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Development of a high sensitivity pinhole type gamma camera using semiconductors for low dose rate fields

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ABSTRACT

We developed a pinhole type gamma camera, using a compact detector module of a pixelated CdTe semiconductor, which has suitable sensitivity and quantitative accuracy for low dose rate fields. In order to improve the sensitivity of the pinhole type semiconductor gamma camera, we adopted three methods: a signal processing method to set the discriminating level lower, a high sensitivity pinhole collimator and a smoothing image filter that improves the efficiency of the source identification. We tested basic performances of the developed gamma camera and carefully examined effects of the three methods. From the sensitivity test, we found that the effective sensitivity was about 21 times higher than that of the gamma camera for high dose rate fields which we had previously developed. We confirmed that the gamma camera had sufficient sensitivity and high quantitative accuracy; for example, a weak hot spot (0.9 μSv/h) around a tree root could be detected within 45 min in a low dose rate field test, and errors of measured dose rates with point sources were less than 7% in a dose rate accuracy test.

1. Introduction

Gamma cameras are well-known as useful instruments to measure distributions of radionuclides for medical or industrial purposes. The severe accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) released a lot of radioactive materials into the environment, and radioactive contamination still remains inside and outside the FDNPP [1]. Therefore, gamma cameras visualizing a radiation intensity distribution of a wide area in a short time are required both in low and high dose rate fields for which dose rates are from under one to several tens of μSv/h and from one to over one hundred mSv/h, respectively, and some gamma cameras have been developed. For use in particularly high dose rate fields at the FDNPP site, especially the reactor buildings, we developed a pinhole gamma camera [2]. This gamma camera has adequate accuracy to quantify radionuclide contamination because sufficient shielding surrounds the detector. Indeed, we investigated the Unit 1 reactor building of the FDNPP using our pinhole gamma camera and we could remotely identify unknown contaminating sources in dose rate fields with values as high as 659 mSv/h. On the other hand, in low dose rate fields as found in Fukushima Prefecture outside the FDNPP site, there is also a big need for gamma cameras. Just after the accident, such cameras were critical tools to quickly identify positions of radiation sources. Nowadays, they are also necessary to confirm the degree of radioactive contamination, in order to effectively perform decontamination work and to provide safety and peace of mind to workers and the general public. For applications in low dose rate fields, gamma cameras must have not only high sensitivity and ease of use, but they must have good quantitative accuracy also.

There are at least two types of gamma cameras other than pinhole type cameras [3–5] in industrial use: coded aperture cameras [6–10] and Compton cameras [11–15]. They have different imaging principles and characteristics. Recently, coded aperture cameras and Compton cameras have been developed which have higher sensitivities with an appropriate configuration than previously available ones. But it is not necessarily easy for coded aperture cameras and Compton cameras to have enough quantitative accuracy, because they do not directly detect the direction of each gamma ray but have to reconstruct images of radiation distributions from a lot of detected events. The principle of pinhole cameras is the simplest and most robust, so from the viewpoint

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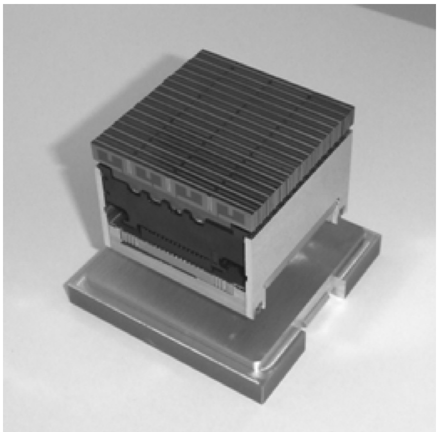

Fig. 1. Semiconductor detector module originally developed for medical use; the module has 256 (16 × 16) pixels consisting of CdTe and ASICs.

of quantitative accuracy they have the best potential among the three types of cameras. Therefore, we selected the pinhole type.

Pinhole type gamma cameras are generally known to have low sensitivity. To overcome this limitation, we adopted three methods: a signal processing method to set the discriminating level lower, a highly sensitive pinhole collimator, and a smoothing image filter that improves the efficiency of the source identification. And then we fabricated a pinhole gamma camera which has both high sensitivity and high quantitative accuracy for low dose rate fields.

In this paper, we present the methods to increase the sensitivity and the results of performance tests of our original gamma camera for low dose rate fields as found in Fukushima Prefecture outside the FDNPP site.

2. High sensitivity pinhole type gamma camera for low dose rate fields

2.1. Compact pixelated semiconductor detector module

Radiation detectors are one of the most important components of gamma cameras. Recently, most gamma cameras, regardless of their type, have adopted semiconductor detectors instead of scintillators. This is because the semiconductor detectors are compact, can be pixelated more densely and can have higher energy resolution than scintillators, and from those features, high performance gamma cameras were developed.

Our gamma camera has a compact detector module with a pixelated CdTe semiconductor (Fig. 1), which was originally developed for medical applications [16–18]. Because the band gap of the CdTe is as wide as 1.44 eV, and the temperature dependence of the signal gain is much less than that of scintillators [19], the gamma camera using CdTe can function at ambient temperatures inside and outside buildings. The detector module has 256 (16 × 16) CdTe pixels; the thickness of each is 5 mm, and the pixel pitch is 2.5 mm, corresponding to the module size of 40 mm square. The signal from CdTe is processed by custom application-specific integrated circuits (ASICs) that are able to determine the energy of gamma rays precisely and to identify radionuclides.

2.2. Three methods to improve sensitivity of the pinhole camera

In order to increase sensitivity of the pinhole camera, we adopted three methods, labeled A, B and C: a signal processing method to set the discriminating level lower, a highly sensitive pinhole collimator, and a smoothing image filter that improves the efficiency of the source identification.

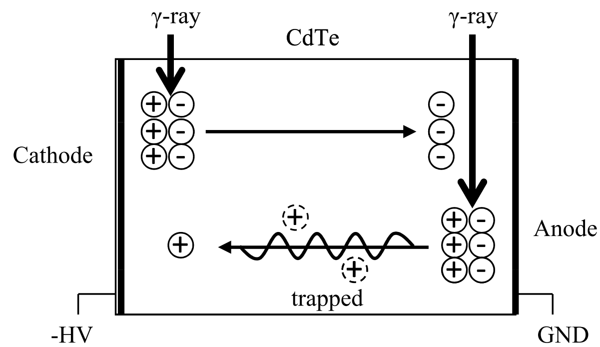

Fig. 2. Conceptual scheme of detection principle of CdTe semiconductor detector.

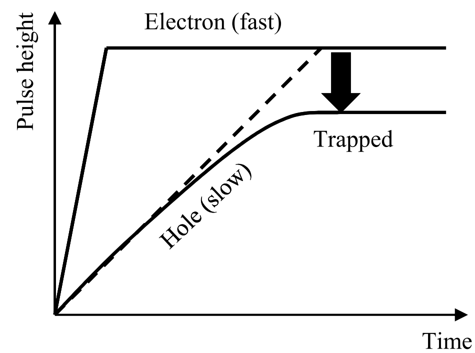

Fig. 3. Characteristic diagram of an electron dominant signal and a hole dominant signal.

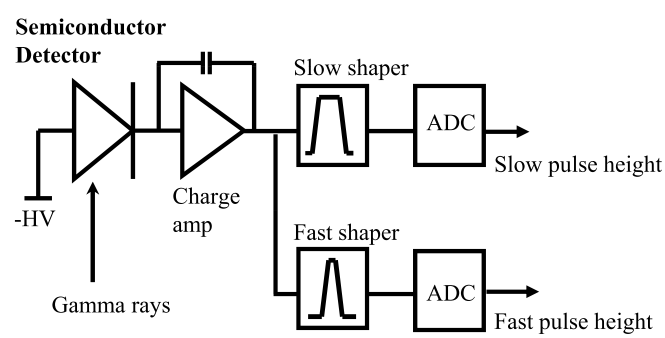

Fig. 4. Simplified circuit diagram of the signal processing method with two reading circuits of different time constants.

Method A: Signal processing method to set the discriminating level lower.

We adopted Schottky CdTe detectors which operate as diodes to suppress leakage current under high voltage application. However, there are some unstable CdTe detectors which intermittently generate noise events. It is not necessarily cost-effective to remove all such defective CdTe detectors, so a discriminating level has had to be set higher to reject signals of noise events. To increase desired signal events, we have adopted a signal processing method which could set the threshold of the low-level discriminator (LLD) lower.

Fig. 2 shows a conceptual scheme of the gamma ray detecting principle of a CdTe semiconductor detector and Fig. 3 shows a characteristic diagram of an electron dominant signal and a hole dominant signal. Signals of the CdTe detector are derived by the transfer of electrons and holes which are produced by gamma ray interactions with the CdTe detector. By paying attention to the big difference of mobilities which are 1000 $cm^2/V/s$ for electrons and 100 $cm^2/V/s$ for holes [20], we adopted a signal processing method [21–24] using two