Alpha radiation detection using Si PIN diodes

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***Abstract*—Positive – intrinsic – Negative (PIN) photodiodes have been widely studied in recent times for detecting and measuring different types of ionizing radiations owing to their superior characteristics when compared to conventional gas-filled or scintillator based detectors. PIN diodes are also explored for detecting neutrons with a suitable converter layer (10B or 6LiF). PIN diode energy resolution is influenced by various experimental conditions and is not completely understood. In the present work, role of diode leakage current, applied reverse bias, alpha source-detector distance, diode size and gamma radiation on the PIN diode performance in terms of energy resolution (FWHM) when exposed to alpha radiation (239Pu, 241Am,244Cm) is studied. The results presented in this work will be useful while considering the PIN diodes for various radiation sensing applications.**

***Index Terms*—Radiation detection, PIN diode, Energy resolution**

I. Introduction

Nuclear radiation detectors are of paramount importance for the safe and successful operation of nuclear reactors. They also find widespread applications in medicine, space and nuclear physics experiments [1]. Silicon based semiconductor detectors such as PIN diodes represent a very useful technology for detecting and monitoring photons, ionizing particles and neutrons [2]. Si detectors are compact, require low voltage for operation and have good energy resolution when compared to conventional gas filled detectors or scintillators. For these reasons, Si detectors are extensively studied for detecting and measuring alpha, beta particles, heavy ions such as nuclear fission fragments and neutrons [3-6]. For neutron detection, PIN diodes are typically coated with a converter material (^{10}B, ^{6}LiF) to convert incident neutron to charge particles. The thin depletion layer $(200 - 500 \mu m)$ in PIN diodes gives them a low sensitivity for gamma rays, but it is thick enough for the full collection of the electron–hole pairs generated by charged particles [6]. PIN diodes are therefore, ideal candidates for detecting charge particles emanating from neutron converter layer due to $(n - \alpha)$ reactions. In order to increase the efficiency, PIN diodes with 3D micro/nano patterns with conformally backfilled converter layers are being studied [7]. Large area PIN diodes are also being explored for nuclear physics experiments and radiation monitoring at CERN [8].

The energy resolution of PIN diodes depends critically on various parameters such as diode leakage current, applied bias, diode dimensions and gamma discrimination ability. A thorough understanding of these parameters is essential to effectively implement the PIN diodes for the above said radiation detection applications. In the present work, therefore, a systematic study was undertaken to understand the role of diode leakage current, applied reverse bias, alpha source-detector distance, diode size and gamma radiation sensitivity on the Full width Half Maximum (FWHM) of PIN diodes for the detection of alpha radiation.

II. Experimental

PIN diodes are essentially PN junctions which when reverse biased, provide large depletion region (active region), due to the presence of sandwiched intrinsic layer. When ionizing radiation impinges on the diode, electron-hole pairs are created in the active region and are swept towards the electrodes due to the applied reverse bias. Current pulse thus produced in the external circuit is proportional to the number of free charge carriers generated which in turn is proportional to the energy of the incident radiation. In the present work, alpha spectroscopy measurements were performed on commercially available Si PIN diodes (M/s BEL, Bangalore, active area: 10 mm x 10 mm or 7 mm x 7 mm) in pulse mode operation. Block diagram of the experimental setup used for radiation measurements is shown in fig. 1 below.

PIN diodes were placed in a specially designed vacuum chamber along with a triple energy alpha source (^{239}Pu - 5.155 MeV, ^{241}Am - 5.486 and ^{244}Cm - 5.806 MeV) initially with a separation distance of 16 mm. Since the range of alpha particles in the air is typically a few μm, the experiments were

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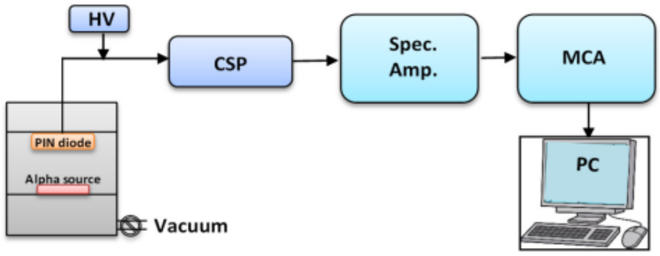

Fig. 1. Experimental setup used for recording PIN diode response when exposed to alpha radiation.

conducted under a vacuum of 10^{-3} torr. PIN diode was reverse biased using the internal HV power supply available in MCA, and the current pulse from the detector was measured using the charge sensitive preamplifier (CSP, CEAN A1422, sensitivity – 45 mV/MeV). Output from CSP was fed as input to the spectroscopic amplifier cum multichannel analyzer (MCA, GBS 527), which in turn was interfaced to a PC through a USB port. Alpha energy spectra were recorded using the software winSPEC, and from the stored data Full- Width Half Maximum (FWHM) values were extracted. Experiments were repeated by varying the following experimental parameters: 1) Diodes with different leakage currents [$\sim 10^{-9}$ – $\sim 10^{-7}$ A] 2) Reverse bias voltage [0 – 50V] 3) Diode size [10 mm x 10 mm & 7 mm x 7 mm] 4) Alpha source – detector distance [8 – 48 mm] 5) Gamma radiation sensitivity [^{22}Na & ^{133}Ba].

Ahead of alpha spectroscopy measurements, the reverse leakage current of the PIN diodes was measured using a source measurement unit (Keysight B2912A) by placing the diode inside a miniature sample holder under dark conditions. CV measurements were performed using a LCR meter (Agilent E4980A) and a HV power supply. Typical current-voltage (IV) characteristics of several PIN diodes studied in the present work are shown in fig. 2 (a). From this figure, it is evident that at the applied reverse bias of 100 V, leakage current of some of the diodes is as high as $\sim$ 300 nA. Apart from leakage current dependence studies, for all other measurements, PIN diodes with leakage current $<$ 10 nA were used. Figure 2(b) shows the CV data in a typical diode from which it is clear that with increasing reverse bias, device capacitance decreases. After $\sim$ -40V capacitance value remains constant, indicating that the device is completely depleted.

III. Results and Discussions

A. Diode leakage current

Reverse leakage currents are important characteristics of a PIN diode, whose increase is known to substantially compromise the energy resolution of the detector. The reverse current of an ideal diode consists of only a diffusion current, but practically several other parameters such as impurities, contaminations and process induced defects in silicon, Si/SiO_2 interface states also contribute to the measured leakage current [9,10]. Leakage current is severely detrimental to signal production in these devices as they limit the applied bias to the device

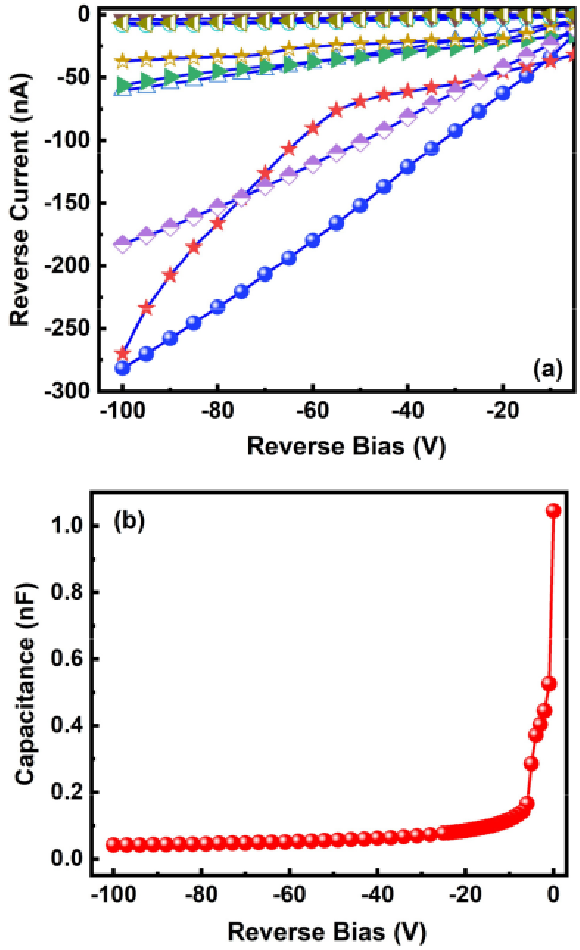

Fig. 2. (a) Reverse leakage current characteristics and (b) Typical CV characteristics of various PIN diodes studied in the present work.

and decreases the S/N ratio [11]. The diode leakage current characteristics and breakdown voltage directly depend on the quality of the diode fabrication process [12]. For example, introduction of guard rings on the detector surface was found to reduce the leakage current by orders of magnitude [10]. Therefore, for any spectroscopy measurements, it is important to understand the role of leakage current on the detector energy resolution.

Fig. 3 (a) and 3(b) show the reverse bias characteristics of two typical 10 mm x 10 mm PIN diodes whose leakage current at an applied reverse bias of 100V is 4 nA and 281 nA, respectively. Diodes with such huge leakage currents were deliberately chosen in order to study their role on the energy resolution of the detector. Fig. 3(c) and 3(d) show the corresponding alpha spectra recorded on these two diodes, respectively. From these figures, it is evident that peaks are better resolved with narrow FWHM when the leakage current is less (figure 3(c)). Similar experiments were repeated on several diodes with different leakage current and fig. 3 (e) shows the variation of FWHM for all three alpha energies with the measured reverse leakage current of diodes at 50V bias.

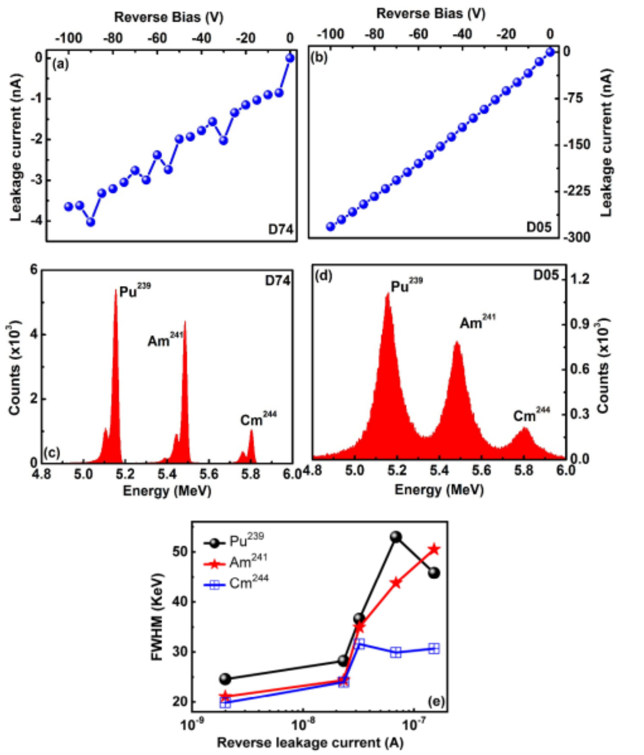

Fig. 3. Typical reverse bias characteristics of two PIN diodes and their respective alpha spectra are shown in figure (a) - (d). (e) Variation of FWHM with increasing reverse leakage current.

For all these measurements, experimental parameters such as source detector distance, shaping time and pre-amplifier were kept the same. From figure 3 (e), it is evident that with increasing leakage current, detector resolution decreases. When the diode leakage current is $< 2\times10^{-8}$ A, the resolution of the detector is $<$ 30 keV. However, when the leakage current is above this value, resolution decreases drastically. Similar observation was reported by Linyue Liu et al. [13] while studying the SiC PIN diode characteristics under harsh neutron irradiation. These authors found that when detectors are irradiated with 14 MeV neutrons, leakage current increases significantly with increasing neutron fluence, which in turn deteriorates their energy resolution by 4 %. It is also interesting to note that even at higher leakage currents, the resolution of the detector for ^{244}Cm radiation remains fairly constant.

B. *Effect of applied reverse bias*

Apart from the reverse leakage current, for a given diode, detector performance will also depend on the applied reverse bias. This is because with increasing reverse bias, reverse leakage current is known to increase and is attributed to the increase in the minority concentration of charge carriers in the diode [14]. Fig. 4 (a) and 4(b) show the typical alpha spectra recorded on a 10 mm x 10 mm diode when the applied reverse bias was 0 and 50V, respectively. Fig. 4 (c) shows the variation of FWHM extracted from these spectra for all the three alpha energies with increasing reverse bias. From these

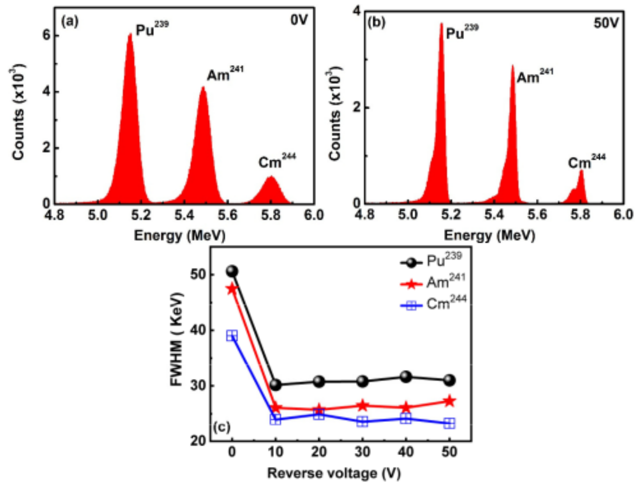

Fig. 4. Typical alpha spectra recorded at (a) 0V and (b) 50V bias on 10 mm x 10 mm diodes (c) Variation of FWHM with applied reverse bias.

figures following observations can be made. 1) Even at 0V, alpha energy peaks are clearly resolved. 2) FHWM improves upon applying 10V reverse bias, and deteriorates marginally (∼3%) with a further increase in voltage. 3) At a given voltage, ^{244}Cm had maximum resolution and is followed by ^{241}Am and ^{239}Pu. The sensitivity of PIN diodes even at zero bias could be due to the diffusion current generated by the radiation induced charge carriers in the large intrinsic region of PIN diodes. Once the bias voltage is applied, the charge carriers gain momentum and will drift towards the electrodes, thereby increasing the resolution. Moreover, diode is almost depleted at 10V (see CV data in figure 2(b)) and therefore entire alpha particle energy is absorbed in the detector. This might be the reason for near-constant resolution after 10V. However, the marginal reduction in resolution with increasing bias could be due to the increase in background noise with increasing HV. The lower resolution of ^{239}Pu when compared to ^{241}Am and ^{244}Cm could be due to the existence of subsidiary peak near 5.143 MeV in this isotope which is unresolved [15].

Several authors have studied the effect of applied bias on the detector response. For example, Simon et al. [16] studied the spectroscopic features and charge transport properties of commercial PIN diodes at different reverse bias values between 0 to -100V while exposing them to 2 MeV He+ ions. Similar to our work, they found a well-defined peak even at the zero bias. With increasing bias voltage, peaks were more resolved and peak width (FWHM) was found to reduce. They attributed the same to the simultaneous increase in depletion region in all the directions. Day et al. [17] studied the effect of reverse bias on neutron detection efficiency in thin semiconducting boron carbide films. They also found, built-in voltage produces a narrow depletion region in which charge collection could occur even at zero bias. The addition of a bias to the device increases the collection of charges produced by both reaction products, resulting in a peak position that varied linearly with the applied voltage. Similar observations were reported by Hong et al. [18] while studying the effect of applied reverse bias on the neutron detection efficiency of semiconducting boron carbide films. They found that with increasing applied bias, the pulse height spectrum was broadened, and shifted to higher channel numbers. They attributed the same to the increase in depletion width, which allowed the charge collection over large region and internal electric field, which accelerates the charge carriers.

C. PIN diode size

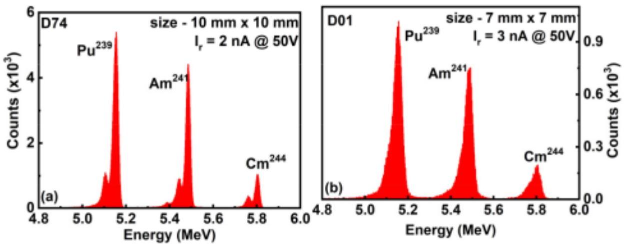

Fig. 5. Typical alpha spectra recorded using diodes of different size (a) 10 mm x 10 mm and (b) 7 mm x 7 mm.

Fig. 5 (a) and (b) show the typical alpha spectra recorded on 10 mm x 10 mm and 7 mm x 7 mm PIN diodes, respectively. The Table 1 below shows the estimated FWHM from these spectra. The leakage current at 50V in both the diodes was in the order of a few nA. Similarly, all other experimental conditions such as reverse bias, source detector distance, etc., were kept the same for both measurements. Somewhat counter intuitively, with reducing diode size, detector resolution was found to deteriorate. It might be due to increase in the incomplete charge collection in the partially depleted peripheral regions in smaller diodes as alpha source is not collimated.

TABLE I

FWHM VALUES EXTRACTED FROM FIGS. 5(A) AND 5(B).

Sl. No	**Diode Size** (mm x mm)	**FWHM** (KeV)		
		^{239}Pu	^{241}Am	^{244}Cm
1.	7 x 7	35.44	32.93	28.86
2.	10 x 10	24.6	21.11	19.84

D. Alpha source-detector distance

Fig. 6(a) and 6(b) show the typical alpha spectra recorded on a 10 mm x 10 mm PIN diode at 50V bias when the distance between the alpha source and detector was maintained at 8 mm and 48 mm, respectively. Fig. 6 (c) shows the variation of FWHM extracted from spectra for all three alpha energies with increasing source-detector distance. From these figures following observations can be made. 1) When the source-detector distance was increased by six times, detector resolution was found to improve by $\sim$ 62%. 2) In fig. 6 (a), the high energy side of the peak was found to closely fit to the Gaussian, while there exists a trailing at the low energy side. 3) At a higher source-detector distance, satellite peaks on the left of main peaks are seen for all three alpha energies.

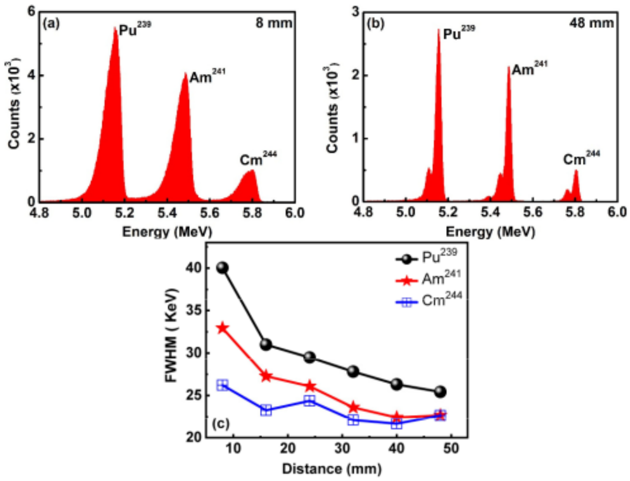

Fig. 6. Typical alpha spectra recorded when source detector distance is (a) 8mm and (b) 48 mm. (c) Variation of FWHM with increasing source-detector distance.

The tail at the low energy side seen in fig. 6 (a) might be due to the incomplete charge collection in the partially depleted peripheral regions on the edge of detectors [19]. When alpha particles are absorbed in the non-depleted region of the detector substrate below the guard ring and adjacent area, the generated carriers move towards the electrodes by the diffusion mechanism and only partially get collected by the electrodes. Therefore, such incidents lead to counts on the low-energy side [20]. With increasing source-detector distance, these incomplete charge collections resolve into a satellite peak, as seen in figure 6 (b). An increase in the distance also reduces the probability of alpha particles with angles less than 90º entering the diode surface. It is well known that these satellite peaks can be removed by collimating the alpha source or by biasing the guard rings [14]. However, in the present work, PIN diode guard rings are floating, and therefore satellite peaks are clearly seen.

E. Gamma radiation sensitivity

Fig. 7 (a) and 7(b) show the typical spectra recorded on a 10 mm x 10 mm PIN diode and at 50 V bias when they are exposed to gamma radiation sources of Na22 (1.27 MeV) and Ba133 (30 KeV, 81 KeV), respectively. These experiments were performed in air-tight chamber (no vacuum). It may be noted, as PIN diode thickness is less ($\sim$ 300 μm) gamma rays will escape, i.e. entire energy will not be deposited in the diode. Also, in these two experiments, no counts were recorded at higher energies, i.e. close to alpha energy peaks. However, it will be of concern while performing neutron detection experiments where the PIN diode has to detect significantly lower energy charged particles (1.47 MeV, 1.77 MeV (Li) and 0.83 MeV, 1.01 MeV (α)) from (n, α) reaction in ^{10}B.

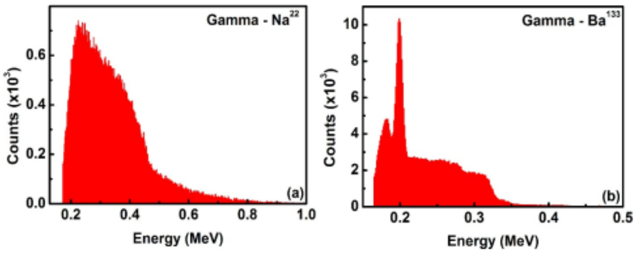

Fig. 7. Typical spectra recorded when PIN diodes were exposed to (a) ^{22}Na and (b) ^{133}Ba gamma radiation test sources. It may be noted no counts were recorded at high energies.

IV. Conclusions

PIN diodes were studied for the detection of alpha radiation. The role of various experimental parameters on the energy resolution of the detector was studied. Experiments performed in the present work revealed that the FWHM of alpha spectrum recorded using PIN diodes 1) is almost constant with applied reverse bias from 10 to 50 V, 2) increases with an increase in alpha source-detector distance and 3) decreases with reducing diode size from 10 mm x 10 mm to 7 mm x 7 mm. It was found that the energy resolution of the detector did not deteriorate until the diode leakage current was $< 1 \times 10^{-8}$ A. Both ^{22}Na and ^{133}Ba gamma sources were found to give counts in low energy region typically < 1 MeV. These results will be of value while exploring the PIN diodes for various radiation detection experiments.

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