SWISS CONTRIBUTION

AGH

Magnetic Tunnel Junctions for spintronics applications

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NANOSPIN

Polish-Swiss Research Programme

Electric-field controlled spintronic devices (E-CONTROL)

Cooperation and financial support

AGH Department of Electronics:
M.Czapkiewicz (micromagnetic simulations, magnetoptics)
J.Kanak (structure: XRD, AFM/MFM)
W.Skowronski (e-lithography ACMiN AGH, TMR, CIMS,Spin-diode,ST-FMR)
P.Wisniowski (MR-sensors, noise measurements and analysis)
W.Powroźnik (technical service)
M.Frankowski, Phd student (micromagnetic simulations)
M.Dąbek, PhD student (noise in sensors)
S.Ziętek PhD student (e-litography, multiferroics)
M.Banasik, gradueted student

ACMiN AGH: A.Żywczak (e-litography, PLD deposition, magnetic measurements)

Singulus AG: J. Wrona (sputtering deposition at Singulus AG, CIPT-capres measurements)

IFM PAN: J.Barnaś (UAM), P.Balaz (UAM), J.Dubowik, H.Głowiński, P.Ogrodnik (PW), F.Stobiecki

EPFL, Switzerland: J-Ph. Ansermey, A.Vetro

University of Bielefeld, Germany : G.Reiss

Aalto University, Espoo, Finland: S. van Dijken

SWISS CONTRIBUTION

NANOSPIN

Electric-field controlled spintronic devices (E-CONTROL)

AGH

Outline

- Motivation Green I(nformation) T(echnology)
- Spintronics devices road map
- Technology of magnetic tunnel junctions (MTJs)
  - sputtering
  - nanofabrication (electron-litography)
- Magentizations dynamics ⇒ Spin Transfer Torque
  - current Induced Magnetization Switching (CIMS) in MTJs with in plane and out of plane anizotropy⇒ STT-RAM
  - spin dynamics: ST-FMR ⇒ ST- Oscillator
- Voltage-induced magnetic anistropy
  - Static anisotropy changes – tunable sensor
  - voltage induced precession
  - rectification of spin polarized rf current in multiferroics PMN-PT/NiFe
- Conclusions

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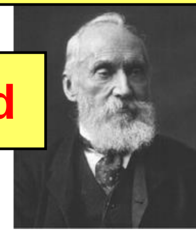
Magnetoresistance
MR ratio (RT & low H)

Device applications

Year

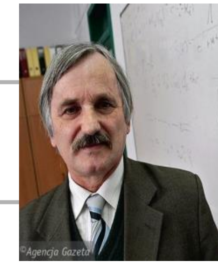
1857 — **AMR effect** MR = 1~2% — **HDD head**



Lord Kelvin

Inductive head

A. Fert, P. Grünberg, J. Barnaś



1967

1985 — **GMR effect** MR = 5~15%

1990 — **MR head**

1995 — **TMR effect** MR = 20~70%

1996 — T. Miyazaki, J. Moodera — **GMR head**

STT J. Slonczewski, L. Berger

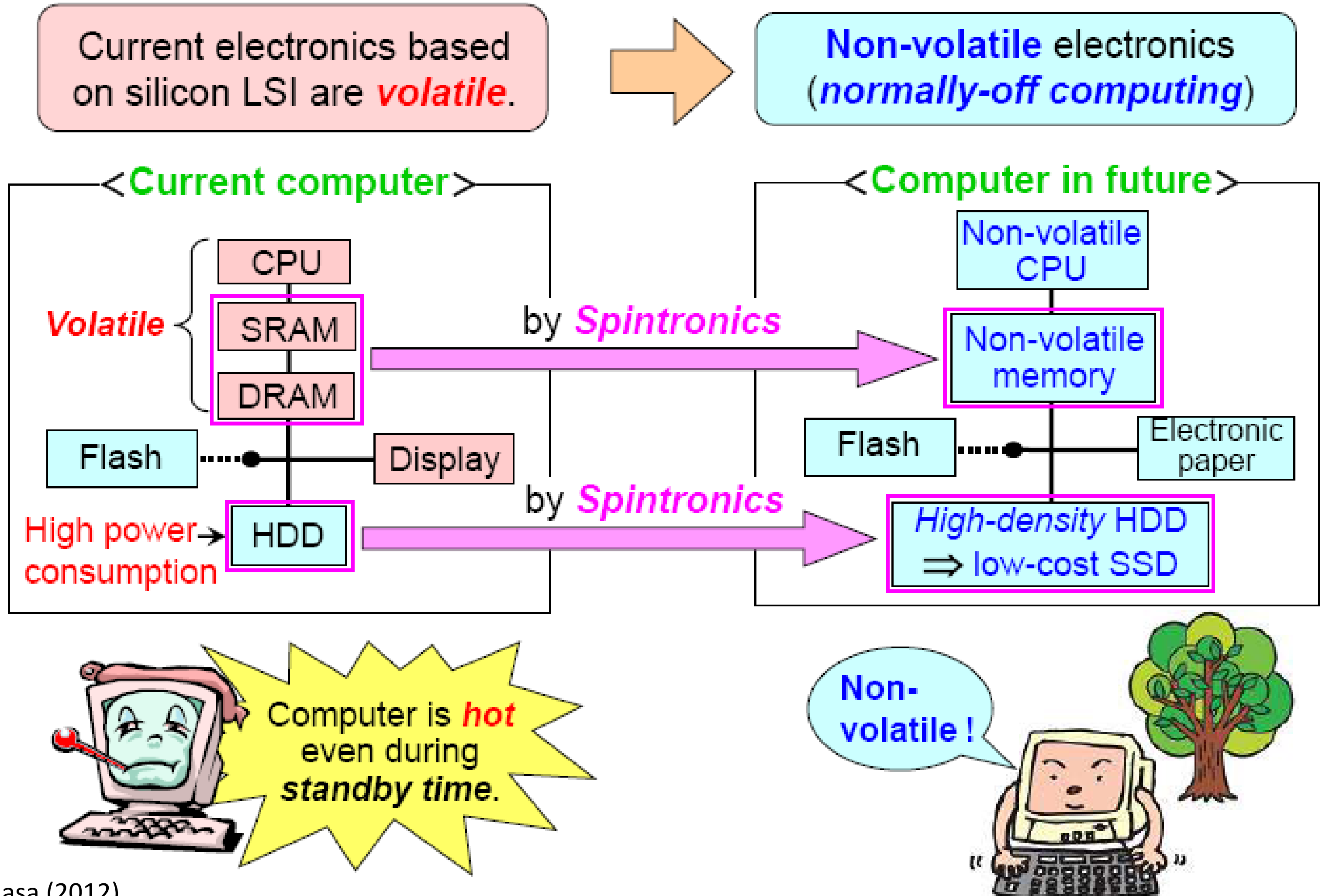
2000 — **Memory**

2005 — **Giant TMR effect** MR = 200~1000% — **TMR head** — **MRAM** — **Novel devices**

2013 — **MgO -TMR head** — **Spin Torque MRAM** — **Microwave, E-control.**

Green IT

Paradigm shift from *volatile* electronics to *non-volatile* electronics

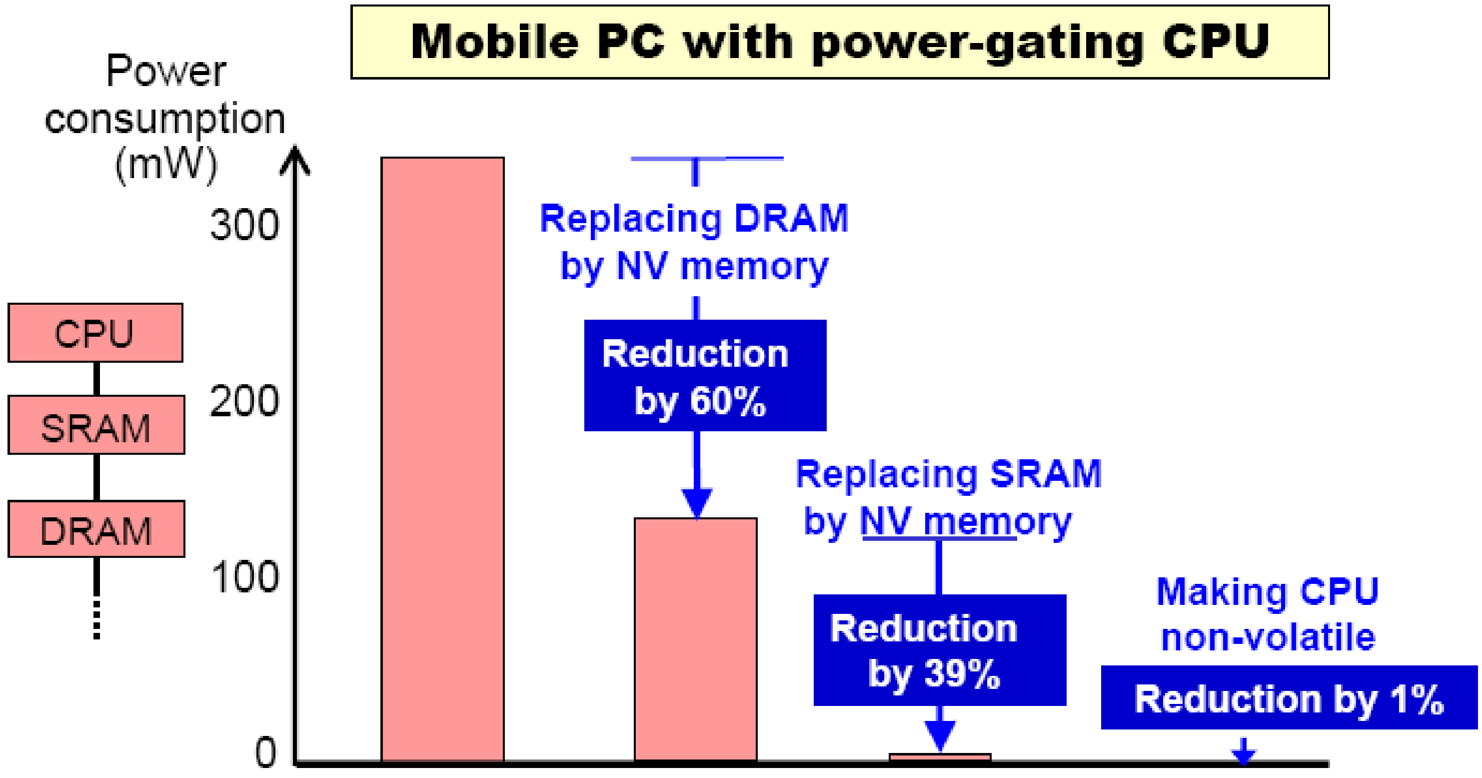


after S. Yuasa (2012)

AGH

Green IT

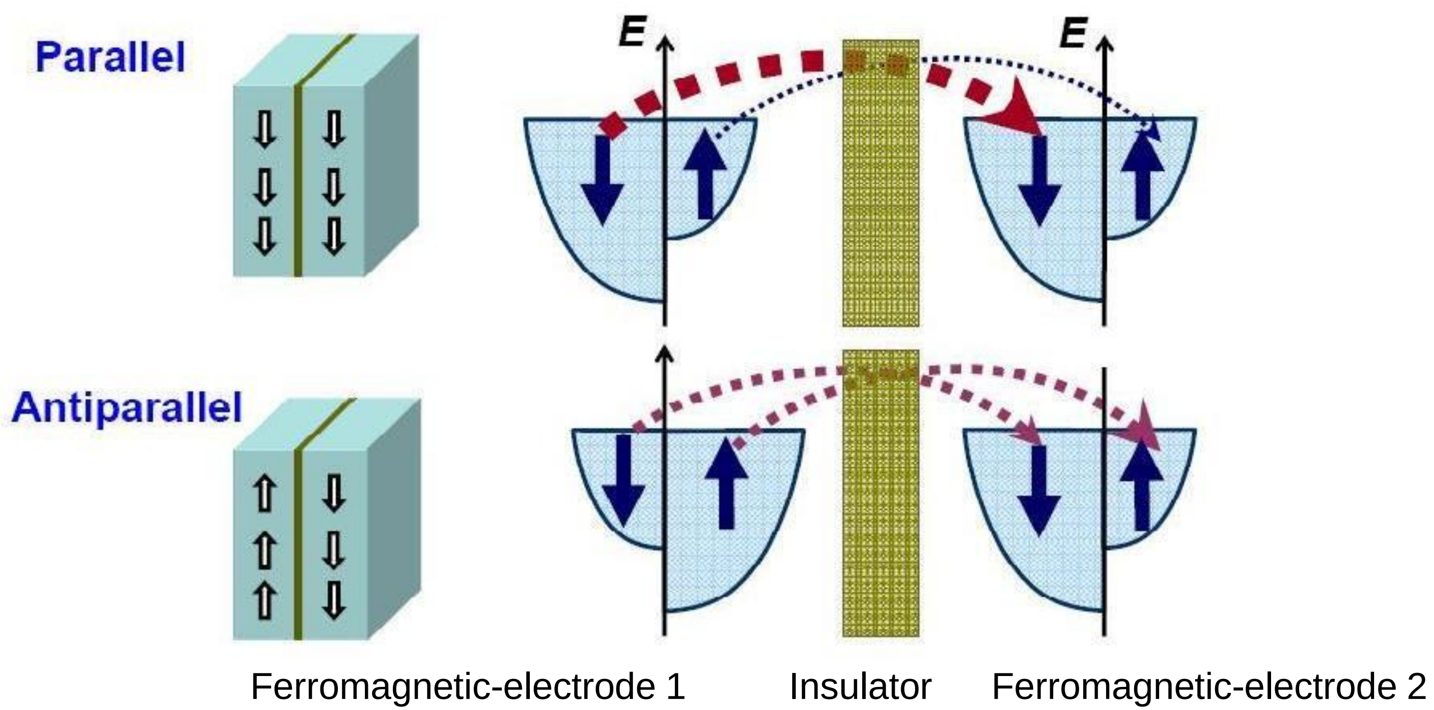
Power consumption of a computer during input stand-by time



By using spintronics technology, it will be possible to develop new NV memory that can replace DRAM and SRAM.

after S. Yuasa (2012)

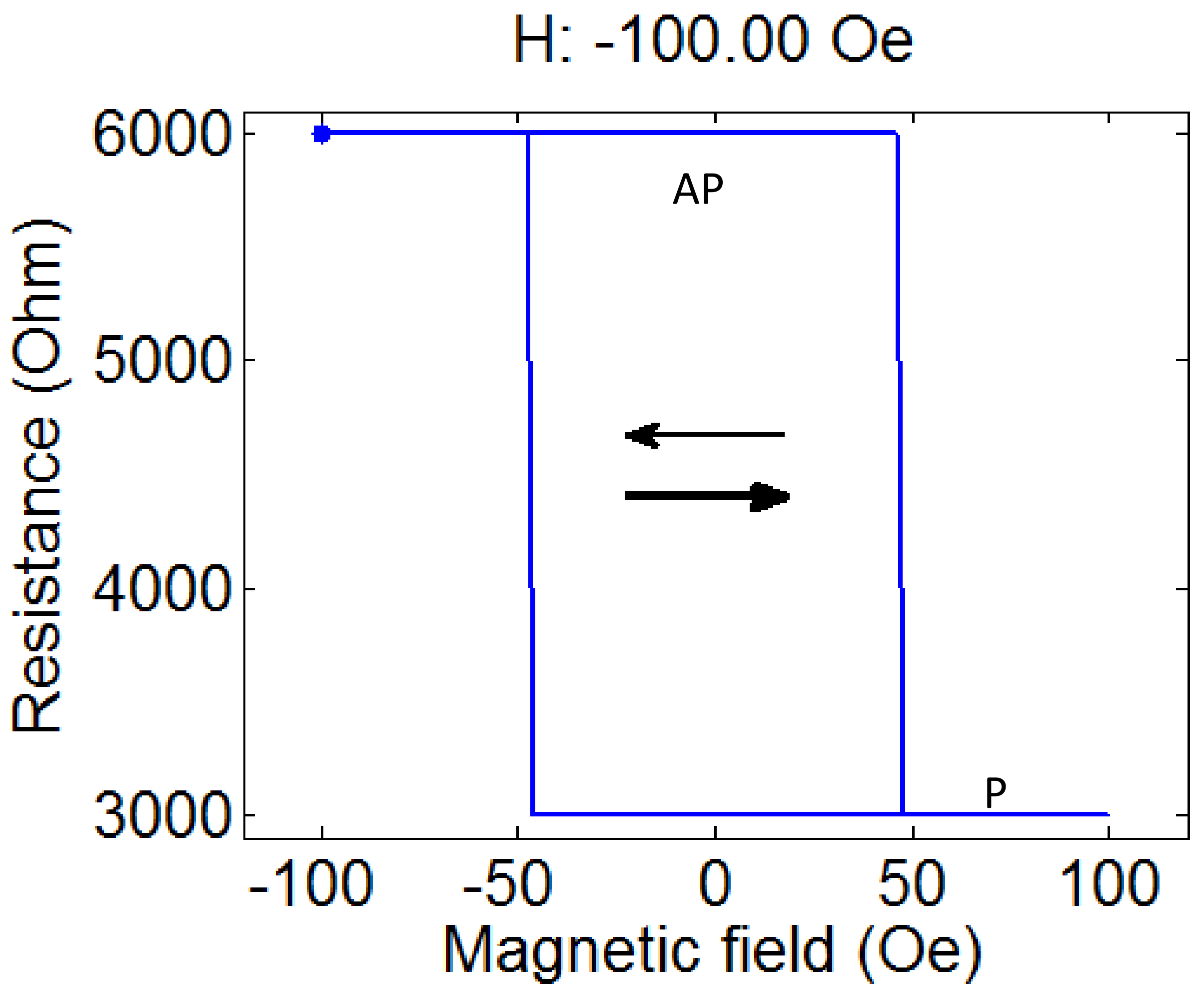
Tunneling – Julliere's model



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

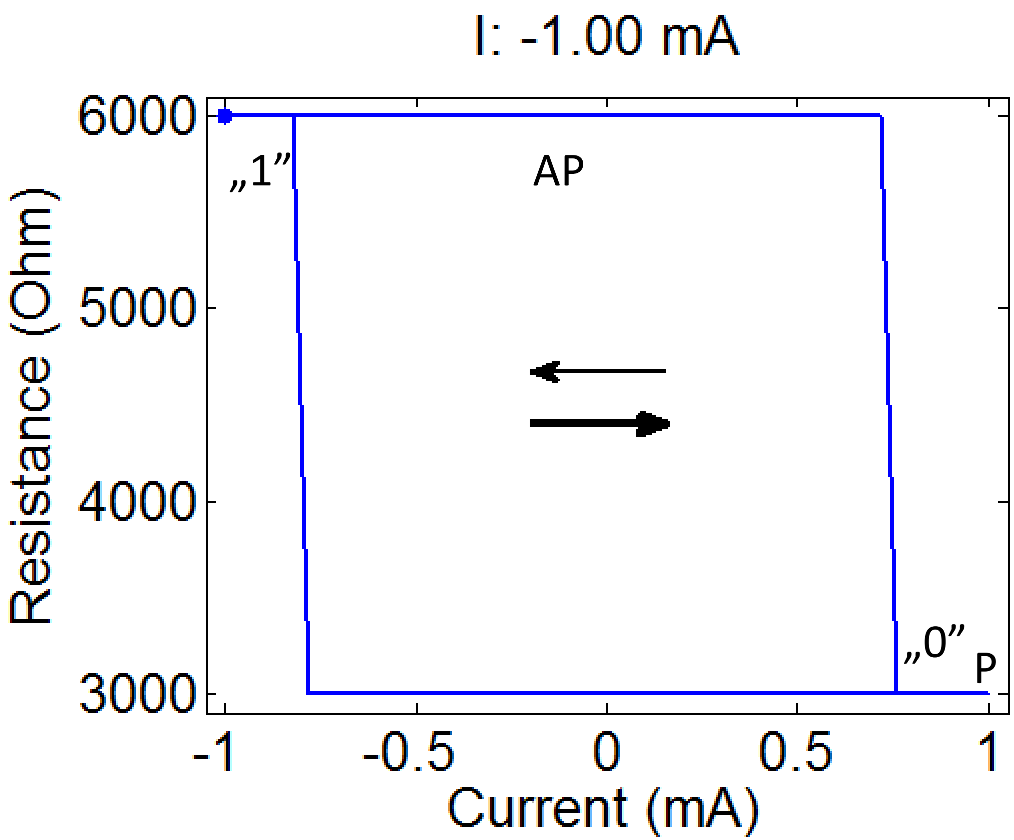
Spin Polarization *P*

Magnetic field switching



TMR = 100%

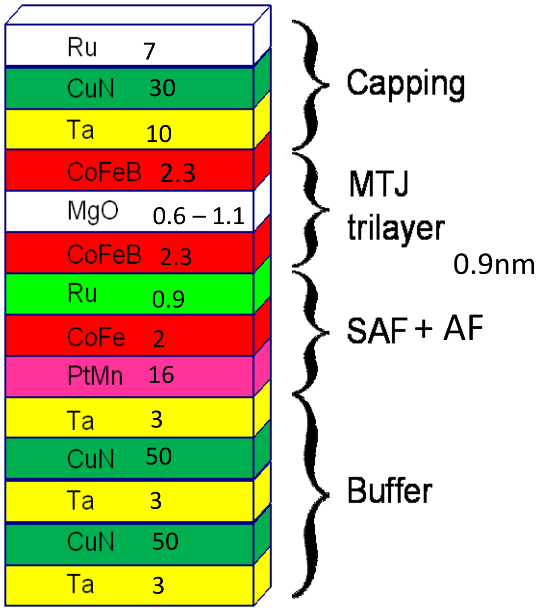
Curent Induced Magnetization Switching - CIMS

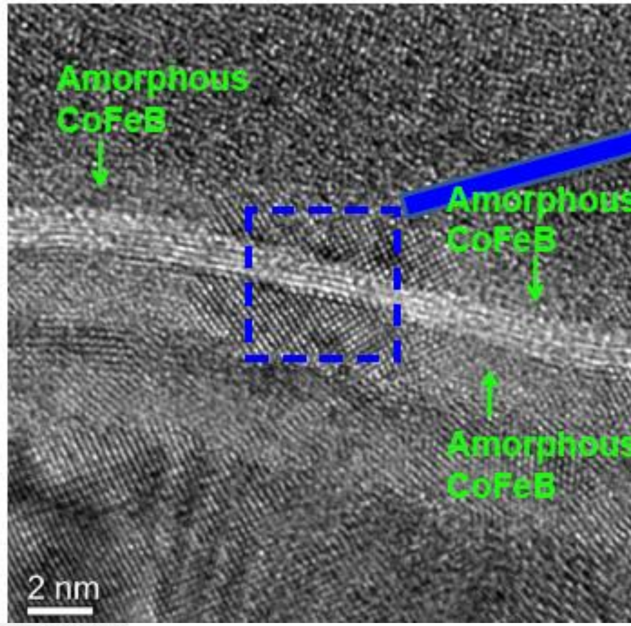


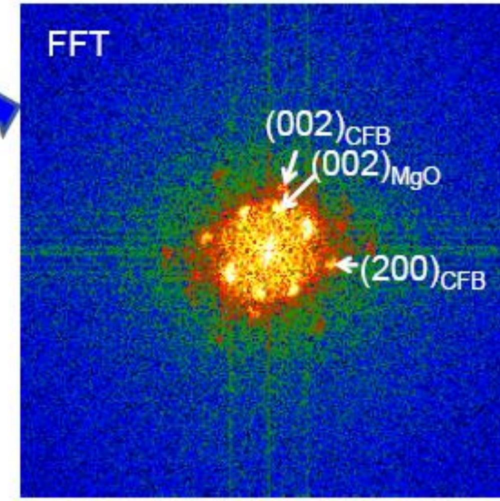
TMR = 100%

Resistance switching ? → by spin polarized current from SpinTransfer Torque (STT)

Transmission electron Microscopy (TEM) of TMR multilayers

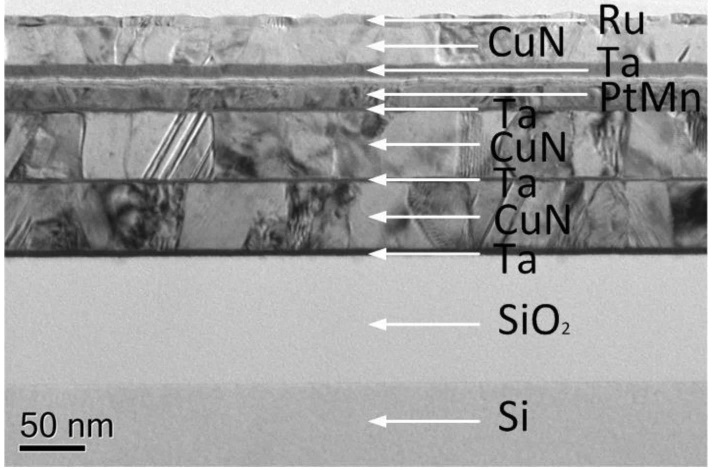






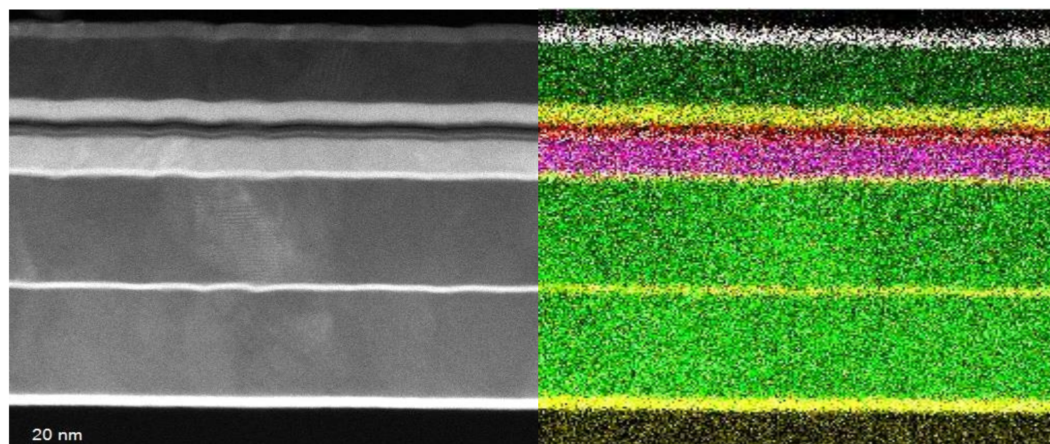
L. Yiao, S. van Dijken Aalto Univ.

details in poster P-5-39



TEM

EDX



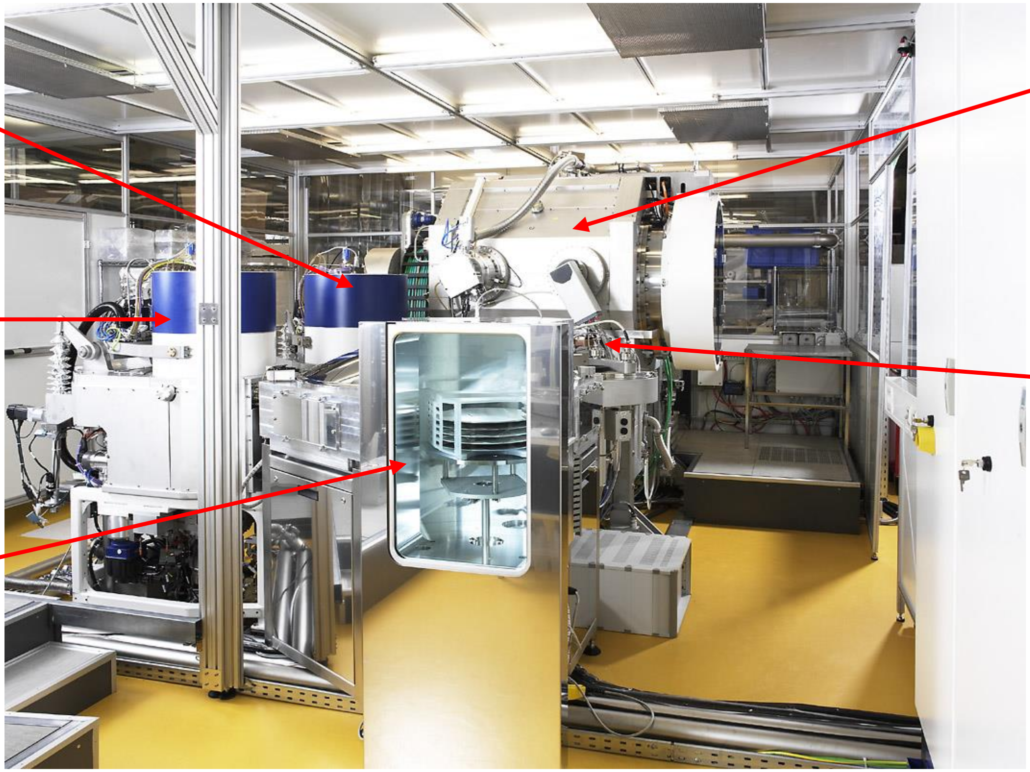
Sputtering deposition (industrial process)

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)



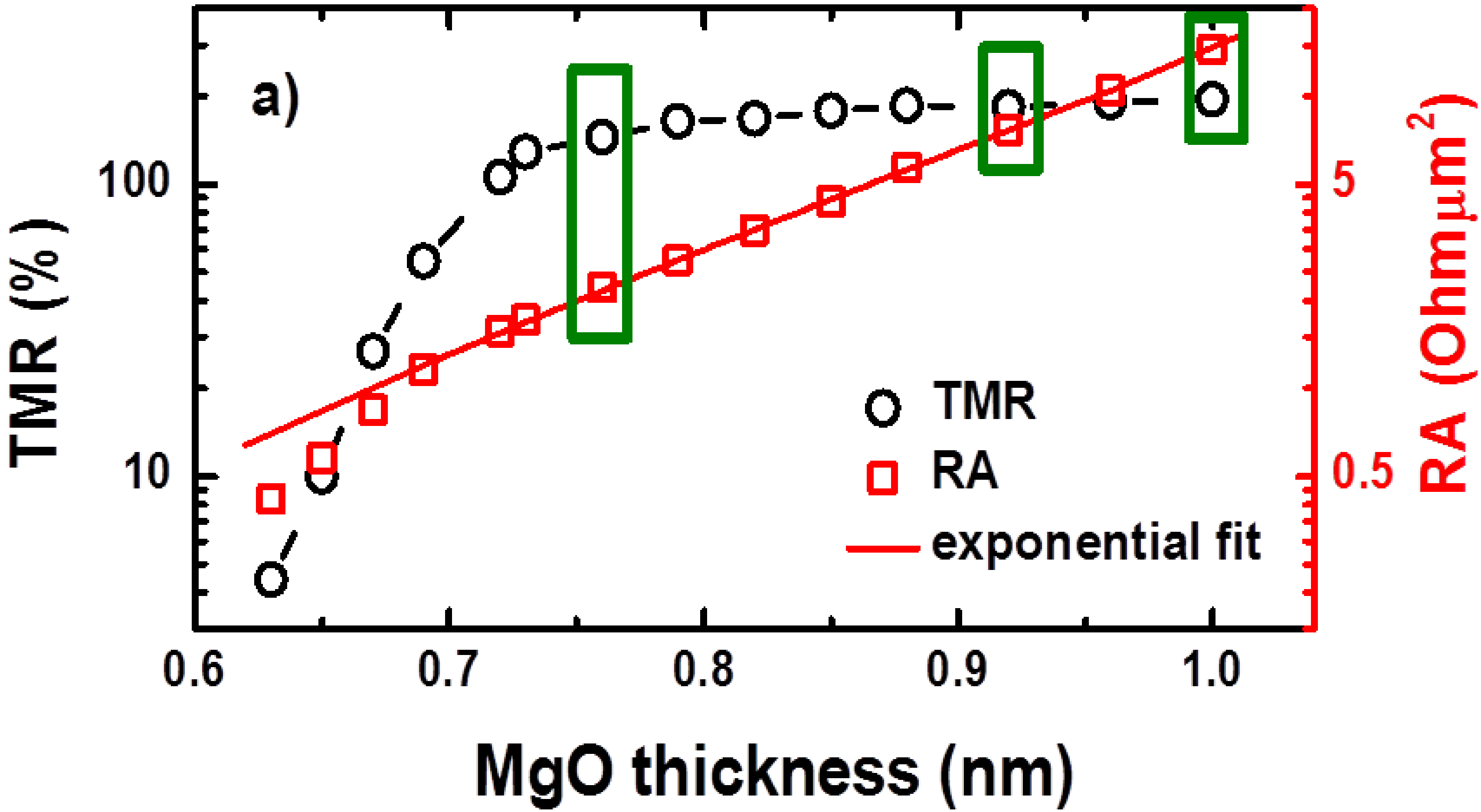
Multi Target Module
Top: Target Drum with 10 rectangular cathodes; Drum design ensures easy maintenance;
Bottom: Main part of the chamber containing LDD equipment

Transport Module
(UHV wafer handler)

Ultra – High – Vacuum Design:	Base Pressure ≤ 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)

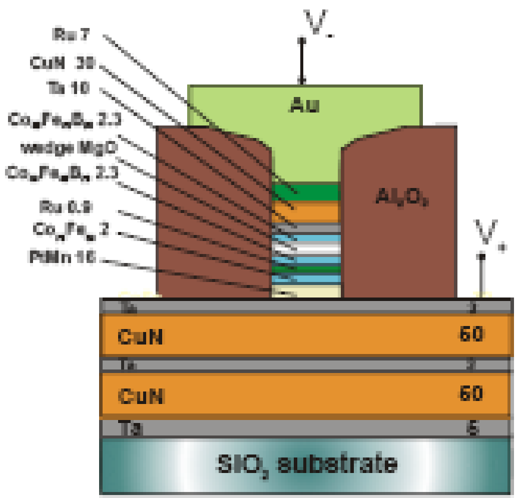
Courtesy of
SINGULUS

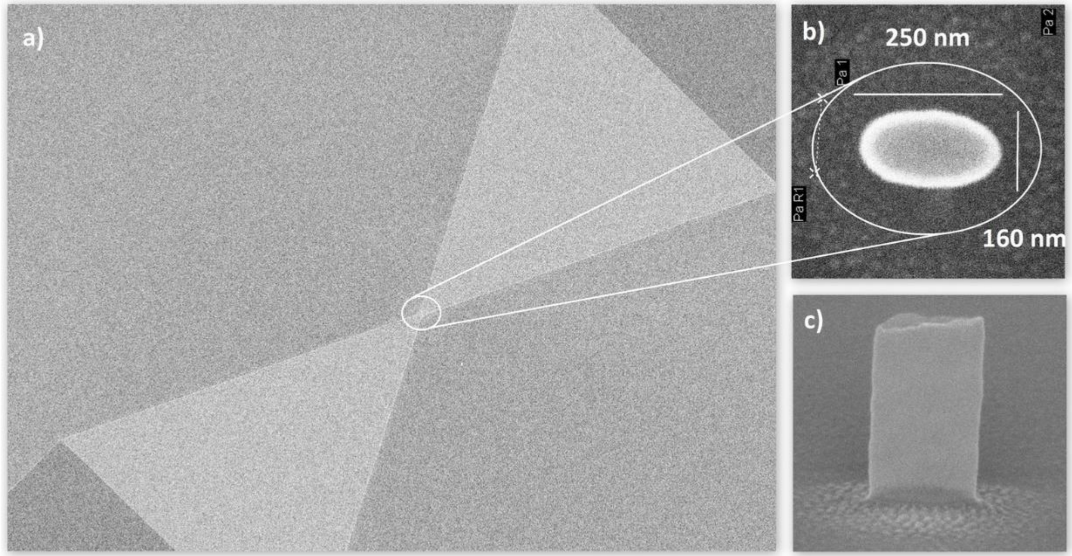
TMR & RA vs. MgO barrier thickness



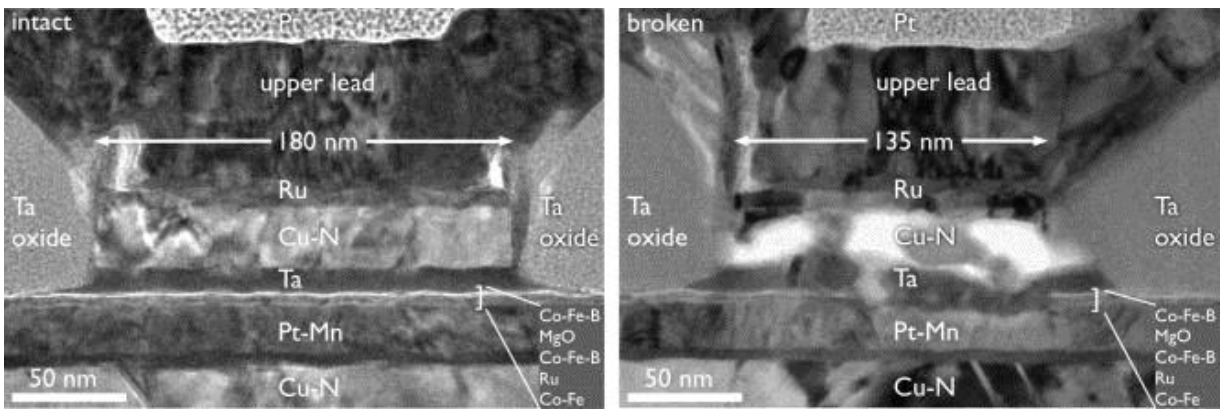
W. Skowronski , T. Stobiecki, et al. J. Appl. Phys. (2010), 093917
A. Zaleski, W. Skowroński , et al. Appl. Phys. (2012), 033903

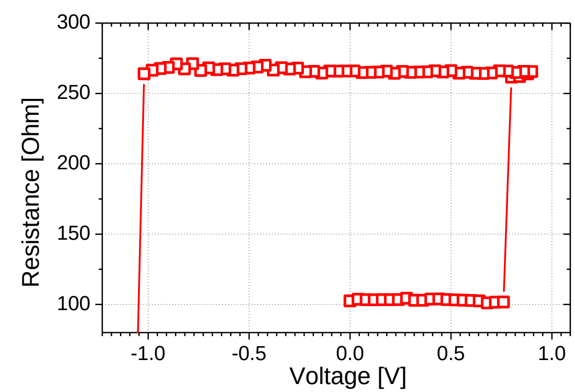
Nanofabrication by electron-beam lithography





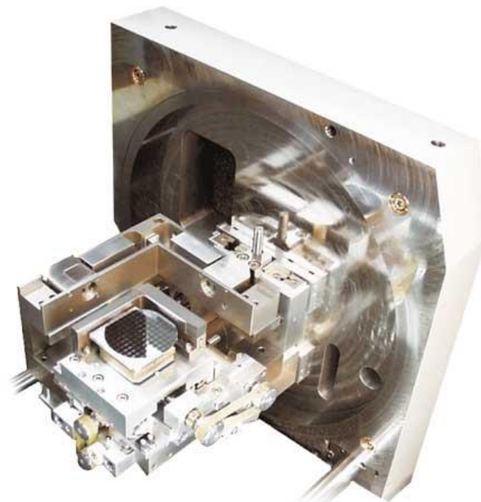
e-litography by RAITH system



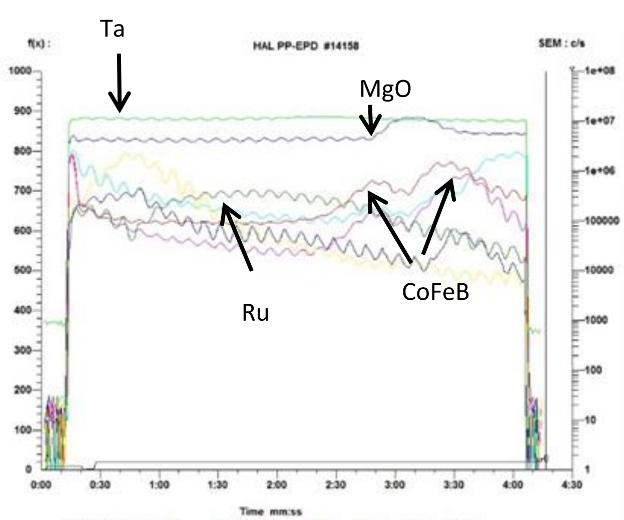


Nanopillar 3 step: e-beam litography, ion etching, lift-off

Nanofabrication by electron-beam lithography



Mass spectrometer



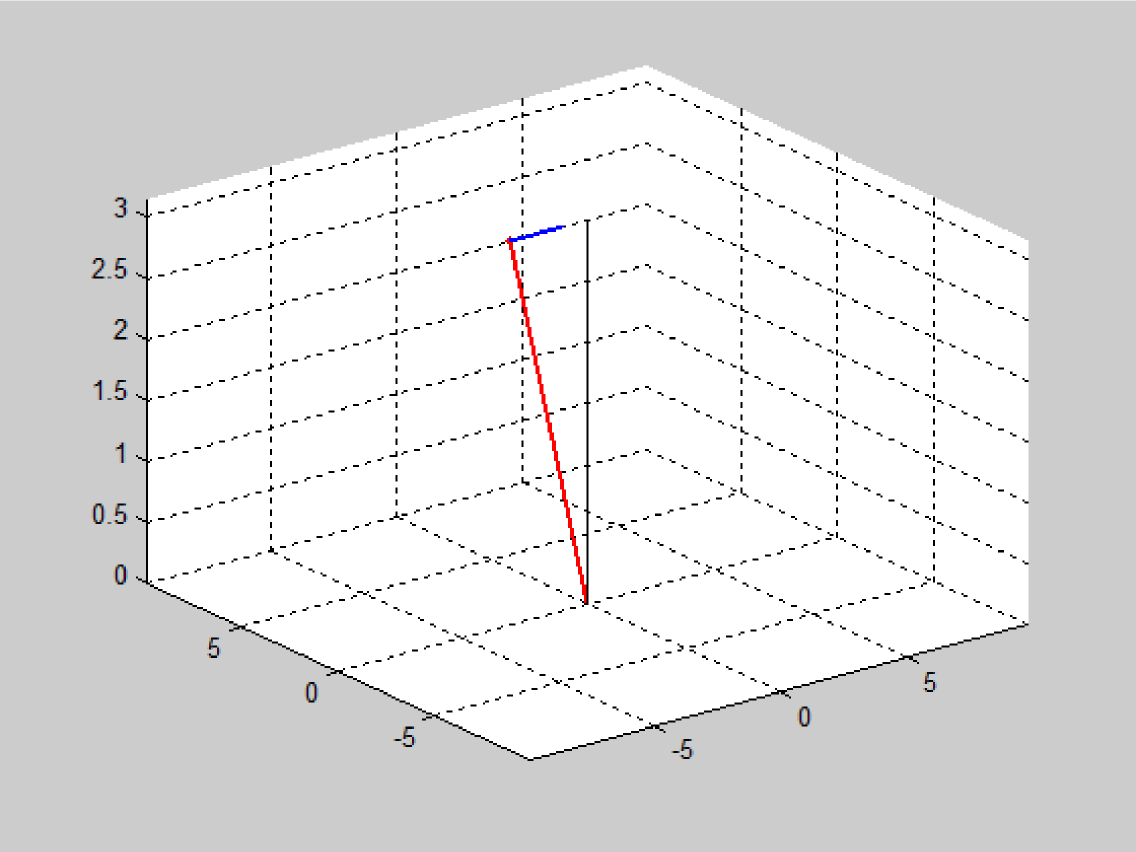
Microsystem Ion sys 500 – Ar^+ etching

Magnetization dynamics LLG

precession damping

$$\frac{dm}{dt} = -\gamma m \times H_{eff} + \alpha m \times \frac{dm}{dt}$$

L(andau) **L**(ifszic) **G**(ilbert) dynamics



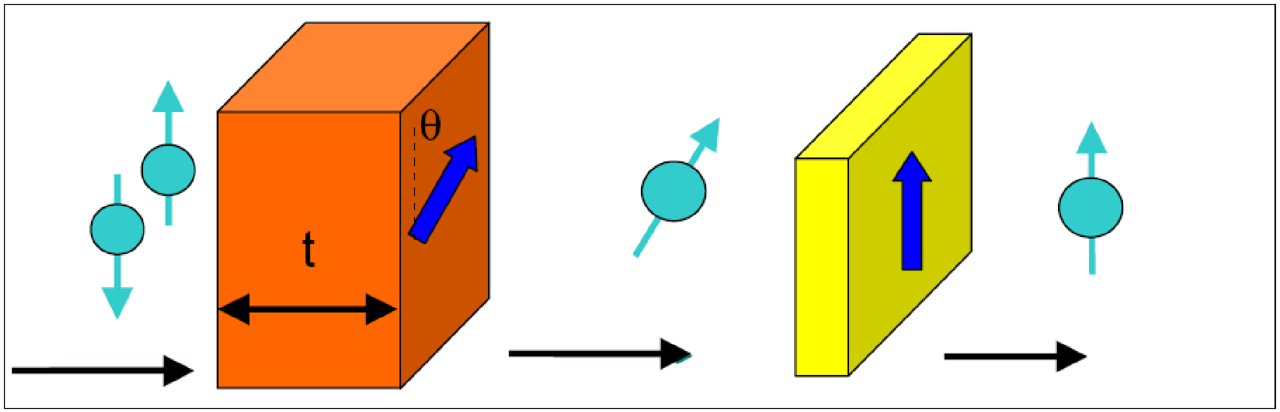
Spin Transfer Torque (STT)

Unpolarized electrons

Polarized electrons

Transmitted electrons

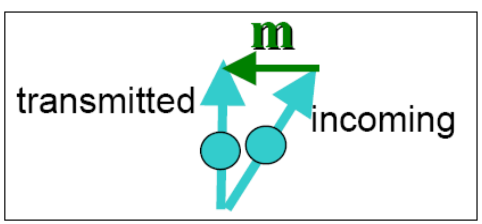
Electron flow



Polarizer P

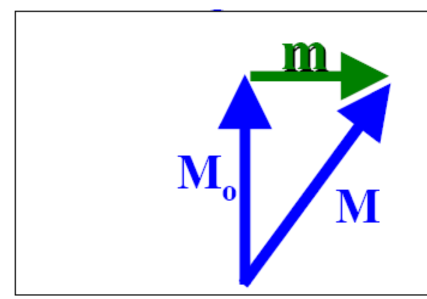
Free layer M

Conduction Electrons



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

Local magnetization

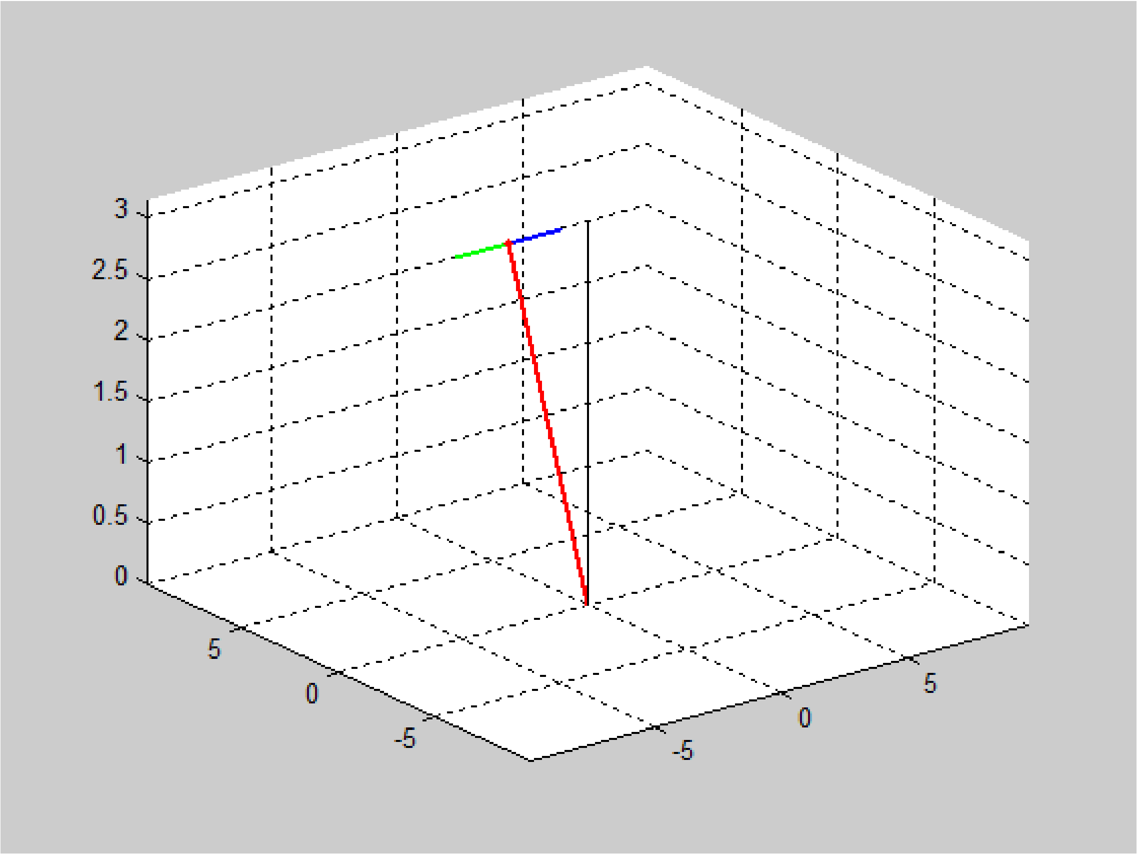


ST tends to align M (anti-)parallel to P

Spin Transfer Torque (STT)

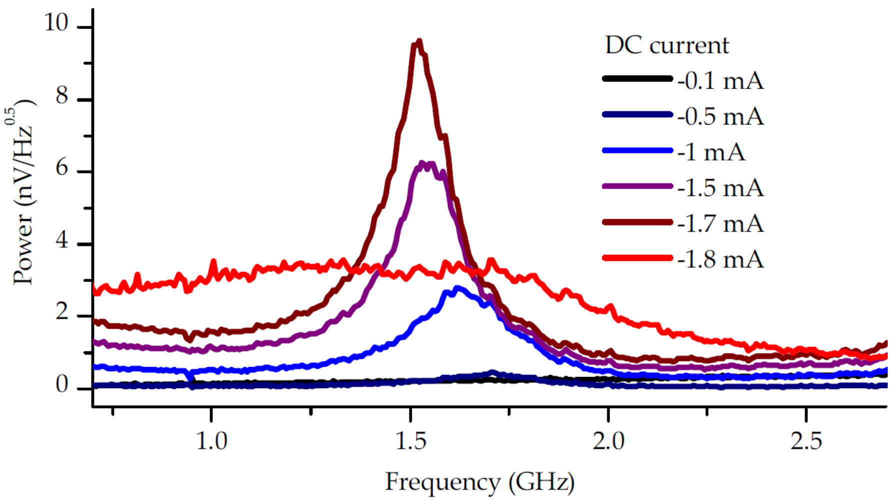
precession **damping** **STT**

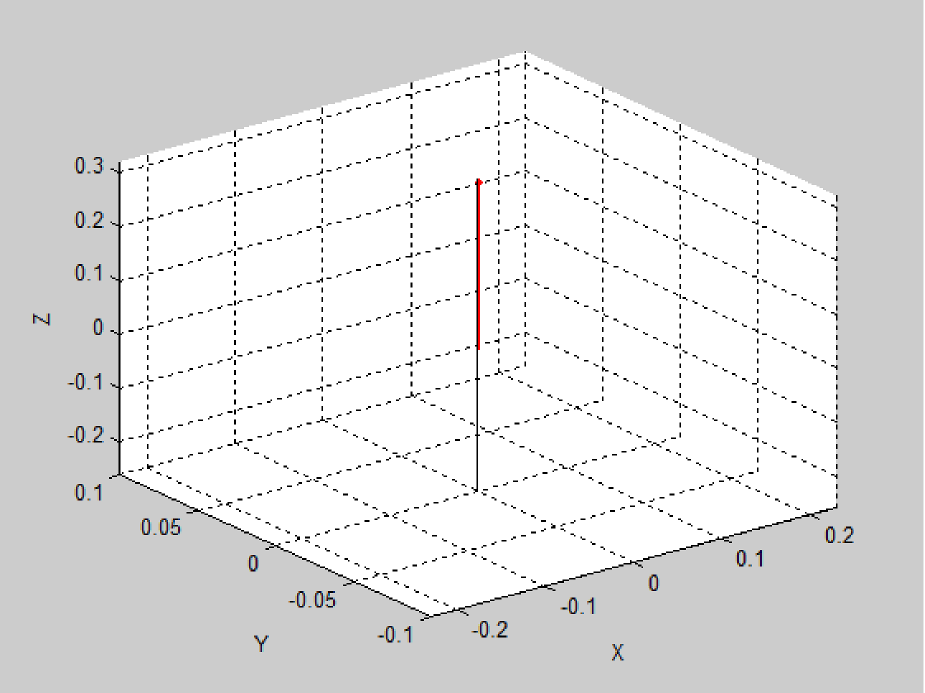
$$\frac{dm}{dt} = -\gamma m \times H_{eff} + \alpha m \times \frac{dm}{dt} - \gamma \frac{\tau_{\parallel}}{M_S Vol} m \times (m \times M) - \gamma \frac{\tau_{\perp}}{M_S Vol} m \times M$$



Zero-magnetic field STO

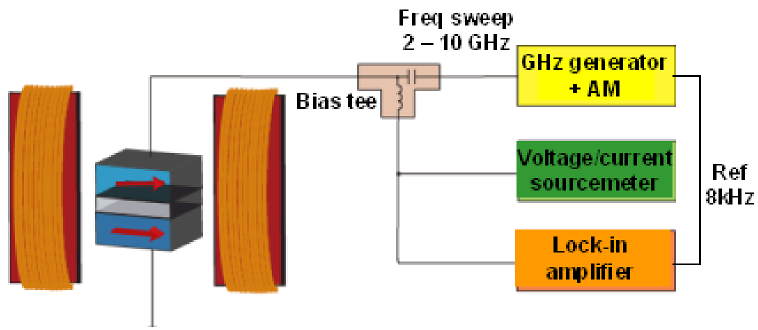
- Use of:
  - Perpendicular anisotropy of thin CoFeB on MgO
  - Ferromagnetic coupling between FL and RL (0.9 nm MgO)
- In-plane STT-induced oscillations



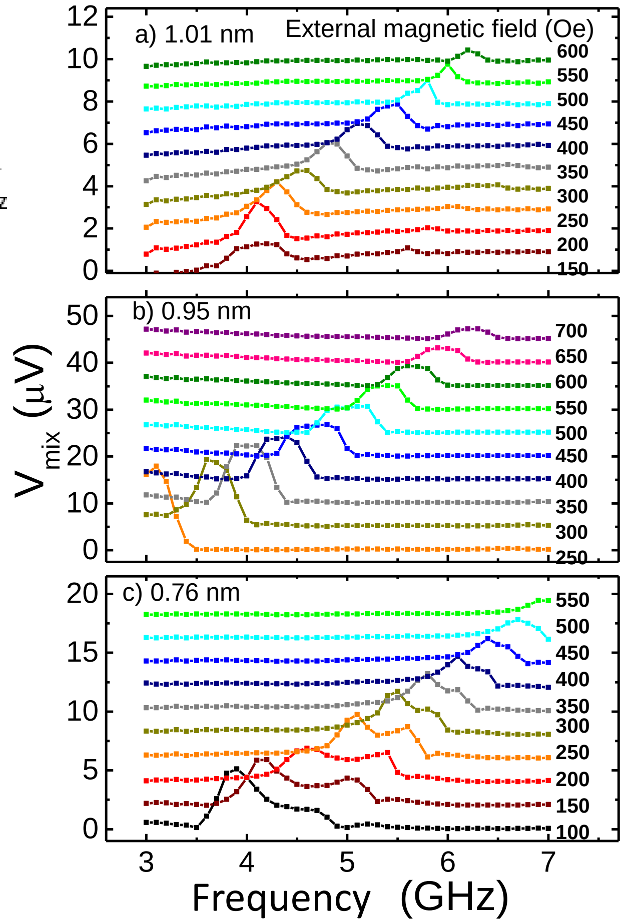


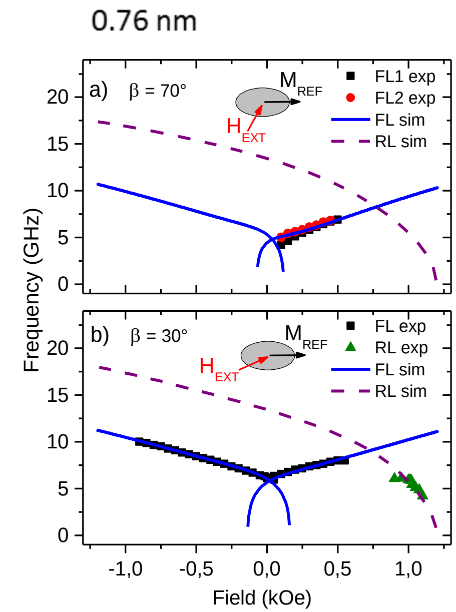
*W.Skowroński, T.Stobiecki et al. APEX **5**, 063005 (2012)*

Spin Torque vs. ST-FMR



- MTJ sample placed in the magnetic field and tilted by a certain degree
- amplitude modulated RF current supplied to the MTJ through a bias tee
- small DC voltage (Vmix) measured by voltmeter or lock-in detection





PHYSICAL REVIEW B **87**, 094419 (2013)

Influence of MgO tunnel barrier thickness on spin-transfer ferromagnetic resonance and torque in magnetic tunnel junctions

Witold Skowroński,* Maciej Czapkiewicz, Marek Frankowski, Jerzy Wrona, and Tomasz Stobiecki
Department of Electronics, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland

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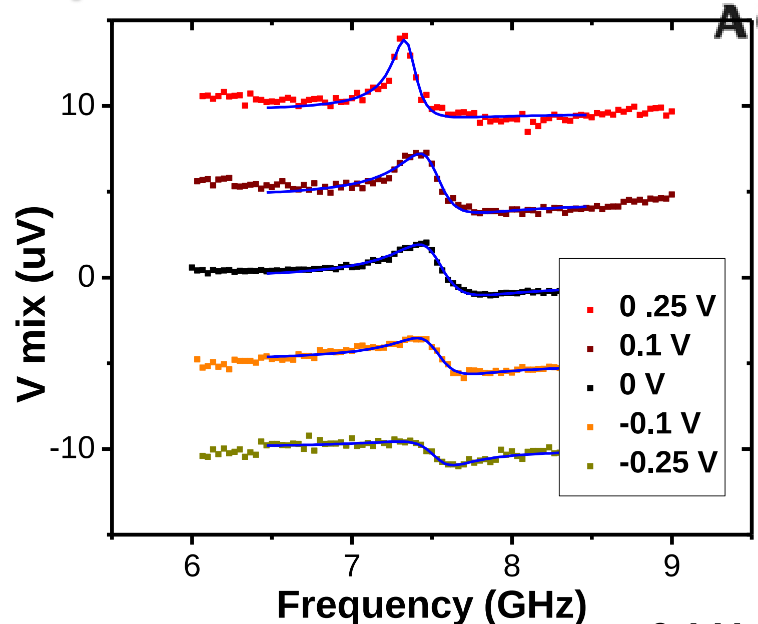
Torkances and torques

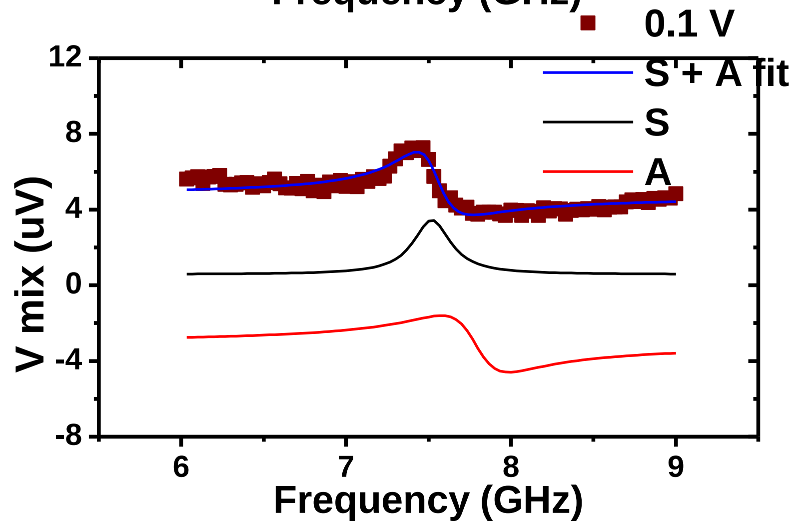
•V_{mix} is derived from the LLGS equation

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



•**S** and **A** are symmetric and asymmetric lorentzians:

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



Wang et al. PRB 79, 224416, 2009

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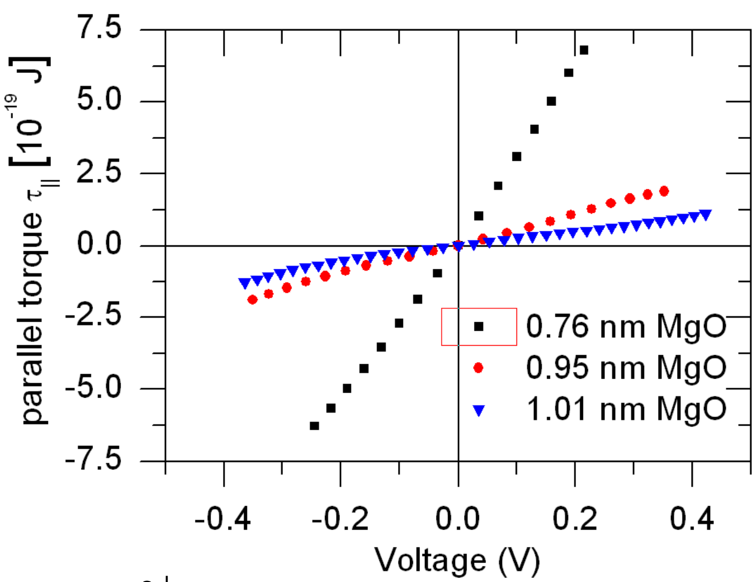
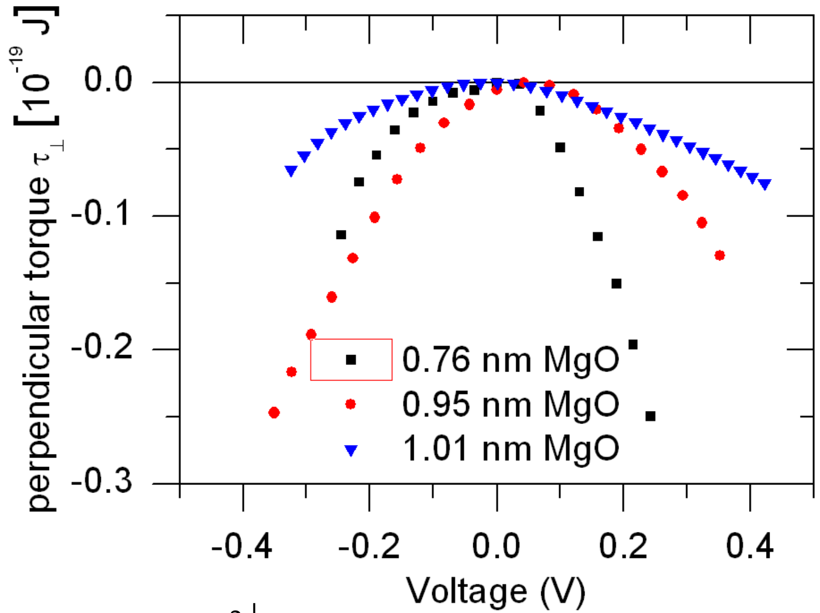
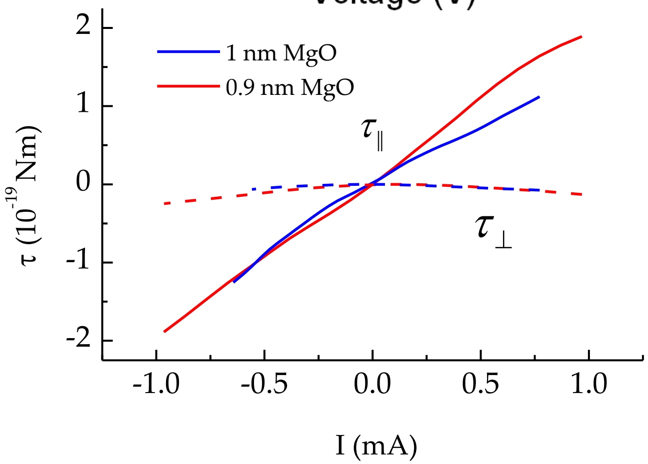
Torque (STT) components

in plane component

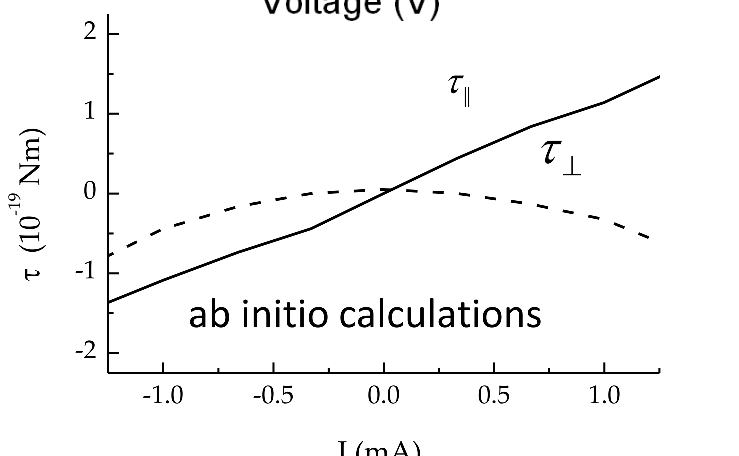
out of plane component







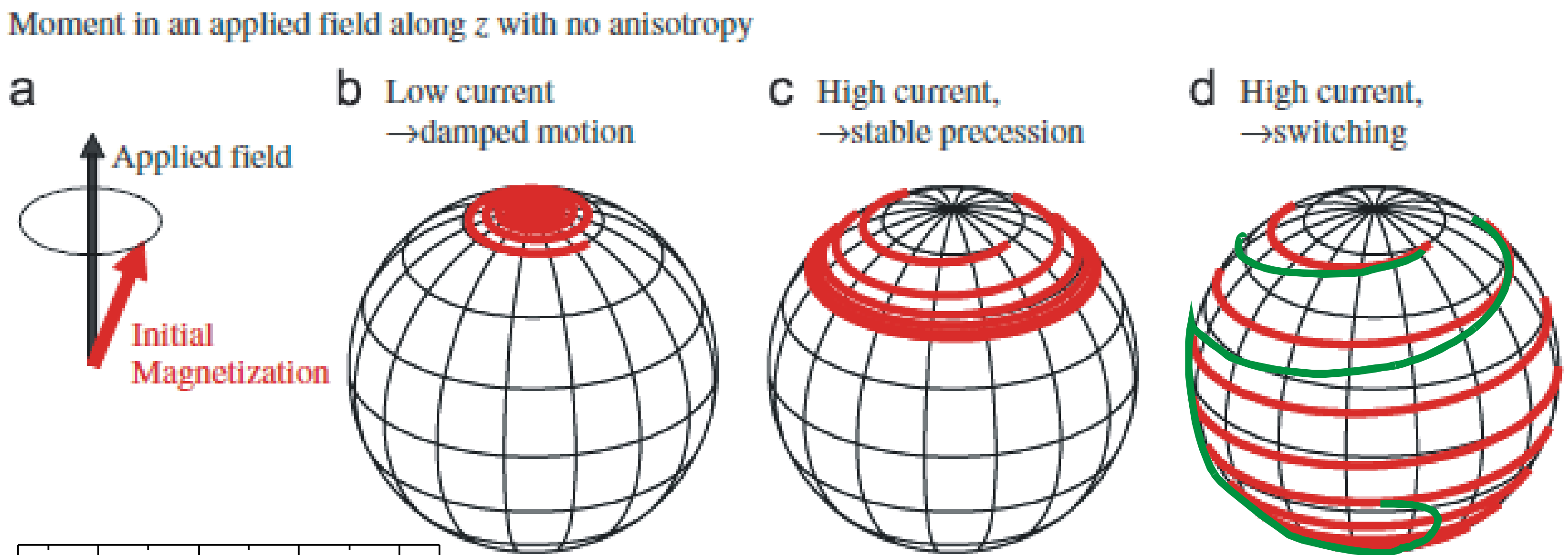
W.Skowroński, T.Stobiecki et al. PRB ***87****, 094419 (2013)*

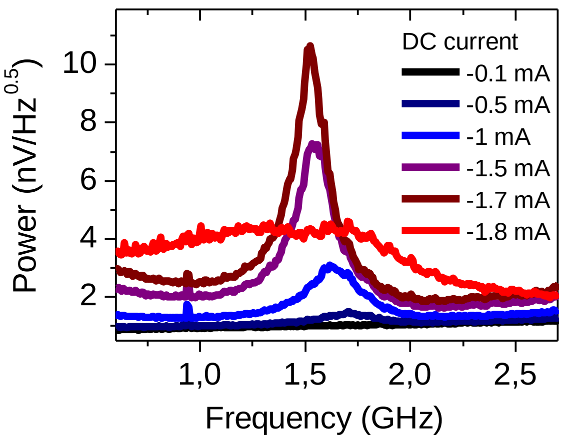


Heiliger, Stiles *PRL* ***100****, 186805, (2008)*

STT – CIMS

Spin Transfer Torque→ Curent Induced Magnetization Switching





$I = I_{Critical}$

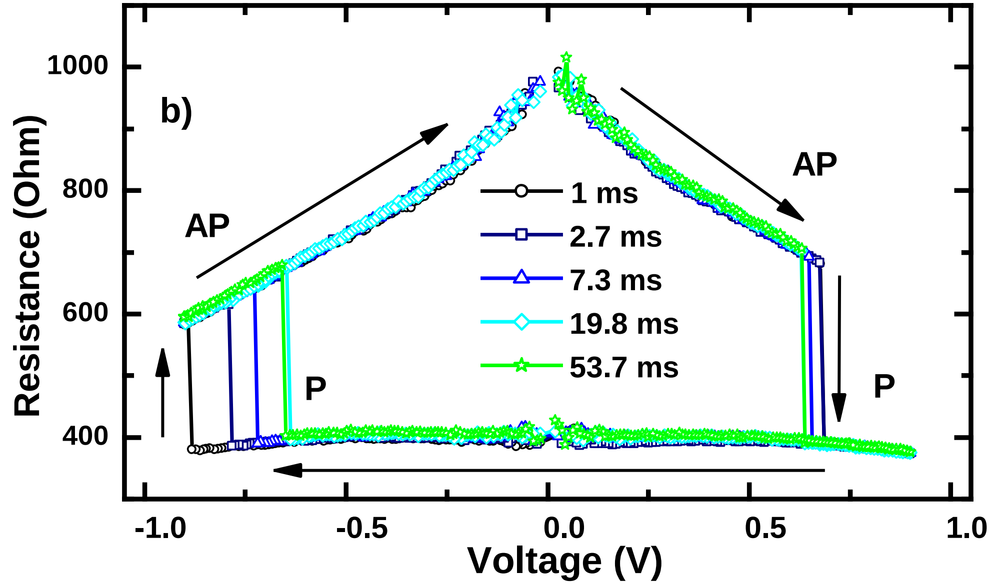
*W.Skowroński, T.Stobiecki et al. APEX **5**, 063005 (2012)*

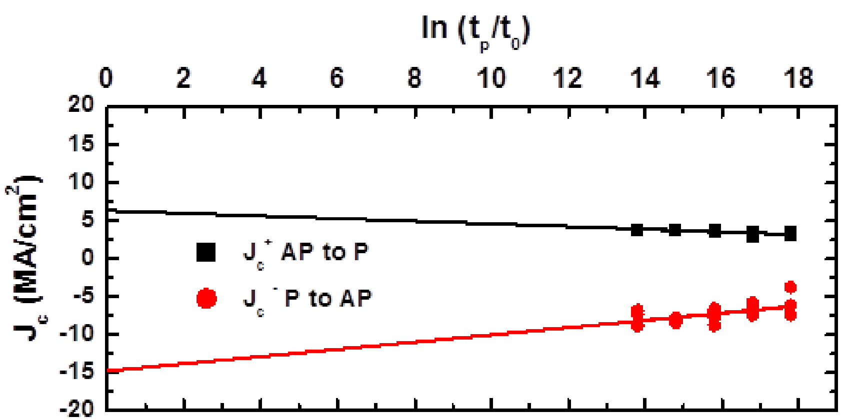
CIMS – critical current J_{c0} in MTJ with in plane anisotropy

- MTJ with 0.96 nm MgO barrier and CoFeB free layer 2.3 nm

$$J_c = J_{c0}\left[1 - \frac{2k_B T}{H_C M_S V}\cdot \ln\left(\frac{\tau_P}{\tau_0}\right)\right]$$

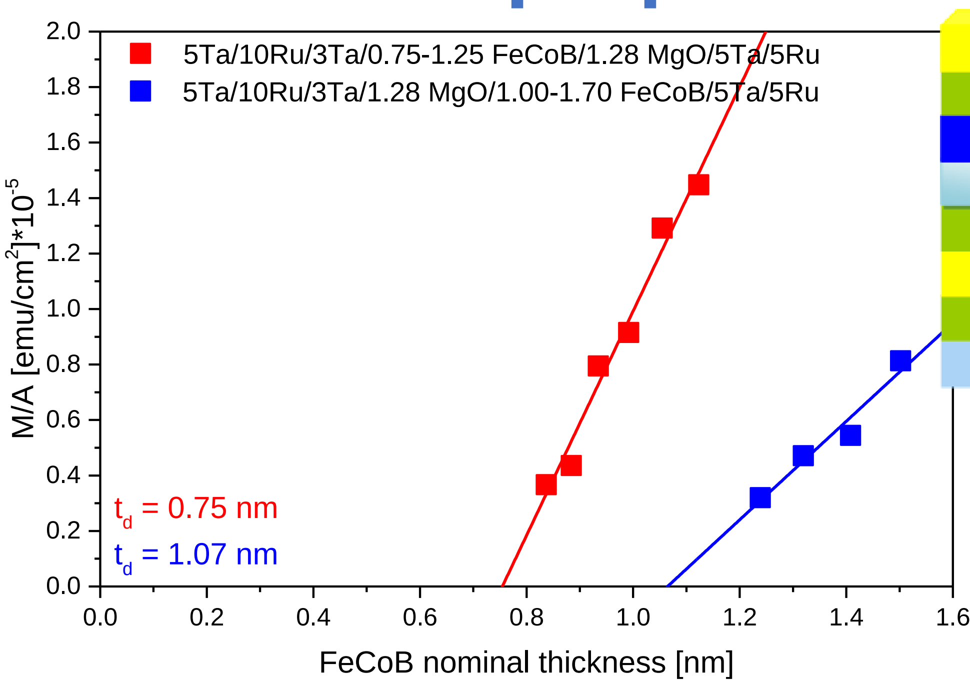
Stability factor	AP → P	P → AP
$\left(\frac{H_C M_S V}{2k_B T}\right)_{exp}$	36	35

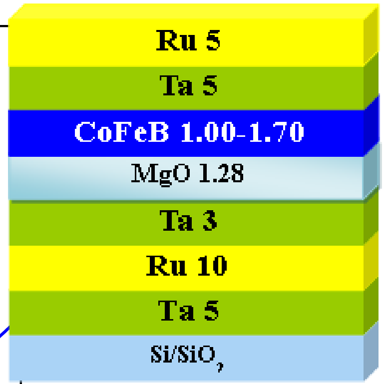




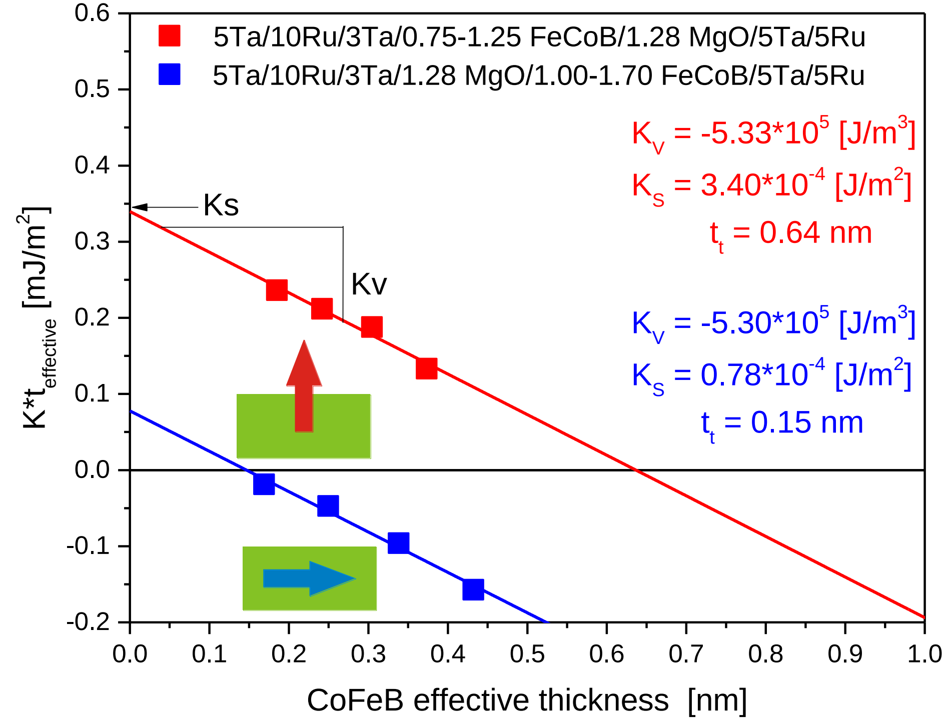
*W.Skowroński, T.Stobiecki et al. JAP **107**, 093917 (2010)*

MTJ with perpendicular anisotropy



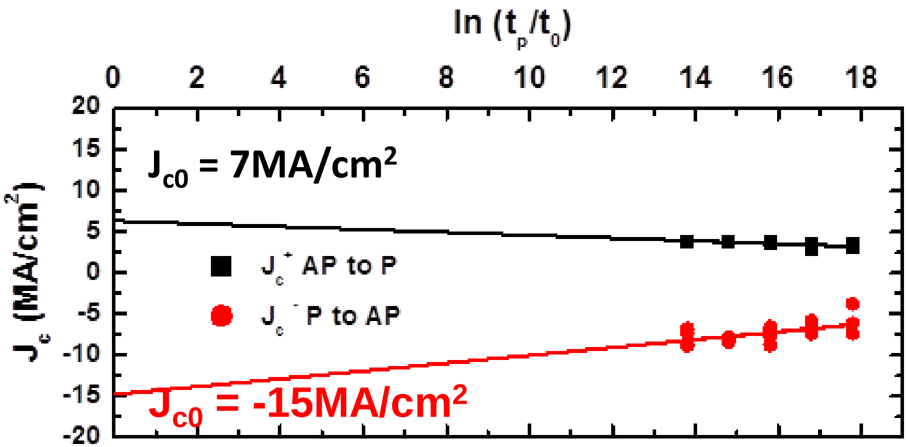


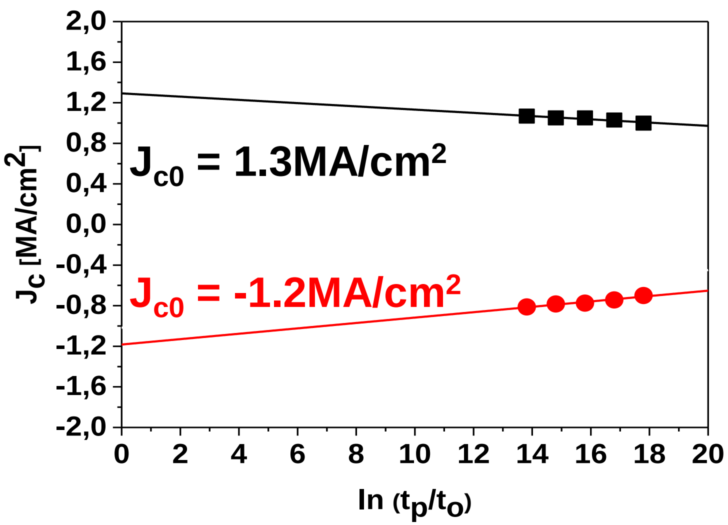
$$K_{eff}t = K_V t + K_S$$



details in oral presentation O-4-02

CIMS ⇒ critical current in MTJs with perpendicular anisotropy



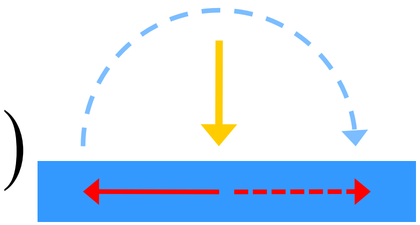


Critical current

$$I_{C0} = \alpha \frac{\gamma e}{\mu_B \eta} M_S V H_{eff}$$

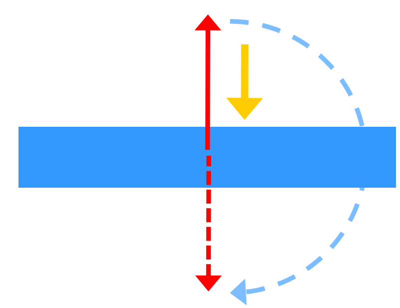
M in plane

$$H_{eff} = \pm\left(H_a + 2\pi M_S\right)$$



M out of plane

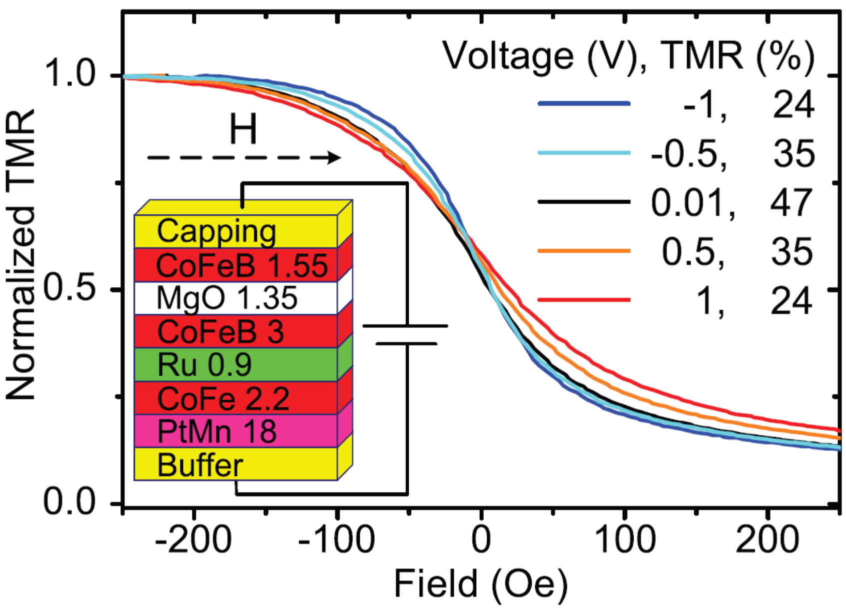
$$H_{eff} = \pm\left(H_a - 4\pi M_S\right)$$

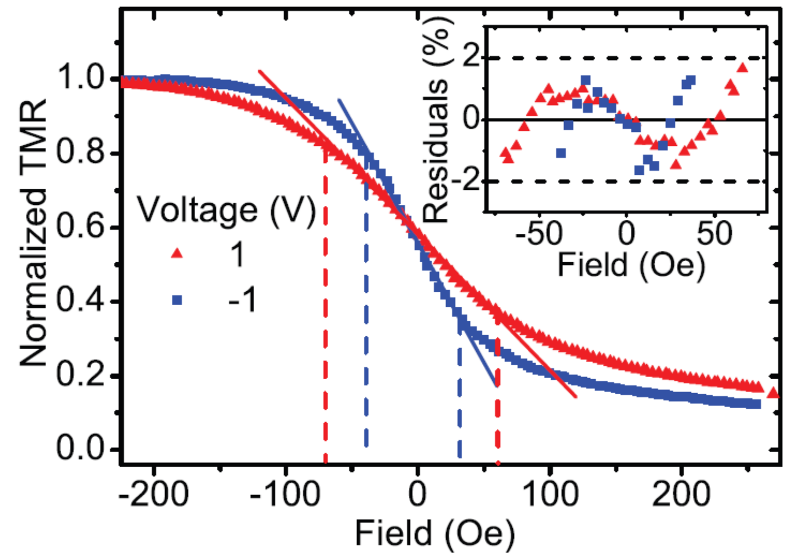


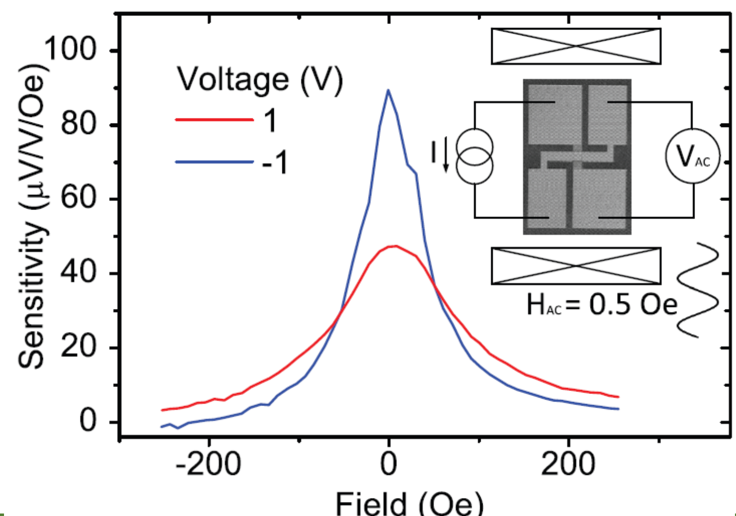
Perpendicular magnetisation reduces the critical switching current about 10 times!

Voltage-tunable magnetic field sensor

- bias voltage changes the perpendicular magnetic anisotropy +V increase out of anisotropy
- thin CoFeB layer
- Thick MgO (1.35 nm) – no STT present



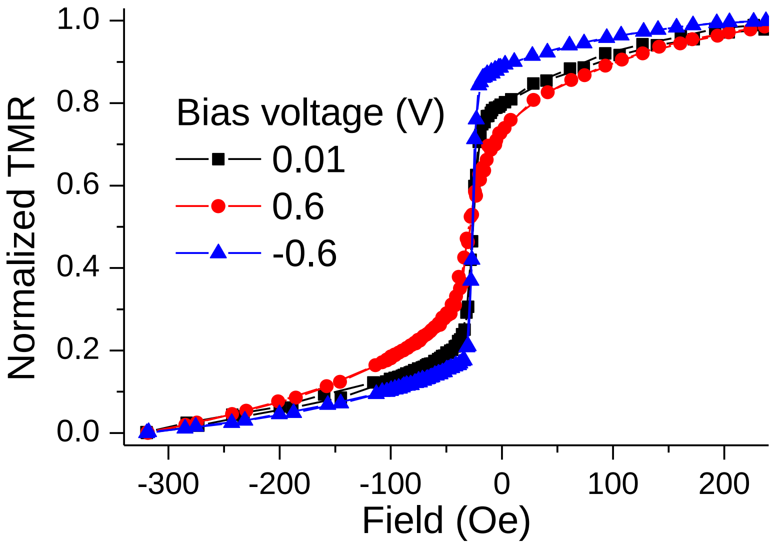


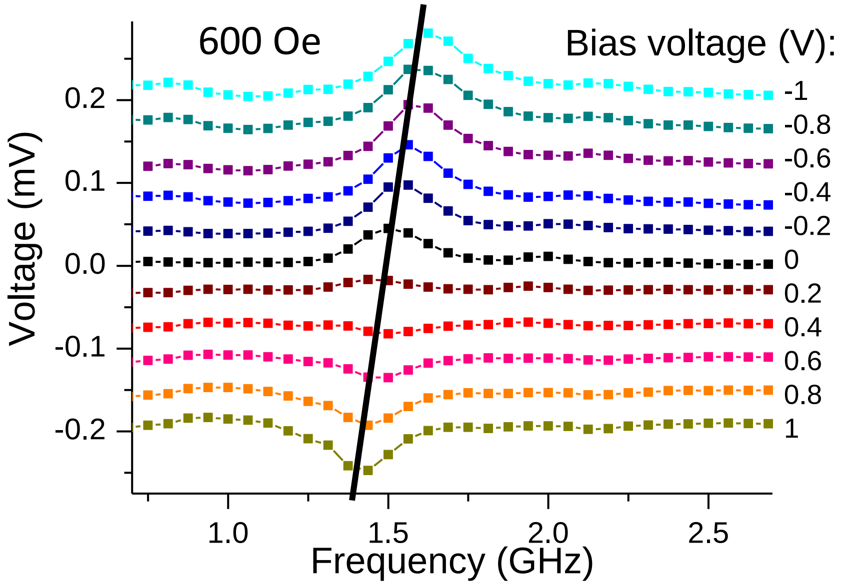


W.Skowroński, P.Wiśniowski et al. *APL 101, 192401, 2012*

Voltage-induced dynamics

- MTJ with thick MgO (2nm) – high resistance, low current



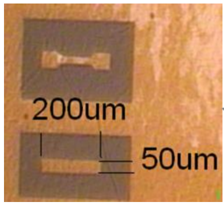


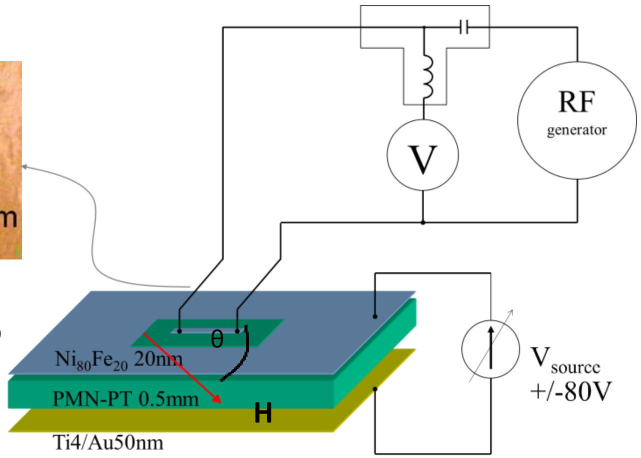
- voltage-induced FMR precession in MTJ
- the resonance frequency change of 97MHz/V which corresponds to the change in the perpendicular magnetic anisotropy of 4 $kJ/m^3/V$

W. Skowroński, T. Stobiecki et al. *MMM2013*

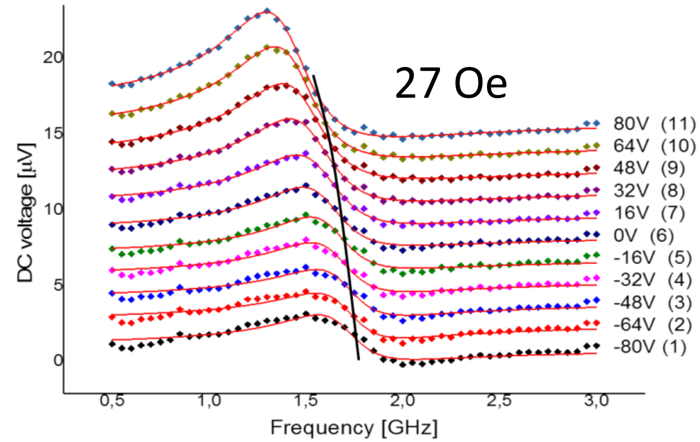
details in poster P-4-06

Rectification of spin polarized rf current in PMN-PT/NiFe

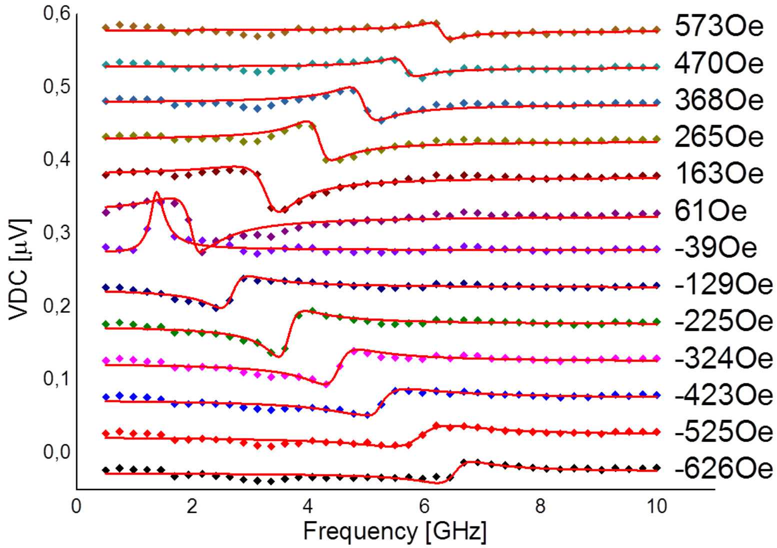




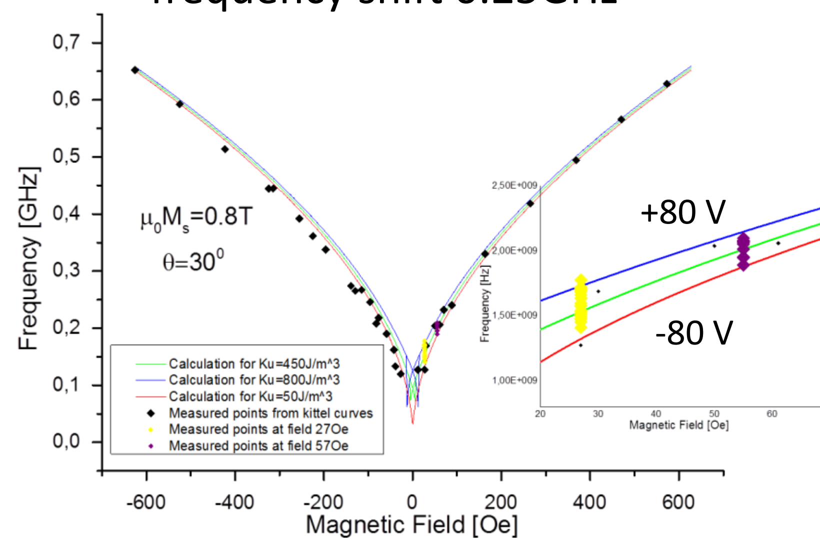
AMR =0.75%



θ=30°



frequency shift 0.25GHz



$$V(\omega) = A(\omega)\frac{\Delta R}{w\, t_{NiFe}}\sin(2\theta)\cos(\theta)$$

details in poster P-3-51

Conclusions

- **Successful fabrication of MTJ nanopillars with a ultrathin MgO barrier.**
- **Spin Transfer Torque (STT) effect in MTJs was quantitavely analysed.**
- **Current Induced Magnetization Switching (CIMS) and and ST- oscillations in MTJs with in plane and out of plane anizotropy were demonstrated.**
- **Voltage-Induced magnetic anisotropy – tunable sensor and RF-signal detection were demonstrated.**

Dziękuje za uwagę