Study on Fabrication of X-ray Collimators by X-ray Lithography Using Synchrotron Radiation

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X-ray lithography using synchrotron radiation enables the microfabrication of plastic solid materials in scale from micrometers to millimeters with high aspect and nanoscale surface roughness. We investigate fabrication of X-ray collimator mold for the space telescope using the X-ray lithography. A honeycomb-like structure consisting of hexagonal columns with diameter of several hundred micrometers is required for the X-ray collimator. In this study, target resin molds for manufacturing a metallic X-ray collimator were created from polymethyl methacrylate (PMMA) substrate. We succeeded in producing a honeycomb pillar array structure with diagonal length of 100 μm and its distance of 14.1 μm between pillars.

Keywords: Synchrotron radiation, X-ray, LIGA, Microfabrication

1. Introduction

In 2016, the Focusing Optics X-ray Solar Imager (FOXSI) was started to study particle acceleration and coronal heating on the Sun through unprecedented high-resolution imaging in the X-ray energy band region. An observation device equipped with a telescope and an X-ray detector is launched by a rocket, and soft X-rays and hard X-rays are captured in outer space to continuously photograph the sun at high speed.

The purpose of FOXSI is to understand high-energy phenomena in the solar corona [1-4]. For example, elucidation of the mechanism of nanoflare [5] can be mentioned. This flare is about one billionth of normal flare. However, while the temperature of the normal corona is several million degree Kelvin (MK), it is thought that 10 MK of plasma is generated when nanoflare occurs. Accelerated plasma is called non-thermal plasma and cannot be analyzed without capturing the X-rays generated by the plasma. Information on the position, time, and energy of each X-ray photon can be obtained from the image obtained by FOXSI. It is thought that the understanding of particle acceleration of solar flares will be improved by examining the presence or absence of the constant

existence of 10 MK plasma in the solar corona from the obtained information.

This research aims to improve the X-ray collimator [6-9] of the observation device. A X-ray collimator is a component that removes stray light during observation and allows light parallel to the telescope to pass through to reduce image noise. Improvements include spectral accuracy and weight. Improving the spectral accuracy means narrowing the incident angle of the light entering the observation device so that only light with higher parallelism can be extracted. A collimator picks out parallel light by reflecting light inside a metal cylinder, as illustrated in Fig. 1(a). The angle of incidence can be reduced and more parallel light rays can be obtained if the cylinder is longer and if the inner diameter is smaller. Thus, fabricating a cylindrical structure with a high aspect ratio and a small inner diameter will improve spectral accuracy and eliminate noise from stray X-rays.

Weight reduction is very important from the viewpoint of rocket weight limitation. In order to reduce the weight, it is necessary to use a honeycomb structure [10,11] with a large aperture ratio as shown in Fig. 1(b). This structure becomes possible to secure the strength while reducing the

materials required for manufacturing the collimator, leading to weight reduction. Furthermore, from the viewpoint of strength and X-ray blocking, it is required to make the above structure from metal.

In the previous studies [1-4], a collimator was created using a metal 3D printer to remove light outside 18° with an aspect ratio of 190. In order to improve the performance, it is necessary to make it finer with a higher aspect ratio. However, a collimator that removes light outside the 14° with an aspect ratio of 250 is required to have a processing accuracy of about 10 μm , and it is difficult to manufacture due to the limitation of the powder size (about 30 μm). In order to create a finer and higher-aspect structure, attention was focused on the X-ray lithography using the synchrotron radiation (SR) facility New SUBARU, which can perform deep processing on the order of microns [12-14].

X-ray lithography is the most appropriate technique for the nano- or microfabrication of structures with both nanoscale surface roughness and high aspect ratios. This is because X-ray processing using SR is the only technique to date that has a deep depth of focus and can process large area at once as a top-down process [12-20]. Further, the LIGA process, which combines lithography (Lithographie), electroforming (Galvanoformung), and molding (Abformung), allows for the manufacture of metallic nano- to microscale structures which are otherwise difficult to fabricate.

In this study, we demonstrate deep X-ray lithography for the fabrication of X-ray collimators.

Fig. 1. Schematics of (a) the structure of a collimator in cross-section, (b) a collimator mold comprising laminated honeycomb membranes.

2.Experimental

In X-ray lithography, an X-ray mask is typically placed above the target surface to direct and limit exposure of the substrate. The vertical gap between the X-ray mask and the substrate results in the formation of a tapered structure, which is not desirable for a collimator cylinder. To address this, we employed a novel X-ray masking procedure, illustrated in Fig 2(a). The Au X-ray mask is directly fabricated on the surface of the polymethylmethacrylate (PMMA) substrate, which improves transferability. The optical photograph in Fig. 2(a) is a typical resulting structure; the example shown produces hexagonal cylinders with an aperture ratio of 70% and a hole diameter of 100 μm . The aperture ratio is defined as the ratio of the area of the hole to the total cross-sectional area of the collimator. Masks to create molds for cylinders with hole diameters of 50, 100, 200, and 300 μm and aperture ratios of 80%, 70%, 60%, and 50% were prepared.

The irradiation experiments were performed using beamline BL11 at the New SUBARU synchrotron radiation facility at the University of Hyogo [14]. The X-ray beam obtained from the bending magnet is condensed using a mirror and subsequently passed through two Be filters to reduce the photon energy to below 2 keV. The energy spectrum of BL11 is shown in Fig. 2(c); the X-ray bandwidth comprises energies between 2 and 8 keV, and has a flux maximum at approximately 5 keV. The operation electron energy of the storage ring was set at 1.5 GeV and the storage current value ranged from 320 to 160 mA. In this operation mode, the storage current decreased exponentially during exposure. The irradiation doses to PMMA in this experiment were 1 J/mm² and 3 J/mm².

As described above and schematically illustrated in Fig. 2(a), a contact Au metal mask was prepared directly on the surface of 2-mm-thick PMMA substrate, which was purchased from Nippon Jushi Kogyo Co., Ltd. Fig. 2(b) shows a schematic diagram of the experimental setup for X-ray irradiation. The exposure stage was moved vertically over a range of ± 50 mm at a speed of 5 mm/s to enable vertical scanning with the beam. The SR dose was controlled by the number of scans, which were performed under 0.05 atm of helium gas that was introduced into the chamber after vacuuming with a scroll pump. The temperature of the irradiated surface was maintained at room temperature by heat exchange with the helium gas. The Au contact mask was fabricated by combining Au electroplating and magnetron sputtering to

Fig. 2. Schematics of (a) the method and structure of a direct contact X-ray mask, (b) the X-ray exposure experimental setup in the chamber in the beamline BL11 of NewSUBARU at the University of Hyogo, and (c) Photon intensity distribution as a function of photon energy at the beamline BL11.

create an array of hexagonal Au masks, with a hole diameter of about 50 – 300 μm and a distance between hexagons of about 4.51 – 76.2 μm. The Au plating solution (Microfab Au640) and sputtering target were purchased from Tanaka Precious Metals Co., Ltd. After irradiation, the PMMA was developed with a GG-developer to prepare the structure. Before Au electroplating, hexagonal

patterns were fabricated by UV lithography using Cr glass mask. Tracking dimensional accuracy was measured using an optical microscope.

3. Results and discussion

Scanning electron microscope (SEM) images of typical PMMA molds fabricated with X-ray lithography are shown in Fig. 3 and 4. We found that X-ray mask lithography can produce honeycomb PMMA microstructures with a diameter of 100 – 300 μm, a distance between pillars of 14.1 – 76.3 μm. From SEM images, we found the height was about 300 μm at 1 J/mm² and about 550 μm at 3 J/mm². Fig. 5 shows summary of topview optical micrographs of the PMMA molds developed after X-ray 1 J/mm² irradiation. Here, we found that the pillar structures collapsed under the severer design conditions as pointed by an arrow in Fig. 4 and 5. In Fig. 4, the part indicated by the arrow is broken. Looking at Fig. 5, it can be seen that the hexagonal structure is not orderly. This is because the hexagonal columns collapse and the distance between the columns is not constant. From pointed by the arrow in Fig. 5, a microstructure with a distance between pillars of less than 14.1 μm resulted in collapse. 14.1 μm is the distance when the diameter is 100 μm and the aperture ratio is 70%. In addition, when irradiating at 3 J/mm², there was

Fig. 3. SEM images of PMMA mold (aperture ratio: 70%, hole diameter: (a) 50 μm, (b) 100 μm, irradiation dose: 1 J/mm²)

Fig. 4. SEM images of PMMA mold (aperture ratio: 70%, hole diameter: (a) 50 μm , (b) 150 μm , irradiation dose: 3 J/mm^2).

Fig. 5. Optical micrographs of the topview of PMMA molds developed after X-ray exposure.

a part that collapsed in most patterns. This is likely because of the influence of surface tension during development, which, if too large, causes sticking and the collapse of the hexagonal columns. This phenomenon is especially likely to occur when the structure is taken out of the developer.

Despite this limitation, the X-ray lithography technique described here can be reliably employed to produce a structure with an aspect ratio of 3, a diameter of 100 μm , and a line width of 14.1 μm , suitable for producing a collimator. However, in order to achieve the target aspect ratio of 250, it is very difficult to make it because it is necessary to laminate 84 layers of the same structure. We found that there are process issues in this direct contact

mask method. However, as shown in Figs. 3 – 5, this process can achieve the high processing accuracy for the top surface. Table 1 and 2 show summaries of the tracking dimensional accuracy for each process completion in this direct contact mask method and conventional mask procedure, respectively. Here, the evaluation results are shown as the results of the conventional procedure in the dihedral corner reflector arrays (DCRA) fabricated in the previous study [13]. The difference in size between the Cr glass mask and the product is less than 2.80 μm for the collimator mold, while 5.39~13.21 μm for the DCRA. These numbers were derived from a comparison of the numbers for

each process in Table 1.2. The collimator mold made with the contact mask transfers the mask pattern more accurately. This is attributable to that

the pattern distortion due to diffraction hardly occurs due to the direct bonding of the X-ray mask to the substrate

Table 1. The tracking dimensional accuracy for each process completion in this direct contact mask method.

	Cr glass mask	Contact mask	PMMA mold	Design value
Diameter	97.8±0.81 μm	96.7±0.89 μm	96.8±0.58 μm	100 μm
Line width	16.5±0.58 μm	16.5±0.3 μm	15.6±0.66 μm	14.1 μm
Sample number	10	10	10

Table 2. The tracking dimensional accuracy for each process completion in conventional mask method.

	Cr glass mask	DCRA structure	Design value
Diameter	202.0±0.90 μm	208.2±2.19 μm	200 μm
Line width	41.7±0.91 μm	32.4±3.0 μm	40 μm
Sample number	10	10

4. Conclusion

A honeycomb structure for an X-ray collimator mold was produced by microfabrication of PMMA using X-ray lithography. From multiple conditions, the higher the aspect ratio and the shorter the distance between the pillars, the greater the risk of structural collapse. From the experimental results, a structure having a hole diameter of 100 μm , an aperture ratio of 70%, and a height of 300 μm and an aspect ratio of 3 was achieved. However, in order to create the target structure, it is necessary to create a large number of similar structures. It is considered necessary to develop a novel process that can improve the aspect ratio that can be processed at one time. In addition, a method is required for preventing the sticking.

As mentioned above, although there are process issues to be improved, it has been shown that there is a direct contact mask method as one of the novel structure fabrication methods which can achieve high processing accuracy.

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