A neutron polariser based on magnetically remanent Fe/Si supermirrors
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outline

introduction
  multilayer, supermirror

reflectometers at SINQ
  Amor, Morpheus, Narziss

topics of the neutron optics group at PSI
  supermirrors, interfaces
  focusing devices, polariser

magnetically remanent neutron polarisers
  principle
  production
  applications
The graph shows the reflectivity $R$ of a supermirror as a function of the scattering vector $q/\text{Å}^{-1}$. The graph indicates a sharp decrease in reflectivity at small values of $q/\text{Å}^{-1}$, approaching zero as $q/\text{Å}^{-1}$ increases. The substrate is indicated on the right side of the graph.
multilayer: causes 'Bragg peaks'
**intro**

**supermirror**

**multilayer:** causes 'Bragg peaks'

**stack of multilayers:** overlapping 'Bragg peaks'

![Sketch of a multilayer stack and reflectivity graph](image)
**intro**  supermirror

**multilayer:** causes 'Bragg peaks'

**stack of multilayers:** overlapping 'Bragg peaks'

**supermirror:** 'multilayer' with layer-thickness gradient
instruments

SINQ: continuous flux spallation source
⇒ combination of the disadvantages of reactor- and spallation sources!

flux: $10^{14}$ n/cm²/s

cold source: liquid deuterium
instruments  Amor

TOF reflectometer, user instrument
- $0 \text{ Å}^{-1} < q_z < 0.4 \text{ Å}^{-1}$, $\Delta q_z/q_z > 0.5\%$
- single counter and area detector
- polarisation option
  (with analysis)
**instruments** Morpheus
test diffractometer and reflectometer for in-house research and sample alignments
- angle-dispersive
- \(2 \text{Å} < \lambda < 7 \text{Å},\)
- single counter and area detector
- all SINQ sample environment \( (H < 1 \text{T}) \)
- 4-circle set-up
- polarisation option
  (with analysis)
instruments   Narziss  

new reflectometer, dedicated to neutron optics research, only.

– $\lambda = 5\,\text{Å}$
– polarisation option, with analysis
– sample magnet $-1000\,\text{Oe} < H < 1000\,\text{Oe}$
  $600 \times 150 \times 50\,\text{mm}^3$
topics of the neutron optics group

– high-$m$-sm & band-pass filters

– interface design

– *fundamental* monochromators

– focusing devices

– remanent polarisers
**topics** high-\(m\)-sm / band pass filter

**ideas:**
- prevent interdiffusion by introducing a blocking layer
- flatten the accumulated roughness by substituting some layers by a smoothening material as e.g. Cr works good for not too many layers!
  fails for \(m > 2.5\).
**topics**  **interface design**

non-sharp but laterally homogeneous interfaces

- annealing: interdiffusion
  limited by diffusion length, melting
  and grain-formation/growth \(\Rightarrow\) roughness

- artificial intermixing:
  intermediate films between the layers
topics  fundamental monochromator

extreme limit: sinusoidal profile

⇒ only fundamental Bragg peak, no higher harmonics

applications:
– monochromator
– wavelength filter
  (e.g. for Narziss)
topics focusing devices

bi-elliptic neutron guide
together with TUM
built by SwissNeutronics

1:10 model of a neutron guide. Ideally only 2 reflections from source to image openings: $4 \times 8 \text{mm}^2$, length: 2 m
topics remanent polarisers

... fills rest of the presentation!
remanent polariser  
alapplication principle

$H_M \approx 150 \text{ Oe, } \ H_g < 20 \text{ Oe}$

Si wafer with supermirror

electro magnet

unpolarised / polarised neutrons
remanent polariser material

ferromagnetic material: Fe

- might show easy axis of magnetisation
- almost matches Si for $|\rightarrow\rangle$
- low absorption (required for transmission, less radiation damage)

spacer material: Si

- low potential
- matches the substrate (for transmission)
- low absorption
- can be influenced (potential and stress) by reactive sputtering

but

- rather low contrast for $|+\rangle$
  $\Rightarrow$ larger number of layers required
- total reflection for low $q$
remanent polariser  ideal ml

\[(\bar{b}_f + \bar{p}_f)\rho_f \gg \bar{b}_s\rho_s, \quad \bar{p}_s = 0, \quad \text{ferromagnet, spacer}\]

\[(\bar{b}_f - \bar{p}_f)\rho_f = \bar{b}_s\rho_s\]
**remanent polariser**

**real ml: Fe/Si:N:O**

\[
(\bar{b}_f + \bar{p}_f)\rho_f \gg \bar{b}_s\rho_s, \quad \bar{p}_s = 0, \quad \text{ferromagnet, spacer}
\]

\[
(\bar{b}_f - \bar{p}_f)\rho_f \approx \bar{b}_s\rho_s
\]

![Graph showing reflectivity and interdiffusion](image)

- **Reflectivity**
  - \( R^\uparrow \)
  - \( R^\downarrow \)

- **Interdiffusion**
  - \( \Rightarrow \) mag. dead layers
  - \( \Rightarrow \) 2nd order peak

\( \omega / ^\circ \)
**remanent polariser**  **magnetic properties**

anisotropic in-plane stress

causes anisotropic magnetic properties (magnetostriction)

reason: shape of sputter target and aperture (ca. \(100 \times 400 \text{ mm}^2\))

⇒ spread of angle of incidence of sputtered atoms is anisotropic

⇒ growth and thus strain formation is effected

⇒ easy axis of magnetisation requires strained films!
**remanent polariser production**

all our multilayers are produced by magnetron sputtering:

**parameters:**
- power
- velocity
- Ar gas pressure
- reactive gases (O$_2$, N$_2$)
- apertures

**properties of the films:**
- contrast (matching)
- stress minimisation (stable films)
- anisotropic stress (to get an easy axis of magnetisation)
- interface quality (roughness, interdiffusion)
remanent polariser  sputter plant

sputter-plant: Leybold Z600

- cleaning of the substrates by glow discharge
- 3 cathods
- 1+3 gas inlets per cathod

aperture used to increase the anisotropy and thus the remanence

consequences:
- unstable discharge
- lower deposition rate
- no influence on the magnetic properties
**remanent polariser** performance

\[ M \uparrow H_g \]

(magnetisation parallel to the guide field)

\[ H_g = 15 \text{ Oe} \]

\[ \lambda = 4.74 \text{ Å} \]

\[ R: P = 90\% - 97\% \]

\[ T: P = 96\% - 99\% \]
remanent polariser performance

\[ \mathbf{M} \parallel H_g \]
(magnetisation antiparallel to the guide field)

\[ H_g = 15 \text{ Oe} \]
\[ \lambda = 4.74 \text{ Å} \]

\[ R: P = 90\% - 96\% \]
\[ T: P = 96\% - 99\% \]
remanent polariser  \( H_c \) vs. layer thickness

saturation in \( H = -700 \text{ Oe} \)

transmission measured in guide fields
\( H_g = +5 \ldots +45 \text{ Oe} \)

![Graph showing transmission and magnetisation over spin up and spin down orientations with varying \( H_g \) values.](image-url)
remanent polariser    off-specular scattering
polarised beam, no spin analysis
Fe/Si:N:O sm, $m = 2.4$

assymetric off-specular signal
⇒ weak spin-flip scattering
remanent polariser  applications: analyser
at Morpheus, Narziss (SINQ)

coating  Fe / Si:N:O
        $m = 3$, 599 layers
substrate  Si-wafer, 0.6 mm
mirror size  $200 \times 60 \text{ mm}^2$
magnet size  $200 \times 100 \times 100 \text{ mm}^3$

$B_M$  200 Oe
$B_g$  20 Oe
$P_{T, \uparrow \uparrow}$  $> 97 \%$
$P_{T, \downarrow \downarrow}$  $> 95 \%$
remanent polariser applications: switchable polariser at Amor (SINQ)

- FeCoV/TiN on glas
- operated in reflection mode
- saturation fields: \( \pm 400 \text{ Oe} \)
- guide field: \( +20 \text{ Oe} \)
remanent polariser applications: white beam polariser at SANS I (SINQ)

coating \( \text{Fe} / \text{Si:N:O} \)

\[ m = 2.4, \text{299 layers} \]

substrate Si-wafer, 0.6 mm

mirror size \( 200 \times 6 \text{ cm}^2 \)
conclusion:

- we produced supermirrors with Fe and Si:N:O which
- polarise neutrons \((P > 95\% \text{ to } P = 99\%)\)
- can be operated in transmission and reflection mode
- show a magnetic remanence
- thus need guide fields of 20 Oe, only
- can be operated antiparallel to the guide field

the reactive gases \(\text{N}_2\) and \(\text{O}_2\) in Si are needed to
- match the potentials for \(|-\rangle\)
- tailor strain in Fe layers (anisotropic stress), but
- keep the overall stress small

limitations:
- stress limits the number of layers \(\Rightarrow m < 3\)
- FeSi layer causes 2nd Bragg peak
  \(\Rightarrow |-\rangle\) contamination in reflection mode
THE END