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X-ray Tomography using Thin Scintillator Films

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Abstract

2-14 μm thin CsI:Tl scintillation screens with high spatial resolution were prepared by the thermal deposition method for low energy X-ray imaging applications. The spatial resolution was measured as a function of the film thickness. It was proposed that the spatial resolution of the prepared conversion screens can be significantly improved by an additional deposition of a carbon layer.

Keywords

CsI:Tl; thin scintillation films; high spatial resolution; X-ray imaging; vacuum deposition method; carbon layer.

1 Introduction

CsI:Tl scintillator films are widely applied as the conversion screens for indirect X-ray imaging. CsI:Tl is characterized by one of the highest conversion efficiencies of any known scintillators [1]. Many authors have studied different approaches to the performance of the scintillation films. The methods to fabricate thin scintillators using a vacuum deposition process have been developed since the 1960s by C.W. Bates [2]. In general, there are two approaches to improve the spatial resolution of the X-ray image obtained using scintillators. The first one consists of the growth of the CsI:Tl scintillator with micro-columnar structure [3–5]. The micro-structure of the crystals decreases the lateral spreading of the scintillating light. The second approach considers post-deposition additional coating by carbon to decrease multiple scattering of photons inside the scintillator volume [6]. It is observed that the intrinsic properties of the structured CsI:Tl screens are heavily influenced by post deposition carbon coating. In this work the influence of carbon layer on the spatial resolution and the light output of the films with different thicknesses and energy of incident X-ray photons is studied. Additionally, the paper is dedicated to demonstrate the X-ray imaging applications of thin scintillation films.

2 Experimental Setup

2.1 Preparation of CsI:Tl Scintillation Films

The CsI:Tl scintillation films were manufactured by the thermal deposition method. Glass substrates with 150 μm thickness and 25x25 mm^2 area have been used. The source material CsI:Tl is held in a tantalum boat. The doping concentration of Tl is about 0.08 mol%. During the deposition process the tantalum boat temperature was set to 680°C as nominal value. To achieve homogeneous substrate coverage of the scintillator a relatively low deposition rate (17 ± 2 Å/s) was used. All samples were prepared at a pressure of $5\cdot10^{-3}$ Pa and a substrate temperature at 25°C as recommended by the Thornton Zone Model [8]. A rotated disk with substrates was situated at a distance of 65 cm from the tantalum boat. Four thicknesses of CsI:Tl films were prepared: about 2, 4, 8 and 14 μm.

It was observed that the Tl concentration decreases with the increase of deposition time. The Tl density in the 8 μm sample is 80% the one of the 2 μm sample, due to larger evaporation velocity of Tl relative to CsI. The deposited CsI:Tl scintillator is characterized by sufficient Tl concentration for thicknesses less than 10 μm. For larger thicknesses a serial deposition procedure has to be used increasing the CsI:Tl layer step by step. The scintillator morphology of the CsI:Tl film deposited on

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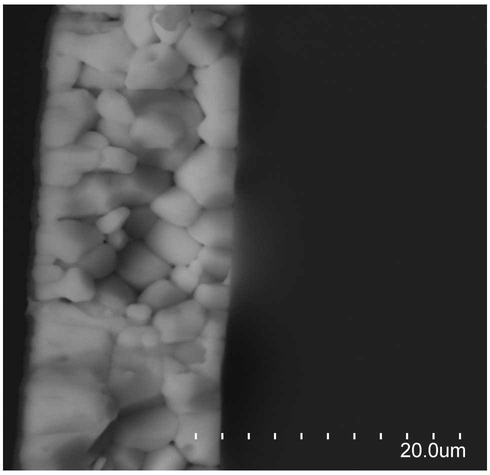

Fig. 1: The cross section of the CsI:Tl film deposited on a glass substrate with thickness 14.4±0.4 μm

the glass substrate was investigated by a scanning electron microscope and is shown in Fig. 1. The film consists of a well-defined grain structure with a typical size of the grain about 3±2 μm.

In order to the improve spatial resolution of the prepared screens an additional carbon layer is deposited on the CsI:Tl surface by the magnetron deposition method using the AUTO 500 Vacuum Coater (BOC EDWARDS). All images that will be shown below were generated using CsI:Tl films with a 70 nm carbon layer, unless otherwise stated.

2.2 Micro-structure measurement and quantification of X-ray imaging performance

The examination of the thin film scintillators was carried out at the "Microscopy and tomography" beamline of the VEPP-3 synchrotron source (BINP, Novosibirsks). The stability of the electron orbit in the VEPP-3 storage ring was better than 50 μm and the electron bunch with a size of 0.5x1.5 mm^2 provided a spatial resolution around 1 μm. The X-ray working wavelength was selected by a double-crystal Si(111) monochromator used in the parallel Bragg-geometry and installed at a distance of 14.5 m from the synchrotron radiation (SR) emission point. The energy of the photons of the X-ray monochromatic beams, used in the experiments, varied from 5 to 40 keV. Slits installed upstream the sample were applied for suppression of parasitic reflections from the monochromator and formed a 2x2 mm^2 collimated X-ray beam. The scintillator was placed at a distance of 16.5 m from the SR source. The scintillator was pre-aligned in a translated axis with an accuracy of 10 μm and in a rotation axis with an accuracy of 0.01 degrees. The visible light from the scintillator was collected by the precise digital camera Hamamatsu ORCA-Flah2.8, placed at a distance of 5 cm from the scintillator screen. The CsI:Tl film was fixed facing to the X-ray source while the glass substrate was directed to the optical detector.

3 Results and Discussion

3.1 Spatial resolution

In order to test the intrinsic spatial resolution of the resulting system images of gold patterns produced at BINP are taken. The patterns are manufactured by e-beam lithography (SEM HITACHI S 3400 type II with Nanomaker system). The PMMA 950k e-beam positive tone resist with a 2 μm thickness was used. The X-ray absorber pattern was obtained by gold electroplating. Fig. 2 was obtained using the X-ray imaging technique with a 2 μm thick CsI:Tl screen where the numbers indicate the width of the corresponding gold line. The image of the pattern with 6 μm width can be reasonable resolved. The image also demonstrates that the response of the X-ray conversion screen is uniform across the area of the film. The total spatial resolution of the system is caused, predominantly, by the following factors:

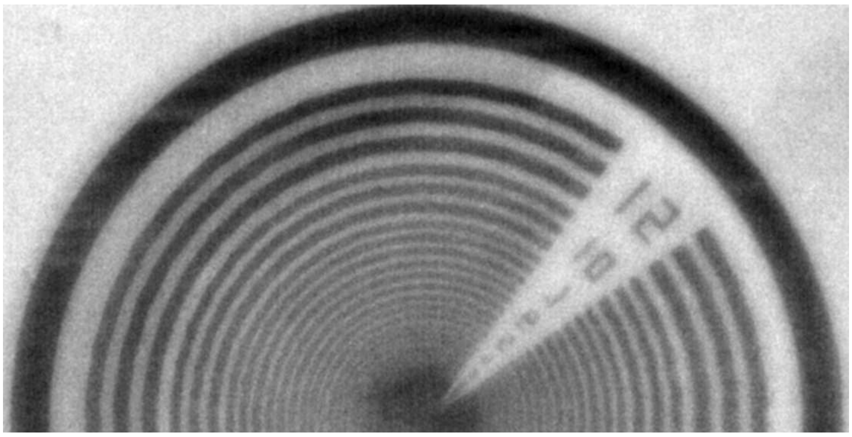

Fig. 2: Image of gold patterns obtained by X-ray imaging technique using CsI:Tl films

non-collinearity of the incident X-ray beam, mechanical oscillation of the holder of the detector relative to beam line and lateral spreading of visible photons inside the scintillator volume. The last two effects contribute about equally. An anti-vibration platform is used to reduce the contribution of the vibrations.

In order to perform a measure of the ability of our imaging detector to reproduce image contrast at various spatial frequencies in the range of 0 to 160 line-pairs/mm (lp/mm) the modulation transfer function MTF(f) is given by the following equation:

$$MTF(f) = \frac{FFT[LSF](f)}{FFT[LSF](f=0)} \tag{1}$$

where f means the spatial frequency (the inverse of the frequency equals the distance in millimeters between two resolved lines), FFT - the Fast Fourier Transform and LSF - the line spread function. A steel plate placed in front of the scintillator with thickness 1 mm is utilized to obtain the edge image, from which the oversampled LSF is calculated [9]. The MTF at each line-pair frequency can be defined as a function of the brightness of the line pairs as (max. brightness - min. brightness)/(max. brightness + min. brightness). So, the higher MTF corresponds to the better sharpness and resolution of an image.

Fig. 3 shows the MTFs for screens of various thicknesses. It is seen that there is a reduction in resolution with increased film thickness due to lateral light spreading and imperfect channeling inside the scintillator volume. This dependence is in agreement with previous results reported in Refs. [6, 7] and illustrates that the scintillation screens are characterized by micro-columnar structure. The most thin 2 μm screen provides the highest spatial resolution required by low energy micro-tomography of biological objects as well as the high stopping power of the X-ray beam. For example, the conversion efficiency of the X-ray beam in the 2 μm screen is still 20% at 9 keV energy of the incident X-ray.

In order to demonstrate the improvement of resolution, related with the carbon deposition, MTF(f) of patterns with different conditions are calculated. Lines 1, 2, and 3 in the Fig. 3 correspond to a screen with 14 μm thickness of CsI:Tl and with 0, 70, and 140 nm of carbon, respectively. The improvement can be explained as following. The additional carbon layer suppresses the reflection of scintillation photons on the interface between the carbon layer and the CsI:Tl, removing the multiple scattering of visible photons inside the scintillator volume. Simultaneously, the additional carbon layer leads to a decrease of light output by a factor 3 ± 1. The factor is significantly larger than 2, indicating the presence of multiple reflection between scintillator surfaces. Also the MTFs were investigated as a function of the incident X-ray energy. It was observed that there is no significant improvement of the spatial resolution with an increase of the X-ray energy from 5 to 40 keV.

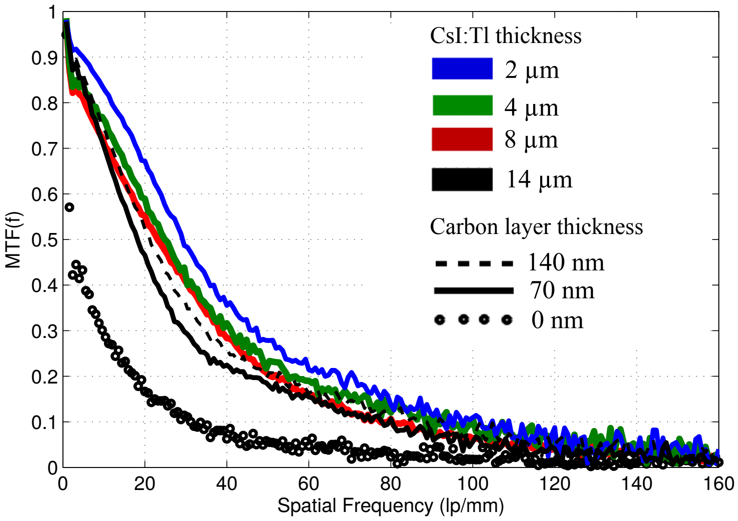

Fig. 3: Measured MTF curves with different thicknesses of CsI:Tl scintillating screens and carbon layers

Fig. 4: The example of the tomography of drosophila

3.2 3-D tomography

The high resolution images obtained by the screens were used to reconstruct 3D structures of different samples with the X-ray computer tomography method. Each tomography scan consists of 720 projections with an angular step of 0.25° (from 0° to 180°) obtained at monochromatic beam with photon energy of 15 keV. Small angle SR deviation of about 0.2 mrad makes it possible to use an algorithm for a parallel beam geometry, which simplifies the process of the 3D reconstruction of the object and significantly improves the quality of the image. The example of the tomography of drosophila can be found in Fig. 4.

To nondestructively investigate objects which are bigger than field of view of the detector the local computed tomography mode and a polychromatic beam with an average photon energy of about 25 keV are used. For example, kimberlite is an important source of diamond deposits that contain xenoliths. One of the possible types of xenoliths are garnet peridotite depleted of silicon and aluminum and rich of magnesium and iron. The study of diamondiferous xenoliths by X-ray computer tomography allows to determine the spatial distribution of rock-forming minerals and to characterize genetic relationships and the process of crystallization in the deep areas of our planet. Fig. 5 depicts a 3D image of garnet distribution on the diamondiferous rock.

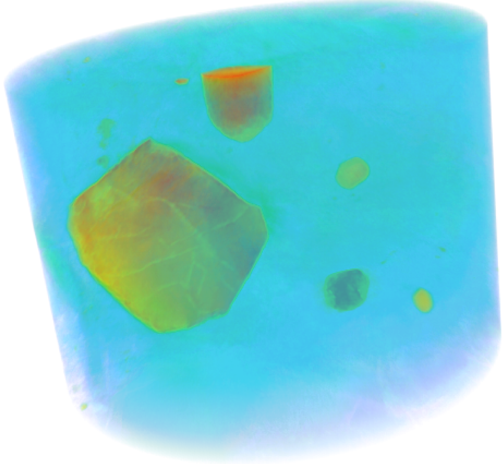

Fig. 5: 3D image of garnet distribution on the diamondiferous rock

3.3 Other prospects

Also thin CsI:Tl films deposited on mylar substrates can be used for non-destructive diagnostics of the spatial profiles of low energy beams of charged particles (such as muon beams at the MEG experiment). The proposed method allows to perform the beam monitoring simultaneously with the experimental data acquisition. Also the developed technique of CsI:Tl deposition allows to perform low cost X-ray converters with arbitrary thickness, that can be used in medicine and other fields.

4 Conclusion

The technique of the production of thin CsI:Tl films with the thermal deposition method has been developed. The spatial resolution of the produced conversion screens can be significantly improved by additional deposition of a carbon layer with a thickness of about 100 nm which is designed to absorb photons propagating in backward direction. All X-ray low energy radio-graphic methods can be employed with films in polychromatic and monochromatic modes to investigate the internal structure of a large variety of objects varying from 10 μm of biological tissue up to 10 cm of dense rock.

References

[1] Martin Nikl, Scintillation detectors for x-ray, Meas. Sci. Technol. **17** (2006).

[2] C.W. Bates, Scintillation Processes in Thin Films of CsI(Na) and CsI(Tl) used to Low Energy X-rays, Electrons and Protons, in Photo-Electronic Image Devices, pp. 451-459, Academic Press, (1969).

[3] V.V. Nagarkar, et al., Structured CsI(Tl) Scintillators for X-ray Imaging Applications. IEEE Trans. Nucl. Sci, **45**, pp. 492-496, (1998).

[4] V.V. Nagarkar, et al., A Comparative Study of CsI(Tl) Screens for Macromolecular Crystallography, Proc. SPIE, Vol. **4508**, pp.15-19, (2001).

[5] D. Yao, et al., IEEE Transactions on Nuclear Science, **60**, 3 (2013).

[6] F. Zhao-Dong, et al., Chinese Phys. C **39** 078202 (2015).

[7] B.Z. Zhao, et al., Chinese Physics C, **38** 116003 (2009).

[8] J.A. Thornton, "Influence of apparatus geometry and deposition conditions on the structure and topography of thick sputtered coatings", J. Vac. Sci. Technol. **11** (1974).

[9] H. Illers, et al., Radiat Prot Dosimetry, **114**, 214-219 (2005).