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Spectroscopy of neutron irradiation induced deep levels in silicon by microwave probed photoconductivity transients

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ABSTRACT

A contactless technique for simultaneous measurements of the carrier lifetime and the parameters of deep levels has been applied. This method is based on microwave probed pulsed photoconductivity (MW-PC) spectroscopy in the wavelength range between 0.5 and 4 μm. Several deep levels in the range of 0.2–0.6 eV have been resolved from spectral analysis of microwave probed photoconductivity amplitude variations in the samples of Si grown by magnetic field applied Czochralski (MCz) technology. An amplitude of the revealed MW-PC spectral steps showed an increase with neutron irradiation fluence indicating an enhancement of density of the specific defects. Simultaneous variations of recombination lifetime with fluence of the reactor neutrons from 10^{12} to 3×10^{16} n/cm^2 in the MCz Si samples have been examined. Recombination features of the irradiated and annealed MCz Si structures are discussed by comparing carrier recombination parameters and deep-level MW-PC spectral data with characteristics measured by deep-level-transient spectroscopy (DLTS) in the range of moderate irradiation fluences.

1. Introduction

Spectroscopy of radiation-induced deep levels by using standard methods such as deep-level transient spectroscopy (DLTS) [1,2] is limited to rather moderate irradiation fluences. These spectroscopy techniques do not provide information on the role of these levels within carrier recombination which is the most important issue in the analysis of radiation tolerance of Si particle detectors. Photon–electron coupling and carrier capture cross-sections ascribed to deep levels within the material is one of the main signatures of a defect and its charge state [3]. These parameters are routinely extracted from the registered thermal emission rates when using contact/junction methods such as TSC [4] and DLTS [1–3,5] with various modifications of measurement regimes by the control of a capacitance, dark-current and optical-DLTS. Also, uncertainty occurs due to the product of cross-section and filling of levels when using spectral measurements of absorption coefficient.

In this article, a contactless technique for simultaneous measurements of the carrier lifetime and the parameters of deep levels have been developed. This method is based on microwave probed pulsed photoconductivity (MW-PC) spectroscopy in the excitation wavelengths range between 0.5 and 4 μm.

2. Experimental technique and samples

Several light sources have been combined to implement a pulsed low-level excitation of the photoresponse probed by microwaves (MW). The peak amplitudes and carrier decay transients have been synchronously probed by microwaves at 22 GHz, by using a slit MW antenna together with adjusted MW bridge circuit, and recorded by a 1 GHz digital oscilloscope TDS-5104. Short pulses of 40 fs have been employed, to eliminate a decrease of the photoresponse due to recombination in the spectral range from 1 to 4 μm, by using an optical parametric oscillator (OPO) coupled with differential frequency generators (DFG) pumped by the Spectra Physics Ti-sapphire fs laser at 800 nm wavelength. Calibration measurements were carried out by recording the excitation light energy spectral data and by normalizing the number of photons to the maximal quanta employed. Light transmission measurements were additionally performed to evaluate the absolute values of the absorption coefficient in the spectral range of the sample transparency.

The magnetic field applied Czochralski (MCz) grown Si wafer samples irradiated by the reactor neutrons with fluences from 10^{12} to 3×10^{16} n/cm^2 have been examined. Wafer surfaces were passivated with thermal oxide.

3. Observations of the photo-ionization spectra

The photoconductivity amplitude normalized to a fixed density Φ of photons of energy $h\nu$ is proportional to photo-ionization

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intensity. The transient photo-response signal $U_{MW\text{-}PC}$ probed by microwaves is proportional to the density n_{ex} of excess carriers and satisfies $U_{MW\text{-}PC}(t) = n_p\ exp(-t/\tau_R)$. The initial (time $t = 0$) photoresponse amplitude $U_{MW\text{-}PC}(0) = n_P$ is related to a peak density n_p of the excess carriers. For an excitation pulse with duration τ_L significantly shorter than the recombination lifetime τ_R, the amplitude $U_{MW\text{-}PC}(0)$ is a direct measure of the intensity of the photo-ionization of deep levels below the Fermi energy. Spectral variations of the $U_{MW\text{-}PC}(0)$ are also related to the absorption coefficient through $\alpha(h\nu) = n_p/\Phi$ at a constant Φ, and also with cross-section σ of the photon–electron coupling associated with a deep level. The spectral function $\sigma_i(h\nu) = AE_i^{1/2}(h\nu - E_i)^{3/2}/h\nu^3$ of the cross-section σ_i is given by the model of Lucovsky [6] with A as a multiplicative factor for a deep level with activation energy E_i. During the measurement of spectral variations of $U_{MW\text{-}PC}$, Φ is kept constant over the entire spectral range. On the other hand, the absorption coefficient is linked with concentration N_i of filled deep level by relation $\alpha(h\nu) = \sigma_i(h\nu)N_i$ and through $U_{MW\text{-}PC}(0) = \sigma_i(h\nu)N_i\Phi$. The excess carrier density generated due to photo-ionization is $n_{pi} = N_iF \cong N_i$ for fixed $\sigma_i(h\nu)\Phi$ if most of the i-type deep centres are ionized. The extraction of E_i is thus possible for constant N_i and Φ even if the density N_i of deep levels is unknown. Each step in the $U_{MW\text{-}PC}$ spectrum, which is identified by a measured change of $U_{MW\text{-}PC}$, is simulated by fitting both the shape and the amplitude of the $\sigma_i(h\nu)$ step.

A spectrum measured for the as-irradiated sample is illustrated in Fig. 1. It contains three inherent segments, namely, the range of intrinsic absorption, of absorption edge and of bulk absorption due to deep levels. The third segment in the photoconductivity spectrum occurs for photon energies below 0.8 eV (Fig. 1). This segment contains a step-like structure of the photoconductivity amplitude, and its absolute value for each step increases with irradiation fluence as can be noticed in the inset of Fig. 1.

4. Discussion

A simulated MW-PC spectrum for the as-irradiated sample is presented in Fig. 2. The results of simulations of the spectral steps performed using the Lucovsky' model are shown by curves in Fig. 2 which are fitted to experimental data (symbols).

Three to four deep levels have been extracted for all investigated samples. For neutron as-irradiated Si samples, the

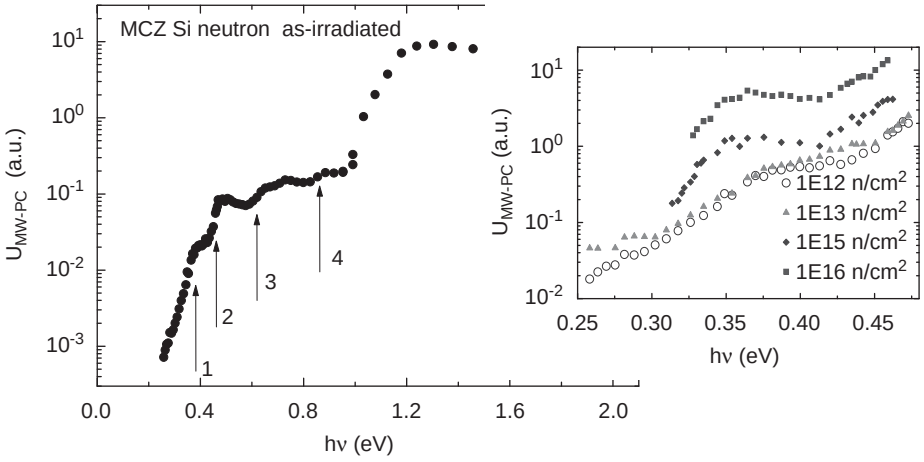

Fig. 1. Variations of the photoconductivity amplitude for surface and bulk excitations. In the inset are fluence-dependent variations of photoconductivity spectral steps in the range of bulk excitations.

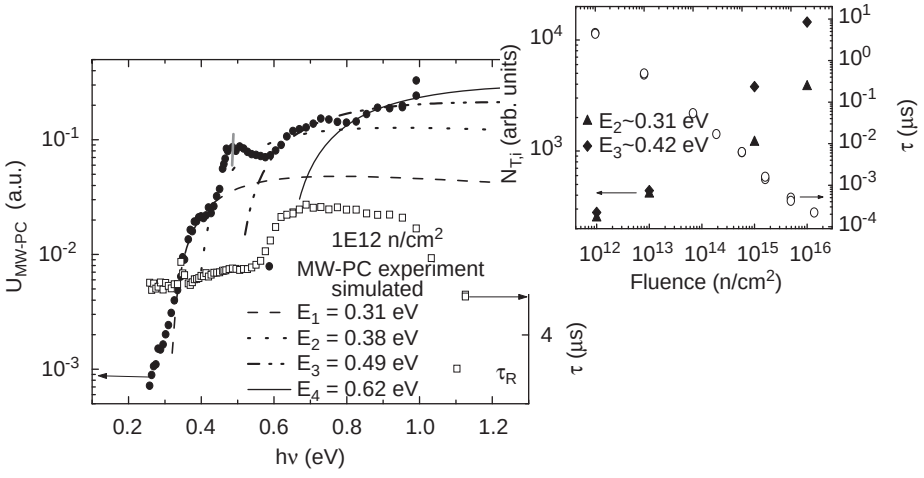

Fig. 2. Variation of recombination lifetime with spectral steps in the as-irradiated sample (symbols). Spectral steps simulated by using Lucovsky' model are shown by lines. In the inset: relative values of the MW-PC peaks fitted to different deep levels as a function of neutron irradiation fluence (left axis, solid symbols) and variation of recombination lifetime with irradiation fluence (right axis, open symbols).

deep levels with activation energies 0.31 ± 0.01 (s1), 0.40 ± 0.02 (s2), 0.51 ± 0.02 (s3) and 0.61 ± 0.02 eV (s4) are resolved using the described simulation procedures. The values obtained for levels 1–4, denoted in Fig. 1, are in good agreement with those extracted by DLTS and TSC, i.e. E_C−0.32, E_C−0.42, E_C−0.55 and E_V+(0.55−0.66) eV [7],—i.e. (s1) E_C−0.32 eV (VOH complex, cluster), (s2) E_C−0.42 eV (di-vacancy), (s3) E_C−0.55 eV (I-center, V_2O complex) and (s4) E_V+(0.55–0.66) eV (I-center, cluster), respectively. Relative values of the MW-PC spectra peaks fitted to several deep levels of nearly the same activation energy as a function of neutron irradiation fluence are shown in the inset of Fig. 2. These values represent a relative density $N_{T,i}$ of various radiation defects.

Recombination lifetime for spectrally resolved excitation with different energy photons slightly varies, (as shown in Fig. 2) and it increases for the step ascribed to a deep level with activation energy E_C−0.50 eV.

It can be deduced from the inset of Fig. 2 that introduction rate for different defects increases non-linearly with enhancement in neutron irradiation fluence. This hints on transformation of multi-vacancy related defects in larger agglomerates with enhancement of the neutron irradiation fluence. The recombination lifetime, evaluated from transients, measured at fixed 1062 nm excitation wavelength and characterized by a single-exponential decay in the as-irradiated material, is determined by the dominant centre. This recombination lifetime decreases linearly with enhancement of neutrons irradiation fluence (inset of Fig. 2). However, recombination lifetimes for spectrally resolved excitation with different energy photons slightly vary as shown in Fig. 2.

Heat treatments, made after irradiations and measurements on the as-irradiated material, induce variations of the concentration of deep levels, when density of these levels also depends on irradiation fluence. The density of the deepest levels decreases under annealing for samples irradiated with a fluence of 10^{12} n/cm^2 while an opposite change is obtained for the sample irradiated with a fluence of 10^{16} n/cm^2. The excess carrier density relaxation becomes non-exponential of two components with increase in temperature of isochronal anneals. The changes of the effective lifetimes of the initial and asymptotic decays appear to be different for various irradiation fluences. This implies the complicated transformations of radiation defects under heat treatments. Two components within carrier decay transients are caused by a competition of recombination and trapping centres, induced by annealing in redistribution of excess carrier capture flows. Qualitatively it can be understood when cluster defects dominate.

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