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Novel ultra-lightweight and high-resolution MEMS X-ray optics for space astronomy

Ikuyuki Mitsuishi[a,*], Yuichiro Ezoe[b], Kensuke Ishizu[b], Teppei Moriyama[b], Makoto Mita[a], Noriko Y. Yamasaki[a], Kazuhisa Mitsuda[a], Yoshiaki Kanamori[c], Kohei Morishita[d], Kazuo Nakajima[d]

[a] Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
[b] Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
[c] Tohoku University, 6-6-1, Aramaki-Aza-Aoba, Aoba, Sendai, Miyagi, 980-8579, Japan
[d] Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

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ABSTRACT

We report on our first X-ray imaging test of our novel ultra-lightweight and high-resolution MEMS X-ray optics for future space astronomical missions. We have fabricated a single-stage test optic made of Si from a Si (1 1 1) wafer with a thickness of 300 μm. We conducted a dry etching and made 20 μm line and space through holes to use their side walls for X-ray mirrors. We have smoothed the side walls by annealing and plastically bending the wafer to a spherical shape with a curvature of radius of 1000 mm.We have irradiated Al Kα 1.49 keV to the test optic and, for the first time, have verified X-ray focusing. An evaluated angular resolution ranged from 26 to 130 arcmin, which is two orders of magnitude worse than our goal of 15 arcsec. We found that this degraded resolution is mainly due to a large surface roughness of the side walls >10 μm scale and possibly the deformation process. An estimated X-ray reflectivity was also an order of magnitude lower than the theoretical value assuming flat side walls. We concluded that this could be due to the loss of the reflective area by the rough surface. Therefore, the future improvement on the large scale surface roughness is indispensable for the better angular resolution and effective area.

1. Introduction

Because X-rays are difficult to focus refractively, grazing incidence optic is often utilized in astrophysics. However, the critical angle is typically less than several degrees. Thus, the reflective area of one mirror seen from the optical axis must be extremely small. Therefore, to effectively collect X-rays from astronomical objects, tens to hundreds of thick mirrors must be prepared. Each mirror must be smooth, comparable to the wavelength of an incident X-ray light, i.e., nm or less. Consequently, the mirror fabrication process is laborious and the telescope becomes heavy. This is contrary to stringent requirements on the mass limitation of satellite missions. From this point of view, micro pore optics have been proposed as the next generation telescope. A breakthrough idea of the micro pore optics is to utilize microscale to millimetre sized tiny pores as X-ray mirrors. Thanks to the size reduction of the X-ray mirrors, the micro pore optic achieves more than one order magnitude better mass to area ratio, keeping the fine angular resolution. Three types of the micro pores have been invented and under development. The first type is high-resolution pore optic (HPO), in which silicon wafers are bent into a cone and assembled to form pore structures [1]. The second one is micro channel plate (MCP), using glass fiber tubes [2]. The third one is our MEMS X-ray optics based on micromachining etching and lithography techniques [3,4]. For X-ray telescopes, key parameters are the angular resolution and the mass to the effective area ratio. Fig. 1 summarizes expected performances of these three micro-pore optics compared to the conventional X-ray optics on board the previous satellites. According to Fig. 1, a negative correlation between an angular resolution and lightness can be seen in the past telescopes used in space missions, while the micro pore optics can be lighter and is expected to achieve high angular resolution at the same time.

2. MEMS X-ray optics

Among the micro pore optics, thanks to the smallest pores on the order of 10 μm, our MEMS X-ray optics can be the lightest. Recently to improve an angular resolution keeping its lightness, a new method has been invented [5]. Previously, we adopted wet etching to fabricate X-ray mirrors. However, in spite of angstrom-scale smoothness on an etched surface, a reflecting plane is restricted to planar structure along with

* Corresponding author.
E-mail address: mitsuisi@astro.isas.jaxa.jp (I. Mitsuishi).

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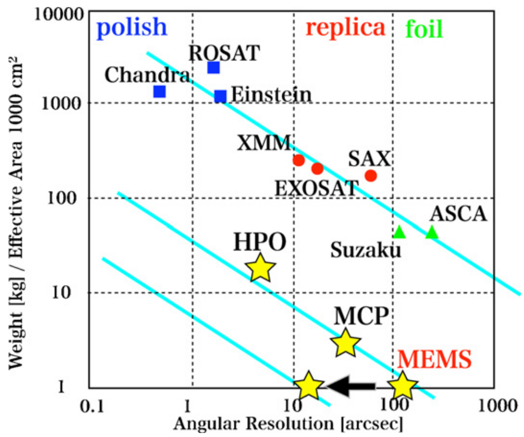

Fig. 1. Performance comparison of the X-ray space telescopes. The horizontal axis is the angular resolution, while the vertical axis is weight necessary to achieve effective area 1000 cm^2 at 1 keV. Square, circle and triangle marks show each performance onboard previous satellite missions, which are classified into the polish-, replica- and foil-type optics. Stars indicate expected performances of the micro pore optics. This figure is a revised version of Fig. 1 in ref. [1].

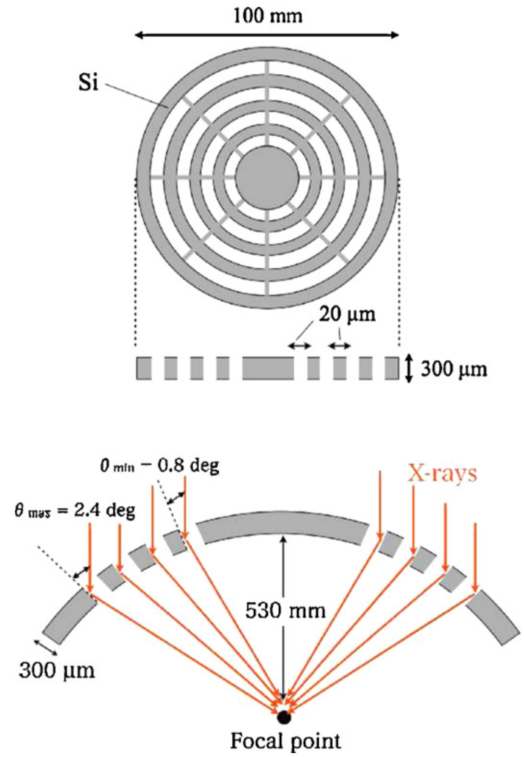

Fig. 2. Concept of the MEMS X-ray optics before and after deformation.

a crystal plane. This effectively limits an angular resolution to ~60 arcsec. Therefore we changed the wet etching to the dry etching, in order to realize curvilinear structures. Since the etched surface after the dry etching is at least on the order of 10 nm, we need additional smoothing processes. Thus, we introduced an annealing process [6] and a magnetic field assisted finishing process [7,8].

The fabrication process is thus composed of three steps. Firstly, curved micro pore structures are made by the DRIE (deep reactive ion etching) process. Secondly, the DRIE-processed wafer is annealed and polished by the magnetic fluid, in order to achieve satisfactory low surface roughness of the order of nm or less. Thirdly, the wafer is spherically deformed [9] to focus parallel X-rays from astronomical objects at a focal point. The concept of the MEMS X-ray optics before and after deformation is shown in Fig. 2.

The angular resolution of the MEMS X-ray optics depends on the geometrical accuracy of the mirrors (i.e., side walls), while the effective area of the optics depends on the surface roughness of the mirrors at small scales ($<\sim 10\,\mu m$). The theoretical limit on the angular resolution comes from the X-ray diffraction in each pore. This can be described as $\lambda/d \sim 13$ arcsec, where λ is the wavelength of incident X-rays and d is the width of the micro pore.

3. Test optic

We fabricated a test deformed optic made of Si from a 4 in. Si (1 1 1) wafer with a thickness of 300 µm. For uniform deformation, a special wafer without the orientation flat was used. With the DRIE, 20 µm line and space micro pores were made. In this design, the aperture ratio is about 30%, which gives the effective area of 400 mm^2 per a two-stage system in 0.6 keV [10]. For large effective area, thicker and larger wafer (e.g., 600 µm and 8 in.) will be adopted. The wafer was then annealed at 1300 °C for 2 h in Ar atmosphere for the side wall smoothing. Then, it was bent to a spherical shape with a curvature of radius of 1000 mm. The fabricated optic is shown in Fig. 3.

To evaluate the deformation accuracy, we measured the 3-dimensional surface profile of the deformed optic with the NH-3 (Mitaka-Kouki) as shown in Fig. 4. We firstly extracted cross sectional surface profiles from the obtained 3-dimensional surface profile at various positions in the test optic and fitted with a circular function. An example of the cross sectional profile along with the dashed line in Fig. 4 is shown in Fig. 5. As a result, a good spherical deformation with a radius of curvature of 1060 ± 1 mm (1σ error) was confirmed in all the measured cross sectional profiles. On the other hand, the obtained radius of curvature of 1060 mm was significantly larger than the design value of 1000 mm. As shown in Fig. 2, this radius influences the focal length because a half the radius corresponds to the focal length in the single reflection geometry. The focal length of this optic should be 530 mm.

In the single-stage optics, we can correspond to this focal length shift by tuning the optic-detector distance. For our goal, i.e., the two-stage optics, the radius of curvature of the two optics must be accurately defined. Specifically, the radius of curvature of the second stage should be 1/3 of the first stage because an incident photon with the incident angle of θ for the first stage is incoming with the incident angle of 2θ for the second stage which requires 1/3 radius of curvature of the first stage corresponding to the tilt of 3θ to realize the incident angle of θ at the second stage. Otherwise, the angular resolution will be degraded. Thus, a further optimization is required for the deformation process.

We then calculated the rms deviation using the residuals between the best-fit circular function and the data as shown in Fig. 5 (bottom panel). We found that the rms deviation is relatively small within 3–10 µm. Since these values are negligible compared to the radius of curvature of 1060 mm,these small deviations will not affect the image performance of the optic.

Having estimated the best focal length and confirmed the good spherical shape, we conducted an optical imaging test as described in [11]. In this test, we confirmed an optical focusing although the image quality against X-rays was uncertain because the optical lights easily diffracts in the 20 µm line and space micro pores. To remove the diffraction effect and to evaluate the X-ray imaging quality, we proceeded to an X-ray imaging test at the 30 m beamline in ISAS/JAXA.