Investigation of magnetostatic interactions in NiFe/Au/Co/Au multilayers

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Investigation of magnetostatic interactions in NiFe/Au/Co/Au multilayers

In cooperation between:

Institute of Molecular Physics, Polish Academy of Sciences, Poznań, Poland

Department of Physics , University of Kassel, Kassel, Germany

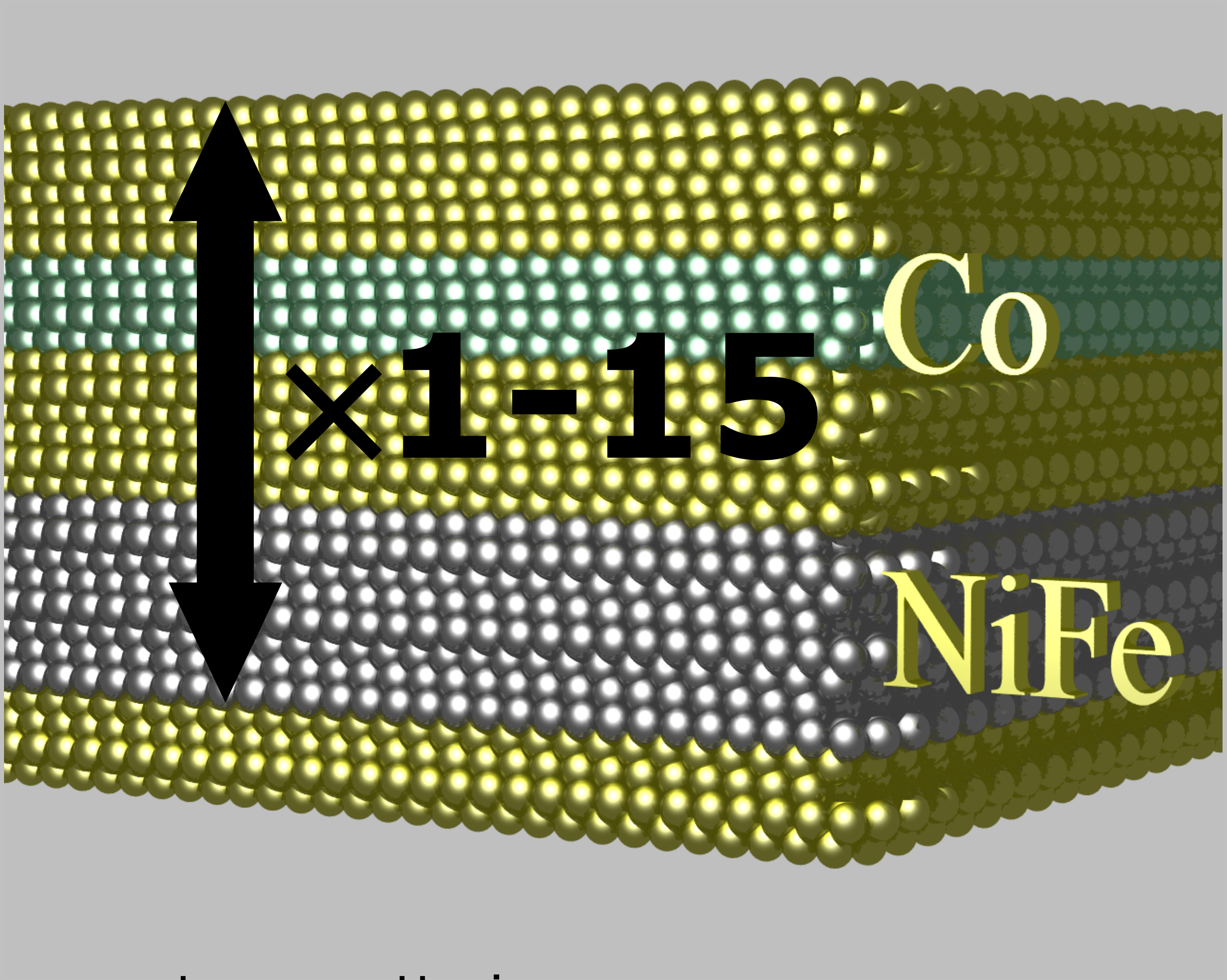
Institute of Electronic Materials Technology, Warszawa, Poland

Laboratory of Magnetism, Faculty of Physics, University of Białystok, Poland

Investigation of magnetostatic interactions in NiFe/Au/Co/Au multilayers

- Introduction
- NiFe/Au/Co/Au multilayers
- Magnetic and transport properties
- Mössbauer spectroscopy investigations
- SXRMS measurements
- Conclusions

Introducing $[NiFe/Au/Co/Au]_N$ – the structure



Substrate:
naturally oxidized
Si(100)

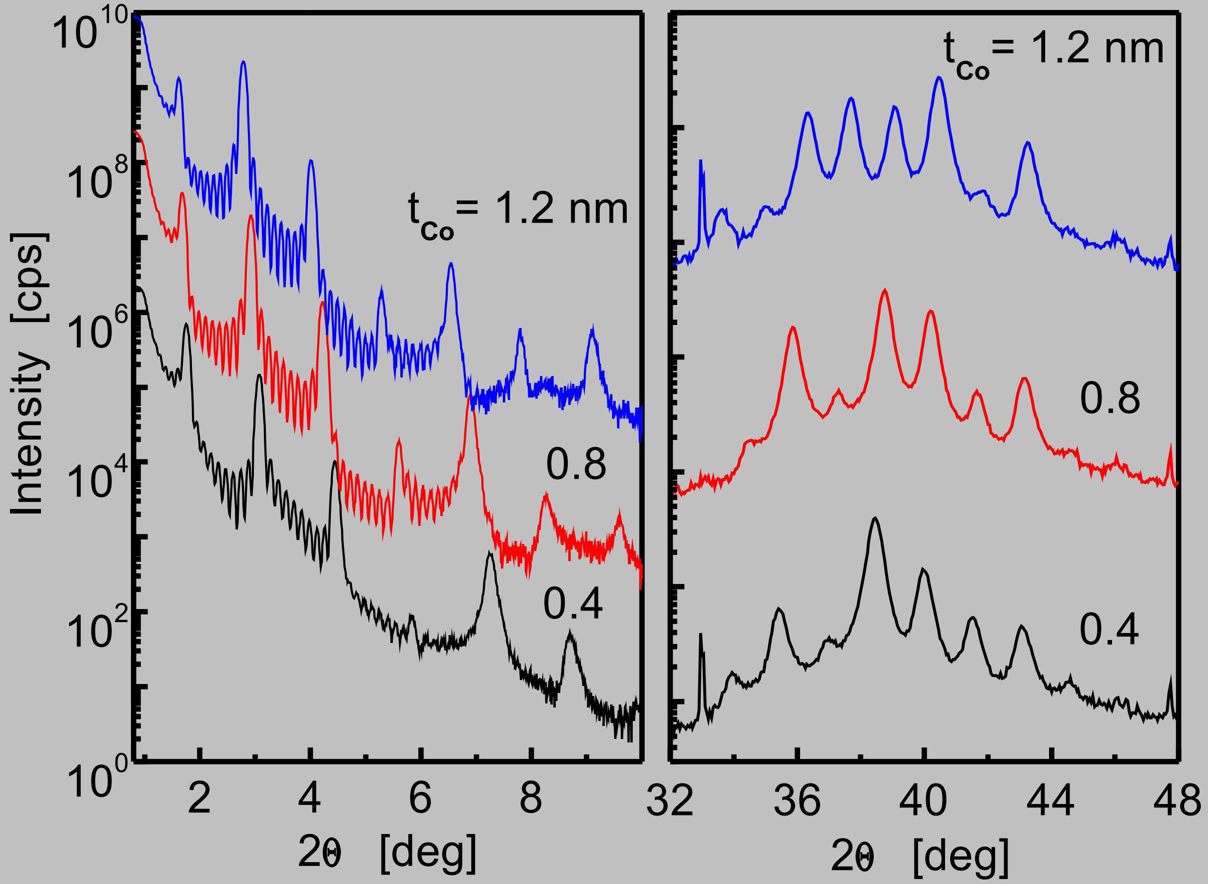
t_{Co}=0.2-1.5 nm

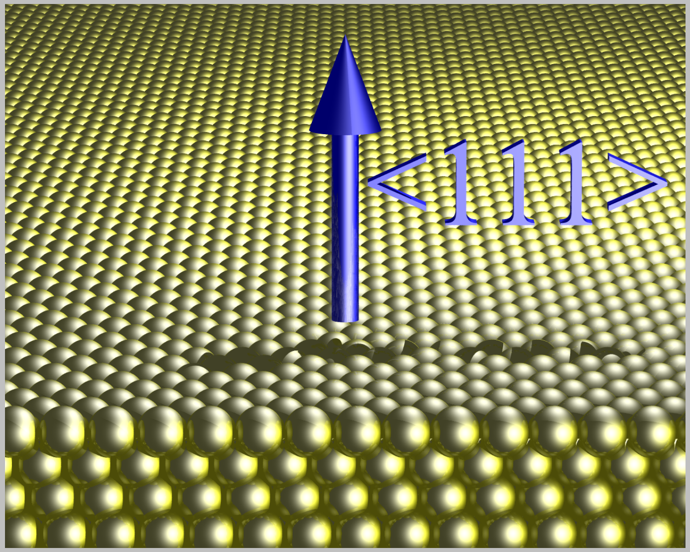
t_{Au}=1.5-3 nm

t_{NiFe}=0.5-4 nm
($Ni_{80}Fe_{20}$)

magnetron sputtering

Introducing $[\mathrm{NiFe/Au/Co/Au}]_N$ – the structure

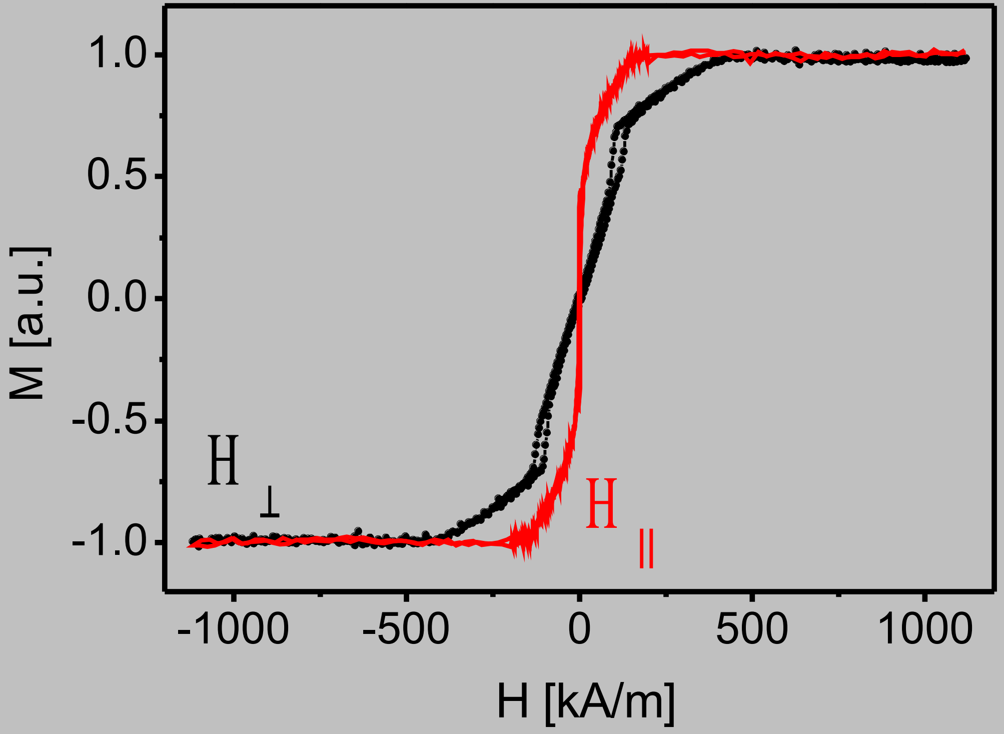


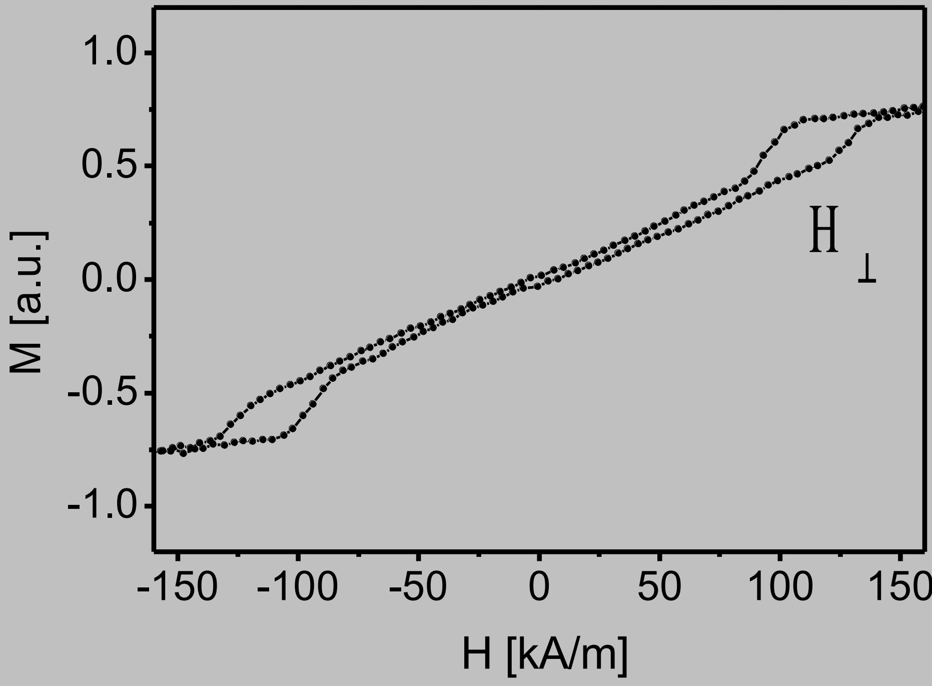


$[\mathrm{Ni_{80}Fe_{20}}(2\ \mathrm{nm})/\mathrm{Au}(1.9\ \mathrm{nm})/\mathrm{Co}(t_{\mathrm{Co}})/\mathrm{Au}(1.9\ \mathrm{nm})]_{10}$

Cu Kα

Introducing $[NiFe/Au/Co/Au]_N$ – magnetic properties

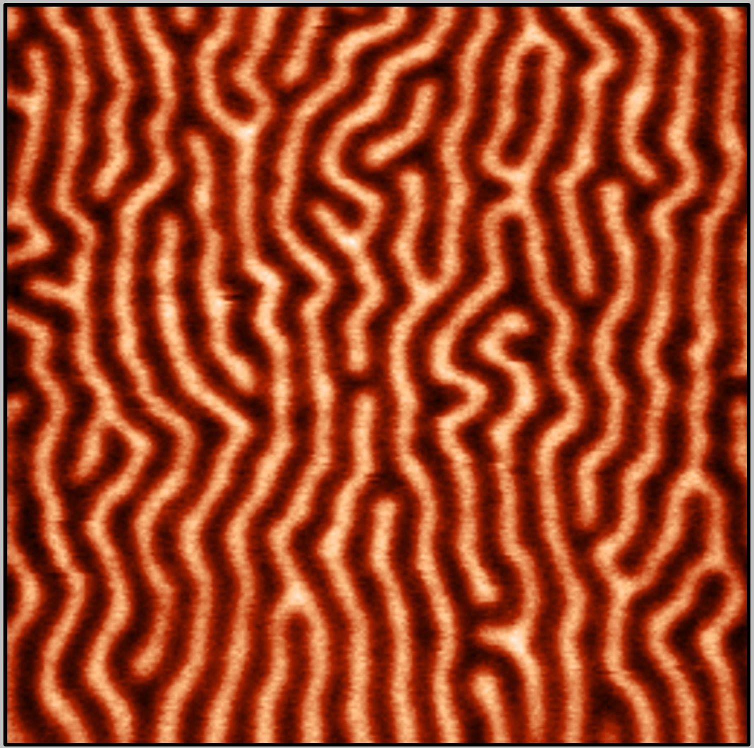




- Small field range of hysteresis with field applied perpendicularly is characteristic of systems with stripe domains.
- In both field configurations NiFe and Co layers reverse quasi independently.

$[Ni_{80}Fe_{20}(2\ nm)/Au(1.9\ nm)/Co(0.8\ nm)/Au(1.9\ nm)]_{10}$

Introducing $[\text{NiFe/Au/Co/Au}]_N$ – magnetic properties



AC demagnetized sample
$5\text{x}5\mu\text{m}^2$

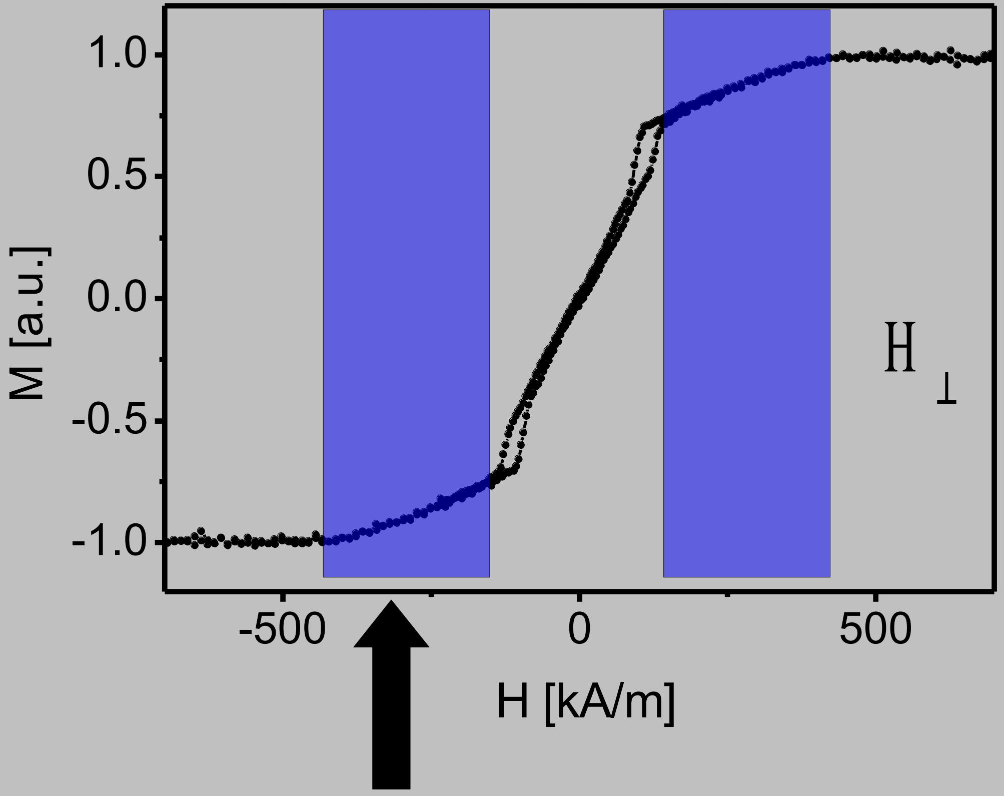
period 400-1000 nm

- MFM measurements prove the presence of the stripe domains which are characteristic for systems with perpendicular anisotropy.
- A period of the domain structure depends strongly on the thickness of Co and Au layers.

$[\text{Ni}_{80}\text{Fe}_{20}{}^*(2\text{ nm})/\text{Au}(2.4\text{ nm})/\text{Co}(1.2\text{ nm})/\text{Au}(2.4\text{ nm})]_{10}$

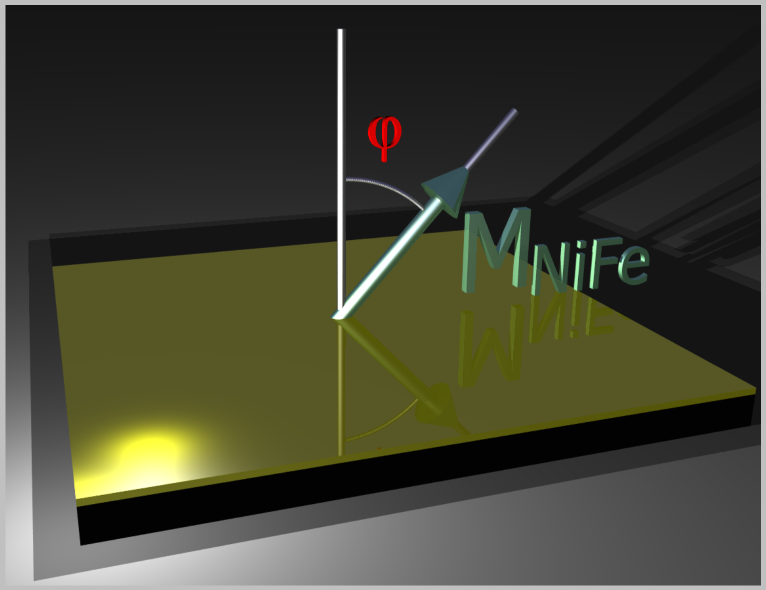
* with ^{57}Fe

Introducing $[NiFe/Au/Co/Au]_N$ – magnetic properties



Reversal of NiFe only

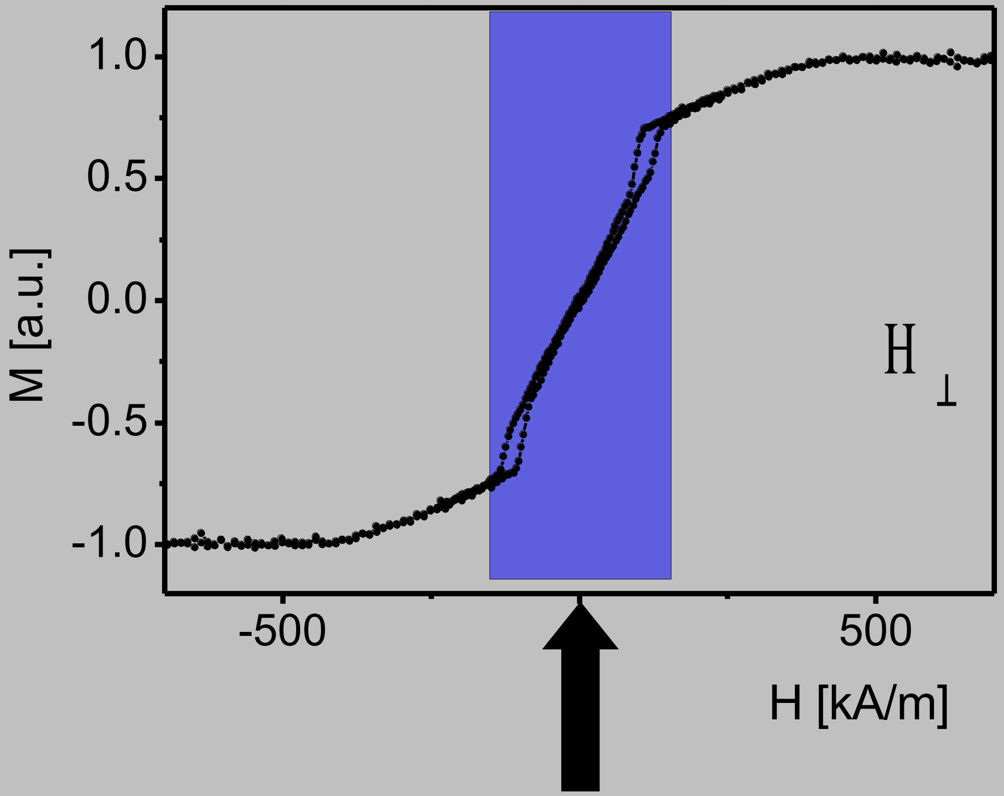
$$K_u = \frac{1}{2}\mu_0 (M_S^{NiFe})^2$$



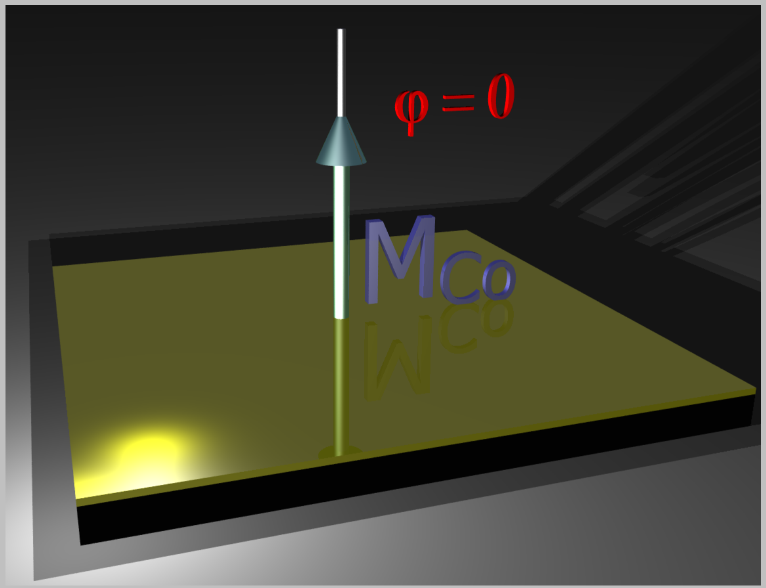
Shape anisotropy:

$$\cos(\varphi) = \frac{H}{M_S}$$

Introducing $[NiFe/Au/Co/Au]_N$ – magnetic properties

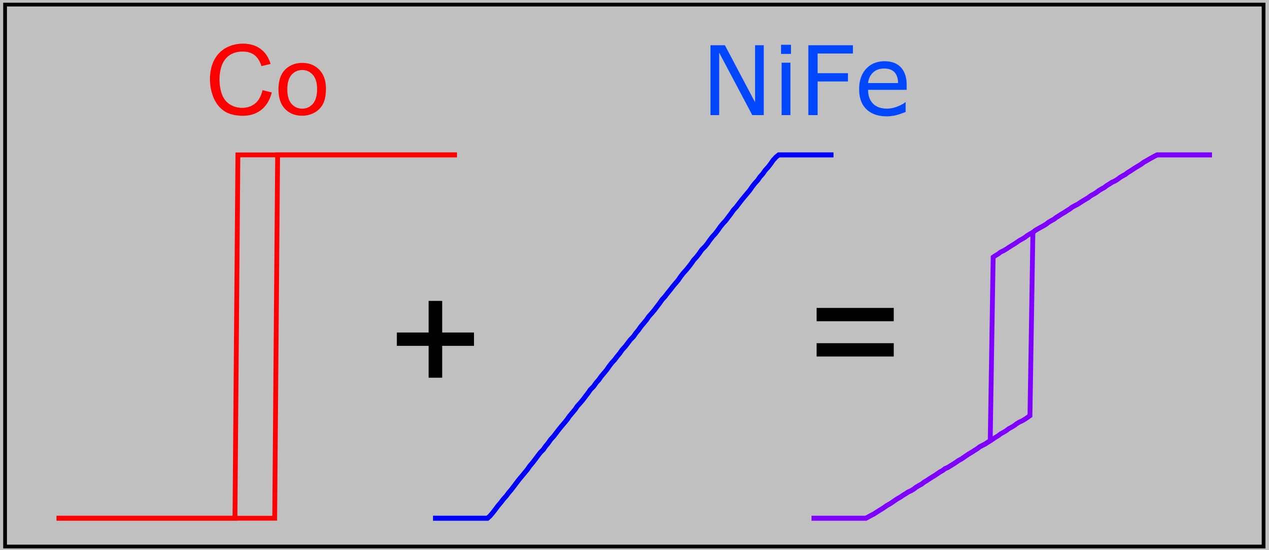


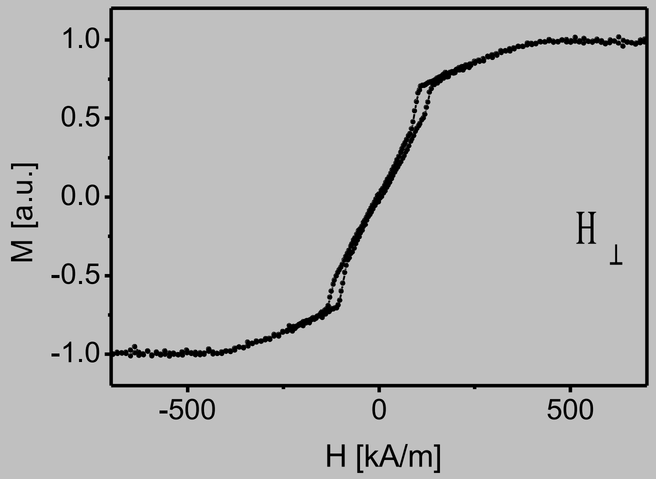
Simultaneous reversal
of
NiFe and Co



An easy axis of the Co layers is perpendicular to surface of multilayer.

Introducing $[\mathrm{NiFe/Au/Co/Au}]_N$ – magnetic properties

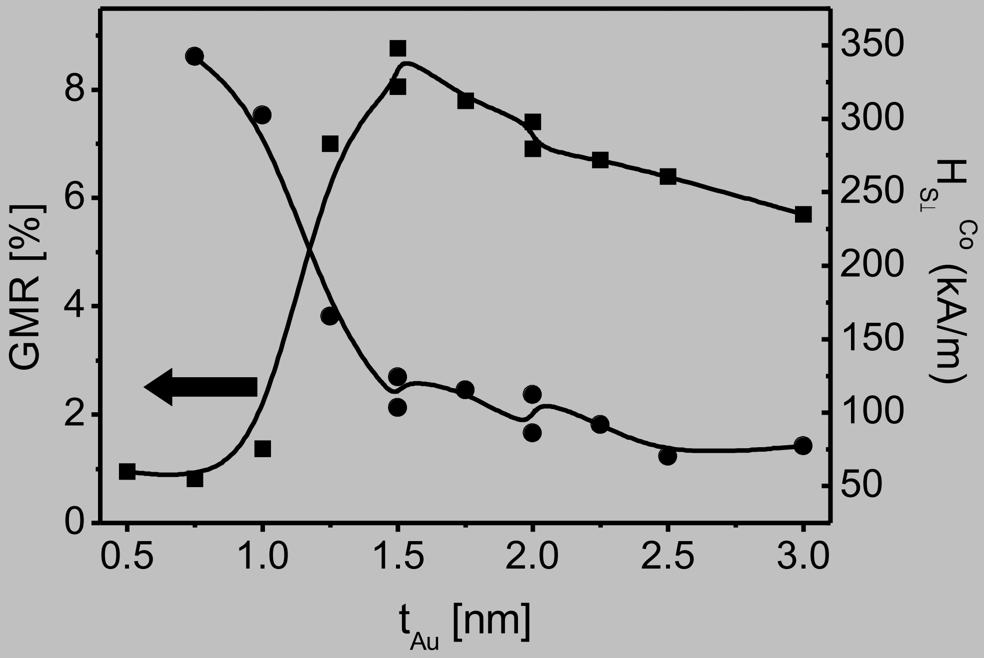




In the first approximation Co and NiFe layers can be thougt of as uncoupled.

M(*H*) dependence of the NiFe/Au/Co structure is then an arithmetic sum of the *M*(*H*) dependencies of Co and NiFe layers.

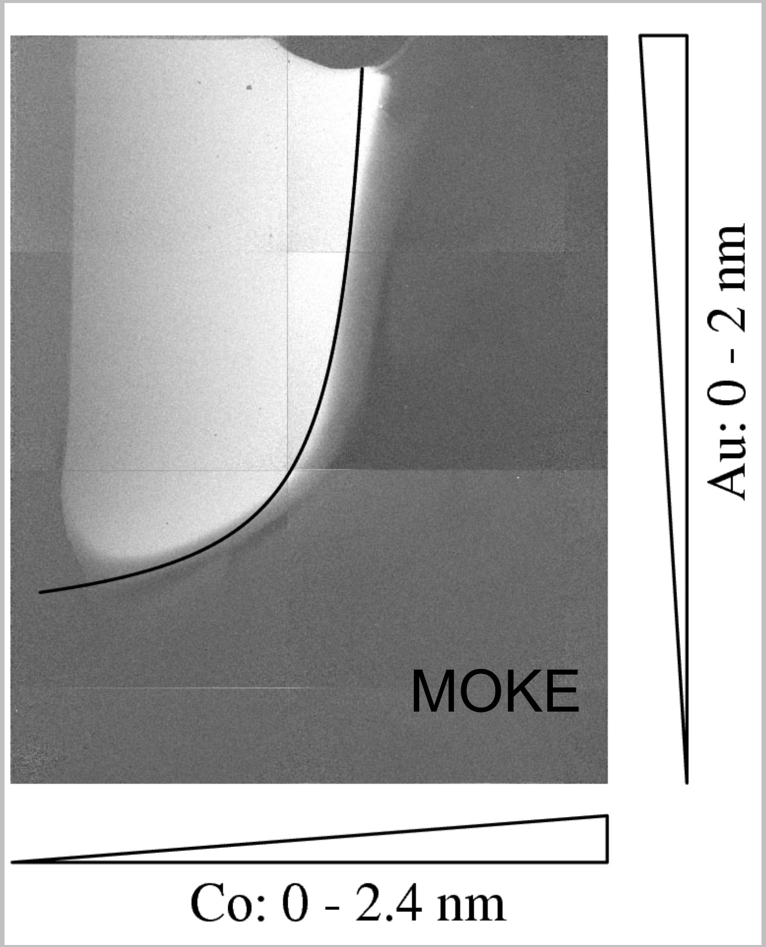
Introducing $[NiFe/Au/Co/Au]_N$ – direct NiFe-Co coupling



$[Ni_{80}Fe_{20}(2\ nm)/Au(\boldsymbol{t_{Au}})/Co(0.6\ nm)/Au(\boldsymbol{t_{Au}})]_{15}$

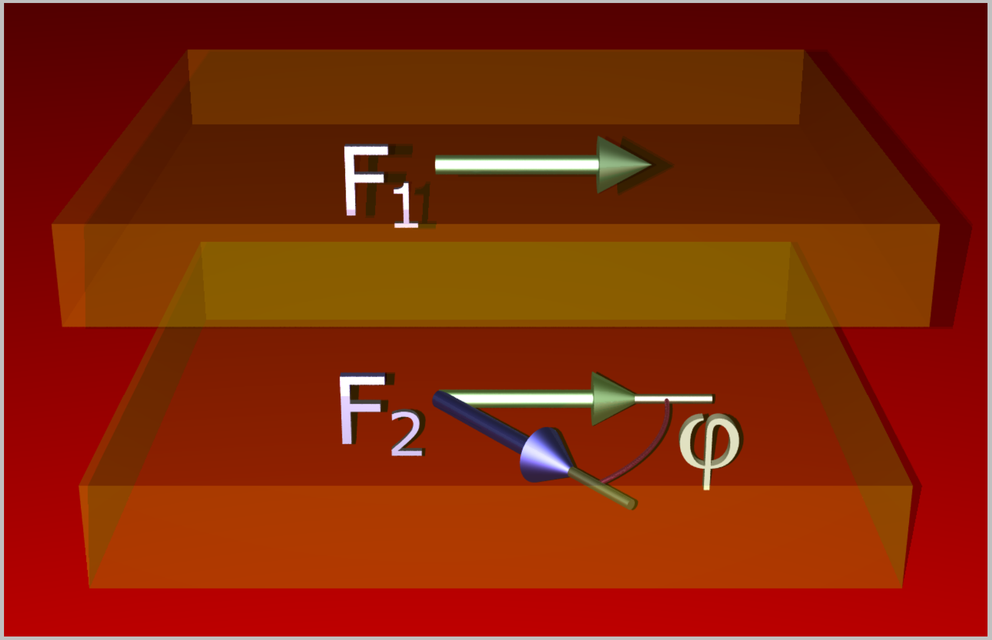
For small t_{Au} ferromagnetic bridges (pinholes) lead to the direct coupling between Co and NiFe layers.

F. Stobiecki et al., JMMM, **282** (2004) 34



White - magnetic moments perpendicular to the sample plane

Giant Magnetoresistance (GMR)- Nobel 2007 (Fert, Grünberg)



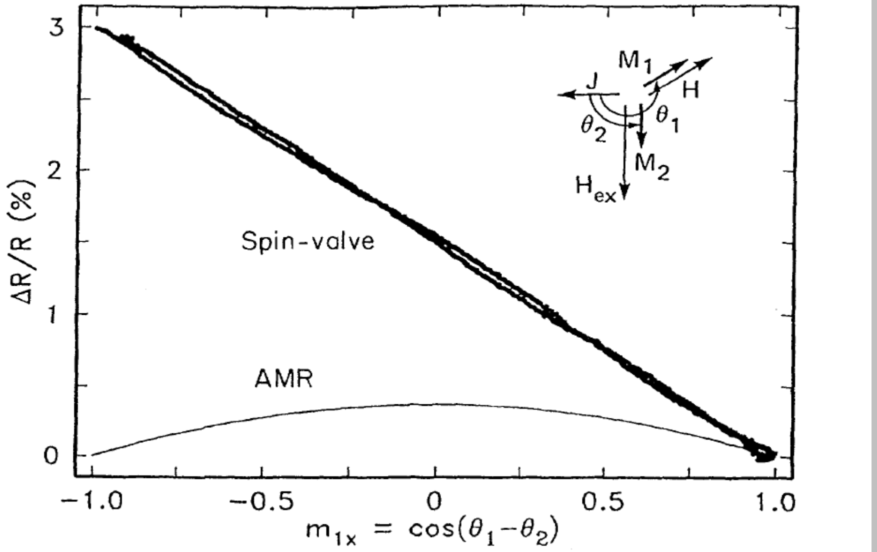
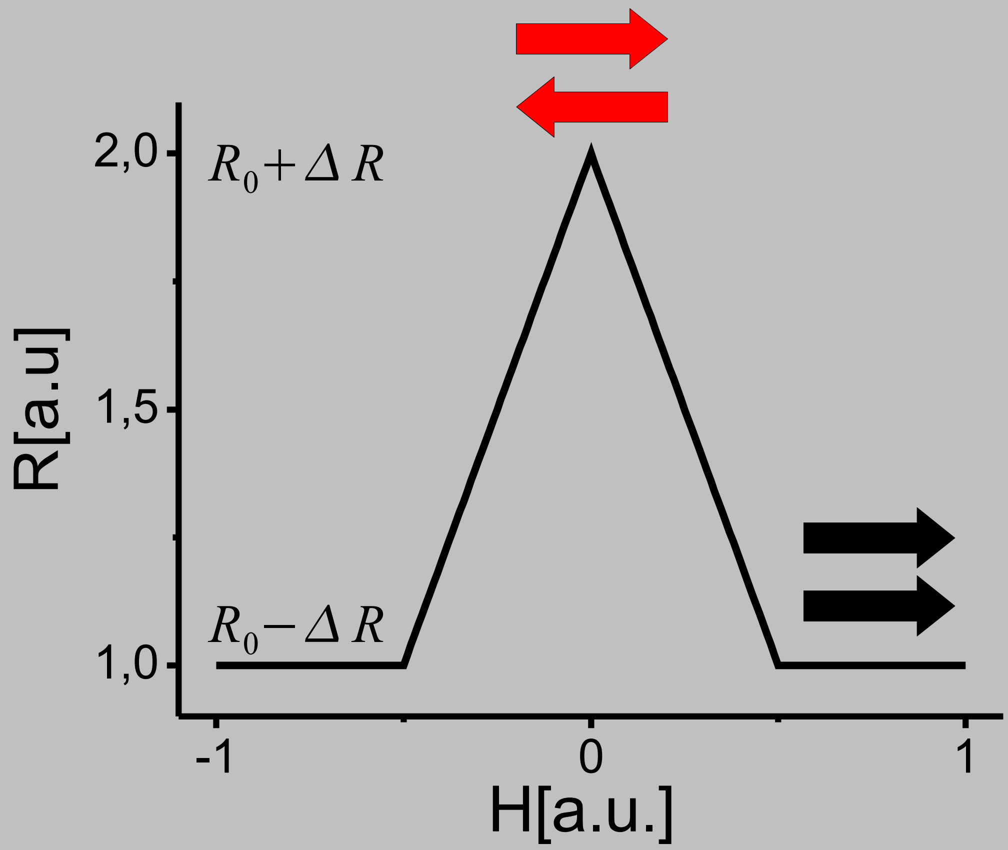


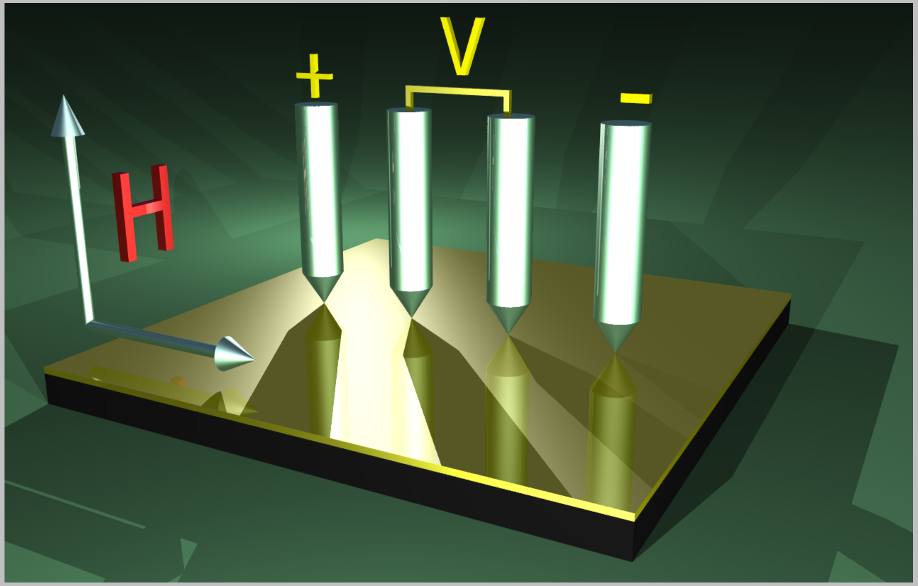
FIG. 2. Relative change in resistance vs the cosine of the relative angle between the magnetizations of the two NiFe layers of Si/(60-Å NiFe)/(26-Å Cu)/(30-Å NiFe)/(60-Å FeMn)/(20-Å Ag). Inset shows the orientation of the current *J*, exchange field H_{ex}, applied field H, and magnetizations M_1 and M_2.

$$\Delta R \propto \cos(\varphi)$$

B. Dieny et al., Phys. Rev. B, **43** (1991) 1297

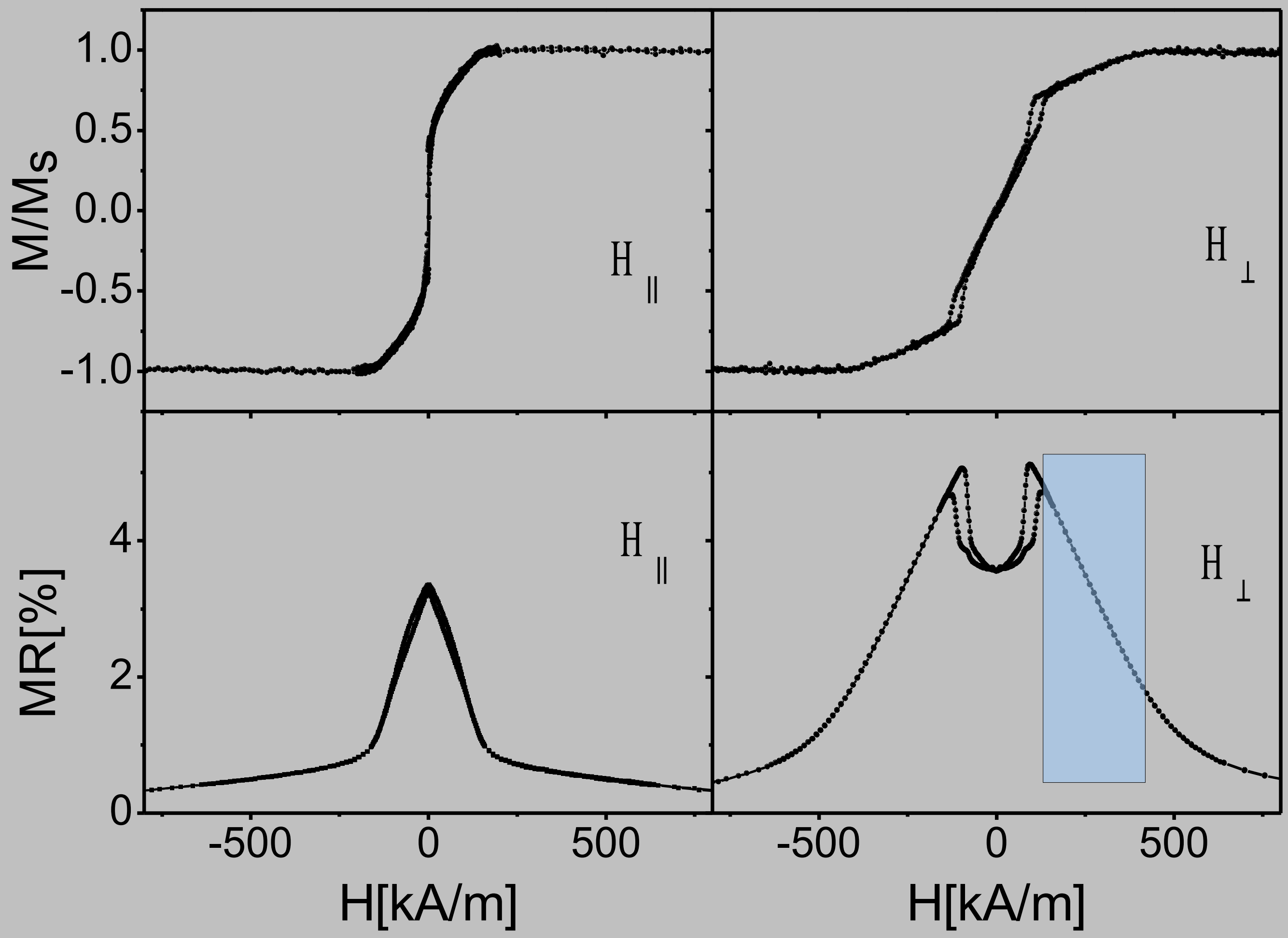
Giant Magnetoresistance (GMR)- Nobel 2007 (Fert, Grünberg)





$$R = R_0 - \Delta R \cos(\varphi)$$

Giant Magnetoresistance in NiFe/Au/Co/Au



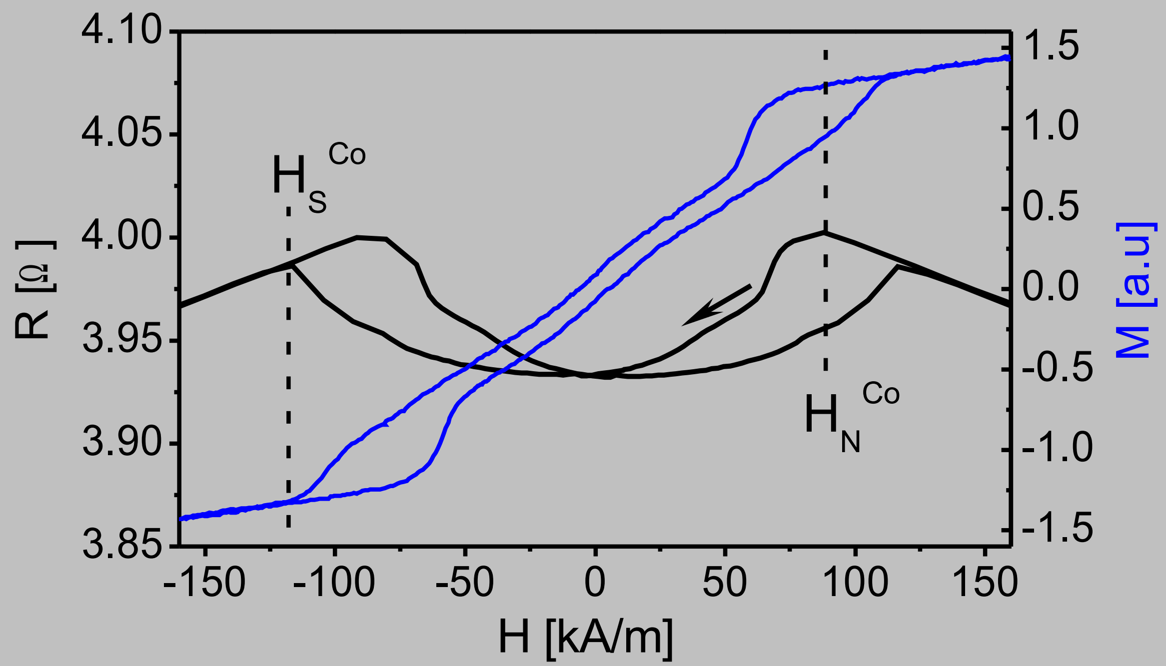
Broad linearity range in $R(H)$ dependence:

- magnetic layer magnetized along hard axis

- no hysteresis in linear range

$[Ni_{80}Fe_{20}(2\ \mathrm{nm})/Au(1.9\ \mathrm{nm})/Co(1\ \mathrm{nm})/Au(1.9\ \mathrm{nm})]_{10}$

Giant Magnetoresistance in NiFe/Au/Co/Au

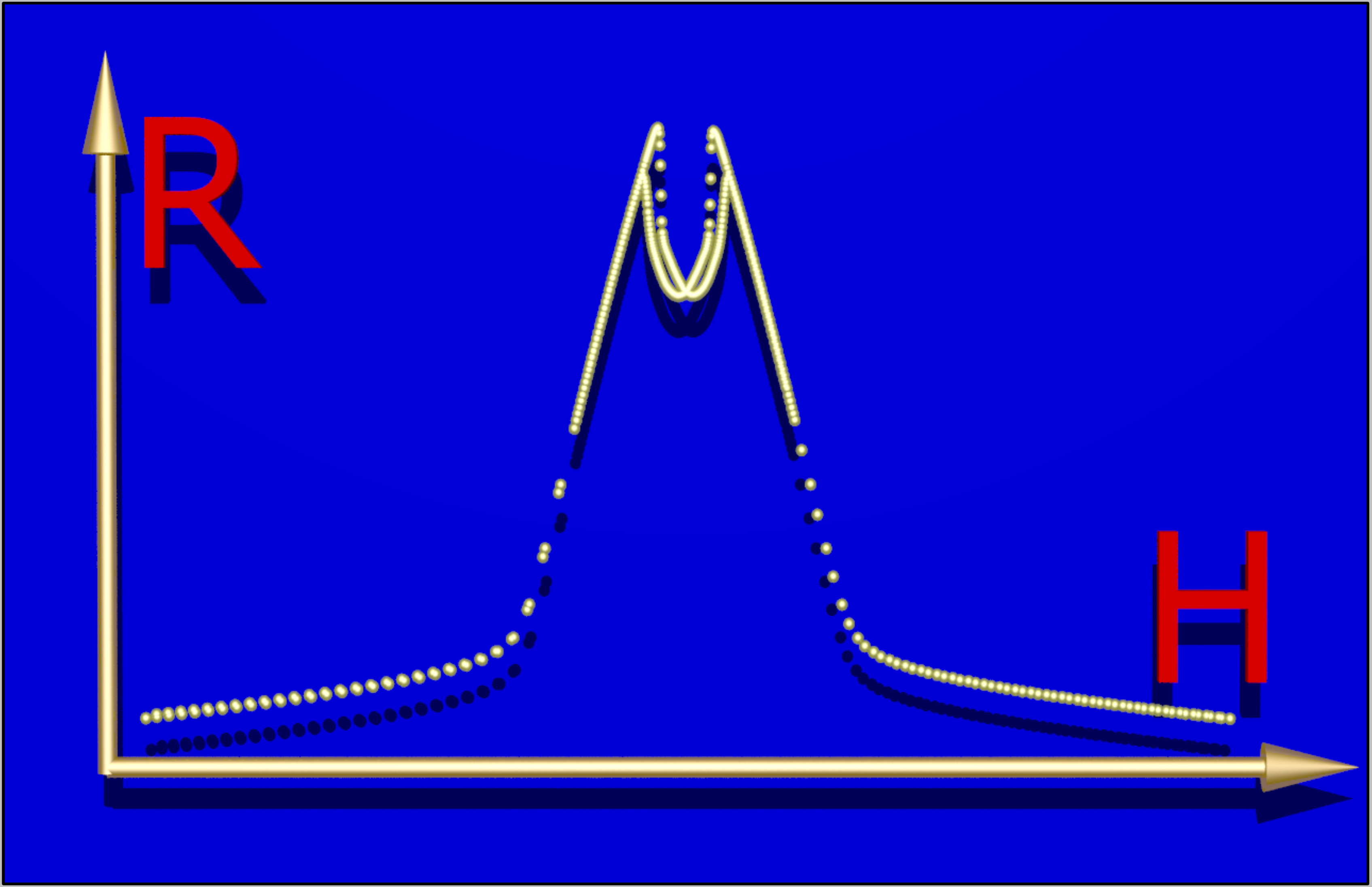


There is a local minimum of resistance in the *R*(*H*) dependence.

The nucleation field (creation of the domain structure) and the annihilation field (saturation of Co layers) are visible both in *R*(*H*) and *M*(*H*) dependencies.

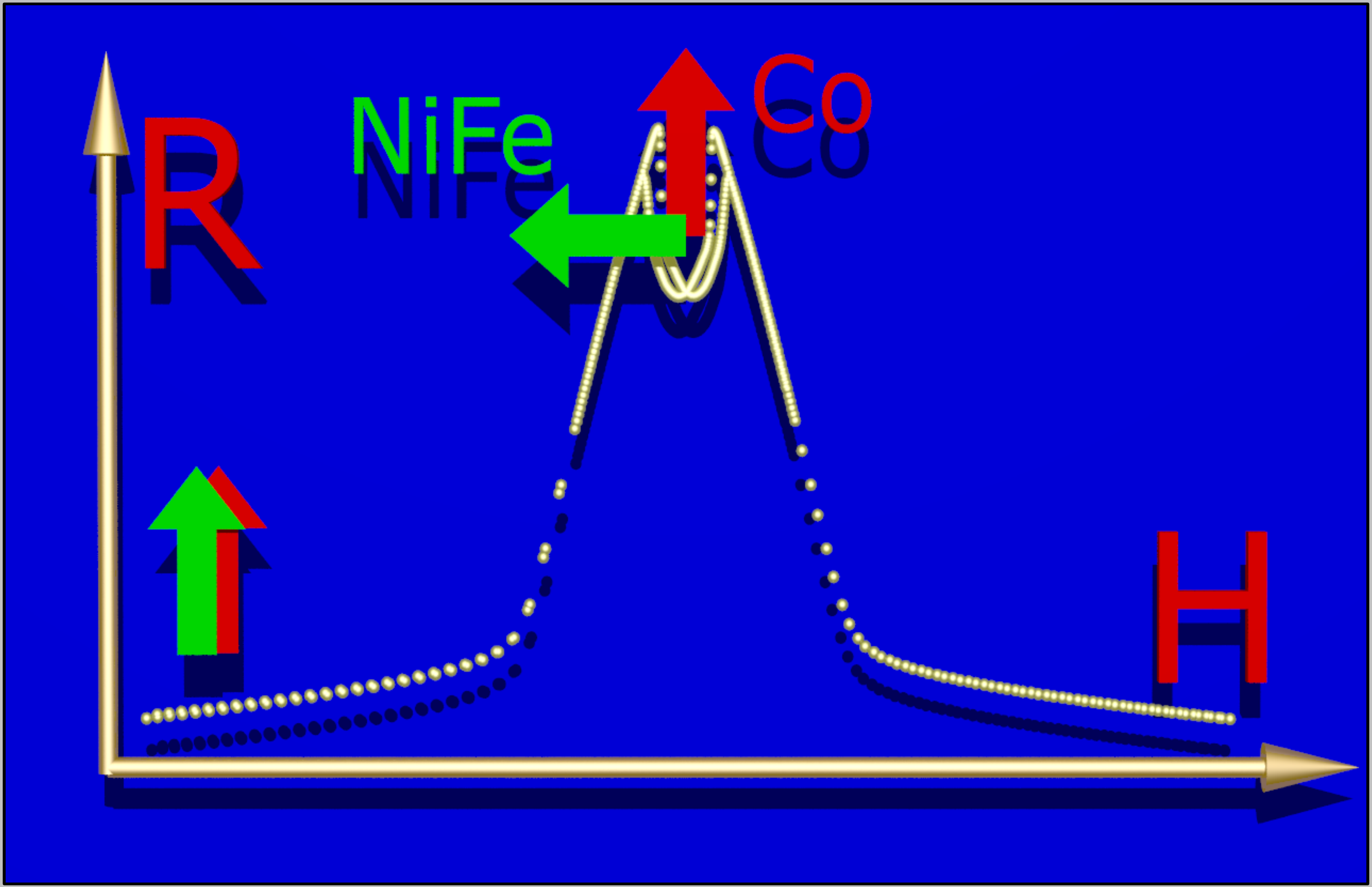
Giant Magnetoresistance in NiFe/Au/Co/Au

Explaining the R(H) dependence



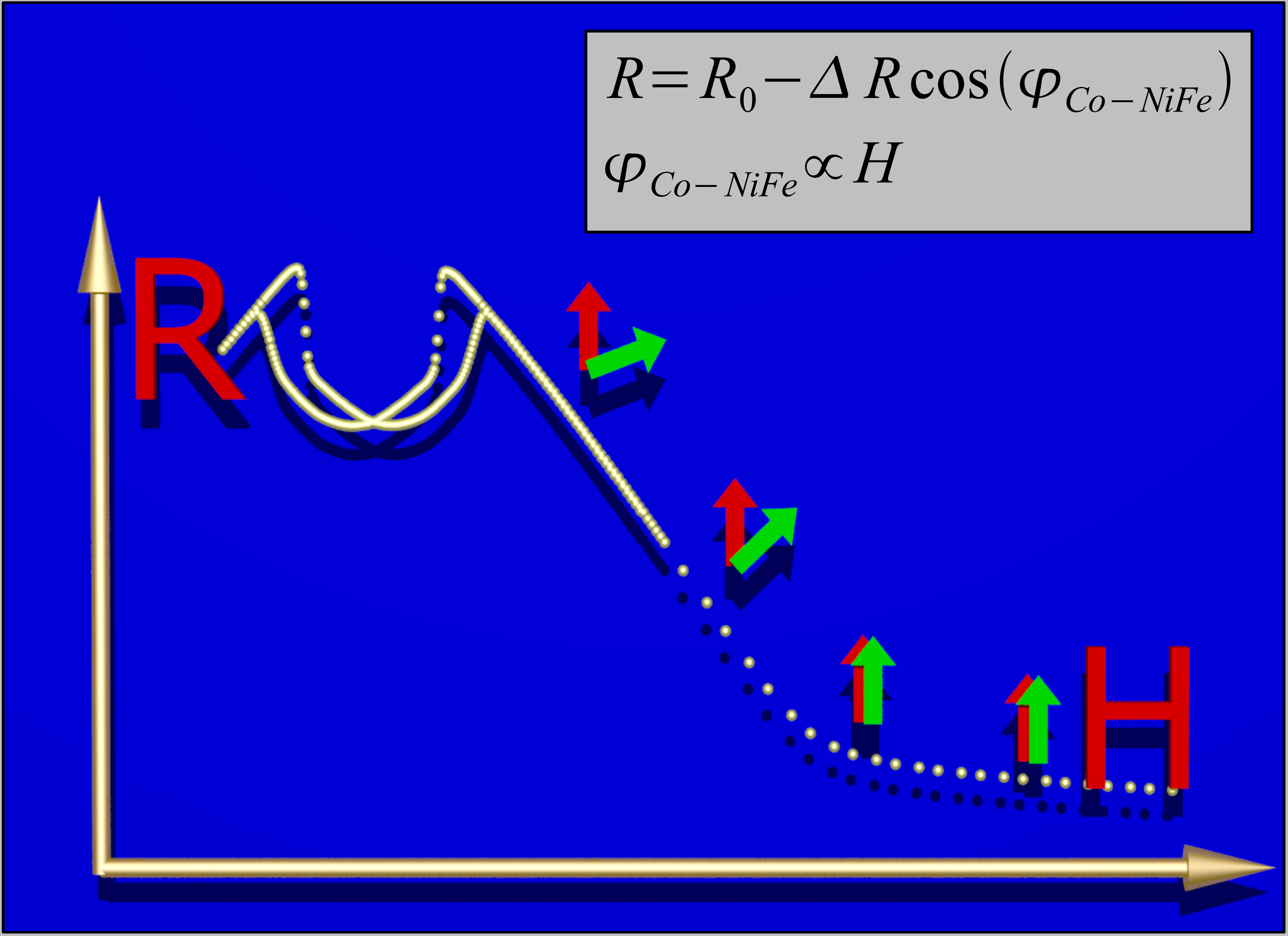
Giant Magnetoresistance in NiFe/Au/Co/Au

Explaining the R(H) dependence



Giant Magnetoresistance in NiFe/Au/Co/Au

Explaining the R(H) dependence

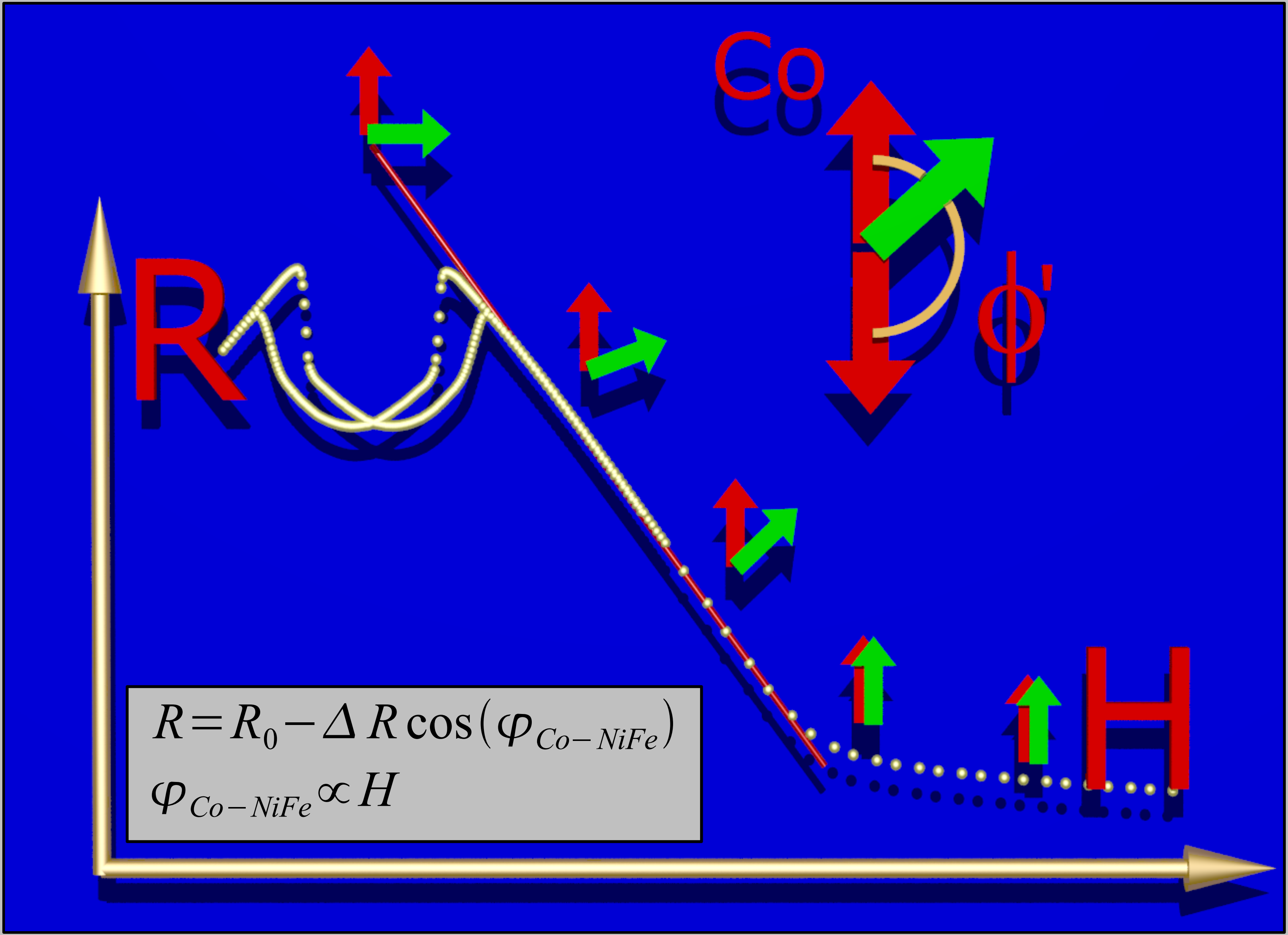


$$R = R_0 - \Delta R \cos(\varphi_{Co-NiFe})$$

$$\varphi_{Co-NiFe} \propto H$$

Giant Magnetoresistance in NiFe/Au/Co/Au

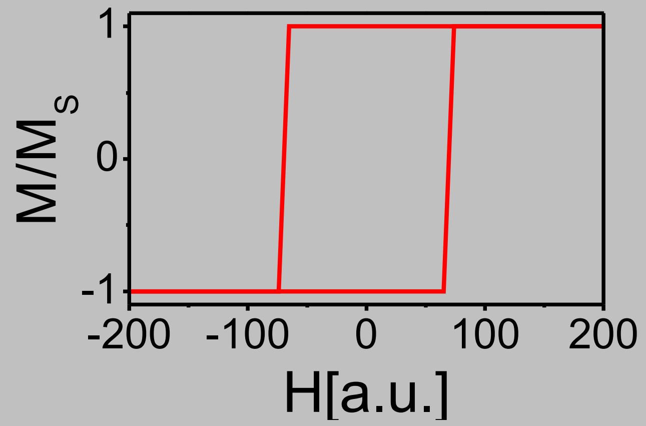
Explaining the R(H) dependence



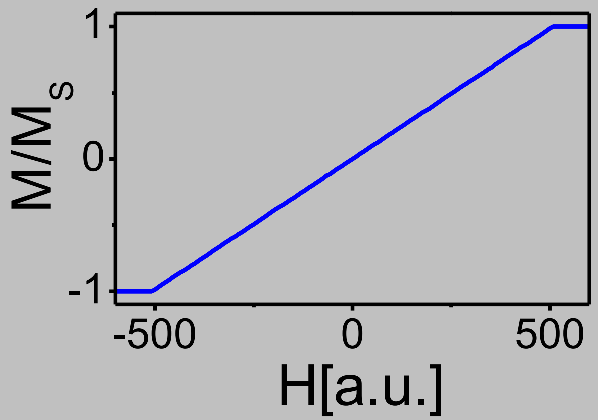
$$R = R_0 - \Delta R \cos(\varphi_{Co-NiFe})$$

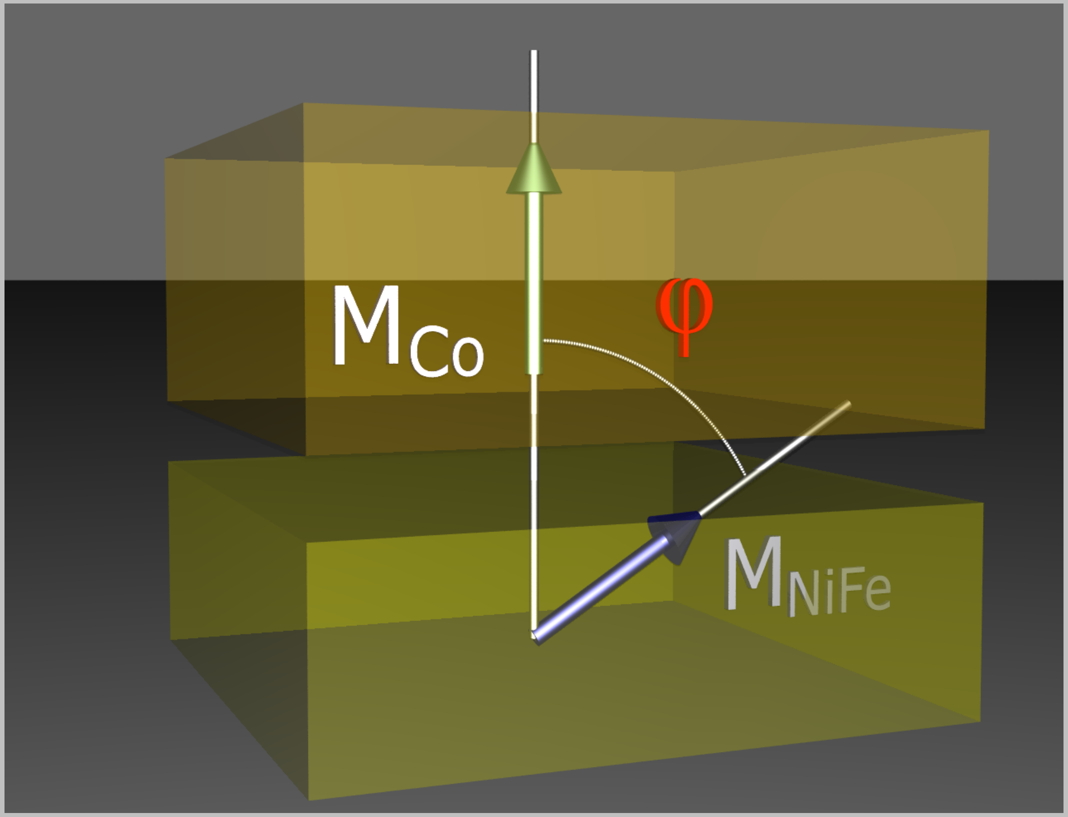
$$\varphi_{Co-NiFe} \propto H$$

Giant Magnetoresistance in NiFe/Au/Co/Au-model



$$\Delta R \propto \cos(\varphi)$$

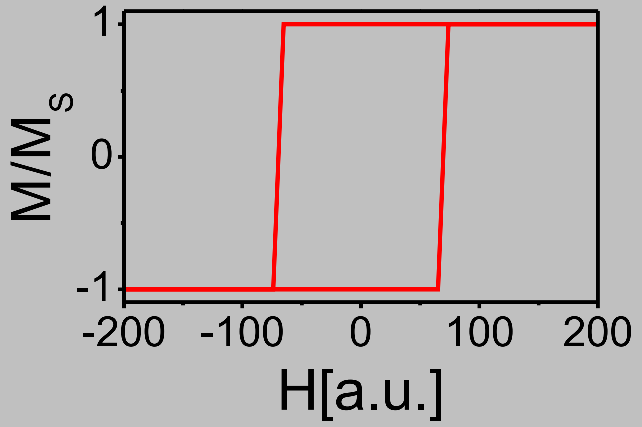


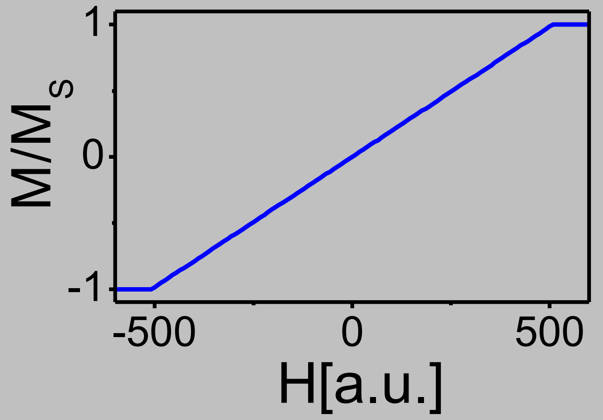


Model assumptions:

- magnetic moments in Co layers are perpendicular to the plane of the sample
- NiFe layer: easy-plane shape anizotropy
- magnetic field applied perpendicularly

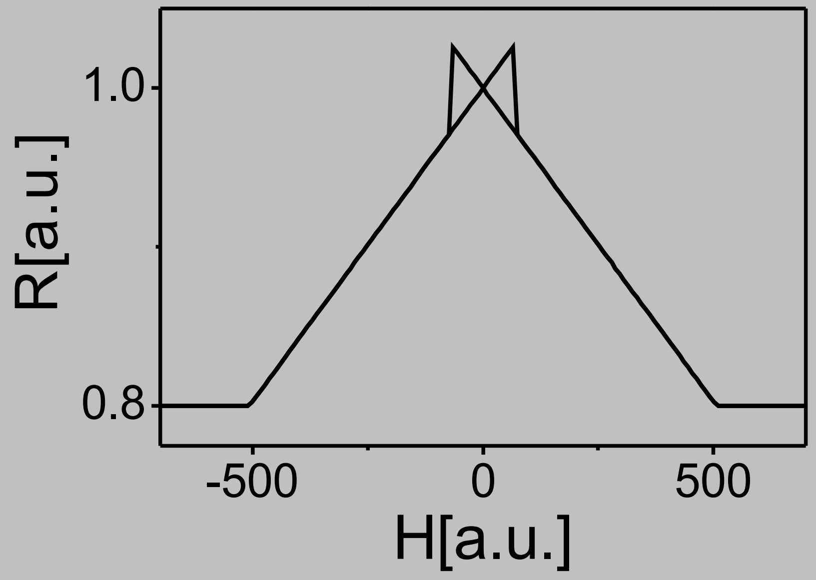
Giant Magnetoresistance in NiFe/Au/Co/Au-model





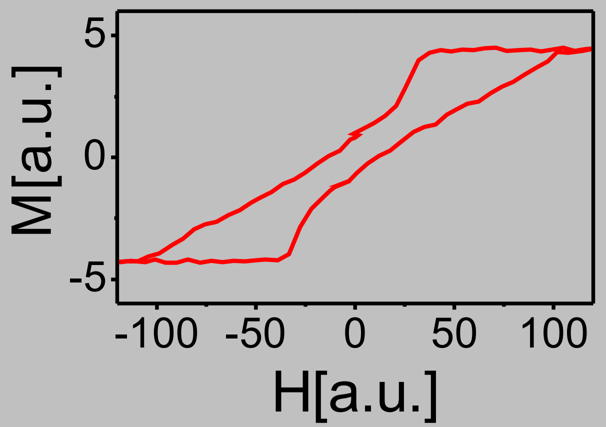
$$\Delta R \propto \cos(\varphi)$$

$$R(H)=a(R_0-\Delta R\cdot\cos(\varphi))+(1-a)(R_0+\Delta R\cdot\cos(\varphi))$$

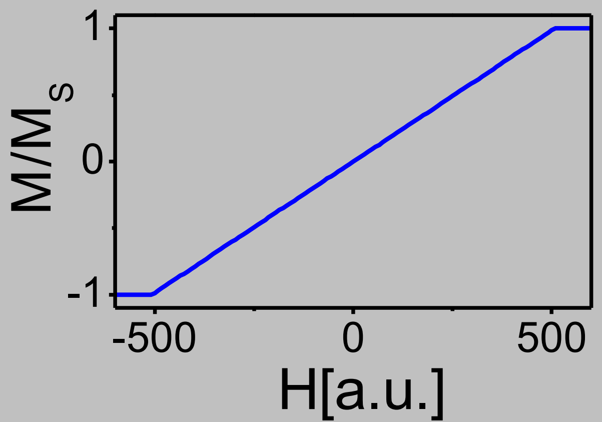


$$a(H)=\frac{1}{2}\left(\frac{M^{Co}(H)}{M_S^{Co}}+1\right)$$

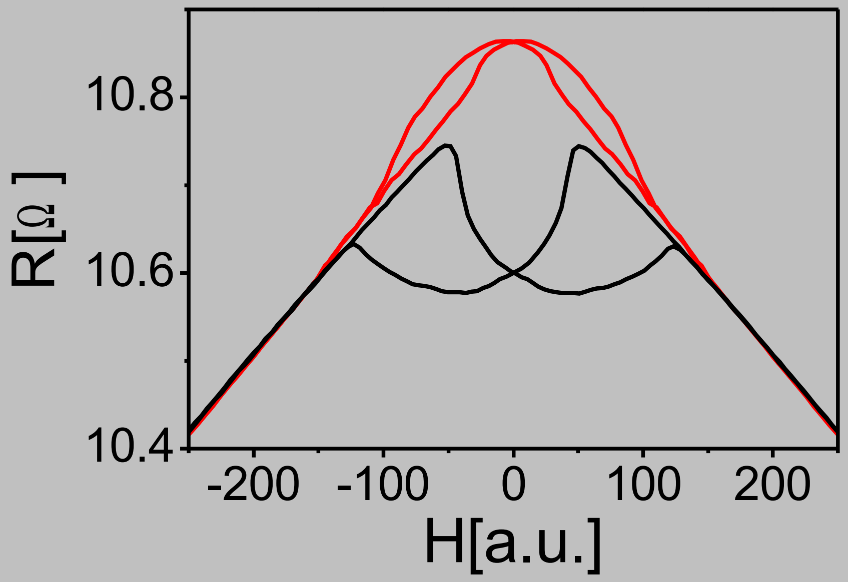
Giant Magnetoresistance in NiFe/Au/Co/Au-model



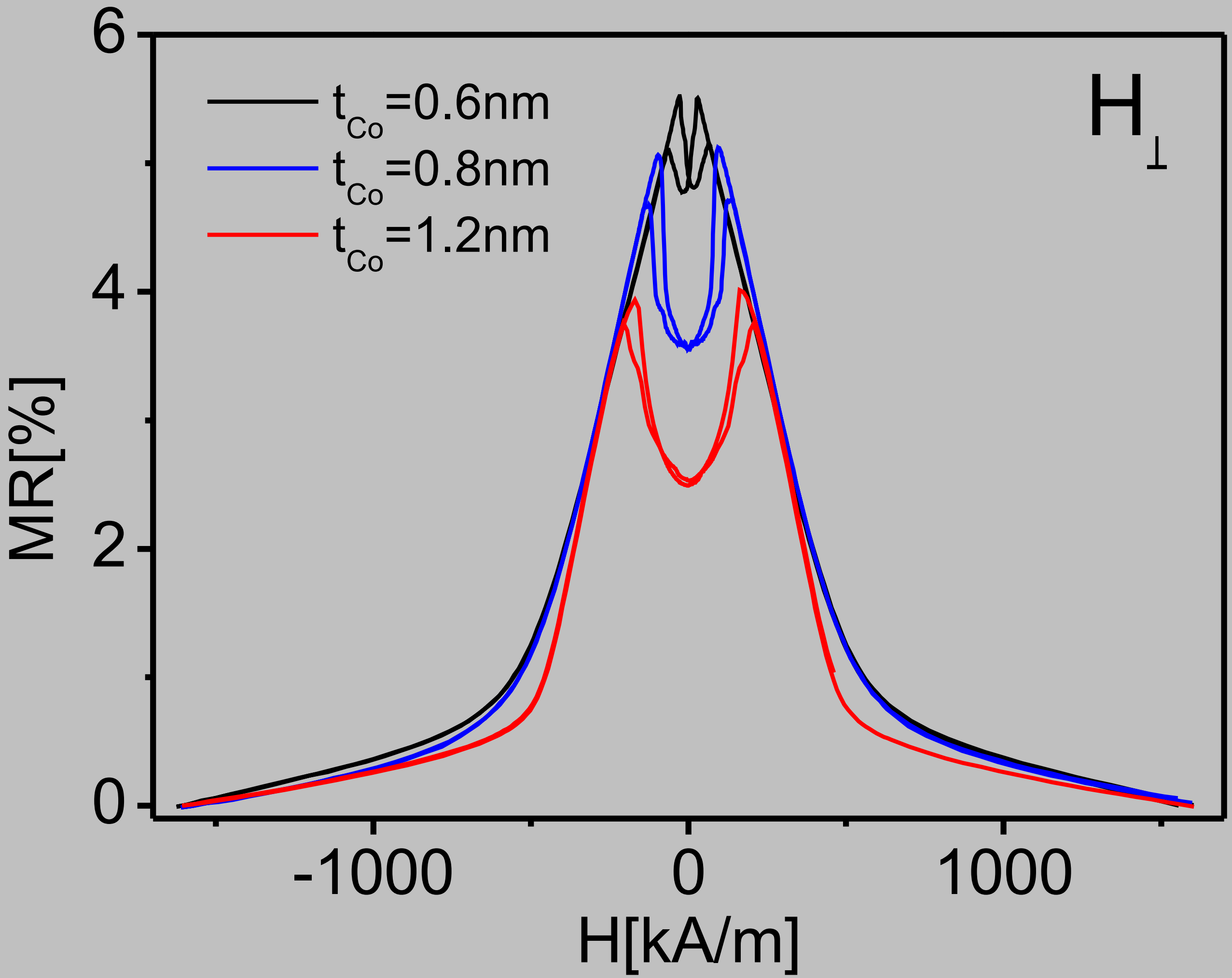
$$\Delta R \propto \cos(\varphi)$$



The independent reversal of Co i NiFe does not result in the local minimum of resistance



Giant Magnetoresistance in NiFe/Au/Co/Au

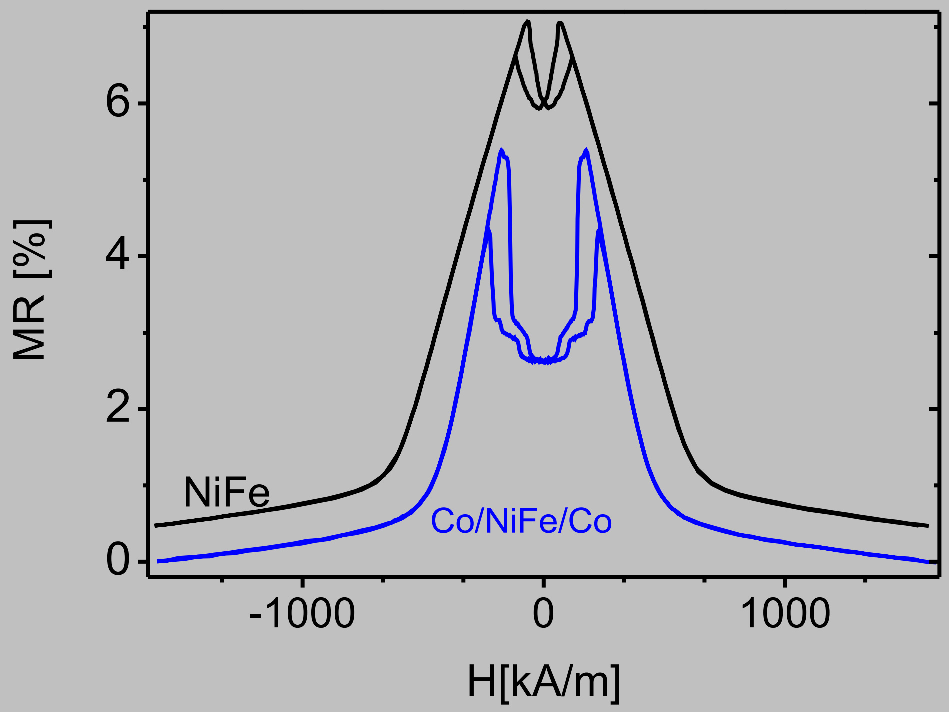


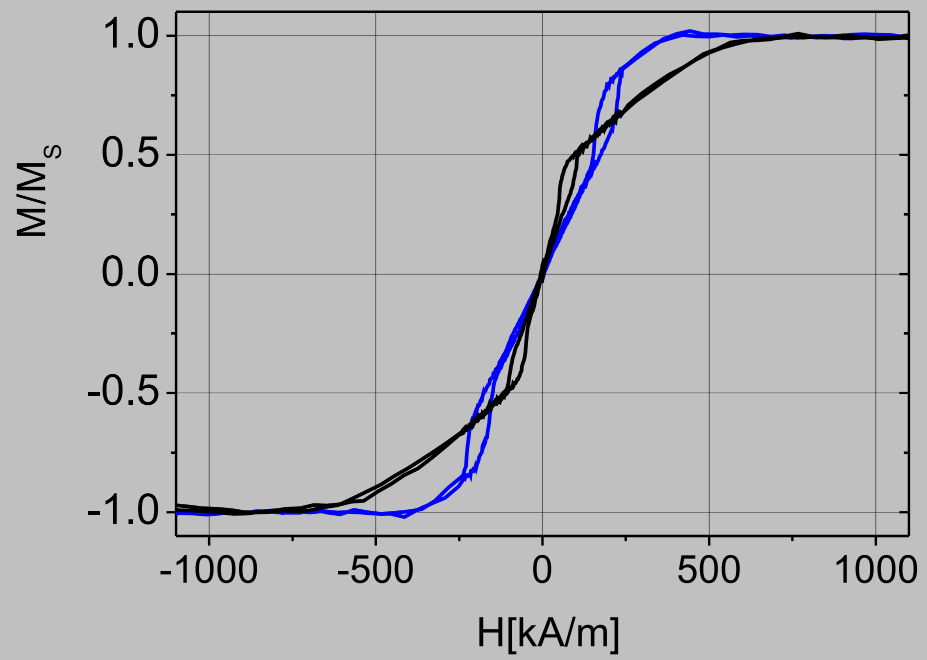
A relative "depth" of resistance minimum is a strong function of Co layers thickness.

$[Ni_{80}Fe_{20}(2\ nm)/Au(1.9\ nm)/Co(\boldsymbol{t}_{\mathbf{Co}})/Au(1.9\ nm)]_{10}$

Modification of the structure of easy-plane anisotropy layer

$[Co_1/Ni_{80}Fe_{20}/Co_1/Au/Co/Au]_N$

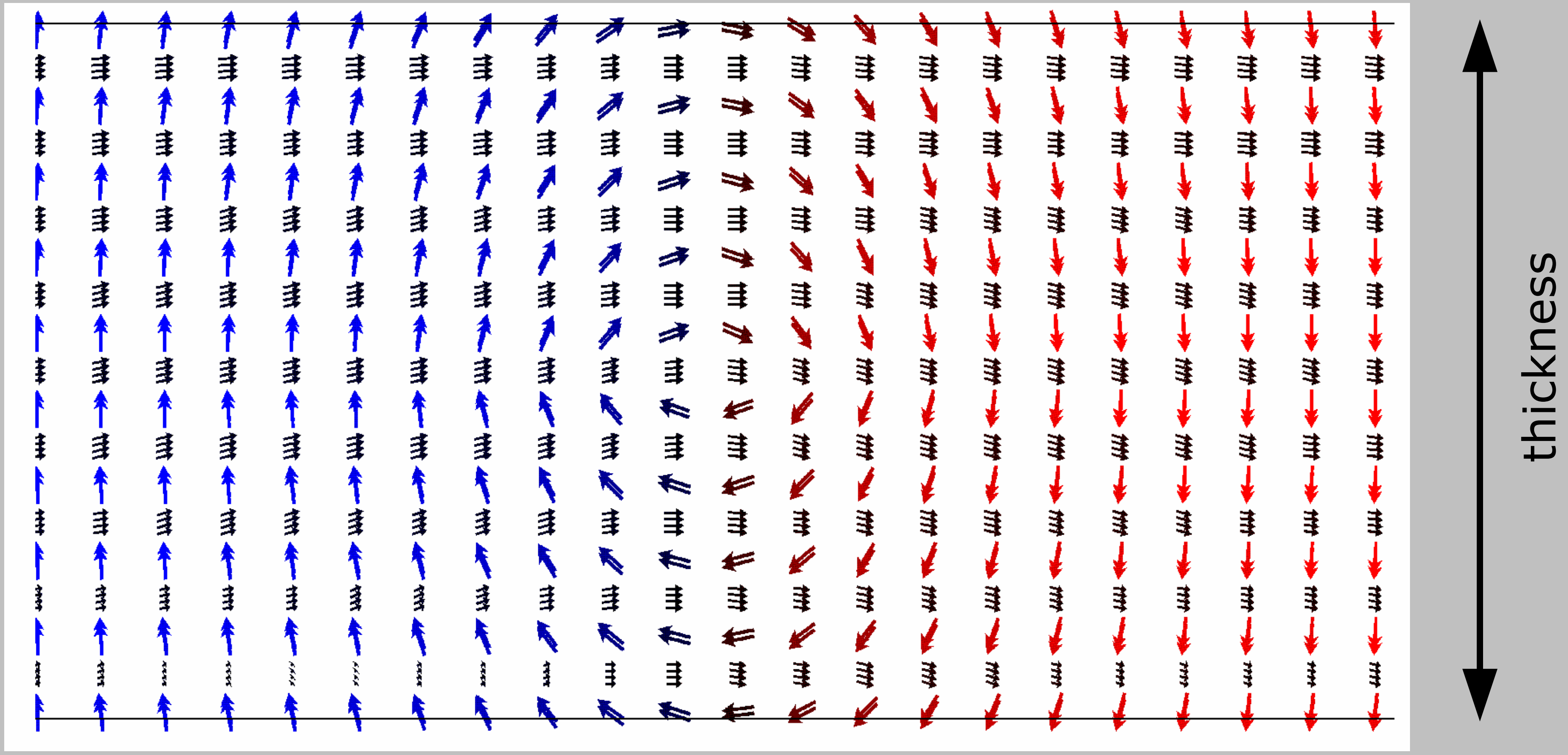




NiFe layer was replaced by a Co/NiFe/Co hybrid trilayer – this leads to the decrease of the effective easy-plane anisotropy.

The local minima of resistance are more pronounced.

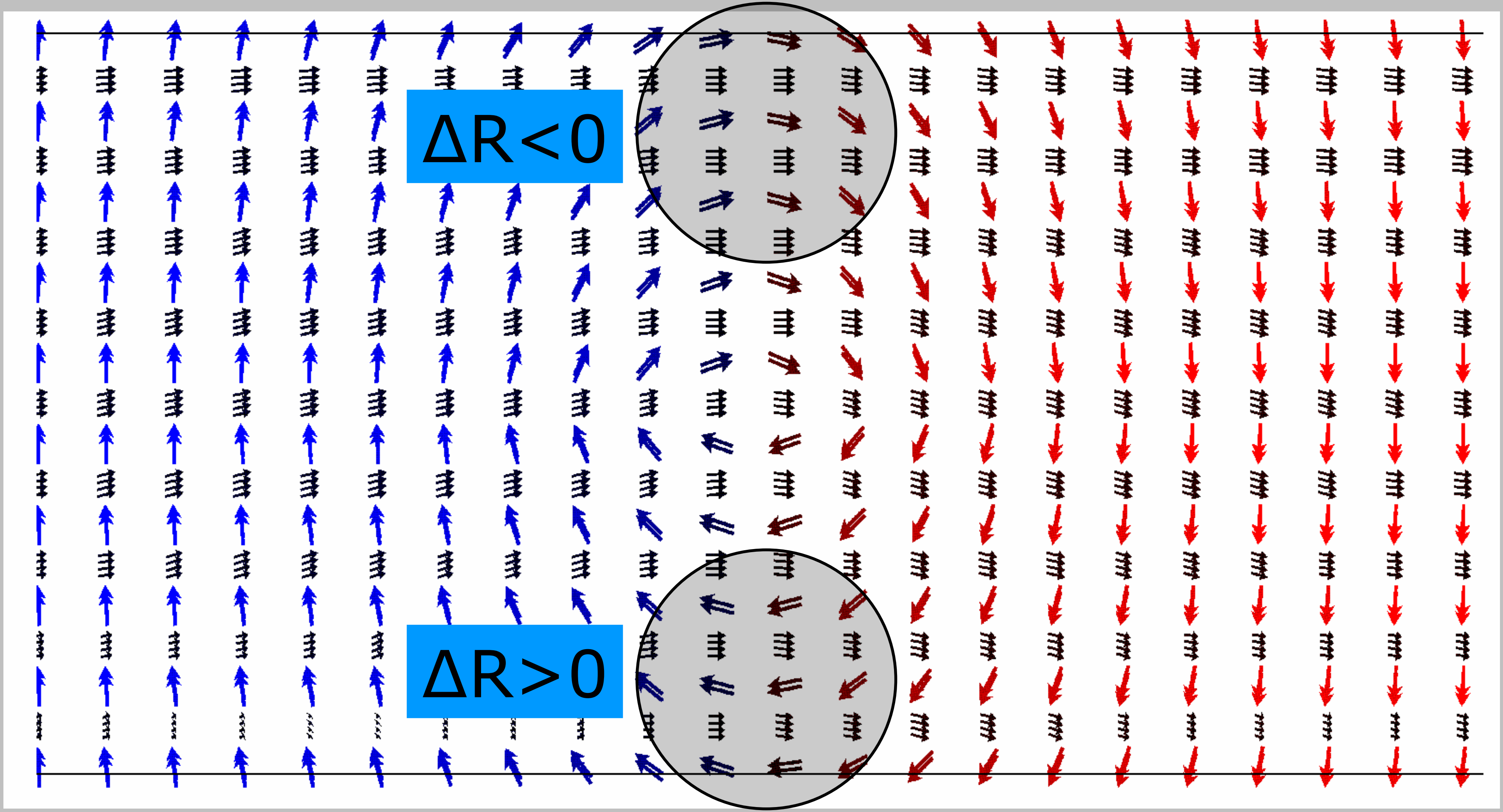
The domain structure of NiFe/Au/Co/Au - simulation*



[Co(1nm)/Au(1.5nm)/$Ni_{80}Fe_{20}$(2 nm)/Au(1.5 nm)$]_9$/Co(1nm) $H=0$

*Simulation with free oommf package from NIST; (1×1 μm^2)×55nm; Co domains 200 nm wide; α=0.5; regular mesh with cell size of (5×0.5×50nm^3); stiffness: Co: 30e-12 J/m, NiFe: 13e-12 J/m

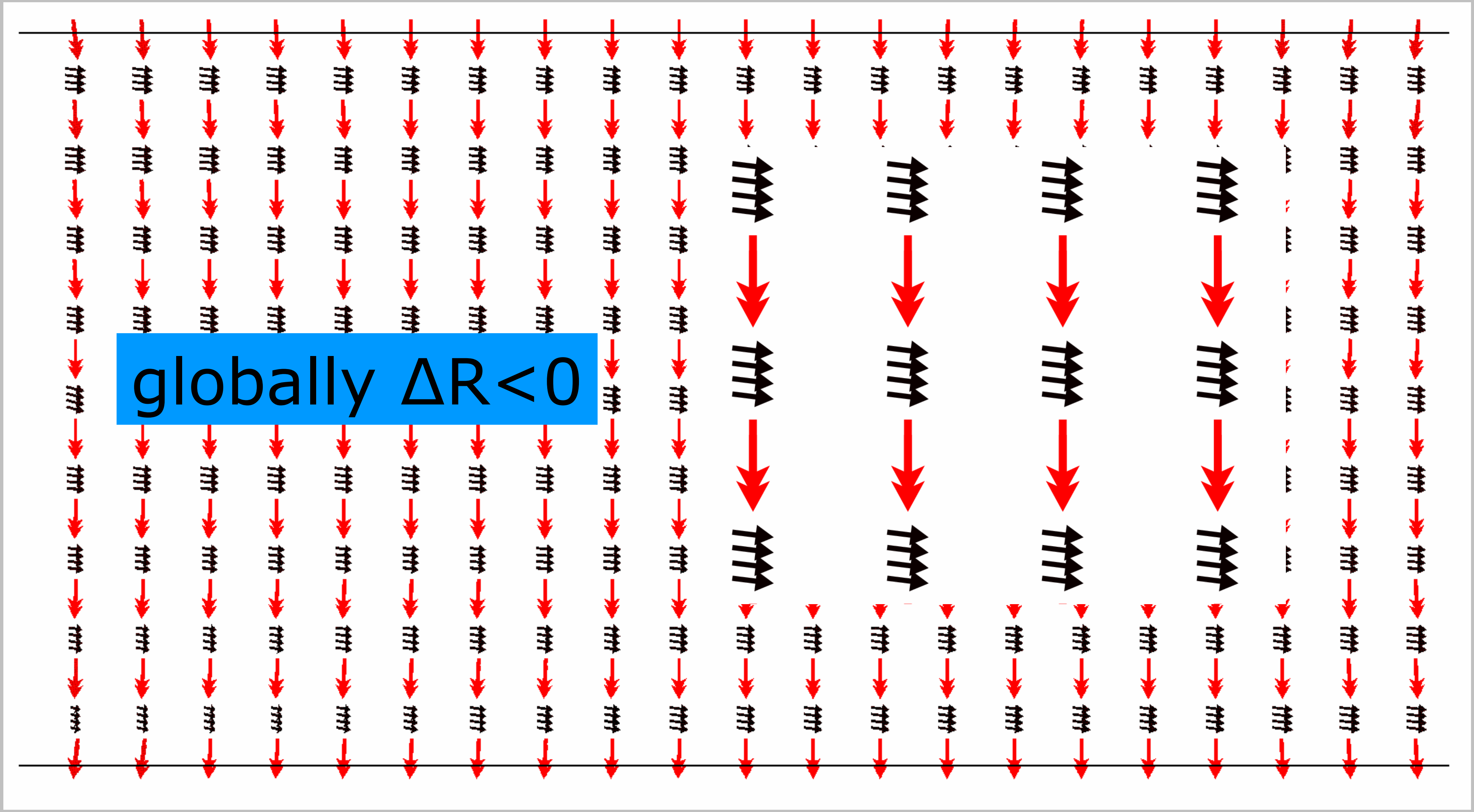
The domain structure of NiFe/Au/Co/Au - simulation



$$\Delta R \propto \cos(\varphi)$$

$H=0$

The domain structure of NiFe/Au/Co/Au - simulation

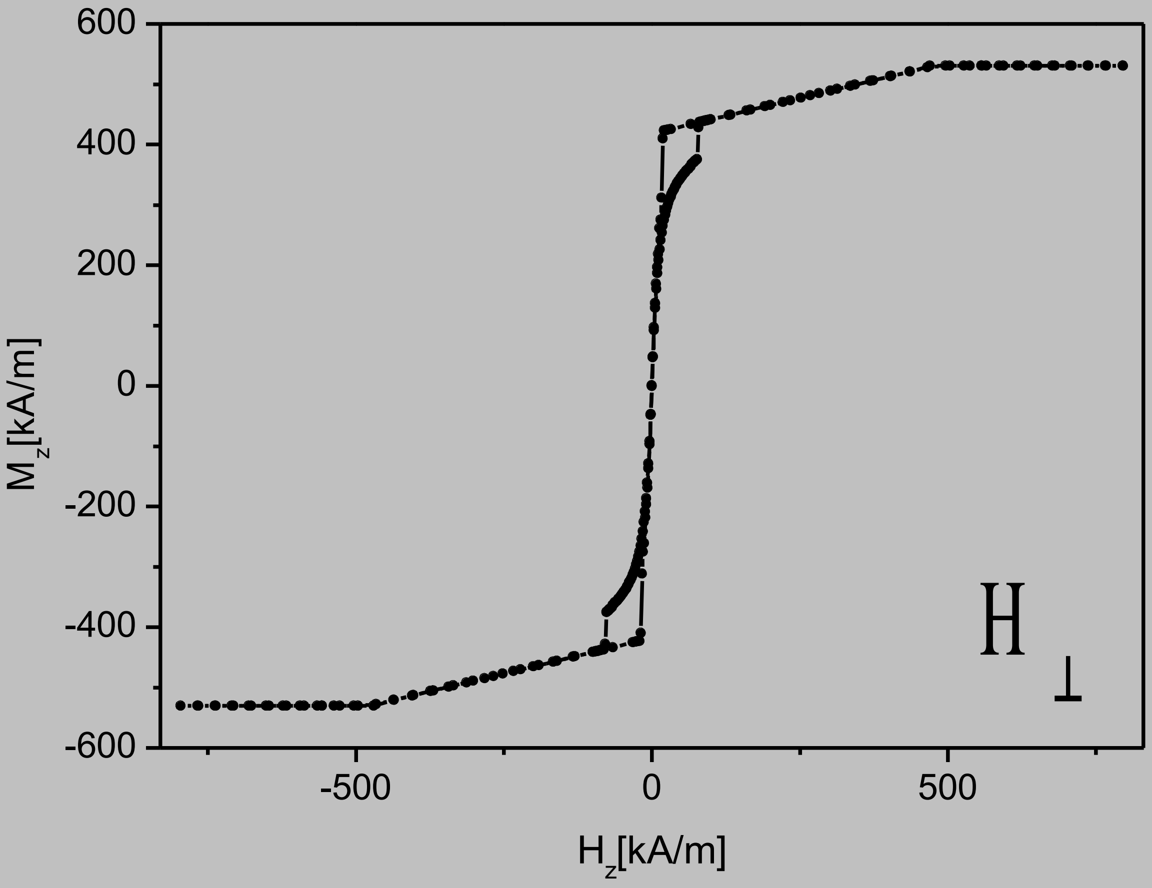


globally ΔR<0

$$\Delta R \propto \cos(\varphi)$$

$H=0$

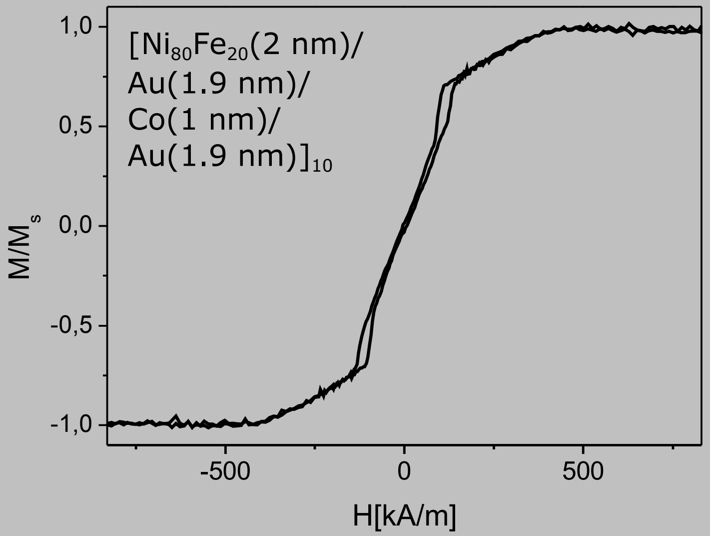
The GMR of NiFe/Au/Co/Au - simulation*



Co-perpendicular anisotropy

NiFe-shape anisotropy

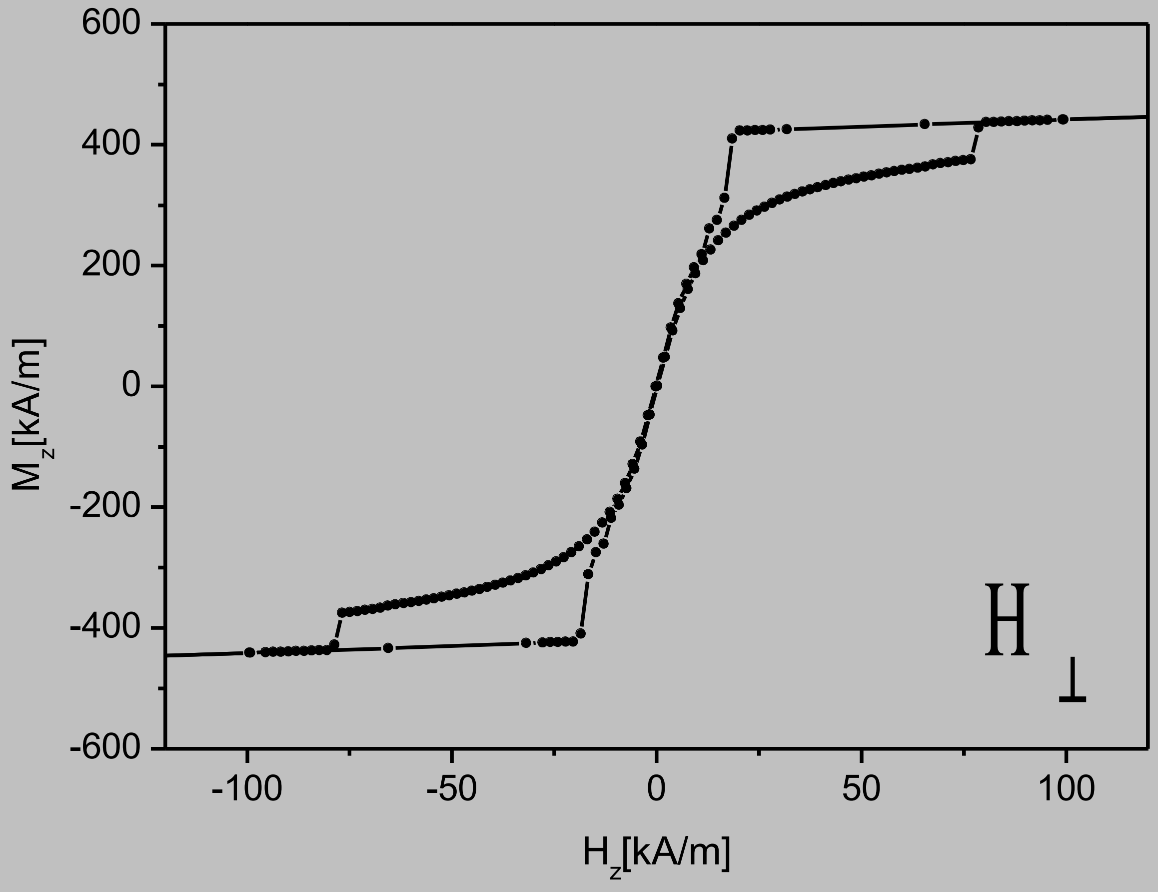
measurement:



$[Co(1nm)/spacer(1nm)/NiFe(1nm)/spacer(1nm)]_4/Co(1nm)$

*Simulation with free oommf package from NIST (M.J. Donahue and D.G. Porter);
α=0.5;regular mesh with cell size of (5×**20000**×1nm^3);
stiffness: Co: 30e-12 J/m, NiFe: 13e-12 J/m

The GMR of NiFe/Au/Co/Au - simulation



Co-perpendicular anisotropy

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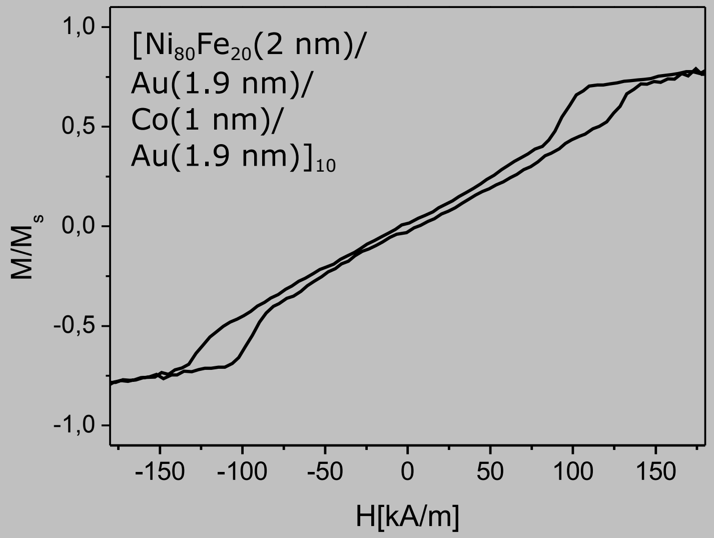
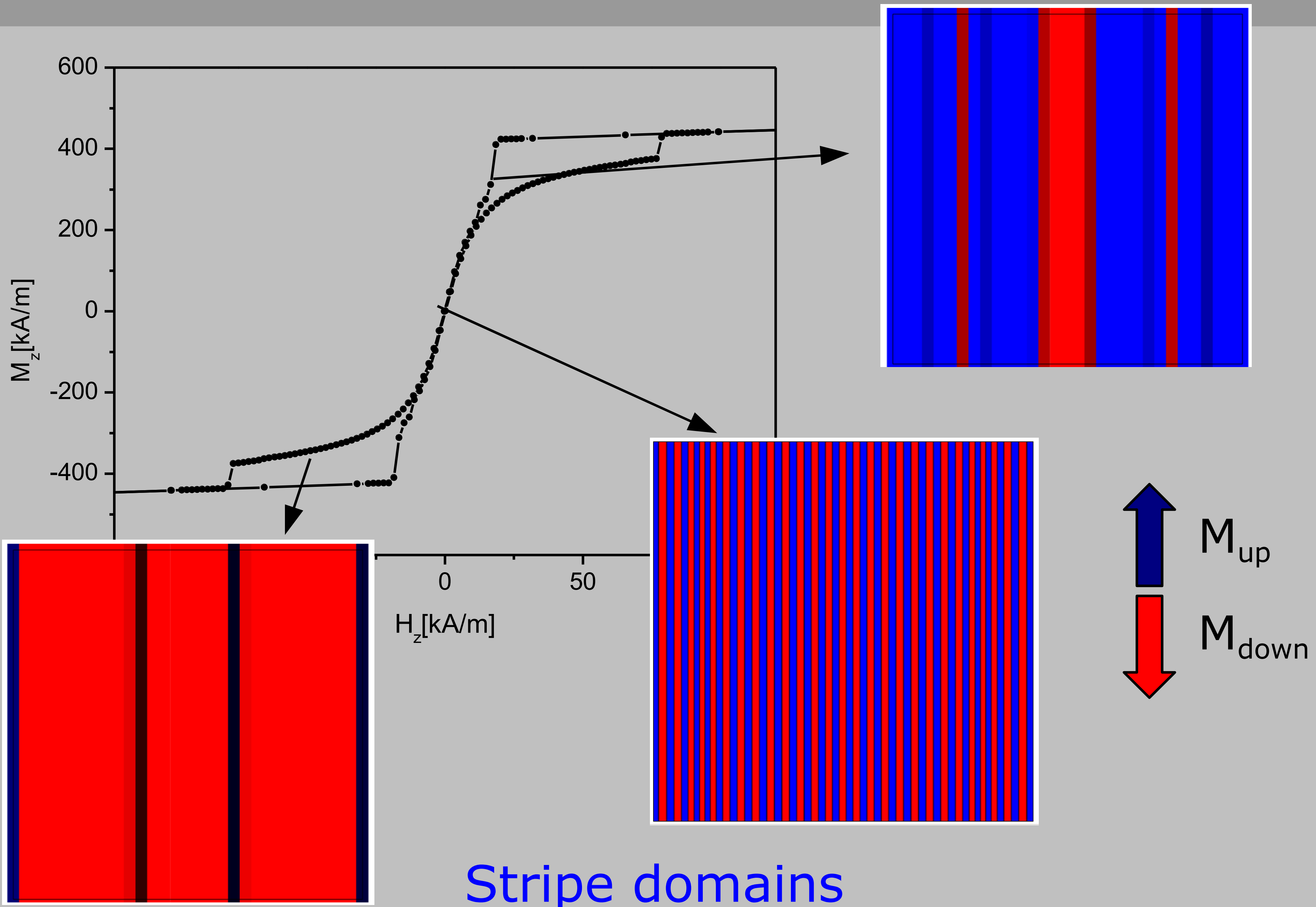


$[Co(1nm)/spacer(1nm)/NiFe(1nm)/spacer(1nm)]_4/Co(1nm)$

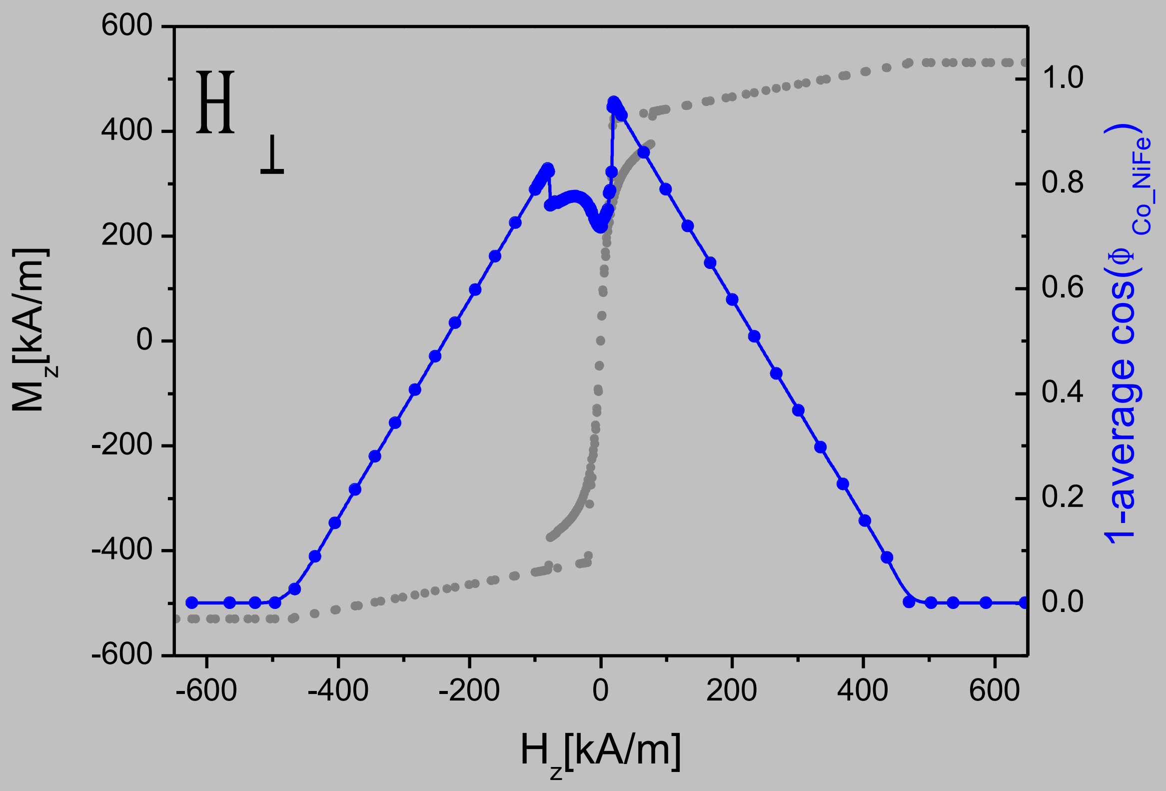
No attempts were made to exactly mirror the M(H) dependence ,i.e. , nucleation and annihilation fields.

The GMR of NiFe/Au/Co/Au - simulation

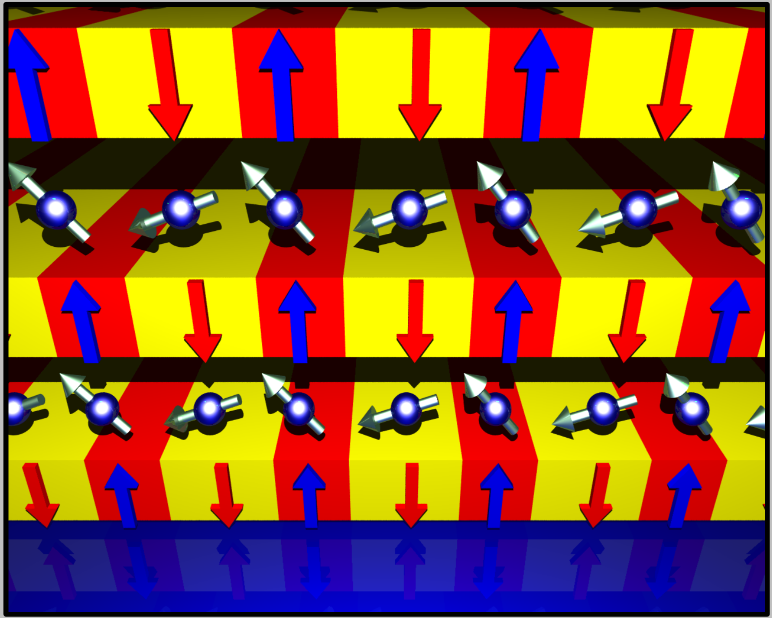


Stripe domains

The GMR of NiFe/Au/Co/Au - simulation

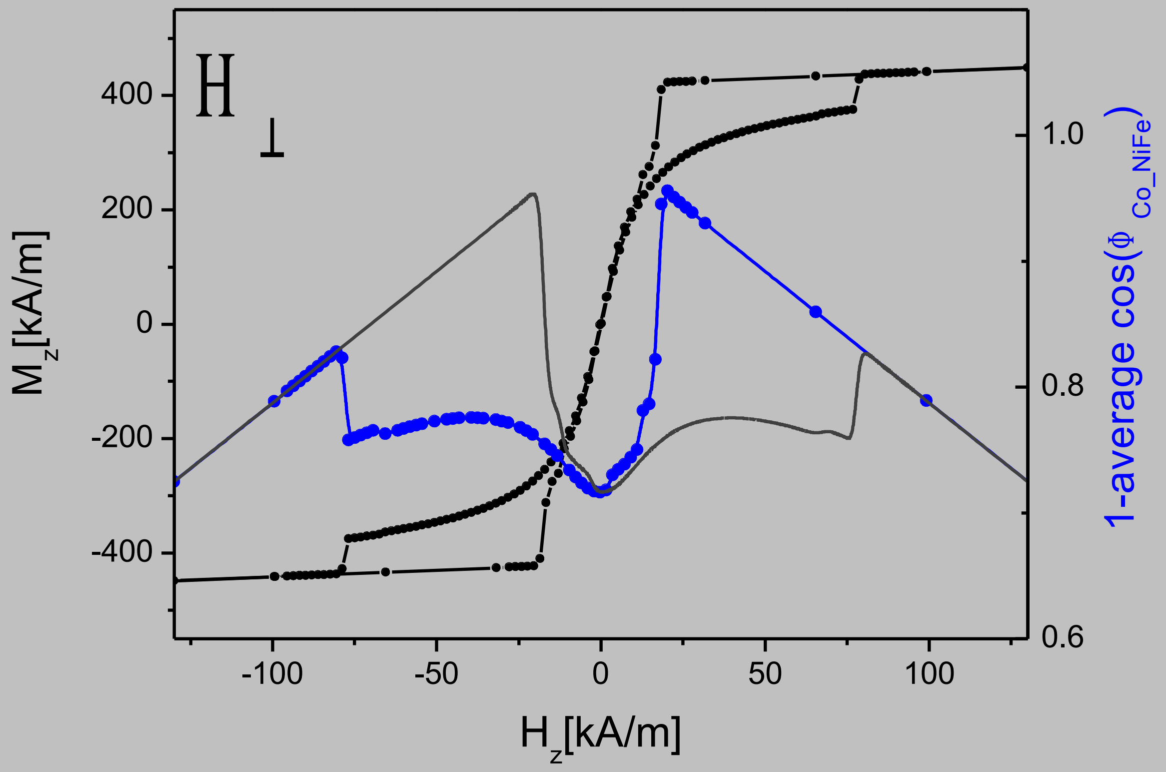


The GMR(H) dependence was calculated as proportional to an average cosine of the angle between magnetic moment direction of juxtaposed NiFe and Co cells.

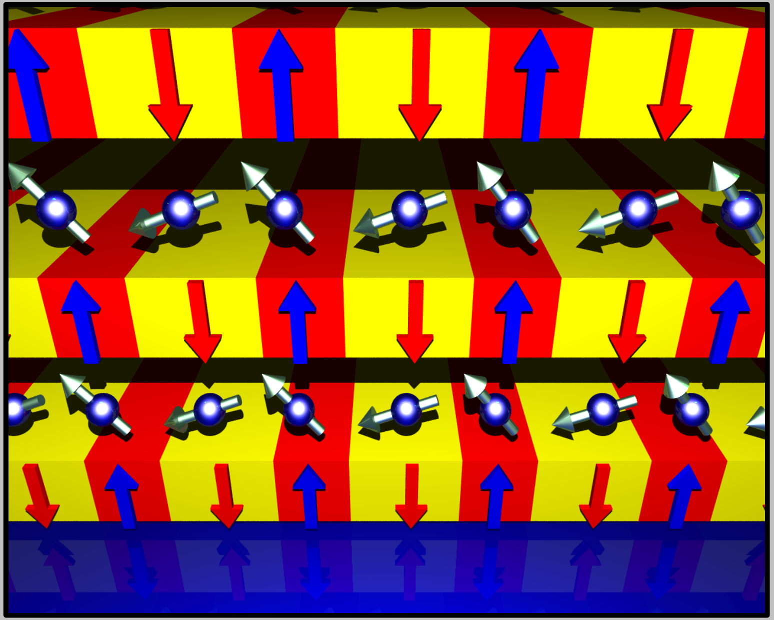


Giant magnetoresistance dependencies of NiFe/Au/Co/Au multilayers can be approximated from micromagnetic simulations.

The GMR of NiFe/Au/Co/Au - simulation

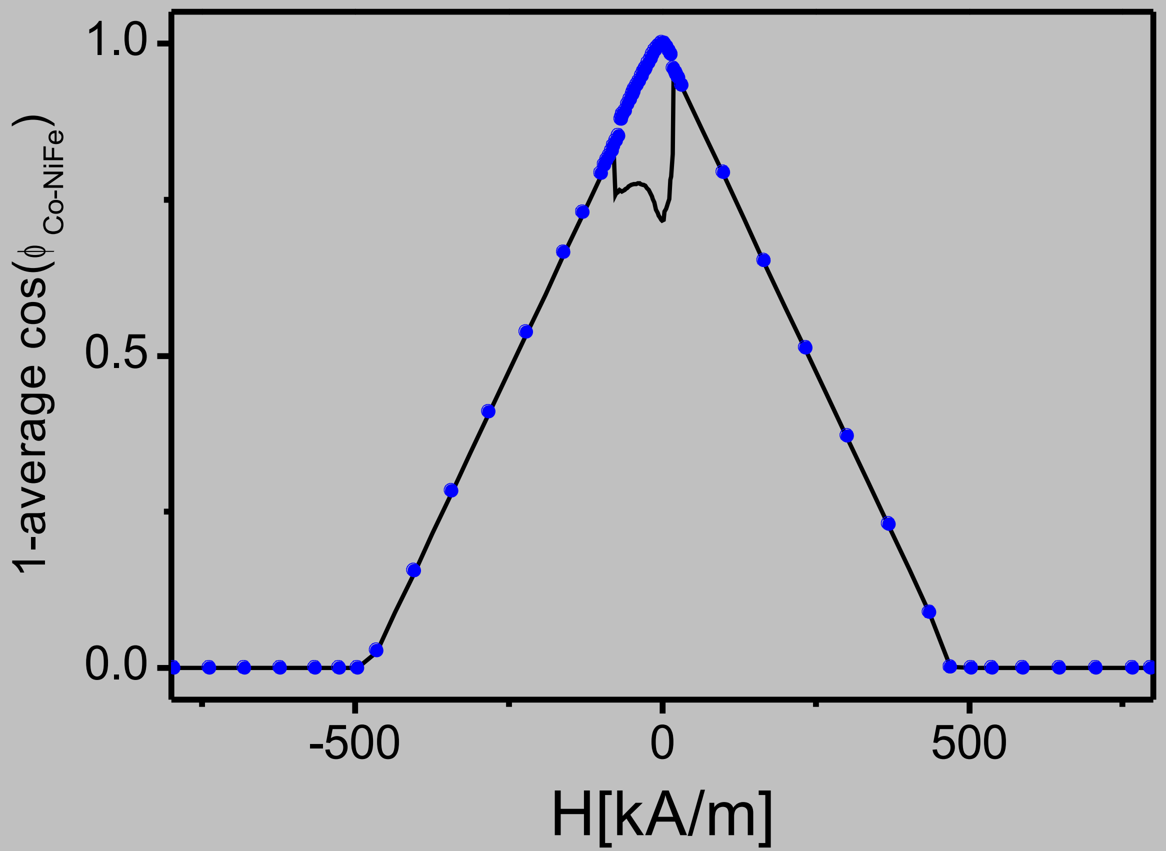


The GMR(H) dependence was calculated as proportional to an average cosine of the angle between magnetic moment direction of juxtaposed NiFe and Co cells.



Giant magnetoresistance dependencies of NiFe/Au/Co/Au multilayers can be approximated from micromagnetic simulations.

The GMR of NiFe/Au/Co/Au - simulation

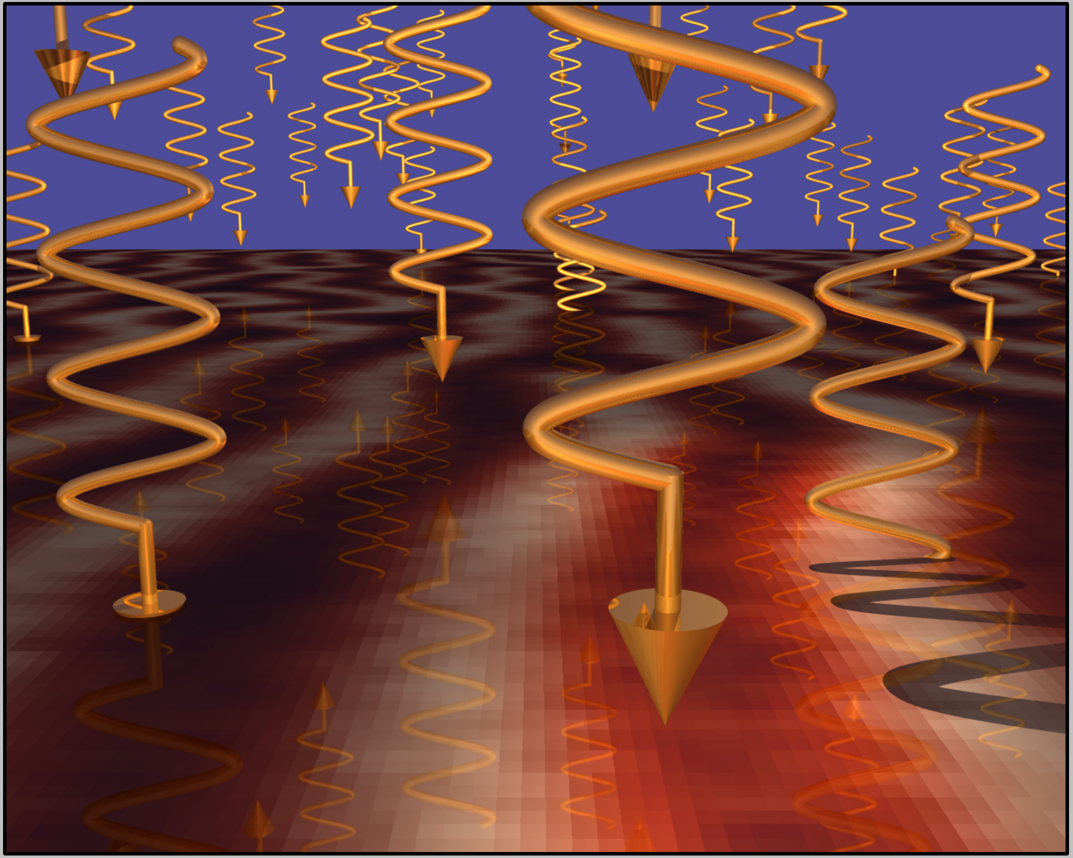


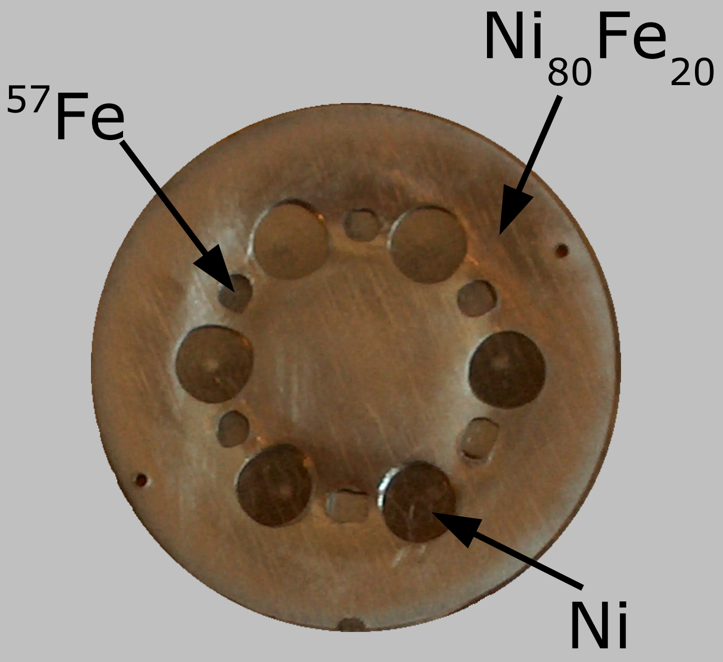
The GMR(H) dependence was calculated as proportional to an average cosine of the angle between magnetic moment direction of juxtaposed NiFe and Co cells.

● ● ● ● ● – no coupling

Without magnetostatic coupling between Co and NiFe layers there are no local minima of resistance.

Mössbauer spectroscopy



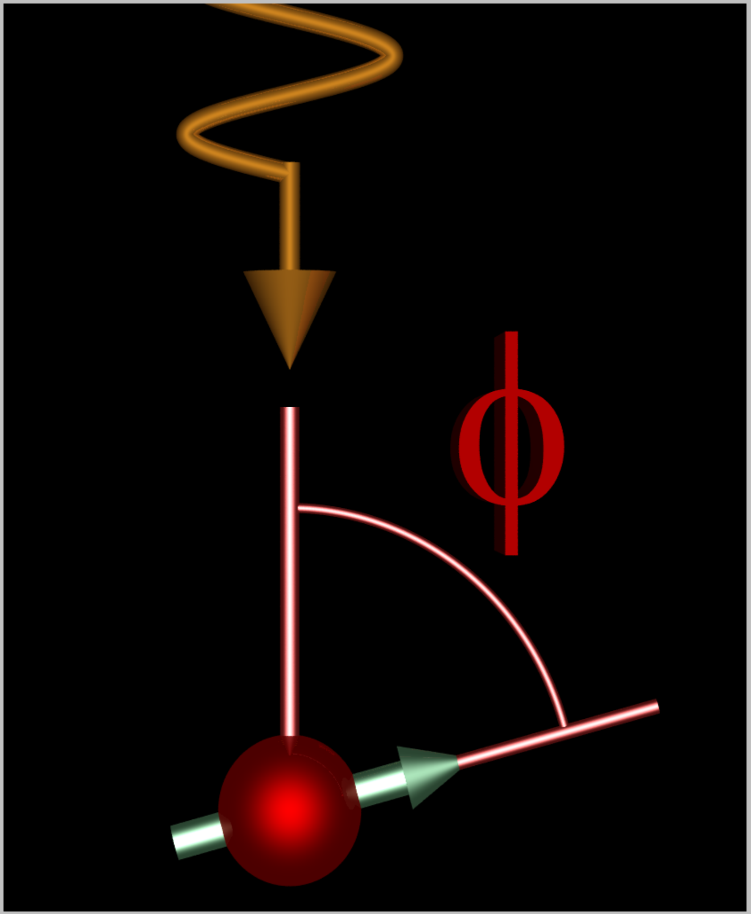


Conversion electron Mössbauer spectroscopy (CEMS)
^{57}Co source
^{57}Fe 95.3 at.%

^{57}Fe

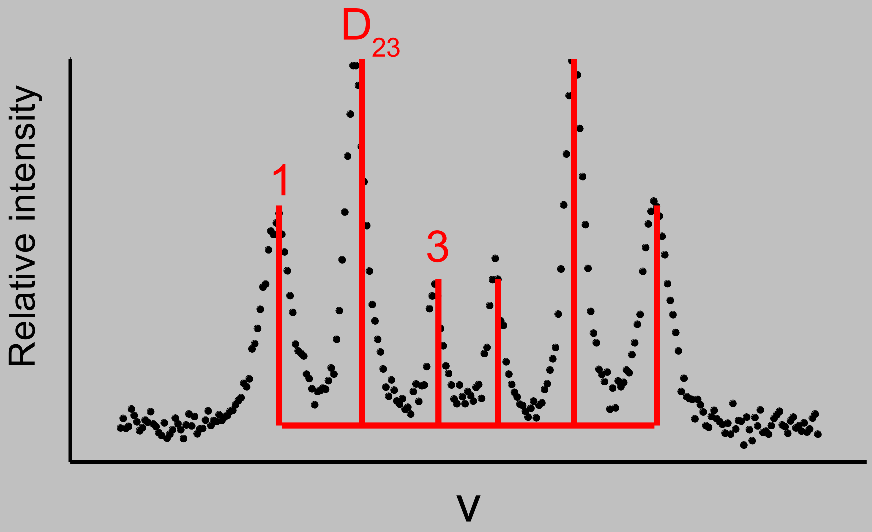
$[Ni_{80}Fe_{20}/Au/Co/Au]_{10}$

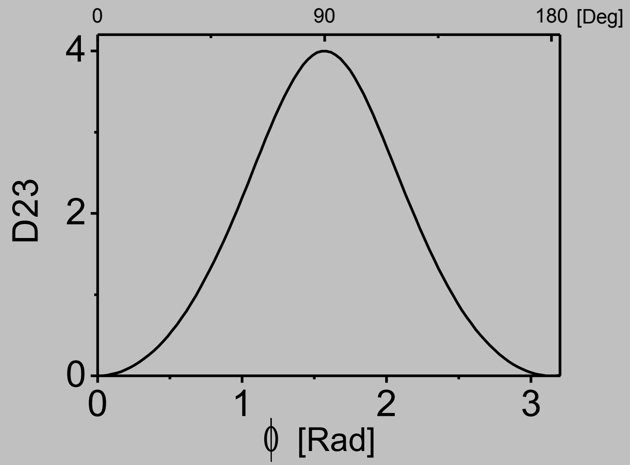
Mössbauer spectroscopy



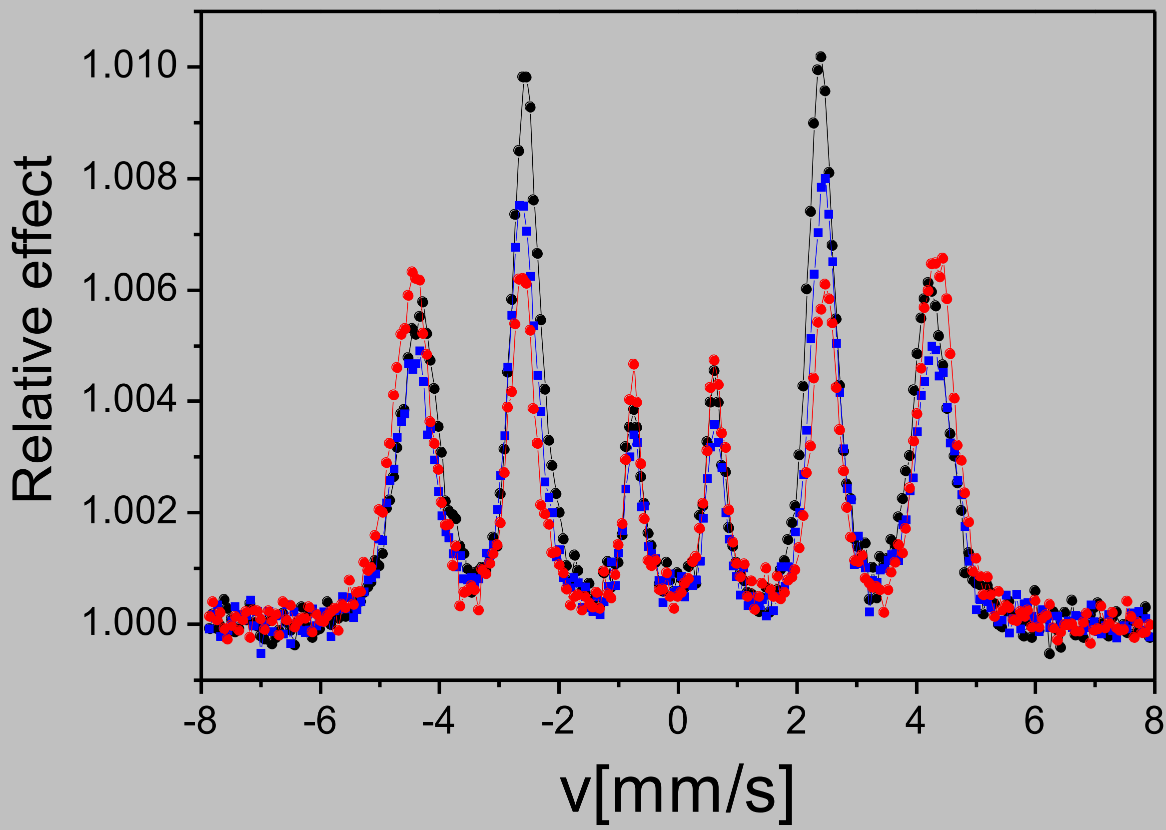
Relative intensities of the hyperfine lines vary with the angle φ between the incident γ-ray and the magnetic moment.

$$D_{23} = \frac{4\sin^2(\phi)}{(1+\cos^2(\phi))}$$





Mössbauer spectroscopy

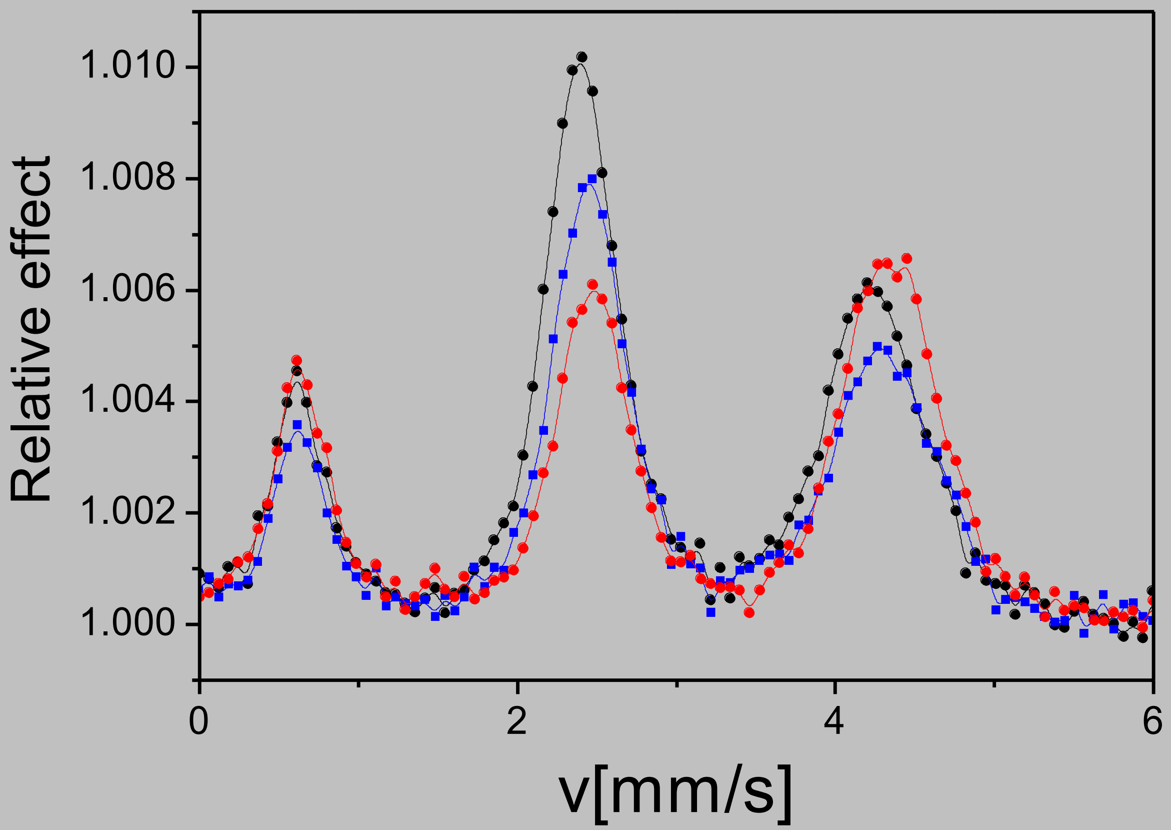


[$Ni_{80}Fe_{20}$(3.2 nm)/Au(2.4 nm)/Co(0.8 nm)/Au(2.4 nm)$]_{10}$

[$Ni_{80}Fe_{20}$(2.6 nm)/Co(0.6 nm)/Au(2.4 nm)/Co(0.8 nm)/Au(2.4 nm)$]_{10}$

[Co(0.6 nm)/$Ni_{80}Fe_{20}$(2.6 nm)/Au(2.4 nm)/Co(0.8 nm)/Au(2.4 nm)$]_{10}$

Mössbauer spectroscopy

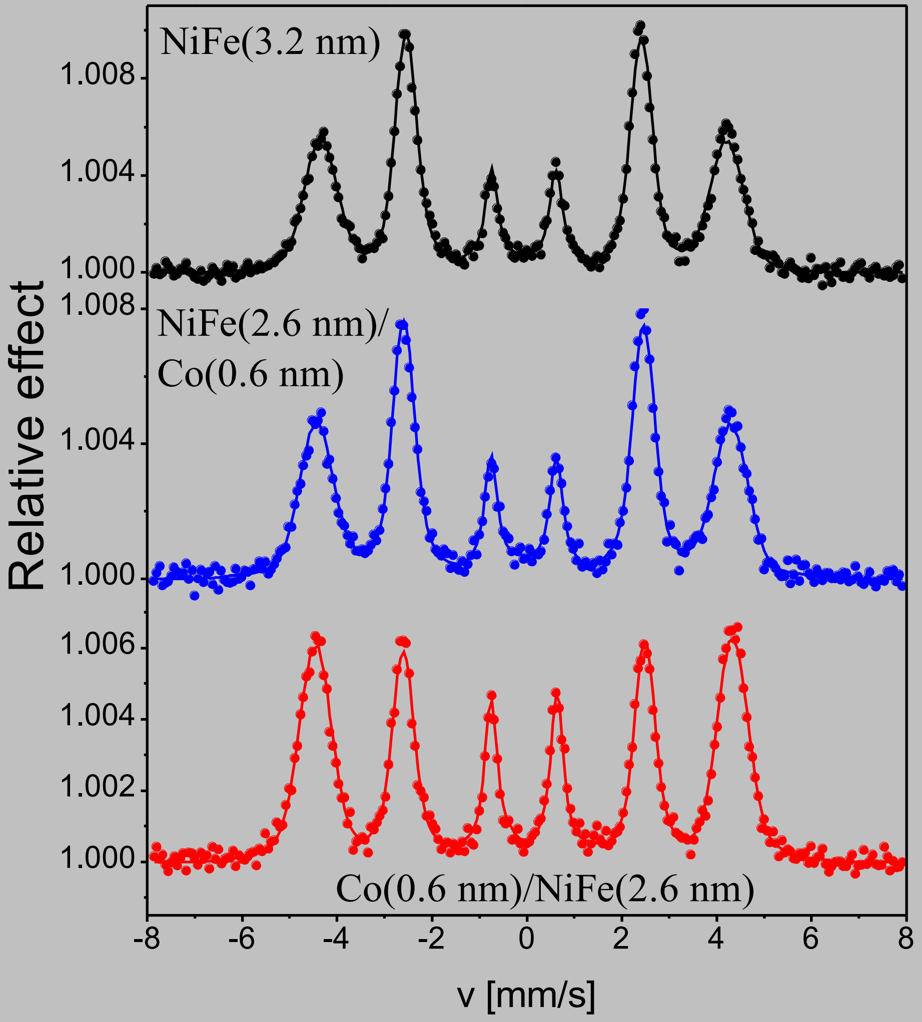


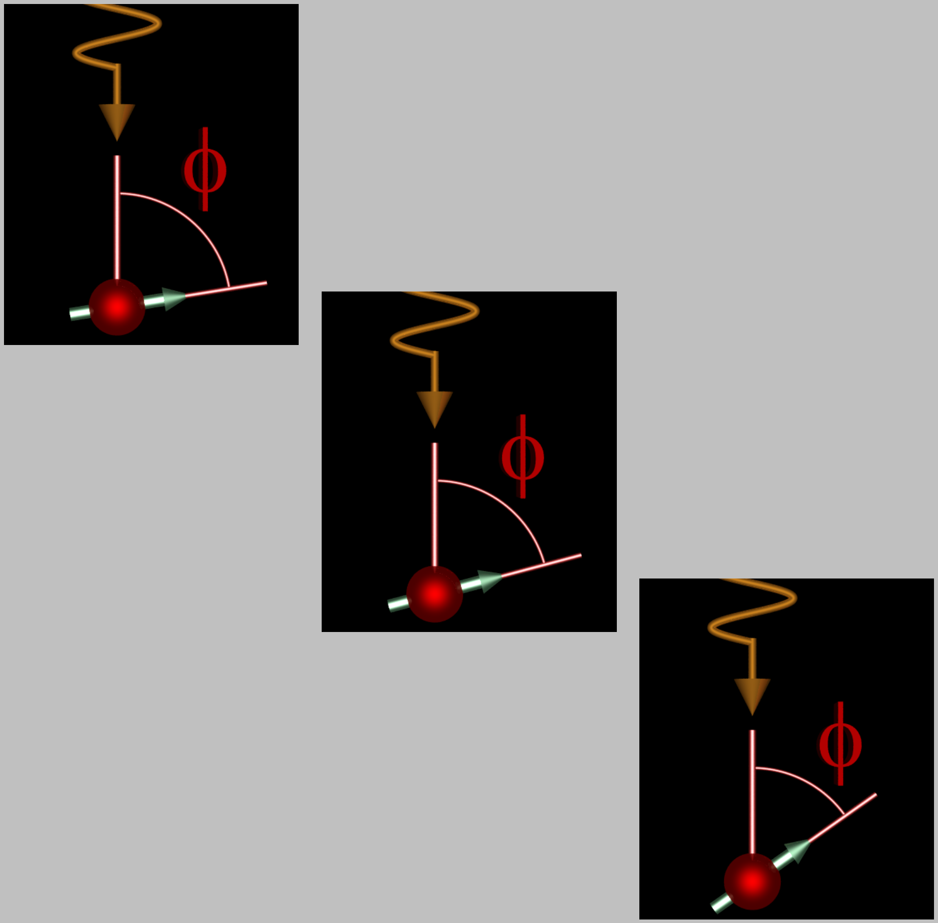
$[Ni_{80}Fe_{20}(3.2\ nm)/Au(2.4\ nm)/Co(0.8\ nm)/Au(2.4\ nm)]_{10}$

$[Ni_{80}Fe_{20}(2.6\ nm)/Co(0.6\ nm)/Au(2.4\ nm)/Co(0.8\ nm)/Au(2.4\ nm)]_{10}$

$[Co(0.6\ nm)/Ni_{80}Fe_{20}(2.6\ nm)/Au(2.4\ nm)/Co(0.8\ nm)/Au(2.4\ nm)]_{10}$

Mössbauer spectroscopy



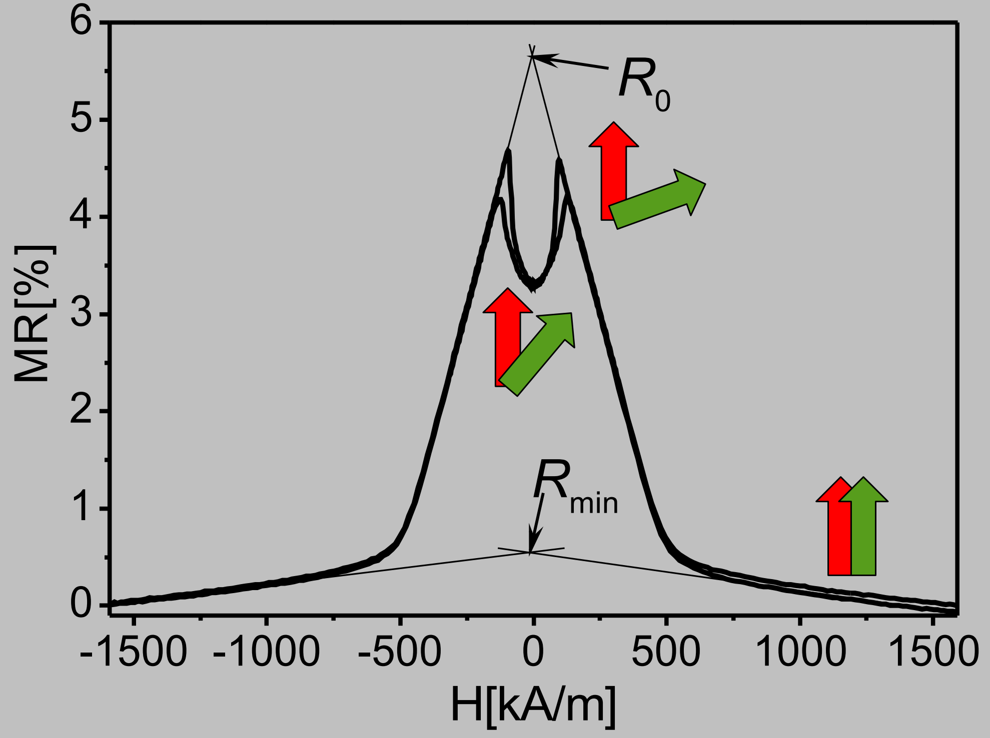


$[\mathrm{Ni}_{80}\mathrm{Fe}_{20}(3.2\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})/\mathrm{Co}(0.8\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})]_{10}$

$[\mathrm{Ni}_{80}\mathrm{Fe}_{20}(2.6\ \mathrm{nm})/\mathrm{Co}(0.6\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})/\mathrm{Co}(0.8\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})]_{10}$

$[\mathrm{Co}(0.6\ \mathrm{nm})/\mathrm{Ni}_{80}\mathrm{Fe}_{20}(2.6\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})/\mathrm{Co}(0.8\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})]_{10}$

Mössbauer spectroscopy

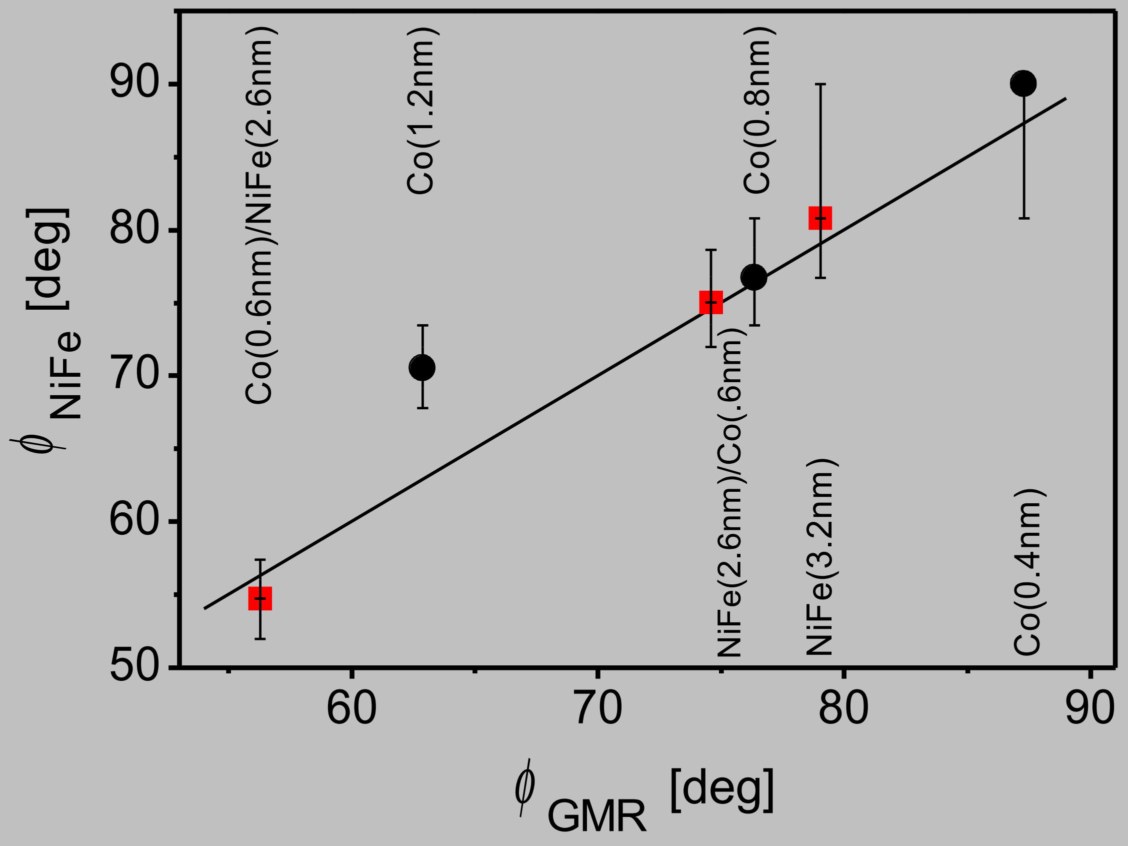


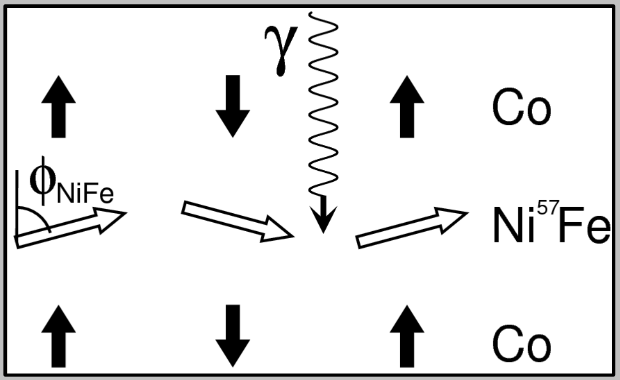
$$R = R_0 - (R_0 - R_{min})\cos(\varphi_{Co-NiFe})$$

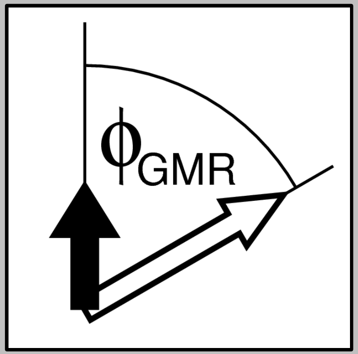
Resistance measurements allow the determination of the average cosine of the angle between magnetic moments of Co and NiFe layers.

$[Ni_{80}Fe_{20}(2\ nm)/Au(2.4\ nm)/Co(1.2\ nm)/Au(2.4\ nm)]_{10}$

Mössbauer spectroscopy versus GMR





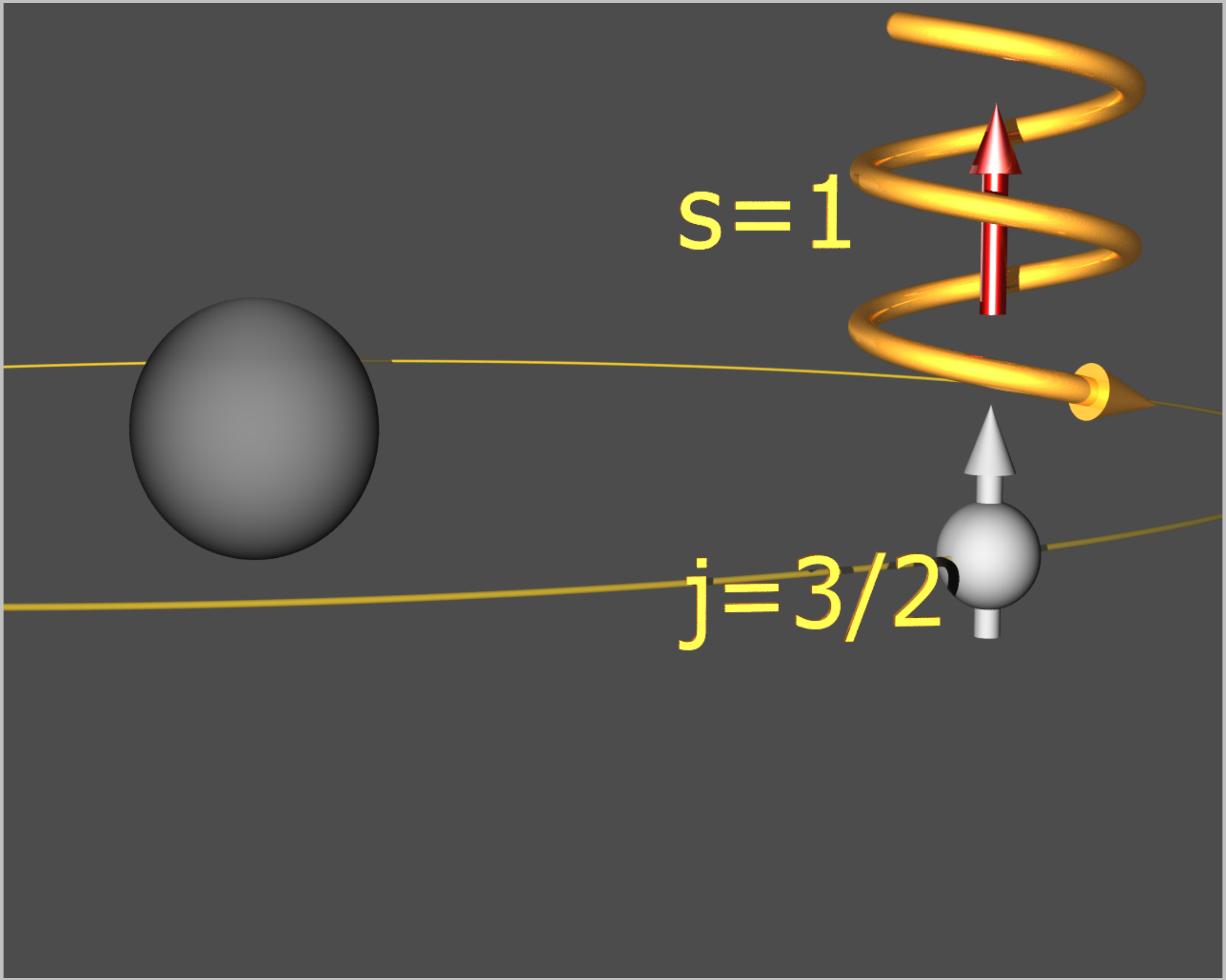


The magnetostatic fields of the Co domains cause the deflection of the magnetic moments of the NiFe layers. The deflection is stronger if the effective easy-plane anisotropy of NiFe layers is weaker.

[**X**/Au(2.4 nm)/Co(0.8 nm)/Au(2.4 nm)]$_{10}$

[Ni$_{80}$Fe$_{20}$(2 nm)/Au(2.4 nm)/**Co**/Au(2.4 nm)]$_{10}$

Soft x-ray resonant magnetic scattering (SXRMS)



Circularly polarized light

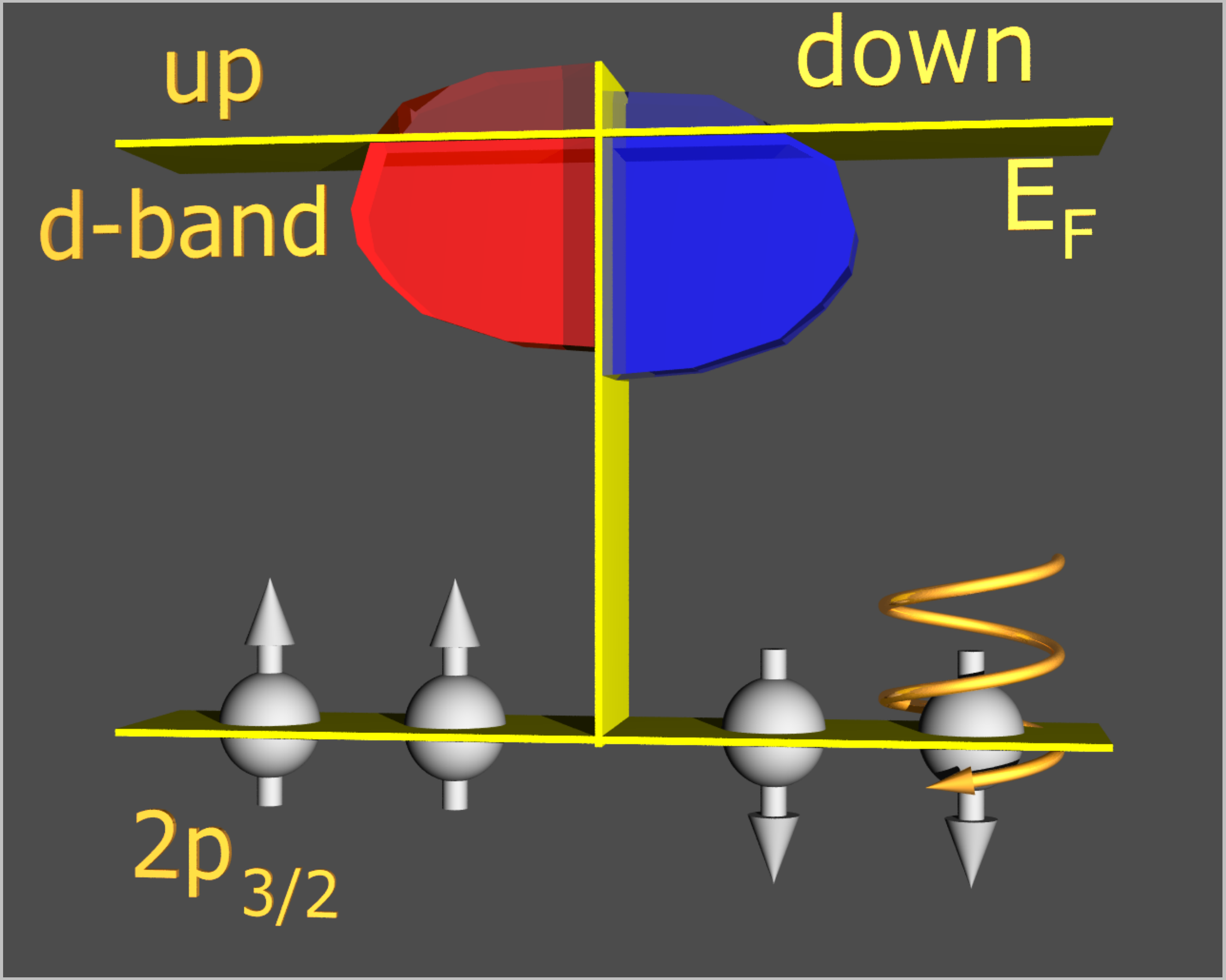
$\lambda \approx 1.4$ nm

interaction with core electrons

photon energy tuned to absorption edge
⇩
elemental selectivity

ALICE diffractometer at the undulator beamline UE56/2-PGM2 at BESSY II (Berlin)

Soft x-ray resonant magnetic scattering (SXRMS)



Circularly polarized light

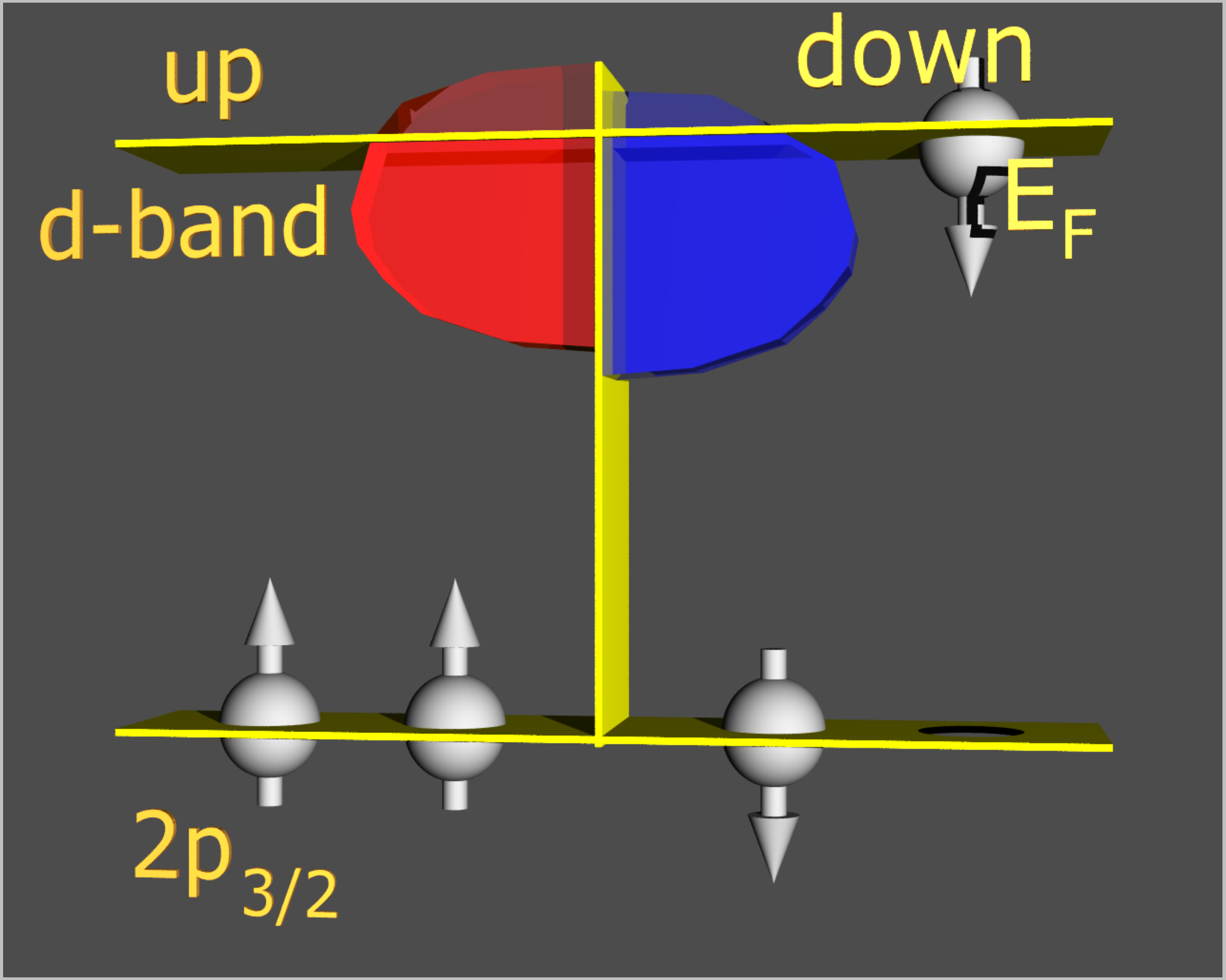
λ≈1.4 nm

interaction with core electrons

photon energy tuned to absorption edge
⇩
elemental selectivity

J. Stöhr, Journal of Electron Spectroscopy and Related Phenomena **75** (1995) 253

Soft x-ray resonant magnetic scattering (SXRMS)



Circularly polarized light

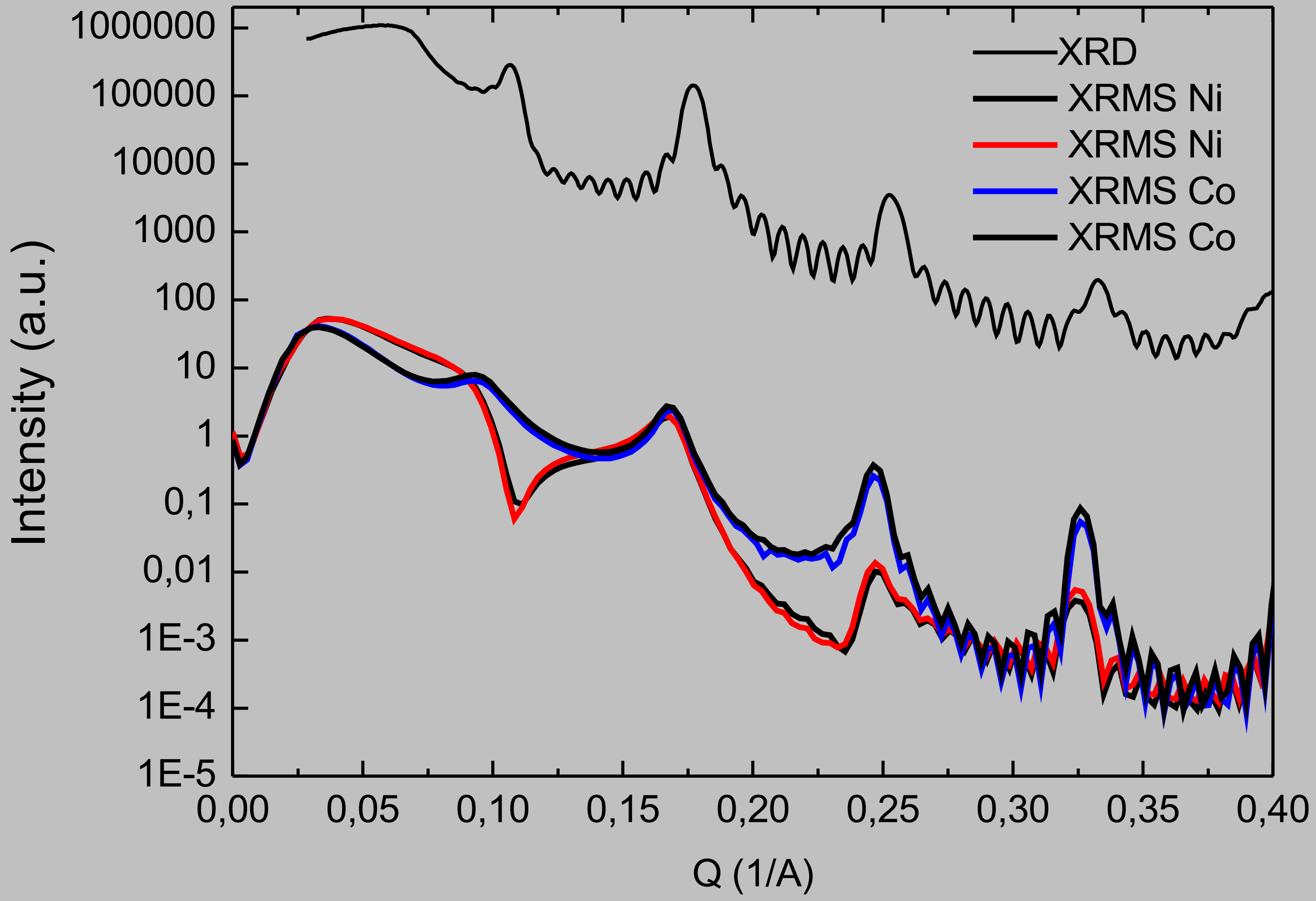
λ≈1.4 nm

interaction with core electrons

photon energy tuned to absorption edge
⇩
elemental selectivity

In ferromagnetic metals an imbalance in empty spin-up and spin-down states exists and valence shell can act as a **"spin detector"**.

Soft x-ray resonant magnetic scattering (SXRMS)

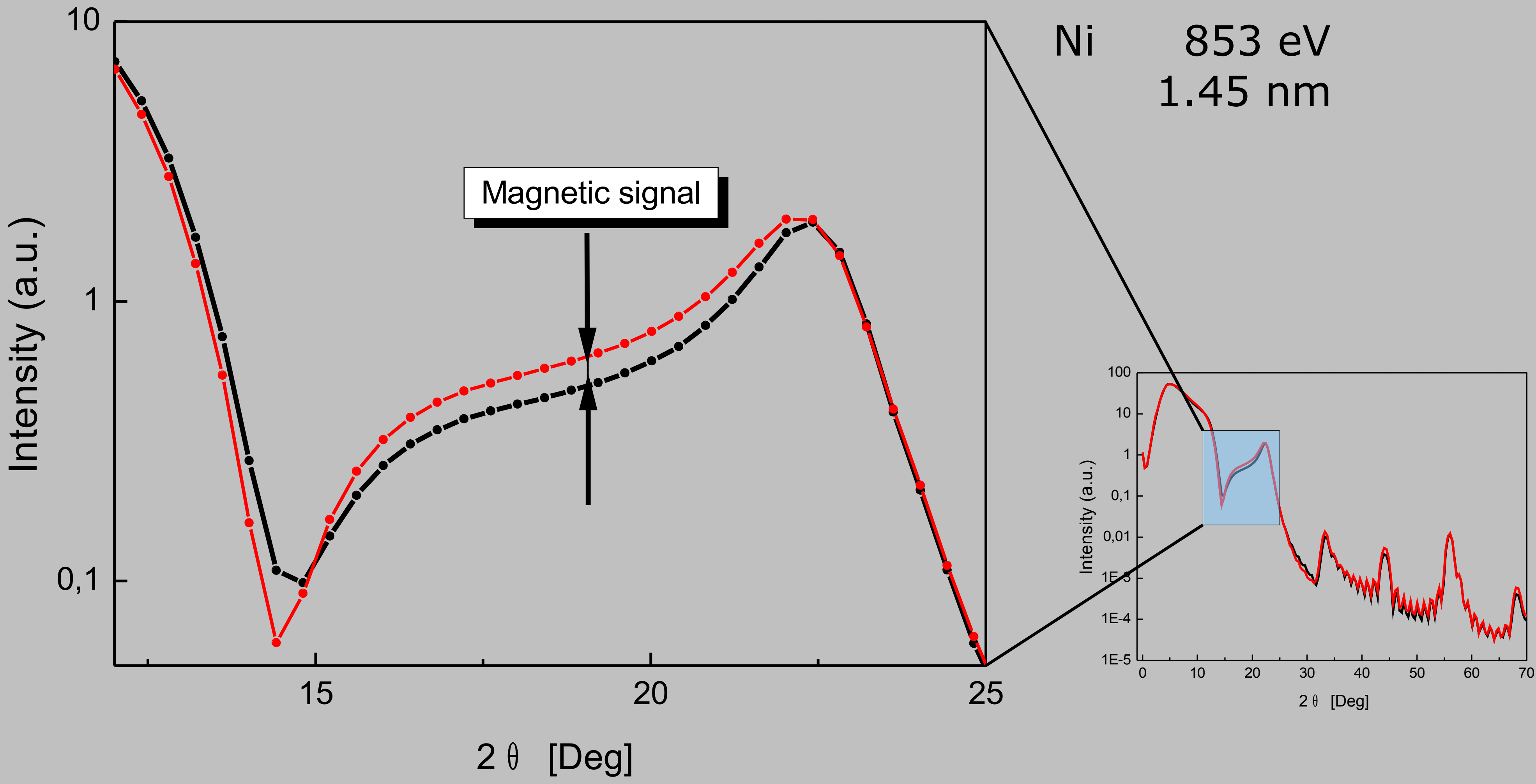


Cu K_α	8048 eV
Ni	853 eV
Co	778 ev

$[Ni_{80}Fe_{20}(2\ nm)/Au(2\ nm)/Co(0.8\ nm)/Au(2\ nm)]_{10}$

ALICE diffractometer at the undulator beamline UE56/2-PGM2 at BESSY II (Berlin)

Soft x-ray resonant magnetic scattering (SXRMS)



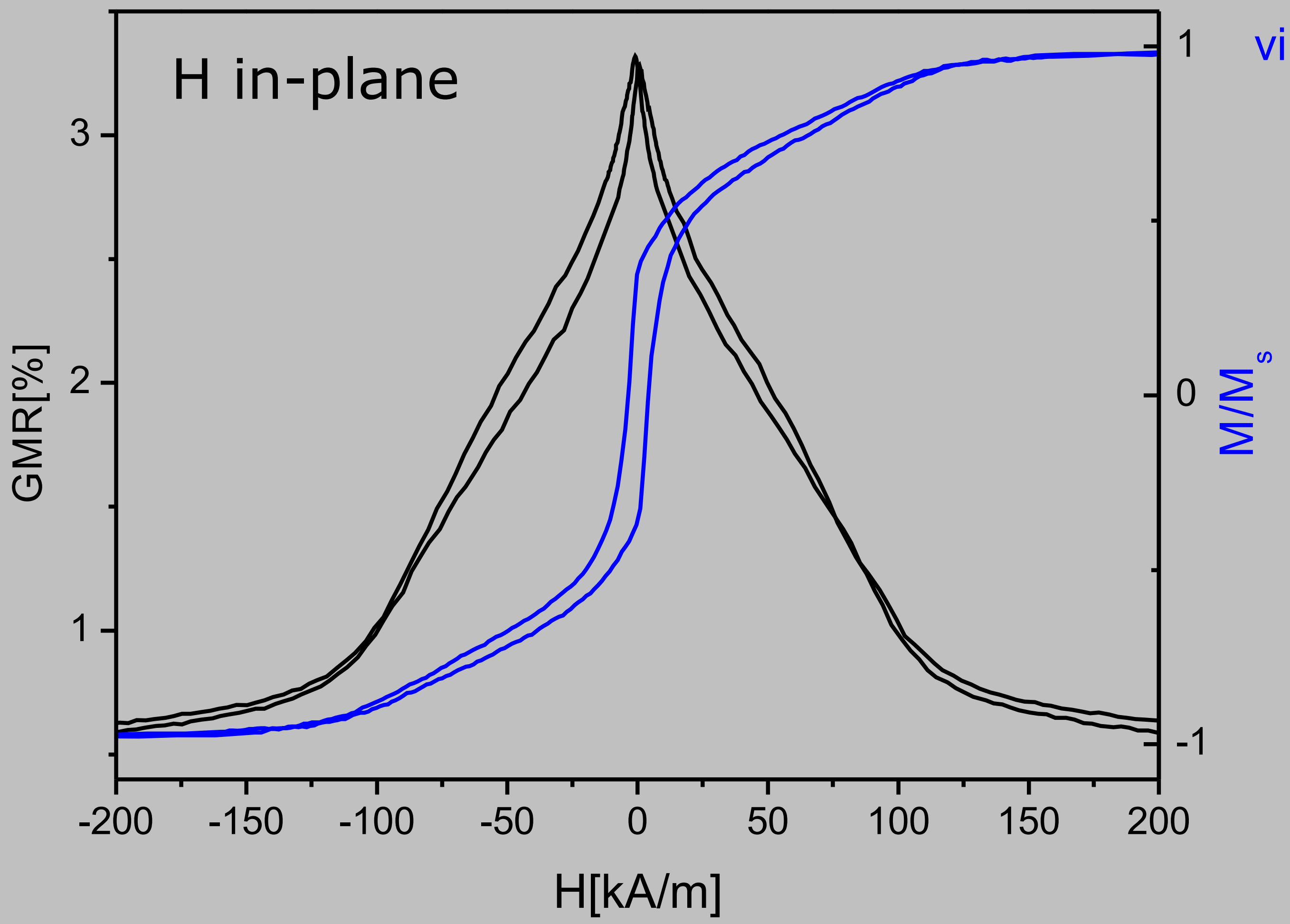
Magnetic signal

Ni 853 eV
1.45 nm

$[Ni_{80}Fe_{20}(2\ nm)/Au(2\ nm)/Co(0.8\ nm)/Au(2\ nm)]_{10}$

ALICE diffractometer at the undulator beamline UE56/2-PGM2 at BESSY II (Berlin)

Soft x-ray resonant magnetic scattering (SXRMS)

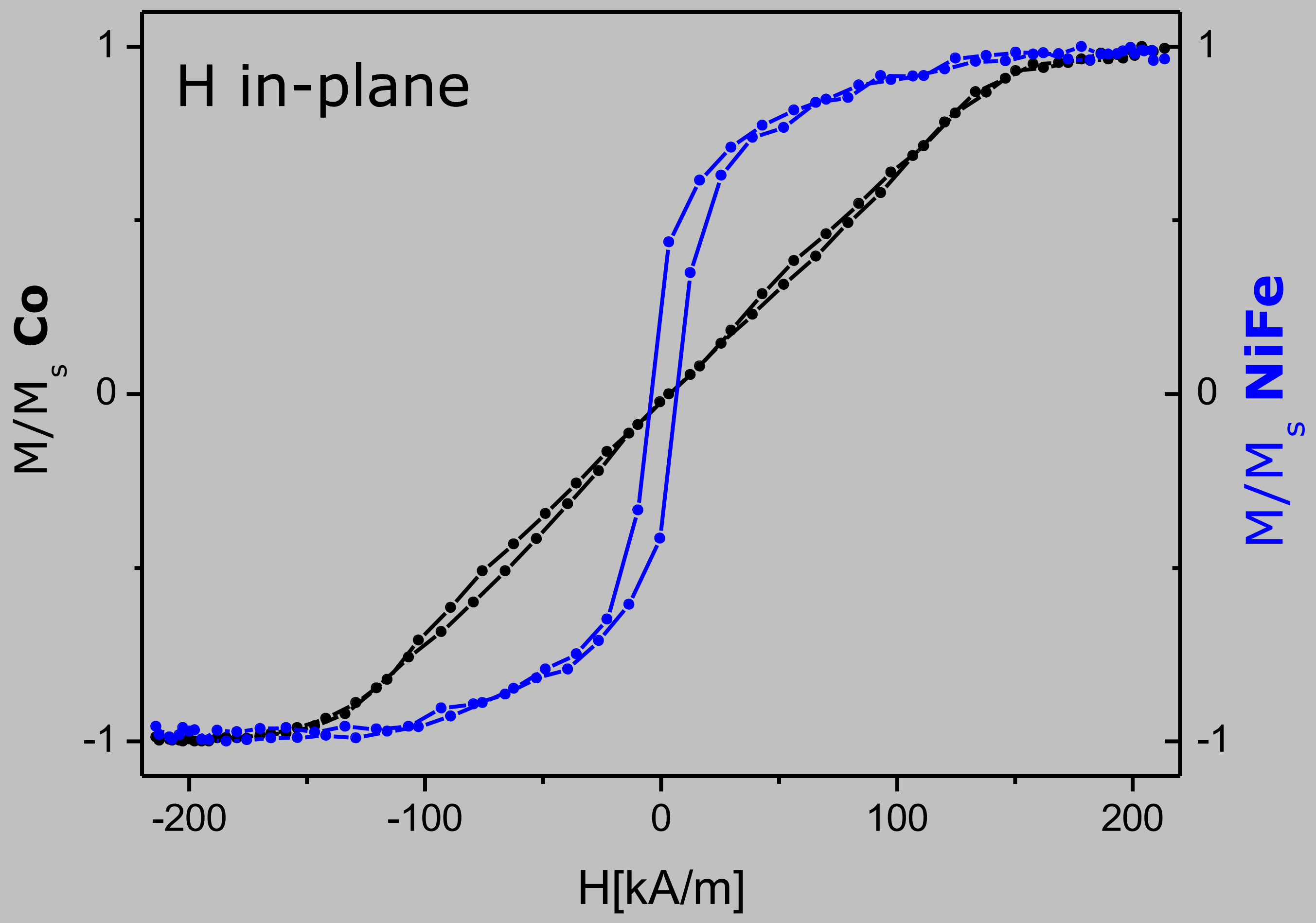


vibrating sample magnetometry

R(H)⟺M(H)

$[Ni_{80}Fe_{20}(2\ nm)/Au(2\ nm)/Co(1.1\ nm)/Au(2\ nm)]_{10}$

Soft x-ray resonant magnetic scattering (SXRMS)



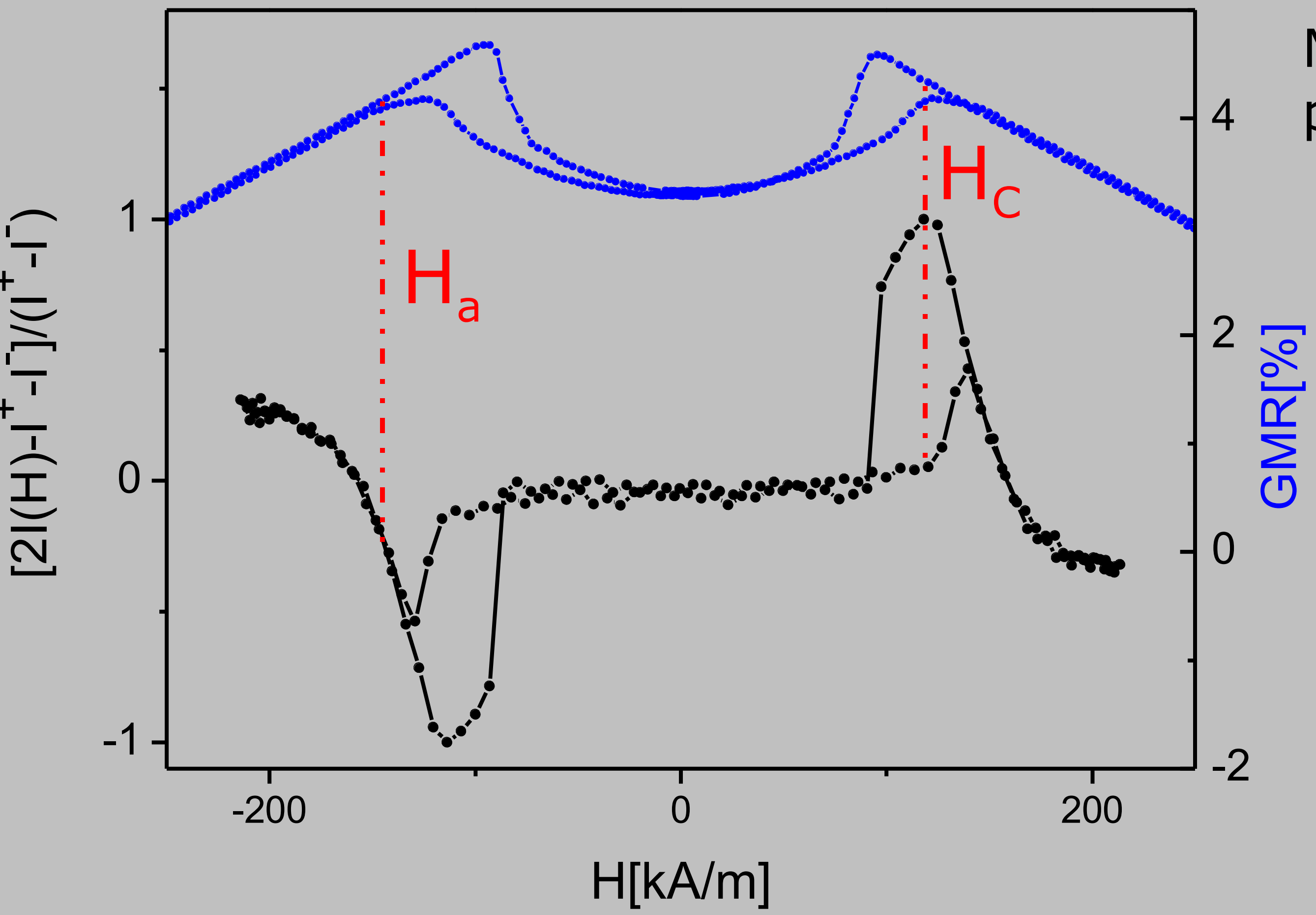
XRMS allows independent measurement of M(H) dependence of **Co** and **NiFe** layers.

Θ=8.5Deg
E=853eV (Ni L_3)
E=778eV (Co L_3)

$$\boxed{M/M_s \propto [2\mathrm{I}(H) - I^+ - I^-]/(I^+ - I^-)}$$

[$\mathbf{Ni_{80}Fe_{20}}$(2 nm)/Au(2 nm)/**Co**(1.1 nm)/Au(2 nm)]$_{10}$

Soft x-ray resonant magnetic scattering (SXRMS)



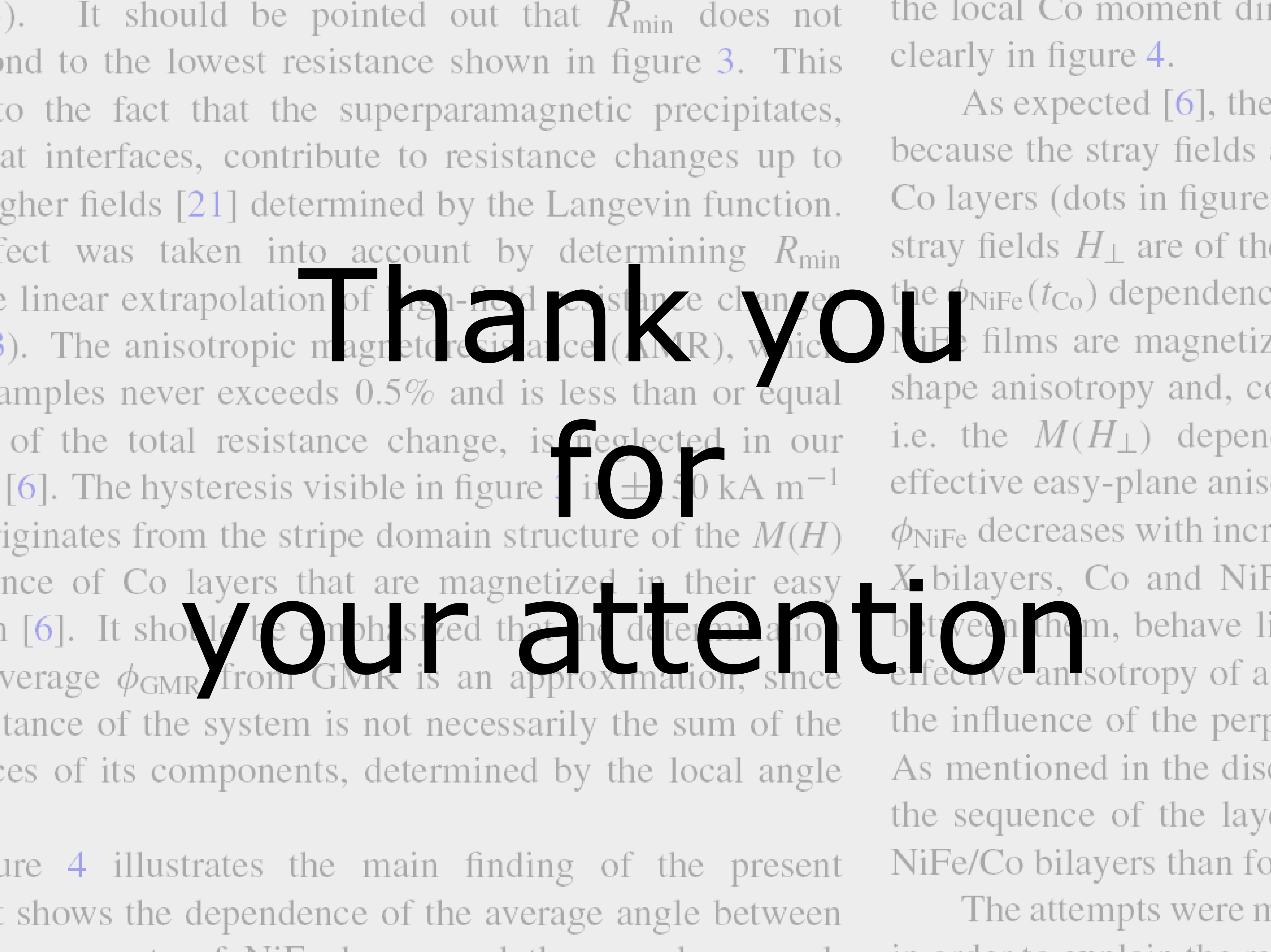
Magnetic field applied perpendicularly

SXRMS signal from **NiFe layers** shows fields characteristic for Co layers reversal:
-creation of the stripe domain structure (H_C)
-annihilation field of domain structure (H_a)

[$\mathbf{Ni_{80}Fe_{20}}$**(2 nm)**/Au(2 nm)/Co(1.1 nm)/Au(2 nm)]$_{10}$

Conclusions

- Element specific measurements of magnetization in NiFe/Au/Co/Au multilayers confirm the influence of stray fields on the magnetization processes
- Micromagnetic simulations approximate main features of R(H) dependencies



Thank you
for
your attention