Temperature study of spin torque efficiencies in Ta/CoFeB/MgO with perpendicular magnetic anisotropy

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SWISS CONTRIBUTION

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MOTIVATION

Comprehensive approach to spin transfer torque via spin Hall effect in Ta/CoFeB requires precise characterization of Ta microstructure, examination of Ta/CoFeB interface and Ta layer influence on magnetic properties, which leads to extension of spin diffusion model:

$$\Theta_{SH} \equiv \Theta_{SH}(\theta^N_{SH}, \theta^I_{SH}, \theta^F_{AH})$$

- Effective spin Hall angle: Θ_{SH}
- spin Hall angle of nonmagnetic metal: θ^N_{SH}
- spin Hall angle of the interfacial layer: θ^I_{SH}
- anomalous Hall angle of the ferromagnetic metal: θ^F_{AH}

SAMPLES CHARACTERIZATION

d_N Ta/ 0.9 $Co_{40}Fe_{40}B_{20}$/ 5 MgO/ 1 Ta d_N = 5, 10, 15 [nm]

Sputtering deposition method, 20 min post-annealing in 330˚

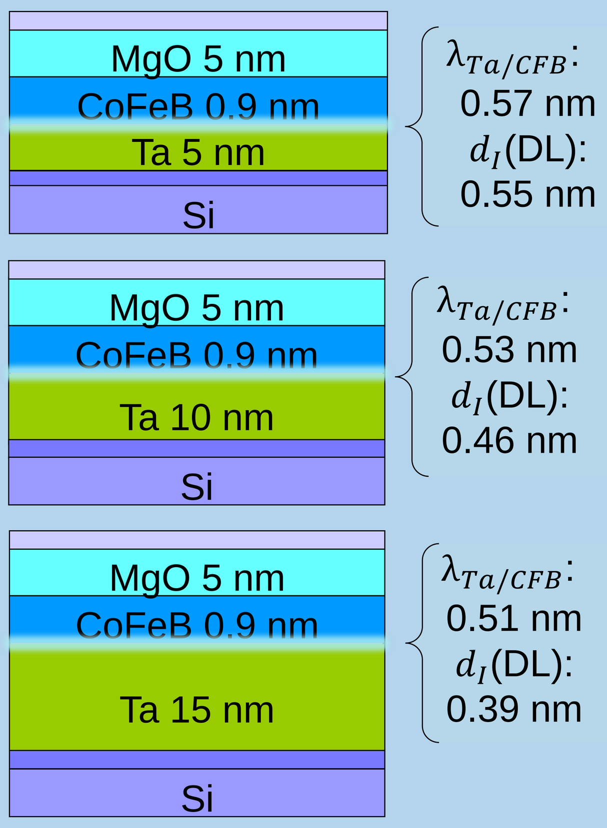
XRD: amorphous 5 nm Ta, β-phase in 10 nm and 15 nm of Ta

XRR: rough Ta/CoFeB interface $\lambda_{Ta/CFB} \sim 0.57 - 0.51$ nm

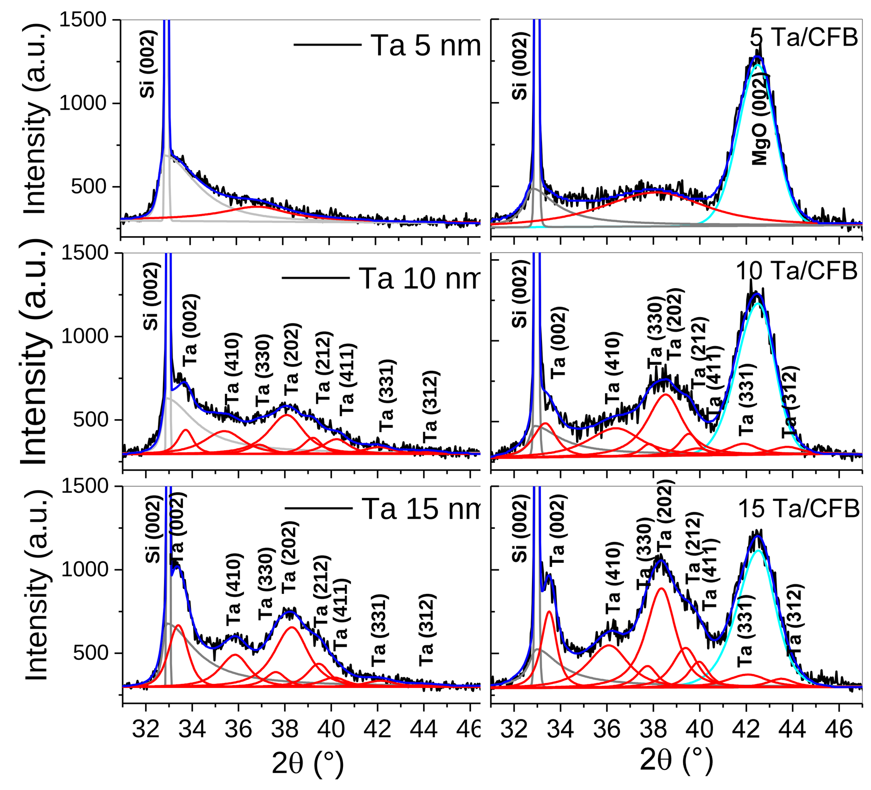
The highest resistivity for amorphous 5 nm Ta

Magnetic properties: Perpendicular magnetic anisotropy, Bloch low temperature dependence of spontaneous magnetization M, characteristic minimum of saturation magnetization M_S for $d_N \approx 3\ nm$

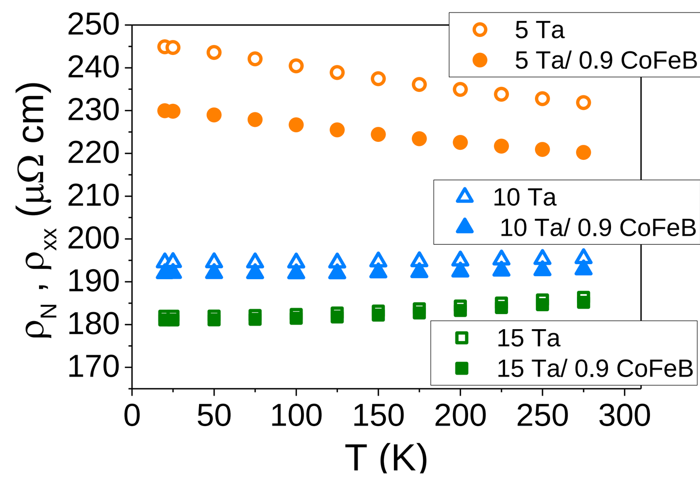
Significant magnetic dead layer (DL) thickness ≈ 0.55-0.39 nm



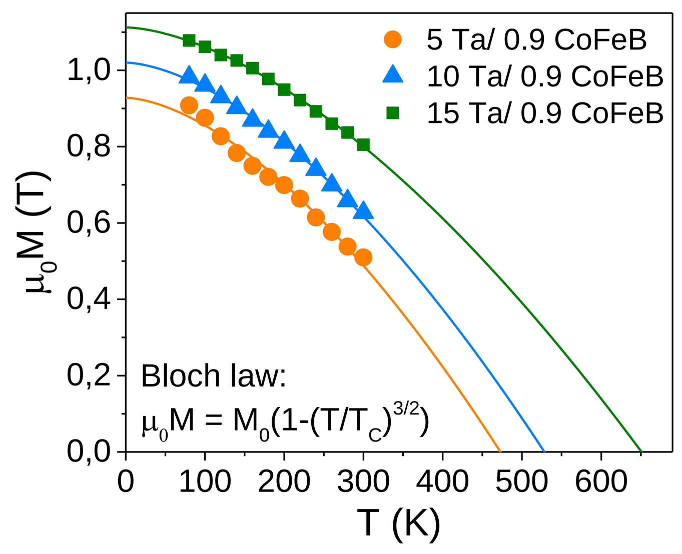
θ-2θ XRD



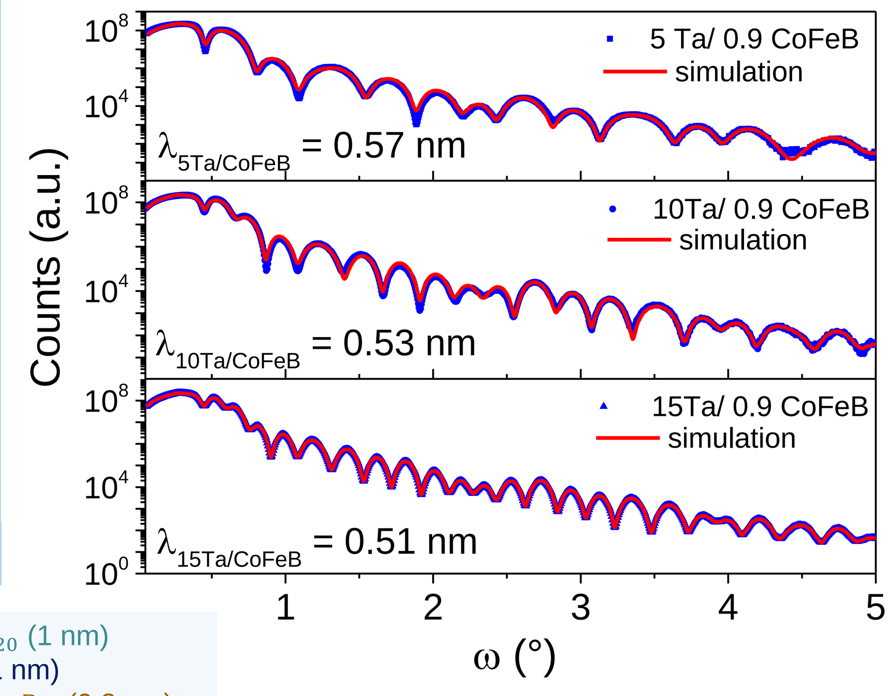
RESISTIVITY

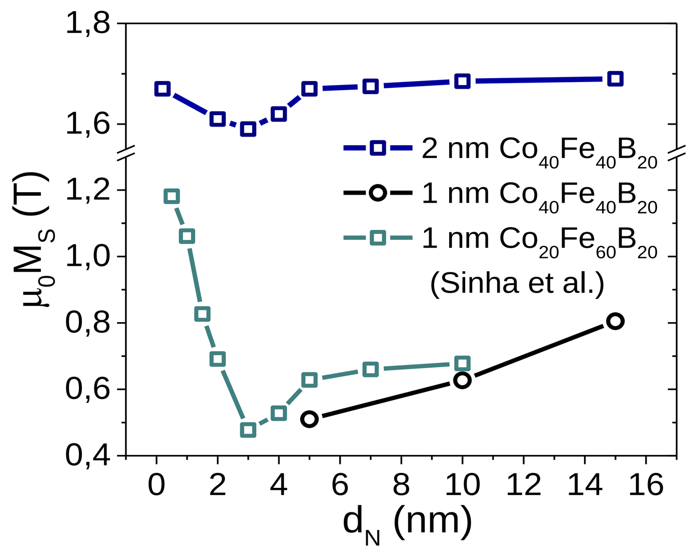


MAGNETIC PROPERTIES



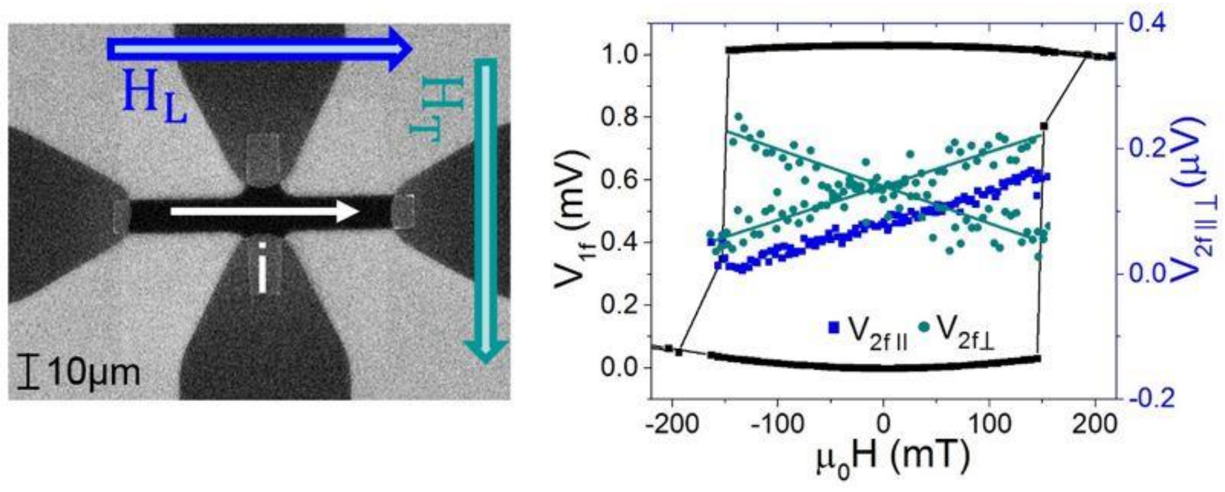
XRR



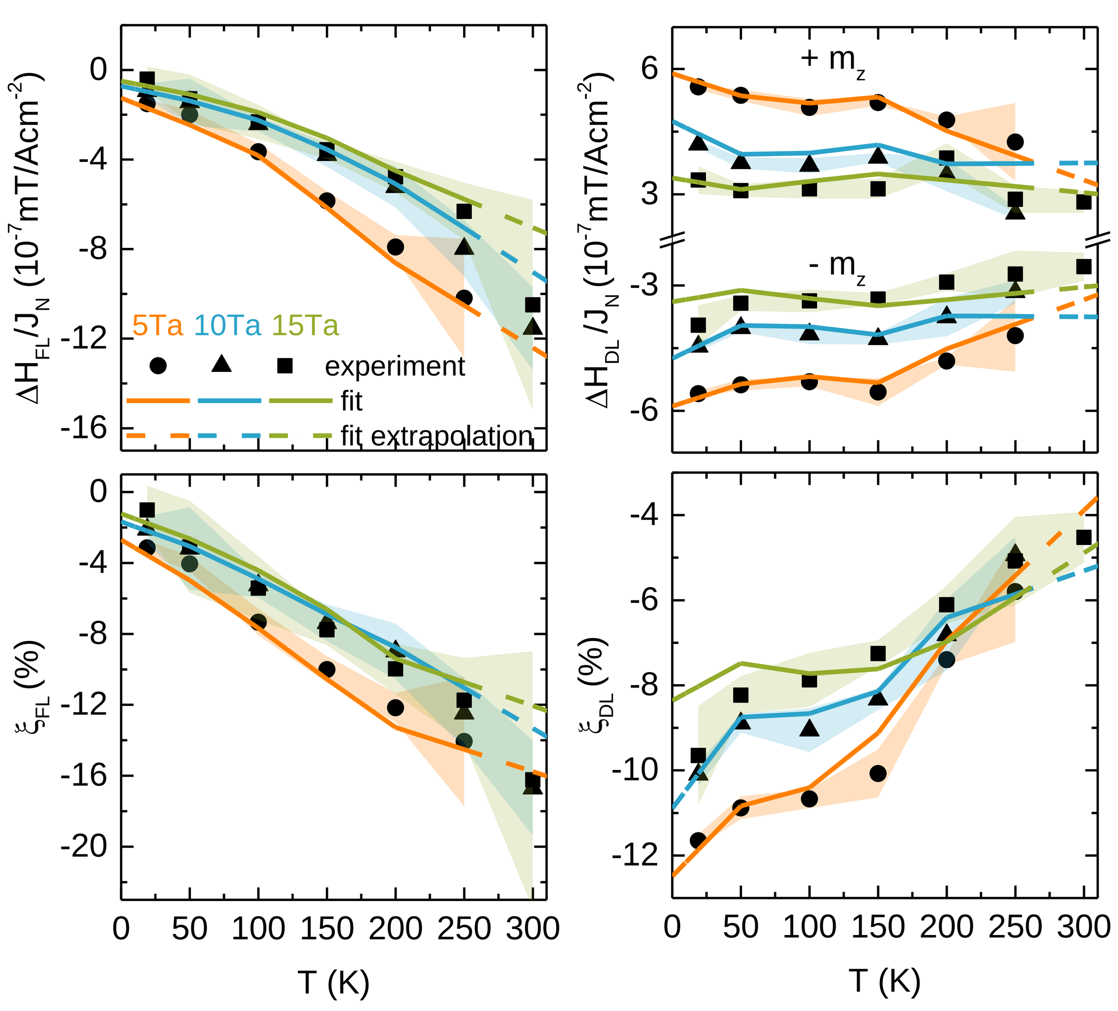


J. Sinha et al. APL **102**, 242405 (2013) Ta(0-10 nm)/$Co_{20}Fe_{60}B_{20}$ (1 nm)
J. Kim et al. PRB **89**, 174424 (2014) Ta(1.3 nm)/$Co_{20}Fe_{60}B_{20}$ (1 nm)
X. Qiu et al. Scientific Reports **4**, 4491 (2014) Ta(2 nm)/$Co_{40}Fe_{40}B_{20}$ (0.8 nm)
C. Avci et al. PRB **89**, 214419 (2014) Ta(3 nm)/$Co_{60}Fe_{20}B_{20}$ (0.9 nm)
L. Liu et al. (after C. Avci) Ta(6 nm)/CoFeB(1 nm)
C. Zhang et al. Appl. Phys. Lett. **103**, 262407 (2013) Ta(2.5 nm)/CoFeB(1 nm)

HARMONIC HALL VOLTAGE MEASUREMENTS



RESULTS AND FITTING



SPIN TORQUE EFFICIENCIES

Longitudinal ((anti)damping-like DL) and transverse (field-like FL) components of spin-orbit torque-induced effective field:

$$\Delta H_{DL,\,FL} = -2\frac{\partial V_{2f}/\partial H_{DL,FL}}{\partial^2 V_{1f}/\partial H^2_{DL,FL}} \qquad \frac{\Delta R_{PHE}}{\Delta R_{AHE}} < 3\ \%$$

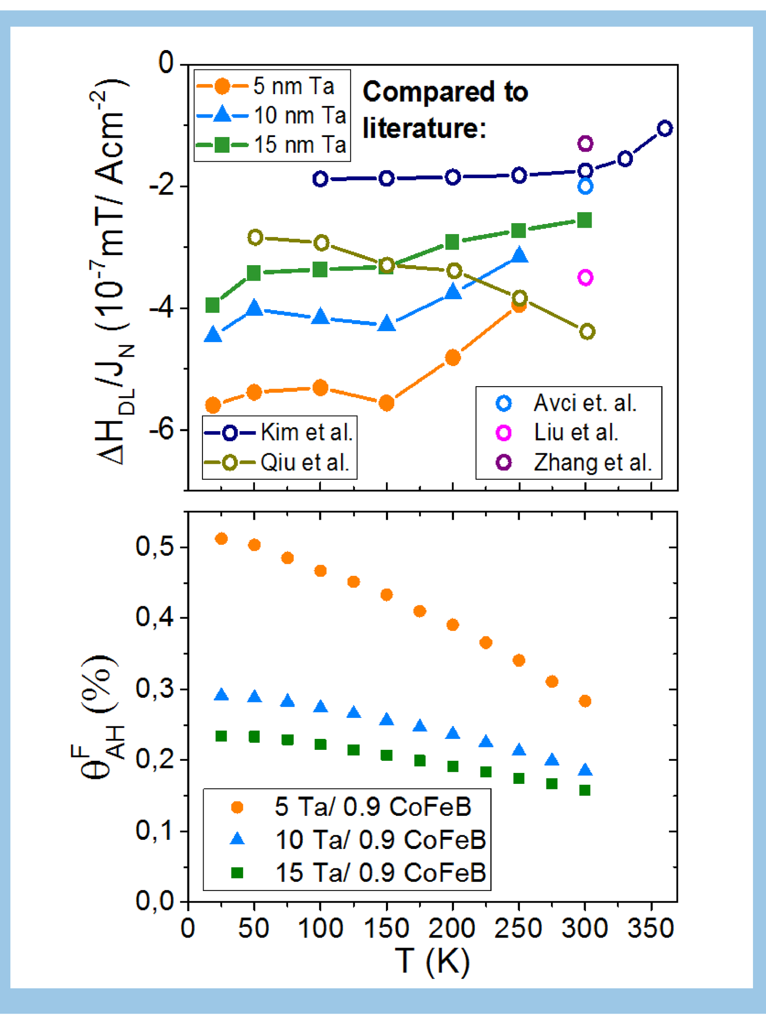
(Anti)damping-like and field-like torque efficiencies:

$$\xi_{DL,\,FL} = \Delta H_{DL,FL} \cdot 2e\mu_0 M_S d_F / J_N \cdot \hbar$$

ANOMALOUS HALL EFFECT

Anomalous Hall angle as a ratio of AH resistivity and longitudinal resistivity :

$$\theta^F_{AH} = \frac{\rho_{AHE}}{\rho_{xx}} < 0.5\ \%$$



EXTENTION TO SPIN DIFFUSION MODEL

Assumptions:

- SML = 5 %
- $\lambda_N = 1.5$ nm (spin diffusion length in Ta)
- λ_{N}, SML ~ const (T)

Spin Memory Loss:

$$\text{SML} = \left(1 - \exp\left(\frac{d_I}{\lambda_I}\right)\right) \cdot 100\%$$

(d_I – interface thickness, λ_I – spin diffusion length)

Drift diffusion equations for spin currents in the nonmagnetic metal (N) and in the interface layer (I):

$$j^N_s(z) = -\frac{1}{2e\rho_N}\frac{\partial \mu^N_s(z)}{\partial z} - \theta^N_{SH} J_{N\hat{y}}$$

$$j^I_s(z) = -\frac{1}{2e\rho_I}\frac{\partial \mu^I_s(z)}{\partial z} - \theta^I_{SH} J_{N\hat{y}}$$

$$\theta^I_{SH} = \alpha \cdot \theta^N_{SH}$$

(Anti)damping-like component:

$$\Delta H_{DL} = \mp\frac{\hbar}{2e}\frac{J_N}{\mu_0 M_S d_F}\theta^N_{SH}\frac{\tanh\left(\frac{d_N}{2\lambda_N}\right)\mathrm{csch}\left(\frac{d_I}{\lambda_I}\right)+\alpha\left[\tanh\left(\frac{d_I}{2\lambda_I}\right)\coth\left(\frac{d_N}{\lambda_N}\right)-\frac{\rho_I\lambda_I}{\rho_N\lambda_N}\right]}{\coth\left(\frac{d_N}{\lambda_N}\right)\coth\left(\frac{d_I}{\lambda_I}\right)+\frac{\rho_I\lambda_I}{\rho_N\lambda_N}}\frac{g_r(1+g_r)+g_i^2}{(1+g_r)^2+g_i^2},\ \begin{matrix}+m_z\\-m_z\end{matrix}$$

Field-like component:

$$\Delta H_{FL} = -\frac{\hbar}{2e}\frac{J_N}{\mu_0 M_S d_F}\theta^N_{SH}\frac{\tanh\left(\frac{d_N}{2\lambda_N}\right)\mathrm{csch}\left(\frac{d_I}{\lambda_I}\right)+\alpha\left[\tanh\left(\frac{d_I}{2\lambda_I}\right)\coth\left(\frac{d_N}{\lambda_N}\right)-\frac{\rho_I\lambda_I}{\rho_N\lambda_N}\right]}{\coth\left(\frac{d_N}{\lambda_N}\right)\coth\left(\frac{d_I}{\lambda_I}\right)+\frac{\rho_I\lambda_I}{\rho_N\lambda_N}}\frac{g_i}{(1+g_r)^2+g_i^2}$$

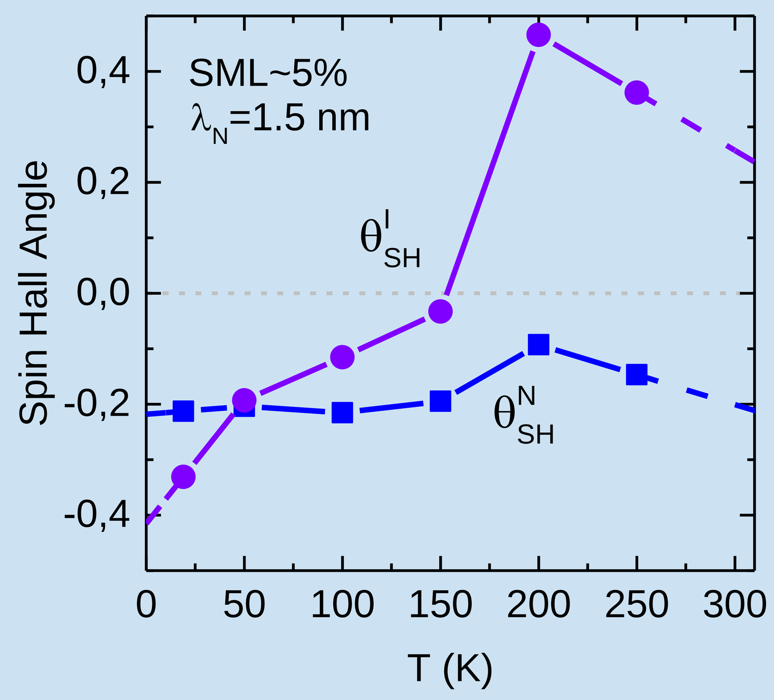
Real and imaginary parts of spin-mixing conductance

G_r(T) ~ const,
G_i (T) ~ T

$$g_{r,i} = 2G_{r,i}\frac{\coth\left(\frac{d_N}{2\lambda_N}\right)\coth\left(\frac{d_I}{\lambda_I}\right)+\frac{\rho_I\lambda_I}{\rho_N\lambda_N}}{\frac{1}{\rho_I\lambda_I}\coth\left(\frac{d_N}{\lambda_N}\right)+\frac{1}{\rho_N\lambda_N}\coth\left(\frac{d_I}{\lambda_I}\right)}$$

CONCLUSION

Extended spin diffusion model allows to obtain the temperature dependences of θ^N_{SH} and θ^I_{SH} components.



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