Optical properties of plastic scintillators coated with copper, aluminum and silver by magnetron sputtering

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Copper, aluminum, and silver thin films are fabricated on plastic scintillators by magnetron sputtering to improve the optical properties. The film morphology is measured by contact mode atomic force microscopy. The optical properties are determined by UV/visible spectrophotometry as well as a single-particle microbeam with proton energy of 2 MeV. Our theoretical analysis suggests a 10.28% increase in the collection efficiency compared to the uncoated plastic scintillator. The improvement in the optical properties is investigated experimentally and the Monte Carlo program SRIM 2008 is employed to investigate the influence of the metal film thickness on the ion stopping and scattering in the materials. Our study suggests that deposition of thin reflecting Cu, Al, and Ag films improves the energy and space resolution of scintillator-based particle spectrometers.

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1. Introduction

Radiation detection is required in many areas such as medical diagnostics, imaging, industrial radiation monitoring, dosimetry, nuclear medicine, and high-energy physics [1–8]. A scintillator which is a luminescent material that absorbs high-energy particles and then emits visible light has important applications in radiation detection. Six types of scintillators including single crystals, polycrystalline ceramics, glasses, powders, plastics, and inert gases have been developed [9]. Among them, plastic scintillators have some advantages because they can be easily made into a variety of shapes while having good mechanical, radiation, and temperature properties as well as low cost [10–18]. In practice, it is necessary to put reflecting materials such as an aluminum foil and Teflon on plastic scintillators in order to enhance the photon collection efficiency. However, if the reflecting materials are used, energy loss and beam scattering become significant and the energy resolution and special resolution of scintillator-based spectrometers will degrade. Therefore, it is necessary to replace the traditional thick reflecting foil with a thinner one with good reflectivity. In the work reported here, nano-scale metal films such as copper, aluminum, and silver are deposited on plastic scintillators by magnetron sputtering [19–20]. The optical properties are assessed by a UV/visible spectrophotometer and single-particle microbeam (SPM). Our experimental results reveal that the magnetron sputter-deposited metal film can effectively improve the optical properties of plastic scintillators.

2. Experimental details

Commercially available plastic scintillators (Saint-Gobain, BC400) were used in our experiments. The base materials were polyvinyltoluene with a softening point of 70 °C and refractivity of 1.58. The wavelength of maximum emission was 423 nm and thickness of plastic scintillators was 15 and 50 μm, respectively. Twelve samples were processed using different conditions and the main instrumental parameters are displayed in Table 1. The samples were first...
ultrasonically cleaned in ethanol and deionized water for 5 min and then dried under nitrogen. All the sputtering targets were 99.9 wt.% pure. The metal films were subsequently fabricated on samples by DC magnetron sputter deposition. During deposition, the distance between the sample and sputtering target was 7 cm.

An atomic force microscope (AFM) made by Park Scientific Instruments/Auto Probe CP was used to determine the surface morphology and thickness of the metal films. The AFM image depicted in Fig. 2 was obtained by the contact mode. A step that was fabricated by partially covering the sample with a piece of silicon during magnetron sputtering was probed by AFM to determine the step height or the film thickness. The reflectance and transmittance spectra of the control and 12 films were obtained on an ultraviolet-visible (UV/vis) spectrophotometer (Perkin Elmer, Lambda 750). The optical properties were further investigated by a SPM system using 2 MeV protons [13]. The influence of the coatings on the ion stopping and scattering was theoretically investigated using Monte Carlo SRIM 2008 [21].

3. Results and discussion

3.1. Monte Carlo simulation results

The Monte Carlo program SRIM is widely used to simulate ion stopping and ranges in solids and SRIM 2008 is used here to study the phenomena. The transverse views obtained by 2 MeV protons are shown in Fig. 1. Fig. 1(a) shows the simulation results of the Teflon foil on the plastic scintillator including air whereas Fig. 1(b) shows the results of a plastic scintillator with a 400 nm thick silver coating plus air. The images are analyzed using the ImageJ software available from NIH (http://rsb.info.nih.gov/ij/) and the simulation details and results are shown in Table 2. Comparing the 400 nm Ag film deposited on plastic scintillator to the 10 µm Teflon reflecting foil, the beam diameter (10,000 hits) decreases from 7.26 µm to 4.99 µm, the depth of high energy particles increases from 41.1 mm to 56.2 mm, and the beam diameter decreases by 31.3%. The simulation results indicate that with the 400 nm metal film, the depth of high energy particles increases and energy scattering is reduced significantly.

3.2. Film thickness

Representative AFM images of samples C, F, I, and L are shown in Fig. 2(a), (b), (c), and (d), respectively. The root mean square surface roughness values of all the samples are below 10 nm suggesting that magnetron sputtering is a reliable method to fabricate the reflecting coatings. The thicknesses of the 12 coatings are shown in Fig. 3.

3.3. Optical properties and detection efficiency

The optical properties are measured using a Perkin-Elmer Lambda 750 UV/vis spectrophotometer with wavelengths ranging from visible to ultraviolet light. The untreated plastic scintillator shows nearly full transmission in the visible region as shown in Fig. 4. Fig. 5 plots the reflectivity versus thickness relationship obtained from the Cu, Al, and Ag coated samples. At a wavelength of 423 nm (the emission peak of plastic scintillator), the reflectivity of the Ag coated samples increases from 76.97% to 92.80% when the thickness increases from 140 nm to 630 nm (Fig. 5(a)). In comparison, the reflectivities of the Al and Cu coated samples are higher in the ultraviolet region but lower in the visible light region compared to the Ag coated sample (Fig. 5(c) and (d)). Consequently, Ag is chosen in this work. In addition, according to Fig. 5(a), the reflectivity of the sample deposited for 3 min is almost the same as that deposited for 5 min. In order to lessen the damage to

![Fig. 1. Radial comparison (incident depth of 10 mm) simulated in: (a) Teflon foil + plastic scintillator + air and (b) Plastic scintillator coated with 50 nm thick copper + air.](image-url)
the plastic scintillator induced by magnet sputtering and ensure higher reflectivity, a deposition time of 3 min is selected.

When ions pass through the plastic scintillator, the emitted light can be viewed as a line source. Fig. 6 shows the rays passing the scintillator–air interface. Since the solid angle of scintillator illumina-
tion is 4π, the light can be separated into two parts. That is, one part is 0 to 2π and the second part is 2π to 4π. In the first part (0 to 2π region), as the angle θ is increased, it will reach a situation (see ray a) in which the refracted ray points along the surface and the angle of refraction is 90°. If the angle of incidence is larger than this critical angle θc, there is no refraction in air. The luminous flux of the first part Φ1 is given by:

$$\phi_1 = \frac{1}{2} \phi_0 \frac{\Omega_1}{2\pi} = \frac{1}{2} \phi_0 \frac{2\pi(r^2 + h^2)(1 - \cos \theta)}{2\pi(r^2 + h^2)} = \frac{1}{2} \phi_0 (1 - \cos \theta) \ldots (1)$$

where Φ0 is the luminous flux of the emitting light, Ω1 is the solid angle of the first part, and h is the thickness of plastic scintillator. With regard to the second part (2π to 4π region), as the angle α is increased, it will reach a situation in which the light of reflection of ray b points along the surface similar to ray a (see ray b). The luminous flux of the second part is given by:

$$\phi_2 = \frac{1}{2} \phi_0 \frac{\Omega_2}{2\pi} R = \frac{1}{2} \phi_0 \frac{2\pi(r^2 + h^2)(1 - \cos \theta)}{2\pi(r^2 + h^2)} R = \frac{1}{2} \phi_0 (1 - \cos \theta) R \ldots (2)$$

where Ω2 is the solid angle of the second part and R is the reflectivity of thin metal film reflector.
The total luminous flux can be collected by the photomultiplier tube (PMT) and is given by:

\[ \Phi_t = \Phi_1 + \Phi_2 \]  

(3)

The collection efficiency is:

\[ E_1 = \frac{\Phi_1}{\Phi_0} = \frac{1}{2} \frac{\Phi_0 (1 - \cos \theta)}{\Phi_0} = \frac{1}{2} (1 - \cos \theta) \]  

(4)

and

\[ E_2 = \frac{\Phi_2}{\Phi_0} = \frac{1}{2} \frac{\Phi_0 (1 - \cos \theta)}{\Phi_0} + \frac{1}{2} \frac{\Phi_0 (1 - \cos \theta) R}{\Phi_0} = \frac{1}{2} (1 - \cos \theta) (1 + R) \]  

(5)

where \( E_1 \) is the collection efficiency of the scintillator and \( E_2 \) is the collection efficiency of the scintillator deposited by metal film reflector. We can obtain \( \theta \) from the law of refraction:

\[ n \sin \theta = n_0 \sin \frac{\pi}{2} \]  

(6)

With regard to the scintillator in air, \( n = 1.58 \) and

\[ \cos \theta = \sqrt{1 - \frac{n_0^2}{n^2}} = \sqrt{1 - \left(\frac{1.58}{1.58}\right)^2} = 0.7742 \]  

(7)

Taking \( R = 91.03\% \) and from Eqs. (4), (5), and (7), we obtain \( E_1 = 11.29\% \) and \( E_2 = 21.57\% \). Ignoring absorption by the plastic scintillator, a 10.28% increase in the collection efficiency is achieved while the detection radius doubles simultaneously (Fig. 6).

SPM analysis is performed to further assess the optical effects of the plastic scintillators after metal deposition. Three samples are tested using 2 MeV protons under similar conditions. The first one is the uncoated BC400 plastic scintillator serving as the control. The second one is the same plastic scintillator deposited with a Ag film (Sample B) and the third one is the same scintillator wrapped with a 7 µm thick Al foil. The spectra in Fig. 7 indicate peaks at 266, 642 and 852 channels, respectively. This is due to the increased reflected luminous flux from the scintillator collected by the PMT. Although the background noise observed from the plastic scintillator with the metal film is slightly bigger than that of the plastic scintillator wrapped with

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**Fig. 5.** Reflectivity spectra of thin films deposited on the plastic scintillator by magnetron sputtering: (a) Silver (substrate thickness = 15 µm), (b) Silver (substrate thickness = 50 µm), (c) Aluminum, and (d) copper.

**Fig. 6.** Schematic diagram of light passage in the plastic scintillator coated by a metal thin film.
In the Al foil, it can meet the requirement for setting of the discrimination threshold perfectly\footnote{22}.

4. Conclusion

Thin reflecting metal thin films with excellent optical properties have been fabricated by magnetron sputtering on plastic scintillators. Our results suggest that the copper and aluminum thin films have high reflectivity in the ultraviolet region whereas the silver thin film has high reflectivity in the visible light region. At 423 nm, the silver thin film has better reflectivity than aluminum and copper thin film with the same thickness. The use of a thin metal film deposited on scintillator instead of a thick reflecting foil wrapped around the scintillator increases the incident depth of the high energy particles. This method improves the energy and space resolution of scintillator-based particle spectrometers.

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References


Fig. 7. 2 MeV protons beam magnitude spectra: (A) Plastic scintillator, (B) Plastic scintillator+400 nm Ag film, and (C) Plastic scintillator+7 μm Al foil.