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Investigation of radiation damage in a Si PIN photodiode for particle detection

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Abstract

The spectral response of a Hamamatsu S5821 Si PIN photodiode was investigated with a 2 MeV proton microbeam with high lateral resolution as a function of particle fluence and applied bias following irradiations with the same particles at the same energy without bias. It has been found that for reasonable high electric fields in the detector, between 10 and 100 V applied reverse bias, the signal amplitude (or charge collection efficiency) decreases linearly, whereas spectral peak FWHM increases within the investigated beam fluences up to 5×10^{11} protons/cm^2. Since these detrimental changes vary inversely with the electric field, therefore operating the detector at the highest possible bias value will minimize the influence of the radiation damage on the spectral performance.

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Keywords: Radiation hardness; IBIC; Si PIN photodiode; Microbeam; Charge collection efficiency

1. Introduction

By nowadays, commercially available Si PIN photodiodes have reached such high quality, which makes their application as an X- and γ-ray and/or charged particle detector [1] attractive both in nuclear reaction analysis and nuclear analytics. Their performance is comparable with that of dedicated semiconductor detectors, while the price/quality value makes them more competitive.

We have been using for several years Si PIN photodiodes at our nuclear microbeam facilities for different purposes, i.e. nuclear physics or beam current monitoring [2,3]. Recently Si PIN diodes have become very popular for thin sample analysis by scanning transmission ion microscopy (STIM) technique [4]. Our experience shows that besides their favourable properties Si PIN photodiodes tend to suffer performance degradation even at relatively low charged particle doses which can deteriorate the reliability of the analytical results [5,6]. Others also reported similar damage effects [7,8] for MeV protons; highly energetic neutrons and protons [9] or heavy ions (15 MeV Ni) [10] (15 MeV O and 10 MeV Au) [11].

The aim of this work is to investigate systematically the influence of radiation damage on the detection properties of a Si PIN diode with high lateral resolution from the point of view of microbeam applications. It is known that irradiation creates new energy levels in the forbidden energy gap of the detector material, which cause changes in the leakage current, the capacitance and charge collection efficiency (CCE). Although all three quantities influence spectral performance, the emphasis in the present work is put on the last one: the variation of the mean value of CCE; i.e. spectral peak position shift and the increase of the statistical fluctuation of CCE, i.e. spectral peak width widening (FWHM energy resolution) caused by radiation induced damage.

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2. Experimental

A Hamamatsu S-5821 Si PIN photodiode (1.2 mm in diameter, max. reverse bias 20 V, typical leakage current 50 pA at room temperature, 3 pF terminal capacitance at 10 V) has been chosen for our investigation because of its excellent properties i.e.: low noise, high energy resolution, high overbias capability, low price.

In order to study the radiation hardness of the PIN diode radiation damage was induced with area selective irradiations of the PIN diode with a focussed 2 MeV H^+ beam. The variation of the spectroscopic features as a function of particle fluence and applied bias was measured 'in situ' applying Ion Beam Induced Current (IBIC) method. These measurements were done at the nuclear microprobe facility of the Ruđer Bošković Institute. The 1 MV Tandem accelerator provided the beam which was focussed with an Oxford-quadrupole–doublet system down to $2 \times 5\ \mu m^2$. For the irradiations of 3×3 array of separate squares of a $100 \times 100\ \mu m^2$ area with 20 μm gap in between each were scanned with fluences, Φ, in logarithmic steps i.e.: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 and 5×10^{11} ion/cm^2. During irradiation the particle rate and irradiation time for the squares varied from 2×10^3 to $50 \times 10^3\ s^{-1}$ and from 1 to 20 min, respectively. For IBIC characterization the whole area was scanned afterwards including an additional virgin $330 \times 30\ \mu m^2$ area as a reference for each bias values. This was necessary to correct the possible drift of the system (beam energy, overall gain of the electronics, etc.). The IBIC scans were repeated with 2005 keV protons but the rate was kept below $10^3\ s^{-1}$ and the total dose was 10% of the minimum dose and 0.02% of the maximum dose applied for the irradiations. Bias voltages $U = 0$, 1, 2, 5, 10, 20, 50 and 100 V were set for IBIC runs while all irradiations were done at 0 V. Standard NIM electronics was used for signal processing. In order to suppress radiation induced current noise and diminish the effect of diffusion governed slow charge collection from the undepleted region $T = 0.25$ μs shaping time was set. Pulse height spectra were collected in a 256×256 pixel array in an event-by-event mode with the Spector data acquisition software [12]. From the listmode files IBIC data were extracted by position and spectra were generated. Since these spectra were mainly composed of a single peak with very few events in the low energy background and higher energy pile-up, as well, therefore they were fitted with simple Gaussians. Signal amplitudes, charge collection efficiencies and FWHM values are presented as a function of bias and irradiation fluence.

3. Results and discussion

Since the range of 2 MeV protons is about 50 μm in silicon[13] and the thickness of the diode is about 100 μm, it is important to know the thickness of the depleted region at each bias for the interpretation of the experimental data. Separate capacitance–voltage (C–V) measurements confirmed that the C–V curve does not change within the applied fluence range, therefore the same relationship can be used for the determination of the depletion depth as shown in Fig. 1. It can be seen that the depleted region is about 3 μm wide without external bias and 70 μm at 100 V.

Fig. 2 shows the IBIC maps of the whole area measured at 0 V and 100 V bias. The 3×3 array of the areas (with a gap in between) irradiated at varied fluences are denoted. Charge collection efficiency (CCE) was calculated as the measured signal amplitudes divided by the amplitude of non-irradiated regions obtained by extrapolation to infinite bias. Please note the range differences of CCEs at 0 and 100 V bias. This difference is primarily caused by the extent of the depleted region at the two bias values. Due to the short shaping time, mainly charge carriers created within the depleted region contribute to the measured signal pulse heights. Considering the actual depletion depth values, in addition to charge carrier drift there is a significant contribution of charge carrier diffusion from the undepleted region in the zero bias case. For 100 V reverse bias, protons completely stop within the depleted region and therefore CCE is close to 1.

In addition to the extremely large difference in CCE (~0.5 at 0 V and ~0.995 at 100 V) fine details of the radiation damage can also be observed on the maps. While at 100 V bias the contours of the irradiated regions are sharp and straight and the gaps can be distinguished; at 0 V bias the contours are smeared and rounded corresponding to inhomogeneous CCE distribution even within the squares in a form of a strong boundary effect. Similar inhomogeneous beam damage depending on the scanning size can be found in [7]. According to our experience this boundary effect occurs if the size of the irradiated area is commensurable with the proton range and the depletion layer thickness is smaller than the range. In our case these conditions meet at low bias voltages. So, despite the relatively well defined damage areas due to small lateral straggling of 2 MeV protons; electrons and holes created during

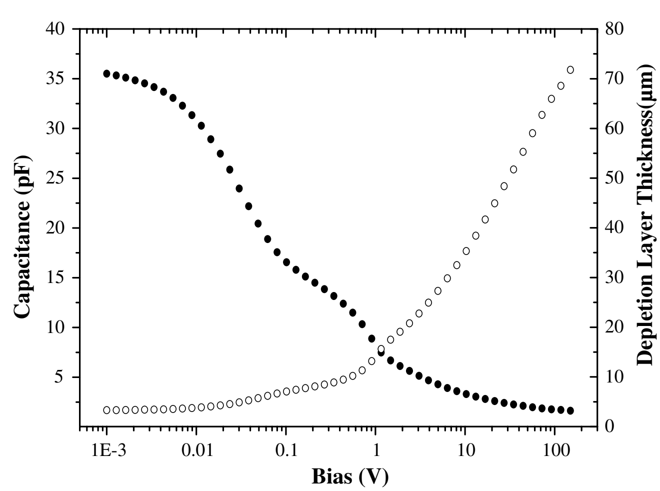

Fig. 1. Capacitance and depletion layer thickness as function of reverse bias for the Hamamatsu S-5821 diode.

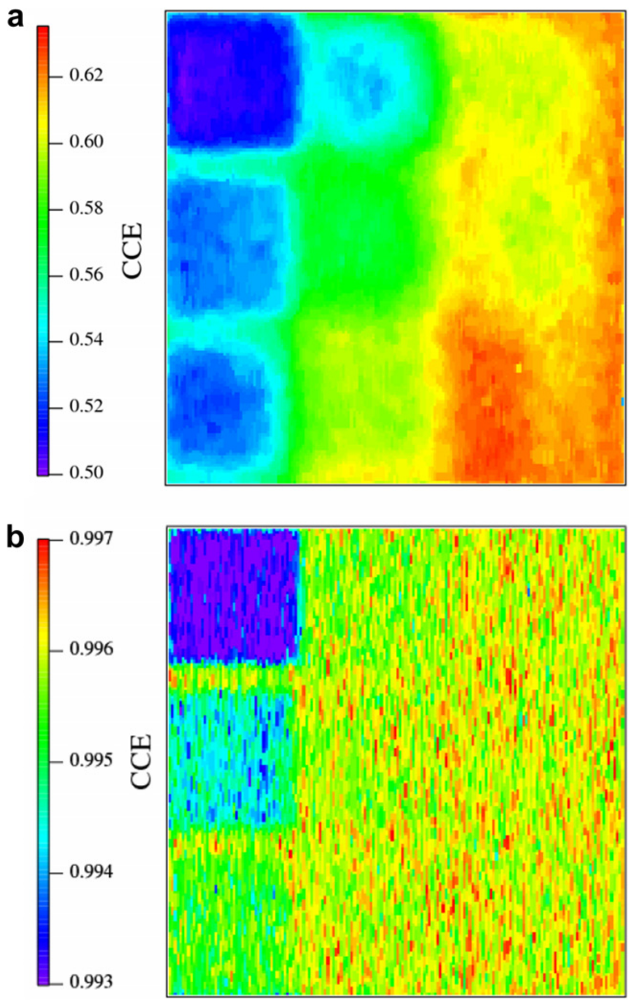

Fig. 2. IBIC map of the full irradiated area ($340 \times 340\ \mu m^2$) showing the individually irradiated $100 \times 100\ \mu m^2$ squares with fluences of 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 and 5×10^{11} ion/cm², respectively from bottom to top and right to left. Top: 0 V bias; bottom: 100 V bias. For discussion please see the text.

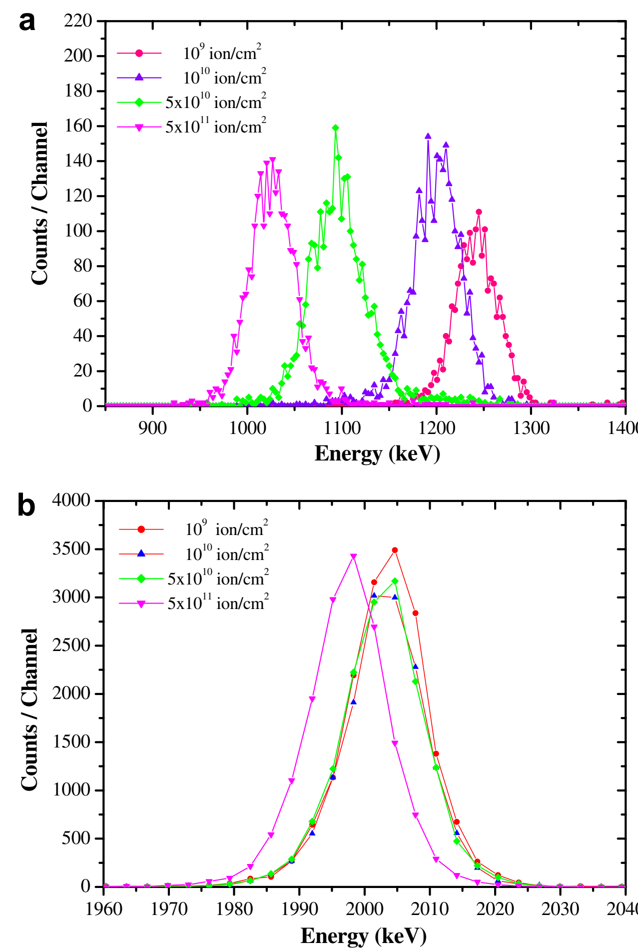

Fig. 3. Pulse height amplitude spectra obtained from the central $40 \times 40\ \mu m^2$ parts at various fluences of 2005 keV protons. (a) $U = 0$ V and (b) $U = 100$ V.

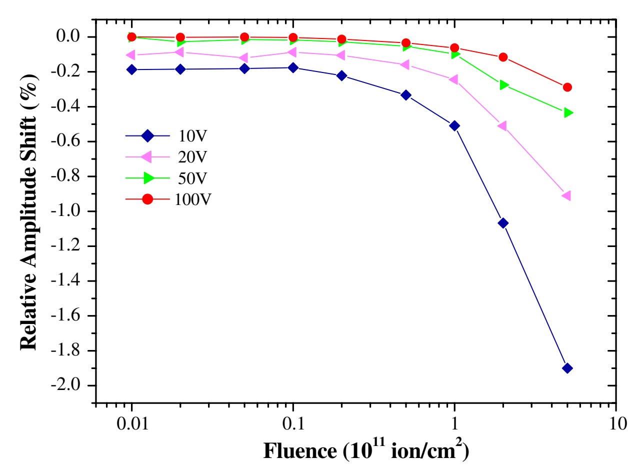

Fig. 4. The fluence dependence of the relative peak amplitude shift for 2005 keV protons. Peak amplitudes are determined as Gaussian mean value of spectra shown in Fig. 3(a) and (b). Please note that due to the semilogarithmic scale experimental data actually show linear dependence.

IBIC scans can have much larger lateral movement due to thermal diffusion in the undepleted region and even in the depleted region, too. Thus, charge carrier efficiency is the weighted average of the contribution from many carriers traversing regions with or without damage. Therefore, inhomogeneous charge collection distribution can be expected within (and outside) an irradiated area. This can be seen in Fig. 2(a) and (b): the effect is more pronounced at higher fluence and lower bias voltages.

To minimize the adverse effect of CCE non-uniformity we report in this paper spectra were taken only from the central $40 \times 40\ \mu m^2$ area of the $100 \times 100\ \mu m^2$ irradiated regions. Such spectra at 0 and 100 V at selected fluences are shown in Fig. 3(a) and (b).

Although spectra were taken in a wide bias range we report the results here only for bias voltages between 10 and 100 V, which are important from the point of view of applications as a particle detector. Relative peak shift and energy resolution as a function of cumulative fluence are shown in Figs. 4 and 5, respectively. In order to cover the whole fluence range the results are plotted in logarithmic abscissa scale.

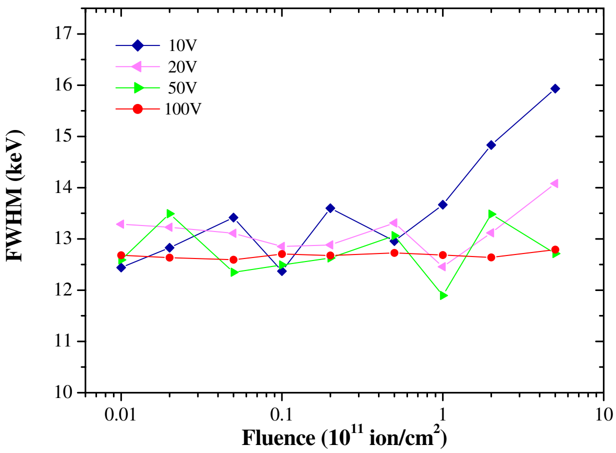

Fig. 5. The fluence dependence of the peak FWHM for 2005 keV protons. FWHM values are determined as fitted Gaussian FWHM of the spectra shown in Fig. 3(a) and (b). The energy resolution is between 12.4 keV and 13.5 keV within a wide range of fluences and bias voltages. Data at 100 V were taken with better statistics than at other voltages.

The pulse height variation rate is constant upto 10^{10} ion/cm^2 fluences. Its value is 2 keV/10^{10} ion/cm^2 and 1.6 keV/10^{10} ion/cm^2 at 20 V and 100 V respectively. Higher fluences cause more damage and the corresponding values are e.g. 18 keV/5×10^{11} ion/cm^2 (20 V) and 5.8 keV/5×10^{11} ion/cm^2 (100 V). Our results are in harmony with that of Aguer et al. [7] 4.0 keV/(200 protons/μm^2) i.e. 4.0 keV/2×10^{10} ion/cm^2 or Simons et al. [14] for a PIPS detector with 4 MeV He$^+$ ions 4.16 keV/1×10^{10} ions/cm^2.

The actual functional dependence of the peak shift is linear: the d(CCE)/dΦ slope parameter decreases with the increase of the applied bias. More accurately, for this particular diode it has been found to be inversely proportional to the applied bias. From the experimental data the radiation induced loss of CCE (<1) as a function of fluence and detector bias can be written as

$$\delta(\mathrm{CCE})_{\mathrm{rad}} = (-3.3 \pm 0.5) \times 10^{-13}\ [\mathrm{cm}^2\mathrm{V}]\,\frac{\Phi\ [\mathrm{cm}^{-2}]}{U\ [\mathrm{V}]}. \qquad (1)$$

This loss adds linearly to any loss existing without radiation damage.

Our results clearly show that contrary to the $U_{\max} = 20$ V bias value stated in its datasheet, several S5821 diodes successfully operate at much higher (even over 300 V) bias. This is advantageous in such cases where there is a risk of radiation damage whose effect can be suppressed by increasing the bias.

Contrary to the decrease of peak amplitude (or CCE), peak FWHM values increase with proton fluence. This increase is smaller the higher the bias. It can also be stated that the FWHM values obtained are approximately equivalent to that of dedicated PIPS detectors, they are more or less independent of the bias voltage without radiation damage and that practically there is no observable deterioration of the energy resolution up to the highest fluence of 5×10^{11} cm^{-2} – at the highest bias of 100 V used in our experiment. We also observed the effect reported by Aguer et al. [7], i.e. within a size range depending on many factors (the measure of the radiation damage and its depth distribution, scanning particle range, depletion depth) the smaller the irradiated area the larger the CCE in-homogeneity and correspondingly the larger the FWHM value from the whole area spectrum of such a region.

Due to the modest statistics of the spectral peaks from the small selected central areas of the irradiated regions and to the highest relative error in width estimation, the establishment of the quantitative dependences is not as straightforward as in the case of the amplitudes. The FWHM being the measure of fluctuation of the amplitude is more sensitive to the CCE non-uniformity than the mean amplitude. The total amplitude fluctuation is the quadratic sum of contributions from independent processes like (a) fundamental charge carrier creation statistics ('Fano noise'); (b) electronic noises; and (c) charge carrier loss "noise" caused by radiation induced excess trapping and/or recombination in addition to the effect of trapping/recombination already existing in the non-irradiated state. Despite the weak statistics a rather simple empirical relationship could be extracted from the experimental data for the radiation induced FWHM contribution, Δ_{rad}

$$\Delta_{\mathrm{rad}}\ [\mathrm{keV}] = (4.0 \pm 1.5) \times 10^{-5}[\mathrm{keVcmV}]\,\frac{\sqrt{\Phi\ [\mathrm{cm}^{-2}]}}{U\ [\mathrm{V}]}. \qquad (2)$$

This contribution adds quadratically to any FWHM resolution Δ_0 existing without radiation damage, resulting in a total resolution

$$\Delta = \sqrt{\Delta_0^2 + \Delta_{\mathrm{rad}}^2}. \qquad (3)$$

In order to confirm the above expression for the Δ_{rad} contribution more elaborate experiments are planned.

4. Conclusions

Selected areas of a small size Hamamatsu silicon PIN photodiode have been irradiated with various fluences of 2 MeV protons in the range of 1×10^9–5×10^{11} ion/cm^2 without applying any bias. In order to investigate the impact of the irradiation on the particle detection response of the diode the radiation induced changes were measured with IBIC mapping using also 2 MeV protons in a wide range of reverse bias, from 0 to 100 V in logarithmic steps. The major influence of the irradiation is the decrease of the charge collection efficiency (CCE), i.e. the shift of the spectral peak position towards lower energies and the increase of the dispersion of CCE, i.e. the widening of the spectral peaks, in other words the increase of FWHM values. Since within the irradiated regions these quantities show strong position dependence due to boundary effect, the evaluation of the experimental data is restricted to the central homogenous parts. Quantitative empirical relationships for the radiation induced contributions to the CCE and FWHM are derived in the form of Eqs. (1) and (2). These contributions add linearly to irradiation free CCE and quadratically to FWHM values, respectively. Since the effect of the irradiation – both on CCE and FWHM – is inversely proportional to the applied bias voltage, it can be significantly reduced by applying the possible highest bias without breakdown or increase of electrical noises due to increased leakage current.

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