

OPTICALLY INDUCED CURRENT DEEP LEVEL SPECTROSCOPY OF RADIATION DEFECTS IN NEUTRON IRRADIATED Si PAD DETECTORS

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Identification of the prevailing radiation defects of large density remains a considerable issue for particle detectors made of high resistivity Si. To clarify the dominant radiation induced traps within CERN standard Si pad detectors, the capacitance (C-) and current (I-) deep level transient spectroscopy (DLTS) techniques have been combined. Additionally, the optical (O-) injection I-DLTS regime has been employed to cover a wide range of neutron irradiation fluences of 10^{12} – 10^{16} cm⁻². The spectra of C-DLTS and O-I-DLTS have been recorded using the temperature scans in the range of 20–300 K. The radiation induced vacancy (V) attributed defects such as V-O, V₂, and clusters have been identified, the density of which increases with irradiation fluence in the range of 10^{12} – 10^{14} cm⁻², while this density saturates for the collected neutron fluence of more than 10^{14} cm⁻².

Keywords: C-DLTS, I-DLTS, O-I-DLTS, Si particle detectors, neutron irradiation

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1. Introduction

Si based particle detectors are commonly made of high purity and large resistivity material [1]. These detectors should be radiation tolerant up to an extremely large fluence of 10^{16} cm⁻². However, the effective doping density N_{eff} of the material varies during detector operation due to charged radiation defects inevitably introduced. As a result, the charge collection efficiency, being the most important characteristic of detector functionality, is reduced [2].

To predict changes of detector parameters, it is necessary to control the spectra of the introduced radiation defects. The standard and widely used spectroscopy technique is the capacitance deep level transient spectroscopy (C-DLTS) which is a sufficiently sensitive and straight spectroscopy technique for characterization of deep radiation traps [3]. However, the standard application of C-DLTS is limited by the trap concentration, which should not be larger than the doping density [4]. The measurement of generation current (I-DLTS) is an option of the DLTS tech-

nique, which can be approved for the spectroscopy of high density carrier traps in silicon detectors made of large resistivity material [5]. An electrical filling of deep traps by manipulating the carrier injection pulses exploited in standard DLTS techniques can be inefficient for the radiation affected junction of the detectors. Therefore, an additional modification of DLT spectroscopy is implemented by using an optical carrier injection leading to the optical current DLTS (O-I-DLTS) regime [4]. Optical excitation employing the laser or LED light illumination fills both types of the majority and minority carrier traps. However, it is impossible to distinguish the current components ascribed to the majority and minority carrier traps within the generation current transients. This is a disadvantage for usage of O-I-DLTS [6].

In this study, C-DLTS and O-I-DLTS techniques have been combined to identify the prevailing radiation traps and to cover a wide range of the trap and effective doping densities. A set of reactor neutron irradiated Si detectors covering the fluence range from 10^{12} to 10^{16} n/cm² was examined. The radiation

induced vacancy attributed defects such as V-O, V_2 , and clusters have been identified, the density of which increases with irradiation fluence in the range of 10^{12} to 10^{14} cm^{-2} , while this density saturates for the collected neutron fluence of more than 10^{14} cm^{-2} .

2. Samples and measurement regimes

The standard CERN pad detectors made of the n -type magnetic Czochralski (MCZ) Si were examined. A window of about 2 mm in diameter in the centre of the detector metallic electrode is left non-metalized [7, 8] for optical excitation. A set of the same detectors was irradiated by reactor neutrons varying fluence from 10^{12} to 10^{16} cm^{-2} .

The different regimes of DLT spectroscopy have been implemented using a HERA-DLTS System 1030 spectrometer. The temperature scans are performed in the range of 20–300 K using a closed-cycle He cryostat. The temperature sensors are connected to a *LakeShore* temperature control device. The barrier capacitance transients are directly recorded by using a *Boonton* capacitance meter when implementing the C-DLTS mode. This capacitance meter is connected to the basic unit of the spectrometer. The basic unit is equipped with a voltage source, a low pass filter, an amplifier, and a current meter. A reverse bias is commonly set at 10 V, and the electrical injection pulse of voltage of 0.5 V and duration of 0.1 s is as usual kept. The I-DLTS mode is implemented by using a current meter installed within the basic module of the spectrometer. The O-I-DLTS regime has been implemented by using optical 20 ms injection pulses generated by an yttrium aluminium garnet neodymium (Nd:YAG) laser at 1064 nm wavelength. All the measurement and data processing procedures are controlled by a personal computer equipped with *PhysTech* software.

3. Deep level spectra

The C-DLTS temperature scan spectra have been examined on a Si particle detector irradiated with a neutron fluence of 10^{12} cm^{-2} to separate traps of majority and minority carriers. The recorded spectrum is illustrated in Fig. 1.

For diodes irradiated with the larger neutron fluence it is impossible to record a spectral structure using C-DLTS due to the introduced trap density which exceeds that of doping. A weak nearly invariable signal

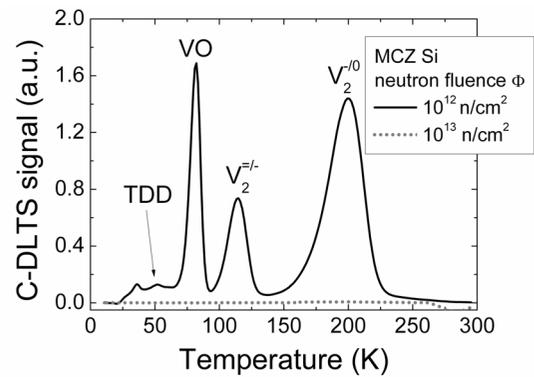


Fig. 1. C-DLTS spectra of the detector irradiated with a neutron fluence of 10^{12} n/cm^2 compared with the C-DLTS signal for the detector irradiated with a fluence of 10^{13} n/cm^2 .

of barrier capacitance can only be detected for a diode irradiated with a neutron fluence of 10^{13} cm^{-2} as illustrated in Fig. 1. This happens due to a decrease of barrier capacitance and synchronous increase of leakage current. Then, it is impossible to govern the irradiated junction structure by a small harmonic test signal due to the enhanced generation/leakage current, which yields an inappropriate reduction of the quality factor in a *Boonton* capacitance meter.

Thereby, the C-DLTS analysis of radiation defects was only possible for the diodes irradiated with a neutron fluence of 10^{12} cm^{-2} . The Arrhenius plots are commonly employed to extract the capture cross-section σ , activation energy E_A , and trap density parameters for the definite defect responsible for the appeared peak in the C-DLTS temperature scan spectrum. Each radiation trap has been identified by comparing the DLTS signatures (T_{peak} , σ , E_A) extracted from the Arrhenius plots with the defect signature library data integrated within the *PhysTech* interface of a HERA-DLTS System 1030 spectrometer. The dominant majority carrier traps (denoted in Fig. 1) have been identified as follows: the C-DLTS peak at about 50 K is attributed to the dual thermal donor (TDD), the peak at 95 K is ascribed to the oxygen-vacancy complex (V-O), and the peaks at 120 and 210 K are associated with the double-charged ($V_2^{=}$) and single-charged ($V_2^{-/0}$) divacancy, respectively. The minority carrier traps are mainly associated with the formation of a complex of interstitial impurities of C_i and O_i .

The O-I-DLTS spectra recorded on the diodes irradiated with neutron fluences in the range of 10^{13} – 10^{16} cm^{-2} are shown in Fig. 2. In these spectra, the traps identified by the C-DLTS technique (Fig. 1),

namely TDD, V-O, and V_2 , are resolved. Additionally, the O-I-DLTS peaks at 170 K and at >300 K appear for the diodes irradiated with a neutron fluence $\geq 10^{15}$ cm^{-2} . The appearance of additional deep traps (denoted as E_4 and E_6 in Fig. 2) is in agreement with results obtained by alternative spectroscopy techniques applied on the same irradiated diodes using temperature scans of generation current and instantaneous carrier trapping lifetime [7]. The trivial interpretation of the E_4 peak using the *PhysTech* library would lead to its attribution to the C_i-O_i complex with the mentioned uncertainty, when traps of the majority and minority carriers cannot be distinguished by the I-DLTS technique. However, the origin of the trap which is responsible for the appearance of the peak at 170 K is debated in literature [8]. The clear formation of the E_6 peak at >300 K cannot be resolved by using the HERA-DLTS System 1030 spectral instrument.

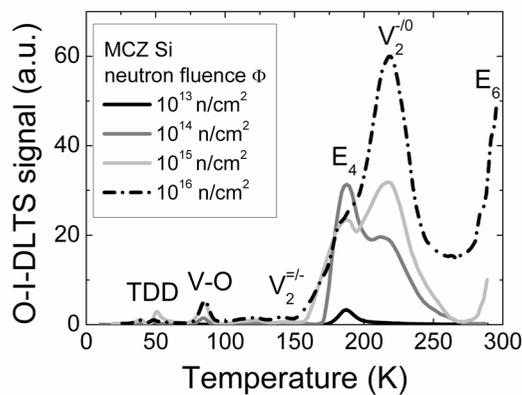


Fig. 2. O-I-DLTS spectra of samples irradiated with reactor neutrons of different fluences.

4. Discussion

The peak amplitude in the C- and O-I-DLTS spectra represents roughly the density of the definite type traps. The fluence dependent variation of density of the traps, which can be resolved over the entire range of irradiation fluences, is represented in Fig. 3.

It can be deduced from Fig. 3 that density of all the observed radiation traps increases near-linearly in the range going from the smallest fluences up to a fluence value of 10^{14} cm^{-2} . The values of the trap density start to saturate for the V-O and V_2 radiation defects in the fluence range of $>10^{14}$ cm^{-2} . The density of E_4 type traps saturates for even smaller fluences, while the density of TDD defects varies non-mo-

tonically relative to the fluence scale. The density of E_6 type traps, as deduced from the changes of the peak amplitude (Fig. 2), increases even faster than the density of divacancies with the enhancement of neutron fluence in the range of $\geq 10^{15}$ cm^{-2} .

The V-O defect (known as the A-centre within the DLTS nomenclature) is the most investigated radiation induced complex [9]. Changes of the relative amplitudes of TDD and V-O peaks within the O-I-DLTS spectra clearly indicate the creation of the vacancy associated complexes through the radiation induced vacancy migration. Incorporating of the isovalent impurities, such as Ge, may considerably suppress the formation of V-O centres, and the TDD density prevails then over the density of V-O complexes [10].

The amplitude of the DLTS peak at 170–190 K also saturates, which might be related to the interstitial impurity complexes $C_i O_i$ [11] acting as the hole traps. On the other hand, this peak can be ascribed to the inter-centre interplay [8] or multi-vacancy complexes with oxygen [12, 13]. These latter defects can also be ascribed to vacancy clusters [8]. The single-charged divacancies $V_2^{-/0}$ seem to be the most stable vacancy complexes [14], the density of which saturates only in the range of the highest neutron fluences. The observed changes of the E_4 and $V_2^{-/0}$ deep centre density can be understood as a result of vacancy migration mediated reactions of the non-equilibrium radiation defects.

The deepest centre E_6 can be ascribed to the cluster type defects which introduce the mid-gap levels. These defects are the most efficient carrier killers [15], which affect the operational characteristics of the detectors.

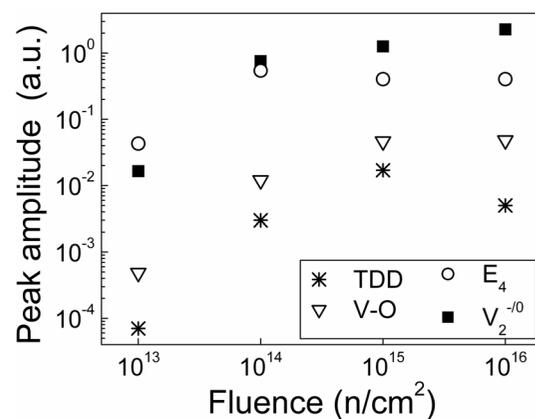


Fig. 3. Dependence of the amplitude of O-I-DLTS spectral peaks on neutron irradiation fluence obtained for MCZ Si detectors.

5. Summary

The neutron fluence dependent variation of radiation defect spectra in MCZ Si pad detectors has been examined by combining C-DLTS and O-I-DLTS regimes. The TDD, V-O, and V_2 ascribed peaks have been observed within C-DLTS spectra measured in diodes irradiated with a fluence of 10^{12} n/cm². Up to six O-I-DLTS peaks have been resolved within the temperature scan spectra measured in the range of 20–300 K. These DLTS peaks have been ascribed to the TDD, V-O, V_2 , and multi-vacancy complexes. The radiation induced vacancy attributed defects such as V-O, V_2 , and clusters have been identified, the density of which increases with irradiation fluence in the range of 10^{12} – 10^{14} cm⁻², while this density saturates for the collected neutron fluence of more than 10^{14} cm⁻².

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NEUTRONAIS APŠVITINTŲ SI DETEKTORIŲ RADIACINIŲ DEFEKTŲ GILIŲJŲ LYGMENŲ OPTIŠKAI ŽADINAMOS SROVĖS SPEKTROSKOPIJA

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Santrauka

Darbe analizuotos giliosios krūvininkų gaudyklės, susiformavusios CERN standarto Si detektoriuose po apšvitos greitaisiais neutronais varijuojant įtėkį 10^{12} – 10^{16} cm⁻² intervale. Giliųjų lygmenų parametrai įvertinti pasitelkus giliųjų lygmenų talpinį (C-DLTS) ir giliųjų lygmenų optiškai

žadinamos generacinės srovės (O-I-DLTS) temperatūrinės žvalgos metodus. C-DLTS ir O-I-DLTS spektruose identifikuoti radiaciniai defektai. Paaiškėjo, kad didelių įtėkių srityje vyrauja apšvita sukurtos divakansijos ir sankaupiniai defektų kompleksai. Aptikta, jog generacinių centrų tankio augimas įsisotina ties 10^{14} n/cm⁻².