Nuclear Inst. and Methods in Physics Research B 442 (2019) 28–30

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

The study of low temperature irradiation induced defects in p-Si using deep-level transient spectroscopy

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ARTICLE INFO

Keywords:
Silicon
Irradiation
Vacancy
DLTS

ABSTRACT

Primary defects introduced in boron-doped silicon by an alpha-particle source with a fluence rate of $7 \times 10^6\,cm^{-2}\,s^{-1}$ at cryogenic temperatures were investigated using deep-level transient spectroscopy (DLTS). The data showed that the defects observed between 35 K and 120 K were not detectable when irradiation was carried out at room temperature. The defect levels were observed at 0.10 eV, 0.14 eV and 0.18 eV above the valence band maximum. These levels were attributed to the boron-substitutional vacancy complex, the mono vacancy and a vacancy-related defect respectively.

1. Introduction

For over 50 years, defects in Si have been investigated, but a clear understanding of their nature and occurrence still lacks. This is because at room temperature some point defects such as interstitials (I) and vacancies (V), are difficult to investigate in Si as they become mobile above cryogenic temperatures [1]. It is of paramount importance to gain a more complete understanding of the properties of point defects and their evolution with temperature. Interstitials and vacancies are difficult to produce in p-type Si but it can be done by irradiating at cryogenic temperatures [2].

Effective defect engineering of electronic materials will depend on a thorough understanding of the generation of electrically active defects, which are responsible for the changes observed in the devices' properties at their operating temperatures [3]. In the case of Si detectors, degradation manifests itself as an increase in leakage current, free carrier concentration removal and a decrease in charge collection efficiency. This makes the radiation tolerance of Si detectors an issue of great concern to which much effort has been devoted in recent years [4].

When compared to n-type semiconductors, there are fewer articles on the subject of Schottky barriers on p-type materials because their barriers are generally so much lower. Moreover, the low impedance of the resulting devices makes measurement difficult. The hurdle in fabricating quality Schottky contacts on p-type Si for reliable electrical characterisation reduces technological interest in the p-type material [5]. This is why there are more studies on implantation-induced defects on electron traps than reports on hole traps [6].

Work on irradiating p-Si at low temperatures has been reported by Zangenberg and Nylandested Larson [1,2]. Immediately after irradiation they observed the vacancy with the trap energy at 0.137 eV, the divacancy at 0.189 eV and two of the three configurations of the boron substitutional vacancy ($B_S - V$) designated by them as AA1 and AA2. The AA1 configuration was found to be at 0.175 eV. The AA2-defect was too unstable and small for thorough analysis. These authors made use of 2 MeV electrons and a temperature range of 20–50 K [1]. Gorelkinskii et al. [7] also reported on low temperature irradiation using H^+ and He^{++} (at 30 MeV and 4.7 MeV, respectively) at 77 K. The samples contained the defect levels H1 (E_V + 0.13 eV), H2 (E_V + 0.20 eV) and H3 (E_V + 0.29 eV) which have been identified as the vacancy (+ +/0), divacancy (+/0) and carbon interstitial trapped by a substitutional carbon ($C_i - C_s$) (+/0).

Deep-level transient spectroscopy (DLTS) has been useful in deducing most of the characteristics of defects introduced in several semiconductors during crystal growth, radiation with different particle types, and by several device fabrication processes [8]. DLTS is a highly sensitive technique, which is capable of detecting impurities at low concentrations and measures their electronic properties such as energy level(s) in the band gap, defect concentration and apparent capture cross sections for electrons and holes [8,9].

In this article, we report on defects introduced in boron-doped p-type Si after irradiation by alpha particles at 35 K. Low temperature irradiation enables us to observe primary defects which are not normally seen after room-temperature irradiation. To the best of our knowledge previous studies have been carried out at temperatures around 77 K using liquid nitrogen based systems or on systems. In this

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https://doi.org/10.1016/j.nimb.2019.01.015
Received 1 September 2018; Received in revised form 30 December 2018; Accepted 9 January 2019
Available online 17 January 2019
0168-583X/

study, irradiation was carried out in a closed-cycle helium cryostat that can reach 35 K. This allows for measurements in a wider temperature range after irradiation. Previous researchers were limited by instrumentation [10,11]. Moreover, cryogenic temperatures are required to freeze in most primary defects [12].

2. Experimental techniques

Aluminium (Al) Schottky diodes were made on boron-doped *p*-type float zone (FZ) Si wafers with a carrier concentration of $1.9 \times 10^{15}\,\mathrm{cm}^{-3}$. The samples were first cleaned using a three-step degreasing method by making use of trichloroethylene, isopropanol and methanol. Thereafter, the samples were rinsed in deionised water and then etched in hydrofluoric acid to remove the native oxide layer. Flowing nitrogen gas was used to dry the samples before loading them into a resistive evaporation chamber. In this study, the Al diodes were made using resistive evaporation because this method is known not to introduce defects in concentrations that can be detected by DLTS [13].

Indium–gallium eutectic liquid alloy was painted on the other side of the wafer to form the ohmic contact. After contact fabrication, irradiation was performed at a temperature of 35 K with alpha particles. This was achieved by making use of a 5.4 MeV Am-241 radioactive source with a fluence rate of $7 \times 10^{6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The samples and the alpha-particle source were mounted in a closed-cycle helium cryostat, with the alpha-particle source at room temperature and mounted 10 mm above the sample. Irradiation temperature was controlled using a Lakeshore 332 temperature controller and a heated stage. All samples were irradiated for 132 hours to a fluence of $1.3 \times 10^{13}\,\mathrm{cm}^{-2}$. Deep-level transient spectroscopy (DLTS) was conducted after irradiation.

The samples were kept below 35 K until DLTS measurements were performed in the 35–110 K temperature range at a scan rate of 2 K/min. The quiescent reverse bias was −1 V, the filling pulse amplitude 0.5 V and the filling pulse width 1 ms.

Arrhenius analysis was done according to the equation

$$e_p = \sigma_p \langle v_p \rangle \frac{g_o}{g_1} N_v \exp\left(\frac{E_V - E_T}{k_B T}\right) \tag{1}$$

This equation gives the emission rate as a function of temperature T, where $\langle v_p \rangle$ is the thermal velocity of electrons, $(E_V - E_T)$ is the activation energy. N_v is the effective density of states in the valence band and g_0 and g_1 are the degeneracy terms referring to the states before and after hole emission and k_B is the Boltzmann constant. The signatures (energy level in the band gap, E_T and apparent capture cross section, σ_p) of the induced defects were calculated from the slope and *y*-intercept, respectively using log (e_p/T^2) versus $(1000/T)$ Arrhenius' plots, according to the equation [14].

3. Results and discussion

Fig. 1 illustrates the DLTS spectrum obtained shortly after irradiation. The hole traps observed were: H(0.10), H(0.14) and H(0.18), where the number in brackets refers to $E_V - E_T$. As is often the case with radiation induced defects [15–17], the peaks were on a skewed baseline. The skewed baseline is often attributed to a continuum of defect states on the surface of the material induced by particle irradiation [18]. This baseline made Laplace-DLTS impossible.

The defect level H(0.10) was identified as the metastable $B_S - V$ in the B configuration [1]. This defect has two other configurations, i.e. configurations A1 and A2 which were not observed in this experiment [1,19].The apparent capture cross-section of H(0.10) was calculated to be $1.7 \times 10^{-14}\,\mathrm{cm}^2$ from the Arrhenius plot shown in Fig. 2.

H(0.14) was identified as the mono vacancy [1]. The apparent capture cross-section was $1.1 \times 10^{-14}\,\mathrm{cm}^2$. Watkins et al. found the trap to be at $E_V + 0.13$ eV [20]. In a theoretical paper by Antonelli et al. [21], two configurations of the single vacancy were reported. One is a metastable configuration which could be similar to the AA1-defect measured by Zangenberg et al., the other, a stable configuration of the vacancy [1].These configurations were not observed in this work.

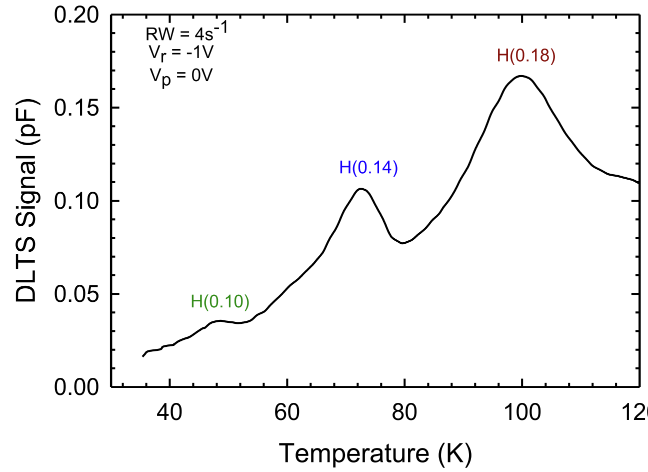

Fig. 1. DLTS spectrum showing the defects obtained soon after alpha-particle irradiation at a fluence of $3 \times 10^{13}\,\mathrm{cm}^{-2}$.

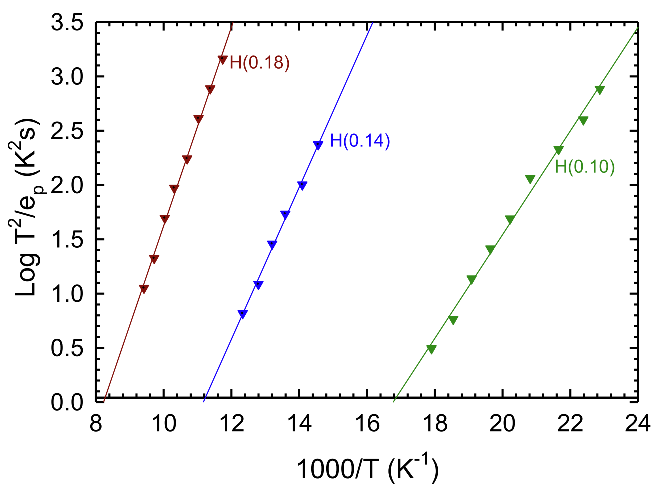

Fig. 2. Arrhenius plots of the DLTS peaks shown in Fig. 1.

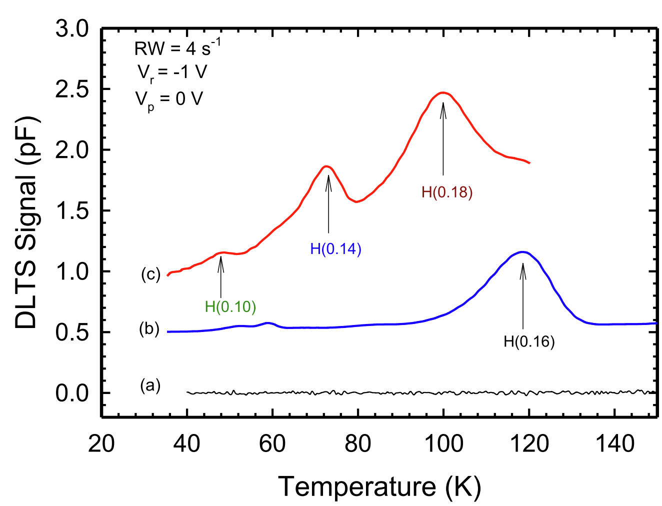

Fig. 3. DLTS spectra illustrating (a) the as-deposited sample, (b) room temperature alpha-particle irradiation and (c) low temperature alpha-particle irradiation.

The defect level H(0.18) was identified as a divacancy-related

Table 1
List of parameters obtained from Arrhenius plots.

Defect	DLTS parameters in this work		Comment	Literature
	E_T ± 0.3 (eV)	σ_p ± 5% (cm^2)		
$B_S - V$	0.10	1.7×10^{-14}	B configuration	0.105 eV [1] 0.11 eV [2]
V	0.14	1.1×10^{-14}	(+/++) charge states	0.137 eV [1] 0.13 eV [12]
V_2	0.18	5.6×10^{-15}	(0/+) charge states	0.189 eV [1] 0.19 eV [22] 0.20 eV [7]

defect. This defect had an apparent capture cross-section of 5.6×10^{-15} cm^2. A similar defect at 0.189 eV was observed by Zangenberg et al. [1,2]. Trauwaert et al. observed a defect at the H (0.19) level in both Czochralski (Cz) and FZ material with a capture cross-section between 5.0×10^{-16} cm^2 and 1.0×10^{-15} cm^2 using conventional Arrhenius analysis. This defect was attributed to the donor level of the Si divacancy [22]. Gorelkinskii et al. performed irradiation experiments using H^+ and H^{++} at 77 K. These researchers observed the V(++/0), V_2, and C_i which they referred to as H1, H2 and H3 respectively. These authors observed an electron trap they called E1in their experiments. However, they did not observe the metastable defect $B_S - V$ because of the temperature ranges they conducted their measurements in.

Fig. 3 shows a comparison between room temperature irradiation and low temperature irradiation, spectra (b) and (c) respectively. Spectrum (a) is a reference spectrum of an unirradiated sample. Fig. 3 shows that when irradiation is carried out at room temperature, the defects introduced during low-temperature irradiation are not observed. While one defect at 0.16 eV is measured in the 35–115 K range after irradiation at room temperature, 3 defects are measured in the same temperature range after irradiation at 35 K. This is because the vacancies and interstitials produced upon irradiation at room temperature, recombine or react to form secondary defects [23]. The defects measured in this work are listed in Table 1 with their characteristic signatures (E_T, σ_p) and data from literature.

4. Conclusion

Defects introduced in boron-doped p-type silicon after low-temperature irradiation by alpha particles were observed. Irradiation was carried out at 35 K in a closed cycle cryostat. This allowed the observation of the H(0.10), H(0.14) and H(0.18) defects. The defect H (0.10) was identified as the configuration B of the $B_S - V$ defect, H (0.14) was identified as the mono vacancy and H(0.18) was identified as a divacancy-related defect. Defects observed after low temperature alpha-particle irradiation were not observed after room temperature alpha-particle irradiation measured in the same temperature range. Due to a skewed baseline, Laplace-DLTS measurements were not successful.

Acknowledgements

The authors would like to thank the South African National Research Foundation (NRF) and the University of Pretoria for financial support. Views and opinions expressed in this article are those of the authors and not of the NRF. We also thank Mr P.J. Janse van Rensburg and Mr M.J. Legodi for their technical assistance. The Laplace DLTS software and hardware used here was received from L. Dobaczeweski (Institute of physics, Polish Academy of Science) and A. R. Peaker (Centre for Electronic Materials Devices and Nano-structures, University of Manchester.

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