High efficiency carbon-based multilayers for LAMP at 250 eV

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ABSTRACT

X-ray reflection near the Brewster's angle by multilayer mirrors can be used to detect the polarization from X-ray sources. The photon emission spectra from some isolated neutron stars and AGN/blazars etc. show that their emission is peaked at low energies near 250eV, which is just below carbon K-absorption edge. The Lightweight Asymmetry and Magnetism Probe (LAMP) is proposed as a micro-satellite mission dedicated for astronomical X-ray polarimetry working at 250 eV and is currently under early phase study. Co/C multilayers are selected and designed at the energy near 250eV with a grazing incident angle of 45°. The carbon layer thickness ratio is optimized to get the highest integral reflectivity which means larger effective signals in the astrophysics observation. The multilayer coatings were manufactured by direct current magnetron sputtering on D263 glasses and electroformed nickels and characterized using Grazing incidence X-ray reflectometry at 8keV. Reactive sputtering with 4%, 6% and 8% nitrogen were used to improve the Co/C multilayer interfaces respectively. Reflectivity for s-polarization and p-polarization light was measured at BEAR beamline in Elettra synchtron facility. Co/C multilayer deposited with 6% nitrogen exhibits the best performance comparing to other multilayers with different nitrogen content.

Keywords: Soft X-ray; Polarimetry; Co/C multilayer; Reactive sputtering

1. INTRODUCTION

The Lightweight Asymmetry and Magnetism Probe (LAMP) is proposed as a micro-satellite mission dedicated for astronomical X-ray polarimetry working at 250 eV and is currently under early phase study. The major scientific goals of LAMP [1] are to measure the geometry of neutron stars magnetic field, to discover the bare quark stars if they exit and to observe the magnetic field structure at the base of the relativistic jets launched around accreting black holes. The optics system of LAMP consists of 16 identical paraboloidal multilayer mirror sectors mounted circularly around central

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detectors to do the focus. There are two candidates for the substrate mirrors: hot slumped glasses [2, 3] and electroformed nickels, both of which can be shaped to a desired surface.

The working energy of LAMP is 250 eV which is near the carbon K absorption edge. In order to detect an effective signal at the incidence angle of Brewster's angle, which almost equals to 45 degree in the soft X-ray region, high efficiency polarized multilayers should be designed and fabricated. Co/C and Cr/C multilayer are chosen in this paper due to their high reflectivity. Cr/C and Co/C multilayer mirrors have a wide application in synchrotron radiation [4, 5] and astrophysics observation [6, 7] used as polarizers. The reflectivity for 73.9% s-polarized beam of Cr/C multilayer was 14% at 168 eV [4] while it is 18% at 282 eV for Co/C multilayer with a d-spacing of 3.03 nm [8]. Both Cr/C and Co/C multilayers were prepared by using direct current (DC) magnetron sputtering [9]. A reactive sputtering with nitrogen [10, 11] was also used to improve the reflectivity of two multilayers. The R_s of Cr(N)/C(N) multilayer was slightly higher than that of non-reactive sputtering while the reflectivity of Co(N)/C(N) multilayer was improved. Here, we will mainly focus on the results of Co/C multilayers fabricated using reactive sputtering with nitrogen.

High efficiency Co/C multilayers were designed and fabricated by using a reactive sputtering with different proportion of nitrogen. The films were deposited on the substrates of flat thin glasses and electroformed nickels due to the application of LAMP in the future. The structure of multilayers was characterized by grazing incidence X-ray reflectivity (GIXRR) measurements at 8keV. The reflectivity was measured at the BEAR beamline [12, 13] of Elettra synchrotron in Italy.

2. EXPERIMENTAL DESIGN AND DETAILS

In order to get a high throughput of photons for LAMP, we have to maximize the integral reflectivity $\int (R_s\text{-}R_p)\, dE$. R_s and R_p are reflectivity for s-polarization and p-polarization light, respectively, at the incidence of Brewster's angle. As R_p almost equals to zero according to Brewster's law, we only have to optimize the multilayer structure to get a high Rs with broad bandwidth to reach the maximum integral reflectivity $\int R_s\, dE$. Both Cr/C and Co/C multilayers have a reflectivity of more than 35% calculated with a carbon layer thickness ratio (Γ_c) of 0.7. However, the bandwidth of Co/C multilayer is significantly wider. As a result, we choose Co/C multilayer in this study.

The structure of Co/C films was optimized based on the calculations using IMD software [14] . Fig. 1(a) shows R_s of Co/C multilayer as a function of photon energy calculated with different Γ_c. The highest R_s is found where Γ_c=0.7. However, the bandwidth of the reflective curve is narrower than that of other curves. The integral… $\int R_s\, dE$ was calculated as a function of Γ_c which is shown in Fig. 1(b) (black squares). The maximum integral bandwidth of the reflective curves is 2.2 eV when Γ_c=0.6. We also calculated the R_s using different inter-layer roughness shown with red squares in Fig. 1(b). The integral area decreases with increasing roughness significantly which indicates we have to decrease the roughness of multilayer during fabrication.

Co/C multilayer with a period thickness of d =3.55 nm and Γ_c=0.6 exhibits a good optical performance according to our calculation. Thus we choose Co/C multilayer as the candidate in this study. The Co/C multilayers were deposited on the substrates of 15 mm×15 mm nickels and 10 mm×10 mm×0.3 mm thick D263 glasses. The glasses were produced by Schott. The ncikel substrates were fabricated by the Media-Lario technology company in Italy. The surface root-mean-square (rms) roughness is approximately 0.40 nm measured using atomic force microscope (AFM) in the range of 2 μm×2 μm. Fig. 2 shows the surface height image of the D263 glass. The rms roughness is 0.23 nm, which indicates that multilayer deposited on D263 glass substrates should have a better performance than those in nickel.

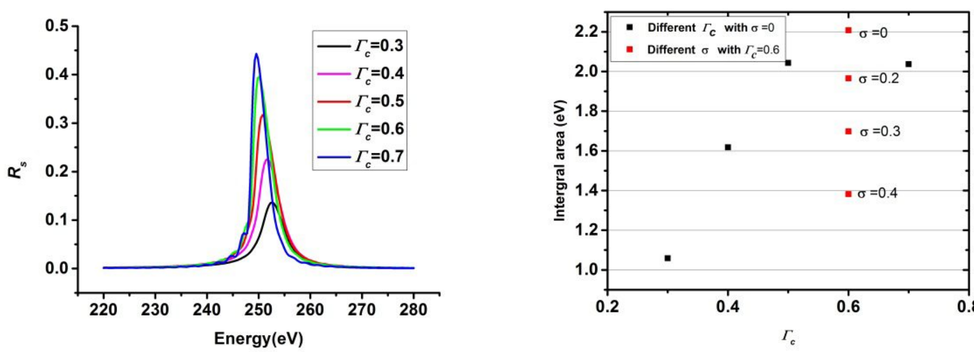

Fig. 1 (a) Rs of Co/C multilayer as a function of photon energy calculated with different carbon layer thickness ratio; (b) Integral bandwidth of the reflective curves calculated with different carbon layer thickness ratio and inter-layer roughness.

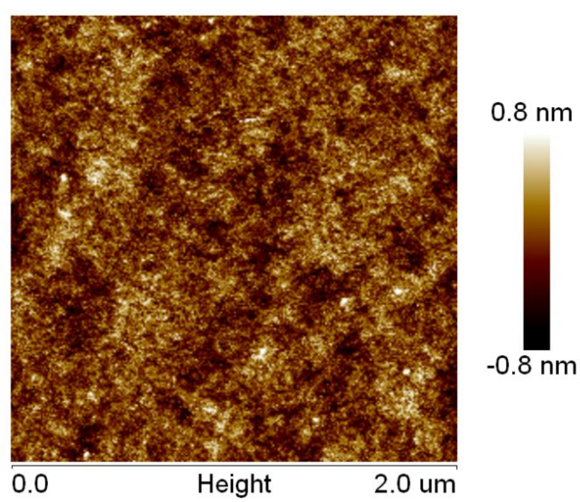

Fig. 2 AFM image of D263 glass substrate. The rms roughness is 0.23 nm.

Co/C films were fabricated using both the DC magnetron sputtering and the reactive sputtering with different proportion of nitrogen. The base vacuum was 1.0×10^{-4} Pa for all the multilayers. For non-reactive sputtering, the working gas is high purity argon with a pressure of 0.133Pa. Reactive sputtering using a mixture gas of 4%, 6% and 8% nitrogen with argon and a working pressure of 0.133Pa was applied to fabricate Co:N/C:N multilayers. All the multilayer samples are first examined by GIXR using the lab-based diffractometer (D1 system, Bede Inc.) with Cu K_{α} radiation. The thickness of multilayer coatings was determined by fittings using Bede Refs software.

3. RESULTS AND DISCUSSION

3.1 Grazing incidence X-ray reflectivity

Fig. 3 shows the GIXRR curves of Co/C multilayers manufactured using different methods. The fitted curves were not provided here due to the absence of refractive index of nitrogen and the content. The period thicknesses of the coatings are approximately 3.50 nm. The total bilayer number is 100 with Γ_c=0.6. As shown in Fig. 3(a), the four samples were deposited on 0.3 mm thick D263 glasses. The Co/C coatings exhibit sharp and clear Bragg peaks up to the 3rd order except the one fabricated using 8% nitrogen. The height of Bragg peaks decrease with increasing proportion of nitrogen. We can also compare the reflective curve with the coatings deposited on a nickel substrate with the same multilayer structure which is shown in Fig. 3(b) (red line). The absence of the third Bragg peaks indicates that the quality of Co/C films deposited on the nickel substrate is slightly lower than the coatings deposited on D263 glass.

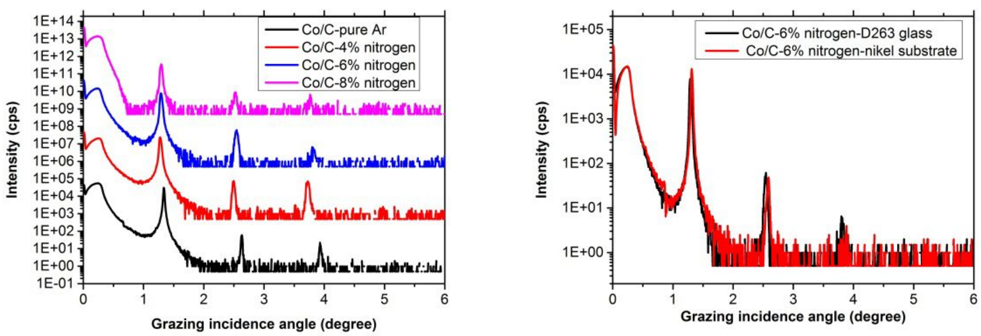

Fig. 3 (a) GIXRR measurements of Co/C multilayers deposited on D263 glass substrates using the non-reactive sputtering and the reactive sputtering with different proportion of nitrogen. (b) GIXRR curves of Co/C films deposited on a flat D263 glass and a nickel substrate respectively. The multilayers were fabricated using the reactive sputtering with 6% nitrogen. The incidence angles are 45 degree.

3.2 Polarization measurement of Co/C multilayer

S-polarized X-ray reflectivity of Co/C multilayer was measured at the BEAR beamline at Elettra Synchrotron Radiation in Italy and the results are shown in Fig. 4(a). Details on the experimental setup and the measurements achieved are reported in another paper [15] of this SPIE volume. The reflectivity of the multilayer fabricated using a working gas of pure Ar is 15.5% while the highest R_s was approximately 18.6% achieved when using 6% proportion of nitrogen. The reflectivity decreased if the proportion of nitrogen was increased to 8%. Multilayers deposited by the reactive sputtering with 4% and 6% nitrogen achieved a better performance than films prepared using non-reactive sputtering. Although the height of Bragg peaks for the sample using 4% nitrogen is higher than that of 6% nitrogen in GIXRR measurements, the R_s is lower.

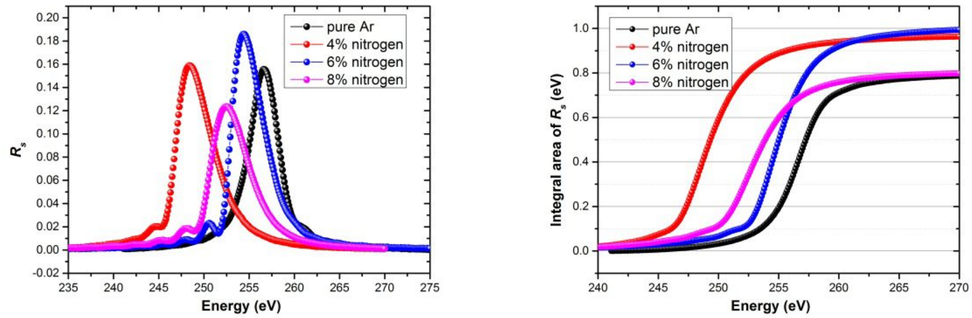

Fig. 4 (a) Rs curves of Co/C multilayers as a function of photon energy. (b) Integration of Rs as a function of photon energy. The coatings were deposited on D263 glass substrates using the non-reactive sputtering and the reactive sputtering with different proportion of nitrogen. The incidence angles are 45 degree.

For the application of LAMP, the integral reflectivity $\int R_s \; dE$ is of further importance than R_s. Fig. 4(b) shows the integration of R_s as a function of photon energy at an incidence angle of 45 degree. The best integrated bandwidth of the reflective curve (the blue line, 6% nitrogen) is 1.0 eV. The integral area of all the fabricated Co:N/C:N multilayers is larger than that of Co/C films manufactured using non-reactive sputtering.

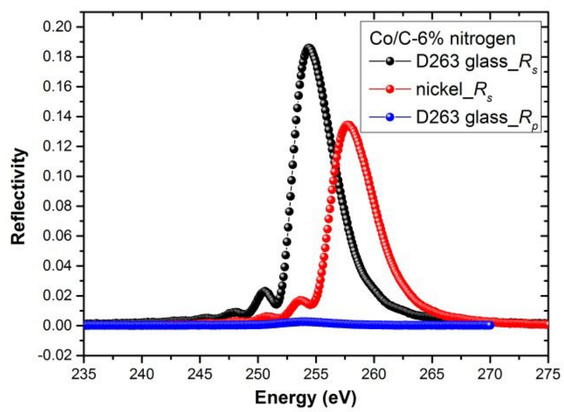

Fig. 5 Rs (black spots) and Rp (blue spots) of Co/C multilayer deposited on D263 glass substrate with 6% nitrogen at an incident angle of 45 degree. The red spots are Rs of the similar multilayer structure deposited on the nickel substrate.

We also make a comparison between the coatings deposited on two different substrates which is shown in Fig. 5. Both samples were deposited in the same sample holder at the same time. The multilayer mirror using glass substrate exhibits significantly better performance than nickel. The similar phenomenon can also be found in other types of Co/C films. The main reason may owe to the extreme low surface roughness of D263 glasses.

Reflectivity for p-light was also measured at an incidence angle of 45 degree which is shown with blue line in Fig. 5. R_p is less than 0.3% for the best sample (6% nitrogen) mostly due to the small residual (2%) elliptical polarization of the beam. The R_s/R_p ratio for the Co:N/C:N multilayer is more than 71, which is enough for the application of LAMP.

4. CONCLUSION

Co/C multilayers were deposited with methods of both reactive and non-reactive sputtering on the substrates of D263 glasses and nickels. The deposited films were characterized by GIXRR and reflectivity measurement. The s-beam integrated reflectivity of 1 eV was acquired for Co/C multilayer. The results show that reactive sputtering with 6% nitrogen can effectively improve the quality of Co/C multilayers, which may be used in LAMP in future work.

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