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Enhanced Columnar Structure in CsI Layer by Substrate Patterning

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Abstract

Columnar structure in evaporated CsI layers can be controlled by patterning substrates as well as varying evaporation conditions. Mesh-patterned substrates with various dimensions were created by spin-coating polyimide on glass or amorphous silicon substrates and defining patterns with standard photolithography technique. CsI(Tl) layers 200-1000 μm were evaporated. Scintillation properties of these evaporated layers, such as light yield and speed, were equivalent to those of the source materials. Spatial resolution of X-ray detectors consisting of these layers and a linear array of Si photodiodes was evaluated by exposing them to a 25μm narrow beam of X-ray. The results obtained with 200μm thick CsI layers coupled to a linear photodiode array with 20 dots/mm resolution showed that the spatial resolution of CsI(Tl) evaporated on patterned substrates was about 75 μm FWHM, whereas that of CsI(Tl) on flat substrates was about 230 μm FWHM. Micrographs taken by SEM revealed that these layers retained the well-defined columnar struature originating from substrate patterns. Adhesion and light transmission of CsI(Tl) were also improved by patterning the substrate.

I. INTRODUCTION

One of the essential components of a radiation imaging chain is a radiation input converter. In most applications of position-sensitive radiation detection, conventional radiography[1,2,3], and digital radiography[4], a scintillator screen is used to convert the incoming radiation into visible light which is then detected on film or other position sensing device. Such scintillators are usually required to have high resolution and high output brightness characteristics. The brightness of the light output is, in part, a function of the thickness of the scintillation layer, which determines the amount or x-ray energy absorbed, and of the inherent scintillation efficiency. However, as this layer is made thicker, the spatial resolution is decreased because light photons emitted in response to the absorption of x-ray photons or charged particles will emerge from the scintillator surface at points further away in the transverse direction. Such lateral light spreading is caused by two factors: first, the scintillator emits light photons isotropically from the point at which a radiation particle, such as the x-ray photon, is absorbed; second, even light photons which are traveling more or less perpendicularly to the surface may be scattered in the lateral direction before they reach the surface. Thus, the actual thickness of the scintillation layer is a compromise between the desired high radiation absorption that may be obtained from thicker layers and the required or desired resolution which improves as the thickness of the layer is reduced. Obviously, it would be desirable to increase the thickness of the scintillation layer without degrading the spatial resolution. This can be accomplished by suppressing the lateral light spread within the layer. Certain techniques for forming small cracks perpendicular to the scintillator surface to limit light spread have been developed[4-6], and the characteristics of evaporated CsI(Tl) layers coupled to a-Si:H photodiodes have been reported[2].

One early approach to form a light-guide structure in a luminescent layer was to deposit a thin scintillation layer of CsI on the substrate[4] and impart thermal shocks to the CsI layer, producing cracks therein due to the different thermal expansion coefficients of the substrate and the CsI layer. Another light-guide structure fabrication method was made [7], in which the substrate had a very thin AlO_3 layer on the top; when baked it cracked the AlO_3 layer, forming small grooves on the substrate. This type of cracked or net-like mosaic substrate further enhances the columnar structure of the scintillation material deposited on it. However, a scintillation layer prepared by these processes has the following drawbacks:1), the columns defined by cracks have an irregular structure, which decreases the light collimation and thus decreases the resolution. 2), it is difficult to ensure the reproducibility of the size of the columns. For these reasons, CsI x-ray scintillation layers (150-200μm thick) made by these methods have spatial resolution of 4 to 6 line-pair/mm at the 10 percent level.

In the present paper we report a new approach for the fabrication of a scintillation layer by forming a sequence of columns of regular, controlled size (diameter) perpendicular to the substrate (or detector), which provides a high light collimation property, thereby improving the resolution of the radiation detection. The preparation and morphology of CsI on these patterned substrates are described in the next section. The optical properties of evaporated CsI(Tl) layers, such as line spread function, transmission and modulation transfer function are discussed.

II. PREPARATION AND MORPHOLOGY OF THE EVAPORATED CsI(Tl)

This work was supported by the Director, Office of Energy Research, office of High Energy and Nuclear Physics, Division of High Energy Physics, and Office of Health and Environmental Research, Division of Physics and Technological Research of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

Since there is a close contact between the substrate and the CsI layer, it was expected that the substrate treatment could influence the outgrowth of the deposited materials. Mesh-like substrates with various dimensions, as shown schematically in Fig.1.

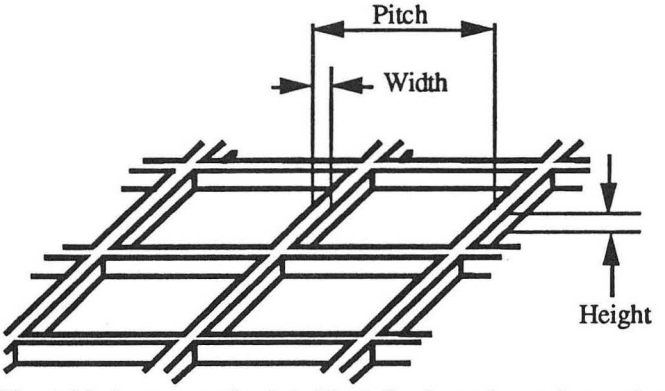

Fig. 1 Mesh pattern of polyimide defined on glass substrate by photolithography. (Pitch=40~80μm, Width=8μm, Height=4~15μm)

Initially the polyimide material, Du Pont PI2555, was used to form 4 μm high ridges on the substrate. Subsequently, it was found that thicker polyimide patterns produced a narrower line spread function. The following procedure is the preferred one for creating a ridge pattern 10~15 μm high in a polyimide film. In order to simplify processing, photosensitive polyimide, Du Pont PI 2722 which is a soluble polyimide precursor containing photo-reactive materials, was used in place of the PI 2555 polyimide. Glass substrates were well dehydrated in order to prevent the formation of bubbles inside the following deposited polyimide layers. The photosensitive polyimide was spin-coated on the substrate surface to produce a polyimide layer of ~ 10-15μm thick. After a proper soft bake, the polyimide film was directly patterned by standard photolithography techniques. The exposed polyimide layer was wet-etched directly by Du Pont DP 6018 solvent and rinsed by the appropriate Du Pont etch and rinse solvents. The patterned polyimide was cured at a temperature in the range of120 °C to 450 °C, and then was hard-baked for further processing. Cesium iodide (Tl doped) was deposited in a vacuum evaporator onto the patterned substrate, at a temperature of 100 °C at a low evaporation rate (< 3 μm/min).

Our deposition experiments show that considerable differences in morphology exist for layers deposited on flat substrates and patterned substrates. For the present discussion, we take the mesh-like patterned substrate with ridges 8μm wide and 80 μm spacing between them as a typical representative, for comparison with the thermally induced CsI structure on a flat substrate.

The first SEM(scanning electron microscope) photograph (Fig.2) shows a CsI(Tl) layer evaporated on a conventional flat substrate. It is clearly seen that the layer consists of a large number of pillars or columns, roughly perpendicular to the substrate and running from the substrate up to the top surface. These pillars do not extend to the surface continuously. Furthermore, the layer also consists of a number of grains whose boundary will scatter the scintillation light, hence degrading the imaging resolution.

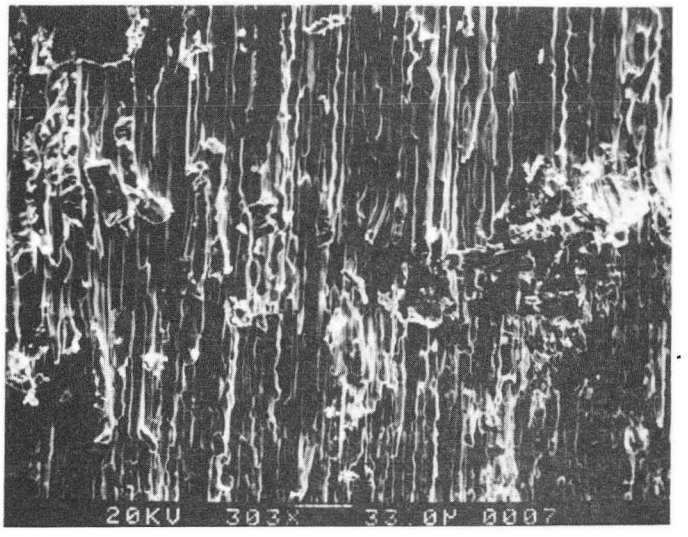

Fig. 2 SEM picture of the sectional view of the thermally induced column CsI on a flat substrate

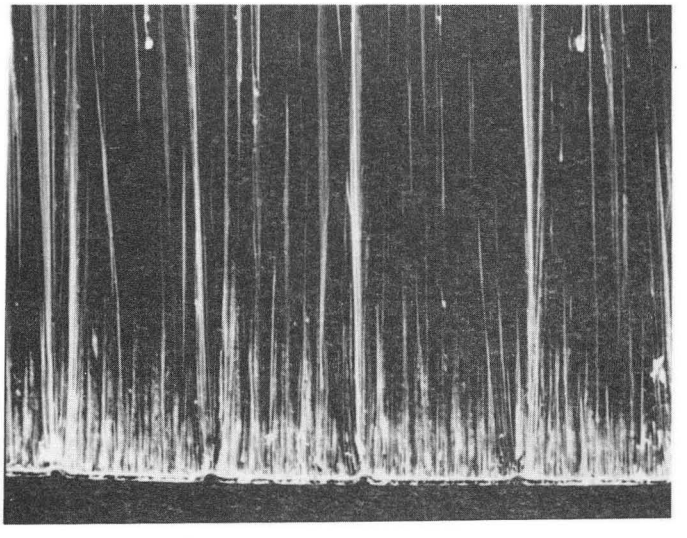

Fig. 3 Patterned ridge induced columns. The columns extend to a height of 450μm from the substrate.

The morphology and preferred orientation of the CsI(Tl) layers on patterned substrates are shown in Fig.3. Since the cracks are initiated on the ridges, a deformation stress along the crack is created, which controls further growth of CsI(Tl).In this way, columns were formed without any discontinuity and which extend perfectly to the surface. If the CsI layer is made considerably thicker, the cracks tend to vanish on the top part of the layer, as shown as Fig.3. The favorable columns extend up to about 450 μm high from the substrate; the rest of the layer has a similar structure as that on a flat substrate losing its preferred growth orientation. Factors which influence the column length are the height and width of the ridges on the

substrate. Generally, higher and wider ridges on the substrate will induce longer columns in the CsI layer.

III. EXPERIMENTAL RESULTS

A. Light Transmission

The experimental study of light transmission (or absorption) in the scintillator layer is conveniently performed by direct excitation of the CsI(TI) layers by a LED light source with wave length 565 nm, which simulates well the peak (λ =550 nm of the CsI(TI) emission spectrum[9]. A Hamamatsu photodiode, S1723-04, was used to measure the light intensity. Six CsI(TI) samples evaporated on patterned substrates and on flat substrates with 300~600μm thickness were measured. The results showed that the light transmission of CsI on the patterned substrate was about 10-15 percent greater than that of the flat substrates. The main reason is that the thermally induced columns of CsI on flat substrate are not as straight as the ones on the patterned substrate, as shown in Fig.2 and Fig.3. Moreover, many grains exist randomly inside the CsI film; the boundaries of these grains will absorb as well as scatter the scintillation light. Furthermore, since the distribution of these grains is random, it will affect the uniformity of the scintillating efficiency, hence will increase the noise of the whole imaging system. By contrast, columns of CsI on patterned substrates extended perfectly through all of the bulk, withlittle or no grain structure. Thus the light transmission is enhanced by the light guide mechanism.

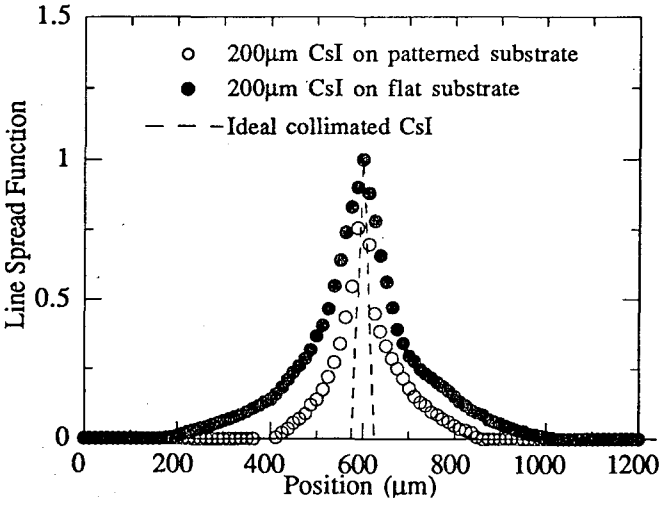

Fig. 4 Spatial resolution measurement on evaporated CsI(TI) layers. Line spread functions were obtained with a narrow beam (25μm) of X-ray. Solid circles, open circles and dashed line show the line spread functions for 200μm thick CsI layers on flat substrate , patterned polyimide layers and ideal collimated CsI layers, respectively.

B. Spatial Resolution

The scintillation light spread inside evaporated CsI(TI) layers (200μm thick) was characterized by exposing a scintillator to a narrow beam of X-rays and detecting the light output with a position sensitive detector. The low energy x-ray beam was generated by an x-ray tube operated at 30 kv and viewed through a 25 μm wide slit. The penetration depth is small enough so that the most of the irradiation energy could be deposited inside the CsI(TI) film. A linear silicon photodiode array (EG&G Reticon RL0256SBU-001) was used as the light sensor and it had 20 dots/mm resolution. The output signals were digitized and stored by a Tektronix 2430 oscilloscope and the data was transferred to a computer for further analysis. The line spread function for each scintillator was obtained by this method.

The line spread functions normalized for each scintillator are shown in Fig.4. The spatial resolution of the 200μm thick CsI(TI) layer on the flat substrate is about 220μm FWHM. A CsI(TI) layer 200μm thick on patterned substrate gives a resolution of 75 μm FWHM. If the cracks in the CsI were perfect light collimators all of the lateral light spread would have been limited to one column (for example 40 μm width). As shown by the dashed line in Fig.4. Therefore, the wider line spread function indicates that some amount of the lateral light escapes from the column in which that photons were originally produced; photons whose incidence angles to the cracks are close 90° would be able to transverse the cracks. This effect is the main contribution to the long tails of the line spread functions, as seen as both sides of these curves in the Fig.4. Of course, the tails of the line spread function (middle curve)for column-enhanced CsI(TI) have been suppressed compared to these of conventional CsI.

C. Modulation Transfer Function

The spatial resolution of an imaging system can be expressed as a frequency in the spatial domain, and is described in term of the modulation transfer function (MTF).

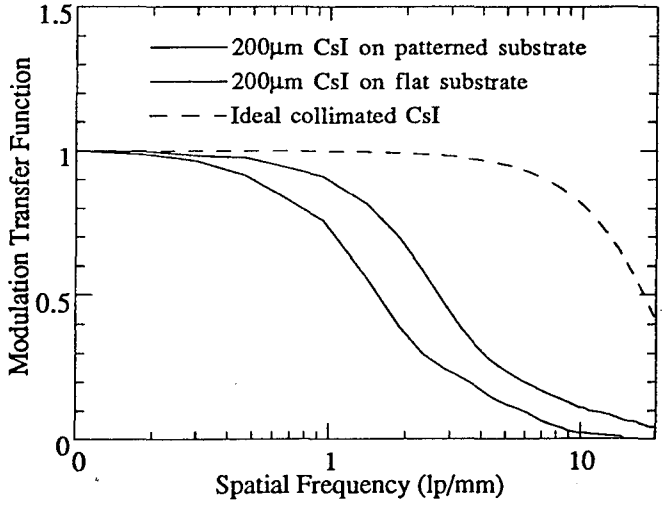

Fig. 5 The modulation transfer funstions of 200μm CsI(TI) layers on patterned substrate and flat substrate, as well as a hypothetically ideal CsI film.

The MTF was determined by Fourier analysis of the line spread function. Mathematically, the MTF is expressed as

$$MTF = \left| \frac{\int_{-\infty}^{x} L(x) \exp[-2\pi j f x]\, dx}{\int_{-\infty}^{x} L(x)\, dx} \right|$$

The line spread function L(x) was experimentally obtained as shown as Fig.4.

The relative advantages of utilizing a layer comprising the well-defined columns of luminescent material prepared as described above are readily seen in the modulation transfer functions in Fig.5. Data for all three curves was obtained from the measured point spread by calculation using Eq. (1). The upper solid curve of Fig.5 represents the MTF data for a 200μm thick column-enhanced CsI(TI) layer. The second solid curve shows the MFT for a conventional 200μm thick CsI(TI) layer. The structured CsI(TI) has a spatial resolution at the 10% level of up to 10 line pairs per millimeter, while the conventional 200 μm CsI layer has a spatial frequency only about 4~5 line-pair/mm at the same level. The uppermost dashed line curve in Fig.5 represents the MTF data for an ideal light spread suppressing structure CsI. The improved resolution of the column-enhanced CsI(TI) is still poorer than the ideal structure. The reason for this is a long tail in line spread function, which comes from the light leakage as discussed above.

IV. DISCUSSION

High spatial resolution CsI(TI) layers were made by fabricating a sequence of columns of regular and controllable geometry perpendicular to the substrate, in which the lateral dispersion of the scintillation light through the layer is substantially reduced. Another advantage of the patterned substrate coating is the improvement in the adhesion between CsI and the substrate. The present improvement in spatial resolution alternatively allows the utilization of thicker and therefore more absorbing (of X-rays) scintillation layers without sacrificing high resolution and high contrast.

The type of material described here is limited to CsI(TI). Other evaporable luminescent materials, such as CsI(pure,Na), potassium iodide, gallium selenide, cadmium tungstate and so on may be made as high spatial resolution scintillation layer by patterning substrates as described above. Further improvement in spatial resolution for scintillator layer may be obtained by optimizing the geometry of the patterned substrate.

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