Transport-dependent current-induced switching of symmetric and asymmetric spin valves

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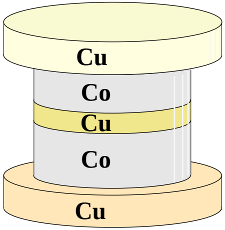
Spin valves

Definition (Spin valve)

Nanostructure which consists of stacked layers of magnetic and nonmagnetic materials, that alternates its electrical resistance depending of alignment of magnetic layers.



Layers

- Reference (fixed) layer
- Sensing (free) layer

Magnetization Dynamics

Landau-Lifshitz-Gilbert equation

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

- γ_g gyromagnetic ratio, μ_0 vacuum permeability
- $\hat{\mathbf{s}}$ unit vector along the net spin moment
- α the damping parameter
- M_s saturated magnetization
- d_3 thickness of the sensing layer

Effective field

$$\mathbf{H}_\mathrm{eff} = -H_\mathrm{ext}\hat{\mathbf{e}}_z - H_\mathrm{ani}\,(\hat{\mathbf{s}} \cdot \hat{\mathbf{e}}_z)\,\hat{\mathbf{e}}_z + \mathbf{H}_\mathrm{demag}$$

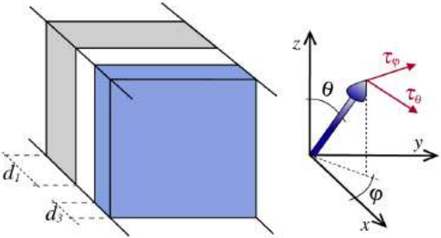
Spin-torques

In-plane component

$$\tau_\theta \propto I\,\hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \hat{\mathbf{S}})$$

Out-of-plane component

$$\tau_\phi \propto I\,\hat{\mathbf{s}} \times \hat{\mathbf{S}}$$



Ballistic transport

J. C. Slonczewski
Current-driven excitations of magnetic multilayers
J. Magn. Magn. Mater. **159**, L1-L7 (1996)

In-plane component

$$\boldsymbol{\tau}_\theta = \frac{g\mu_\mathrm{B} I}{(1+\alpha^2)de}\,\epsilon(\theta,\eta)\,\hat{\mathbf{s}}\times(\hat{\mathbf{s}}\times\hat{\mathbf{S}})$$

Out-of-plane component

$$\boldsymbol{\tau}_\phi = -\frac{g\mu_\mathrm{B}\alpha I}{(1+\alpha^2)de}\,\epsilon(\theta,\eta)\,\hat{\mathbf{s}}\times\hat{\mathbf{S}}$$

Spin torque efficiency function

$$\epsilon(\theta,\eta) = \left[-4+(1+\eta)^3\,(3+\cos\theta)\,/4\eta^{3/2}\right]^{-1}$$

- η effective Fermi-level polarization factor
- d thickeness of sensing layer
- θ angle between sensing and reference layer magetization

Diffusive transport

J. Barnaś, A. Fert, M. Gmitra, I. Weymann, V. K. Dugaev
From giant magnetoresistance to current-induced switching by spin transfer
Phys. Rev. B **72**, 024426 (2005)

In-plane component

$$\boldsymbol{\tau}_\theta = a\, I\, \hat{\mathbf{s}} \times (\hat{\mathbf{s}} \times \hat{\mathbf{S}})$$

Out-of-plane component

$$\boldsymbol{\tau}_\phi = b\, I\, \hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

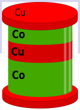
Angular dependence of spin-tranfer torque

$$a = \frac{\hbar}{Ie^2}\left[\mathrm{Re}\{G_{\mathrm{mix}}\}\left[\cot\theta\,(g_x\cos\varphi + g_y\sin\varphi) - g_z\right] + \frac{\mathrm{Im}\{G_{\mathrm{mix}}\}}{\sin\theta}\,(g_x\sin\varphi - g_y\cos\varphi)\right]$$

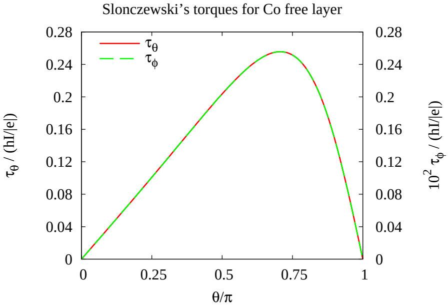
$$b = -\frac{\hbar}{Ie^2}\left[\frac{\mathrm{Re}\{G_{\mathrm{mix}}\}}{\sin\theta}\,(g_x\sin\varphi - g_y\cos\varphi) - \mathrm{Im}\{G_{\mathrm{mix}}\}\left[\cot\theta\,(g_x\cos\varphi + g_y\sin\varphi) - g_z\right]\right]$$

- $\mathbf{g} \equiv (g_x, g_y, g_z)$ spin accumulation (vector in spin-space)
- G_{mix} mixing conductance (interfacial parameter)
- θ angle between sensing and reference layer magetization

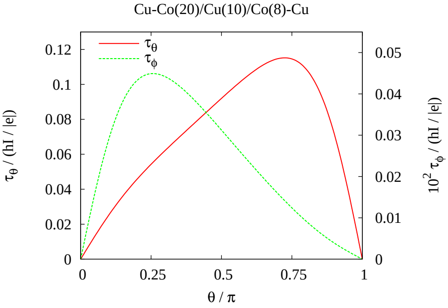
Cu-Co(20)/Cu(10)/Co(8)-Cu



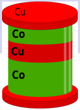
Ballistic regime



Diffusive regime

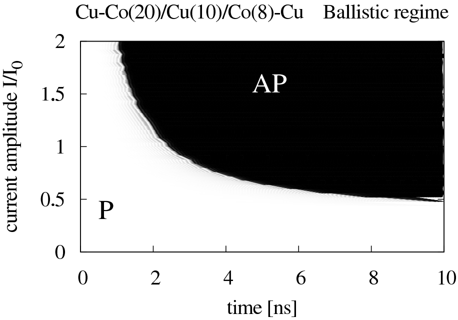


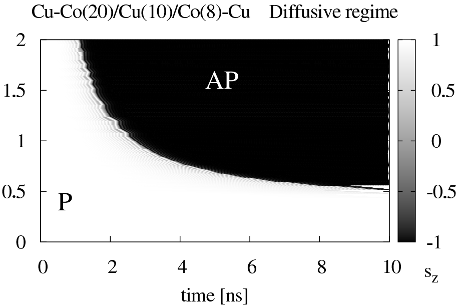
Cu-Co(20)/Cu(10)/Co(8)-Cu



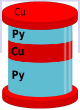
Ballistic regime

Diffusive regime

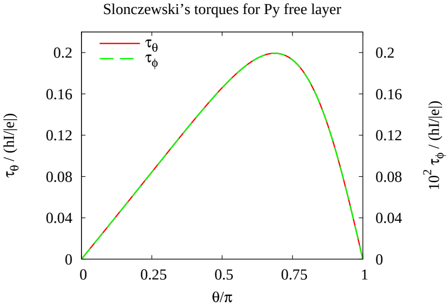




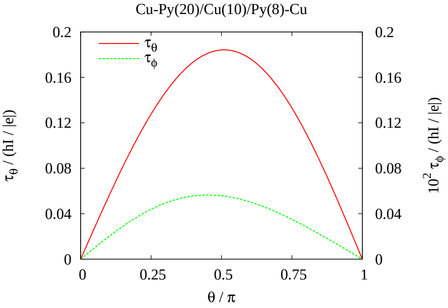
Cu-Py(20)/Cu(10)/Py(8)-Cu



Ballistic regime



Diffusive regime



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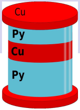
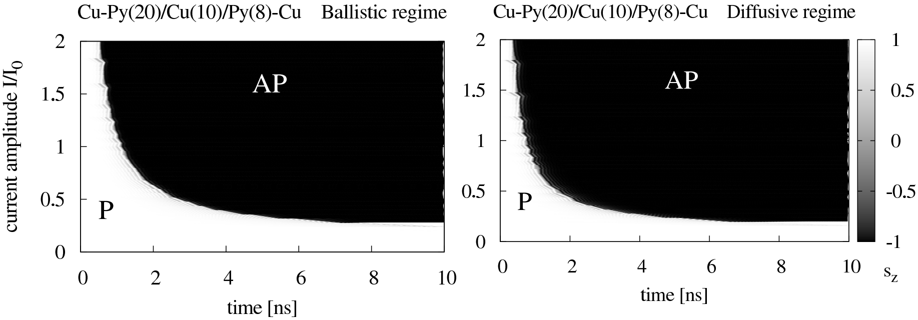
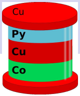


Ballistic regime

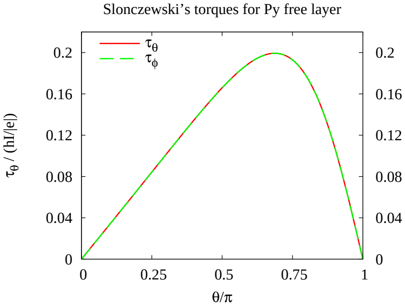
Diffusive regime



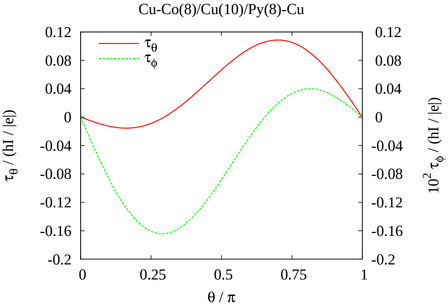
Cu-Co(8)/Cu(10)/Py(8)-Cu



Ballistic regime



Diffusive regime



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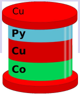
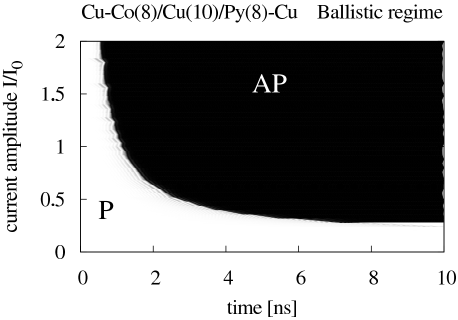
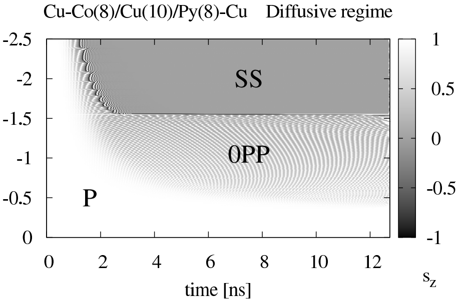


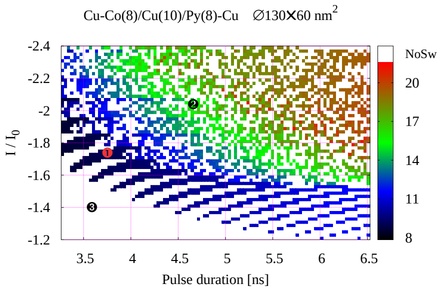
Ballistic regime

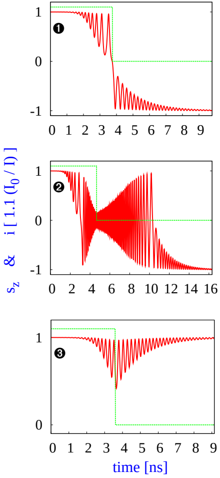
Diffusive regime



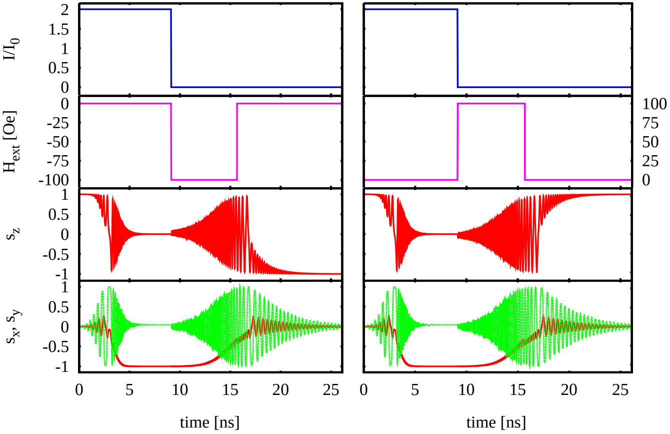


Switching in Co/Cu/Py valve: *pulse switching diagram*





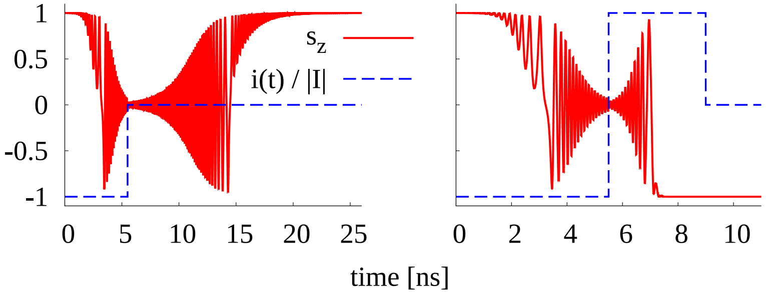
Combined current-field switching scheme



Double rectangular pulse switching scheme

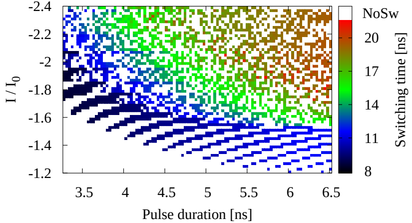
Single rectangular pulse

Symmetric double pulse



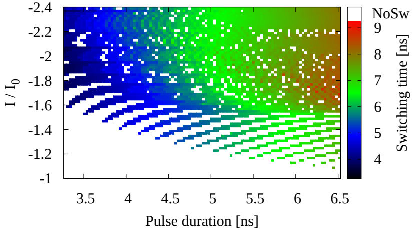
Pulse switching diagrams for Co/Cu/Py

Single rectangular pulse



$$i(t) = \begin{cases} I & \text{if } 0 \leq t < t_\mathrm{p}, \\ 0 & \text{if } t \geq t_\mathrm{p}. \end{cases}$$

Symmetric double pulse



$$i(t) = \begin{cases} I & \text{if } 0 \leq t < t_\mathrm{p}, \\ -I & \text{if } t_\mathrm{p} \leq t < 2t_\mathrm{p}, \\ 0 & \text{if } t \geq 2t_\mathrm{p}. \end{cases}$$

Summary

- We have compared the torques exerted on a sensing layer of spin valve in dependance of the electron transport regime (Ballistic *vs.* Diffusive). In the case of asymmetric spin valve have been found significant differencies due to *wavy*-torque.

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- The dynamical switching diagram of several spin valve structures have been calculated in both, ballistic and diffusive, transport limits. In case of asymmetric spin valve the novel dynamical modes (*out-of-plane precession* and *stable state*) have been found.

Summary

- We have compared the torques exerted on a sensing layer of spin valve in dependance of the electron transport regime (Ballistic *vs.* Diffusive). In the case of asymmetric spin valve have been found significant differencies due to *wavy*-torque.
- The dynamical switching diagram of several spin valve structures have been calculated in both, ballistic and diffusive, transport limits. In case of asymmetric spin valve the novel dynamical modes (*out-of-plane precession* and *stable state*) have been found.
- Because of P/AP *bistable* behaviour found in *pulse diagrams* constructed for Co/Cu/Py spin valve, two different efficient switching schemes for asymmetric spin valves have been proposed and examed.

Thank you for your attention

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