Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research B 260 (2007) 304–308
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

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

A. Simon [a,*], G. Kalinka [a], M. Jakšić [b], Ž. Pastuović [b], M. Novák [a], Á.Z. Kiss [a]

[a] Institute of Nuclear Research of the Hungarian Academy of Sciences, P.O. Box 51, H-4001 Debrecen, Hungary
[b] Department of Experimental Physics, Ruđer Bošković Institute, P.O. Box 180, 10002 Zagreb, Croatia

Available online 14 February 2007

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.

PACS: 29.40.Wk; 41.75.−I; 61.80.−x; 61.82.Fk; 72.20.Jv

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.

* Corresponding author. Tel.: +36 52 509 211; fax: +36 52 416 181.
E-mail address: a.simon@atomki.hu (A. Simon).

0168-583X/$ - see front matter
doi:10.1016/j.nimb.2007.02.038

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

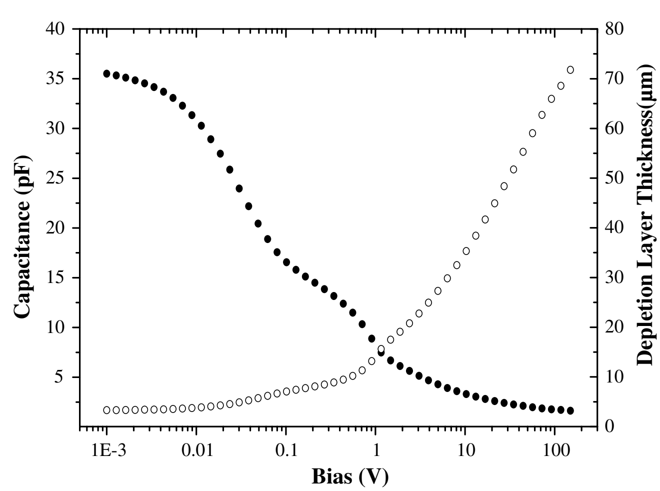

Fig. 1. Capacitance and depletion layer thickness as function of reverse bias for the Hamamatsu S-5821 diode.