Novel nanocrystalline Gd$_2$O$_3$(Eu) scintillator screens with a micro-pixel structure for high spatial resolution X-ray imaging

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**Abstract**

We developed a novel pixel-structured scintillation screen with nanocrystalline Gd$_2$O$_3$:Eu particle sizes for high spatial resolution X-ray imaging detectors. Nanocrystalline Gd$_2$O$_3$:Eu scintillators were successfully synthesized with a hydrothermal method and a subsequent calcination treatment, which were used as a material for converting incident X-rays into visible light. In this work, silicon-based pixel structures with different 100, 50, and 30 μm pixel sizes, a 10 μm wall width and a 120 μm thickness were fabricated through standard photolithography and the deep reactive ion etching (DRIE) process. Subsequently, a micro-pixel-structured scintillation screen was fabricated by adding the synthesized nanocrystalline Gd$_2$O$_3$:Eu scintillating phosphor to pixel-structured silicon arrays. Additionally, X-ray imaging performance such as relative light intensity, X-ray to light response and the spatial resolution in terms of modulation transfer function (MTF) were measured by using an X-ray source and a lens-coupled charge coupled device (CCD) camera system. The light intensity of the pixel-structured nanocrystalline Gd$_2$O$_3$:Eu screen was much higher than that of a pixel-structured sample made with a commercial microcrystalline Gd$_2$O$_3$:Eu product due to the density of the nanocrystalline Gd$_2$O$_3$:Eu scintillating powder-filled silicon structure. As the pixel size of the pixel-structured silicon decreased, the light intensity decreased. However, as the pixel size decreased, the spatial resolution significantly improved with no evident crosstalk from the emitted optical photons between adjacent scintillating pixels. The MTF of pixel-structured nanocrystalline Gd$_2$O$_3$:Eu screens with a 100 and a 50 μm pixel size was 20% and 30% at 6 lp/mm, respectively. As a result, this new technology showed that a microchannel structure based on a nanocrystalline Gd$_2$O$_3$:Eu scintillator could provide higher light intensity and high spatial resolution imaging compared to conventional microcrystalline scintillating phosphor.

**1. Introduction**

Indirect detection methods for digital X-ray imaging requires a scintillator film (a material that converts X-rays to visible light) and a 2D imaging sensor such as a-Si:H flat panel, CCD or CMOS imaging devices. The spatial resolution of an indirect X-ray imaging detector, unlike direct X-ray conversion methods, is currently limited by a lateral spreading effect (or crosstalk) of emitted light that depends on the thickness of the used scintillating layer [1]. Higher spatial resolution X-ray imaging is needed for medical diagnostic applications such as mammography, dental imaging and micro-CTs (computed tomography). An alternative solution for solving the spreading effect problem is to use pixelated scintillation films with polymer or silicon based-pixel structure arrays in order to prevent crosstalk between optical photons to individual neighboring pixels [2,3]. In this study, pixel-structured silicon arrays were used as light guides and filled with advanced nanocrystalline scintillator instead of conventional microcrystalline scintillating phosphor to obtain a higher packing density [4]. Our new nanocrystalline europium-doped gadolinium oxide (Gd$_2$O$_3$:Eu) scintillating phosphor was fabricated through hydrothermal synthesis. Using a pixel-structured silicon array with different pixel sizes fabricated through the DRIE process on a silicon wafer, we prepared pixel-structured screens in various sizes with nanocrystalline Gd$_2$O$_3$:Eu scintillating phosphor. Additionally, we tested X-ray imaging performance, including relative light intensity, X-ray to light response, spatial resolution in terms of modulation transfer function (MTF), and object phantom of fabricated samples.

**2. Materials and methods**

Nanocrystalline Gd$_2$O$_3$:Eu scintillating powders with an average particle size of 100 nm were synthesized by a hydrothermal process. And a synthesized sample with an optimal calcination...
temperature and time was heat-treated in an electric furnace in order to obtain the nanocrystalline Gd$_2$O$_3$:Eu scintillating powders, which had high light output under incident X-ray exposure [5,7]. Powdered-Gd$_2$O$_3$:Eu scintillating screens were manufactured with a 120 μm thickness with a particle in binder (PIB) method and screen printing (SP). The detailed fabrication procedures of paste-type Gd$_2$O$_3$:Eu solution were previously described in Ref. [6]. The pixel-structured nanocrystalline Gd$_2$O$_3$:Eu scintillating screens were fabricated by filling the fabricated paste, including nano-sized Gd$_2$O$_3$:Eu powders, into pixel-structured silicon array molds with 100, 50 and 30 μm pixel sizes with a vacuum process [2,6].

The microstructures of nanocrystalline Gd$_2$O$_3$:Eu scintillating screens with or without pixel-structured silicon arrays were investigated with FE-SEM (JEM-2100F HR). X-ray imaging performance parameters, such as relative light output, the light response to X-ray exposure dose and spatial resolution, were measured. A lens-coupled CCD imaging device with a 1024 × 1024 pixel and an effective 39 μm pixel size (Andor DV-434) was used as a readout pixel array for visible photons emitted from the fabricated Gd$_2$O$_3$:Eu scintillating screens in an experimental X-ray radiographic system [6].

### 3. Results and discussion

An optical image of the pixelated Gd$_2$O$_3$:Eu scintillation screen with a 2.5 × 2.5 cm$^2$ size and SEM images of pixel-structured silicon arrays with 100 and 50 μm pixel sizes, a 120 μm pore depth generated by photolithography and deep reactive ion etching (DRIE) process are shown in Fig. 1. Cross-section and surface images of nanocrystalline Gd$_2$O$_3$:Eu scintillating screens filled with pixel-structured silicon arrays for the 100 and 50 μm pixel sizes are shown in Fig. 2. Also, the cross-section and top views of the pixel-structured silicon array molds filled with commercial Gd$_2$O$_3$:Eu scintillator (Phosphor Technology, UK), which had an average particle size of 5 μm are shown in Fig. 3. From both Figs. 2 and 3 SEM images, the micro-pixel-structured Gd$_2$O$_3$:Eu scintillating screens using the nano-sized powders fabricated through a hydrothermal synthesis showed better uniformity and higher packing density with fewer voids compared to the commercial Gd$_2$O$_3$:Eu scintillator.

The relative light output from the fabricated Gd$_2$O$_3$:Eu scintillation screens was measured by the average pixel value of a region of interest (ROI) from X-ray images acquired under 50 kVp, 30 mAs X-ray exposure conditions. As the pore size of the pixel-structured silicon array decreased, the light output of the nanocrystalline and microcrystalline Gd$_2$O$_3$:Eu scintillating screens was reduced significantly. This trend is evident in Fig. 4. However, the light output of the pixel-structured Gd$_2$O$_3$:Eu scintillation screen with synthesized nanocrystalline powders was higher than the light output for commercial micro-sized particles since the nanocrystalline Gd$_2$O$_3$:Eu scintillator fabricated with a hydrothermal process showed light intensity that was 1.5 times higher than the commercial product (Fig. 4). There were also fewer voids and more densely packed filling of nanocrystalline scintillating particles in the pixel-structured silicon array (see Figs. 2 and 3). However, the relative light intensity of pixel-structured Gd$_2$O$_3$:Eu screens with both commercial microcrystalline particles and nanocrystalline particles was much lower than the light intensity of non-pixel structured (or continuous) Gd$_2$O$_3$:Eu screens since...
the visible photons generated within the scintillating layers were scattered and absorbed in the silicon wall surfaces \[8,9\]. The light intensities of pixel-structured samples with 30, 50 and 100 \(\mu\)m pixel sizes were approximately 5%, 11% and 22%, respectively, compared to the continuous 150 \(\mu\)m-thick nanocrystalline Gd\(_2\)O\(_3\):Eu scintillating screens.

The X-ray to light response of nanocrystalline Gd\(_2\)O\(_3\):Eu scintillating screens with different pixel sizes was measured as a function of X-ray dose and the measured results were plotted in Fig. 5. As the X-ray exposure dose increased, light output of all the fabricated nanocrystalline Gd\(_2\)O\(_3\):Eu scintillation screens with and without a pixel-structured silicon array showed a linear increase. The MTF results are plotted in terms of spatial resolution in Fig. 6 and the X-ray images obtained with a memory chip phantom are displayed in Fig. 7. The spatial resolution of non-pixel-structured and pixel-structured nanocrystalline Gd\(_2\)O\(_3\):Eu scintillating screens with 100 and 50 \(\mu\)m pixel sizes had 10%, 20% and 30% MTF values at a spatial frequency of 6 lp/mm. Sharper X-ray images were obtained by using nanocrystalline Gd\(_2\)O\(_3\):Eu scintillating screens with micro-pixel-structured silicon arrays, which are shown in Fig. 7. It was expected that the spatial resolution would largely be enhanced by a pixel-structured scintillating
screen with a smaller pixel size. However, because smaller pixel size
in pixel-structured nanocrystalline Gd2O3:Eu screens was used to
improve spatial resolution, there was a significant decrease in the
light intensity. As such, additional research to enhance the spatial
resolution of X-ray imaging without sacrificing light intensity is
needed.

4. Conclusion

Novel micro-pixel structured screens with nanocrystalline Gd2O3:
Eu scintillating phosphor were fabricated and the X-ray imaging
parameters, such as relative light output, X-ray linearity and spatial
resolution were characterized. In this study, the nanocrystalline
Gd2O3:Eu scintillator fabricated through a hydrothermal process
instead of a commercial microcrystalline Gd2O3:Eu scintillator was
utilized to increase the light intensity and the packing density of the
pixel-structured scintillating screens while maintaining a high spatial
resolution. However, substantial effort is still required to improve the
light guiding efficiency of pixel-structured scintillation screens while
maintaining high spatial resolution for X-ray imaging.

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