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Deep defect level spectra in the neutron irradiated Si ionizing radiation detectors

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In the framework of WODEAN project of CERN-RD50 collaboration the photoconductivity spectra of p^+-n-n^+ Si detectors were investigated depending on irradiation by high energy neutrons. The samples were irradiated by neutrons to the fluencies 1×10^{13} –1×10^{16} cm^2. The extrinsic photoconductivity spectra indicated that upon irradiation deep levels (DL) below the middle of the band gap were created. Their activation energies were in the ranges of 0.49-0.52 eV, 0.77-0.81 eV, 0.88-0.91 eV, and 1.02-1.11 eV. The effective concentrations of these levels were depending on the fluencies and on the isochronal thermal treatments at low temperatures. The changes of DL population induced by annealing have been compared with the steady state lifetimes and photoconductivity decay constants.

1 Introduction High resistivity silicon single crystals or epitaxial layers are promising for the high energy physics applications. Because of their unique properties, at the moment it is impossible to replace them by any other material for the upgrade of detectors in super-LHC [1]. Investigations of many other modern materials that seemingly should demonstrate better radiation hardness (including diamond, SiC, and GaN) proved that these materials appear behind Si by their properties. Nevertheless functionality of silicon detectors is also strongly dependent both on irradiation and on the low temperature annealing [2].

Many investigations demonstrated influence of different defects and clusters on the material properties but the situation is still not understood well. An in-depth analysis of the deep level parameters and their transformations during different treatments is necessary in order to understand which levels are responsible for the space charge built-up in the ionizing radiation detector structures, and what is the role of the defect clusters in trapping and recombination of non-equilibrium carriers [3, 4]. In many methods effects related to the thermal activation of deep levels are employed; therefore defects located in the upper and lower halves of the energy gap were analyzed by different methods or regimes of investigation. High densities of the radiation-induced carrier traps also restrict applications of the most sensitive characterization techniques for evaluation of the deep level parameters, e.g., DLTS.

It is well known that photoconductivity is a powerful tool for the investigation of the deep levels in semiconductors [5, 6]. In the present work the photoconductivity spectral dependencies are used to analyse the deep levels as they are influenced by irradiation and thermal treatment in highly irradiated p^+-n-n^+ Si detectors.

2 Samples and methods The p^+-n-n^+ diodes fabricated on magnetic Czochralski silicon (MCZ) were investigated. The samples were irradiated in Ljubljana University TRIGA reactor by the reactor neutrons with fluencies in the range from 10^{13} to 1×10^{16} n/cm^2. The isochronal annealings for 15 h were performed at different temperatures from 80 ^{0}C up to 180 ^{0}C. The I-V characteristics were measured both at room temperature and at 18 K. The photoconductivity spectra were measured at 18 K at 50 V reverse bias. At this bias the full depletion of the samples irradiated by low fluencies was reached, as it was demonstrated both by I-V and by C-V measurements. Therefore the photoconductivity in the weakly irradiated samples was caused by the extracted non-equilibrium carriers. Meanwhile the I-V characteristics of the highly irradiated samples were almost linear, indicating that photoconductivity of such samples was determined by the free carrier lifetime. These two regimes of photoconductivity in differently irradiated samples have to be kept in mind. The spectral scans were performed first by increasing photon energy and afterwards by reducing it. Differences of these spectra indicated appearance of the persistent current induced by excited non-equilibrium carriers. The decay of the persistent current could be characterized by instantaneous time constants of few hundreds of seconds.

The photoconductivity spectra were analyzed by Lucovsky deep centre model with δ-potential [8]. According to this model the photocurrent is given by:

$$I \sim n_M \Delta E_M^{0.5} (h\nu - \Delta E_M)^{1.5} / (h\nu)^3 , \qquad (1)$$

here ΔE_M is the optical activation energy of the deep centre, $h\nu$ is the photon energy, n_M is the initial trap filling.

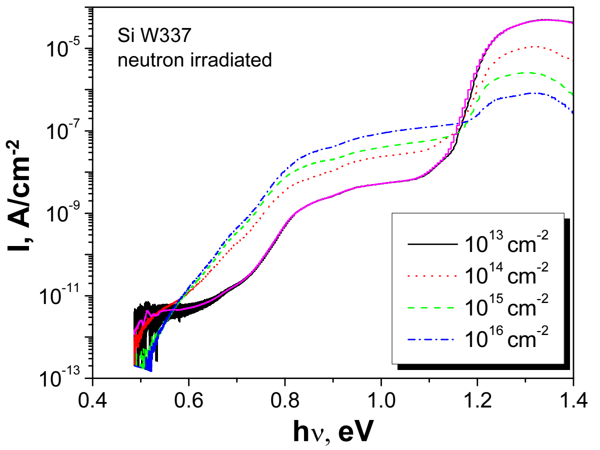


Figure 1 Photoconductivity spectra in irradiated samples, as indicated in the inset.

3 Results Measurements of the spectral dependencies of photoconductivity enable determination both of the optical activation energies of the deep levels and their relative concentrations. As mentioned above, the persistent current was observed below 125 K, by scanning spectra first from lower photon energies and then backwards. It could be induced by the pre-excitation of the samples by the photons with energy exceeding 0.8 eV. The decay time constant of the persistent current at 18 K was several hundred seconds. To avoid its influence the spectra were usually scanned by increasing photon energy.

The photocurrent spectra in the irradiated samples are presented in Fig. 1. The drop of the intrinsic photocurrent above ~ 1.2 eV at high irradiation fluencies is caused by the decrease of the free carrier lifetime. Meanwhile the defect-related extrinsic photoconductivity grows in the region 0.58-1.1 eV, and starts to decrease below 0.55 eV. The decrease of the steady state lifetime observed at the photoconductivity maximum is most probably given by the growing recombination via the radiation induced defects. This follows from Fig. 2 in which growing impurity photoconductivity below band gap at 1.05 eV shows the same trend as the reciprocal value of the intrinsic conductivity at lower fluencies. Deviation from the coincidence of these dependences at higher fluencies can appear due to the two-step excitation of electron-hole pairs, the rate of which (i.e., the absolute value of extrinsic photoconductivity) might be reduced because of the decreasing lifetime.

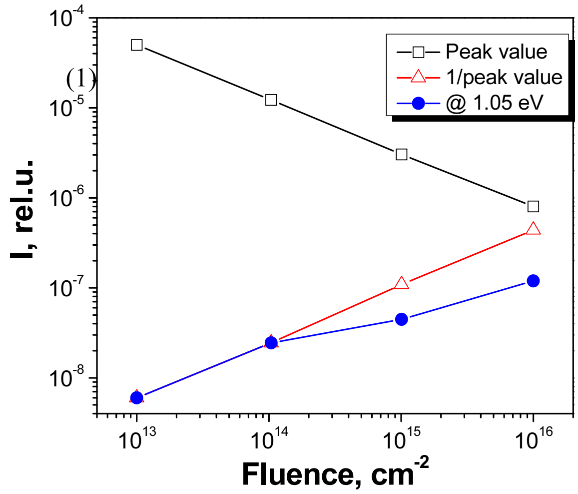
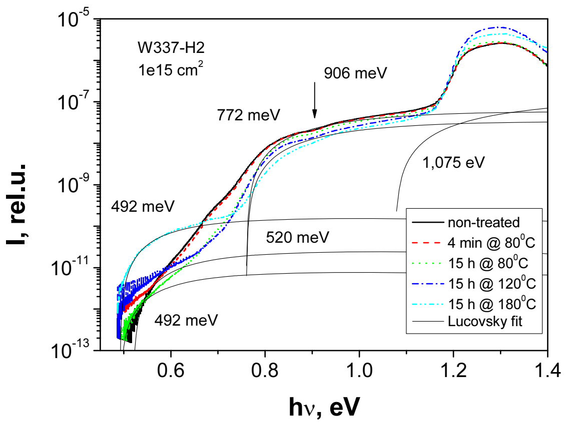


Figure 2 Dependence of the photoconductivity peak value and of the main impurity band at 1.05 eV on the neutron fluence.

Low temperature annealing changes deep level spectra, i.e., their relative contribution. Figure 3a shows the photoconductivity spectra in the sample irradiated by 10^{15} cm^{-2} neutrons. In Fig. 3b the extrinsic regions of these spectra are shown in linear scaling to demonstrate changes of the main deep levels during the isochronal annealing.

4 Discussion Comparison of the dependence of the steady state lifetime and of the photoconductivity decay time constant [9] shows their different dependencies on the fluence. The steady state lifetime depends on irradiation as a square root of fluence (Fig. 2), meanwhile photoconductivity decay constant shows linear dependence [9]. This is because increase of the defect number by irradiation enhances carriers trapping, slowing down their recombination, which therefore do not influence the main part of decay constant.

The optical activation energy values obtained from the photoconductivity spectra can be related with the excitation of free electrons from the filled deep centres or generation of free holes by excitation of electrons from the valence band to the empty levels. The observed most shallow level at 0.5 eV describes defect states near the Fermi level.



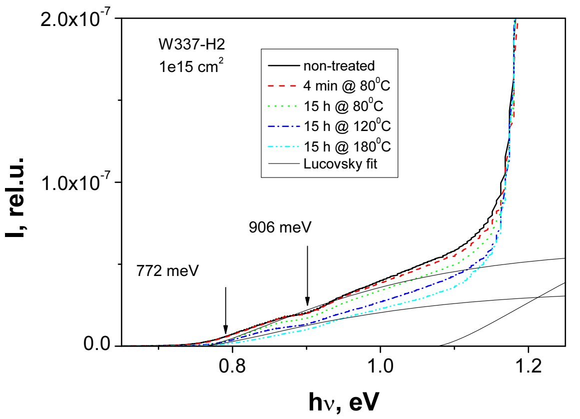


Figure 3 Photoconductivity spectra in the neutron irradiated Si at fluence 10^{15} cm^2 after isochronal annealing. The thin lines represent fitting of the experimental data by the Lucovsky model, the deep level energies are given on the Figure. a) full spectra, b) a part of it in linear scaling.

During irradiation and annealing two groups of near-continuous distribution of levels were observed: levels in the regions of optical activation energy of 0.49-0.52 eV and 0.77-0.91 eV below the conduction band. These levels probably are related to the defects in the vicinity of clusters, as it is implied by the big scatter of their activation energy values. The variation of their activation energies is related to the defect potential barrier. Such conclusion coincides with the results of the vacancy cluster simulation during the neutron irradiation [9]. The best expressed deep levels appear at 0.77-0.81 eV, the levels at 0.88-0.91 eV are also clearly distinguishable.

The deepest levels with optical activation energy at 1.02-1.11 eV are located close to the valence band. As their activation energy varies from 50 to 150 meV, probably they are related to the disordered regions around the clusters. Upon annealing of the irradiated samples their defect densities usually changed, some levels could appear and/or be quenched. Characteristically these changes were non-monotonous, reflecting most probably statistical processes involving different defect complexes. These results do not coincide with the observed changes in DLTS and TSC measurements where different defect concentrations used to change gradually. Most probably this is caused by the different active spatial regions scanned in DLTS, TSC and photoconductivity measurements.

The Frank-Condon shift for several deep levels in Si was evaluated in [6], and the obtained value is 40-50 meV. This enables comparison of the deep level parameters evaluated from thermally activated experiments [8] and that obtained in our work using optical excitation. The conclusion might be drawn that the levels related to the clusters at E_V +330 meV and at E_V +360 meV belong to the main local level group responsible for the extrinsic photoconductivity. The centres E_V +420 meV and E_C -545 meV belong to the discussed group of levels at 0.52-0.57 eV.

5 Conclusions The spectral dependencies of photoconductivity represent a sensitive method to analyze the deep levels in the neutron irradiated silicon. The neutron irradiation induced a set of deep levels, which was dependent both on the irradiation fluence and the low temperature treatment.

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References

[1] M. Moll, Nucl. Instrum. Methods A **565**, 202 (2006).
[2] J. H. Bleka, L. Murin, E. V. Monakhov, B. S. Avset, and B. G. Svensson, Appl. Phys. Lett. **92**, 132102 (2008).
[3] E. Fretwurst, F. Honniger, G. Kramberger, G. Lindstrom, and I. Pintilie, R. Roder, Nucl. Instrum. Methods A **583**, 58 (2007).
[4] L. I. Murin, J. L. Lindstrom, G. Davies, and V. P. Markevic, Nucl. Instrum. Methods B **253**, 210 (2006).
[5] S.T.Pantelides, Deep Centers in Semiconductors (Gordon and Breach, New York, 1986).
[6] R. Passler, H. Pettersson, H. G. Grimmeiss, and K. Schmal, Phys. Rev. B **55**, 4312 (1997).
[7] G. Lucovsky, Solid State Commun. **3**, 299 (1965).
[8] I. Pintilie, E. Fretwurst, A. Junkes, and G. Lindström, Proc. NSS, 2008, Dresden (to be published in TNS).
[9] M. Huhtinen, Nucl. Instrum. Methods A **491**, 194 (2002).
[10] E. Gaubas, T. Čeponis, A. Uleckas, and J. Vaitkus. Proc. RESDDM 2008, Florence. Nucl. Instrum. Methods A (to be published).