Novel X-ray imaging using a CdTe sensor

Hidenori Mimura, Yoichiro Neo and Toru Aoki

Research Institute of Electronics, Shizuoka University
3-5-1 Johoku Naka-ku Hamamatsu 432-8011 Japan
E-mail: mimura@rie.shizuoka.ac.jp

Abstract

We have developed photon-counting-type one and two dimensional CdTe X-ray image sensors with an energy-discrimination function. The one and two dimensional CdTe image sensors consist of 64 CdTe diodes with a pixel size of 0.8 mm × 0.5 mm × 0.5 mm (thickness) and 512 CdTe diodes with 0.8 × 2.0 mm × 0.5 mm (thickness), respectively. Using these image sensors, we have demonstrated energy-discriminated X-ray images and material distinguished X-ray computer tomography (CT) images. In addition to them, to realize ultra high resolution in the future, we have developed a novel CdTe X-ray image sensor which consists of a CdTe diode and a matrix-driven field emitter array (FEA). We also describe the preliminary results obtained in the CdTe-FEA X-ray sensor.

Keywords: X-ray image sensor, CdTe, field emitter array, energy discrimination, photon counting

1. Introduction

An X-ray photon has very large energy as compared with that of visible light. Thus, X-ray photon generates many hole-electron pairs inside a semiconductor detector, depending on its energy. For example, about 30,000 pairs are generated in a CdTe detector by one X-ray photon with 120 keV [1]. The number of charges generated by an X-ray photon is proportional to the photon energy. Therefore, when the number of charges generated by one X-ray photon is measured, we can know the energy of the incident X-ray photon.

CdTe has been widely used for an X-ray or gamma-ray detector, because CdTe has good properties such as wide energy band gap, high atomic number, and relatively high mobility. The wide band gap and high mobility lead to high energy resolution at room temperature, and the high atomic number achieves high sensitivity due to the high absorption coefficient.

We have developed photon-counting-type CdTe X-ray imaging devices with energy-discrimination function. We have fabricated one and two dimensional CdTe image sensors, and have demonstrated energy-discriminated X-ray images and material distinguished X-ray computer tomography (CT) images [2, 3]. For imaging devices, it is important to reduce the pixel size and to arrange the pixels in high density array for high spatial resolution images. However, smaller pixel size and higher-density arrangement are difficult for CdTe devices, because the fineness of the process significantly degrades the device performance. Therefore, we have also developed a novel CdTe X-ray image sensor which consists of a CdTe diode and a matrix-driven field emitter array (FEA) [4].

In this paper, we describe novel X-ray imaging using the CdTe sensors developed by our group.

2. Photon counting X-ray imaging

We have developed the CdTe imaging device with 4 × 128 (512 pixels) structured M-π-n CdTe diodes. The pixel size is 0.8 mm (width) × 2.0 mm (length) × 0.5 mm (thickness). The detector array is connected to a 64ch ASIC and system-control MPU. This imaging device is controlled by a laptop computer through a USB 2.0 interface. The CdTe diode was fabricated by
the excimer laser doping method [3]. An n-type CdTe layer was formed by using indium (In) dopant as a donor source.

Figure 1 shows an energy spectrum of a Co-57 radioisotope detected by the CdTe detector at room temperature. The detector was operated at a bias voltage of 250 V. The full-width of half maximum (FWHM) of the peak at 122 keV is 2.8 keV.

Photon counting X-ray imaging system was built with the 512 pixels detector unit, a 90 keV microfocus X-ray source, and a mechanical scanning system. An X-ray image of a Japanese 500-yen coin is shown in Fig. 2. The coin patterns on the front and back sides were clearly shown in this figure. The pattern step of the leaf tip is 50 μm, which is about 3% of total thickness. The picture was taken under a X-ray tube voltage of 90 keV, a tube current of 30 μA, a distance of 60 cm between the X-ray tube and CdTe detector, and an energy window of 60-70 keV. In the picture, the striped noise is due to the uneven properties of the CdTe detector, ASIC circuits etc.

Figure 3 shows energy-discriminated X-ray images. Linear attenuation coefficient drastically changes at K-edge energy, and each material has different K-edge energy. Therefore, materials of gold (Au), molybdenum (Mo), and copper (Cu) wires were distinguished.

3. Material distinguished X-ray CT

In Fig. 3, we utilize the K-band edge property. In general, even if we use the photon counting X-ray image sensor with an energy-discrimination function, we measure only total amount of absorption in X-ray imaging. Therefore, in order to obtain material distinguished images, linear attenuation coefficient and thickness should be separated, because total amount of absorption is expressed as the product of linear attenuation coefficient and thickness, and linear attenuation coefficient depends on material. In X-ray computer tomography (CT), linear
attenuation coefficient is automatically extracted from the total amount of absorption, and reconstructed images are drawn as a 2 dimensional mapping of linear attenuation coefficient. Thus, X-ray CT is suitable for material distinguished X-ray imaging.

X-ray CT images were obtained by the 1 dimensional CdTe detector with 64 pixels and a conventional X-ray tube. The size of the CdTe detector was 0.8 mm × 0.5 mm with a thickness of 5 mm [2]. Figure 4 shows an X-ray CT image of two alkali dry batteries (LR6). To reconstruct the image, we used only “back projection filtered method”, which is the simplest method for the image reconstruction. Typical reconstruction for X-ray CT images needs complex calculation. However, our calculation is very simple, because our imager has an excellent linearity between the number of the incident photon and output signal.

Figure 5 shows a cross sectional CT image of an USB type flash memory. This flash memory operates even after the exposure of X-ray, because the amount of the exposure is small.

Fig. 4 Material distinguished X-ray CT image of two alkali batteries (LR6).

Fig. 5. Material distinguished X-ray CT images of an USB flash memory. Left; visible image, Center; X-ray image, and Right; Cross sectional X-ray images.

4. CdTe X-ray sensor using a field emitter array

Figure 6 shows operation principle of the CdTe X-ray sensor using a FEA [4]. Sb_S_3 is a landing material for an electron beam and acts as an electron blocking layer. The In side of the CdTe diode was positively biased with respect to the FEA. When an electron beam irradiates the Sb_S_3, the Sb_S_3 layer is charged up and the CdTe diode is reversely biased by the bias voltage. Then, when an X-ray irradiates the diode, electron-hole pairs are generated in the CdTe diode. The holes drift by the bias voltage and are stored on the Sb_S_3 surface. Electrons emitted from FEA recombine with the holes stored on the Sb_S_3 surface, and simultaneously the output current, which is proportional to the amount of the stored holes, flows in the output circuit.
X-ray images are obtained by addressing the FEA in sequence. In this device, the pixel separation is not necessary for high resolution and the resolution of this image sensor is determined by the electron beam size. Therefore, ultra high resolution is expected.

We have fabricated a 2 dimensional FEA with a $12 \times 12$ matrix structure. Figures 7(a) and 7(b) show a whole picture and specifics of the matrix-structured FEA mounted on a ceramic package, respectively. Figures 7(c) and 7(d) show scanning electron microscopy (SEM) images of the 1 pixel and the emitter tip of the matrix-structured FEA, respectively. The FEA is surrounded with a focusing electrode. FEA area was $150 \mu m \times 150 \mu m^2$ and a distance between pixels (pixel pitch) was 0.9 mm.

Figure 8 shows output current characteristics under the exposure of electron beam with and without X-ray irradiation. In the figure, the X-ray tube voltage was changed from 20 to 80 kV at intervals of 10 kV. The X-ray tube current was 111 $\mu A$. A shown in Fig. 8, output current was obtained only when X-ray was irradiated. The output current clearly depended on the X-ray tube voltage, indicating that the output current is proportional to the X-ray intensity. The output current saturated at the X-ray tube voltage of 70 kV. The reason is that the number of holes generated in the CdTe diode by the incident X-ray is larger than the number of electrons supplied from the FEA.
Fig. 8. Output current characteristics under the exposure of electron beam with and without X-ray irradiation. The X-ray tube voltage was changed from 20 to 80 kV at intervals of 10 kV. The X-ray tube current 111 μA.

5. Summary
We have developed photon-counting type one and two dimensional CdTe image sensors with an energy-discrimination function. We have demonstrated energy-discriminated X-ray images and material distinguished X-ray CT images. We have also demonstrated the CdTe X-ray sensor which consists of a CdTe diode and a 12 × 12 matrix-structured FEA.

References