Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp141-142

C-2-04

Sensitivity Properties of a Direct Conversion Silicon X-ray Sensor with Trench-Structured Photodiodes

Tetsuya Ariyoshi, Shota Funaki, Kenji Sakamoto, Akiyoshi Baba, and Yutaka Arima

Center for Microelectronic Systems, Kyushu Institute of Technology,
680-4, Kawazu, Iizuka, Fukuoka 820-8502, Japan
Phone: +81-948-29-7590 E-mail: ariyoshi@cms.kyutech.ac.jp

Abstract

We developed a direct conversion-type silicon X-ray sensor pixel containing photodiodes with a trench structure. The X-ray sensor pixel was able to directly detect X-rays with high sensitivity because of the trench structure of the photodiodes. The conversion efficiency of the device was 85% at a bias voltage of 20 V. An X-ray sensor with such high sensitivity can enable the radiation dose in X-ray diagnosis to be lowered.

1. Introduction

X-rays are widely used in medical care and industrial video diagnosis devices because of their high material permeability. However, medical X-ray diagnosis inevitably entails the problem of radiation dose. In Japan, 3.2% of carcinogenesis has been attributed to such radiation dosage [1]. To lower the radiation dose needed in such X-ray diagnosis, the sensitivity of X-ray sensors needs to be improved.

Two kinds of detection methods are used in X-ray sensors: indirect conversion and direct conversion. In indirect conversion X-ray sensors, incident X-rays are converted into visible light using scintillators, and this visible light is measured by conventional image sensors. However, the signal conversion efficiency of X-rays is very low because the absolute fluorescence efficiency of scintillators is only about 10% [2]. In direct conversion X-ray sensors, there is no loss of fluorescence efficiency, allowing higher X-ray signal conversion efficiency. However, because X-rays have high material permeability, it is necessary to devise a suitable sensor structure. The detection efficiency can become close to 100% if deeper sensor length than the penetration depth of X-rays can be realized. Therefore, sensitivity can be increased by about 10 times using direct conversion rather than conventional indirect conversion.

Materials with a large effective atomic number such as CdTe, HgI_2 or Se are used in direct conversion X-ray detectors. However, these materials are expensive, and their charge carrier transport properties are poor [3]. A photodiode sensor with a striped line structure that allows X-rays to be injected from the side of the silicon substrate has been proposed [4]. In this direct conversion sensor, the distance between the electrodes in each photodiode is 500 µm, so the bias voltage becomes as high as 600 V. In an attempt to realize a direct conversion silicon X-ray sensor with low bias voltage that displays suitable device lifetime, reliability, noise immunity, and power consumption, here we fabricate a direct conversion X-ray sensor using photodiodes with a trench structure. The sensitivity of this sensor is estimated.

2. Proposed Direct Conversion X-ray Sensor Pixel

Figure 1 shows part of a cross-sectional structure of the proposed X-ray sensor pixel. In the pixel, numerous trench photodiodes are formed in parallel. To spread the depletion layer over most of the pixel at sufficiently low bias voltage (tens of volts), a P-type FZ (Floating Zone) silicon wafer substrate with a resistivity of 1500±500 Ωcm and thickness of 550 µm was used. Each trench in the photodiode was about 170 µm deep, 17 µm wide, and spaced at a distance of 120 µm. By detecting X-rays from the side of the sensor chip or stacking several sensor chips, it was possible to achieve an effective sensor length to realize an X-ray sensor with high photoelectric conversion efficiency. Figure 2 shows a photograph of the fabricated sensor, while Fig. 3 displays cross-sectional SEM images of the trench structure of the device.

3. Estimation of the X-ray Sensitivity Properties

Among absorbed X-rays in the sensor pixel, we estimated which ratio was converted into an electrical signal. In this estimation, the tube voltage of the X-ray generator was fixed at 80 kV, and tube current was set to 1.0, 2.0, 3.0, and 4.0 mA. The pixel size was 1.0 mm^2. Using an X-ray spectrometer, the incident X-ray energy spectrum over an area of 1.0 mm^2 was measured. From the energy spectrum and permeability properties of the pixel, the current conversion of signal carriers generated in a pixel of volume 1.0 mm × 1.0 mm × 550 µm was derived. This current conversion value corresponds to the upper limit that the pixel can detect of the current signal. We then measured current signals in the device with and without X-ray irradiation by applying bias voltages of 1, 5, 10, 15, 20, and 25 V. Then, net X-ray detection current was obtained by subtracting the offset without X-ray irradiation from the value during X-ray irradiation.

Figure 4 illustrates the relationship between current signal and bias voltage applied to the trench photodiode. In Fig. 4, points represent the net X-ray detection current, and the solid lines show the current conversion value of signal carriers generated in the pixel, respectively. The net X-ray detection current approaches the upper limit with rising bias voltage. At bias voltages above 20 V, because the formed depletion layer appears to reach the trench space, large changes of the net X-ray detection current are not observed. These results reveal that the proposed X-ray sensor with a trench pixel structure operates at a sufficiently low bias voltage of 20 V.

According to Fig. 4, the mean conversion efficiencies of

X-rays to signal electric current were 85% at a bias voltage of 20 V. The volume of the trench cavity as the insensitive region is 3.3% of the fabricated pixel. Therefore, the theoretical limit of the conversion efficiencies of X-rays to signal electric current is 96.7%. Each photodiode trench is 170 μm deep, which is shallow compared with the sensor thickness of 550 μm. In addition, there are no bias electrodes on the backside of the substrate. The conversion efficiency of this device may be further improved by refining these issues.

4. Conclusions

A direct conversion silicon X-ray sensor composed of photodiodes with a trench structure was fabricated, and its sensitivity was estimated. For a trench depth of 170 μm and bias voltage of 20 V, the conversion efficiency of the proposed X-ray sensor pixel was 85%. By increasing the trench depth and preparing backside bias electrodes, the conversion efficiency of X-ray sensors with a trench structure is expected to further improve.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 26390104.

References

[1] A. Berrington de González *et al.*, Lancet **363** (2004) 345.
[2] D. Gastler *et al.*, Phys. Rev. C **85** (2012) 065811.
[3] N. E. Hartsough *et al.*, IEEE Trans. Nucl. Sci. **51**(4) (2004) 1812.
[4] M. Danielsson *et al.*, U.S. Patent 8183535 B2 (2012).

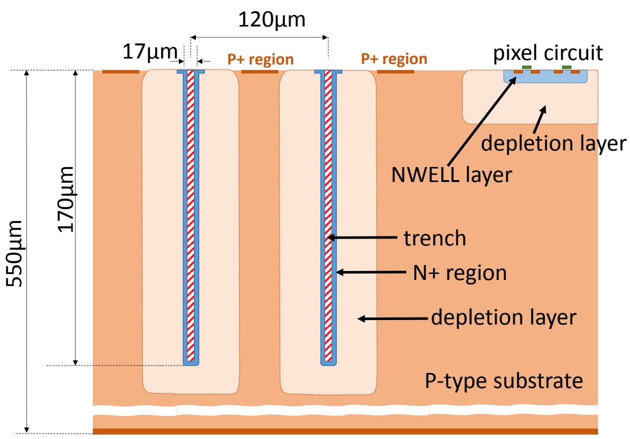

Fig. 1 Cross-sectional structure of X-ray sensor pixel.

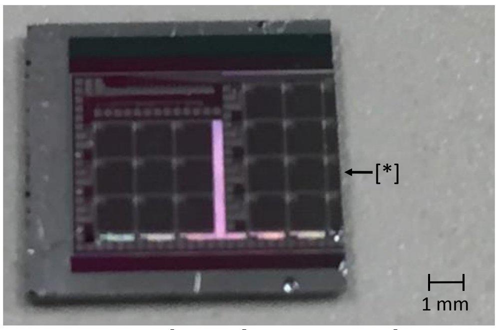

Fig. 2 Fabricated X-ray sensor chip.

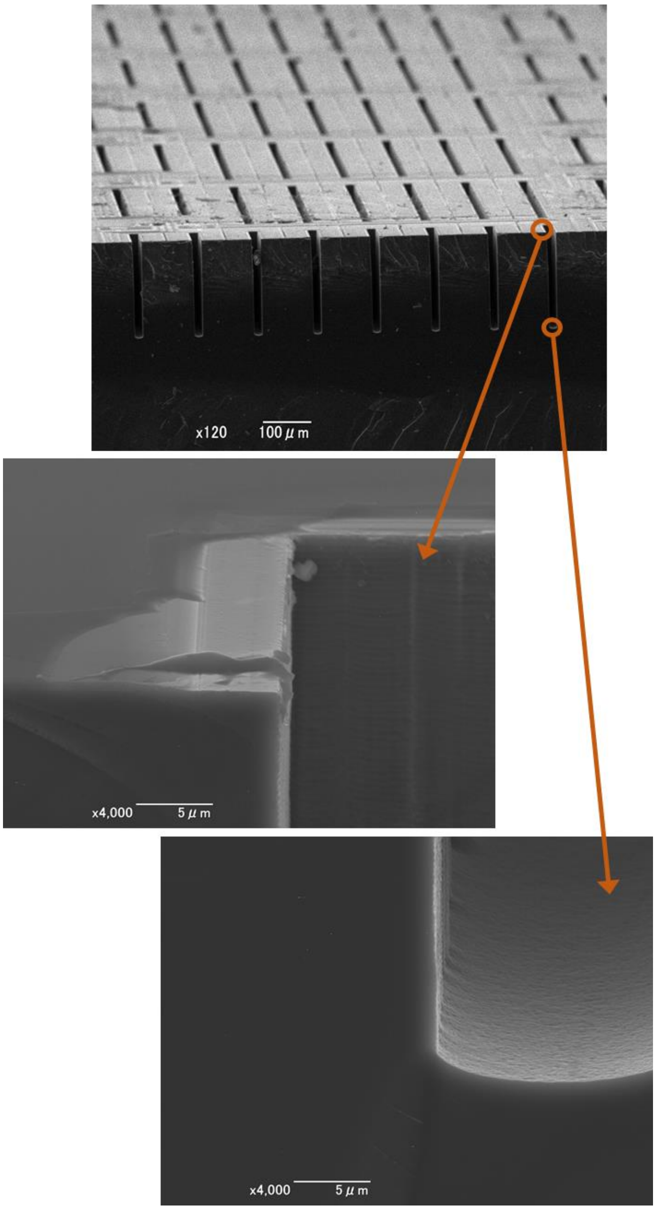

Fig. 3 Cross-sectional SEM images of the sensor (taken at the point indicated by [*] in Fig. 2).

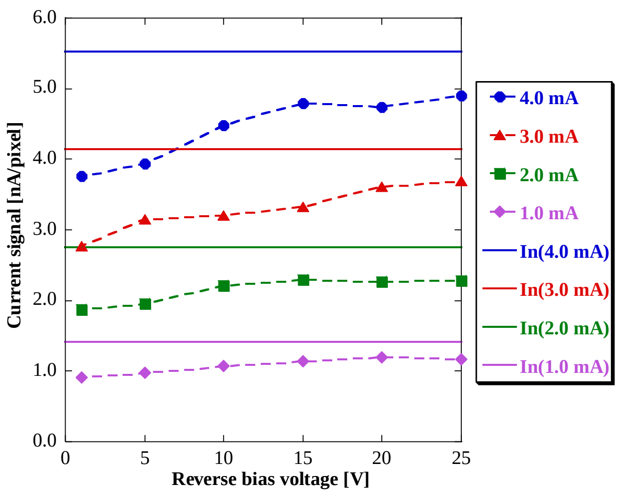

Fig. 4 Relationship between current signal and bias voltage. Tube voltage of X-ray generator: 80 kV, tube current: 1.0 – 4.0 mA.