Understanding stability diagram of perpendicular magnetic tunnel junctions

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Perpendicular magnetic tunnel junctions (MTJ) with a bottom pinned reference layer and a composite free layer (FL) are investigated. Different thicknesses of the FL were tested to obtain an optimal balance between tunneling magnetoresistance (TMR) ratio and perpendicular magnetic anisotropy. After annealing at 400 °C, the TMR ratio for 1.5 nm thick CoFeB sublayer reached 180% at room temperature and 280% at 20 K with an MgO tunnel barrier thickness corresponding to the resistance area product $R_A = 10 \text{ Ohm} \mu\text{m}^2$. The voltage vs. magnetic field stability diagrams measured in pillar-shaped MTJs with 130 nm diameter indicate the competition between spin transfer torque (STT), voltage controlled magnetic anisotropy (VCMA) and temperature effects in the switching process. An extended stability phase diagram model that takes into account all three effects and the effective damping measured independently using broadband ferromagnetic resonance technique enabled the determination of both STT and VCMA coefficients that are responsible for the FL magnetization switching.

Results

Wafer-level characterization. The multilayers with the following structure were deposited: bottom electrode/Ta seed/[Co (0.5)/Pt (0.2)] × 6/Co (0.6)/Ru (0.8)/Co (0.6)/[Pt (0.2)/Co (0.5)] × 3/W (0.25)/CoFeB (1.0)/MgO (0.8)/CoFeB ($t_{FL}$)/W (0.2)/CoFeB (0.5)/MgO (0.75)/Ta (3.0)/top electrode (thicknesses in nm), with $t_{FL}$.
ranging from 1.1 up to 1.6 nm. The schematics of the multilayer stack is presented in Fig. 1. The bottom Co/Pt super-lattices coupled by a thin Ru spacer are characterized by high perpendicular magnetic anisotropy (PMA). The W-based separator between the superlattices and the reference layer ensures high ferromagnetic coupling between the top super-lattice and the RL. In addition, it provides structural transition from a face center cubic SyF14 to a body center cubic CoFeB and contributes to the absorption of B atoms from CoFeB during annealing and crystallization processes. Damping parameter was measured using ferromagnetic resonance (FMR) (see Methods section). Figure 1 presents the dependence of the \( \Delta H \) on the excitation frequency.

Vibrating sample magnetometry (VSM) measurements of a representative sample with \( t_{FL} = 1.1 \) nm presented in Fig. 2 reveal independent switching of the FL (at small magnetic fields below 50 kA/m) and RL (at high magnetic fields between 150 and 300 kA/m), which ensures bistable parallel (P) and antiparallel (AP) state. The FL magnetization was calculated and yielded \( \mu_0M_S = 1.12 \) T. An inset of Fig. 2 depicts the TMR ratio dependence on \( t_{FL} \) measured using CIPT method.

Figure 3 presents the TMR vs. magnetic field dependence measured in the MTJ nanopatterned into pillars of 130-nm in diameter with different \( t_{FL} \). Increase in \( t_{FL} \) leads to an increase in TMR ratio and decrease in the...
coercive field. The offset field of about $H_S = 25 \text{ kA/m}$ originates from the stray field, which depends on the MTJ lateral size (not shown here).

**Stability diagram.** To further elucidate the properties of the fabricated MTJ, current (voltage)-induced switching loops were measured in the presence of the perpendicular magnetic field. An inset of Fig. 3 presents a representative resistance vs. voltage switching loop measured in an external magnetic field of $H = 25 \text{ kA/m}$, obtained at $T = 300 \text{ K}$ (squares) and $T = 20 \text{ K}$ (circles).

**Figure 3.** TMR vs. magnetic field loop of MTJs with different $t_{FL}$ measured at room temperature (300 K). Significantly smaller coercive field $H_C$ is measured for $t_{FL} = 1.5 \text{ nm}$, which increases at $T = 20 \text{ K}$. An inset presents a resistance vs. voltage switching loop measured in an external magnetic field of $H = 25 \text{ kA/m}$, obtained at $T = 300 \text{ K}$ (squares) and $T = 20 \text{ K}$ (circles).

**Figure 4.** Voltage vs. magnetic field stability diagram measured in the MTJ with $t_{FL} = 1.1 \text{ nm}$ at $T = 20 \text{ K}$ (open symbols) and $T = 300 \text{ K}$ (full symbols). Dotted lines represents approximation based on Eq. (4). An extended model based on correction presented in Eq. (5) is represented by dashed (20 K) and solid (300 K) lines.
In addition, for the precise derivation of the STT coefficients, the magnetization damping was calculated based on an independent FMR measurement presented in Methods section and included in Table 1.

### Discussion

Fitting the experimental stability diagram to the Eqs (4) and (5) yielded the temperature coefficients of \( k = 0.0014 \) 1/K. This parameter was kept constant for MTJs with different \( t_{FL} \). Remaining parameters of the stability diagrams for each \( t_{FL} \) were modeled independently. For \( t_{FL} = 1.1 \) nm, the following STT components were obtained \( a_{DL} = 0.024 \) T/V and \( a_{FL} = 0.02 \) T/V, however, we note that the modeled stability diagram is only little sensitive to \( a_{FL} \), which agrees with another macrospin approach based on LLG equation presented in Ref. 17. Damping-like torque \( \tau_{DL} \) was thereafter recalculated using Eq. (1):

\[
\tau_{DL} = \frac{M_s \mu_0 \gamma_{LLG}}{\gamma}
\]

where \( \psi \) is the FL volume and \( \tau_{LLG} = -\left(\gamma a_{DL}\right) \), where \( \gamma \) is the gyromagnetic ratio (see details in Methods section). As the result we obtained \( \tau_{DL} = 4.5 \times 10^{-19} \) Nm/V, which agrees well with literature values of STT in case of an in-plane MTJ.\(^{16-20}\) Regarding the VCMA, the best results for MTJ with \( t_{FL} = 1.1 \) nm were obtained for \( k_c = 0.12 \) T/V. Based on the following relation: \( k_c = k_0 \mu_0 M_s a_{DL} \), where \( a_{DL} = 0.82 \) nm is the tunnel barrier thickness, VCMA coefficient of \( k_c = 46 \) fJ/Vm was calculated, which fits well the commonly measured values for CoFeB/MgO devices.\(^{21,22}\) VCMA and STT coefficients of all investigated MTJs are gathered in Table 1.

The damping-like torque component obtained from the stability diagram is almost constant as a function of \( t_{FL} \), which is explained by little dependence of the TMR ratio, and thus the spin polarization, on the ferromagnetic layer thickness in the investigated regime. The VCMA coefficient is comparable for MTJs with \( t_{FL} = 1.3 \) nm and \( 1.5 \) nm and greater than in MTJ with \( t_{FL} = 1.1 \) nm. This behavior is expected, as for thicker \( t_{FL} \), the absolute value of the effective magnetization is reduced and it is more susceptible to the anisotropy change induced by the electric field.\(^{23}\) Moreover, in the same thickness regime, where the transition between perpendicular and in-plane anisotropy occurs, the effective damping increases, which may be attributed to an increase in the level of magnetization disorder.\(^{24}\)

In conclusion, we investigated perpendicular MTJs with composite CoFeB/W/CoFeB FL of different thickness and SyF Co/Pt/Ru-pinned RL. In the investigated FL thickness range we observed an increase of the effective damping extracted from the broadband FMR measurements with increasing FL thickness, which is mainly caused by the reduction of the effective anisotropy. After patterning MTJs into nano-meter scale pillars, we measured the resistance vs. voltage loops for different external magnetic field amplitudes and created the stability diagrams for each FL thickness. To model the experimental data, we included the thermal and VCMA terms into the theoretical STT-switching phase diagram. Based on the fitting procedure, we obtained STT components together with the VCMA coefficient. Our findings shine more light on the switching process of MTJs applied in future MRAM technologies.

### Methods

#### Sample deposition and nano-fabrication.

Multilayer samples were deposited using Singulus TIMARIS sputtering system on chemically-mechanically polished 4-inch Si wafers. After the deposition, the samples were annealed at 400 °C to induce proper crystallographic orientation of Fe-rich CoFeB and PMA of the CoFeB/MgO interfaces. Wafer-level parameters of the deposited multilayers were investigated by CIPT,\(^{25}\) VSM and broadband FMR methods.\(^{26}\) The latter was performed by measuring the complex transmission coefficient (S 21) in a dedicated coplanar waveguide with a 10 × 8 mm unpatterned sample placed face down. The frequency of the vector network analyzer is kept between 4 and 22 GHz, while sweeping the perpendicular magnetic field in ±550 kA/m range.

Selected MTJs were patterned into circular cross-section pillars with diameter ranging from 130 up to 980 nm by means of electron-beam lithography, ion-beam etching and lift-off process.

The transport properties presented in this work were measured for the smallest devices with the area of \( A = 0.013 \) \( \mu m^2 \) in a dedicated probe station equipped with magnetic field source. Four-probe method with a voltage source was used to apply 1-ms long pulses and measure the resistance during this voltage-pulse application. The stability diagrams were determined by sweeping the voltage pulses amplitude in the presence of a given magnetic field. Selected devices were characterized at low temperatures of \( T = 20 \) K in order to determine the temperature influence on the magnetization switching properties.

#### Modelling

Magnetization damping was calculated based on linewidth \( \Delta H \), which was measured using FMR technique and fitted by the Eq. (2):

\[
\Delta H = 4 \pi M_s \alpha \frac{f}{\gamma_0} + \Delta H_0
\]
Magnetization direction of the FL ($\vec{m}_{FL}$) was calculated based on the Landau-Lifschitz-Gilbert (LLG) equation with the following STT components taken into account:

$$\frac{d\vec{m}_{FL}}{dt} = -\gamma_0\vec{m}_{FL} \times \vec{H}_{eff} + \alpha \vec{m}_{FL} \times \frac{d\vec{m}_{FL}}{dt}$$

$$= -\gamma_0\vec{m}_{FL} \times \vec{H}_{eff} + \alpha \vec{m}_{FL} \times \frac{d\vec{m}_{FL}}{dt}$$

$$= -\gamma_0 a_{DL} R \frac{V R_p}{R} (\vec{m}_{FL} \times (\vec{m}_{FL} \times \vec{m}_{RL}))$$

$$= -\gamma_0 a_{FL} \frac{V R_p}{R} (\vec{m}_{FL} \times \vec{m}_{RL})$$

(3)

where $\gamma_0 = \gamma \mu_B$ with the gyromagnetic ratio $\gamma = (\mu_B g)/h = 28 \text{GHz}/T$, $\mu_B$ is the permeability of the free space, $g$ is the Lande spectroscopic splitting factor, $\mu_B$ is the Bohr magneton, $h$ is the reduced Planck's constant, $a_{DL}$ and $a_{FL}$ are the damping-like and field-like STT coefficients expressed in T/V and T/V² units, respectively, $\alpha$ is the magnetization damping, $R$ and $R_p$ are the MTJ resistance in a given state and minimal (parallel state) resistance, $H_{eff}$ is the effective magnetic field: $H_{eff} = H \pm H_W + H_s$, where $H$ is the external perpendicular field, $H_W$ is the switching field and $H_s$ is the offset field.

Stability diagram was modeled based on ref. 13:

$$V_C = \frac{a_{DL} R}{2\alpha a_{FL} R_p} \left[ a_{FL} R_p \right]^2 - \frac{\mu_B g}{a_{FL} R_p} H_{eff}$$

(4)

where, $V_C$ is the switching voltage. It was assumed that damping-like (field-like) torque component is a linear (quadratic) function of the applied current 20. To account for the additional physical effects that contribute to the stability diagram, namely VCMA and temperature, $H_W$ is scaled by the factor:

$$H_W = H_c (1 - k_v V - \sqrt{k_v} T)$$

(5)

where $V$ is the applied voltage, $H_c$ is the coercive field, $k_v$ is the VCMA coefficient 27, 28 and $T$ is the ambient temperature. The dependence of the switching field on the temperature is represented by $k_v$, which in the first approximation is a square-root function 29.

We note that for the discussed device size, the switching process may not be entirely uniform, however in Ref. 30 the authors found substantial deviations from the macrospin evolution only for MTJs of diameter greater than 150 nm.

The damping factor was measured independently by the broadband FMR technique. For each microwave frequency $f$, the complex magnetic susceptibility vs. magnetic field $\chi(H)$ is extracted from $S_2$, measurement by subtracting the magnetic independent offset and time-dependent drift 31:

$$\chi(H) = \frac{M_{eff}(H - M_{sat})}{(H - M_{eff})^2 - H_i^2 - \frac{1}{2} H_i^2 (H - M_{sat})}$$

(6)

where $M_{sat} = M_s - H_K$ is the effective magnetization, magnetization saturation and perpendicular magnetic anisotropy field, respectively, $\Delta H$ is the linewidth and $H_i = 2\pi f(\gamma \mu_B)$.

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Acknowledgements
The authors would like to express their gratitude to Prof. T. Stobiecki for a fruitful discussion and his critical remarks. The project is supported by Polish National Center for Research and Development grant No. LIDER/467/L-6/14/NCBR/2015. Nanofabrication process was performed at Academic Center for Materials and Nanotechnology of AGH University. J.Ch. acknowledges the scholarship under Marian Smoluchowski Krakow Research Consortium KNOW programme. Numerical calculations were supported by PL-GRID infrastructure.

Author Contributions
J.W. designed sample stack, performed sample deposition and carried out VSM and CIP measurements, S.Z. and W.S. performed FMR measurements and carried out nanostructurization process, P.R., S.Z. and W.S. performed transport measurements, M.C. created the stability diagram model and performed fitting with an input from W.S., J.Ch. analyzed FMR data and calculated STT and VCMA parameters together with M.F. W.S. wrote the manuscript and supervised the project. All authors reviewed the manuscript.

Additional Information
Competing Interests: The authors declare that they have no competing interests.

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