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Study of the development of defects in Si PIN diodes exposed to 23 GeV/c protons

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ABSTRACT: Studying the development of crystallographic defects in PIN diodes is the focus of the RD-50 (CERN) research project. The study was carried out on Si PIN diodes manufactured and used in the Czech Republic. The Si PIN diodes were irradiated with 23 GeV/c protons at doses ranging from 0.5 to 43 Gy. The Si PIN diodes were calibrated in a 23 GeV/c proton source [1], and the energy traps of the defects produced were measured by the DLTS method. The IV characteristics and the parameters of the defects were studied. The 23 GeV/c protons produce typical crystallographic defects and, at higher doses, bring about their regrouping thus giving rise to a new generation of defects. Defects are classified by their energy levels in the forbidden band from the conduction band. The mechanism influencing the parameters of the defects is discussed. The study of defects in silicon is important for silicon-based electronic elements used in cosmic research because of their effects on the operability and reliability of electronic equipment installed in satellites. Another application is the dosimetry measurements involving various types of particle accelerators.

KEYWORDS: Radiation damage evaluation methods; Radiation damage monitoring systems; Radiation damage to electronic components; Radiation damage to detector materials (solid state)

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Contents

1 Introduction

Studies of crystallographic defects in semiconductors by Deep Level Transient Spectroscopy (DLTS) were pursued since the second half of the last century (1974). This method was pioneered by D.V. Lang [2]. This method is one of the most sensitive physical methods. The damage caused to the crystallographic structures generates electrically active traps which are traceable by DLTS.

The study of radiation damage due to relativistic protons is connected with the experiments conducted at CERN [8]. Learning more about the mechanism of formation of these radiation defects occurring in semiconductor crystals is useful for optimizing semiconductor tracking detection structures. The structures used for dosimetry are suitable for exploiting radiation defects as a function of the dose received. The dose is obtaind with the measured voltage in the forward direction with constant current, as the difference of voltage readings before and after irradiation [9]. Our results apply to the interaction of photons $(^{60}\mathrm{Co})$ and fast neutrons $(^{252}\mathrm{Cf})$ with the crystal lattice of silicon for the S1 diode [6, 7]. Unfortunately, the production of type S1 diodes was terminated and only type S2 diodes were available. Therefore, type S1 diodes could no longer be used in this experiment, unlike the previous article [6, 7]. The S1 and S2 diodes differ in volume; the volume of the S1 diode is half of the S2 diode. Our task was to obtain feedback diodes for various types of radiation thereby gaining a universal component for measuring different types of radiation.

2 Manufacture of type S2 PIN diodes

The S2 diodes are made of wafers of N-type silicon single crystals having a resistivity ranging from 0.7 to 2 Ohm.m. The bulk material is FZ thus containing a low amount of oxygen atoms, less than $10^{15}\,\mathrm{cm}^{-3}$, which is good for dosimetry because oxygen atoms increase the radiation hardness [3]. The final thickness of polished and etched wafers is about 2.5 mm. Application of new single crystal production technologies, developed during the last decade (dislocation-free single crystals, in combination with nuclear transmutation doping), brought considerable quality improvements to the silicon materials. The diffusion processes at 1000°C were replaced by ion implantation, thus allowing precision doping at low temperatures within very short time periods. Ion implantation is done with phosphorus and boron, at a total fluence of $10^{16}\,\mathrm{cm}^{-3}$. The magnetron

2015 JINST 10 P03021

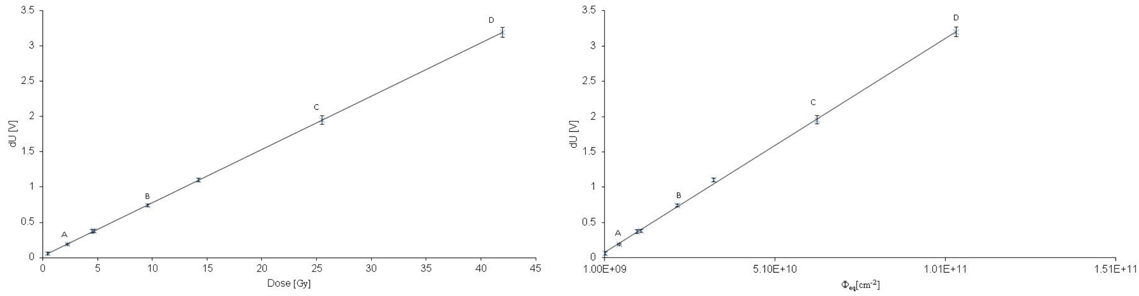

Figure 1. S2 PIN diode calibration curve for protons 23 GeV/c dose in Gray (left side) and in NIEL (right side).

sputtering technology brought about an increase in quality and, thus, an improved durability of metallic contacts, both in terms of their contact resistance and in terms of improved assembling of the measuring contacts. Thanks to all these methods, it can be guaranteed that the silicon material will be exposed to thermal stressing for only very brief periods, thus reducing the amount of change of the electrical parameters of silicon. The wafers are annealed at 900°C for 20 minutes. Then they are subdivided into different systems of 2.4 by 2.4 by 2.5 mm^3 in size, having previously removed the surface oxide and applied titanium and, subsequently, nickel contacts. Finally, the diodes thus made are fitted with soldered wire leads and encapsulated.

The main benefit derived from the new production processes has been the stabilization of the electric parameters of the diodes. In type S2 diodes, the standard deviation of initial voltage determined at the current of 25 mA was reduced to 1%. All these measures have contributed to unifying and standardizing the diode characteristics.

3 Experimental

In order to enlarge the application range of the PIN diodes type S2, our experiments were aimed at studying the behavior of the PIN diode when exposed to 23 GeV/c protons. The PIN diode was irradiated using the PS accelerator at CERN. Prior to radiation exposure, the PIN diodes were measured in a dedicated setup which generated a constant forward current 25 mA with a pulse of 40 ms and measured the voltage drop on the PIN diode itself. The duration of pulse is chosen on purpose so as to avoid heating the measured diode. Thus, the voltage measuring error of the PIN diode could almost entirely be attributed to the error of the digital voltmeter, which usually does not exceed 1 mV.

4 Results and conclusion

For S2 dosimeter diodes the calibration curve was already obtained (figure 1) [1]. For example, the difference of voltage for forward current for the diode exposed to dose of 43 Gy was 3.1 V. On the basis of these data, DLTS measurements were performed for the minority carriers on the apparatus. The time window was 0.02–2.06 ms, the time period was from 5 to 60 ms and pulse duration was 900 μs. The diodes were irradiated with doses ranging from 0.5 to 43 Gy. Traps were

2015 JINST 10 P03021

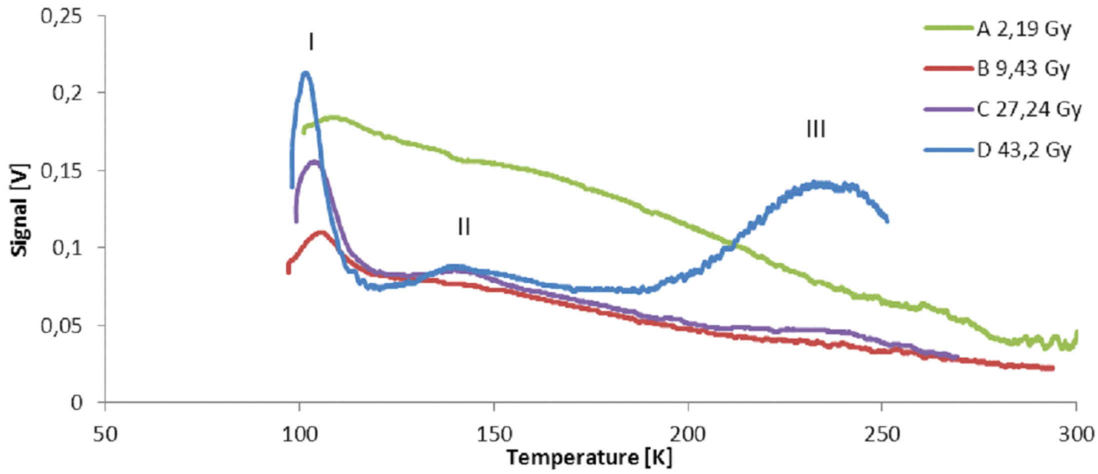

Figure 2. DLTS spectra for a PIN diode irradiated by high energy protons.

Table 1. Results of energy traps E_c in Si PIN diode irradiated by high energy protons.

Dose [Gy]	**Peak I [eV, type of traps]**		**Peak II [eV, type of traps]**		**Peak III [eV, type of traps]**	
0.5–14	0.17± 0.03	0.170, VO [4] 0.163, $VO^{-/0}$ [5]				
25–43	0.17± 0.03	0.170, VO [4] 0.163, $VO^{-/0}$ [5]	0.23± 0.03	0.230, VO^{2-} [4] 0.229, $VO^{=/-}$ [5]	0.41± 0.04	0.420, $V_2^{-/0}$ [4] 0.421, $V_2^{1-} + VP$ [5]

Table 2. Electron capture cross section for silicon diode irradiated by high energy protons.

Energy [eV]	$E_c - 0.17$		$E_c - 0.23$		$E_c - 0.41$	
Electron capture cross section [cm^{-2}]	5.98×10^{-14}	1×10^{-14} [4, 5]	2.31×10^{-13}	1×10^{-13} [4]	7.53×10^{-13}	4×10^{-13} [4]

found in these irradiated diodes. The development of these traps, is the measure of the dose, is illustrated in figure 2 for lower doses formed traps with energy 0.17 eV; at higher doses, two more traps occurred with energies of 0.23 eV and 0.41 eV when the 25 to 43 Gy dose range was reached. The calculation was made using an Arrhenius plot for individual traps, and the results are shown and compared with published data in tables 1 and 2.

The experimental results confirm that the evolution of traps in the FZ-Si material can be established in the range from 0.5 to 43 Gy. The existence of the traps measured is reflected in the calibration curve for the measurement of high-energy protons [1]. The defects of a diode irradiated with high-energy protons are homogeneously distributed throughout the volume of the detector and are identified as point defects. A very substantial finding has been the dependency on the proton dose as evidenced by the DLTS measurements. Type I defects are di-vacancies caused by the interaction of vacancies among themselves; type II defects are oxygen vacancies with different charge

2015 JINST 10 P03021

states, and type III defects are phosphorus vacancies. Their dose dependent formation corresponds to the concentrations of $10^{15}\,\mathrm{cm}^{-3}$ oxygen atoms and $10^{13}\,\mathrm{cm}^{-3}$ phosphorus atoms in the silicon crystal. According to the type of fault occurring, it is possible to distinguish the type of interaction and thus radiation. In case of the field of fast neutrons and gamma radiation the response to gamma radiation is a thousand times smaller than the response to fast neutrons [6, 7].

Acknowledgments

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