Modulation transfer function analysis of silicon X-ray sensor with trench-structured photodiodes

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Abstract: A silicon X-ray sensor with trench-structured photodiodes was studied and the influence of Compton scattering was estimated. By irradiating the target pixel with X-rays and measuring the signal from adjacent pixels, X-ray scattering and pixel blur of the proposed sensor was determined. An X-ray sensor with a length of 22.6 mm was designed and fabricated, and its modulation transfer function (MTF) was obtained. A sensor structure to improve the MTF level to that of CdTe was proposed.

Keywords: X-ray sensor, silicon sensor, silicon wafer, trench photodiode, Compton scattering, modulation transfer function (MTF)

Classification: Integrated optoelectronics

References

[1] N. Gehrels, \textit{et al.}: “Hard X-ray and low-energy gamma-ray spectrometers,” Sol. Phys. \textbf{118} (1988) 233 (DOI: 10.1007/BF00148595).
[2] M. Ruat and C. Ponchut: “Characterization of a pixelated CdTe X-ray detector using the timepix photon-counting readout chip,” IEEE Trans. Nucl. Sci. \textbf{59} (2012) 2392 (DOI: 10.1109/TNS.2012.2210909).
[3] A. Owens and A. Peacock: “Compound semiconductor radiation detectors,” Nucl. Instrum. Methods Phys. Res. Sect. A \textbf{531} (2004) 18 (DOI: 10.1016/j.nima.2004.05.071).
[4] XCOM: Photon Cross Sections Database: https://www.nist.gov/pml/xcom-photon-cross-sections-database.
[5] T. Ariyoshi, \textit{et al.}: “Silicon trench photodiodes on a wafer for efficient X-ray-to-current signal conversion using side-X-ray-irradiation mode,” Jpn. J. Appl. Phys. \textbf{57} (2018) 04FH04 (DOI: 10.7567/JJAP.57.04FH04).
[6] R. D. Evans: \textit{The Atomic Nucleus} (McGraw-Hill Book Co, New York, 1955) 712.
[7] D. Durini and D. Arutinov: in \textit{High Performance Silicon Imaging}, ed. D. Durini (Woodhead Publishing Ltd., Sawston, Cambridge, 2014) 25 (DOI: 10.1533/9780857097521.1.25).
[8] T. Sato, \textit{et al.}: “Features of particle and heavy ion transport code system (PHITS) version 3.02,” J. Nucl. Sci. Technol. \textbf{55} (2018) 684 (DOI: 10.1080/00223131.2017.1419890).
1 Introduction

For non-destructive X-ray inspection, reduction of the radiation dose is required, and thus high sensitivity of the X-ray sensor is expected for medical diagnoses.

In X-ray sensors, an indirect X-ray detection type using a scintillator has been developed, but even the NaI scintillator with high absolute fluorescence efficiency possesses the efficiency value of only 13% [1].

Cadmium telluride (CdTe) has a high effective atomic number and has been studied as a direct X-ray detection-type sensor material [2]. However, compared with silicon [3], the carrier lifetime of CdTe is three orders of magnitude shorter and its hole mobility is about one fifth. Therefore, an X-ray sensor with the CdTe material exhibits a low energy resolution, a narrow dynamic range, and toxic compared with that of the silicon X-ray sensor.

In this study, silicon is used as the material for a direct X-ray detection type sensor. Silicon features excellent processability and has none of the problems exhibited by CdTe as described above. X-rays penetrate silicon with a thickness of several tens of millimeters [4]. Herein, the effective sensor length was expanded by forming trench-structured photodiodes on the silicon wafer, thus improving the X-ray detection efficiency to that exhibited by CdTe or better. The theoretical limit of X-ray-to-current conversion efficiency of 83.8% was achieved for X-rays with a tube voltage of 80 kV [5].

In the silicon sensor, the effect of Compton scattering increases [6, 7], which may induce blur. In this paper, a proposed silicon X-ray sensor was designed and fabricated, and the image sharpness owing to Compton scattering was investigated by the modulation transfer function (MTF). In addition, we proposed a sensor structure to suppress the degradation of the image sharpness owing to Compton scattering.

2 Design and fabrication of the proposed X-ray sensor

2.1 Trench-structured X-ray photodiode

Fig. 1 shows the cross-sectional structure of the proposed X-ray sensor wherein a pn junction photodiode was formed in a trench shape. The effective sensor length can be expanded using this trench-structured photodiode, and the X-rays could be detected efficiently. Furthermore, to completely deplete the inside of the X-ray sensor with a low reverse bias voltage of several tens of volts, a P-type floating zone wafer with a resistivity of 1500 ± 500 Ωcm and a thickness of 550 µm was used as a sensor substrate.
2.2 Test chip of the proposed X-ray sensor

A photograph of the fabricated X-ray sensor chip is shown in Fig. 2, wherein each X-ray sensor chip consisted of 108 pixel cells. In each pixel cell, as shown in Fig. 3, five trench-structured photodiodes of $17 \mu m \times 4.26 mm$ were formed in one row. The sensor length was 22.6 mm and the depth of the trench was about 300 $\mu m$.

Fig. 1. Structure of proposed silicon X-ray sensor. The photodiode is formed in a trench shape. In this study, the wafer substrate is P-type and the signal detection side is N-type.

Fig. 2. Photograph of the fabricated X-ray sensor chip. The chip size is $22.6 \times 18.2 mm^2$ and each chip consists of 108 pixel cells.

Fig. 3. Layout figure of the pixel cell. The cell size is $22.6 mm \times 166.6 \mu m$ and each cell consists of five trench-structured photodiodes, where the length of each trench photodiode is 4.26 mm and the depth is about 300 $\mu m$. X-rays are irradiated from the side of the cell.
3 Compton scattering estimation experiment

3.1 Sensor test board
Fig. 4 shows the assembly configuration of the X-ray sensor chip and the test board. A semiconductor parameter analyzer was connected to the target pixel cell to measure the X-ray detection current. Further, a constant reset voltage $V_{\text{pix}}$ was applied to each of the three pixel cells on both sides of the target cell. With this method, signal charges generated in the peripheral cells were collected by the cells itself; therefore, leakage of the charges to the target cell could be prevented and the X-ray detection current from only the target cell was obtained. A reverse bias voltage $V_{\text{bias}}$ was applied to the anode electrode, which was connected to the surface and the backside of the test chip. The sensor was then irradiated with X-rays through a 4.0 mm-thick tungsten collimator with 1.0 mm$^2$ square hole, where the distance from the X-ray tube to the sensor was 345 mm. By shifting the sensor and measuring the X-ray detection current from the target pixel cell at each position, the influence of Compton scattering could be estimated.

3.2 Estimation of X-ray scattering
Fig. 5(a) shows the X-ray detection intensity of the target pixel cell with each sensor position at a tube voltage of 80 to 160 kV, a tube current of 2 mA, and a reverse bias voltage of 25 V applied to the sensor. The vertical axis in Fig. 5 shows the detection current ratio of the target pixel cell to the aperture. In addition, the case where there is no scattering is plotted (gray line in Fig. 5(a)), and the signal portion beyond this line is owing to the scattered X-ray. Fig. 5(b) shows the measured and simulated results for X-rays with a tube voltage of 120 kV, where the simulation was executed using the particle and heavy ion transport code system.
The simulation results are in good agreement with the experimental results. In Fig. 5, the edge image of the collimator hole is differentiated to obtain the line spread function (LSF), and a discrete Fourier transform is executed on this LSF to obtain the modulation transfer function (MTF). Fig. 6 shows the MTF of the fabricated X-ray sensor at a tube voltage of 120 kV from the data of Fig. 5, as well as the MTF of a CsI scintillator type sensor [9] and the CdTe sensor [10] shown as reference. Because Compton scattering increases in silicon, the MTF of the fabricated sensor is inferior to that of CdTe. However, the spatial resolution in a conventional CT is 1.5 cycles/mm at 10% MTF; therefore, the spatial resolution of the proposed direct-conversion-type silicon trench photodiode is superior to that of the conventional type.

To improve the MTF, or the spatial resolution, it is necessary to suppress the scattered X-rays. This can be accomplished by forming another trench around the pixels and filling this trench with gold, which prevents the scattered X-rays from leaking to adjacent pixels. The MTF simulation results for the case when the width of the buried gold is 10 to 40 µm are also shown in Fig. 6, and it is expected that this configuration with 30 µm-wide gold film will improve the MTF to a value above that of CdTe in the high spatial frequency region. The shielding effect in the high spatial frequency could be predicted, and the X-ray image sharpness could be improved. To allocate the pixel region, the width of the filled gold should not exceed 30 µm.

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4 Conclusion

An X-ray sensor with trench-structured silicon photodiodes was designed and fabricated, and the blur owing to Compton scattering was investigated. X-ray response characteristics of the sensor were measured using a tungsten collimator. Simulated and observed results were consistent with each other. It was predicted that an MTF at the same level as that of CdTe could be achieved by forming gold trench shielding film between the pixels to suppress the scattered X-rays.

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