Pixel-Structured Scintillator with Polymeric Microstructures for X-Ray Image Sensors

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ABSTRACT—We introduce a pixel-structured scintillator realized on a flexible polymeric substrate and demonstrate its feasibility as an X-ray converter when it is coupled to photosensitive elements. The sample was prepared by filling $Gd_2O_2S:Tb$ scintillation material into a square-pore-shape cavity array fabricated with polyethylene. For comparison, a sample with the conventional continuous geometry was also prepared. Although the pixelated geometry showed X-ray sensitivity of about 58% compared with the conventional geometry, the resolving power was improved by about 70% above a spatial frequency of 3 mm^{-1}. The spatial frequency at 10% of the modulation-transfer function was about 6 mm^{-1}.

Keywords—X-ray image sensor, scintillator, flexible substrate, MEMS, modulation-transfer function (MTF).

I. Introduction

The indirect-conversion method using a scintillation material that converts incident X-rays into optical photons is more widely used in digital X-ray imaging than the direct-conversion method because scintillators have a relatively higher atomic number and higher physical density compared with photoconductors, which are typically used in the direct-conversion method [1], [2]. Another advantage of the use of scintillators in digital X-ray imaging is that, in contrast with the direct conversion method, the noise-aliasing problem is negligible [1], [2].

Moy [2] contended that, for optimal imaging performance, the ideal modulation-transfer function (MTF) should be as large as possible below the Nyquist limit, and then drop rapidly. This may be achieved if the scintillator is structured to match with the underlying pixel pitch of the photosensitive elements. Figure 1 shows the geometry of conventional and pixel-structured indirect-conversion detectors [1].

Although substantial effort has been devoted to this new detector design, pixel-structured scintillators have only been realized on hard substrates, such as silicon wafers and SU-8 photoresistors [3], [4]. Flexible X-ray image sensors are very attractive [5] as they offer robustness and can be produced by a cost-effective fabrication process such as jet-printing [6]. While flexible photosensors have already been developed [5], a flexible scintillator has not yet to be reported. In this study, a pixel-structured scintillator is realized on a flexible polymeric substrate. The combination of a flexible pixelated scintillator and photosensor is a good candidate for intra-oral imaging because the conventional digital intra-oral sensors cause considerable discomfort to patients.

II. Materials and Methods

1. Sample Preparation

The pixel-structured scintillator was designed to have a pixel pitch of 400 μm with a septum thickness of 70 μm. Figure 2 shows the fabrication process for the pixel-structured scintillator. Based on micro-electromechanical systems technology, the fabrication process has three main steps: fabrication of the nickel mold, polymer replication, and filling of the scintillation material. Fabrication starts with a photolithographic process using a silicon wafer. Then, the silicon surface is vertically etched to a 200 μm depth by using deep reactive ion etching. Next, a layer of 2000 Å thick Cr,

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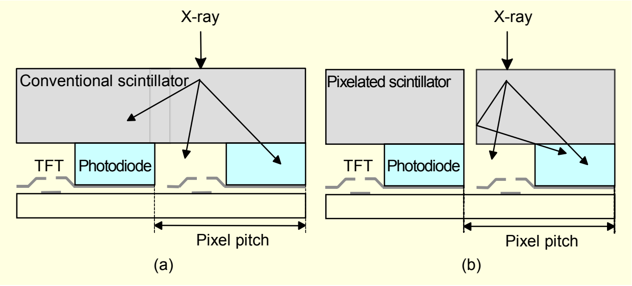

Fig. 1. Scintillator designs: (a) conventional and (b) pixel-structured.

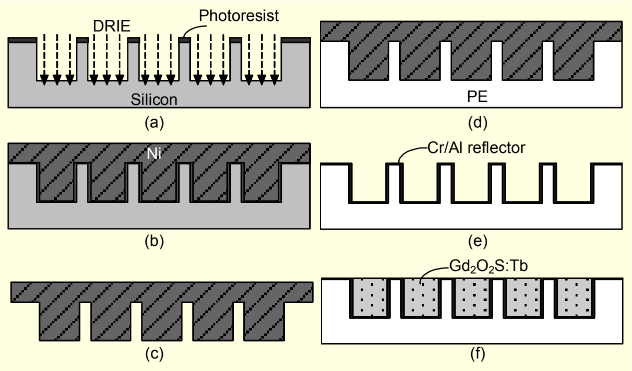

Fig. 2. Microfabrication process: (a) photolithography and silicon dry etching, (b) nickel electroforming, (c) silicon wet etching, (d) PE hot embossing, (e) Cr/Al deposition, and (f) Gd_2O_2S:Tb filling.

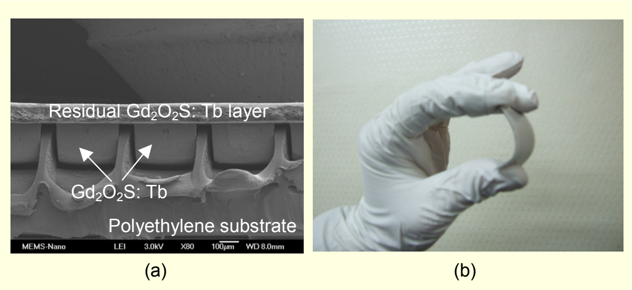

Fig. 3. Fabricated pixel-structured scintillator: (a) a SEM photo of a cross-sectional view and (b) a photo demonstrating its flexibility.

which serves as a conducting seed layer in the following electroforming process, is deposited on the silicon microstructures, followed by nickel electroforming. In the next step, the silicon is etched away using potassium hydroxide solution to produce a pillar-shaped nickel micromold. After the nickel micromold and the PE (polyethylene) substrate are aligned, they are heated and pressed in a vacuum using hot embossing. Then, Cr (1000 Å)/Al (5000 Å) layers that serve as reflectors are sequentially deposited on the microstructured PE substrate using sputtering. In the next step, solution-type Gd_2O_2S:Tb precursor (Phosphor Technology, UK) with organic binders is precipitated into the cavities.

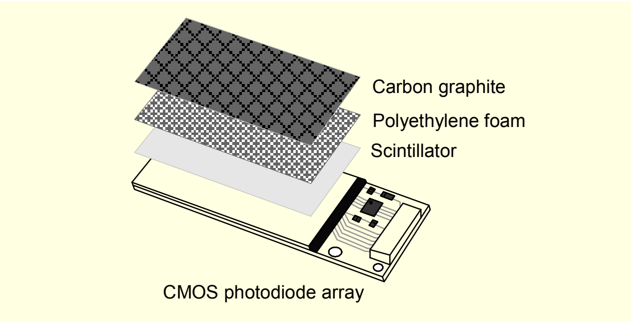

Fig. 4. Preparation of sample detector for X-ray measurement.

Figure 3(a) shows a cross-sectional scanning electron microscope image of the fabricated sample. It should be noted that the residual Gd_2O_2S:Tb layer remained after the precipitation process and was not removed, which was inevitable at that time. Figure 3(b) shows the flexibility of the fabricated sample, which has an area of 2 cm × 3 cm. For comparison, a scintillator with a conventional continuous geometry and a thickness of about 240 μm was separately prepared.

2. Experimental

A CMOS photodiode pixel array (RadEye, Rad-icon Imaging Corp., USA) was employed as a readout device of optical photons emitted from both structured and non-structured Gd_2O_2S:Tb samples. The CMOS photodiode array has a format of 512 × 1024 pixels with a pitch of 48 μm. The sample scintillators were directly overlaid onto the active area of the CMOS photodiode array. As shown in Fig. 4, to minimize the air gap that may occur between the bottom of the scintillator and the top surface of CMOS photodiode array, a thin polyurethane foam layer was applied for compression between the scintillator and the CMOS photodiode array, which were held in place by a 1 mm thick graphite cover. During measurement, the readout time was fixed at 550 ms.

For the X-ray source, a 45 kV spectrum from a fixed tungsten anode and a 125 μm thick beryllium exit window (Series 5000 Apogee, Oxford Instruments, USA) were used. An additional aluminum filter with a thickness of 0.5 mm was used. The sensitivity was measured by averaging the pixel values in the obtained images as a function of the source tube current. The MTF was measured using a slanted-slit method to avoid aliasing.

III. Results and Discussion

The measured X-ray sensitivity results are plotted in Fig. 5. The pixel-structured sample has a sensitivity (analog-to-digital

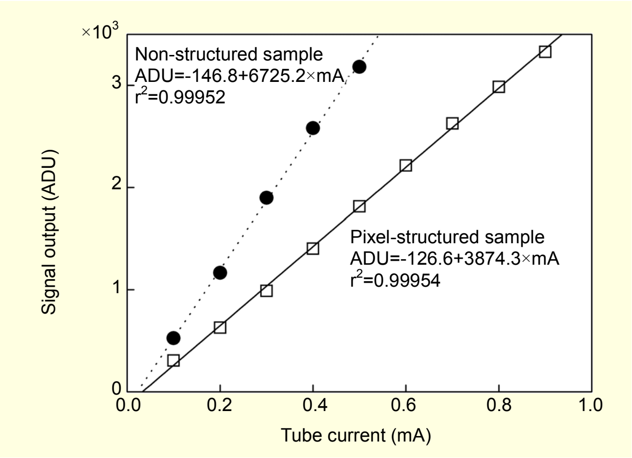

Fig. 5. Signal output as a function of tube current, which illustrates the X-ray sensitivity of the fabricated samples.

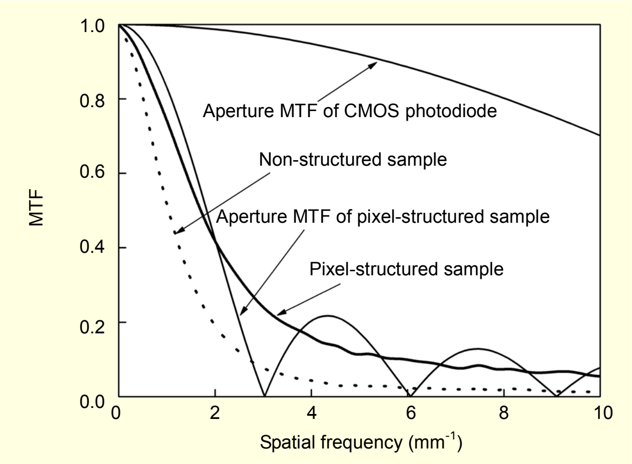

Fig. 6. MTF results of two samples measured at similar signal output levels compared to two theoretical MTF curves describing the apertures of the CMOS photodiode and the pixel-structured design.

conversion unit or ADU per mA) of about 58% compared with the sample having a conventional geometry. This lower value is likely due to the fill factor and the trapping of optical photons in the surrounding walls.

The MTF results of two samples measured at a similar signal levels are shown in Fig. 6. For comparison, theoretical MTF curves describing the aperture functions of CMOS photodiodes and pixel-structured scintillators are included. In the calculations, fill factors of 87% and 68% of two apertures are considered respectively. In these results, the effect due to the pixel size of the CMOS photodiode array is negligible. The spatial frequency at 10% of the MTF with the conventional geometry is about 2.6 mm^{-1} while that with the pixel-structured geometry is about 6 mm^{-1}. Above the spatial frequency of 3 mm^{-1}, the MTF of the pixel-structured geometry gives roughly 70% higher values compared with the conventional design geometry. It is noted that the measured MTF of the pixel-structured geometry agrees well with the theoretical estimation.

Direct comparison of the measurement results for the two prepared samples is not relevant due to their different thicknesses. The pixel-structured sample has an additional continuous Gd_2O_2S:Tb layer with a thickness of about 100 µm as shown in Fig. 3(a). Thus, the pixel-structured sample is about 60 µm thicker than the conventional geometry sample. Therefore, the actual X-ray sensitivity would be even lower compared with the conventional geometry. On the contrary, the actual MTF of the pixel-structured sample would be further optimized when the residual continuous scintillator layer is completely removed, because the MTF is mainly dependent upon the optical photon scattering. These results correspond well with previously reported trends [4].

IV. Conclusion

The pixel-structured Gd_2O_2S:Tb scintillator with latticed polymeric microstructures offers attractive features of good spatial resolution and flexibility. Flexibility is very important in medical applications, especially for dental X-rays. Moreover, the simplicity of the microfabrication process with polymer hot embossing will result in low fabrication costs and high throughput. Through the performance evaluation of fabricated scintillators, we have confirmed that they could be easily applied in next generation flexible X-ray image sensors.

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