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Characterization of the radiation-induced defects in Si detectors by carrier transport and decay transients

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Abstract

Temperature variations of the microwave probed photoconductivity (MW-PCD) transients have been shown to be a non-invasive tool for separation of recombination and trapping centers associated with radiation induced defects in Si detectors. Peaks in the asymptotic carrier decay lifetime temperature changes, attributed to carrier capture/recombination effects, are analyzed. The correlative investigations of the MW-PCD transients and kinetics of the carrier transit within detector are simultaneously performed in the proton irradiated Si pad detectors to clarify field redistribution effects. Carrier decay and transit regimes varying applied electric field are analyzed. The recombination and trapping lifetime variations with irradiation fluence are discussed.

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Keywords: Carrier lifetime; Recombination and trapping; Si particle detectors; Carrier transit; Radiation defects

1. Introduction

High concentrations of carrier traps in heavy irradiated detectors, with proton fluences more than $10^{14}\,cm^{-2}$ of high resistivity Si material with initial carrier densities less than $10^{12}\,cm^{-3}$, restrict implementation of the most sensitive characterization techniques, such as DLTS, for evaluation of the carrier decay parameters [1]. Carrier recombination and transit times are limiting factors for the charge collection efficiency of detectors. The transient current technique (TCT) [2] is a powerful instrument to control variations of the carrier transport and electric field distribution within depth of the heavily irradiated detectors. However, carrier recombination via radiation-induced defects can be only estimated by assuming the charge mono-exponential decay [3] and by artificially reconstructing the lost carrier density [4] when using the latter TCT method. Therefore, the direct methods for control of the carrier recombination, trapping and transport characteristics are preferential.

In this work, carrier recombination and transport parameters have been examined by combining the microwave probed photoconductivity (MW-PCD) transients [5], current extraction transients under linearly increasing voltage (CELIV) pulses [6] and the TCT techniques. Simultaneously, the carrier decay (MW-PCD) and transport (TCT) transients have been measured varying pulsed excitation wavelength and junction of the Si detector.

2. Experimental techniques and samples

Pad-detectors fabricated on n-type float zone (FZ) Si have been investigated. The optical window of about 2 mm diameter in the center of the diode was left non-metallized to perform optical excitation. The non-metallized detector areas have been exploited for the measurements of the carrier recombination and transport characteristics by the contactless MW-PCD and contact TCT as well as CELIV methods. Carrier recombination and transport characteristics have been measured on detectors irradiated by

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24 GeV/c protons with fluences in the range from 10^{14} to 10^{15} cm^{-2}.

The MW-PCD technique [5] is based on MW absorption by excess free carriers. The direct analysis of the carrier decay shape and relaxation rates has been implemented using photo excitation with either 531 or 1062 nm light generated by pulsed (700 ps) laser. The 22 GHz cw MW probed PCD transients have been recorded by a digital oscilloscope TDS-5104. The bulk carrier decay processes are examined to separate recombination and trapping components when using 1062 nm excitation laser beams. An initial carrier domain of sharp profile has been induced either nearby the n^+ or p^+ electrode of diode by using 531 nm laser beam focused onto diode optical window or directed by fiber. These measurements have been carried out simultaneously with records of TCT signals varying bias voltage in the range of 1–600 V. Spectrum and density of excitation light have been manipulated by using spectral and neutral filters. Carrier lifetime has been determined from MW-PCD transients, while carrier drift time has been extracted from TCT transients at the same excitation and biasing conditions. The field distribution effective depths, dielectric relaxation time and capacitance parameters have been evaluated by using the CELIV method.

3. Experimental observations

Room temperature (RT) carrier decay transients, illustrated in Fig. 1a, are one-componential and vary in the nanoseconds timescale with effective lifetimes dependent on irradiation fluence. The carrier decay transients become two-componential in the range of low temperatures when an initial fast decay constituent represents recombination, while asymptotic one appears due to carrier capture processes. The last decay component varies with temperature non-monotonically (Fig. 1b), and its temperature peak is ascribed to di-vacancy associated capture of majority carriers. These observations imply competition of several centers those redistribute carrier decay flows. Recombination lifetime values at RT slightly depend on carrier injection level when excess carrier densities vary from about of 10^{11} to 10^{16} cm^{-3}, as shown in Fig. 2.

Dependence of recombination lifetime on injection level can be attributed to level filling effect. High injection level lifetime, which is independent of trap filling effects, can be assumed for lifetime values measured by TG technique at excess carrier densities $>10^{16}$ cm^{-3} for recombination centers with concentration $<10^{16}$ cm^{-3}. An increase of recombination lifetime (of about two times) with decrease of injection level (more than four orders of magnitude when comparing data of MWR and TG techniques) indicates qualitatively that concentration of electrically active centers is much less than 10^{16} cm^{-3}. However, the decrease of lifetime values with irradiation fluence from 80 to 8 ns in the investigated range of fluences from about of 10^{14} to 10^{15} p/cm^2, seems to be mainly determined by the increase of the density of recombination centers.

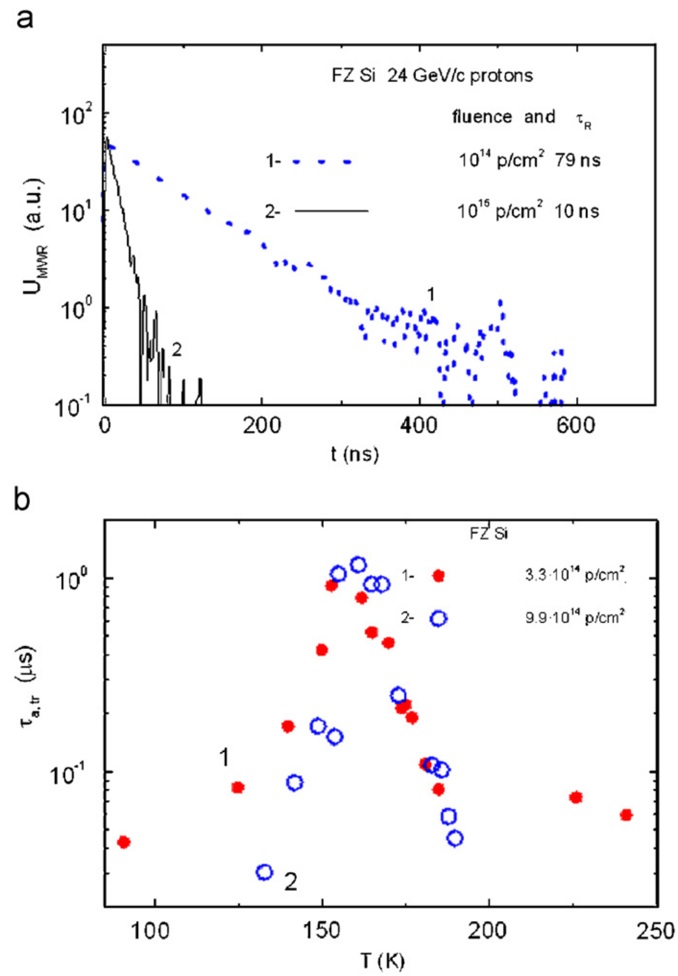

Fig. 1. (a) Carrier decay transient measured by MW-PCD in FZ Si diodes irradiated with 24 GeV/c protons of fluence 10^{14} cm^{-2} (1) and 10^{15} cm^{-2} (2). (b) Asymptotic (trapping) lifetime variation with temperature in FZ Si diodes irradiated with protons of fluence 3×10^{14} cm^{-2} (1) and 10^{15} cm^{-2} (2).

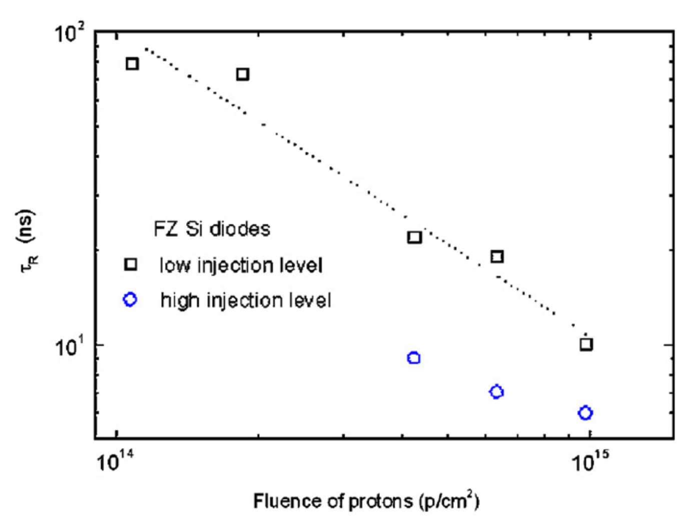

Fig. 2. Variation of the recombination lifetime with fluence of 24 GeV/c protons, measured at low (with excess carrier density of $<10^{12}$ cm^{-3}) and high (with excess carrier density $>10^{16}$ cm^{-3}) carrier injection levels.

The recombination decay timescale of 8–80 ns is much longer (Fig. 1a) than TCT signal timescale (2–3 ns) observed varying biasing and excitation density as illustrated in Figs. 3 and 4 for the 10^{14} and 6×10^{14} p/cm^2 irradiated diodes. However, the carrier transit time is in the sub-nanosecond scale when duration of the rise and drop-off slopes of the TCT signal are of about of 1 ns, with inherent time resolution of the experimental circuit. These transients have been obtained at small bulk excitation densities. The TCT transients hold their shape for relatively low bulk excitation densities (Fig. 3b). However, a long tail component appears in the current transients, measured at the highest excitation densities, which can be ascribed to a diffusion current component caused by carrier light-generated within bulk.

The TCT signal retains its shape, similar to that illustrated in Fig. 3a, when the sharp surface domain of excess carriers is injected by 531 nm (Fig. 4a) light pulse and varying its density (Fig. 4b) irrespective of either on n$^+$ or p$^+$ electrode side for all the irradiated diodes. The recombination decay time (Fig. 2) is again longer, by an order of magnitude, than carrier transit times observed

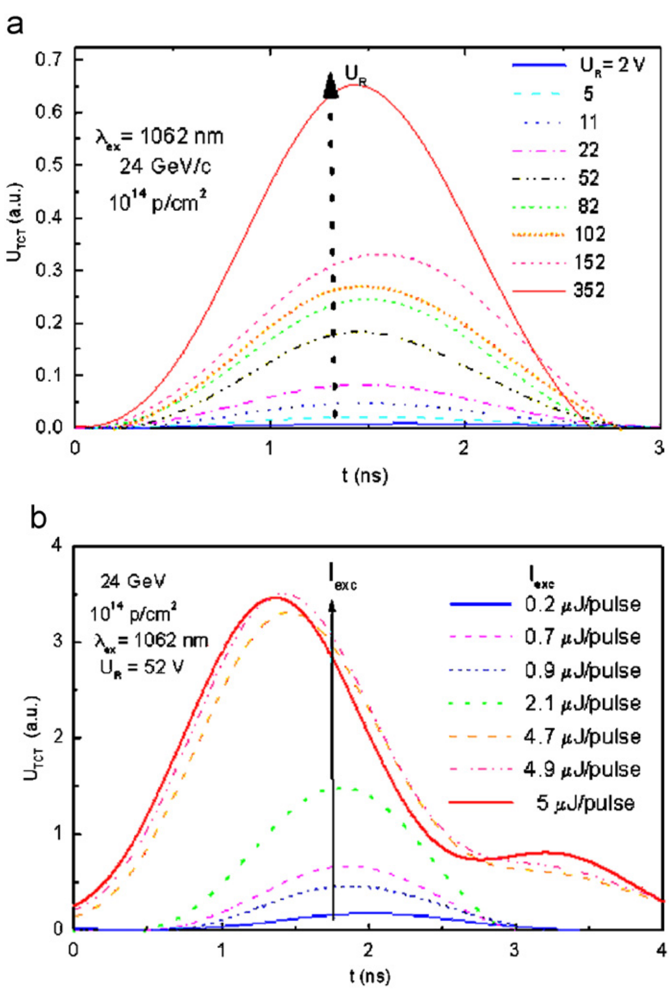

Fig. 3. Current transients measured in FZ Si diode irradiated with protons of fluence 10^{14} cm^{-2} varying bias voltage (a) and 1062 nm 700 ps pulsed excitation density (b).

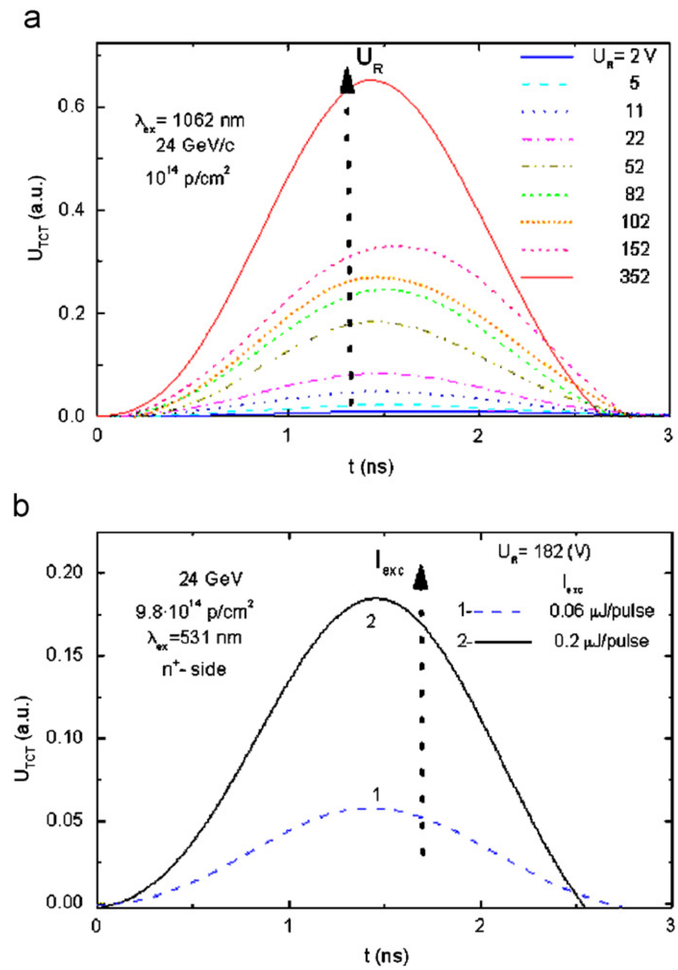

Fig. 4. Current transients measured in FZ Si diode irradiated with protons of fluence 6.4×10^{14} cm^{-2} varying bias voltage (a) and n$^+$ surface excitation density (b) at bias voltage 182 V.

Table 1
Parameters extracted by CELIV technique in diode irradiated with 10^{14} p/cm^2 fluence

U_p (V)	C_g (pF)	C_s (pF)	τ_σ (µs)	σ_{nc} (Ω^{-1} cm^{-1})	d_{tr}/d	τ_{tr} (ns)
2.4	13	240	0.50	10^{-8}	0.054	$\leqslant 1$
11.1	13	170	0.50	4×10^{-9}	0.076	<1
35.8	13	110	0.50		0.109	<1
212.0	13	60			0.22	<1

varying biasing (Fig. 4a) and excitation density (Fig. 4b) for diode irradiated with fluence 6.4×10^{14} cm^{-2}.

The typical parameters of geometrical (C_g) and structural (C_s) capacitance, of dielectric relaxation time (τ_σ) ascribed to the bulk conductivity, conductivity (σ_{nc}) ascribed to near-contact range, a ratio (d_{tr}/d) of the carrier transit length (d_{tr}) to geometrical thickness (d), and estimation of carrier transit time (τ_{tr}) determined by CELIV technique at different peak voltage (U_p) values of saw-shape pulse, are listed in Table 1. These values have been measured by varying saw-shape pulse duration and voltage.

4. Discussion

The recombination processes prevail at RT, as revealed from the analysis of MW-PCD transients, and a decrease of recombination lifetime with proton irradiation fluence is determined by enhancement of concentration of recombination centers (Figs. 1 and 2). Large capture cross-section of the order of magnitude of 10^{-12}–$10^{-14}\,\mathrm{cm}^2$ can be deduced from the absolute values of recombination lifetime, at defects concentration of the order of magnitude of about 10^{13}–$10^{15}\,\mathrm{cm}^{-3}$, as estimated for the investigated range of proton fluences [7,8]. This implies formation of the extended defects. Although, the di-vacancy associated point defects act as majority carrier capture centers that can be associated with inter–center recombination in the range of low temperatures.

The TCT transients can be attributed to the several levels when a layered structure is formed under radiation induced space charge inversion conditions [7,8]. The increase of capacitance of the biased diode structure with time, during the saw-shape pulse, and subsequent its saturation has been revealed in the timescale longer than dielectric relaxation time constant by CELIV technique. The effective carrier transit length increases with increase of pulsed bias voltage, while at low bias peak voltages a value of carrier transit length is nearly 20 times less than geometrical thickness of the diode and this d_{tr} remains four times less than d even in the range of high U_{p} voltages. Such a layered structure contains the increased bulk resistivity with intricate field distribution nearby contact area and within bulk dependent on applied voltage and caused by polarization effects. Variations of the extraction length d_{tr} and transit time as a function of the CELIV peak voltage are presented in Fig. 5. A slope of the increase of the extraction length is slower than that of applied voltage; therefore, the transit time decreases with enhancement of voltage. Carrier lifetime relatively to capture (τ_{C}) processes depends on trap (of concentration M_{tr}) filling ($M_{\mathrm{tr}}-m$) by density of trapped carriers m with inherent cross-section s_{tr} at carrier thermal velocity v_{th} as $\tau_{\mathrm{C}} = 1/s_{\mathrm{tr}}v_{\mathrm{th}}(M_{\mathrm{tr}}-m)$. This capture time (even in the initial capture phases, when $M_{\mathrm{tr}} \gg m$) should be longer than carrier transit time to have the observable TCT and CELIV transients. Hereby, an order of magnitude of the capture lifetime has been estimated as $\tau_{\mathrm{tr}} < \tau_{\mathrm{C}} < \tau_{\mathrm{R}}$ from our experiments, and it is in the range of $3\,\mathrm{ns} < \tau_{\mathrm{C}} \leqslant 8\,\mathrm{ns}$ for the samples irradiated with the highest fluence, as evaluated from the carrier transit time-scale and recombination lifetime.

In summary, a TCT signal is determined by relatively thin transit length with inherent transit times in the sub-nanosecond scale, as observed in our experiments (Figs. 3 and 4), for these proton-irradiated samples with fluence more than $10^{14}\,\mathrm{p/cm}^2$. The dielectric relaxation and recombination lifetimes are much longer than the carrier transit time τ_{tr}. Carrier transit time also indicates rather high carrier mobility; thus, a rather weak role is of carrier scattering centers, as it was corroborated by carrier diffusion measurements on the same samples [9].

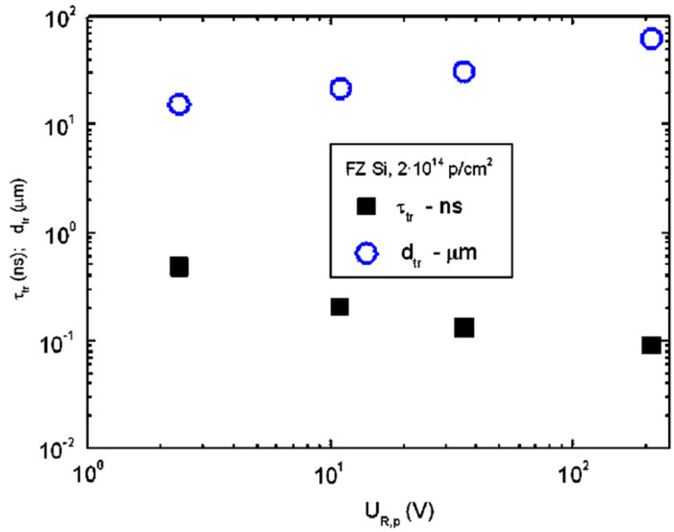

Fig. 5. Carrier extraction length and transit time as a function of bias voltage measured by CELIV technique in FZ Si diode irradiated with protons of fluence $10^{14}\,\mathrm{cm}^{-2}$.

Acknowledgment

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