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Numerical and analytical studies of current induced magnetization switching (CIMS) and back-hopping in MTJs with different thickness of MgO barrier

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Transdisciplinary cooperation and applications of nanoscience
21-22 February 2013, Cracow,

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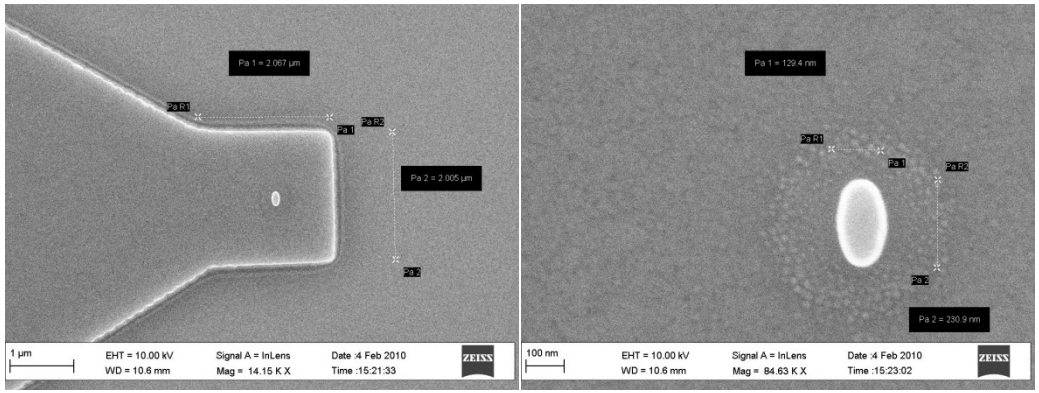
1. Experimental data and background

- The following structure has been fabricated:

Ta(5) / CuN(50) / Ta(3) / CuN(50) / Ta(3) / PtMn (16) / $Co_{70}Fe_{30}$(2.1) / Ru(0.9) / $Co_{40}Fe_{40}B_{20}$(2.3) / MgO(0.76 – 1.01) / $Co_{40}Fe_{40}B_{20}$(2.3) / Ta(10) / CuN(30) / Ru(7) (thickness in nm)



Elliptical shape of nanopillars: 146 x 246 nm, area = 0.028 µm^2

Tunnel junctions with MgO barrier of thickness: 1.01 nm, 0.95 nm and 0.76 nm have been characterized.

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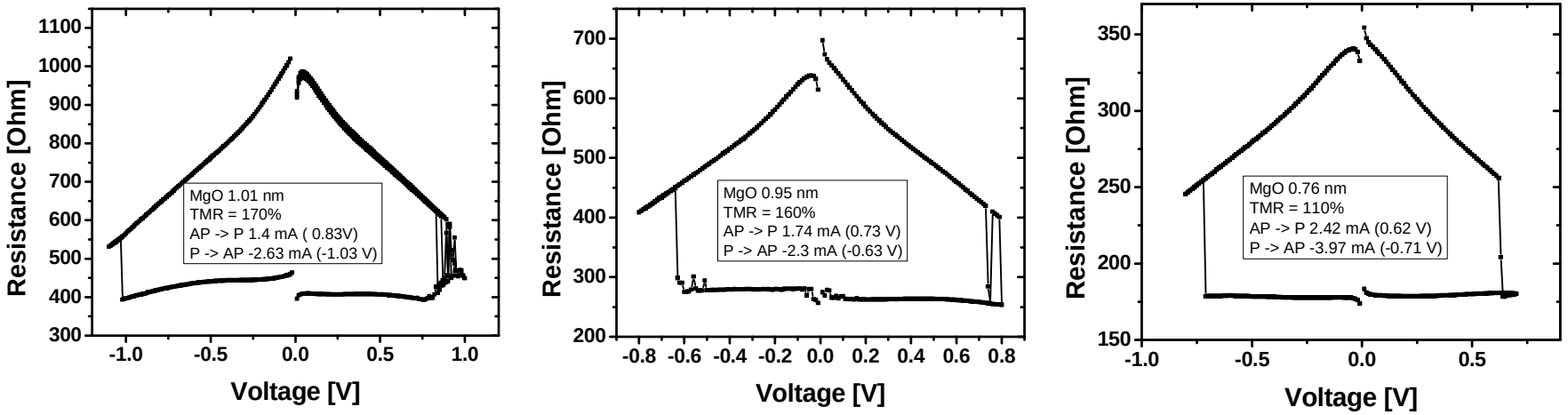
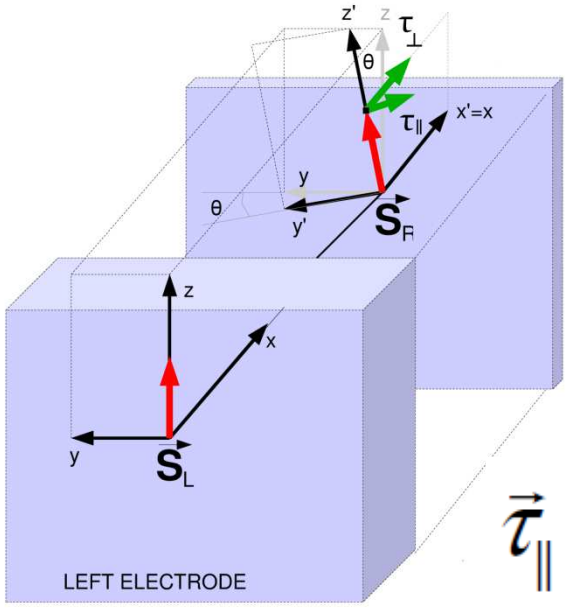
We focused on current induced switching in these 3 samples.
Experimental resistance loops vs. bias are presented below:



For positive voltages(electrons flow from reference layer to the free one)we observe **back-hopping effect**(for MgO thickness 1.01 and 0.95nm)

The aim is to simulate experimental resistance loops and description of dynamics in terms of linear stability analysis with use the switching phase diagram.

2. Model:



Dynamics described by Landau-Lifschitz-Gilbert equation:

$$\frac{d\vec{s}_R}{dt} + \alpha\vec{s}_R \times \frac{d\vec{s}_R}{dt} = \vec{\Gamma}$$

with current induced torques:

$$\vec{\tau}_{\parallel} = \tau_{\parallel}\vec{s}_R \times \left(\vec{s}_R \times \vec{s}_L\right) \qquad \vec{\tau}_{\perp} = \tau_{\perp}\vec{s}_R \times \vec{s}_L$$

Dimensionless LLG equation in the spherical coordinates:

$$\begin{cases} \dfrac{d\theta}{d\tau} = -\alpha \sin\theta\cos\theta - h_P \cos\phi \sin\theta \times \\ \times (\alpha\cos\theta\cos\phi + \sin\phi) - h_{\parallel}\sin\theta + \alpha h_{\perp}\sin\theta \\ \dfrac{d\phi}{d\tau} = -\cos\theta + h_P\cos\phi(\alpha\sin\phi - \cos\theta\cos\phi) + \\ +\alpha h_{\parallel} + h_{\perp} \end{cases}.$$

where: τ - dimensionless time

$h_P = K_P / K$ - planar anisotropy

$h_{\perp} = \tau_{\perp} / 2Kd_f$ $h_{\parallel} = \tau_{\parallel} / 2Kd_f$ - normalized out-of-plane and in-plane torques

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3. Method of linear stability analysis

We linearize the LLG equation near two main equilibrium points:
θ = 0 (parallel state) and θ = π (antiparallel state) for which:

$$\frac{d\theta}{d\tau} = 0, \frac{d\phi}{d\tau} = 0$$

Their stabilities(or unstabilities) can be determined from eigenvalues of linearized LLG equation.

For points coresponding to P and AP state, eigenvalues have the following forms:

θ = 0:

$$\mu_{1,2=} -\left\{\frac{2h_{\parallel}+\alpha\left(\left(2+h_p\right)-2h_{\perp}\right)}{2} \pm \frac{\sqrt{-4\alpha^2{h_{\parallel}}^2+4\alpha h_{\parallel}\left(\left(2+h_p\right)-2h_{\perp}\right)+\left(\left(-4-4h_p+\alpha^2{h_p}^2\right)+4\left(2+h_p\right)h_{\perp}-4{h_{\perp}}^2\right)}}{2}\right\}$$

θ = π:

$$\mu_{1,2} = -\frac{1}{2}\left\{2\alpha-2h_{\parallel}+\alpha h_P+2\alpha h_{\perp} \pm \sqrt{-4-8\alpha h_{\parallel}-4\alpha^2{h_{\parallel}}^2-4h_p-4\alpha h_{\parallel}h_p+\alpha^2{h_p}^2-8h_{\perp}-8\alpha h_{\parallel}h_{\perp}-4h_ph_{\perp}-4{h_{\perp}}^2}\right\}$$

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Classifying the equilibrium points:

$$\mu_{1,2} = A \pm \sqrt{B}$$

A	B	$\mu_{1,2}$	EQUILIBRIUM
-	-	Imaginary	Stable point
+	-	Imaginary	Unstable point
Real	+	$\mu_{1,2} < 0$	Stable point
Real	+	$\mu_{1,2} > 0$	Unstable point
Real	+	$\mu_1 < 0 < \mu_2$	Saddle point

Eigenvalues depend on $h_p, h_{\perp,\parallel}, \alpha$, which in our case can be measured.

Dimensionless normal torque $h_{\perp}$ consists of two parts: current induced torque and interlayer coupling. Interlayer coupling originates from exchange coupling of two magnetized layers as well as stray fields due to pillar shape of the structure.

All these components were measured in the experiment. The values of the other junctions' parameters and characteristics can be taken from experimental data as well:

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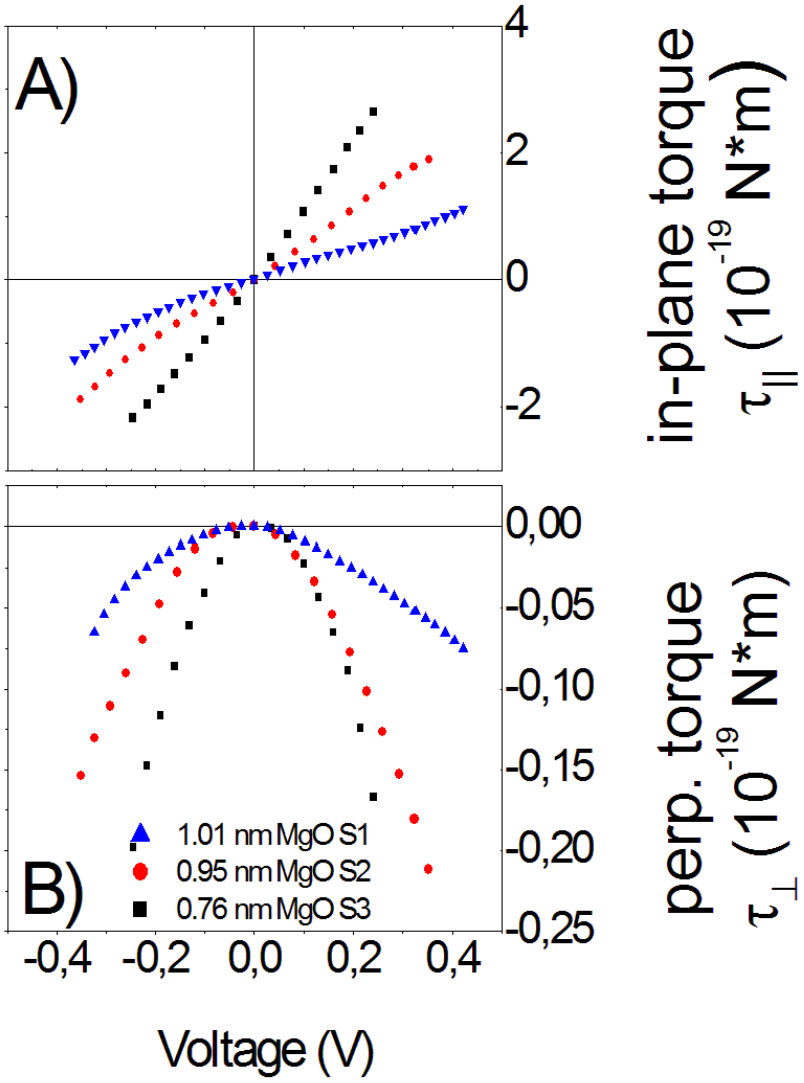

Experimentally determined two components of current induced torques: in-plane component(top) and out-of-plane component(bottom).

For |V|>0.4, the experimental torques' determination is difficult due to low signal-to-noise ratio as well as the risk of junction's breakdown. Thus, in simulations, in-plane and out-of-plane torques' dependancies on higher voltages are extrapolated as linear and quadric functions respectively.

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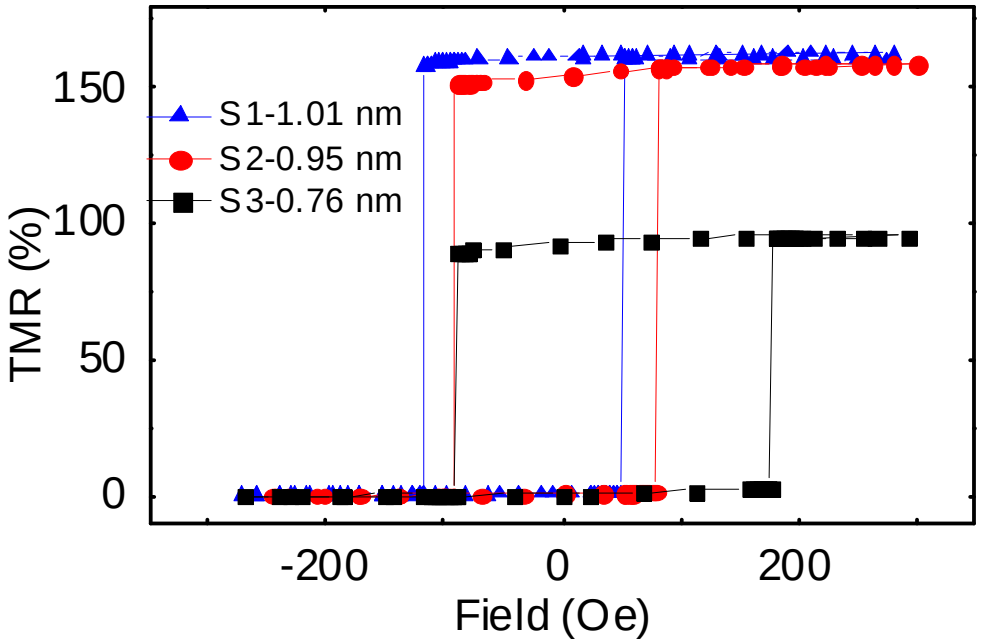

TMR loops for 3 samples with different MgO thickness

Sample	TMR	Total coupling field	Coercive field
S1(1.01 nm MgO)	165%	-33 Oe	86 Oe
S2(0.95 nm MgO)	160%	-10 Oe	90 Oe
S3(0.76 nm MgO)	100%	+44 Oe	134 Oe

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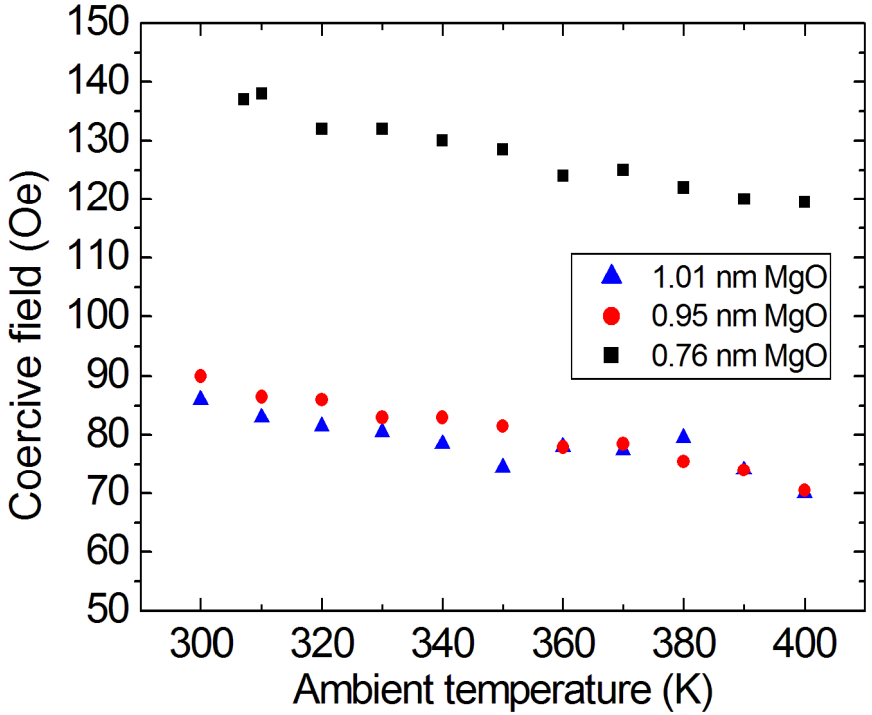
Joule heating of junction influences on the coercive field. Simulations show that for bias of order 1V, the temperature of the junction rises to over 400K. It was necessesary to find out how the increasing temperature decreases coercive field:



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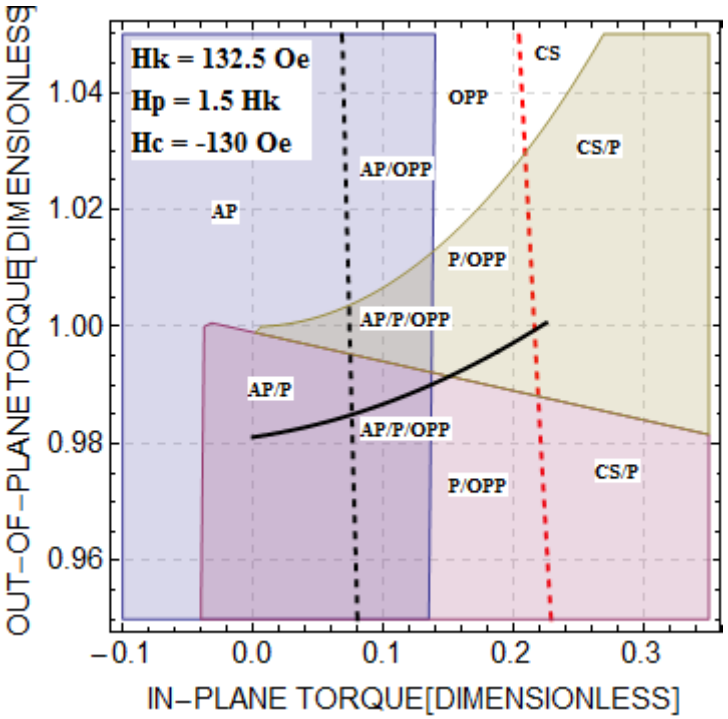
5. Stability diagram

Based on analysis of eigenvalues of the LLG equation, as well as numerical methods, we are able to create stability diagram:



Example of diagram for semi-experimental data (very weak planar anisotropy is assumed)

AP – stable antiparallel state

P - stable parallel state

CS – stable canted state

OPP – stable out-of-plane oscillations

black solid line – experimental normalized torques for 1.01nm MgO

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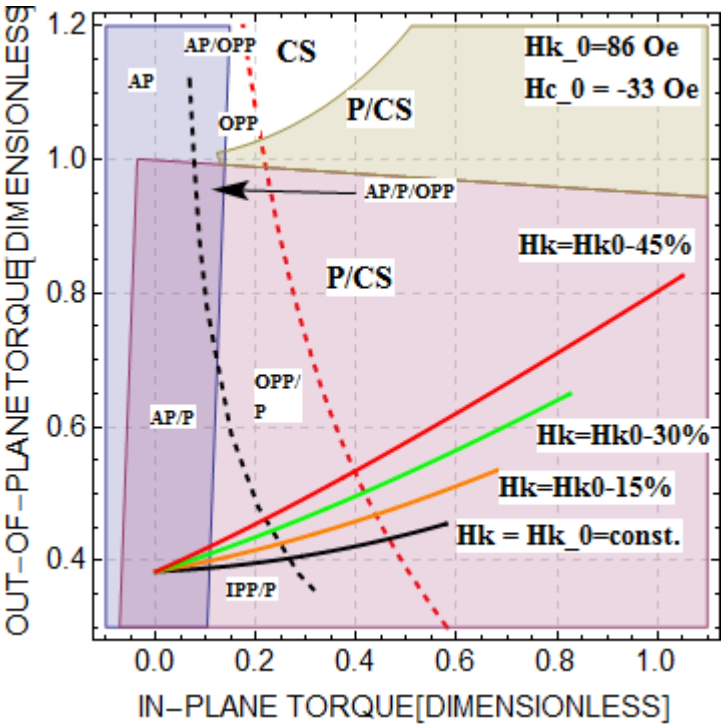
The effect of coercive field reduction on the stability diagram



Hk – coercive field,
Hc_0 – total coupling field

Color solid lines – experimental torques with different reduction of coercive field for voltages from 0V to 1V.

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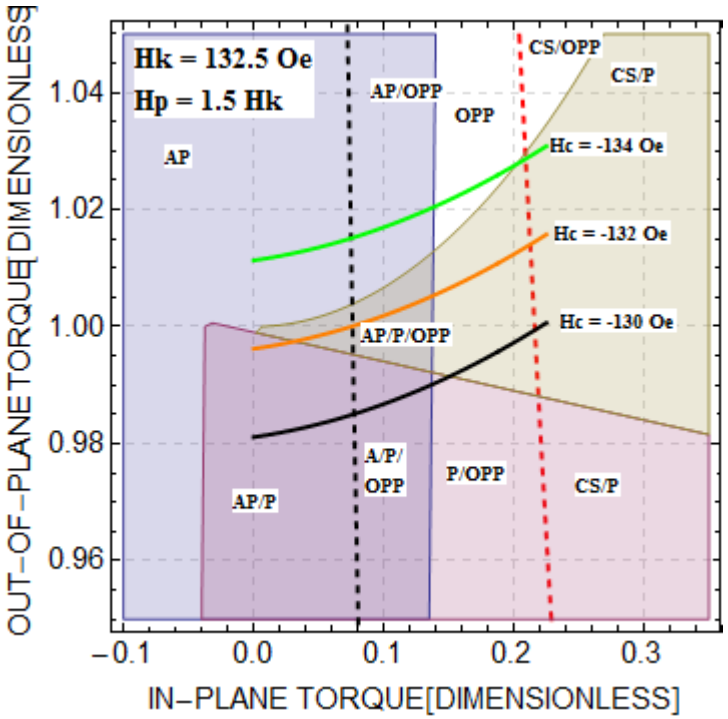
The effect of different interlayer coupling on stability diagram:



Change of Hc field (coupling Field) causes shift of torque lines (color solid lines) along the y-axis.

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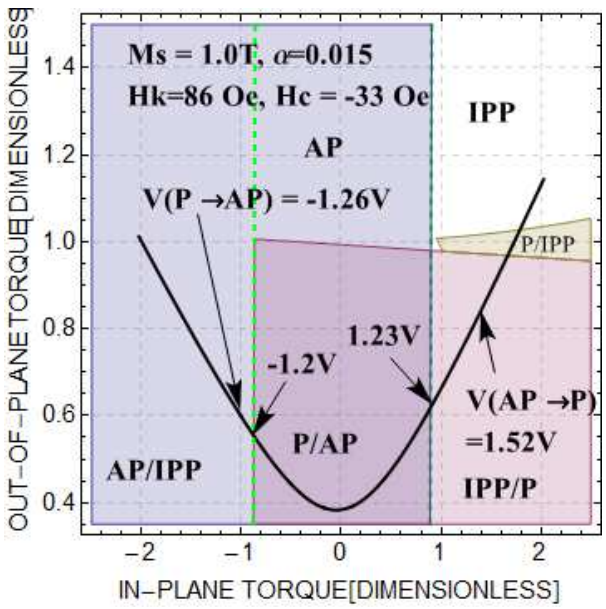
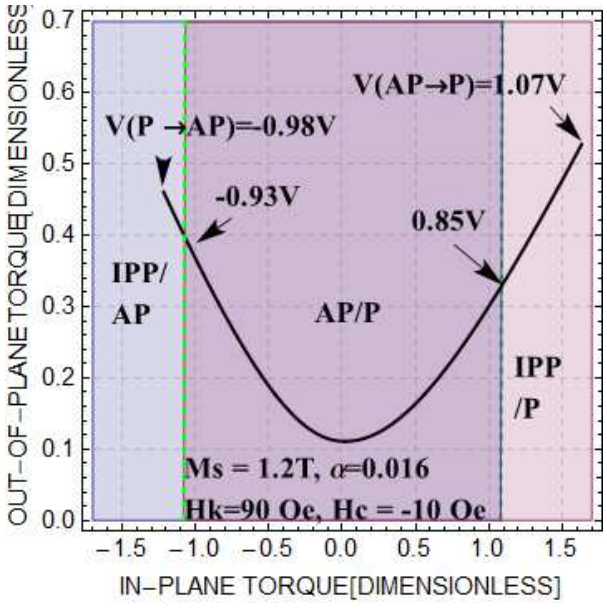
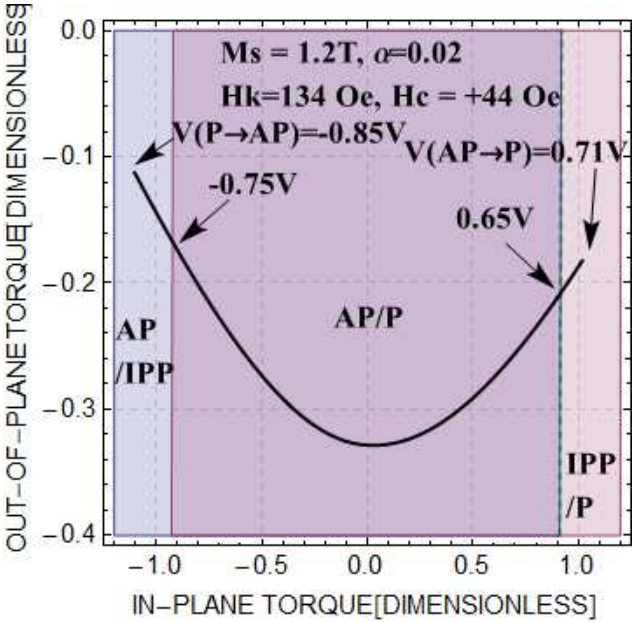
Experimental value of saturation magnetization allow to estimate anisotropy (according to formula $E = \frac{1}{2}\mu_0 M_s^2$). We assume 30% reduction of coercive field for 1V. For the all parameters taken from the experiment we find the following diagrams:







S1 (1.01nm) S2 (0.95nm) S3(0.76nm)

IPP – inplane oscillations, black solid line – experimental torques

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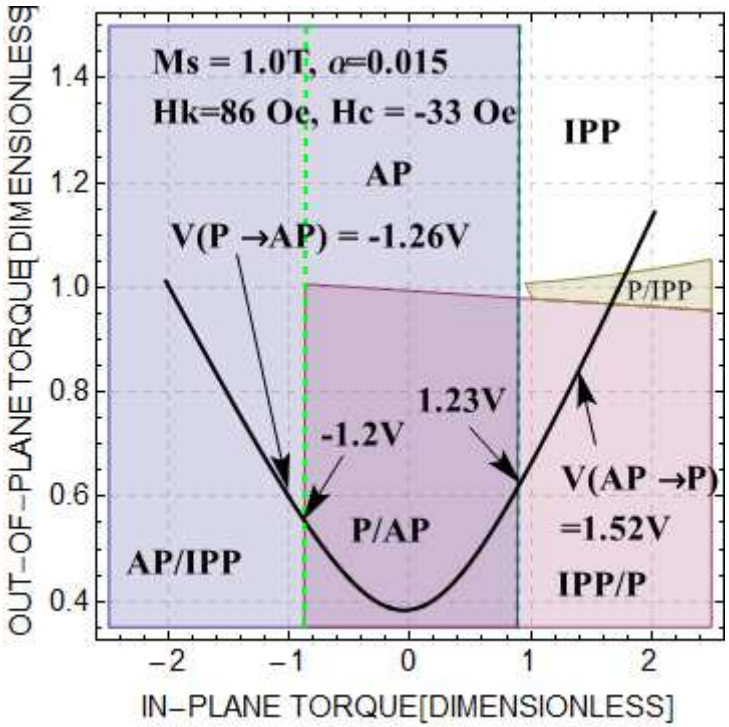
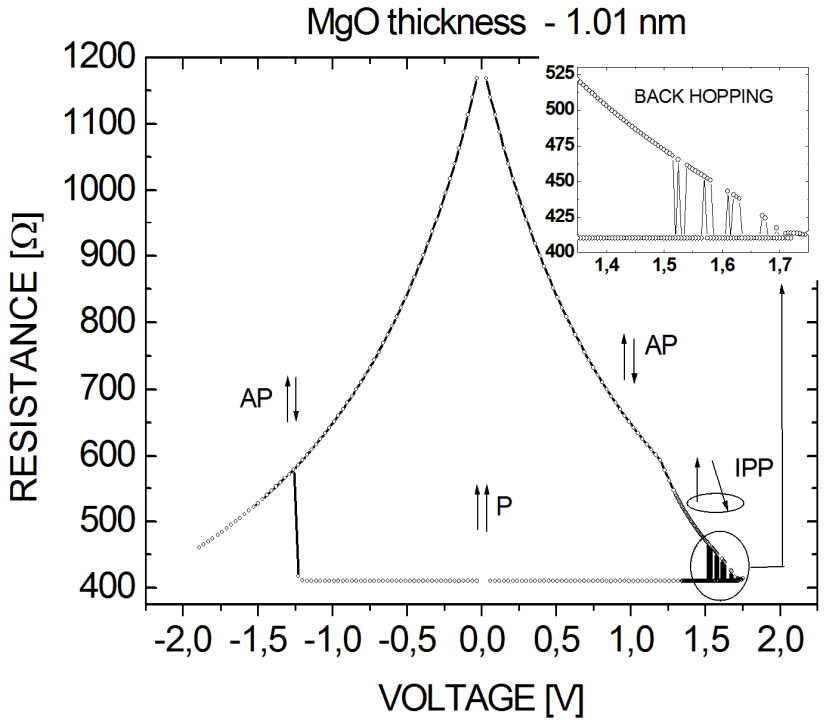
6. Numerical solution of the LLG equation versus switching diagram **(S1 – 1.01 nm)**





Back-hopping between IPP and P state occurs

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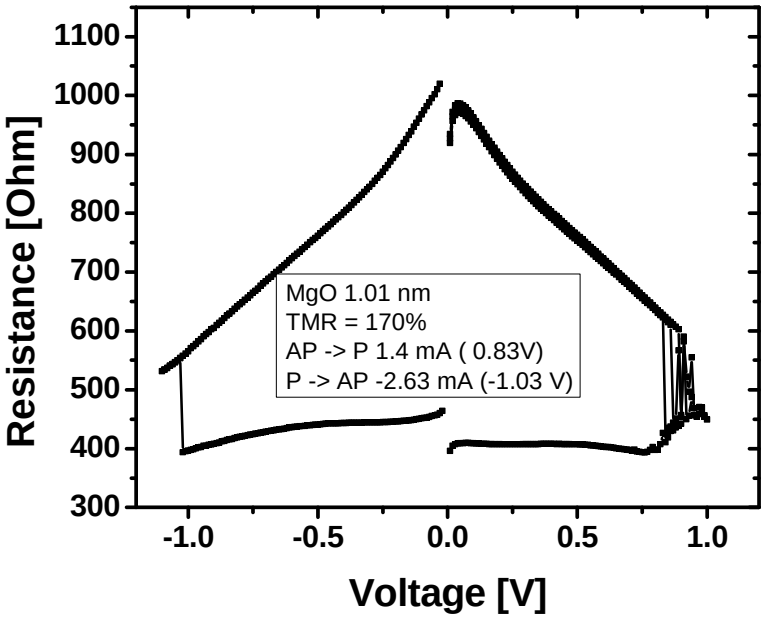
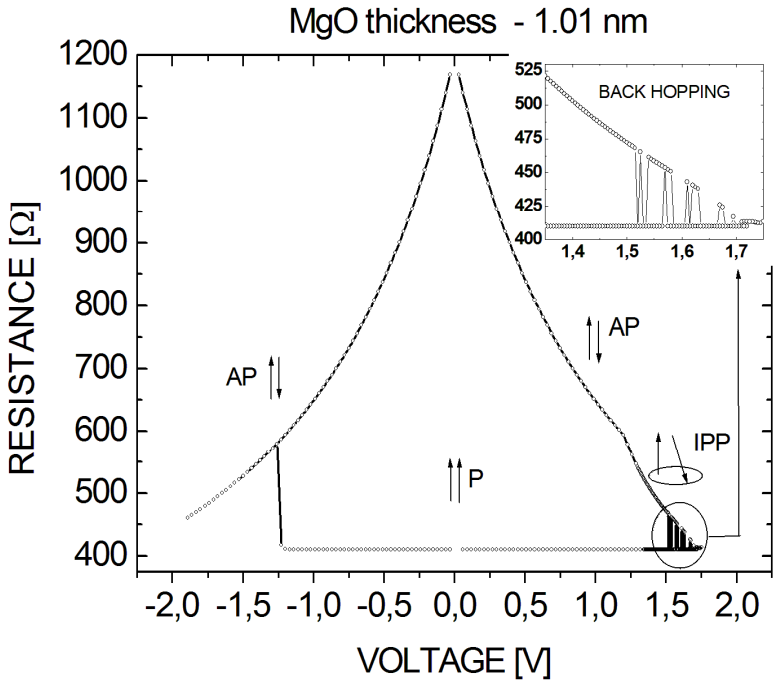
Experiment vs. numerical simulation:





Back-hopping occurs at higher voltage but simulation qualitatively agrees with the experiment

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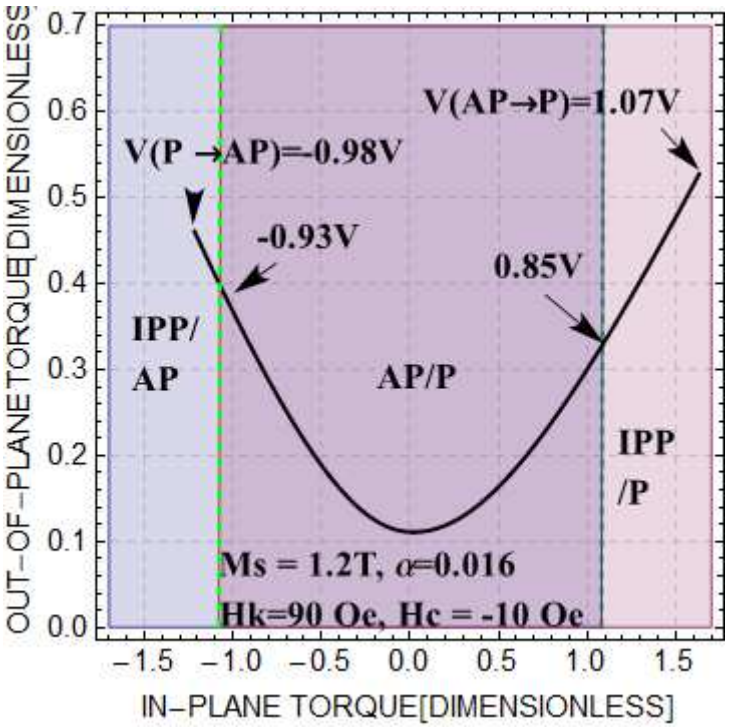
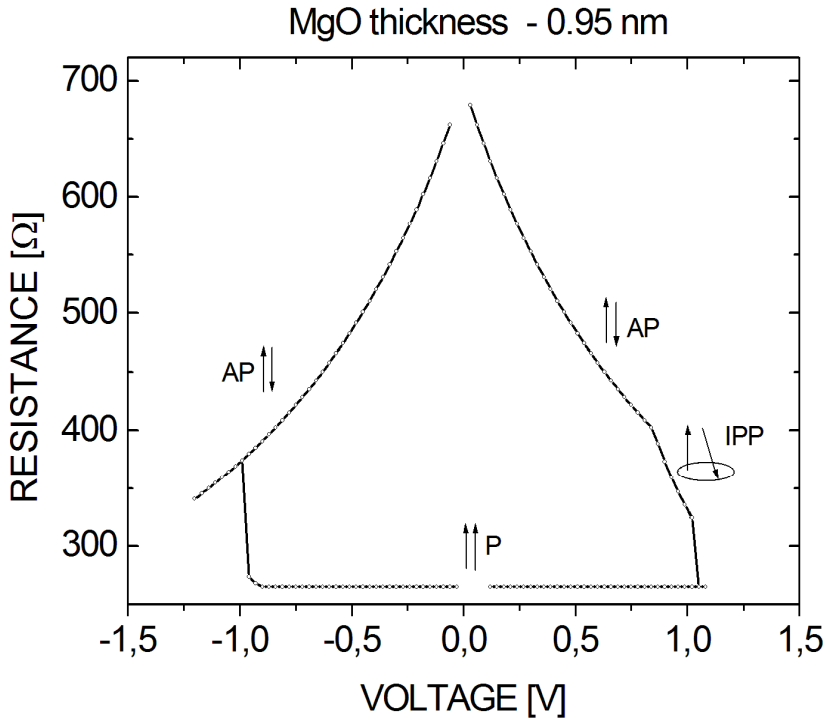
7. Numerical solution of the LLG equation versus switching diagram **(S2 – 0.95 nm)**





back-hopping – not observed (but still it is possible)

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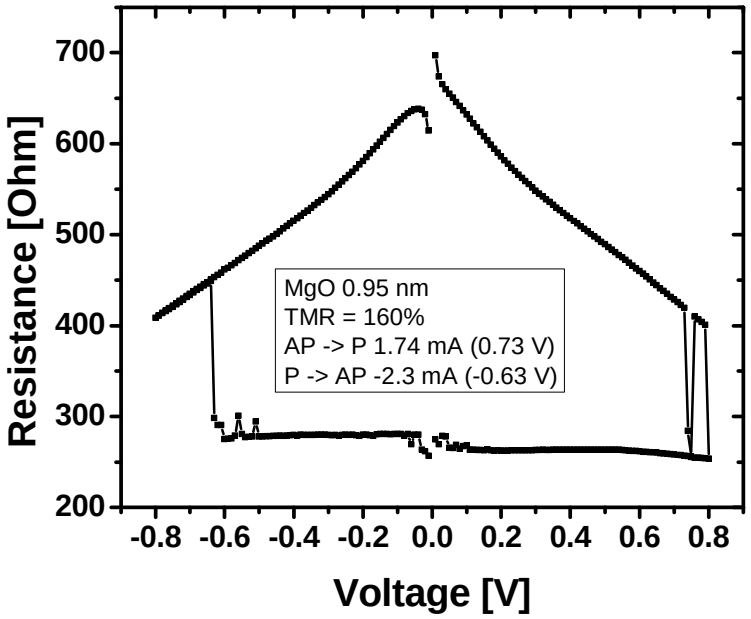
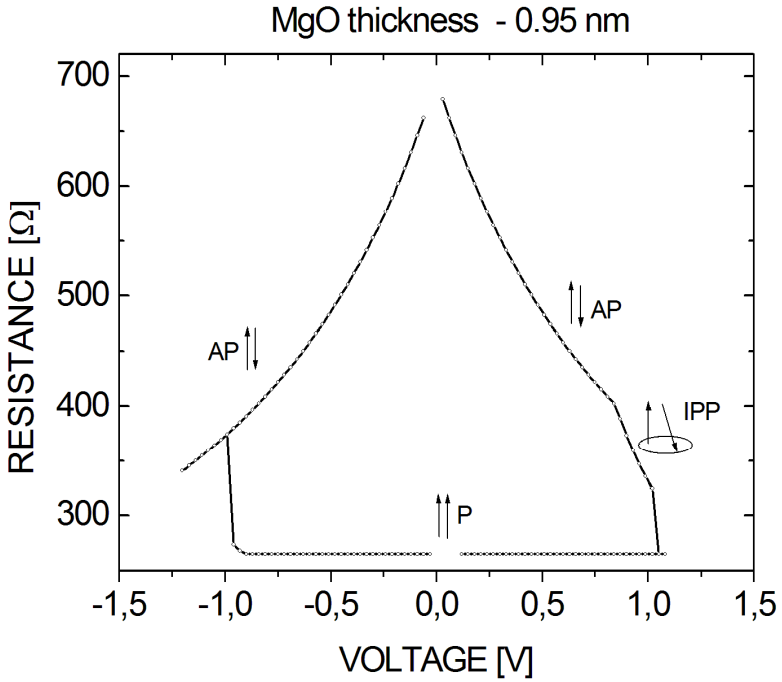
Experiment vs. numerical simulation:





Back-hopping is limited to only one event. Probability of back-hopping is very low.

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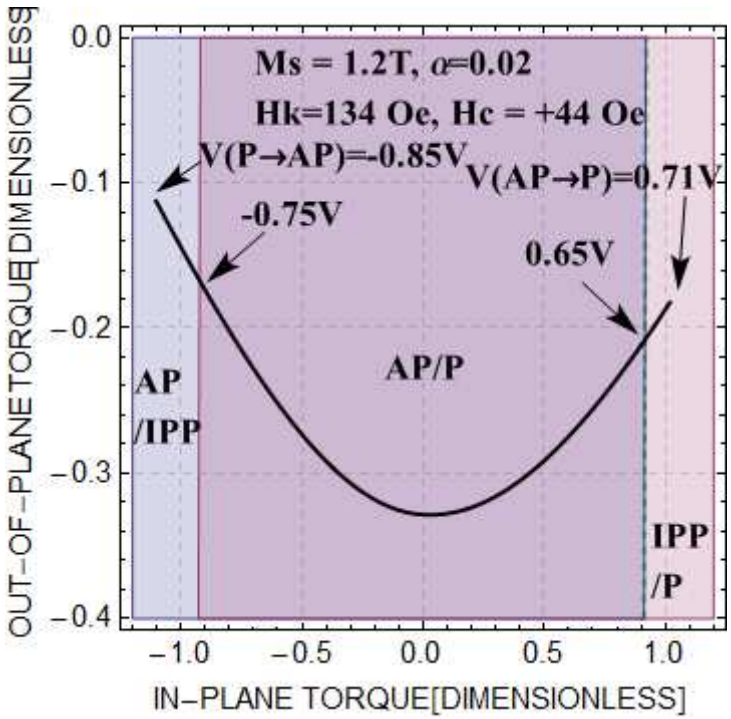
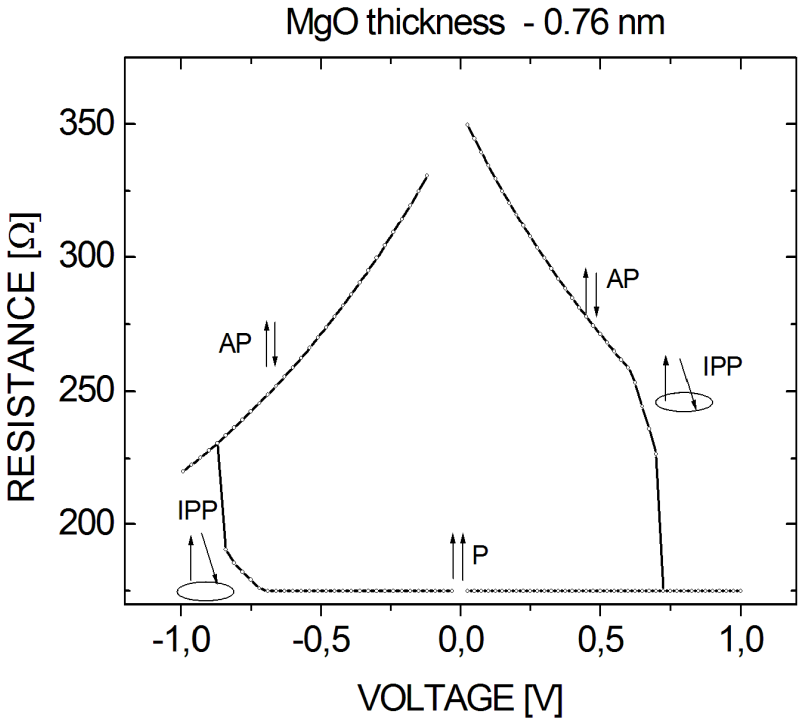
7. Numerical solution of the LLG equation versus switching diagram **(S3 – 0.76 nm)**





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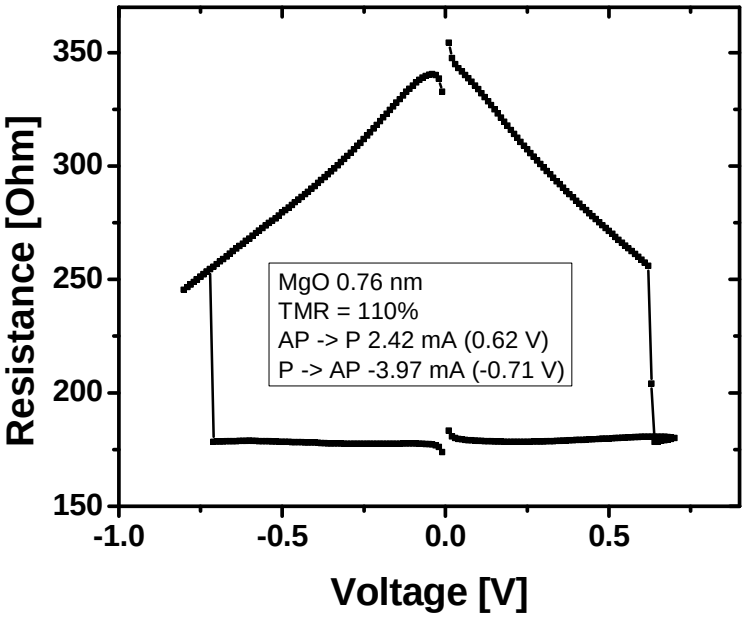
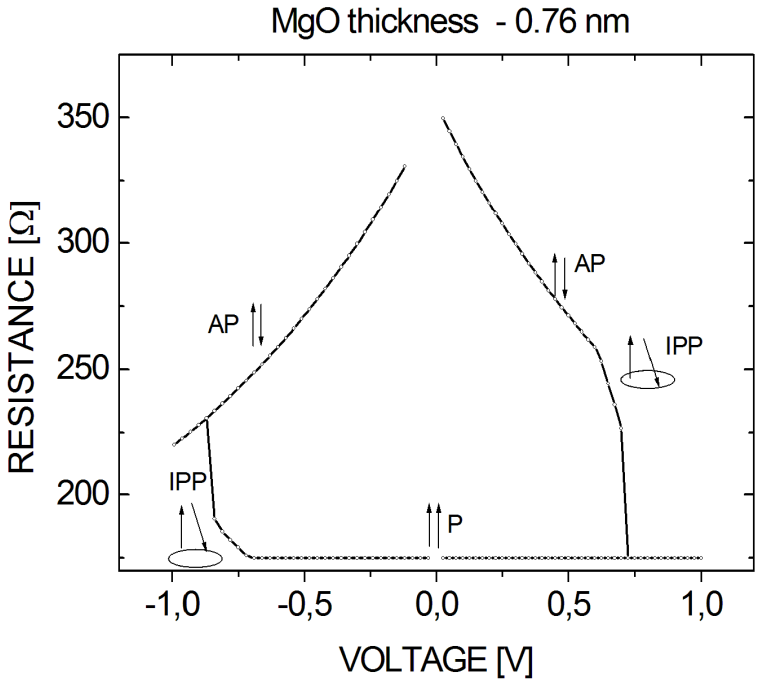
Experiment vs. numerical simulation:





Absence of back-hopping in the experiment as well as in the simulations. Switching occurs at similar voltages.

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Conclusions:

- We reproduced experimenal resistance loops

- LLG equation allows to create the stability diagram which is consistent with experimental results.

- coupling influences on probability of back-hopping

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Thank you for your attention

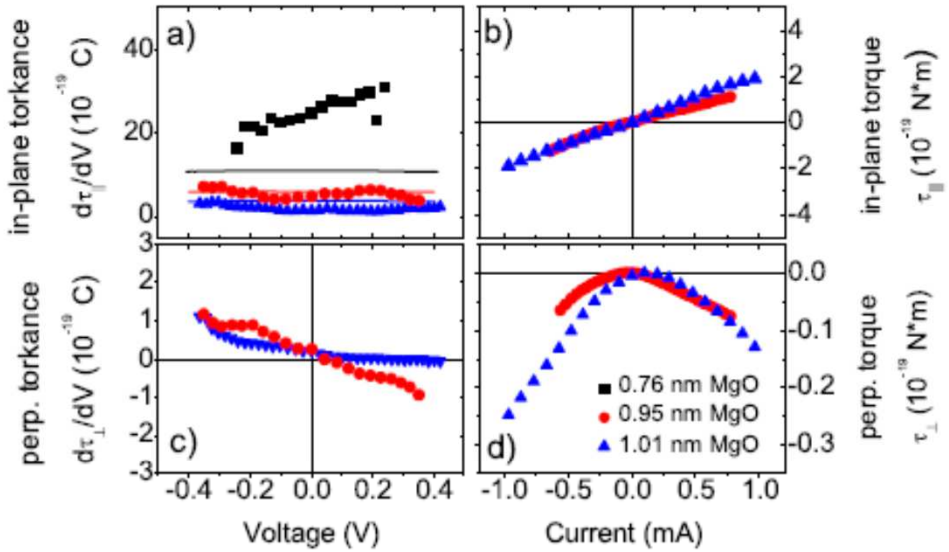

FIG. 5: Bias dependence of the in-plane torkance (a), in-plane torque (b), perpendicular torkance (c) and perpendicular torque (d) for MTJs with different MgO barrier thickness. The theoretical values in (a) (solid lines) were calculated using Eq. 3. Torque values are numerically integrated from measured torkances.