One-dimensional neutron focusing with large beam divergence by 400mm-long elliptical supermirror

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Abstract. Reflective optics is one of the most useful techniques for focusing a neutron beam with a wide wavelength range since there is no chromatic aberration. Neutrons can be focused within a small area of less than 1 mm² by high-performance aspherical supermirrors with high figure accuracy and a low smooth substrate surface and a multilayer interface. Increasing the mirror size is essential for increasing the focusing gain. We have developed a fabrication process that combines conventional precision grinding, HF dip etching, numerically controlled local wet etching (NC-LWE) figuring, low-pressure polishing and ion beam sputtering deposition of the supermirror coating to fabricate a large aspherical supermirror. We designed and fabricated an plano-elliptical mirror with large clear aperture size using the developed fabrication process. We obtained a figure error of 0.43 μm p-v and an rms roughness of less than 0.2 nm within an effective reflective length of 370 mm. A NiC/Ti supermirror with m=4 was deposited on the substrate using ion beam sputtering equipment. The results of focusing experiments show that a focusing gain of 52 at the peak intensity was achieved compared with the case without focusing. Furthermore, the result of imaging plate measurements indicated that the FWHM focusing width of the fabricated mirror is 0.128 mm.

1. Introduction

In recent years, high-intensity proton accelerator facilities have been constructed for neutron research such as J-PARC in Japan, ISIS-TS2 in UK and SNS in USA. High-intensity pulsed neutron beams with a wide wavelength range are produced from these facilities. These beams are used extensively in combination with the time-of-flight (TOF) method to reduce the measurement time in various experiments using neutron beams. A neutron-focusing device is required to improve the S/N ratio and resolution and reduce the measurement time. Solid-state lenses and magnetic lenses have been developed and used for focusing cold neutron beams [1,2]. However, it is difficult to focus a neutron beam including thermal neutrons onto a small point without chromatic aberration. On the other hand, reflective optics is one of the most useful techniques for focusing a neutron beam with a wide
wavelength range since there is no chromatic aberration. Neutrons can be focused within a small area of less than 1 mm² using high-performance aspherical supermirrors with high figure accuracy and a smooth substrate surface and a multilayer interface. We have developed a numerically controlled local wet etching (NC-LWE) technique [3] to figure aspherical mirror substrates and an ion beam sputtering deposition technique [4] to deposit a NiC/Ti multilayer to realize practically applicable aspherical supermirror optics. Previously, we fabricated a plano-elliptical supermirror with a clear aperture of size of 90 × 40 mm² by applying these techniques and obtained a focusing gain of 6 and a reflectivity of 0.64-0.7 in the near-critical-angle region for \( m = 4 \) [5,6], where \( m \) is the ratio of the effective critical angle of the supermirror to that of nickel.

Increasing the mirror size is essential for increasing the focusing gain. We have developed a fabrication process that combines conventional precision grinding, HF dip etching, NC-LWE figuring, low-pressure polishing and ion beam sputtering deposition of the supermirror coating to fabricate a large aspherical supermirror [7]. Here, we report fabrication result of an elliptical supermirror with large clear aperture size and the focusing performance of the neutron beam.

2. Elliptical supermirror with large clear aperture

2.1. Optical design

It is effective to increase the length of the mirror to increase the focusing gain. We designed a plano-elliptical neutron-focusing mirror that can be applied to reflective small-angle scattering measurement in SUIREN (Apparatus for Surface and Interface Investigations with Reflection of Neutrons) of JRR-3M (Japan Research Reactor No.3 (Modified) of Japan Atomic Energy Agency) and BL17 at J-PARC. The effective reflective area, magnification, focal length and incident angle at the mirror center were 370 mm × 30 mm, 1:1, 1050 mm and 1.4° assuming that an \( m = 4 \) supermirror was deposited, respectively. The designed shape of the mirror surface is given by

\[
\frac{x^2}{1050.31^2} + \frac{y^2}{25.66^2} = 1 \quad \text{(unit: mm).} \tag{1}
\]

For the designed mirror with a length of 370 mm, the maximum depth of the mirror is 420 μm.

![Figure 1. Schematic of the setup for measuring the neutron beam profile (top view).](image-url)
2.2. Fabrication of neutron-focusing elliptical supermirror with large clear aperture size

We have developed a fabrication process that combines conventional precision grinding, NC-LWE figuring, low-pressure polishing and ion beam sputtering deposition of the supermirror coating to fabricate a large aspherical supermirror.

For the efficient figuring of the mirror shape, precision grinding was conducted with a computer-based numerically controlled grinding machine using resin-bond diamond wheels of #325, #1200 and #3000 in turn, whose feed pitches were 3 mm, 1 mm and 0.5 mm, respectively. The mirror material was synthetic quartz glass with dimensions of 458 mm × 100 mm × 35 mm, and the figured and evaluated area was 370 mm × 50 mm. Grinding techniques make it possible to obtain micrometer form accuracy in a short time. We performed HF dip etching and a first polishing process using CeO2 slurry before figure correction by NC-LWE to remove the subsurface damage after figuring by grinding.

The NC-LWE technique enables an aspherical shape to be figured deterministically with submicrometer form accuracy because it utilizes a noncontact chemical removal process that is insensitive to external disturbances such as vibration and/or thermal deformation. As the processing parameters in NC-LWE figuring, we applied 37 wt% HF solution with a temperature of 41.6°C, a circular nozzle with a diameter of 15 mm and a feed pitch of 0.5 mm.

In NC-LWE figuring, raster-type numerically controlled scanning is applied to correct the residual figure error. After raster scanning, shallow periodic grooves are inevitably generated on the figured surface by the overlapping of the scanned etching path. We applied a second polishing process with a hard polishing pad to remove low-spatial-frequency roughness (LSFR: \( \lambda_s > 1 \text{ mm} \)) such as tool marks.

The mid-spatial-frequency roughness (MSFR: 1 mm > \( \lambda_s > 1 \mu\text{m} \)) and high-spatial-frequency roughness (HSFR: 1 \( \mu\text{m} > \lambda_s > 1 \text{ nm} \)) components of the figured surface increase after NC-LWE. A possible interpretation of the increases in MSFR and HSFR is that subsurface damage appears because the etching rate of the damaged layer is different from that of the undamaged layer. It is essential to minimize the surface roughness to obtain higher reflectivity and thus realize the practical application of the neutron-focusing mirror. Therefore, a third polishing process using a soft polishing pad was applied to improve the MSFR and HSFR of the figured mirror substrate.

The surface of the plano-elliptical substrate was deposited with NiC/Ti multilayers by ion beam sputtering (IBS) to fabricate a supermirror for increasing the critical angle of neutron reflection. We used the IBS system installed at JAEA, which has an effective deposition area of 0.2 m² (diameter of 500 mm) [8]. The NiC layer was obtained by Ni-C cosputtering. The carbon atoms added to the nickel layer suppressed interfacial roughness by reducing the crystal grain size of the nickel layer [9-12]. Majkrzak and Wood have reported achieving greater than 90% reflectivity at \( m = 3 \) [9, 11]. Maruyama et al. have succeeded decreasing diffuse intensity by more than one order of magnitude by adopting NiC/Ti multilayers instead of conventional Ni/Ti multilayers and achieving 80% reflectivity at \( m = 4 \) [13]. A NiC/Ti supermirror with \( m = 4 \) was fabricated on the figured substrate. The thickness and total number of multilayers were 6 \( \mu\text{m} \) and 1200, respectively.

2.3. Evaluation of focusing performance and reflectivity

The focusing performance of the fabricated elliptical supermirror was evaluated at NOBORU at J-PARC of JAEA. We show a schematic of the setup for measuring the neutron beam profile in Figure 1. A flat supermirror with \( m = 4 \) is used to reflect the neutrons into the focusing device to reduce the background and the gamma radiation from the direct beam. The wavelength of the neutron beam was varied from 3.5 to 10 Å by calibration using a chopper. The sagittal plane of the mirror was installed horizontally on a goniostage to focus the neutron beam vertically. The mean incident angle of the neutron beam was 1.40 °. The horizontal divergence of the neutron beam was 0.60 °. Two-dimensional images of focused and nonfocused direct neutron beams were measured using an imaging plate (Fujifilm BAS-ND; resolution: 50 μm). The width of the slit in this experiment was 0.10 mm. The magnification of the optical design was 1.
3. Results and discussion

We designed and fabricated a plano-elliptical mirror with large clear aperture size using the proposed fabrication process. The shape of the mirror substrate was measured with a laser autofocus measuring machine (Mitaka Kohki NH-5N; z resolution: 10 nm). We were able to reduce the figuring time of NC-LWE to 1 day by applying grinding and obtained a damage-free mirror substrate by applying HF dip etching and the first polishing process. The maximum difference from the designed shape was 0.43 μm after the third polishing process. This result indicates that the residual figure error was corrected deterministically with sub-micrometer form accuracy when NC-LWE was used to figure the mirror substrate with a large clear aperture (370 mm) and high mirror depth (ca. 420 μm) and that the second and third polishing processes that we developed and applied were effective for improving the surface roughness while maintaining sub-micrometer form accuracy. Figure 2 shows the surface roughness of the figured mirror substrate after the third polishing process. The surface roughness was measured using a scanning white-light interferometer (Zygo NewView 200CHR). To remove the undesirable surface structures, a soft polishing pad was applied in the third polishing process to a removal depth of about 40 nm. This result indicates that the surface morphology was improved and that an rms roughness of less than 0.2 nm was obtained by applying the third polishing process.

From these results, it is concluded that the mirror fabrication process combining precision grinding, NC-LWE and low-pressure polishing is a highly effective method of fabricating an ultraprecision aspherical mirror substrate with a large clear aperture size, sub-micrometer form accuracy and sub-nanometer surface roughness.

Figure 3 shows the surface roughness of the mirror surface after NiC/Ti supermirror deposition. There was no difference between the surface roughness after deposition and the surface roughness of the mirror substrate, indicating that the surface of the mirror substrate has sub-nanometer surface roughness dominated by the crystal grain aggregate of NiC.

Figure 4 shows two-dimensional images of the neutron beam detected using the imaging plate. A neutron beam with a wide wavelength range was uniformly focused on the mirror where it had an effective width of 30 mm. The neutrons detected beyond the mirror were due to the horizontal divergence of the neutron beam. The shape of nonfocused beam is asymmetric. This is because the center of the slit could be out of alignment from the center of the upstream collimators or slits. Figure 5 shows detailed profiles of both focused and nonfocused direct neutron beams along cross section A-A’. The full width at half maximum (FWHM) of the focused beam was 0.128 mm, and a focusing gain of 52 in terms of the peak intensity was achieved compared with the nonfocused direct beam. The intensity of the focused neutron beam was 16.7 times greater than that of the nonfocused beam at a width of 0.5 mm. Figure 6 shows the result of TOF measurement. The neutron beam with a wavelength range of 3.5-10 Å was focused effectively. These results suggest that the fabricated elliptical supermirror enables to focus neutron beams with wide wavelength range to be focused onto samples of sub-millimeter size with high intensity.

Figure 2. Surface roughness after 3rd polishing (0.211 nm rms in 64 x 48 μm²).

Figure 3. Surface roughness after supermirror deposition (0.202 nm rms in 64 x 48 μm²).
4. Conclusions

We fabricated a 370-mm-long elliptical neutron-focusing supermirror by a combined fabrication process consisting of precision grinding, HF dip etching, NC-LWE figuring, low-pressure polishing and ion beam sputtering deposition. We succeeded in obtaining a figure error of 0.43 \( \mu \)m p-v with a surface roughness of less than 0.2 nm rms, an FWHM of 0.128 mm and a focusing gain of 52 at the peak intensity for a neutron beam with a wavelength range of 3.5-10 Å.

NC-LWE figuring technique has higher material removal rate than other chemical figuring techniques, such as ion beam figuring (IBF) [14], plasma chemical vaporization machining (PCVM) [15], and elastic emission machining (EEM) [16]. Therefore our process can be applied to fabrication of elliptical supermirror with a length of more than 1 m efficiently.

The magnification of the optical system we designed was 1 because the fabricated mirror is a prototype for evaluation of the fabrication process, the mirror shape and the surface roughness. We can achieve a spot size as small as a previous results using bending mirror system [17, 18] and a focusing gain higher than a
previous results [19] by designing an optical system with high magnification. The figured mirror is more cost-effective than the bending mirror system and needs no time to align a mirror shape.

We aim to develop a multiple aspherical supermirror devices using high-precision figured aspherical focusing supermirror to focus neutron beam with high intensity, because multiple mirror collect very large beam divergence. In the case of the multiplexing of supermirrors, mirror substrates must be thin to reduce the absorption loss of incident neutron beams. Our process can be applied to fabrication of precise millimeter-thick elliptical supermirror since NC-LWE technique is no-contact removal process without machining pressure. In our future study, we will attempt to fabricate and evaluate a multiple mirror system using a millimeter-thick large aspherical supermirror.

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