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Wafer-scale pixelated scintillator and specially designed data acquisition system for fiber optic taper array-coupled digital x-ray detector

Zhigang Zhao, Ji Li, Yaohu Lei, Ru Wang, Jianping Ren, Jian Qiao, Hanben Niu*

Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

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ABSTRACT

A digital x-ray detector scheme based on a pixelated scintillator coupled with a fiber optic (FOT) array is suitable for many high-resolution x-ray imaging applications. However, certain challenges need to be addressed for fabrication of wafer-scale uniform pixelated x-ray scintillators. In addition, difficulties associated with implementation of the data acquisition system for acquiring output image data from the multiple image sensors used in the detector also need to be addressed. In this paper, a 2 × 2 FOT array-coupled digital x-ray detector scheme using a 5-in. pixelated scintillator is proposed. A novel fabrication setup along with the corresponding processes for fabricating the wafer-scale pixelated scintillator and implementation of a specially designed embedded data acquisition system based on a single embedded micro-processer (ARM) and four field-programmable gate array (FPGA) chips are discussed in detail. Preliminary experiments demonstrate that this pixelated scintillator-based digital x-ray detector scheme with an active imaging area of about 100 mm × 100 mm shows considerable potential for use in high-resolution x-ray imaging.

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1. Introduction

Scintillator-based x-ray imaging detectors are widely used in digital x-ray imaging systems. Resolution of these scintillators are significantly reduced due to lateral spreading of visible light generated by the incident x-rays [1–4]. This effect is also seen in commercial needle structure thallium doped cesium iodide (CsI:Tl) scintillators. Pixelated x-ray scintillators, which restrain light by using separate individual pixelated microstructures, efficiently reduce lateral spreading of light [5–9]. Silicon pore array scintillators have extremely high resolution in comparison to the other proposed pixelated scintillators described in literature [1,10–13]. The high-aspect-ratio silicon pore array which is the most important component in pixelated scintillators can be fabricated using low-cost and simple methods based on photoelectrochemical etching [10,12].

However, these pixelated scintillators cannot meet the requirements for relatively larger area x-ray imaging systems for applications such as macromolecular crystallography and image-guided intervention [14–16], due to size limitation as the largest fabricated pixelated scintillator is no larger than 4 cm^2 [9–11]. Fabrication of a wafer-scale pixelated x-ray scintillator with high uniformity is challenging. In this paper, fabrication of ultra-high-aspect-ratio silicon pore arrays on 5-in. silicon wafers using a novel photoelectrochemical etching equipment and corresponding processes [17] is presented. The fabricated the pores were filled with CsI:Tl to form a large area uniform pixelated scintillator.

Pore walls in pixelated scintillators take up part of the active imaging area of the scintillator and visible light is partially absorbed by the pore walls. This results in a lowered sensitivity for the pixelated scintillators compared to conventional scintillators. Light transmission efficiency using fiber optic taper (FOT) coupling method is significantly higher than the typical lens coupling method [18–20]. Therefore, use of a FOT array is more suitable as the optical coupling component between the wafer-scale pixelated scintillator and charge-coupled device (CCD)/complementary metal-oxide-semiconductor (CMOS) image sensors. At the same time, the x-ray detector was designed for multipurpose use in scientific experiments. Due to this, coupling between the small ends of the FOT array and the corresponding CCD/CMOS image sensors needs to be demountable and adjustable. Conventional glued coupling methods could not be used for this detector. These requirements, along with the need for remote control of the detector in the x-ray radiation environment and restrictions pertaining to specific geometrical structure of the FOT array, resulted in

* Corresponding author.
E-mail addresses: szuoptoelectronics@163.com, hbniu@szu.edu.cn (H. Niu).

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considerable difficulties with the implementation of the data acquisition system for acquiring output image data from the multiple image sensors used in the detector. Here, in this paper, to meet all the above requirements, a specially designed embedded Ethernet data acquisition system based on an embedded micro-processer (ARM) combined with four field-programmable gate array (FPGA) chips was implemented.

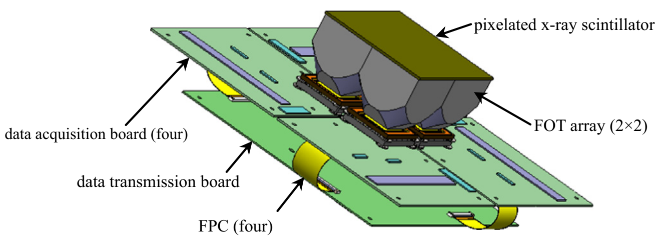

Fig. 1. Schematic representation of the 2×2 FOT array-coupled digital x-ray detector.

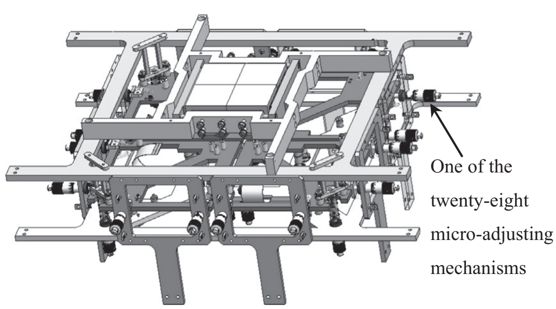

Fig. 2. Sketch of the six-dimensional adjustable coupling system between the FOT array and the four CMOS image sensors.

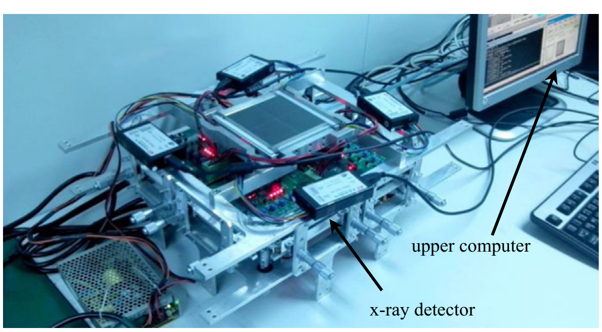

Fig. 3. Photograph of the 2×2 FOT array coupled digital x-ray detector without the pixelated scintillator.

2. System structure and mechanical design

A scheme of the pixelated scintillator with a 2×2 FOT array-coupled x-ray detector is shown in Fig. 1. The pixelated scintillator was fabricated on a 5-in. n-type silicon wafer. Diameter of the active imaging area was 110 mm. Each FOT had an image area of 50 mm $\times$ 50 mm at the large end and 25 mm $\times$ 25 mm at the small end. The pixel size of the FOT was 12 μm at the large end and 6 μm at the small end. The large ends of the four FOTs were butted precisely to form the 2×2 FOT array. Width of butted seams between adjacent FOTs was smaller than 36 μm. The four CMOS image sensors used were LUPA-4000 sensors from Cypress with a pixel size of 12 μm, and a total of 2048×2048 pixel. Four data acquisition boards (DABs) combined with a single data transmission board (DTB) made up the data acquisition and transmission system. The detector was connected to the upper computer using a 100 Mbps Ethernet cable.

A six-dimensional adjustable coupling system was installed between the FOT array and the four CMOS image sensors. This allowed the device to meet requirements for multipurpose scientific applications. Fig. 2 shows the mechanical structure of the six-dimensional adjustable coupling system. Twenty-eight micro-adjusting mechanisms with the accuracy of 0.001 mm were used in the coupling system. This allowed adjustment of all four DABs to be relative to the translational and rotational motion in the *X*, *Y* and *Z* directions.

Fig. 3 shows a photograph of the assembled 2×2 FOT array-coupled digital x-ray detector without the pixelated scintillator.

The main focus and emphasis of this paper is related to the fabrication of the uniform wafer-scale silicon pixelated scintillator and the implementation of the embedded data acquisition system discussed in the following sections.

3. Fabrication of uniform wafer-scale pixelated scintillator

To fabricate the silicon pore array pixelated scintillator, high-aspect-ratio pore arrays are formed by photoelectrochemical etching of the entire silicon wafer. Next, surface of the pore array is oxidized to form the total reflection layer, and CsI:Tl is melted into the pore array. Finally, the fabrication of the pixelated scintillator is completed by sealing the device into packaging [9,10].

Formation of a uniform wafer-scale pore array with high aspect ratio is the crucial stage in the fabrication of a pixelated scintillator. Otherwise, size of the pixelated scintillator would be limited to less than two centimeters. Changes in the temperature of HF electrolyte

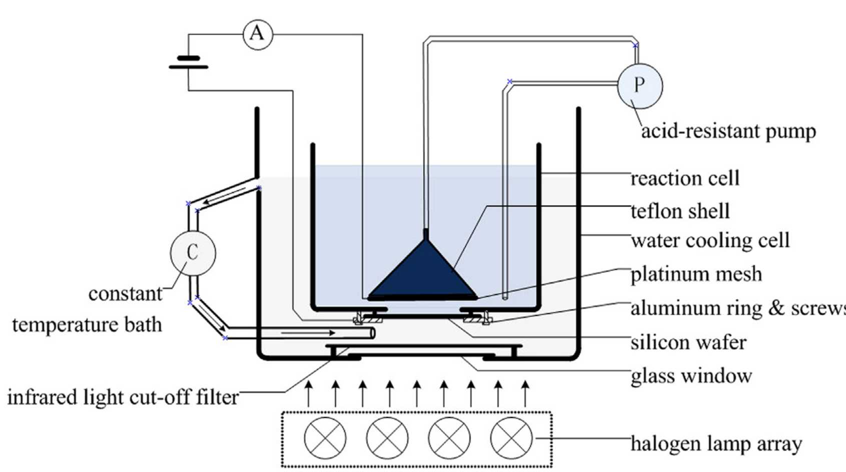

Fig. 4. Schematic diagram of the photoelectrochemical etching setup.

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