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Nuclear Instruments and Methods in Physics Research A 576 (2007) 83–86
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Radiation detector based on liquid crystal light valve for large-area imaging applications

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Available online 3 February 2007

Abstract

Currently most large-area radiation detectors rely on the use of a phosphor screen and an optical sensor. In such conversion process, there will be signal loss due to inefficiencies in coupling between phosphor screen and later light-detection components. This paper presents a radiation detector based on X-ray induced light transmittance of liquid crystal (LC) as a function of radiation. Our detector incorporates a europium-doped gadolinium oxide (Gd_2O_3:Eu) phosphor and an amorphous selenium (a-Se)-coupled LC light valve. The Gd_2O_3:Eu is synthesized using a low-temperature solution–combustion method, and the optical properties of the Gd_2O_3:Eu are investigated as a function of a sintering temperature. The transmission–voltage (T–V) curve and the optical response of the detector are also investigated. Our experimental results show good T–V characteristics of the LC, switching between 12% and 86% transmission. The radiation dose is also presented in this work. The results show that our detector can operate at low X-ray dose and, therefore, a promising application is the medical-imaging detector.

Keywords: Radiation detector; Liquid crystal light valve; Large area imaging; Amorphous selenium; Gd_2O_3:Eu nano phosphor

1. Introduction

A novel liquid crystal (LC)-based radiation detector, which combines a LC light valve with a phosphor screen, has been reported earlier [3–5]. The light valve has a simple structure consisting of a photoconductor layer and a LC layer. These electro-optic light valves should be sensitive to electrostatic potential variations and it should have a fast, monotonic and preferably linear response. Thermally evaporated amorphous selenium (a-Se) thin films have the potential to fulfill the demanding requirements of a novel light valve-based radiation detector, because of their good photo-to-dark impedance ratio, large-area coverage, tunable wavelength response, and low-temperature deposition. Pure a-Se crystallizes over time and crystalline selenium is unsuitable as a photoconductor because it has a much lower dark resistance than a-Se, which leads to a dark current that is orders of magnitude greater than in amorphous solids. Alloying pure a-Se with small amount of arsenic (As, 0.2–0.5%) prevents crystallization from the amorphous phase. Although arsenic has an adverse effect on hole lifetime, because it creates deep hole traps, it was found that if the alloy is doped with chlorine (10–20 ppm), the lifetime of hole carriers can be improved. This alloy is called stabilized selenium alloy [1–2].

The dark current in a-Se is very low, usually 0.01 nA/cm^2 with conventional electrodes even for an applied electric field as high as 10 V/μm. Large-area stabilized a-Se films can be easily coated as thick films (e.g., 500–1000 μm) onto suitable substrates through conventional vacuum deposition techniques.

Visible photons are generated in phosphor film after incident X-rays penetrated an object and then the light absorption in the photoconductive detector controls the electro-optic spatial variations of liquid crystal cells via the

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0168-9002/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.nima.2007.01.125

creation of charge carriers and finally, the X-ray imaging is obtained using an external light source and detect the light transmission trough the LC with an optical sensor (CCD, CMOS, etc.). In this detection method, since the X-ray detector is electrostatic and the photo charge is strongly coupled to the light valve, a high-resolution imaging is possible. Moreover, the amplification achieved by external light modulation can improve the conversion efficiency and the signal-to-noise ratio (SNR) [6–7].

In these detectors, X-ray sensitivity is an issue since the phosphor-light valve's image charge, and thus the light valve potential, is limited by the X-ray exposures that can be safely used in medical imaging. So, radiation phosphor materials with fine crystalline particles are the key materials to be used for high resolution and highly efficient X-ray imaging systems. In practice, small particles may also reduce aging effects by forming a densely packed film layer. Recently, sub-micron grain size Gd_2O_3:Eu phosphor is widely used as CRT and radiation phosphor, and the research on small-grain Gd_2O_3:Eu is expected to improve the luminescent properties further, because their electrical, optical, and structural properties differ significantly from the bulk.

This paper includes background review of the two key components of the novel radiation detector: the X-ray fine phosphor and the LC light valve. Specially, a systematic investigation of the influence of the sintering temperature as well as the Eu^{3+} concentration on the structure and the luminescent properties of Gd_2O_3:Eu phosphor fine particles are discussed. The flat light valve based on a-Se and twisted-nematic (TN) liquid crystal was fabricated and the electro-optical properties were also evaluated from the light transmittance and X-ray response characteristics.

2. The luminescent characterization of Gd_2O_3:Eu fine phosphor

Gadolinium acetate hydrate ($(CH_3CO_2)_3Gd$) and europium acetate hydrate ($(CH_3CO_2)_3Eu$) were used as starting materials. Specified amounts of $(CH_3CO_2)_3Gd$ and $(CH_3CO_2)_3Eu$ were dissolved in methanol separately and formed two solutions, and then mixed under stirring. This mixed solution containing gadolinium (Gd) and europium (Eu) was evaporated by chemical evaporation method. This Gd–Eu compound powder was sintered at 500, 700, and 900 °C, respectively.

Fig. 1 shows the photoluminescence spectra of the synthesized Gd_2O_3:Eu particle after sintered during 1 h. From the experimental result mean the emission spectrum consists of lines in the red spectral area. These lines correspond to the transition from the excited $^5D_0$ level to ^7F_J ($J = 0,1,2,3$) level of the $^4F_6$ configuration of the Eu^{3+} ion. The emission spectra of the phosphor particles consisted of a single emission band originating from the intra-ionic transitions in the Eu^{3+} ion.

From the photoluminescence spectroscopy of Gd_2O_3:Eu, except for the contribution from monoclinic structure, the transition that comes from the cubic phase can be identified as well, and the emission corresponding to the $^5D_0 \rightarrow {}^7F_2$ transition at 612 nm is dominant, and the strongest luminescent intensity was achieved at 900 °C.

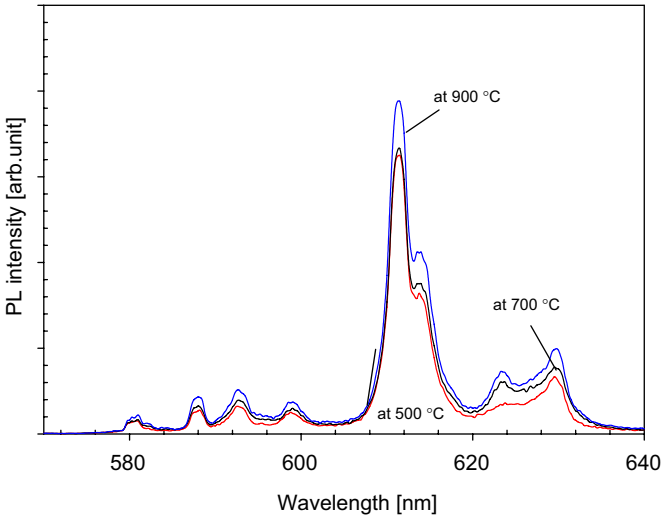

Fig. 1. Photoluminescence spectrum of Gd_2O_3:Eu phosphor as a function of sintering temperature.

3. The X-ray characterization of Gd_2O_3:Eu-coupled a-Se light valve

Modulation of light by means of LC devices is an important problem that has been widely investigated in the past years and whose development is still far from being exhausted. The matter is crucial both from the point of view of fundamental physics and for possible technological applications. This issue has received much less attention with regard to applications in radiation detection. In this spectral region, very few studies deal with LC electro-optical light modulators. In this work, an optical characteristic of a TN electro-optical light valve applied to the a-Se is described.

As a bottom electrode for collecting electric charges, indium tin oxide (ITO) was evaporated on a slide glass ($2 \times 5\,cm^2$) through sputtering evaporation. And then, a-Se is deposited on an ITO glass substrate by thermal evaporation and the substrate temperature is kept fixed at about 60 °C throughout the process. A transparent ITO layer ($1.5 \times 1.5\,cm^2$) as the top electrode was also coated on the a-Se layer. It is a sandwich structure composed of the following layers from the bottom up: a glass substrate with a transparent, conductive ITO coating, a 20 μm thick a-Se: a 1000–5000 Å thick polyimide (PI) alignment layer, a 4.75 μm thick LC cell formed by spacers for uniform separation between the substrates and doped nematic LC, and a top glass substrate with a conductive ITO coating and PI alignment layer. Finally, the Gd_2O_3:Eu phosphor layer of about 270 μm thickness is deposited by screen printing method on a-Se film.