Single Crystal Diamond Photon-Counting Imager

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ABSTRACT

We have developed an X-ray imaging detector using single-crystal diamond. The detector utilizes the unique properties of diamond, including its high radiation tolerance and effective atomic number similar to human tissue, making it suitable for radiotherapy measurements. The imaging system consists of an indium plate electrode, an 80μm pitch pixelated silver electrode, and a photon-counting readout integrated circuit (ROIC) operating in hole or electron collection mode. We successfully imaged a 1 mm-thick lead plate using X-rays emitted from a 100 kV X-ray tube. These results provide motivation for further optimizing the image detector process specifically for single-crystal diamond.

1 Introduction

Diamond is a wide bandgap semiconductor with desirable properties, such as excellent radiation tolerance, which enables measurement of high-dose beams in nuclear engineering, accelerator beam monitors, and radiation therapy applications [1]. Our research focuses on harnessing the physical properties of diamond to develop detectors capable of effectively detecting α-rays [2]. Moreover, diamond's atomic number (Z = 6) closely resembles that of human tissue (Z = 6.5), resulting in similar radiation absorption characteristics [3].

Diamond detectors function as X-ray photoconductors, directly converting X-ray photons into electron-hole pairs [1]. Unlike indirect detectors that rely on scintillation, diamond detectors offer high spatial resolution due to the absence of light diffusion. To enhance the spatial resolution for dosimetry in radiotherapy, we evaluated a pixelated diamond detector..

Diamonds include natural diamonds, HPHT diamonds, and homoepitaxial diamonds, all of which have high charge collection efficiency but are difficult to manufacture in large areas. Heteroepitaxial diamonds have a good charge collection efficiency and can be produced in large areas. In this report, we have succeeded in growing high-quality heteroepitaxial diamonds and applied them to an imaging device.

2 Experiment

2.1 Structure of imager

The semiconductor detector consists of chemical vapor deposition (CVD) single-crystal diamond. The heteroepitaxial diamonds used in this study were grown on sapphire substrates using a step growth method and self-exfoliated single-crystal substrates were used. The crystal, fabricated by Orbray Co., Ltd., measures 3mm × 3mm × 0.5mm. Indium thin film electrodes were sputtered to form plate electrodes. The opposing side, without electrodes, is connected to the ROIC through silver paste contacts during stacking.

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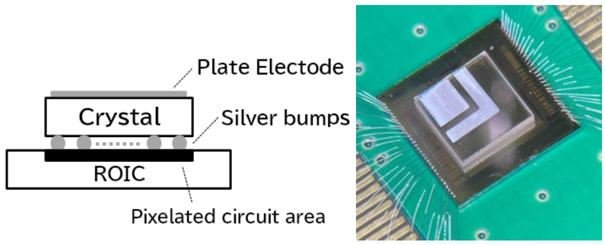

Fig. 1 illustrates the structure of the assembled Diamond X-ray imager (left) and the structure after stacking (right). The diamond detector is stacked onto the ROIC using silver-paste bumps. It features an indium plate electrode and pixelated silver electrodes. The ROIC's inputs/outputs, located around the pixelated circuit area, are externally connected through wire bonding.

For the ROIC, we used a photon and charge counting type ASIC that we have developed. This is a proprietary process that directly digitizes the charge generated in the detector element by a single X-ray photon using an ultra-micro switched capacitor to extract a PWM digital signal. This ASIC, which has a proven track record in CdTe and TlBr, was used this time because it can be used for detectors with different carrier transfer rates, i.e., different rise times, by adjusting the clock. The ROIC comprises 40 × 40 electrodes with an 80μm pitch, with a maximum crystal size of 3.2mm × 3.2mm. However, due to the smaller crystal size, the detection area measures 3.0mm × 3.0mm with 38 × 38 pixels. Silver paste bumps were formed on the ROIC electrodes using a Super Inkjet Printer SIJ-S050 manufactured by SIJTechnology, Inc., for crystal connection.

The ROIC's readout architecture was designed by our group [4], [5], and the transistor-level circuit was designed by Brookman Technology, Inc. (currently TOPPAN Inc.). It was fabricated using a 0.13μm CMOS process from Taiwan Semiconductor Manufacturing Company Limited (TSMC). Fig. 1 depicts the assembled diamond imager and its stacked structure.

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2.2 Methods

The ROIC operated in electron acquisition mode with a bias voltage of -500 V applied to the plate electrode. The ROIC had a frame rate of 200 Hz. A 10-second (2,000 frames) imaging session was performed, and the counts were summed to obtain a single image.

An X-ray tube with a tube voltage of 100 kV served as the X-ray source, positioned 20 cm away from the detector. To shield the X-rays, we used 3mm × 3mm lead plates with a thickness of 1 mm, shaped like the Japanese letter. The shielding object, which was placed 5 mm away from the detector, between the X-ray tube and the detector.

3 Results

Fig. 2 compares the cases with and without X-ray irradiation, without shielding. The counts increased with X-ray irradiation, confirming the detection of X-rays as expected. The rightmost and bottommost two rows, designated as unconnected pixels, remained unaffected, confirming that the ROIC does not detect X-rays through absorption, but solely through the crystal.

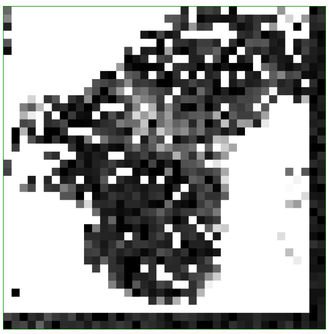

Figure 2 presents a series of imaging results obtained in the electron collection mode. The left image represents the result without X-ray irradiation, while the right image shows the result captured solely with X-rays.

Next, we imaged a shielding object placed in front of the detector. Fig. 3 demonstrates that the shape of the shielding object could be obtained as an image.

Although image quality could be improved, such as reducing the number of hot pixels observed in non-irradiated conditions, the quality of crystals and the operating conditions of the ROIC can be optimized to address this issue.

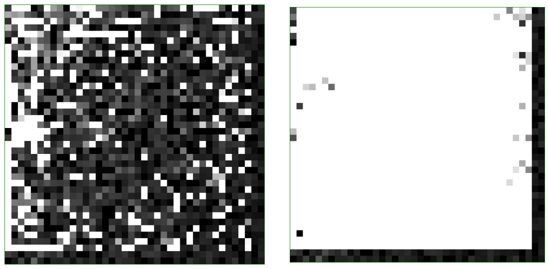

Figure 3 displays the imaging results obtained with the presence of an object.

4 Conclusions

This study presents an initial evaluation of a pixelated diamond imaging detector. X-ray imaging using the developed detector yielded promising results. Considering the non-diamond-specific nature of the process and ROIC, the obtained results are satisfactory.

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