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RESEARCH ARTICLE

Development of multilayer mirrors for space-based astronomical X-ray optics

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Abstract X-ray reflectivity of single layer coated X-ray mirror is confined to small grazing angles ($< 1^\circ$) grazing incidence X-ray telescopes usually are bulky and have large focal lengths in trade of effective area which is expensive for a space based telescope. Critical angle for total external reflection of a mirror varies inversely with the energy of the incident photon. This practically limits the possibility of making an X-ray telescope sensitive to higher energy X-rays ($<10\,\mathrm{keV}$). Use of multilayer mirrors makes it possible to operate the instrument at higher angles and also significantly improves the high energy sensitivity (80 keV). Fabricated W/B_4C multilayer mirror provides a peak reflectivity of 19% at first Bragg peak (2.3°) when tested with 8.047 keV X-rays. Multi-wavelength reflectivity analysis of W/B_4C multilayer mirror from 9 to 16 keV is presented with a discussion on applications of multilayer mirrors in high energy astronomy.

Keywords Multilayer mirrors · X-ray optics · Bragg reflection

Introduction

Due to recent advancements in fabrication technology, multilayer mirrors open a wide range of possibilities in the field of X-ray astronomical instrumentation. Reflectivity of single layer coated mirrors is confined to very low incidence angles from the surface. Critical angle for total external reflection of X-ray for any surface is directly proportional to the density of the coated material and inversely proportional to the incident photon energy [1]. This property of materials practically limits higher energy X-ray reflectivity from the surface. However, by replacing single layer coated mirrors with multilayer mirrors, an X-ray telescope can increase its high energy cut-off from 10 to 79 keV (NuSTAR, HITOMI [2]). Multilayer mirrors can be used as linear polarization analysers for soft X-rays by optimizing the coating parameters to reflect a narrow band soft X-rays at 45° as the Brewster angle at X-rays is close to 45° for any surface [3, 4]. Multilayer mirrors make it possible to develop near normal incidence narrow band soft X-rays ($<$ 0.5 keV) and Extreme Ultra Violet (EUV) telescopes [5] and also large numerical aperture, wide field, broad band X-ray telescopes. As the band width of multilayer mirrors is very narrow, they can also be used for high resolution X-ray spectroscopy. Due to many potential applications of these mirrors in the field of X-ray and EUV astronomy, development of high efficient multilayer mirrors is considered very important for future high energy astrophysical research.

Potential applications of multilayer mirrors for various types of astronomical X-ray and EUV instruments are discussed in section two. Design parameters of multilayer mirrors are explained in section three. Fabrication and test results are presented in section four.

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Applications of multilayer mirrors in high energy astrophysics

Hard X-ray telescope

NuSTAR hard X-ray telescope has successfully demonstrated the use of depth-graded multilayer mirrors for hard X-ray reflecting telescopes [2, 9]. In depth-graded multilayers, the thickness of each layer is varied, w decreasing from the top of the multilayer to the bottom where the substrate is present. This enables optimal reflectivity over a broad range of X-ray energies. When continuum X-rays are incident on the mirror surface, lower energies are reflected from the thick top layers and higher energies are reflected from the inner thin layers at their respective Bragg peaks. The thickness of the thinnest layer (innermost layer close to substrate) defines the mirror reflectivity cut-off, at a given angle. Conventional single layer coated mirrors have a practical upper cut-off in limit of 10 keV but replacing it with multilayer mirrors in the same geometry, pushes the upper cut-off to $\sim$ 80 keV.

Normal incidence soft X-ray and EUV telescopes

Use of multilayer mirrors makes it uniquely possible to develop high efficient narrowband normal incident telescopes for soft X-rays under 400 eV and EUV telescopes. According to Bragg's law, lower the energy of the photon, larger the angle at which X-rays are reflected for a given layer thickness. Hence for lower energies, multilayer mirrors can be fabricated to operate at normal incidence. Use of normal incidence telescopes increases the sensitivity of the instrument as the effective area of the telescope is higher for a given geometric area. It is also possible to obtain diffracted resolution limited imaging using such mirrors.

Very soft X-ray polarimeter

X-ray polarimetry is one of the last observational windows that are poorly explored in the field of X-ray astronomy. There are several laboratory techniques that are now available to measure the linear polarization of Hard X-rays (Compton and Thompson scattering polarimeters) and soft X-ray (photo-electron tracking). But for very soft X-rays ($<$ 2 keV) the above techniques are less efficient. Using multilayer mirrors, one can reflect very soft X-rays at Brewster angle ($\sim$ 45° at X-ray energies). This acts as a linear polarization analyser for 180° azimuthal rotation.

X-ray reflecting spectrographs

Due to a very narrow band pass for constant period multilayer mirrors at Bragg peaks, they can also be used as reflecting dispersive elements whose spectral resolution ($\sim$ 10 eV) is better than the spectral resolution of existing X-ray detectors. Use of lamilar gratings i.e. multilayer mirrors with lateral groves, further enhances the spectral resolution of the mirrors ($\sim$ 1 eV) [6].

Design parameters of multilayer mirrors

Multilayer mirrors consist of periodic repetitions of low and high refractive index material coatings which work on the principle of Bragg reflection for X-rays. A typical multilayer mirror is made by coating large number of bilayers. Each bi-layer is a combination of two different a low refractive index, low absorption spacer and other a high refractive index reflector. At angles higher than the critical angle for a multilayer mirror, most of the rays get transmitted through the top layer of coating and get divided into transmitted and reflected components at every bi-layer interface. The specifications of the bi-layer coatings can be optimized to interfere constructively all the reflected components from each bi-layer to enhance the overall reflectivity of the mirror. When monochromatic X-rays are incident on a multilayer mirror at different angles, large X-ray reflectivity occurs only at some particular angles called Bragg peaks. Similarly, when a continuum of X-rays is incident on the mirror at a specific angle, a few select wavelengths are specularly scattered. The multilayer mirrors usually have a very narrow spectral response. However the bandwidth can be increased by using a depth-graded multilayer mirrors [7–9] where the thickness of each bilayer is varied for inner layers.

Many coating parameters need to be optimized to fabricate stable, high efficiency multilayer mirrors. Spacer and reflector elements are chosen such that they have high contrast in their density and refractive index. Thickness of one spacer layer (d_s) and one reflector layer (d_r) together is defined as the bilayer thickness ($d = d_s + d_r$). The bilayer thickness d is chosen by the requirement of operational energy and the suitable angle of incidence as per Bragg's law. Ratio of thickness of d_r and d is called gamma factor also governs the overall reflectivity of the mirror and the suppression of higher order Bragg peaks. As the number of repetitions of bi-layer coatings is increased, the overall reflectivity increases. But the maximum number of effective number of bilayers is limited by the absorption of X-rays inside the coating material. Practical issues like adhesion of coating, surface and interlayer roughness, and stress on multilayers limits the use of certain combination of materials and coating specifications for multilayer mirrors [10].

Fabrication and testing of multilayer mirror

Fabrication of multilayer mirrors is done using magnetron sputtering system at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. Magnetron sputtering is a physical vapour deposition method of thin films. In the basic sputtering process, a target (cathode) plate is bombarded by energetic ions generated by discharge plasma, situated in front of the target. The bombardment process causes the removal of the target atoms, which then condense on the substrate as a thin film. Secondary electrons are also emitted from the target surface as a result of the ion bombardment and these electrons play an important role in maintaining the plasma.

Magnetron sputtering uses magnetic field, configured parallel to the target surface, which can constrain secondary electron motion. Magnets are arranged in such a way to increase the probability of atoms–electron collision. In the system we used, there are two target sources: one for reflector and another for spacer, placed separately one above the other. For multilayer coatings, substrate holder moves from spacer target to reflector target periodically. After evacuating the chamber to ultra-high pressures of about 3×10^{-8} mbar, 99% pure Argon (Ar) gas is sent into the chamber, which acts as the sputtering gas. Ar gas is filled until the pressure reaches $\sim 4.8 \times 10^{-3}$ mbar. When high voltages (DC or RF) are applied to target sources, plasma is formed. In practice, DC voltage is applied to reflector material and RF to spacer. In the sputtering system, we applied a DC power of 70 W to tungsten target and 700 W RF power to B4C. Depending on the bi-layer thickness (d) and, substrate is placed in-front the source for a pre-calculated time during each exposure. Typical distance between the source and the substrate is 10–15 cm. Amount of time that the substrate should be placed near source for achieving required thickness depends on the applied voltage and also the type of source. Generally, reflectors sputter faster than that of spacers. A multilayer mirror with Tungsten as reflector and Boron Carbide as spacer is fabricated with bi-layer period of 1.88 nm and 170 bilayers with the ratio of W layer to bilayer period 0.4.

Test results

Testing of multilayers to determine mirror's reflectivity and specifications is done by X-ray reflectivity (XRR) measurements using a monochromatic X-ray source. XRR gives data on reflectivity as a function of incident angle at a given wavelength. It also helps to derive mirror's coating specifications like period of bilayers, number of bi-layers, interface roughness and density of the materials. It is a non-destructive test which can be conducted any number of times without spoiling the sample. Figure 1 shows the XRR test results of the fabricated W/B_4C multilayer mirror tested at 8.047 keV (Cu-K α lab source). Red curve shows measured data and blue curve is the best fit obtained by IMD software from XOP (X-ray oriented programming) package [11]. The best fit curve matches well with the measured curve. The best fit results indicate that the periodicity of multilayer mirror is 1.88 nm. Mirror is having a very good reflectivity of 19% at first Bragg peak (2.3°) when tested at 8.047 keV X-rays. Occurrence of Bragg peak is a function of bi-layer period and wavelength of X-rays used to test the mirror as governed by Bragg's law.

Reflectivity of multilayer mirror at Bragg peak is also a function of the photon energy. It is due to the energy-dependence of absorption properties of materials in the mirror's coating. Figure 2 shows the multi wavelength XRR test results of the fabricated multilayer mirror from 9 keV to 16 keV. Multi wavelength XRR tests are conducted at Beam line 16, Indus-2 synchrotron radiation facility, RRCAT, Indore. The peak reflectivity at the first Bragg peak at different energies is not same and is strongly dependent on the real part of refractive index (n) and extinction coefficient (k) of the reflector material. Extinction coefficient gives the measure of absorption coefficient of the material as a function of incident photon energy.

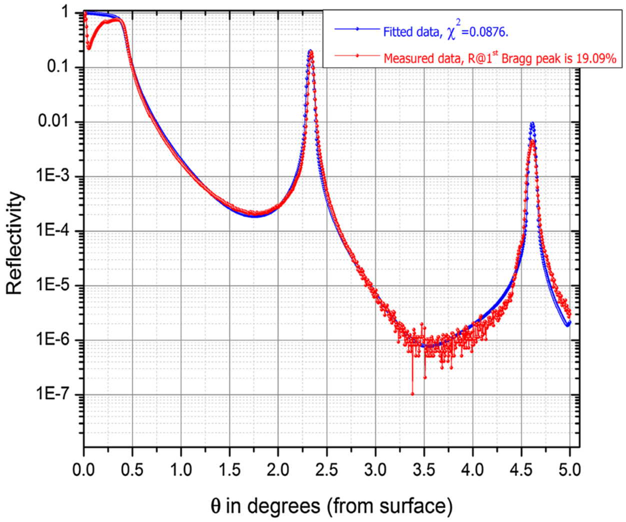

Fig. 1 Reflectivity profile at 8.047 keV of the W/B_4C multilayer mirror as a function of the angle of incidence as measured from the surface. Peak reflectivity of 19% is achieved at the first Bragg peak

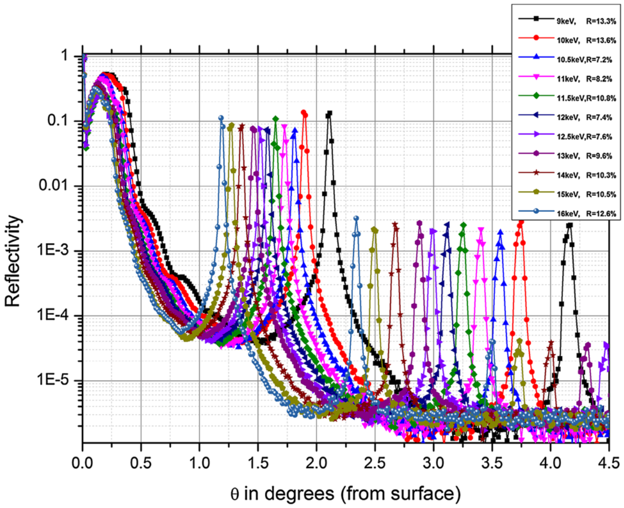

Fig. 2 Multi wavelength reflectivity analysis of W-B4C multilayer mirror from 9 to 16 keV

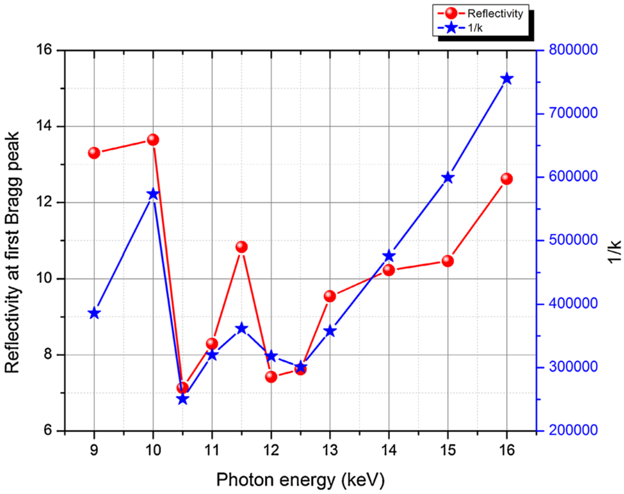

Fig. 3 Peak reflectivity at the first Bragg peak of a multilayer mirror as a function of the photon energy in comparison to the inverse of extinction coefficient of the Tungsten at respective energies. Tungsten's Lyman absorption edges are at 10.2068, 11.544 and 12.0988 keV

Hence to have more reflectivity, the factor 1/k should be large. Figure 3 shows the plot of peak reflectivity at the first Bragg peak of the mirror at different energies in comparison with 1/k factor of the Tungsten element which is the reflector element in the multilayer mirror. One can observe that there are sharp $L_{III}, L_{II}\ and\ L_I$ absorption edges of Tungsten which corresponds to 10.2068, 11.544 and 12.0988 keV respectively. Around this absorption edges, reflectivity of the mirrors is very low when compared to the reflectivity at other energies.

Long time performance analysis of the multilayer mirror

Application of multilayer mirrors to a space-borne payload demands a stable performance of the mirror over a long time. Reflectivity of the mirror is expected to reduce over time due to effects like increase in inter layer diffusion, accumulation of impurities in the coating material and external humidity and temperature. In a space environment, the degradation may also take place due to rapid temperature variations. As an exercise to understand the continued performance of the mirror over time since manufacture, we have conducted XRR tests of multilayer mirrors over a span of 6 months. Figure 4 shows the XRR data of the multilayer mirror when tested immediately after coating, after a month and after 6 months from the day of fabrication. It is observed that reflectivity at first Bragg peak remained nearly constant over time. However, modulations above critical incidence angle are observed. This indicates a change in electron density on the surface layer. This is be due to the Oxygen contamination in the top surface (B4C) of the multilayer mirror. To verify the presence of Oxygen layer, we have conducted Energy Dispersive X-ray analysis (EDX) from scanning electron microscope and observed about 10% of Oxygen (by weight) on the top surface. However, in an X-ray telescope, the mirrors are usually operated at a fixed angle at Bragg peak. Hence the effect contamination in the top layer which is seen between critical angle and Bragg peak, is very low on the reflectivity performance. The peak reflectivity of this mirror at first Bragg peak reduced to ∼ 18 from 19% over the first 6 months.

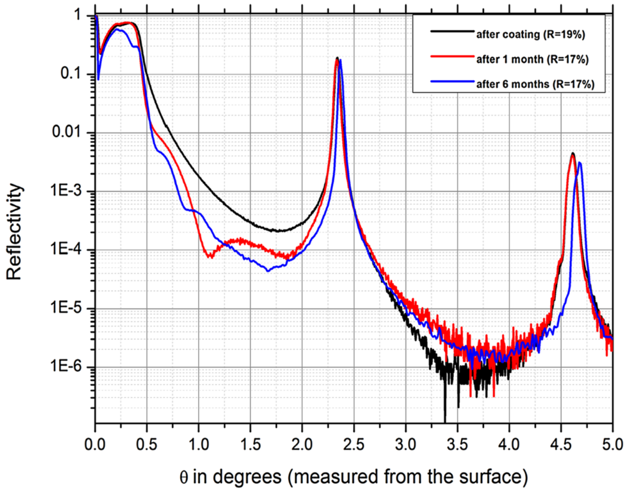

Fig. 4 Reflectivity profile of the multilayer mirror over a period of 6 months from the date of fabrication tested at 8.047 keV X-rays. Peak reflectivity at first Bragg peak has reduced from 19 to 17%

Conclusion and future work

Use of multilayer mirrors makes it uniquely possible to realise the next generation astronomical X-ray and EUV instruments. Replacing single coated mirrors with multilayer mirrors in conventional Wolter type X-ray telescopes, makes the instrument compact, small and more efficient making it more suitable for a space payload with specific applications.

Fabricated W/B_4C multilayer mirror's performance is tested at multi wavelength X-rays and also its stability over time. Peak reflectivity of 19% at first Bragg peak when tested at 8.047 keV, and has reduced by $\sim 1\%$ over 6 months. These results are useful to proceed with further developments towards the design of an astronomical X-ray instrument.

Our future work includes understanding the performance of the mirrors under space environment. Major contribution for potential degradation of mirrors in space could arise from rapid temperature variations (day and night). These effects can be simulated on ground. A set of multilayer mirrors are fabricated and subjected them to thermal cycling process. Reflectivity profile of the mirror before and after thermal cycling should yield long term performance of the mirror for space.

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