

Fabrication of a multilayered optical device based on submicron polyimide film

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Abstract. A submicron polyimide film (<1 μ m) with high thickness uniformity was prepared via spin-coating method. Aluminum foil and patterned nickel mesh were sequentially fabricated on the surface of polyimide film using magnetron sputtering and micro-electroforming. Transmittance of the device in UV-vis waveband indicated that the thickness of aluminum plays a dominant important role rather than the other layers. The results of atomic oxygen erosion experiment of the multilayered structure, investigated by ground-based simulation facility, suggests that the Al foil was capable of protecting PI film from atomic oxygen erosion.

1. Introduction

Soft X-ray detection has been an important objective for the X-ray astronomy space missions [1-3]. Due to the proximity of soft X-ray(1-10 nm) to ultraviolet and visible (UV-vis) waveband(10-780 nm) in energy, an optical device capable of selectively filtering UV-vis radiation is necessary to achieve detection of soft X-ray with high resolution and low noise. Once the flight vehicle of soft X-ray detection was launched into low earth orbit, an altitude ranging from 100 to 1000 km, it will survive harsh environment such as atomic oxygen(AO) erosion, thermal cycling and space debris. Taken into account these challenges, the device for that purpose is required to feature excellent mechanical properties, outstanding thermal stability and resistance to irradiation.

Previous work had been implemented to fulfill the objective of filtering undesired UV-vis radiation by using Be, Ag or Sn films [4,5] as the functional layer of the optical device. In comparison with its counterparts, thin Al foil possesses much higher absorption and reflectivity in UV/visible/infrared waveband [6] and more broad transmittance in the X-ray region [7], which makes it a promising candidate for the application in soft X-ray detection. On the other hand, to address the frequent thermal cycling in space, a supporting layer is essential to minimize the cracking of the brittle Al foil. Polyimide (PI) films, well-known for its mechanical properties, temperature stability and irradiation durability, are extensively applied in space missions [8-11]. In this paper, submicron PI films, functionalized as a supporting material for the Al foil, were fabricated by combining polymerization and spin-coating. In order to withstand the vibrational and acoustic influence caused by launch, a patterned nickel mesh was affiliated to the PI films by using UV-photolithography combined with micro-electroforming technology. The transmittance of the optical device was investigated through varying Al foil thickness, by which the optimal thickness of Al foil could be determined. In addition, the AO erosion experiment was conducted using a ground-based simulation facility, which exhibited negligible differences in mass loss and surface morphology of the device .

2. Experimental Section

2.1 Preparation of PI film

The PI film was prepared via a classic two-step polycondensation reaction(i.e. polymerization and thermal imidization). The synthetic route is given in Fig. 1 as described in our previous work[12,13]. PI films less than one micron were obtained by conducting a curing program at 80 °C for 60 min, 230 °C for 120 min, and 350 °C for 120 min with a ramp rate of 1 °C/min.

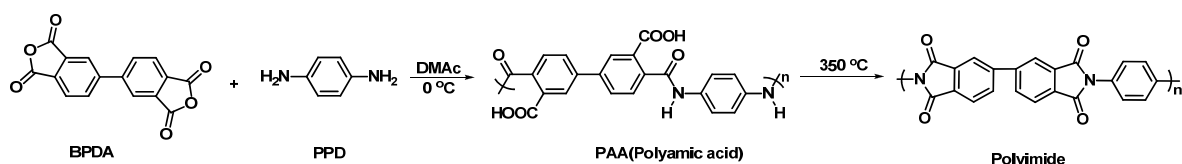


Fig.1 Reaction scheme for the synthesis of PAA and polyimide

2.2 Fabrication of nickel mesh and Al foil on PI film

As presented in Fig. 2, the fabrication of nickel mesh adhered to PI film was carried out by UV-lithography followed by micro-electroforming process. A patterned seed layer of Cr (50 nm)/Cu (50 nm) were deposited using a customized magnetron sputtering under radio frequency mode. Prior to that, positive tone photoresist AZ P4620 was spin-coated to form a thin film about 5 μm thick on the PI film. The wafer was prebaked, exposed under a mask aligner and developed in a 25 vol% AZ 400K aqueous solution, followed by magnetron sputtering Cr and Cu seed layer. After immersing the wafer in acetone to lift-off the undesired photoresist, the seed layer pattern complementary to the photomask could be achieved. SU-8 2150 and Omnicoat was applied to obtain the pattern for the following Ni mesh electroforming. The parameters used in the procedure can be found in our previous work [13].

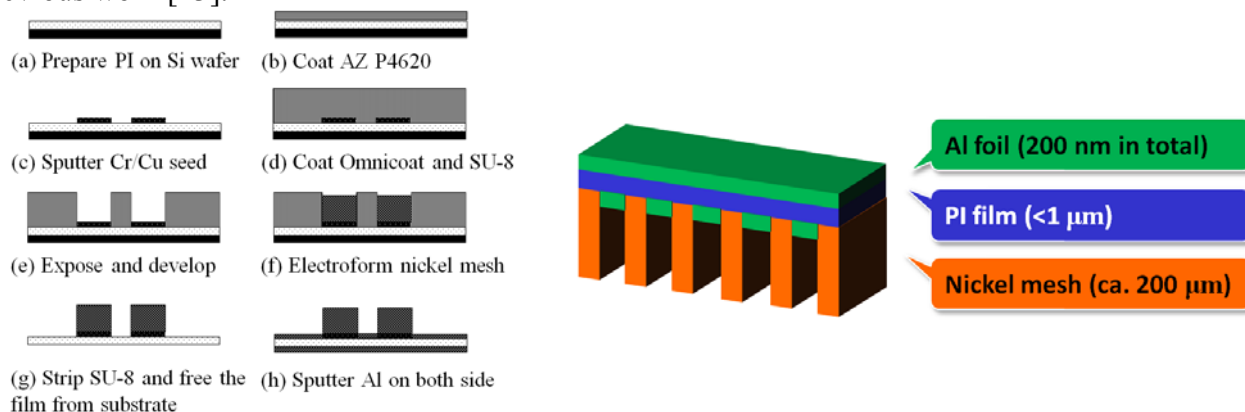


Fig.2 Fabrication workflow of the optical device(left) and illustration of the device structure(right)

Nickel mesh was electroformed along the gaps fabricated by SU-8 2150. The thickness nickel mesh was 200 μm by electroplating for about 20 hours. The components of the electrolyte, their concentration and electroplating conditions has been described elsewhere[13]. The self-supporting structure was then immersed in a hot water bath (50 $^{\circ}\text{C}$) and carefully stripped off from the wafer with the help of a surgical blade. Finally, devices having Al foils with varied thicknesses were sputtered on both side of the self-supporting film in order to decrease defects caused by single side deposition.

3. Results and discussion

3.1 Device fabrication

As a conductive medium for the subsequent micro-electroforming, a seed layer consisted of Cu or Au as well as an adhesive layer of Cr or Ti, was usually deposited on the entire surface of the PI film[14,15]. Based on our experience, the removal of unwanted seed layer using corrosive solution could cause potential damage to the PI film and jeopardize the adhesion between PI film and the seed layer. Therefore, a patterned seed layer of Cr (50 nm)/Cu (50 nm) was deposited through magnetron sputtering (Fig 2c).

SU-8 2150, an epoxy-base negative photoresist, could be used to fabricate thick patterns with high aspect ratios [16-18]. However, the complete removal of exposed SU-8 photoresist was typically conducted by either dry or wet etching protocols [19,20], which is not applicable to this device because the underlying PI film could be easily thinned and even decomposed under those conditions. Therefore, Omnicoat was spin-coated as a sacrificial layer [21,22]. By optimizing the condition employed in the photolithography to minimize internal stress, a SU-8 pattern up to 400 μm thick and an aspect ration more than 10 could be obtained (Fig.3).

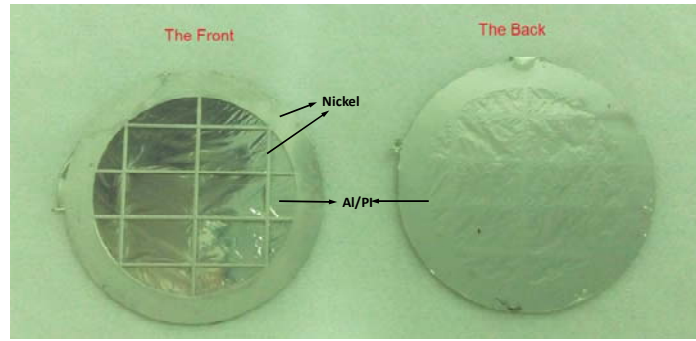


Fig.3 The photograph of the optical device used in this study

3.2 UV-vis Transmittance

The capacity of the device to block UV and visible light could be readily obtained by recording its absorbance spectra in UV-vis waveband. As shown in Fig.4, devices with varying Al foil thicknesses exhibited completely different profiles when keeping constantly the thickness of PI film of 500 nm. It has been proved that PI film less than 1 μm thick only displayed absorbance peaks below 400 nm [23,24]. Strong transmittance peaks at 400 nm, 580 nm and 690 nm appeared when the Al foil thickness was 60 nm, and a similar profile was observed to 120 nm thick Al foil. This could be ascribed to the absorbance of Al or Al_2O_3 nanoparticles with different particle sizes [25]. The transmittance was depressed to less than 0.5% when the thickness of Al foil exceeded 180 nm, indicating the device could effectively blocked UV and visible light.

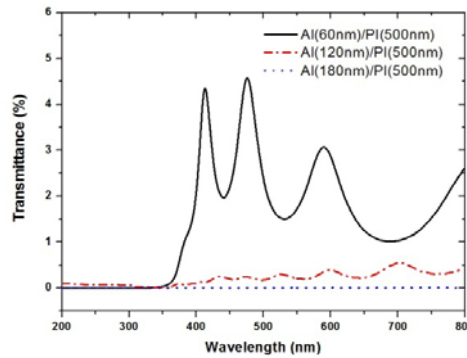


Fig.4 Transmittance of device with Al foil in different thickness

3.3 Atomic Oxygen Erosion Experiment

AO can severely erode the surface of organic and polymer film and result in thinning even complete degrading of these materials due to the highly oxidative species in AO atmosphere. Metallic and their oxide foil could serve to protect PI films from being eroded because of their inertness upon exposing to AO atmosphere [26-27]. Therefore, the thin Al layer could not only block the undesired UV and visible radiation, but functionalize as an AO resistant layer for the underlying PI film.

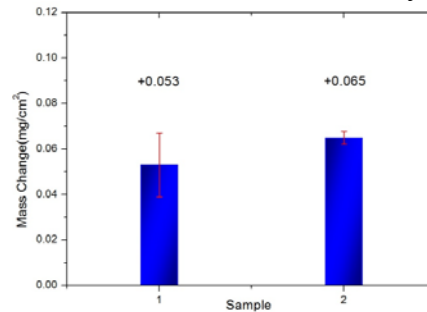


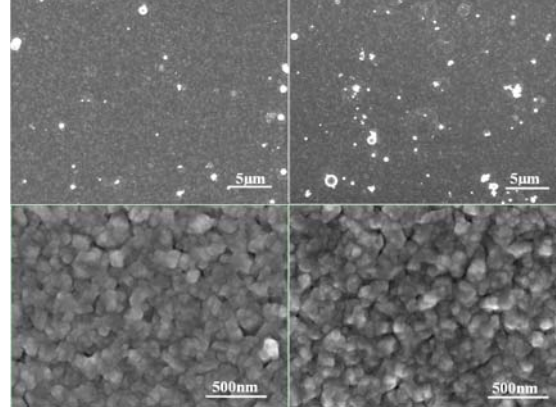
Fig.5 Mass change of the device after AO exposure

The atomic oxygen (AO) erosion experiment was conducted in a ground-based simulation facility. The AO flux (F , atoms/($\text{s} \cdot \text{cm}^2$)) of the facility was calibrated, which could be obtained using the following formula[27]:

$$F = \Delta m / (\rho E t A) \quad (1)$$

where Δm is the mass loss of the Kapton sample, ρ represents the density of Kapton, t and A are the time and area of the Kapton exposed to AO, and E is the erosion rate of Kapton ($3.0 \times 10^{-24} \text{ cm}^3/\text{atom}$).

An overall AO fluence of 9.29×10^{20} atoms/cm² was performed on the device composed of Al (100 nm) /Ni (200nm) /PI (500 nm)/ Al (100 nm), corresponding to AO irradiation for a period of 516 h.. Unexpectedly, the mass of the device after AO exposure was found to increase slightly (Fig.5). It might be caused by the oxidation between Al/Ni and highly oxidative AO atmosphere. The SEM results in Fig.6 showed that no obvious morphology changes could be observed at both nano- and microscale, revealing that Al foil was able to protect the underlying PI film from AO erosion.



Before AO exposure

After AO exposure

Fig.6 SEM images of Al foil surface of the device before and after AO exposure. The white dots in the upper pictures indicate the Al clusters with different domains were formed while sputtering.

4. Summary

A self-standing optical device consisting of Al/Ni/PI/Al multilayer structure was fabricated by following an optimized procedure combining chemical synthesis, spin-coating, UV-lithography and micro-electroforming technologies. By comparing the transmittance spectra with Al foil in different thicknesses, the device was found to be able to completely filter of UV and visible light when the Al foil thickness was higher than 180 nm. No obvious change in mass and surface morphology were observed after AO erosion experiments, which suggested that Al foil could effectively increase the AO resistance of the device. Further studies such as transmittance in soft X-ray region and mechanical performance of the device are currently underway in our laboratory.

Acknowledgements

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