Epoxy replication of hard X-ray supermirrors

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The direct replication of W/Si supermirrors is investigated systematically. W/Si supermirrors are fabricated by direct current (DC) magnetron sputtering technology. After deposition, the supermirrors are replicated from the supersmooth mandrels onto ordinary float glass substrates by epoxy replication technique. The properties of the supermirrors before and after the replication are characterized by grazing incidence X-ray reflectometry (GIXR) measurement and atomic force microscope (AFM). The results show that before and after replication, the multilayer structures are almost the same and that the surface roughness is 0.240 and 0.217 nm, respectively, which are close to that of the mandrel. It is demonstrated that the W/Si supermirrors are successfully replicated from the mandrel with good performance.

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With the use of hard X-ray telescopes, we can perform not only an imaging observation with arcmin resolution in hard X-ray regions for various extended objects, but also an observation of very weak sources by focusing optics. In recent years, developments on hard X-ray telescopes have been mainly aimed at increasing the collecting area and extending high-energy response. To increase the collecting area within the limit of the telescope size, tightly nested structures were utilized and substrates were required to be as thin as possible. It has been shown that extremely light, thin X-ray optics can be fabricated by epoxy replication technique[1−6]. One advantage of such replication technique is that the optical figuring and polishing are done on a replication mandrel, instead of a thin and floppy mirror shell, allowing us to obtain high accuracy profile and low microroughness. Another advantage is the possibility of making many identical shells from one mandrel, which is very attractive in the case of multi-nested telescopes.

Based on the requirement of the development of space science in China, hard X-ray telescopes with nested Wolter-I geometry are being developed as part of an important space plan. To achieve high performance of hard X-ray telescopes, the fabrication of grazing incident multilayer optics with high quality is a key point to develop such system. In this letter, our main aim is to investigate a new fabrication method of X-ray supermirrors used on hard X-ray telescopes by direct replication technique. The X-ray supermirrors were designed using an analysis and numerical optimization method, fabricated with multilayer structure that is upside down relative to the designed one by using direct current (DC) magnetron sputtering system, and replicated by using epoxy replication technique. The quality of the replicated mirrors was characterized by grazing incidence X-ray diffractometer (GIXRD) and atomic force microscope (AFM). These measurements indicate that the multilayer mirrors were successfully replicated and that the performance of the replicated mirrors was almost the same with those deposited with multilayer structure as the designed one.

According to the application of hard X-ray telescopes, multilayer supermirrors were designed with energy response at 8.0 keV and the corresponding angular response extending to 0.9°. For the materials of the mirrors, tungsten and silicon were used as the material combination due to their high reflectivity and the good performance of their thermal and temporal stability[7,8]. The structures of the supermirrors were optimized by an analysis and numerical optimization method based on the combination of power-law method[9] and simplex algorithm[10]. W/Si supermirrors with layer number N of 60 were deposited by using a high-vacuum DC magnetron sputtering system. The base pressure of the system was better than 2.0×10^{-4} Pa before deposition. During the depositing process, high-purity argon gas (>99.99%) was used as the working gas, with the working pressure maintained at 0.133 Pa. The distances between the targets and the substrates were 80 mm for both W and Si. The deposition rates of W and Si were about 0.06 and 0.09 nm/s, respectively.

As the surface roughness of the mandrel has strong effect on the quality of the replicated mirror, superpolished borofloat glasses were chosen as mandrels. The mandrel was first coated with a platinum (Pt) layer (∼6 nm) and then deposited with the W/Si supermirror. Since the multilayer structure will be turned upside down after the replication, the W/Si supermirror was deposited with its structure reversed relative to the designed one. For comparison, another W/Si supermirror was also deposited on a superpolished mandrel with the same structure as the designed one and with the separate layer as the topmost layer. The thin Pt layer was used as a separating agent between the mandrel and the multilayer and was helpful in making the separation process easy because of the weak adhesion strength between the mandrel and the Pt layer. The Pt layer also had an enhancing effect in the reflectivity at small incident angles by total reflection[11].

After deposition, the direct replication of W/Si supermirror was carried out onto commercially available float glass substrate. In order for the replica to have good per-
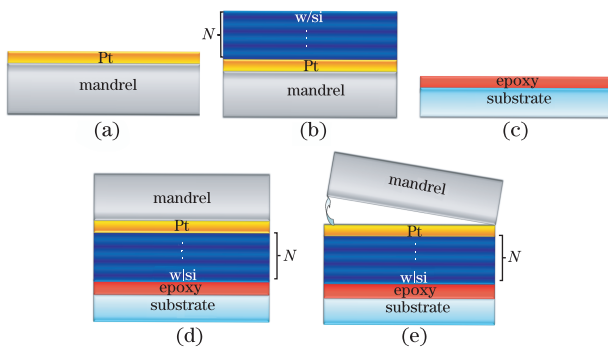
Fig. 1. Schematic of epoxy replication.

Fig. 3. AFM surface images of (a) mandrel and (b) float glass substrate with $\sigma = 0.276$ and 0.474 nm, respectively.

formance, the replication should be performed with bare spots, surface blemishes, or loss of surface smoothness as few as possible. A two-component epoxy resin was first mixed and then diluted with toluene. The surface of the substrate was sprayed with the fluid epoxy and attached with the mandrel. To eliminate the air in the epoxy, which can hinder the accurate copying of the mandrel surface and can result in the degradation of the surface quality of the replicated mirrors, the bonding process was performed in vacuum. The bonded mandrel and substrate were then heated at 50 °C for about 14 h to cure the epoxy. Afterwards, the mandrel was detached from the substrate by water separation method, leaving the supermirror replicated onto the substrate. The surface of the replica was cleaned by deionized water and dried by nitrogen. The schematic diagram of the replication process is shown in Fig. 1.

The properties of W/Si supermirrors before and after replication were characterized by grazing incidence X-ray reflectometry (GIXR) measurement using Cu Kα line (8.04 keV). Figure 2(a) shows the measured results of GIXR, as well as the theoretical curve. The dotted and triangle lines represent the reflectivity of the as-deposited supermirror and the replicated one, respectively, and the square line is the calculated result. Figure 2(b) presents the layer thickness distribution of W (dot) and Si (square) in the designed multilayer structure.

As shown in Fig. 2(a), the reflectivity curves of the supermirrors before and after replication were almost the same with each other, indicating that the W/Si supermirrors have been successfully replicated onto the substrates from the mandrels without multilayer structure destruction or performance degradation. Figure 2(b) indicates that the thicknesses of many layers of W or Si were very

close to each other, leading to the indistinguishability of the deposition time caused by the limitation of the deposition system. The difference between the measured and calculated curves was mainly caused by the deviations of the thickness of the deposited layer.

To evaluate the surface roughness of the samples quantitatively, the measurement was performed using AFM[12]. All the AFM images presented in this study were obtained in the tapping mode, with each image covering a typical scan area of 10×10 (μm). To ensure the accuracy of data, several measurements in different regions were made for each specimen, and the results show good reproducibility.

Figures 3(a) and (b) present the AFM images of the mandrel and the float glass substrate, respectively. And the root mean square (RMS) roughnesses were 0.276 and 0.474 nm, respectively. The measurements demonstrate that the surface roughness of the mandrel was much smaller than that of the substrate. The surface roughness of W/Si supermirror was also measured before and after the replication, as shown in Fig. 4, where the roughnesses were 0.240 and 0.217 nm, respectively. Although the roughness of the float glass substrate was larger, the surface roughness of the replicated supermirror was almost the same as that of the mandrel, which indicates that the ultrasmooth surfaces of the mandrels were successfully replicated. The slight difference in roughness between the mandrel and the supermirror was mainly due to the differently measured area of the surface. This replication process is capable of producing high-quality multilayer mirrors with ordinary substrates at low cost, which can meet the mass production requirement of mirrors by X-ray telescopes.

In conclusion, W/Si broad angular supermirrors are directly replicated from superpolished mandrels
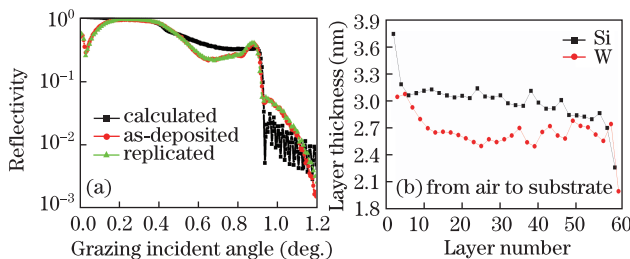

Fig. 2. (a) Reflectivity of broad angular W/Si supermirrors before and after replication versus the grazing incident angle; (b) layer thickness distribution of W and Si in the designed multilayer structure.
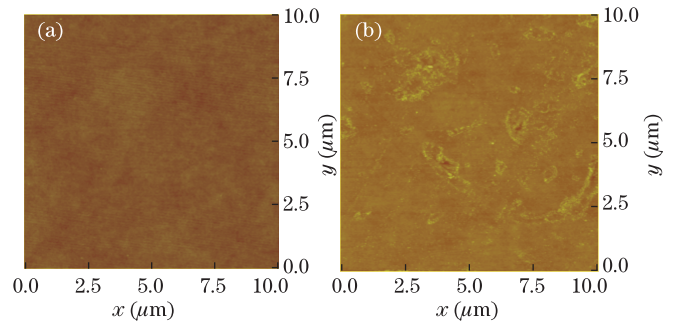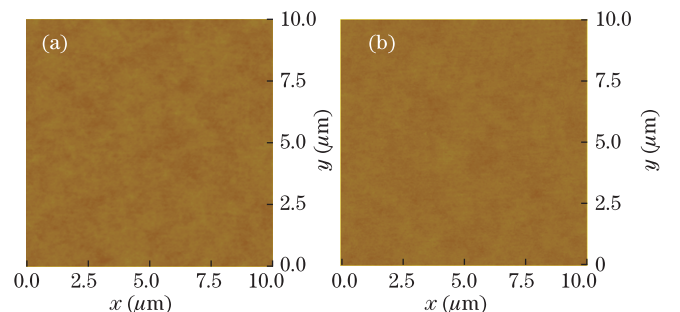

Fig. 4. AFM surface images of W/Si supermirrors (a) as-deposited and (b)after replication.

onto ordinary float glass substrates. The performances of these supermirrors are characterized by GIXR and AFM before and after replication. The measurements show that the reflectivity curves of the replicated supermirrors are almost the same as the deposited ones. In addition, the surface roughnesses of the supermirrors before and after replication are 0.240 and 0.217 nm, respectively, which are similar to that of the mandrel. This direct replication technique is capable of producing high-quality multilayer mirrors at low cost by using ordinary glass substrates. Based on this technique, our further research will focus on fabricating hard X-ray mirrors using Al thin foil substrates for future astronomical telescope applications.

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