Thick and Large Area PIN Diodes for Hard X-ray Astronomy

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Abstract

Thick and large area PIN diodes for hard X-ray astronomy in the 10 to 60 keV range are developed. To cover this energy range in a room temperature and in a low background environment, Si PIN junction diodes of 2 mm in thickness with 4 cm^2 in effective area were developed, and will be used in the bottom of the Phoswich Hard X-ray Detector (HXD), on-board the ASTRO-E satellite. Problems related to a high purity Si and a thick depletion layer during our development and performance of the PIN diodes are presented in detail.

Key words: Thick; Si PIN diode; Na contamination; Hard X-ray Astronomy

1 Introduction

CCD is the best detector in X-ray astronomy below 10 keV from space. CCDs afford not only a high spatial resolution but also a high energy resolution of almost 100 eV(FWHM) at 4.6 keV without a heavy cryogenic system. CCDs also show a very low background when combined with a focusing X-ray mirror. However the mirrors limit the energy range of the CCDs to below 10 keV [1]. On the other hand, above 30 keV, scintillation counters are very common and yield a very high efficiency. A low background profile can be also achieved using two different crystals with a different decay time constant (Phoswich). However in the 10 to 50 keV range, there was no good detector with both high detection efficiency and low background. Gas counters were common but have low efficiency in the high energy end. We have surveyed several possible detectors for room temperature operation. CdTe, CdZnTe, and Si PIN junction detectors are the candidates. However at the time of our design start in 1990, CdTe and CdZnTe were very tiny in size and not useful to make up a large area detector. HXD on-board ASTRO-E is required to have a large collecting area of at least 200 cm^2. Only large area and thick Si PIN junction diodes can satisfy the requirements. They should be at least 2 mm in thickness to cover the energy up to 50 keV. Problems related to thick PIN diodes are discussed.

2 Raw material

To cover up to 50 keV with Si, we originally considered to develop 2 mm thick PIN diodes and stack two of them into 4 mm thickness [4–6,8]. However we are now considering a single 2 mm diode to have better energy resolution. We searched for a high purity N-type Si ingot with 3 or 4 inches in diameter. Two companies sent samples in stock but only TOPSIL in Denmark accepted our small order to manufacture them in a commercial base. We checked the quality of the TOPSIL ingot using the photo-luminescent method [10]. Illuminating the Si substrate with laser light in the liquid He, we measured the intensities of the luminescent lines as shown in figure 1. We also measured a Si wafer of Japan Industrial Standard(JIS) with known impurities as a reference. The luminescent peaks from Si lattice (I_{TO}) and also from the impurities of P and B are clear. The measured impurities of the TOPSIL material are less than the JIS sample. The measured impurities are roughly $7 \times 10^{11}\mathrm{cm}^{-3}$ for B and P, and these values support the 15-20 kohm-cm quality comparing the JIS sample of 10 kohm-cm and the Komatsu of 8 kohm-cm. A required voltage of the 2 mm depletion depth is $V = qNW^2/2\epsilon$ where N, W, and ϵ are the impurity, depth, and dielectric constant respectively. For N, the difference of $N_P - N_B$ is more important and might be at approximately $10^{11}\mathrm{cm}^{-3}$. Based on these values, we estimated a required full depletion voltage of about 500

volts. Thus, we set a target voltage for the electrode breakdown to be more than 1000 volts.

3 Design of Electrodes

Thick PIN junction diodes with small leakage current without a breakdown up to 1000 volts are not easy to produce. At the start of our design, we noticed that the depletion layer developed parallel to the surface together with the depth. Simple and smaller electrodes (figure 2E) are favorable from the point-of-view of an effective use of Si, but could not satisfy the higher breakdown requirement. The depletion front extends and is easy to touch dicing edges where dislocations are many. Figure 2A, with more space, showed a higher breakdown but could not satisfy the requirement. Then, we tested the breakdown voltage by adjusting a location of only one guard-ring electrode relative to the anode of P^+. Figure 2B shows the best location for a higher breakdown. It is well known that there is a best location for a guard-ring [11] but one guard-ring did not satisfy the 1000 volts, even when we used the field plates and a N^+ stop to avoid touching a depletion front to the edge of the substrate. Then, we tested multi guard-rings to divide the 1000 voltage into several PN junctions. This truly increased the breakdown voltage depending on the number of guard-rings but also resulted in a larger leakage current. Finally we used two guard-rings together with the field plates on each guard and the N^+ stop at the edge of the substrate. This design, figure 2F, satisfied the breakdown voltage of more than 1000 volts and also a low leakage of less than 1 nA at -20 degree C [7].

4 Protection from Dusts and Humidity

The gaps between each guard-ring electrodes and P^+ are very narrow. Small dust and humidity easily produce a discharge. In fact, for the bare diodes, we observed a discharge between the bonding wire and the edge of the inner field plate. Thus, we were forced to consider a thin layer of a protective coating. This should be thin enough to detect 10 keV photons. An elastic silicone resin was first considered. The resin protected the surface from dusts and humidity, but during the acceleration test of the silicone, a quick decrease of the breakdown voltage was observed as shown in figure 3. We think that the decrease is a contamination from the coated material to the high purity Si. The acceleration condition used for the test was a continuous 500 volts for the junctions at 50 degree C. The decrease took a time of several hours to a day. We analyzed impurities of the silicone such as K and Na by SIMS

(Secondary Ion Mass Spectroscopy) and discovered high Na concentration of about $10^{20}\mathrm{cm}^{-3}$ not only in the surface but also at the Si-SiO_2 interface as shown in figure 4. To make sure of the Na effect, we boiled the same PIN diodes in a salted water and observed the same decrease. The Na ions trapped in the interface prevented the depletion front from freely expanding and resulted in a strong electric field concentration. This understanding is justified by simulating electric fields using 2D device simulator (ATLAS) [12] as shown in figure 5a, b, and c. Without the Na concentrations, the depletion front develops freely but with Na ions of the same amount measured by SIMS, the depletion front cannot expand to the substrate. We guess that not only the ions screening but also the ion movement against the anode due to the strong electric field is also the key to the decrease. Thus, we applied a protective coating of 3 μm polyimide. The polyimide did not produce any decrease of the breakdown voltage. The high purity Si is very sensitive to contaminations.

5 Protection from Vibration

These PIN diodes will be used for HXD on-board ASTRO-E [4,5,8], which will be launched by the M-V solid motor in the year 2000. We must clear the vibration environment of 20 G (rms) in 20-2000 Hz. The distance between the anode and the ceramic base is 3 mm. The bonding wires of 10 micron gold in diameter are not safe for the level. The potential difference between the field plate and the bonding wires is 1000 volts during the test. To protect the gaps and wires from mechanical tolerance during the launch, we again require a small amount of elastic silicone resin to hold the bonding wires. Although the elastic silicone resin was carefully used only on the protective polyimide coating to avoid Na contamination, we observed again a quick decrease of the breakdown voltage during the acceleration test. A strong electric field in the silicone resin drifts the ions and cancels the parallel electric field. This field cancelation resulted the stronger electric field at the both edges of the junction and then N^+ side breaks. After removing the silicone resin from the gap of junctions but not from the field electrodes, the breakdown was not observed.

6 Performance

We achieved good performances of the 2 mm thick Si PIN diodes with 4 cm^2 in effective area. The leakage current is 1 nA at -20 degree C and at the full depletion of 500 volts. Typical I-V curves are shown in figure 6. The noise contribution of 1 nA leakage at -20 degree C, which can be attainable without any cryogenic cooling system in the ASTRO-E satellite, is negligible compared

with the capacitance of 20 pF. An energy resolution of roughly 3 keV (FWHM) is observed at 2 μsec. These will be placed in the bottoms of the Phoswich scintillators of the HXD detector [4,5,8] to reduce the background. We expect a background level of 10^{-5} counts cm^{-2} s^{-1} keV^{-1} at 50 keV.

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Figure Captions

Figure 1

Photo-luminescent spectra of the JIS sample, the Komatsu sample and the TOPSIL sample. The resistivity of the JIS sample is about 10 kohm-cm and 8 for Komatsu sample. TOPSIL is estimated to be more than 15 kohm-cm.

Figure 2

Several electrode designs tested. Design F was closer as giving the lowest leakage current.

Figure 3

Sudden decrease in breakdown voltage. There was no breakdown at the start of the test, but decreased to several tens of volts after the acceleration test. This decrease was recovered a little after several weeks in a room temperature.

Figure 4

Na concentration by SIMS at the surface and the Si-SiO_2 interface.

Figure 5a, b, c

2D ATLAS simulation of the Na ion effect. a) Schematic view of the design parameters. b) Without the Na ions and c) With the Na ions. The depletion front in the figure 5c extends freely but not with Na ions.

Figure 6

I-V curves from -30 degree C to $+20$ degree C. Typical leakage current at -20 degree C and at 500 V is roughly 1 nA for the 2mm thick and 4 cm^2 in effective area PIN diodes.