Spintronika – co nowego?

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Katedra Elektroniki AGH

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INNOVATIVE ECONOMY NATIONAL COHESION STRATEGY
FNP Foundation for Polish Science
EUROPEAN REGIONAL DEVELOPMENT FUND
INNOWACYJNA GOSPODARKA NARODOWA STRATEGIA SPÓJNOŚCI
UNIA EUROPEJSKA EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

Swiss-PL NANOSPIN Nanoscale spin torque devices for spin electronics

Plan

☛Mapa drogowa spintroniki

☛co nowego w urządzeniach
- głowice TMR/HDD
- pamięci operacyjne STT-RAM
- nano-oscylatory mikrofalowe STO

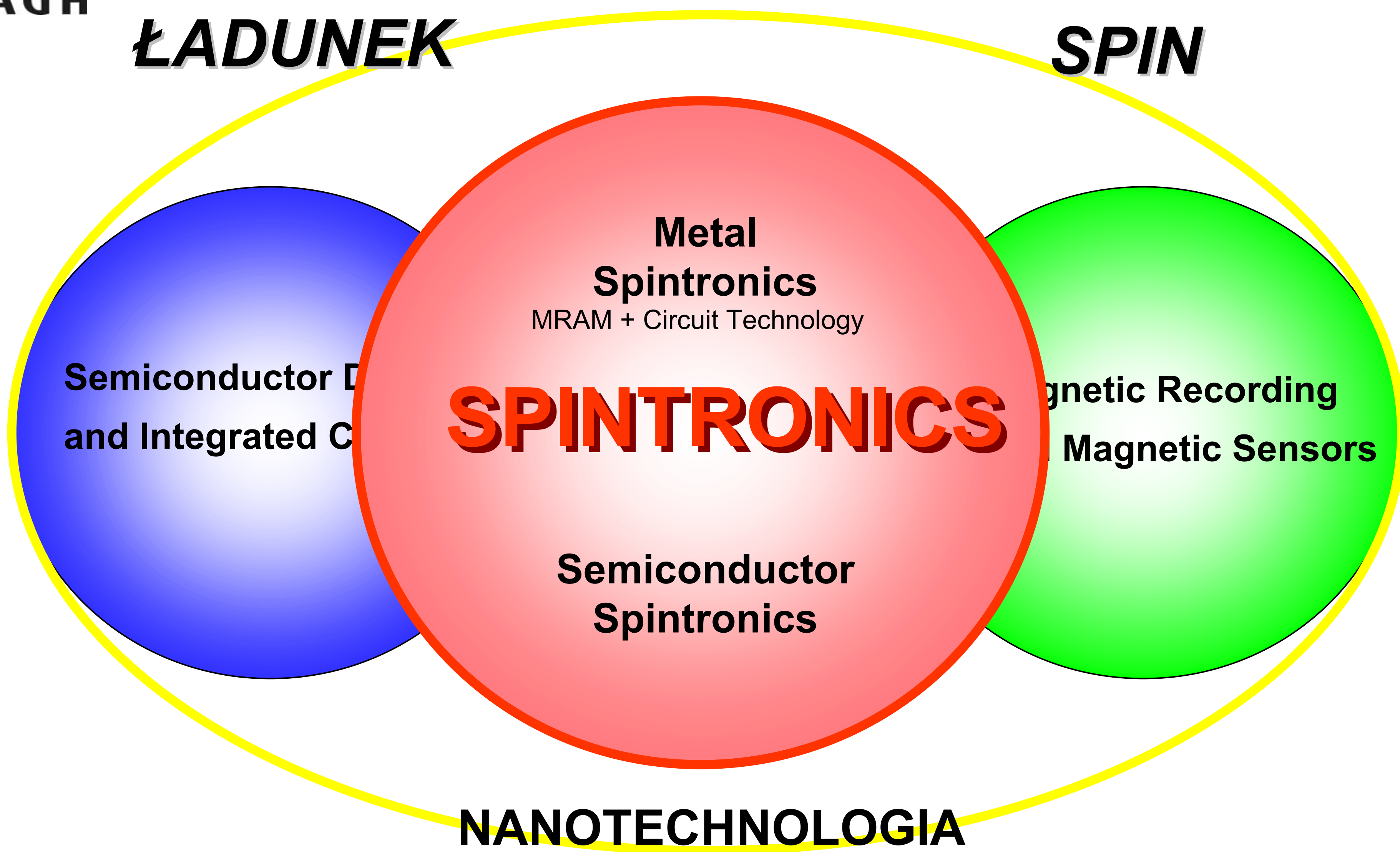
☛Technologia magnetycznych nano-złącz tunelowych (MTJ)
- nanoszenie układu wielowarstwowego - sputtering
- elektronowa litografia

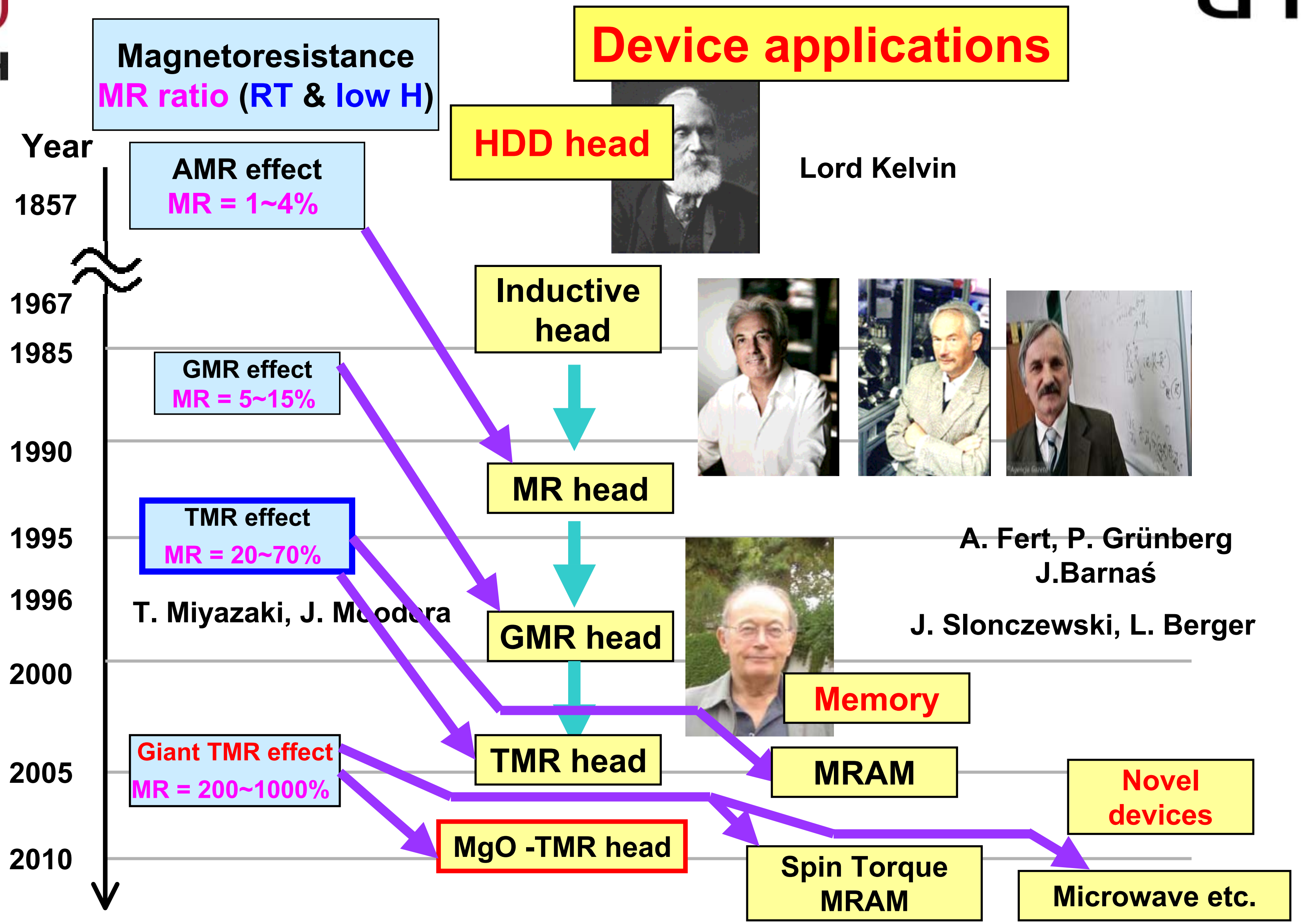
☛ Spin transfer torque
- Przełączanie prądem spinowo-spolaryzowanych elektronów (CIMS)
- ST- oscylator

☛ Podsumowanie

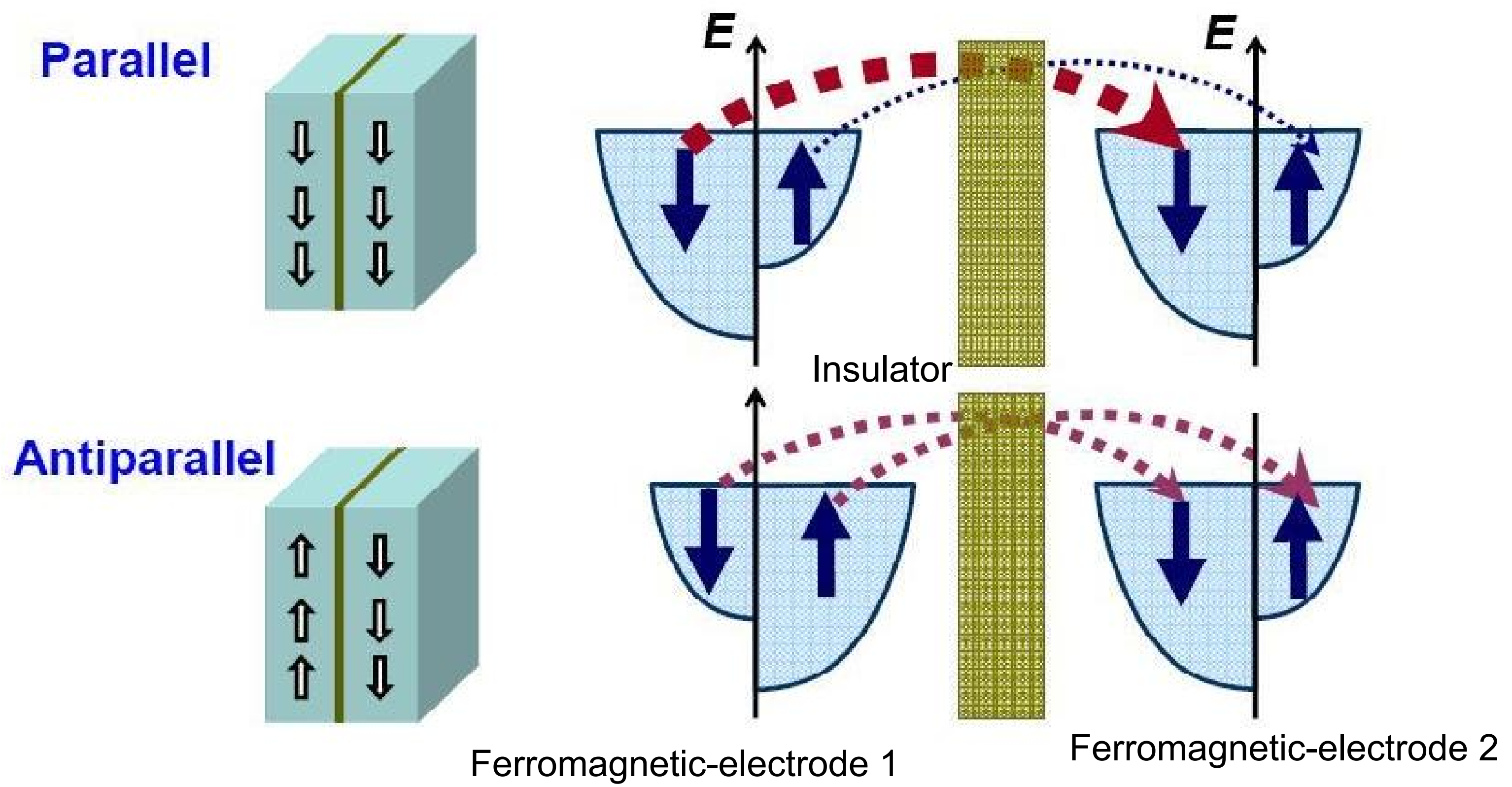
☛ Projekt SPINLAB

Dlaczego spintronika jest ważna?




Magnetoresistance
MR ratio (RT & low H)
Device applications
Year
1857
1967
1985
1990
1995
1996
2000
2005
2010
AMR effect
MR = 1~4%
HDD head
Lord Kelvin
Inductive head
GMR effect
MR = 5~15%
MR head
TMR effect
MR = 20~70%
A. Fert, P. Grünberg
J.Barnaś
T. Miyazaki, J. Moodera
GMR head
J. Slonczewski, L. Berger
Memory
Giant TMR effect
MR = 200~1000%
TMR head
MRAM
Novel devices
MgO -TMR head
Spin Torque MRAM
Microwave etc.

MTJ tunneling – Julliere's model



Assumption: tunneling of up- and down-spin electrons are two independent processes, so the conductance occurs in the two independent spin channels.

$$\mathrm{MR} \equiv (R_{AP} - R_P)/R_P = 2P_1P_2/(1 - P_1P_2), \quad P_\alpha = \frac{(D_{\alpha\uparrow}(E_F) - D_{\alpha\downarrow}(E_F))}{(D_{\alpha\uparrow}(E_F) + D_{\alpha\downarrow}(E_F))}, \quad \alpha = 1, 2.$$

Spin Polarization P

Green IT

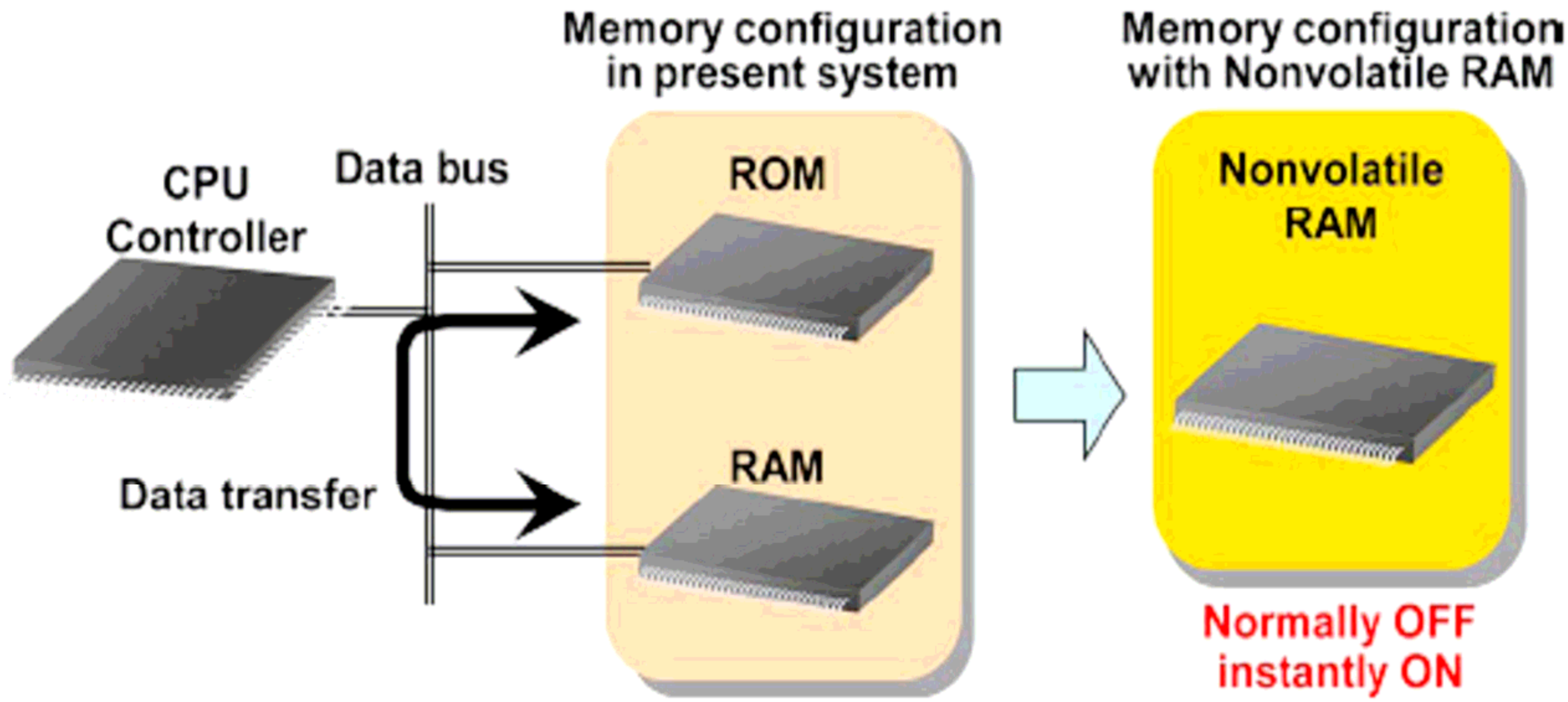
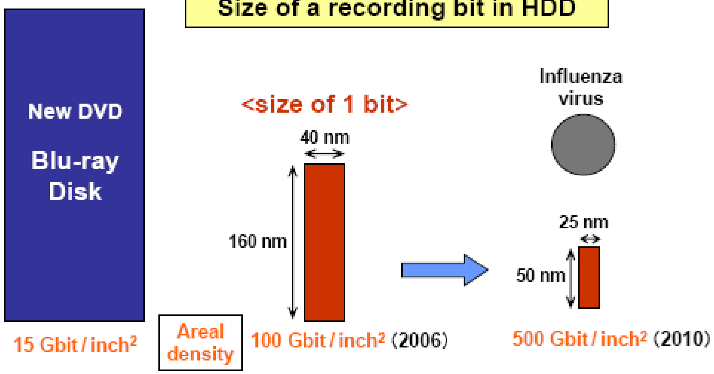


Fig. 2. Nonvolatile RAM application in IT equipment.

R. Takemura et al. IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 45, NO. 4, APRIL 2010

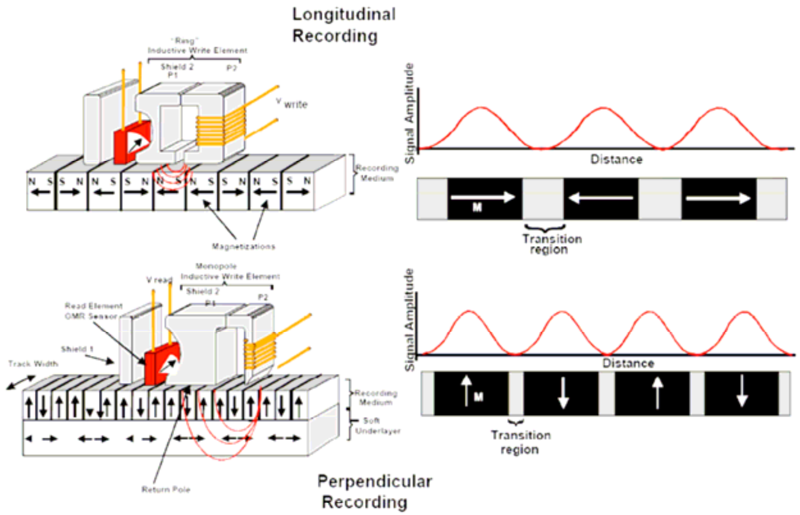
HDD- head

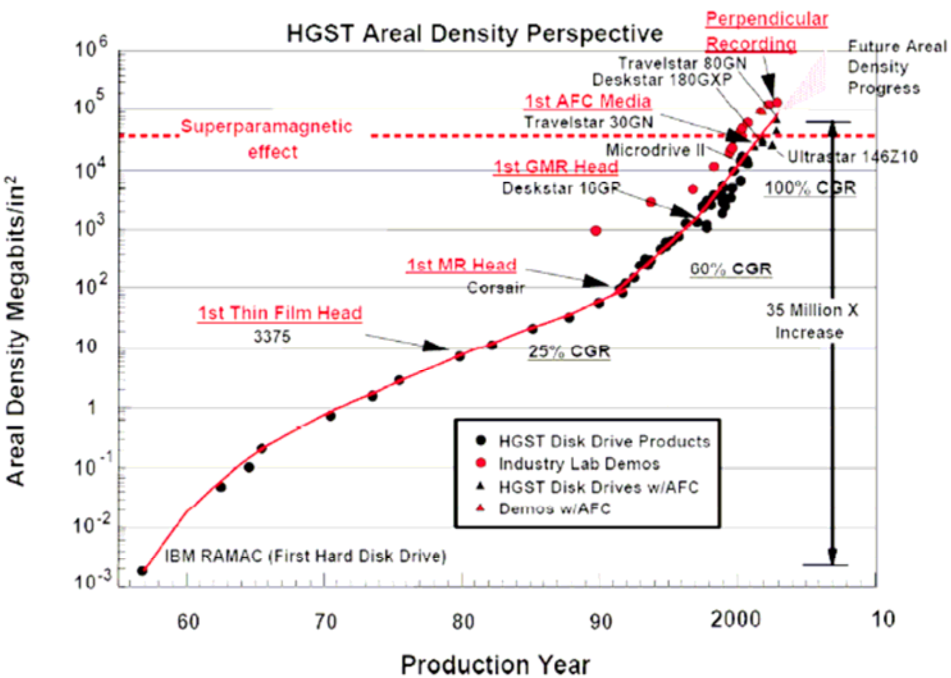
Size of a recording bit in HDD



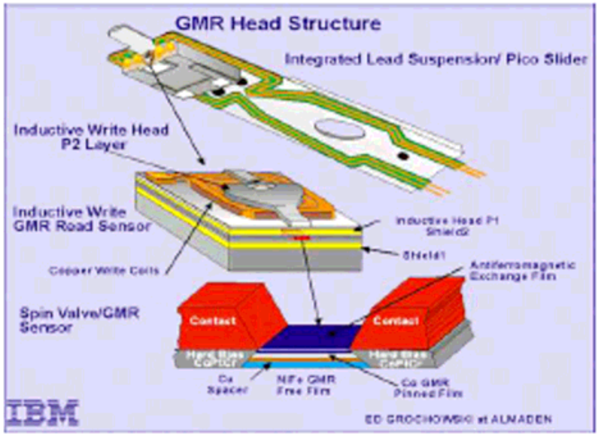
The S / N ratio decreases as the bit size shrinks.

Highly sensitive read head (higher MR ratio) is required.





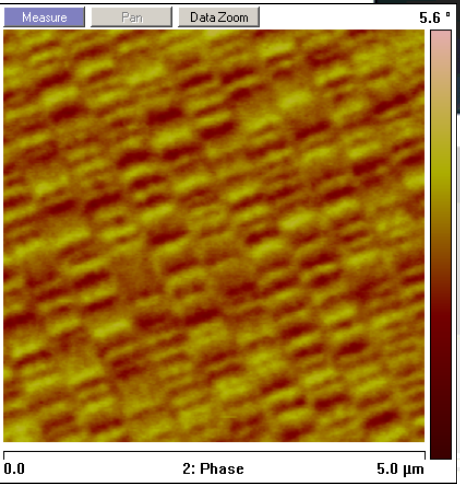
No more, MR≈10%

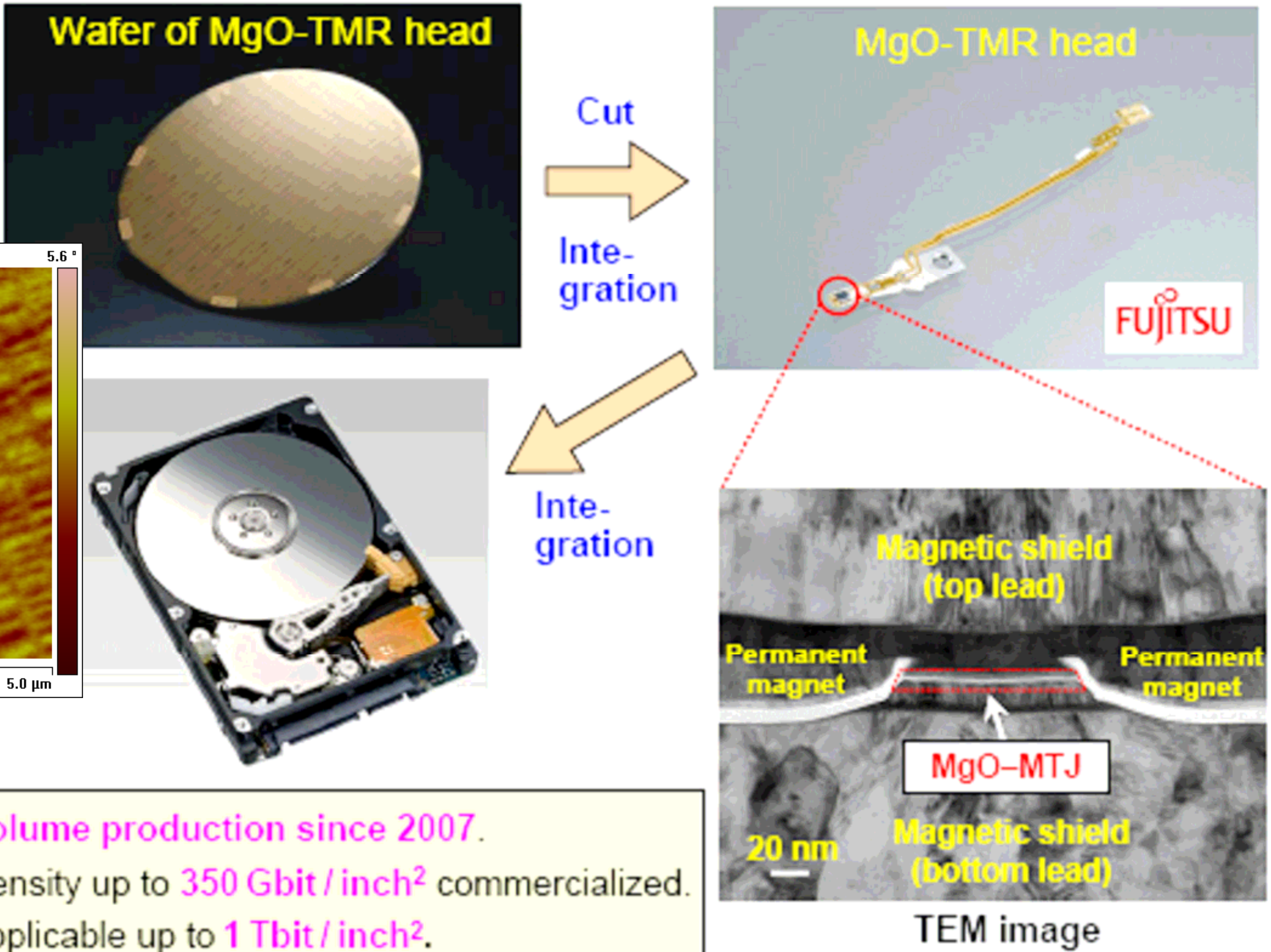


HDD- head

MgO-TMR head for ultrahigh-density HDD

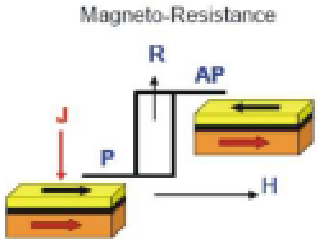
J. Kanak
MFM

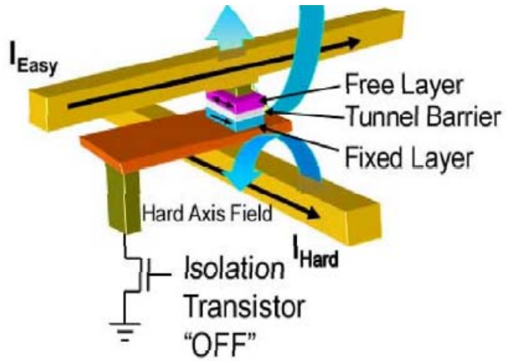


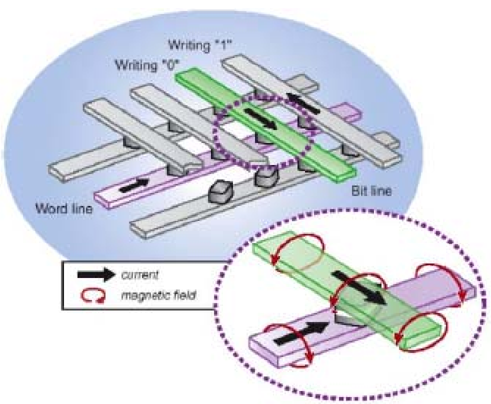


- Volume production since 2007.
- Density up to 350 Gbit / inch^2 commercialized.
- Applicable up to 1 Tbit / inch^2.

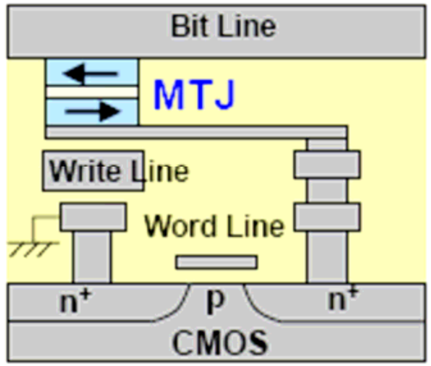
MRAM



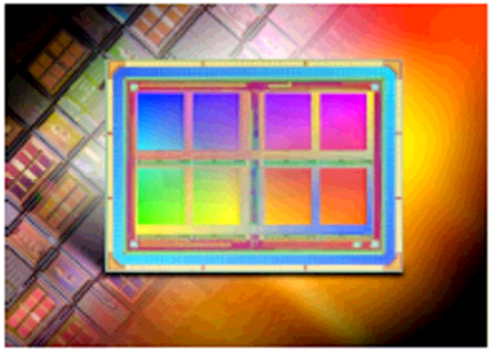




Magnetoresistive Random Access Memory (MRAM)



Cross-section structure



Freescale's 4 Mbit-MRAM based on Al-O MTJs
Volume production (2006)

Non-volatile, high speed, infinite write endurance, *etc.*

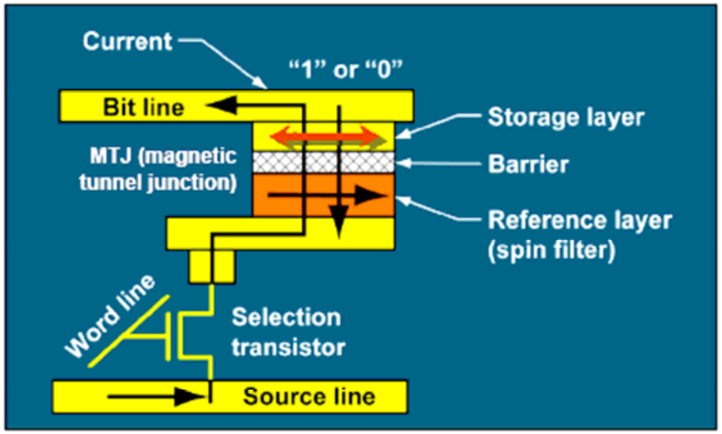
High-density MRAM is difficult to develop.

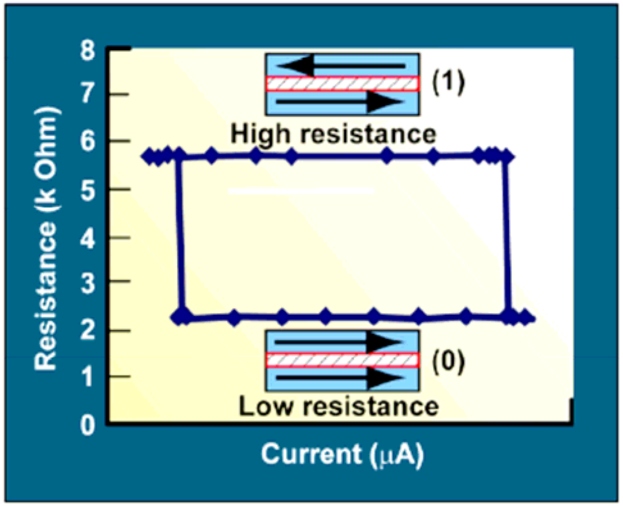
2008 –japoński satelita był wyposażony w pamięć MRAM w miejsce FLASH

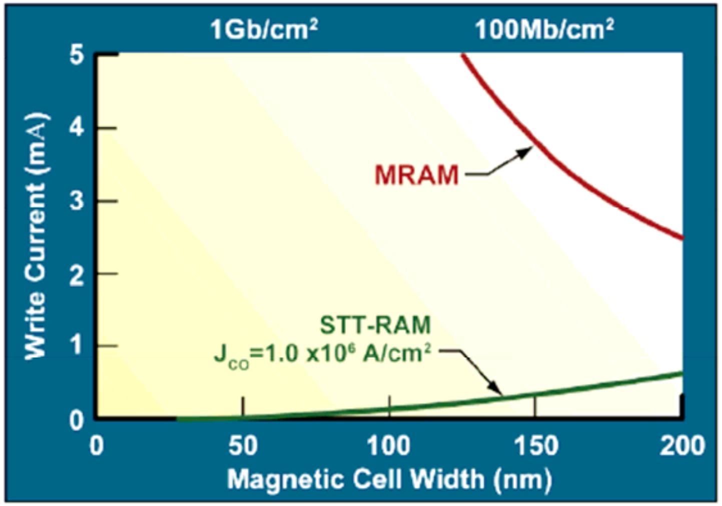
STT Write Mechanism

GRANDIS Pioneer in STT-RAM Technology

- **Spin-transfer torque writing**
  - Uses spin-polarized current instead of magnetic field to switch magnetization of storage layer
  - Has low power consumption and excellent scalability



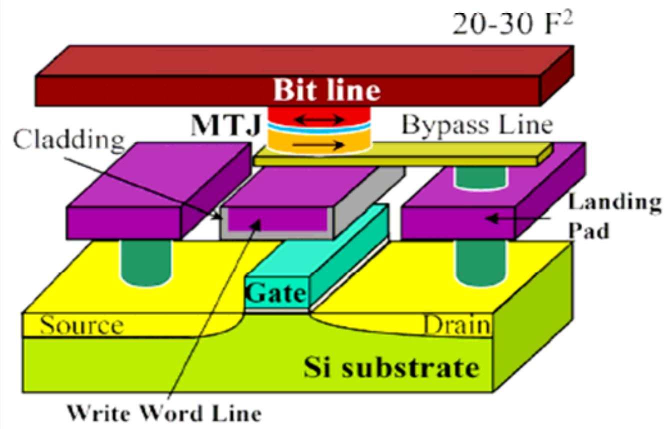




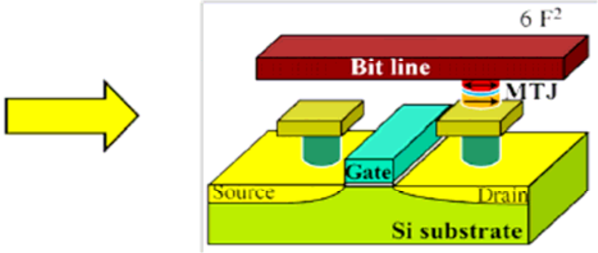
STT-RAM versus Conventional MRAM

GRANDIS
Pioneer in STT-RAM Technology

Conventional MRAM Cell



STT-RAM Cell



Write Current: $I_{sw} \sim 1 / Volume$ $\qquad$ $I_{sw} \sim Volume$

Key Advantages over conventional MRAM:

- **Excellent write selectivity** <— Localized spin-injection within cell
- **High scalability** <— Write current scales down with cell size
- **Low power consumption** <— Low write current (<100 μA)
- **Simpler architecture** <— No write line, no by-pass line and no cladding
- **Faster operation** <— Multibit (parallel) writing compatible

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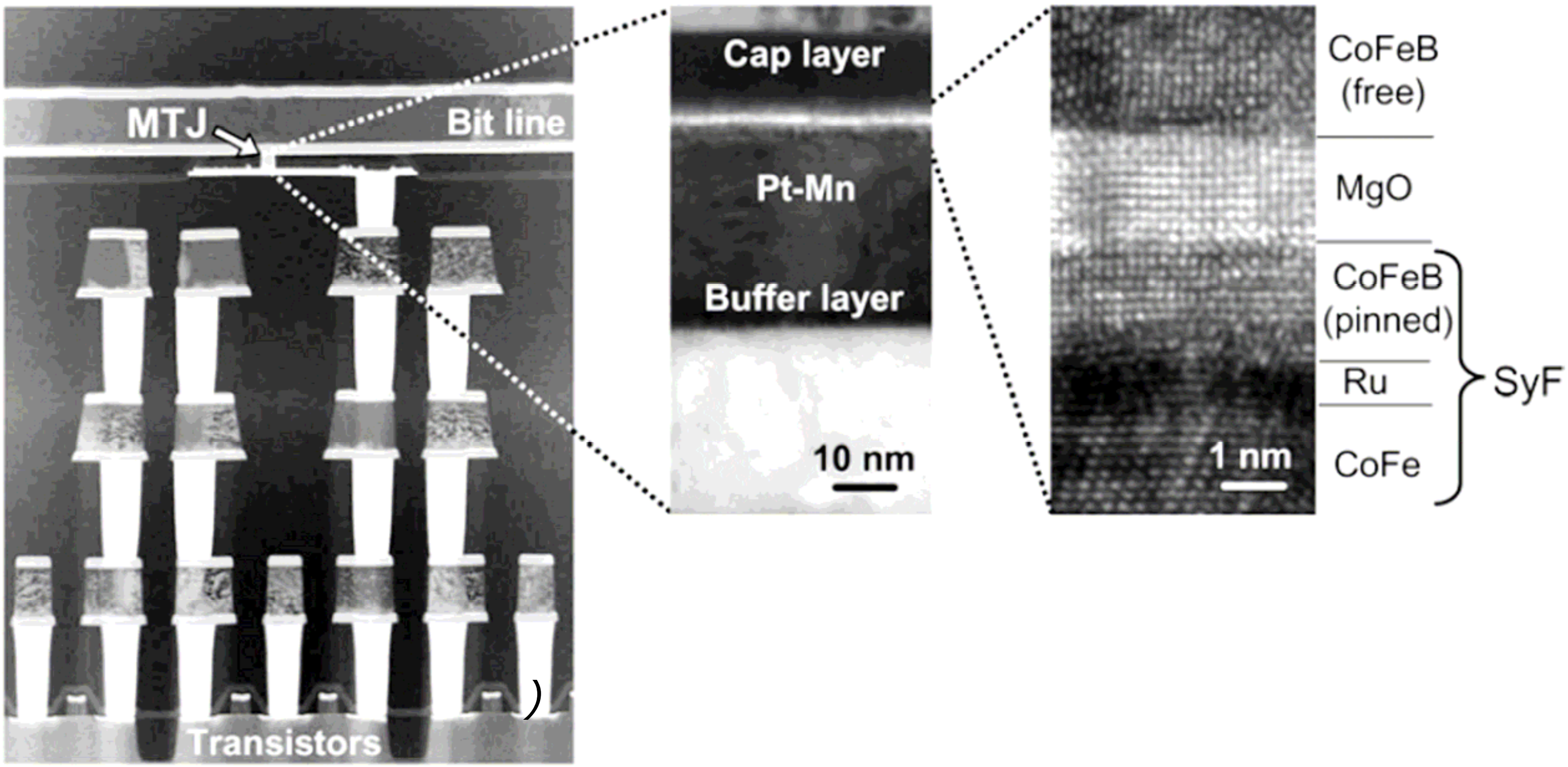
MRAM example

- Existing MRAM – up to 64 MB capacity
- Obstacle – critical current density



Toshiba, ISSCC conference (2010)

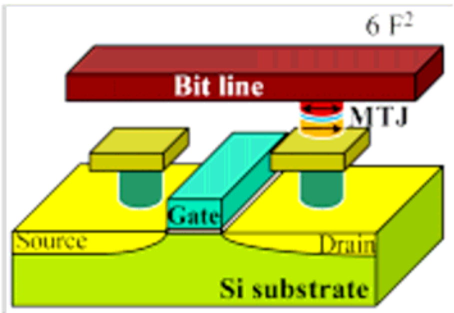
Memory Technology Comparison

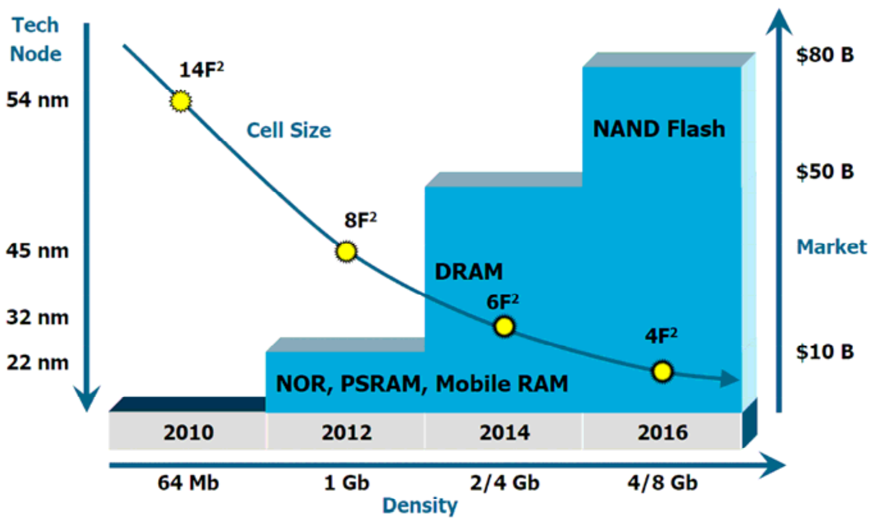
GRANDIS Pioneer in STT-RAM Technology

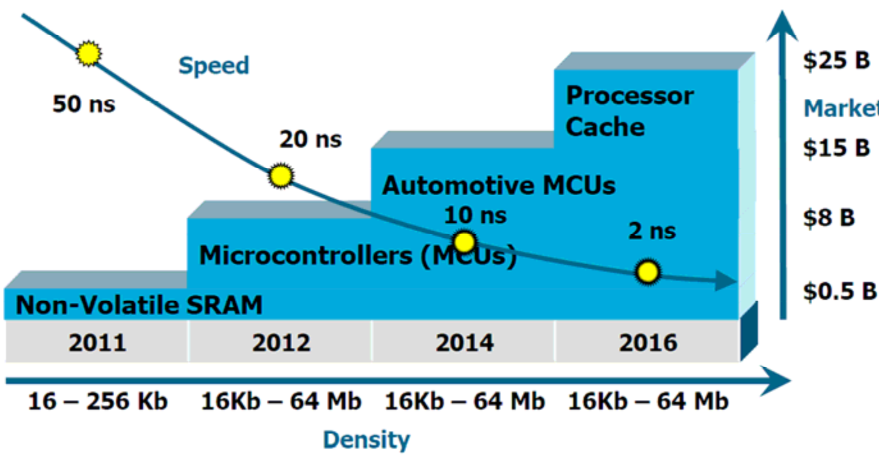
	SRAM	DRAM	Flash (NOR)	Flash (NAND)	FeRAM	MRAM	PRAM	RRAM	STT-RAM
Non-volatile	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cell size (F^2)	50–120	6–10	10	5	15–34	16–40	6–12	6–10	6–20
Read time (ns)	1–100	30	10	50	20–80	3–20	20–50	10–50	2–20
Write / Erase time (ns)	1–100	15	1 µs / 10 ms	1 ms / 0.1 ms	50 / 50	3–20	50 / 120	10–50	2–20
Endurance	10^{16}	10^{16}	10^5	10^5	10^{12}	$>10^{15}$	10^8	10^8	$>10^{15}$
Write power	Low	Low	Very high	Very high	Low	High	Low	Low	Low
Other power consumption	Current leakage	Refresh current	None	None	None	None	None	None	None
High voltage required	No	3 V	6–8 V	16–20 V	2–3 V	3 V	1.5–3 V	1.5–3 V	<1.5 V
	Existing products						*Prototype*		

MRAM vs. Semiconductor RAMs

STT-RAM Cell







Intensified Worldwide Interest in STT-RAM

GRANDIS
Pioneer in STT-RAM Technology

Jun. 2009:	NEC tips new MRAM technology using STT at VLSI conference, expects it to be scalable beyond 55 nm process
Oct. 2009:	Crocus Technology announces it will transition to STT-RAM from its existing heat-assisted TAS-MRAM in 2010
Nov. 2009:	Korean Government updates on progress of $50M STT-RAM program with Samsung and Hynix, installs 300 mm STT-RAM facility at Hanyang University
Dec. 2009:	TSMC and Qualcomm describe 45 nm low power embedded STT-RAM process and design at IEDM
Dec. 2009:	Also at IEDM, Hitachi & Tohoku University present MTJ SPICE model, and Intel presents design space study and requirements for STT-RAM in embedded applications
Dec. 2009:	France launches €4.2M SPIN project with 11 partners including LETI, Spintec & Crocus, one of project goals is to develop magnetic FPGAs
Jan. 2010:	Everspin introduces 1 Mb MRAM for RAID storage applications
Jan. 2010:	Toshiba achieves 9 μA switching current in perpendicular STT-RAM
Feb. 2010:	Toshiba describes a 64 Mb STT-RAM using perpendicular MTJs and 65 nm CMOS at ISSCC conference, Fujitsu also presents a paper

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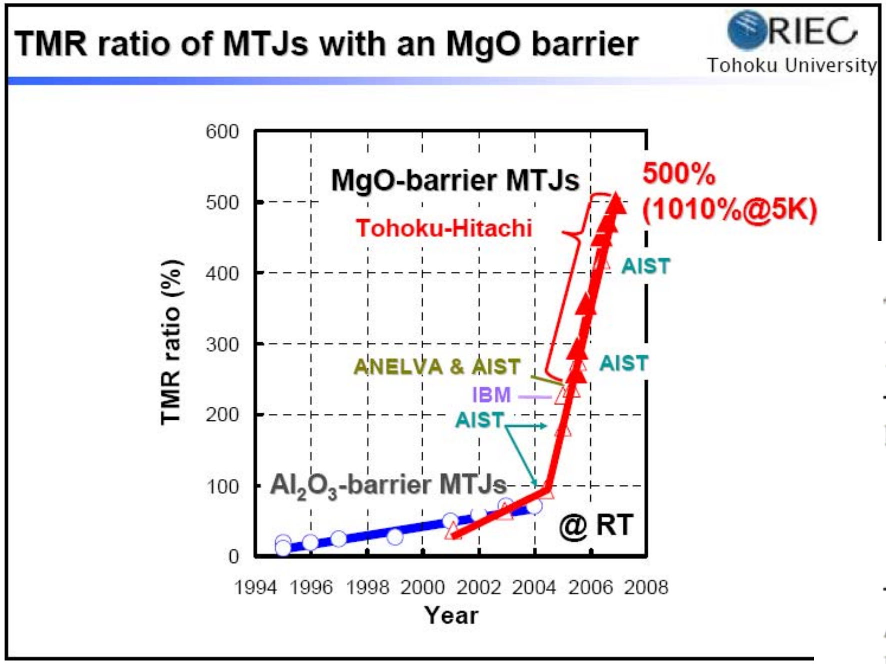
Cele

Optymalizacja struktury warstwowej magnetycznego złącza tunelowego pod kątem zjawiska spinowego transferu momentu pędu (STT).

Wytworzenie tunelowego magnetycznego nanozłącza dla zastosowań na komórki pamięci STT-RAM i ST-oscylatory.

AGH

spin LAB



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).

Table 3

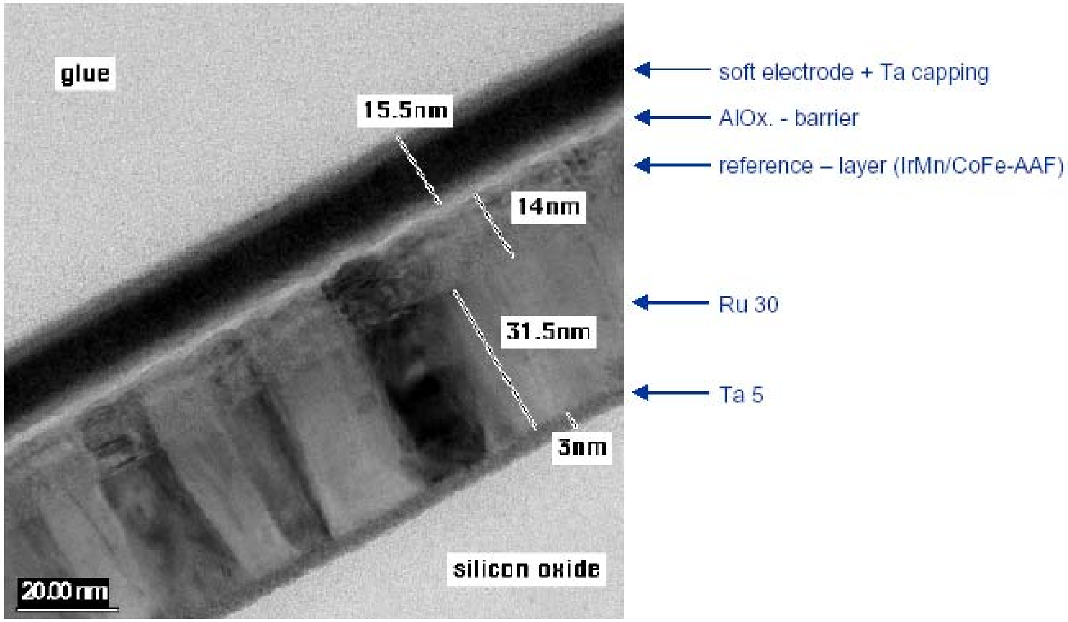
RA, TMR and H_{in} of MTJs with Al–O and MgO barrier

Buffer	Al–O MTJs				MgO MTJs			
	RA-P (MΩ µm²)	RA-AP (MΩ µm²)	TMR (%)	H_{in} (kA/m)	RA-P (MΩ µm²)	RA-AP (MΩ µm²)	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

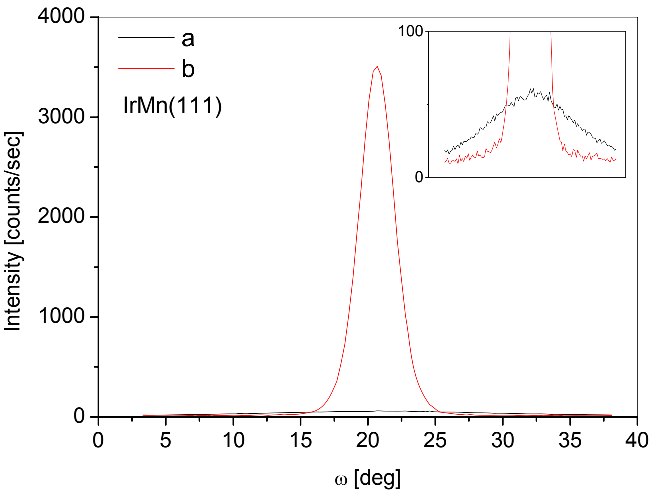
RA-P and RA-AP were measured in parallel and antiparallel orientation of magnetizations of free and pinned layer, respectively.

P. Wisniowski, J. Kanak, et al. J. Appl. Phys. 100 (2006) 013906
J. Kanak, et al. Vacuum 82 (2008)1057

Barrier quality

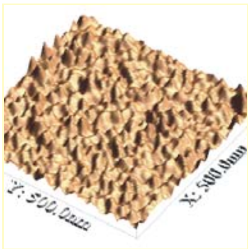


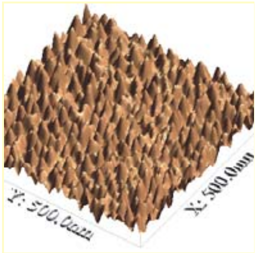
XRD – rocking curve

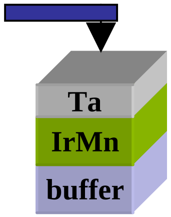


AFM

a) RMS = 0.3 nm b) RMS = 0.6 nm



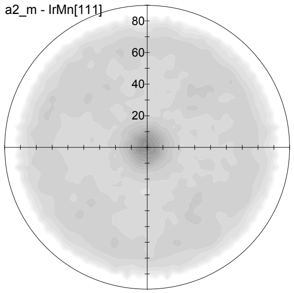




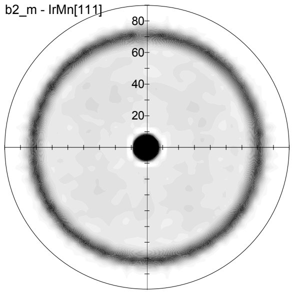
J. Kanak

XRD – pole figure

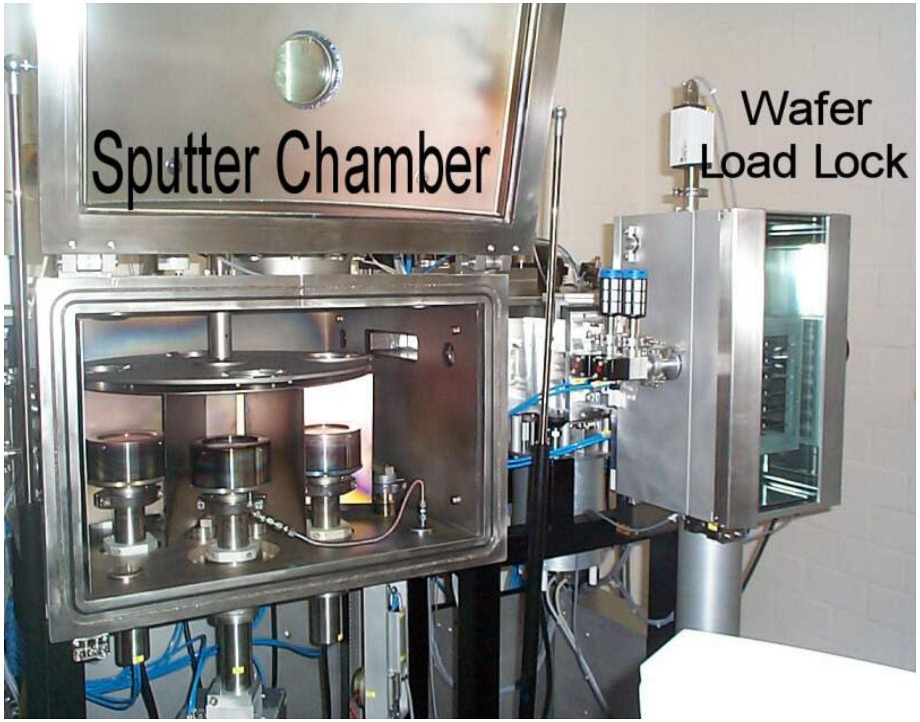
a)



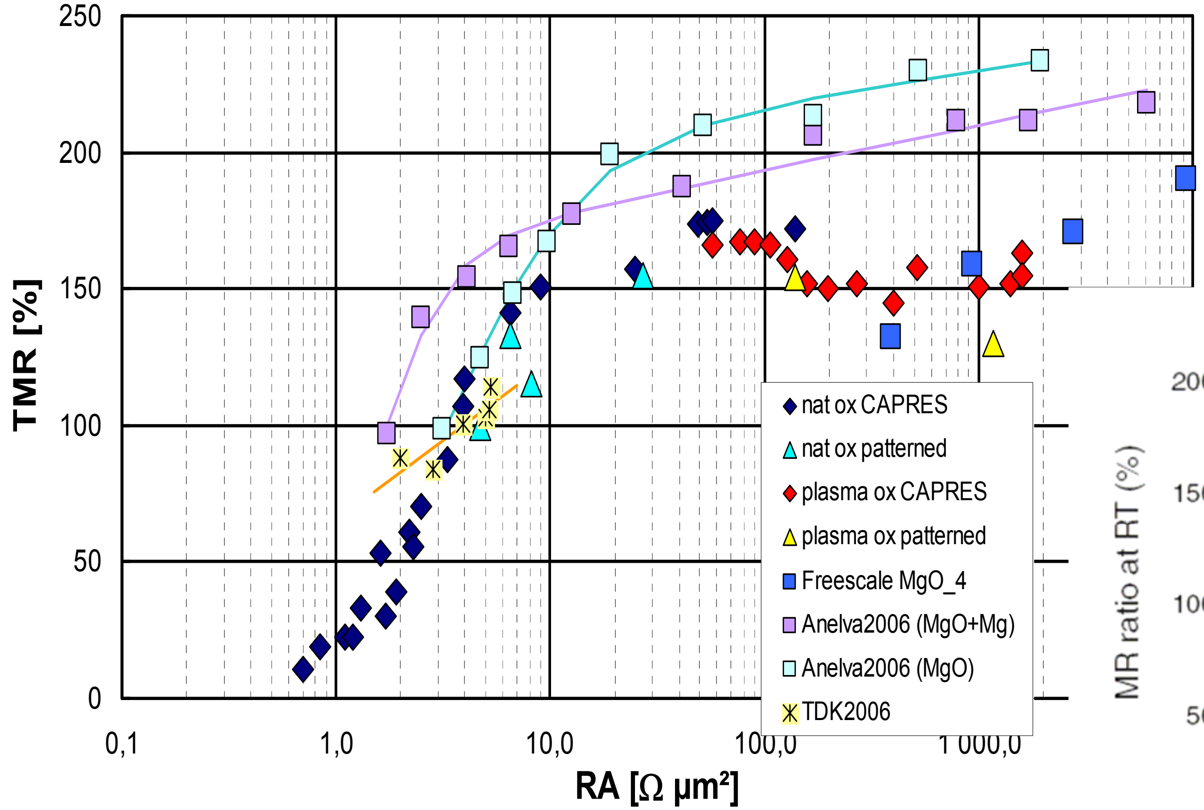
b)

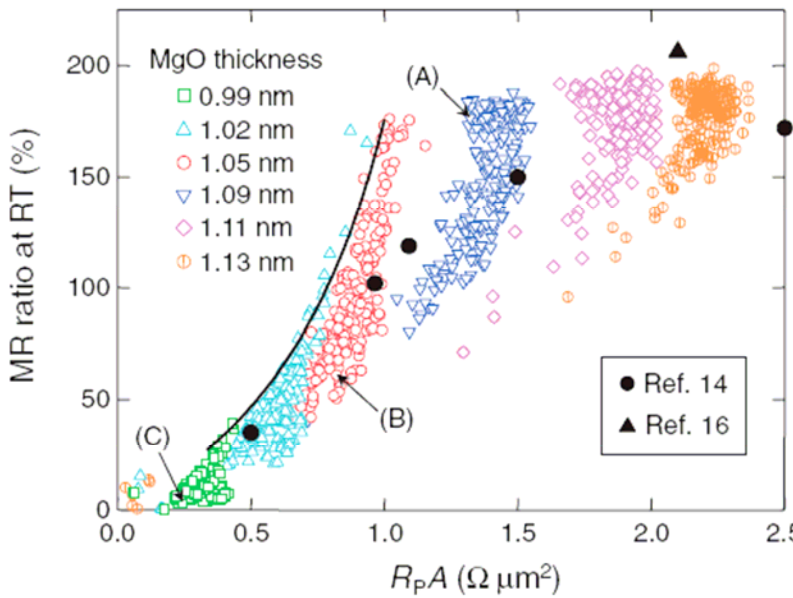


Sputtering system (uni lab)



MgO - TMR vs. RA





H. Maehara et al. Applied Physics Express 4 (2011) 033002

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Sputtering deposition

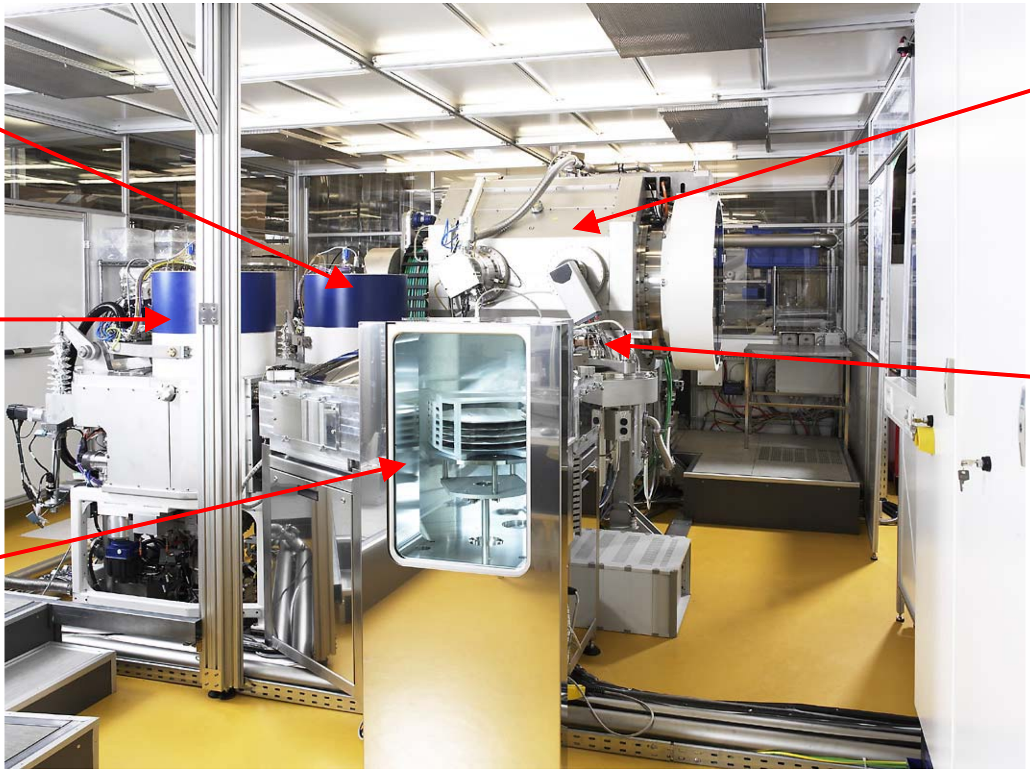
Singulus TIMARIS

J. Wrona

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)



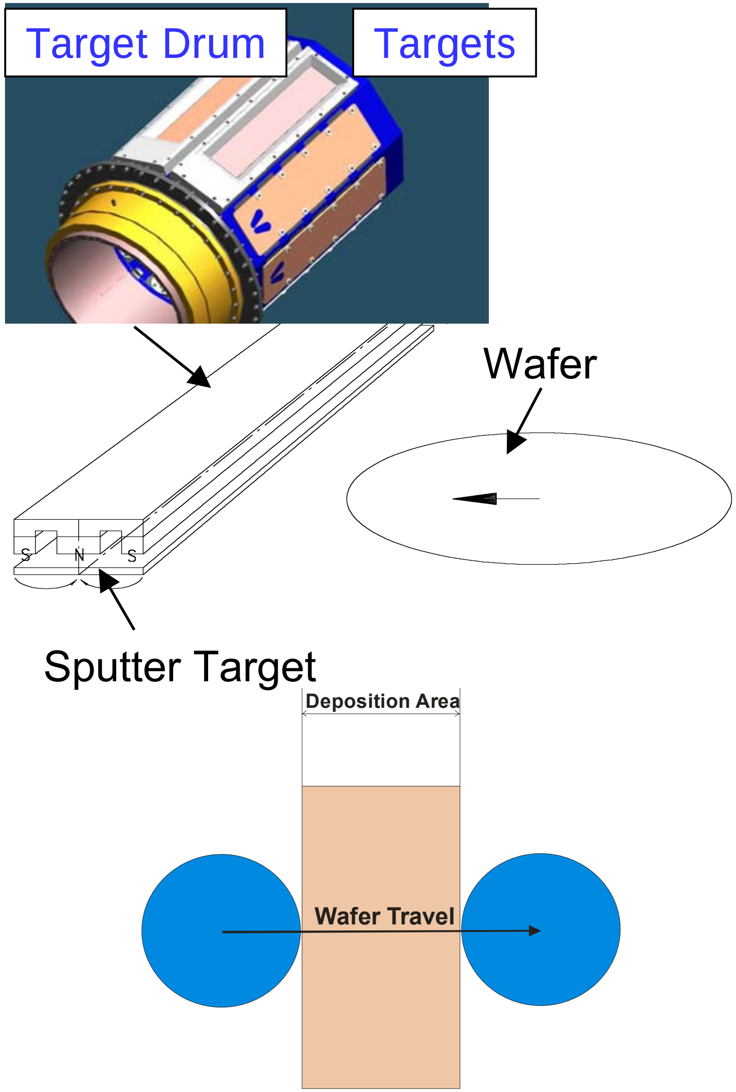
Multi Target Module
Top: Target Drum with 10 rectangular cathodes; Drum design ensures easy maintenance;
Bottom: Main part of the chamber containing LDD equipment

Transport Module
(UHV wafer handler)

Ultra – High – Vacuum Design:	Base Pressure ≤ $5*10^{-9}$ Torr (Deposition Chamber)
High Throughput (e.g. MRAM):	9 Wafer/Hour (1 Depo-Module)
High Effective Up-time:	18 Wafer/Hour (2 Depo-Module)

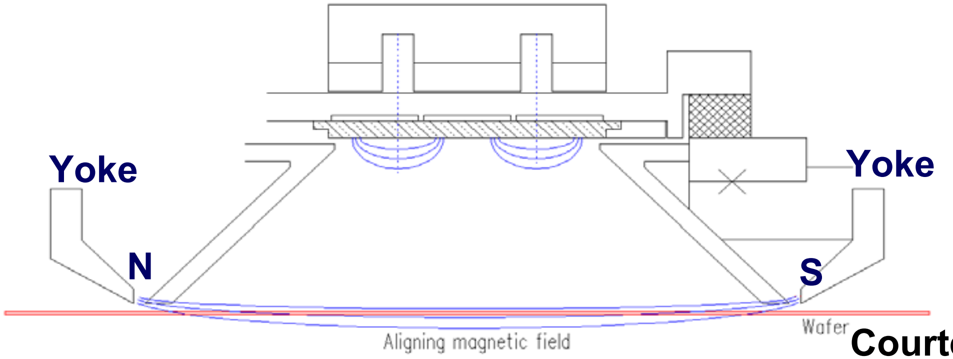
Courtesy of
SINGULUS

Linear Dynamic Deposition (LDD)



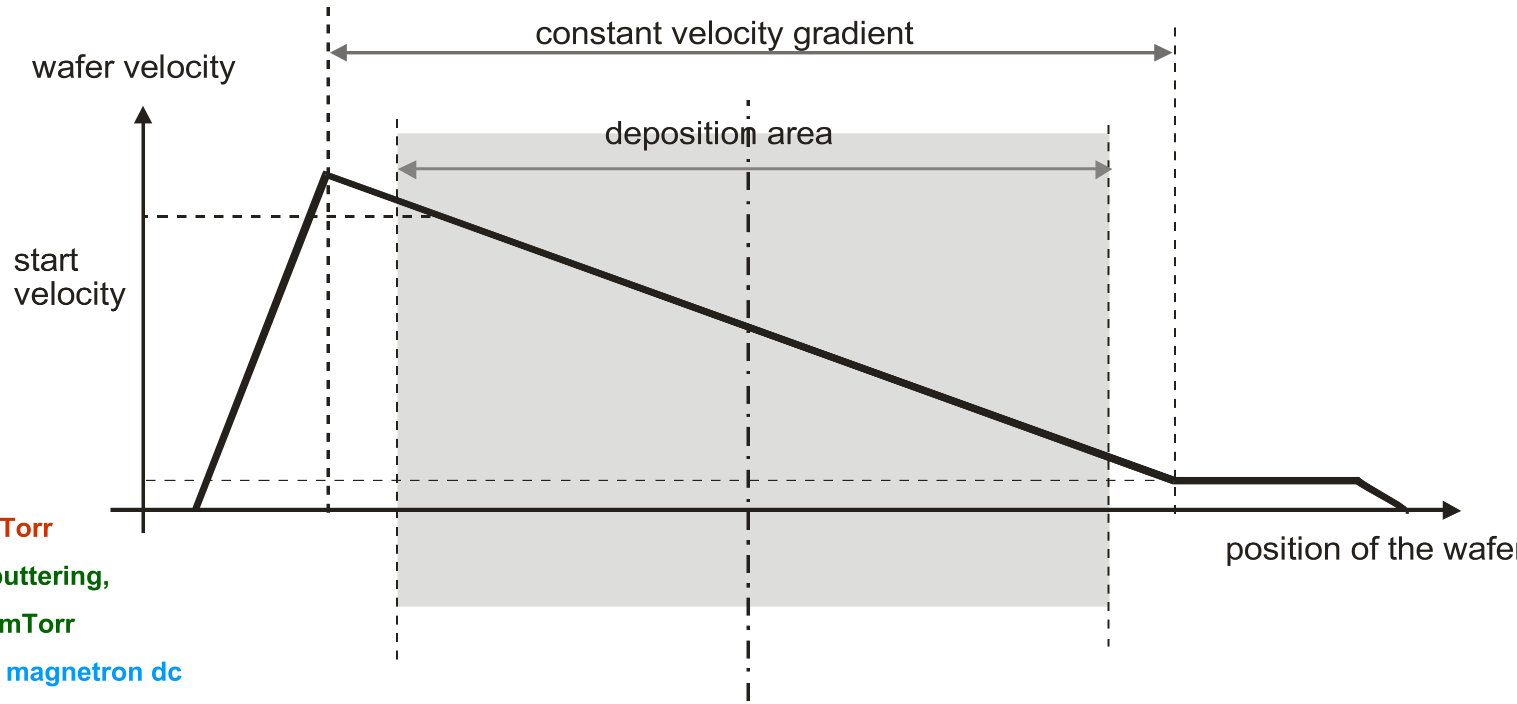
Advantages:

- **Short Target-Substrate Distance:**
  - **Good thickness uniformity and coating efficiency**
- **Thickness adjusted by wafer speed:**
  - **Precisely control & repeatability**
- **Leakage field of cathode parallel to wafer travel direction:**
  - **Ideal symmetry for magnetic film applications**
- **Stationary Aligning Magnetic Field (AMF):**
  - **AMF can be optimized with cathode**

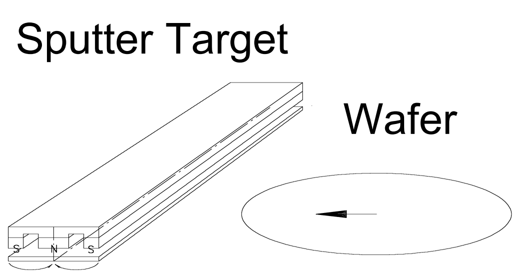


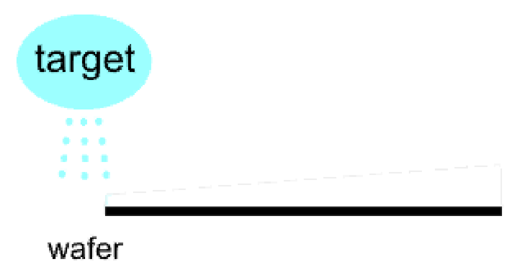
Courtesy of SINGULUS

Wedge technology



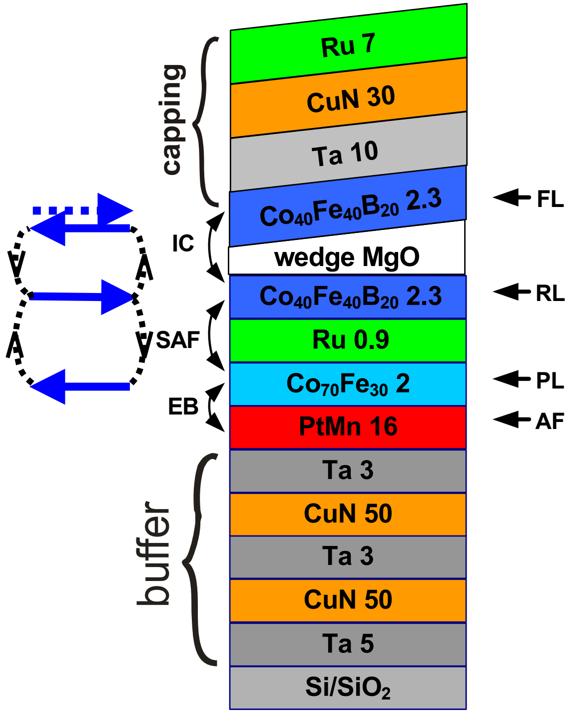
- base pressure: $p_0 \leq 5 \times 10^{-9}$ mTorr
- MgO - 4kW, rf magnetron sputtering, variable Ar pressure 1 – 15 mTorr
- CuN – 4 kW, reactive (Ar+N) magnetron dc
- Ta,Ru,CoFeB – 1.5 kW magnetron dc





J. Wrona, T.Stobiecki et al. J.Phys. Conf. Ser. 200, (2010).

Multilayer stack



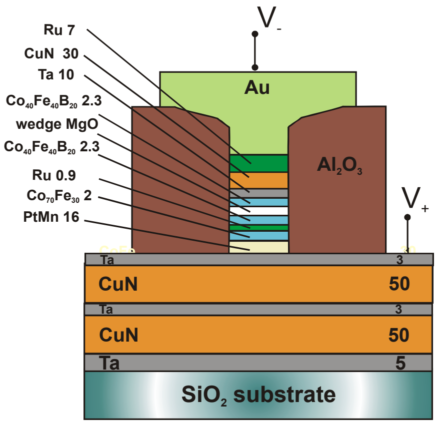
- MTJ stack deposited **in Singulus**
- MgO wedge thickness: 0.6 nm up to 1nm (slope 0.017 nm/cm)

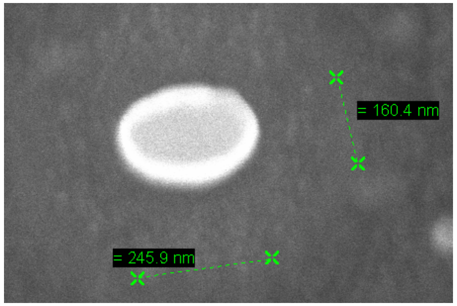
Wafer characterization microstructure – XRD, AFM

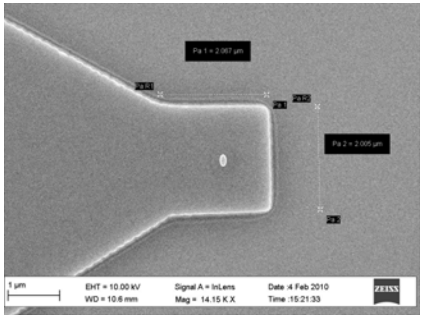
- electrical, magnetic: TMR, RA, MOKE-loops

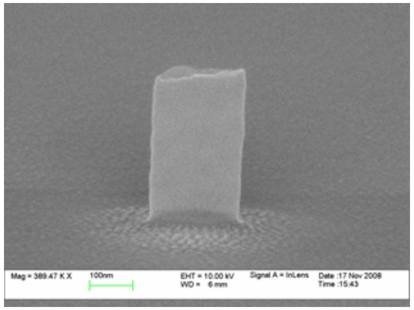
Nanopillars

- 2 step e-beam lithography,ion etching, lift-off



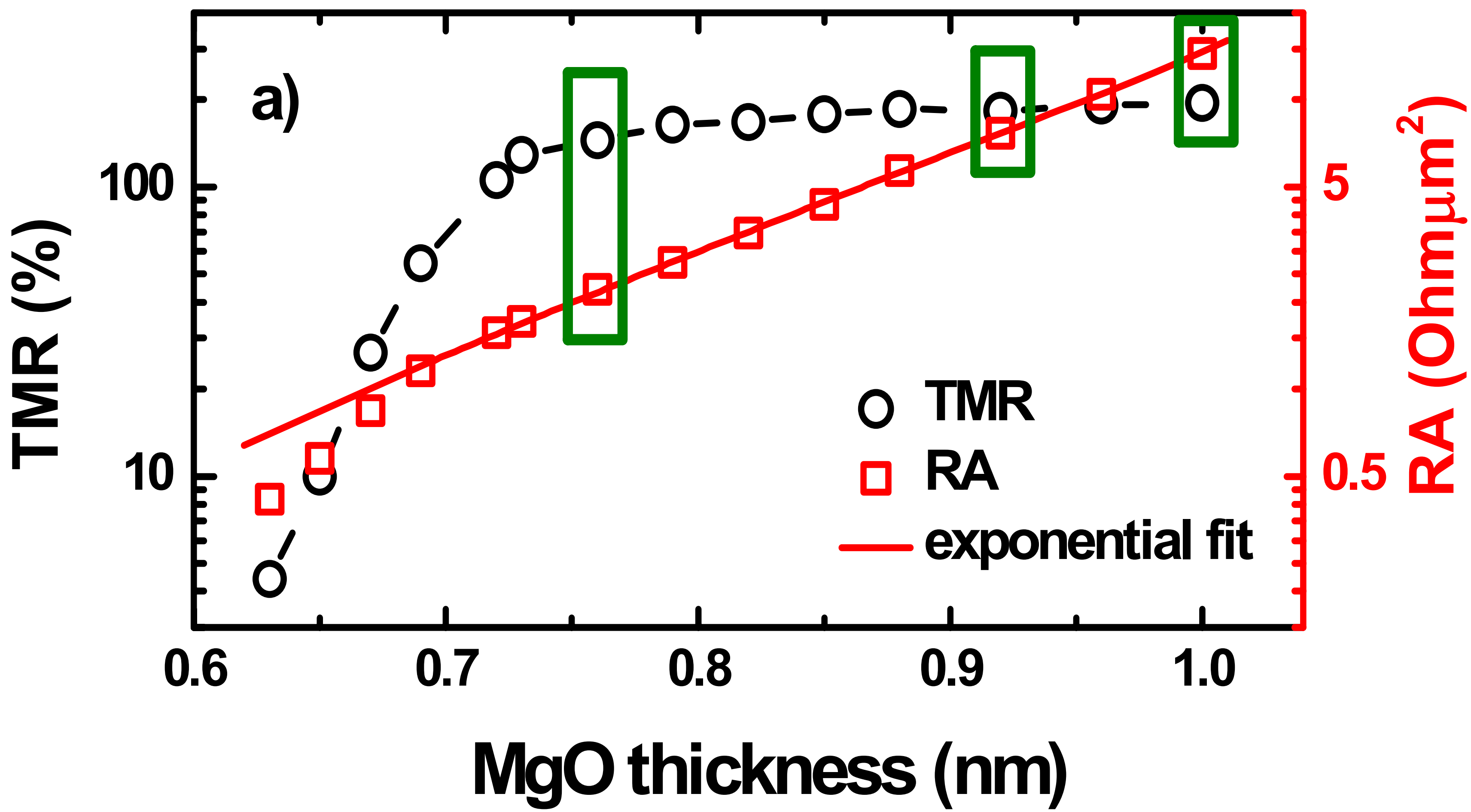






W. Skowroński

TMR & RA vs. MgO thickness



Plan

- Mapa drogowa spintroniki

- co nowego w urządzeniach
  - głowice TMR/HDD
  - pamięci operacyjne STT-RAM
  - nano-oscylatory mikrofalowe STO

- Technologia magnetycznych nano-złącz tunelowych (MTJ)
  - nanoszenie układu wielowarstwowego - sputtering
  - elektronowa litografia\

- **Spin transfer torque**
  - **Przełączanie prądem spinowo spolaryzowanych elektronów (CIMS)**
  - **ST- oscylotor**

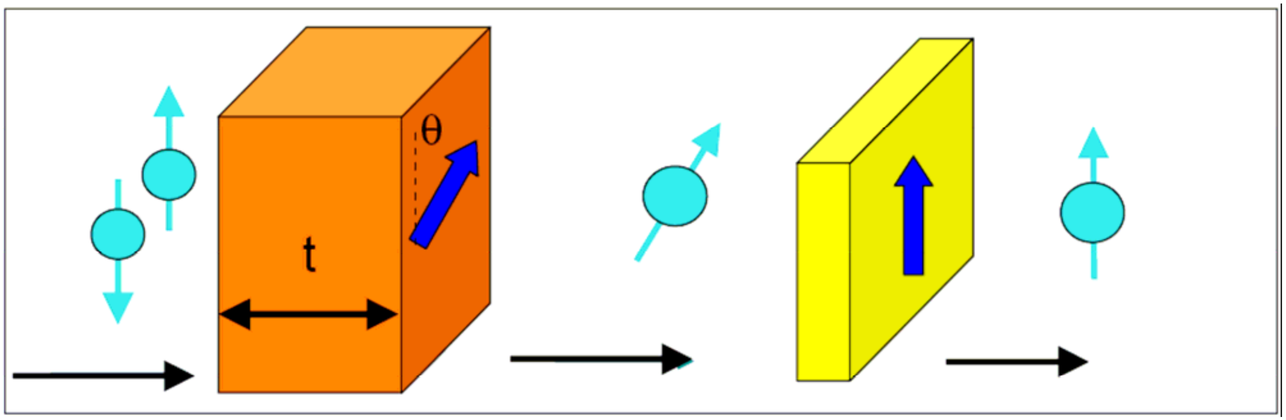
- Podsumowanie

- Projekt SPINLAB

Spin Transfer Torque

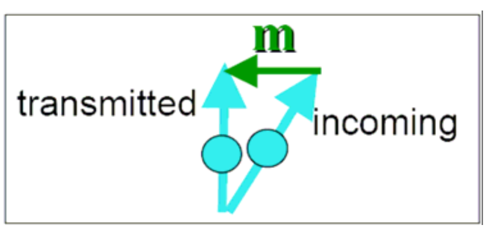
Unpolarized electrons | Polarized electrons | Transmitted electrons

Electron flow →



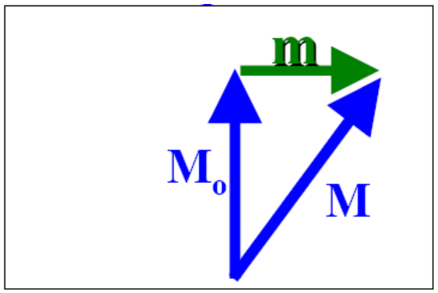
Polarizer P | **Free layer M**

Conduction Electrons



Transfer of transverse moment m
=
Torque
(Spin Torque ST)

Local magnetization



ST tends to align M (anti-)parallel to P

Spin Transfer Torque (STT)

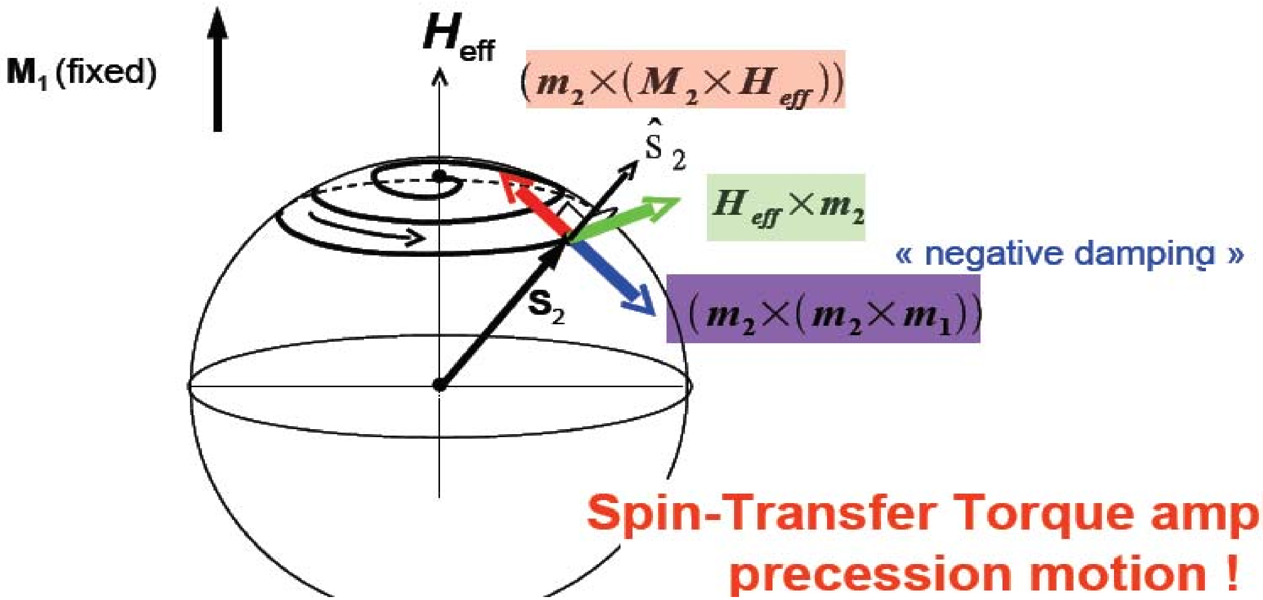
L(andau)L(ifszic)G(ilbert)S(lonczewski) dynamics

$$\frac{1}{\gamma_0}\cdot\frac{dm_2}{dt}=H_{eff}\times m_2+\frac{\alpha}{\gamma_0}m_2\times\frac{dm_2}{dt}$$

M_2, m_2- FL magnetic moment
M_1, m_1- RL magnetic moment

Slonczewski '96

$$\frac{1}{\gamma_0}\cdot\frac{dm_2}{dt}=H_{eff}\times m_2+\frac{\alpha}{\gamma_0}m_2\times\frac{dm_2}{dt}+p_{effective}J\frac{(\hbar)}{e\mu_0 t_2 M_{S2}}\left(m_2\times\left(m_2\times m_1\right)\right)$$



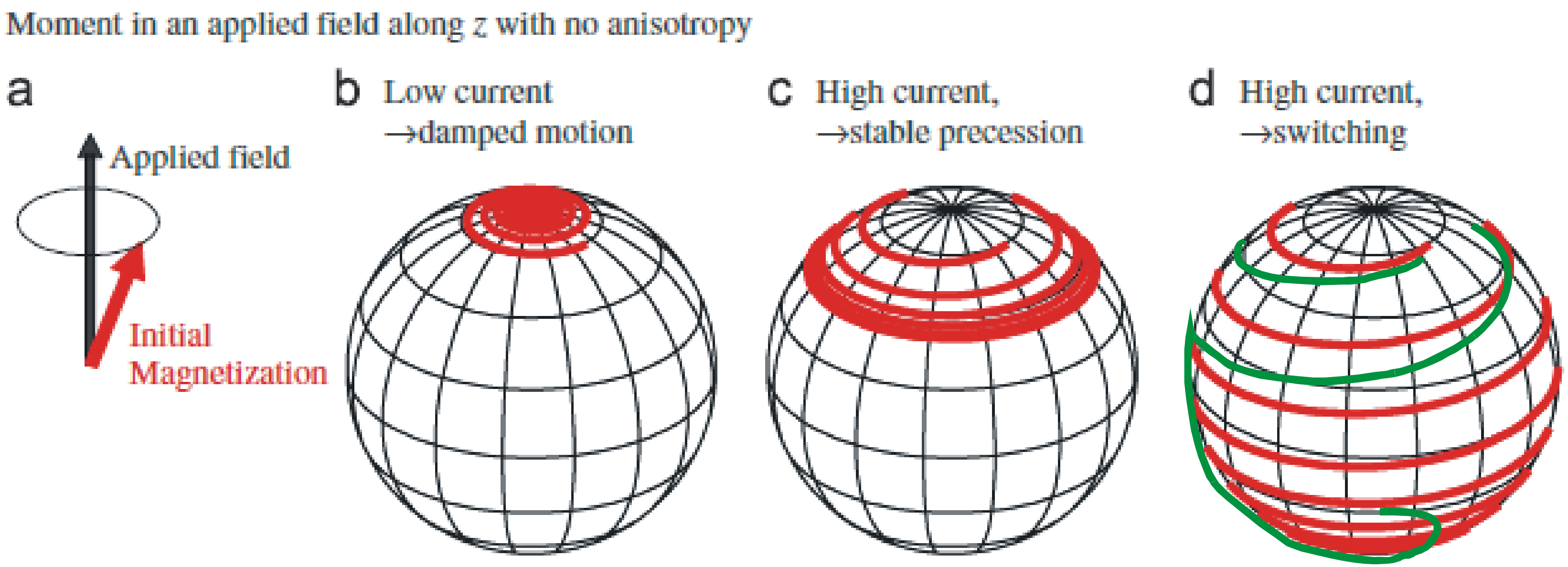
I > 0 favors P state

I < 0 favors AP state

Spin-Transfer Torque amplifies precession motion !

STT – CIMS

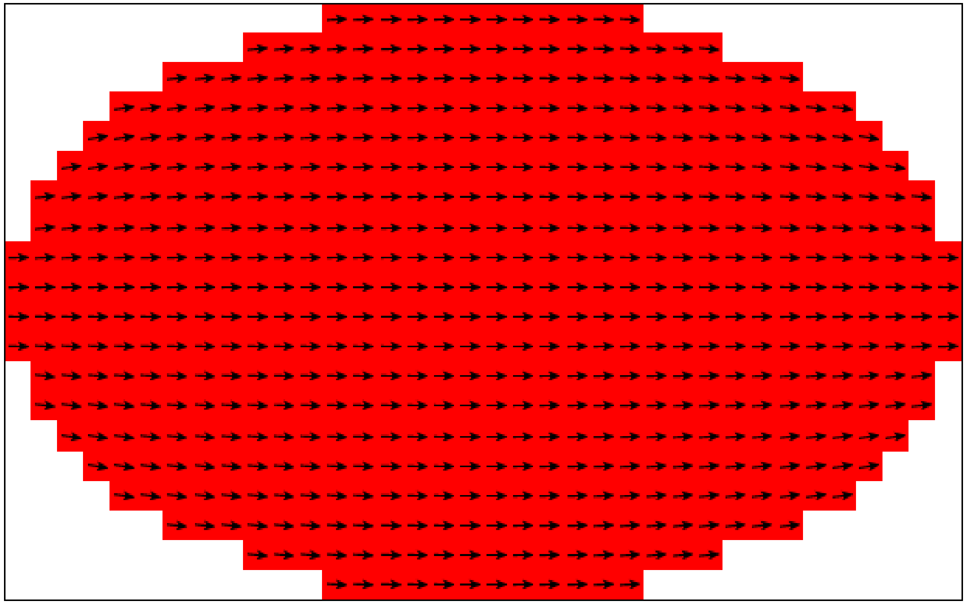
Spin Transfer Torque→ Curent Induced Magnetization Switching

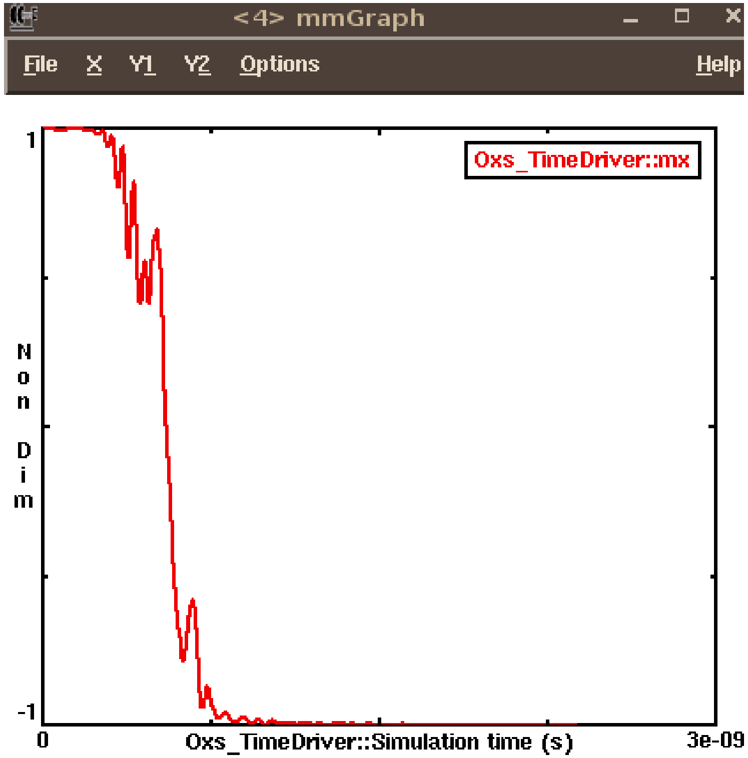


$I = I_{Critical}$

Micromagnetic switching (OOMMF)

M. Czapkiewicz



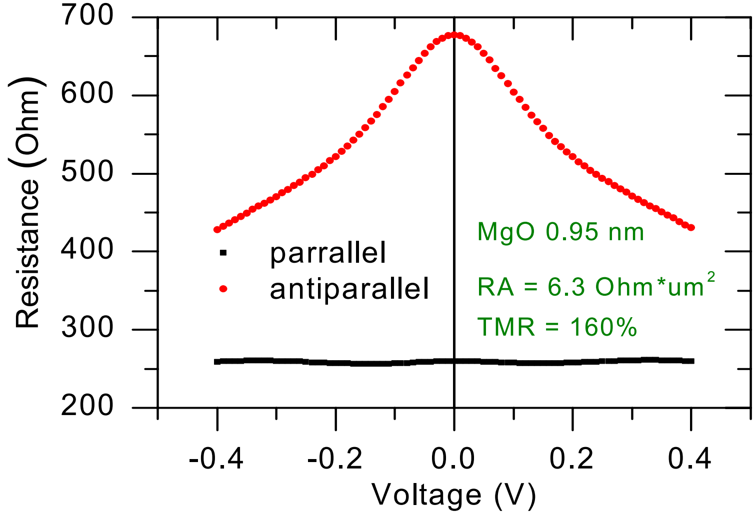


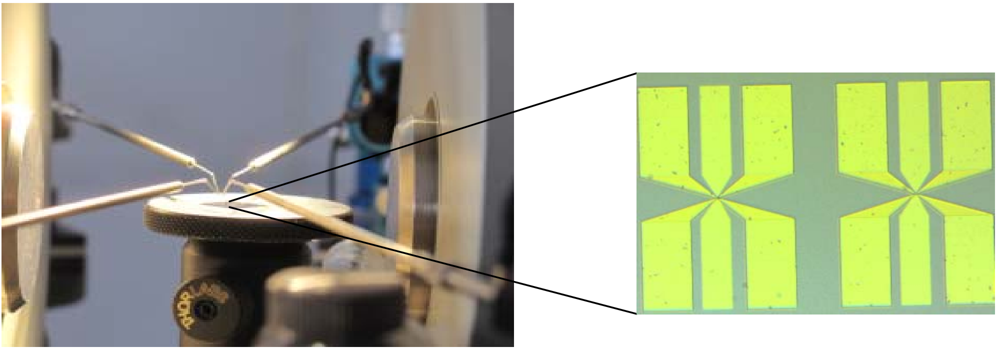
I= 7 mA, P=0.7 α=0.01

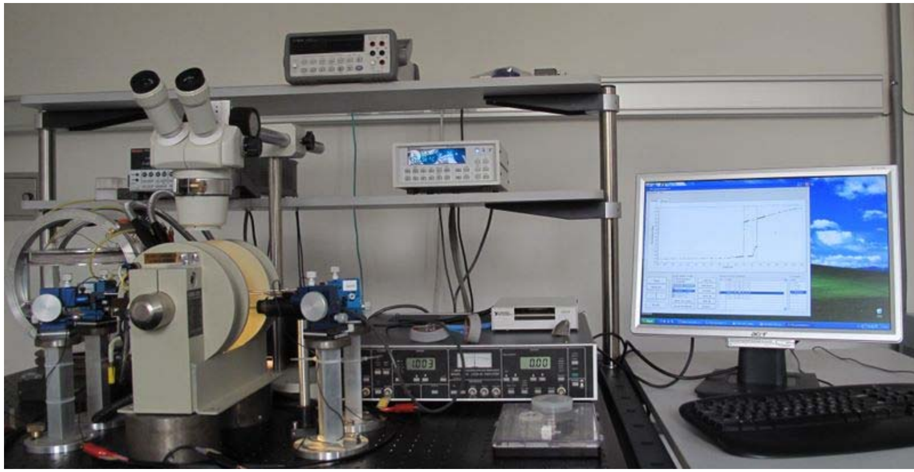
Static measurements

- Standard TMR, I(V), dI/dV in magnetic field using quasi-DC methods
- CIMS – down to 1 ms length pulses

Skowroński et al. JAP ***107****, 093917 (2010)*







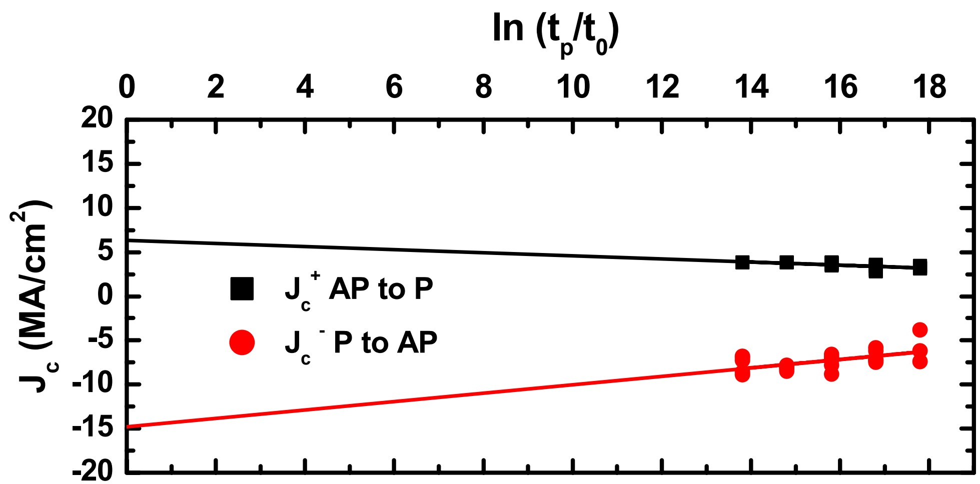
CIMS measurements

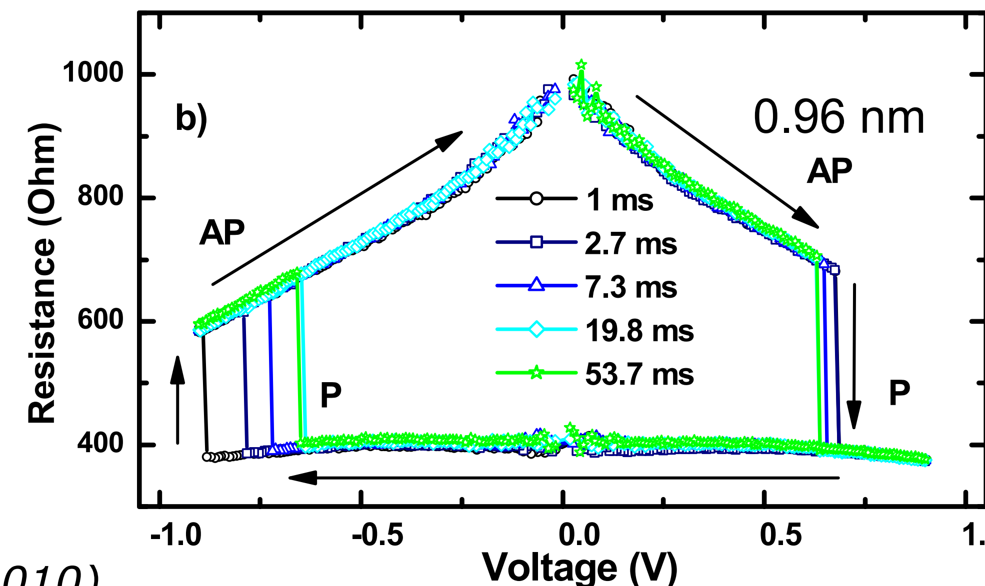
- results of MTJ with 0.96 nm thick MgO barrier
- J_{c0} estimation

$$J_c = J_{c0}\left[1 - \frac{2k_BT}{H_CM_SV}\cdot\ln\left(\frac{\tau_P}{\tau_0}\right)\right]$$

Stability factor	AP → P	P → AP
$\left(\frac{H_CM_SV}{2k_BT}\right)_{exp}$	36 ± 7	35 ± 11

$$\left(\frac{H_CM_SV}{2k_BT}\right)_{Calc} \approx 30$$





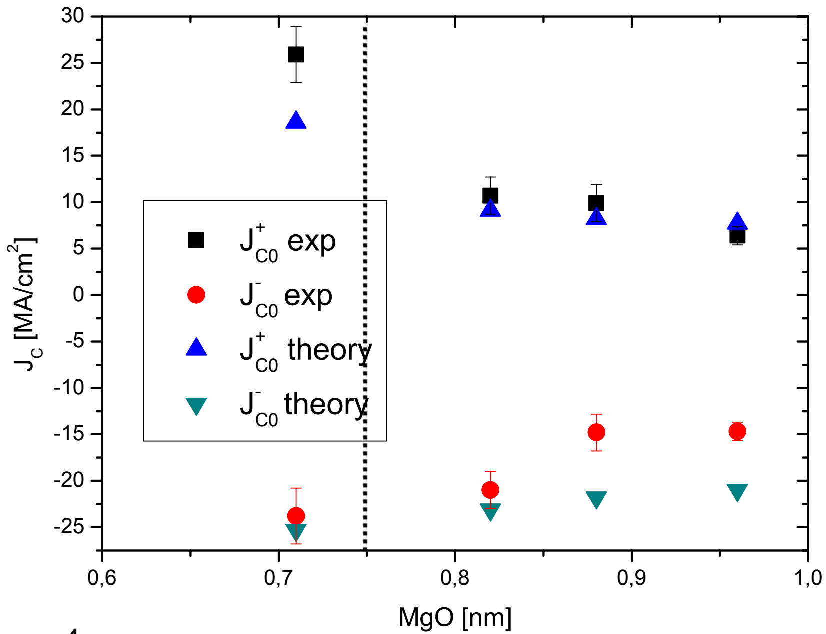
Skowroński et al. JAP ***107****, 093917 (2010)*

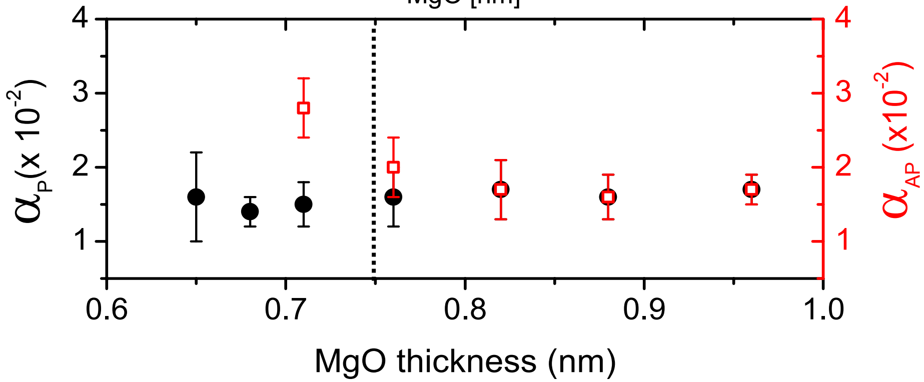
Critical current Slonczewski's model

$$J_{c0} = \frac{2e\alpha\mu_0 M_S t_F \left(H_{ext} \pm H_k \pm H_d\right)}{\hbar\eta}$$

$$\eta = \frac{p}{2(1+p^2\cos\theta)}$$

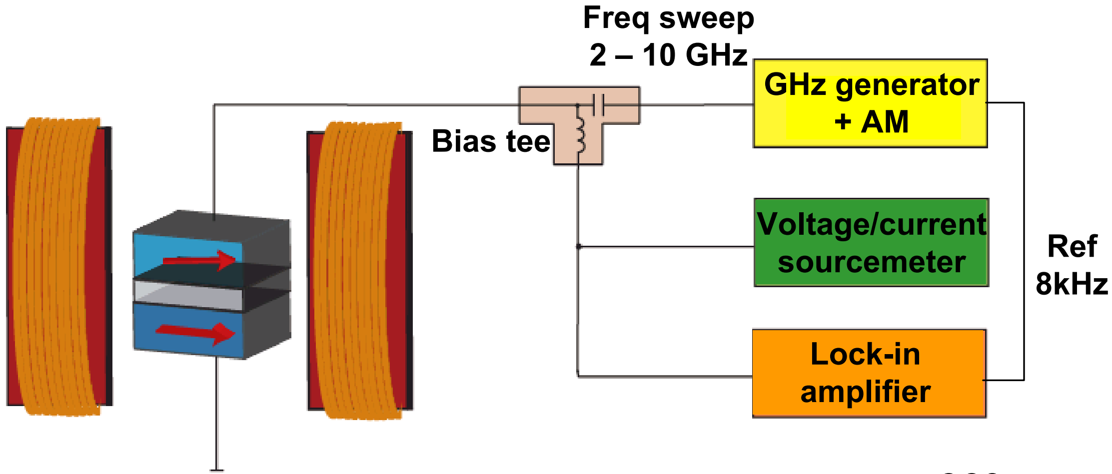
$$p = \sqrt{\frac{TMR}{2+TMR}}$$





W. Skowronski , T.Stobiecki, J. Appl. Phys. (2010), 093917

Measurement setup for spin dynamics



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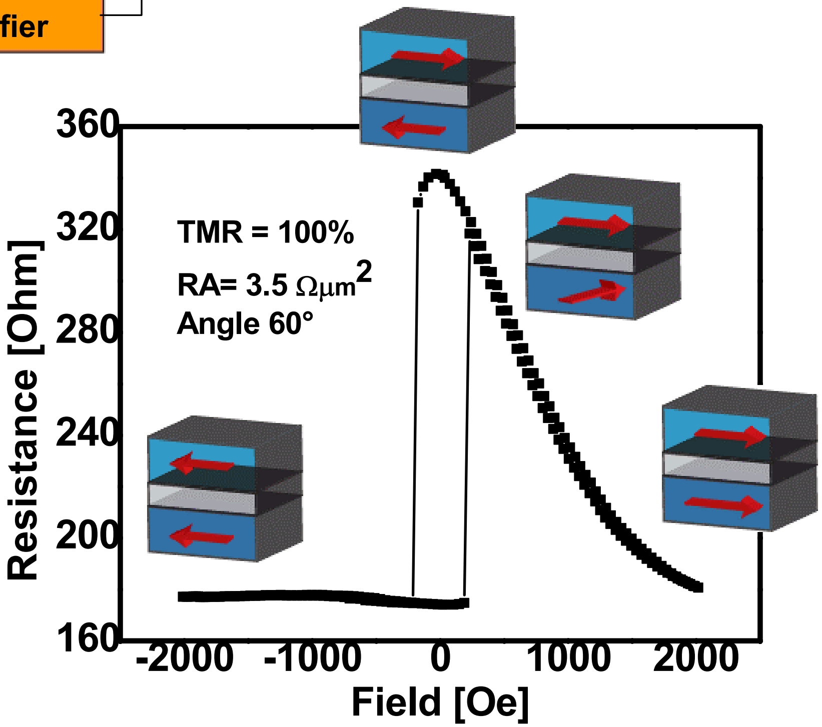
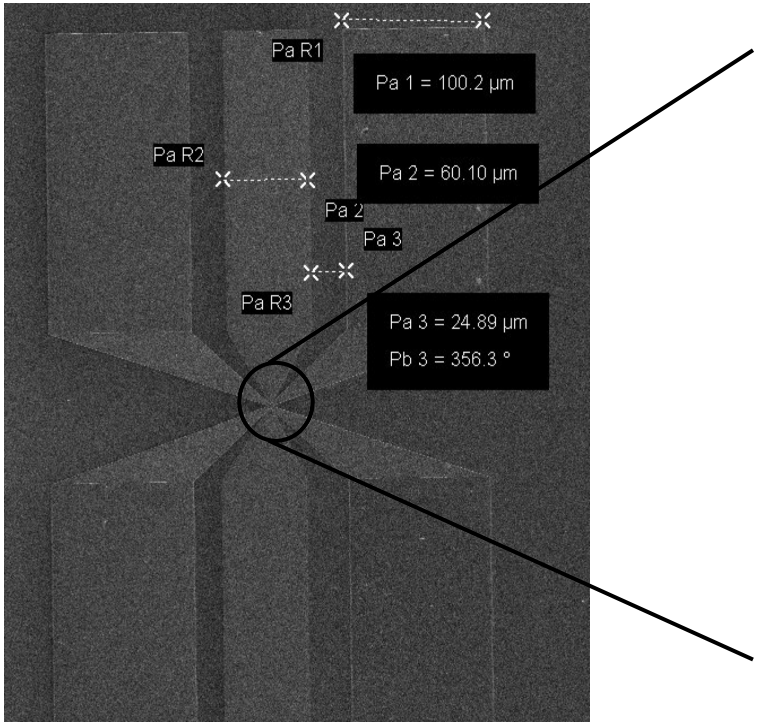
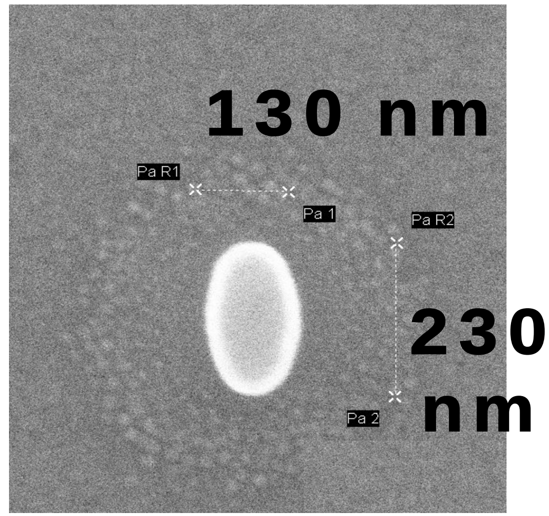
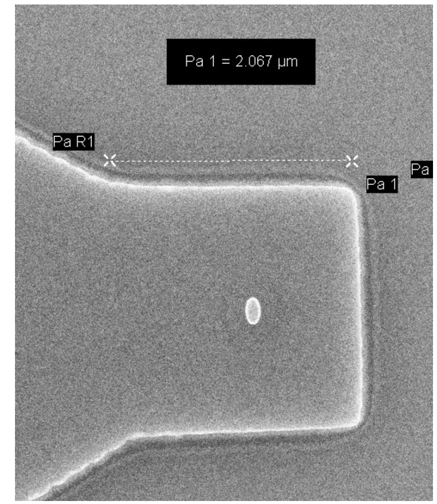
- MTJ sample placed in the magnetic field and tilted by a certain degree
- Amplitude modulated RF signal supplied to the MTJ through a bias tee
- Small DC signal measured using lock-in detection



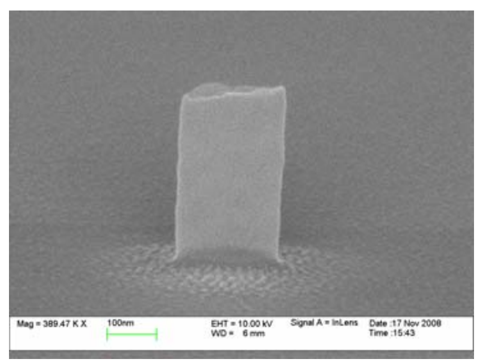
Nanopillar with coplanar wave guide



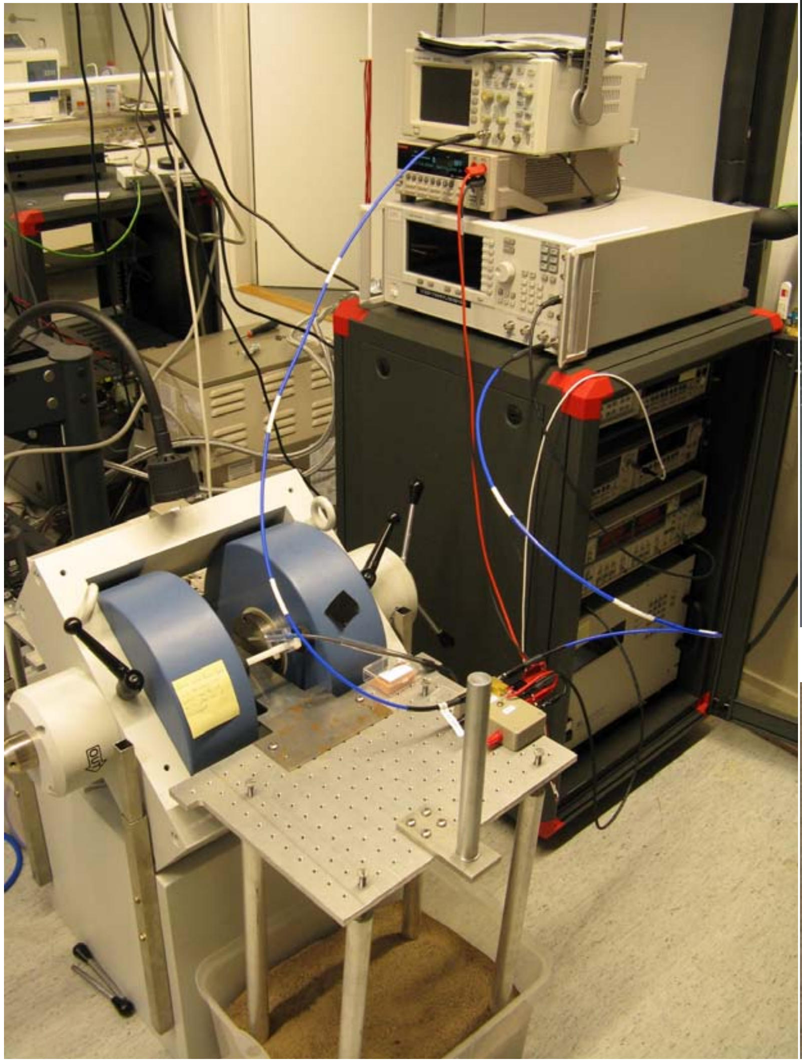




leads 50 Ω



Measurement setup for spin dynamics



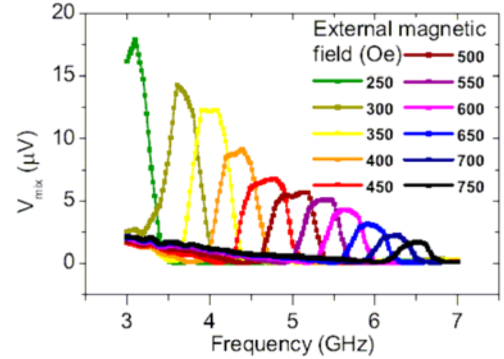


FIG. 1: ST-FMR spectra measured with different external magnetic field applied.

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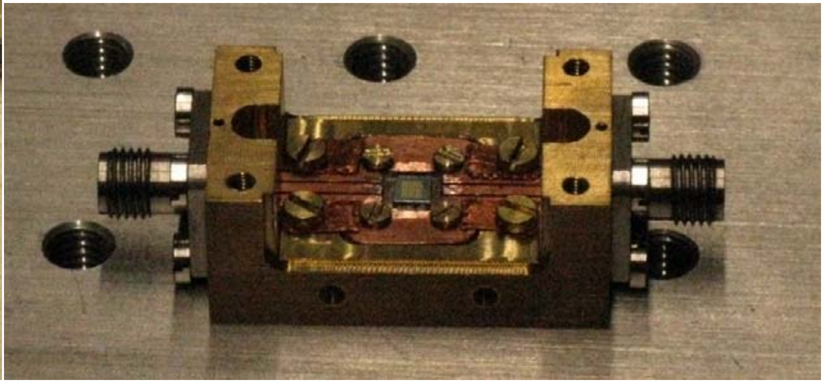
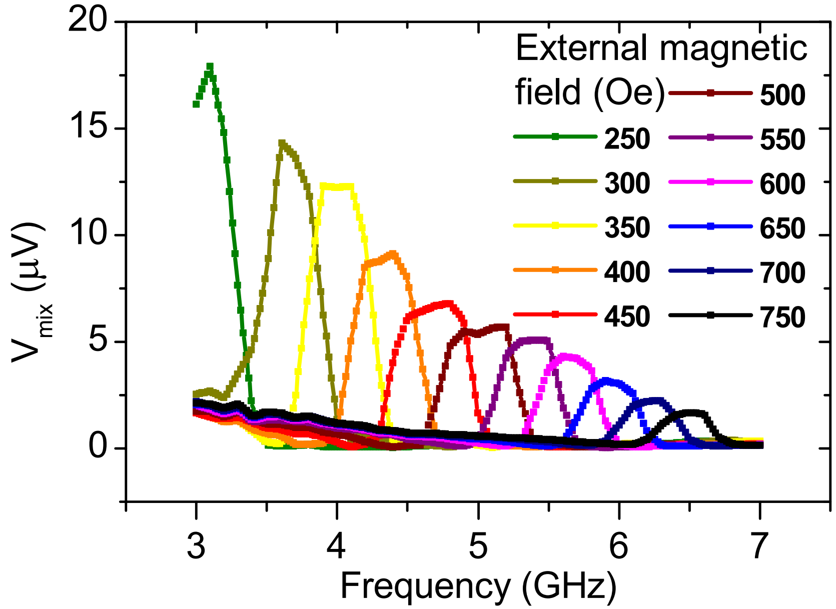
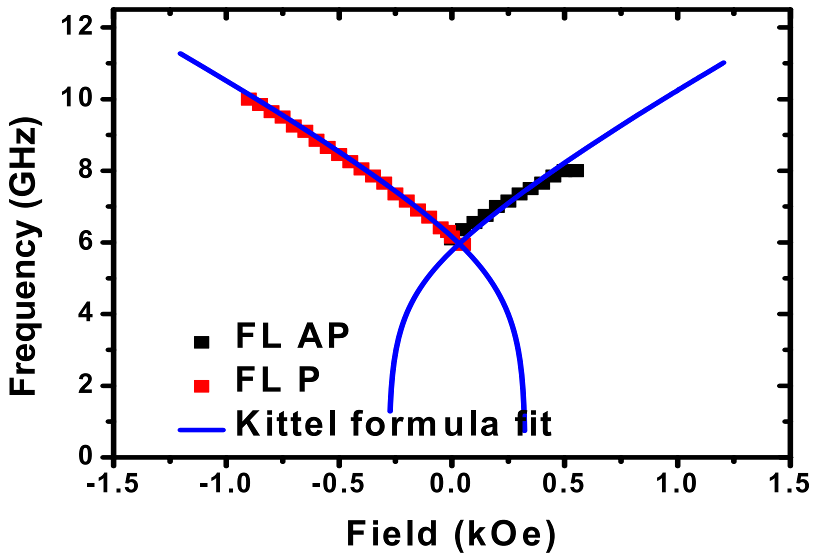


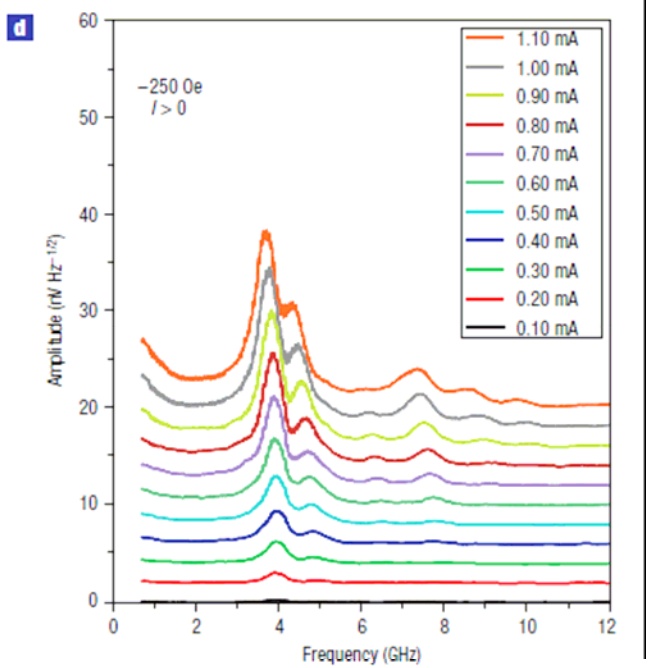
ST-FMR oscillations

- MTJ supplied with a RF signal
- Generates DC voltage at tunable resonant frequency
- Inverse effect applicable as microwave generator





STT oscillators

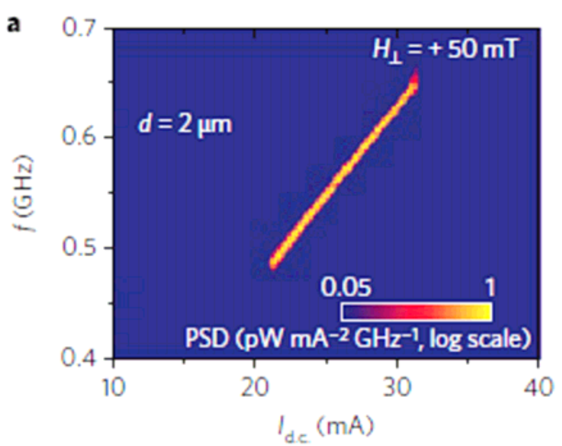


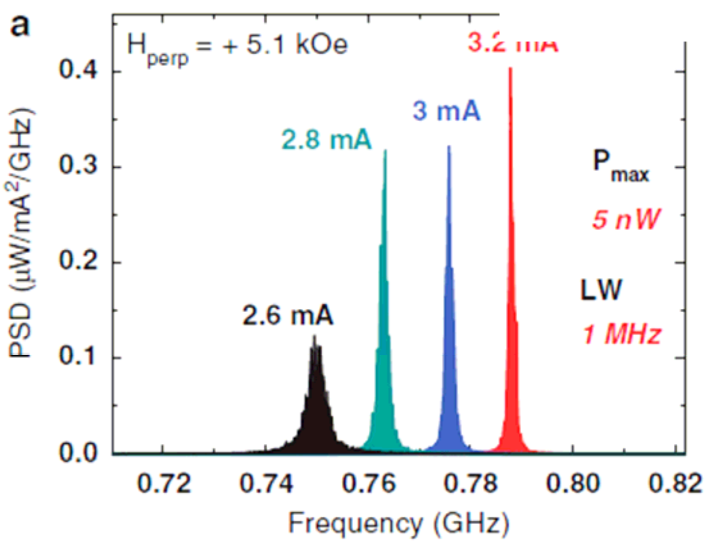
- Nano – STT oscillators
- Tunable with field/DC current

*Routolo et al. NatNano **4**, 528, 2009*

Dussaux et al. NatComm 1:8, 2010

*Daec et al. NatPhys **4**, 803, 2008*



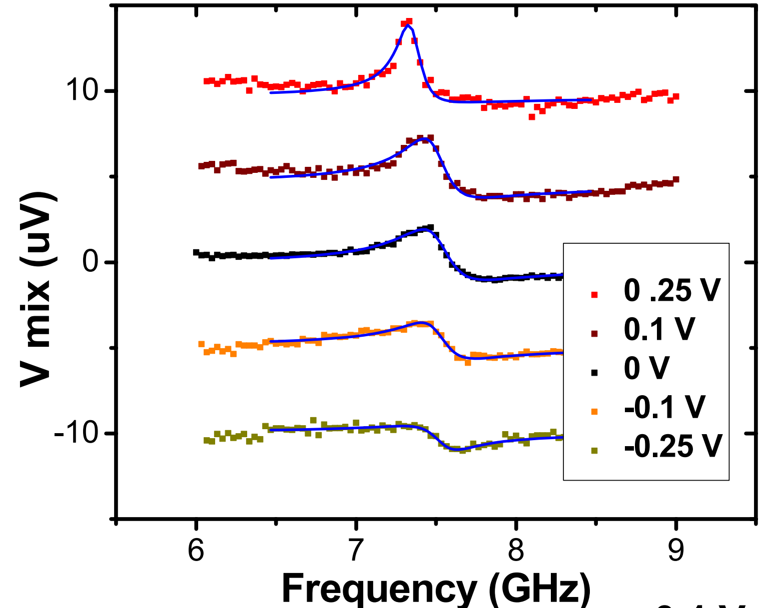


Torkances and torques

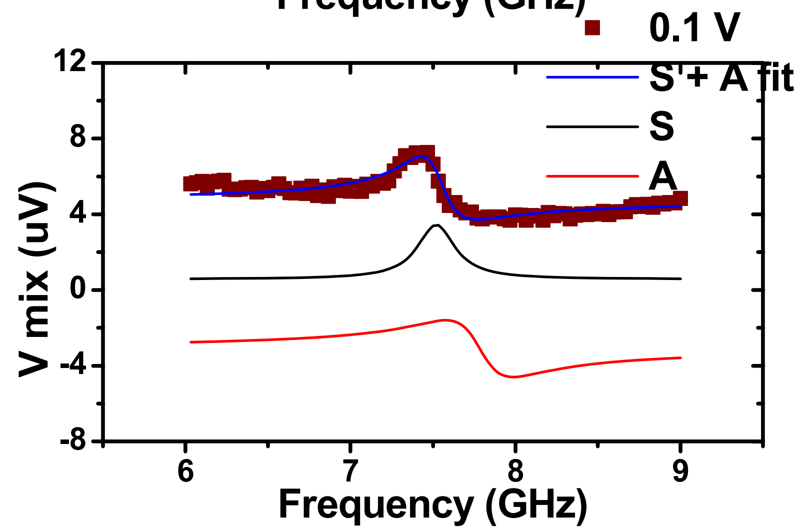
- V_{mix} is derived from the LLGS equation

$$V_{mix} = \frac{1}{4}\frac{\partial^2 V}{\partial I^2} I_{RF}{}^2 +$$

$$+\frac{1}{2}\frac{\partial^2 V}{\partial I \partial \theta}\frac{\hbar\gamma \sin\theta}{4eM_S Vol\sigma} I_{RF}{}^2 \left[\xi_{\|} S(\omega) - \xi_{\perp}\Omega_{\perp} A(\omega)\right]$$



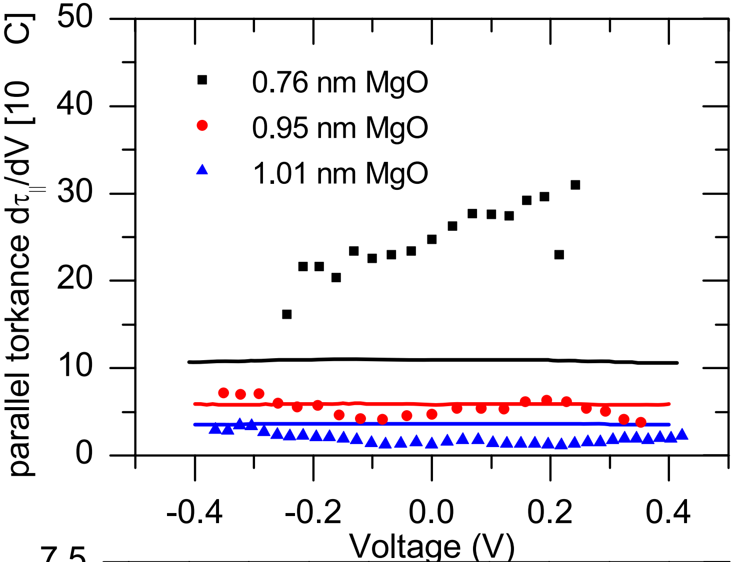
- S and A are symmetric and asymmetric lorentzians:



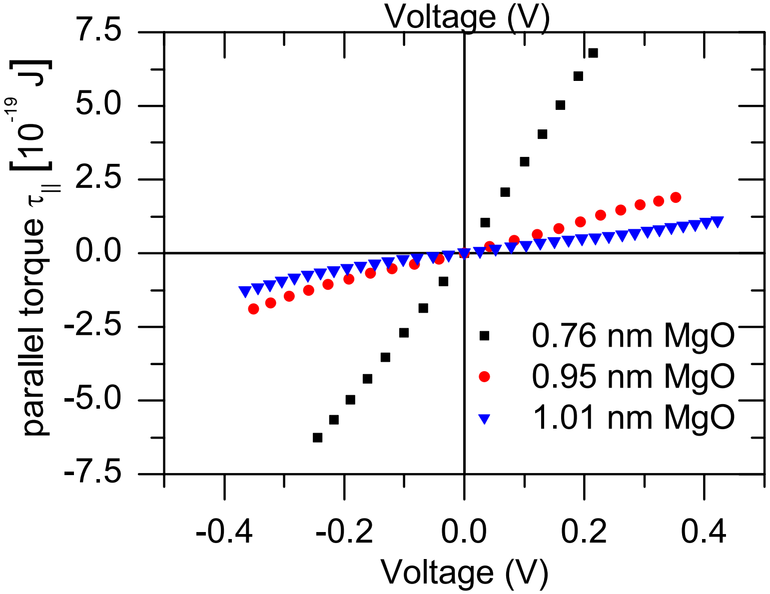
$$\xi_{\|} = \frac{2e}{\hbar}\sin\theta \frac{dV}{dI}\frac{dT_{\|}}{dV} \qquad \xi_{\perp} = \frac{2e}{\hbar}\sin\theta \frac{dV}{dI}\frac{dT_{\perp}}{dV}$$

Wang et al. PRB 79, 224416, 2009

Parallel torkance vs. MgO thickness



$$\frac{d\tau_{\parallel}}{dV} = \frac{\hbar}{2e}\frac{2p}{1+p^2}\left(\frac{dI}{dV}\right)_{\parallel}$$



Absolute torque values increases with decreasing barrier thickness

Sankey et al. Nat. Phys. ***4****, 67, 2008*

Podsumowanie

- Z sukcesm wytworzono nano-złącza tunelowe z ultracienką barierą tunelową wykazujące efekt STT.

- Zademonstrowano:
- przełączanie magnetyzacji prądem spinowo spolaryzowanych elektronów (CIMS) w komórce pamięci STT-RAM
- oscylator na częstościach GHz.

Krajowe Centrum Nanostruktur Magnetycznych do Zastosowań w Elektronice Spinowej - SPINLAB

Stanowiska do osadzania warstw metodami epitaksji z wiązki molekularnej, ablacji laserowej, oraz osadzania z wykorzystaniem działa jonowego

Wyposażenie laboratoriów przystosowanych do pomiarów strukturalnych (dyfraktometria rentgenowska, mikroskopia sond skanujących) - (T. Dietl, T. Baczewski, T.Stobiecki))

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Femtosekundowy laser i kriostat z nadprzewodzącymi magnesami do badań magnetooptycznych (A. Maziewski)

Zestaw pomiarowy do charakteryzacji właściwości nanostruktur i nano-urządzeń elektroniki spinowej w warunkach statycznych i dynamicznych (T. Stobiecki)

Stanowisko do badania dynamiki namagnesowania nanostruktur magnetycznych przy pomocy szerokopasmowego rezonansu ferromagnetycznego i impulsowej magnetometrii mikrofalowej (F. Stobiecki)

Mikroskop PEEM-LEEM (Photoemission Electron Microscope – Low Energy Electron Microscope) zapewniający obserwacje z wysoką zdolnością rozdzielczą , a w połączeniu z użyciem promieniowania synchrotronowego pozwalający na uzyskanie magnetycznej i czasowej rozdzielczości, a także selektywności chemicznej (J. Korecki)

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