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# RADIATION HARDNESS STUDIES OF PIN-DIODE DETECTORS IRRADIATED WITH HEAVY IONS*

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Evaluation of the properties of a set of PIN-diode-type semiconductor detectors was performed at the Heavy Ion Laboratory University of Warsaw in Poland with the $\alpha$ particles from $^{241}$Am. In order to monitor the radiation damage process in a controlled conditions, the in-beam irradiation experiments were performed using heavy-ion beams: $^{12}$C and $^{20}$Ne at HIL in Warsaw, and $^{132}$Xe at JINR in Dubna. The properties of the irradiated PIN-diode detectors were tested using the positron annihilation spectroscopy. The preliminary results of the experiments are presented.

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## 1. Introduction

The damage of semiconductor detectors caused by the ionizing radiation is a widely known phenomenon. In particular, the radiation resistance of PIN diodes used in various measuring systems have been the subject of research in the past. The response of such detectors to the high flux of gamma quanta [1], neutrons [2], protons and electrons [3] was studied. The information on the influences of high-flux heavy-ion interaction on the PIN-diode-type detectors is, however, very scarce. Particularly, a comprehensive studies of charge collection efficiency in 300 $\mu$m thick PIN diodes were performed as reported in [4]. Furthermore, the qualitative deterioration of the

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acquired energy spectrum of the registered particles could be found. This effect is of paramount importance when designing the particle detection systems to work in the exposure to high flux of heavy ions.

In this paper, we report on the attempt which was made at the Heavy Ion Laboratory in Warsaw and at the Joint Institute for Nuclear Research in Dubna to document the radiation damage process of the 300 $\mu$m PIN-diode-type detectors. We present the preliminary results of the experiment where one PIN-diode detector was irradiated using controlled $^{12}$C, $^{20}$Ne and $^{132}$Xe ion beams. The off-beam tests of the set of 167 PIN diodes performed with the radioactive $\alpha$ source are also presented and discussed.

## 2. Motivation

A PIN-diode-type detector is made of a silicon semiconductor material of a typical layer structure: p (acceptor), n (donor) and an intrinsic-type semiconductor. Such detectors serve as the ionisation radiation monitors, for example, at Heavy Ion Laboratory where PIN diodes are used as a charged particle detection system in the Coulomb excitation experiments. In particular, the system of PIN-diode detectors was used in November 2016 with $^{32}$S beam of 70 MeV energy impinging on $^{45}$Sc target [5]. In this measurement, PIN-diode detectors were placed at the angles near 90°.

The detector received about 5000 pps from the scattered projectiles. After 5 days of beam taking, it was noted that the PIN-diode performance as the heavy-ion detector significantly deteriorated.

## 3. Evaluation of the PIN-diodes performance

In order to study the various properties of PIN diodes, a dedicated detection station was assembled at HIL as shown in figure 1. A set of 167 PIN detectors with different previous exposure to heavy-ion beams (including also the PIN diodes used in the Coulomb excitation experiment performed in November 2016) were systematically tested.

A conducting plate with the attached PIN diode was placed in the centre of the vacuum chamber (figure 1 panel (a)) and a 40 kBq $^{241}$Am $\alpha$ source was placed right above the detector surface during the measurement. During the study, every PIN diode was polarised with 100 V. Leakage current of the PIN diode was noted at the beginning and at the end of a 300 s measurement of $^{241}$Am $\alpha$ spectrum.

Figure 2 shows the examples of the collected data where three PIN diodes (PIN 1, 2 and 3) exhibiting significantly different spectroscopic properties are compared. The Gaussian fit parameters and measured leakage current are used to describe the differences between investigated detectors. The

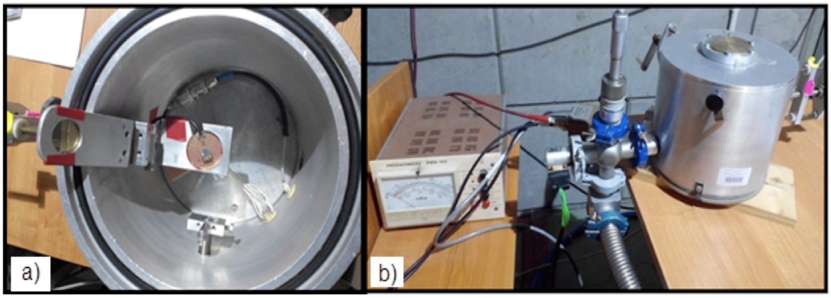


Fig. 1. (Colour on-line) (a) A vacuum chamber with a PIN diode placed in the centre; (b) The experimental setup used for the PIN-diodes evaluation.

grey/red spectrum corresponds to the malfunctioning diode (PIN 3), the light grey/green to a slightly deteriorated one (PIN 2), and the black/blue shows a well-functioning detector (PIN 1). In the latter case, the leakage current value does not exceed 0.2 $\mu$A, it has a good FWHM of 20(2) keV and plenty of counts in the integral (15500 (1100)). The energy peak of the medium-quality PIN 2, shown in light grey/green, overlaps the black/blue peak (reference PIN diode) which indicates the full charge collection. However, it is significantly worse in terms of FWHM (167(4) keV) and the overall shape is more distributed. The leakage current is much higher reaching 1.5 $\mu$A. The total number of counts is comparable in both PIN diodes al-

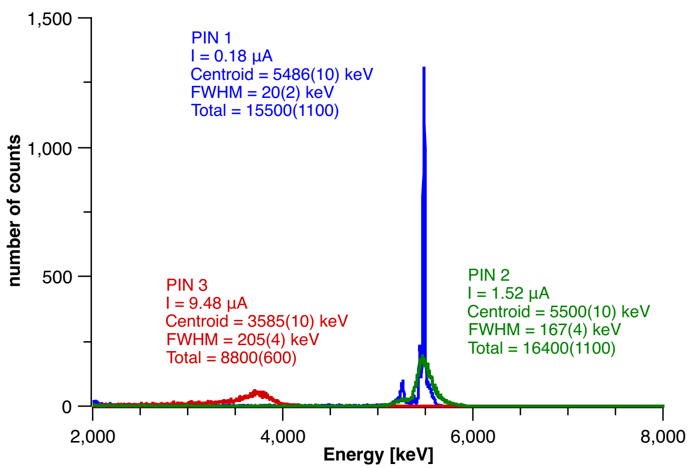


Fig. 2. (Colour on-line) Example spectra of different PIN-diode detector behaviour. The grey/red spectrum corresponds to the malfunctioning diode, the light grey/green — a slightly deteriorated one, and the black/blue shows a well-functioning detector.

though the peak height is much lower in the case of the light grey/green spectrum and the low-energy tail of the peak starts to appear. Both diodes would be considered to be useful in an experiment judging by the above-mentioned parameters. The PIN diode presented in grey/red (PIN 3) has an extremely high leakage current of 8 $\mu$A. Its $\alpha$ energy spectrum shows clear signs of the radiation damage indicated by its high current. The peak is shifted towards lower energies and the total number of counts is cut in half in comparison to PIN 1 and 2. There is also an increase in FWHM to 205(4) keV.

The measured dependence of the centroid as a function of leakage current collected for 167 PIN detectors is shown in figure 3. The centroids of the $\alpha$ peak in PIN diodes for which the leakage current does not exceed 6 $\mu$A is clearly distinguishable and follows the stable linear trend. Once the leakage current exceeds 8 $\mu$A, the position of the calibration peak shifts towards smaller values. When the detector capacity increases and the charge collection efficiency decreases its energy resolution deteriorates manifesting in the worsening of the measured FWHM. The results of the study are shown in Ref. [6] and were one of the additional motivations to further investigate an impact of irradiation on the PIN-diode performance under controlled experimental conditions.

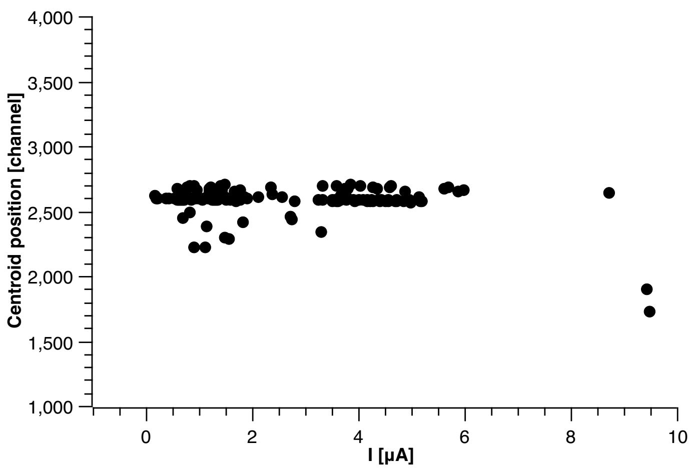


Fig. 3. Dependence of centroid position as a function of leakage current for 167 investigated PIN diodes.

## 4. In-beam irradiation experiments

In June and November 2019, two dedicated experiments of the same type were carried out at the Heavy Ion Laboratory aiming at the controlled destruction of a PIN-diode semiconductor detector using a heavy-ion beam. In the first experiment, a $^{12}$C beam of 68 MeV energy was first impinged on a 9 mg/cm$^2$ gold foil in order to scatter the beam and further monitor the number of implanted ions/cm$^2$ (fluence) in the dedicated collimated silicon detector placed at 20°. In the second measurement performed using the same experimental setup, $^{20}$Ne beam of 53 MeV energy was first impinged on a 4 mg/cm$^2$ gold foil. Here, the fluence was monitored in the silicon detector at 45°. In both experiments, the PIN-diode detector was placed at 0° and the degree of damage of the PIN detector was monitored by measuring the leakage current. The experimental setup is presented in figure 4.

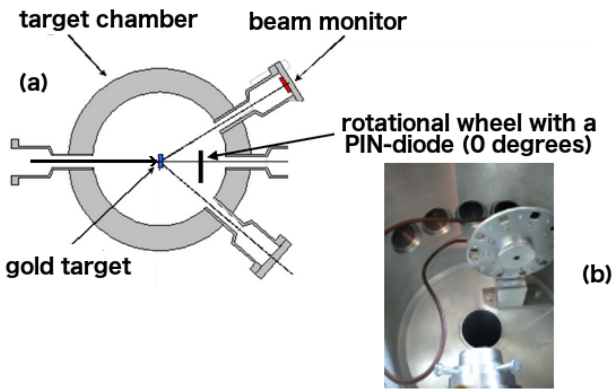


Fig. 4. Schematic view of the experimental setup (a) with the wheel (b) placed directly at 0° with respect to the $^{12}$C and $^{20}$Ne beam direction where the PIN-diode detector was placed.

Additionally, during the first experiment, the spectroscopic properties of the irradiated PIN-diode detector were periodically checked by measuring the spectrum collected off-beam with the $^{241}$Am $\alpha$ source. It was noted that the ratio between the full-energy peak and its low-energy tail was changing which indicated the possible modification of the crystal structure of the detector which could be caused by the incomplete charge collection. This effect is a subject of the on-going analysis.

The third irradiation experiment was performed at JINR in Dubna, Russia where the PIN-diode detector was bombarded by the $^{132}$Xe beam of 167 MeV energy and the fluence of $\sim 10^{14}$ ions/cm$^2$.

In order to investigate the effects of the radiation damage caused by the heavy ions, the set of three irradiated PIN diodes and the chosen reference PIN diode which was not exposed to the high-flux heavy-ion beam were measured using the positron annihilation spectroscopy. This is a sensitive tool for the investigation of the open-volume defects as vacancies and their clusters [7, 8]. In the performed experiment, the technique of positron lifetime (LT) was used. More details related to experimental setup is given in Ref. [9]. The results from the positron annihilation spectroscopy are presented in figure 5. Positron lifetimes observed for three irradiated samples are much higher in comparison to non-defected PIN diode which indicates the existence of radiation-induced defects. The fast increasing of the LT with the ion fluence is also visible which can be interpreted as the slow expansion of defect size. The most interesting observation is a fact that registered positron lifetimes are lower than those reported in literature for monovacancies [10, 11]. Further works are recommended in this topic.

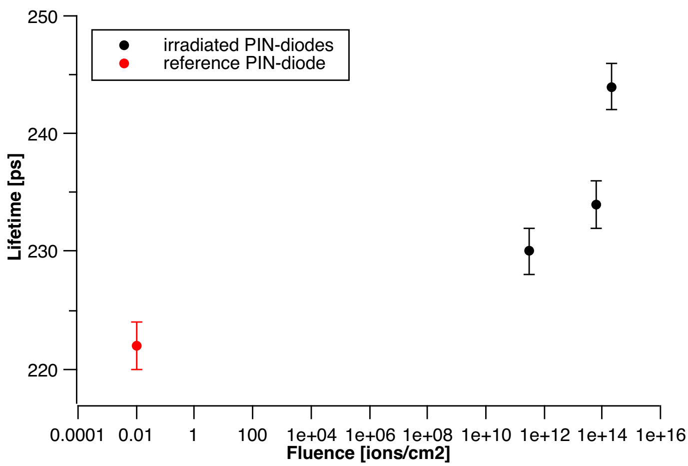


Fig. 5. (Colour on-line) The results from the positron annihilation spectroscopy — the positron lifetimes observed for irradiated samples (marked in black) as a function of the fluence. Grey/red point corresponds to the reference PIN diode which was not exposed to the high-flux heavy-ion beam.

## 5. Conclusions

The evaluation of the effects of heavy-ion irradiation on the PIN-diode-type detector was carried out at HIL Warsaw and at JINR in Dubna. The observed radiation damage of the PIN detector was manifested in the changes in the leakage current, worsening of the FWHM and in the clear increasing trend of the LT as a function of the ion fluence. It has been shown that the fluence of less than $10^{13}$ ions/cm$^2$ did not allow to completely destroy the PIN-diode detector, however, the deterioration of the spectroscopic quality was observed.

The presented results could be vital for the data analysis from the Coulomb excitation experiments as the incomplete registration of the scattered ions could affect the data due to the decreased charge collection efficiency of the particle detector. Further studies are necessary to determine the number of implanted particles (fluence) which could cause a severe and irrecoverable radiation damage resulting in a complete disabling of a PIN-diode-type detector.

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## REFERENCES

[1] B. Abi, F. Rizatdinova, «Study of the radiation hardness performance of PiN diodes for the ATLAS Pixel Detector at the SLHC upgrade», Topical Workshop on Electronics for Particle Physics, Paris, France, September 21–25, 2009, pp. 390–393 (CERN-2009-006).

[2] V. Sopko *et al.*, *JINST* **8**, C03014 (2013).

[3] A.H. Johnston, «Radiation damage of electronic and optoelectronic devices in space», 4$^{\text{th}}$ International Workshop on Radiation Effects on Semiconductor Devices for Space Application, Tsukuba, Japan, October 11–13, 2000.

[4] M. Boscardin *et al.*, *IEEE Symposium Conference Record Nuclear Science* **2**, 904 (2004).

[5] M. Matejska-Minda *et al.*, *Acta Phys. Pol. B* **49**, 567 (2018).

[6] K. Krutul, M.Sc. Thesis, University of Bialystok, 2017.

[7] F. Tuomisto, I. Makkonen, *Rev. Mod. Phys.* **85**, 1583 (2013).

[8] R. Krause-Rehberg, S.H. Leipner, «Positron Annihilation in Semiconductors», *Springer*, Berlin 1998.

[9] P. Horodek, *Vacuum* **164**, 421 (2019).

[10] J.M. Campillo Robles, E. Ogando, F.J. Plazaola, *J. Phys.: Conf. Ser.* **265**, 012006 (2011).

[11] J.M. Campillo Robles, E. Ogando, F.J. Plazaola, *J. Phys. Condens. Matter* **19**, 176222 (2007).