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Influence of substrate heating on optical, morphological and photoemission properties of CsI thin films for imaging application

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ABSTRACT

Optical and morphological properties of semi-transparent Caesium Iodide (CsI) thin films for three different film thicknesses deposited at a substrate temperature of 120^0C have been investigated. The photoemission properties were also studied to know the performance of such photocathodes. A comparison between the films deposited by keeping the substrate at room temperature (27^0C) and the films deposited at 120^0C is presented. Effect of substrate temperature on the morphological, optical and photoemission properties are presented. Optimization requirement of a semi-transparent photocathode for high sensitivity performance is discussed here.

1. Introduction

CsI photocathodes have been proven as efficient photoemitters in the ultraviolet (UV) spectral range for their high quantum efficiency [1,2]. CsI photocathodes coupled to gaseous electron multipliers (GEM) [3] are currently being used in gaseous photomultiplier, Ring Imaging Cherenkov (RICH) detectors, fast readout of scintillators to detect and image UV photons in the field of particle physics experiments [4–8].

Gaseous photomultipliers in a single electron detection mode are realized using GEM detector and a photocathode. The photocathode (PC) can be operated either in reflective (Ref) mode or semi-transparent (ST) mode. In case of Ref mode, a thick CsI layer (>200 nm) is deposited on GEM. For ST mode a thin CsI layer is coated on a UV transparent substrate like quartz. The working principle of GEM based gaseous photomultiplier operating in Ref and ST mode is well explained in [9,10]. CsI in Ref mode has higher quantum efficiency and are used in several applications [4,11]. However in GEM based detectors coupled with CsI in Ref configuration, the effective geometric area for UV detection is reduced due to the optical transparency provided by GEM holes. Effective geometric area is not limited in ST PC coupled to GEM leading to higher sensitivity. ST PC coupled to GEM offers lower ion back flow (IBF), as low as 1% with tuning of drift field [12,13]. Recent efforts in developing bi-alkali PC based visible photo detectors, where PCs are very sensitive to IBF and degrade very fast, are based on ST PCs [14].

The film thickness plays a crucial role for the sensitivity and spectral response of ST PC. For a thicker film, a large portion of the photons are absorbed at a greater depth than the photoelectron escape length. If the film is much thinner, most of the photons will be lost by transmission [15]. The conflicting requirements of higher photon absorption and efficient photoelectron escape decide the optimized film thickness which is few tens of nm [16]. Thin CsI films show a discontinuous morphology and are highly sensitive to short term exposure in humid air compared to thicker CsI film [15,17].

For UV imaging application with high sensitivity, ST CsI film coupled with GEM must have maximum surface area coverage with higher quantum efficiency. Otherwise a film with a discontinuous surface morphology will not be able to sense those photons which are falling on some uncoated region of the substrate affecting the sensitivity. In order to optimize the film parameters one has to compromise between quantum efficiency (which decreases with film thickness) and surface area coverage (which increases with film thickness). The aim of this work is to enhance the surface area coverage without significantly increasing the thickness. Heat treatment to the substrates during deposition process could be the solution to modify the surface morphology. The film structure and morphology mainly depends on the adsorption and the diffusion rate at the surface of the substrate. Presence of water vapour is responsible for increased diffusion rate [18]. Heating the substrate removes residual water from substrate and film. The diffusion is also influenced by the thermal energy of the depositing atoms/molecules. Diffusion rates due to thermal energy depend on the reduced temperature T_S/T_M [19], where T_S is the substrate temperature and T_M is the melting point of the film material. Therefore the film structure is expected to change as a function of T_S/T_M. Melting temperature of CsI is 621 °C [20]. According to literature CsI thin film structures are best

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in the range of $0.5 \geq T_S/T_M \geq 0.3$ where surface diffusion becomes important [18]. The arriving molecules have enough energy to move around and arrange properly on the surface of the substrate.

In the present work, we have deposited CsI films at two different substrate temperatures (27 °C and 120 °C). The optical absorbance and transmittance for the film were studied in the spectral range of 185 nm to 900 nm. The surface morphologies were examined by Scanning Electron Microscopy (SEM) technique. The photocurrent measurements of these CsI films were performed in the UV spectral range. These studies were carried out for films of different thicknesses.

2. Experimental procedure

The experimental setup for thin film deposition consists of a stainless steel vacuum chamber pumped through a diffusion pump. The vacuum achieved in the chamber was of the order 10^{-5} mbar. A high purity (99.999%) CsI powder was placed in a molybdenum boat inside the vacuum chamber. Optically polished quartz samples (2×2 cm^2) were used as substrates. Substrates were cleaned thoroughly with DI water and then followed by acetone and IPA using an ultrasonic bath. Cleaned quartz substrates were placed at 30 cm above the molybdenum boat. The chamber was baked at 70 °C for several hours under the vacuum to remove water vapour from the chamber. Before deposition, the boat and CsI powder were heated to allow outgassing under a shutter. The CsI thin films were deposited on quartz substrates by maintaining a deposition rate of 1.5nm/sec. The thickness of the film was monitored with the help of a Digital Thickness Monitor. Special care was taken during the transfer of deposited samples into a desiccator for optical and surface morphological characterization. This ensured only a few seconds exposure of film to humid air (relative humidity of ~50%).

3. Results and discussion

3.1. Optical analysis

The optical properties of ST CsI films have been studied in the spectral range of 185 nm to 900 nm. For optical absorbance measurement a 30 nm, 70 nm and 90 nm thick CsI films have been deposited on quartz substrate for two different substrate temperatures. The substrate was kept at room temperature (27 °C) for the first case and then the substrate was heated and maintained at 120 °C during deposition by a substrate heater for all the films. The absorption spectra were recorded using Shimadzu MPC3600. Fig. 1(a) shows the absorbance of CsI thin films deposited by keeping the substrate at room temperature for different film thicknesses in the spectral range of 185–300 nm. Two absorption peaks are observed for all three CsI films. Similar results of optical absorbance are also reported in [21]. It is clear that, 90 nm film shows higher absorption compared to others. This is mainly because of the increased film thickness, which leads to a high absorption rate.

In Fig. 1(b), the absorption spectra are shown for 70 nm thick film deposited on quartz substrate kept at 27 °C and after heating of quartz substrate at 120 °C during deposition. The absorption in these heat treated films show higher value compared to the other room temperature deposited film. Higher absorption value indicates the film uniformity and more surface area coverage. This can be confirmed from the surface morphology studies.

3.2. Surface morphology analysis

The results obtained from SEM are shown in Fig. 2 where grains are clearly visible on a dark background. The grain size and surface area coverage of the films were determined from SEM micrographs. The grain size and surface area coverage increase with increasing film thickness. In case of 30 nm, the film is very discontinuous and exhibits a surface area coverage of only about 28% (Fig. 2a). The grain size is found to be varying from 20 nm–200 nm and the average grain size evaluated from the histogram is found to be about 125 nm in this figure (inset). Grain size and surface area coverage both increases with film thickness. For 70 nm film, surface area coverage improves up to 65% and shows interconnected grains of discontinuous structure (Fig. 2c). The grain size is varying from 100 to 400 nm and the average grain size is found to be about 218 nm. The surface morphology becomes uniform for 90 nm film. Here, 90 nm film shows further improved surface area coverage of about 75% (Fig. 2(e)). The grain size is found to be in the range of 150–800 nm and the average grain size is increased to 342 nm.

The surface morphology of 30 nm, 70 nm and 90 nm films deposited when substrate temperature was kept about 120 °C is illustrated in Fig. 2(b), 2(d) and 2(f) respectively and compared with the films deposited when substrate was kept at 27 °C. The heat treated films show an enhancement of surface area coverage with reduced grain size. In case of 30 nm, the heat treated film shows a slight improvement (~5%) in surface area coverage compared to Fig. 2(a). The grain size varies from 20–200 nm. For thicker films (70 nm and 90 nm), surface morphology becomes quite uniform and almost fully covered with grains. The surface area coverage is found to be 85% and 95% for 70 nm and 90 nm heat treated films respectively. However, the grain size becomes more uniform and falls in the range of 20–600 nm and 50–600 respectively.

The grain size of CsI molecules are influenced by its diffusion during film deposition. Diffusion of CsI molecules mainly happens due to presence of water vapour inside the chamber and on the substrate because of hygroscopic nature of the film and due to thermal energy provided during deposition [18]. At room temperature, presence of water vapour reduces activation energy for diffusion and hence enhances diffusion rate [18] influencing the formation of larger grains due to coalescence process. As the substrate temperature is increased, water vapour layer present on the substrate is reduced. This reduces coalescence of grains resulting in net smaller grain size with better surface area coverage. In case of 30 nm heat treated film, the improvement of surface area coverage is only 5%. This improvement is more than 20% in case of 70 nm and 90 nm films. As the thickness of the depositing film is further increased grain size also starts increasing. Thus the higher substrate temperature not only removes water molecules from the surface but also controls the grain size and the surface area coverage.

3.3. Photocurrent measurement

To measure the photocurrent, 70 mm diameter quartz substrate was coated with a thin layer (3 nm) of chromium (Cr). A 100 nm thick and 10 mm wide layer of gold was coated around the periphery of the Cr coated surface to provide the electrical connections (Fig. 3(a)). The rest of the surface area was covered by CsI. A Cu ring was attached very close to the PC to provide high voltage. The PC was separated from the anode at a distance 8 mm by spacers made of Teflon. The photocurrent was measured at anode by a digital picoammeter. The schematic diagram of photocurrent measurement setup is shown in Fig. 3(b). A low pressure Hg lamp having spectral range of 100–280 nm was used as a UV source. The source was kept 3 cm above the photocathode.

The photocurrent (normalized) of freshly evaporated films (30 nm, 70 nm and 90 nm thick) at 27 °C and 120 °C substrate temperature is shown in Fig. 4 as a function of drift voltage. The photocurrent increases with drift voltage applied between the mesh and readout. The increase in photoelectron at higher drift voltage is related to the extraction of photoelectrons from CsI film. The photoelectron extraction from CsI is more at higher drift field due to higher extraction efficiency [22]. It is observed that the 90 nm thick film shows higher photocurrent compared to 30 and 70 nm thick films deposited at room temperature. This variation in photocurrent is related to the surface morphology of CsI films. Improved surface area coverage results higher photocurrent up to a certain range. After certain thickness of CsI film (about 100 nm), the film starts behaving as reflective rather than semi-transparent. So in ST mode, the film thickness should be less than 100 nm, otherwise