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

Pavel Baláž

Institute of Molecular Physics in Poznań
Polish Academy of Sciences
and
Faculty of Physics
A. Mickiewicz University in Poznań

Univerzita Karlova, 5 December 2013
Nanoscale spin torque devices for spin electronics
Joint research project under the framework of Polish-Swiss research programme

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
1 Introduction

2 Spin-torque in metallic spin valves

3 Dual spin valve

4 Nonlinear magnetoresistance in dual spin valves

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

2 Spin-torque in metallic spin valves

3 Dual spin valve

4 Nonlinear magnetoresistance in dual spin valves

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


G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn

*Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange*


R. E. Camley and J. Barnaś

*Theory of giant magnetoresistance effects in magnetic layered structures with antiferromagnetic coupling*


T. Valet and A. Fert

*Theory of the perpendicular magnetoresistance in magnetic multilayers*

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

**Slonczewski’s model (ballistic)**


\[
\tau_{\text{Sloncz}} = \frac{I g(\theta)}{e} \hat{s} \times (\hat{s} \times \hat{S})
\]

where

\[
g(\theta) = \left[ -4 + (1 + P)^3 \frac{3 + \cos \theta}{4P^{3/2}} \right]^{-1}
\]
Magnetization can be **switched by electric current** without need of magnetic field

**Slonczewski’s model (ballistic)**

\[ \tau_{\text{Sloncz}} = \frac{Ig(\theta)}{e} \hat{s} \times (\hat{s} \times \hat{S}) \]

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)

\[ \tau_{\theta} = a(\theta) I \hat{s} \times (\hat{s} \times \hat{S}) \]
\[ \tau_{\phi} = b(\theta) I \hat{s} \times \hat{S} \]

---

J. Barnaś, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev

*From giant magnetoresistance to current-induced switching by spin transfer*

Equation of motion

**Landau-Lifshitz-Gilbert equation**

\[
\frac{d\mathbf{s}}{dt} = -|\gamma_g| \mu_0 \mathbf{s} \times \mathbf{H}_{\text{eff}} - \alpha \mathbf{s} \times \frac{d\mathbf{s}}{dt} + \frac{|\gamma_g|}{M_s d} (\tau_\theta + \tau_\phi)
\]

**Effective magnetic field**

\[
\mathbf{H}_{\text{eff}} = -H_{\text{ext}} \hat{e}_z - H_{\text{ani}} (\mathbf{s} \cdot \hat{e}_z) \hat{e}_z + \mathbf{H}_{\text{demag}}
\]

**Spin-transfer torque**

\[
\tau_\theta = a(\theta) I \mathbf{s} \times (\mathbf{s} \times \mathbf{S})
\]

\[
\tau_\phi = b(\theta) I \mathbf{s} \times \mathbf{S}
\]
Spin-torque in metallic spin valves

Introduction

Spin-torque in metallic spin valves

Dual spin valve

Nonlinear magnetoresistance in dual spin valves

Current-induced switching in metallic spin valves with perpendicular polarizers
Spin-torque in metallic spin valves

Mathematical description

Two channels model

bulk resistivities

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

interface resistances

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

\( \beta \) bulk asymmetry parameter

\( \gamma \) interfacial asymmetry parameter

Diffusive transport

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

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

J. Barnaš, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev

*From giant magnetoresistance to current-induced switching by spin transfer*

Spin-torque in metallic spin valves

Mathematical description

Two channels model

bulk resistivities

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

interface resistances

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

\[ \beta \] bulk asymmetry parameters

\[ \gamma \] interfacial asymmetry parameter

Diffusive transport

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

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

for electrochemical potentials we get

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

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

J. Baraš, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev

From giant magnetoresistance to current-induced switching by spin transfer

Mathematical description

**Magnetic layer**

\[ \frac{\dot{\bar{\mu}}}{\bar{\mu}_0} = \bar{\mu}_0 \hat{\text{i}} + g \sigma_z \]

\[ \bar{\mu}_0 = \frac{\bar{\mu}_\uparrow + \bar{\mu}_\downarrow}{2}, \quad g = \frac{\bar{\mu}_\uparrow - \bar{\mu}_\downarrow}{2} \]

with \( g \) being spin accumulation

\[ \dot{j} = -\rho(E_F)\bar{D} \frac{\partial \bar{\mu}}{\partial x} \]

\[ \dot{j} = \frac{1}{2} (j_0 \hat{\text{i}} + j_z \sigma_z) \]

**Diffusive transport**

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

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

for electrochemical potentials we get

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

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

J. Barnaš, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev

*From giant magnetoresistance to current-induced switching by spin transfer*

Mathematical description

Nonmagnetic layer

has no natural quantization axis

\[ \tilde{\mu} = \mu_0 \tilde{1} + \mathbf{g} \cdot \tilde{\sigma} \]
\[ \tilde{j} = \frac{1}{2} (j_0 \tilde{1} + \mathbf{j} \cdot \tilde{\sigma}) \]

where

\[ \mathbf{g} = (g_x, g_y, g_z), \quad \mathbf{j} = (j_x, j_y, j_z) \]

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

Diffusive transport

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

for electrochemical potentials we get

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

J. Barnaš, A. Fert, M. Gmitra, I. Weymann, V.K. Dugaev

From giant magnetoresistance to current-induced switching by spin transfer
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*

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

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

**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
  \[ e^2 j_0 = (G^\uparrow + G^\downarrow)(\bar{\mu}^F_0 - \bar{\mu}^N_0) + (G^\uparrow - G^\downarrow)(g^F_z - g^N_z) \]

- **spin current component parallel to the magnetization** is continuous across the interface
  \[ e^2 j_z = (G^\uparrow - G^\downarrow)(\bar{\mu}^F_0 - \bar{\mu}^N_0) + (G^\uparrow + G^\downarrow)(g^F_z - g^N_z) \]

- **transversal component of the spin current** vanishes in the magnetic layer – jump at the interface
  \[ e^2 j_x = -2Re\{G^\uparrow\downarrow\}g^N_x + 2Im\{G^\uparrow\downarrow\}g^N_y \]
  \[ e^2 j_y = -2Re\{G^\uparrow\downarrow\}g^N_y - 2Im\{G^\uparrow\downarrow\}g^N_x \]

---

**Components**

- in-plane
  \[ \tau_{\theta} = -\frac{\hbar}{2} j_y'|N/F \]

- out-of-plane
  \[ \tau_{\phi} = \frac{\hbar}{2} j_x'|N/F \]
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. Dual spin valve
4. Nonlinear magnetoresistance in dual spin valves
5. Current-induced switching in metallic spin valves with perpendicular polarizers
What is a dual spin valve?
Spin accumulation in dual spin valve

spin accumulation in single spin valve

![Diagram of spin accumulation in single spin valve](image-url)
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*

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

\[ \frac{\text{STT}}{\langle h I / |e| \rangle} \]

Dual SV

Single SV
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
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
Noncollinear configurations in dual spin valves

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

Current-induced dynamics

We calculated average

\[ \langle s_z \rangle = \frac{1}{t_{\text{end}} - t_{\text{eq}}} \int_{t_{\text{eq}}}^{t_{\text{end}}} s_z \, dt \]

and dispersion

\[ \mathcal{D}(s_z) = \sqrt{\langle s_z^2 \rangle - \langle s_z \rangle^2} \]

for each couple of \( I \) and \( \Omega \) to map the dynamic behaviour.
Noncollinear configurations in dual spin valves

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

1 Introduction

2 Spin-torque in metallic spin valves

3 Dual spin valve

4 Nonlinear magnetoresistance in dual spin valves

5 Current-induced switching in metallic spin valves with perpendicular polarizers
Nonlinear magnetoresistance in dual spin vales

Experimental works

*Nonlinear giant magnetoresistance in dual spin vales*

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 vales*

N. Banerjee, J. W. A. Robinson, A. Aziz, M. Ali, B. J. Hickey, and M. G. Blamire
*Nonlocal Magnetization Dynamics in Ferromagnetic Hybrid Nanostructure*

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

\[ \rho^* = \rho_0^* + q \langle g \rangle \]
\[ \beta = \beta_0 + \xi \langle g \rangle \]
\[ R^* = R_0^* + q' g(x_i) \]
\[ \gamma = \gamma_0 + \xi' g(x_i) \]

where

- \( g(x) \) is spin accumulation
- \( \rho_0^* \) and \( R_0^* \) are *zero-current* bulk resistivity and interfacial resistance
- \( \beta_0 \) and \( \gamma_0 \) are *zero-current* bulk/interfacial asymmetry parameters
- \( q, \xi, q', \xi' \) are phenomenological parameters
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. Barnaš

Nonlinear magnetotransport in dual spin vales

for $\tilde{q} = 0.1$, $\tilde{\xi} = 0.1$, $I_0 = 10^8$ 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 $\Delta R$ is symmetric with current density

P. Baláž, and J. Barnaš

*Nonlinear magnetotransport in dual spin vales*

Perpendicular polarizer

Outline

1. Introduction
2. Spin-torque in metallic spin valves
3. Dual spin valve
4. Nonlinear magnetoresistance in dual spin valves
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*
Transport through the polarizer

- We considered the perpendicular polarizer as a magnetized ballistic scatterer 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*  

- In our formalism the scatterer corresponds to a single interface.
Transport through the polarizer

- We considered the perpendicular polarizer as a magnetized ballistic scatterer 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*

- In our formalism the scatterer corresponds to a single interface.
Transport through the polarizer

- We considered the perpendicular polarizer as a magnetized ballistic scatterer 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*

- In our formalism the scatterer corresponds to a single interface.

Outputs of the calculation:

- channel conductances $G_\uparrow$, $G_\downarrow$

- mixing conductance
  $G_{\uparrow\downarrow} = g_{\uparrow\downarrow}^r + i g_{\uparrow\downarrow}^i$

- mixing transmission conductance
  $T_{\uparrow\downarrow} = t_{\uparrow\downarrow}^r + i t_{\uparrow\downarrow}^i$

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

\[
e^2 \begin{pmatrix} j_0 \\ j_z \end{pmatrix} = \begin{pmatrix} \tilde{G}_{\uparrow} + \tilde{G}_{\downarrow} & \tilde{G}_{\uparrow} - \tilde{G}_{\downarrow} \\ \tilde{G}_{\uparrow} - \tilde{G}_{\downarrow} & \tilde{G}_{\uparrow} + \tilde{G}_{\downarrow} \end{pmatrix} \begin{pmatrix} \mu^R_0 - \mu^L_0 \\ \mu^R_z - \mu^L_z \end{pmatrix}
\]

Transverse components

\[
e^2 \begin{pmatrix} j_{R\perp} \\ j_{L\perp} \end{pmatrix} = \begin{pmatrix} G & T' \\ T & G' \end{pmatrix} \begin{pmatrix} \mu^R_{\perp} \\ \mu^L_{\perp} \end{pmatrix}
\]

where

\[
\mathbf{j}_{R/L\perp} = \begin{pmatrix} j_{R/Lx} \\ j_{R/Ly} \end{pmatrix} \quad \mathbf{\mu}_{R/L\perp} = \begin{pmatrix} \mu_{R/Lx} \\ \mu_{R/Ly} \end{pmatrix}
\]

and

\[
\mathbf{G} = 2 \begin{pmatrix} -g_{r\uparrow\downarrow} & g_{i\uparrow\downarrow} \\ -g_{i\uparrow\downarrow} & -g_{i\uparrow\downarrow} \end{pmatrix} \quad \mathbf{T} = 2 \begin{pmatrix} t_{r\uparrow\downarrow} & -t_{i\uparrow\downarrow} \\ t_{i\uparrow\downarrow} & t_{r\uparrow\downarrow} \end{pmatrix}
\]


*Nonlocal Magnetization Dynamics in Ferromagnetic Hybrid Nanostructure*

Perpendicular polarizer

Spin transfer torque

Spin torque acting on the free layer

\[ \tau_\perp = I \hat{s} \times [\hat{S}_{\text{OP}} \times (a_{\text{OP}} \hat{S}_{\text{OP}} + a_{\text{IP}} \hat{S}_{\text{IP}})] \]

\[ \tau_\parallel = I \hat{s} \times (b_{\text{OP}} \hat{S}_{\text{OP}} + b_{\text{IP}} \hat{S}_{\text{IP}}) \]

\[ a_{\text{OP}} = \frac{-\hbar j'_{1y} |N_1/F_1|}{2 I \sin \theta_{\text{OP}}} \]

\[ a_{\text{IP}} = \frac{-\hbar j''_{2y} |F_1/N_2|}{2 I \sin \theta_{\text{IP}}} \]

\[ b_{\text{OP}} = \frac{\hbar j'_{1x} |N_1/F_1|}{2 I \sin \theta_{\text{OP}}} \]

\[ b_{\text{IP}} = \frac{\hbar j''_{2x} |F_1/N_2|}{2 I \sin \theta_{\text{IP}}} \]

where \( \cos \theta_{\text{OP}} = \hat{s} \cdot \hat{S}_{\text{OP}} \) and \( \cos \theta_{\text{IP}} = \hat{s} \cdot \hat{S}_{\text{IP}} \)
**Perpendicular polarizer**

**Studied structures**

\[
\text{Cu} - \text{PP}_1 / \text{Cu}(6) / \text{Py}(5) / \text{Cu}(12) / \text{Py}(20) - \text{Cu}
\]

\[
\text{PP}_1 = \text{Co}(2 \text{ ML}) / [\text{Cu}(2 \text{ ML})/\text{Co}(2 \text{ ML})]_{L-1}
\]

\[
\text{PP}_2 = \text{Pt}(6 \text{ ML}) / [\text{Co}(2 \text{ ML})/\text{Pt}(3 \text{ ML})]_L / \text{Co}(3 \text{ ML}) / \text{Cu}(2 \text{ ML}) / \text{Co}(3 \text{ ML})
\]
Results for PP\textsubscript{1}
Spin transfer torque

**Perpendicular polarizer**

Co(2 ML) / [Cu(2 ML)/Co(2 ML)]\textsubscript{L−1}

![Graphs showing spin torque for PP and IP polarizers](image)

- **PP polarizer**
  - Graph (a) shows the spin torque as a function of angle $\theta_P$.
  - Graph (c) shows the spin torque at $10\tau$ as a function of $\theta_P$.

- **IP polarizer**
  - Graph (b) shows the spin torque as a function of angle $\theta_I$.
  - Graph (d) shows the spin torque at $10\tau$ as a function of $\theta_I$.

*Wavelike* angular dependence for the perpendicular polarizer
Results for PP\textsubscript{1}  
Current-induced switching from $\uparrow$ to $\downarrow$ at $T = 300 \text{K}$
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)

Clean PP

Disordered PP

Spin torque $\tau$

angle $\theta_P$/
Results for PP$_2$
Current-induced switching from $\uparrow$ to $\downarrow$

Pt(6 ML) / [Co(2 ML)/Pt(3 ML)]$_L$ / Co(3 ML) / Cu(2 ML) / Co(3 ML)
Noncollinear diffusive model is an useful and flexible framework for dealing with spin dependent electronic transport in metallic multilayers

- spin transfer 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)
Thank you for your attention