Silicon Micro-pore X-ray Optics

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Abstract

We present our development of novel light-weight and low-cost micro-pore X-ray optics based on the MEMS (Micro Electro Mechanical SYstems) technologies. We successfully fabricated X-ray mirror chips with surface roughness less than several nm and an accurately-defined optic mount. Our studies suggest this type of optics is a promising device for X-ray optics in many research fields such as space research, nuclear physics, and microanalysis.

Key words: grazing X-ray optics, micro-pore optics, MEMS
PACS: 07.85;07.10.C;41.50;95.55.K

1 Introduction

In recent years micro-pore X-ray optics have attracted increasing attention in space research as light-weight and high-performance grazing-incidence optics. The micro-pore optics use sidewalls of tiny pores, made by lead glasses or polished silicon wafers with a diameter of 20-100 μm, as X-ray mirrors. The thickness of the optics, i.e., the length of the mirrors, is short and hence the optics become light. As shown in figure 1, they will be more than one order-of-magnitude lighter than the generic space telescopes. Thus, the micro-pore optics are well suited to achieve optics for space missions with a large effective area or a large field-of-view (e.g., [1,2]).

The basic idea of the micro-pore optics is the fabrication of fine through-hole structures and the usage of their sidewalls as X-ray mirrors. The semiconduc-

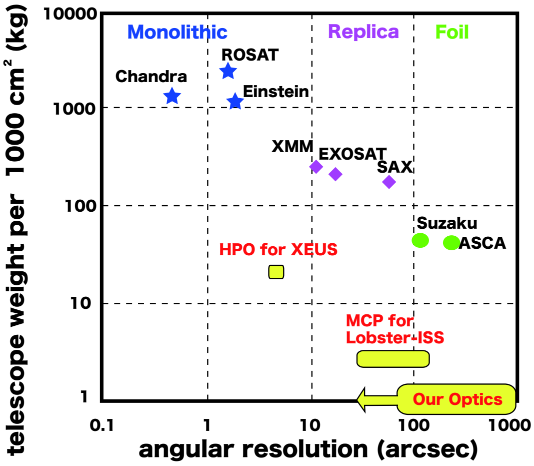

Fig. 1. Comparison of micro-pore optics to the past space X-ray telescopes. Stars, diamonds and circles indicate differently fabricated mirrors for the past telescopes. Yellow squares represent three types of micro-pore optics for future missions. We revised figure 1 in Bavdaz et al. (2004) [1]

tor micro structure fabrication technology, MEMS (Micro Electro Mechanical Systems), is ideal for the first purpose. In fact, there were attempts to use etching of silicon wafers [3,4], although large surface roughness hindered practical use. During the past decades, there are significant improvements to the MEMS technologies. In this paper, we show our development of novel micro-pore optics based on the recent MEMS technologies.

2 MEMS technologies for micro-pore X-ray optics

MEMS are defined as devices with moving parts in the μm to mm range and are manufactured through many processes: growth of layers, photolithography, etching, dycing and so on. Among them, two methods are generally used for 3-dimensional micro strctures. One is anistropic wet etching and the other is D-RIE (Deep Reactive Ion Etching). The former uses different etching rates (at most 250) among crystal planes [5]. The etched surfaces are smooth with rms roughness of at least several nm [6], but the shapes are limited due to the crystal planes. On the other hand, the latter has a high degree of freedom for shapes but relatively large roughness (typically 10-200 nm) [7].

Our idea is combination use of the wet and dry etching processes for micro-pore X-ray optics. We use the former to obtain smooth sidewalls and the latter optic shapes. Because the wet etching is inexpensive, if possible, mass production and integration of X-ray mirrors will be easy and low cost. Furthermore, because of the small thickness of wafers (200-500 μm), this optics will be one of the lightest micro-pore optics.

Figure 2 presents the manufacturing process of our optics. It consists of a large number (typicall 100-300) of mirror chips and an optic mount. The two components are connected by thin adhesives such as the UV curing adhesive so as to accurately arrange the mirror chips. By stacking this single-stage optic, the focal length will be short. The angular resolution of the optics is limited by alignment of these optical elements and also the size of the mirror chip itself. The performance based on our studies is plotted in figure 1 in the yellow box, while the best one we expect is shown in the left arrow.

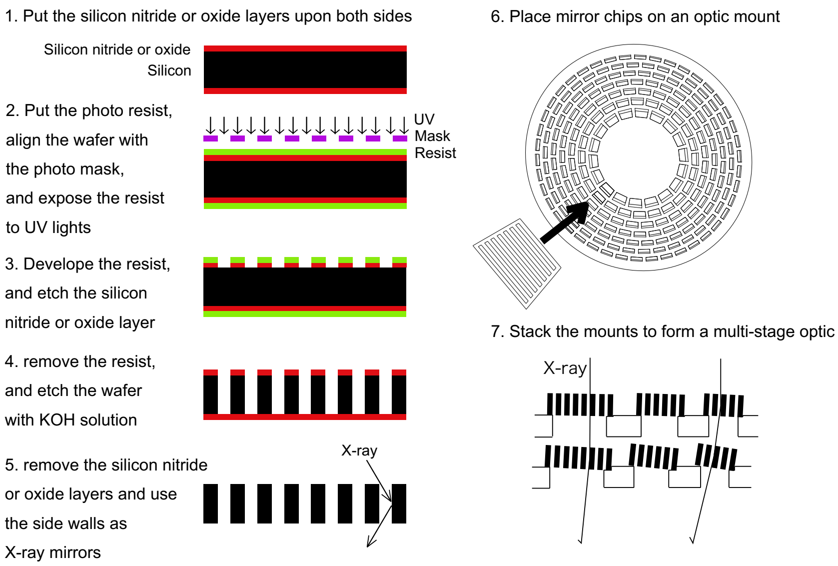

Fig. 2. Manufacturing concept of silicon micro-pore X-ray optics.

3 Mirror chips

As a first step of R&D, we have fabricated a sample mirror chip from a 220μm-thick silicon (110) wafer with 2 μm SiO_2 layers. The 33 wt. % KOH solution in 80 °C was chosen as etchant. Smooth silicon (111) planes vertical to the wafer face appear after the etching. Figure 3a exhibits the obtained mirror chip. The rms roughness of the (111) side walls, measured with the atomic force microscope (AFM), was 1-2 nm. The X-ray reflection of the side walls were measured under constant illumination of quasi-parallel X-ray beam by changing the rotation angle of the walls against the beam. Figure 3b shows the obtained angular response. Excess above a simple collimator profile (solid line) below 1 deg can be seen. When the energy becomes higher, the excess decreases. This strongly suggests X-ray reflection on the (111) side walls. Compared to the ray-tracing simulations, the roughness of the side walls was estimated as 3-5 nm, which is consistent with the AFM results. This is the first detection of X-ray reflection on this type of mirrors. The detailed analysis is described in [6].

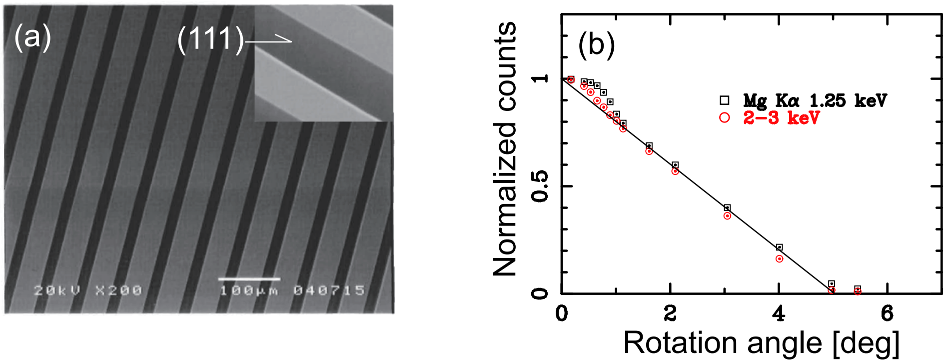

Fig. 3. (a) Scanning electron microscope images of a sample mirror chip. (b) Angular responses of the sample in two energy ranges.

In order to increase the X-ray reflectivity even more, we need to suppress the roughness, which is below 1 nm in the past X-ray telescopes. The roughness of the etched surface depends on the etching uniformity. Therefore, bubble removal during the etching could be a critical problem. We then changed the agitator from a magnetic stirrer to three frequency ultrasonic waves. According to the previous report by Ohwada et al. (1995), this provides a uniform etching rate independent of patterns [8] . From their results, we expected smoother side walls. The results are shown in figure 4 and table 1. Clearly the surface morphology has changed. Also the rms roughness has been improved to less than 1 nm on these scales. These are ones of the smoothest etched silicon surfaces and results will be summarized in [9].

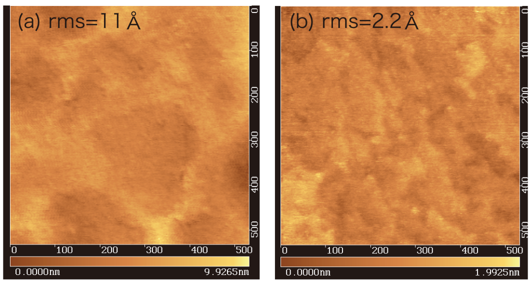

Fig. 4. 500×500nm^2 AFM images of (111) side walls using (a) the magnetic stirrer and (b) the ultrasonic waves.

Table 1
The average roughness obtained with the ultrasonic waves.

scale (nm^2)	rms (nm)
500	0.34±0.06
1000	0.54±0.09
3000	0.83±0.13

We also studied the release of the mirror chips from the wafer using a dycing machine. Initial results are found in [10]. The best geometrical accuracy is within ±5 μm. With this accuracy, we can correctly align the mirror chips to the optic mount (see figure 2). If the mirror chip has a square shape with a side length of 5 mm, the misalighnment angle will be within ±3 arcmin.

4 Optic mount

To establish the manufacturing process shown in figure 2, the optic mount was manufactured by using the DRIE technique. Together with the study on the dycing of the mirror chips, initial results are presented in [10]. It is composed of through holes and step-like structures on the latter of which the mirror chip is mounted. The widths of the holes change according to the radius from the center, in order to control the inclination angle of the mirror chips (see figure 2 step 7). Careful control of the etching speed (less than 1 μm min^{-1}) is necessary, so as to obtain an accurate shape. Table 2 presents design parameters of our sample optic mount. We chose to use a 4-inch bare silicon wafer as a material. Then, from the wafer size and the usable reflection angle of Si at 1 keV (1.7 deg), the focal length is determined as 750 mm. Because of this relatively short focal length, the angular size of the mirror chip is large ($\sim$11 arcmin) and hence the angular resolution will be dominated by this size.

Figure 5 shows the fabricated optic mount. The geometrical accuracy of the mount is extremely high within $\pm$1 μm in the 3-dimensional directions. This suppresses the misalignment angle of the mirror chips within $\pm$2 arcmin in this design. We thus confirmed that an accurately defined optic mount is manufacturable with the D-RIE.

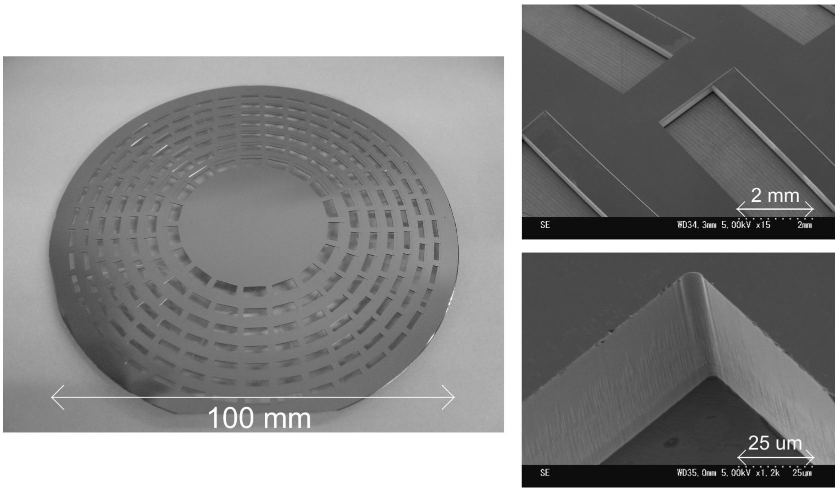

Fig. 5. Photographs of a sample optic mount.

Table 2
Design parameters of a sample optic mount.

Diameter	4 inch(=100 mm)	Thickness	300 μm
Step depth	50 μm	Mirror incl. angle	0.76$\sim$1.7 deg
Focal length[a]	750 mm	Angular resolution[a]	$\sim$11 arcmin

[a] A single-stage optic is assumed.

5 Conclusion

We have studied the new micro-pore optics using the MEMS etching techniques. For the first time, we have experimentally shown that the anisotropic wet etching is an excellent way to obtain high-performance X-ray mirror chips and the dry etching an accurate optic mount. We next develop a connecting method of these optical elements and test our sample optic using the parallel X-ray beam.

Even though we need to complete the manufacturing process, we believe that our optics will be suitable for future small satellite missions and ground experiments such as nuclear physics and microanalysis. In small satellites, there are rigid limitations on the mass and the size of the payload. This type of optic, even if four stage with a radius of 50 cm, only weights several hundreds grams. Such extremely light-weight optics are ideal for small satellite missions such as the Japanese dark baryon search program mission [11].

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