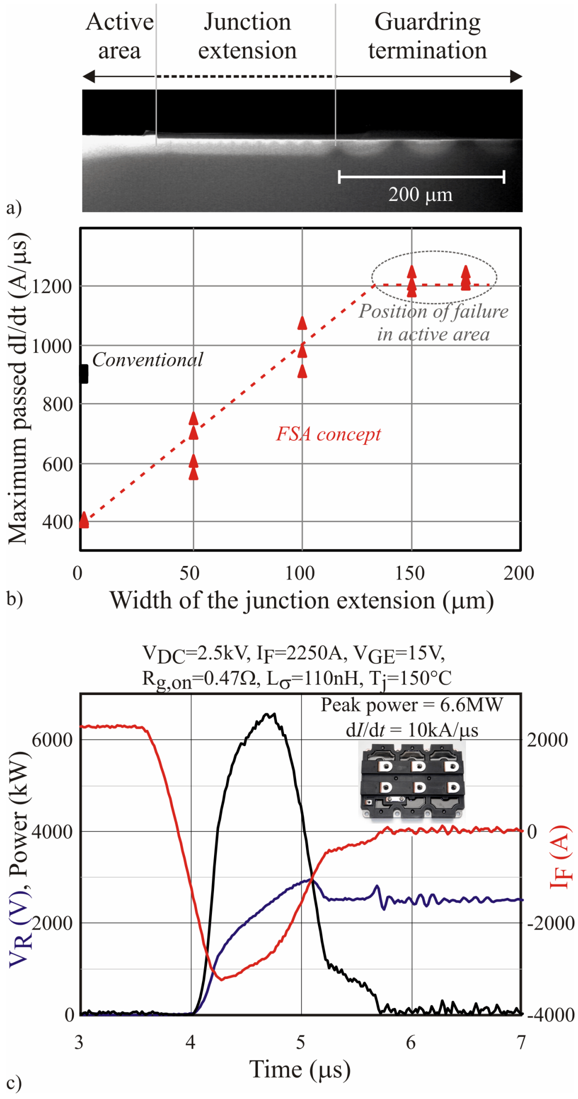

Figure 5. a) Scanning electron image of a cross-section of the introduced main junction extension. b) Maximum passed d*I*/d*t* vs. width of the junction extension region (V_{DC}=2.5kV, L =1200nH, T_j=150°C) of a single chip. c) Measured diode SOA waveform on module-level under the above given conditions. The inset shows the 3.3kV / 1500A rated module.

The inset in Fig. 5c shows a high-temperature module rated at 3.3kV and 1500A with 12x diodes and 24x IGBTs inside. The high ruggedness on chip-level is well reproduced even under such heavy parallel conditions. The diodes are commutated with more than 10kA/µs. During the reverse current tail phase (Fig. 5c. between 4µs and 5µs) the diode is subjected to strong dynamic avalanche.

It has been shown experimentally that a junction extension ensures a rugged diode performance in terms of the reverse bias safe operation area. Contrary to the case of static reverse blocking, during reverse recovery and under an equivalent diode voltage the electric field is much higher due to the holes passing through the space charge region with saturation velocity. As a result, their positive space charge adds to that of the ionized donors, the gradient of the electric field grows and so does the peak electric field. As this field generates additional free carriers, this effect reflects in the waveform of current in the tail time. One can observe this in Fig. 5c after I_{RM} between 4μs and 5μs. As will be shown below, this effect is pronounced at the diode junction periphery.

A two-dimensional numerical simulation (Dessis$_{\mathrm{TCAD}}$ device simulator) of two 1.7kV FSA-diodes is shown in Fig. 6 for the temperature of 400K during reverse recovery under identical operation conditions. The only difference between the simulated diodes is the junction extension region, which is introduced only in diode "2". As pointed out above, due to the dynamic avalanche the electric field at the p-n junction is enhanced in the positions with a high current density. Consequently, in diode "1" a high electric field and current crowding lead to an early device failure. In contrast to this, the junction extension suppresses the current crowding in this region effectively and hence lowers the electric field and yields a very robust device. Please note that the junction extension for these 1.7kV rated diodes in the simulation is about half the width required for the 3.3kV diode investigated experimentally.

D. *Dynamic parameters – surge current*

The last dynamic parameter addressed herein is the surge current capability which highlights the positive effect of the contact anode Fig. 2. The surface concentration on the anode side for the FSA variants is identical to the conventional diode resulting in a superior surge current protection as shown in Fig. 7. Even after 100x applied pulses of 10ms, each of them exceeding nine times the nominal current, no degradation was observed. This confirms the importance of the high contact anode doping that needs to be combined with the local axial lifetime control to ensure the contradicting parameters.

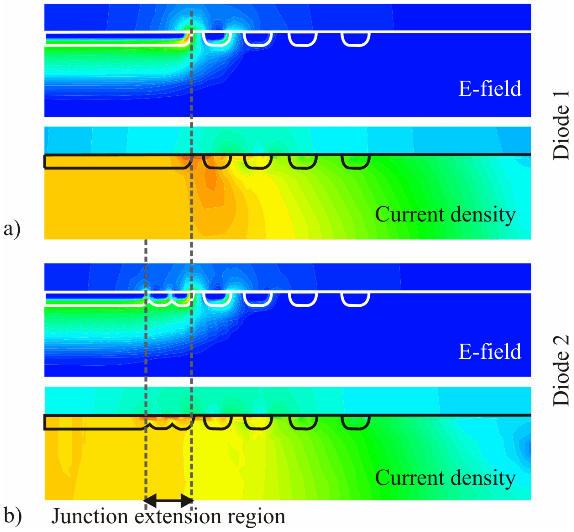

Figure 6. Cross-section of the electric field *E* and current density during dynamich avalanche of two 1.7kV FSA-diodes. All plots are with idenitcal color-scales. a) FSA without junction extension. b) FSA with junction extension.

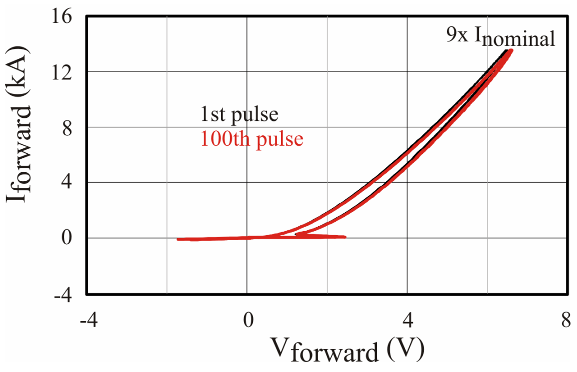

Figure 7. Surge current capability of the FSA-diode on module-level. A 10ms surge current pulse is applied 100x times exceeding 9x the nominal current without degrading the device.

IV. CONCLUSION

In this paper we have introduced the field-shielded anode concept for chip-diodes. It was shown experimentally that the spatial separation of the zone with radiation defects and the space charge region forming during reverse blocking ensures superior static blocking capability compared to conventional diodes applying local axial carrier-lifetime principles. It was proven that a soft reverse recovery behavior is achievable by sensitive tuning of the buffer doping concentration matching the behavior of a conventional diode. The introduced junction extension region prevents current crowding efficiently. The confirmed diode SOA on chip-level exceeds the robustness of our conventional reference diode without the low-doped p-buffer region. In addition, the surge current is kept at the same level due to the high doping profile section of the new anode. In conclusion, the FSA concept combines the advantages of emitter-controlled principles in the low-current regime with the advantages of local axial carrier lifetime principles in high current regimes.

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