Numerical and experimental studies of current-induced magnetization switching and back-hopping in magnetic tunnel junctions with MgO barriers

P.Ogrodnik [a,b], W.Skowroński [d], T.Stobiecki [d], R.Świrkowicz [a] and J.Barnaś [b,c]

[a]Faculty of Physics, Warsaw University of Technology, 00-662 Warsaw, Poland

[b]Insitute of Molecular Physics, Polish Academy of Science, 60-179 Poznań, Poland

[c]Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland

[d]Department of Electronics, AGH University of Science and Technology, 30-059 Kraków, Poland

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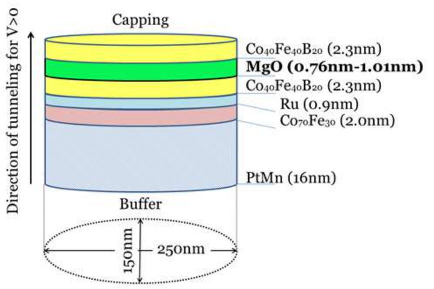
INTRODUCTION

Current Induced Magnetization Switching (CIMS) due to Spin Transfer Torque (STT) in magnetic tunnel junctions (MTJs) has been extensively studied in recent years. This was stimulated by possible applications of the effect in the next generation of non-volatile magnetic random access memory cells (STT-RAM). An important issue of the current studies concerns the design of voltage-controllable and thermally stable structures. Non-deterministic behavior of MTJ-based memory cells may occur at higher bias voltages as multiple returns from the parallel (P) to the antiparallel (AP) states [1,2]. Such a behavior is clearly visible in experimentally measured resistance vs. bias voltage loops, and is referred to as the back-hopping effect. Below we present the comparison of experimental and theoretical results on MgO thickness-dependent back-hopping effect [3].

EXPERIMENT

The multilayer structures were deposited in the Singulus Timaris System.:



Structrures were annealed at 340˚C in a magnetic field of 1 T. Next, the MTJs with 3 thickness of MgO barrier **(0.76,0.95 and 1.01 nm)** were patterned using electron-beam litography, ion-milling and lift-off processes. TMR values for the performed MTJs differs from 110% (0.76 nm MgO) to 170% (1.01nm MgO).

From the shift of resistance loops measured in external magnetic field at zero-voltage bias, the values of the net interlayer coupling (IC) were estimated:

IC1 = -33 Oe (antiferromagnetic coupling) for sample with **1.01** nm of MgO

IC2 = -10 Oe (antiferromagnetic coupling) for sample with **0.95** nm of MgO

IC3 = +44Oe (ferromagnetic coupling) for sample with **0.76** nm of MgO

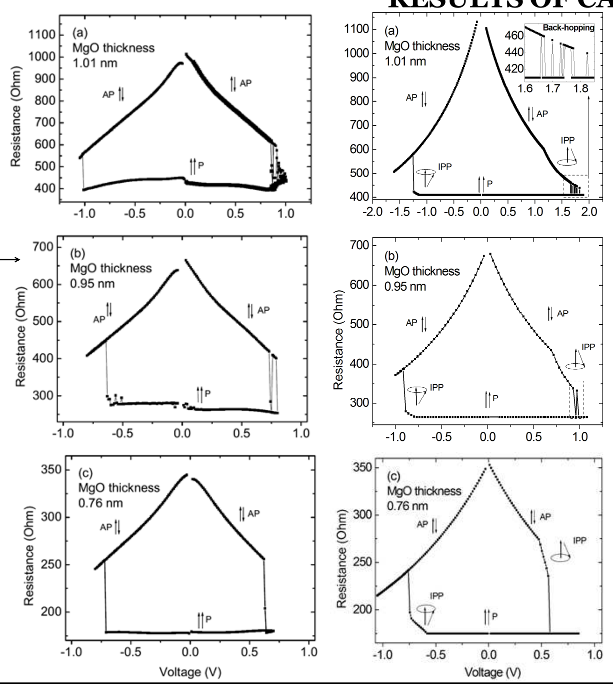
The CIMS measurements were carried out on these 3 samples by applying voltage pulses with a duration of 10ms and amplitudes from 0 to +/- 1 V :

In the sample with strong antiferromagnetic coupling back-hopping effect has been observed.

Decreasing the antiferromagnetic coupling causes the reducing of back-hopping.

In the sample with strong ferromagnetic coupling, back-hopping does not occur

CIMS MEASUREMENTS:



THEORETICAL MODEL AND ANALYSIS

The observed magnetization bahaviours in the MTJs with different MgO tunnel barrier thickness have been simulated and described with use of Landau-Lifschitz-Gilbert(LLG) equation with additional terms corresponding to current induced torques and to interlayer coupling as well.

The LLG equation in dimensionless form expressed in spherical coordinates:

$$\frac{d\theta}{d\tilde{\tau}} = \sin\theta\,[-h_P\cos\phi\,(\alpha\cos\theta\cos\phi + \sin\phi) - \alpha\cos\theta - (h_\parallel + h_\perp)\,]$$

$$\frac{d\phi}{d\tilde{\tau}} = h_P\cos\phi\,(\alpha\sin\phi - \cos\theta\cos\phi) - \cos\theta + \alpha h_\parallel - h_\perp$$

h_P - planar anisotropy, $h_\parallel$-in-plane torque, $h_\perp$-out-of-plane torque (originates from applied voltage and interlayer coupling), $\tilde{\tau}$ - dimensionless time, $\theta(\phi)$-polar(azimuthal) angle.

$\theta = 0(\pi)$ - parallel(antiparallel) configuration of magnetization

$\phi = \frac{\pi}{2}$ –magnetization aligned in the easy plane of the sample

To analyse back-hopping effect, the following calculations have been carried out:

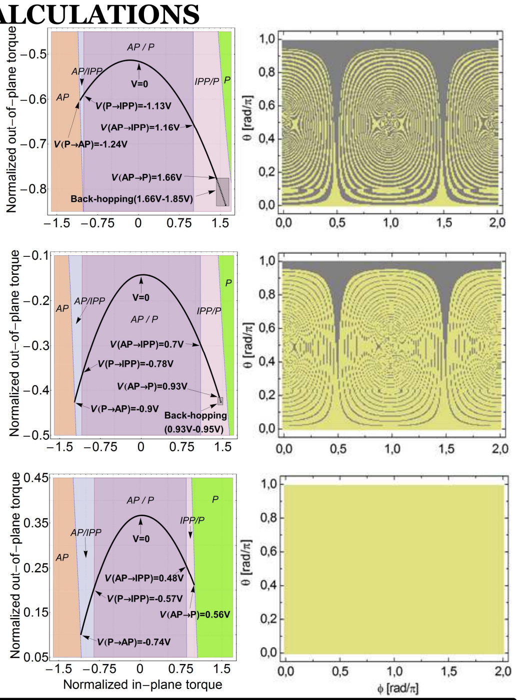
1) The LLG equation has been solved numerically with parameters(coercive fields, magnetization saturation, current induced torques, interlayer coupling, damping coefficients) measured in the experiment .

2) The following procedure has been applied in order to create the stability diagrams for each of the experimental samples:

LLG equation in general form: $\frac{d\vec{x}}{dt} = f(\vec{x})$, $\vec{x} = (\theta, \phi)$ → Linearization → Linearized LLG in the form: $\frac{d\vec{x}}{dt} = D_{P(AP)}\vec{x}$, $D_{P(AP)}$ – dynamical matrix near P(AP) state → Eigenvalues of D matrix → Sign and value(real or imaginary) of eigenvalues give the information about stablity of P(AP) state → If P(AP) state becomes unstable, in-plane oscillations(IPP state) may occur → Numerical investigations on stability of IPP state (searching of bifurcation)

3) Bassins of attraction for 3 experimental samples have been calculated numerically at voltages slightly above the AP to P switching voltages.

RESULTS OF CALCULATIONS



Conclusion: Theoretical calculations show that back-hopping occurs between IPP and P state when both component of torque have similar magnitudes and opposite signs. This is the case of thick junction with strong antiferromagnetic interlayer coupling. For thin junction with ferromagnetic coupling back-hopping is impossible because both component favors the same magnetic configuration for V>0. In turn, for v<0 out-of-plane torque is too weak to trigger back-hopping and can even change its sign for high negative voltages.

SWISS CONTRIBUTION

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[3] Skowroński W. et al., to be published

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