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Development of a Neutron Supermirror Polarizer for a Low External Magnetic Field

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A magnetically very soft neutron polarizing supermirror have been developed. The supermirror consists of Supersendust($Fe_{86.8}Ni_{3.2}Si_6Al_4$) and germanium multilayers. Since the potential energy of the Supersendust layers for ↓ spin neutron is almost equal to that of germanium, a high efficiency of neutron polarization is realized. We show the performance of Supersendust/Ge multilayer as a polarizer using polarized neutron reflectometer installed in C3-1-2 beam port of JAERI.

KEYWORDS: polarizer, reflectometry, cold neutron, supermirror

§1. Introduction

Multilayer mirror is one of the most useful devices for slow neutron experiments (c. f. see the reviews and references therein[1)]). The multilayer mirror consists of alternating layers of two materials with different potential energies for the neutron. It is an artificial lattice with a large lattice spacing and gives one-dimensional optical potentials for cold neutrons. A magnetic multilayer mirror consisting of ferromagnetic layers and nonmagnetic layers is useful to polarize neutron beam, in general, it needs above several tens mT in order to magnetically saturate the ferromagnetic layers. Recently, Kawai and co-workers developed Permalloy45($Fe_{55}Ni_{45}$)/Ge multilayer mirrors which were magnetically saturated in a lower external field less than 5 mT.[2)] Such neutron mirrors are not only easy to handle and useful to miniaturize polarized neutron instruments but also contribute to realize new experiments for fundamental physics.[3–5)] Thus, the development of mirrors working in a lower external magnetic field is great importance. The mirrors were fabricated with three processes. In this paper, we report their performances of Supersendust($Fe_{86.8}Ni_{3.2}Si_6Al_4$)/Ge multilayer mirrors as a function of strength of applied magnetic field. For many applications, a broad-band polarized beam is frequently required, and we also show Supersendust/Ge multilayer as a supermirror whose lattice spacing are changed in a controllable way.[1,6)]

§2. Fabrication of Magnetic Multilayer

Figure 1 shows the structure of multilayer fabrication system in the Kyoto University Reactor.[7)] As shown in Fig. 1, magnetic multilayer mirror was evaporated on a polished silicon wafer in the applied magnetic field of 14 mT in order to magnetically saturate the films in lower magnetic field.[2)] Indeed, Permalloy45($Fe_{55}Ni_{45}$)/Ge multilayers without the applied magnetic field did not work in the magnetic field of 5 mT. It is necessary for

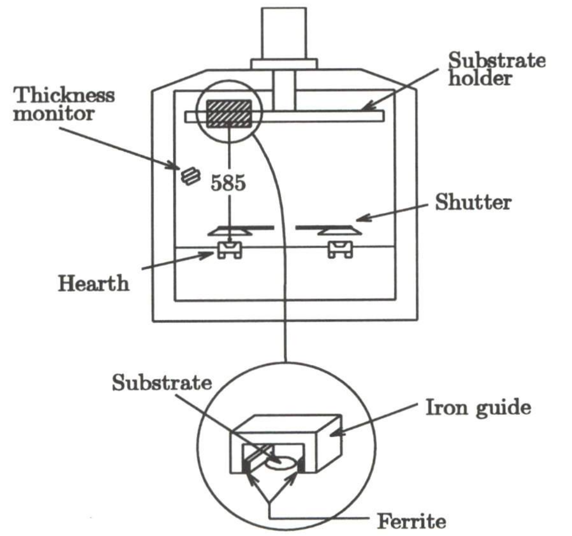

Fig. 1. Schematic view of the instrument for the fabrication of multilayers.

the use of Permalloy45/Ge multilayer as neutron polarizer to apply the magnetic field during the evaporation.

The dimension of silicon wafers was 75mm in diameter and 3mm in thickness. The silicon wafer was located on the circular shaped substrate holder with 950 mm. The substrate holder is cooled with water and rotates to unify the thickness of the evaporation and to attain evaporation of a wider of area. Permalloy45/Ge multilayers, however, did not work in the magnetic field of 5 mT when the substrate holder rotated with 20 rpm during the evaporation. It is not easy to fabricate supermirror polarizer working in the low external magnetic field. Thus we investigated Supersendust/germanium multilayers as a new neutron polarizer for lower magnetic field, which fabricated with the following conditions during evaporation; (i) the applied magnetic field of 14 mT and the substrate holder stopped,[8)] (ii) no applied magnetic field and the substrate holder stopped, (iii) no applied magnetic field and the substrate holder rotated.

The pressure in vacuum chamber at the beginning of the evaporation was about 0.8×10^{-5} Torr and the growth rate of these multilayer was below 1.0 Å/sec. The layer thicknesses of each films were measured by a quartz crystal oscillator during the evaporation.

§3. Experimental Result and Discussions

The measurement of polarizing efficiency of the multilayer mirror was carried out at C3-1-2 port of the JRR-3M reactor in Japan Atomic Energy Research Institute(JAERI). The wavelength resolution and the divergent angle are 12.6±0.44(FWHM) Å and 1.0 mrad, respectively. Figure 2(a) shows reflectivity of ↑ spin neutrons by a Supersendust/Ge multilayer in a constant magnetic field of 0.9 mT. This multilayer was fabricated with the applied magnetic field of 14 mT and the substrate holder stopped during the evaporation. These experimental data are well reproduced by the theoretical lines calculated with one-dimensional Schrödinger equation.[10,11] Here the average nuclear and the magnetic potentials of the Supersendust layers were assumed to be 185 neV and 81.4 neV, respectively , and the nuclear one of germanium was 94 neV. The average nuclear and magnetic potentials of Permalloy45 layer are 220 neV and 96.5 neV, and then the potential for ↓ spin neutrons is more closer to the germanium's nuclear potential than that of Permalloy45. The number of the bilayers is 30 and the layer thicknesses of Supersendust and germanium are estimated to be 11.0 and 9.0 nm, respectively. At incident angle of 2.10° in the Bragg condition, the reflectivity of ↑ spin neutrons was estimated to be above 95 %. Figure 2(b) and (c) show reflectivity of ↑ and ↓ spin neutrons by Supersendust multilayer mirror in the constant magnetic field of 0.9 mT. These mirrors were fabricated without the applied magnetic field during the evaporation and the number of bilayers for these mirrors is 30. In Fig.2(b), the mirror was fabricated on silicon wafers placed on the substrate holder stopped. In Fig.2(c), the mirror was fabricated on silicon wafers placed on the substrate holder rotating with 20 rpm. These measured reflectivity of ↑ and ↓ spin neutrons also reproduce theoretical lines, where the average nuclear and magnetic potentials of each layer were as well as those of Fig 2(a). The layer thicknesses of Supersendust and germanium in Fig 2(b) are estimated to be 9.7 and 9.0 nm, respectively, and those in Fig 2(c) are 11.2 and 9.5 nm, respectively. In Figs 2(b) and (c), the reflectivities of ↑ spin neutrons at the Bragg angles of 2.21° and 2.05° were estimated to be above 92 and 96 %, respectively,

Figures 3(a), (b) and (c) show magnetic hysteresis loops for these multilayer mirrors fabricated with the three conditions. These closed and open circles indicate measured reflectivities of ↑ and ↓ spin neutrons, respectively. The reflectivities of Figs 3(a), (b) and (c) were measured at the Bragg conditions shown in Figs 2(a), (b) and (c) , respectively. The magnetic field was changed as 0.9 mT → −1 mT → 0.9 mT. In Fig. 3(a), neutron polarizing efficiency is above 95 % in a low magnetic field of 0.5 mT and the coercive force is estimated to be 0.5 mT. On the other hand, the Supersendust/Ge mirror fabricated without the applied magnetic field during the evaporation is about 90 % in external magnetic field of 2 mT although the coercive force without the applied magnetic field is a little smaller than with the field, as shown in Fig. 3(b). Thus it is confirmed that applying magnetic field to the substrate during evaporation is effective to fabricate a cold neutron polarizer with high reflectivity. In Fig. 3(c), the coercive force is 1 mT and neutron polarizing efficiency is above 95 % in the magnetic field of 1 mT. Although the coercive force of this mirror is doubled that of the mirror shown in Fig. 3(a), the reflectivity and polarizing efficiency are excellent.

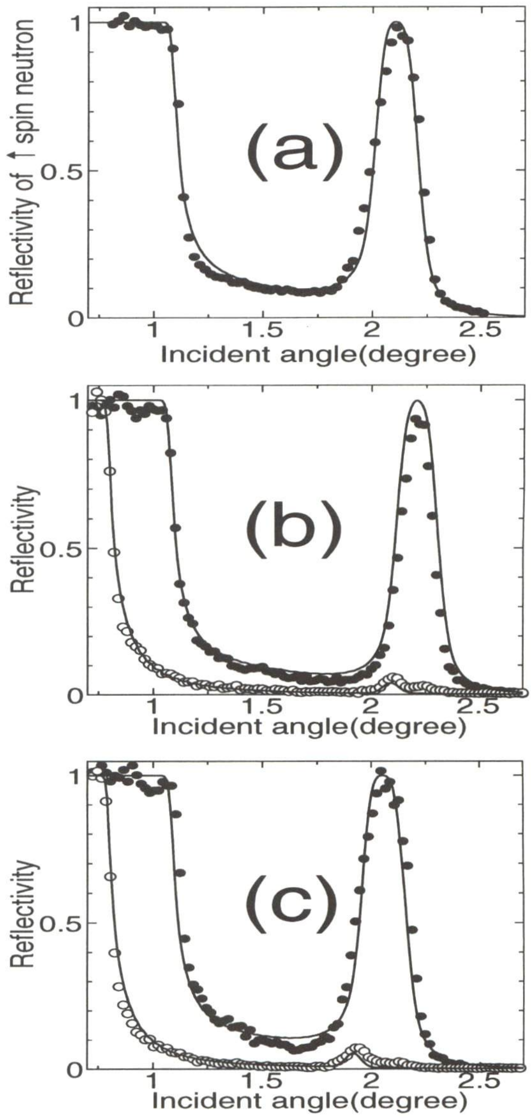

Fig. 2. Reflectivity of ↑ (•) and ↓ (∘) spin neutrons for the Supersendust/Ge multilayer mirror as a function of the incident angle. (a) The mirror was fabricated with applied magnetic field and the substrate holder stopped. (b) These mirrors were fabricated without applied magnetic field and the substrate holder stopped. (c) These mirrors were fabricated without applied magnetic field and the substrate holder rotated with 20 rpm.

Figure 4 shows performance of Supersendust/Ge supermirror in the constant magnetic field of 0.9 mT. The supermirror was fabricated without applied magnetic field and the substrate holder rotated with 20 rpm. The sequence of layers for supermirror is deigned using the

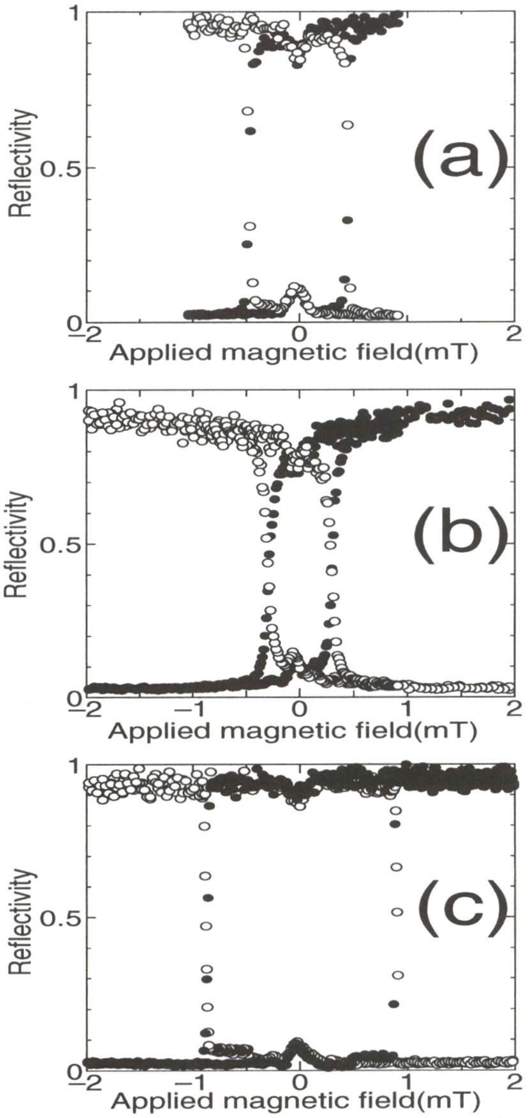

Fig. 3. Reflectivities of ↑ (•) and ↓ (∘) spin neutrons for the Supersendust/Ge multilayer mirror as a function of magnetic field. (a), (b) and (c) are measured in the Bragg conditions shown in Figs 2(a), (b) and (c) , respectively.

method of Ebisawa and Tasaki.[12] The number of the bilayers is 34 and the minimum lattice spacing is 170Å and the critical angle of the supermirror is 1.7 times larger than that of nickel. These experimental data are almost reproduced by the theoretical lines, where the average nuclear and the magnetic potentials of the Supersendust layers were assumed to be 170 neV and 90.5 neV, respectively , and the nuclear one of germanium was 94 neV. Here the reduction of measured reflectivity for ↑ spin neutron is considered as roughness of interface and unsuitable thickness of the layer. We can avoid most of these unhoped effects using sputtering method and the deviation from ideal mirror is expected to be negligible. It is difficult to fabricate polarizing supermirror for low magnetic field.[1,9,13,14] Our results indicate a feasibility to fabricate broad-band supermirror polarizer using sputtering method for the magnetic field of 1 mT. It has a chance to use as a neutron switching polarizer with high frequency[15] which contributes to realize new

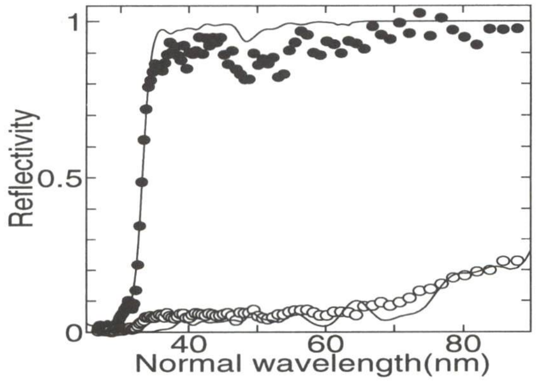

Fig. 4. Reflectivities of ↑ (•) and ↓ (∘) spin neutrons the Supersendust/Ge supermirror in the constant magnetic field of 0.9 mT

experiments based on time-dependent quantum mechanics.

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