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Detection of neutron-induced events and neutron/γ-ray discrimination with an imaging capability of a P-channel X-ray CCD

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ABSTRACT

We report a direct detection method of fast neutrons and neutron/γ-ray discrimination using a P-channel X-ray CCD. The CCD has a depletion layer of $\sim 300\,\mu m$ and has a pixel size of $15\,\mu m \times 15\,\mu m$. With such a thick depletion layer, this device has a capability of being a neutron imager without any external converters. We conducted neutron irradiation experiments with the P-channel X-ray CCD by using a fast-neutron source ^{252}Cf, which also emits γ-rays with an average energy of 0.85 MeV. We found two types of events in CCD images; one has a small point-like shape and the other has an elongated shape with a head–tail structure. Electrons scattered by the MeV γ-rays travel much longer than silicon nuclei kicked by the fast neutrons. Therefore it is likely that the point-like events are produced by the neutrons, while the head-tail events are due to the γ-rays. By analyzing the event shapes quantitatively, we conclude that the P-channel X-ray CCD can detect fast neutrons and the imaging capability of the CCD makes it possible to distinguish neutron-induced events from γ-ray-induced events. The detection efficiency of the neutrons and the rejection factor of the γ-rays with the CCD detector are about 0.4% and 70%, respectively.

1. Introduction

Various types of neutron detectors such as gas detectors, scintillators, and semiconductors have been developed for several decades. They are essentially the same as ionization detectors used for detecting charged particles except for the primary neutron-to-charged particle conversion process.

Recent progress on neutron detectors enables us to take radiographic neutron images, which are applied to non-destructive testing techniques for example. High spatial resolution and high detection efficiency are necessary for such a purpose as well as a low background level. Ordinary neutron imaging systems are too large to be portable. Therefore we need more compact detectors with sufficient spatial resolution and sensitivity.

An X-ray charge-coupled device (CCD) is a popular X-ray imager with spatial resolution of $\sim 10\,\mu m$ and is used in various applications such as astronomical X-ray observations. We have developed a P-channel (P-ch) X-ray CCD with a very thick depletion layer of $\sim 300\,\mu m$ in order to detect higher-energy X-rays above 10 keV [1,2].

As an application of the P-ch X-ray CCD, we consider a fast-neutron imaging detector. A CCD with a thick depletion layer would provide a sufficient detection efficiency without any additional neutron-to-charged particle converters. Moreover, such a solid detector has a large detection efficiency per unit volume. The interaction probability per detector thickness (or the attenuation coefficient) of the CCD reaches about $10\%\,cm^{-1}$, which is much higher (by a factor of $\sim 10^3$) than those of gas detectors and comparable to those of the most sensitive scintillators ($\sim 15\%\,cm^{-1}$) [3]. Therefore the CCD is a candidate for a handy-size neutron imager. The most remarkable merit of using the CCD is the excellent spatial resolution, which is determined by the pixel size (typically $\sim 10\,\mu m$). It is difficult to achieve such high resolution with gas detectors or scintillators. Some converter-based detectors for fast neutrons (e.g. [4]) also have both high detection efficiency and imaging capability. Because of the propagation of secondary particles, however, event positions registered at the sensor part are randomly displaced from the neutron interaction points. The mean displacement is approximately proportional to the thickness of the conversion part. Thus, there is a trade-off between the detection efficiency and the spatial resolution with converter-based neutron detectors. In fact, typical spatial resolution of those detectors with high detection efficiency more than $\sim 1\%$ are not better than several $\times 100\,\mu m$ [4]. Therefore, the direct neutron detection with the CCD can achieve superior spatial resolution even compared to the converter-based neutron imager. The overall features expected for a fast neutron imager with the P-ch X-ray CCD are summarized as

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follows: (1) exclusive spatial resolution, (2) sufficient detection efficiency relative to other types of detectors, and (3) possibility of being handy-size detector thanks to the high density. Such a detector would be a candidate of portable sensors for non-destructive testing with excellent spatial resolution.

For any neutron detectors, suppressing γ-ray backgrounds are indispensable to attain a high signal-to-noise ratio. Scintillation detectors use the pulse-shape discrimination between neutrons and γ-rays [5]. Such a method, however, cannot be available with CCD detectors. Instead of the pulse-shape discrimination, we would be able to distinguish neutron-induced events from γ-ray-induced events by their event shapes in CCD images.

Here we describe how to detect fast neutrons and distinguish them from γ-rays with the P-ch CCD detector. The primary interaction of elastic scattering between incident fast neutrons and the CCD initiates the release of a recoil silicon nucleus. The energy of the recoil silicon nucleus is determined by the geometry of the scattering as well as the energy of the fast neutron. The maximum energy of the silicon nucleus is only $\sim 13\%$ of the energy of the incident neutron because of the large silicon-to-neutron mass ratio. The average silicon energy is about half of the maximum energy and will be about 60 keV for an 1-MeV neutron. Then the silicon nucleus travels through the detector ionizing surrounding silicon atoms. A charge cloud produced along the track of the silicon nucleus is accumulated to electrodes. Some fraction of the silicon-nucleus energy is also deposited into nuclei of surrounding atoms. For a 60-keV silicon nucleus, $\sim 30\%$ of its energy will be used for ionization [6,7] and a signal charge of $\sim 5.0 \times 10^3$ e will be collected. This means that we need a low noise level in order to detect relatively low-energy neutrons. Even for 1-MeV neutrons, we should suppress noise otherwise small signals caused by low-energy recoil silicons will be lost. Thus the CCD detector should be operated at sufficiently low temperature in order to reduce the dark currents.

The range or the primary charge-cloud size of a 60-keV silicon nucleus (by an 1-MeV neutron) is $\sim 0.1\,\mu$m. As this size is much smaller than the pixel size of the CCD ($\sim 10\,\mu$m), MeV-neutron-induced events would have compact and point-like shapes. On the other hand, the Compton scattering by background MeV γ-rays produces MeV electrons. These electrons travel much longer paths ($\sim$ a few $\times 100\,\mu$m on average) than the pixel size, and elongated events would be seen in the CCD image. Thus it would be possible to distinguish neutron-induced events from γ-ray-induced events by analyzing their event shapes (as previously studied by [8] and the references therein). Cosmic ray particles passing through the detector produce events with a size similar to the detector thickness, which can also be distinguished from neutrons.

The P-ch CCD detector is unique for its thick depletion layer which would enable us to directly detect fast neutrons. Then we conducted neutron irradiation experiments for demonstrating the neutron detection and the neutron/γ-ray discrimination with the P-ch X-ray CCD.

2. Experiments

2.1. Neutron irradiation with ^{252}Cf

We conducted neutron irradiation experiments using a fast neutron source ^{252}Cf. The energy distribution of neutrons from ^{252}Cf is approximated by the Maxwellian with a temperature (kT) of 1.42 MeV [9]. The neutron source ^{252}Cf also emits γ-rays with an average energy of ~ 0.85 MeV [10]. We used a 0.835-MeV γ-ray source ^{54}Mn for the purpose of comparison. We used a device called Pchmini-03 developed by Hamamatsu Photonics KK as a neutron detector (Fig. 1). The basic properties of the device are summarized in Table 1.

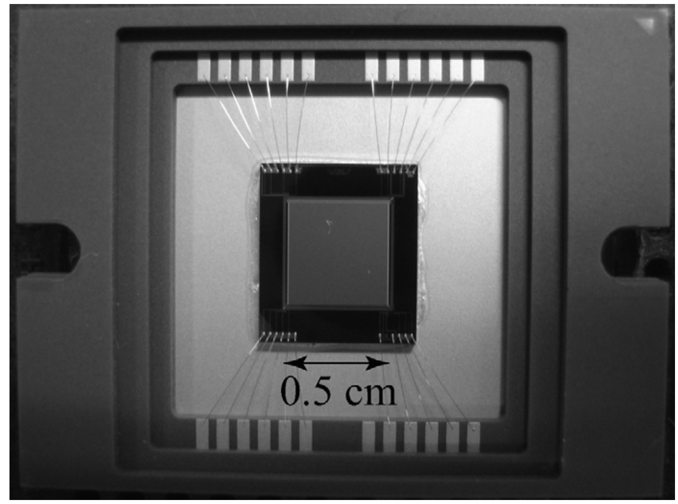

Fig. 1. Face-on view of Pchmini-03 CCD used in the experiments.

Table 1
Basic properties of Pchmini-03 CCD.

Wafer	N type
Channel	P type
Depletion layer thickness	$\sim 300\,\mu$m
Field-free layer thickness	$\sim 325\,\mu$m
Pixel size	$15 \times 15\,\mu m^2$
Format	320×320 pixels
Imaging area	$0.5 \times 0.5\,cm^2$
Illumination type	Front illumination
Transfer type	Full-frame transfer

2.2. Setup of the experiments

Figs. 2 and 3 show the experimental setup. The Pchmini-03 CCD was cooled to $\sim -80\,^{\circ}$C in a vacuum chamber by a stirling cooler (SRS2110) made by Sumitomo Heavy Industrials (Fig. 2). For driving and reading out the CCD, we used a camera control system (C4742-98) made by Hamamatsu Photonics KK. The read-out noise of the CCD is about 30 e (at 1σ) with a pixel clock of 156.25 kHz. The chamber is equipped with a beryllium window with the thickness of $\sim 500\,\mu$m and neutrons/γ-rays were irradiated through it (Fig. 3a). We also conducted experiments by inserting a lead shield with a thickness of 3 cm (Fig. 3b). An exposure time for each image was 90 s. The log of the experiments is summarized in Table 2.

3. Analysis and results

3.1. Imaging analysis

Here we describe the procedures of the imaging analysis, which is based on the ASCA grade analysis described in Ref. [11]. We first binned each image because the charge clouds produced in the CCD would diffuse while drifting to the electrodes. The diffusion size is roughly proportional to the distance between the interaction point and the electrode. Thus the diffusion, rather than the initial charge cloud size, would determine the event size, especially for the P-ch CCD with the thick depletion layer.