Study of the PIN detector's radiation tolerance

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Abstract PIN detectors have been extensively used to detect charged particles and X-ray. The new type PIN detectors were irradiated by different energy protons, and their irradiation tolerance was investigated. Relative charge collection efficiency, energy spectrometer and relative energy resolution were also measured. With the increasing of irradiation dose, charge collection efficiency decreased and relative energy resolution grown. The results suggested that the irradiation tolerance in the PIN detector depended on the range of the protons in the detector. The maximum tolerance irradiation doses of the detector for the impacts of 3.5 and 7.2 MeV protons were 3×10^{10} p/cm^2 and 7.2×10^{9} p/cm^2, respectively.

Key words PIN detector, radiation damage, irradiation dose

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1 Introduction

A PIN detector includes three layers, N region and P region and an intrinsic region (region I) in between. The I region, in which the density of free electrons and holes equal to each other, is also named as active region. The PIN detectors were used extensively in nuclear detection due to the advantages of fast time response, high sensitivity and big volume [1—5]. The irradiation damage is unavoidable during the procession of the detection [6, 7]. Three kinds of defects: vacancy, interstitial and substitutional atoms are produced by the impact of particles on the Si crystal [4]. The characteristics of the detector become worse because of the defects, such as the increasing of dark current, the decreasing of charge collection ratio and so on .The goal of this study is to evaluate the irradiation tolerance of the PIN detector for impact of protons with different energies.

2 Experimental setup

The schematic drawing of the experimental equipments is shown in Fig. 1. The protons, which were accelerated to an energy of 3.5 or 7.2 MeV, impacted on the gold foil. The thickness of the gold foil are 10 μm for 3.5 MeV and 40 μm for 7.2 MeV, respectively. Parts of the protons was scattered by gold atoms and went into the PIN detector. The angle is 45 degree between the normal direction of the detector and the proton beam. The energy of scattered protons is considered to be the same as original because the energy loss of protons in gold foil, which is several keV, can be neglected [8]. However, the energy broadening of the 3.5 and 7.2 MeV protons are different for the different thickness of the scattering gold foils. The energy and dose of scattered protons were controlled by adjusting of the parameters of the accelerator.

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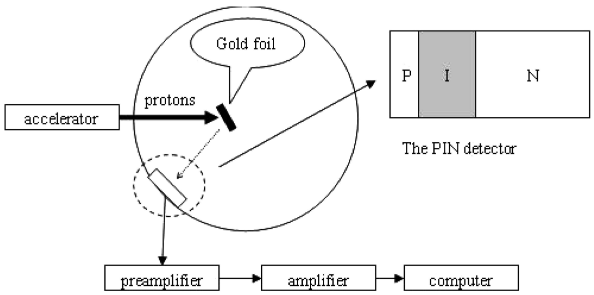

Fig. 1. the schematic drawing of the experimental equipments.

The configuration of the PIN detector is also shown in Fig.1. The region P is a layer of gold with a thickness of 50 nm, the region I has a thickness of 300 μm and region N has a thickness of several mm. The detector was biased with negative voltage −180 V. The distance from target to the detector was 20 cm and the detector had a solid angle of 5.02×10^{-3} sr. The base pressure in the target chamber was 1.0×10^{-2} Pa.

3 Experimental results

3.1 The relationship between range and radiation tolerance of detector

The protons with the energies of 3.5 or 7.2 MeV were implanted into the PIN detector. The protons with different energies have different ranges in the PIN detector. Table 1 shows the ranges of the protons in Si material[8, 9]. The ranges of protons in PIN detector approximately equal to the ranges of protons in Si material because the gold layer is too thin to be account. As can be seen from Table1, the range of the 3.5 MeV protons in the PIN detector is smaller than the thickness of the I region of the detector while the 7.2 MeV protons can just reach the N region of the detector.

Table 1. Protons energy versus the project range in the silicon material.

Energy (E/MeV)	project range (R/μm)	Straggling (ΔR/μm)
3.5	118	5
6	294	12
7.2	402	16

3.2 The relationship between the relative charge collection efficiency and the irradiation dose

The energy spectra of PIN under different irradiation doses and different proton energies are shown in Fig. 2 and Fig. 3. The energy channels decreased with the increases of the irradiation doses. Under the impact of the 3.5 MeV protons, the energy channel is 550 for a dose of 1×10^9 p/cm^2 and then changed from 530 to 307 as the irradiation dose increased from 1×10^{10} p/cm^2 to 1×10^{11} p/cm^2. As for the 7.2 MeV protons, the peak channels are 486 and 250 for irradiation doses of 7.2×10^9 p/cm^2 and 5×10^{10} p/cm^2, respectively. One can find from Fig.2 and Fig.3 that the full width at half maximum (FWHM) for the 3.5 MeV protons is smaller than that of the 7.2 MeV protons. This was because the target foils for 7.2 MeV and 3.5 MeV proton beams are different in thickness and thus result in different energy broadening.

The peak channel is proportional to the total charge which was induced by the impaction of the protons and collected by the detector. The charge induced by the protons with a definite energy is constant. The shift of the channel was due to the decrease of the charge collection efficiency (CCE). Fig. 4 shows the relationship between relative CCE and irradiation dose. The relative CCE is defined as

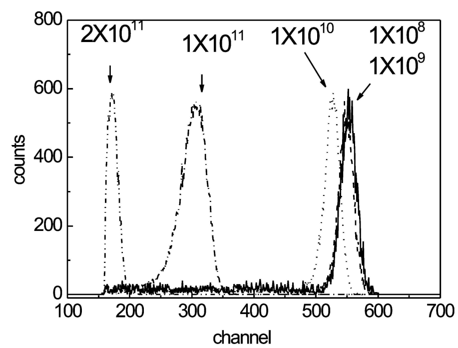

Fig. 2. The energy spectrum of PIN under various irradiation doses of 3.5 MeV protons.

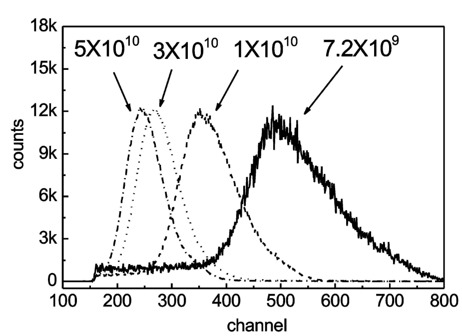

Fig. 3. The energy spectrum of PIN under various irradiation doses of 7.2 MeV protons.

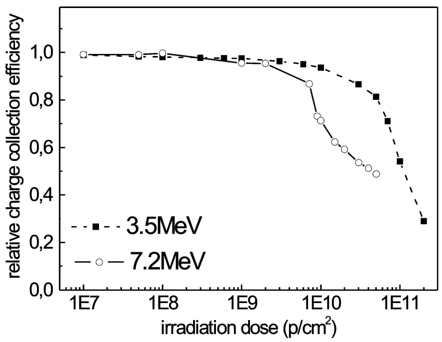

Fig. 4. The dependency of relative charge collection efficiency on the irradiation dose. ■ the protons with energy of 3.5 MeV, ○ the protons with energy of 7.2 MeV.

$$\text{Relative charge collection efficiency} = \frac{\sum Q(D)}{\sum Q(0)} \ . \quad (1)$$

Where the $\sum Q(D)$ is the total charge collected by the detector at a specific irradiation dose, the D is the irradiation dose, and the $\sum Q(0)$ is the total collected charge without irradiation. In practice, the $\sum Q(0)$ was replaced by $\sum Q(10^7 \ \mathrm{p/cm^2})$ because the $\sum Q(0)$ can not be attained by experiment. Fig. 4 shows that the relative CCE was almost constant when the irradiation dose was lower than 10^{10} p/cm^2 for the impact of 3.5 MeV protons. It decreased dramatically as the irradiation dose increased from 3×10^{10} p/cm^2 to 2×10^{11} p/cm^2. The relative CCE with impact of 7.2 MeV protons had same trend with that of 3.5 MeV when the irradiation dose was lower than 7.2×10^9 p/cm^2. The relative CCE dropped fast when the irradiation dose was larger than 1×10^{10} p/cm^2.

3.3 The relative energy resolution versus the irradiation dose

The relative energy resolution is one of the important parameters for the detector. It is defined as

$$\text{The relative energy resolution} = \Delta E/E\times100\% \ . \quad (2)$$

Where E is the projectile energy and ΔE is the FWHM of the peak that was measured. The ΔE is defined as following

$$\Delta E = \sqrt{\Delta E_i^2 + \Delta E_e^2 + \Delta E_s^2} \ . \quad (3)$$

Where ΔE_i, ΔE_e and ΔE_s are the broadening of projectile energy, the system error and the statistic error, respectively. The typical resolution of a semiconductor detector is 4% for ideal single energy ions. The broadening of projectile energy and the statistic error didn't change during the measurement. Fig. 5 gives

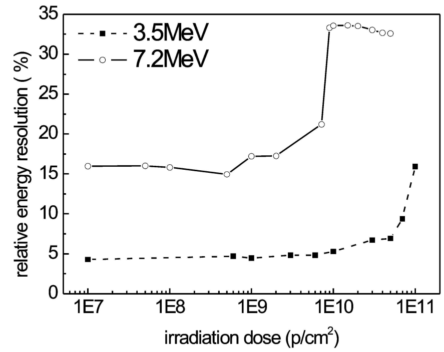

Fig. 5. The relationship between irradiation dose and relative energy resolution. ■ the protons with energy of 3.5 MeV, ○ the protons with energy of 7.2 MeV.

the dependency of the relative energy resolution on irradiation dose of different incident energies. The irradiation dose had few influence on the relative energy resolution below the specific thresholds which are 3×10^{10} p/cm^2 and 7.2×10^9 p/cm^2 for impacts of 3.5 and 7.2 MeV protons, respectively. When the irradiation dose was above the threshold, the relative energy resolution increased quickly. The relative energy resolution of 7.2 MeV protons is worse than that of 3.5 MeV protons because the broadening of the 7.2 MeV protons is bigger than that of 3.5 MeV protons.

4 Discussions

When a proton hits the detector, it excites the electrons out of their energy level and consequently leaves the holes. The electrons driving by electric field move to N region. The signal of the detector is the displacement current that produced by thousands of electrons. The amplitude of the signal depends on the number of the electrons which can arrive at N region. Three kinds of defects, vacancy, interstitial and contaminant, can be produced by irradiation of the protons in the detector. The interstitial and contaminant can capture and "trap" electrons. More and more electrons were trapped due to the increasing number of interstitial and contaminant during irradiation. As a result, the charge collection efficiency of the detector decreased and the peak position shifted to a lower channel. The protons with energy of 3.5 MeV produced all kinds of defects in I region but had no influence on N region for its range was less than 300 μm. The protons with energy of 7.2 MeV can produce defects in both I region and N region. Both vacancy and interstitial defects could exist in the I region, whereas all of the defects were produced in the N region. The specific threshold of the irradiation tolerance of 3.5 MeV protons is several times lager than that of the 7.2 MeV protons. Comparing with different irradiation energy, one can find that the tolerance of the detector depends on the energy of projectile and N region is more sensitive to irradiation than the I region.

5 Conclusions

The protons with energy of 3.5 and 7.2 MeV were bombarded on gold foil and part of the protons were scattered by gold atoms into the PIN detector. The spectra of scattered protons were measured with different irradiation doses. The influence of the irradiation dose on the relative energy resolution and the relative CCE was studied. The relative CCE and the relative energy resolution grew when the irradiation dose of protons increased. The maximum of the tolerance irradiation dose of the 3.5 and 7.2 MeV protons are 3×10^{10} p/cm2 and 7.2×10^{9} p/cm2, respectively. The results suggest that the radiation tolerance in the PIN detector depends on the range of protons in the detector. The N region was more sensitive to irradiation than I region.

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