A New Degree of Freedom in Diode Optimization:Arbitrary Axial Lifetime Profiles by Means of Ion Irradiation

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ISPSD, May 2000, Toulouse, France

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Abstract—A novel approach to lifetime control in fast recovery power diodes, arbitrary axial lifetime profiles by single-step ion irradiation, is presented. The principle is based on irradiation through a single mask which is inserted between the ion source and the device. The density and lateral/axial structures of the mask determine the final lifetime profile. Experimental results show that this new technique is fully capable to replace multiple single-energy ion irradiations and to guarantee superior diode performance.

***Index terms*—lifetime control, fast power diode, ion irradiation**

I. INTRODUCTION

Contemporary power electronics demands for fast power diodes with soft recovery down to very low on-state currents switched against high line voltages in snubberless circuits. The achievement of excellent ratings necessitates the application of several lifetime controlling steps in combination [1],[2], of which the multiple-energy ion irradiation gives outstanding results [3]. However, the multiple-energy irradiation by two or more consecutive single-energy irradiation steps is expensive thus limiting practical usage of this novel lifetime control technique.

In this paper, a novel concept capable to replace the combination of different lifetime treatments by one single irradiation step is presented. This concept is applied to 4.5kV fast recovery diodes where both the anode and base region has to be locally lifetime treated [1-3]. The lifetime killing in the anode region brings about soft reverse recovery even at high line voltages and low on-state currents. The killing of the N-base lifetime suppresses the dynamic avalanche caused by mobile charge carriers adding to ionized donors within the anode space charge region at high line voltages and current densities.

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II. THE PRINCIPLE OF THE METHOD

This novel approach to lifetime control is based on axial lifetime structuring using a single-energy, masked ion irradiation [4]. The aim of the single non-contact mask, which is inserted into the beam line between the ion source and the device, is to change the energy distribution of the ions entering the target and, consequently, shape the axial defect profile in the device. The resulting axial defect and, hence, lifetime profile is given by the density of the mask and its lateral/axial structure. This technique is in contrast to a previously proposed masked irradiation where a contact mask suppressing ion penetration into well-defined regions was used for lateral lifetime structuring [5].

In the simplest case of double-energy ion irradiation, which is shown in Fig. 1, the mask is formed by a foil with well-defined holes. In this case, the resulting defect profile is equal to the sum profile of two single-energy ones. The depth location of the deeper profile is determined by the primary energy E_0 (ions getting through the holes), that one of the shallower profile by the energy loss ?E in the foil (proportional to the density and thickness of the foil). The proportion between the profiles is set by the ratio of masked to uncovered (hole) area which sets the Φ_1:Φ_2 dose ratio.

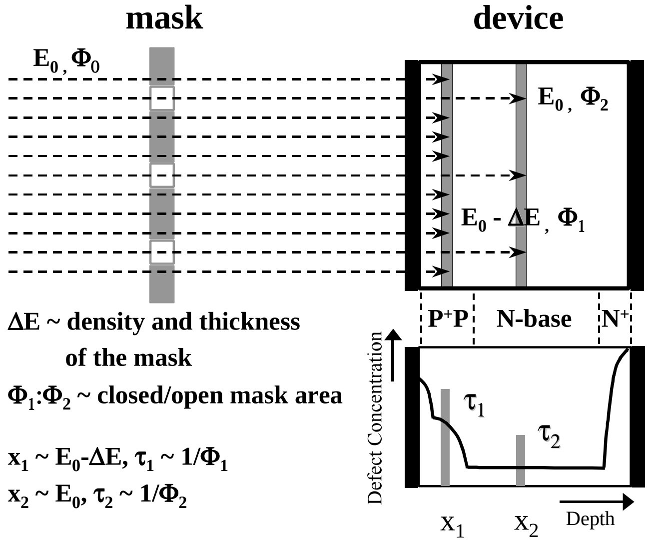

Fig.1. Principle of the arbitrary axial lifetime profile production by a single-step ion irradiation (shown for a double-peak profile).

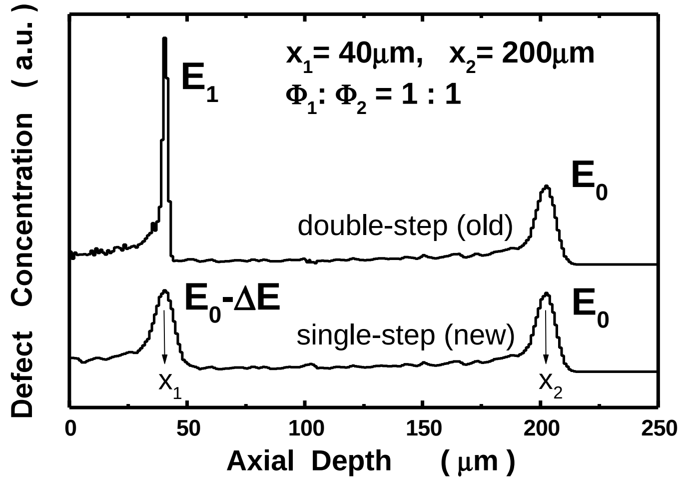

Fig.2. Simulated defect distribution after double-energy proton irradiation using the old double-step (energies E_0 and E_1) and the new single-step (energy E_0 only) technique.

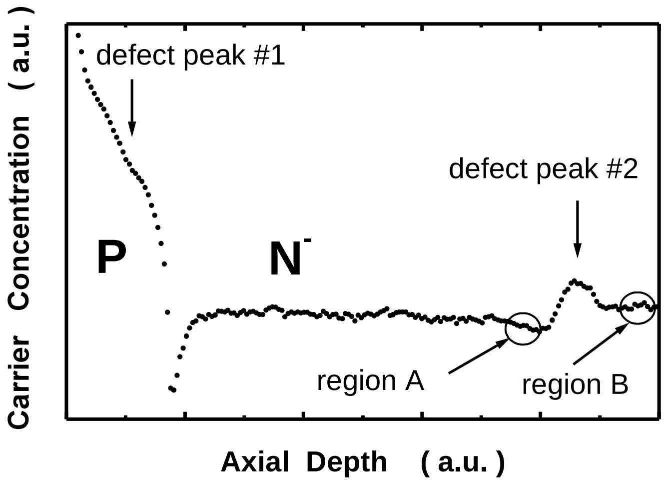

Fig.3. Axial carrier concentration profile of a diode subjected to a single-step double-energy ion irradiation (SR measurement).

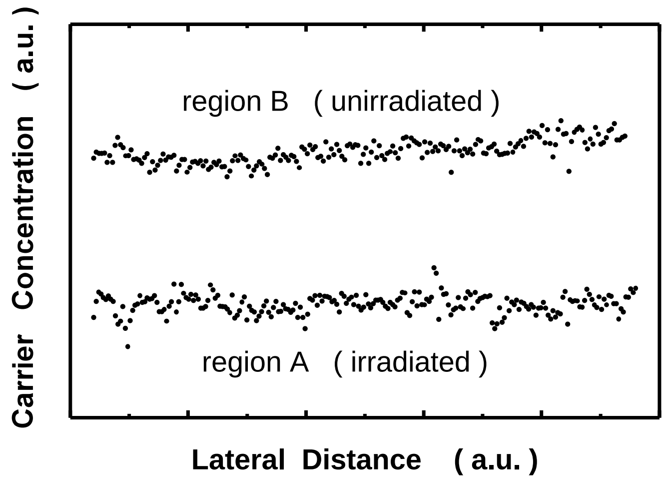

Fig.4. Comparison of the lateral homogeneity of the carrier concentration in the irradiated region A and the unirradiated region B of the axially profiled diode from Fig. 3 (SR measurement). The scanned distance in Fig. 4 is approx. 5 times larger than that one in Fig. 3.

In order to achieve a high degree of lateral homogeneity of the resulting defect concentration (lifetime), a geometrical projection of the mask onto the wafer has to be avoided by either moving the wafer in a carousel or by having a blurred beam projection. More complex multiple-peak lifetime profiles can be easily made by using more structured masks or by a combination of a few simple masks together. The application of the method is easy and does not need any special movable parts, e.g. previously proposed profile shaper [6].

III. VERIFICATION OF THE METHOD

Fig. 2 shows the simulated defect distributions resulting from the standard double-energy proton irradiations to 40 and 200µm performed in two successive steps with energies E_0 and E_1 (upper part of the figure) and from the new single-step double-energy irradiation through the mask with only one basic energy E_0 (lower part of the figure). In principle, both profiles are identical (with respect to peak positions and integrated damage) except for the width of the shallower peak which is given in case of the masked irradiation by the dispersion of energy E_0-? E caused by the ion penetration through the foil.

The capability of the method to create a laterally homogeneous and axially structured double-peak defect profile is shown in Figs. 3 and 4 presenting the axial and lateral carrier concentration profiles measured by the spreading resistance (SR) technique on a P-i-N diode subjected to a masked proton irradiation. The accelerator voltage and the mask dimensions were chosen in that way to locate the shallower defect peak (#1) in the anode and the deeper one (#2) well within the N-base. Both peaks are clearly visible in Fig. 3. Hydrogen-related donors located in the region of maximum damage close to the hydrogen penetration range create a dip in the anode acceptor profile (shallower peak #1) and an increase of the donor concentration in the N-base around the deeper defect peak #2. Fig. 4 shows the lateral carrier concentration profiles measured in the irradiated (region A in Fig. 3) and unirradiated (region B) parts of the diode. The decrease of the carrier concentration in the irradiated region A, which is caused by radiation-induced deep defects, is uniform thus giving evidence that the axially structured damage is laterally homogeneous.

The capability of the new masked irradiation to substitute the double-step ion irradiation was further proved by the comparison of static and dynamic parameters of diodes irradiated by both techniques. In either case, the shallower peak was located in the anode area and the deeper one well within the N-base. The total dose and the dose ratio between the deeper and shallower peak were identical. After irradiation, both diodes exhibited identical forward voltage drops. The reverse recovery waveforms of the irradiated diodes measured in two different conditions of resistive snubberless switching namely V_{DC}=3.4kV, J_F=1A/cm^2 and V_{DC}=2.7kV, J_F=10A/cm^2 are shown in Figs. 5 and 6, respectively. Both the current and voltage

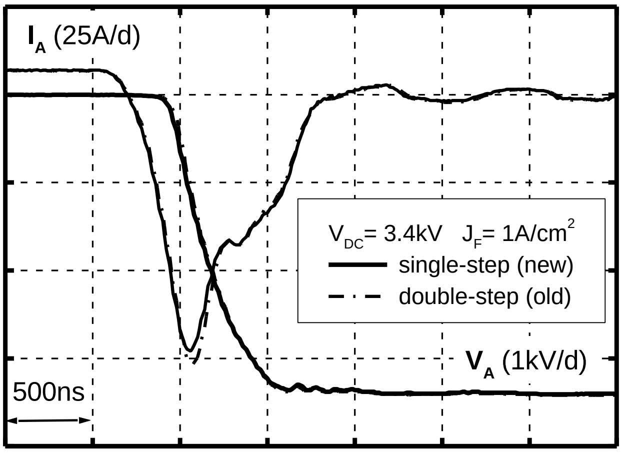

Fig.5. Measured reverse recovery characteristics of double-energy proton-irradiated devices (second peak well within the N-base): comparison between the old double-step and the new single-step (masked) irradiation. Resistive switching circuit, V_{DC}=3.4kV, J_F=1A/cm^2.

waveforms are identical under different turn-off conditions and thereby confirm that the new single-step method can fully replace the standard multiple-energy ion irradiation with respect to soft reverse recovery when switching low on-state currents against high line voltages. Repetition of the experiment with different positions of the second damage peak, which was moved closer to the cathode, gave identical results for the new single-step method compared to the standard multiple-energy ion irradiation as well.

IV. Application and Advantages

The novel concept of a double-energy proton (d-p) irradiation through a mask outperforms the traditional combination of proton and electron (p&e) irradiation in terms of extended SOA of the irradiated device and improved device parameters. This is due to a favorable on-state carrier distribution with lower and higher concentrations at the anode and cathode sides of the N-base, respectively, of a d-p irradiated diode in comparison to a p&e irradiated device [3].

Table I compares the forward static parameters of two diodes subjected to the traditional p&e and to the novel d-p irradiation technique. Besides the forward voltage drop V_F, the crossing point current I_{XING} (current at which the temperature coefficient of the forward voltage drop of the diode is neutral) is listed because of its importance for the paralleling of devices. Both diodes have the principal damage peak located in the anode area. The second damage peak of the d-p irradiated diode, which is located well within the N-base, substitutes for the electron irradiation. The irradiation doses are chosen to guarantee the best

TABLE I

Forward Static Parameters of Diodes Exposed to the Traditional and to the Novel Irradiation Method

Irradiation	V_F @ 2kA, 25°C	V_F @ 2kA, 125°C	I_{XING}
Standard (p&e)	5.54 V	6.23 V	475 A
Novel (d-p)	4.80 V	5.78 V	300 A

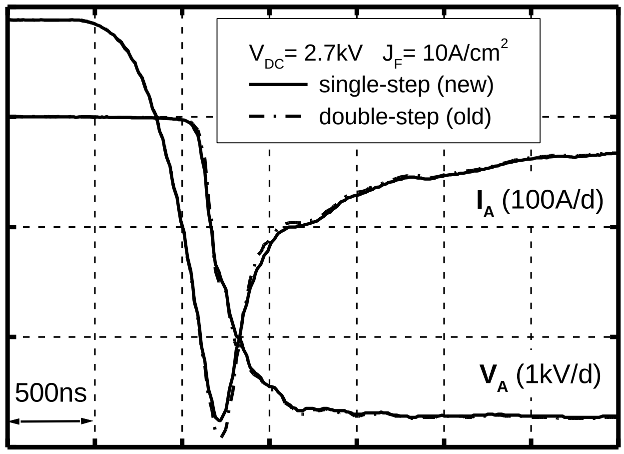

Fig.6. Measured reverse recovery characteristics of double-energy proton-irradiated devices (second peak well within the N-base): comparison between the old double-step and the new single-step (masked) irradiation. Resistive switching circuit, V_{DC}=2.7kV, J_F=10A/cm^2.

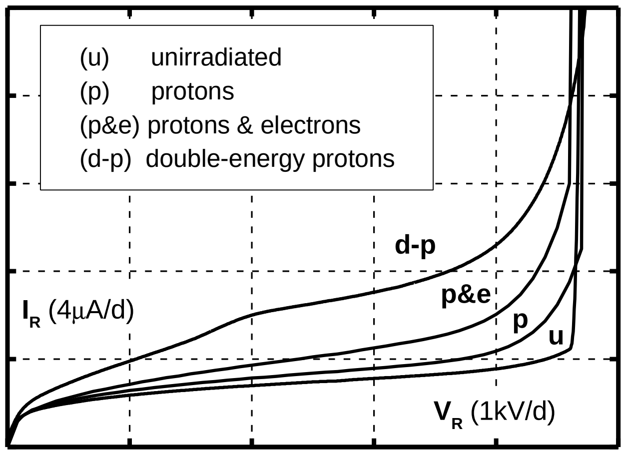

Fig.7. Blocking characteristics of an unirradiated diode (u) and of diodes irradiated by protons (p), protons and electrons (p&e) and double-energy protons (d) measured at 25°C.

device performance. It is evident from Table I that d-p irradiated diodes show a superior performance in the exhibited static parameters. This is only paid by a little increase of the leakage current which is depicted in Fig. 7 comparing blocking characteristics of p&e and d-p irradiated diodes. For reference, the blocking characteristics of an unirradiated diode (u) and of a diode with a single proton irradiation in the anode area (p) are also shown in Fig. 7. The increase of the leakage current with voltage is steeper in case of the d-p irradiation due to the higher portion of generation centers (divacancies) created by ions as compared to electrons. In addition, the characteristics of the d-p irradiated diode shows a clearly visible step at a V_R magnitude where the edge of the space charge region touches the defect peak in the N-base. On the other hand, the placement of the second defect peak well within the N-base has no detrimental effect on the breakdown voltage magnitude.

The superior dynamic behavior of d-p irradiated diodes with respect to soft reverse recovery is shown in Fig. 8a where clamped inductive commutation (V_{DC}=2.8kV,

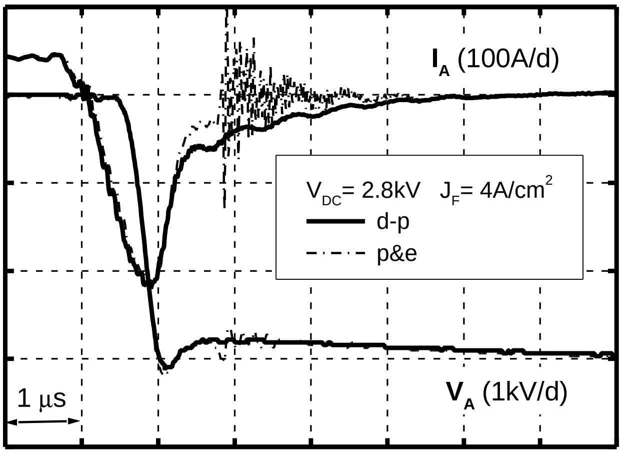

Fig.8a. Measured reverse recovery characteristics of diodes subjected to the novel single-step d-p and to the traditional p&e irradiation. Clamped inductive switching circuit, V_{DC}=2.8kV, J_F=4A/cm^2.

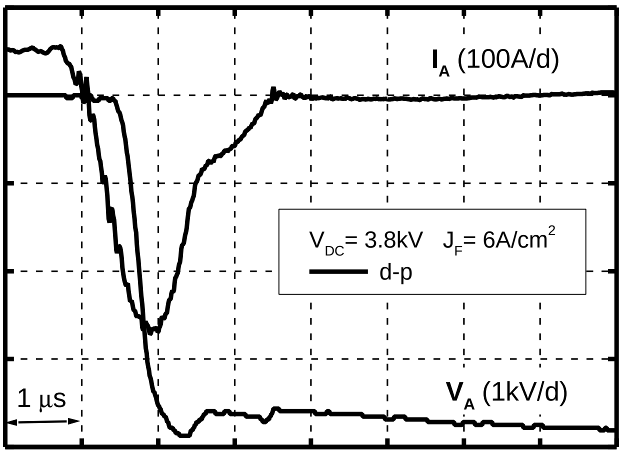

Fig.8b. Measured reverse recovery characteristics of a diode subjected to the novel single-step d-p irradiation. Clamped inductive switching circuit, V_{DC}=3.8kV, J_F=6A/cm^2.

J_F=4A/cm^2) waveforms of a d-p irradiated diode (solid curve) are compared to that ones of a standard p&e irradiated diode (dashed curve). The static parameters of the two devices are shown in Table I and Fig. 7. Whereas the p&e irradiated device (dashed curve in Fig. 8a) exhibits a snappy reverse recovery behavior at a line voltage of 2.8kV, the diode subjected to the d-p masked irradiation shows soft recovery (solid curve) and withstands voltages up to 3.8kV (Fig. 8b), i.e. a approx. 1000V higher line voltage for a 4.5kV device. Summarizing, the novel lifetime treatment prevents the diodes from snappy reverse recovery behavior and destruction, respectively, even when the diodes are switched off from low on-state current densities at very high line voltages. This is additionally shown in Fig. 9 which compares the reverse recovery waveforms of two diodes with identical on-state voltage drops but different lifetime profiles measured under resistive switching, snubberless turn-off conditions (V_{DC}=3.4kV, J_F=1A/cm^2). Again, the diode subjected to the novel d-p masked irradiation shows soft recovery and a smaller maximum reverse recovery current, while the p&e irradiated device exhibits a higher reverse peak current and significant snap-off. Moreover, the d-p irradiated diode can

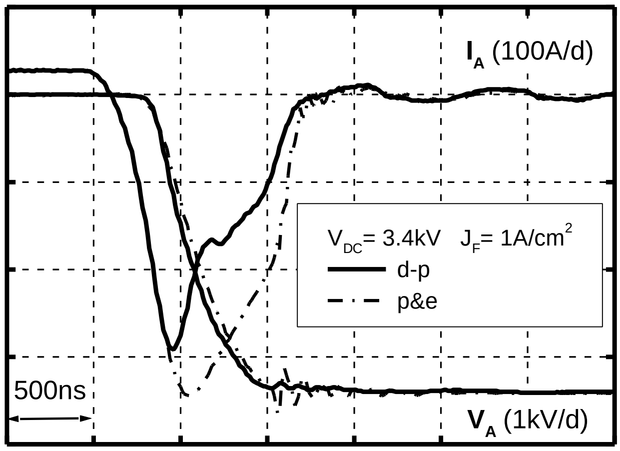

Fig.9. Measured reverse recovery characteristics of diodes subjected to the novel single-step d-p and to the traditional p&e irradiation. Resistive switching circuit, V_{DC}=3.4kV, J_F=1A/cm^2.

withstand a peak power of 1MW/cm^2 [3].

V. CONCLUSIONS

A novel concept for lifetime control in fast recovery power diodes capable to create arbitrary lifetime profiles by single-step ion irradiation was presented. The results of both static and dynamic measurements on irradiated fast power diodes show that the new method is fully capable to replace the technique of multiple single-energy ion irradiations and to guarantee a superior performance of the device. As the method provides the adjustment of an arbitrary axial lifetime profile by using a single accelerator arrangement only, the cost demands remain at the same time at the level of a single-step ion irradiation.

ACKNOWLEDGEMENT

The authors like to acknowledge the help of Mark Frecker and Hans Vetsch of the Production Test department of ABB Semiconductors in device testing and of Erich Nanser of the Research and Development Department for the SR measurements.

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