Магнетизм наноструктурированных композитов и многослойных материалов

Julia Fedotova, Julia Kasiuk

Institute for Nuclear Problems
Belarusian State University

Collaborators:

AGH University of Science and Technology, Krakow

Prof. Cz. Kapusta

Dr. Hab. J. Przewoznik

Niewodniczanski Institute of Nuclear Physics PAN, Krakow

Prof. M. Marszalek

Mgr. A. Maximenko

Belarusian State University of Informatics & Radioelectronics, Minsk

Prof. S. Lazaruk

Mgr. O.Kupreeva

Institute of Materials Science, Vietnam Academy of Science and Technology, Hanoi

T.N. Anh Nguyen, D. H. Manh, D. L. Vu

Nanostructures with perpendicular magnetic anisotropy

Applications:

Spintronic devices
High density recording media
Magnetic field sensors
Magnetic tunneling junction sensors

Scope of the talk

Correlation between morphology, structure and magnetic properties in two types of nanostructured films:

I. **Composite metal-insulator films FeCo-CaF_2, FeCo-Al_2O_3**

II. **Porous thin multilayered films of Co/Pd and Co/Pt**

Investigation with complimentary techniques:

X-ray diffraction, *Empyrean PANalytical diffractometer, Cu* K_{α}

Transmission electron microscopy, *Philips EM400T microscope, 120 kV*

High-resolution electron microscopy, *Philips CM200, 200 kV*

X-ray absorption spectroscopy *(EXAFS (Extended X-ray Absorption Fine Structure) and XANES (X-ray Absorption Near Edge Structure) ranges), European Synchrotron Radiation Facility*

^{57}Fe Mössbauer spectroscopy, *77 K, 300 K, Co/Rh source, 40 mCi*

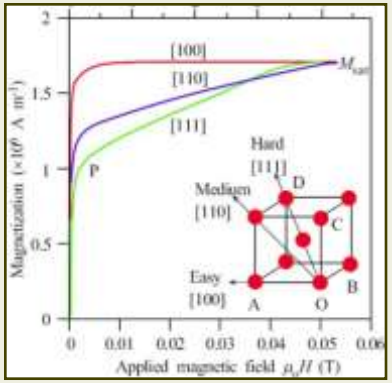
Vibrating sample magnetometer, *Quantum Design PPMS, magnetic induction H up to 9 T, temperature T up to 2 K*

Perpendicular magnetic anisotropy:

Easy axis magnetization pointing perpendicular to the films plane

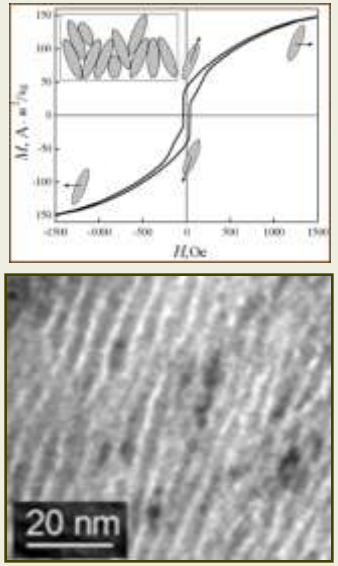
Magnetocrystalline anisotropy

Spin-orbit interaction



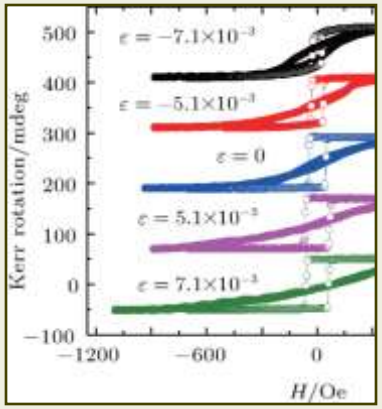
Shape anisotropy

Non-spherical shape of nanoparticles



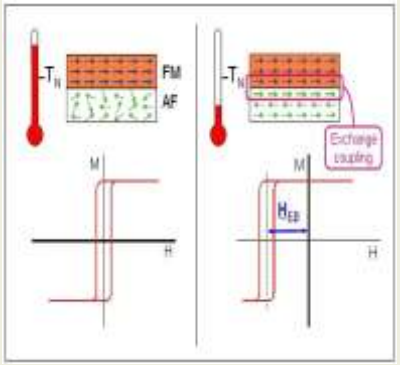
Stress anisotropy

Effects of magnetostriction



Interfacial & exchange anisotropy

Exchange interaction between AFM and FM layers



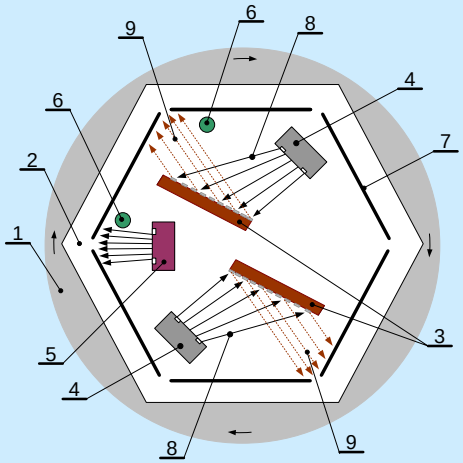
I. Composite metal-insulator films FeCo-CaF_2, FeCo-Al_2O_3

- tunable magnetic and electric properties
- microminiature scale & arbitrary shape
- compatibility with silicon processing planar technology
- reproducible and reliable processing
- low cost & low power consumption

Perfect high-frequency properties:

high magnetization M_S
low coercive force H_C
high magnetic susceptibility μ
high electrical resistivity ρ

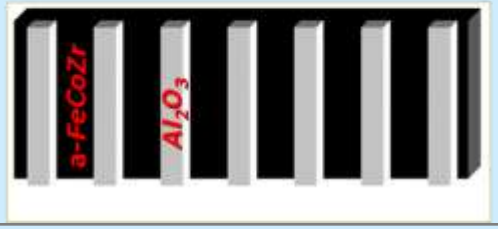
Ion-beam sputtering at variable regimes: substrate T
target composition
atmosphere of deposition (Ar, N_2, O_2)



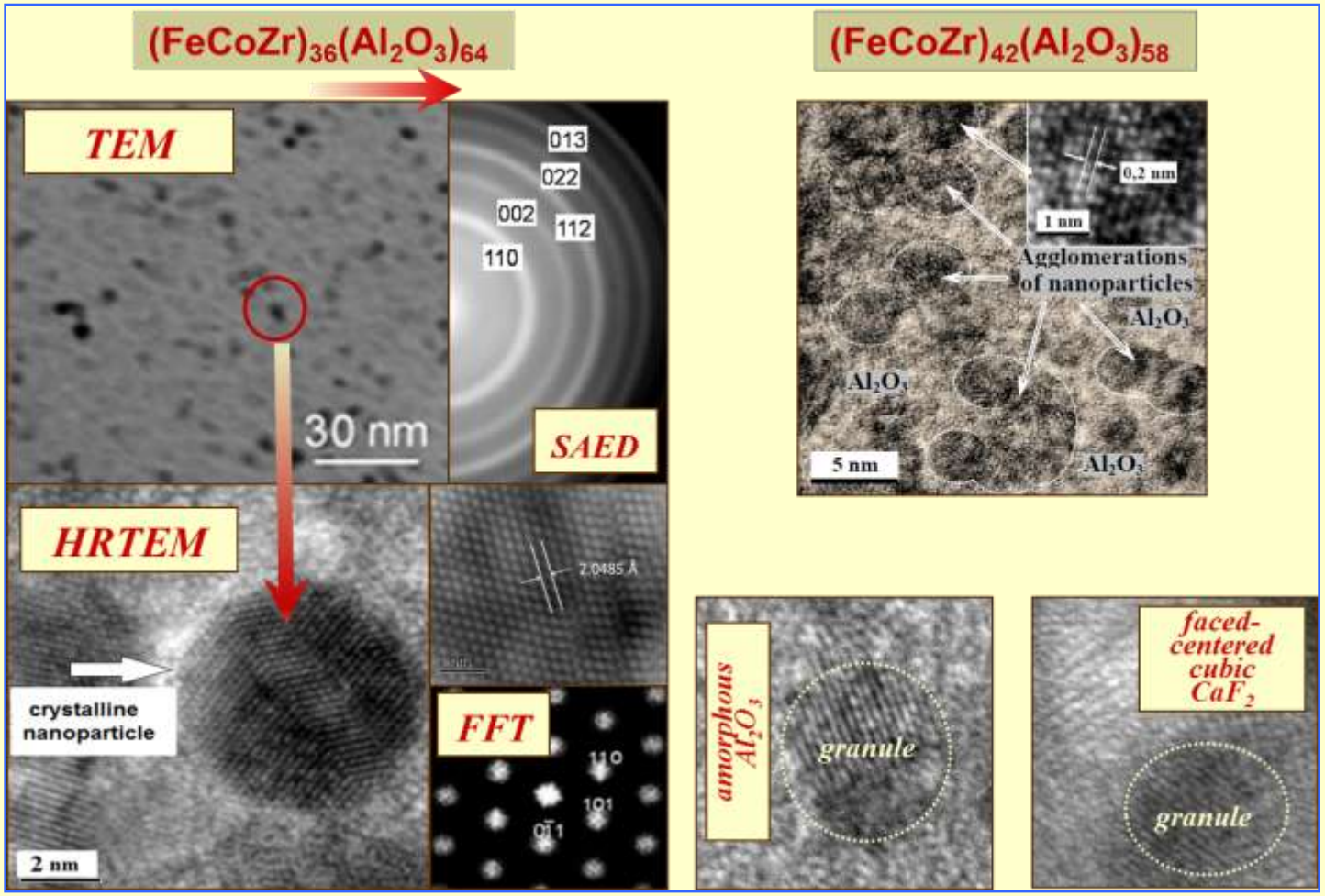
Chamber for deposition of films

1 – vacuum chamber
2 – circling drum for substrates
3 – sputtered targets
4 – ion-beam source
5 – source for ion-beam cleaning
6 – compensators
7 – dielectric substrates
8 – ion beams
9 – sputtered ions

Compound target to synthesize M_x-I_{100-x} composition



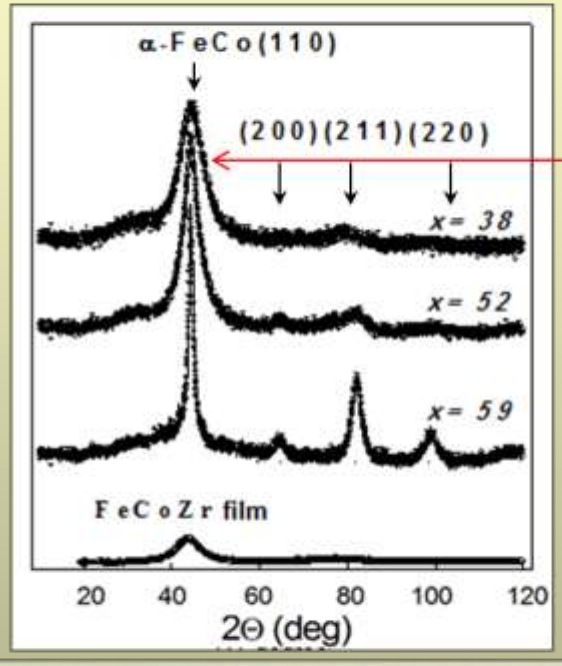
Typical structure and magnetic properties



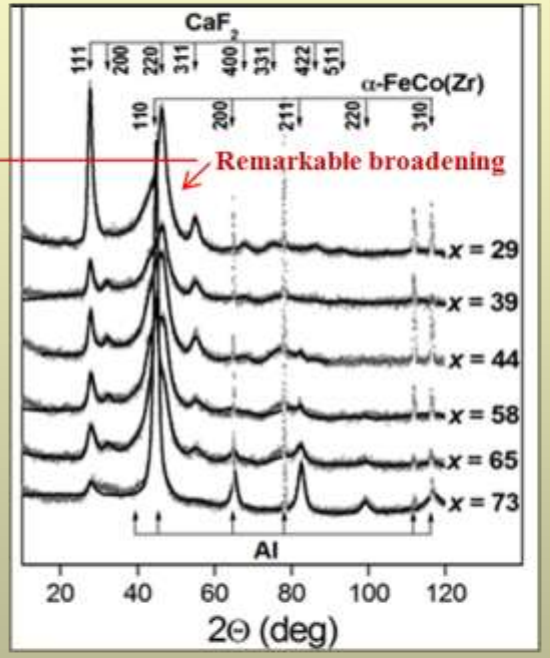
Experimental

X-ray diffraction, Cu K_α, grazing incidence of 5 degree

$(FeCoZr)_x(Al_2O_3)_{100-x}$



$(FeCoZr)_x(CaF_2)_{100-x}$



Comprehensive characterization

- Identification of phase composition of granules and matrix
- Reasonable size characterization (estimation of D^{coh})

Phase identification:
Rietveld refinement by *FullProf* program

Grain size estimation:
Scherrer formula

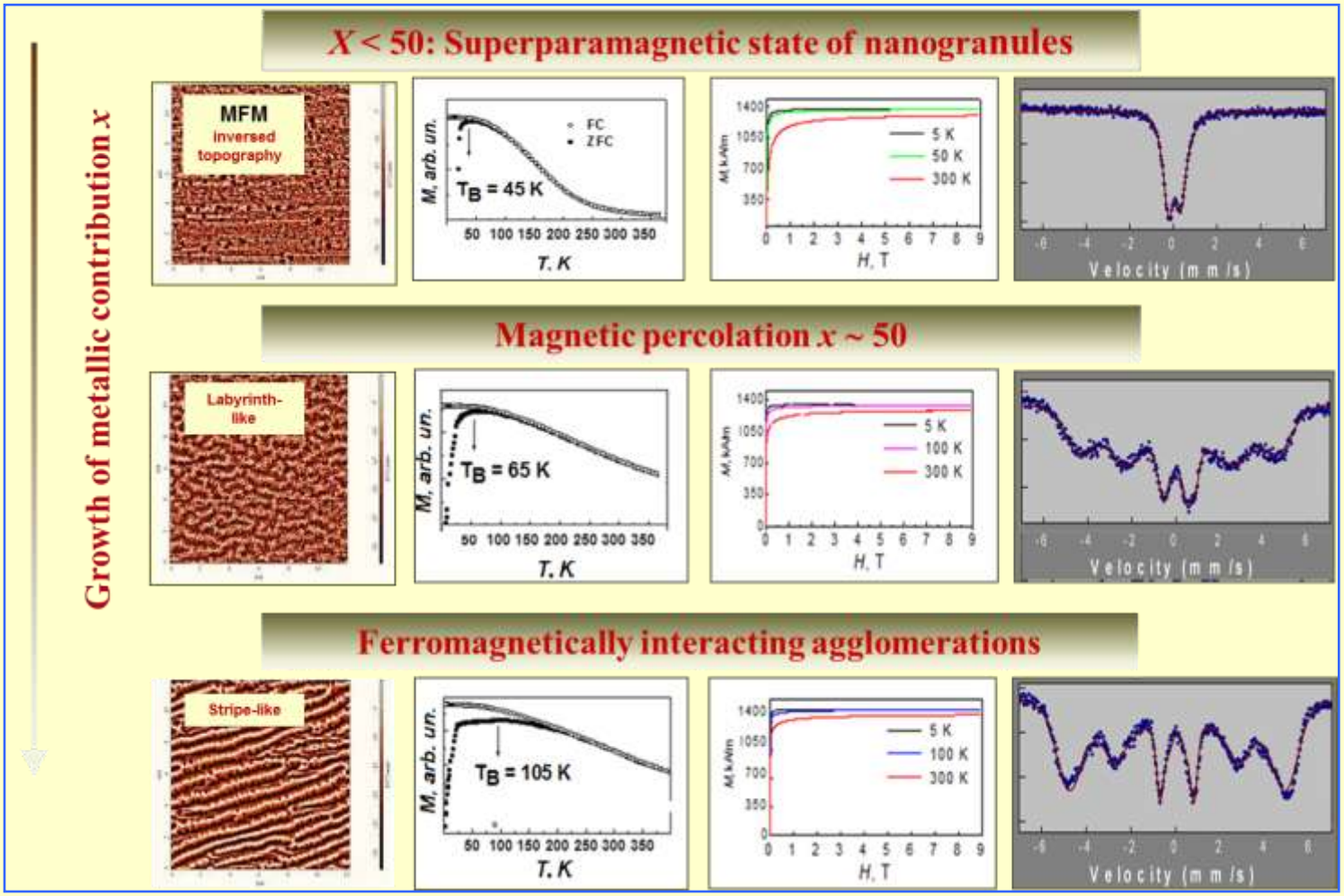
$$\Delta(2\theta)_L = \left(\frac{2}{\pi}\right)\left(\frac{180}{\pi}\right)\frac{\lambda}{D\cos\theta}$$

D^{coh} ~ 1-4 nm

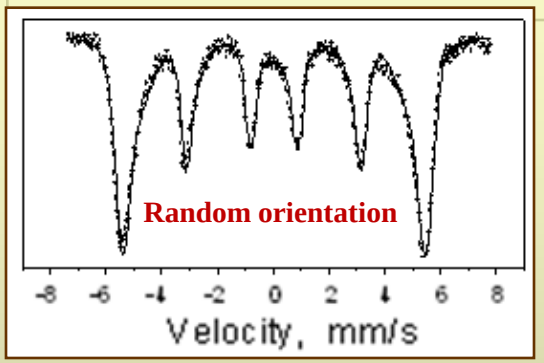
Modern approach:
Fourier transform of diffraction patterns

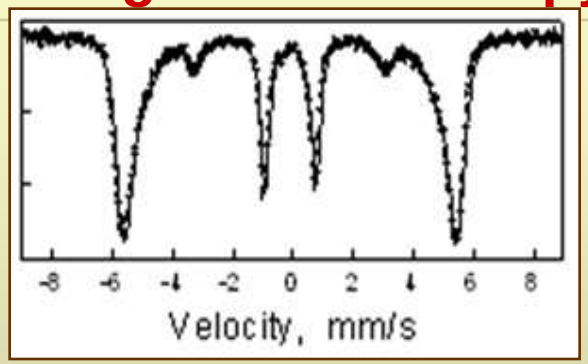
B.D.Hall *et al*
J. Appl. Crystallography 33 (2000)

Typical magnetic properties of metal-insulator films: random or in-plane orientation of magnetic moment



Exclusion: $(FeCo)_x(CaF_2)_{100-x}$, $x \geq 46$ reveal non-planar magnetic anisotropy



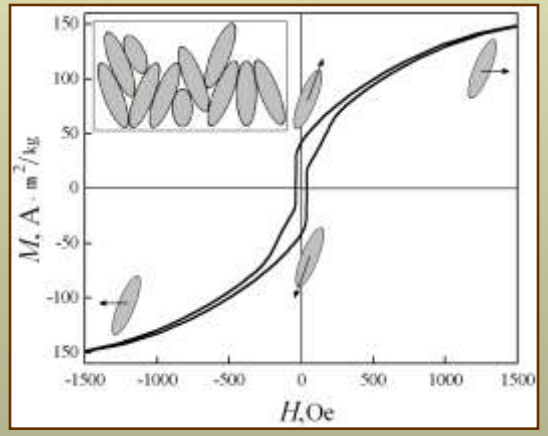


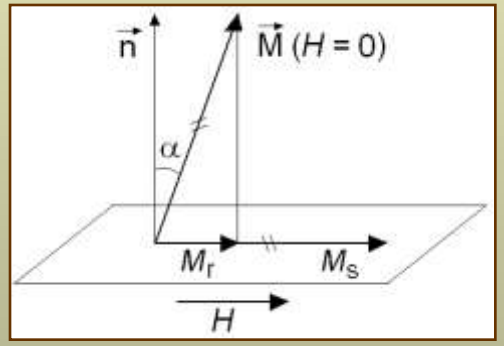
$h_3:h_2:h_1 \approx 3 : \sim 0{,}3 : 1$

$\theta = \arccos\,[(4-K)/(4+K)]^{1/2}$,

$K = h_2:h_1$

estimated $\alpha \sim 20^o$

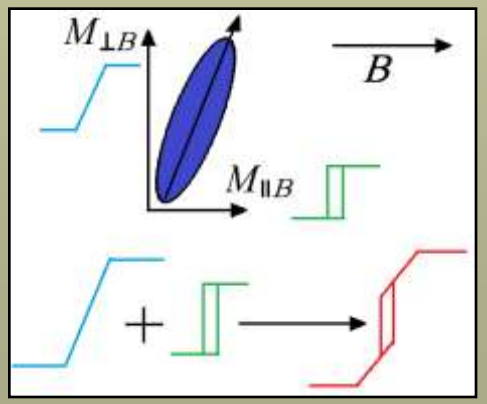




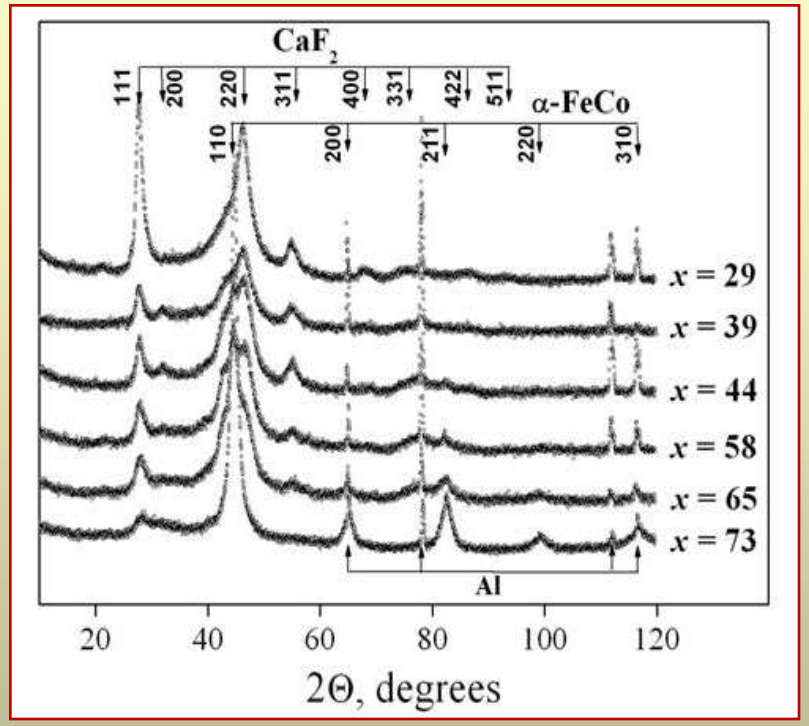
$\theta = 90^o - \arccos(M_r/M_s)$

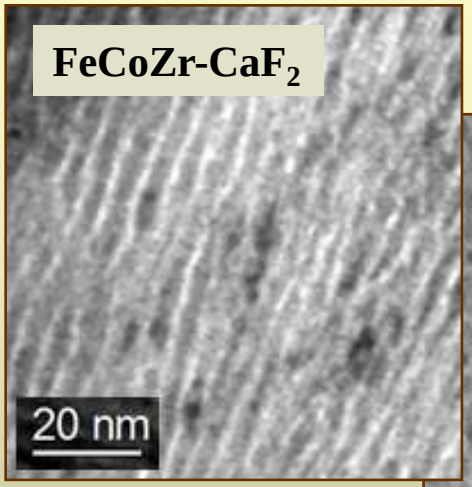
estimated $\alpha \sim 16^o$

Superposition of ⊥ anisotropy (granules) & || anisotropy (film)

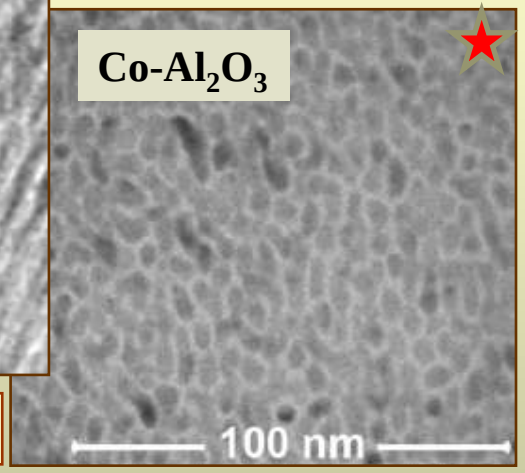


FeCoZr-CaF_2: Structure and phase composition



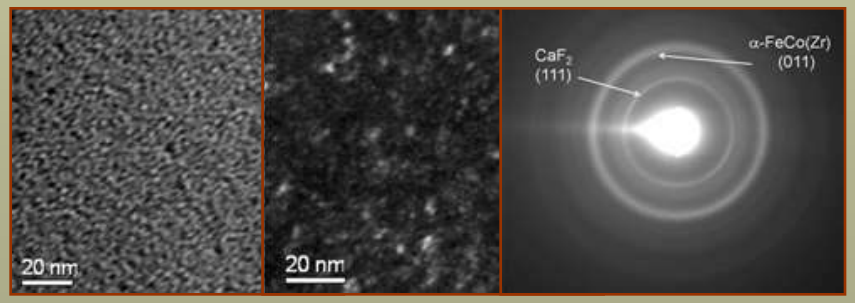


Cross-section TEM



Shape anisotropy

V.M.Kalita et al. J.Appl. Phys. 110 (2011)



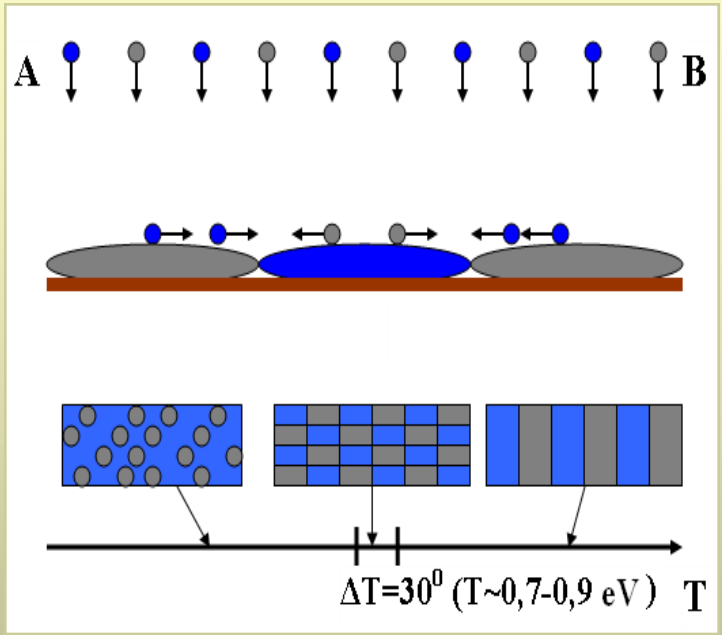
Origin of growth-induced anisotropy:

- Surface oxidation of granules
- Effect of matrix composition
- Substrate temperature

Formation of granular structure in nanocomposite *M-I* films

Criteria:

- no chemical compounds
- low solubility between components
- high difference in *M* and *I* surface energies



Factors:

- temperature of the substrate
- energy of sputtered atoms or clusters
- concentration of atoms or clusters on the surface

Easy cases

$FeCo-Al_2O_3$
$FeCo-SiO_2$
$FeCo-CaF_2$

Hard case

$FeCo-PbTiO_3$

(multiferroic film)

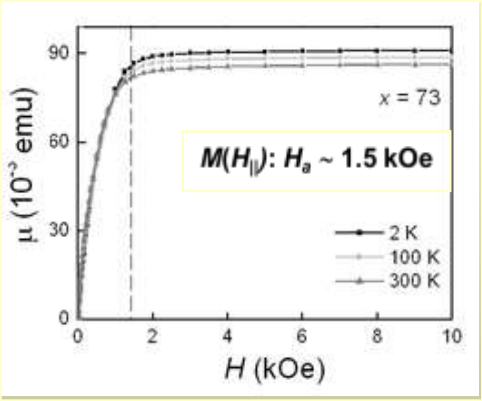
Way out

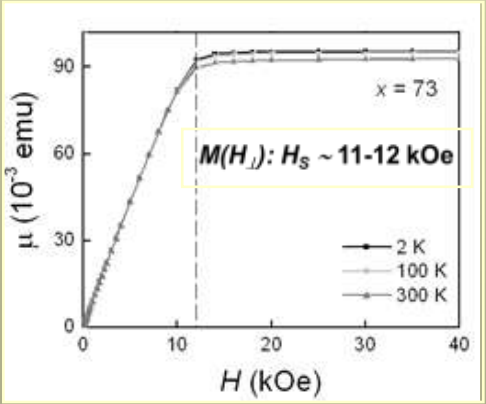
Stabilization of granular structure with "core-shell" nanoparticles

Evaluation of magnetization curves: to estimate anisotropy field H_a and angle α

Difficulties: (i) *M(H)* reflects superposition of *in-plane* and *out-of-plane* anisotropies

(ii) dispersion of easy axis orientations



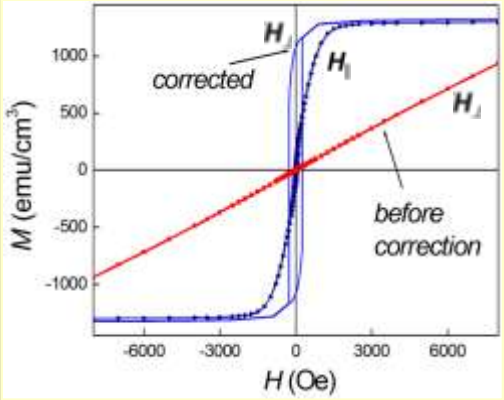


To separate H_a and H_d contributions

⇓

correction of $M(H_\perp)$ curve in assumption of self-consistent fields:

$$H^i = H - 4\pi \cdot M(H) \cdot f_i,$$



$M_r/M_S = 0.82$

⇓

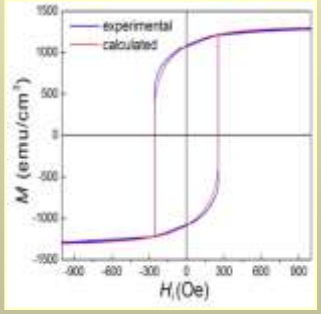
NPs are tilted

α - tilt angle

Stoner-Wohlfarth model :

$$h \cdot \sin\theta + \frac{1}{2}\sin 2(\theta - \alpha) = 0$$

$$h = H^i / 4\pi \cdot \Delta N \cdot M_S$$



H_a = 500 Oe

α` = 35⁰

⇧

modified by interaction

Shape anisotropy for individual cylinder NP:

$H_a = 4\pi \cdot \Delta N \cdot M_S$ ⟶ H_a ~ 8 kOe

Neel approach for NP set [Ref]:

$H_a = 4\pi \cdot \Delta N \cdot M_S (1 - f_V)$ ⟶ H_a = 3.5 kOe

Application of energy equation [Cullity]

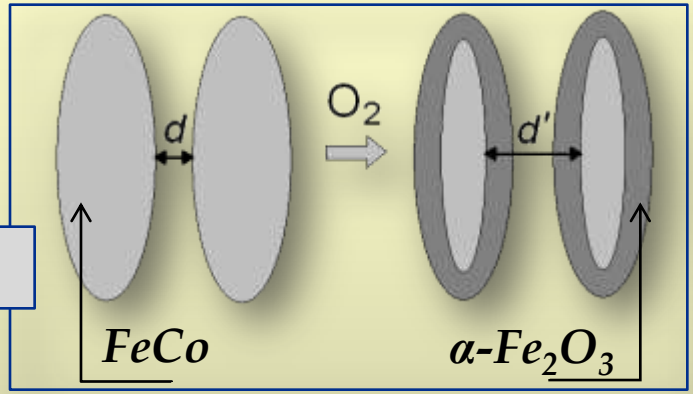
$$\varepsilon = K_u \cdot \sin^2(\theta - \alpha) + K_f \cdot \cos^2\theta - M_S \cdot H_\perp \cdot \cos\theta$$

$\theta_{equilibr}$ = 35° ⟶ H_a = 1.4 kOe, α = 15 ⁰C

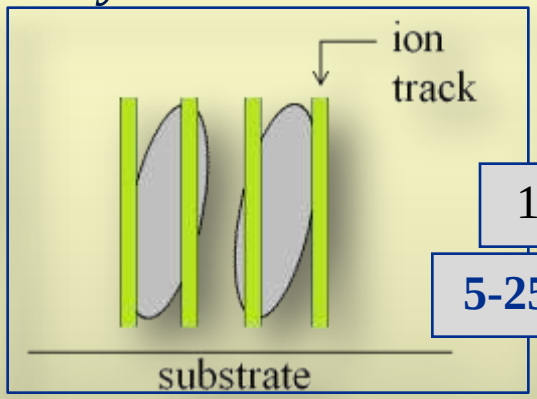
The way out: decrease of nanoparticles interaction

- by partial oxidation

P_O ~ 4 mPa



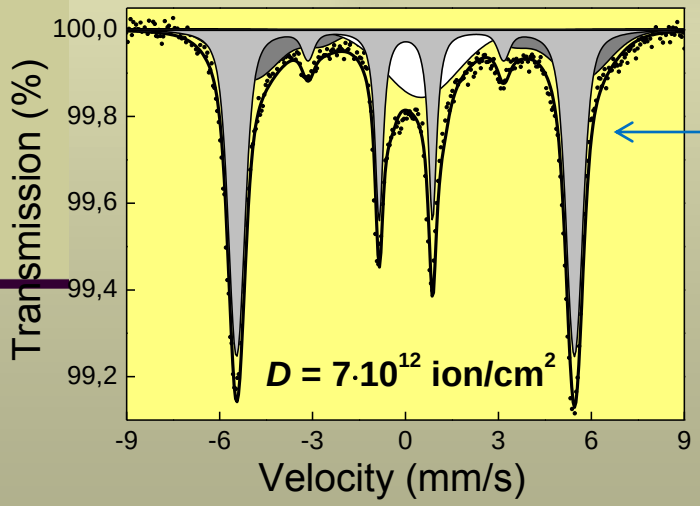
- by ion irradiation



167 MeV **Xe**

5-25·10^{12} ion/cm^2

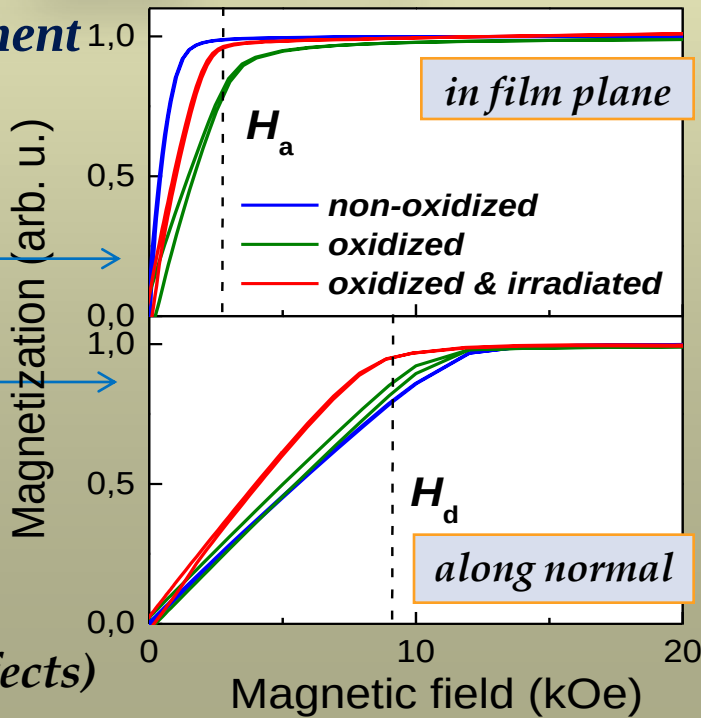
- by combined treatment



dispersion angle α drops to 15°

H_a achieves 3.5 kOe

H_d decreases down to 7.5 kOe



- *decrease in nanoparticles interaction* (*ferromagnetic cluster breaking*)
- *magnetic moments ordering* (*exchange coupling effects*)

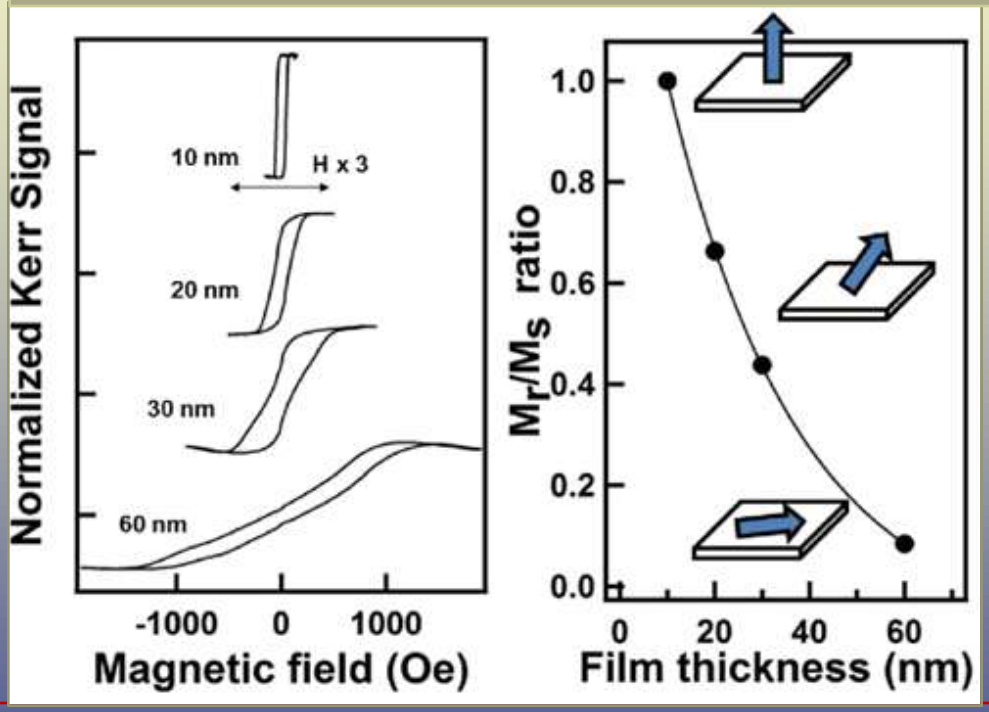
Conclusions on metal-insulator granular films:

- Ion-beam sputtering on uncooled substrate allows fabrication of metal-insulator films with non-planar, close to perpendicular magnetic anisotropy with angle α of deviation from the film's normal $\approx$ 20 degrees
- Perpendicular magnetic anisotropy is associated with the columnar-like shape of agglomerations of metallic nanoparticles
- Magnetic properties of films as a whole are governed with the competition between magnetostatic interaction and shape anisotropy of NPs at high metallic contribution
- Magnetostatic interaction leads to the decrease in shape anisotropy (from ~ 8 to 1.5-2 kOe) and to the increase in angle α against films normal (from ~15° to 35°) in external magnetic field that can be corrected by additional NPs treatment including NPs partial oxidation and films irradiation by heavy ions

II. MLs with perpendicular magnetic anisotropy: Co/Pt, Co/Pd, Co/Au, etc.:

high anisotropy constant
$K_u = 10^8$ **erg/cm^3**

- perpendicular recording media
- perpendicular spin-valve (p-SVs)
- magnetic tunnel junction (p-MTJ) devices



Magnetic anisotropy origin:

1) Interfacial anisotropy:

- Interface electronic effects – hybridization between Co 3*d* and Pd 4*d* at the interface;
- Stress caused by lattice mismatch between Pd and Co.

Roughness, intermixing, alloy formation at the interface play crucial role

2) Magnetocrystalline anisotropy:

L_{10} crystalline structures (Co_3Pt, Fe_3Pt)

Not only applied point is important:

Thin porous films are perfect objects for

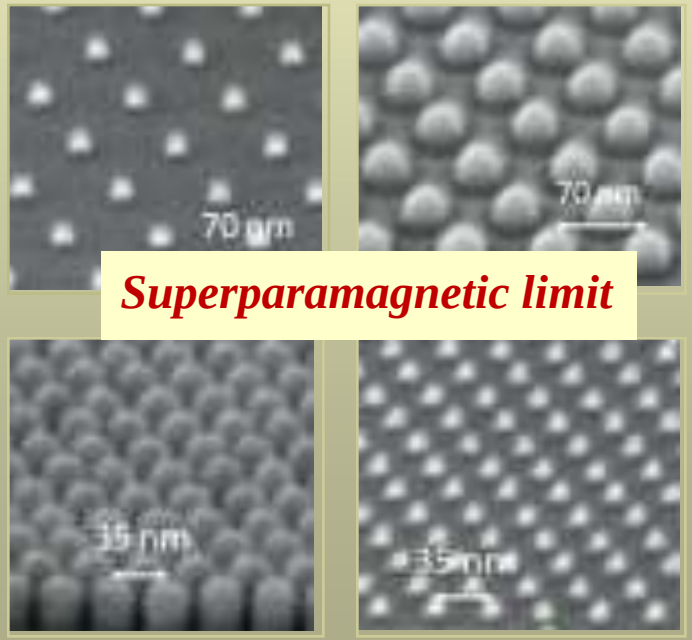
1) **Modelling of magnetization reversal mechanisms;**
2) **Tuning of applied parameters: switching fields, coercive force, ratio between saturation magnetization and remanence**

Chang, *J. Alloys Comps* 710(5):37-46 · March 2017

MLs with perpendicular magnetic anisotropy: *Co/Pt, Co/Pd, Co/Au, etc.*: High-density recording media

Ordered arrays of nanodots

Recording density is up to 5 Tbit/in^2
(Hitachi GST, Toshiba и Fujitsu)



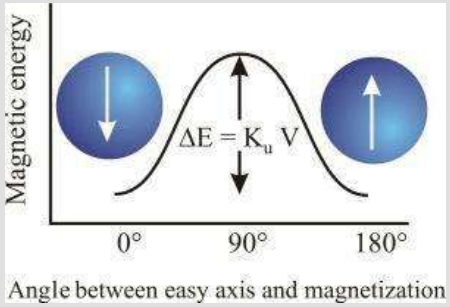
Superparamagnetic limit

Superparamagnetic limit:

The maximum number of bits per square inch that is commercially feasible on a magnetic storage device (several hundred gigabits per square inch)

Superparamagnetic state:

Magnetic moment is oriented along an easy magnetization axis governed with total magnetic anisotropy



For small nanoparticles energy of anisotropy $K_aV = k_BT$, and magnetic moment fluctuates

Quasi-paramagnetic behavior of very small magnetically ordered and weakly interacting particles

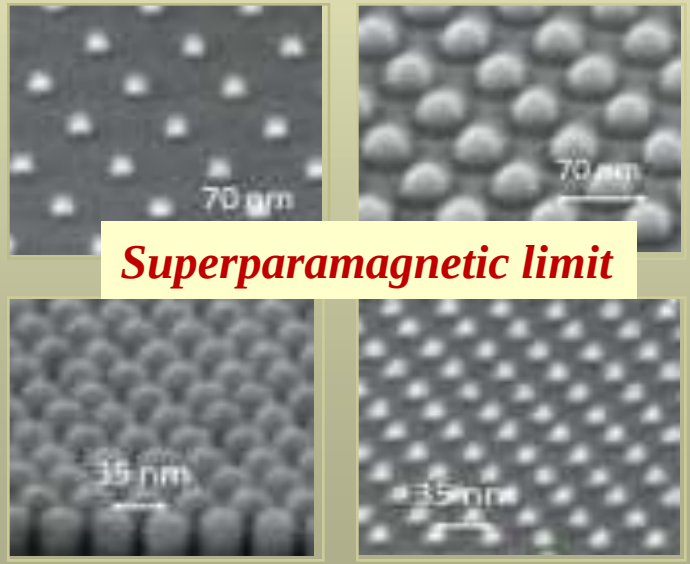
Observation of SP state is possible when observation time is larger than time of superparamagnetic relaxation

Motivation

MLs with perpendicular magnetic anisotropy: *Co/Pt, Co/Pd, Co/Au, etc.*: High-density recording media

Ordered arrays of nanodots

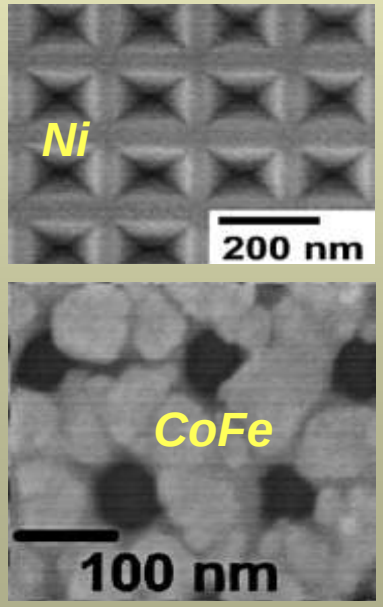
Recording density is up to 5 Tbit/in^2
(Hitachi GST, Toshiba и Fujitsu)

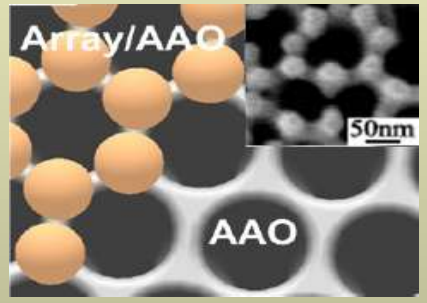


Superparamagnetic limit

The way to overcome SP

Continuous films with nanoporous structure («antidots»)





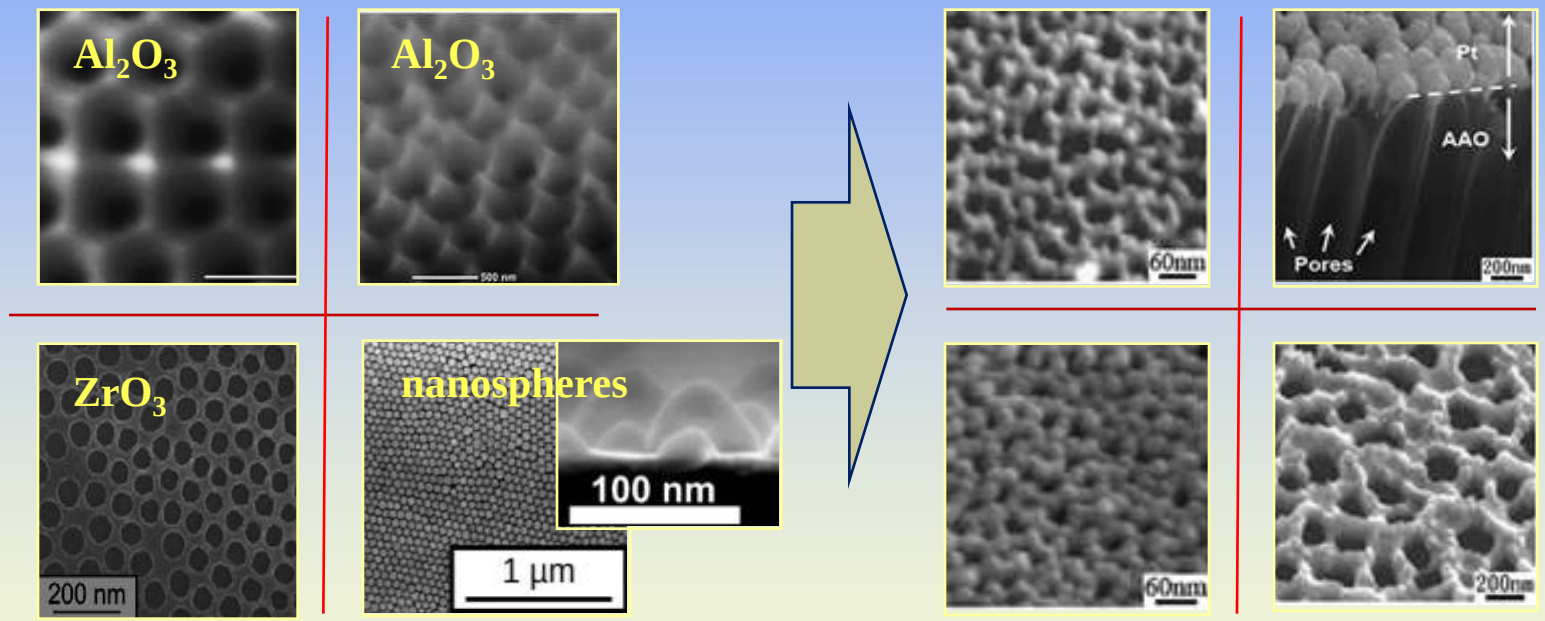
[F. Castano APL85 (2004)]

Enhanced stability (large coercive force) due to pinning effects

Porous self-ordered templates for PPM: Morphology requirements

U-shaped surface morphology: alteration of "hills" and "pits"

Developed morphology of MLs

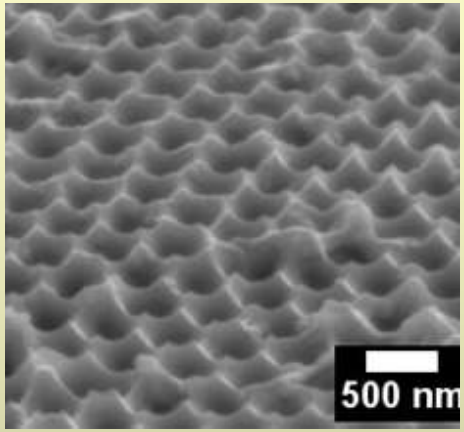


[C. Schulze, *Nanotechnology* 21 (2010)]

- Developed morphology of porous metallic films
- Local misalignment of magnetic moments & distorted perpendicular magnetic anisotropy

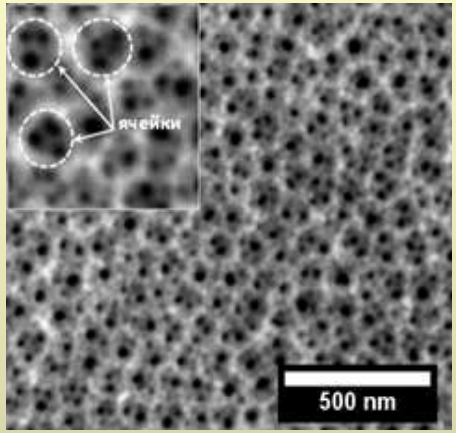
Morphology of templates is a crucial issue

Co/Pd films on porous Al_2O_3 templates: SQUID-magnetometry



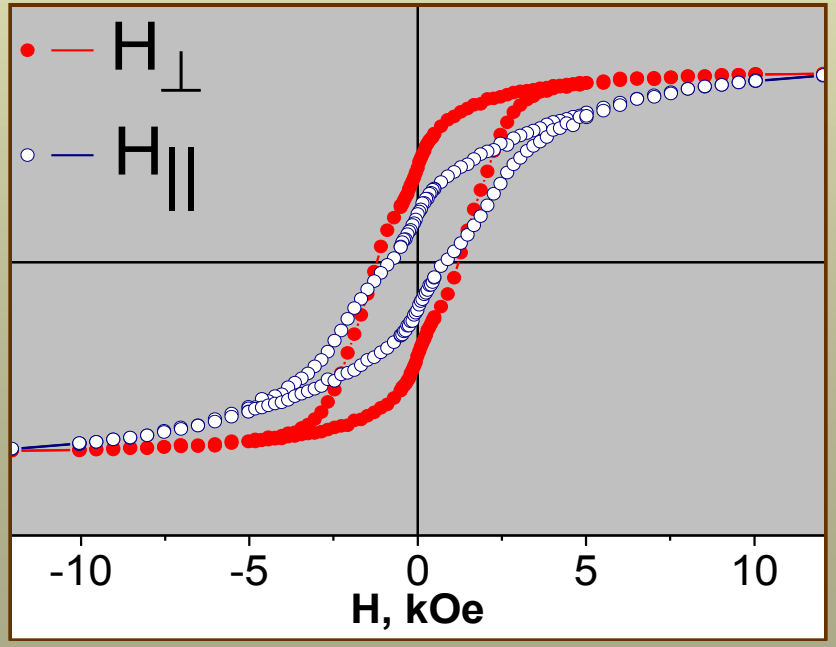
$H_C < 1200$ Oe

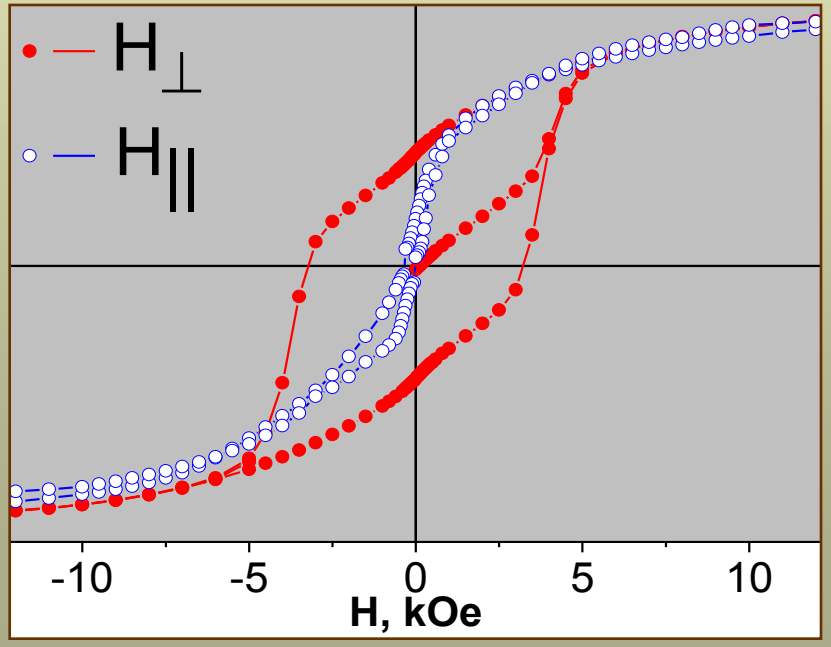
$M_r/M_S \approx 0.5$



$H_C > 3100$ Oe

$M_r/M_S \approx 0.5$

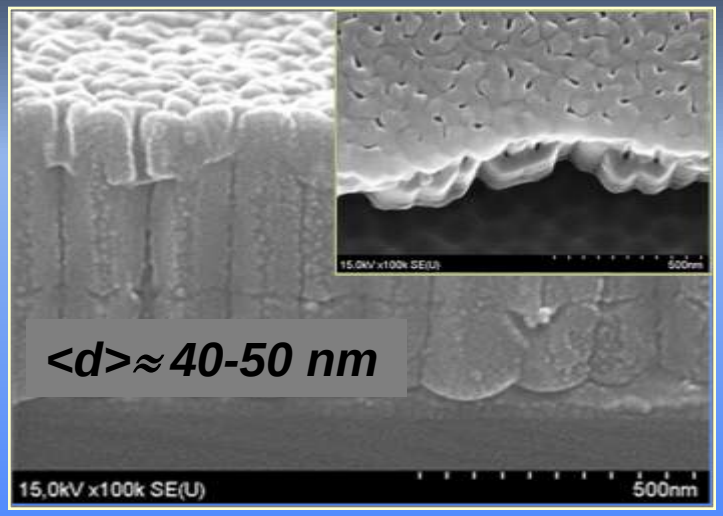




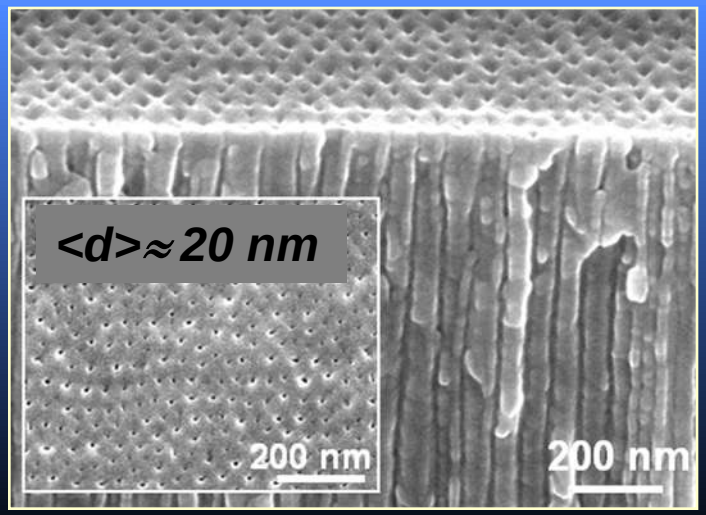
Motivation

The way out: preparation of template with flattened interpore areas by combination of anodization regimes and Ar ion-beam polishing

Thick-walled TiO_2 nanotubes



Flat-surface Al_2O_3 nanotubes



Fabricated templates: flattened relief at the expense of ordering

Main objectives research:

1. To fabricate flat-surface templates – anodized porous matrixes, and prepare porous Co/Pd, Co/Pt ML thin films

2. To investigate how the surface relief of Pd/Co/Pd MLs affects magnetic properties of Pd/Co/Pd antidots

Main task of research:

To fabricate percolated perpendicular media of Pd/Co/Pd MLs with perpendicular magnetic anisotropy, enhanced coercive force (H_C >2000 Oe) and high squareness ($M_r/M_S \approx 0.8$)

Experimental

TiO_2 or Al_2O_3 templates on Ti/Al foil

- Ti or Al foil is cleaned and oxidized in electrolyte (0.3 % of NH_4F or H_2SO_4, respectively)
- Two-stage anodization of Ti (Al) foil in two-electrode electrochemical cell in the combined regime
- Ion-plasma Ar etching during 20 min. is applied for smoothing of templates surface

TiO_2 or Al_2O_3 templates on Si wafer

- Ti or Al film of 0.27 or 0.4 μm thickness is deposited by magnetron sputtering on Si wafer
- Ti (Al) film is cleaned, oxidized and anodized (two-stage anodization)
- Ion-plasma Ar etching during 10 min. is applied for smoothing of templates surface

[S.K. Lazarouk et al, *Thin Solid Films*, 526, (2012)]

Multilayered films

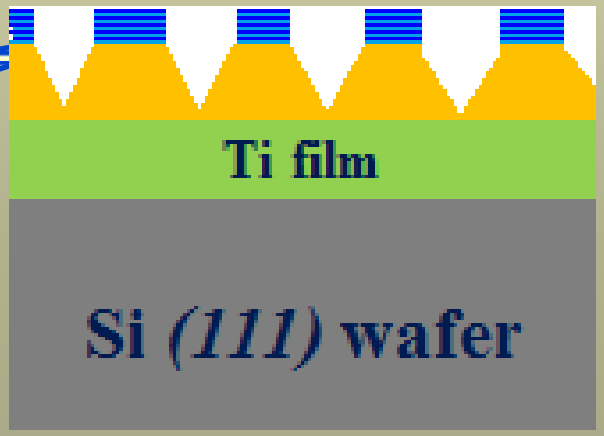
- **Thermal evaporation in UHV chamber ($P = 10^{-9}$ mBarr)**

$Pd_{10\ nm}[Co_{0.3\ nm}/Pd_{0.55\ nm}]_{x15}Pd_{2\ nm}$ MLs

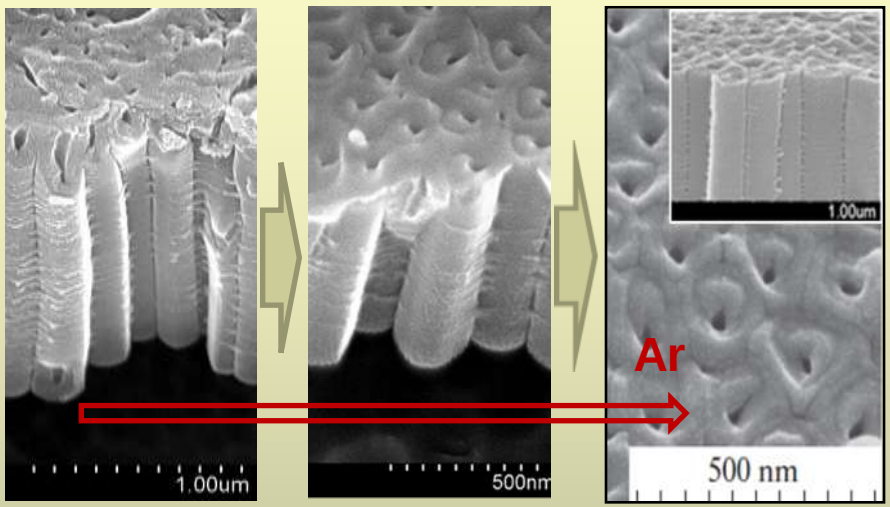
- **Magnetron sputtering**

$Ta_{5\ nm}/Pd_{15\ nm}/[Co_{0.5\ nm}/Pd_{1\ nm}]_{x5}/Pd_{3\ nm}$ MLs

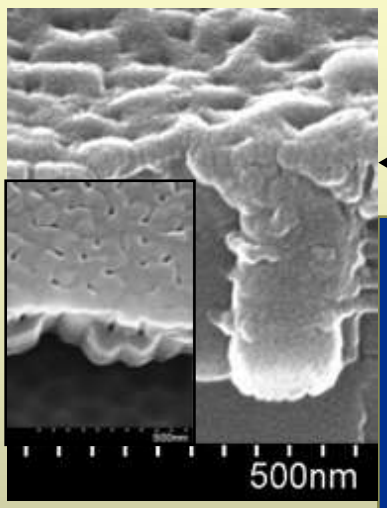
$Ta_{5\ nm}/Pt_{15\ nm}/[Co_{0.4\ nm}/Pt_{0.8\ nm}]_{x5}/Pt_{3\ nm}$ MLs



$[Co/Pd]_n$ multilayers on porous TiO_2 templates (NTs)



TiO_2/Ti foil



TiO_2/Si wafer

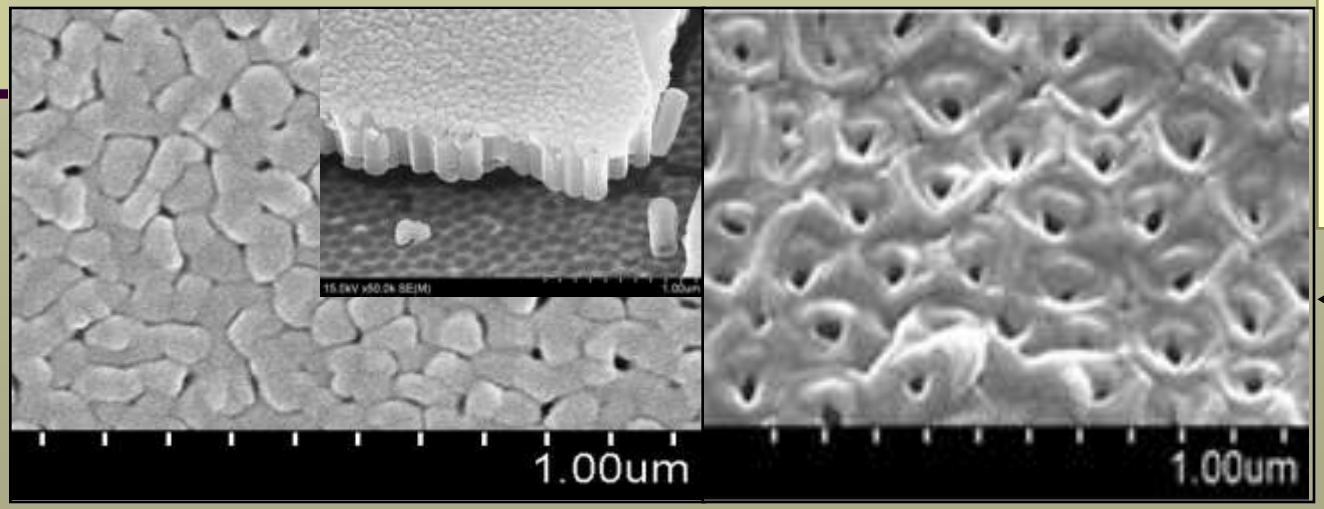
Templates

Flattened surface randomly distributed pores

Equivalent diameter of cells:
<*D*> = 150-200 nm

Internal diameter:
<*d*> = 30-50 nm

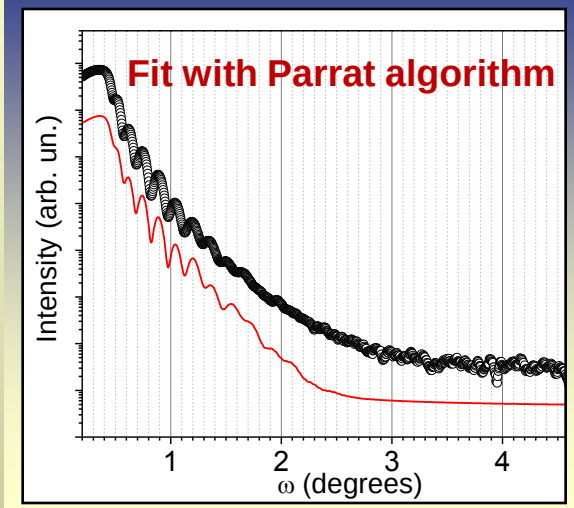
Medium interpore distance:
<*w*> = 120-180 nm

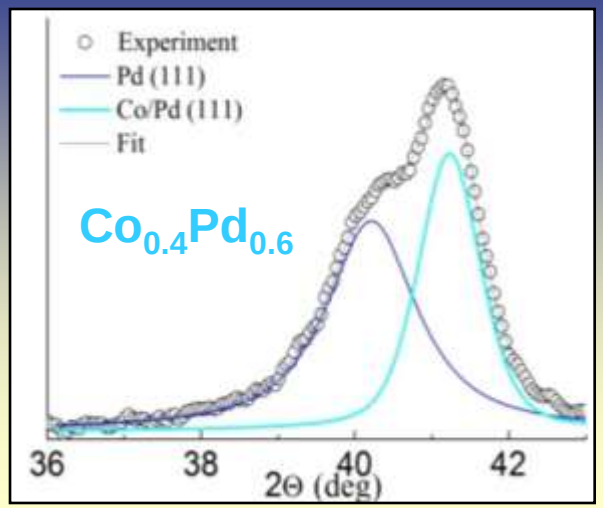


Multilayers

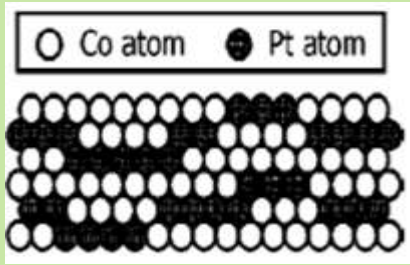
X-ray reflectometry, X-ray diffraction & *FT* EXAFS oscillations

Reference sample: $Pd/[Co_{0.3\ nm}/Pd_{0.5\ nm}]_{15}/Pd//Si$

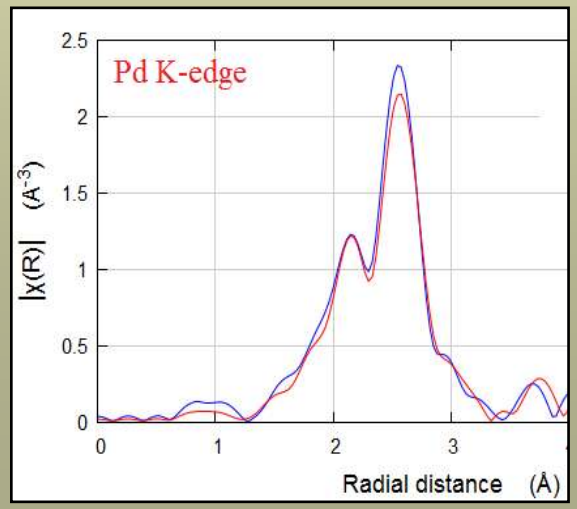


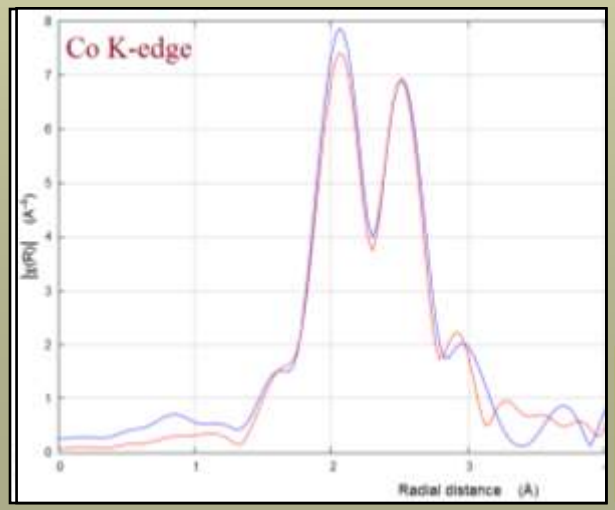


Co_xPd_{100-x} quasi-alloy



[H. Nemoto et al, JAP 97 (2005)]

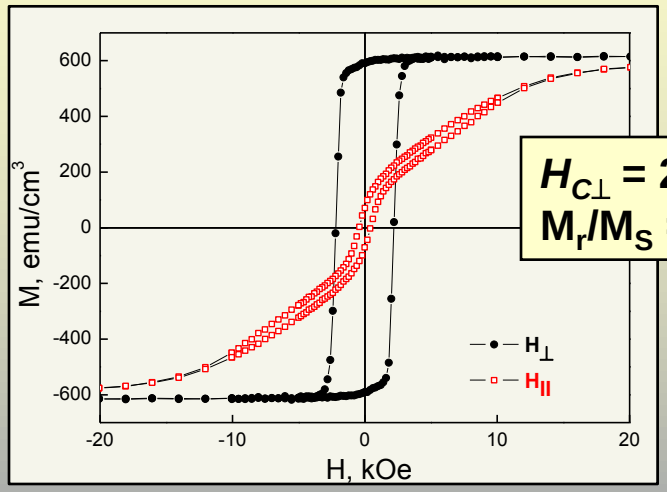




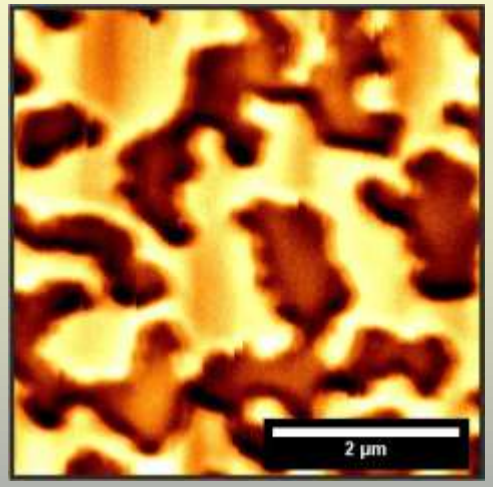
a_{Pd} (Å)	a_{CoPd} (Å)
Continuous MLs	
3.88	**3.79**
Porous MLs	
3.87	**3.81**

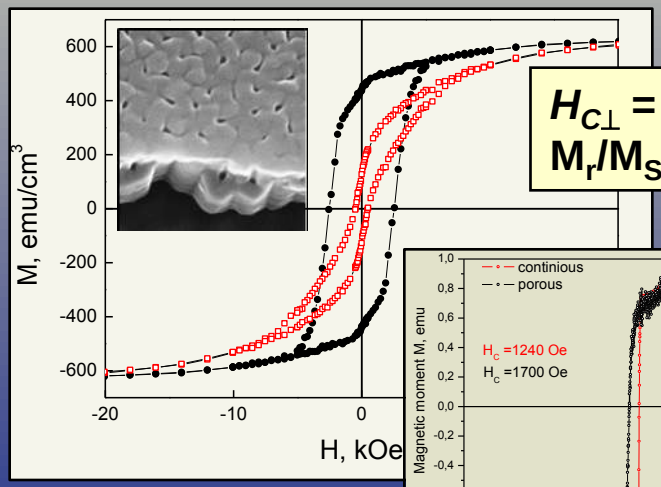
XRR and XRD proves layered structure and CoPd quasi-alloy at the interface

Magnetic properties: SQUID-magnetometry & MFM

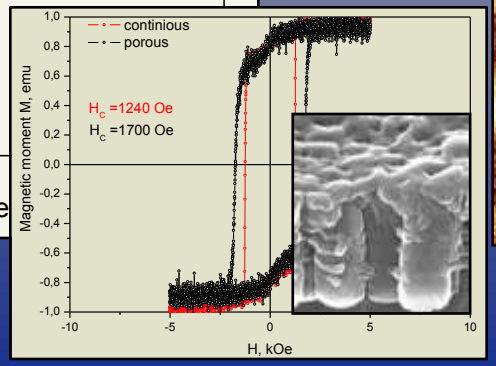


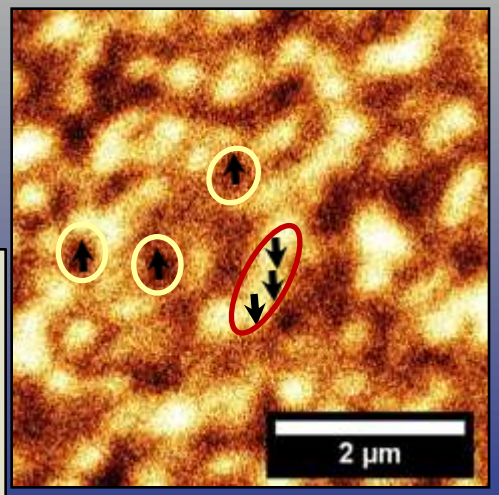
$H_{C\perp}$ = 2200 Oe
M_r/M_S = 0.96





$H_{C\perp}$ = 2700 Oe
M_r/M_S = 0.7

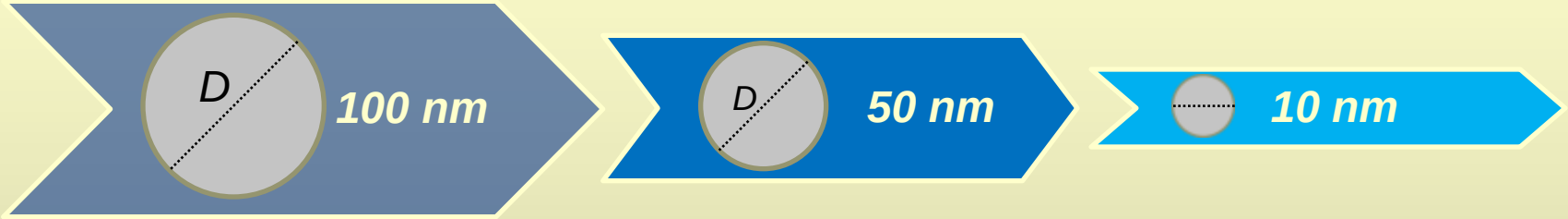


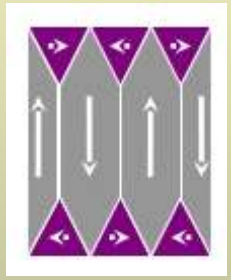


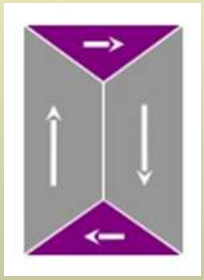
Refinement of magnetic domains due to the pinning

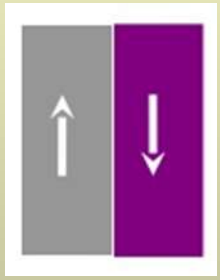
Mechanisms of magnetization reversal:

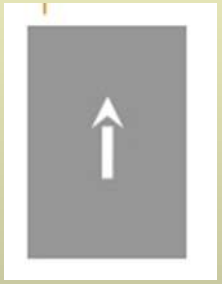
crossover from *Kondorsky* (in continuous film) to *rotational* (in porous film)



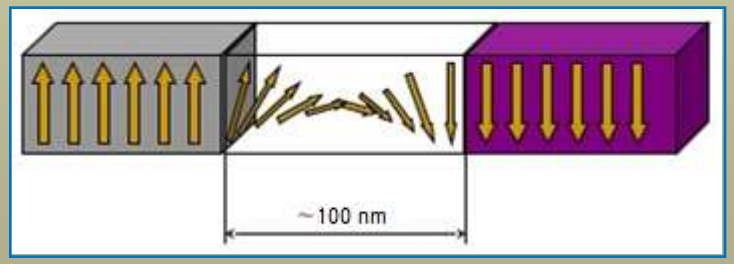


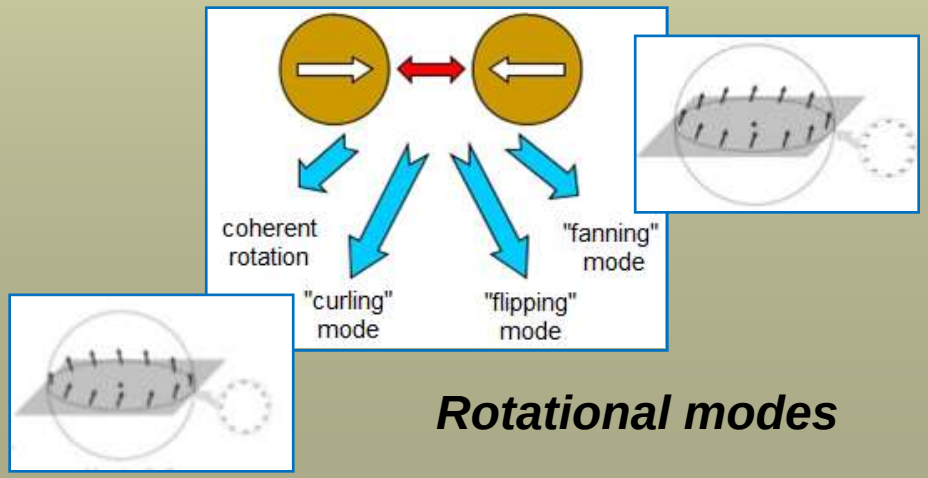






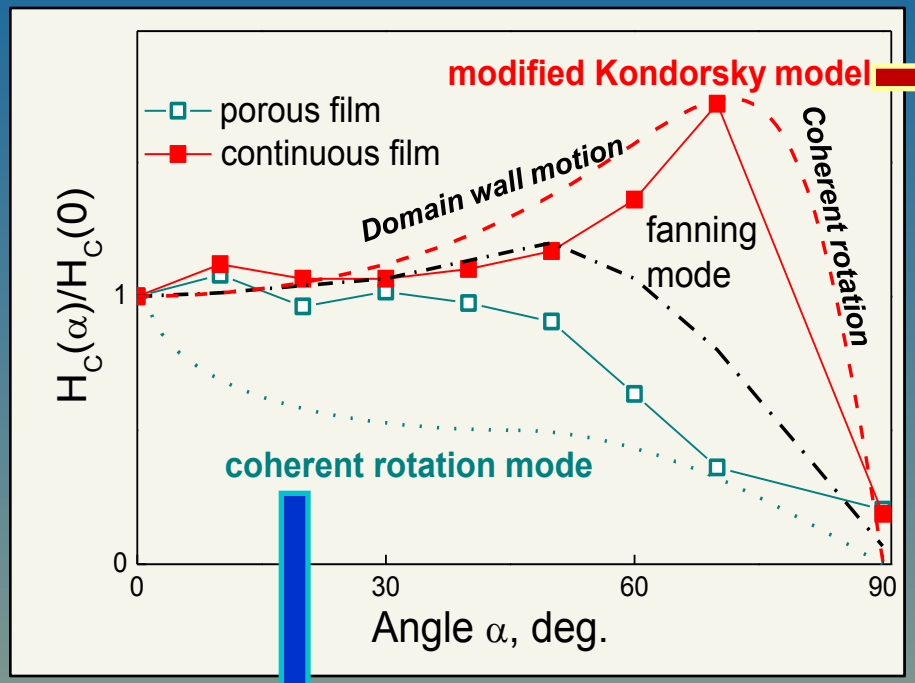
Domain walls motion



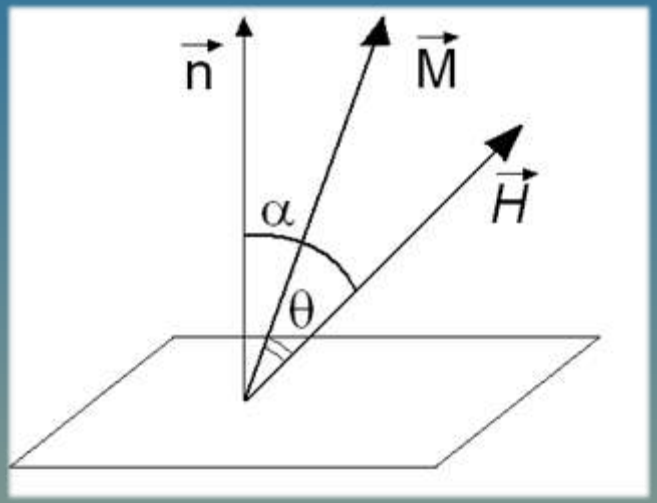


Rotational modes

Mechanisms of magnetization reversal:
crossover from *Kondorsky* (in continuous film) to *rotational* (in porous film)

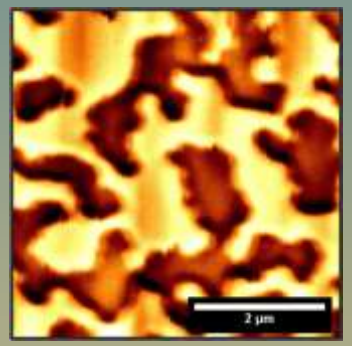


$$H_C(\alpha)/H_C(0) = \frac{(N_x + N_N)\cos\alpha}{N_z \sin^2\alpha + (N_x + N_N)\cos^2\alpha}$$

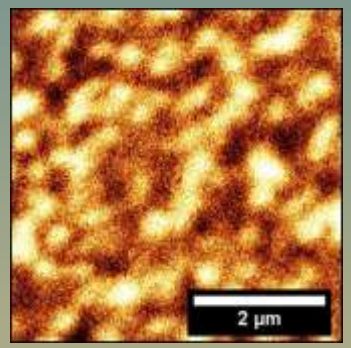


Stoner-Wohlfahrt model

$$H/H_{eff} \cdot \sin\alpha + \frac{1}{2} \cdot \sin 2(\theta - \alpha) = 0$$



Continuous



Porous

Magnetic properties *vs* substrate: estimation of K_{eff}

$$K_{eff} = K_{//} - K_{\perp} = \int_{0//}^{M_{S//}} \mu_0 H dM - \int_{0\perp}^{M_{S\perp}} \mu_0 H dM$$

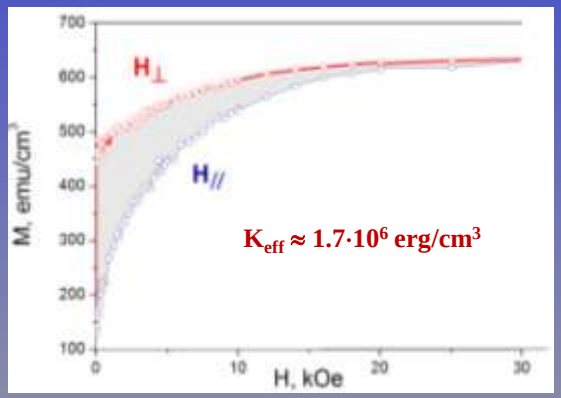
$K_{eff} = 5.1 \cdot 10^6$ erg/cm^3

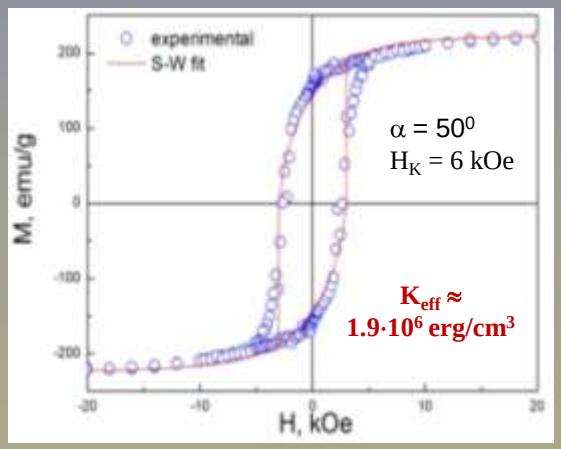
S-W model

$$\frac{H}{H_K} \cdot \sin\theta + \frac{1}{2} \cdot \sin 2(\theta - \alpha)$$

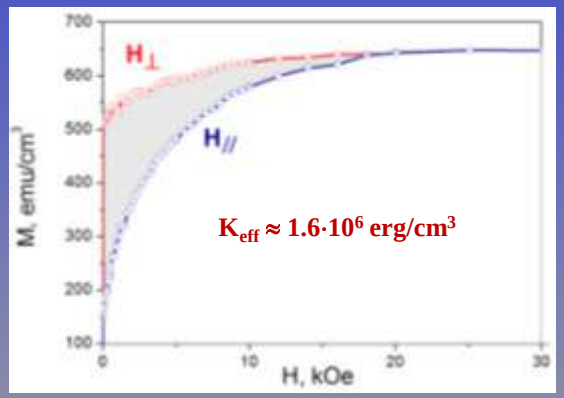
$K_{eff} = H_K \cdot M_S/2$

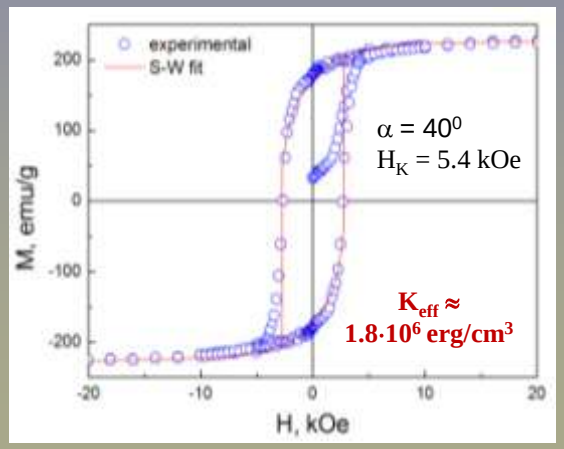
$Co/Pd/TiO_2$ // Ti foil



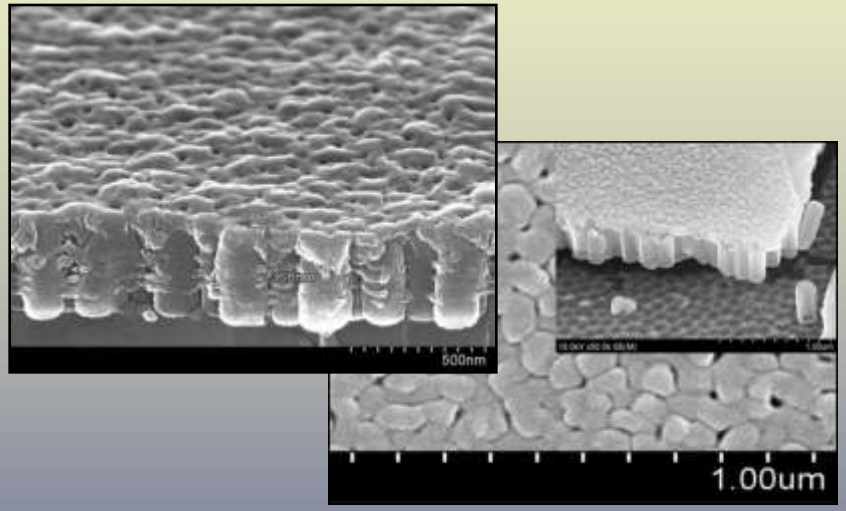


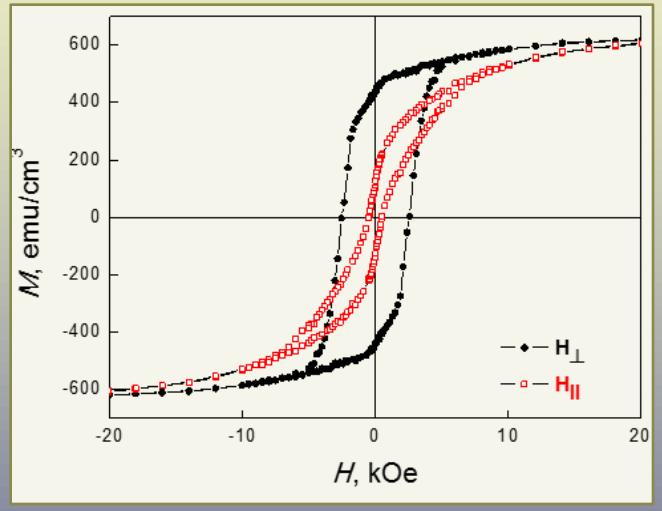
$Co/Pd/TiO_2$ // Si wafer





In resume: $[Co/Pd]_n/TiO_2$ porous multilayers: Effect of flat-surface template on magnetic properties





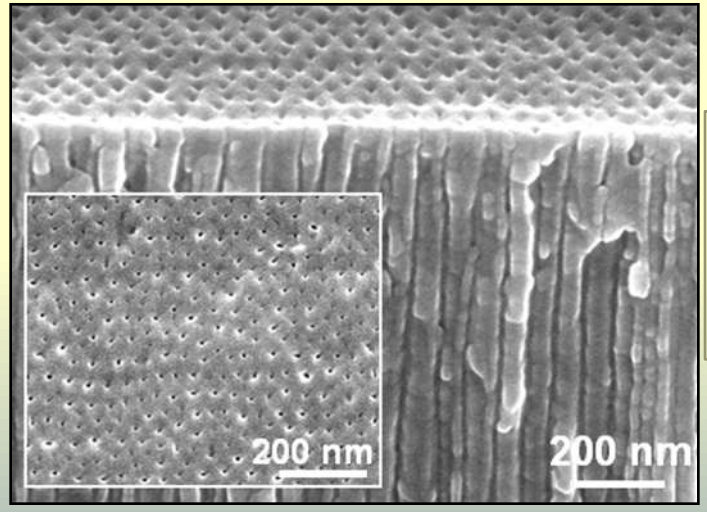
<u>Conserved perpendicular anisotropy</u>

- **Coercive force H_C = 2700 Oe**
- **Squareness: M_r/M_S = 0.7**
- **K_{eff} = 1.9·10^6 erg/cm^3**

$[Co/Pd]_n/Al_2O_3//Si$

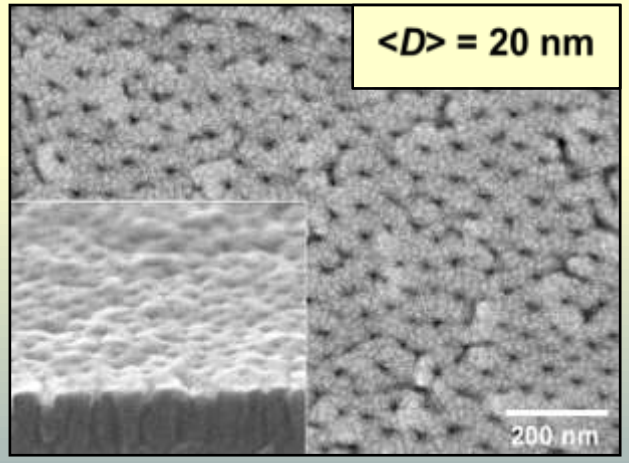
Belarusian State University, Minsk, Belarus

Flat-surface Al_2O_3 templates ➡ $[Co/Pd]_n$ porous MLs with smoothed surface

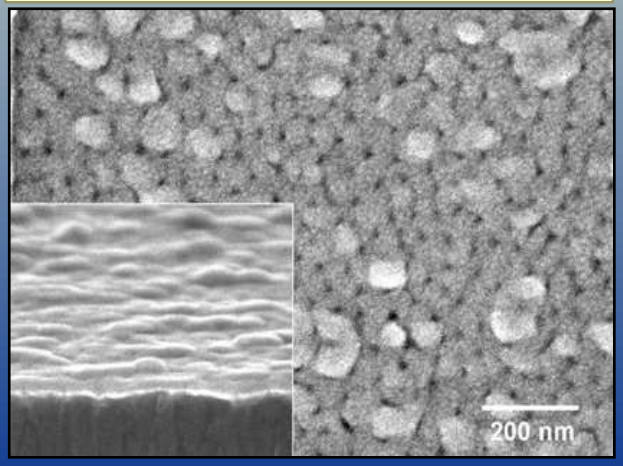


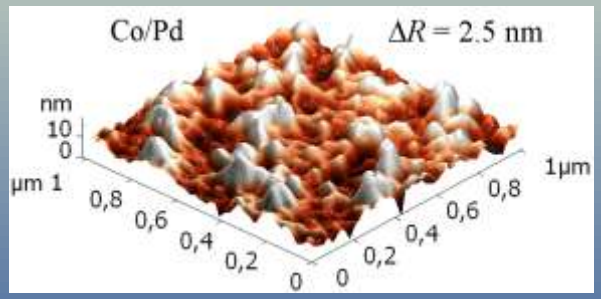
Template

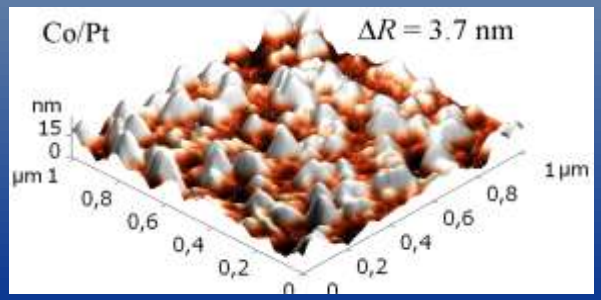
$Pd_{15\ nm}/[Co_{0.5\ nm}/Pd_{1\ nm}]_5/Pd_{3\ nm}$



$Pt_{15\ nm}/[Co_{0.4\ nm}/Pt_{0.8\ nm}]_{x5}/Pt_{3\ nm}$



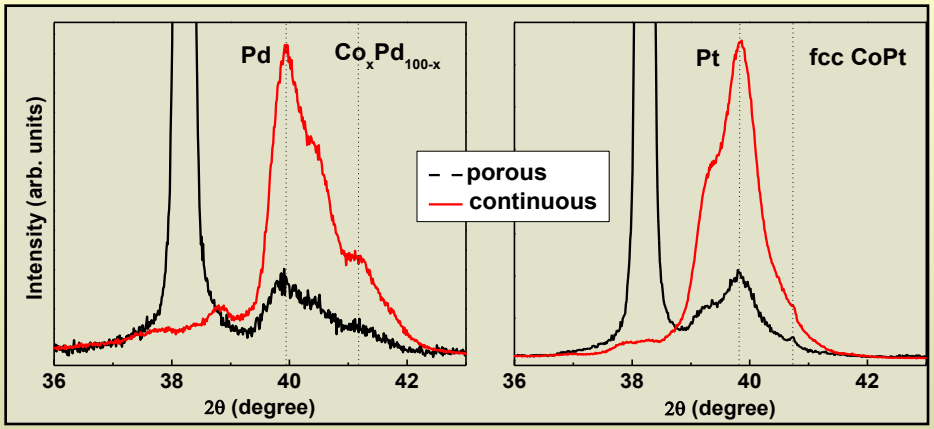




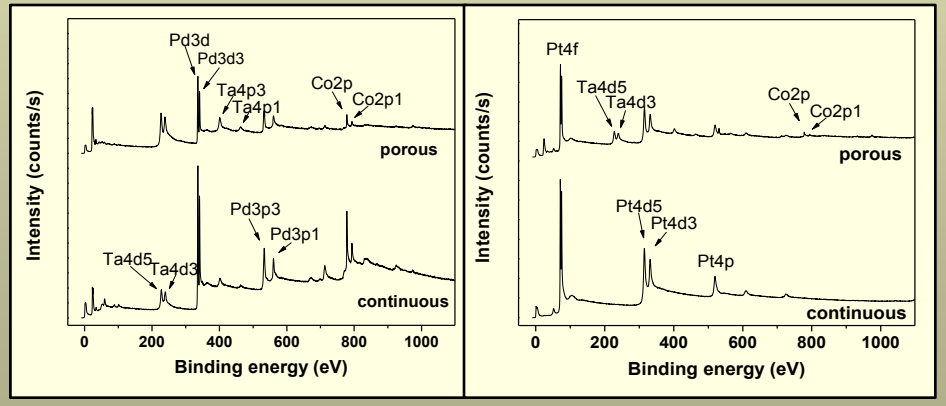
$[Co/Pd]_n/Al_2O_3//Si$

Belarusian State University, Minsk, Belarus

X-ray diffraction

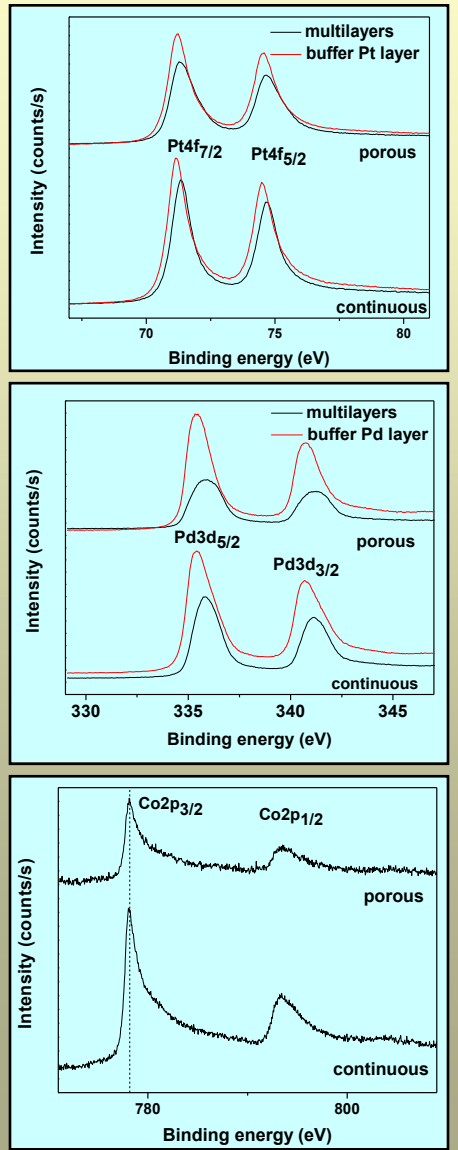


X-ray photoelectron spectroscopy



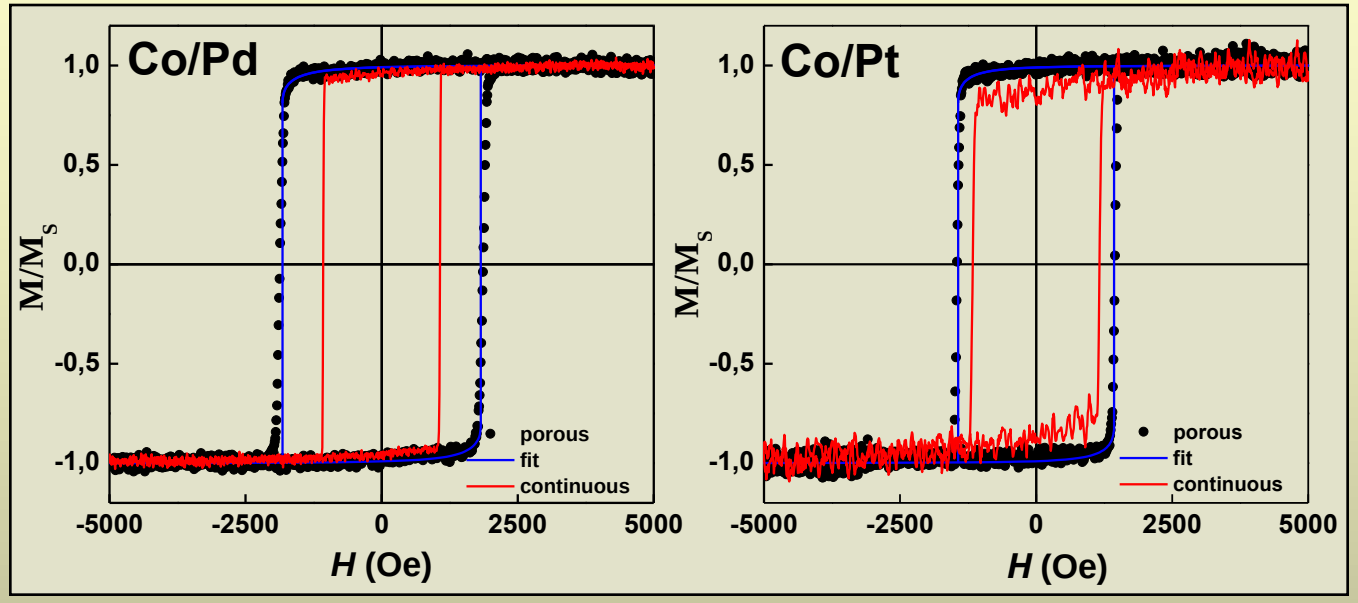
Ordering in Co/Pd and Co/Pt MLs is not affected by the surface morphology

High-resolution XPS



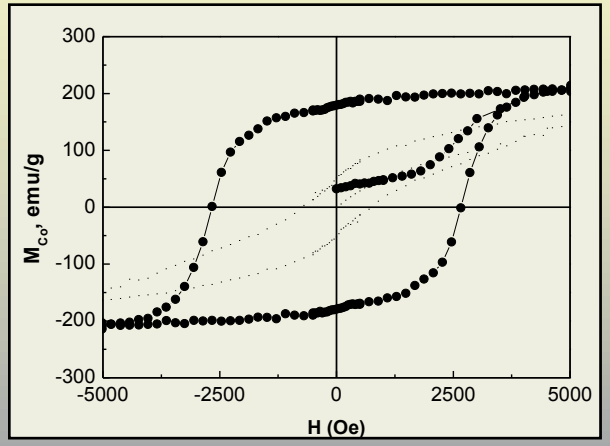
Layer - by - layer sputtering

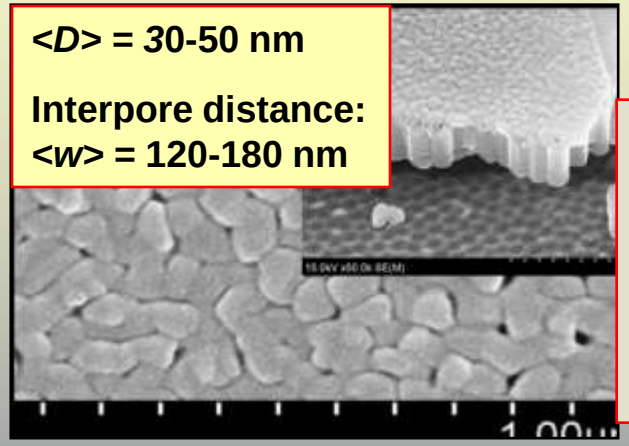
Magnetic properties: fitting with S-W model



	Coercive field H_C, Oe	M_r/M_S	H_K, Oe
	Continuous MLs		
Co/Pd; Co/Pt	1100 – 1200	0.99	
	Porous MLs		
Co/Pd	1900	0.99	2600
Co/Pt	1500	0.99	2000

Comparison of magnetic properties of porous Co/Pd reflects difference between morphology TiO_2 and Al_2O_3 templates

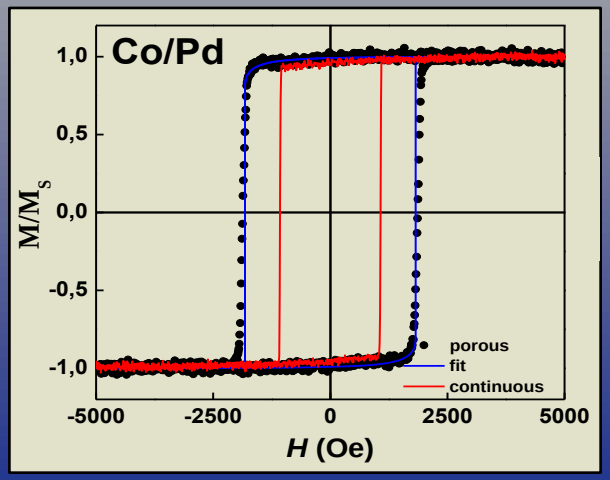


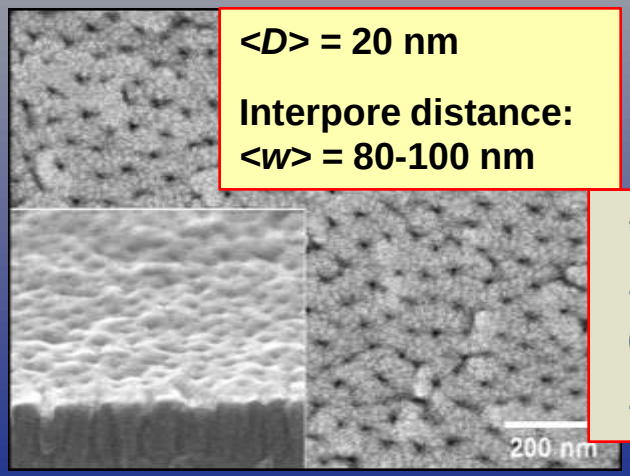


<*D*> = 30-50 nm

Interpore distance:
<*w*> = 120-180 nm

- H_C = 2700 Oe (more pinning centers)
- M_r/M_S = 0.7
- H_k = 6000 Oe
- K_{eff} = $1.9 \cdot 10^6$ erg/cm^3



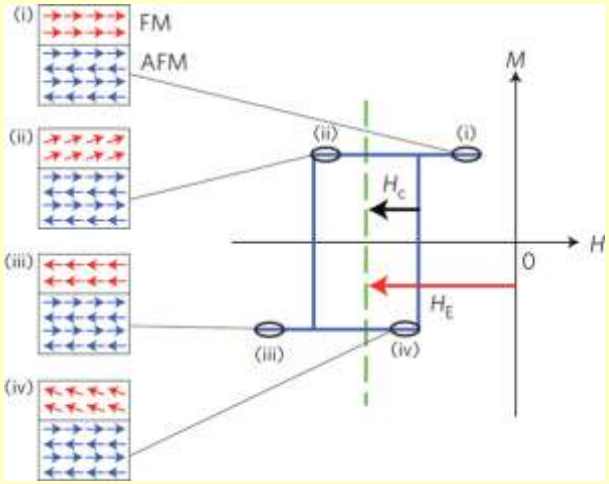


<*D*> = 20 nm

Interpore distance:
<*w*> = 80-100 nm

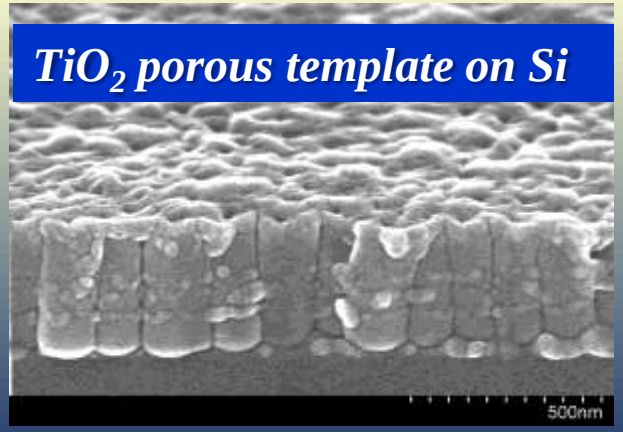
- H_C = 1900 Oe
- M_r/M_S = 0.99 (smoothed relief)
- H_k = 2600 Oe

Fabrication of FM/AFM porous ML with perpendicular exchange bias: coupling between IrMn (AFM) and Co/Pt (FM) layers



AFM layer to pin the magnetization of FM film in a particular direction by interfacial exchange interaction with an AFM layer

AFM layer – IrMn:
resistant to corrosion
possess high $T_N \approx 400$ °C



TiO_2 porous template on Si

$Si/TiO_2//IrMn/CoFe/[Pt/Co]_2$

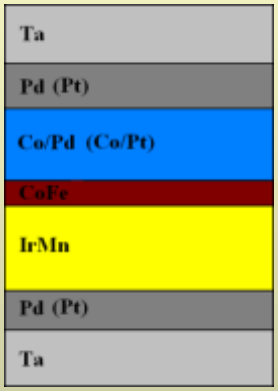
$Si/TiO_2//CoFe/[Pt/Co]_2/IrMn$

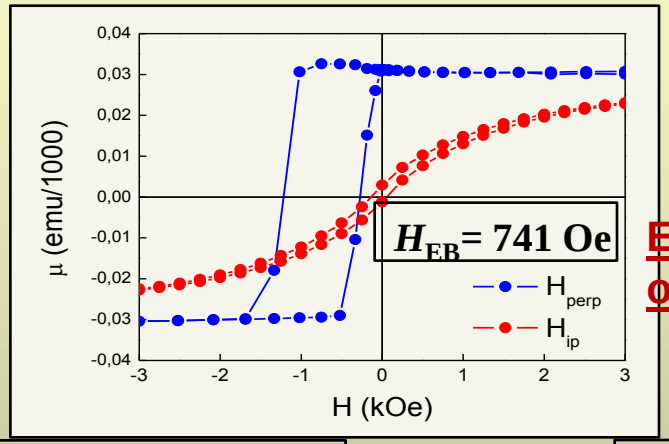
Dr. Dmitriy Mitin
Experimentalphysik IV
Institut für Physik
Universität Augsburg

Universität Augsburg University

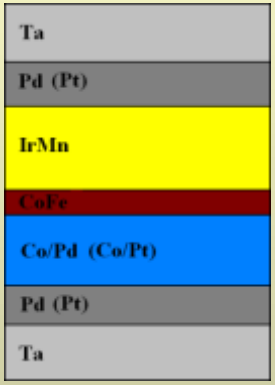
First magnetometry results: experimental evidence for exchange bias in FM/AFM porous MLs

Continuous MLs: $Si/SiO_2//IrMn/CoFe/[Pt/Co]_2$

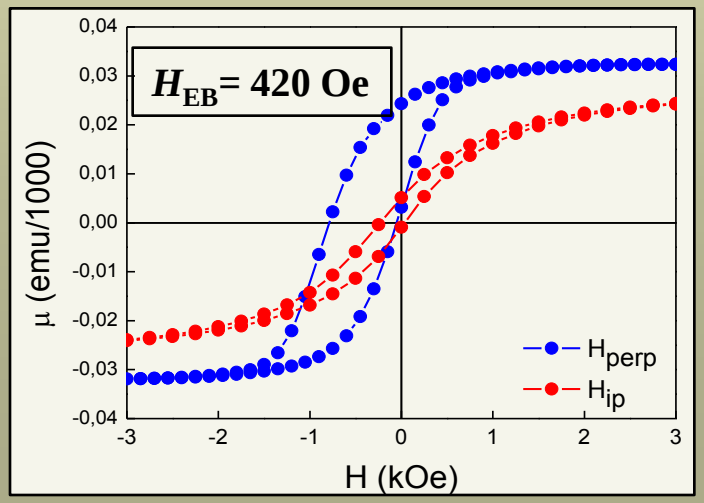




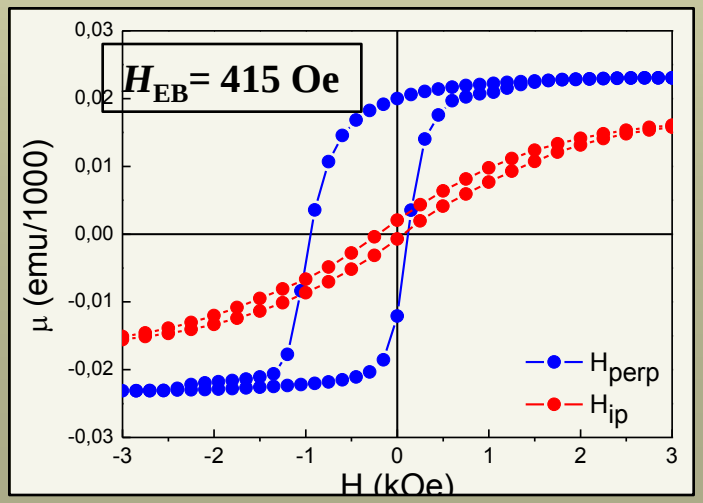
Exchange bias observed at RT



$Si/TiO_2//IrMn/CoFe/[Pt/Co]_2$

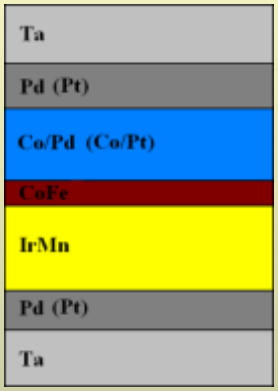


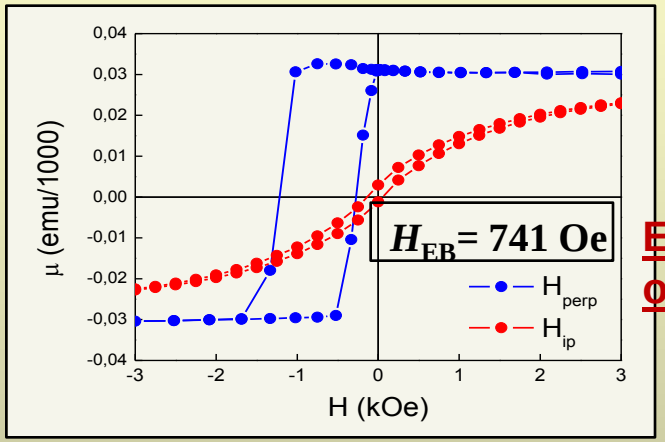
$Si/TiO_2//CoFe/[Pt/Co]_2/IrMn$



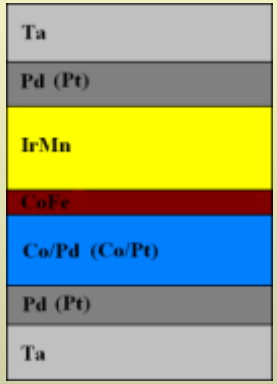
First magnetometry results: experimental evidence for exchange bias in FM/AFM porous MLs

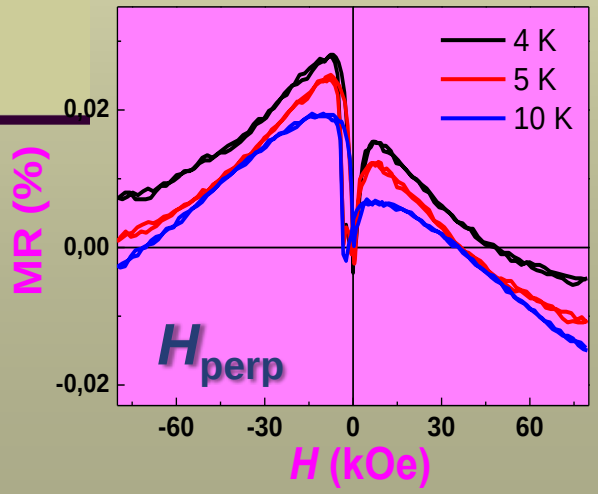
Continuous MLs: $Si/SiO_2//IrMn/CoFe/[Pt/Co]_2$





Exchange bias observed at RT

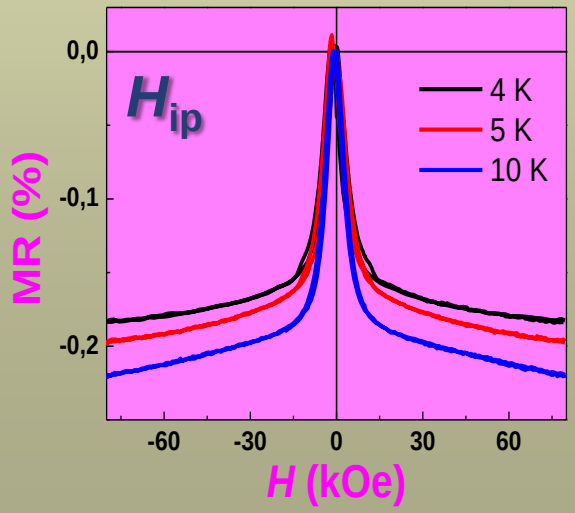




Magnetoresistivity

Co/Pt//IrMn MLs

- *non-symmetric MR effect in the film normal direction*
- *different types of MR effect in two opposite directions*



Belarusian State University, Minsk, Belarus

Journal of Magnetism and Magnetic Materials 400 (2016) 200–205

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Magnetic characteristics of CoPd and FePd antidot arrays on nanoperforated Al_2O_3 templates

A. Maximenko [a,b,*], J. Fedotova [b], M. Marszałek [a], A. Zarzycki [a], Y. Zabila [a]

[a] The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Radzikowskiego Str. 152, 31-342 Kraków, Poland
[b] Research Institute for Nuclear Problems of Belarusian State University, Bobruiskaya Str. 11, 220030 Minsk, Belarus

Applied Surface Science 427 (2018) 649–655

Contents lists available at ScienceDirect

Applied Surface Science

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

Full Length Article

Effect of flattened surface morphology of anodized aluminum oxide templates on the magnetic properties of nanoporous Co/Pt and Co/Pd thin multilayered films

T.N. Anh Nguyen [a,b,c,*], J. Fedotova [d], J. Kasiuk [d], V. Bayev [d], O. Kupreeva [e], S. Lazarouk [e], D.H. Manh [a], D.L. Vu [a], S. Chung [b,c], J. Åkerman [b,c], V. Altynov [f], A. Maximenko [d]

[a] Institute of Materials Science, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Hanoi, Viet Nam
[b] Material Physics Department, Royal Institute of Technology, 164 40 Kista, Sweden
[c] Department of Physics, University of Gothenburg, Gothenburg, 41296, Sweden
[d] Institute for Nuclear Problems, Belarusian State University, Minsk, Belarus
[e] Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus
[f] Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

Journal of Magnetism and Magnetic Materials 434 (2017) 157–161

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Structure and magnetic properties of Co/Pd multilayers prepared on porous nanotubular TiO_2 substrate

A. Maximenko [a,b], M. Marszałek [a,*], J. Fedotova [b], A. Zarzycki [a], Y. Zabila [a], O. Kupreeva [c], S. Lazarouk [c], J. Kasiuk [b], S. Zavadski [c]

[a] Institute of Nuclear Physics Polish Academy of Sciences, Pl. 31-342 Kraków, Poland
[b] Research Institute for Nuclear Problems of Belarusian State University, Bobruiskaya str. 11, 220030 Minsk, Belarus
[c] Belarusian State University of Informatics and Radioelectronics, P.Brovka str. 6, 220013 Minsk, Belarus

Физика твердого тела, 2017, том 59, вып. 9

05,13

Магнитные свойства многослойных пленок Co/Pd на пористых темплатах Al_2O_3 с развитой субструктурой ячеек

© А.А. Максименко [1,2], Ю.В. Касюк [2,¶], Ю.А. Федотова [2], M. Marszałek [1], Y. Zabila [1], J. Chojenka [1]

[1] Institute of Nuclear Physics of Polish Academy of Science, Krakow, Poland
[2] Институт ядерных проблем Белорусского государственного университета, Минск, Беларусь

ISSN 1063-7834, Physics of the Solid State, 2016, Vol. 58, No. 11, pp. 2312–2319. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © Yu.V. Kasyuk, A.A. Maksimenko, Yu.A. Fedotova, M. Marsalek, S.K. Lazaruk, O.V. Kupreeva, 2016, published in Fizika Tverdogo Tela, 2016, Vol. 58, No. 11, pp. 2229–2236.

MAGNETISM

Effect of the Morphology on the Mechanisms of the Magnetization Reversal of Multilayer Thin Co/Pd Films

Yu. V. Kasyuk[a], A. A. Maksimenko[a, b], Yu. A. Fedotova[a], M. Marsalek[b], S. K. Lazaruk[c], and O. V. Kupreeva[c]

[a] Institute of Nuclear Problems, Belarussian State University, ul. Bobruiskaya 11, Minsk, 220030 Belarus
[b] The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[c] Belarussian State University of Informatics and Radioelectronics, ul. Petrusya Brovki 6, Minsk, Belarus
e-mail: julia-mechaj@yandex.ru

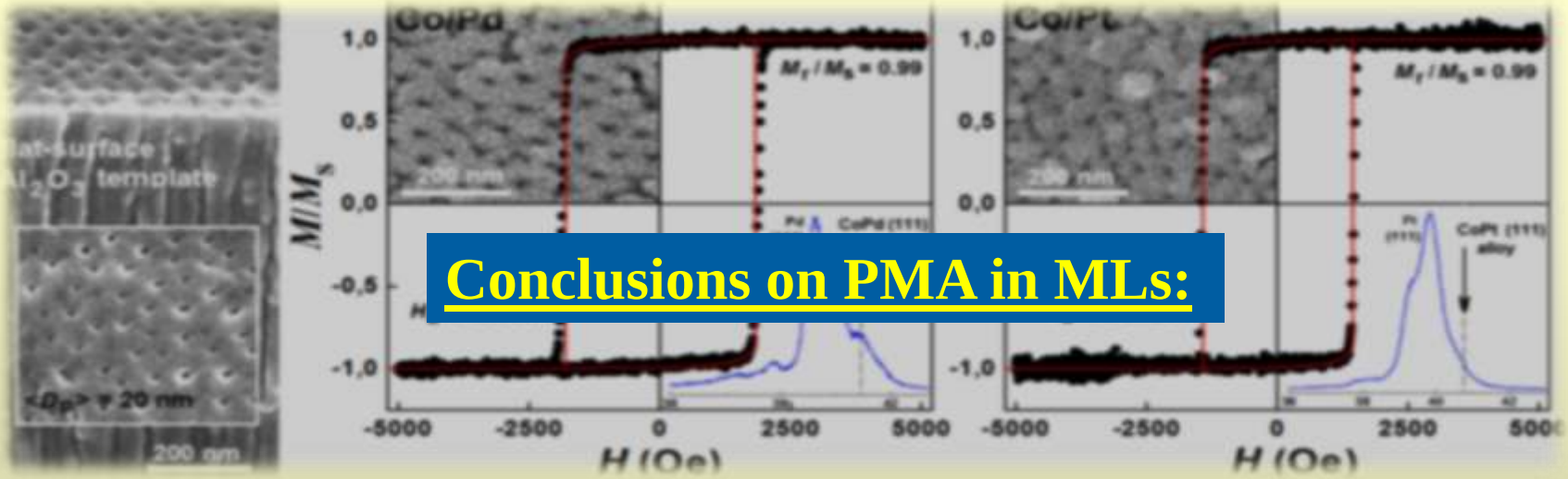
Received April 19, 2016

PHYSICS, CHEMISTRY AND APPLICATION OF NANOSTRUCTURES, 2017

INVITED

CORRELATED EVOLUTION OF SURFACE MORPHOLOGY, STRUCTURE AND MAGNETIC PROPERTIES OF NANOPOROUS Co/Pd FILMS WITH PERPENDICULAR MAGNETIC ANISOTROPY

J. Fedotova, J. Kasiuk, V. Bayev



Conclusions on PMA in MLs:

- Anodized templates of TiO_2 and Al_2O_3 with flattened interpore areas favors conservation of perpendicular magnetic anisotropy in porous Co/Pd and Co/Pt thin ML films with smoothed surface relief.
- Magnetization reversal in porous films proceeds by rotational mechanism and could be considered within Stoner-Wohlfarth model because of the refinement of magnetic domain structure.
- Further progress in fabrication of porous films for spintronic devices should be focused on porous FM/AFM films with FM layers possessing perpendicular magnetic anisotropy.

Financial support:

1. *Polish Ministry of Science and Education*
2. *Project VAST.HTQT.BELARUS.03/16-17*
3. *National Foundation for Science and Technology Development of Vietnam, Project 103.99-2015.83*
4. *Belarusian State program "Functional materials", BRFFR grant F16V2-004*

Collaborators:

Synthesis of templates

Prof. S. Lazarouk
Ms. Sci. O.Kupreeva
Belarusian University of Informatics and Radioelectronics, Minsk

MLs fabrication, XRD, AGM

T.N. Anh Nguyen
D. H. Manh
D. L. Vu
Institute of Materials Science, Hanoi

MLs fabrication, SQUID, MFM

Prof. M. Marszalek
Ms. Sci. A. Maximenko
Niewodniczanski Institute of Nuclear Physics, Cracow

Magnetometry, AFM

Dr. J.Kasiuk
Dr. V. Bayev
Institute for Nuclear Problems Belarusian State University, Minsk

Thank you for attention!