SWISS CONTRIBUTION

NANOSPIN

Spin dependent transport and current-induced magnetization dynamics in metallic spin valves

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Polish Academy of Sciences
and
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A. Mickiewicz University in Poznań

Uniwersität Duisburg-Essen, 4 December 2012

AGH

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Nanoscale spin torque devices for spin electronics

Joint research project under the framework of Polish-Swiss research programme

SWISS CONTRIBUTION

NANOSPIN

nanospin.agh.edu.pl

Partners

- AGH University of Science and Technology in Kraków
  T. Stobiecki – coordinator
- Institute of Molecular Physics in Poznań, Polish Academy of Sciences
  J. Dubowik – experiment, J. Barnaś – theory
- Ecolé Polytechnique Fédérale in Lausanne
  J.-Ph. Ansermet

Objectives

jointly developing novel nanoscale spintronic devices based on the spin transfer torque effect, which promises unrivaled future scaling, flexibility and low power consumption

AGH

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IFM PAN

www.zfmezo.amu.edu.pl

Head: prof. Józef Barnaś

Research activities

- Single Molecular Magnets and Adatoms
- Kondo effect in quantum Dots
- Quantum and Spin Hall Effect
- Electronic transport in graphene
- Current-induced dynamics in magnetic spin valves
- Current-induced domain wall motion

Recent projects

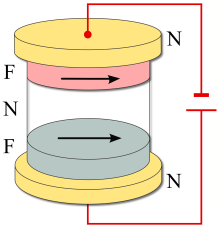
- European Marie Curie Research Training Network SPINSWITCH
- National Centre for Magnetic Nanostructures SpinLab
- Polish-Swiss Research Project NanoSpin

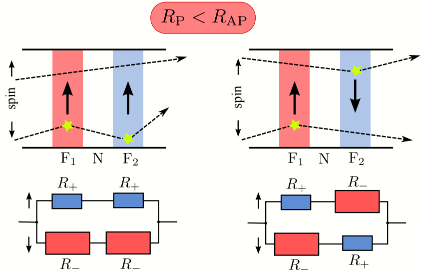
  with Polish Academy of Sciences, University of Technology Kraków, and École Polytechnique Fédérale de Lausanne

UAM

Outline

Spin valves and Giant magnetoresistance





M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas
Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices
Phys. Rev. Lett. **61**, 2472–2475 (1988)

G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn
Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange
Phys. Rev. B **39**, 4828–4830 (1989)

R. E. Camley and J. Barnaś
Theory of giant magnetoresistance effects in magnetic layered structures with antiferromagnetic coupling
Phys. Rev. Lett. 63, 664–667 (1989)

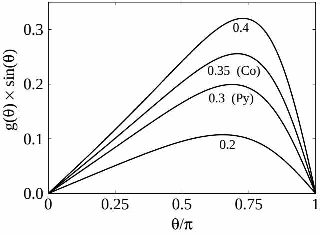
T. Valet and A. Fert
Theory of the perpendicular magnetoresistance in magnetic multilayers
Phys. Rev. B 48, 7099–7113 (1993)

Current-induced dynamics and magnetization switching

Magnetization can be switched by electric current without need of magnetic field

Slonczewski's model (ballistic)

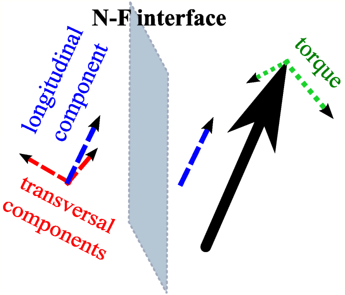
J. Magn. Magn. Mater. **159**, L1-L7 (1996)

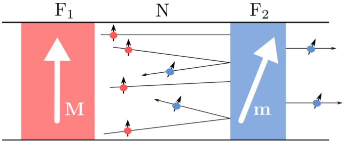


$$\tau_{\mathrm{Slonc}z} = \frac{Ig(\theta)}{e}\hat{\mathbf{s}}\times\left(\hat{\mathbf{s}}\times\hat{\mathbf{S}}\right)$$

where

$$g(\theta) = \left[-4+(1+P)^3\frac{3+\cos\theta}{4P^{3/2}}\right]^{-1}$$





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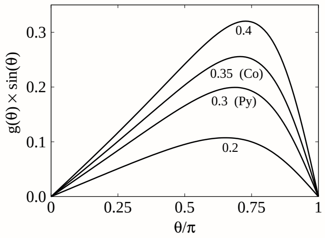

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Unified description (diffusive)

Description of spin-transfer torque should be consistent with description of giant magnetoresistance (Valet-Fert model)

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)

Spin-transfer torque

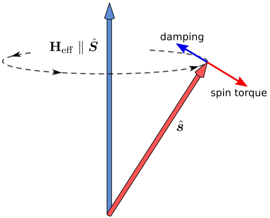
$$\tau_\theta = a(\theta)\, I\, \hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}}\right)$$

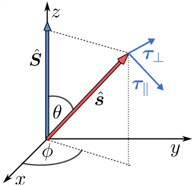
$$\tau_\phi = b(\theta)\, I\, \hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

Equation of motion

Landau-Lifshitz-Gilbert equation

$$\frac{d\hat{\mathbf{s}}}{dt} = -|\gamma_g|\mu_0\,\hat{\mathbf{s}} \times \mathbf{H}_{\rm eff} - \alpha\,\hat{\mathbf{s}} \times \frac{d\hat{\mathbf{s}}}{dt} + \frac{|\gamma_g|}{M_s d}\left(\tau_\theta + \tau_\phi\right)$$





Effective magnetic field

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

Spin-transfer torque

$$\tau_\theta = a(\theta)\,I\,\hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}}\right)$$
$$\tau_\phi = b(\theta)\,I\,\hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

Outline

Mathematical description

Two channels model

bulk resistivities

$$\rho_{\uparrow(\downarrow)} = 2\rho^{*}\,(1 \mp \beta)$$

interface resistances

$$R_{\uparrow(\downarrow)} = 2R^{*}\,(1 \mp \gamma)$$

Diffusive transport

$$\frac{\partial^2 \bar{\mu}_\uparrow - \bar{\mu}_\downarrow}{\partial x^2} = \frac{1}{l_{\text{sf}}^2}(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)$$

$$\frac{\partial^2 \bar{\mu}_\uparrow + \bar{\mu}_\downarrow}{\partial x^2} = \eta\,\frac{\partial^2 (\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)}{\partial x^2}$$

β bulk asymmetry paramters
γ interfacial asymmetry parameter

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for electrochemical potentials we get

$$\bar{\mu}_\uparrow = (1+\eta)\left[A e^{x/l_{\mathrm{sf}}} + B e^{-x/l_{\mathrm{sf}}}\right] + Cx + G$$

$$\bar{\mu}_\downarrow = (\eta - 1)\left[A e^{x/l_{\mathrm{sf}}} + B e^{-x/l_{\mathrm{sf}}}\right] + Cx + G$$

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Mathematical description

Magnetic layer

$$\check{\mu} = \bar{\mu}_0 \check{1} + g \check{\sigma}_z$$

$$\bar{\mu}_0 = \frac{\bar{\mu}_\uparrow + \bar{\mu}_\downarrow}{2}, \qquad g = \frac{\bar{\mu}_\uparrow - \bar{\mu}_\downarrow}{2}$$

with g being spin accumulation

$$\check{j} = -\rho(E_F)\check{D}\frac{\partial \check{\mu}}{\partial x}$$

$$\check{j} = \frac{1}{2}\left(j_0 \check{1} + j_z \check{\sigma}_z\right)$$

with j_z being spin current

Diffusive transport

$$\frac{\partial^2 \bar{\mu}_\uparrow - \bar{\mu}_\downarrow}{\partial x^2} = \frac{1}{l_{\mathrm{sf}}^2}\left(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow\right)$$

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Phys. Rev. B **72**, 024426 (2005)

Mathematical description

Nonmagnetic layer

has no natural quantization axis

$$\check{\mu} = \bar{\mu}_0 \check{1} + \mathbf{g}.\check{\sigma}$$
$$\check{j} = \frac{1}{2}\left(j_0 \check{1} + \mathbf{j}.\check{\sigma}\right)$$

where

$$\mathbf{g} = (g_x, g_y, g_z)\,, \qquad \mathbf{j} = (j_x, j_y, j_z)$$

are 3D vectors written in the coordinate system of one of the adjacent magnetic layers

Diffusive transport

$$\frac{\partial^2 \bar{\mu}_\uparrow - \bar{\mu}_\downarrow}{\partial x^2} = \frac{1}{l_{\mathrm{sf}}^2}(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)$$
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Boundary conditions at N/F interface

- particle current is continuous across all interfaces

$$e^2 j_0 = (G_\uparrow + G_\downarrow)(\bar{\mu}_0^F - \bar{\mu}_0^N) + (G_\uparrow - G_\downarrow)(g_z^F - g_z^N)$$

- spin current component parallel to the magnetization is continuous across the interface

$$e^2 j_z = (G_\uparrow - G_\downarrow)(\bar{\mu}_0^F - \bar{\mu}_0^N) + (G_\uparrow + G_\downarrow)(g_z^F - g_z^N)$$

- transversal component of the spin current vanishes in the magnetic layer – jump at the interface

$$e^2 j_x = -2Re\{G_{\uparrow\downarrow}\} g_x^N + 2Im\{G_{\uparrow\downarrow}\} g_y^N$$
$$e^2 j_y = -2Re\{G_{\uparrow\downarrow}\} g_y^N - 2Im\{G_{\uparrow\downarrow}\} g_x^N$$

A. Brataas, Yu.V. Nazarov, G.E.W. Bauer
Spin-transport in multi-terminal normal metal-ferromagnet systems with non-collinear magnetizations
Eur. Phys. J. B **22**, 99 (2001)

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Spin-transfer torque

$$\tau = \frac{\hbar}{2}(\mathbf{j}_{\perp L} - \mathbf{j}_{\perp R})$$

Boundary conditions at N/F interface

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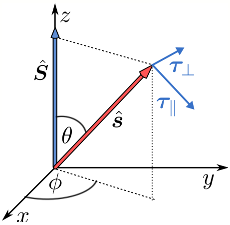


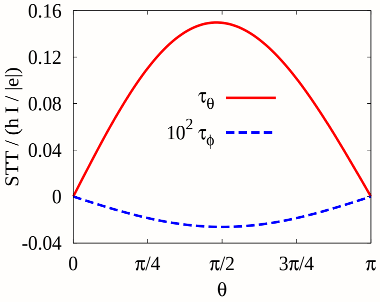
Components

in-plane	$\tau_\theta = -\frac{\hbar}{2} j'_y|_{\mathrm{N/F}}$
out-of-plane	$\tau_\phi = \frac{\hbar}{2} j'_x|_{\mathrm{N/F}}$

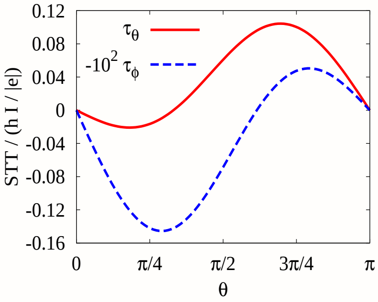
Results

Calculations for real structures

Standard spin valve Py(20)/Cu(10)/Py(8)

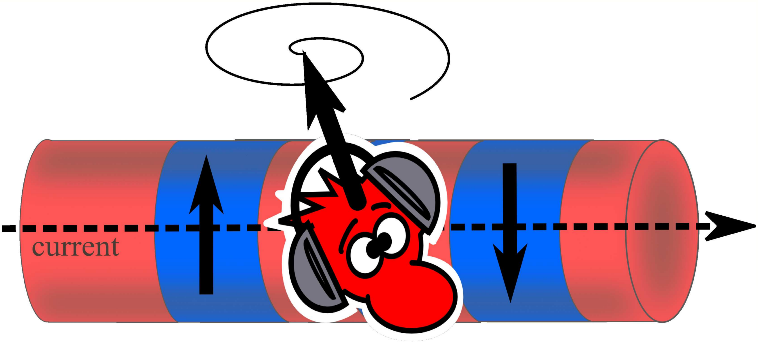


Nonstandard spin valve Co(8)/Cu(10)/Py(8)



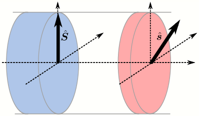
Outline

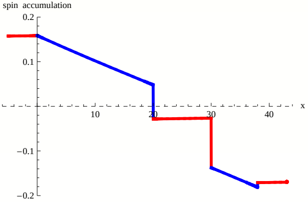
What is a dual spin valve?



Spin accumulation in dual spin valve

spin accumulation in single spin valve





Spin accumulation in dual spin valve

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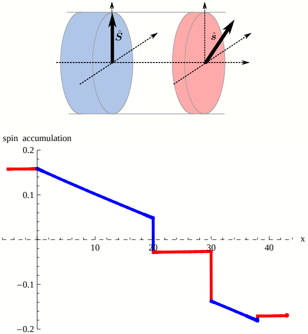
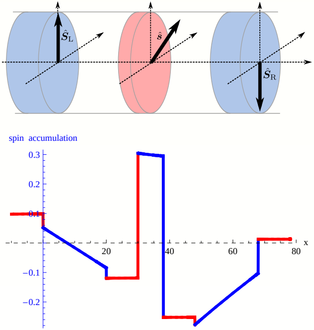


spin accumulation in dual spin valve



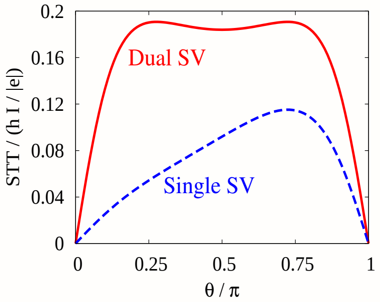
L. Berger
Multilayer Configuration for Experiments of Spin Precession Induced by a DC Current
J. Appl. Phys. **93**, 7683 (2003)

Enhancement of switching

single *vs.* dual spin valve

Co(20)/Cu(10)/Co(8) *vs.* Co(20)/Cu(10)/Co(8)/Cu(10)/Co(20)

Spin-transfer torque



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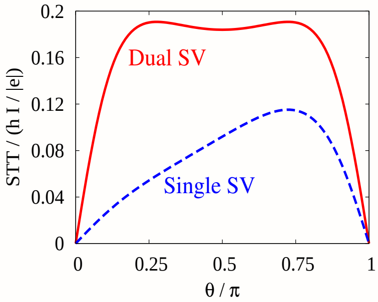
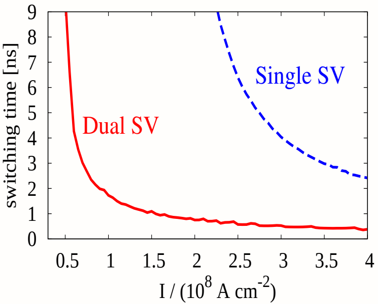


Switching time



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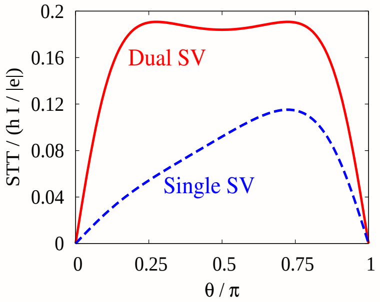

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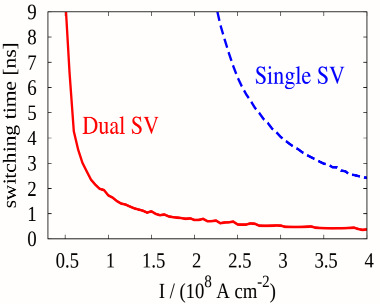
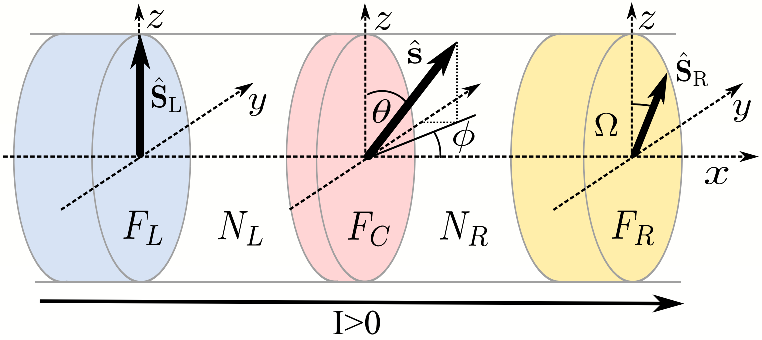


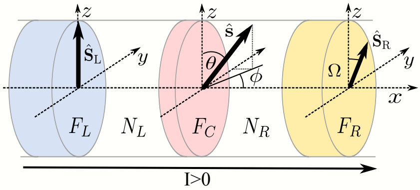
Is this all?

Question: How torque changes in non-collinear configurations?



Noncollinear configurations in dual spin valves

Co(20)/Cu(10)/Py(4)/Cu(4)/Co(10)/IrMn(8)



P.B., M. Gmitra, J. Barnaś
Current-induced dynamics in non-collinear dual spin-valves
Phys. Rev. B **80**, 174404 (2009)

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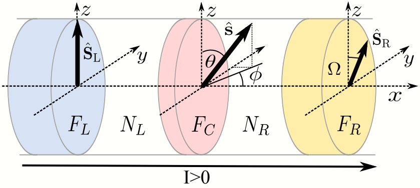

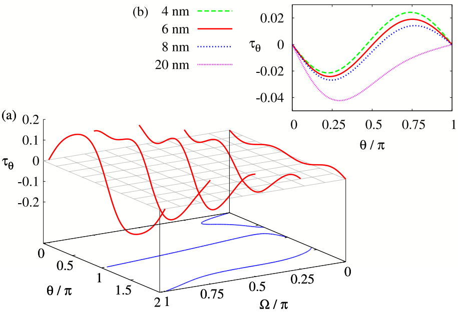

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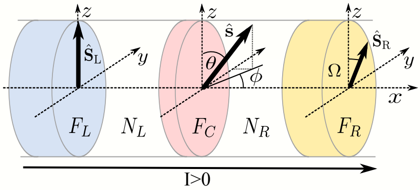
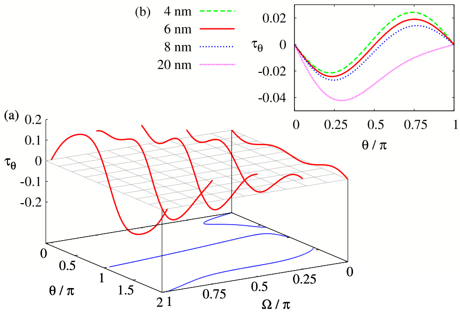




P.B., M. Gmitra, J. Barnaś

Current-induced dynamics in non-collinear dual spin-valves

Phys. Rev. B **80**, 174404 (2009)

Current-induced dynamics

We calculated average

$$\langle s_z \rangle = \frac{1}{t_{\rm end} - t_{\rm eq}} \int_{t_{\rm eq}}^{t_{\rm end}} s_z \, {\rm d}t$$

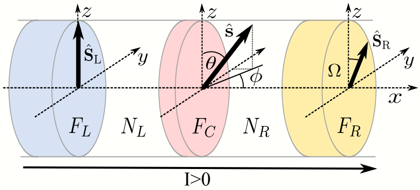
and dispersion

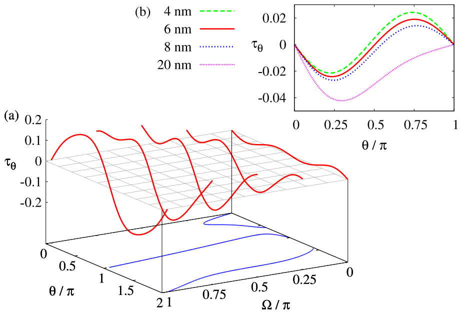
$$\mathscr{D}(s_z) = \sqrt{\langle s_z^2 \rangle - \langle s_z \rangle^2}$$

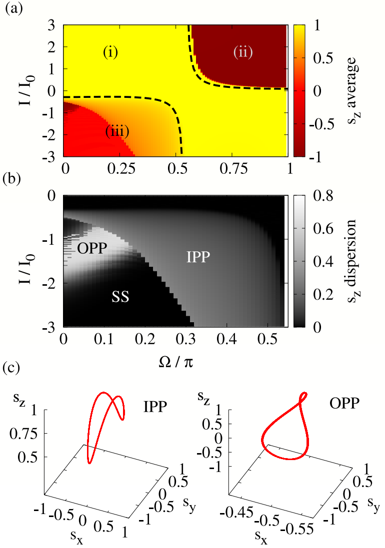
for each couple of I and Ω to map the dynamic behaviour.

Noncollinear configurations in dual spin valves

Co(20)/Cu(10)/Py(4)/Cu(4)/Co(10)/IrMn(8)

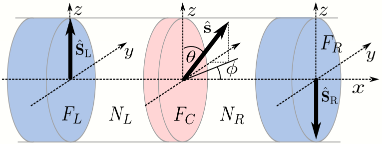






Outline

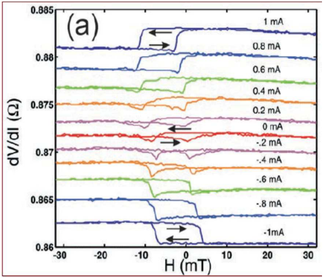
Nonlinear magnetoresistance in dual spin vales

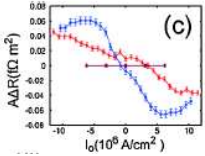


Experimental works

A. Aziz, O. P. Wessely, M. Ali, D. M. Edwards, C. H. Marrows, B. J. Hickey, and M. G. Blamire
Nonlinear giant magnetoresistance in dual spin valves
Phys. Rev. Lett. **103**, 237203 (2009)

N. Banerjee, A. Aziz, M. Ali, J. W. A. Robinson, B. J. Hickey, and M. G. Blamire
Thickness dependence and the role of spin transfer torque in nonlinear giant magnetoresistance of permalloy dual spin valves
Phys. Rev. B **82**, 224402 (2010)





Experimental results [Aziz *et al*, PRL (2009)]: (b) minor loops for $Co_{90}Fe_{10}$(6)/Cu(4)/Py(1)/Cu(2)/$Co_{90}Fe_{10}$(6)/IrMn(10) (c) Py thickness: 1 nm (blue), 2 nm (red), and 8 nm (magenta)

Nonlinear magnetoresistance in dual spin vales

Model's assumptions

- Spin accumulation in the central layer changes density of states on Fermi level
- This may change bulk/interfacial material parameters in the central layer

We extended the diffusion transport model

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)

Bulk contribution

$$\rho^* = \rho_0^* + q\,\langle g \rangle$$
$$\beta = \beta_0 + \xi\,\langle g \rangle$$

Interfacial contribution

$$R^* = R_0^* + q'\,g(x_{\mathrm{i}})$$
$$\gamma = \gamma_0 + \xi' g(x_{\mathrm{i}})$$

where

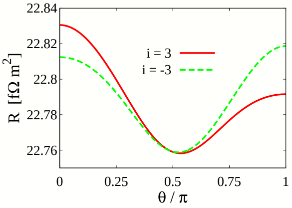
- $g(x)$ is spin accumulation
- ρ_0^* and R_0^* are *zero-current* bulk resistivity and interfacial resistance
- β_0 and γ_0 are *zero-current* bulk/interfacial asymmetry parameters
- q, ξ, q', ξ' are phenomenological parameters

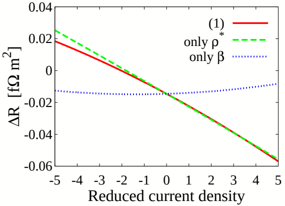
P. Baláž, and J. Barnaś
Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

Nonlinear magnetoresistance in dual spin vales

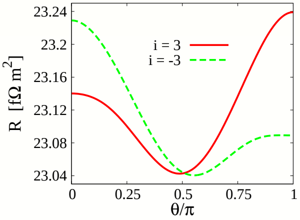
Calculations for Cu - Co(6) / Cu(4) / Py(2) / Cu(2) / Co(6) / IrMn(10) - Cu

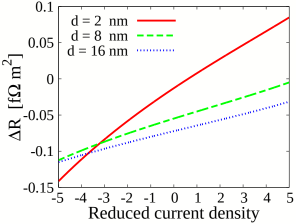
Bulk parameters





Interfacial parameters





P. Baláž, and J. Barnaś

Nonlinear magnetotransport in dual spin valves

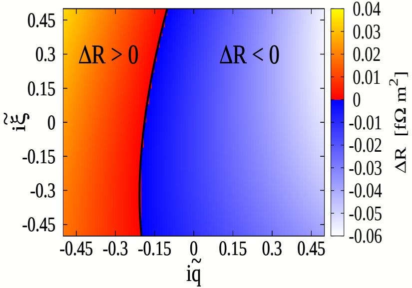
Phys. Rev. B **82**, 104430 (2010)

for $\tilde{q} = 0.1,\ \tilde{\xi} = 0.1,\ I_0 = 10^8 \mathrm{Acm}^{-2}$

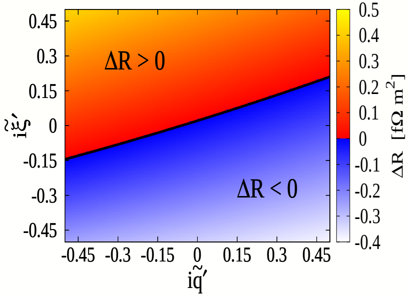
Nonlinear magnetoresistance in dual spin vales

Calculations for Cu - Co(6) / Cu(4) / Py(2) / Cu(2) / Co(6) / IrMn(10) - Cu

Bulk parameters



Interfacial parameters



for interfaces ΔR is symmetric with current density

P. Baláž, and J. Barnaś

Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

Outline

Transverse spin diffusion

Motivation

T. Taniguchi, H. Imamura
Spin pumping in ferromagnetic multilayers
Mod. Phys. Lett. B **22**, 2909 – 2929 (2008)

T. Taniguchi, S. Yakata, H. Imamura, Y. Ando
Determination of Penetration Depth of Transverse Spin Current in Ferromagnetic Metals by Spin Pumping
arXiv:0708.3528v3 [cond-mat.mes-hall]

T. Taniguchi, S. Yakata, H. Imamura, Y. Ando
Penetration Depth of Transverse Spin Current in Ferromagnetic Metals
IEEE Trans. Mag. **44**, 2636 (2008); arXiv:0806.3315v1 [cond-mat.mes-hall]

Estimated transverse spin diffusion (penetration) length

- Py $3.7\,\mathrm{nm}$
- CoFe $2.5\,\mathrm{nm}$
- CoFeB $12\,\mathrm{nm}$
- Co $1.7\,\mathrm{nm}$

Transverse spin diffusion

Modified continuity equation

$$\frac{\mathrm{d}f_0}{\mathrm{d}t} = -\frac{\partial j_0}{\partial x},$$

$$\frac{\mathrm{d}\mathbf{f}}{\mathrm{d}t} = \frac{J}{\hbar}\left(\hat{\mathbf{S}} \times \mathbf{f}\right) - \frac{\partial \mathbf{j}}{\partial x} + \frac{\mathbf{f}}{\tau_{\mathrm{sf}}},$$

Current tensor

$$\check{j} = \begin{pmatrix} j_\uparrow & j_{\uparrow\downarrow} \\ j_{\downarrow\uparrow} & j_\downarrow \end{pmatrix} = -\begin{pmatrix} D_\uparrow \frac{\partial f_\uparrow}{\partial x} & D_\perp \frac{\partial f_{\uparrow\downarrow}}{\partial x} \\ D_\perp \frac{\partial f_{\downarrow\uparrow}}{\partial x} & D_\downarrow \frac{\partial f_\downarrow}{\partial x} \end{pmatrix}$$

where

$$D_{\uparrow(\downarrow)} = D_0/(1 \mp \beta)$$

$$D_\perp = \frac{D_\uparrow + D_\downarrow}{2}$$

A. Shpiro, P. Lévy, and S. Zhang

Self-consistent treatment of nonequilibrium spin torques in magnetic multilayers

Phys. Rev. B **67** 104430 (2002)

Charge and longitudinal components

$$\frac{\partial^2 f_z}{\partial x^2} = \frac{f_z}{\lambda_{\mathrm{sf}}^2}$$

$$\frac{\partial^2 f_0}{\partial x^2} = -\beta \frac{\partial^2 f_z}{\partial x^2}$$

where $\lambda_{\mathrm{sf}} = \sqrt{D_0 \tau_{\mathrm{sf}}}$.

Transverse spin components

$$\frac{\partial^2 f_x}{\partial x^2} = -\frac{f_y}{\lambda_J^2} + \frac{f_x}{\lambda_\perp^2}$$

$$\frac{\partial^2 f_y}{\partial x^2} = \frac{f_x}{\lambda_J^2} + \frac{f_y}{\lambda_\perp^2}$$

where $\lambda_J = \sqrt{\hbar D_\perp / J}$ and $\lambda_\perp = \sqrt{D_\perp \tau_{\mathrm{sf}}}$

Solution for the transver components

Longitudinal spin accumulation

$$\mu_z(x) = A e^{x/\lambda_{\rm sf}} + B e^{-x/\lambda_{\rm sf}}$$

- $\lambda_{\rm sf}$: spin diffusion length

Transverse spin accumulation

$$\mu_x(x) = C_1 e^{x/l_-} + C_2 e^{-x/l_-} + C_3 e^{x/l_+} + C_4 e^{-x/l_+}$$

$$\frac{1}{l_\pm} = \frac{1}{\lambda_t} \pm i \frac{1}{\lambda_p}$$

- λ_t: transverse decay length
- λ_p precessional length

we define $\Delta = \lambda_t/\lambda_p$, which is $\Delta < 1$

$$\frac{1}{l_\pm} = \frac{1 \pm i\Delta}{\lambda_{\rm t}}$$

Solution for the transverse components

Longitudinal charge and spin current

$$\frac{1}{\rho(E_{\mathrm{F}})} j_0 = -2C \frac{D_0}{1-\beta^2}$$

$$\frac{1}{\rho(E_{\mathrm{F}})} j_z(x) = \frac{\beta}{\rho(E_{\mathrm{F}})} j_0 - \frac{2D_0}{\lambda_{\mathrm{sf}}} \left[A e^{x/\lambda_{\mathrm{sf}}} - B e^{-x/\lambda_{\mathrm{sf}}} \right]$$

Transverse spin current

$$\frac{1}{\rho(E_{\mathrm{F}})} j_{x(y)} = \pm \frac{D_\perp}{\lambda_{\mathrm{t}}} \left\{ \left[(\Delta A_1 - B_1) \sin\left(\frac{\Delta x}{\lambda_{\mathrm{t}}}\right) \mp (A_1 + \Delta B_1) \cos\left(\frac{\Delta x}{\lambda_{\mathrm{t}}}\right) \right] e^{x/\lambda_{\mathrm{t}}} \pm \left[(\Delta A_2 + B_2) \sin\left(\frac{\Delta x}{\lambda_{\mathrm{t}}}\right) \pm (A_2 - \Delta B_2) \cos\left(\frac{\Delta x}{\lambda_{\mathrm{t}}}\right) \right] e^{-x/\lambda_{\mathrm{t}}} \right\}$$

Boundary conditions at the N/F interfaces

Longitudinal components

$$e^2 j_0 = (G_\uparrow + G_\downarrow)(\mu_0^\mathrm{F} - \mu_0^\mathrm{N}) + (G_\uparrow - G_\downarrow)(\mu_z^\mathrm{F} - \mu_z^\mathrm{N})$$
$$e^2 j_z = (G_\uparrow - G_\downarrow)(\mu_0^\mathrm{F} - \mu_0^\mathrm{N}) + (G_\uparrow + G_\downarrow)(\mu_z^\mathrm{F} - \mu_z^\mathrm{N})$$

Transversal compoments

$$e^2 j_x = 2\,\mathrm{Re}\left\{G_{\uparrow\downarrow}\right\}(\mu_x^\mathrm{F} - \mu_x^\mathrm{N}) + 2\,\mathrm{Im}\left\{G_{\uparrow\downarrow}\right\}(\mu_y^\mathrm{F} - \mu_y^\mathrm{N})$$
$$e^2 j_y = 2\,\mathrm{Re}\left\{G_{\uparrow\downarrow}\right\}(\mu_y^\mathrm{F} - \mu_y^\mathrm{N}) - 2\,\mathrm{Im}\left\{G_{\uparrow\downarrow}\right\}(\mu_x^\mathrm{F} - \mu_x^\mathrm{N})$$

Current continuity

$$j_x^\mathrm{F} = j_x^\mathrm{N} = j_x$$
$$j_y^\mathrm{F} = j_y^\mathrm{N} = j_y$$
$$j_z^\mathrm{F} = j_z^\mathrm{N} = j_z$$

Spin transfer torque

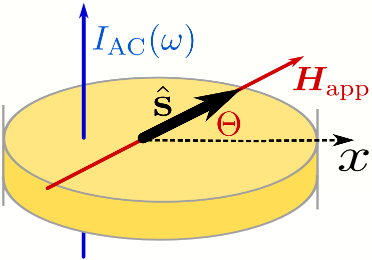
Spin transfer torque

$$\tau_x = \frac{\hbar}{2}\int_{x_\mathrm{L}}^{x_\mathrm{R}} \frac{\partial j_x}{\partial x}\,\mathrm{d}x = \frac{\hbar}{2}\left[j_x(x_\mathrm{R}) - j_x(x_\mathrm{L})\right] \equiv \tau_\perp$$

$$\tau_y = \frac{\hbar}{2}\int_{x_\mathrm{L}}^{x_\mathrm{R}} \frac{\partial j_y}{\partial x}\,\mathrm{d}x = \frac{\hbar}{2}\left[j_y(x_\mathrm{R}) - j_y(x_\mathrm{L})\right] \equiv \tau_\parallel$$

where x_L and x_R are positions of the left and right interfaces of the free layer.

Second harmonic measurement



Second harmonic voltage

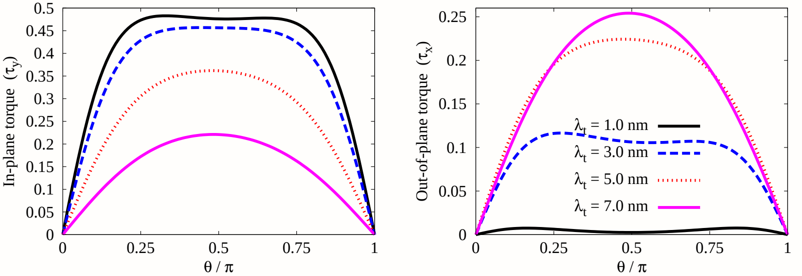
$$U_{2\omega} = -\frac{I_0^2}{4}\frac{\partial R}{\partial v}\Big|_{\phi_0} \sin\phi_0 \, |\chi_\phi|$$

where $\chi_\phi(\phi_0, \Theta) = \frac{|\gamma_g|}{M_s d} \frac{b(\phi_0)}{\omega_2(\phi_0, \Theta)} \sin\phi_0$ is the susceptibility

Numerical results

Cu – CoFe(2.5) / Cu(2.8) / CoFe(2.5) / Cu(2.8) / CoFe(3.5) – Cu

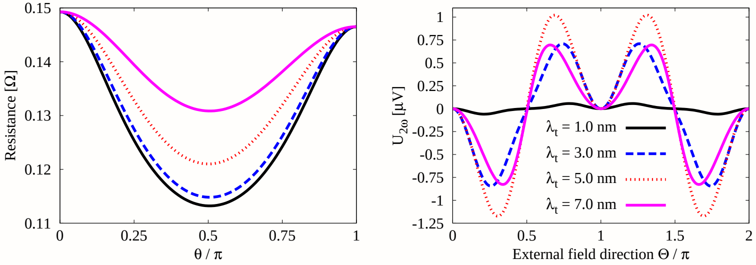
Spin transfer torque



Numerical results

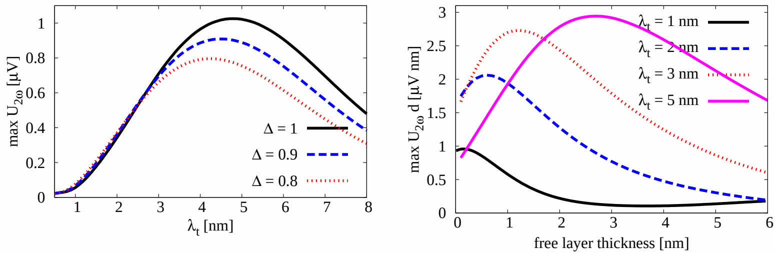
Cu – CoFe(2.5) / Cu(2.8) / CoFe(2.5) / Cu(2.8) / CoFe(3.5) – Cu

Magnetoresistance and second harmonic voltage



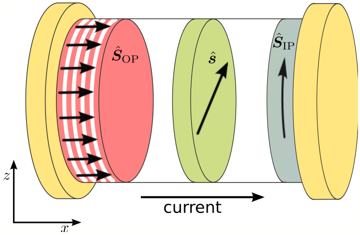
Numerical results

Cu – CoFe(2.5) / Cu(2.8) / CoFe(2.5) / Cu(2.8) / CoFe(3.5) – Cu

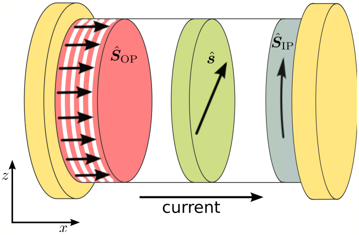


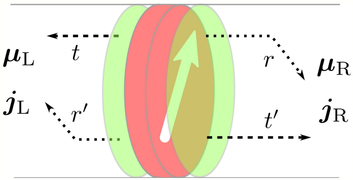
Outline

Modelling of transport through the perpendicular polarizer



Modelling of transport through the perpendicular polarizer



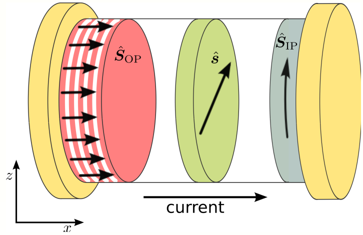


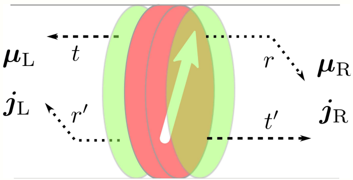
- We considered the perpendicular polarizer as a magnetized ballistic scatterer corresping to a single single interface in our formalism.
- To calculate the transport properties of the polarizer we used *Ab initio* wave function matching method

M. Zwierzycki *et al*
Calculating scattering matrices by wave function matching
Phys. Stat. Sol. (b) **245**, 623 – 640 (2008)

- $G_\uparrow$ majority spin conductance
- $G_\downarrow$ minority spin conductance
- $G_{\rm Sh}$ Sharvin conductance
- $G_{\uparrow\downarrow} = g_r^{\uparrow\downarrow} + i\, g_i^{\uparrow\downarrow}$ mixing conductance
- $T_{\uparrow\downarrow} = t_r^{\uparrow\downarrow} + i\, t_i^{\uparrow\downarrow}$ mixing transmission

Modelling of transport through the perpendicular polarizer





- We considered the perpendicular polarizer as a magnetized ballistic scatterer corresping to a single single interface in our formalism.
- To calculate the transport properties of the polarizer we used *Ab initio* wave function matching method

M. Zwierzycki *et al*
Calculating scattering matrices by wave function matching
Phys. Stat. Sol. (b) **245**, 623 – 640 (2008)

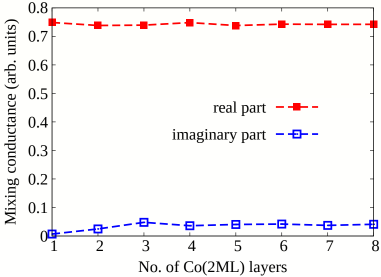
Mixing conductance

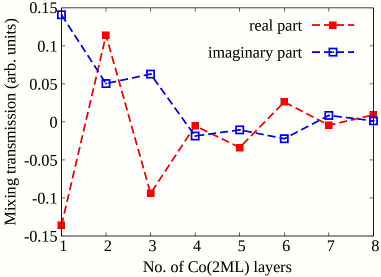
$$G_{\sigma\sigma'} = \sum_{nn'} \left[\delta_{nn'} - r^{\sigma}_{nn'} \left(r^{\sigma'}_{nn'} \right)^* \right]$$

Mixing transmission

$$T_{\sigma\sigma'} = \sum_{nn'} t^{\sigma}_{nn'} \left(t^{\sigma'}_{nn'} \right)^*$$

Numerical calculation of mixing conductance and transmission





Shep correction due to spin diffusion

Longitudinal components

$$\frac{1}{\tilde{G}_{\uparrow}} = \frac{1}{G_{\uparrow}} - \frac{1}{G_{\mathrm{Sh}}}$$

$$\frac{1}{\tilde{G}_{\downarrow}} = \frac{1}{G_{\downarrow}} - \frac{1}{G_{\mathrm{Sh}}}$$

Transversal componets

$$\frac{1}{\tilde{G}_{\uparrow\downarrow}} = \frac{1}{G_{\uparrow\downarrow} + T_{\uparrow\downarrow}^2/(2G_{\mathrm{Sh}} - G_{\uparrow\downarrow})} - \frac{1}{2G_{\mathrm{Sh}}}$$

$$\frac{1}{\tilde{T}_{\uparrow\downarrow}} = \frac{(2G_{\mathrm{Sh}} - G_{\uparrow\downarrow})^2/T_{\uparrow\downarrow} - T_{\uparrow\downarrow}}{4G_{\mathrm{Sh}}^2}.$$

Boundary conditions

Longitudinal components

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

Boundary conditions

Longitudinal components

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

$$e^2 \mathbf{j}_{\perp\mathrm{R}} = -2\Big\{ \Big(g_r^{\uparrow\downarrow}\mu_x^{\mathrm{R}} - g_i^{\uparrow\downarrow}\mu_y^{\mathrm{R}} - t_r'^{\uparrow\downarrow}\mu_x^{\mathrm{L}} + t_i'^{\uparrow\downarrow}\mu_y^{\mathrm{L}} \Big)\hat{\mathbf{e}}_x + \Big(g_r^{\uparrow\downarrow}\mu_y^{\mathrm{R}} + g_i^{\uparrow\downarrow}\mu_x^{\mathrm{R}} - t_r'^{\uparrow\downarrow}\mu_y^{\mathrm{L}} - t_i'^{\uparrow\downarrow}\mu_x^{\mathrm{L}} \Big)\hat{\mathbf{e}}_y \Big\}$$
$$e^2 \mathbf{j}_{\perp\mathrm{L}} = -2\Big\{ \Big(g_r'^{\uparrow\downarrow}\mu_x^{\mathrm{L}} - g_i'^{\uparrow\downarrow}\mu_y^{\mathrm{L}} - t_r^{\uparrow\downarrow}\mu_x^{\mathrm{R}} + t_i^{\uparrow\downarrow}\mu_y^{\mathrm{R}} \Big)\hat{\mathbf{e}}_x + \Big(g_r'^{\uparrow\downarrow}\mu_y^{\mathrm{L}} + g_i'^{\uparrow\downarrow}\mu_x^{\mathrm{L}} - t_r^{\uparrow\downarrow}\mu_y^{\mathrm{R}} - t_i^{\uparrow\downarrow}\mu_x^{\mathrm{R}} \Big)\hat{\mathbf{e}}_y \Big\}$$

Y. Tserkovnyak *et al*
Nonlocal magnetization dynamics in ferromagnetic heterostructures
Rev. Mod. Phys. **77**, 1375 (2005)

Boundary conditions

Longitudinal components

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

Transverse components

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

Spin transfer torque

Spin torque acting on the free layer

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

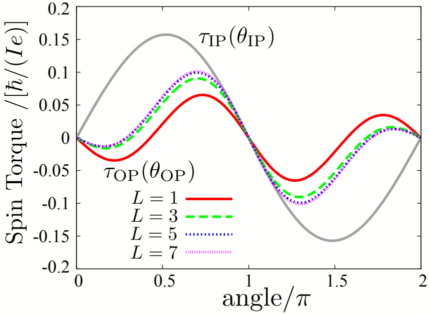
$$a_{\mathrm{OP}} = -\frac{\hbar}{2}\frac{j'_{1y}\,|_{\mathrm{N_1/F_1}}}{I\sin\theta_{\mathrm{OP}}} \qquad b_{\mathrm{OP}} = \frac{\hbar}{2}\frac{j'_{1x}\,|_{\mathrm{N_1/F_1}}}{I\sin\theta_{\mathrm{OP}}}$$
$$a_{\mathrm{IP}} = -\frac{\hbar}{2}\frac{j''_{2y}\,|_{\mathrm{F_1/N_2}}}{I\sin\theta_{\mathrm{IP}}}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

where $\cos\theta_{\mathrm{OP}} = \hat{\mathbf{s}}\cdot\hat{\mathbf{S}}_{\mathrm{OP}}$ and $\cos\theta_{\mathrm{IP}} = \hat{\mathbf{s}}\cdot\hat{\mathbf{S}}_{\mathrm{IP}}$

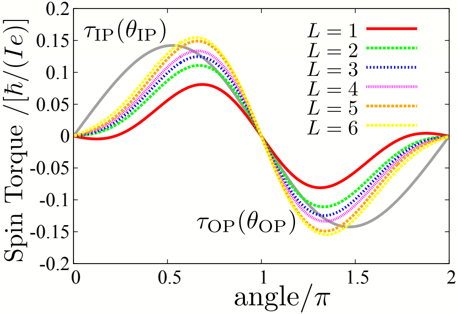
Numerical results: spin transfer torque

Cu-OPP/Cu(6)/Py(5)/Cu(8)/Py(12)-Cu

Co(2ML) / [Cu(2ML) / Co(2ML)]$_L$



Pt(6ML) / [Co(2ML) / Pt(3ML)]$_L$ / Co(3ML)

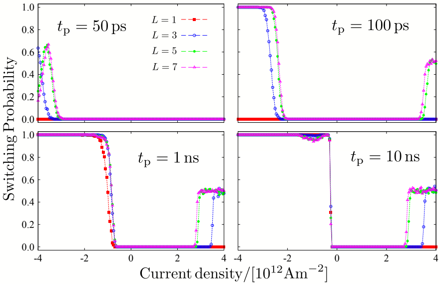


Numerical results: switching probability

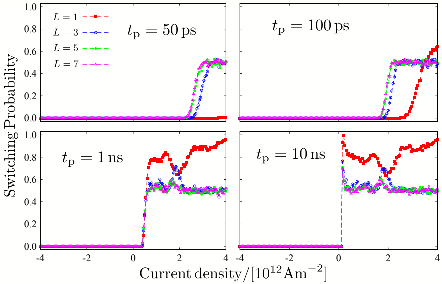
Cu-OPP/Cu(6)/Py(5)/Cu(8)/Py(12)-Cu

- Polarizer Co(2ML) / [Cu(2ML) / Co(2ML)]$_L$
- Temperature T=300 K

from P to AP



from AP to P



Summary

Noncollinear diffusive model is an useful and flexible treatment of spin dependent electronic transport in metalic multilayers, which is able to account for

- spin tranfer torque and magnetoresistance in single and dual spin valves
- nonlinear effects in magnetoresistance
- spin transfer torque due to a perpendicular polarizer

SWISS CONTRIBUTION

NANOSPIN

Thank you for your attention