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High-power silicon P–i–N diode with cathode shorts: The impact of electron irradiation

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ABSTRACT

Large-area silicon P–i–N diodes (V_{RRM} = 4.5 kV, $I_{FAV} \approx 3$ kA, $A_{active} \approx 55$ cm^2) were processed with cathode shorts in order to conserve the softness under reverse recovery, while employing a 10% thinner silicon wafer for a better technology curve for the static and dynamic losses. Contrarily to existing designs, the cathode shorts have approximately one order of magnitude higher surface concentration of the P^+ layer than the N^+ emitter. Except for the implanted N-type buffer, these shorts were processed using the dopant deposition from $POCl_3$ and H_3BO_3. The diodes with and without cathode shorts have been compared for the static parameters. The dynamic behavior has been also compared at reverse recovery of a free-wheeling diode in a standard IGCT circuit. The impact of electron irradiation on the softness of the reverse recovery has been evaluated up to 125 °C.

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1. Introduction

Modern power electronics requires reliable fast recovery P–i–N diodes for free wheeling, clamping and snubber purposes. A required level of failure in time (FIT) is achieved by choosing a proper resistivity of a starting silicon wafer to avoid cosmic ray induced failures already during static reverse blocking. For the dynamic operation, doping profiles have to be designed for high dynamic avalanche ruggedness during reverse recovery, which would otherwise decrease the reverse bias safe operation area (RB SOA) [1]. Last but not least, one has to avoid the overshoots of the anode voltage, which may appear during reverse recovery at high commutating di/dt, low current densities and large circuit stray inductances. This is because the voltage overshoot can exceed the static breakdown voltage of the diode itself or a device connected in parallel and hence cause a system failure.

The snappy behavior of power diodes has been observed since the introduction of fast switches [2,3]. Several methods of device design optimization to reduce the snappiness by lowering the ON-state plasma concentration at the anode side of the N-base were published [4–6]. These methods enabled the introduction of high-power high-voltage fast recovery diodes into an industrial practice.

The disclosure of failures caused by cosmic rays led to the usage of silicon wafers with a higher resistivity for given voltage class [7,8]. As a result, the N-base regions of existing diodes had to be widened with the consequence of increasing both the ON-state and switching losses. This has stimulated the design [9] and development [10] of the cathode structures, which inject additional carriers at the tail phase of reverse recovery in order to eliminate otherwise detrimental chop-off of the diode current leading to the voltage overshoots. This concept was then named Field Charge Extraction (FCE) [10] and later also Relaxed Field of Cathode (RFC) [12]. It has the original N^+ cathode emitter provided with a low-doped P-type shorts and N-buffer. The shorts inject holes during the tail phase of the reverse recovery, while the buffer stops electric field under reverse bias. The comparison of a classical (Reference) diode and the diode with the cathode shorts (FCE) is shown schematically in Fig. 1. The FCE concept has been further combined with different cathode buffer [11] and junction termination structures [12]. Beside the FCE concept, the principle called Controlled Injection Backside Holes (CIBH) has been published, where the P-type regions were buried using a boron implantation with the increased range of implanted atoms [13].

In the large-area fast recovery P–i–N diode, the electron irradiation is necessary to reduce the stored charge (lifetime control) and to adjust an optimal combination of forward voltage drop V_f and reverse recovery losses E_{rec} for a given application. Unfortunately, this can deteriorate the current gain of the parallel PNP transistor from Fig. 1b) and reduce the injection of holes at the cathode side. As a result, the reverse recovery process becomes snappy. To minimize this shortcoming, we have modified the original structure of shorts in order to maintain the injection efficiency of holes of the PNP transistor sufficient to cope with a high electron irradiation dose. Although the stronger shorts enable a significant reduction of device thickness while keeping a required softness, there is always a limiting thickness from which a diode becomes

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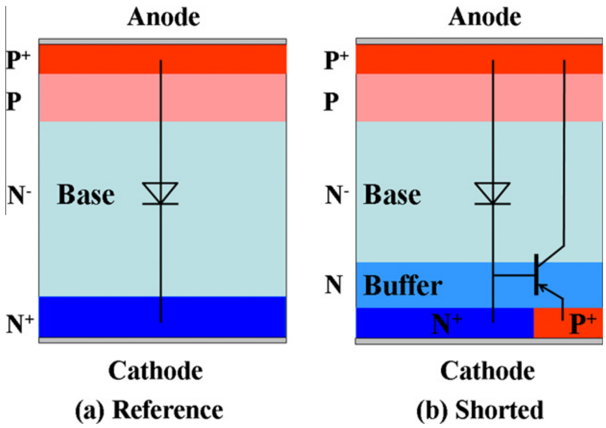

Fig. 1. Classic PIN diode (a) and PIN diode with cathode shorts (b).

snappy for a given set of design parameters of the shorts. The main aim of this paper is to investigate what happens during reverse recovery, when this thickness limit is reached. This is demonstrated for a large-area diode with qualitatively different cathode doping profiles compared to the chip diodes from Ref. [10]. Throughout this paper, we are using the general term *shorts* for the cathode structures under discussion.

2. Experimental

A high-power P–i–N diode with a nominal blocking voltage of 4.5 kV and maximum average ON-state current I_{FAV} up to 3 kA (active area $A_{active} \approx 55\ cm^2$) was processed from the (1 1 1) float zone neutron transmutation doped silicon wafers [14]. The anode doping profiles of both the reference and shorted diodes from Fig. 1 were created by boron and aluminum implantations to provide sufficient reverse blocking capability of the anode junction when terminated by a negative bevel. The cathode side of the reference and shorted diodes were processed differently. That of the reference diode (Fig. 1a) was made by single phosphorus diffusion from $POCl_3$. For the shorted one (Fig. 1b), we have combined the phosphorus diffusion from $POCl_3$ with that of the boron diffusion from H_3BO_3 through a silicon dioxide mask. Contrary to existing publications, no ion implantation has been used for the back-side processing except for the N-type buffer. Diffusion and oxidation temperatures and times were carefully optimized in a way that a doping compensation resulted in the exemplary cathode doping profile shown in Fig. 2a. Contrary to the so far published structures of this type (Fig. 2b left), the P^+ boron surface concentration is higher than that of the N^+ cathode in order to achieve as high as possible amplification factor of the PNP transistor (Fig. 2b right). Since only a single mask has been used, the resulting N^+ surface doping concentration had to be at least one order lower than that of the P^+ layer. Compared to chip diodes, we have also used thicker P^+ and N^+ emitters ($\approx 5\ \mu m$), which are more suitable for the discrete bipolar devices with etched surfaces than the thinner ones for chip devices [10,12,13], which is typically $\approx 1\ \mu m$ thick. The lateral dimensions of mask openings for the boron diffusion (P^+ shorts) were not a subject for optimization. The total shorted area fills between 1–10% of the total cathode area.

Both the reference and shorted diode is proton irradiated through the anode using the same energy and dose in order to reduce the maximal reverse recovery current and to provide the basic softness at reverse recovery [14]. To control the relation between the ON-state and switching losses, the diodes were irradiated by electrons in the MeV range. The doses chosen at 0, 5 and

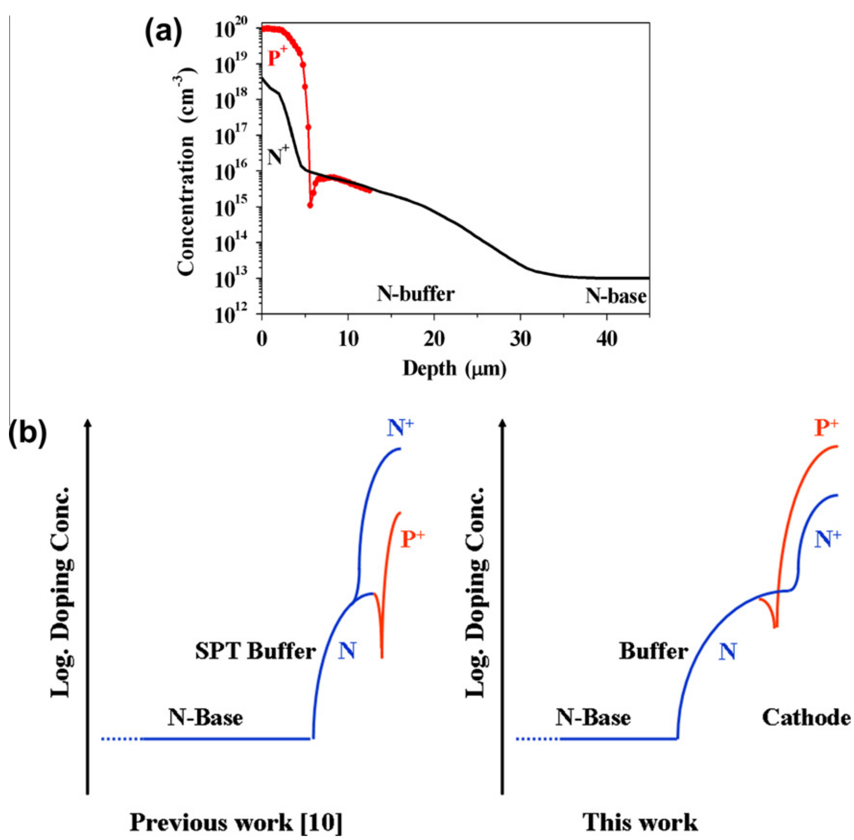

Fig. 2. Doping profile of the cathode with shorts using the spreading resistance technique (a). The profile P^+ belongs to the emitter of the PNP transistor. The profile N^+ is that of the N^+ cathode and N-buffer. The difference in doping profiles between the original approach [10] and the one used in this work is shown schematically (b).

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