Materials Science Forum
ISSN: 1662-9752, Vol. 924, pp 436-439
doi:10.4028/www.scientific.net/MSF.924.436

Submitted: 2017-09-06
Revised: 2018-01-09
Accepted: 2018-03-11
Online: 2018-06-05

Local Lifetime Control in 4H-SiC by Proton Irradiation

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Keywords: Proton Irradiation, Radiation Defects, Lifetime Control, Open Circuit Voltage Decay

Abstract. The effect of local lifetime control by proton irradiation on the OCVD response of a 10 kV SiC PiN diode was investigated. Carrier lifetime was reduced locally by irradiation with 800 keV protons at fluences up to $1x10^{11}$ cm^{-2}. Radiation defects were characterized by DLTS and C-V profiling; excess carrier dynamics were measured by the OCVD and analyzed using the calibrated device simulator ATLAS from Silvaco, Inc. Results show that proton implantation followed by low temperature annealing can be used for controllable local lifetime reduction in SiC devices. The dominant recombination centre is the $Z_{1/2}$ defect, whose distribution can be set by irradiation energy and fluence. The local lifetime reduction, which improves diode recovery, can be monitored by OCVD response and simulated using the SRH model accounting for the $Z_{1/2}$ defect.

Introduction

For years, low carrier lifetime in 4H-SiC epilayers has been a limiting factor for development of useable SiC bipolar devices. Recent progress in the $Z_{1/2}$ defect elimination allowed for fabrication of fast SiC PiN diodes working at high blocking voltages and forward current densities [1]. To improve dynamic characteristics and optimize the trade-off between static and dynamic losses, precise control of the electron-hole plasma distribution in SiC PiN diodes is necessary. Local lifetime reduction by recombination centers introduced by protons can be an excellent tool for this purpose [2]. In this paper, we investigate the effect of local lifetime control by protons on excess carrier dynamics and OCVD (open circuit voltage decay) response of high-voltage SiC PiN diodes.

Experimental

The effect of local lifetime control by proton irradiation was investigated on 10 kV SiC PiN diode chips fabricated on lightly doped ($< 10^{15}$ cm^{-3}) *n*-type 4H-SiC epilayers [1]. Devices were irradiated from the anode side with 800 keV protons to fluences from $5x10^{9}$ to $1x10^{11}$ cm^{-2} using the 3 MeV tandetron facility in NPI CAS Rez [3]. The irradiation energy was chosen in order to place the damage peak beyond the anode junction. Diode static and dynamic parameters were characterized prior to and after proton irradiation. Radiation defects were characterized by capacitance deep level transient spectroscopy (DLTS) and C-V profiling. The excess carrier dynamics were measured by the OCVD and analyzed using the calibrated device simulator ATLAS from Silvaco, Inc. [4]. Recombination models accounting for the effect of introduced deep levels were set according to experimental results obtained by C-V and DLTS.

Results and Discussion

Recombination (carrier lifetime) of excess carriers in the PiN diode is primarily controlled by recombination centers (deep levels) located in the lightly doped *n*-base (epilayer). Fig. 1. compares DLTS spectra measured in the anode side of the *n*-base (up to the depth of 6 μm) prior to and after irradiation with 800 keV protons. Identification parameters of all deep levels produced by

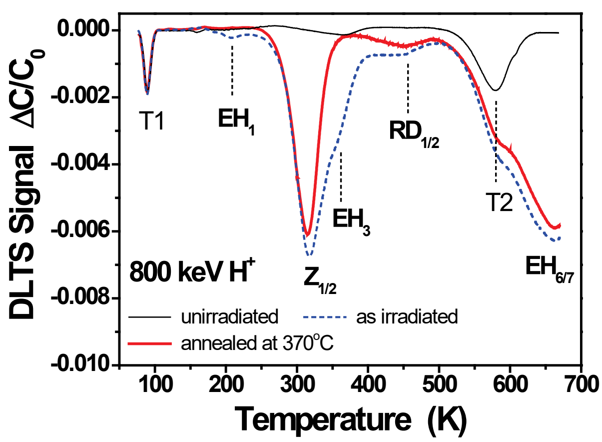

Fig. 1. DLTS spectra of *n*-base of the 4H-SiC PiN diode measured before (black thin) and after (short-dashed) irradiation with 800 keV protons to a fluence of $5x10^9$ cm^{-2} and after annealing at 370°C (red thick), rate window 56 s^{-1}.

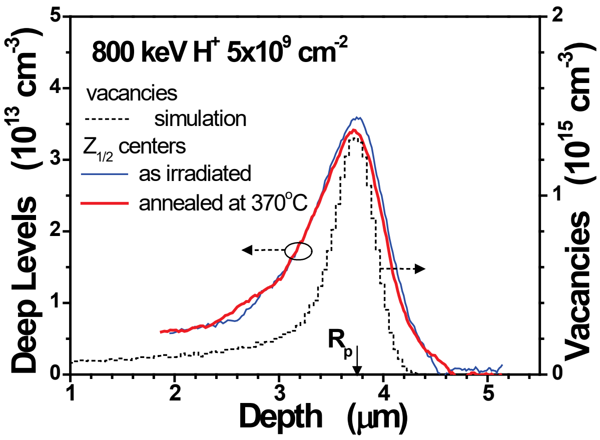

Fig. 2. Profile of the $Z_{1/2}$ centre in the *n*-base of the 4H-SiC PiN diode irradiated with 800 keV protons together with the simulated profile of primary vacancies (short-dashed).

proton irradiation are shown in Table 1. The spectrum recorded prior to irradiation (black thin) shows that the *n*-base of the unirradiated diode contains only two noticeable levels T1 (E_C-E_T=0.17eV) and T2 (E_C-E_T=1.41eV) which are connected with defects originating from diode fabrication. The concentration of these defects is low (~ 10^{12} cm^{-3}), which results in relatively high magnitudes of OCVD lifetime (~ 3 µs) measured on unirradiated diodes. The DLTS spectrum recorded on the as irradiated sample (during the first DLTS temperature scan) shows that 800 keV protons introduce two dominant defect centers $Z_{1/2}$ and $EH_{6/7}$, which are related to the carbon vacancy [5]. These stable defects (their annealing temperature is higher than 1300 K) are accompanied by two unstable levels EH1 and EH3 which can be removed by low temperature annealing (see spectrum recorded after annealing at 370ºC – red thick). Fig. 2 shows that the $Z_{1/2}$ centers, which are well known lifetime killers in SiC, are strongly localized close to the proton's projected range R_P and their distribution follows, in principle, the distribution of primary damage - silicon and carbon vacancies (see Fig. 2). Proton irradiation followed by low temperature annealing can be therefore used for local lifetime reduction in SiC devices. Since the $Z_{1/2}$ centers are deep acceptors, they compensate the lightly doped *n*-base at the damage peak. This is evidenced in Fig. 3, which compares profiles of free carriers (electrons) measured by C-V prior to and after proton irradiation. The compensation does not reduce the blocking voltage of the PiN diode. However, introduced damage decreases carrier mobility [6], which can accelerate undesirable increase of the forward voltage drop.

Local lifetime reduction, which is placed in the proper part of the diode, can substantially speed-up its turn-off without undesirable increase of the forward voltage drop. This is shown in Fig. 4, which presents reverse recovery waveforms measured on the PiN diode prior to and after irradiation with 800 keV protons (the recovery from I_F=2A to V_R=700V). One can see that the

Table 1. Identification parameters of deep levels produced in the n-base of the SiC PiN diode by proton irradiation.

Level	Bandgap position [eV]	Capture cross section [cm^2]	Literature
EH_1	$E_C – 0.44$	$8x10^{-14}$	[7]
$Z_{1/2}$	$E_C – 0.68$	$4x10^{-14}$	[5,6,7]
EH_3	$E_C – 0.72$	$4x10^{-15}$	[7]
$RD_{1/2}$	$E_C – 0.80$	$3x10^{-16}$	[8]
$EH_{6/7}$	$E_C – 1.64$	$4x10^{-13}$	[4,5,6]

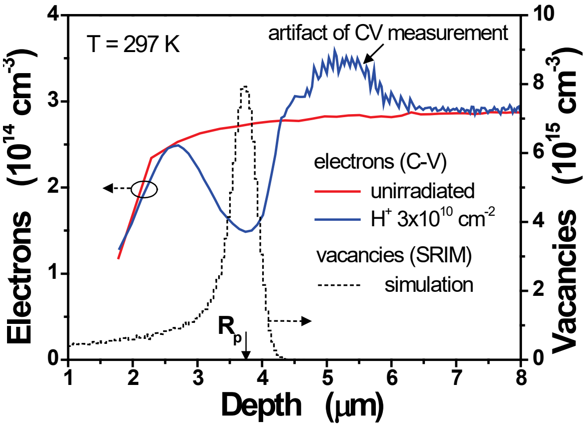

Fig. 3. Free carrier (electron) profiles of an unirradiated SiC PiN diode and a diode irradiated with 800 keV protons to a fluence of 1x10^{11} cm^{-2} together with the simulated profile of primary vacancies (dashed).

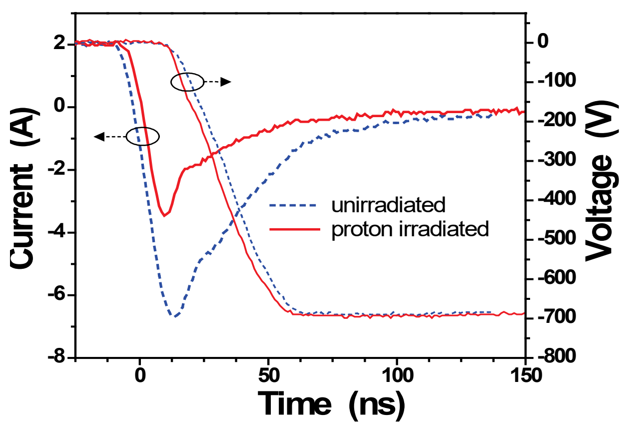

Fig. 4. Measured reverse recovery of an unirradiated SiC PiN diode and a diode irradiated with 800 keV protons to a fluence of 1x10^{11} cm^{-2} (room temperature).

stored charge and consequently the reverse recovery current maximum of the irradiated diode decreased substantially (more than twice) while the forward voltage drop V_F at I_F=2A increased only by one tenth (not shown). On the other hand, the local introduction of deep levels in the anode side of the *n*-base caused an increase in diode leakage of more than one order of magnitude.

Local lifetime killing can be characterized by the OCVD response, which monitors the time dependent component of the post injection voltage [9]. This is shown in Fig. 5, which compares the measured OCVD responses of PiN diodes irradiated with different fluences of 800 keV protons. As one can see in the inset of Fig. 5, which shows the values of the high-level lifetime τ_{HL} extracted from the slope of the dV/dt response at t= 3μs, OCVD is most suitable for monitoring of low irradiation fluences. The response can also be used to calibrate recombination models of device simulators (see Fig. 6). Calibrated simulation is then useful for analysis of excess carrier dynamics and proper design of the local lifetime reduction. This is shown in Figs. 7 and 8, which present simulated spatial distributions of carrier concentration in the unirradiated and irradiated PiN diode during the OCVD recovery. Results show that the local lifetime reduction modifies mainly the initial part of the OCVD recovery (t<1 μs) while the rest of it is almost unaffected. As one can see, proton irradiation decreases the ON state concentration of electron-hole plasma only at the anode

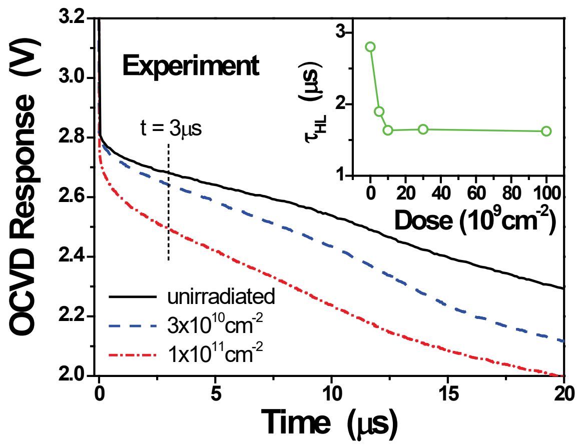

Fig. 5. Measured OCVD responses of 4H-SiC PiN diodes irradiated with different fluences of 800 keV protons. The values of high-level lifetime τ_{HL} (extracted at t= 3μs) for different irradiation fluences are shown in the inset.

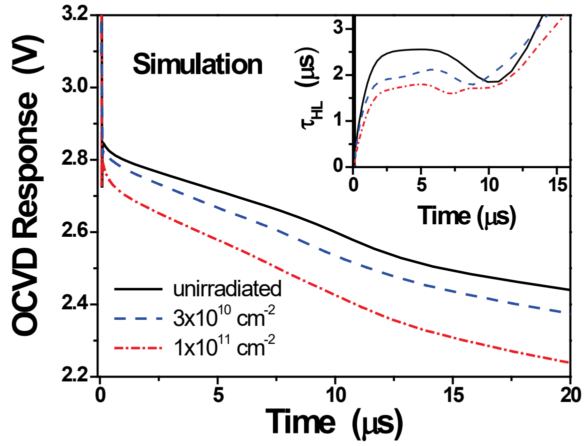

Fig. 6. Simulated OCVD responses of the 4H-SiC PiN diode prior to and after irradiation with 800 keV protons. The temporal evolution of the high-level lifetime τ_{HL} calculated from the course of (dV/dt)$^{-1}$ is shown in the inset.

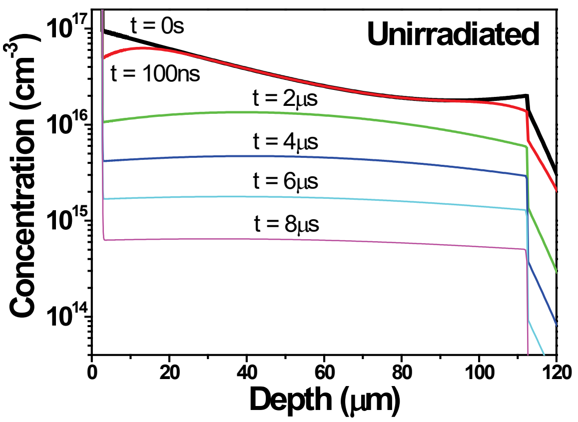

Fig. 7. Simulated spatial distribution of hole concentration in the n-base of the unirradiated 4H-SiC PiN diode at different instants of the OCVD recovery.

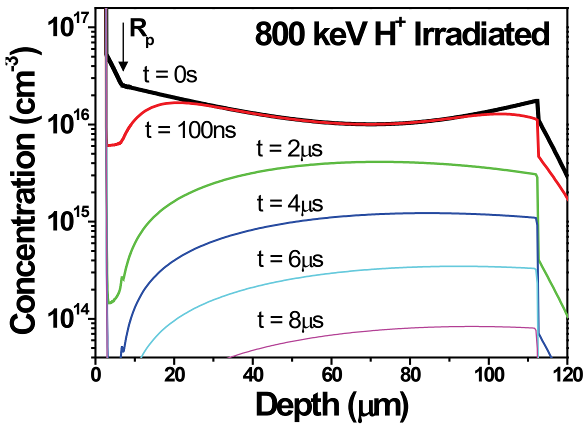

Fig. 8. Simulated spatial distribution of hole concentration in the n-base of the 4H-SiC PiN diode irradiated with 800 keV protons at different instants of the OCVD recovery.

side of the *n*-base where it is necessary for faster turn-OFF. The increase of the V_F with irradiation fluence is then lowered, the diode turns OFF more quickly and the reverse recovery current maximum I_{RRM} decreases (see Fig. 4).

Summary

We showed that proton irradiation followed by low temperature annealing can be used for controllable local lifetime reduction in a 10kV SiC PiN diode. The dominant recombination centre is the $Z_{1/2}$ centre, whose distribution can be easily controlled by irradiation energy and fluence. Proton irradiation allows substantial speed-up of diode turn-off without undesirable increase of the forward voltage drop. Lifetime reduction and excess carrier dynamics can be monitored and analyzed using OCVD measurement and calibrated device simulation.

Acknowledgement

This work was supported by the EU FP7 NMP 604057 project SPEED and the project SGS17/095/OHK3/1T/13 of the CTU Prague. Proton irradiations were carried out at the CANAM infrastructure of the NPI CAS Rez supported through MEYS project No. LM2015056.

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