Interactions between Domain Walls and Spin-polarized Currents

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Present Research Topics

• Spin-dependent transport phenomena
• Interaction of spin-polarized currents with domain walls
• Micromagnetic simulations
• Halfmetallic ferromagnets (HMF)
• Diluted magnetic oxidic semiconductors
• Single molecule magnets (SMM)
Outline

- Motivation (race track memory)
- Resistivity contributions due to domain walls (AMR and DWMR)
- Current-induced domain wall propagation (CIDP): an overview
- Direct observation of CIDP in magnetic zig-zag lines
- Current-induced DW transformations
- The role of temperature
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Race Track Memory: Open up the 3rd Dimension!

- Magnetic domains represent the bits
- Approximately 100 Bits per cell (cell width 100 nm)
- Domain wall positioning by current-induced domain wall motion
- Read: magnetoresistive read elements
- Write: local Oerstedt fields

Race Track Memory: Requirements

- Domains and domain walls, which can be tailored (spin structure, etc.)
- Well-defined domain wall positions
- We need to select the wall motion direction and move all the domain walls synchronously → current-induced motion
- Reproducibility
Magnetoresistive Effects in Presence of Domain Walls
Origin of AMR: spin-orbit-coupling (J vs M)

MR in the %-range

Can be used to determine the location of a DW

Vortex DW (thick, wide wires)

Transverse DW (thin, narrow wires)

PRL 80, 5639 (1998)
APL 86, 032504 (2005)
Magnetoresistive Observation of CIDP in Magnetic Rings

- Voltage measurement between 6 and 7
- Lock-in current at 1
- Current pulses at 2; ground at 8
- Level A $\rightarrow$ DW between contacts
- Level B $\rightarrow$ DW outside contacts
- DW can be reversibly moved between positions A and B by current pulses with opposite polarity ($20 \, \mu\text{sec}; 2 \times 10^{12} \, \text{A/m}^2$)

Domain Wall Magnetoresistance (DWMR)

- **Current-In-Wall** (CIW) and **Current-Perpendicular-To-Wall** (CPW) geometry of epitaxial Co(0001) wires:

- Spin dependent scattering in the presence of **domain walls** leads to an additional resistivity contribution (P.M. Levy et al., PRL 79, 5110 (1997)):

- Use ferromagnets with a large uniaxial anisotropy:

\[
a = \pi \sqrt{\frac{A}{K_U}}
\]

- Estimation: \( \text{DWMR}_{\text{CPW}}(\text{Fe, Co, FePt}): < 1\%, \sim 2\%, > 10\% \)
Current-induced Domain Wall Propagation in Magnetic Nanostructures
Current-induced Domain Wall Propagation (CIDP)

a) Narrow Wall: Momentum transfer to DW

b) Wide wall: Angular momentum transfer

G. Tatara et al., PRL 92, 86601 (2004).
Current-induced Domain Wall Propagation (CIDP)

- Magnetization dynamics: implicit Landau-Lifshitz-Gilbert equation
  \[ \dot{\mathbf{m}} = \gamma_0 \mathbf{H} \times \mathbf{m} + \alpha \mathbf{m} \times \dot{\mathbf{m}} \]
- Spin-transfer model:
  \[ \dot{\mathbf{m}} = \gamma_0 \mathbf{H} \times \mathbf{m} + \alpha \mathbf{m} \times \dot{\mathbf{m}} - (\mathbf{u} \cdot \nabla) \mathbf{m} - \beta \mathbf{m} \times [(\mathbf{u} \cdot \nabla) \mathbf{m}] \]
  \[ \mathbf{u} = \frac{j g P \mu_B}{(2eM_s)}, \quad \beta = \left(\frac{\lambda_J}{\lambda_{sf}}\right)^2 \]
  - Angular momentum conservation → „spin transfer“.
  - Domain walls move in the direction of the electron flow.
  - The effect is proportional to the current density \( j \) and the spin-polarization \( P \) (and inversely to \( M_S \)).

A. Thiaville et al., EPL 69, 990 (2005).
Theoretical Models (Pure Adiabatic Processes: $\beta=0$)

- **Assumption**: adiabatic process, i.e. magnetic moment of conduction electrons is parallel to the local magnetization.
- **Adiabatic** spin-transfer torque on the magnetization.
- DW has **maximum velocity** at the initial application of the current.
- DW **velocity decreases to zero** as the DW begins to deform during motion (W: DW width).
- DW is **unable to maintain** the wall movement.

Theoretical Models (Non-adiabatic Processes: $\beta \neq 0$)

$\beta = (\lambda J / \lambda_{sf})^2 = (\text{exchange length/spin-flip-length})^2$

- **Corrections** to perfect adiabaticity and pure local spin transfer, meaning a modification of the initial spin transfer torque by a second order quantity.

- **For $\beta = 0$:** absence of DW motion for $u < u_c$.

- **For $\beta \neq 0$:** DW motion at any finite $u$; DW velocity $v$ increases with increasing $\beta$.

- Valid for transverse and vortex walls.

- Exp. observed threshold currents are much smaller.

- Up to now: **neglect of thermal fluctuations.**
Direct Observation of CIDP in Magnetic Zig-zag Lines by XMCD-PEEM Imaging
Direct Observation of CIDP in Magnetic Zig-zag Lines by XMCD-PEEM Imaging

(Zig-zag lines with Au contact pads: W=500nm; L=10μm; t=10nm Py)
• Domain walls move in the direction of the electron flow.
• High-resolution imaging reveals the domain wall spin structures (vortex, transverse).
The Stochastic Nature of CIDP (XMCD-PEEM)

Pulses with 146V-156V, 150μs

Current pulse 25μs, $10^{12}$A/m²

Py; 1μm wide, 28nm thick
Current-induced DW Transformations
The Stochastic Nature of CIDP: Vortex Core Nucleation and Annihilation

- Velocity of single vortex walls with no transformations increases with increasing current density (black squares and black line).
- Velocity depends on the number of vortices.
- Extended vortices move more slowly (green down triangles).
- Multi-vortices (double vortex: red; triple vortex: blue) hardly move.
Direct Observation of CIDP in „Zig-Zag“ Lines

- Prediction of periodic transformation of DW type by the nucleation and annihilation of a vortex core: \( TW \) (down) \( \rightarrow VW \) \( \rightarrow TW \) (up) \( \rightarrow VW \).
- \( TW \) is alternating (up/down) but \( VW \) with the same circulation direction but opposite polarity.

\[ W = 1.5 \, \mu m, \ t = 7 \, \text{nm}, \ close \ to \ TW-VW \ phase \ boundary \]

\( A. \ Thiaville \ et \ al., \ EPL \ 69, \ 990 \ (2005). \)

\[ \text{Appears in PRL 2008} \]

Transverse wall (down) after pulse injection (10^{12}A/m^2, 25 \, \mu s)

Vortex wall (clockwise) after pulse injection

Transverse wall (up) after pulse injection

Displaced vortex core gives direct evidence of transformation mechanism!
Direct Observation of CIDP in „Zig-Zag“ Lines

• Vortex core feels a force perpendicular to the current; it moves not only in direction of the electron flow (also towards the edges).

• The y-direction movement depends on the polarity of the vortex core; y-velocity is proportional to $(\alpha-\beta)$ (see: He et al., PRB 73, 184408 (2006)).

\[ \gamma = -\frac{U_x}{\lambda + \alpha^2} \left( (\lambda + \beta \gamma) \frac{\partial \gamma}{\partial x} + (\alpha - \beta) \frac{\partial \gamma}{\partial x} \right) \]

• For large enough currents the vortex core is expelled and a TW is formed; then a new VW with opposite polarity is nucleated and starts to move to the opposite edge of the wire.

• Observation excludes a former claim that $\alpha=\beta$ (PRB 74, 144405 (2006)).

• Excludes thermal-activated or defect-induced transformations as these would result in random rotation senses of the VW magnetization.

• Explains why in earlier experiments TW stopped for a given current density but vortex walls move (pinning at edge irregularities stronger).
DW Spin Structure vs Number of Pulse Injections

- After the first current injection all walls are of vortex-type.
- After a few injections all three walls have stopped moving and undergone a drastic transformation to a distorted transverse wall.
Role of Temperature
Role of Temperature

- The magnetic field needed to depin a domain wall decreases with increasing current density.
- At 0 current, the depinning fields decrease with increasing temperature, at higher currents the opposite occurs.
- Spin torque effect is more efficient at low temperatures!
- Possible explanation of discrepancies between 300K observations and 0K calculations: asymmetric generation of spin waves.

Summary

• Clear observation of current-induced domain wall propagation (CIDP).

• Modification of the domain wall spin structure by spin-polarized currents (stochastic process).

• VW-TW transformations by current pulses; good agreement with micromagnetic simulations.

• Critical current density for CIDP increases with increasing temperature (spin wave generation?).
Domain Wall Phase Diagram for Permalloy Rings