SWISS CONTRIBUTION

NANOSPIN

Spin transfer torque and magnetization dynamics in in-plane and out-of-plane magnetized spin valves

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A. Mickiewicz University in Poznań

Aalto University, 31 October 2013

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

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EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IFMPAN

1. Introduction

2. Spin-torque in metallic spin valves

3. Dual spin valve

4. Nonlinear magnetoresistance in dual spin vales

5. Current-induced switching in metallic spin valves with perpendicular polarizers

Outline

1. Introduction
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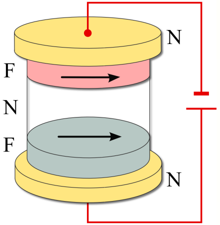
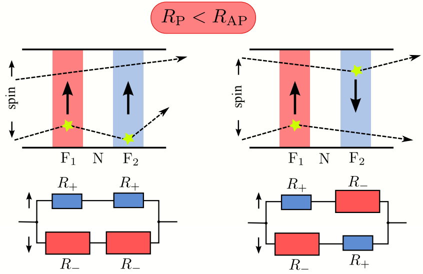
Spin valves and Giant magnetoresistance





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)

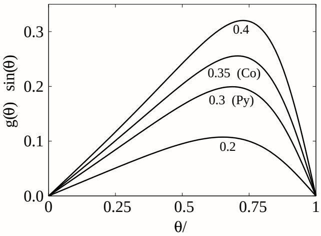
T. Valet and A. Fert
Theory of the perpendicular magnetoresistance in magnetic multilayers
Phys. Rev. B 48, 7099–7113 (1993)

Current-induced dynamics and magnetization switching

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

Slonczewski's model (ballistic)

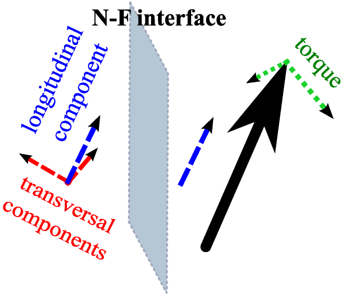
J. Magn. Magn. Mater. **159**, L1-L7 (1996)

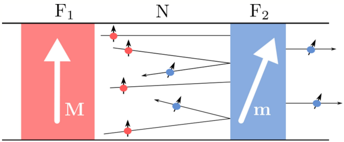


$$\tau_{\text{Sloncz}} = \frac{I g(\theta)}{e} \hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}} \right)$$

where

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





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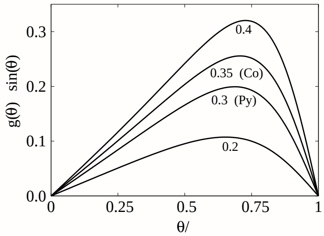

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Unified description (diffusive)

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

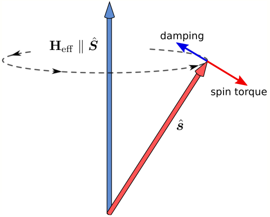
$$\tau_\theta = a(\theta) I \hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}} \right)$$

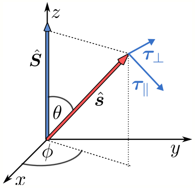
$$\tau_\phi = b(\theta) I \hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

Equation of motion

Landau-Lifshitz-Gilbert equation

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





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

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

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Mathematical description

Two channels model

bulk resistivities

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

interface resistances

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

Diffusive transport

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

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

β bulk asymmetry paramters
γ interfacial asymmetry parameter

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for electrochemical potentials we get

$$\bar{\mu}_\uparrow = (1+\eta)\left[Ae^{x/l_{\rm sf}} + Be^{-x/l_{\rm sf}}\right] + Cx + G$$

$$\bar{\mu}_\downarrow = (\eta-1)\left[Ae^{x/l_{\rm sf}} + Be^{-x/l_{\rm sf}}\right] + Cx + G$$

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Mathematical description

Magnetic layer

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

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

with g being spin accumulation

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

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

with j_z being spin current

Diffusive transport

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

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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

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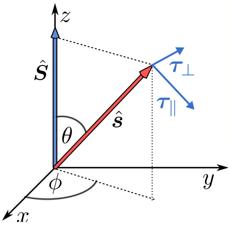


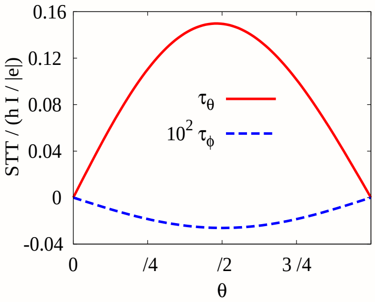
Components

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

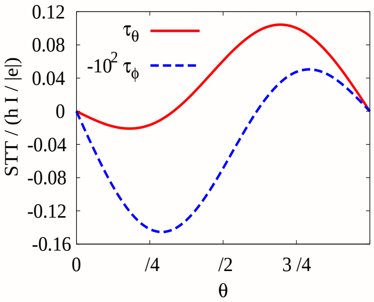
Results

Calculations for real structures

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



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



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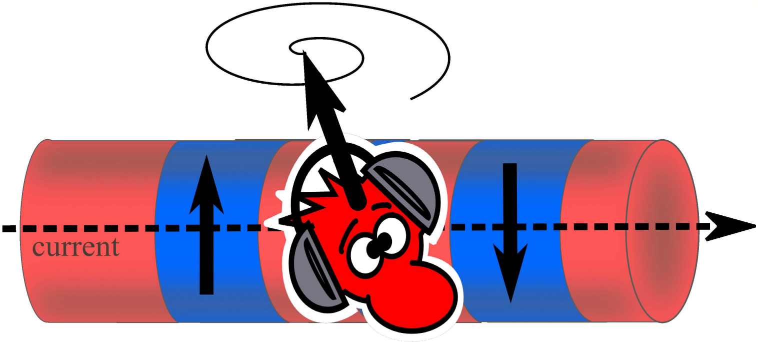
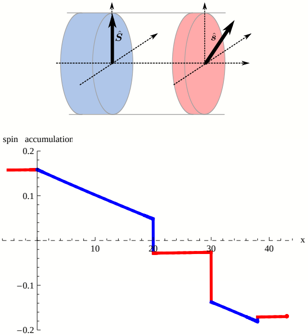
What is a dual spin valve?



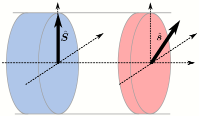
Spin accumulation in dual spin valve

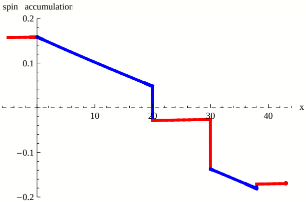
spin accumulation in single spin valve



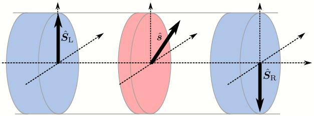
Spin accumulation in dual spin valve

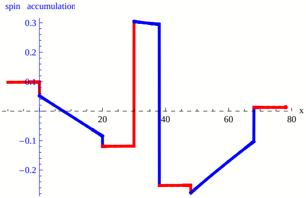
spin accumulation in single spin valve





spin accumulation in dual spin valve





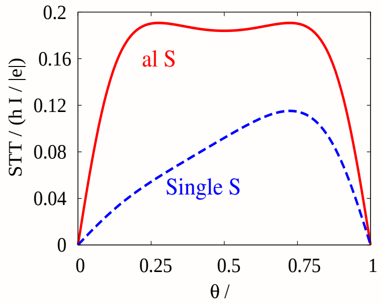
L. Berger
Multilayer Configuration for Experiments of Spin Precession Induced by a DC Current
J. Appl. Phys. **93**, 7683 (2003)

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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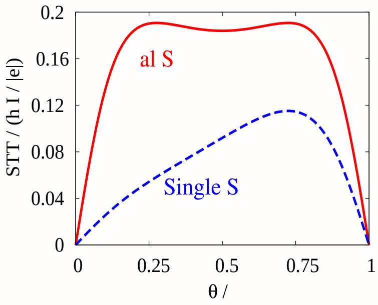
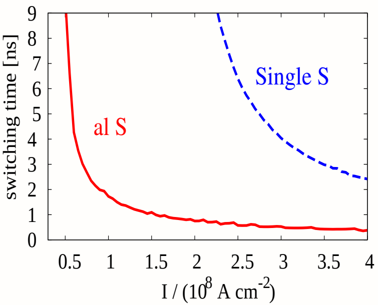


Switching time



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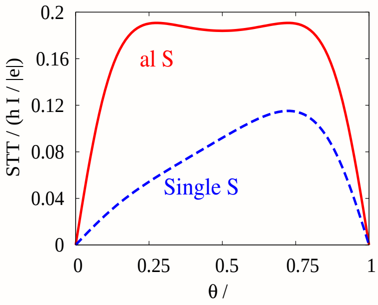

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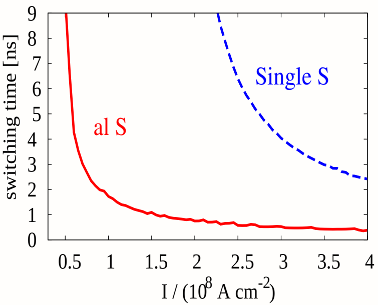
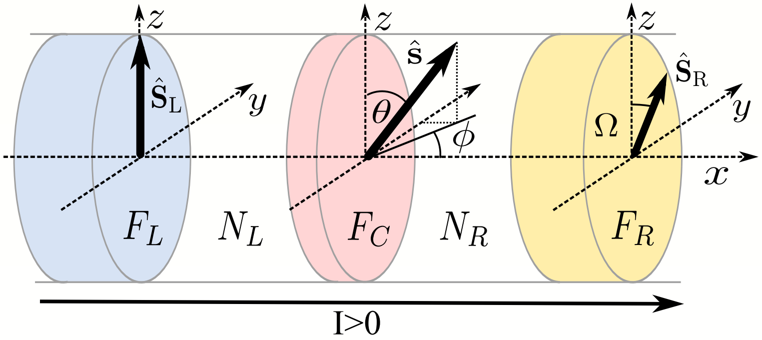


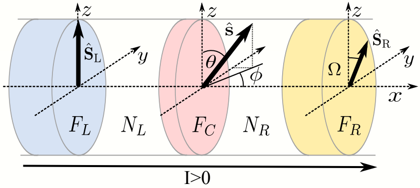
Is this all?

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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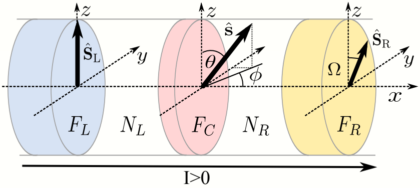

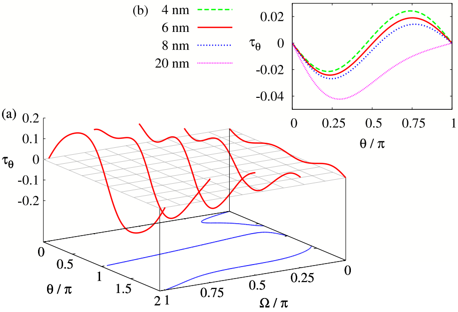

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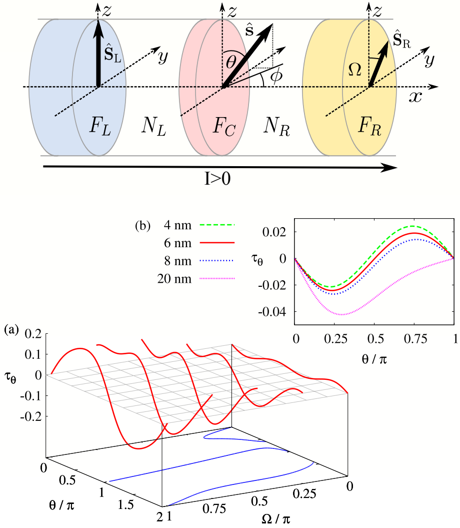

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Current-induced dynamics

We calculated average

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

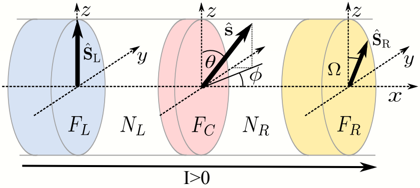
and dispersion

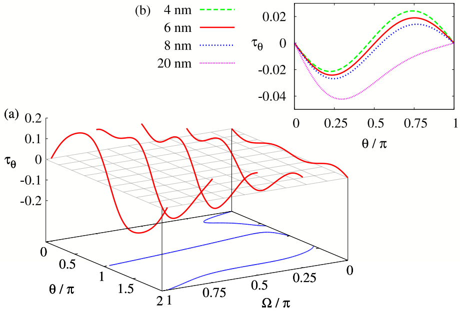
$$\mathscr{D}(s_z) = \sqrt{\langle s_z^2 \rangle - \langle s_z \rangle^2}$$

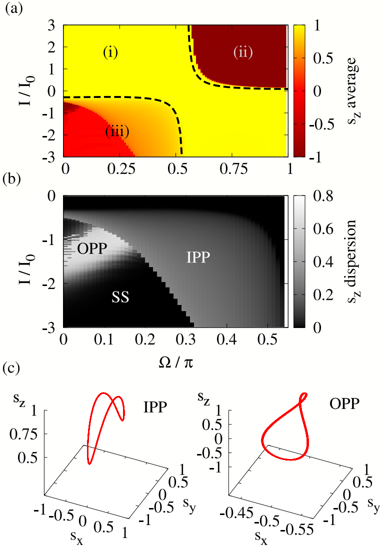
for each couple of I and Ω to map the dynamic behaviour.

Noncollinear configurations in dual spin valves

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







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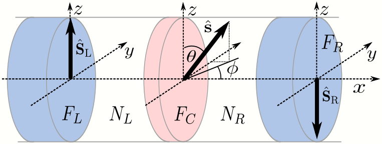
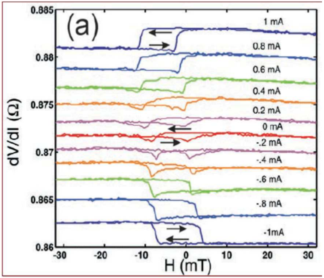
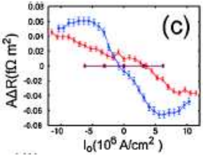
Nonlinear magnetoresistance in dual spin vales







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)

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)

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

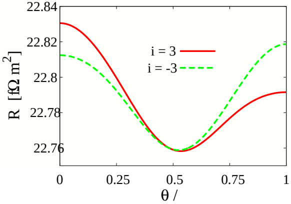
- $g(x)$ is spin accumulation
- ρ_0^* and R_0^* are *zero-current* bulk resistivity and interfacial resistance
- β_0 and γ_0 are *zero-current* bulk/interfacial asymmetry parameters
- q, ξ, q', ξ' are phenomenological parameters

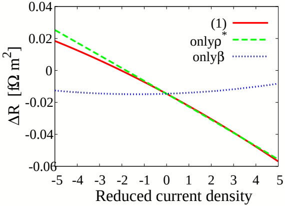
P. Baláž, and J. Barnaś
Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

Nonlinear magnetoresistance in dual spin vales

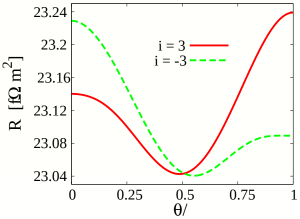
Calculations for Cu - Co(6) / Cu(4) / Py(2) / Cu(2) / Co(6) / IrMn(10) - Cu

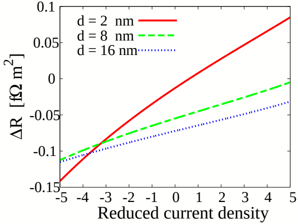
Bulk parameters





Interfacial parameters



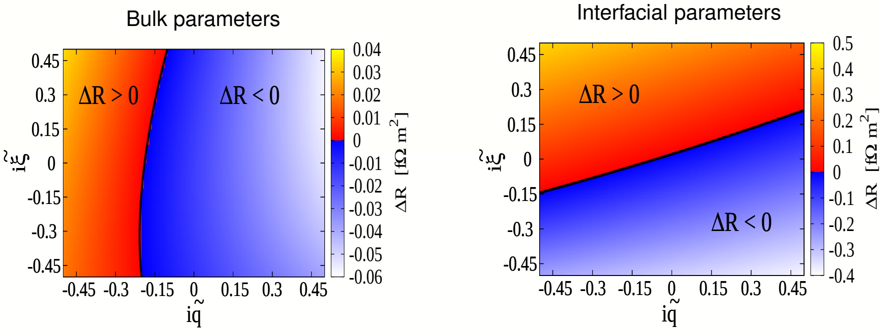


P. Baláž, and J. Barnaś
Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

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



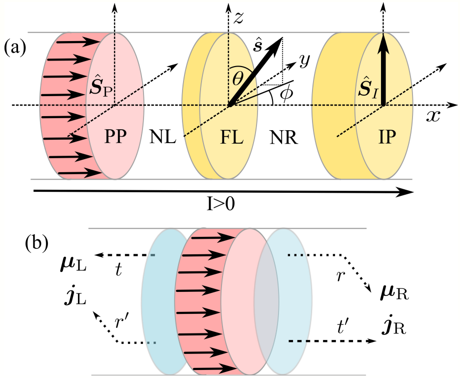
for interfaces ΔR is symmetric with current density

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

Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Dual spin valve
4. Nonlinear magnetoresistance in dual spin vales
5. Current-induced switching in metallic spin valves with perpendicular polarizers

Model of the polarizer



P. Baláž, M. Zwierzycki, J. Barnaś

Spin-transfer torque and current-induced switching in metallic spin valves with perpendicular polarizers

Phys. Rev. B **88** 094422 (2013)

Transport through the polarizer

- We considered the perpendicular polarizer as a magnetized ballistic scaterrer in frame of coherent transport regime
- 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)

- In our formalism the scaterrer coresponds to a single interface.

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M. Zwierzycki *et al*
Calculating scattering matrices by wave function matching
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Outputs of the calculation:

- channel conductances $G_\uparrow$, $G_\downarrow$
- mixing conductance $G_{\uparrow\downarrow} = g_r^{\uparrow\downarrow} + i\, g_i^{\uparrow\downarrow}$
- mixing transmission conductance $T_{\uparrow\downarrow} = t_r^{\uparrow\downarrow} + i\, t_i^{\uparrow\downarrow}$

Differences in definitions

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

$$T_{\sigma\sigma'} = \sum_{nn'} t_{nn'}^{\sigma} \left(t_{nn'}^{\sigma'} \right)^*$$

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

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

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

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

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

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

Studied structures

Cu - PP / Cu(6) / Py(5) / Cu(12) / Py(20) - Cu

Perpendicular polarizer

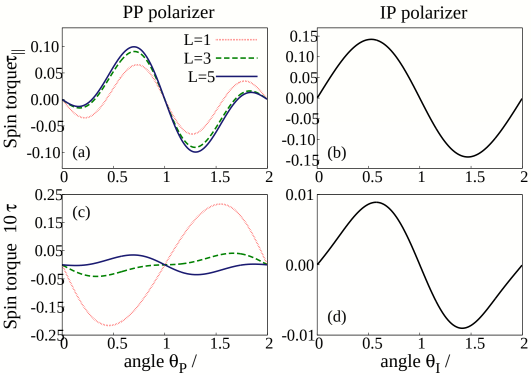
PP_1 = Co(2 ML) / $[\text{Cu(2 ML)/Co(2 ML)}]_{L-1}$

PP_2 = Pt(6 ML) / $[\text{Co(2 ML)/Pt(3 ML)}]_{L}$ / Co(3 ML) / Cu(2 ML) / Co(3 ML)

Results for PP_1

Spin transfer torque

Co(2 ML) / [Cu(2 ML)/Co(2 ML)]$_{L-1}$

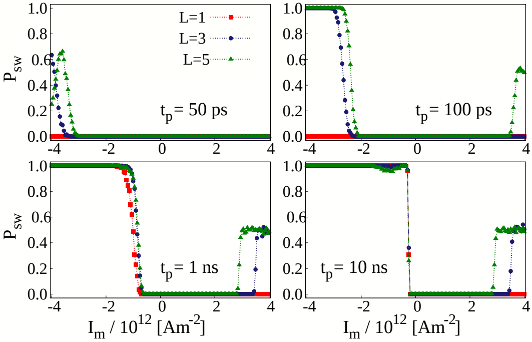


wavelike angular dependence for the perpendicular polarizer

Results for PP_1

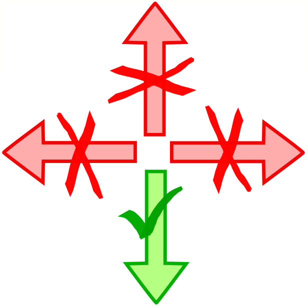
Current-induced switching from ⇑ to ⇓ at $T = 300\,K$

Co(2 ML) / [Cu(2 ML)/Co(2 ML)]$_{L-1}$

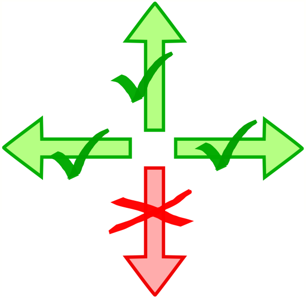


Switching mechanism

For $I < 0$



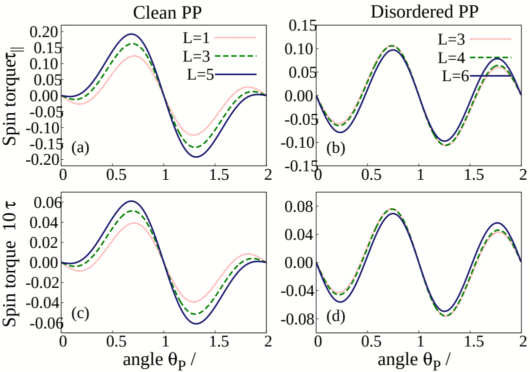
For $I > 0$



Results for PP_2

Spin transfer torque

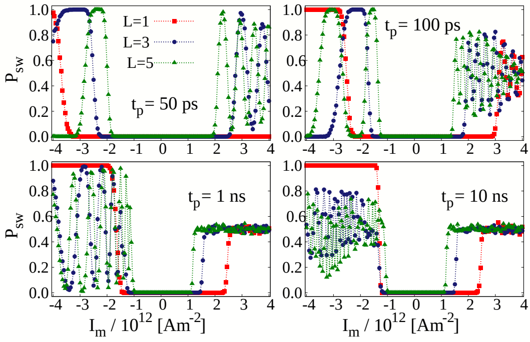
Pt(6 ML) / $[$Co(2 ML)/Pt(3 ML)$]_L$ / Co(3 ML) / Cu(2 ML) / Co(3 ML)



Results for PP_2

Current-induced switching from ⇑ to ⇓

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



Summary

Noncollinear diffusive model is an useful and flexible framework for dealing with spin dependent electronic transport in metalic multilayers

- spin tranfer torque and magnetoresistance in single and dual spin valves
- nonlinear effects in magnetoresistance
- spin transfer torque due to a perpendicular polarizer
- also spin torque and dynamics in composite free layers (synthetic ferro- or antiferromagnets)

SWISS CONTRIBUTION

NANOSPIN

Thank you for your attention

UAM

AGH

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IFM PAN