Journal of the Optical Society of Korea
Vol. 18, No. 3, June 2014, pp. 256-260

ISSN: 1226-4776(Print) / ISSN: 2093-6885(Online)
DOI: http://dx.doi.org/10.3807/JOSK.2014.18.3.256

A TiO_2-Coated Reflective Layer Enhances the Sensitivity of a CsI:Tl Scintillator for X-ray Imaging Sensors

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(Received March 19, 2014 : revised May 8, 2014 : accepted May 12, 2014)

Columnar-structured cesium iodide (CsI) scintillators doped with thallium (Tl) are frequently used as x-ray converters in medical and industrial imaging. In this study we investigated the imaging characteristics of CsI:Tl films with various reflective layers—aluminum (Al), chromium (Cr), and titanium dioxide (TiO_2) powder—coated on glass substrates. We used two effusion-cell sources in a thermal evaporator system to fabricate CsI:Tl films on substrates. The scintillators were observed via scanning electron microscopy (SEM), and scintillation characteristics were evaluated on the basis of the emission spectrum, light output, light response to x-ray dose, modulation transfer function (MTF), and x-ray images. Compared to control films without a reflective layer, CsI:Tl films with reflective layers showed better sensitivity and light collection efficiency, and the film with a TiO_2 reflective layer showed the best properties.

Keywords : CsI(Tl) scintillator, Light output, MTF, X-ray imaging detector
OCIS codes : (170.7440) X-ray imaging; (040.7480) X-rays, soft x-rays, extreme ultraviolet (EUV); (290.5930) Scintillation

I. INTRODUCTION

Direct and indirect digital x-ray imaging sensors have been developed to replace photographic films for industrial and medical imaging applications. However, improvements in signal-to-noise ratio (SNR), detective quantum efficiency (DQE), light collection efficiency, and modulation transfer function (MTF) are needed for electronic sensors and scintillators in medical applications [1].

Since they were first reported by C.W. Bates [2], cesium iodide (CsI) scintillators have been widely used for high-spatial-resolution charged-particle and x-ray detection in many fields, such as medical radiography [3-5]. Thallium-doped cesium iodide (CsI:Tl) is one of the most versatile and efficient scintillators developed for indirect x-ray detection. Its emission is in the visible range with a broad peak at 550 nm, which is easily registered by silicon photo-sensors, and it exhibits one of the highest conversion efficiencies among all known scintillators [6]. The scintillation mechanism and properties of single CsI:Tl crystals have been well known since the 1960s [7], but polycrystalline CsI:Tl crystals are still under investigation [8, 9].

Coating CsI:Tl films with white TiO_2 reflective layers is known to improve the light collection efficiency [10]. In this study, we investigated the imaging characteristics of a CsI:Tl film with various reflective layers of aluminum (Al), chromium (Cr), and titanium dioxide (TiO_2) powder, coated on glass substrates 150 μm thick. We used two effusion-cell sources in a thermal evaporator system to fabricate CsI:Tl films on the different substrates and evaluated their scintillation properties and x-ray imaging characteristics.

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Fabricated CsI:Tl scintillators were observed by means of scanning electron microscopy (SEM), and scintillation characteristics such as emission spectrum, light output, light response to x-ray dose, and modulation transfer function (MTF) were evaluated. Furthermore, x-ray images of a CsI:Tl scintillator memory chip were obtained using an x-ray measurement system.

II. MATERIALS AND METHODS

2.1. Preparation of Reflective Layers

Glass was coated with reflective layers of Al, Cr, or TiO_2 powder to increase light output. Al and Cr were coated using thermal evaporation (100 nm thickness), while TiO_2 powder was coated using a print screen method (20 μm thickness). CsI:Tl scintillator was then deposited on samples with each reflective layer, and on bare glass.

2.2. Deposition of CsI:Tl Films

We used two effusion-cell sources in a thermal evaporator system to deposit CsI:Tl films. An effusion-cell source is commonly used in thin-film fabrication for several reasons: it provides excellent scintillation properties, easy control of Tl doping concentration, and a constant deposition rate owing to easy temperature control and excellent thermal stability. The heating coil in the holder maintains substrate temperature. The substrate was positioned 250 mm above the effusion-cell source. The two effusion-cell sources were placed on each side of a vacuum chamber and operated at different temperatures according to the desired composition ratio of Tl to CsI inside the scintillator. Conditions such as deposition rate, chamber vacuum pressure, heat treatment temperature, and Tl doping concentration affect the microstructures and scintillation properties of CsI:Tl films [11-12]. CsI:Tl scintillator was deposited onto the substrate in a vacuum chamber at 150°C and 10^{-3} Torr at low deposition rate (< 3 μm/min) and Tl doping concentration (0.1 mol%) with substrate plate rotation. The columnar microstructures of fabricated CsI:Tl scintillator films were observed via SEM (Fig. 1). The thicknesses of deposited CsI:Tl layers were measured as 173.40 μm (a), 161.14 μm (b), 165.00 μm (c), and 178.20 μm (d) respectively, as shown in Fig. 1.

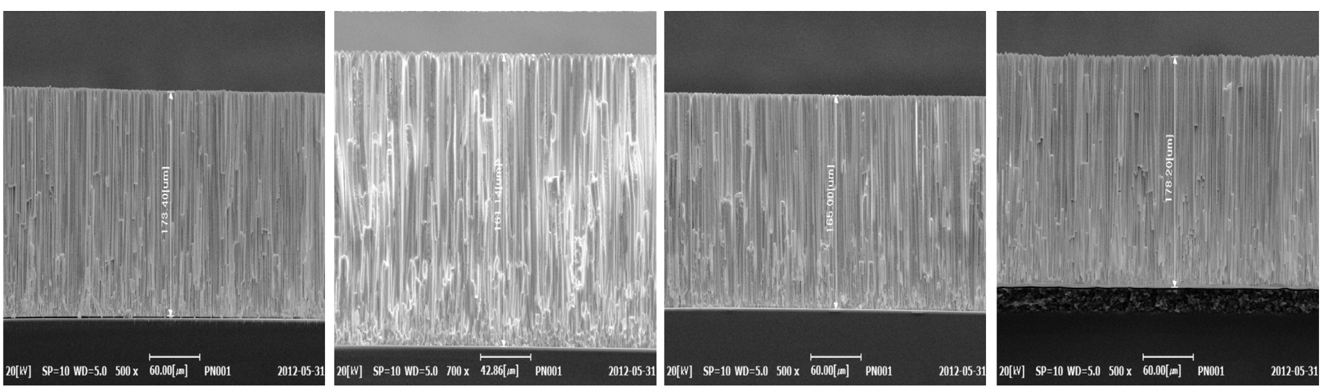
2.3. Measurement of Scintillation Characteristics

The scintillation characteristics of the CsI:Tl film, such as light output, intensity of x-ray induced luminescence (XL) spectra, and emission spectrum, were measured using a UV-visible spectrometer (Spectra Academy, K-MAC, Korea) with an optical cable in a dark chamber equipped with a lens-coupled CCD imaging device (1024 × 1024 active pixels with 13-μm pixel pitch and an effective field of 13.2 mm × 13.2 mm; Andor DV-434, UK) connected to a PCI controller card. The relative light output was measured using an x-ray tube with 4.3-mm spot size and 0.8-mm inherent Al filter with 80-kVp x-ray energy and 30-mAs beam current (BRS-2, LISTEM, Korea), and a lens-coupled CCD imaging device. The data were analyzed using appropriate software to measure x-ray response signals and x-ray images [13]. The distance between the x-ray tube and CsI:Tl films was fixed at 400 mm. The readout noise level was kept low by cooling the lens-coupled CCD camera system. The spatial resolution (MTF) and x-ray images of a memory chip were obtained using the CCD camera system. The MTF curve was measured as a function of spatial frequency of the fabricated CsI:Tl film by capturing edge images using a tungsten phantom of thickness 1 mm [10].

III. RESULTS AND DISCUSSION

3.1. Measurement of Light Output and Emission Spectra

The light output of the CsI:Tl scintillator was measured by average pixel values over the region of interest (ROI)



(a) (b) (c) (d)

FIG. 1. SEM images of cross section of the CsI:Tl films fabricated on different substrates: (a) bare glass, (b) glass coated with aluminum (Al) reflective layer, (c) glass coated with chromium (Cr) reflective layer, and (d) glass coated with titanium dioxide (TiO_2) reflective layer.

of x-ray images acquired through an x-ray imaging sensor. The light output of the CsI:Tl film fabricated on the substrate coated with a TiO_2 reflective layer was higher than that of the other samples (Fig. 2). The x-ray emission spectra of the CsI:Tl films fabricated on each type of reflective layer and on bare glass are shown in Fig. 3. X-ray response was investigated by measuring pixel values of the images as a function of x-ray exposure doses. The x-ray exposure dose was measured by calibrated ion chamber at a fixed 400-mm distance between x-ray source and CsI:Tl scintillator. The response of the CsI:Tl scintillator films to x-ray images increased linearly as the x-ray exposure increased, as shown in Fig. 4.

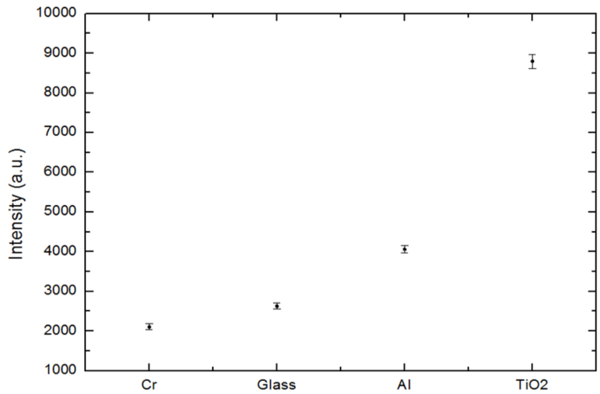


FIG. 2. Light output of CsI:Tl scintillator films fabricated on different substrates.

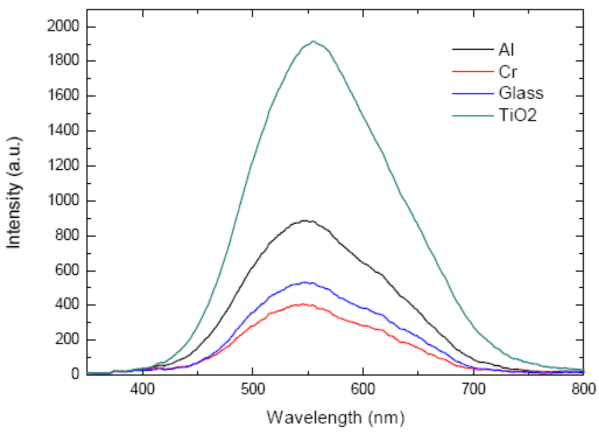


FIG. 3. Emission spectra of CsI:Tl scintillator films fabricated on different substrates.

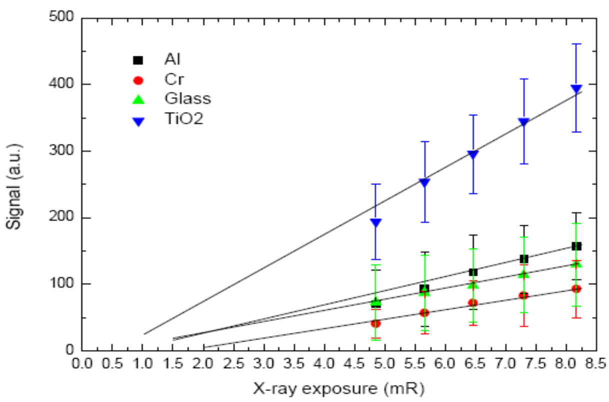
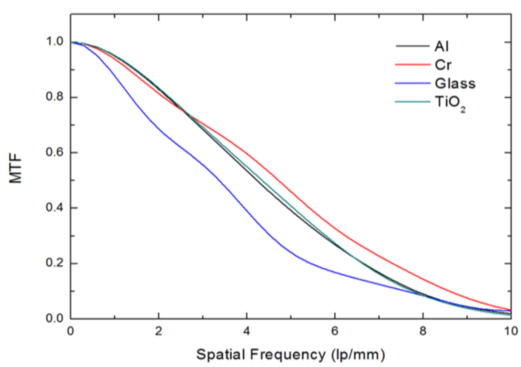


FIG. 4. X-ray responses of CsI:TI scintillator films.

3.2. Measurement of Spatial Resolution and X-ray Images

The modulation transfer function (MTF) curves of CsI:Tl films were measured quantitatively by a slant edge phantom method for evaluating spatial resolution. The modulation transfer function (MTF) of each CsI:Tl film was measured using the obtained edge images. The edge spread function (ESF) was obtained from the angled edge image, and differentiating the ESF yielded the line spread function (LSF). The MTF curve was generated by Fourier transforming the LSF data using MATLAB [14-16]. The MTF curves of the CsI:Tl scintillators fabricated on each type of reflective layer and on bare glass are shown in Fig. 5. The CsI:Tl film fabricated on the TiO_2 reflective layer coated substrate shows the highest spatial resolution. The spatial frequency at 20% of the MTF value of the CsI:Tl scintillator film on bare glass was 5.4 lp/mm, while the MTF values of films on Al, Cr, and TiO_2 reflective layers were 6.6 lp/mm, 7.2 lp/mm, and 6.6 lp/mm respectively.

X-ray images of a memory chip of each of the CsI:Tl



(a)

(b)

FIG. 5. The measured MTF curves of CsI:Tl scintillator films (a) and used tungsten phantom (b).

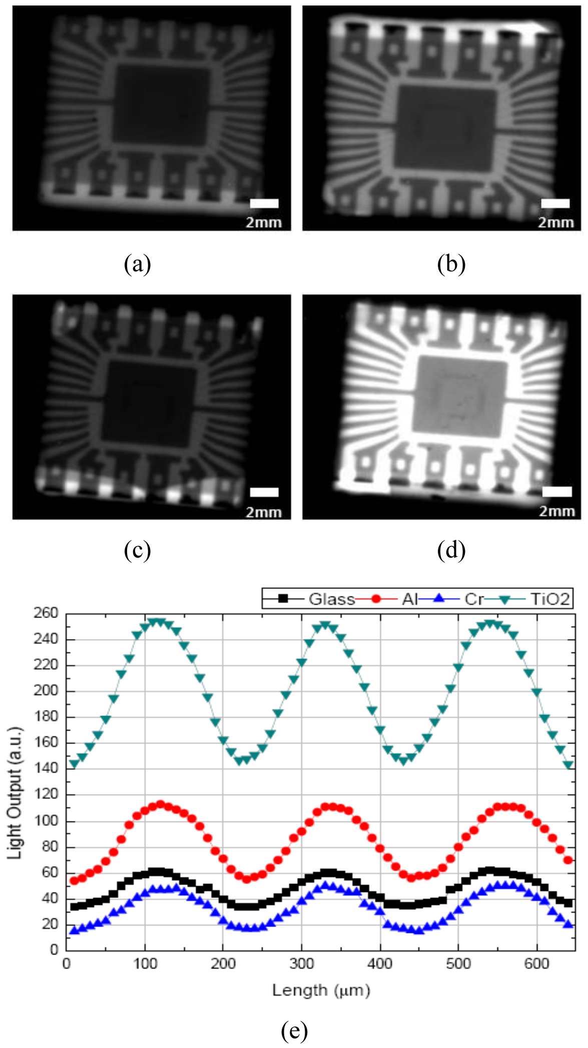


FIG. 6. X-ray images of memory chips of CsI:Tl films fabricated on different substrates: (a) bare glass, (b) glass coated with aluminum (Al) reflective layer, (c) glass coated with chromium (Cr) reflective layer, and (d) glass coated with titanium dioxide (TiO_2) reflective layer. Intensity curve of light output is shown along the lenghth of the film (e).

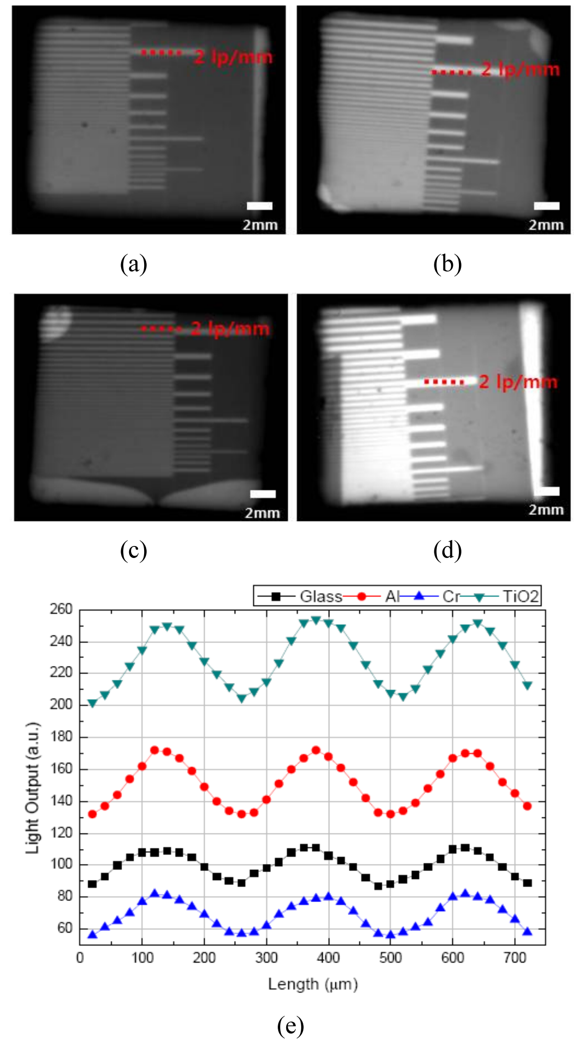


FIG. 7. X-ray images of test patterns of the CsI:Tl films fabricated on different substrates: (a) bare glass, (b) glass coated with aluminum (Al) reflective layer, (c) glass coated with chromium (Cr) reflective layer, and (d) glass coated with titanium dioxide (TiO_2) reflective layer. Intensity curve of light output is shown along the lenghth of the film (e).

films fabricated on different substrates are shown in Fig. 6. Images of a x-ray test pattern (Nuclear Associates P/N 07-553) with 2 lp/mm spatial resolution were shown in Fig. 7. X-ray images and intensity traces along the lengths of CsI:Tl films fabricated on different reflective layers are shown in Figs. 6 and 7.

Although CsI:Tl films with columnar structure deposited via vacuum evaporation are commercially available, there is demand for scintillators with higher sensitivity and spatial resolution for x-ray detectors used in medical imaging to minimize the radiation dose [9]. In this study, we fabricated CsI:Tl scintillators using a thermal evaporation method. CsI:Tl scintillator films were deposited on bare glass and glass with Al, Cr, and TiO_2 reflective layers to increase the light collection efficiency by reducing light loss in the vertical direction. A few years age, Cha et al. also studied the fabrication of CsI:Tl scintillator on substrate and reflective layers [10], but their results were limited by optical loss due to the substrate located between the CsI:Tl scintillator and detector.

The columnar structure was seen at a pressure of 10^{-3} Torr in the vacuum chamber. The CsI:Tl film fabricated on the TiO_2-coated substrate shows the highest light output. Spatial resolution and light output were improved for CsI:Tl scintillator films fabricated on substrates coated with reflective layers, compared to the films fabricated on bare glass.

IV. CONCLUSION

In this study we investigated the imaging characteristics of CsI:Tl films with various reflective layers of aluminum (Al), chromium (Cr), and titanium dioxide (TiO_2) powder, coated on glass substrates. Compared to glass without a reflective layer, CsI:Tl films with a TiO_2 reflective layer showed the best properties. In conclusion, CsI:Tl films with high sensitivity and spatial resolution can be fabricated on a glass substrate coated with a TiO_2 reflective layer.

ACKNOWLEDGMENT

This work was supported by the Korea Health Industry Development Institute (KHIDI) (grant No. A120152) under the auspices of the Ministry of Health and Welfare, the Korea Evaluation Institute of Industrial Technology (KEIT) (grant No, 10047759) funded by the Ministry of Trade, industry & Energy (MOTIE), and Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST) (grant code: 2010-0026094).

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