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Fluence dependent carrier lifetime variations in Si detectors determined by photoconductivity and transient grating techniques

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Abstract

Fluence-dependent carrier lifetime variation in heavily proton-irradiated Si detectors has been investigated by the microwave probed photoconductivity (MW-PCD) and transient grating (TG) techniques. Nearly linear decrease of carrier recombination lifetime, from hundreds of ns to few ns, as a function of fluence has been found in Si detectors fabricated on FZ standard and oxygenated material, after irradiation by 24 GeV/c protons with fluence in the range from 10^{14} to $10^{15}\,\mathrm{cm}^{-2}$. Radiation-defect dependent features of carrier transport and recombination have been analyzed. Models of carrier recombination centers associated with the radiation defects are discussed.

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Keywords: Recombination lifetime; Microwave probed photoconductivity; Transient grating technique; Radiation defects; Silicon detectors

1. Introduction

Carrier lifetime is one of the most significant limiting factors for operational characteristics of the Si particle detectors after high fluence irradiation within harsh environment of LHC [1]. High concentrations of the radiation-induced carrier traps in detectors made of pure initial Si material also restrict applications of the most sensitive and elaborated characterization techniques, such as DLTS and TSC [2]. These techniques are applicable for evaluation of the deep level parameters those can be exploited for simulation of carrier capture process. However, these estimations are insufficient to determine carrier recombination lifetime. The TCT technique [3] is a powerful instrument to control directly variations of the carrier transport parameters including carrier capture rate. However, carrier recombination via radiation-induced defects can be only estimated by assuming the mono-exponential charge decay [4] and by artificially reconstructing an effective time constant [5]. This assumption is valid if a single deep level dominates the carrier decay process and deep level concentration is low, i.e. within Shockley–Read–Hall model (S–R–H) statistics. However, the assumption of low concentration of deep levels is often not valid in heavy irradiated semiconductor. Therefore, the direct methods for control of the carrier recombination and trapping are preferential when a role of several deep levels can be investigated in more detail [6]. Signal decrease in particle detectors, due to capture of carriers by the radiation induced defects, can be phenomenologically characterized by the trapping coefficient [7–9] or effective charge trapping (capture) lifetime [4] when a detailed separation of deep levels into the trapping and recombination centers is unimportant or impossible.

In this work, carrier recombination and diffusion parameters have been examined by contact-less techniques of the microwave probed photoconductivity (MW-PCD) transients [10] and the light induced diffraction on transient grating (TG) [11,12].

2. Samples and measurement techniques

Pad-detectors fabricated on n-type float zone (FZ) Si have been investigated. The optical window of about 2 mm

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diameter in the center of the diode and the boundary (of 1 mm width) of the detector area were left non-metallized. The non-metallized detector area has been exploited for the measurements by the contactless MW-PCD and TG techniques. Carrier recombination and transport characteristics have been measured for two sets of detectors made of standard (sFZ) and oxygenated via diffusion (DOFZ) material. Introduction of oxygen into the detector samples was performed by a high-temperature 24 h diffusion step. These detectors were irradiated by 24 GeV/c protons with fluences in the range from 10^{14} to 10^{15} cm^{-2}.

The microwave probed photoconductivity technique [10] is based on the direct measurements of the carrier decay transients by employing MW absorption by excess free carriers. Carriers are photoexcited using 1062 nm light generated by pulsed (500–700 ps) laser and probed by 22 GHz continuous wave (cw) microwave probe. The transient shape, constitution and relaxation rates of different constituents within the carrier decay process are examined to separate recombination and trapping components.

Transient grating [11,12] technique is based on the measurements of the light diffraction characteristics on the light-induced dynamic grating of the spatial modulation of the material refractive index. Modulation of the refractive index is determined by excess carrier density (Δn) generated by a short light pulse. Excess carrier density contains the sinusoidal profile generated by the interference pattern of two laser beams intersecting at sample surface. The grating spacing (Λ) can be varied by changing an intersection angle between these two laser beams. This grating is transient and ''lives'' while excess carrier profile exists. This profile is erased by the carrier recombination and lateral diffusion processes. The parameters of carrier generation, recombination and diffusion can be extracted by measurements of the diffraction efficiency (η), a ratio of the intensity of the first and zero order diffracted beams. Thus, diffraction efficiency on grating is a measure of the excess carrier density, $\eta_I \propto (\Delta n)^2$ [11,13]. Grating erase in time is measured by using a delayed probe (third) beam pulse relatively to those of grating generation. Variation in time of the probe beam diffraction efficiency $\eta_I(t) \propto \exp(-2t/\tau_{GR})$ allows direct estimating of the grating erase time τ_{GR}, as $1/\tau_{GR} = 1/\tau_R + 1/\tau_D$. A diffusive erase component $\tau_D = \Lambda^2/(4\pi^2 D)$ can be separately estimated by changing a grating spacing (Λ). Thus, parameters of the carrier recombination lifetime (τ_R) and coefficient of ambipolar carrier diffusion (D) (when density of excess carriers exceeds a concentration of equilibrium ones and of traps) can be extracted. In the experiments, transient grating is induced by interference field of the pulsed (30 ps) laser beams at 1064 nm wavelength. Delay of the probe light pulse (1064 nm, 30 ps) is varied with high precision by optical delay line, and diffraction efficiency ($\eta_I(t) \propto \Delta n^2(t)$) is measured with high accuracy, as illustrated in Fig. 1.

3. Experimental results

Variations of the MW-PCD transients measured at room temperature (RT) using low injection level pulsed excitation in sFZ Si detectors irradiated with different fluences of protons are illustrated in Fig. 2. RT MW-PCD transients commonly contain at least two components (curves 1, 2), and the characteristic lifetimes can be separated using a multi-exponential decay approximation. In the samples irradiated with highest fluence, transients are nearly mono-exponential (curves 3–5), when longer decay ''tails'' contain small amplitudes, due to domination of recombination processes. The trapping constituent appears more clearly,

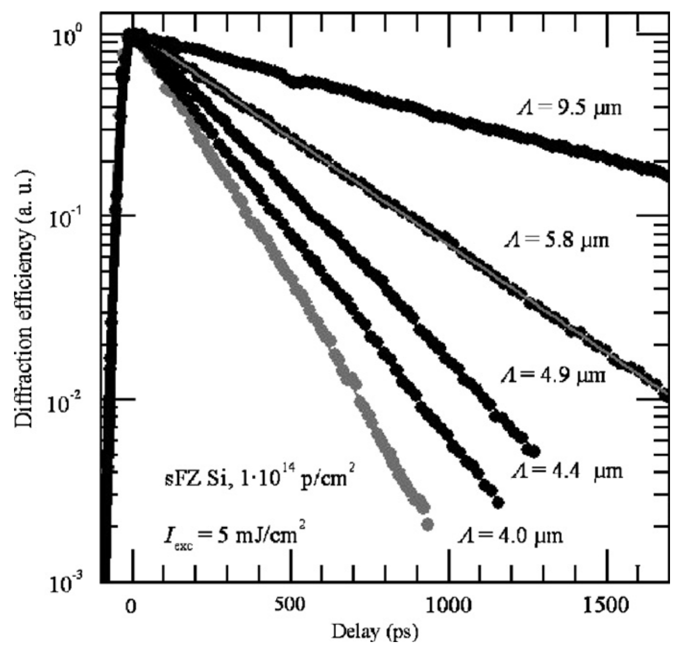

Fig. 1. Variation of diffraction efficiency transients with grating spacing Λ, measured in sFZ Si sample irradiated by protons of 1.06×10^{14} cm^{-2} fluence.

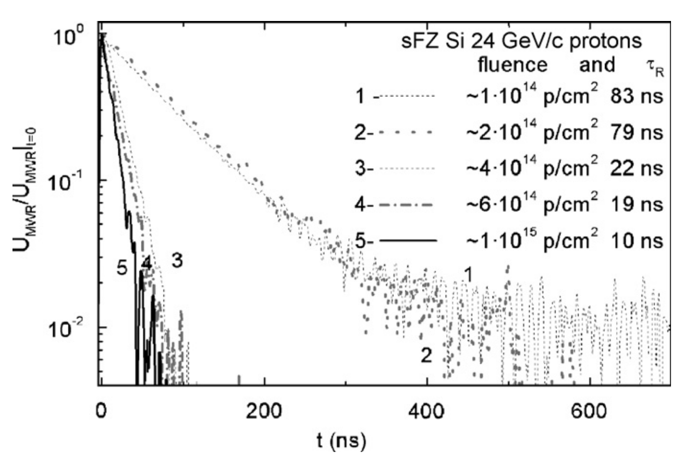

Fig. 2. MW-PCD transients measured at room temperature in sFZ Si detectors irradiated with different fluences of protons.

as an additional asymptotic component, within transient of excess carrier density relaxation at lower temperatures. Values of the effective trapping lifetimes vary in the range from a hundred nanoseconds to few microseconds. At RT, a decrease of the carrier decay lifetime with enhancement of irradiation fluence can be clearly deduced (Fig. 2). Values of recombination lifetime decrease from about a hundred to ten of nanoseconds.

The grating erase transients obtained for samples irradiated with different fluence (the same samples, as in Fig. 2) are shown in Fig. 3a, as measured at RT for a fixed maximal grating spacing. A grating erase time τ_{GR} is determined by exploiting mono-exponential decay approximation. The τ_{GR} values decrease from 27 to 6 ns with enhancement of fluence. Also, a decrease of peak values of diffraction efficiency (within single decay) with increase of irradiation fluence is observed (Fig. 3a). This implies existence of very fast processes of carrier capture with characteristic times (τ_C) shorter than the excitation pulse duration (i.e. $\tau_C < 30$ ps).

Values of the excess carrier lifetime and the coefficient of the ambipolar diffusion have been separated by using a linear dependence of the diffusive component of grating erase time τ_{GR} on square of grating spacing, as illustrated in Fig. 3b, for samples irradiated with different fluence. Values of carrier diffusion coefficient ranging from 12.5 ± 0.4 to $13.4 \pm 0.6\,\mathrm{cm^2/s}$ are extracted from the latter dependence, as denoted in Fig. 3b. The decrease of both parameters, the carrier recombination lifetime and the diffusion coefficient, is obtained with increase of irradiation fluence. An averaged value of $D \approx 13\,\mathrm{cm^2/s}$ shows rather high mobility of carriers.

4. Discussion

The instantaneous or effective lifetimes can only be evaluated in more complicated cases of carrier density relaxation [14–16], when analytical solutions of carrier density relaxation are obtained at simplified assumptions. Therefore, the combined experimental examination of carrier decay is necessary to separate and attribute different decay components and dominant mechanisms. The observed decay characteristics in our experiments can be only understood (under more comprehensive analysis) assuming contribution of both types of carriers (as dominance of the ambipolar diffusion within 2 ns of the initial decay has been clearly revealed by TG) and simultaneous action of several traps (as determined by more detailed analysis of MW-PCD and TG transients).

One of such mechanisms is simultaneous action of trapping and recombination centers. It is well known that an integral curve of carrier density relaxation for the simultaneous recombination–trapping process is non-exponential [7,17] in general, while it can be replaced by two-exponential decay at simplified assumptions [16–18]. Therefore, conventionally such a process is described by asymptotic instantaneous lifetime τ_i ($\tau_i = \tau_R K_{tr} \approx \tau_R (1+\tau_e/\tau_C)$) for multiple ("fast") trapping centers [7]. Generally, lifetime τ_C relatively to carrier capture into level $\tau_C = 1/v_{th}\sigma_{tr}(M_{tr}$-$m)$ depends on trap concentration M_{tr} and its filling (M_{tr}–m) by trapped carriers m. Emission lifetime $\tau_e = 1/v_{th}\sigma_{tr}N_{VM}$ depends on effective density of the band states N_V reduced by the trap activation (ΔE_{tr}) factor, $N_{VM} = N_V \exp(-\Delta E_{tr}/kT)$, with commonly used parameters of the carrier thermal velocity v_{th} and capture cross-section σ_{tr} at temperature T. Due to $\tau_e >> \tau_C$, value of the trapping coefficient can vary over several orders of magnitude raising long asymptotic decay component. Appearance of trapping constituent (in curves 1, 2 of

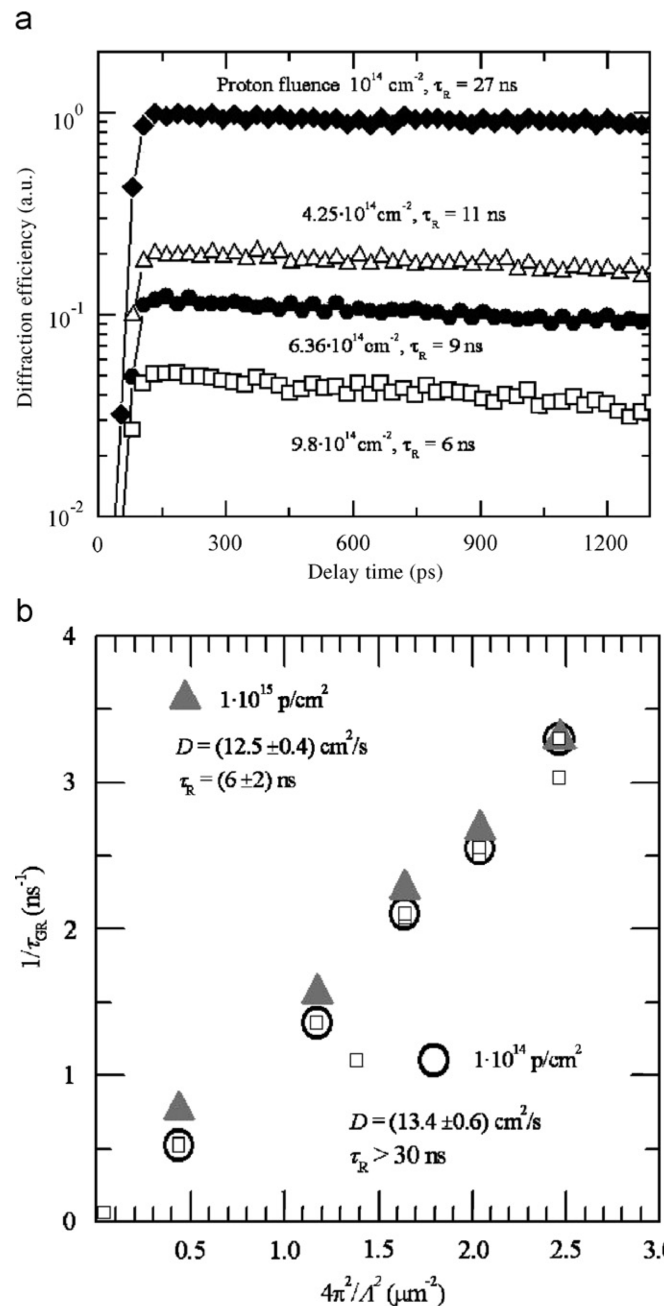

Fig. 3. Radiation fluence dependent variations of grating erase transients at fixed grating spacing Λ (a), and of the inverse TG erase time dependence on reciprocal grating spacing ($4\pi^2/\Lambda^2$) (b), measured in sFZ Si sample.

Fig. 2) depends on the instant excess carrier density Δn, and it dominates within decay asymptotic. Phenomenologically, this asymptotic component τ_i ($\Delta n \to 0$) at $K_{tr} > 1$ could be assumed as an effective trapping lifetime. Experimental verification of prevailing of this mechanism is performed by varying excitation density (Δn) or using bias illumination (BI) (to increase m and, thus, τ_C). A slight shortening of asymptotic lifetime with increase of excitation density and BI has been observed at RT in the investigated samples irradiated with the lowest fluences. A decay of excess carrier density contains constituents characterized by recombination lifetime and thermal emission lifetime, with prevailing τ_R component, in the case of "slow" (single) trapping centers [7,17], inherent for our heavily irradiated samples, when $\tau_R < \tau_C$. The effective trapping lifetimes are obtained to be of >100 ns. Ratio of τ_e/τ_C has been estimated to be in the range of 0.4–12 for the trapping centers by MW-PCD using small injection level.

The extracted (at RT) inverse recombination lifetime values by combining MW-PCD and TG techniques (Figs. 1, 2, 3b) are generalized in Fig. 4. The inverse lifetime, as an indicator of the concentration of the recombination centers, increases almost linearly with fluence both at low and high excitation levels ($\Delta n/n_{dop} \sim 0.1$–$10^4$), at doping concentration n_{dop}. A lifetime decrease with injection level has been obtained combining MW-PCD and TG measurements. Prevalence of recombination centers for irradiation fluences of $>4\times10^{14}$ p/cm^2 has been implied from the nearly mono-exponential decay. Also, resolution of both techniques is sufficient to separate recombination lifetimes of <20 ns reliably. As both the excess electron and hole are mostly free during this time interval, a simple estimate of trap parameters from the character [19] of the lifetime variation with excitation level can be performed by exploiting S–R–H model. Simulations of lifetime decrease with excitation level using the trap parameters specific for irradiated sFZ and DOFZ Si diodes [2] reveal that the dominant recombination centers

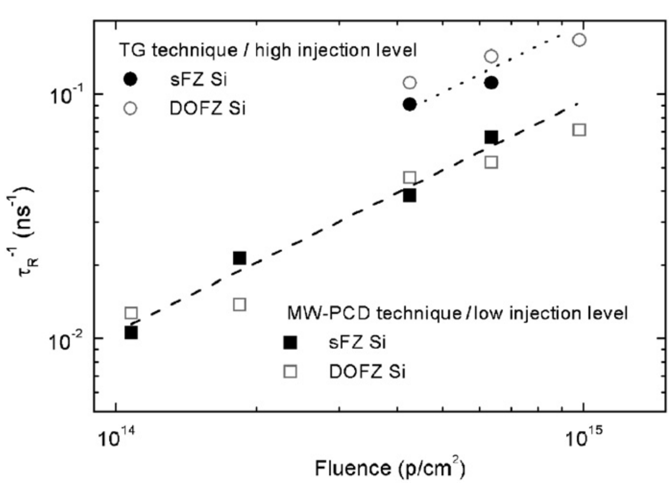

Fig. 4. Variation of the inverse recombination lifetime with fluence of 24 GeV/c protons extracted by MW-PCD and TG techniques for sFZ and DOFZ Si detectors.

(for $>4\times10^{14}$ p/cm^2 irradiated diodes) should be ascribed to di-vacancy defects. Ratio of capture cross-sections σ_n/σ_p, deduced from these simulations, is found to be of about 0.1, which is close to the published data [2]. However, comprehensive and combined consideration of MW-PCD and TG characteristics, which will be discussed elsewhere, indicates that electrons (n) and holes (p) decay with different rates, i.e. at $\Delta n/\Delta p \neq 1$, while $\tau_{Cp}/\tau_{Cn} < 0.1$, due to large concentration of recombination defects.

Large capture cross-sections ($>10^{-14}$ cm^2) are deduced from the short lifetime values obtained. A decrease of the carrier diffusion coefficient (ΔD) to the extent of $\Delta D/D \approx 20\%$ (relatively to an absolute its value D) has been extracted from the grating erase time dependence on grating spacing. This fluence dependent decrease of carrier mobility ($\sim D$), the large values of carrier capture cross-sections extracted from recombination lifetime (MW-PCD and TG) and existence of very short (<30 ps) capture lifetimes (as deduced from the η decrease with fluence enhancement in TG experiments) imply probability of formation of the extended defects in the range of the largest fluence.

In summary, application of the combined contactless techniques of MW-PCD and TG enable us to reveal additional peculiarities of the recombination processes in proton heavy irradiated FZ Si detectors. Effective carrier recombination lifetime has been found to be in the nanoseconds scale for irradiation fluences ranging from 10^{14} to 10^{15} p/cm^2 at RT.

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