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Direct Measurement of Electron-Tracks Using a Charge Coupled Device

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Abstract

We present two-dimensional projections of various electron tracks in silicon. A charge-coupled-device (CCD) was exposed to β-rays (976 keV and 1048 keV) from ^{207}Bi radio isotope. The incident angle of the β-rays was set to be a grazing incidence of $\sim$13 deg. The β-rays deposit charge in the pixels according to their tracks. Thus the obtained images show two-dimensional projections of the β-ray tracks. This experiment is useful for diagnosis of CCDs. We also show a thickness measurement of the depletion layer of a CCD.

1 Introduction

Charge coupled devices (CCDs) as a X-ray detector are now widely used. As well as its imaging capability, a CCD has many advantages as a X-ray detector. If a CCD is used as a photon counting and the incident X-ray intensity is enough low so as to avoid a multiple photon detection, a CCD has a good energy resolution [1,2]. A CCD also can measure polarization of X-ray photons by analyzing the charge cloud distribution produced by a single X-ray[3]. In the X-ray astronomy, now a CCD is one of a standard focal plane detector of X-ray telescopes[1,4,5].

2 Motivation of this work

In order to deduce the maximum capability of CCDs, the measurement of the internal structure of the CCD, such as the thickness of the depletion layer, is important. Also understanding of the behavior of electrons in a CCD is required. In figure 1, a schematic illustration of a cross section of a front illuminated CCD and a behavior of electrons are shown.

A front illuminated CCD has various gate structures on the top of the CCD, which acts as a dead layer for X-ray detection. X-rays, which penetrate the dead layer, are absorbed by Si due to a photo-electric interaction and then a photo-electron is created. The photo-electron ionizes surrounding atoms and produces a number of electron-hole pairs. The number of the electron has an information on the energy of the incident X-ray. However, the behavior of the electrons is complicated, because the internal structure of a CCD is complicated. The electrons created near the boundary of the pixels are divided into two or more number of pixels. Furthermore, if electrons are created in the channel-stop, only a part of the electrons will be detected as a signal[6,7]. Although electric field is strong in the depletion layer and the diffusion of the electrons is small, the electric field is weak below the depletion

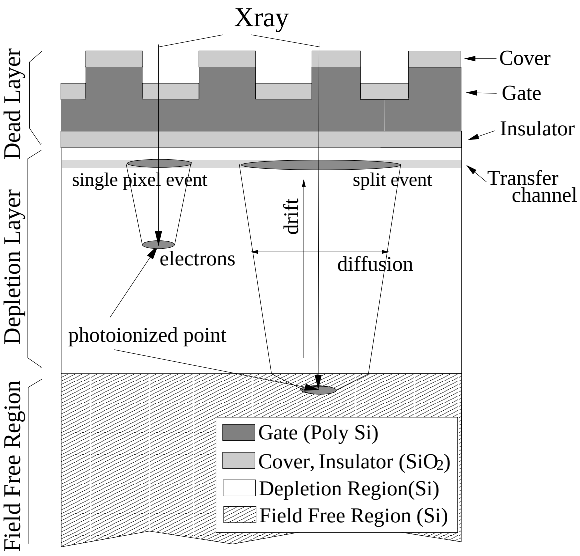

Figure 1: A schematic illustration of a cross section of a front illuminated CCD. Behaviors of electrons which detected in the depletion layer and in the field free region are illustrated.

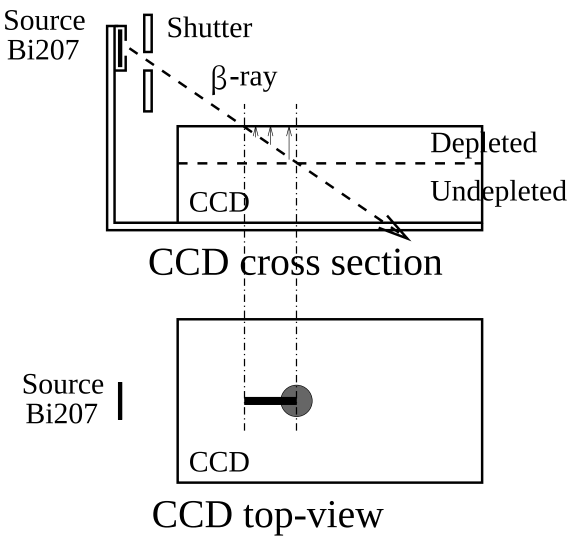

Figure 2: An illustration of the idea of the β-ray experiment. The top figure shows a side view and the bottom figure shows a top view.

layer (field free region) and the electrons diffuse out. Therefore measurement of the energy and even detection of such X-rays absorbed below the depletion layer is difficult.

The determination of the detection efficiency of CCDs is difficult. The major reasons are (1) the detection efficiency depends on the event extraction method. (2) the detection efficiency depends on the used environment, such as a X-ray intensity, applied clock voltages and so on. Many attempts to measure the detection efficiency have been reported [8,9,10,11,12]. The thickness of the depletion layer closely relates to the detection efficiency. However the complex gate structure makes the geometry of the depletion layer complex. If the effective thickness of the depletion layer can be measured, it is useful for modeling the CCD.

For this purpose, we exposed a CCD to β-rays. Figure 2 shows an idea of this β-ray experiment. The incident angle of the β-rays is fixed to be a grazing incidence. Since the CCD operates as a full frame transfer, we used a shutter in order to avoid injections of β-rays during a charge transfer. Thus the incident angle of β-rays can be always derived from the position of an image.

The electron-hole pairs are created according to the track of β-rays. Thanks to the good imaging capability of the CCD, two-dimensional projections of β-ray tracks onto the CCD surface can be seen. Also the charge spread by diffusion of the electrons is measurable. If the β-rays run straightly in the Si, the depth of the secondary electrons created by the β-ray can be determined from the geometry. Then we can find the charge spread as a function of depth of the secondary electrons. The thickness of the depletion layer can be also derived from this measurement. Although for the purpose of the CCD diagnosis, a straight track of β-rays is favorable, the incident β-rays may be sometimes scattered by the atoms and may not run straightly. In any case, we can see two-dimensional projections of β-ray tracks onto the CCD surface.

In this work, we will report the results of the β-ray experiment. Some collections of two-dimensional projections of β-ray tracks are presented. The derived thickness of depletion layer is also presented.

3 Experiments

For a β-ray source, ^{207}Bi radio isotope is selected. ^{207} Bi is a conversion electron source and emits mono-energetic β-rays. The measured spectrum with a windowless Si(Li) detector is shown in figure 3. Two peaks by β-rays (976 keV and 1048 keV) are clearly seen. Some γ-rays are also emitted. Since the range of the β-rays are roughly 2mm, significant fraction of the β-rays will run straightly in Si while it has enough energy.

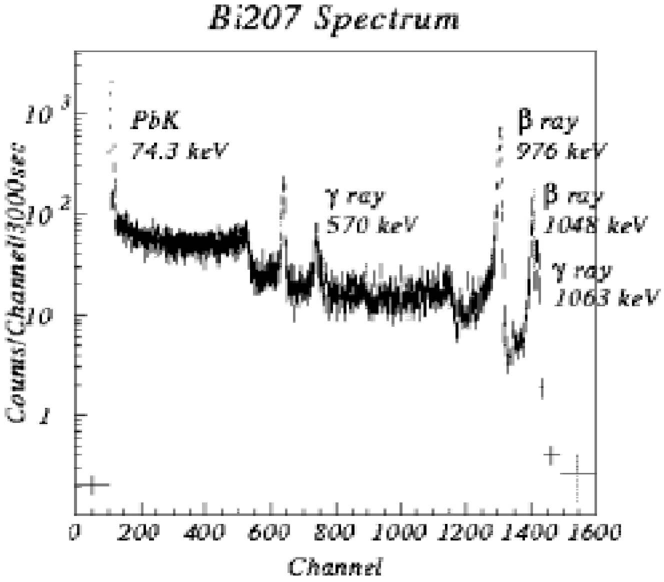

Figure 3: The energy spectrum of ^{207} Bi obtained by a windowless Si(Li) detector. Two peaks at 976 keV and 1048 keV are by mono-energetic electrons.

The used CCD is a front illuminated CCD produced by HAMAMATSU K.K . The pixel size is 12 μm square and the number of pixels are 512 $\times$ 512. The CCD is cooled down to $\sim -100^o$ C using LN_2. A shutter is installed on the front of the ^{207}Bi source. The size of the β-ray source is less than 0.5mm. A schematic illustration of the experimental setup is shown in figure 4 and the pictures are shown in figure 5 and figure 6. The incident angle of the β-ray is ranging from 12 deg to 14 deg according to the position of the imaging area of the CCD. 300 images with an exposure time of 50 sec are obtained.

4 Electron Tracks

One example of the CCD image is shown in figure 7. β-rays were exposed from right side of the figure. Many tracks can be seen. Since the ^{207}Bi emits γ-rays as well as β-rays, we extracted the candidates of β-ray events. The horizontal straight lines with diffuse image at the left end were picked up. Six examples of the extracted images are shown in figure 8. The straight and thin tracks correspond to the electrons from the depletion layer and the diffuse image corresponds to the field free region below the depletion layer.

From these data we can deduce the thickness of the depletion layer and also measure the diffusion of the electron as a function of the depth from the surface. Here we show the results of the measurement of depletion layer thickness. First we extracted an favorable events; straight thin track events with

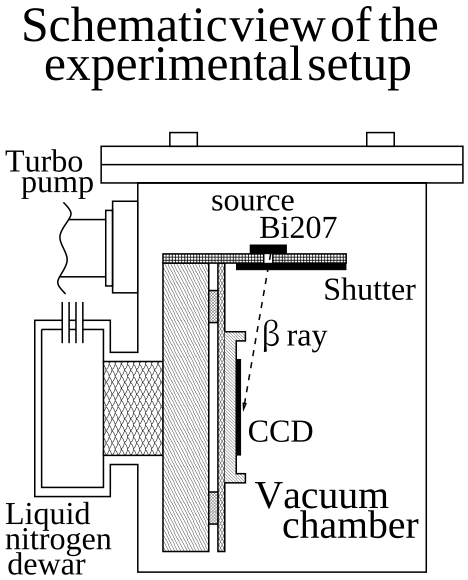

Figure 4: The schematic illustration of the experimental setup.

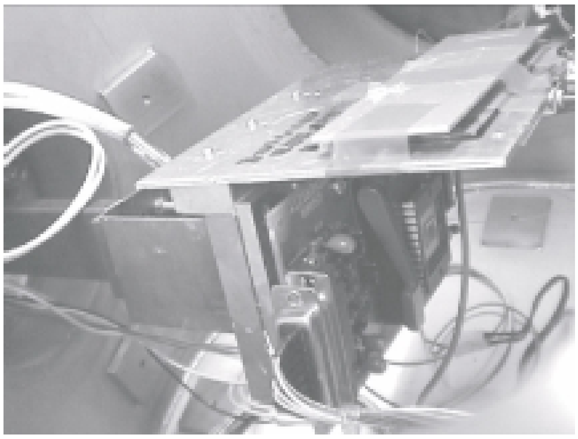

Figure 5: A picture around the CCD. A shutter and a ^{207}Bi radio-isotope are equipped on the upper side in the picture.

diffused end-point. We derive average lengths of the straight and thin region of the tracks. The detail of the extraction criteria will be published elsewhere.

Figure 9 shows the average lengths of the straight part of the tracks as a function of the position of the imaging area of the CCD. The data are fitted by an expected curve with a parameter of the depletion layer thickness. The best fitted curve is plotted in the figure. The preliminary result of the depletion layer thickness is $10.52\pm0.08\mu$m.

5 Summary

We exposed a CCD to β-rays from ^{207}Bi. Many candidates of the β-ray events are obtained. The images of the β-ray events are considered to be two-dimensional projections of the β-ray tracks. The preliminary thickness of the depletion layer is $10.52\pm0.08\mu$m.

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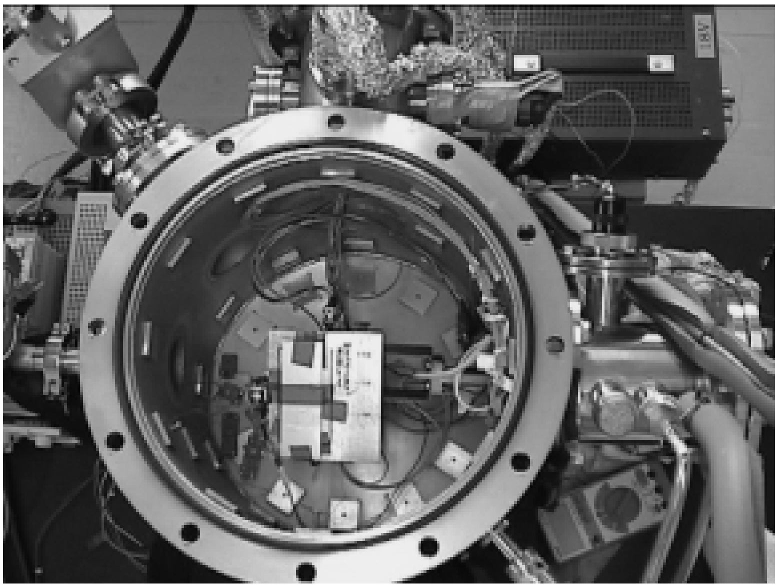

Figure 6: A picture of the experimental setup. The CCD and the β-ray source are installed in a vacuum chamber.

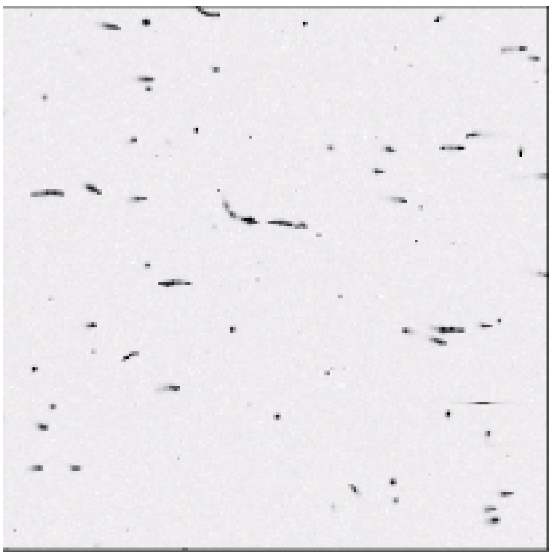

Figure 7: One example of the CCD image. The β-ray was exposed from right side.

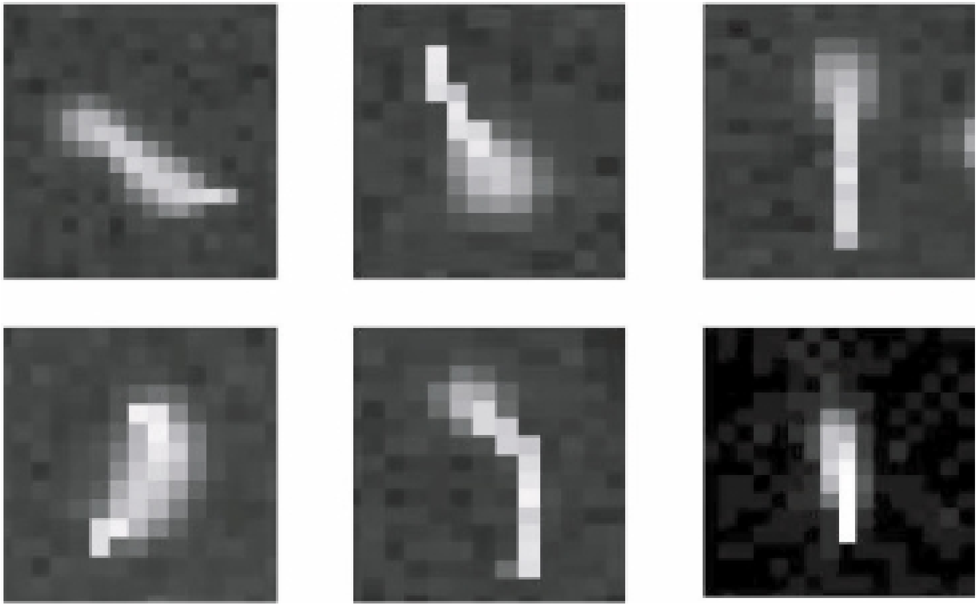

Figure 8: Six examples of images of the β-ray events. The pixel size is 12 μm.

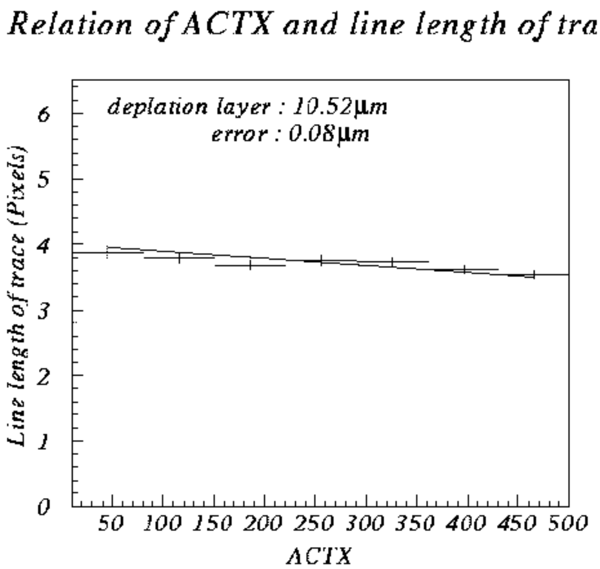

Figure 9: Average length of straight-thin region of the β-ray tracks as a function of the position on the imaging area of the CCD. Best fit expected curve is also plotted.