Nuclear Inst. and Methods in Physics Research, A 875 (2017) 177–184

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Characterization methods for neutron channeling in planar waveguides

S.V. Kozhevnikov [a,*], T. Keller [b,c], Yu.N. Khaydukov [b,c], F. Ott [d], F. Radu [e]

[a] *Frank Laboratory of Neutron Physics, JINR, 141980 Dubna, Russia*
[b] *Max Planck Institut für Festkörperforschung, Heisenbergstr. 1, D-70569 Stuttgart, Germany*
[c] *Max Planck Society Outstation at FRM-II, D-85747 Garching, Germany*
[d] *Laboratoire Léon Brillouin CEA/CNRS, IRAMIS, Université Paris-Saclay, F-91191 Gif sur Yvette, France*
[e] *Helmholtz-Zentrum Berlin für Materialien und Energie, Albert-Einstein Straße 15, D-12489 Berlin, Germany*

ARTICLE INFO

Keywords:
Neutron channeling length
Planar waveguide
Cold neutrons
Beam shaping

ABSTRACT

Neutron planar waveguides produce a narrow neutron beam of submicron width which can be used to scan local microstructures with high spatial resolution. The important parameter of a planar waveguide is the distance over which the neutron wave density decays exponentially during the neutron channeling inside a guiding layer. We review various ways to experimentally characterize neutron channeling lengths. Experimental results are presented and advantages and drawbacks of the different methods are discussed.

1. Introduction

Neutron beams for condensed matter studies have a typical width in the interval 0.1 ÷ 10 mm. For the investigations of small objects smaller beams are requested. Therefore in the last decade the focusing devices in one or two dimensions (such as Fresnel lenses, capillary lenses, elliptical waveguides, bent crystal monochromator, etc.) have been developed [1]. But these devices are restricted by their physical properties and manufacturing technologies and cannot achieve beam sizes smaller than 50 μm. Another disadvantage of the existing focusing devices is that they do not produce "clean" beams. For example, in the case of Fresnel lenses only a fraction 20%–40% of the beam is focused. For capillary lenses, a strong background is scattered. In the case of elliptical guides, the produced beam is strongly structured in space.

More effective focusing devices producing narrower and rather clean microbeams are planar waveguides (Fig. 1). It is a tri-layer film where the middle layer with low neutron optical potential is enveloped by two layers with high neutron optical potential. The upper thin tunneling layer has the thickness $a = 5 \div 20$ nm, the middle waveguiding layer has the thickness about $d = 150$ nm and the bottom thick reflecting layer has the thickness about 50 nm. The initially collimated neutron beam of a macroscopic width enters on a surface under a small grazing angle α_i and tunnels though the upper thin layers into the middle layer. Then the neutron wave is reflected from the bottom thick layer. The part of neutrons then goes out through the upper layer. Another part of neutrons is reflected again from the upper layer, propagates along the middle layer and goes out from the edge as a slightly divergent narrow microbeam. The angular divergence of the microbeam $\delta\alpha_f$ is defined by Fraunhofer diffraction of the neutron wave on a narrow slit $\delta\alpha_f \sim \lambda/d$ where λ is the neutron wavelength and d is the thickness of the middle waveguiding layer. Then the microbeam can be used for scan of microstructures with high spatial resolution. To keep the width of the microbeam minimal, the investigated object must be placed close to the waveguide edge.

In the waveguiding layer, the neutron wavefunction density is resonantly enhanced due to the multiple reflection of neutron waves from the bottom and upper layers. As the neutron wave is reflected from the upper layer partially, the neutron wavefunction density is decayed exponentially during the propagation (channeling) of the neutron wave along the guiding layer (channel). The parameter of the exponential decay of the neutron wavefunction density along x axis is termed as the neutron channeling length x_e. The theory of neutron resonances in thin films is described in [2] and the theory of neutron channeling in planar waveguides is developed in [3]. The neutron channeling length was measured experimentally in [4,5].

The planar waveguides were investigated in [6,7]. Unpolarized neutron microbeams were demonstrated experimentally in [8,9]. Polarized neutron microbeams were obtained in [10]. The combination of nonmagnetic waveguides and polarized neutron reflectometer [11] was used for the scan of magnetic amorphous microwires with high spatial resolution [12,13]. In [14] the angular divergence of the microbeam was measured as a function of the neutron wavelength. In [15] the intrinsic

---

[*] Corresponding author.
E-mail address: kozhevn@nf.jinr.ru (S.V. Kozhevnikov).

http://dx.doi.org/10.1016/j.nima.2017.09.031
Received 7 August 2017; Received in revised form 14 September 2017; Accepted 14 September 2017

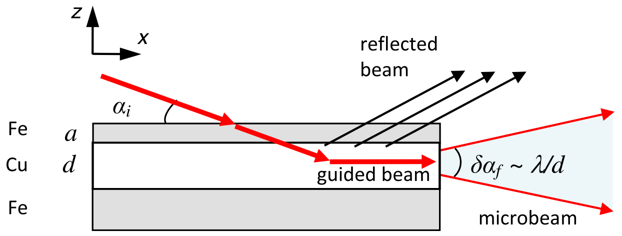

Fig. 1. Geometry of planar waveguides.

spectral width of the neutron resonances in a planar waveguide was estimated experimentally and compared with the theory of resonances [2]. The method of polarized neutron channeling was proposed for the direct determination of magnetization of the weakly magnetic films [16,17].

The main features of neutron microbeams exiting the edge of waveguides are the following: enhanced interaction with matter during the process of channeling and low background because of the separation from the direct and reflected beams. We suppose that it may be used in the future for the development of sensitive and effective methods for the investigations of layered structures. It is known [3] that the neutron channeling length in planar waveguides depends on the parameters of the structure (upper layer thickness, channel width, potential well depth, resonances order, etc.). As we can measure the neutron channeling length directly, it may be potentially used for the characterization and investigations of waveguides.

In this communication we demonstrate the experimental setup and methods for the measurement of the neutron channeling length in planar waveguides. In Section 2 the calculations of the resonances and the short theoretical description of the neutron channeling are presented. In Section 3 the experimental setup and results on the neutron channeling length measurement are shown. In Section 4 we discuss the advantages and drawbacks of presented methods.

2. Neutron channeling length

In Fig. 2, the calculations for a waveguide structure Fe(20 nm)/Cu(140 nm)/Fe(50 nm)//Si(substrate) are presented. The neutron optical potential is shown in Fig. 2a as a function of the coordinate z perpendicular to the sample surface (see Fig. 1). The potential for the layers Fe(up) marked by the thin line corresponds to the neutrons with spin parallel to the applied magnetic field and Fe(down) marked by the thick line corresponds to the neutrons with spin antiparallel to the applied magnetic field. For spin up the potential has a well-like shape. But for spin down the potential is a barrier. In Fig. 2b the calculated wavefunction density for spin up is shown as a function of the coordinate z perpendicular to the surface and the glancing angle of the incident beam α_i. One can see the maxima of the neutron wavefunction density for the resonance orders $n = 0, 1, 2, 3$ in the region of total reflection below the critical angle α_c^+. The same for spin down is shown in Fig. 2c. One can see two maxima above the critical angle α_c^- of total reflection. The neutron wavefunction density integrated over the coordinate z is presented in Fig. 2d as a function of the glancing angle of the incident beam α_i. For spin up (thin line) the enhancement in a potential well is rather stronger than for spin down (bold line) in a potential barrier.

In the following we summarize a few important analytical expressions from the theory of neutron channeling in planar waveguides [3]. Let us introduce notations. The plane neutron wavefunction with the wave vector $\mathbf{k}_0$ falls in vacuum onto the surface of the waveguide (Fig. 3).

The wavefunction in the resonant layer 2 (or channel) has the following expression:

$$\psi(r) = A\exp\left(ik_{0x}x\right)\left[\exp\left(-ik_{2z}z\right) + R_{23}\exp\left(ik_{2z}z\right)\right] \qquad (1)$$

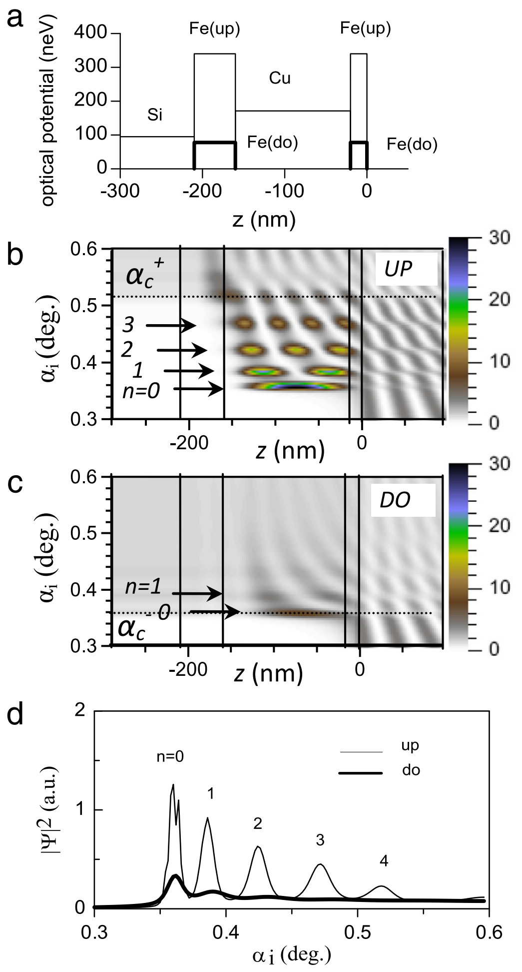

Fig. 2. Calculations for a waveguide of structure Fe(20 nm)/Cu(140 nm)/Fe(50 nm)/ /Si(substrate) for neutrons with spin parallel (UP) and antiparallel (DOWN) to the applied magnetic field. (a) Neutron optical potential as a function of coordinate z perpendicular to the sample surface. (b) Neutron wavefunction density as a function of coordinate z and the glancing angle of the incident beam with spin UP where $n = 0, 1, 2, \ldots$ is the resonance order. (c) Neutron wavefunction density as a function of coordinate z and the glancing angle of the incident beam for spin DOWN. (d) Neutron wavefunction density as a function of the glancing angle α_i for spin UP (thin line) and spin DOWN (bold line).

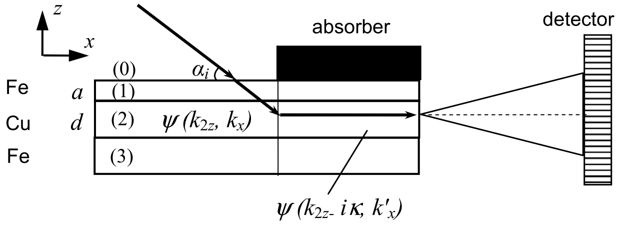

Fig. 3. Geometry of neutron channeling length measurement using a powder absorber. Neutron beam in vacuum (0) falls on the waveguide surface, tunnels from the upper thin layer (1), enters into the channel (2) and is totally reflected from the bottom thick layer (3). One part of the beam is tunneled through the upper layer (1) and goes outside the waveguide through the surface. Another part is reflected back from the upper layer (1), is channeled along the channel (2), goes out from the channel edge as a slightly divergent microbeam and can be recorded by a neutron detector. The absorber absorbs the neutron beam and divides the surface in two parts: illuminated and non-illuminated by the neutron beam. The neutron wavefunction is $\psi\left(k_{2z}, k_x\right)$ and $\psi\left(k_{2z} - i\kappa, k'_x\right)$ respectively under illuminated and non-illuminated part. k_{2z} is the real part of the component of the wave-vector perpendicular to the sample surface, k_x is the real part of the component of the wave-vector parallel to the sample surface under illuminated part, k'_x is the real part of the component of the wave-vector parallel to the sample surface under non-illuminated part, κ is the imaginary part of the neutron wave-vector under the non-illuminated part.