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Badania dyfrakcyjne cienkowarstwowych struktur pod kątem zastosowań w elektronice spinowej

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Katedra Elektroniki, WIEiT AGH



Seminarium WFIS AGH, 25 I 2019

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Laboratorium Badań Strukturalnych

<http://www.lbs.agh.edu.pl/>



Laboratorium
Badań
Strukturalnych
Katedra Elektroniki
WIEIT AGH w Krakowie

W dniu 25 lipca 2013r. Laboratorium uzyskało akredytację
z Certyfikatem Akredytacji Laboratorium Badawczego nr AB 1445





- Motywacja
- Magnetyczne złącza tunelowe (MTJ)
- Układy Co/Pt z prostopadłą anizotropią magnetyczną
- Hybrydowe układy metal spinowo-orbitalny/ferromagnetyk do badań spinowego efektu Halla (Ta/CoFeB/MgO/Ta)



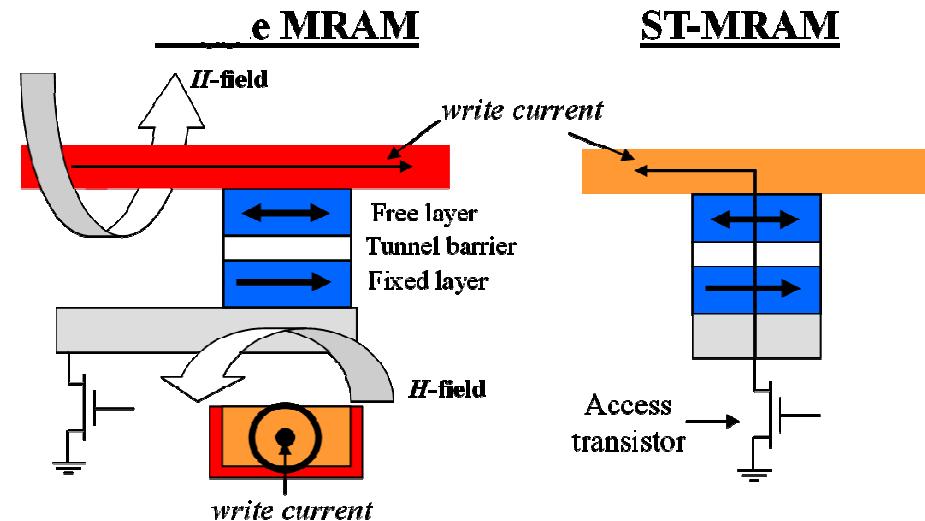
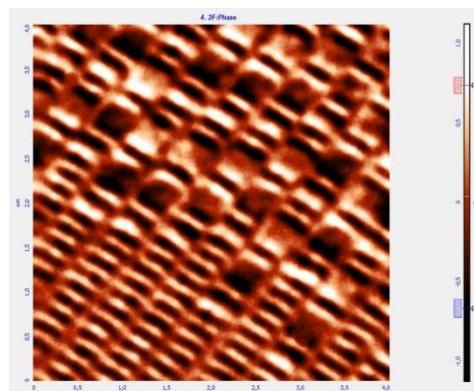
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Spis publikacji



- [1] **J. Kanak**, M. Czapkiewicz, T. Stobiecki, M. Kachel, I. Sveklo, A. Maziewski, and S. van Dijken, phys. stat. sol. (a), 204 (2007) 3950
- [2] **J. Kanak**, T. Stobiecki, V. Drewello, J. Schmalhorst, and G. Reiss, phys. stat. sol. (a), 204 (2007) 3942
- [3] **J. Kanak**, T. Stobiecki, A. Thomas, J. Schmalhorst, G. Reiss, Vacuum, 82 (2008) 1057
- [4] **J. Kanak**, T. Stobiecki, S. van Dijken, IEEE Trans. Magn., 44 (2008) 238
- [5] J. Cao, **J. Kanak**, T. Stobiecki, P. Wisniowski, and P.P. Freitas, Effect of Buffer Layer Texture on the Crystallization of CoFeB and on the Tunnel Magnetoresistance in MgO Based Magnetic Tunnel Junctions, IEEE Trans Magn., 45 (2009) 3464,
- [6] **J. Kanak**, P. Wiśniowski, T. Stobiecki, A. Zaleski, W. Powroźnik, S. Cardoso, P. Freitas, J. Appl. Phys. (2013) vol. 113, 023915,
- [7] M. Cecot, J. Wrona, **J. Kanak**, S. Ziętek, W. Skowroński, A. Żywczałk, M. Czapkiewicz, T. Stobiecki, IEEE Transactions on Magnetism 51 (2015) 6101504
- [8] M. Frankowski, A. Żywczałk, M. Czapkiewicz, S. Ziętek, **J. Kanak**, M. Banasiak, W. Powroźnik, W. Skowroński, J. Chęciński, J. Wrona, H. Głowiński, J. Dubowik, J.-Ph. Ansermet, T. Stobiecki, J. Appl. Phys. 117, (2015) 223908,
- [9] W. Skowroński, M. Cecot, **J. Kanak**, S. Ziętek, T. Stobiecki, L. Yao, S. van Dijken, T. Nozaki, K. Yakushiji, S. Yuasa, Appl. Phys. Lett. 109 (2016) 062407,
- [10] M. Cecot, Ł. Karwacki, W. Skowroński, **J. Kanak**, J. Wrona, A. Żywczałk, L. Yao, S. Dijken, J. Barnaś, T. Stobiecki, Scientific Reports 7, Article number: 968 (2017)
- [11] P. Nawrocki, **J. Kanak**, M. Wójcik, T. Stobiecki, Co-59 NMR analysis of CoFeB-MgO based magnetic tunnel junction, Journal of Alloys and Compounds. 741 (2018) 775-780
- [12] W. Skowroński, Ł. Karwacki, S. Ziętek, **J. Kanak**, S. Łazarski, K. Grochot, T. Stobiecki, P. Kuświk, F. Stobiecki, and J. Barnaś, Physical Review Applied, Accepted 15 January 2019

Motywacja

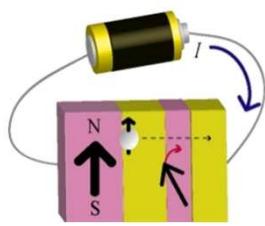


Everspin:
1Gb STT-MRAM chip - grudzień 2018 (256Mb 2016)

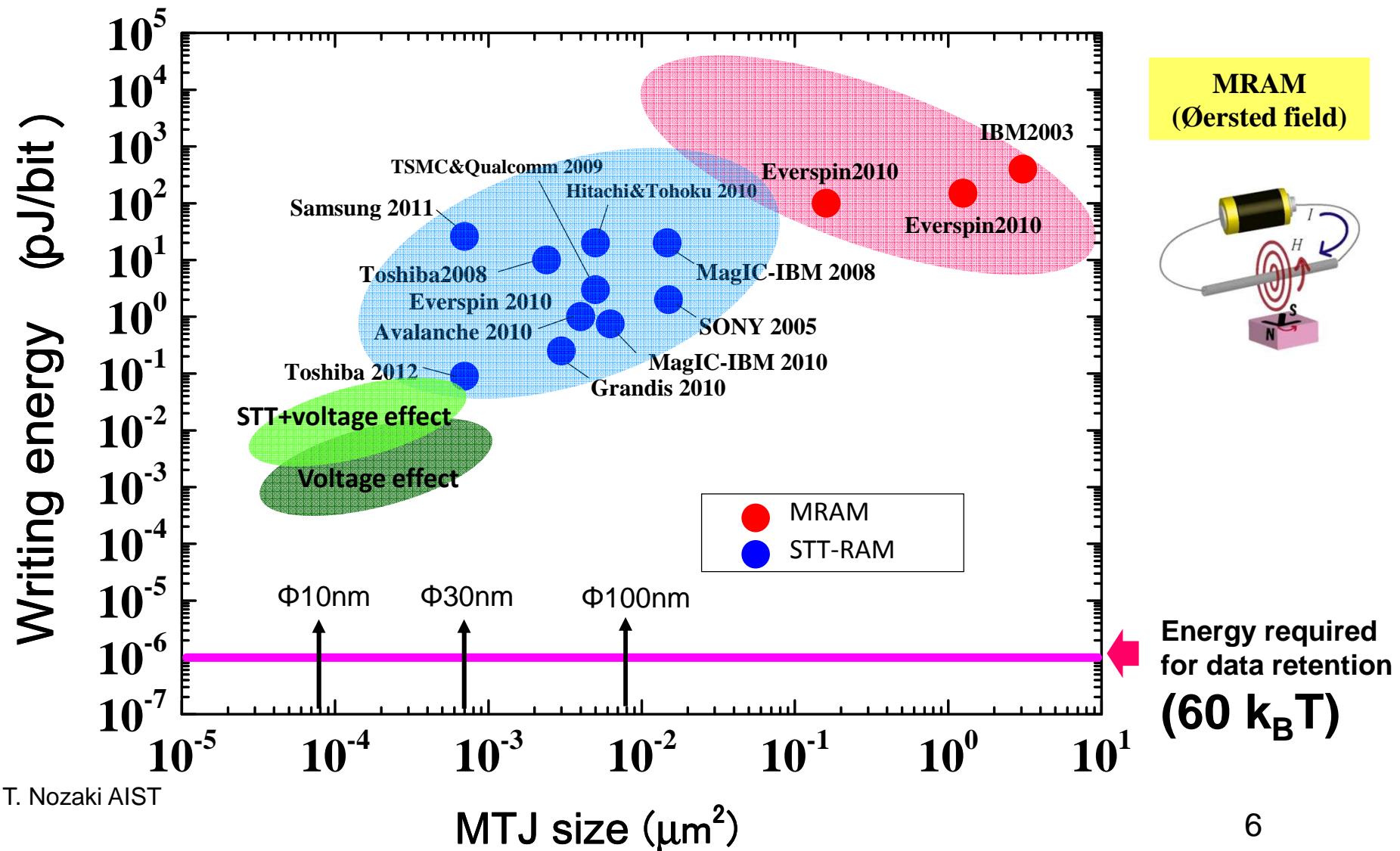
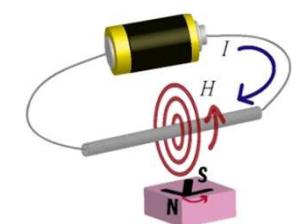
Motywacja



Spin-transfer torque (STT) - RAM



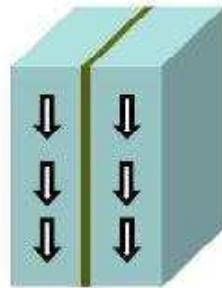
MRAM (Øersted field)



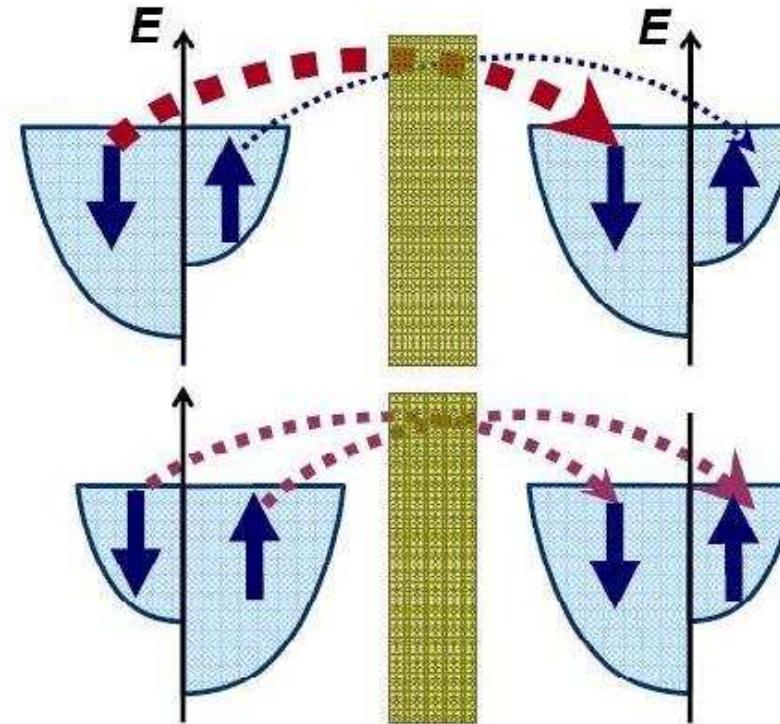
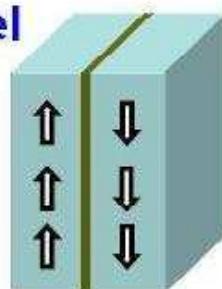
Magnetyczne złącze tunelowe (MTJ)



Parallel



Antiparallel

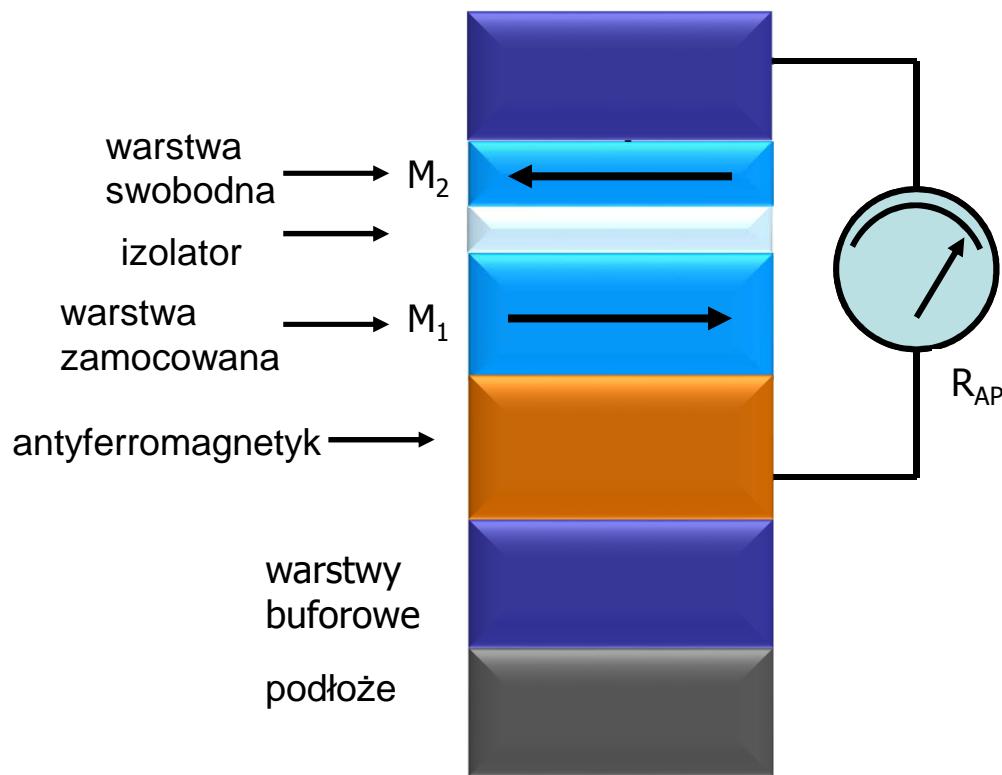


$$MR = (RAP - RP) / RP \sim 1000\%$$

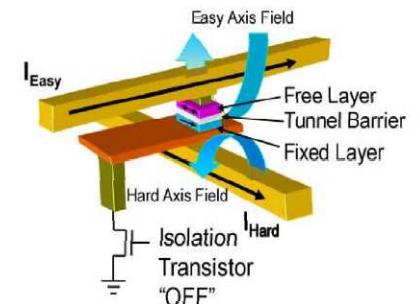
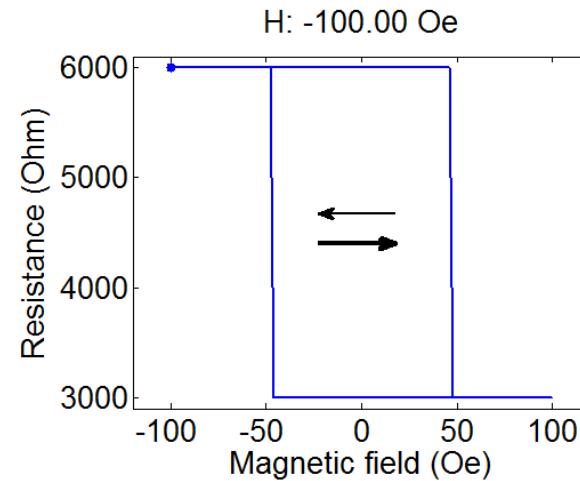
Butler *et al.* PhysRev. B, 63 056614 (2001).

Mathon & Umerski, Phys. Rev. B 220403 (2001).

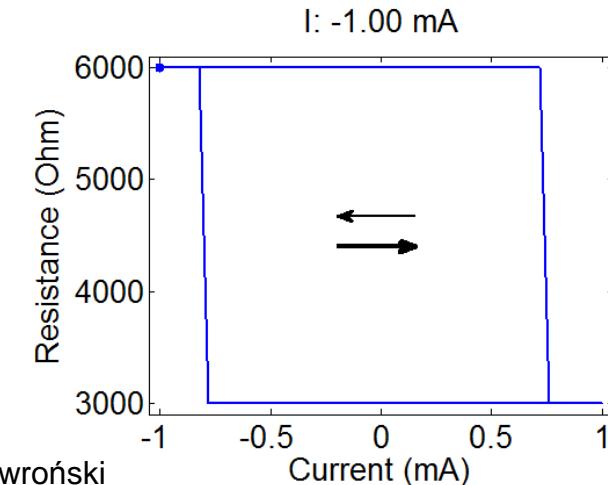
Zawór spinowy MTJ



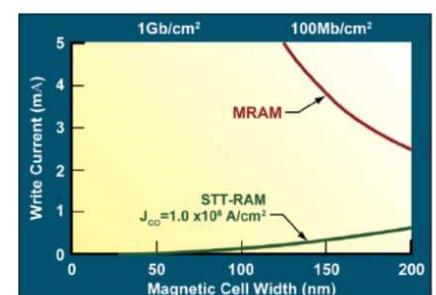
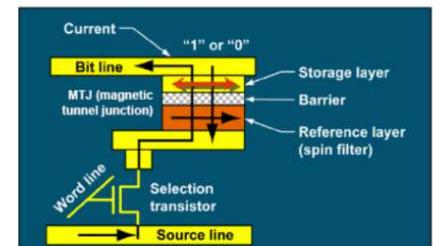
Przełączanie zewnętrznym polem



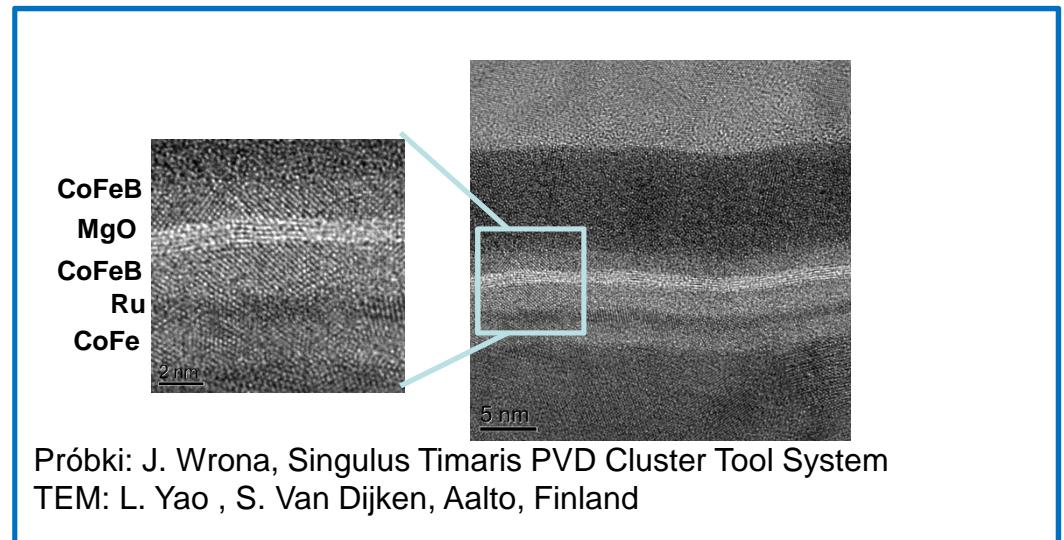
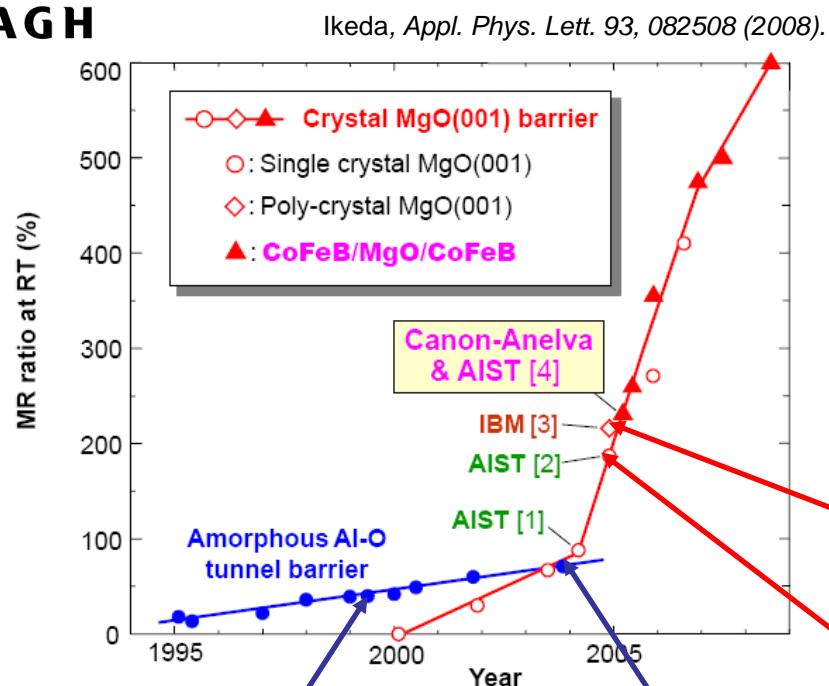
Przełączanie prądem



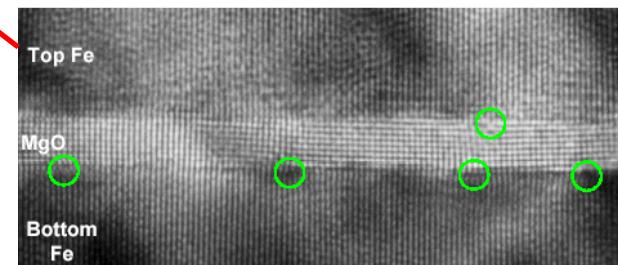
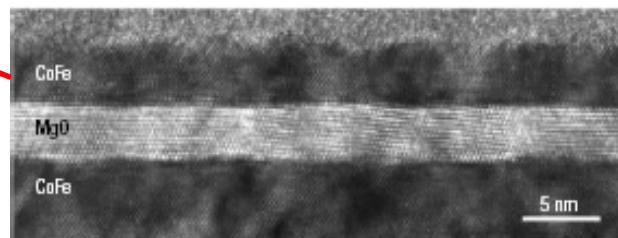
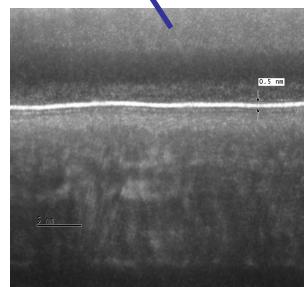
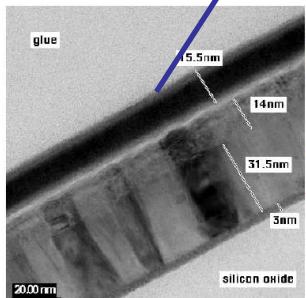
W. Skowroński



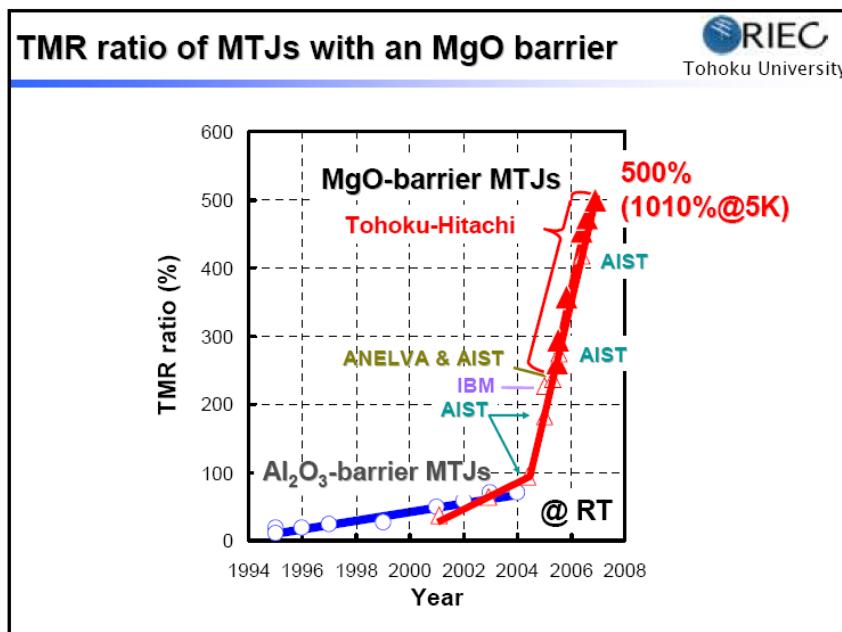
Tunelowa Magnetorezystancja (TMR)



[1] Yuasa, *Jpn. J. Appl. Phys.* 43, L558 (2004). [2] Parkin, *Nature Mater.* 3, 862 (2004).
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Magnetyczne złącze tunelowe (MTJ)



MR ratios up to 1,000% at RT

S. Ikeda et al., *Appl. Phys. Lett.*, **93**, 082508 (2008).
 Jiang et al., *Appl. Phys. Express*, **2**, 083002 (2009).

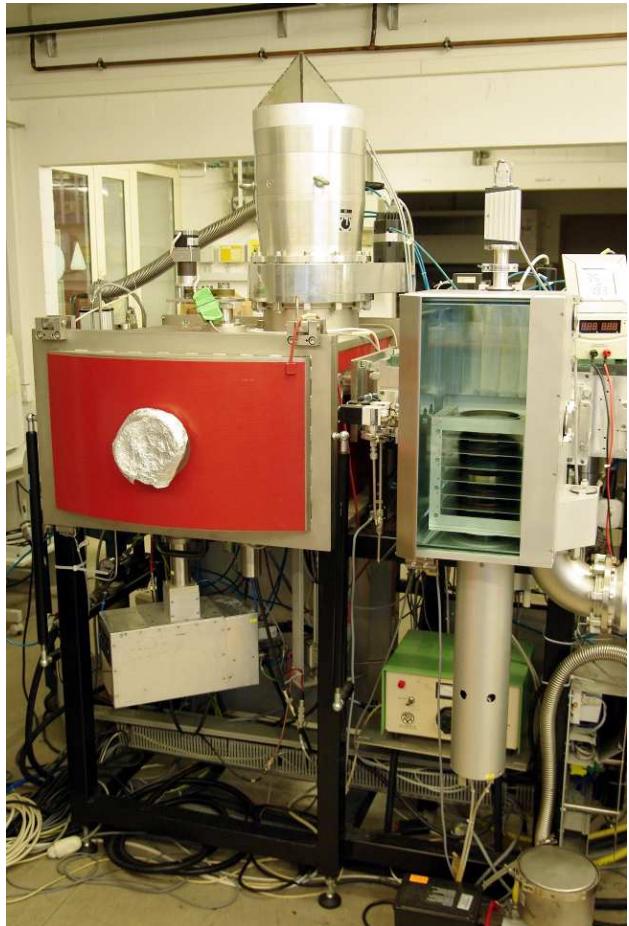
RA, TMR and H_{in} of MTJs with Al-O and MgO barrier

Buffer	Al-O MTJs			MgO MTJs				
	RA-P ($M\Omega \mu m^2$)	RA-AP ($M\Omega \mu m^2$)	TMR (%)	H_{in} (kA/m)	RA-P ($M\Omega \mu m^2$)	RA-AP ($M\Omega \mu m^2$)	TMR (%)	H_{in} (kA/m)
A	10.7	15.5	44	1.1	0.36	0.88	141	0.28
B	4.7	6.9	46	3.2	0.073	0.16	113	1.8

RA-P and RA-AP were measured in parallel and antiparallel orientation of magnetizations of free and pinned layer, respectively.

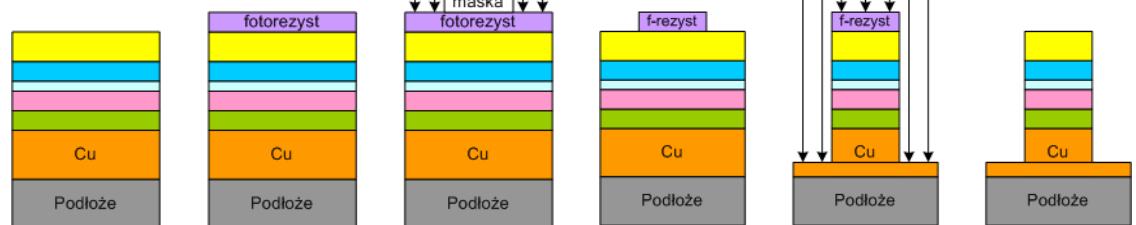
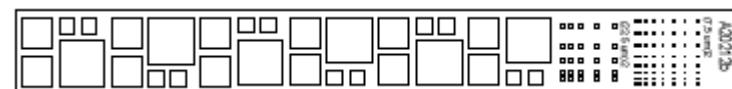
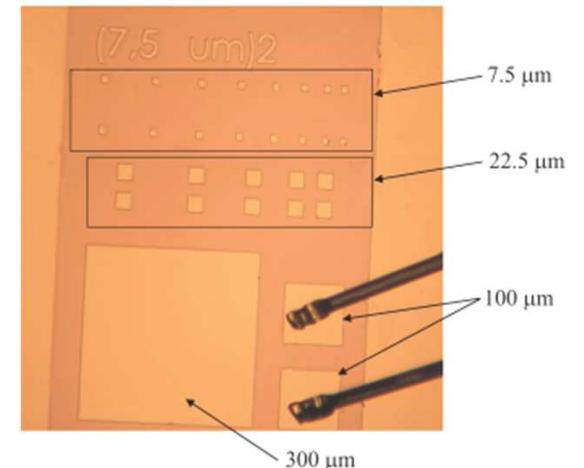
J. Kanak, et al. Vacuum 82 (2008)1057
 J. Kanak, et al. phys. stat. sol. (a) 204 (2007) 3942

Nanoszenie i strukturyzacja



Leybold CLAB600

- sputter deposition
- 6 sources, 4", DC or RF mode
- high vacuum
- automatic sample handling
- plasma oxidation chamber



University Bielefeld - Thin Films and Physics of Nanostructures

Układy MTJ z barierą MgO

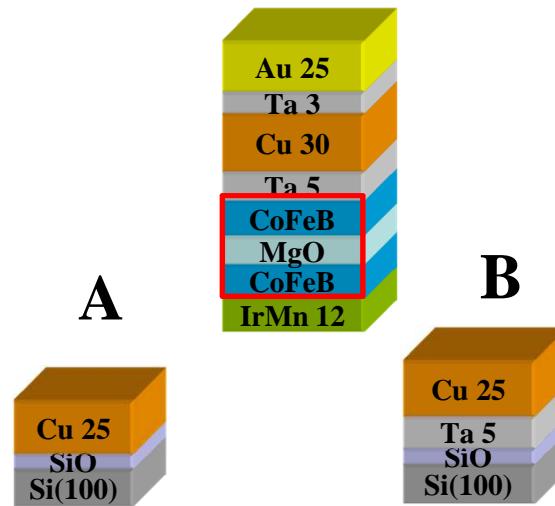


Table 1
Results of XRR fitting

Buffer	SiO ₂		Ta		Cu		IrMn	
	t (nm)	RMS (nm)	t (nm)	RMS (nm)	t (nm)	RMS (nm)	t (nm)	RMS (nm)
A	47	0.26			26.7	0.52	11.9	0.59
B	47	0.26	5.5	0.17	27.0	0.95	11.9	1.03

t, the thickness of the layer, RMS, the roughness on the top of layer.

J. Kanak, et al. Vacuum 82 (2008)1057

J. Kanak, et al. phys. stat. sol. (a) 204 (2007) 3942

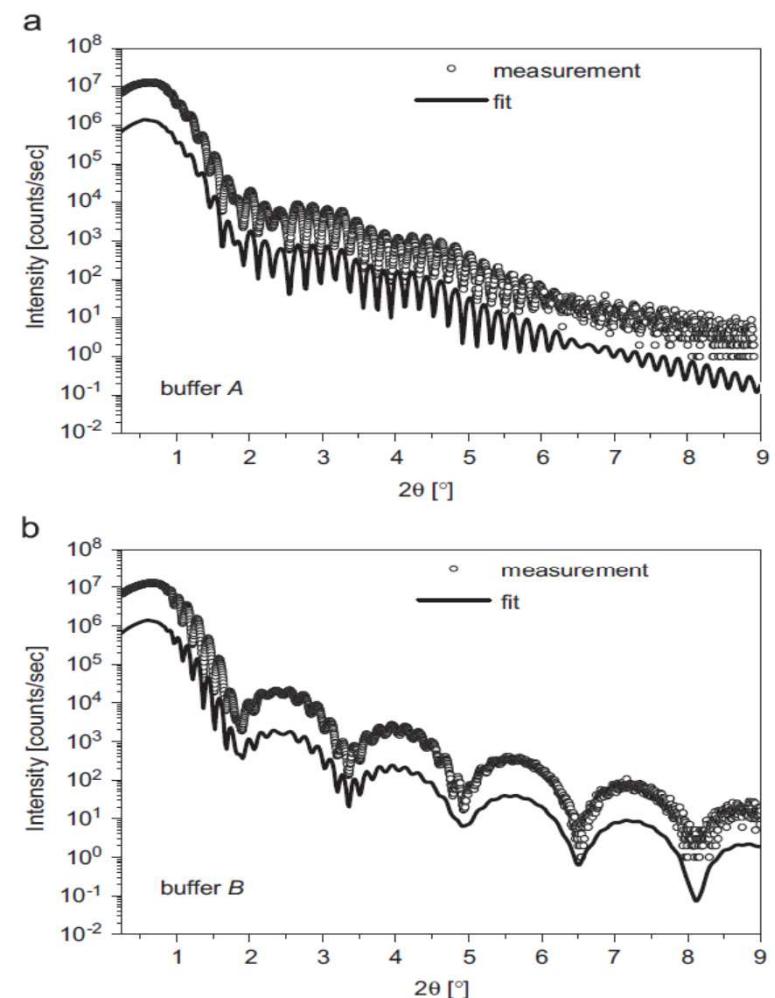


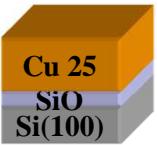
Fig. 3. Specular X-ray reflectivity measurements and fittings for Si/SiO₂/buffer/IrMn 12 nm/Ta 5 nm samples with buffer A: Cu 25 nm (a) and B: Ta 5 nm/Cu 25 nm (b). For better visualization the experimental and fittings curves are split.



Układy MTJ z barierą Al-O i MgO

A

b



B

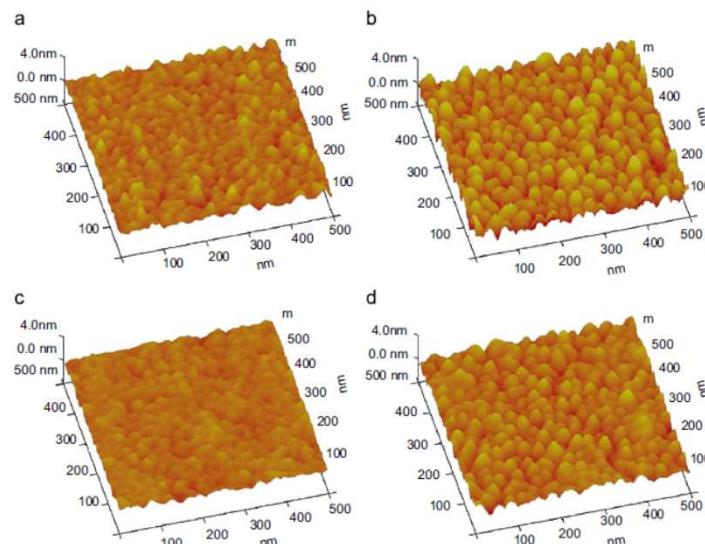
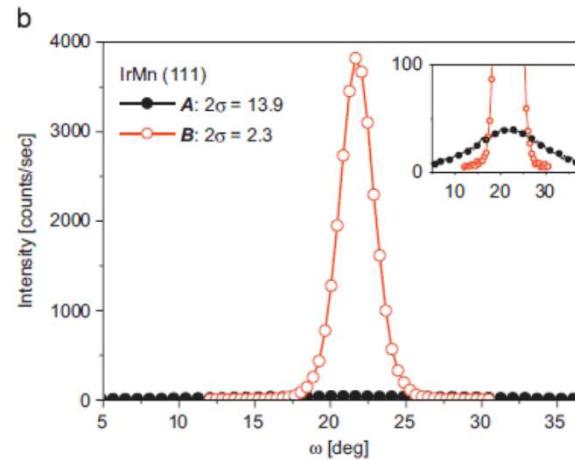
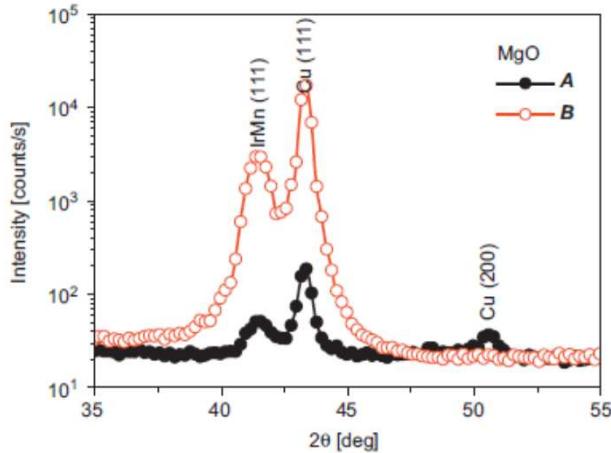
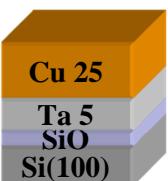
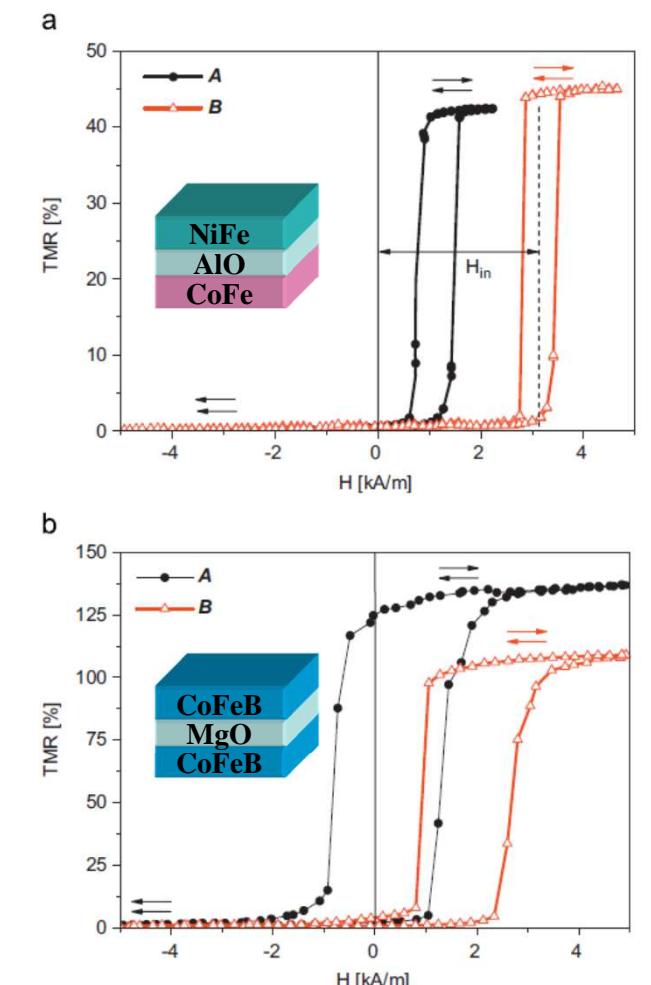


Fig. 4. The AFM images ($500 \text{ nm} \times 500 \text{ nm}$) measured on the top of annealed MTJs with Al-O barrier grown on buffer A Cu 25 nm (a) and B Ta 5 nm/Cu 25 nm (b), and MTJs with MgO barrier grown on buffer A Cu 25 nm (c) and B Ta 5 nm/Cu 25 nm (d).

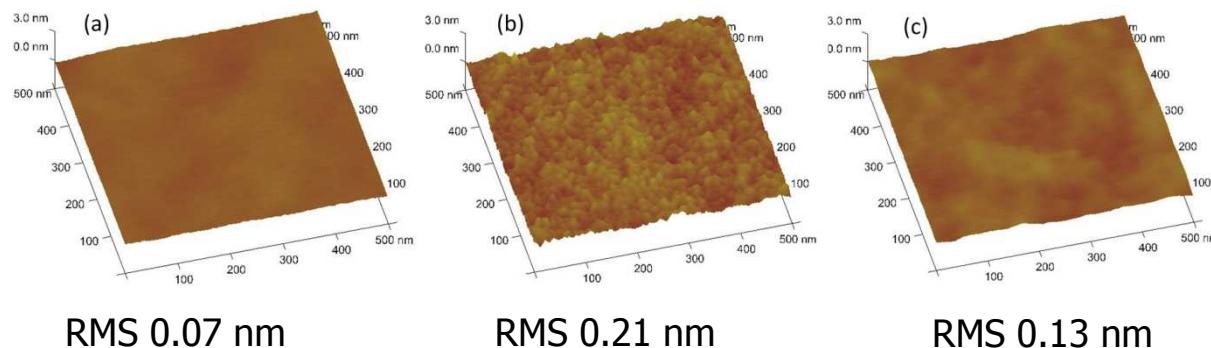
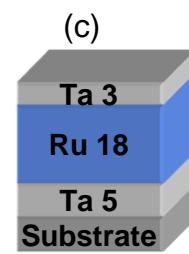
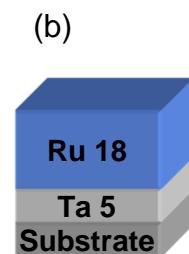
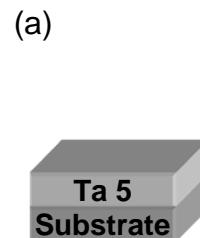
Fig. 5. Room temperature minor magnetoresistance hysteresis loops of junctions with the Al-O (a) and MgO (b) barrier.



Układy PSV i EB-SV na buforze Ru

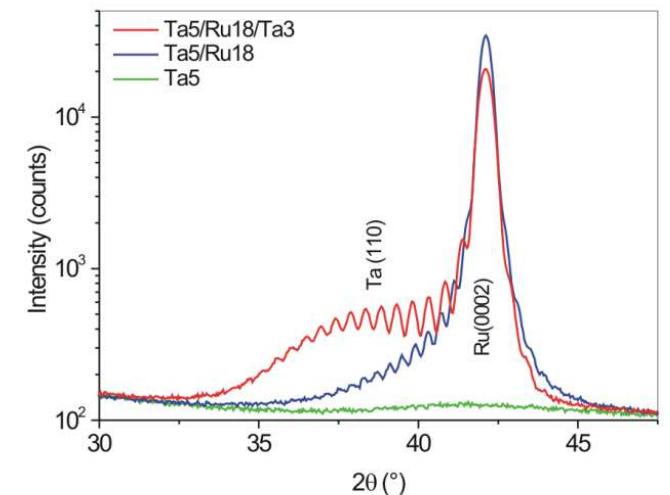
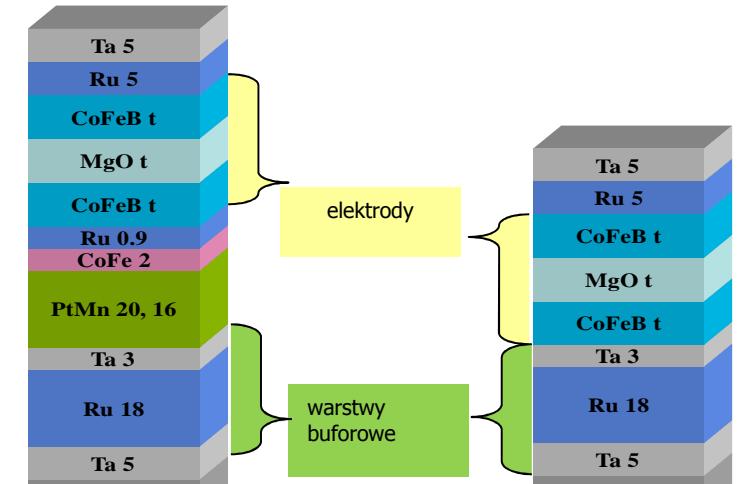


Bufor Ru

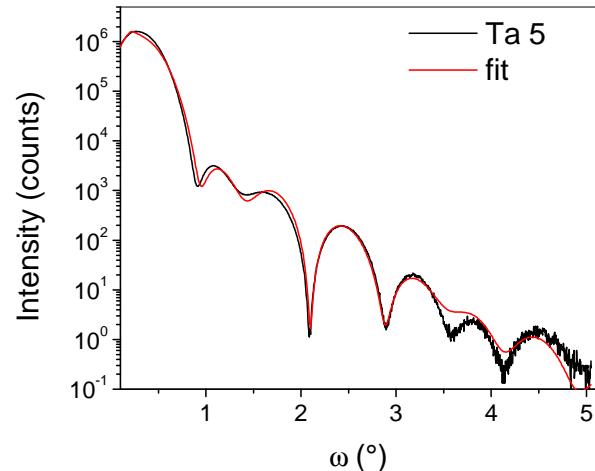


J. Kanak, et al. J. Appl. Phys. 113, (2013) 023915

INESC MN

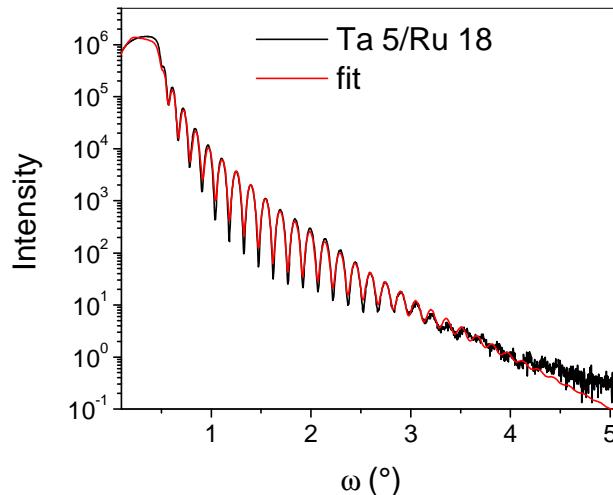
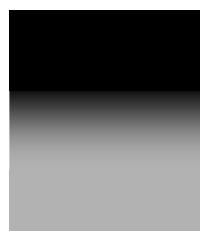


Analiza XRR - bufor Ru

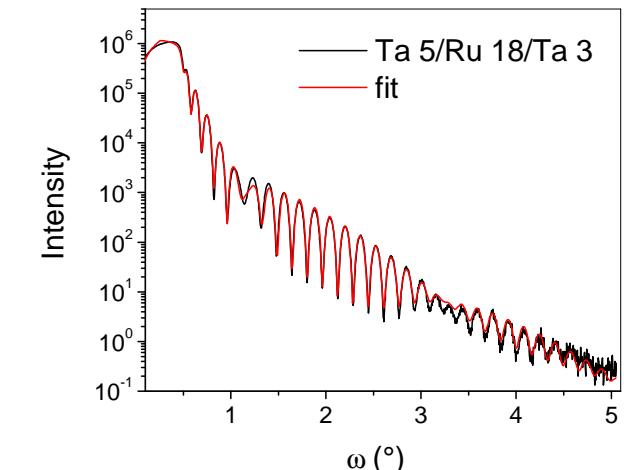


Layer	Thickness	Roughness/ Interdiffusion
Ta	4.49	0.36
Ta-O	1.84	0.36

Roughness Interdiffusion



Layer	Thickness	Roughness/ Interdiffusion
Ta	5.46	0.74
Ru	23.09	0.51



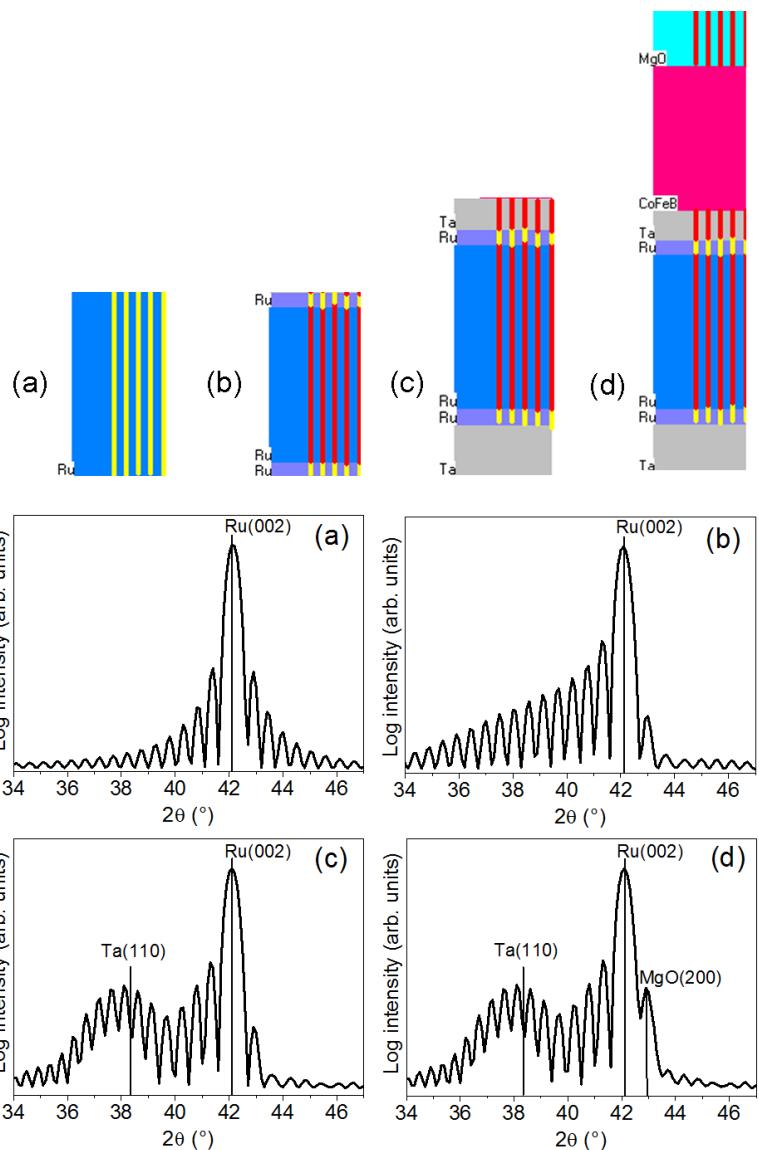
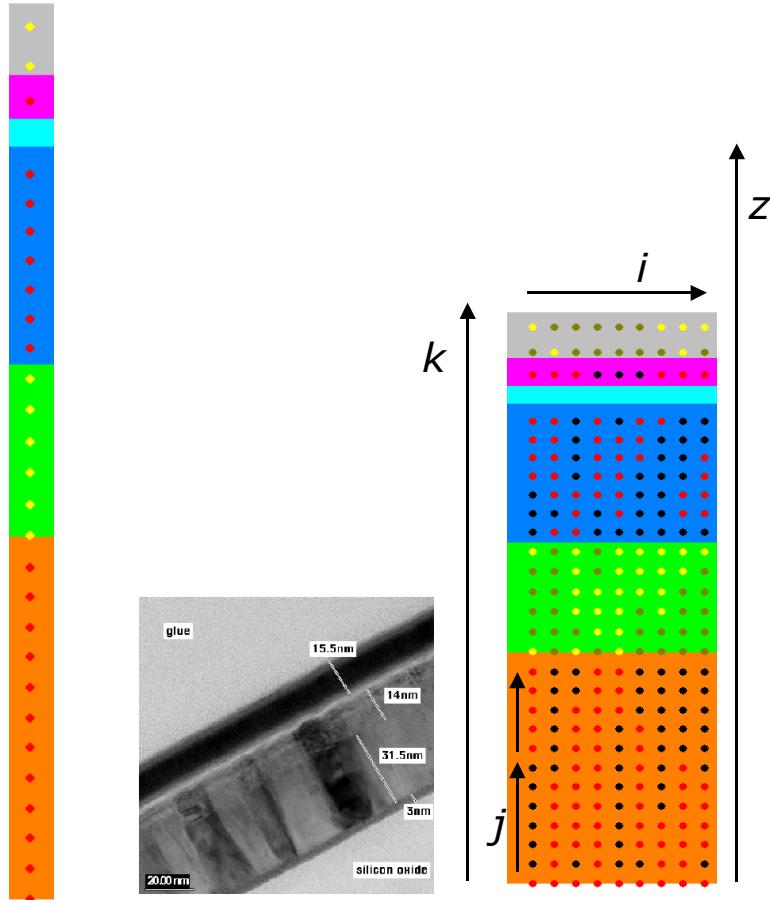
Layer	Thickness	Roughness/ Interdiffusion
Ta	5.62	0.88
Ru	18.06	0.70
Ta	1.99	0.39
Ta-O	2.05	0.39

Symulacje profili XRD



$$I(\theta) = CP(\theta)L(\theta)G(\theta)$$

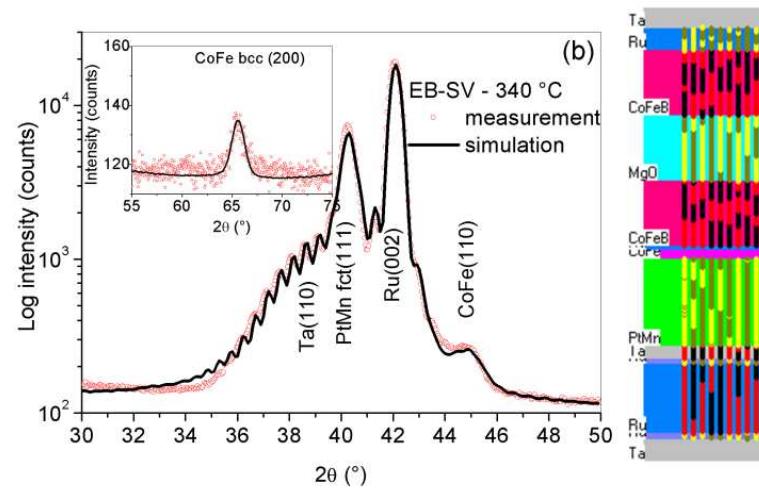
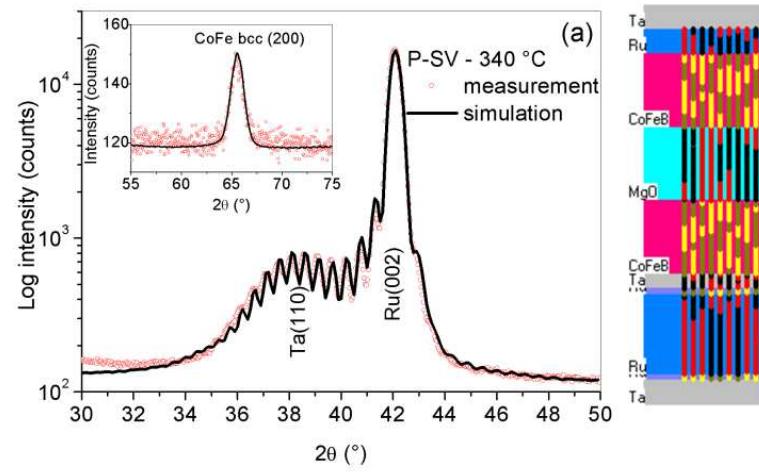
$$\cdot \sum_{i=1}^I \sum_{k=1}^{K_i} \left| \sum_{j=1}^{J_k} f_{i,j,k} \sigma_{i,j,k} t_{i,j,k} \exp\left(\frac{4i\pi z_{i,j,k} \sin \theta}{\lambda}\right) \right|^2$$



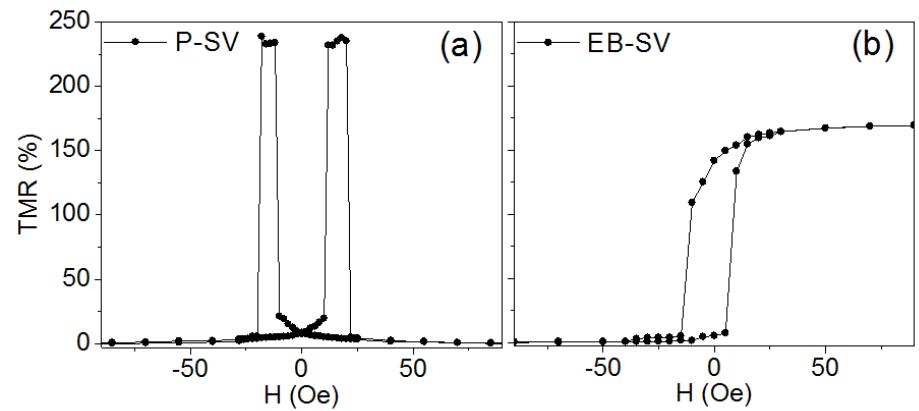
Symulacje profili XRD



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Sample	Ru 18 nm		PtMn 20 nm		CoFeB 15 nm	
	D [nm]	texture coeff.	D [nm]	texture coeff.	D [nm]	texture coeff.
PSV	16	1	-	-	7	0.16
EB-SV	16	1	12	0.56	6	0.12



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Singulus TIMARIS

Oxidation Module

Low Energy Remote
Atomic Plasma Oxidation;
Natural Oxidation;
Soft Energy Surface
Treatment

Soft-Etch Module

(PreClean, Surface
Treatment)

Cassette Module (according to Customer request)



Multi Target Module

Top: Target Drum with 10
rectangular cathodes; Drum
design ensures easy
maintenance;

Bottom: Main part of the
chamber containing LDD
equipment

Transport Module (UHV wafer handler)

Ultra – High – Vacuum Design:

Base Pressure $\leq 5 \times 10^{-9}$ Torr (Deposition Chamber)

High Throughput (e.g. MRAM):

9 Wafer/Hour (1 Depo-Module)

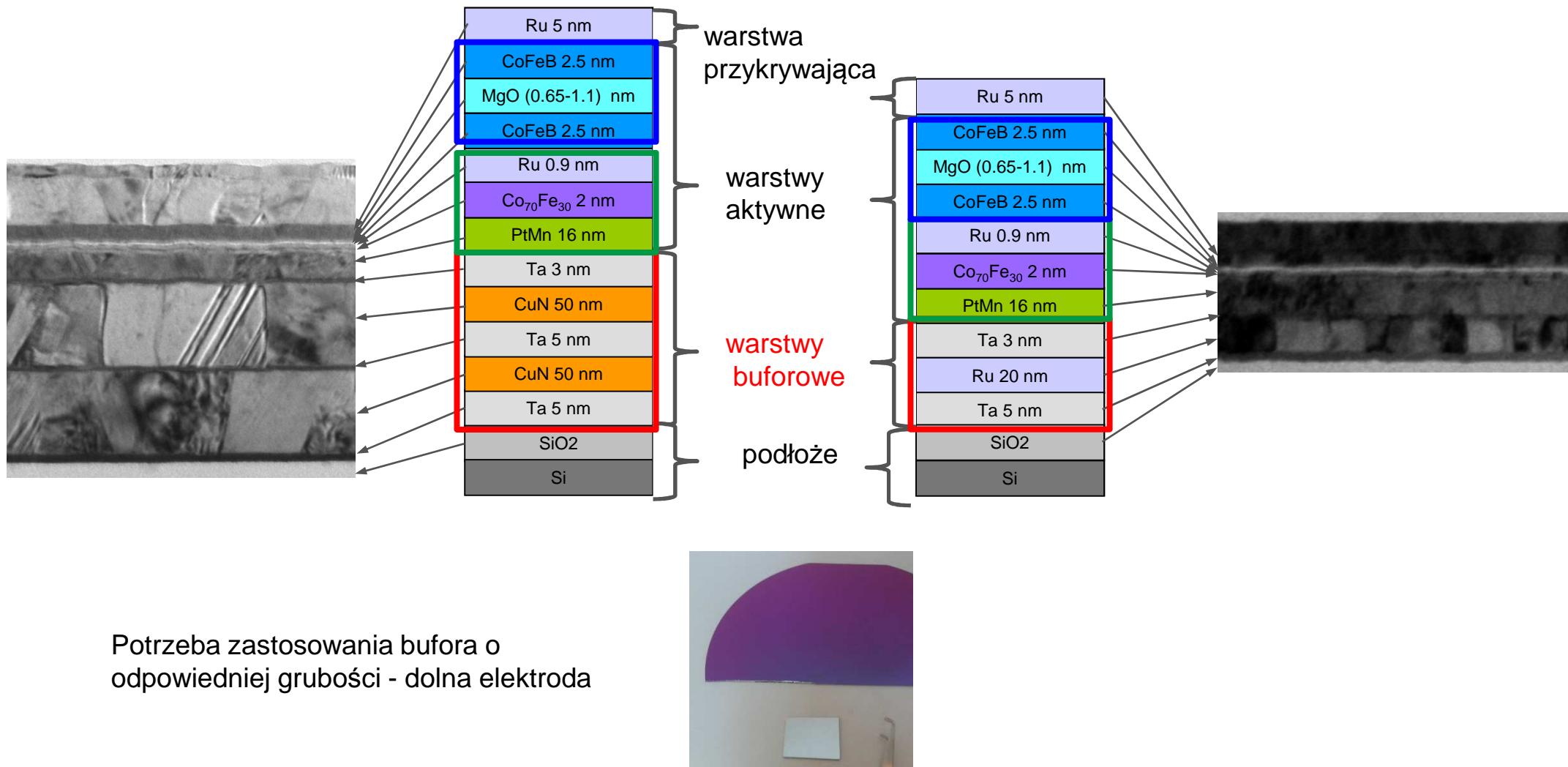
High Effective Up-time:

18 Wafer/Hour (2 Depo-Module)

Courtesy of

SINGULUS 

Optymalizacja struktury bufora



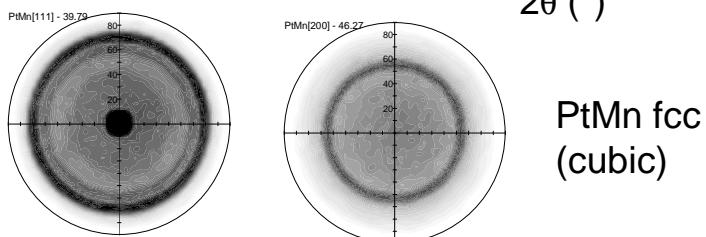
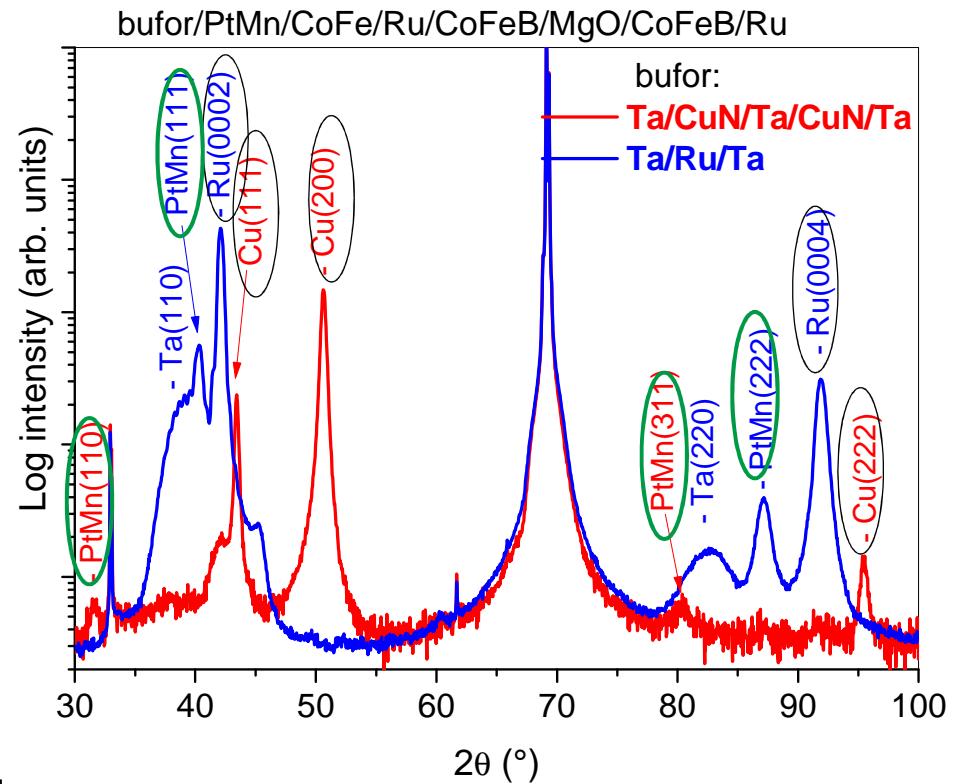
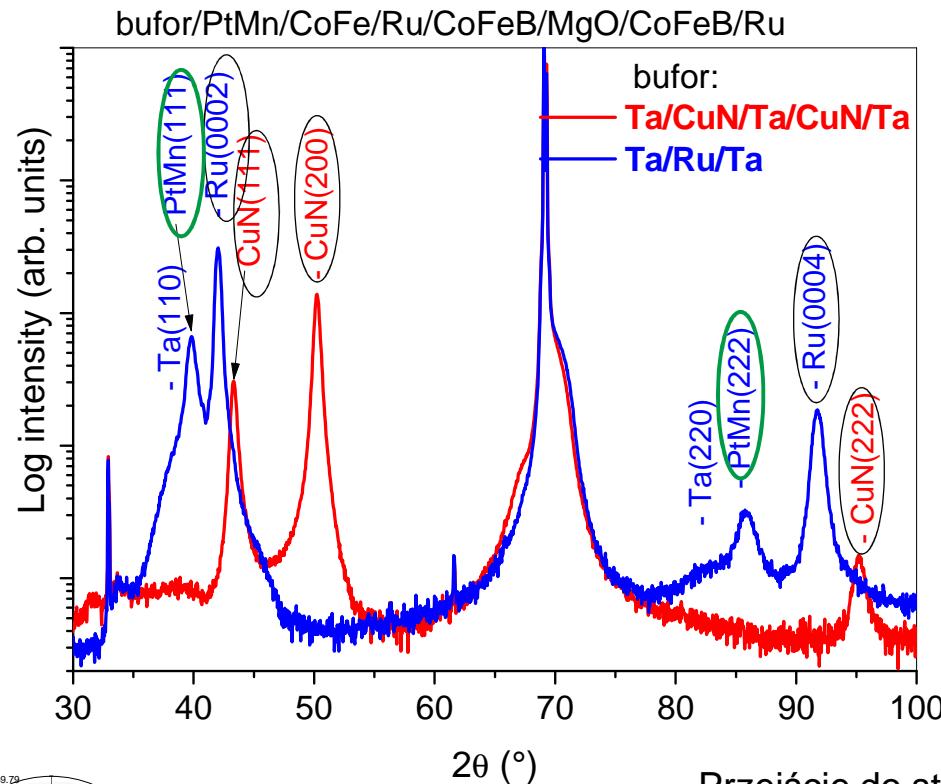
Optymalizacja struktury bufora



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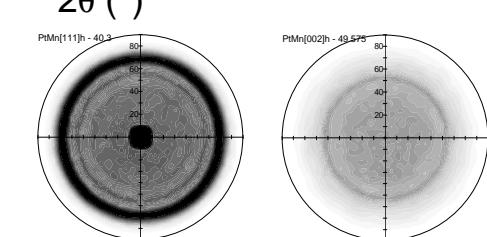
Próbki niewygrzane

Próbki wygrzane:
350 °C, 2 godziny

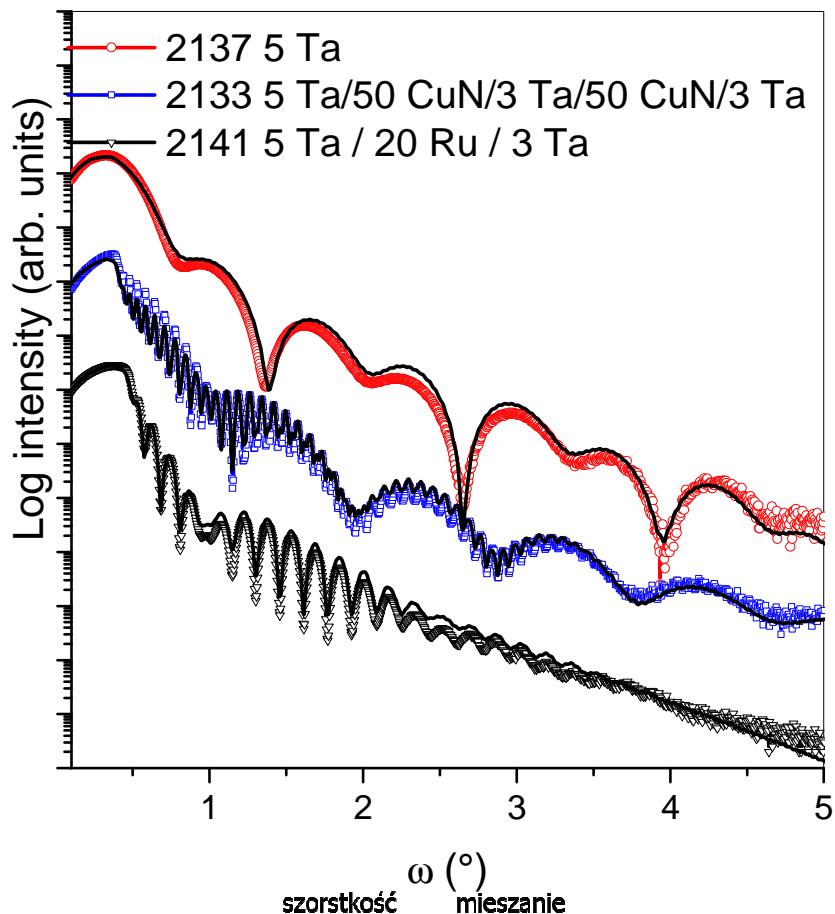


Przejście do stanu antyferromagnetycznego

PtMn fct (tetragonal)



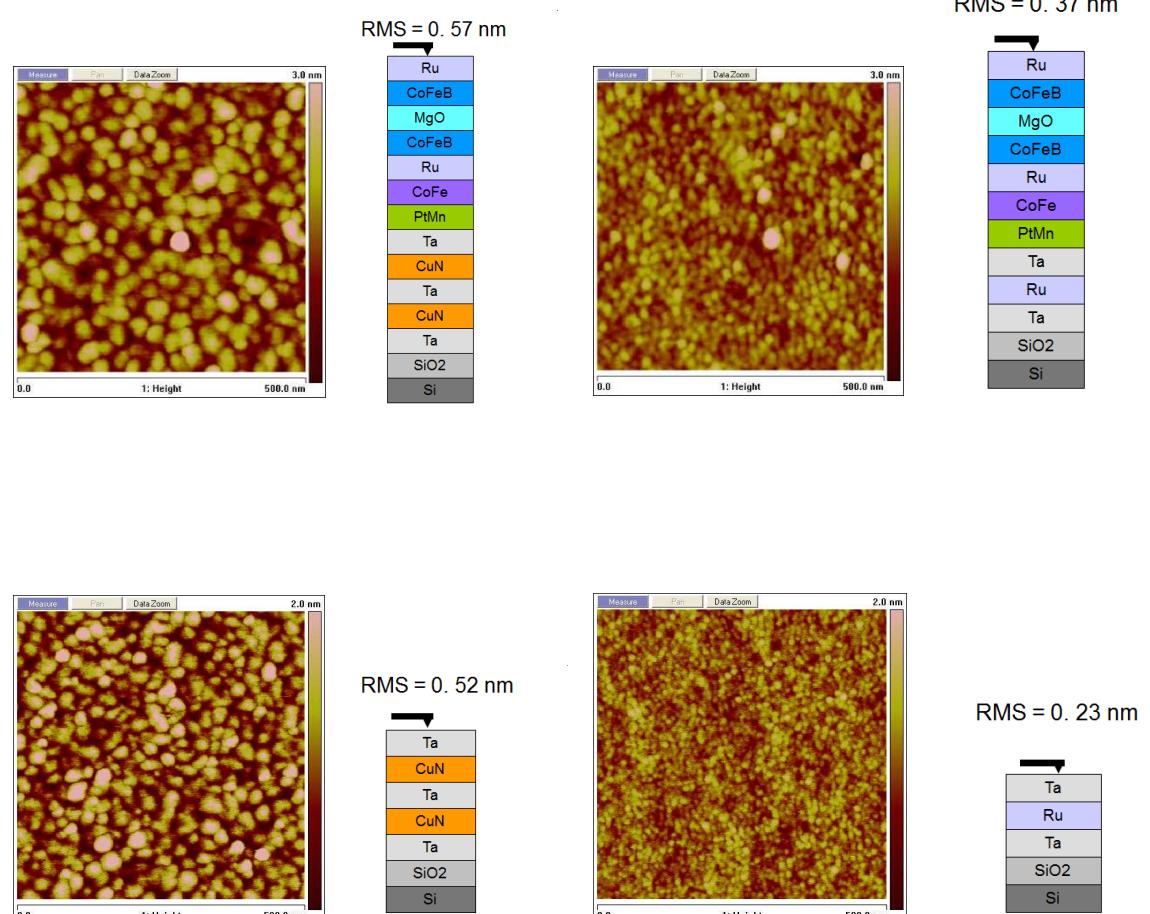
Pomiary XRR, AFM



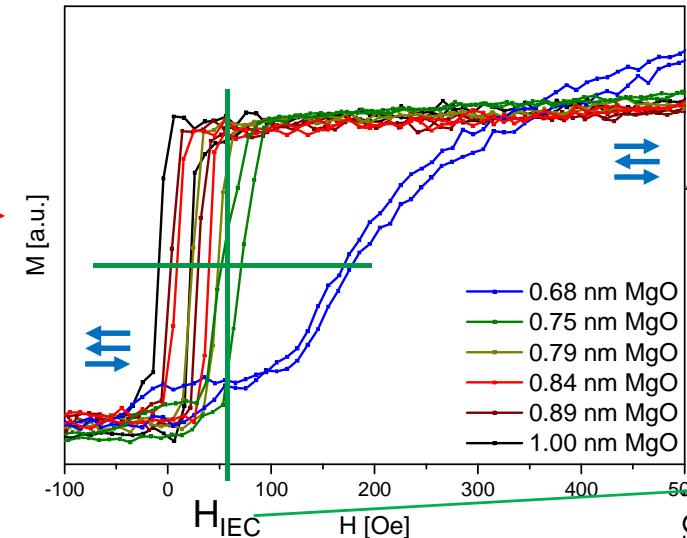
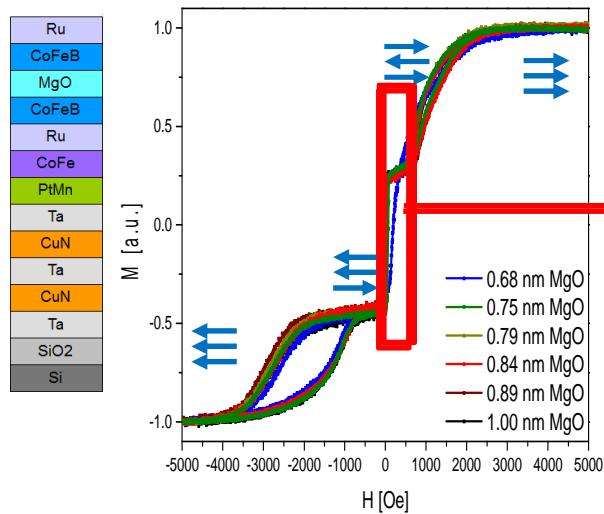
interfejs
Ta/CuN



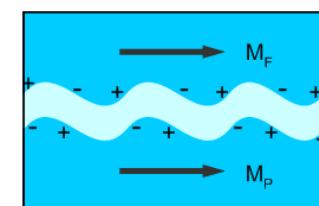
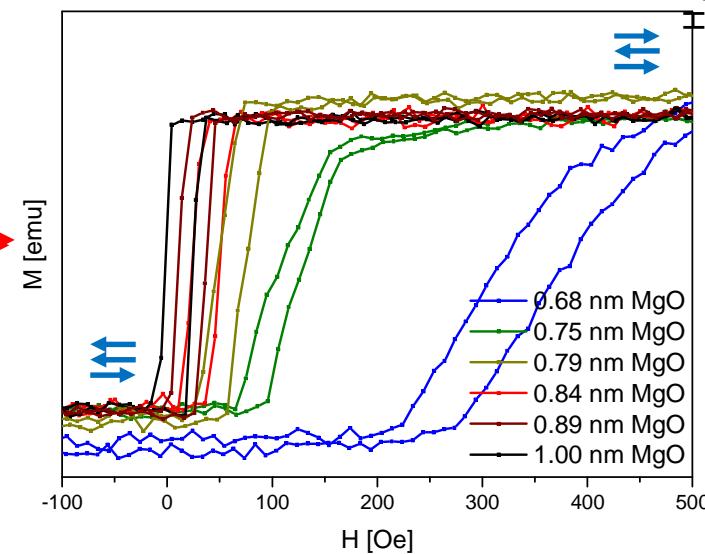
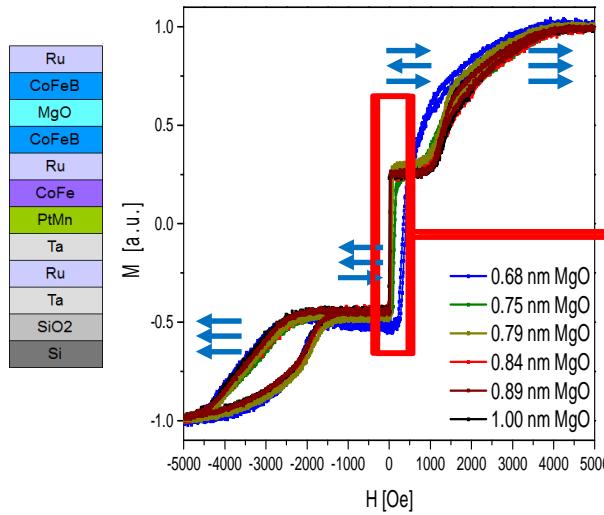
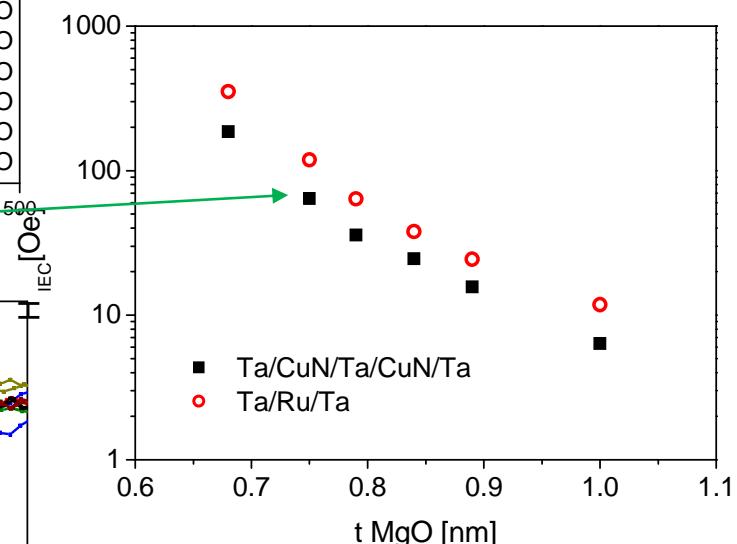
interfejs
Ta/Ru



Wpływ bufora na sprzężenia



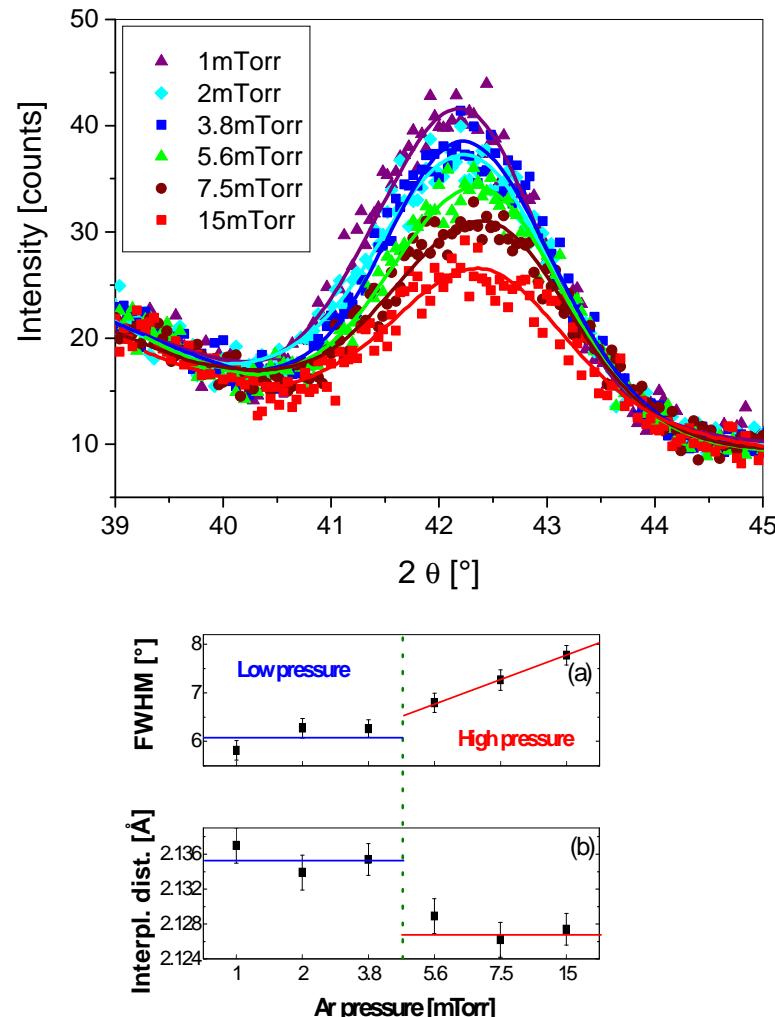
Interlayer Exchange Coupling



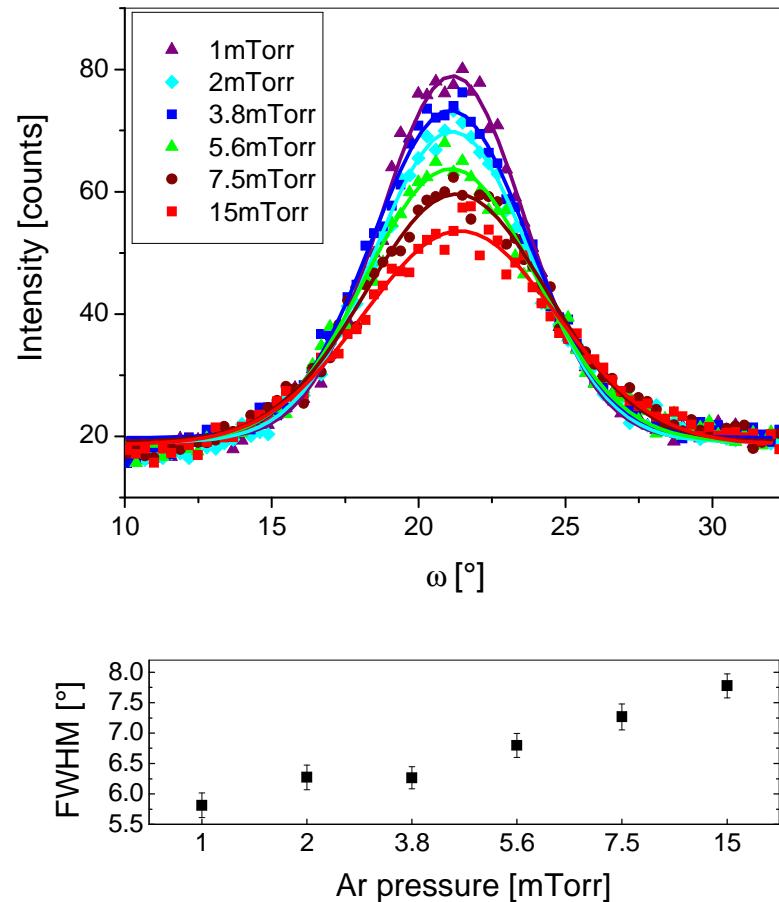
Optymalizacja bariery MgO



XRD θ - 2θ



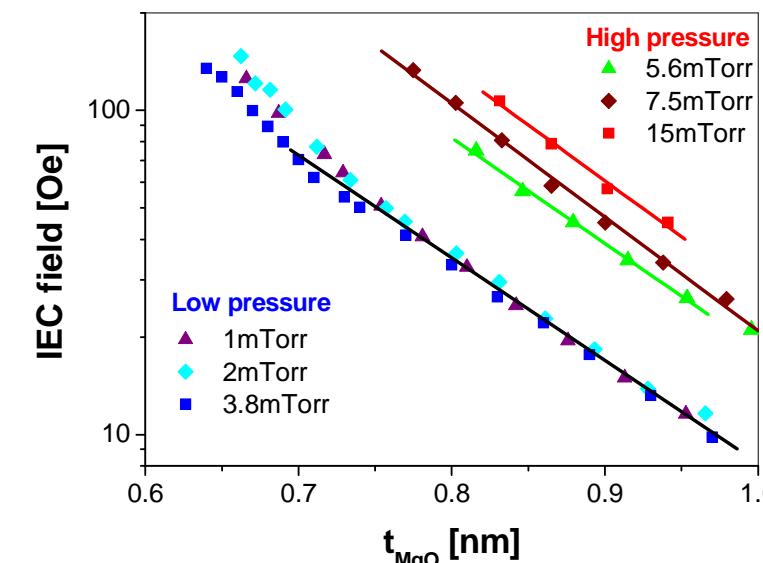
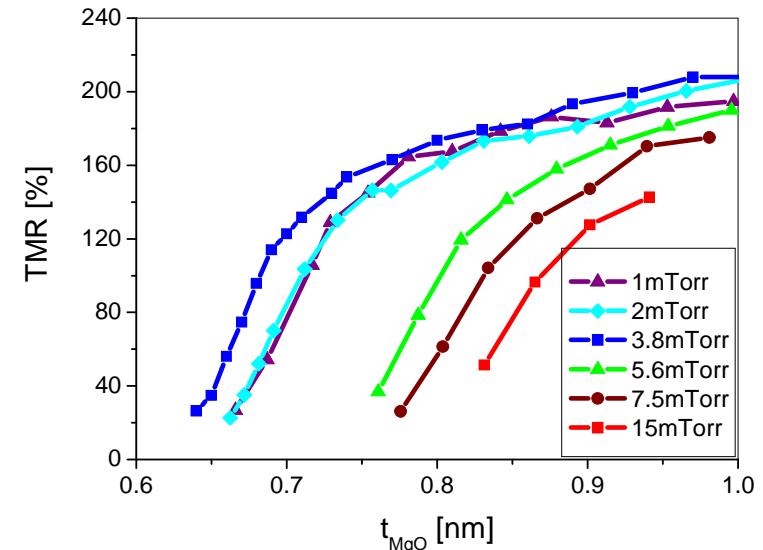
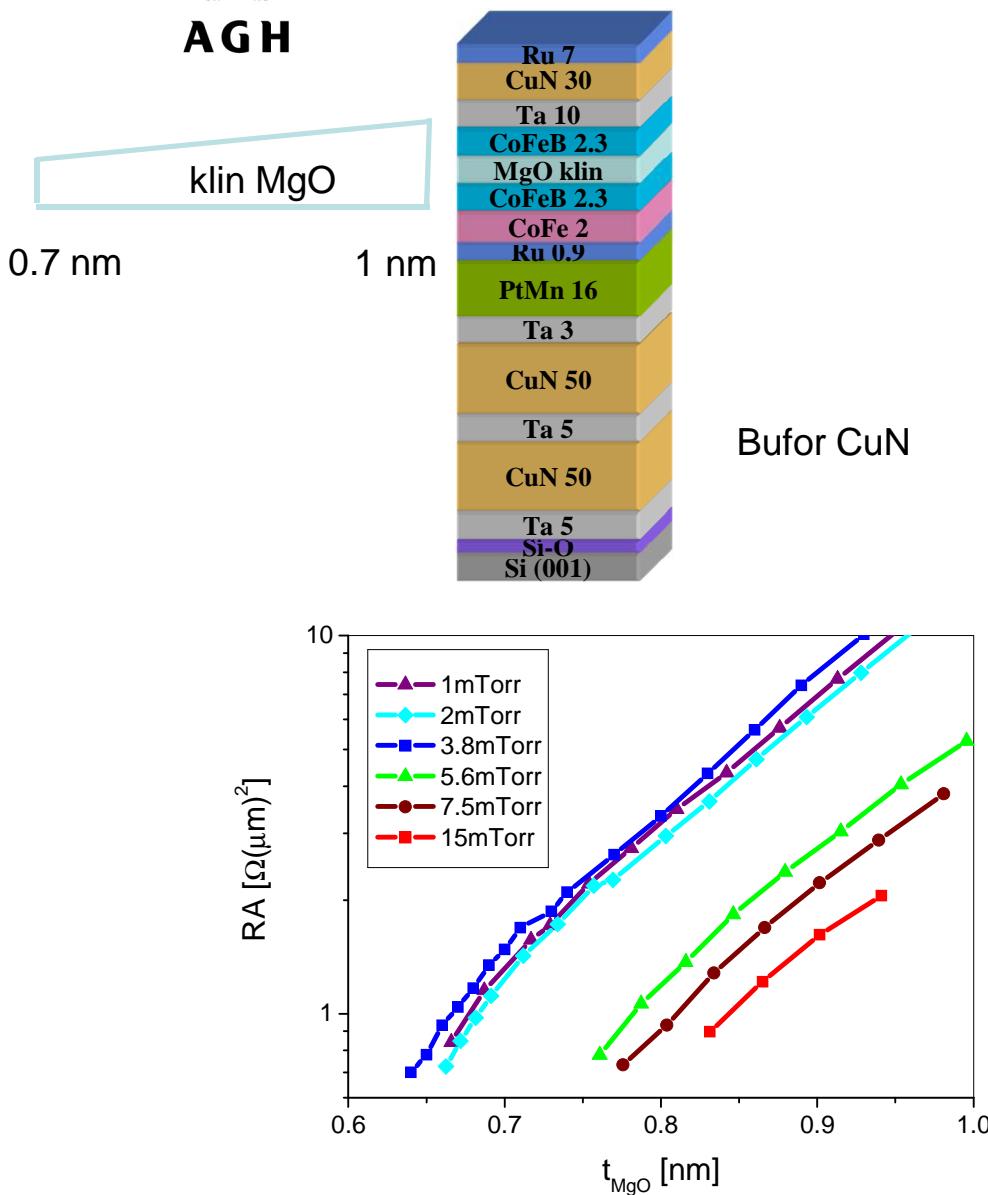
XRD rocking curve



Wygrzewanie – 360°C, 2h pole 1T

J Wrona, J Kanak, et al., Journal of Physics: Conference Series, 200, (2010) 052032

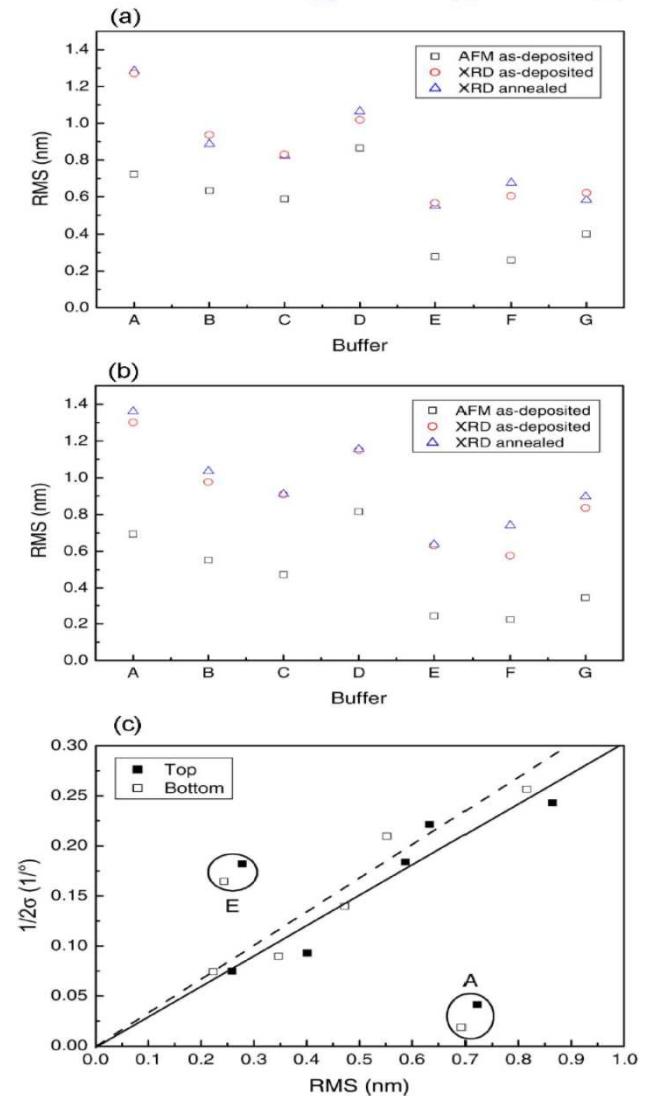
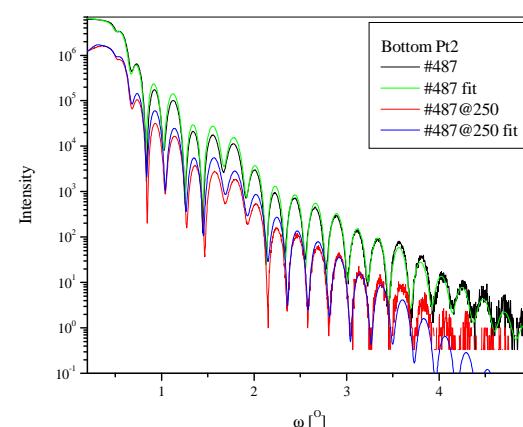
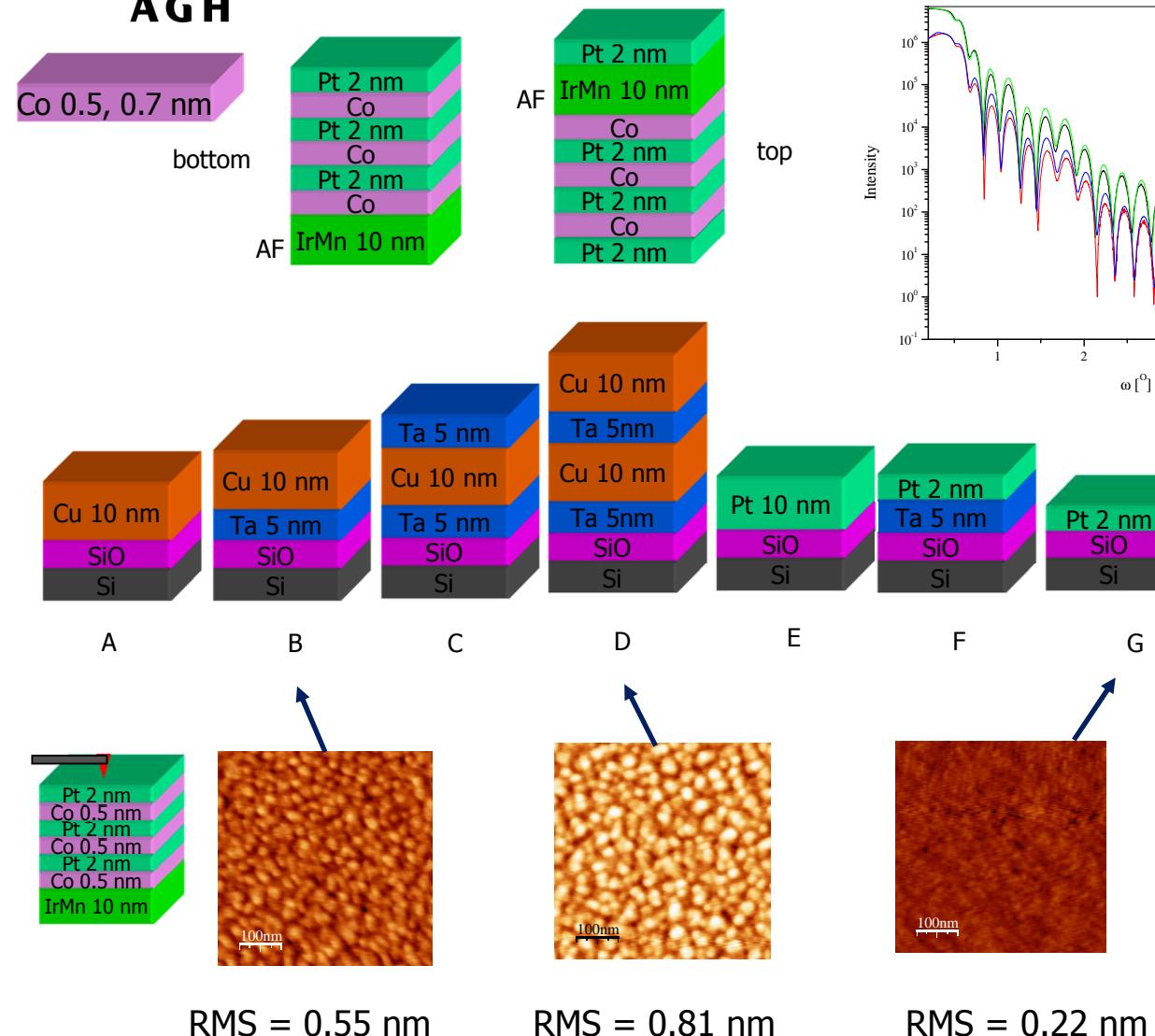
Optymalizacja bariery MgO





AGH

Układy Co/Pt z antyferromagnetykiem



g. 4. RMS surface and interface roughness of (a) top- and (b) bottom-pinned $t/\text{Co}_3\text{-IrMn}$ multilayers grown onto different buffer layers. (c) Correlation between $1/2\sigma$ and the rms surface roughness (measured by AFM). The solid and dashed line in (c) indicate fits to the data of as-deposited top-pinned and bottom-pinned multilayers, respectively (excluding data for buffers A and E).

Układy Co/Pt z antyferromagnetykiem

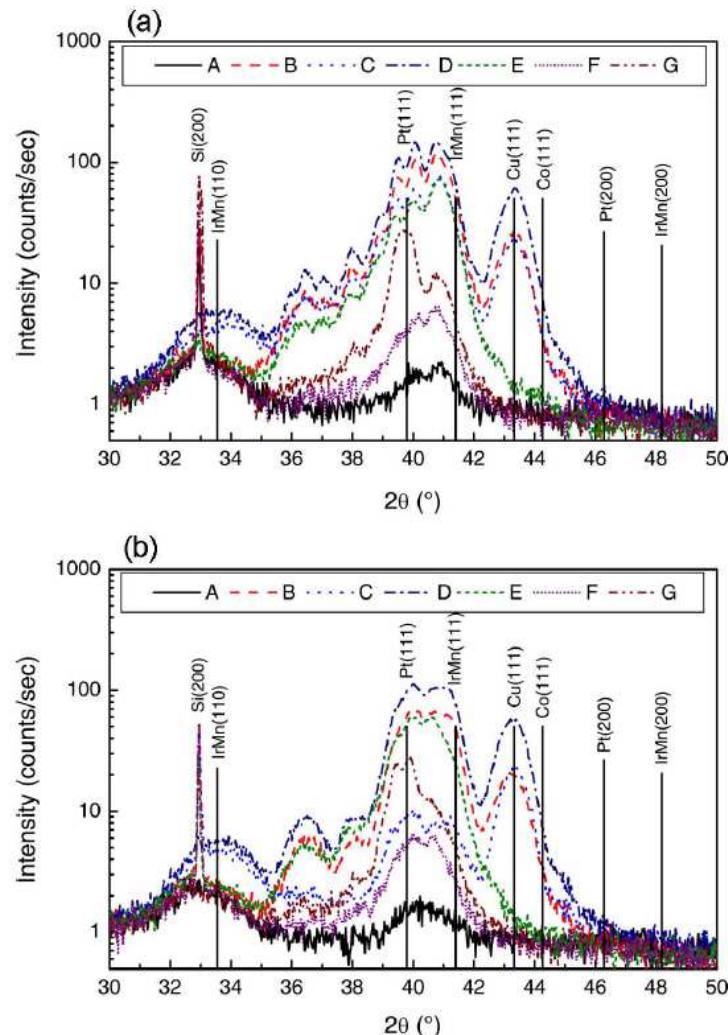


Fig. 1. XRD $\theta - 2\theta$ scans of (a) top- and (b) bottom-pinned $[Pt/Co]_3$ -IrMn multilayers grown onto different buffer layers.

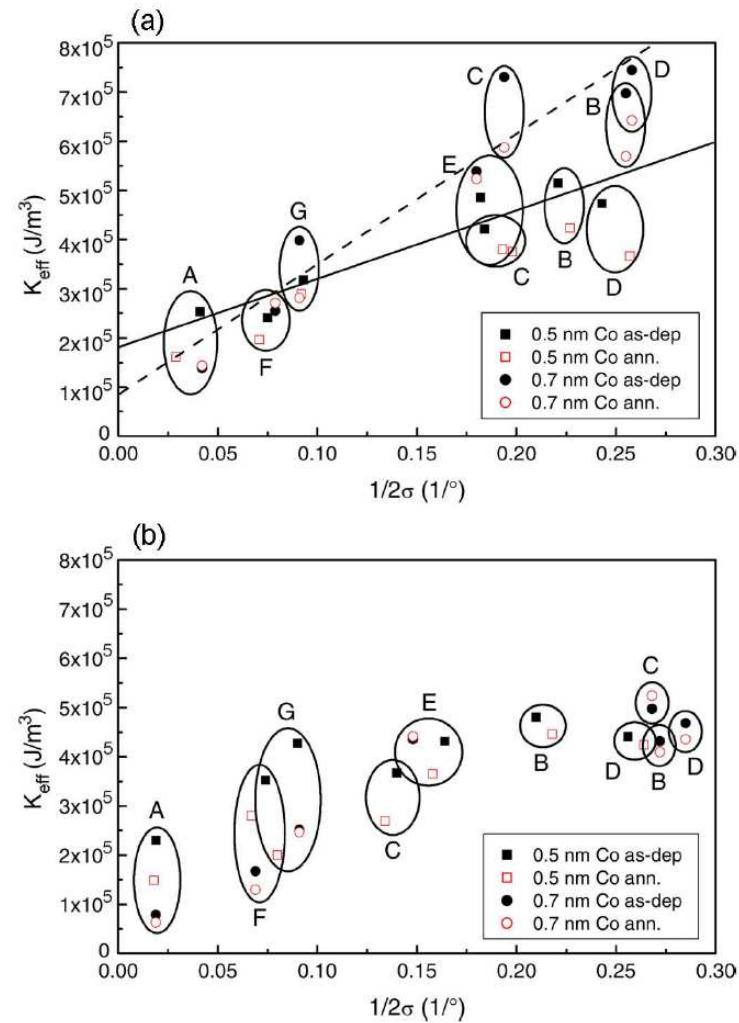


Fig. 5. Effective magnetic anisotropy of (a) top- and (b) bottom-pinned $[Pt/Co]_3$ -IrMn multilayers as a function of $1/2\sigma$. The solid and dashed line in (a) indicate fits to the data of as-deposited top-pinned multilayers with $t_{Co} = 0.5$ nm and $t_{Co} = 0.7$ nm, respectively.

Supersieć Co/Pt

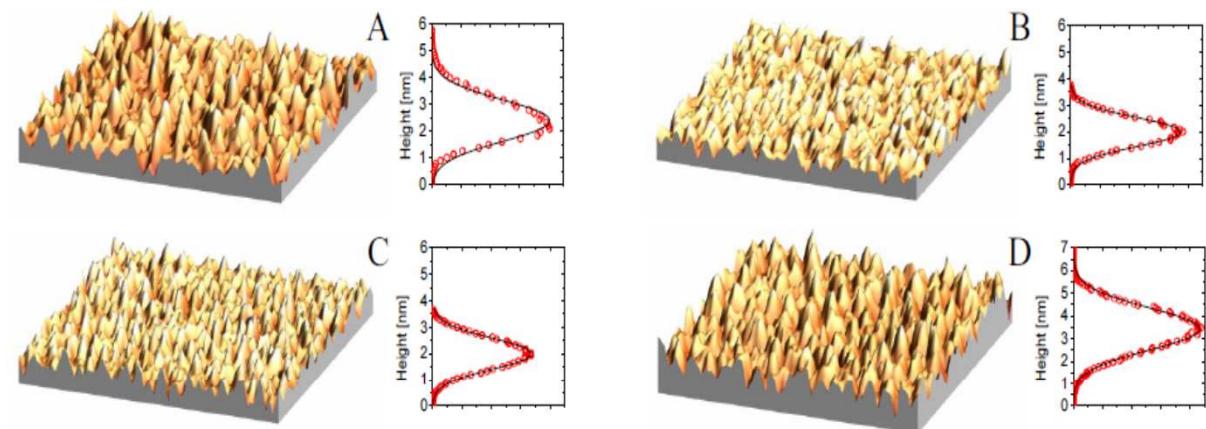
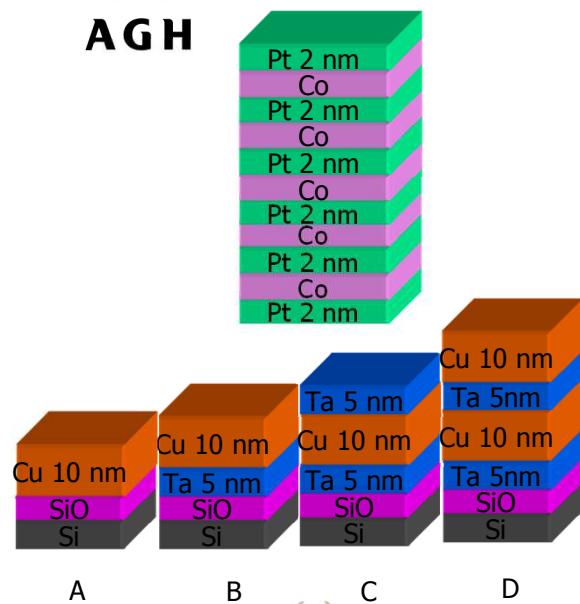


Fig. 2 AFM images and corresponding height distributions of $[2 \text{ nm Pt}/0.5 \text{ nm Co}]_5/2 \text{ nm Pt}$ multilayers on four different buffers. Image size is $500 \text{ nm} \times 500 \text{ nm}$.

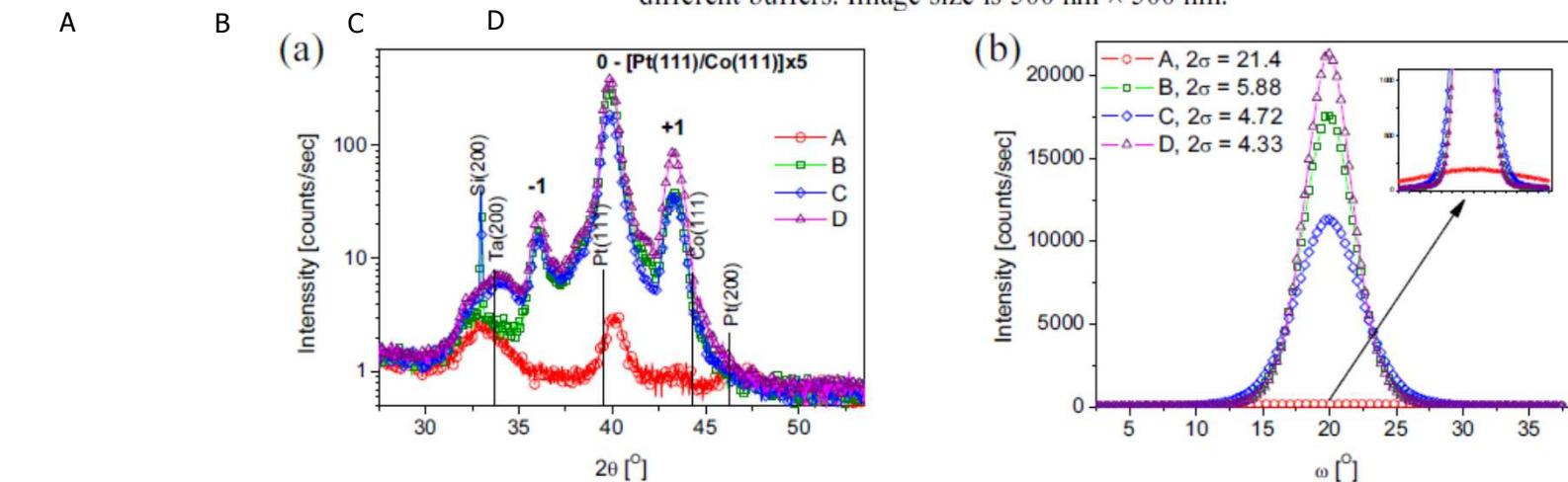


Fig. 1 XRD $0\text{-}2\theta$ scans (a) and rocking curves (b) for Pt/Co multilayers deposited onto buffers A, B, C, and D.

J. Kanak, et al. phys. stat. sol. (a), 204 (2007) 3950

Układy Co/Pt z prostopadłą anizotropią

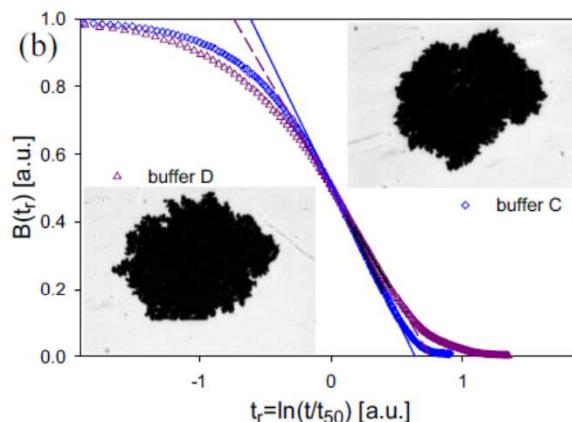
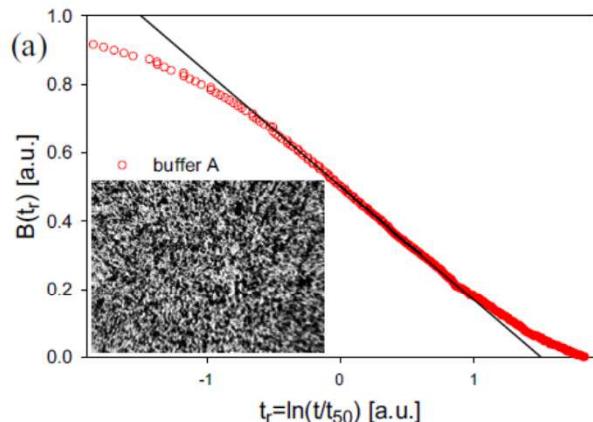


Fig. 4 The reversal magnetization relaxation via nucleation (a) and domain expansion (b) plotted as a function of $\ln(t/t_{50})$, where t_{50} is the time necessary to reverse half of the total magnetization. The lines indicate fits to the maximum slope of the relaxation curves. The insets show MOKE microscopy images taken during reversal of Pt/Co multilayers grown onto different buffer layers. The image area is $200 \times 250 \mu\text{m}^2$.

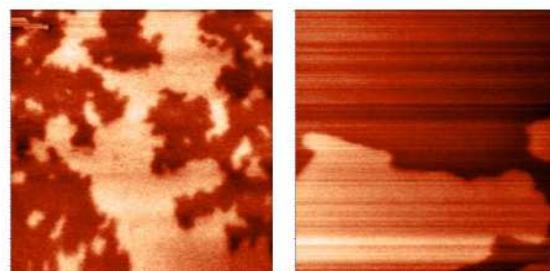


Fig. 5 MFM images of Pt/Co multilayers on buffer A (a) and buffer D (b). The image area is $4 \times 4 \mu\text{m}^2$.

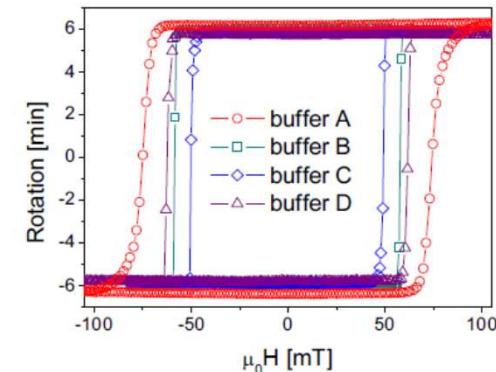


Fig. 3 Polar MOKE hysteresis loops of [2 nm Pt/0.5 nm Co]₅/2 nm Pt multilayers on buffers A, B, C, and D.

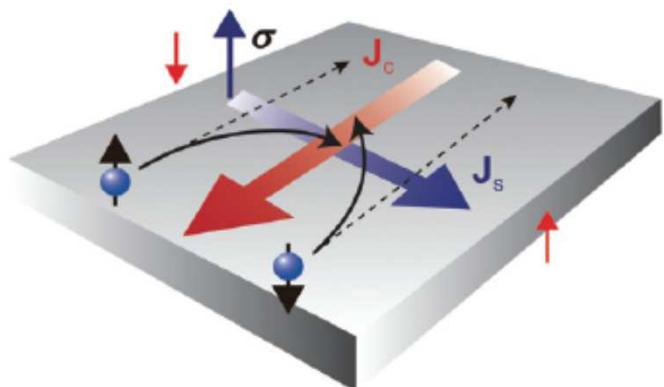
Table 1 Structural and magnetic parameters.

Buffer	A	B	C	D
AFM RMS [nm]	0.76	0.53	0.56	0.92
Reflectivity RMS [nm]	1.19	0.91	0.84	1.30
$1/2\sigma$	0.047	0.250	0.201	0.272
σ_W [meV]	39.0	18.6	17.1	19.2
$\mu_0 H_C$ [mT]	66.12	52.41	46.54	53.19
K_{eff} [kJ/m ³]	446	921	894	931
V_B [nm ³]	1230	1310	1430	1370

Spinowy efekt Halla

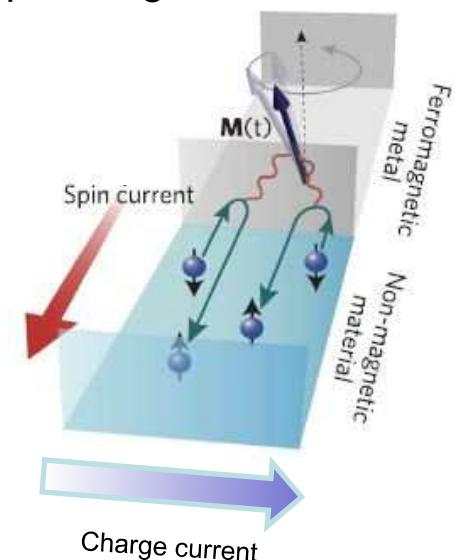


- Spinowo spolaryzowany prąd w metalach ciężkich - *oddziaływanie spin-orbita*
- Materiał ferromagnetyczny Fe, Co, CoFeB
- Materiały: ciężki metal - Ta, W, Pt,



Spinowy kąt Halla θ_{SH} stosunek prądu spinowego do prądu ładunkowego:

$$\theta_{SH} = \frac{\hbar}{2e} \cdot \frac{J_s}{J_e}$$



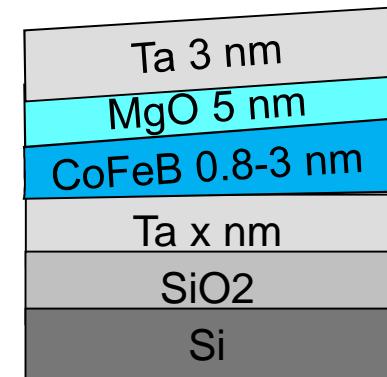
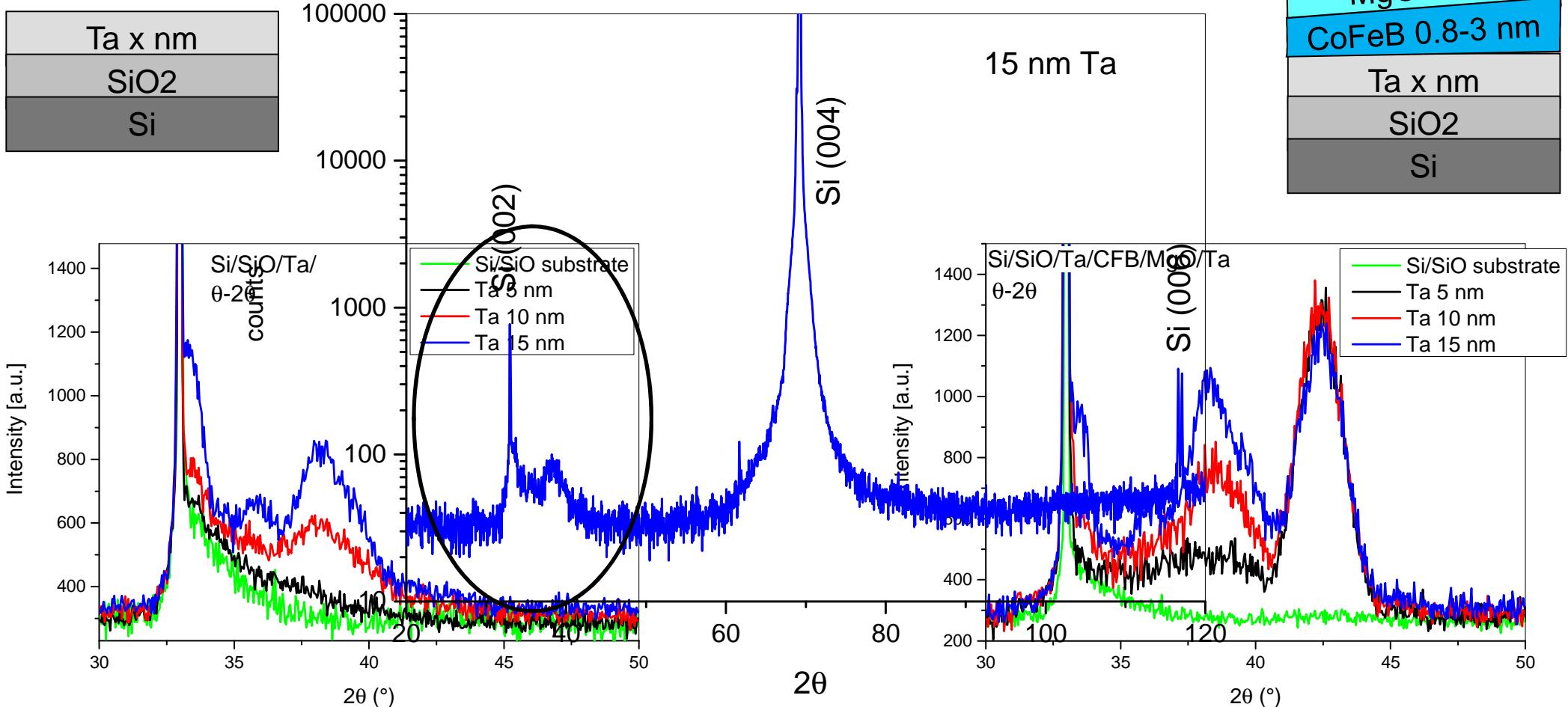
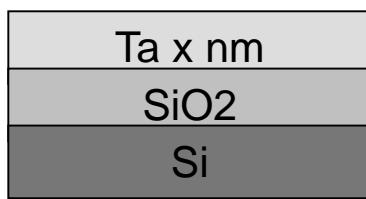
K. Ando, et al., J. Appl. Phys. 109, 103913 (2011)

Ta/CoFeB – badania strukturalne

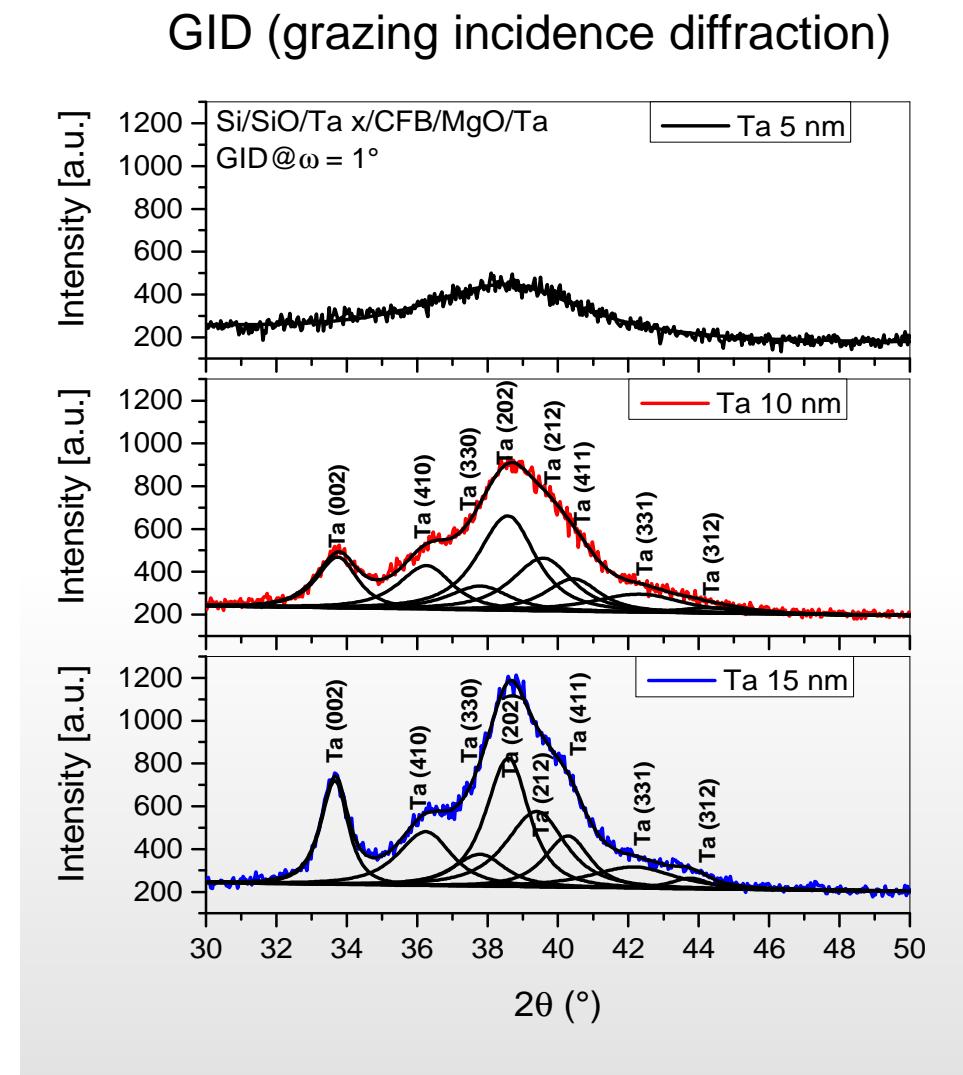
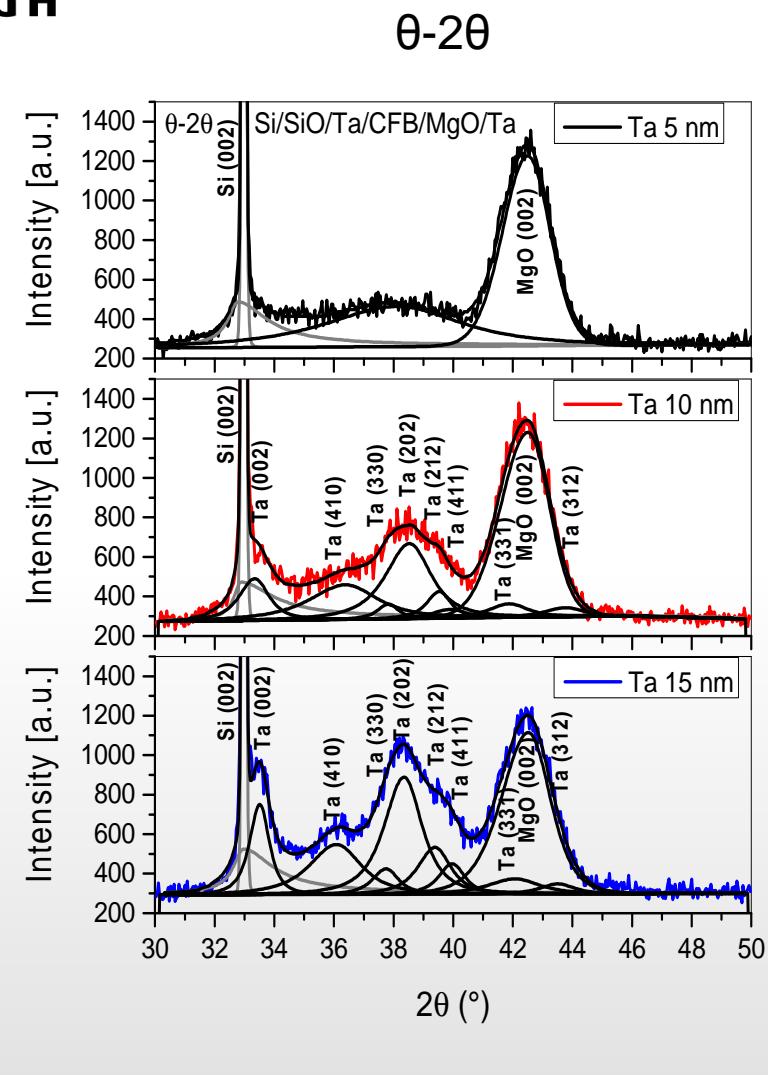


Wygrzewanie: 330 °C, 20 min

Bufory: Ta 5 nm, **10 nm**, **15 nm**



Analiza pomiarów XRD



Struktura warstwy Ta

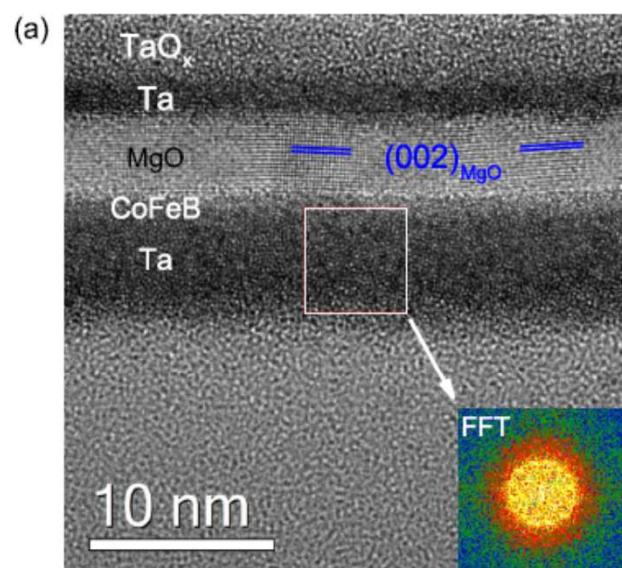
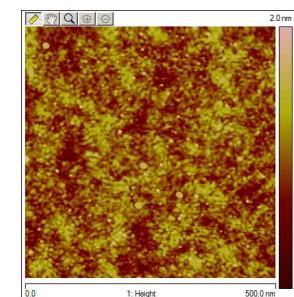
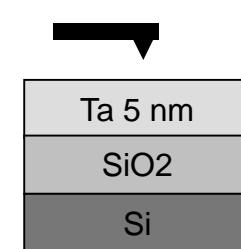
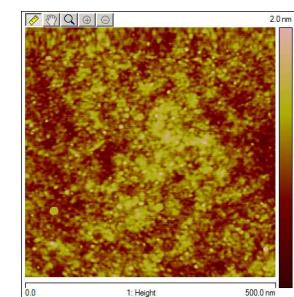


Figure 3. HRTEM images of $\text{Ta}(d_{\text{Ta}})/\text{CoFeB}(1)/\text{MgO}(5)/\text{Ta}(3)$ samples. (a) $d_{\text{Ta}} = 5 \text{ nm}$; (b) $d_{\text{Ta}} = 15 \text{ nm}$. The (002) planes in the MgO layers are marked with blue lines. The insets in (a,b) show fast Fourier transform (FFT) patterns from designated areas. The results indicate that the 5 nm Ta layer is amorphous and the 15 nm Ta layer is polycrystalline.

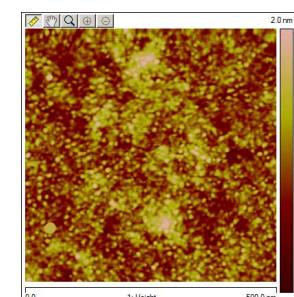
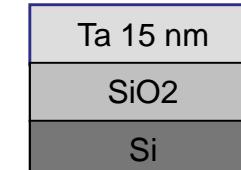
RMS = 0.23 nm

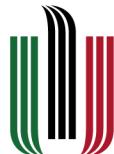


RMS = 0.26 nm



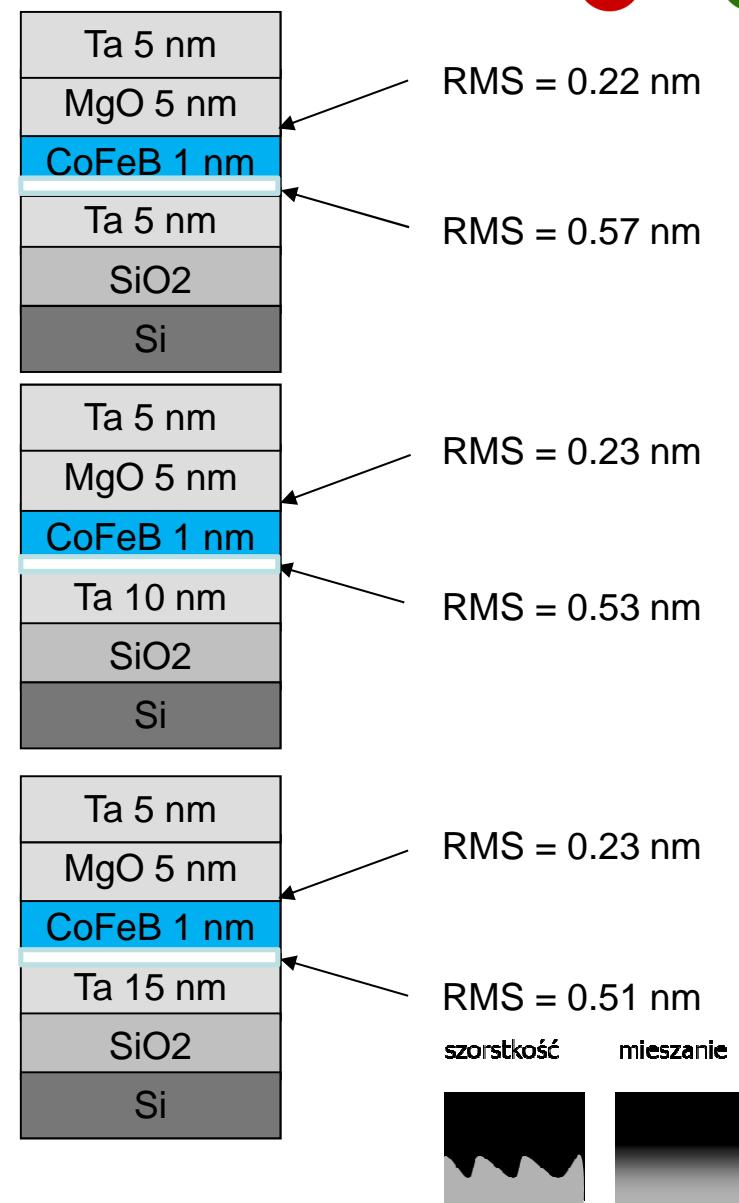
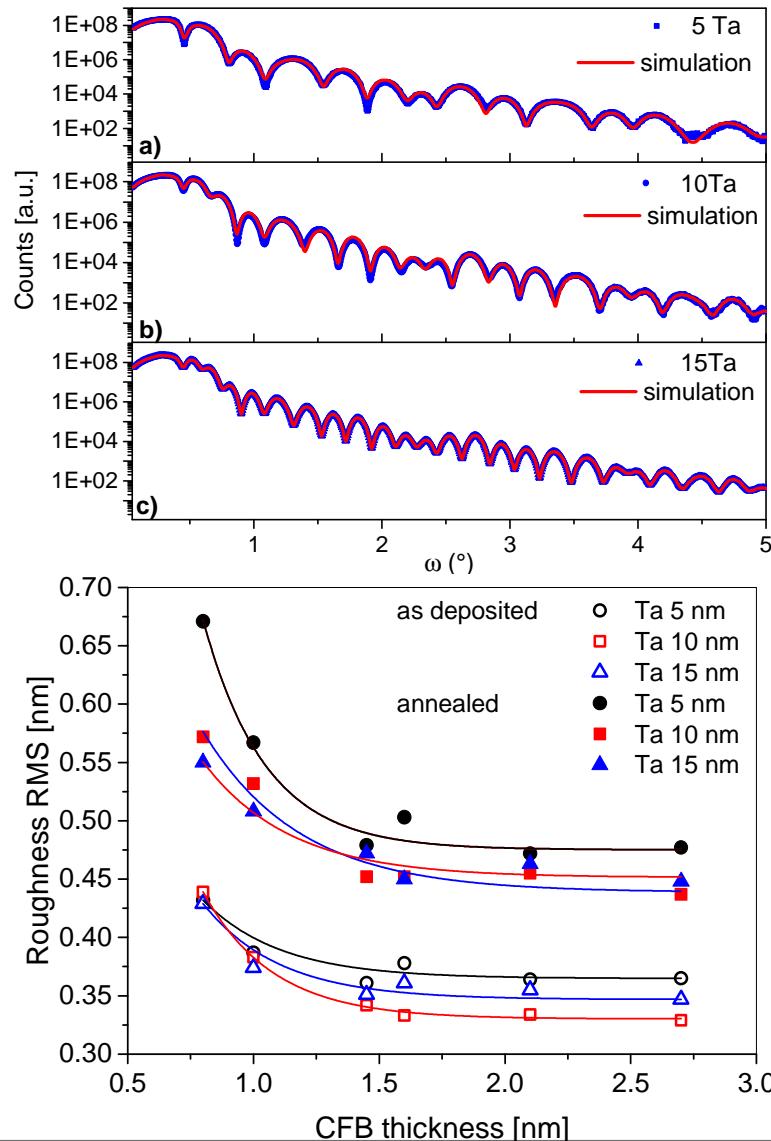
RMS = 0.29 nm

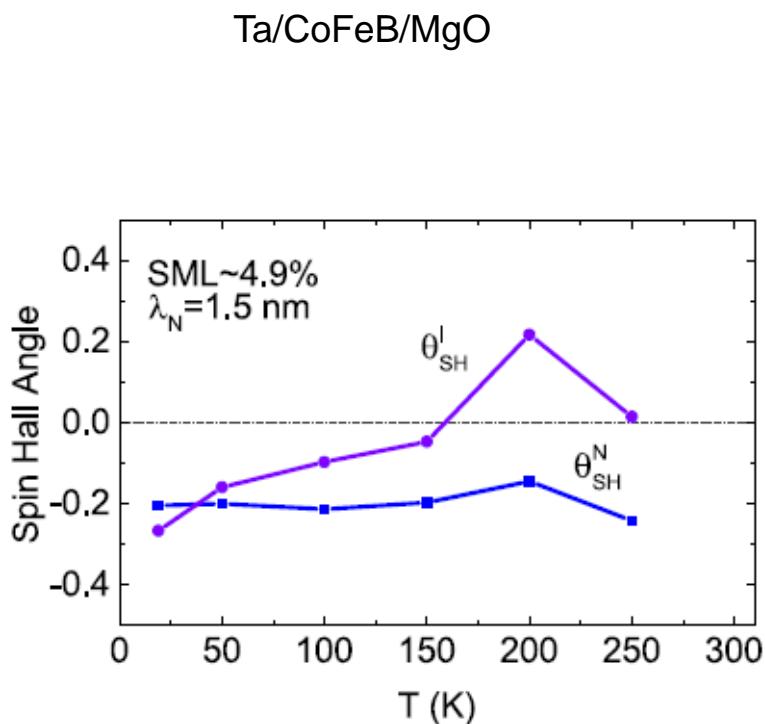




Badanie interfejsu Ta/CoFeB

AGH





Warstwa magnetycznie martwa

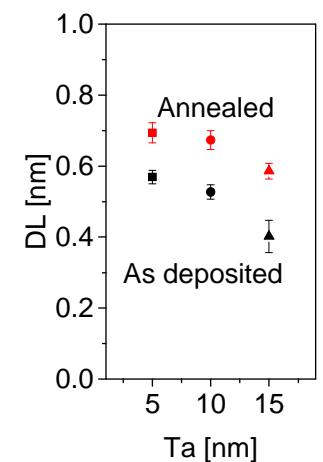
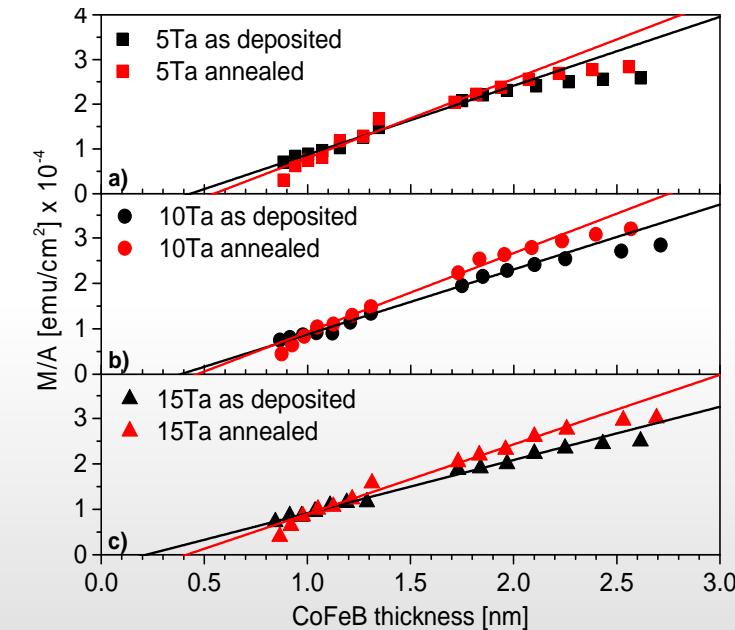


Figure 9. Spin Hall angle of the interface and non-magnetic metal Ta layers obtained from fits to experimental data with indicated parameters of spin memory loss (SML) and λ_N .

Podsumowanie



- W pracy przebadano szeroką gamę materiałów stosowanych w elektronice spinowej
- Wykazano, że dobór materiałów, sposób nanoszenia oraz struktura warstwowa ma ogromny wpływ na własności mikrostrukturalne
- Pokazano wpływ struktury na międzywarstwowe sprzężenia magnetyczne i charakterystyki przełączania

Podziękowania



Katedra Elektroniki, AGH:

- Monika Cecot
- Witold Skowroński
- Sławomir Ziętek
- Tomasz Stobiecki
- Maciej Czapkiewicz
- Wiesław Powroźnik
- Piotr Wiśniowski
- Marek Frankowski
- Stanisław Łazarski
- Krzysztof Grochot

- Antoni Żywczał – ACMiN, AGH
- Jerzy Wrona – Singulus Technologies, Niemcy
- S. van Dijken, L. Yao - Nanomagnetism and spintronics, Uniwersytet Aalto, Finlandia

NCN grant DEC-2012/05/E/ST7/00240 - Struktura krystaliczna, modele oraz własności magnetoelektryczne układów wielowarstwowych nanoelektroniki spinowej



Dziękuję za uwagę