Proc. Int. Symposium on Neutron Optics and Related Research Facilities, Kumatori, 1996
J. Phys. Soc. Jpn. **65** (1996) Suppl. A pp. 195-198

Multichannel Neutron Polarizers Produced in PNPI

A. Schebetov, N. Pleshanov, V. Syromyatnikov, V. Pusenkov,
B. Peskov, G. Shmelev, Z. Soroko, V. Ul'yanov
Petersburg Nuclear Physics, Gatchina, 188350 St.Petersburg, Russia

(Received 23 January 1996; accepted 12 June 1996)

Multichannel polarizing neutron guides are assembled from bent thin ferromagnetic mirrors. Narrow channels with supermirror coatings are used to produce neutron guides of short length, including compact polarizers on the basis of silicon wafers. The factors that affect the neutron transmittance are considered. In multichannel polarizers we use 0.3 mm thin glass coated by sputtering technique with $Co_{68}Fe_{31}V/Ti_{75}Zr_{25}$ supermirrors and $Ti_{60}Zr_{10}Gd_{30}$ underlayers, as well as silicon wafers coated by evaporation technique with ^{54}FeFe/Al supermirrors and Cd antireflective layers. The CoFe/TiZr supermirrors are based on magnetically anisotropic films and, due to remanent magnetization, can be used in applied magnetic fields as low as 25Oe. Polarizing neutron guides on glass for thermal and cold neutrons with minimum wavelength 1.6Å, and 5Å, respectively, were produced. Their transmittance was found to be close to calculated values, their integral polarizing efficiency being >0.96. A standard 8-channel unit for a multichannel analyzer of polarization of a scattered neutron beam of cross section as large as 400×600mm^2 has been worked out in collaboration with GKSS (Germany).

KEYWORDS: neutron, polarizing supermirror, remanent magnetization, multichannel guide, polarizer, analyzer

The polarizers worked out and produced in PNPI[1-5] are assembled from supermirrors[6,7] on thin substrates as multichannel neutron guides.[8,9]

We have produced a number of polarizers which are presently used in Russia (PNPI, JINR), the Netherlands (IRI), Germany (HMI, GKSS) and France (LLB), with the characteristic wavelength varying from 1.6Å, to 8Å, (see examples below). The geometrical and physical parameters of a neutron guide are connected by the following relations:

$$4a/\ell = \beta_* = \lambda_*\Theta_c = \lambda_*/\lambda_c \,, \qquad (1)$$

where a is the width of a neutron guide channel, ℓ is the length of direct view, β_* is the characteristic angle of the neutron guide, Θ_c is the effective critical angle of reflection from the coating, λ_c is the corresponding characteristic wavelength of the coating by definition $\Theta_c = 1/\lambda_c$, and λ_* is the characteristic wavelength of the neutron guide.

The basic performance parameters of a neutron polarizer is the transmittance of spin-up neutrons (T) and the polarizing efficiency (P). In this report the factors that affect T and P are considered, and a survey of experimental data which demonstrate the properties of real polarizers is presented.

The transmittance of a neutron polarizer is

$$T = T_g T_{ch} = (a/b)(\Phi_{transm}/\Phi_{incid}) \,, \qquad (2)$$

where T_g is the geometric transmittance factor connected with the width a and the total (including the neutron absorbing materials) width b of one channel, T_{ch} is the transmittance of a single channel, and Φ_{incid} and Φ_{transm} are the incident and transmitted fluxes, respectively.

Transmission of neutron guide channels T_{ch} with β_* = 4mrad, shown in Fig.1, is calculated by integration over different trajectories of neutrons as a function of the wavelength λ different divergences Δ of the incident beam. Curve 1 corresponds to the divergence after a neutron guide based on nickel coatings, $\Theta_c = \Theta_{Ni}$; curve 2 corresponds to the divergence after a neutron guide based on CoFe/TiZr supermirror coatings, $\Theta_c = \Theta_{Ni}$ on glass; curve 3 corresponds to the divergence after a neutron guide based on Ni/Ti supermirror coatings available presently with $\Theta_c = \Theta_{Ni}$.[10] When no additional collimation is introduced, such a divergence is proportional to wavelength, $\Delta = 2\Theta_c\lambda$. Consequently, the number of reflections from the channel walls of the polarizer increases with λ, and, since the reflectivity from supermirrors is below 1, the gain in transmission of neutron beams of high divergence with the use of supermirror coatings for large wavelengths is not

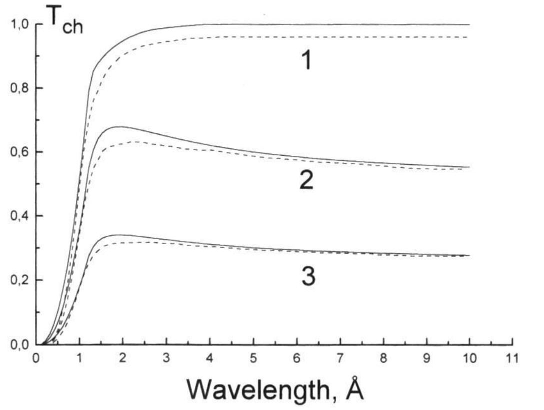

Fig. 1. Calculated transmittance for a single channel of a neutron guide, based on CoFe/TiZr supermirrors on glass, as a function of wavelength λ for different incident beam divergences $\Delta = 2\Theta_c\lambda$ (see text). Solid curves correspond to the waviness $\Delta\beta = 0$. The effect of the waviness on transmission is demonstrated for $\Delta\beta/\beta_* = 0.1$ (dashed curves).

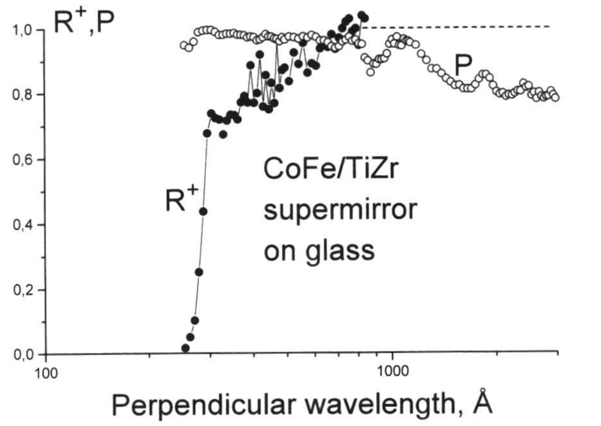

Fig. 2. Reflectivity for spin-up neutrons R^+ and polarizing efficiency P of CoFe/TiZr supermirrors measured at reflectometer ZINA (PNPI) as a function of $\lambda_\perp$. Dotted line corresponds to the region of total reflection.

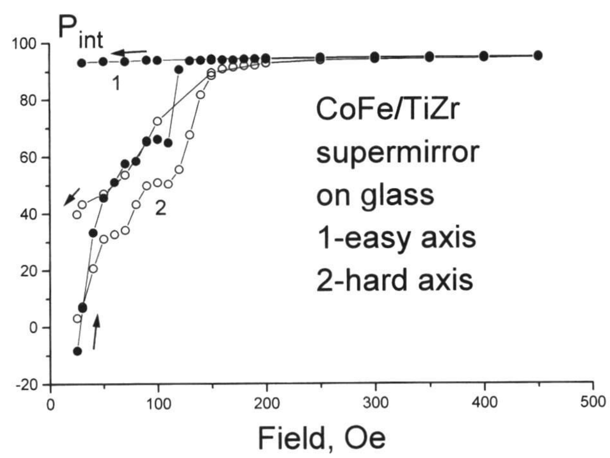

Fig. 3. Polarizing efficiency Pint of supermirrors measured with a "white" beam of thermal neutrons (peak wavelength = 1.4Å) at reflectometer ZINA (PNPI) as a function of the magnetic field applied in easy (1) and hard (2) directions.

as high as near λ_*. The effect of the waviness $\Delta\beta$ on transmission is demonstrated for $\Delta\beta/\beta_*$=0.1 (Fig.1, dashed curves). It is to be noted that one and the same waviness $\Delta\beta$ will reduce stronger transmission of neutron guides with coatings of smaller Θ_c.

The experimental reflectivity for a CoFe/TiZr coating used in calculations is given in Fig.2, as a function of the perpendicular wavelength $\lambda_\perp = \lambda/\sin(\Theta)$ (here Θ is the glancing angle).

More detailed numerical study of the transmission of neutron guides will be given elsewhere.[11)]

Generally, for optimization of parameters of a multichannel polarizer, it is necessary to take the spectrum and the divergence of the incident neutron beam into account as well as the properties of the mirrors.

To minimize the reflectivity of spin-down neutrons and thus to achieve a high polarization of the transmitted neutron beam, it is necessary that the difference between the nuclear and magnetic potentials of magnetic layers be equal to the nuclear potential of the non-magnetic layers, and equal to 0.

CoFe/TiZr supermirrors[1,4,5)] on glass substrates are prepared in a sputtering machine, equipped with three stationary magnetrons and three targets. An alloy of CoFeV has been chosen as the magnetic material. Changing Co and Fe composition of the alloy, one can achieve the equality of the nuclear and magnetic potentials. The same flexibility in changing the potential is achieved by using an alloy of Ti (negative potential) and Zr (positive potential) for non-magnetic layers.

To avoid reflection of spin-down neutrons from the glass substrate, an alloy of TiZrGd is used. Changing the concentration of its components,[12)] one can minimize the reflection of spin-down neutrons from the underlayer.

A carriage with substrates attached moves with respect to the magnetrons. The deposition rate is not controlled during sputtering, it is stabilized by the power supply equipment. Calibration of the deposition rate is made with a quartz sensor placed in the sputtering chamber. Then it is checked by X-ray reflectometry. The composition of the deposited films is found by using XTRFA (X-ray Total Reflection Fruorescence Analysis) spectrometry. The content of oxygen is determined by the RBS technique. The roughness of substrates and sputtered films can be controlled with the profilometer Taylor-Step (product of a British firm "Rank Taylor-Hobson"). The roughness of glass substrates was found to be 5±2.5Å. Neutron reflectivity and polarization efficiency of mirrors are measured with the time-of-flight spectrometer ZINA at WWR-M reactor in Gatchina.

Presently the supermirror layers have the following compositions: $Co_{68}Fe_{31}V$, $Ti_{75}Zr_{25}$, and $Ti_{60}Zr_{10}Gd_{30}$. The nuclear and magnetic potentials of CoFeV layers were found by neutron reflectivity measurements from films with a thickness 700-900Å, to be about 100neV, and the potential of the non-magnetic layers about 10neV. A change in the deposition rate change this quantities, which can be caused by the presence of remanent gases (including oxygen) in the sputtering chambers.

The experimental reflectivity and polarizing efficiency for one of such supermirrors is presented in Fig.2. Note that the polarizing efficiency reaches 0.99 at about λ_c. These polarizing supermirrors are based on magnetically anisotropic films and, due to remanent magnetization, can be used in applied magnetic fields as low as 25Oe (see Fig.3).[4)]

Transmission of a polarizer with λ_* = 1.6Å, for the spectrometer KP (IRI, Delft) measured in IRI is given in Fig.4. Its cross section is 27×60mm^2, its length 700mm, and its channel width and glass thickness 0.92 and 0.33mm, respectively. Its polarizing efficiency is as high as for the polarizer described earlier.[1)]

A standard 8-channel unit of cross section 10×125mm^2 and length 240mm for a multichannel analyzer of polarization of a scattered neutron beam as large as 400×600mm^2 has been worked out in collaboration with GKSS (Germany).[5)] The neutron transmittance and polarizing efficiency of such a unit have been measured in GKSS (Fig.5).

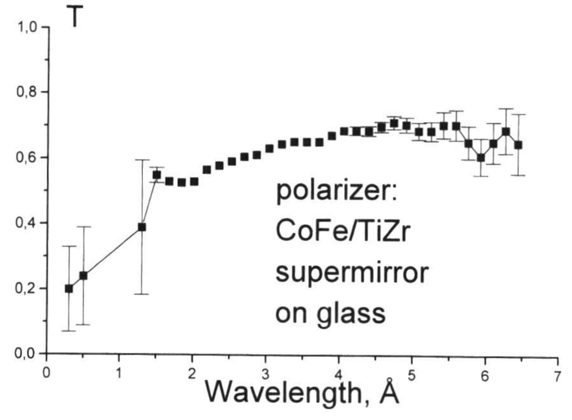

Fig. 4. Experimental transmittance T of a polarizer with λ_{*} = 1.6Å, based on CoFe/TiZr supermirrors on glass, for the spectrometer KP (IRI, Delft) as a function of wavelength λ. The divergence of the incident beam Δ[mrad] = 1.6λ [Å].

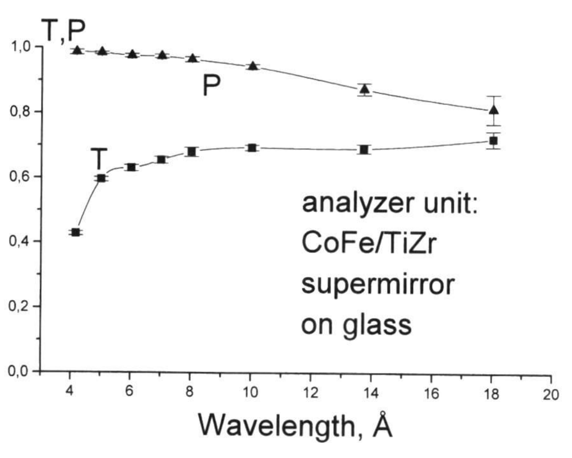

Fig. 5. Experimental transmittance T and polarizing efficiency P of a 8-channel unit, based on CoFe/TiZr supermirrors on glass, for a large-area (400×600mm^2) multichannel analyzer with λ_{*} = 5Å (GKSS) as a function of wavelength λ. The divergence of the incident beam Δ = 0.3mrad.

By thermal evaporation technique, ^{54}FeFe/Al supermirrors have been prepared on silicon wafers with a Cd antireflective layer (Fig.6) .[2] A compact multichannel polarizer have been assembled as a stack of silicon wafers for polarization of a collimated cold neutron beam of the reflectometer EROS (LLB Saclay, France). Silicon wafers serve here as guiding channels for neutrons,[13] increasing the geometric transmittance factor up to 0.99. The cross section of the polarizer is 5×25mm^2, and its length 34mm. The neutron transmittance and polarizing efficiency of such a unit have been measured in LLB (Fig.7).[14] Two polarizers on silicon were also produced for the SANS facility TENSOR (PNPI) to polarize and analyze the neutron beam about λ = 8.5Å, their cross sections being 10×65mm^2, and the length 25mm. Transmittance of such a polarizer is no less than 0.5, and the polarizing efficiency is up to 0.99.[2]

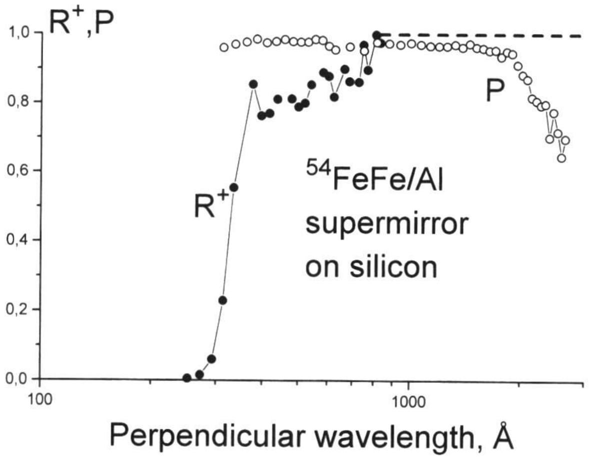

Fig. 6. Experimental reflectivity for spin-up neutrons R^+ and polarizing efficiency P of ^{54}FeFe/Al supermirrors as a function of $\lambda_{\perp}$. Neutrons are reflected from the boundary "silicon-supermirror" Dotted line corresponds to the region of total reflection.

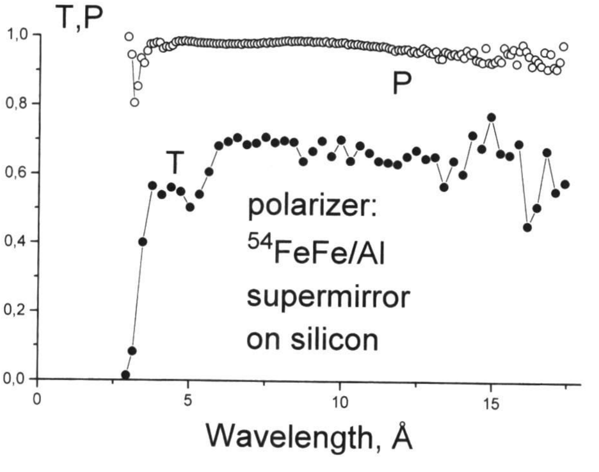

Fig. 7. Experimental transmittance T and polarizing efficiency P of a flat polarizer with $\lambda_{*} = \lambda_c \cdot a/\ell$ = 3.5Å, based on ^{54}FeFe/Al supermirrors on silicon wafers, for the reflectometer EROS (LLB, Saclay) as a function of wavelength λ. The divergence of the incident beam Δ=1mrad.

Conclusions

Certain achievements in preparation of polarizing supermirrors enabled us to produce optical polarizers of really high performance which can be used both for polarization and analysis of neutron beams with spectra ranging from λ = 1.6Å, and higher. We have tested, in collaboration with GKSS, the possibility to produce analyzers of very large cross section. The conclusion was drawn that, practically, there is no limit for increasing this cross section, and now we are sure that the performance of such an analyzer can be really good.

The polarizing CoFe/TiZr supermirrors are based on magnetically anisotropic films and, due to remanent magnetization, can be used in low applied magnetic fields.[4,10] Multichannel neutron guides on the basis of such supermirrors will allow to polarize neutron beams and/or to analyze their polarization in low magnetic (guide) fields. As it was pointed out,[4,10] it can be crucial when the presence of strong magnetic fields is undesirable (spin-echo technique, etc.), or when highly collinear strong magnetic fields in large volumes should be avoided (as in large area neutron polarization analyzers), or simply when there is a lack of room for the magnets in polarizing or analyzing devices.

Compact polarizers for cold neutrons as short as 25mm can be produced on the basis of silicon wafers. Their performance was also shown to be good. Such polarizers can be used also for thermal neutrons. Some efforts can be undertaken to further improve the performance of our polarizers. One possibility is just to increase the supermirror range by increasing the number of layers. Calculations show that a gain in the flux can be then achieved even if the reflectivity in the supermirror region of reflection drops. Another possibility is to use ultra-thin layers of Ti or Co at each interface in the supermirror sequence of layers to reduce the average potential at the interfaces, as proposed in work.[15] Calculations show[16] that the reflectivity of spin-down neutrons due to diffusion and oxidation can be thus strongly suppressed, and the polarizing efficiency of thin-film coatings can be significantly improved.

1) A.F. Schebetov, N.K. Pleshanov, V.M. Pusenkov, B.G. Peskov, G.E. Shmelev, W.H. Kraan, P.T. Por, M.Th. Rekveldt, V.E. Mikhailova: *NIM* B94 (1994) 575.
2) V.G. Syromyatnikov, A.F. Schebetov, Z.N. Soroko: *NIM* A324 (1993) 401; *Physica* B198 (1994) 224.
3) A. Serebrov, A. Alduschenkov, M. Lasakov, I. Kuznetsov, I. Stepanenko: *NIM* A357 (1995) 503.
4) N.K. Pleshanov, A.F. Schebetov, V.M. Pusenkov, V.G. Syromyatnikov, V.A. Ul'yanov : to be published.
5) S. Grigoriev, A. Okorokov, N. Pleshanov, A. Schebetov, G. Shmelev, B. Peskov, V. Pusenkov, E. Siber, Z. Soroko, V. Syromyatnikov, D. Anders, Th. Ebel, H. Eckerlebe, R. Kampmann, Ch. Ruppel: to be published in *NIM* 1996.
6) F. Mezei: *Comm.Phys.* 1 (1976) 81; F. Mezei and P. Dagleish: *ibid* 2 (1977) 41.
7) O. Schaerpf: *Physica* B156-157 (1989) 631; *ibid* B174 (1991) 514.
8) H. Maier-Leibnitz, T. Springer: *J. Nuclear Energy* A/B 17 (1963) 217.
9) A. Farnoux, B. Hennion, J. Fagot: *Proc. Symp. Neutron Inelastic Scattering*, VII, 353, Copenhagen 1968 (IAEA, Vienna, 1968)
10) P.Böni: to be published in Journal of Neutron Research; P. Böni, D. Clemens, H.A. Grimmer, and H.Van Swyygenhoven: *Ann. Rep.* 1994, Annex F3A,PSI Condensed Matter Research and Material Sciences.
11) V.M. Pusenkov, N.K. Pleshanov: under preparation.
12) N.K. Pleshanov: under preparation.
13) M.Th. Rekveldt, W.H. Kraan: *Physica* B120 (1983) 81.
14) V. Syromyatnikov, A. Menelle, V.V. Runov, A. Schebetov: to be published.
15) N.K. Pleshanov : *Preprint PNPI*--1883 (1993).
16) N.K. Pleshanov, V.M. Pusenkov: *Preprint PNPI*--1884 (1993).