CO1-1 **Development of a Large-Scale Flexible Neutron Supermirror Sheet**

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INTRODUCTION: A multilayer with small d-spacing and supermirror with large-m are desirable to enlarge utilization efficiency for neutron scattering experiments. By depositing the multilayer on smooth aspherical surface, it works as a neutron focusing mirror. The reflectivity of multilayer is very sensitive to surface roughness of the substrate. The roughness should be less than 0.5 nm in case of these high-m supermirror and small d-spacing mirror. The requirement is very severe and in general silicon wafer and float glass are used as the substrate only. There are several trials to fabricate smooth aspherical surface with small surface roughness. Even today, it is still very difficult for neutron mirror to make aspherical surface and it requires a lot of time and huge cost. Because neutron source is not far from point but has some volume and then the size of neutron focusing mirror is not small. In order to overcome this problem, we are developing new fabrication technique for neutron focusing mirror.

EXPERIMENTS: Recently, we have succeeded in fabricating self-supporting high-m neutron supermirror and very small d-spacing multilayer sheets using ion beam sputtering (IBS) instrument at KURRI. The sheet was fabricated by using replica technique as shown in Fig.1.

RESULTS: We cut out ϕ 50mm from the edge of the ϕ 460mm supermirror sheet and putted up the sheet on a flat glass to measure the reflectivity of the supermirror sheet. Fig. 2 shows reflectivity of a part of supermirror sheet. The part cut from the ϕ 460mm sheet is not so good condition for the deposition. Even the edge part, the reflectivity was high and it was almost same with that of supermirror on smooth glass. However, the beam profile reflected the sheet was spread very much. It is still very difficult to control the shape precisely and we have to find new technique to control the sheet for practices use.

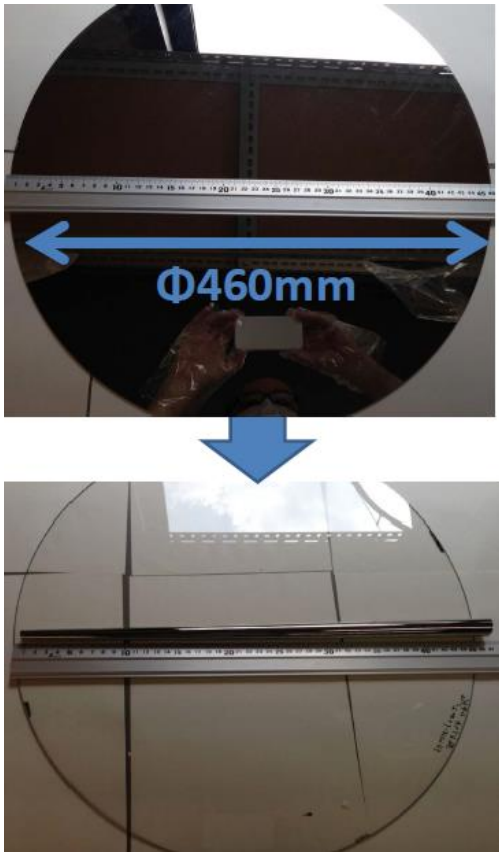

Fig.1 The photograph of NiC/Ti supermirror on glass (up) and the supermirror sheet was peeling off (down).

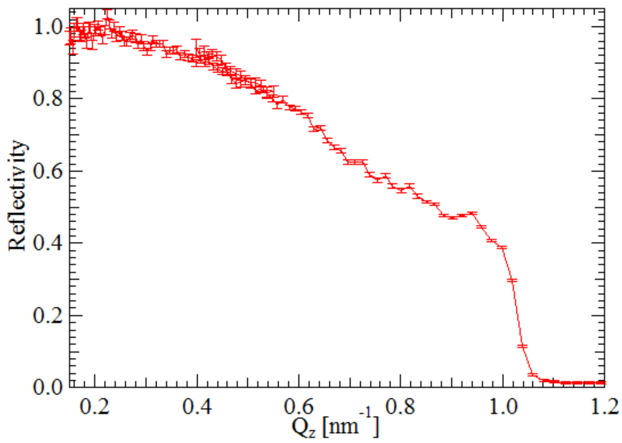

Fig.2 Measured reflectivity of the m=5 flexible NiC/Ti supermirror sheet bounded on flat plate.

採択課題番号 25046　　次期中性子ビーム科学施設のための中性子光学デバイス開発　　共同通常
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CO1-2 Development of Neutron Devices for Fundamental Physics

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INTRODUCTION: Neutrons can be used for studying fundamental physics. For example, neutron lifetime is quite important for the parameter in Big Bang Nucleosynthesis. The permanent electric dipole moment of neutrons (nEDM) signals the violation of time-reversal (T) invariance. Cold neutron beam line 'NOP' was constructed at BL05 in the Materials and Life Science Experimental Facility (MLF) at J-PARC for fundamental physics experiments [1]. We are developing neutron optical devices for the experiments.

DETAIL STUDY OF THE EFFECT OF SURFACE ROUGHNESS TO REFLECTION: For improvement of sensitivity of nEDM experiment, it is quite important to reduce the systematic errors from uncertainties of the environment by increasing density of Ultra-cold neutrons. The motions of the UCNs under high density condition must be understood precisely. In order to discuss some theoretical models for the reflection properties between neutrons and real surface with roughness, off-specular reflection of cold neutrons was measured at SOFIA on BL16 in MLF. The neutron mirrors with various roughness values are prepared by using ion beam sputter machine in KURRI. Clear correlation between the roughness and the off-specular reflection was observed. Detail analysis is in progress.

NEW APPROACH FOR LARGE SCALE MIRROR: The violation of baryon number is required to describe today's matter universe. This leads neutron-antineutron oscillation, which a neutron changes into anti-neutron after long free flight. The upper bound of the oscillation time of 8.6 x 10^7 s is measured by using free flight neutrons at ILL [2]. The sensitivity is proportional to both of the neutron intensity and the square of time of flight. Long baseline experiment with intense slow neutrons is required for next generation neutron-antineutron experiment. Elliptic mirror to focus neutrons into the other side of flight path is important to gain the intensity and path length. We estimate that the mirror has the diameter of 4 m and the length of 40 m.

The magnetron sputtering method is suitable to fabricate the large scale of mirror, however, that cannot handle nickel with ferromagnetic properties, which is the most popular material for neutron mirror. We tried nickel-vanadium alloy for the material of neutron mirror. The monolayer of nickel-vanadium was fabricated by using the magnetron sputter machine at Nagoya University. The properties were measured by X-ray reflectometer at KURRI. The potential for neutron was estimated at about 200 neV, which was similar to that of nickel with 243 neV. The surface roughness was about 1.8 nm in RMS, which was too rough to make multiplayer neutron mirror. The mixture of the alloy and the conditions of the sputtering must be optimized. The other materials can be discussed, for example, nickel-molybdenum alloy and high-density carbon.

EXTREMELY HIGH RESOLUTION DETECTOR: Ultra-cold neutrons in a small cavity can be bound to the discrete energy eigenstates by Earth's gravitational field [3, 4]. Neutrons are localized spatially in the range of the order of micrometer. We are discussing the direct measurement of the spatial distribution of the neutrons with high-resolution detectors. Nuclear emulsion has the advantage in accurate imaging with spatial resolution of the order of micrometer. We tried neutron-sensitive emulsion detector systems. Test experiments were performed at the beam line E2 and CN3 in KUR. Detail analysis is in progress.

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採択課題番号 25068 超冷中性子用反射デバイスの開発 共同通常
（名大・KMI）北口雅暁（名大院・理）広田克也、粟野章吾、伊藤茂康、内藤博之、榊原理紗、杉野智昭、清水裕彦、田村啓輔、梅本篤宏、河原宏晃、長縄直崇、森島邦博、（京大原子炉）日野正裕、（東大・ICEPP）片山領、三島賢二（九大・RCAPP）吉岡瑞樹（理研）関義親

CO1-3 Measurement of the Pulse Shape of Monochromated Neutron Beam from Kyoto University Accelerator Driven Neutron Source (KUANS)

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INTRODUCTION: Compact neutron sources driven by small proton accelerators are developing apparatus in neutron science. Several groups are now studying the effective use of this kind of neutron source. The advantages of such neutron sources are a) compactness, i.e. such source requires one experimental hall for the while system from the accelerator to the neutron shield, and b) easy operation, comparing to the research reactor or large scale accrelator such as J-PARC. In the course of the development, we are planning to install neutron reflectometer and a polarized beam line to Kyoto University Accelerator Driven Neutron Source (KUANS). The wavelength resolution is necessary for such instruments, though the time-structure of the pulsed neutron is complicated and should be checked with experiments.

The aim of the present study is to measure the time-structure of monochromatized neutrons, i.e. intensity change as the time from the instant when the proton pulse hits the target Be. Estimated from the simulation, the time-structure has rise-up period mainly depending on the proton pulse width and decay period due to the thermalization process in the moderator, the latter of which depends on the wavelength of neutron. For shorter wavelength than thermal neutron the decay period is short, and for longer wavelength the decay period tend to be constant.

EXPERIMENTS: The monochromatized beam is created with pyrolytic graphite (pyrographite) and detected with ^{3}He neutron proportional counter. Time width of the time-analyser is taken as 5μsec. The flight time from the moderator to the detector is about 2540mm.

The arrangement of the experiments is as shown in Fig.1. Pulsed thermalized neutrons come from the polyethylene moderator generated by the nuclear reaction with Be and pulsed proton beam. The neutrons are collimated with two slits and hits pyrographite (grade A, *d*-spacing of 0.335nm) with the incident angle of θ. Neutrons satisfying the Bragg condition are reflected toward the neutron detector. The pulse width of the proton beam is estimated as 66μsec. We made experiments with two incident angles: 16 and 13 degree. In both cases, Bragg peaks up to second order are measured.

RESULTS: The examples of the measurements are shown in Fig.2. Fig.2 A and B stand for the neutron wavelength of 0.09 and 0.19nm, respectively. Since the result of Fig.2 A is the second order Bragg peak of Fig.2 B, both results was measured simultaneously. The solid line in these figures represent the fit results of Ikeda-Carpenter function [1] to the measured data. For suitable choice of the parameters, the both agree well.

We are now to measure time-structure for other wavelength.

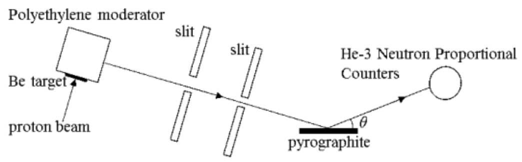

Fig.1 The arrangement for the measurement of monochromatized neutron pulse from KUANS.

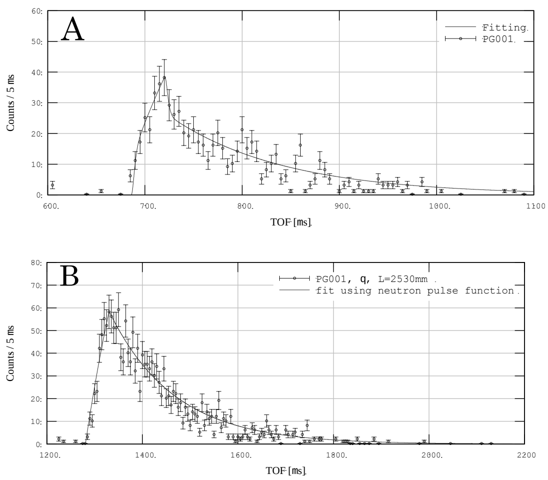

Fig.2 Examples of the results of the time-structure measurements. The figures A and B stand for the neutron wavelength of 0.09 and 0.19 nm, respectively.

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採択課題番号 25076　　波動関数の振幅を制御した多層膜中性子反射鏡の開発　　　　共同通常
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CO1-4 Neutron Reflectivity Measurement of NiC/Ti Supermirror with Ion Bombardment

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INTRODUCTION: One of the most important problems in producing large-m supermirros is the reduction of the interface roughness which becomes larger with the number of bilayers deposited. If the interface roughness can be kept small compared to the bilayer spacing, a high reflectivity for the multilayer mirror can be achieved by stacking a sufficient number of layers.

We have applied ion bombardment in combination with ion beam sputtering deposition to the fabrication of NiC/Ti multilayers. In the process of ion bombardment, particles with the lowest binding energy, which are in a valley of the surface, would be removed first by recoil effects after ion bombardment. New roughening and intermixing on the interface, however, might be taken place by the ion bombardment. The effectiveness, therefore, has to be investigated in details.

In this study, we investigate the effect of ion mass on the surface smoothness under ion bombardment with various kinds of ions such as Ar^+, Kr^+ and He^+. For the prior measurement, the standard samples without ion bombardment were fabricated using polished silicon substrates and neutron reflectivity measurements were conducted.

EXPERIMENTS: A NiC/Ti multilayer, which cover *d*-spacings from 5.6 nm to 7.1 nm, was deposited using the ion beam sputtering system. The coating system is equipped with dual bucket sources which are used to generate ions as shown in Fig,1. Multilayers were deposited on Si(111) substrates with surface roughness of 0.35 nm r.m.s. and 0.65 nm r.m.s. which were measured by using surface profiler (Zygo Maxim GP). The base pressure during the operation was 1×10^{-5} Pa. The processing parameter for ion beam sputtering deposition was accelerator voltage 600 V.

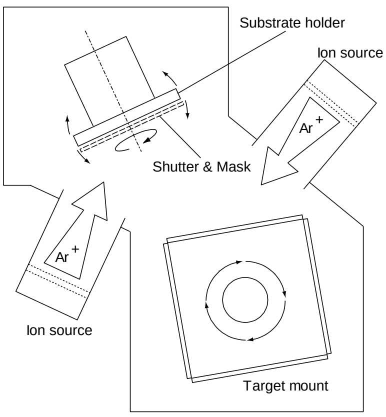

Fig.1 Ion beam sputtering instrument with dual bucket ion sources.

RESULTS: NiC/Ti multilayers with 1949 layers have been coated. Its *d*-spacings cover from 5.6 nm to 7.1 nm and the effective reflection angles of the multilayer corresponds to those between m = 4 and m = 5 of a supermirror. One has been coated on the silicon substrate of 30 mm in width, 50 mm in length and 0.2 mm in thickness with surface roughness of 0.35 nm r.m.s. The other has been coated on the same dimension with surface roughness of 0.65 nm r.m.s.

Neutron reflectivity measurements for two samples were performed using the time-of-flight neutron reflectometer at CN-3 of KURRI. As shown in Fig.2, it is observed that a maximum of reflectivity is 65 % for the sample A, while the sample B, a maximum of reflectivity is 24 %. Calculated reflectivity based on the dynamical theory at theoretical density derives a conclusion that evaluated multilayersurface roughness is 0.5 nm for the sample A and the other is 0.9 nm.

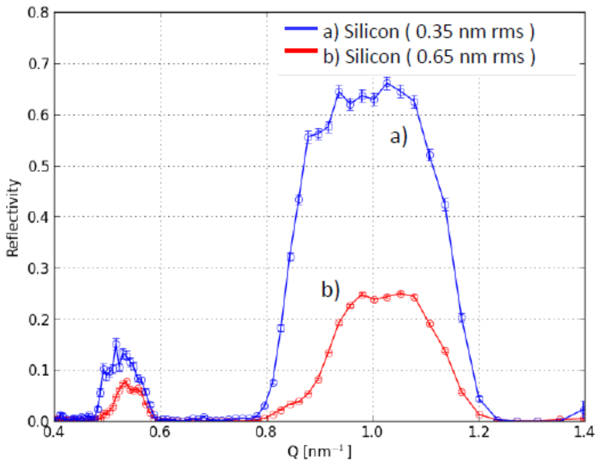

Fig. 2 Reflectivity profiles of NiC/Ti multilayers with the number of layers of 1949 coated on silicon substrates with surface roughness of a) 0.35nm r.m.s. and b) 0.65nm r.m.s..

Because the neutron reflectivity strongly depends on the surface roughness of a substrate, we need to evaluate the dependencies of it to the neutron reflectivity prior to conducting an experiment of ion bombardment. In this study, the reflectivity profiles were successfully obtained for the small *d*-spacing NiC/Ti multilayers with the number of 1949 layers.

These evaluated data will bring us more accurate performance information to investigate ion bombard technique for the advanced neutron optics.

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採択課題番号 25096 中性子鏡面反射によるイオン照射薄膜の表面構造研究 一般通常
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