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# Recombination characteristics in 2–3 MeV protons irradiated FZ Si

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ABSTRACT

Combined analysis of the carrier recombination and generation lifetime as well as reverse recovery durations ($\tau_{RR}$), dependent on proton irradiation fluence in the range of $7\times10^{12}$–$7\times10^{14}$ p/cm$^2$, has been performed in FZ silicon PIN diodes and wafer structures. A δ-layer and triangle profiles of radiation induced defects were formed by varying energy of protons in the range 2–3 MeV. Carrier decay constituents and values of recombination lifetime have been evaluated by employing a microwave probed photoconductivity transient technique, while deep levels spectra ascribed to generation lifetime variations have been examined by exploiting capacitance deep-level transient (DLTS) spectroscopy. Recombination lifetime decreases from several μs to few ns, while DLTS spectra show an increase in the amplitude of a DLTS peak at 170 K with irradiation fluence. Transforms of DLTS spectra and a decrease in density of the majority carrier traps have been revealed after 24 h isochronal anneals in the range of temperatures of 80–420 °C. Inhomogeneous depth distribution of recombination lifetime in proton irradiated samples has been revealed from the cross-sectional scans of the excess carrier lifetime measured by MW-PC technique and compared for δ-layer and triangle profiles of radiation induced defects. After isochronal anneals, the $\tau_{RR}$ changes its behaviour as a function of irradiation fluence.

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## 1. Introduction

The reverse recovery time ($\tau_{RR}$) determines the switching rate of PIN rectifiers and it directly depends on the carrier recombination lifetime in vicinity of the p$^+$–n junction [1]. Also the reverse recovery pulse shape and symmetry, defined by a recovery softness factor, significantly pertain to a location and profile of the distribution of fast recombination centres. The modern technologies [1] of the improved reverse recovery and voltage drop of the on-stage junction characteristics are based on formation of p$^+$–SiGe thin layers and SiGe/Si heterojunctions together with mosaic ohmic p$^+$–n$^+$ region. Irradiation technologies are usually based on formation of the nearly homogeneous profiles of defects or by combining sharp/smooth distribution of recombination centres induced by proton/electron beams [2].

In this work, investigations on the carrier lifetime as well as reverse recovery (RR) time ($\tau_{RR}$) were performed on FZ Si PIN power diodes and wafer structures to identify the optimal technological steps to form a δ-layer and triangle defect distribution profiles of the enhanced recombination by proton irradiations. To identify the dominant radiation defects and their transforms under anneals, the concerted investigations were performed by employing a microwave probed photoconductivity transient technique (MW-PC), capacitance deep level transient spectroscopy (C-DLTS) and RR measurements. Depth distribution of the recombination lifetime for the δ- and triangle profiles of protons stopping has been controlled by the cross-sectional scans of the excess carrier lifetime using the MW-PC technique.

## 2. Samples, irradiations and measurement techniques

Two sets of industrial n–n$^+$ substrates and PIN diodes irradiated with different proton fluences and energy have been examined.

The proton irradiations were performed using a proton accelerator at Helsinki University. A δ-layer and triangle defect distribution profiles of the enhanced recombination were induced and localized by varying protons energy in the range 2–3 MeV. The irradiations were arranged to form recombination enhanced layers within either n-layer of substrates or n-base, i.e. *i*-layer of PIN diodes. Density of radiation defects was varied by changing the irradiation fluence in the range of $7\times10^{12}$–$7\times10^{14}$ p/cm$^2$. To suppress carrier generation centres, the isochronal anneals for 24 h were performed by varying heat treatment temperature in the range 80–420 °C.

Excess carrier decays were examined by microwave probed photoconductivity transient (MW-PC) technique [3]. Excess carriers were generated by a laser operating at 1062 nm wavelength with pulses of 500 ps. A single-mode fiber excitation with beam of 3–10 μm dimensions was exploited for excitation in

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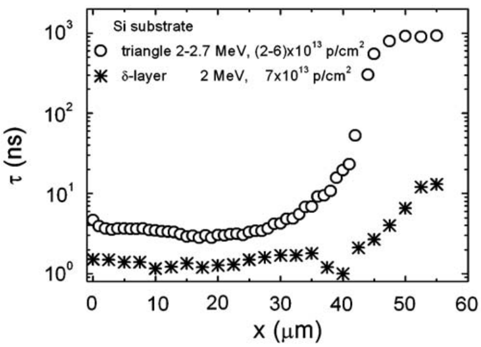


**Fig. 1.** Recombination lifetime depth-distribution profiles obtained for δ-layer (stars) and triangle shape (open circles) of the radiation induced damages by varying protons energy in the range of 2–2.7 MeV.

the cross-sectional scan regime, and location as well as profile of the radiation induced defects was controlled by MW-PC cross-sectional profiling of the carrier lifetime in the post-irradiation state of material.

Capacitance deep level transient spectroscopy (C-DLTS) measurements were performed to identify carrier generation centres by employing a commercial spectrometer DLS-82E. Measurements of the reverse recovery transients were carried out by an industrial tester designed to measure the $\tau_{RR}$ values in the range from 10 ns to 4 μs.

## 3. Results and discussion

Fluence dependent lifetime variations within depth of samples containing a δ-layer and triangle defect distribution profiles of the enhanced recombination formed by varying protons energy in the range of 2–2.7 MeV protons are compared in Fig. 1. A profile of recombination lifetime variations, measured by MW-PC cross-sectional scans within depth of the n-layer of $n–n^+$ Si, correlates rather well with that of defect introduction profile simulated by TRIM. This proves a possibility of designing a positioning of enhanced recombination layers within PIN diode structure by varying energy of the proton beam.

A DLTS spectrum registered for a PIN diode irradiated by 2 MeV protons with $7\times10^{12}$ p/cm$^2$ fluence is illustrated in Fig. 2a. To follow the transforms of the DLTS spectra dependent on fluence and isochronal anneals, a spectrum normalized to the most intense peak at ~170 K was simulated by using up to six peaks shown in Fig. 2a. The simulated distribution of emission time extrema enables one to separate a shift of spectrum peaks, possible due to incomplete filling of traps, from emerging of additional and complex traps under either increased radiation damage with fluence or defect transforms due to heat treatments.

Evolution of the DLTS spectra in the as-irradiated diodes, containing a δ-layer of radiation induced damage by 2 MeV protons, with enhancement of irradiation fluence is illustrated in Fig. 2b. The DLTS spectrum measured for the as-irradiated diodes, containing a triangle profile of radiation induced defects by varying energy of protons in the range of 2–2.7 MeV is illustrated in Fig. 2c and compared with that registered for δ-layer containing diode.

Three main DLTS peaks at 90, 150–170 and 200–250 K have been obtained at the same lock-in filtering and carrier injection parameters. These peaks are well known in the literature [4,5] as caused by radiation defects and ascribed to vacancy related centres. The peaks are denoted by widely accepted signatures in Fig. 2. Activation energy of the latter centres has been evaluated from the Arhenius plots and found to be close to values published

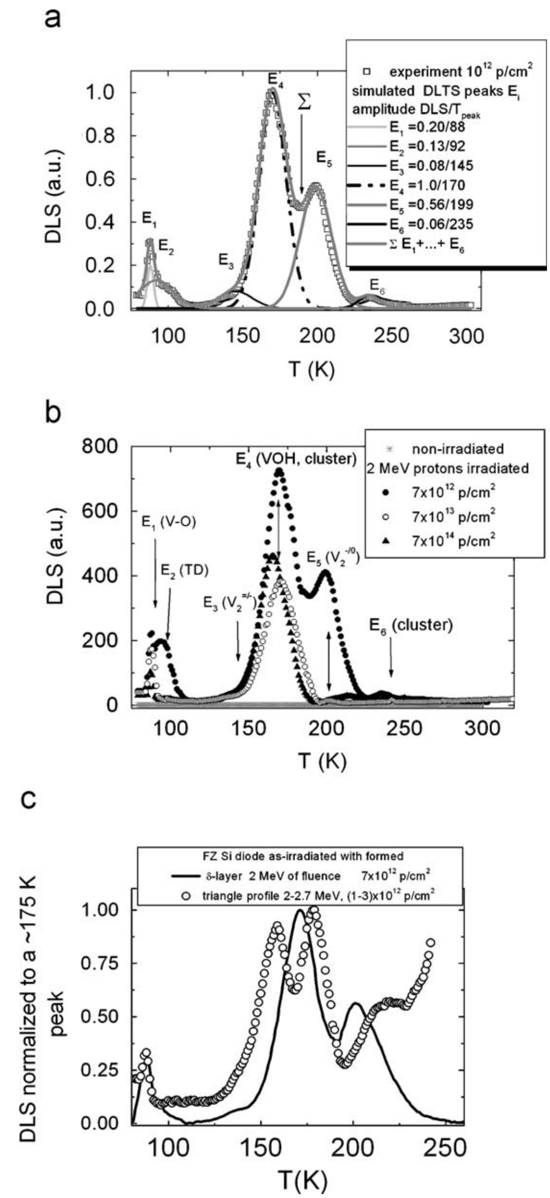


**Fig. 2.** (a) DLTS spectrum registered in diode irradiated by 2 MeV protons with $7\times10^{12}$ p/cm$^2$ fluence and simulated distribution of composed DLTS peaks. Amplitudes within a single spectrum are normalized to the strongest peak at 170 K. (b) Evolution of the DLTS spectra in diodes irradiated by 2 MeV protons with enhancement of irradiation fluence. Structure of the spectra obtained in the 2 MeV proton irradiated diodes is shown on the background of that controlled for the non-irradiated material. (c) Comparison of DLTS spectra for a diode irradiated by protons of varying energy in the range of 2–2.7 MeV (symbols) to form a triangle profile of radiation defect distribution and a δ-layer (line) at fixed location by 2 MeV protons.

in the literature. Additional peaks at 90–100 and at >250 K can be ascribed to thermodonors and vacancy clusters, respectively. Enhanced formation of thermodonors mediated by hydrogen in proton irradiated Si is well known. The DLTS peak at around 170 K was observed in the protons heavily irradiated Si detectors [4] and debated as a feature of either inter-centre recombination, cluster type [6] defects or VOH complex [4,5]. A position of the latter peak between $V_2^{=/-}$ and $V_2^{-/0}$ peaks, which are observed only on 170 K peak sides for $7\times10^{13}$ and $7\times10^{14}$ p/cm$^2$ fluence irradiated diodes, within a DLTS spectrum and the strongest 170 K peak amplitude hint on vacancy ascribed clusters. Position of this peak and its relative amplitude, varying with increase of fluence, also corroborate an assumption of clusters impact.

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