Spin transport and magnetization dynamics in dual spin valves with perpendicular and in-plane polarizers: numerical study

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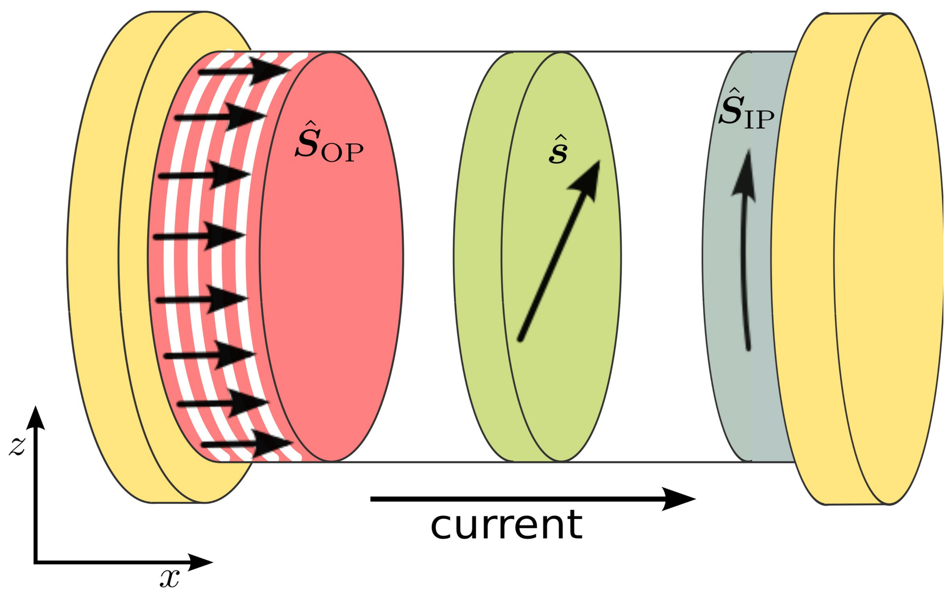
We studied the current-induced magnetization dynamics in a metallic spin valve with one free magnetic layer located between two polarizers separated by nonmagnetic spacers. One of the polarizers is used as an analyzing layer with in-plane magnetization while the second one consists of L thin magnetic films with out-of-plane anisotropy and hence its magnetization is perpendicular to the layer's plane.
The complex out-of-plane polarizer has been modeled as one magnetic layer with effective parameters calculated using a first-principles tight-binding muffin tin orbital wave-function matching scheme. The dynamics of the free layer's magnetization has been modelled in the single-domain approximation by Landau-Lifshitz-Gilbert equation with in-plane and out-of-plane STT components.



Studied structure: Cu-OPP/Cu(6)/Py(5)/Cu(8)/Py(12)-Cu, where OPP is the out-of-plane polarizer $[\mathrm{Co(2ML)/Cu(2ML)}]_{L-1}/\mathrm{Co(2ML)}$, and Py stands for Permalloy. Numbers in the brackets express the layer thicknesses in nanometers. ML=atomic monolayer.

Transport throught the ballistic out-of-plane polarizer

We consider a ballistic polarizer acting as a magnetic scatterer between two nonmagnetic layers, i.e. an effective interface between the left (L) and right (R) nonmagnetic layer. From the diffusive transport model we know the general solutions of the electrochemical potential, $\mu_0^{\rm L/R}(x)$, spin acculation, $\boldsymbol{\mu}^{\rm L/R}(x)$, and spin current, $\boldsymbol{j}^{\rm R/L}(x)$, in both nonmagnetic layers.

Our goal is to etablish equations obeyed at the interfaces of the spin valve which enable us to calculate the unknow parameters.

Longitudinal spin components

The transport of the longitudinal spin components through a ballistic polarizer shall be described in the same way as for a N/F interface:

$$e^2 j_0 = (\tilde{G}_\uparrow + \tilde{G}_\downarrow)(\mu_0^{\rm R} - \mu_0^{\rm L}) + (\tilde{G}_\uparrow - \tilde{G}_\downarrow)(\mu_z^{\rm R} - \mu_z^{\rm L}),$$
$$e^2 j_z = (\tilde{G}_\uparrow - \tilde{G}_\downarrow)(\mu_0^{\rm R} - \mu_0^{\rm L}) + (\tilde{G}_\uparrow + \tilde{G}_\downarrow)(\mu_z^{\rm R} - \mu_z^{\rm L}).$$

where the spin dependent conductances, $\tilde{G}_\uparrow$ and $\tilde{G}_\downarrow$ are *Shep-corrected.*

Transversal spin components

Following Tserkovnyak et al. [Rev. Mod. Phys. **77**, 1375 (2005)], in the local coordinate system of $\hat{s}$, where $\hat{s} = \hat{\mathbf{e}}_z$,

$$e^2 \boldsymbol{j}_{\perp\rm R} = -2\Big\{ \left(g_r^{\uparrow\downarrow}\mu_x^{\rm R} - g_i^{\uparrow\downarrow}\mu_y^{\rm R} - t_r^{\prime\uparrow\downarrow}\mu_x^{\rm L} + t_i^{\prime\uparrow\downarrow}\mu_y^{\rm L}\right)\hat{\mathbf{e}}_x + \left(g_r^{\uparrow\downarrow}\mu_y^{\rm R} + g_i^{\uparrow\downarrow}\mu_x^{\rm R} - t_r^{\prime\uparrow\downarrow}\mu_y^{\rm L} - t_i^{\prime\uparrow\downarrow}\mu_x^{\rm L}\right)\hat{\mathbf{e}}_y \Big\},$$
$$e^2 \boldsymbol{j}_{\perp\rm L} = -2\Big\{ \left(g_r^{\prime\uparrow\downarrow}\mu_x^{\rm L} - g_i^{\prime\uparrow\downarrow}\mu_y^{\rm L} - t_r^{\uparrow\downarrow}\mu_x^{\rm R} + t_i^{\uparrow\downarrow}\mu_y^{\rm R}\right)\hat{\mathbf{e}}_x + \left(g_r^{\prime\uparrow\downarrow}\mu_y^{\rm L} + g_i^{\prime\uparrow\downarrow}\mu_x^{\rm L} - t_r^{\uparrow\downarrow}\mu_y^{\rm R} - t_i^{\uparrow\downarrow}\mu_x^{\rm R}\right)\hat{\mathbf{e}}_y \Big\}.$$

The generalized Ohm law for the transversal spin currents results in

$$e^2 j_{{\rm R}x} = -2g_r^{\uparrow\downarrow}\mu_x^{\rm R} + 2g_i^{\uparrow\downarrow}\mu_y^{\rm R} + 2t_r^{\uparrow\downarrow}\mu_x^{\rm L} - 2t_i^{\uparrow\downarrow}\mu_y^{\rm L},$$
$$e^2 j_{{\rm R}y} = -2g_r^{\uparrow\downarrow}\mu_y^{\rm R} - 2g_i^{\uparrow\downarrow}\mu_x^{\rm R} + 2t_r^{\uparrow\downarrow}\mu_y^{\rm L} + 2t_i^{\uparrow\downarrow}\mu_x^{\rm L},$$
$$e^2 j_{{\rm L}x} = -2g_r^{\uparrow\downarrow}\mu_x^{\rm L} + 2g_i^{\uparrow\downarrow}\mu_y^{\rm L} + 2t_r^{\uparrow\downarrow}\mu_x^{\rm R} - 2t_i^{\uparrow\downarrow}\mu_y^{\rm R},$$
$$e^2 j_{{\rm L}y} = -2g_r^{\uparrow\downarrow}\mu_y^{\rm L} - 2g_i^{\uparrow\downarrow}\mu_x^{\rm L} + 2t_r^{\uparrow\downarrow}\mu_y^{\rm R} + 2t_i^{\uparrow\downarrow}\mu_x^{\rm R},$$

where we considere that $\tilde{G}_{\uparrow\downarrow} = g_r^{\uparrow\downarrow} + i g_i^{\uparrow\downarrow}$ and $\tilde{T}_{\uparrow\downarrow} = t_r^{\uparrow\downarrow} + i t_i^{\uparrow\downarrow}$ are *Shep-corrected* mixing conductance and mixing transmission, respectivelly.

Spin torque definition

Spin transfer torque (STT) acting on the free layer, $\tau_\parallel = \tau_{OP\parallel} + \tau_{IP\parallel}$ and $\tau_\perp = \tau_{OP\perp} + \tau_{IP\perp}$, can be writtens as

$$\tau_\parallel = I\hat{s} \times \left[\hat{\boldsymbol{S}}_{\rm OP} \times \left(a_{\rm OP}\hat{\boldsymbol{S}}_{\rm OP} + a_{\rm IP}\hat{\boldsymbol{S}}_{\rm IP}\right)\right],$$
$$\tau_\perp = I\hat{s} \times \left(b_{\rm OP}\hat{\boldsymbol{S}}_{\rm OP} + b_{\rm IP}\hat{\boldsymbol{S}}_{\rm IP}\right),$$

where I is the current density, which is positive when electrons flow from the layer F_2 towards F_0. The parameters $a_{\rm OP/IP}$ and $b_{\rm OP/IP}$ are calculated in frame of a diffusive transport model [Barnaś et al, PRB **72**, 024426 (2005)]

$$a_{\rm OP} = -\frac{\hbar}{2}\frac{j'_{1y}|_{\rm N_1/F_1}}{I\sin\theta_{\rm OP}}, \qquad b_{\rm OP} = \frac{\hbar}{2}\frac{j'_{1x}|_{\rm N_1/F_1}}{I\sin\theta_{\rm OP}},$$
$$a_{\rm IP} = -\frac{\hbar}{2}\frac{j''_{2y}|_{\rm F_1/N_2}}{I\sin\theta_{\rm IP}}, \qquad b_{\rm IP} = \frac{\hbar}{2}\frac{j''_{2x}|_{\rm F_1/N_2}}{I\sin\theta_{\rm IP}},$$

where the angles $\theta_{\rm OP}$ and $\theta_{\rm IP}$ are given by $\cos\theta_{\rm OP} = \hat{s}\cdot\hat{\boldsymbol{S}}_{\rm OP}$ and $\cos\theta_{\rm IP} = \hat{s}\cdot\hat{\boldsymbol{S}}_{\rm IP}$. In the latter expressions the spin current components are tranformed from their local frame (with j_z component along the z axis) into a local frame of F_i.

Magnetization dynamics

In the macrospin approximation, magnetization dynamics of the free layer is described by the Landau-Lifshitz-Gilbert (LLG) equation,

$$\frac{\mathrm{d}\hat{s}}{\mathrm{d}t} + \alpha\hat{s} \times \frac{\mathrm{d}\hat{s}}{\mathrm{d}t} = \boldsymbol{\Gamma},$$
$$\boldsymbol{\Gamma} = -|\gamma_{\rm g}|\mu_0\hat{s} \times \mathbf{H}_{\rm eff} + \frac{|\gamma_{\rm g}|}{M_{\rm s}d}\boldsymbol{\tau},$$

where $\hat{s}$ is a unit vector along the net spin moment and d stands for thickness of the free layer. The effective magnetic field is

$$\mathbf{H}_{\rm eff} = -H_{\rm app}\hat{\mathbf{e}}_z - H_{\rm ani}(\hat{s}\cdot\hat{\mathbf{e}}_z)\hat{\mathbf{e}}_z + \mathbf{H}_{\rm dem}(\hat{s}) + \mathbf{H}_{\rm int}(\hat{\boldsymbol{S}}_{\rm OP}, \hat{\boldsymbol{S}}_{\rm IP}),$$

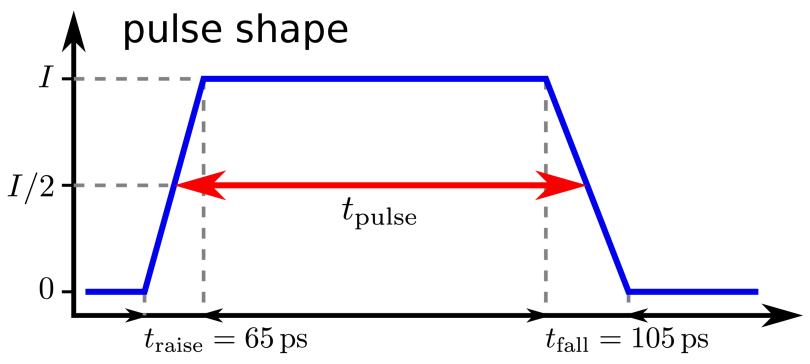
where $\hat{\boldsymbol{S}}_{\rm OP}$ and $\hat{\boldsymbol{S}}_{\rm IP}$ are net spin moment of out-of-plane and in-plane polarizers, respectively. Moreover, $H_{\rm app}$ is the external magnetic field, $H_{\rm ani}$ is the uniaxial anisotropy field, and $\mathbf{H}_{\rm dem}$ is the self-demagnetization field; $\mathbf{H}_{\rm int}$ describes the magnetostatic influence of polarizers on the free layer. Thermal effects have been included via a stochastic field $\mathbf{H}_{{\rm th}\,i}$ which components obey $\langle H_{{\rm th}\,\zeta}(t)\rangle = 0$ and $\langle H_{{\rm th}\,\zeta}(t)H_{{\rm th}\,\xi}(t')\rangle = 2D\delta_{\zeta\xi}\delta(t-t')$, where $\zeta, \xi = x, y, z$, and

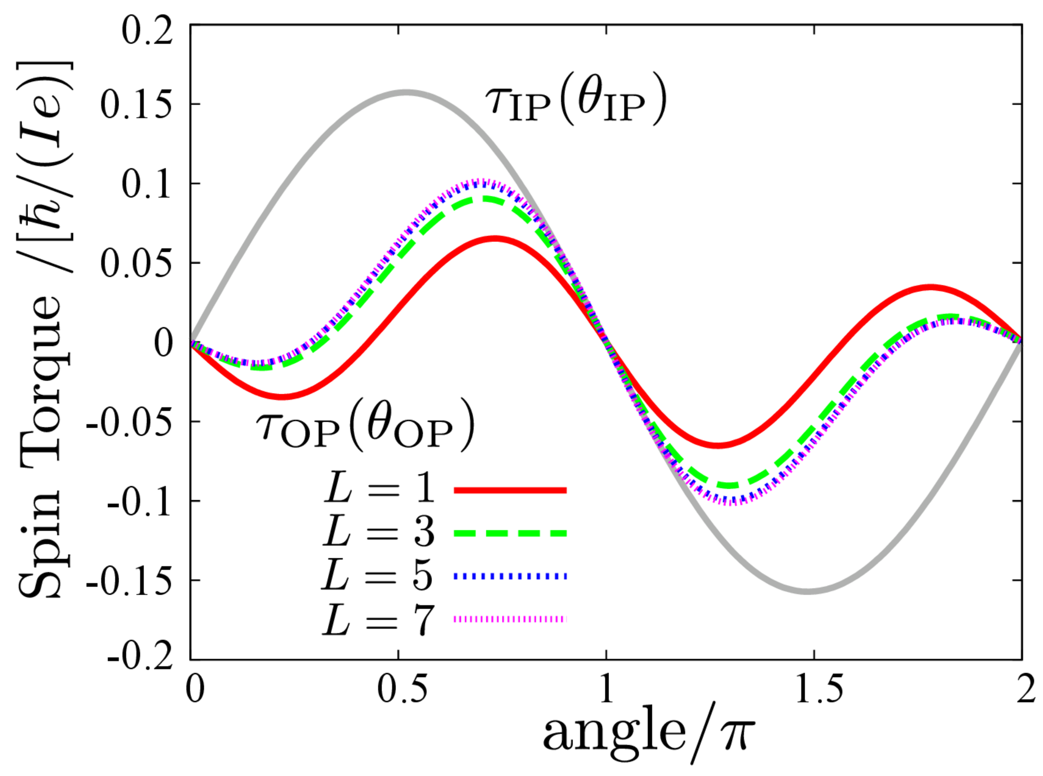
$$D = \frac{\alpha k_{\rm B}T_{\rm eff}}{\gamma_{\rm g}\mu_0^2 M_{\rm s}V},$$

where $k_{\rm B}$ is the Boltzmann constant, and V is the volume of the free layer.

Current-induced switching

We studied the current-induced switching from parallel (P) to antiparallel (AP) magnetic configurations of $\boldsymbol{s}$ and $\boldsymbol{S}_{\rm IP}$ and vice versa under a quasi-rectangular electric pulse at temperature T=300K. The switching probability was calculated from 1000 independent simualtions for several pulse durations as a function of current density.





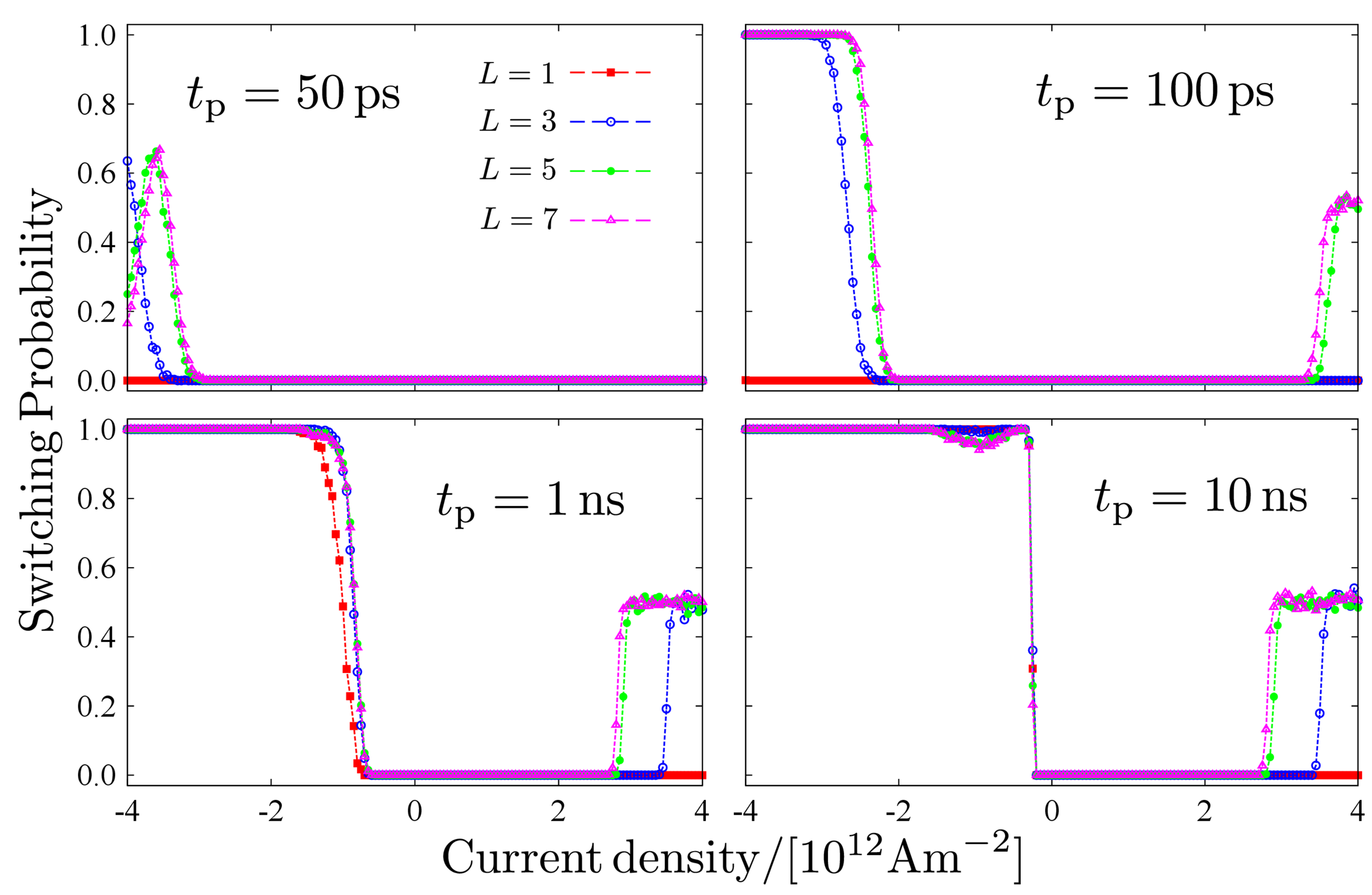
Angular dependence of spin transfer torque

Making use of the diffusive transport model we obtain a standard spin transfer torque acting on the right interface of the free layer (IP) (grey) and wavy-like angular dependence of the spin induced by the out-of-plane polarizer (OP). The wavy torque is modified by the number of Co/Cu layer in the ou polarizer.

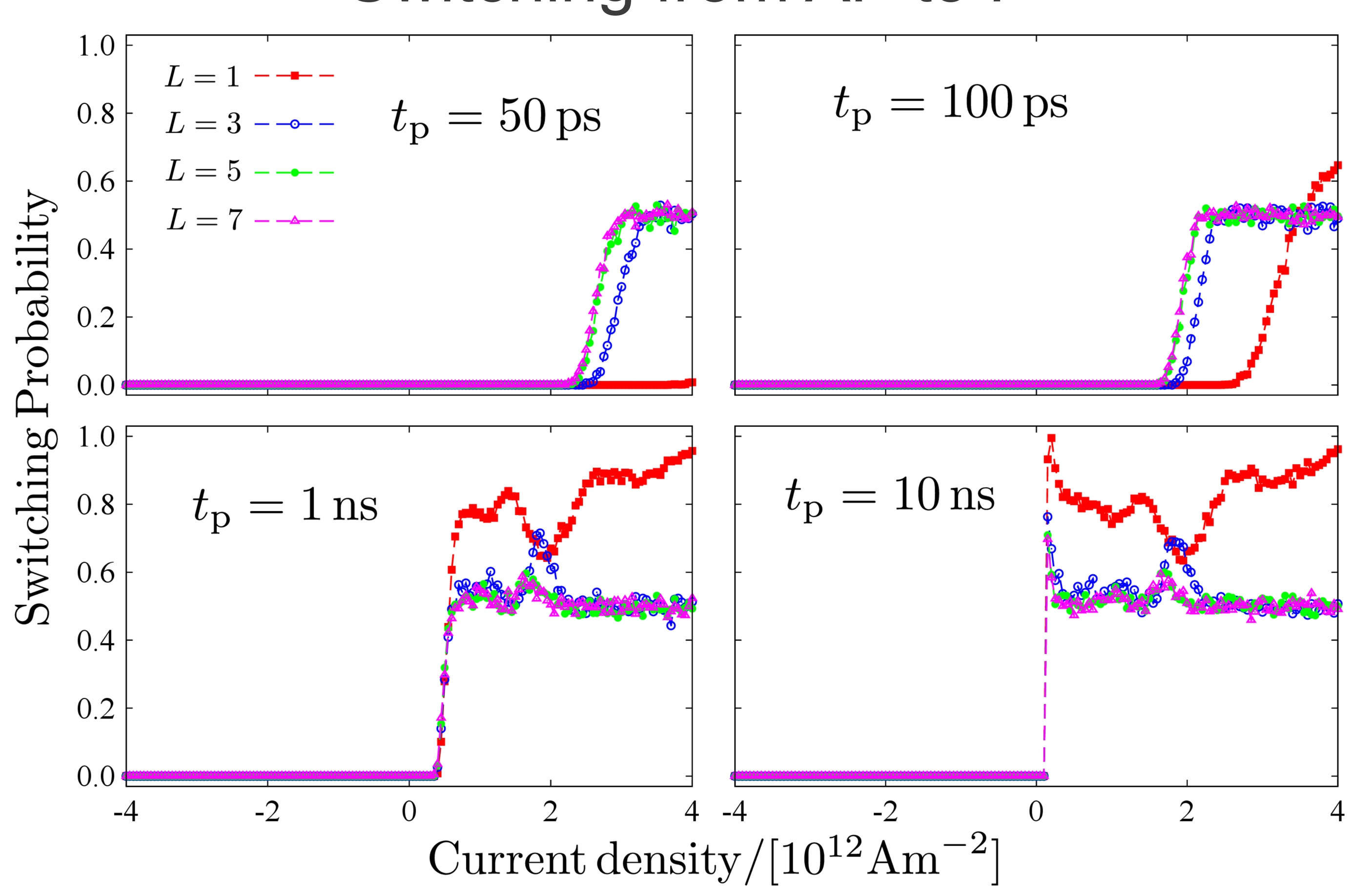
Results

- We introduce a simple model of diffusive spin transport with a ballistic out-of-plane polarizer.
- For short pulses the out-of-plane polarizer improves the switching probability and reduces the criticall current.
- For longer pulses the in-plane polarizer is responsible for the switching while the out-of-plane polarizer decreases the switching probability.
- The wavy torque angular dependence of spin torque induced by the perpendicular polarizer causes a strong asymmetry in the switcihng probability from P to AP and from AP to P configuration.

Switching from P to AP



Switching from AP to P



SWISS CONTRIBUTION