

## Localized Lifetime Control of 10 kV 4H-SiC PiN Diodes by MeV Proton Implantation

Zimo Yuan<sup>1,a\*</sup>, Keijo Jacobs<sup>2,b</sup>, Mietek Bakowski<sup>3,c</sup>, Per Ranstad<sup>4,d</sup>,  
Adolf Schöner<sup>5,e</sup>, Sergey Reshanov<sup>5,f</sup>, Wlodek Kaplan<sup>5,g</sup>, Hans-Peter Nee<sup>2,h</sup>  
and Anders Hallén<sup>1,i</sup>

<sup>1</sup>KTH Royal Institute of Technology, EECS, Isafjordsgatan 22, SE-164 40 Kista, Sweden

<sup>2</sup>KTH Royal Institute of Technology, EECS, Teknikringen 33, SE-100 44 Stockholm, Sweden

<sup>3</sup>RISE Acreo Swedish ICT AB, Box 1070, SE-164 25 Kista, Sweden

<sup>4</sup>LNU Linnaeus University, FTK, SE-35 191 Växjö, Sweden

<sup>5</sup>II-VI Kista AB, SE-164 40 Kista, Sweden

<sup>a</sup>zimo@kth.se, <sup>b</sup>k.jacobs@tutanota.com, <sup>c</sup>mietek.bakowski@ri.se, <sup>d</sup>per.ranstad@lnu.se,

<sup>e</sup>adolf.schoner@ii-vi.com, <sup>f</sup>sergey.reshanov@ii-vi.com, <sup>g</sup>wlodek.kaplan@ii-vi.com,

<sup>h</sup>hansi@kth.se, <sup>i</sup>ahallen@kth.se

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**Abstract.** In this paper, proton implantation with different combinations of MeV energies and doses from  $2 \times 10^9$  to  $1 \times 10^{11} \text{ cm}^{-2}$  is used to create defects in the drift region of 10 kV 4H-SiC PiN diodes to obtain a localized drop in the SRH lifetime. On-state and reverse recovery behaviors are measured to observe how MeV proton implantation influences these devices and values of reverse recovery charge  $Q_{rr}$  are extracted. These measurements are carried out under different temperatures, showing that the reverse recovery behavior is sensitive to temperature due to the activation of incompletely ionized p-type acceptors. The results also show that increasing proton implantation energies and fluencies can have a strong effect on diodes and cause lower  $Q_{rr}$  and switching losses, but also higher on-state voltage drop and forward conduction losses. The trade-off between static and dynamic performance is evaluated using  $Q_{rr}$  and forward voltage drop. Higher fluencies, or energies, help to improve the turn-off performance, but at a cost of the static performance.

### Introduction

Due to the larger band gap, higher breakdown voltage and better thermal performances, 4H-SiC PiN diodes are of interest for high voltage applications, for instance, rectification in resonant soft-switching industrial power supplies, X-ray imaging and snubber circuits [1]. The switching losses of PiN diodes is a significant parameter for system design, especially when high switching frequency is necessary.

The Shockley-Read-Hall (SRH) lifetime in the low-doped drift region, plays an important role in controlling switching losses since it affects how fast the stored charge can be removed when the diode is switched off. If the SRH lifetime can be decreased, switching losses can be lower and better dynamic performance can be achieved. Defect states located deep in the band gap can change SRH lifetime since they provide recombination sites for carriers of opposite charge. As a consequence, it is possible to tailor the lifetime by introducing defects inside the device. Low-dose proton implantation can generate defects locally in the diode without causing many defects elsewhere and this offers an interesting alternative for SRH lifetime modification. As an example given by [2], the drift region of as-processed 4H-SiC PiN diode can have two dominating deep levels at relatively low concentration, yielding a lifetime of several  $\mu\text{s}$ , while, after proton implantation, new types of stable defects will be dominant. These introduced defects have much higher concentration than native defects and can substantially contribute to a localized drop of the SRH lifetime.

In this paper, we carried out reverse recovery measurements at different temperatures of 4H-SiC PiN diodes implanted by different energies and fluencies of protons. High temperature induces larger reverse recovery charge,  $Q_{rr}$ , due to the further ionization of incompletely ionized acceptor dopants, but may also affect the charge carrier lifetime by temperature dependence of the carrier capture cross sections and bandgap position of deep levels. Increasing the proton implantation energy, or dose, has a positive effect on reducing SRH lifetime and switching losses, but will also cause a rise of the forward voltage. The trade-off between conduction and switching losses is discussed, and it is shown that MeV proton implantation offers a possibility to tailor the lifetime and reach an optimal trade-off between on-state and turn-off losses, using an offline process for metalized devices, before encapsulation.

## Experimental

The tested diodes have a 110  $\mu\text{m}$  thick low-doped n-type ( $7.5 \times 10^{14} \text{ cm}^{-3}$ ) drift region, with an active anode area of 0.79  $\text{mm}^2$  [3]. The proton implantations are performed at the Ion Technology Centre in Uppsala, Sweden and the implantation parameters are listed in Table 1. The diodes are classified into groups with one, or two proton implantation treatments. Figure 1 shows the distribution of silicon and carbon vacancy defects created by the proton implantation calculated by SRIM [4]. For the 1.9 MeV implant, a 30  $\mu\text{m}$  Al foil is used to moderate the energy. After the proton implantation, the samples are heat treated by furnace annealing, at 400  $^{\circ}\text{C}$  for half an hour and normal atmosphere, to ensure stable defects at elevated temperatures.

A full bridge rectifier with four 10 kV 4H-SiC diodes connected to an input LCC converter using a transformer shown in Ref. [1] is used as the topology for the measurement. The four equivalent diodes are assembled on a PCB for a balanced behavior. Since the temperature behavior is also of interest, the PCB is placed in hot transformer oil to maintain a stable temperature ambient. The rectifier is operated by a 35 ms pulse, therefore self-heating of tested diodes is neglected. The diode voltage is measured by a high voltage probe and diode current is monitored by the voltage across a shunt resistor, which is connected in series with the tested diode. All the reverse recovery measurements are carried out with a steady state blocking voltage of 4 kV and a turn-off current derivative  $dI/dt = 5.5 \times 10^6 \text{ A/s}$ .

Table 1. Selected doses ( $\text{cm}^{-2}$ ) of protons for the different groups of diodes, using 3 different energies.

Group	Proton Energy [MeV]		
	1.9	3.4	3.7
1	$5 \times 10^{10}$	—	—
2	$5 \times 10^{10}$	$5 \times 10^9$	—
3	$5 \times 10^{10}$	—	$5 \times 10^9$
4	—	$2 \times 10^{10}$	—
5	—	$5 \times 10^{10}$	—
6	—	$1 \times 10^{11}$	—

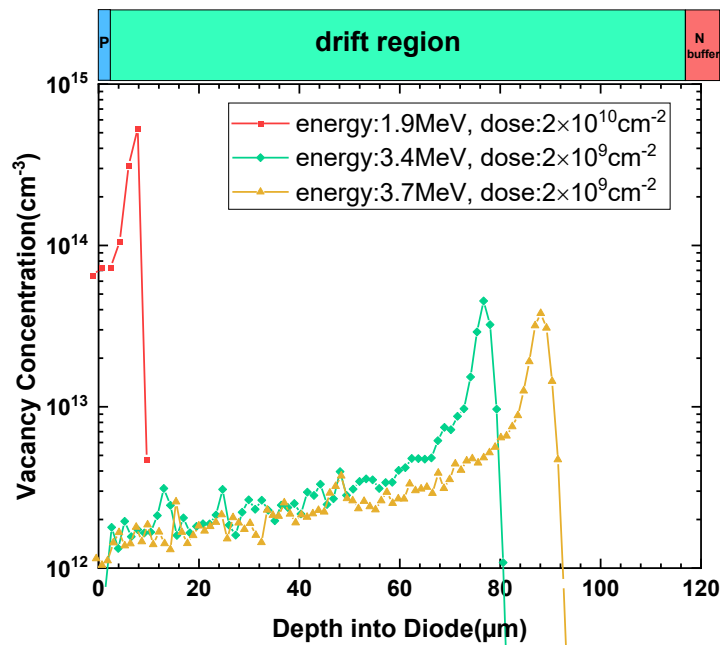


Fig. 1. Vacancy depth distribution calculated by SRIM for different proton energies and doses. On the top is a cross section of the diodes, showing the 110  $\mu\text{m}$  thick drift region.

## Results and Analysis

The turn-off cycle of one of the tested diodes is shown in Fig. 2, including diode reverse current and voltage across the diode. The integrated diode current, starting from when the diode current crosses zero until the diode voltage reaches its maximum blocking voltage, is defined as reverse recovery charge  $Q_{rr}$ . For higher reverse current, there will be a higher  $Q_{rr}$  and more switching losses. Two groups of diodes with the same implantation energy, 1.9 MeV, but different fluencies are selected to illustrate how the implantation fluence affects the dynamic performance (Fig.2 inset). Increasing implantation dose from  $2 \times 10^{10}$  to  $5 \times 10^{10} \text{ cm}^{-2}$  will cause an almost 10% decrease in  $Q_{rr}$  at 30 °C and has a similar effect at 80 °C.

Figure 2 (inset) also shows that increasing temperature from 30 to 80 °C causes an approximately 50% increase in  $Q_{rr}$ , which is clearly visualized by the reverse recovery current peak in Fig. 3. Higher temperature contributes to larger  $Q_{rr}$  and higher turn-off losses. This is due to the fact that the incompletely ionized p-type acceptors are ionized at a higher temperature [5], which improves the hole injection from the  $p^+$  emitter. Different injection levels of holes at different temperatures simulated in Sentaurus TCAD are shown in Fig. 3 (inset). A 30% increase in  $Q_{rr}$  from 30 to 80 °C is found from the integrated hole concentration in the drift region due to the increased ionization of acceptors at a higher temperature and this effect dominates the overall temperature dependence of the reverse recovery.

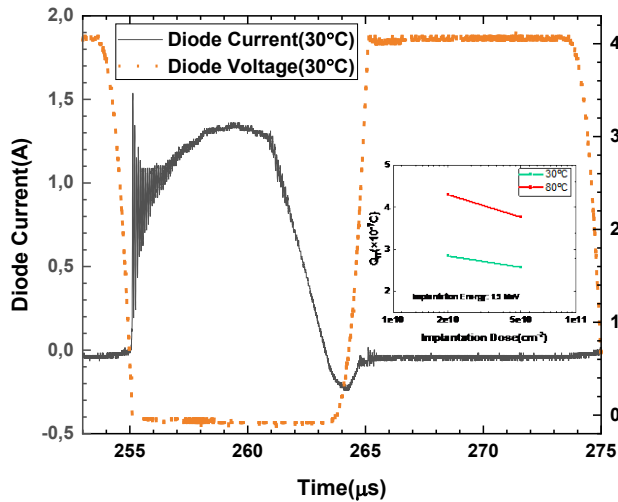


Fig. 2. Current Voltage (IV) characteristics of the turn-off cycle of a representative diode. The inset shows the reverse recovery for two different proton doses and that a higher temperature causes larger  $Q_{rr}$ .

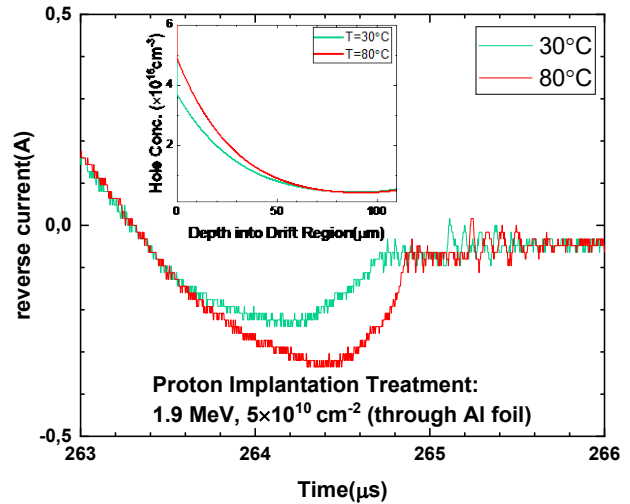


Fig. 3. Higher implantation dose contributes to smaller  $Q_{rr}$  and less switching losses. The inset shows higher injection level at 80 °C (Sentaurus TCAD) as a result of activation of more incompletely ionized acceptors in the  $p^+$  emitter.

Values of the reverse recovery charge of three other groups are shown in Fig. 4 to compare the effect of implantation energy. All the groups have the same first implantation treatment, while two of the groups have obtained an extra implantation. The group without the second implantation is used as a reference group. Figure 4 shows that a higher implantation energy also helps to achieve a smaller  $Q_{rr}$  and lower switching losses, and this effect is especially pronounced when the implantation energy is high enough for the protons to nearly reach the cathode side and thereby affecting most of the drift region.

The  $Q_{rr}$  and the forward voltage, measured at a constant current of 2 A, is plotted as a function of implantation fluence at room temperature in Fig. 5. Proton implantation also increases the on-state losses of the diodes, since a low concentration of defects is formed during the entire proton track (see Fig. 1). These defects will increase the resistivity and forward voltage of the diode. A shorter SRH lifetime improves the dynamic performances by lowering the switching losses, while simultaneously the conduction losses at steady state become larger. This turn-off/on-state trade-off can be effectively tailored for specific applications using proton implantation.

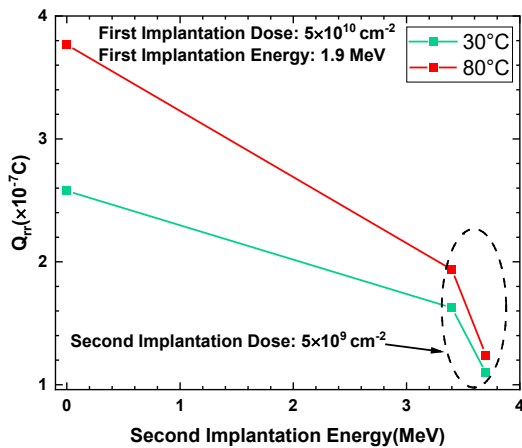


Fig. 4. Higher implantation energy contributes to smaller  $Q_{rr}$  and less switching losses.

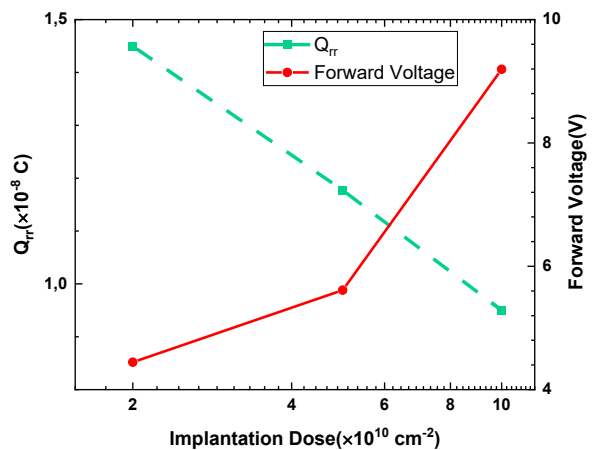


Fig. 5. Proton implantation with higher dose is an effective way to improve the dynamic performance, while the static on-state performance must be sacrificed.

## Summary

The reverse recovery behavior of 4H-SiC PiN diodes with different proton implantation treatment is compared at different temperatures. It is seen that reverse recovery charge  $Q_{rr}$  is increased with 30–35% when going from 30 to 80 °C due to the ionization of Al acceptors in the  $p^+$  emitter. The proton implantation can effectively reduce the SRH lifetime in the drift region, reduce the  $Q_{rr}$  and contribute to lower switching losses. However, the on-state voltage drop is increased by the proton implantation. The measurement results show that localized carrier lifetime control through proton implantation can be used to find a suitable trade-off between static and dynamic performance of SiC PiN diodes.

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