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

Pavel Baláž

A. Mickiewicz University in Poznan
Department of Physics Division of Mesoscopic Physics

University of Regensburg, 21 June 2012

Division of Mesoscopic Physics

A. Mickiewicz University in Poznań

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 Currie Research Training Network SPINSWITCH
- National Centre for Magnetic Nanostructures SpinLab
- Polish-Swiss Research Project NanoSpin

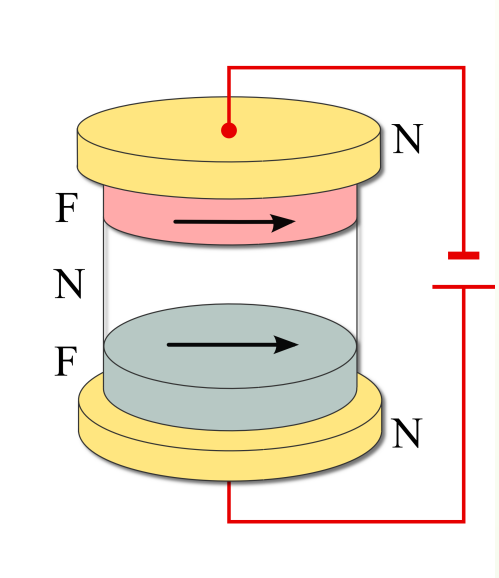
  with Polish Academy of Sciences, University of Technology Kraków, and École Polytechnique Fédérale de Lausanne

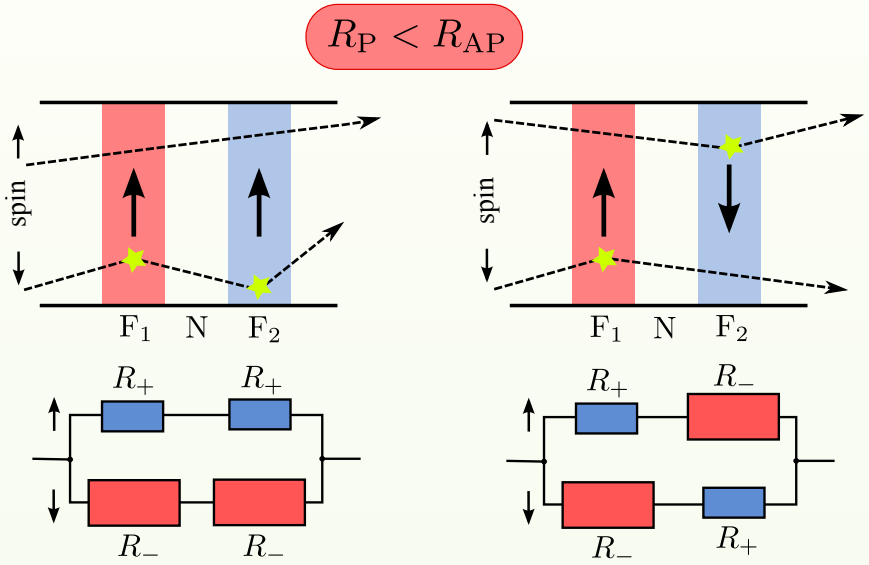
1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

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

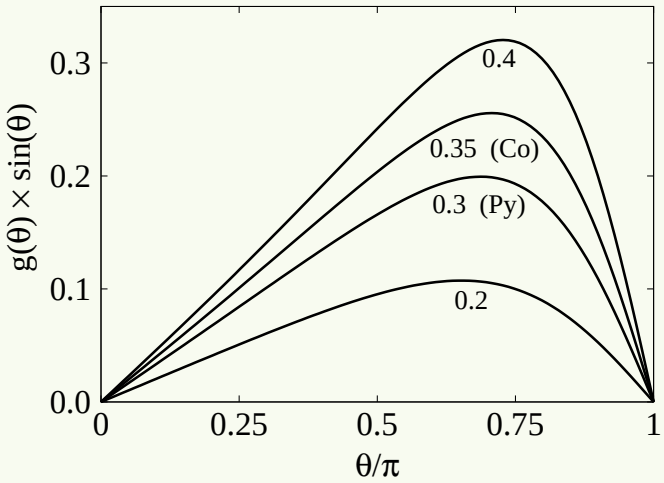
Theory of the perpendicular magnetoresistance in magnetic multilayers
Phys. Rev. B 48, 7099–7113 (1993)

Current-induced dynamics and magnetization switching

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

Slonczewski's model (ballistic)

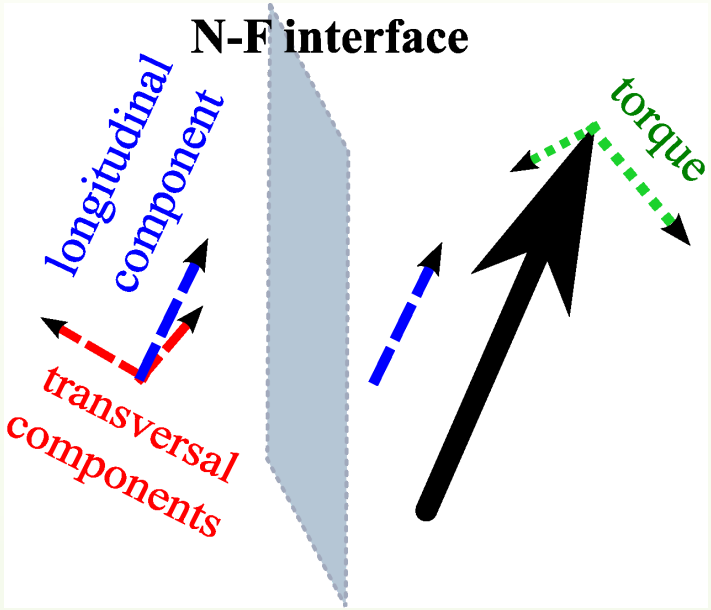
J. Magn. Magn. Mater. **159**, L1-L7 (1996)

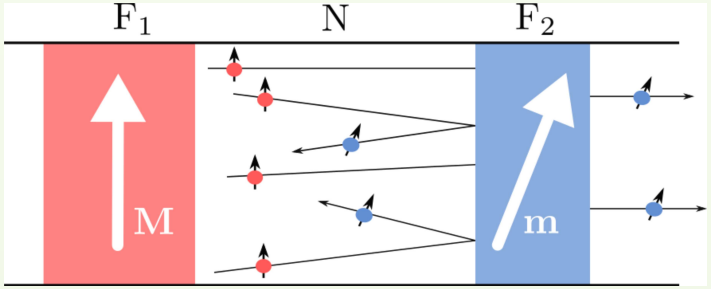


$$\tau_{\text{Sloncz}} = \frac{Ig(\theta)}{e}\hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}}\right)$$

where

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



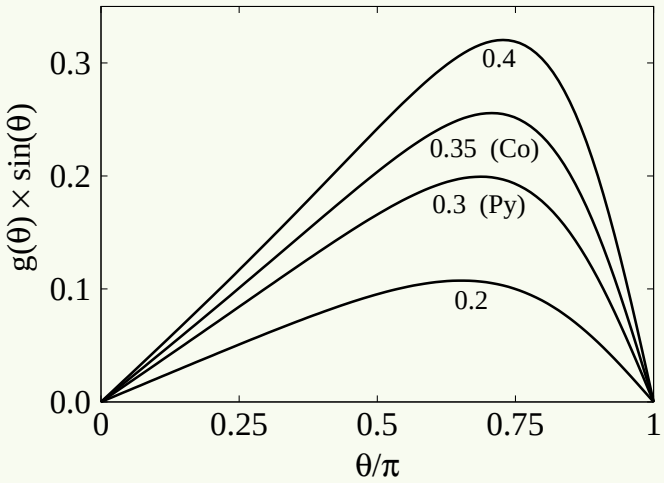


Current-induced dynamics and magnetization switching

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

Slonczewski's model (ballistic)

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



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

where

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

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

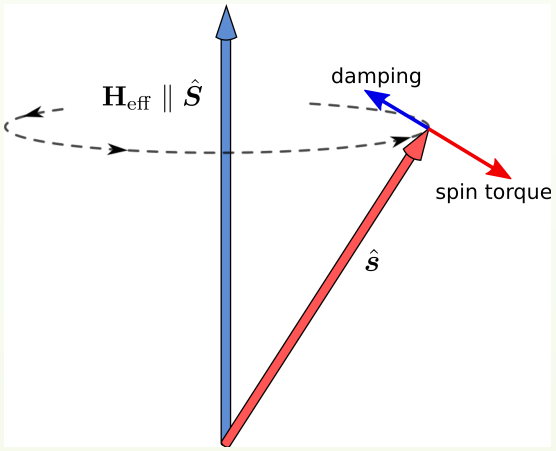
$$\tau_\theta = a(\theta) I \hat{\mathbf{s}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{S}}\right)$$

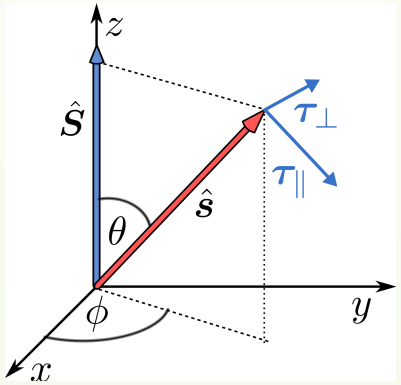
$$\tau_\phi = b(\theta) I \hat{\mathbf{s}} \times \hat{\mathbf{S}}$$

Equation of motion

Landau-Lifshitz-Gilbert equation

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





Effective magnetic field

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

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

1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

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

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

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

β bulk asymmetry paramters
γ interfacial asymmetry parameter

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)

Mathematical description

Two channels model

bulk resistivities

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

interface resistances

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

β bulk asymmetry paramters
γ interfacial asymmetry parameter

Diffusive transport

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

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

for electrochemical potentials we get

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

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

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)

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

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

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

for electrochemical potentials we get

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

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

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)

Mathematical description

Nonmagnetic layer

has no natural quantization axis

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

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

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

for electrochemical potentials we get

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

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)

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)

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

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

Spin-transfer torque

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

Boundary conditions at N/F interface

- particle current is continuous across all interfaces

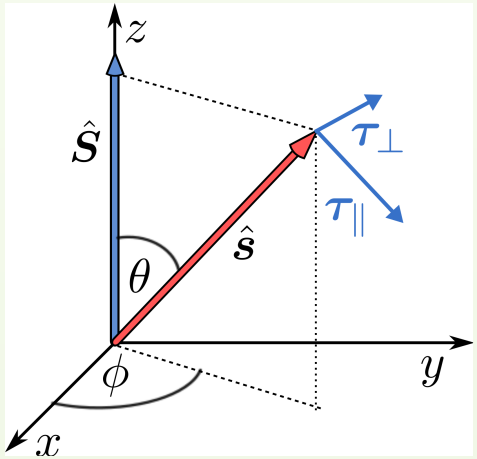
$$e^2 j_0 = (G_\uparrow + G_\downarrow)(\bar{\mu}_0^F - \bar{\mu}_0^N) + (G_\uparrow - G_\downarrow)(g_z^F - g_z^N)$$

- 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

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



Components

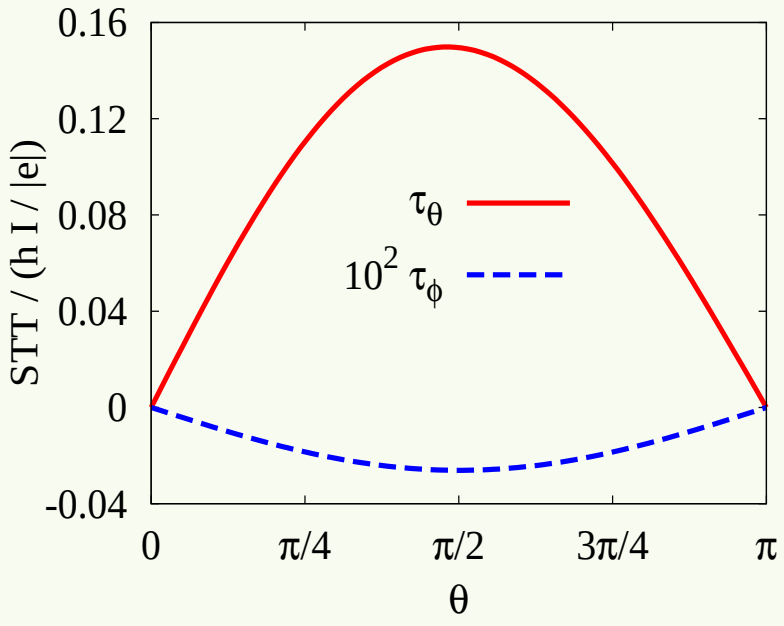
in-plane $\tau_\theta = -\frac{\hbar}{2} j'_y|_{\mathrm{N/F}}$

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

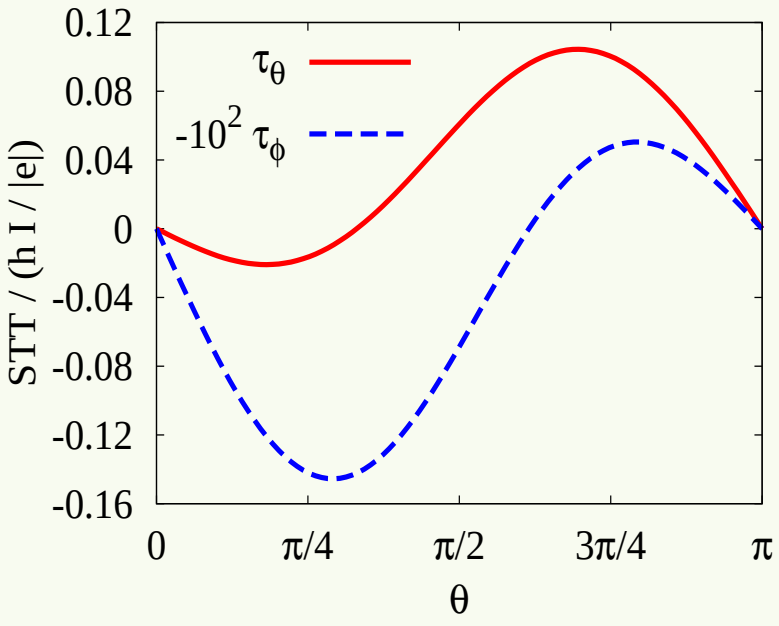
Results

Calculations for real structures

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



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

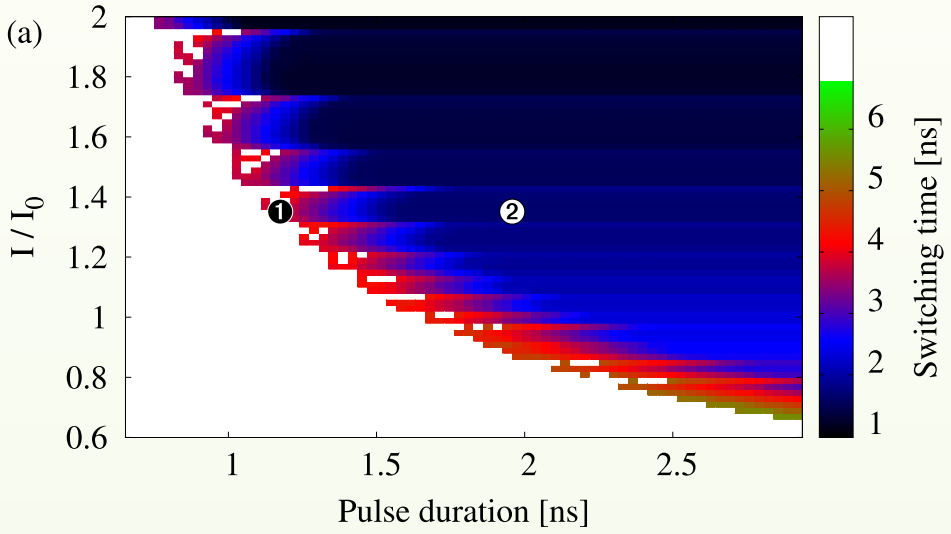


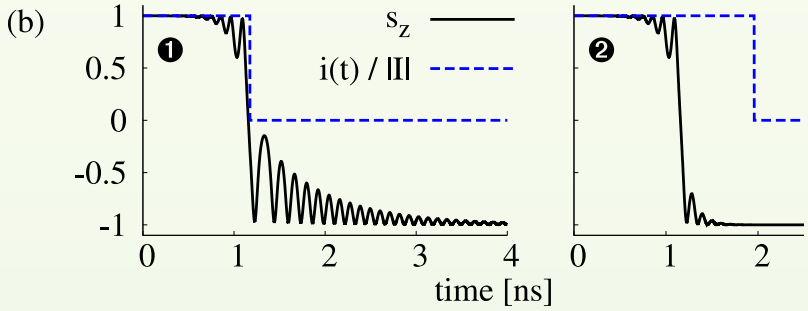
Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

Current-induced dynamics: spin-torque in action

Switching in standard Py/Cu/Py spin valves





(i) no switching

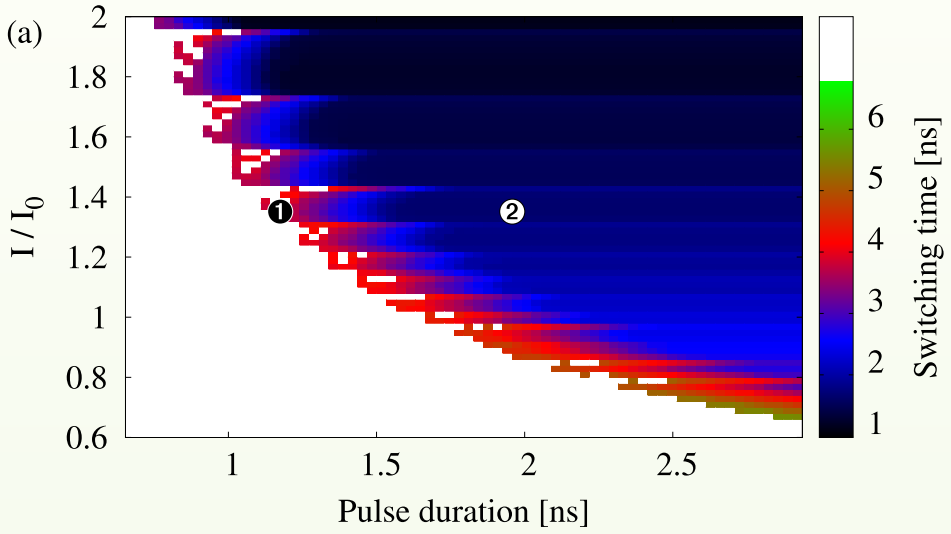
P. B., M. Gmitra, J. Barnaś

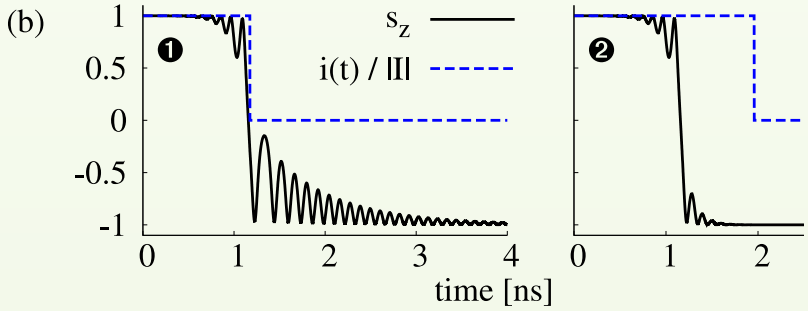
Current-pulse-induced magnetic switching in standard and nonstandard spin-valves

Phys. Rev. B **79**, 144301 (2008)

Current-induced dynamics: spin-torque in action

Switching in standard Py/Cu/Py spin valves





(i) no switching

(ii) retarded switching (several nanoseconds)

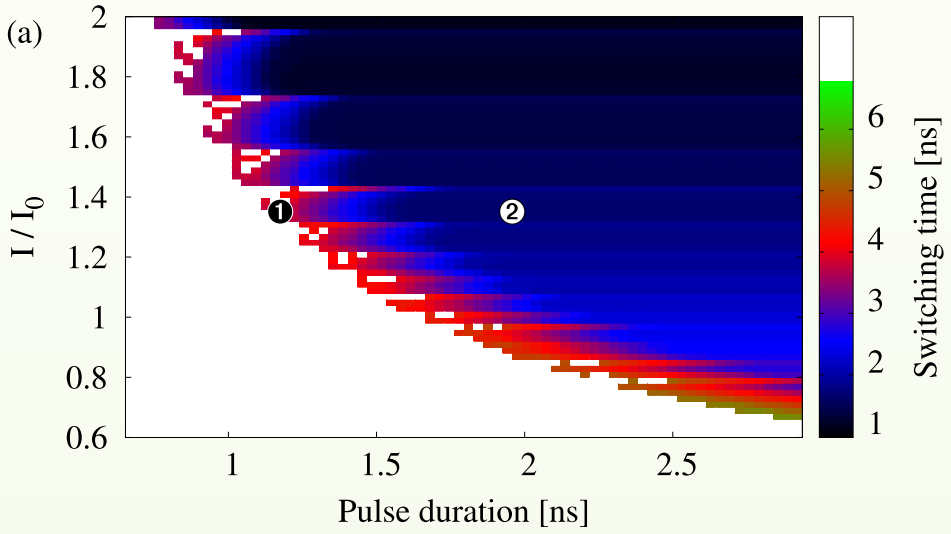
P. B., M. Gmitra, J. Barnaś

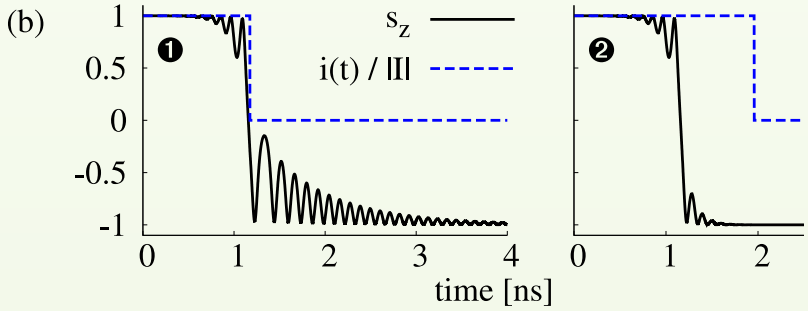
Current-pulse-induced magnetic switching in standard and nonstandard spin-valves

Phys. Rev. B **79**, 144301 (2008)

Current-induced dynamics: spin-torque in action

Switching in standard Py/Cu/Py spin valves





(i) no switching

(ii) retarded switching (several nanoseconds)

(iii) ultra-fast switching (half precessional period)

P. B., M. Gmitra, J. Barnaś

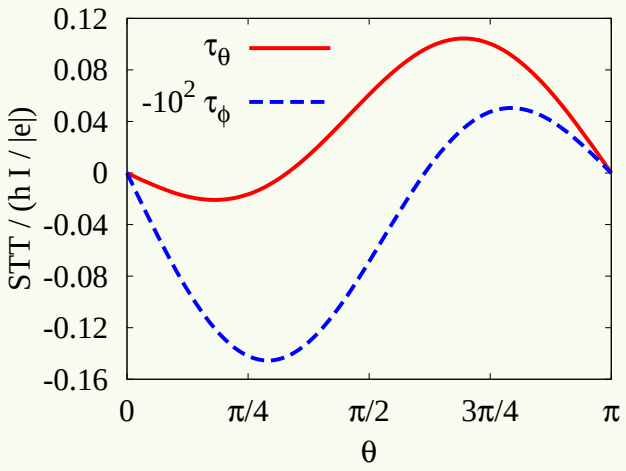
Current-pulse-induced magnetic switching in standard and nonstandard spin-valves

Phys. Rev. B **79**, 144301 (2008)

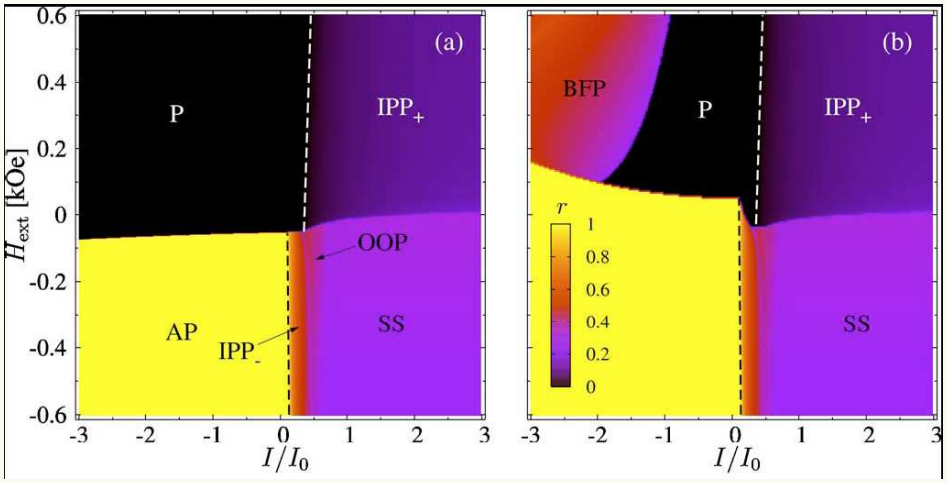
Current-induced dynamics: spin-torque in action

Switching in nonstandard Co/Cu/Py spin valves

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



wavy-torque dynamics



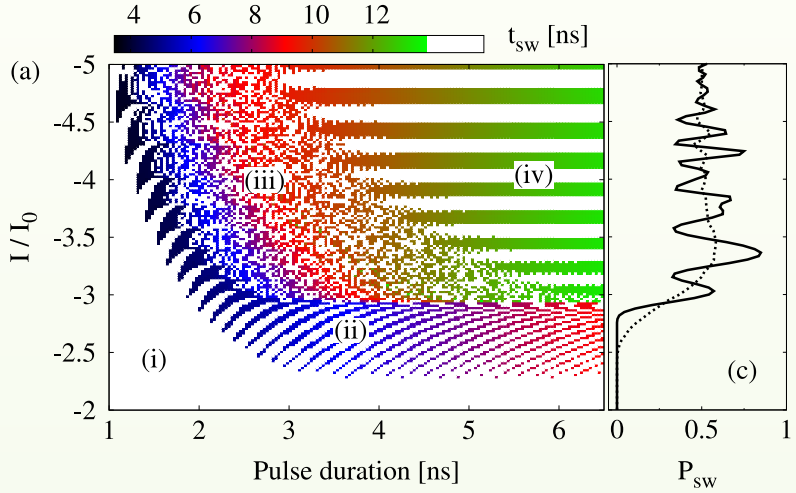
M. Gmitra and J. Barnaś, Appl. Phys. Lett. **89**, 223121 (2006)

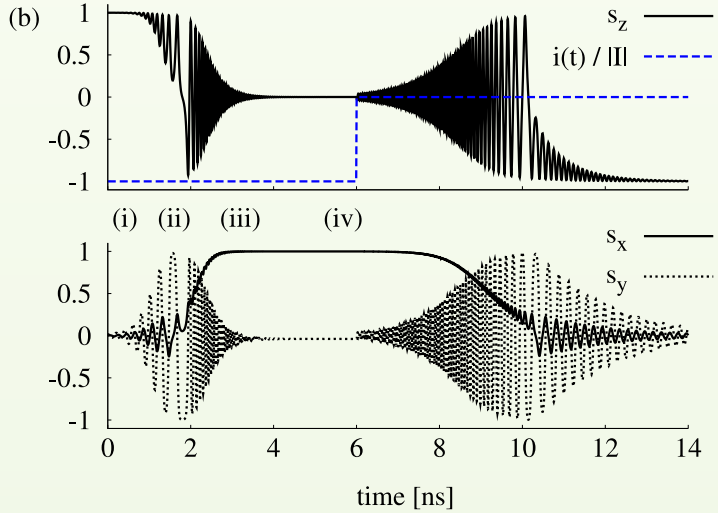
Kovalev et al., Phys. Rev. B **66**, 224424 (2002)
Barnaś et al., Phys. Rev. B **72**, 024426 (2005)
Gmitra and Barnaś Phys. Rev. Lett. **96**, 207205 (2006); Phy. Rev. Lett. **99**, 097205 (2007)
Boulle et al. Nature Phys. **3**, 492 (2007); Phys. Rev. B **77**, 174403 (2008)
Jaromirska et al. J. Appl. Phys. **106**, 113909 (2009); Phys. Rev. B **81**, 014408 (2010)

- Current flowing in one direction destabilizes both collinear configurations (parallel as well as antiparallel)
- Current flowing in the opposite direction stabilizes both collinear configurations

Current-induced dynamics: spin-torque in action

Switching in nonstandard Co/Cu/Py spin valves





(i) no switching

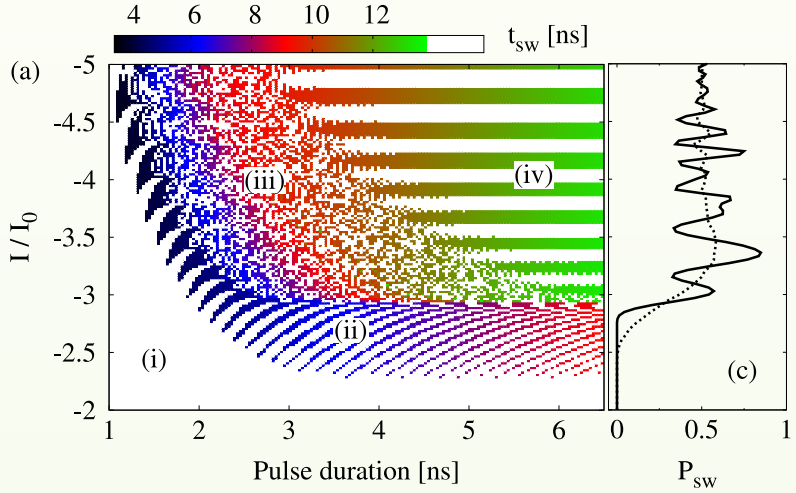
P. B., M. Gmitra, J. Barnaś

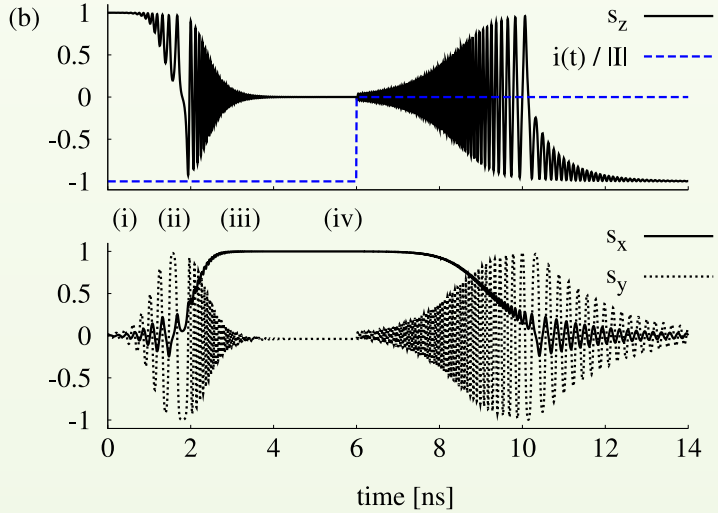
Current-pulse-induced magnetic switching in standard and nonstandard spin-valves

Phys. Rev. B **79**, 144301 (2008)

Current-induced dynamics: spin-torque in action

Switching in nonstandard Co/Cu/Py spin valves



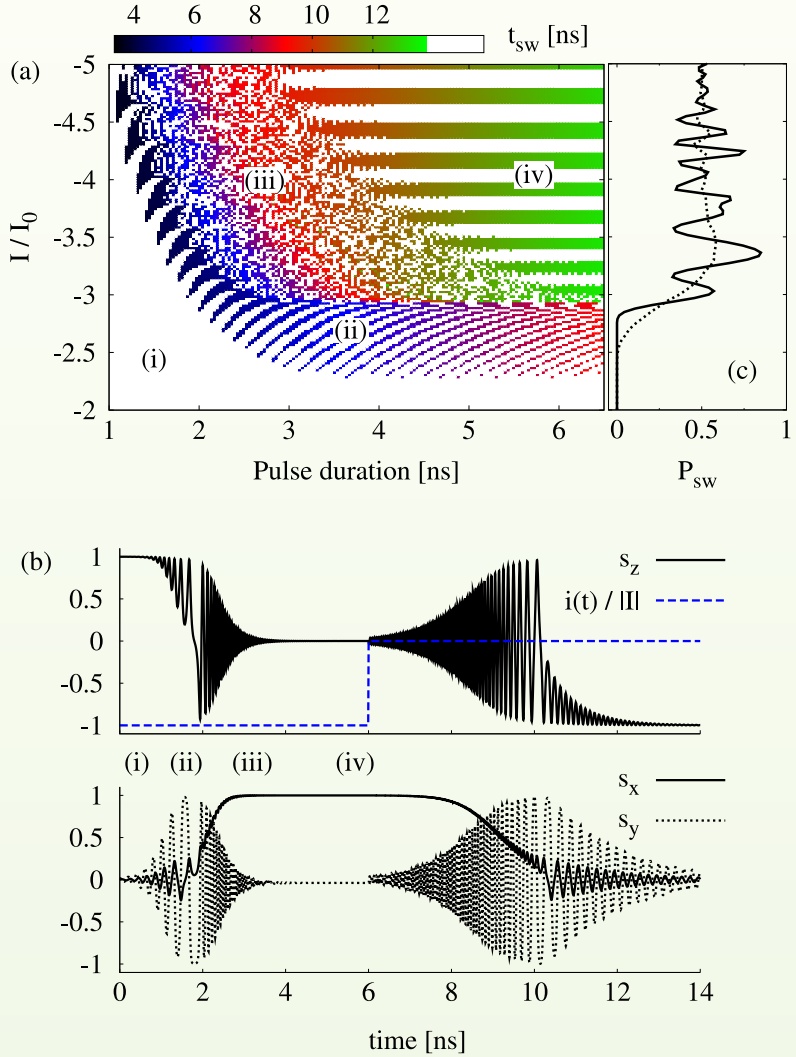


(i) no switching

(ii) in-plane precessions:
fast switching but small area

Current-induced dynamics: spin-torque in action

Switching in nonstandard Co/Cu/Py spin valves



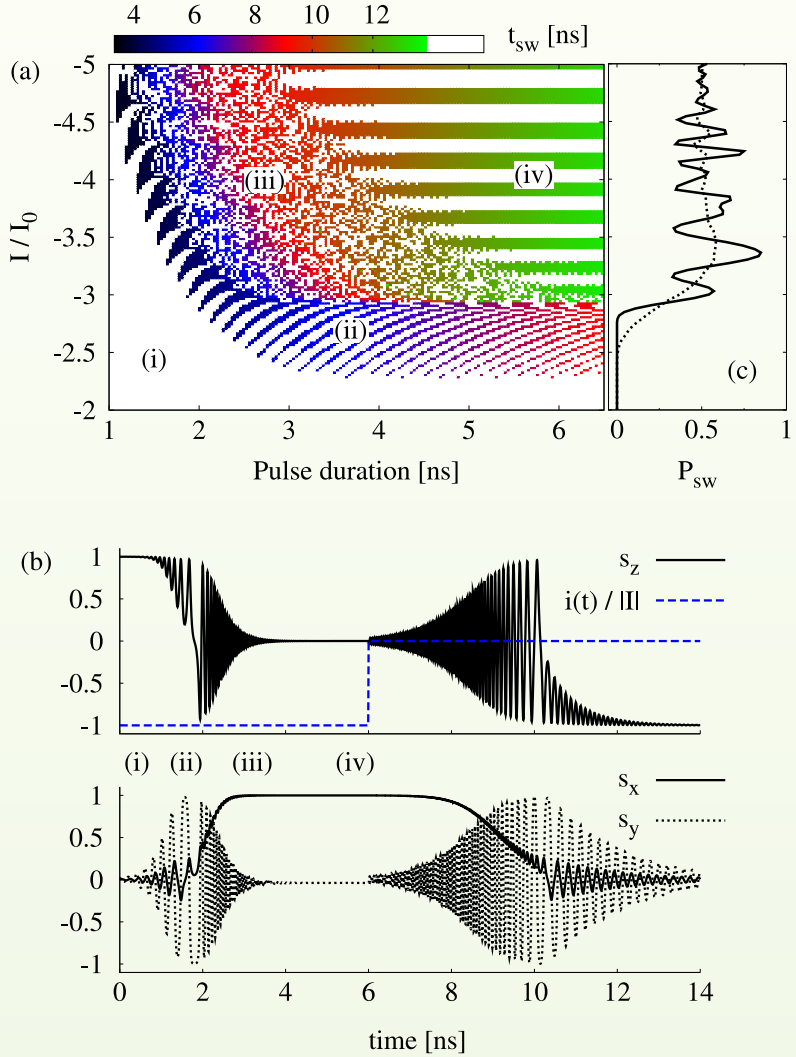
(i) no switching

(ii) in-plane precessions:
fast switching but small area

(iii) out-of-plane precessions:
noisy, no reliable switching

Current-induced dynamics: spin-torque in action

Switching in nonstandard Co/Cu/Py spin valves

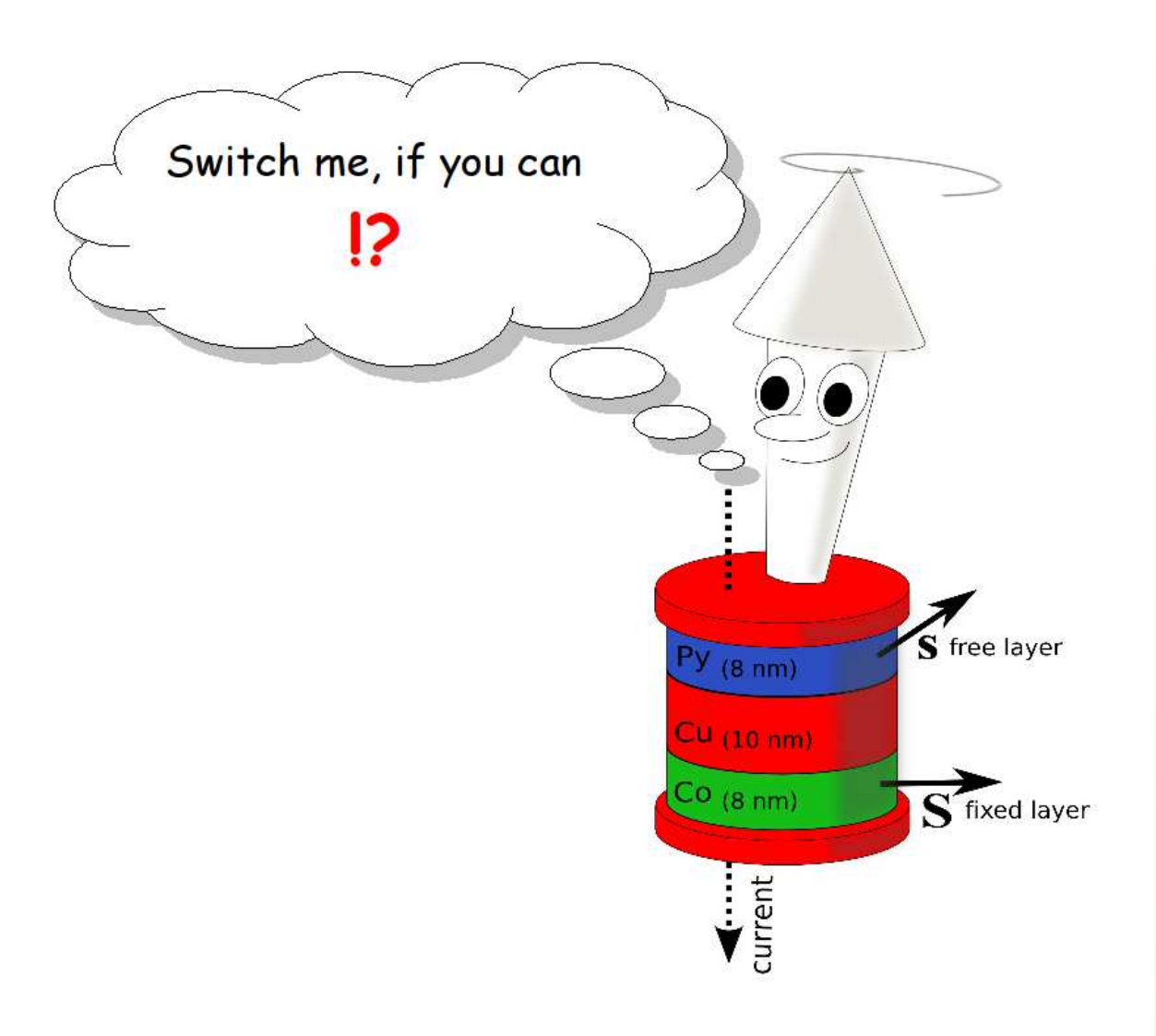


(i) no switching

(ii) in-plane precessions:
fast switching but small area

(iii) out-of-plane precessions:
noisy, no reliable switching

(iv) static state:
quite reliable but slow

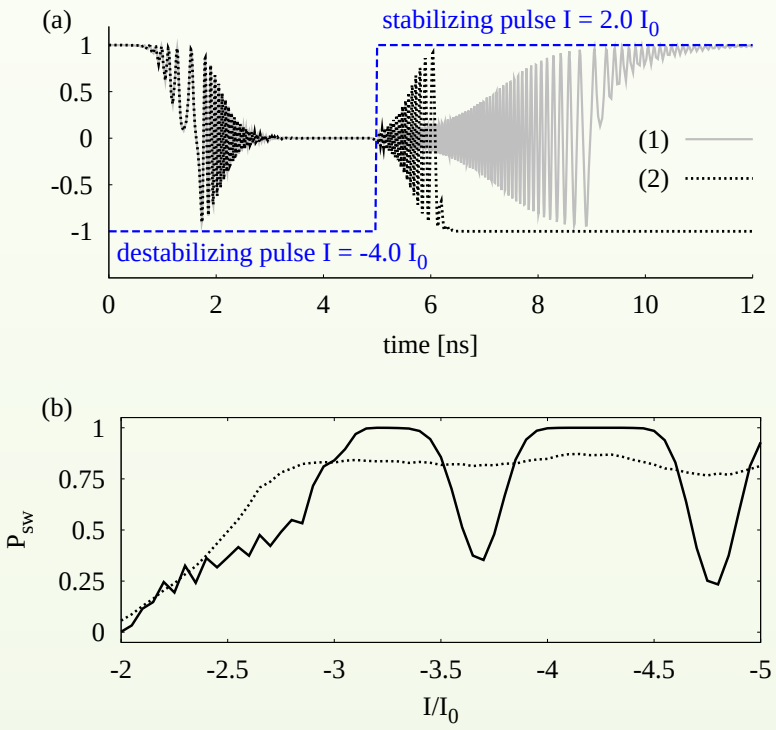


No reliable fast switching?

Non-standard spin valve

Double-pulse switching scheme

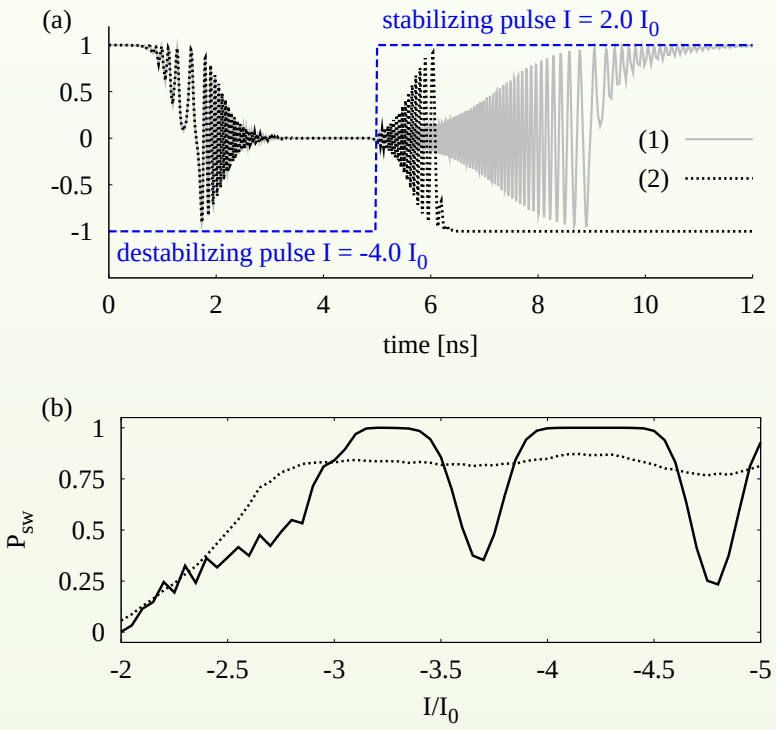
switching enhancement

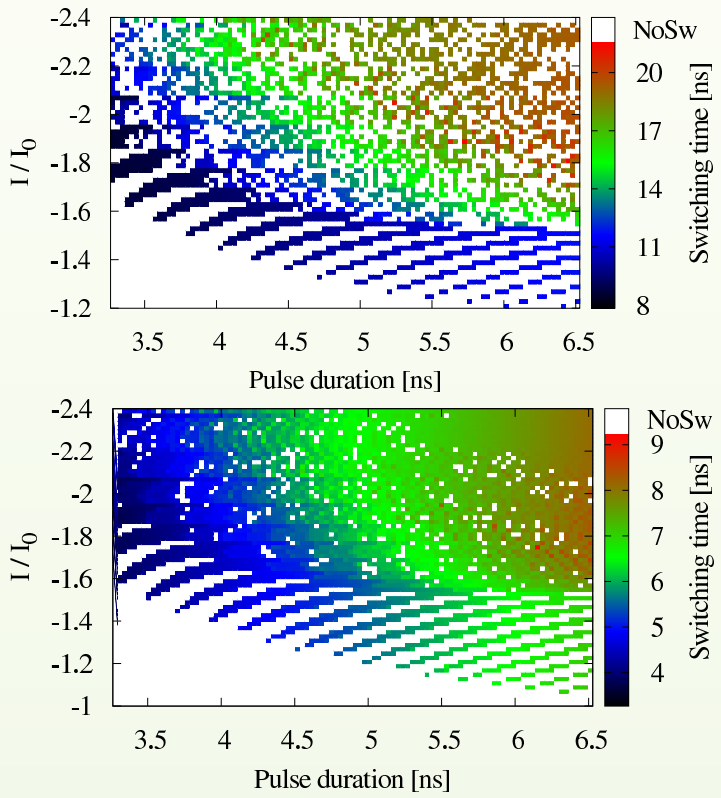


Non-standard spin valve

Double-pulse switching scheme

switching enhancement





Conclusions

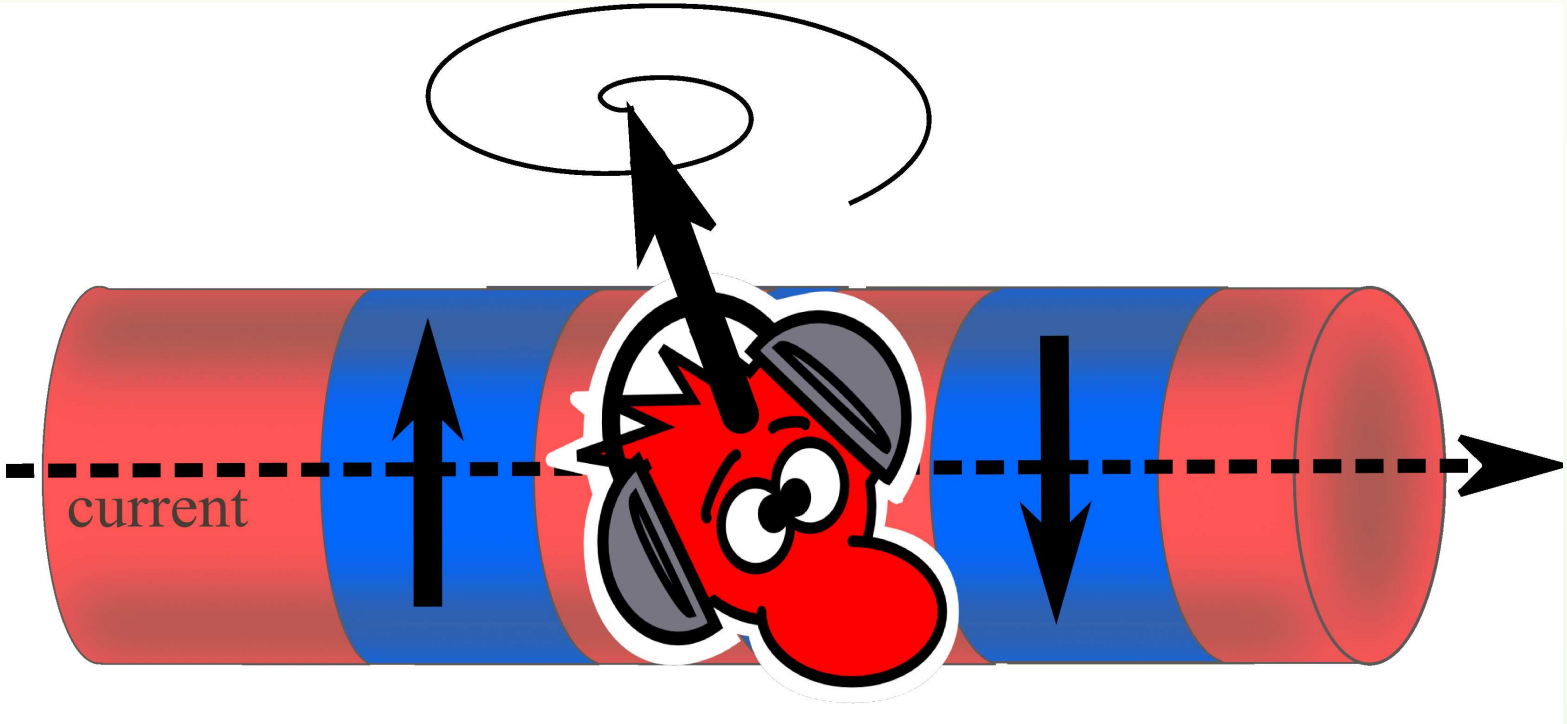
on current-pulse-induced switching

- non-standard *wavy*-torque in Co/Cu/Py spin valve leads to steady-state precessions without need of external magnetic field
- double-pulse switching scheme can enhance the switching time and probabibility in Co/Cu/Py even at non-zero temperature

Outline

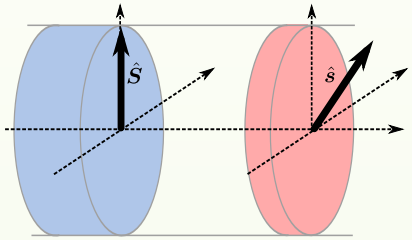
1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

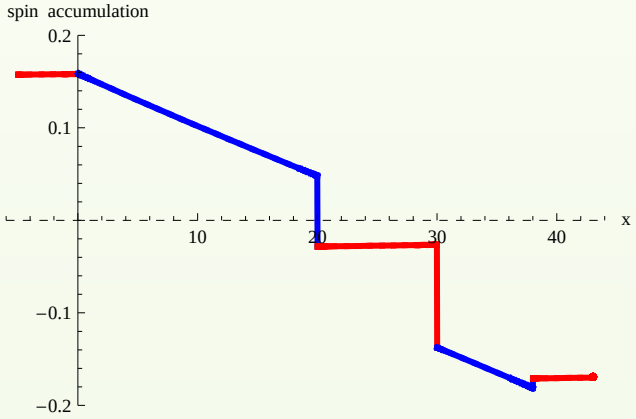
What is a dual spin valve?



Spin accumulation in dual spin valve

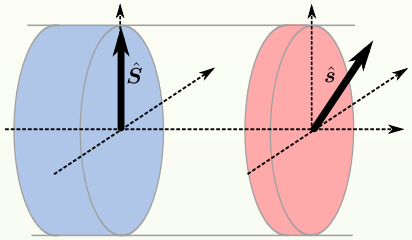
spin accumulation in single spin valve

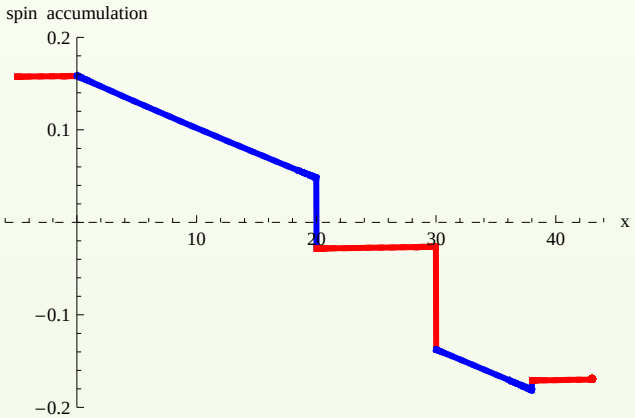




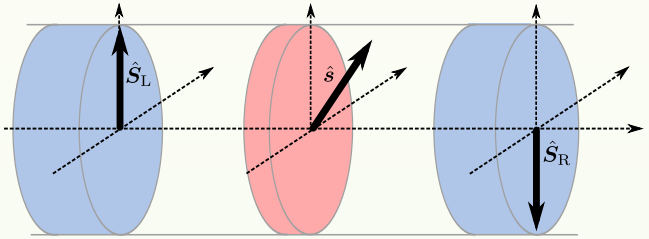
Spin accumulation in dual spin valve

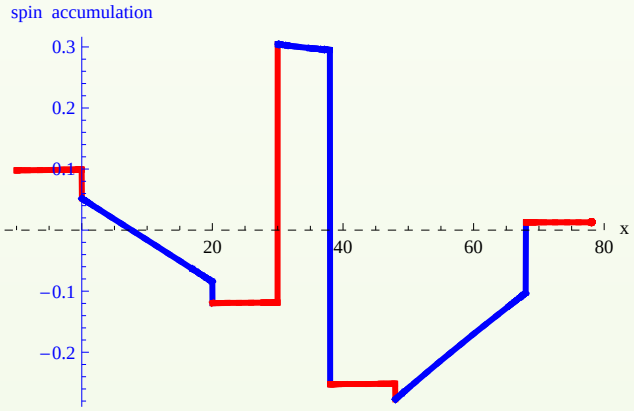
spin accumulation in single spin valve





spin accumulation in dual spin valve





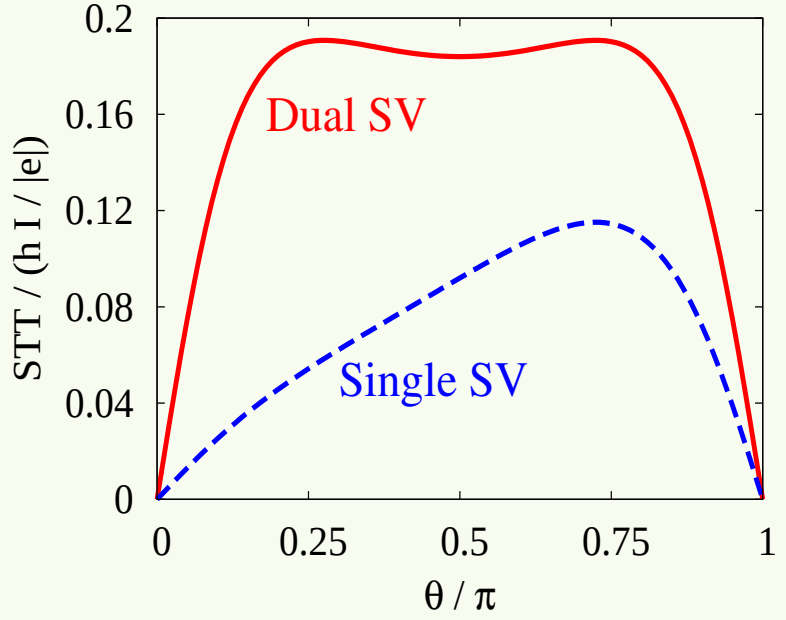
L. Berger
Multilayer Configuration for Experiments of Spin Precession Induced by a DC Current
J. Appl. Phys. **93**, 7683 (2003)

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

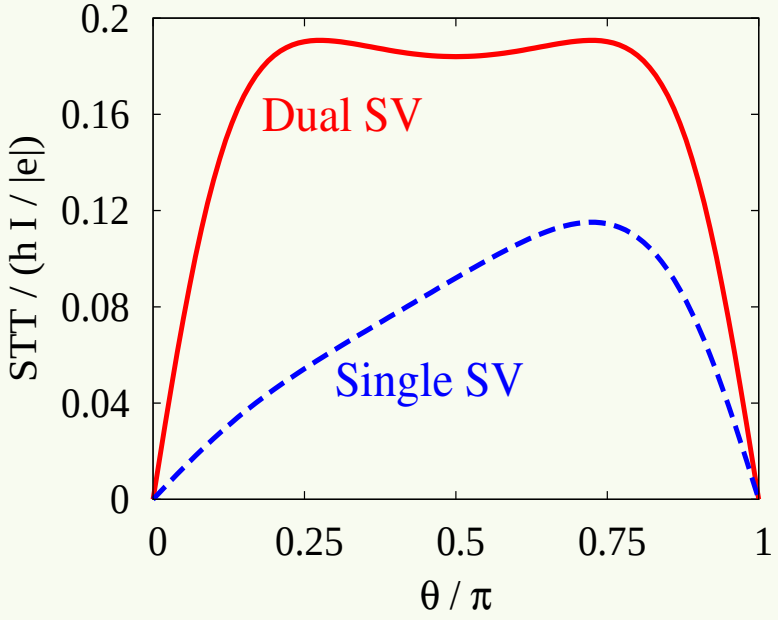


Enhancement of switching

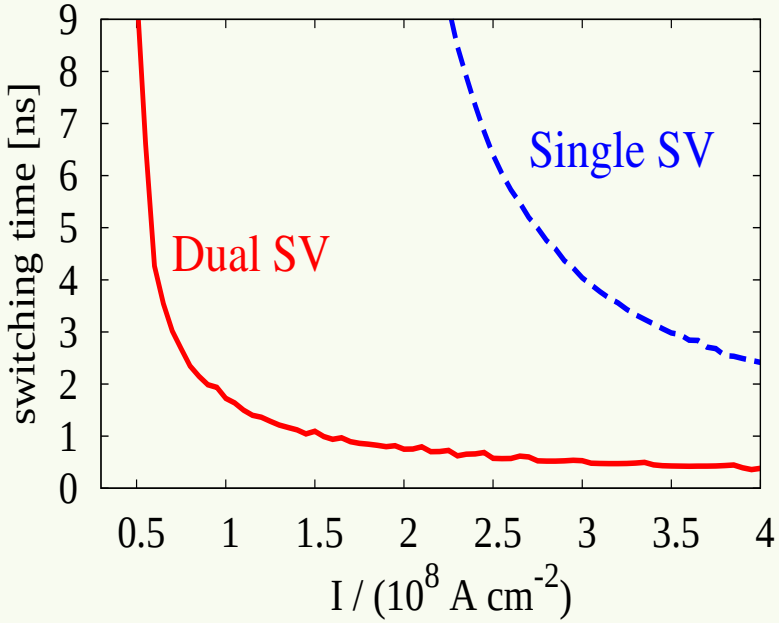
single *vs.* dual spin valve

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

Spin-transfer torque



Switching time

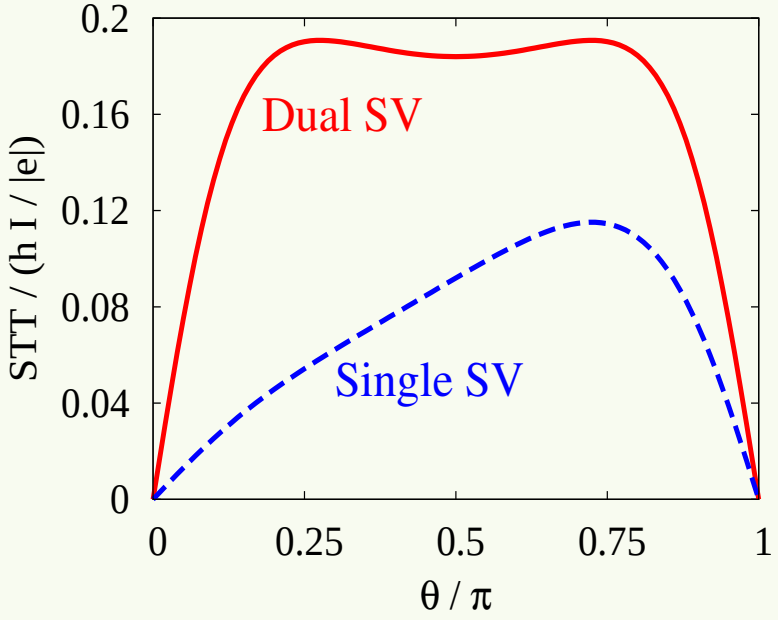


Enhancement of switching

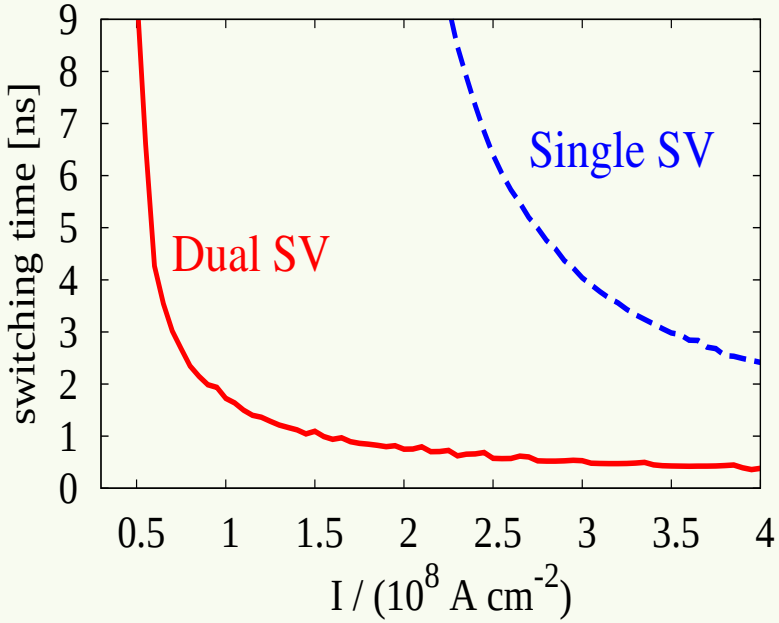
single *vs.* dual spin valve

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

Spin-transfer torque

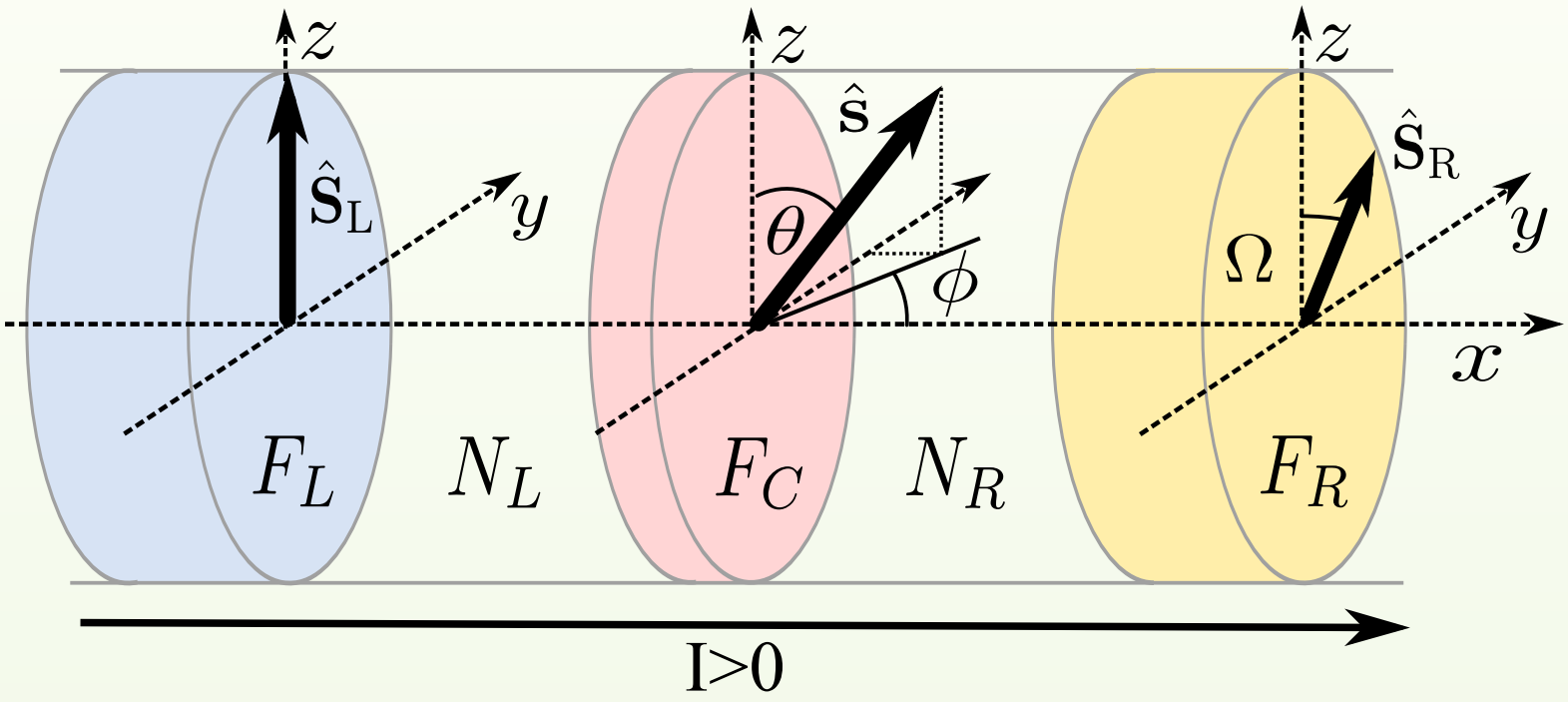


Switching time



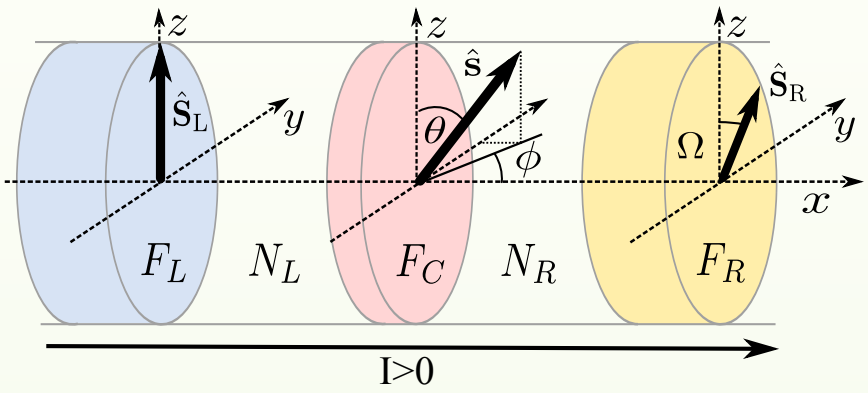
Is this all?

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)



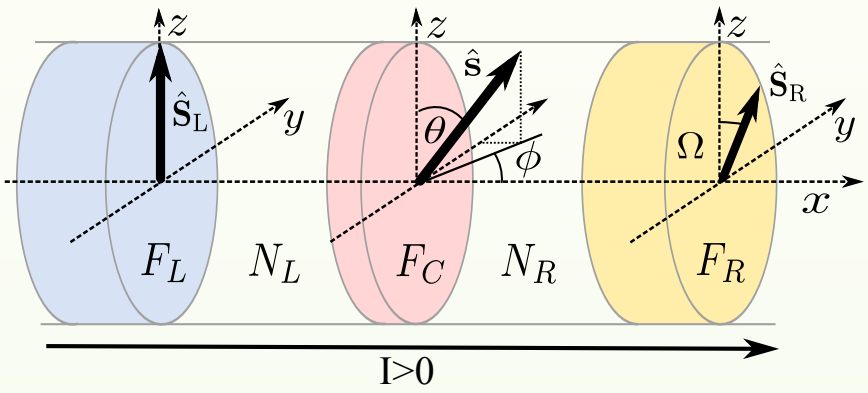
P.B., M. Gmitra, J. Barnaś

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

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

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)

Noncollinear effects in STT

- In-plane torque component

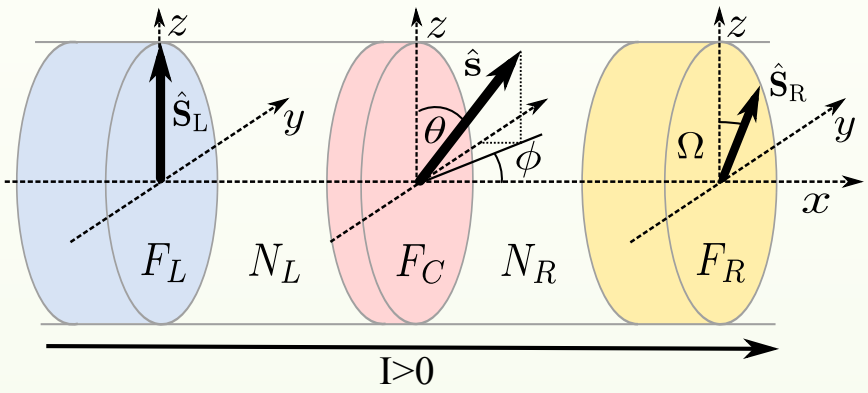
$$\tau_\theta = -(a_\mathrm{L} - a_\mathrm{R}\cos\Omega)I\sin\theta - a_\mathrm{R}I\sin\Omega\sin\phi\cos\theta$$

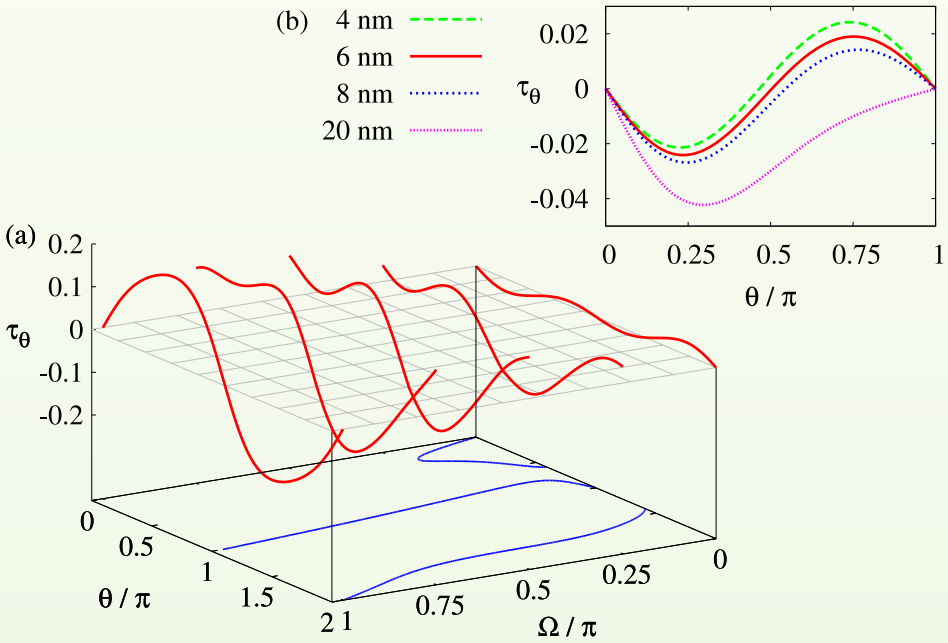
- Out-of-plane torque component

$$\tau_\phi = a_\mathrm{R}I\sin\Omega\cos\phi$$

Noncollinear configurations in dual spin valves

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





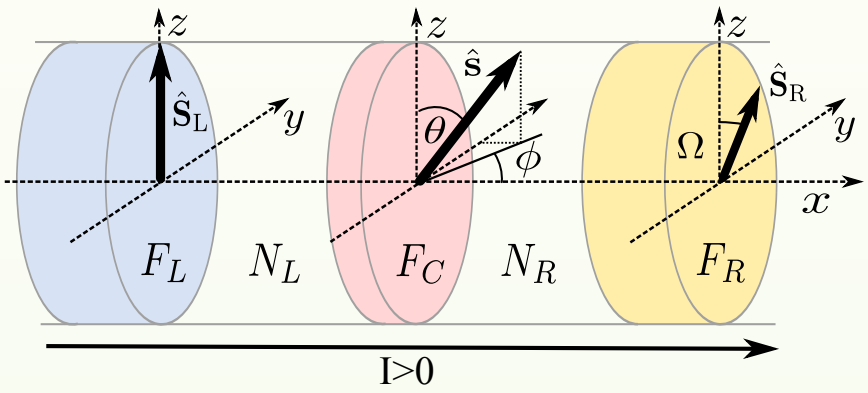
P.B., M. Gmitra, J. Barnaś

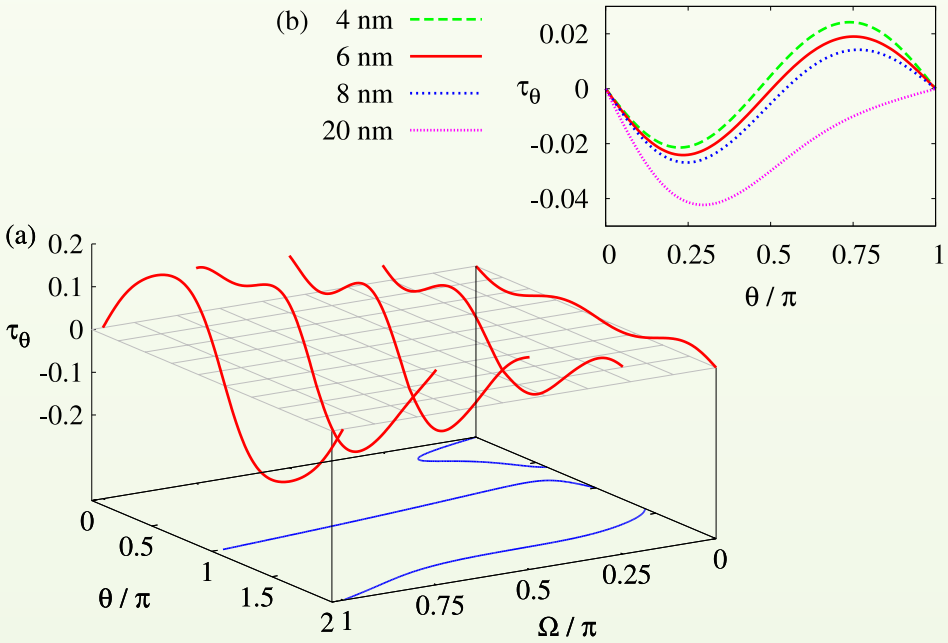
Current-induced dynamics in non-collinear dual spin-valves

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

Noncollinear configurations in dual spin valves

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





Current-induced dynamics

We calculated average

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

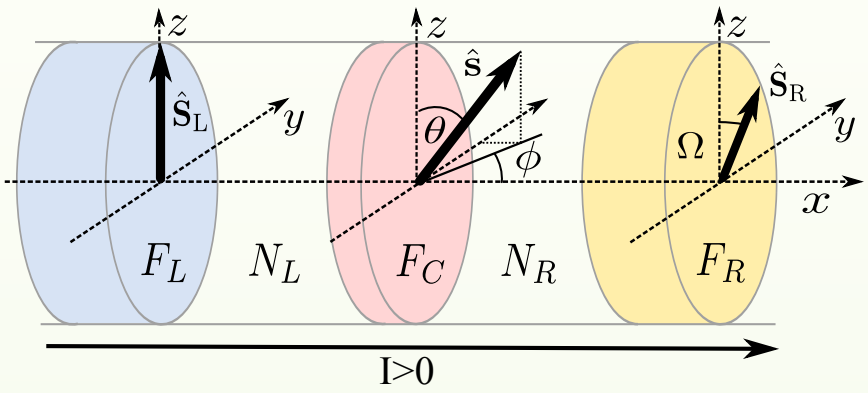
and dispersion

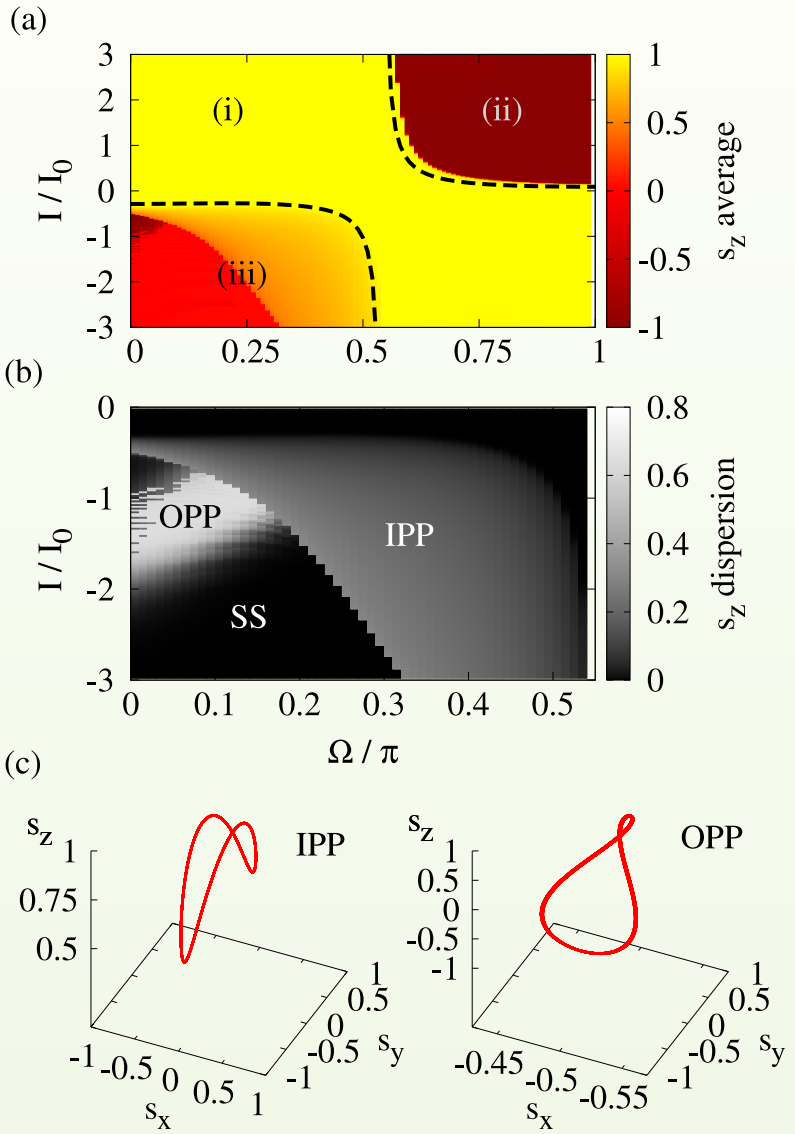
$$\mathscr{D}(s_z) = \sqrt{\langle s_z^2 \rangle - \langle s_z \rangle^2}$$

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)





Critical current density

$$I_c^0 \simeq \frac{\alpha \mu_0 M_s d \left(H_{\mathrm{ani}} + \frac{H_{dx}+H_{dy}}{2} - H_{dz} \right)}{a_L^0(\Omega) - a_R^0(\Omega)\cos\Omega}$$

Conclusions

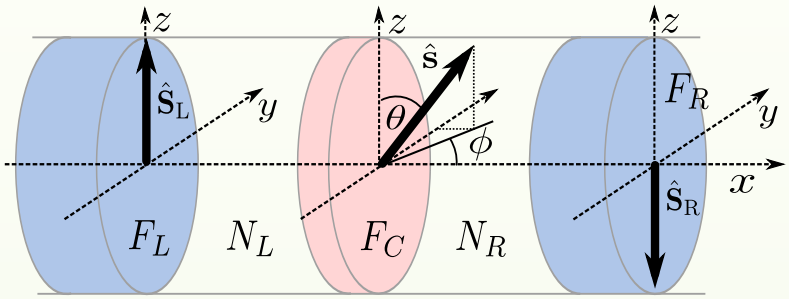
on dual spin valves

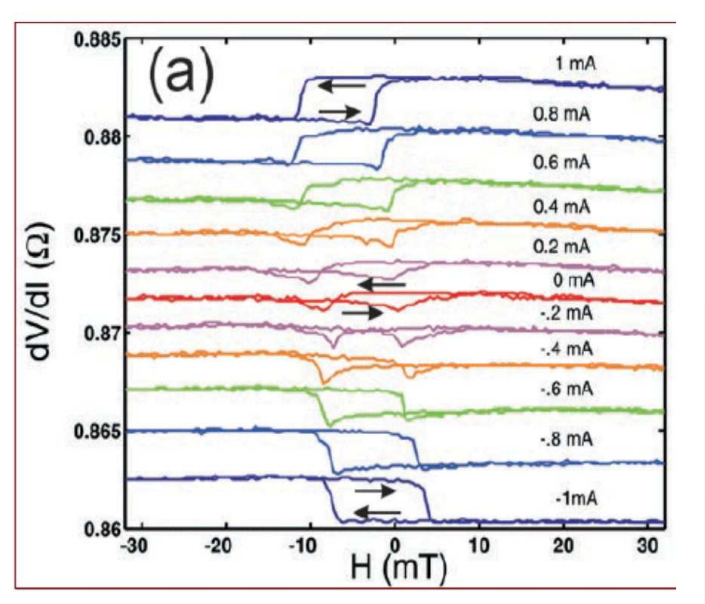
- dual spin valves may decreas the critical current and switching time in antiparallel configuration of outermost layers
- changing the magnetic configuration of outer layers in dual spin valve it is possible to manipulate with spin-tansfer torque angular dependence and hence with the dynamic behaviour

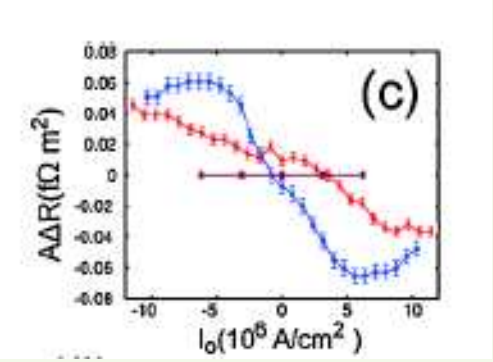
Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

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

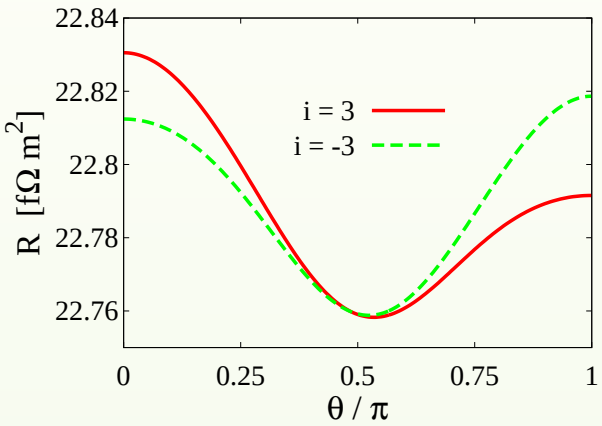
- $g(x)$ is spin accumulation
- ρ_0^* and R_0^* are *zero-current* bulk resistivity and interfacial resistance
- β_0 and γ_0 are *zero-current* bulk/interfacial asymmetry parameters
- q, ξ, q', ξ' are phenomenological parameters

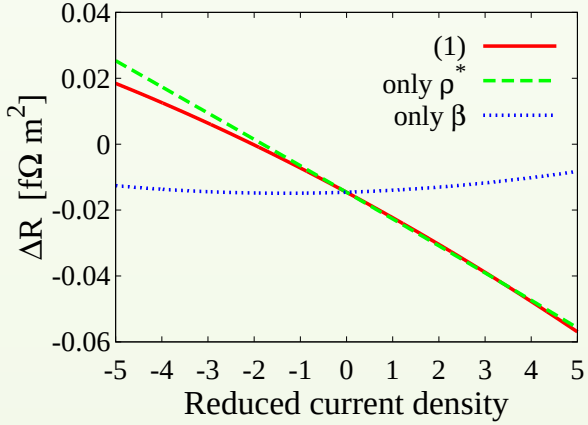
P. Baláž, and J. Barnaś
Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

Nonlinear magnetoresistance in dual spin vales

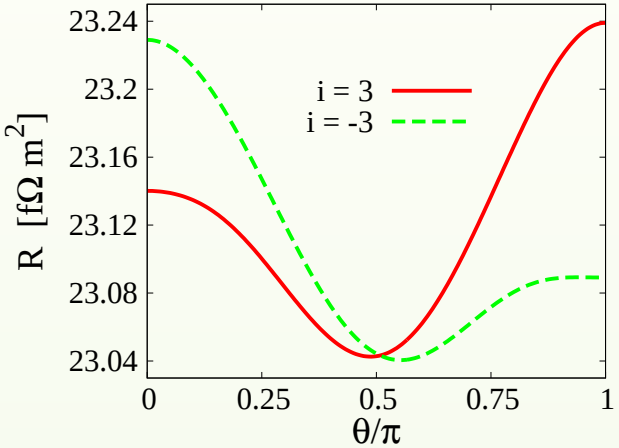
Calculations for Cu - Co(6) / Cu(4) / Py(2) / Cu(2) / Co(6) / IrMn(10) - Cu

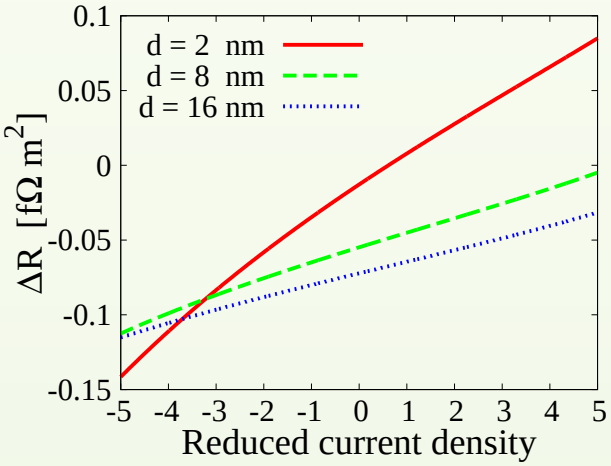
Bulk parameters





Interfacial parameters





P. Baláž, and J. Barnaś

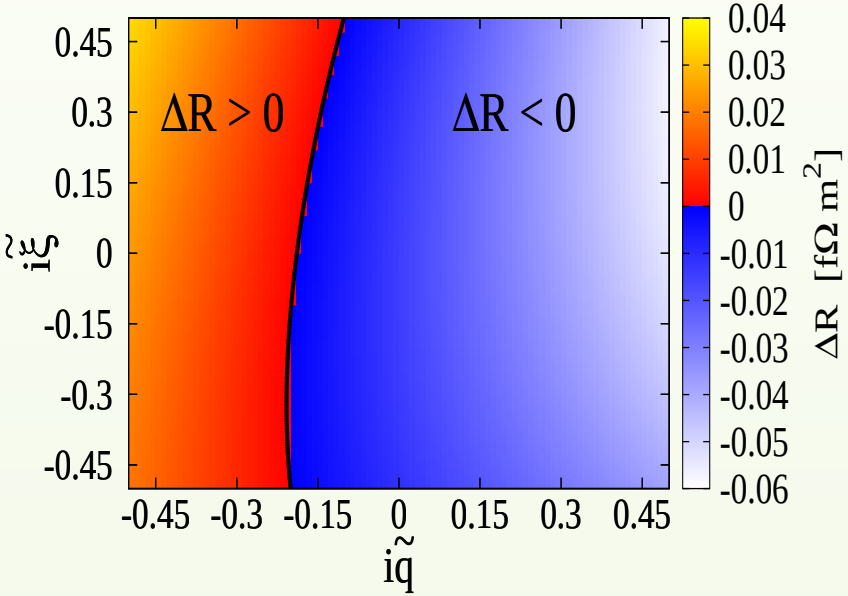
Nonlinear magnetotransport in dual spin valves
Phys. Rev. B **82**, 104430 (2010)

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

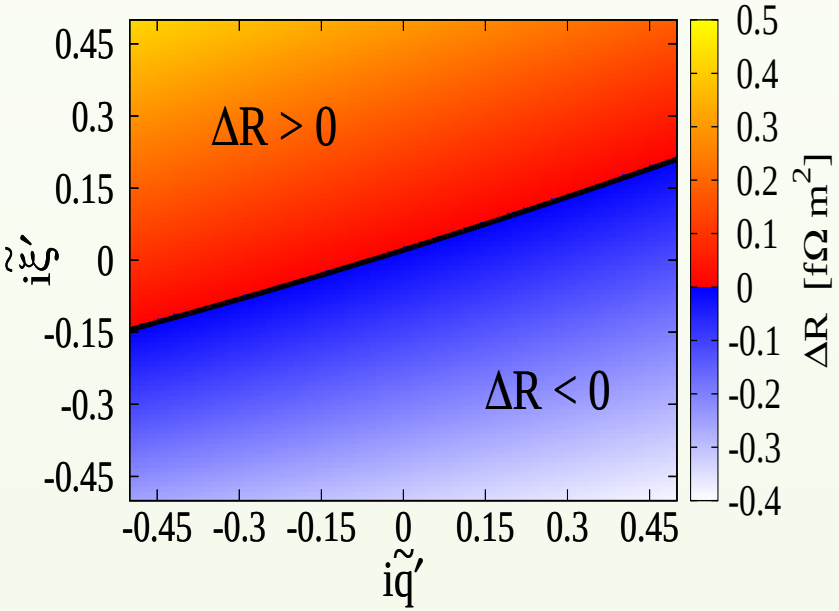
Nonlinear magnetoresistance in dual spin vales

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

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)

Conclusions

on nonlinear magnetoresistance

- We extended standard Valet-Fert model in a phenomenological way considering linear dependence of bulk and interfacial parameters on spin accumulation.
- We found some similarities with experimental results by Aziz *et al*.
  - change in sign of resistance drops ΔR with current direction
  - dependence of ΔR with current density
  - decreasing of the effect with increasing width of central layer
  - symmetry of ΔR with current density
- We identified variation of interfacial parameters as likely to be dominant in the experiment.

Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Current-induced dynamics
4. Dual spin valve
5. Nonlinear magnetoresistance in dual spin vales
6. Transverse spin transport

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

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

$$D_\perp = \sqrt{D_\uparrow D_\downarrow}$$

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

Transversal 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 transversal components

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

where $\frac{1}{l_\pm^2} = \frac{1}{\lambda_\perp^2} \pm i\,\frac{1}{\lambda_J^2}$.

For $\lambda_J \ll \lambda_\perp$: $\frac{1}{l_\pm} \approx \sqrt{\pm\frac{i}{\lambda_J^2}} = \frac{1 \pm i}{\sqrt{2}\lambda_J}$

Solution for the transversal components

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

where $\frac{1}{l_\pm^2} = \frac{1}{\lambda_\perp^2} \pm i\,\frac{1}{\lambda_J^2}$.

For $\lambda_J \ll \lambda_\perp$: $\frac{1}{l_\pm} \approx \sqrt{\pm\frac{i}{\lambda_J^2}} = \frac{1 \pm i}{\sqrt{2}\lambda_J}$

Penetration length

$$\frac{1}{\lambda_\mathrm{t}} = \mathrm{Re}\left\{\frac{1}{l_+}\right\} = \frac{1}{\sqrt{2}\lambda_J}$$

Solution for the transversal components

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

where $\dfrac{1}{l_\pm^2} = \dfrac{1}{\lambda_\perp^2} \pm i\,\dfrac{1}{\lambda_J^2}$.

For $\lambda_J \ll \lambda_\perp$: $\dfrac{1}{l_\pm} \approx \sqrt{\pm\dfrac{i}{\lambda_J^2}} = \dfrac{1 \pm i}{\sqrt{2}\lambda_J}$

Penetration length

$$\frac{1}{\lambda_t} = \mathrm{Re}\left\{\frac{1}{l_+}\right\} = \frac{1}{\sqrt{2}\lambda_J}$$

Transverse spin accumulation

$$\mu_x = \left[A_1 \cos\left(\frac{x}{\lambda_t}\right) + B_1 \sin\left(\frac{x}{\lambda_t}\right)\right] e^{x/\lambda_t} + \left[A_2 \cos\left(\frac{x}{\lambda_t}\right) + B_2 \sin\left(\frac{x}{\lambda_t}\right)\right] e^{-x/\lambda_t}$$

$$\mu_y = \left[A_1 \sin\left(\frac{x}{\lambda_t}\right) - B_1 \cos\left(\frac{x}{\lambda_t}\right)\right] e^{x/\lambda_t} - \left[A_2 \sin\left(\frac{x}{\lambda_t}\right) - B_2 \cos\left(\frac{x}{\lambda_t}\right)\right] e^{-x/\lambda_t}$$

Solution for the transversal components

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

where $\dfrac{1}{l_\pm^2} = \dfrac{1}{\lambda_\perp^2} \pm i\,\dfrac{1}{\lambda_J^2}$.

For $\lambda_J \ll \lambda_\perp$: $\dfrac{1}{l_\pm} \approx \sqrt{\pm\dfrac{i}{\lambda_J^2}} = \dfrac{1 \pm i}{\sqrt{2}\lambda_J}$

Penetration length

$$\frac{1}{\lambda_t} = \mathrm{Re}\left\{\frac{1}{l_+}\right\} = \frac{1}{\sqrt{2}\lambda_J}$$

Transverse spin current

$$\frac{1}{\rho(E_F)}\, j_x = \frac{D_\perp}{\lambda_t}\left\{\left[(A_1 - B_1)\sin\left(\frac{x}{\lambda_t}\right) - (A_1 + B_1)\cos\left(\frac{x}{\lambda_t}\right)\right] e^{x/\lambda_t} + \left[(A_2 + B_2)\sin\left(\frac{x}{\lambda_t}\right) + (A_2 - B_2)\cos\left(\frac{x}{\lambda_t}\right)\right] e^{-x/\lambda_t}\right\}$$

$$\frac{1}{\rho(E_F)}\, j_y = -\frac{D_\perp}{\lambda_t}\left\{\left[(A_1 - B_1)\cos\left(\frac{x}{\lambda_t}\right) + (A_1 + B_1)\sin\left(\frac{x}{\lambda_t}\right)\right] e^{x/\lambda_t} - \left[(A_2 + B_2)\cos\left(\frac{x}{\lambda_t}\right) - (A_2 - B_2)\sin\left(\frac{x}{\lambda_t}\right)\right] e^{-x/\lambda_t}\right\}$$

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

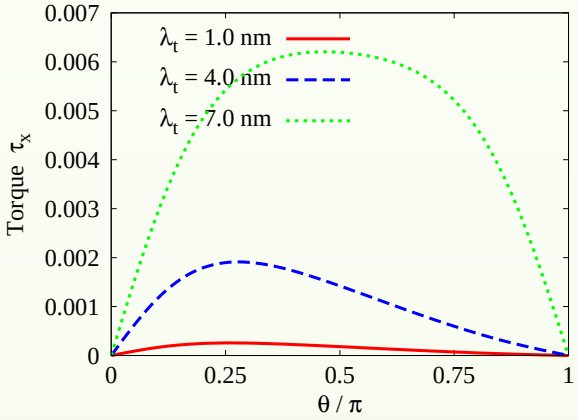
$$\tau_x = \frac{\hbar}{2}\int_{x_\mathrm{L}}^{x_\mathrm{R}} \frac{\partial j_x}{\partial x}\,\mathrm{d}x = \frac{\hbar}{2}\left[j_x(x_\mathrm{R}) - j_x(x_\mathrm{L})\right] \equiv \tau_\perp$$

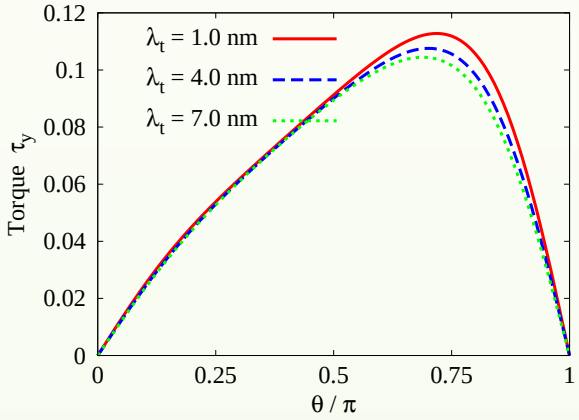
$$\tau_y = \frac{\hbar}{2}\int_{x_\mathrm{L}}^{x_\mathrm{R}} \frac{\partial j_y}{\partial x}\,\mathrm{d}x = \frac{\hbar}{2}\left[j_y(x_\mathrm{R}) - j_y(x_\mathrm{L})\right] \equiv \tau_\parallel$$

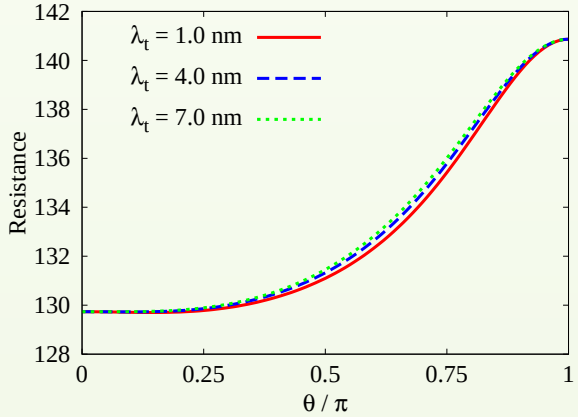
where x_L and x_R are positions of the left and right interfaces of the free layer.

Numerical results

Single spin valve Co(20)/Cu(10)/Co(8)

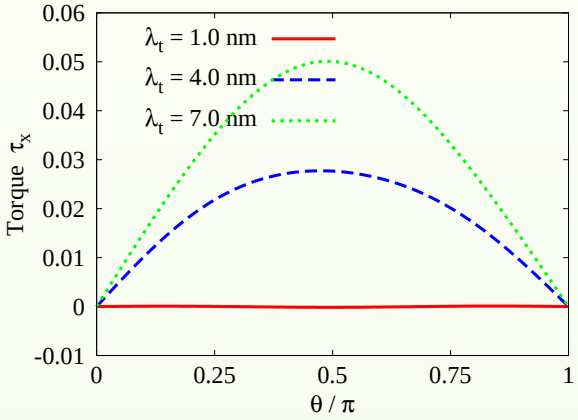


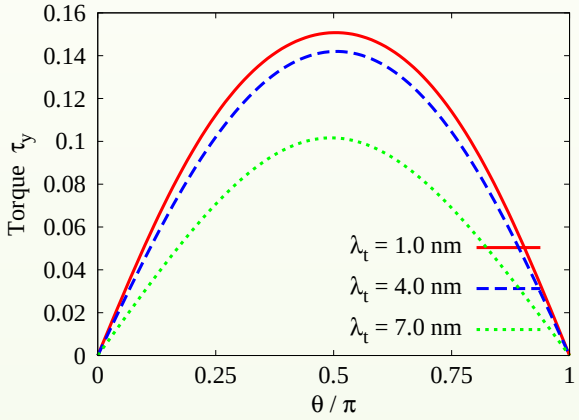


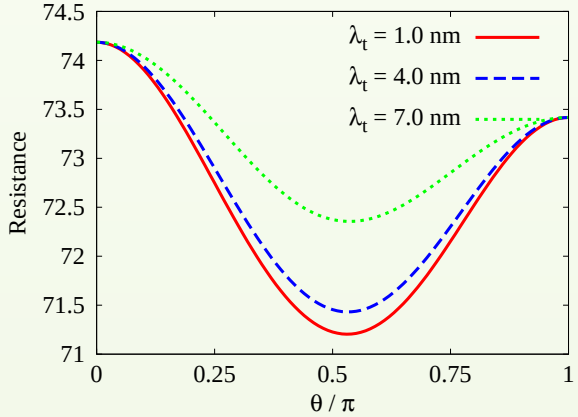


Numerical results

Single spin valve Co(20)/Cu(10)/Co(8)







Conclusions

on transverse spin diffusion

- The diffusive spin transfer torque model was extended to transverse spin components
- In dual spin valves the enhancement of the out-of-plane spin torque is observed.

A. Mickiewicz University in Poznań

Institute of Molecular Physics - Polish Academy of Sciences

Thank you for your attention

M. Currie European Research Training Network

Polish-Swiss Research Project NANOSPIN