Interactions between Domain Walls and Spin-polarized Currents

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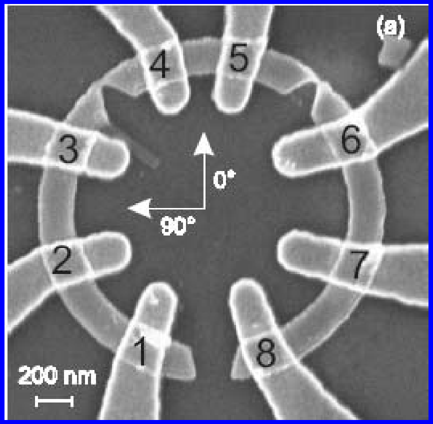
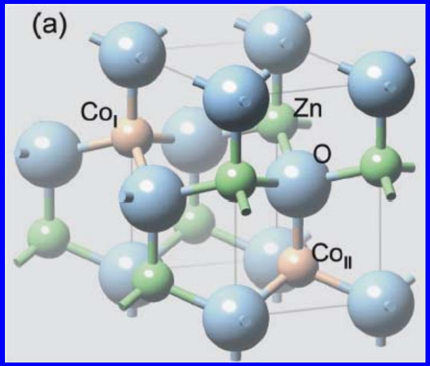
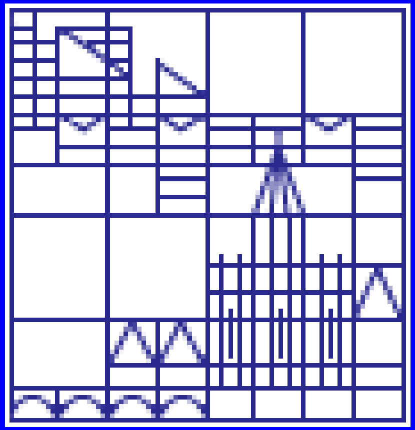
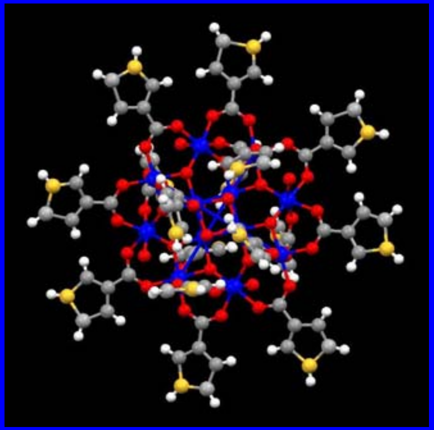
Present Research Topics

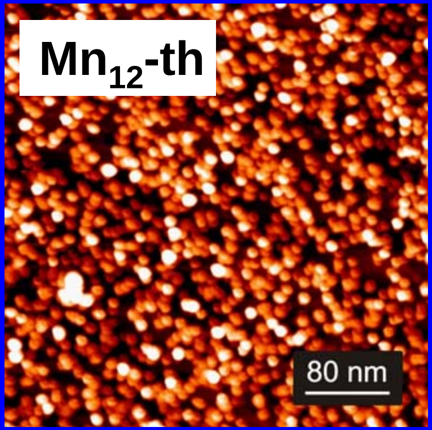
- Spin-dependent transport phenomena
- Interaction of spin-polarized currents with domain walls
- Micromagnetic simulations
- Halfmetallic ferromagnets (HMF)
- Diluted magnetic oxidic semiconductors
- Single molecule magnets (SMM)

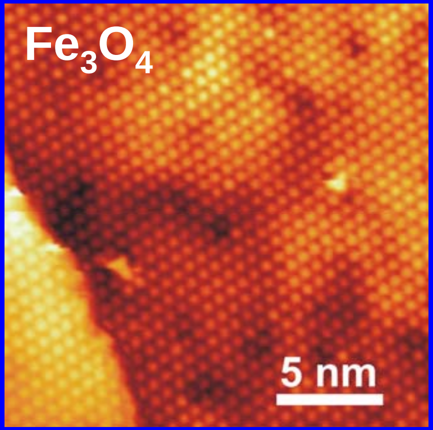


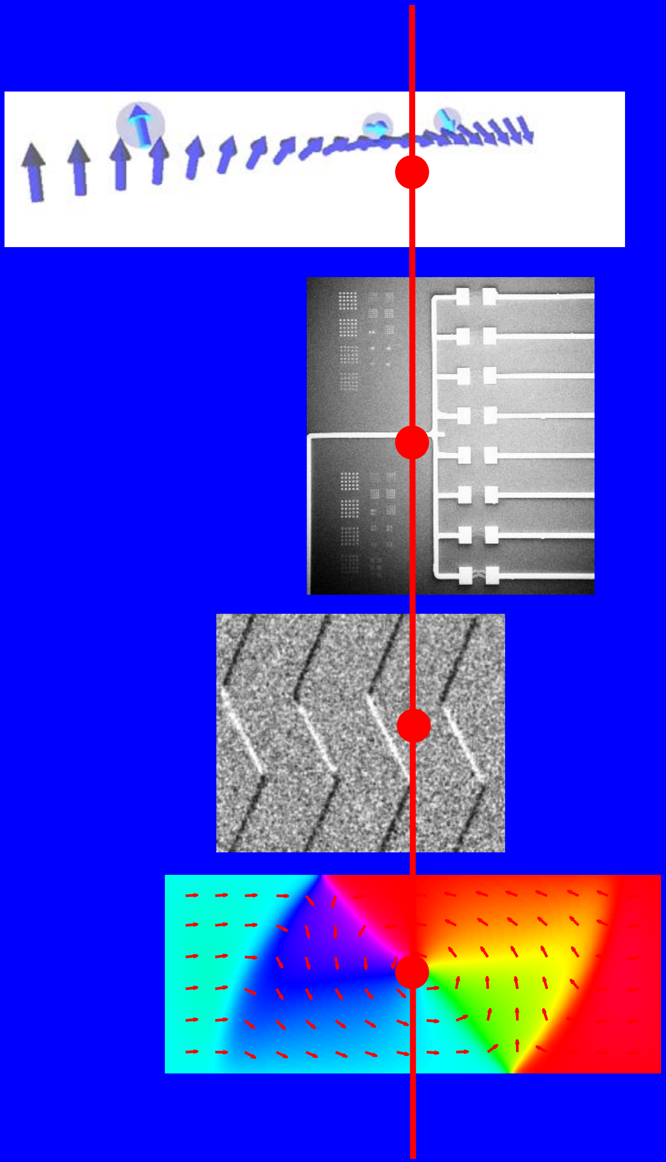












Outline

- 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

Research Group/Collaborations

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- *R.E. Dunin-Borkowski (U. of Cambridge)*
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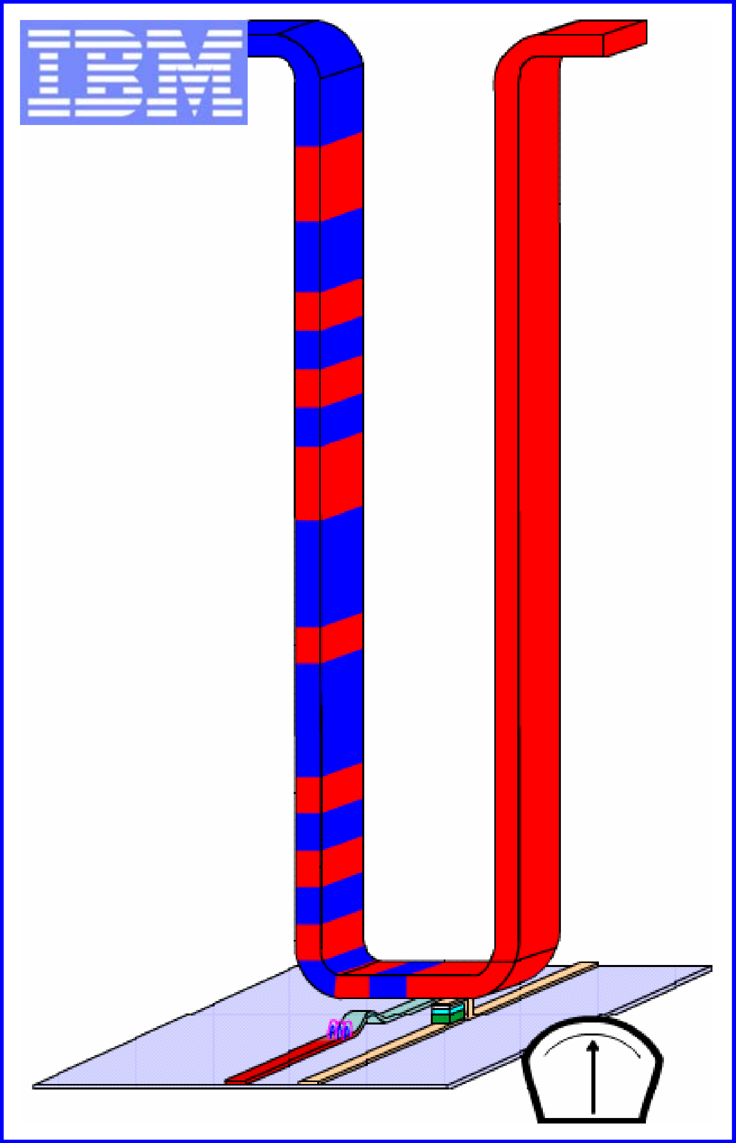
- *A.D. Kent (New York University)*

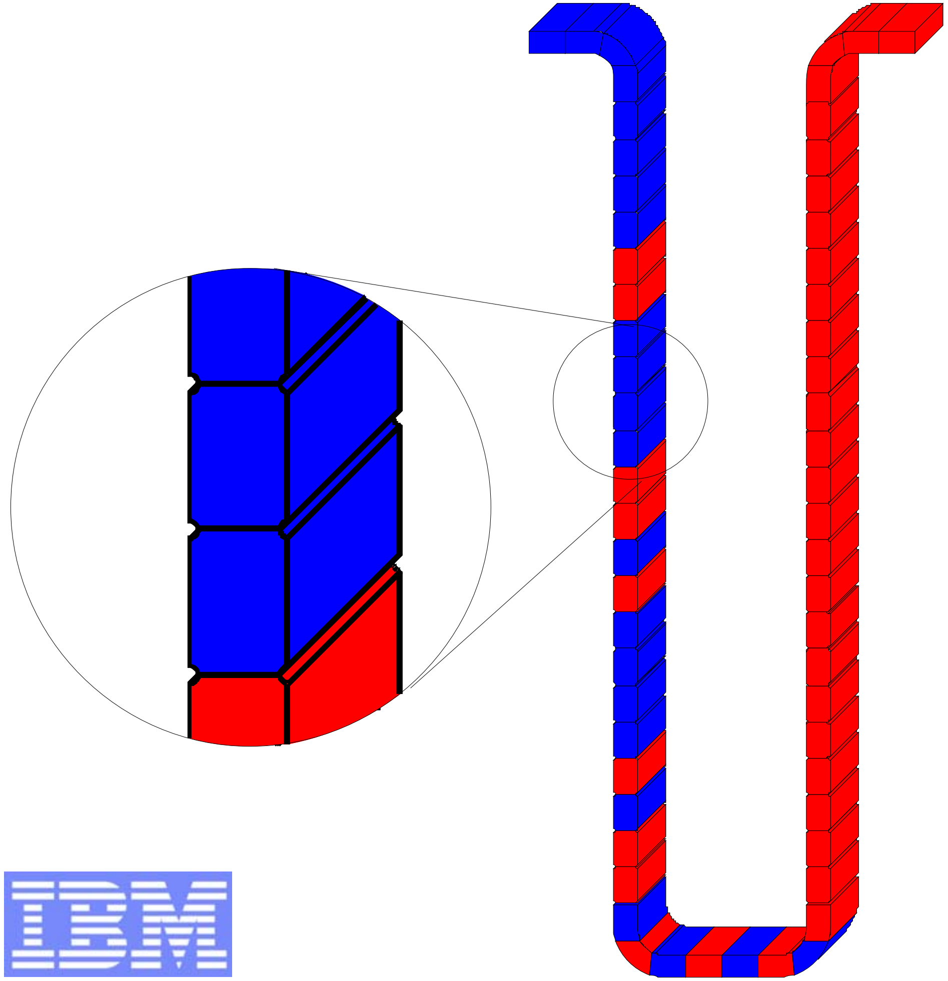
Race Track Memory: Open up the 3rd Dimension!



S. S. P. Parkin; US Patent No. 6834005 (2004).

- 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

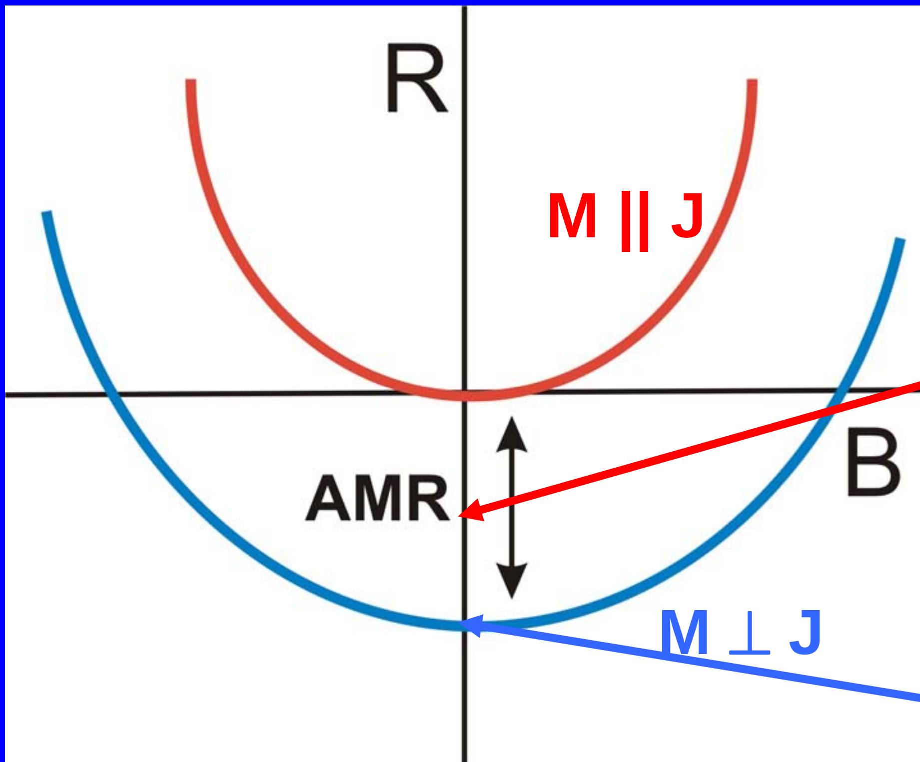
Race Track Memory: Requirements



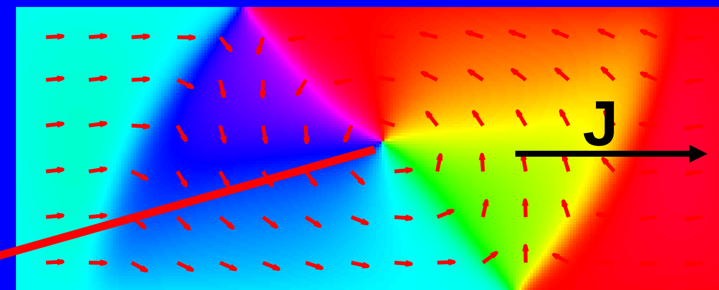
- Domains and domain walls, which can be tailored (spin structure, etc.)
- Well-defined domain wall positions
- We need to select the wall motion direction and move all the domain walls synchronously → ***current-induced motion***
- Reproducibility

Magnetoresistive Effects in Presence of Domain Walls

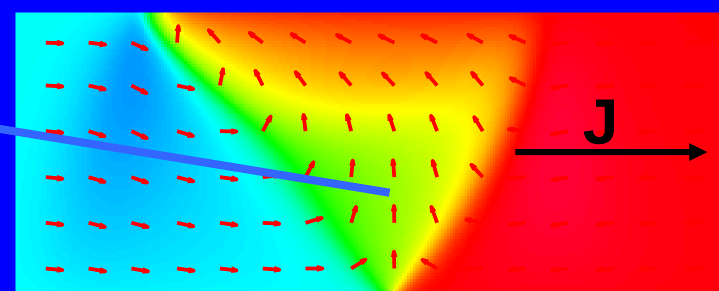
Anisotropic Magnetoresistance Contribution (AMR)



Vortex DW (thick, wide wires)



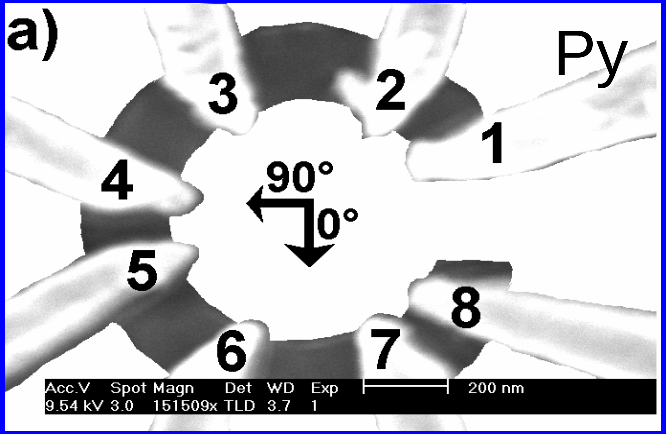
Transverse DW (thin,narrow wires)



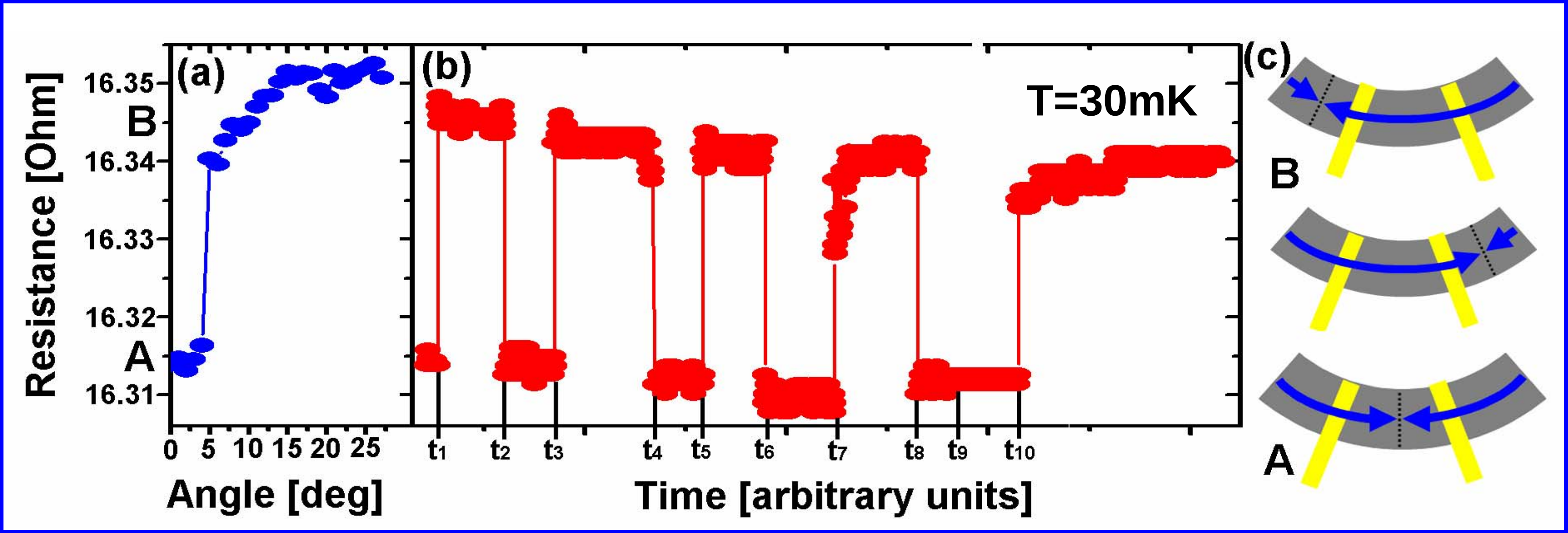
*PRL **80**, 5639 (1998)*
*APL **86**, 032504 (2005)*

- Origin of AMR: spin-orbit-coupling (J vs M)
- MR in the %-range
- Can be used to determine the location of a DW

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 ➔ DW between contacts
- Level B ➔ DW outside contacts
- DW can be reversibly moved between positions A and B by current pulses with opposite polarity (20 μsec; 2×10^{12} A/m^2)

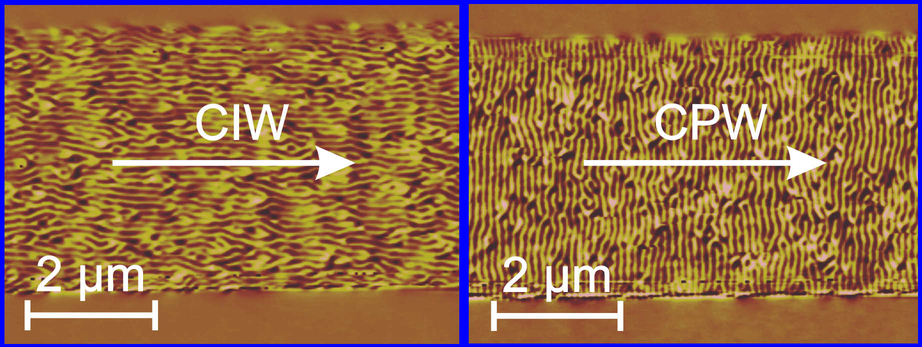


PRL ***94***, *106601 (2005).*

Domain Wall Magnetoresistance (DWMR)

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

MFM



PRB ***59****, 11914 (1999)*

- 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**:

$$a = \pi \sqrt{\frac{A}{K_U}}$$

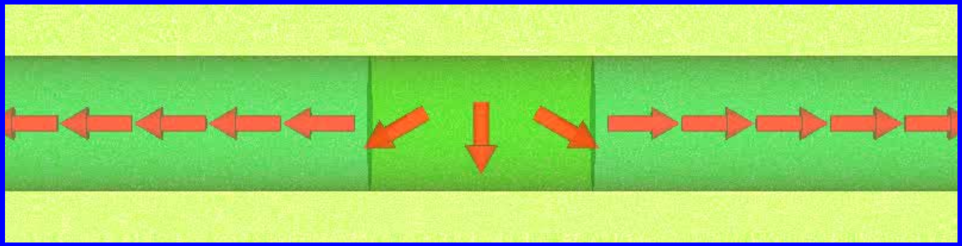
a_{Fe}=40 nm
a_{Co}=15 nm
a_{FePt}<5 nm

- **Estimation:** $DWMR_{CPW}$(Fe, Co, FePt): < 1%, ~2 %, >10 %

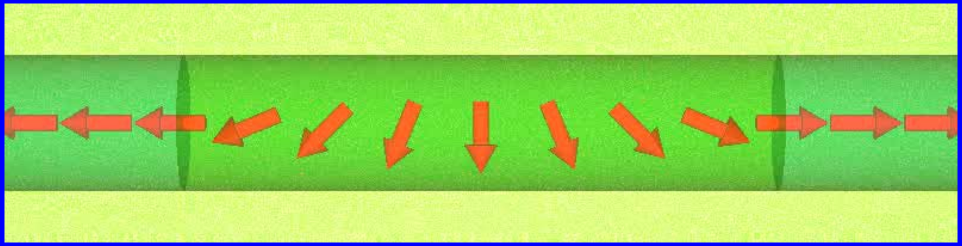
Current-induced Domain Wall Propagation in Magnetic Nanostructures

Current-induced Domain Wall Propagation (CIDP)

a) Narrow Wall: Momentum transfer to DW

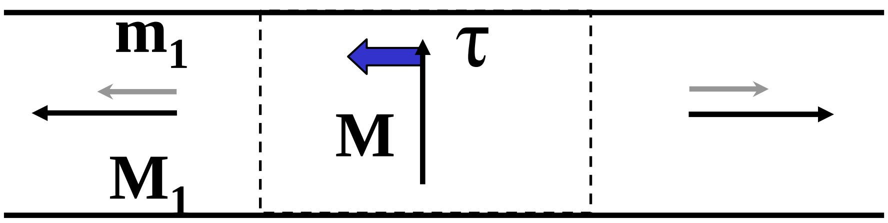


b) Wide wall: Angular momentum transfer



*G. Tatara et al., PRL **92**, 86601 (2004).*

Current-induced Domain Wall Propagation (CIDP)



- Magnetization dynamics: implicit Landau-Lifshitz-Gilbert equation

$$\dot{\vec{m}} = \gamma_0 \vec{H} \times \vec{m} + \alpha\, \vec{m} \times \dot{\vec{m}}$$

- Spin-transfer model:

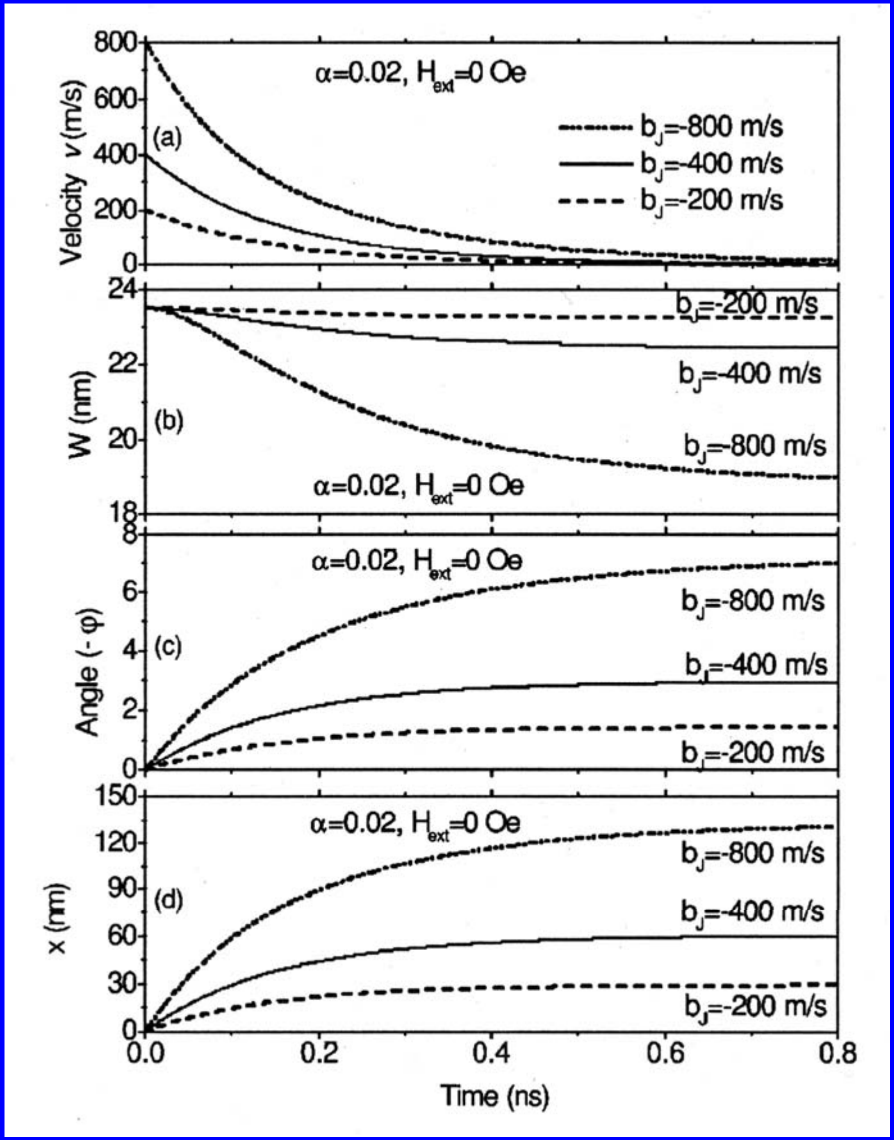
$$\dot{\vec{m}} = \gamma_0 \vec{H} \times \vec{m} + \alpha\, \vec{m} \times \dot{\vec{m}} - (\vec{u} \cdot \vec{\nabla})\, \vec{m} - \beta\, \vec{m} \times [(\vec{u} \cdot \vec{\nabla})\, \vec{m}]$$

$$\vec{u} = \vec{j} g P \mu_B / (2 e M_s), \quad \beta = (\lambda_J / \lambda_{sf})^2$$

- Angular momentum conservation $\rightarrow$ „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).*

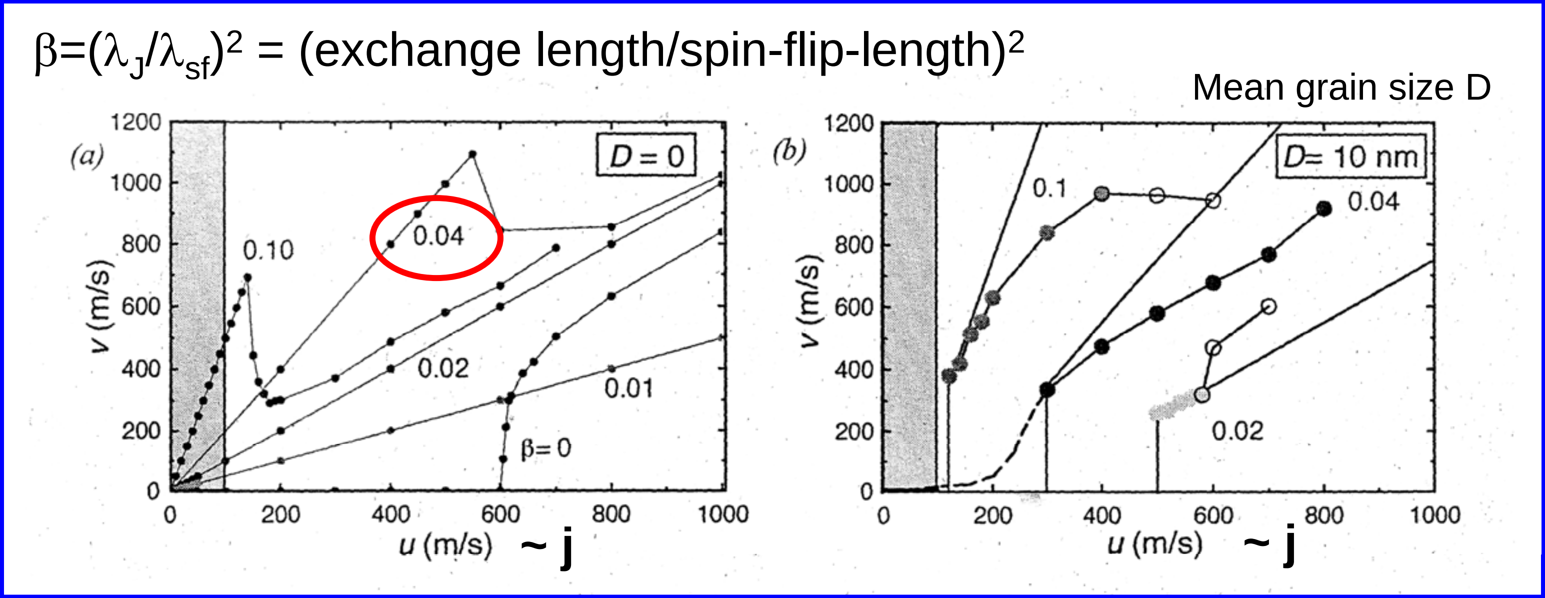
Theoretical Models (Pure Adiabatic Processes: β=0)



Z. Li and S. Zhang, Phys. Rev. B ***70****, 024417 (2004).*

- **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: $\beta \neq 0$)



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

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

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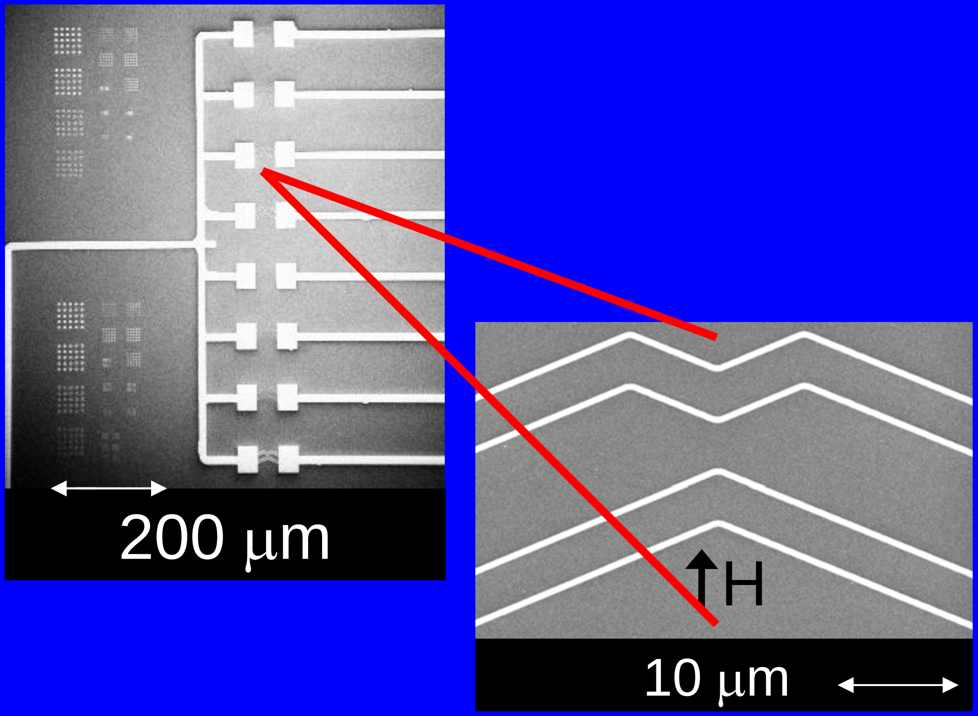
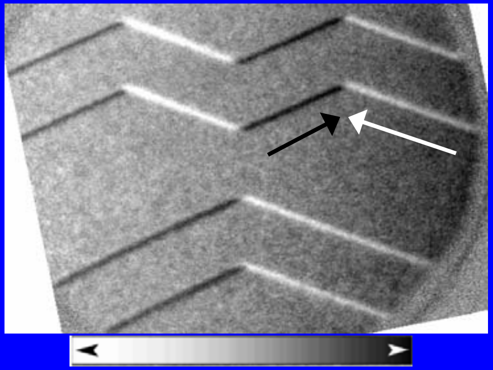


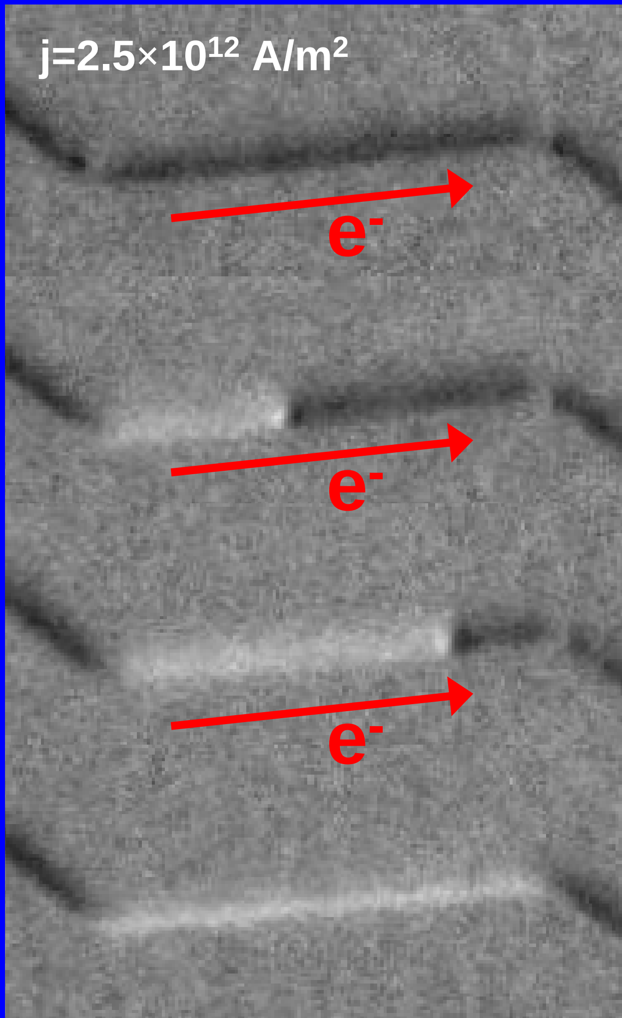


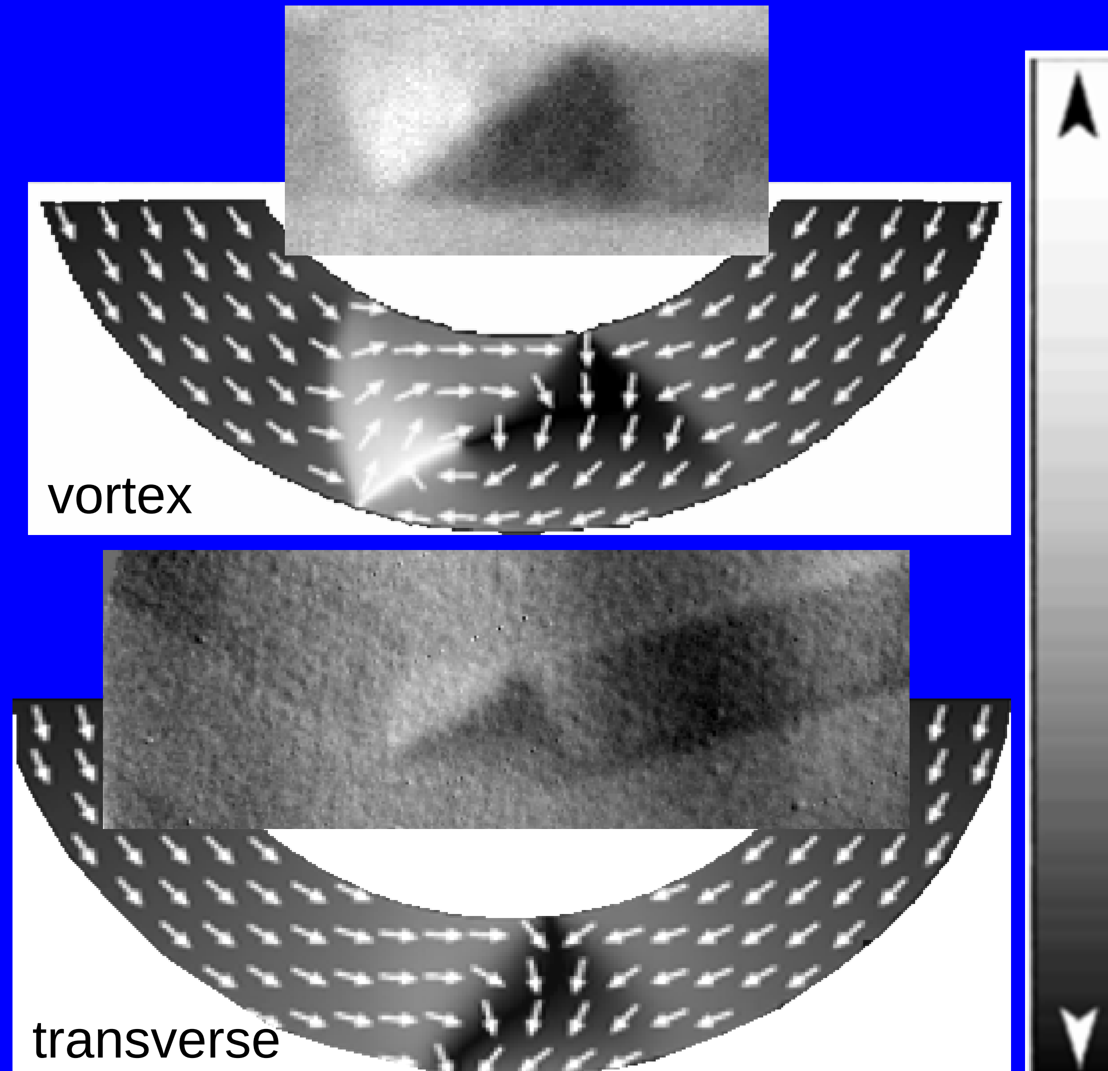
XMCD-PEEM
Imaging

Vortex Wall

(Zig-zag lines with Au contact pads: W=500nm; L=10μm; t=10nm Py)

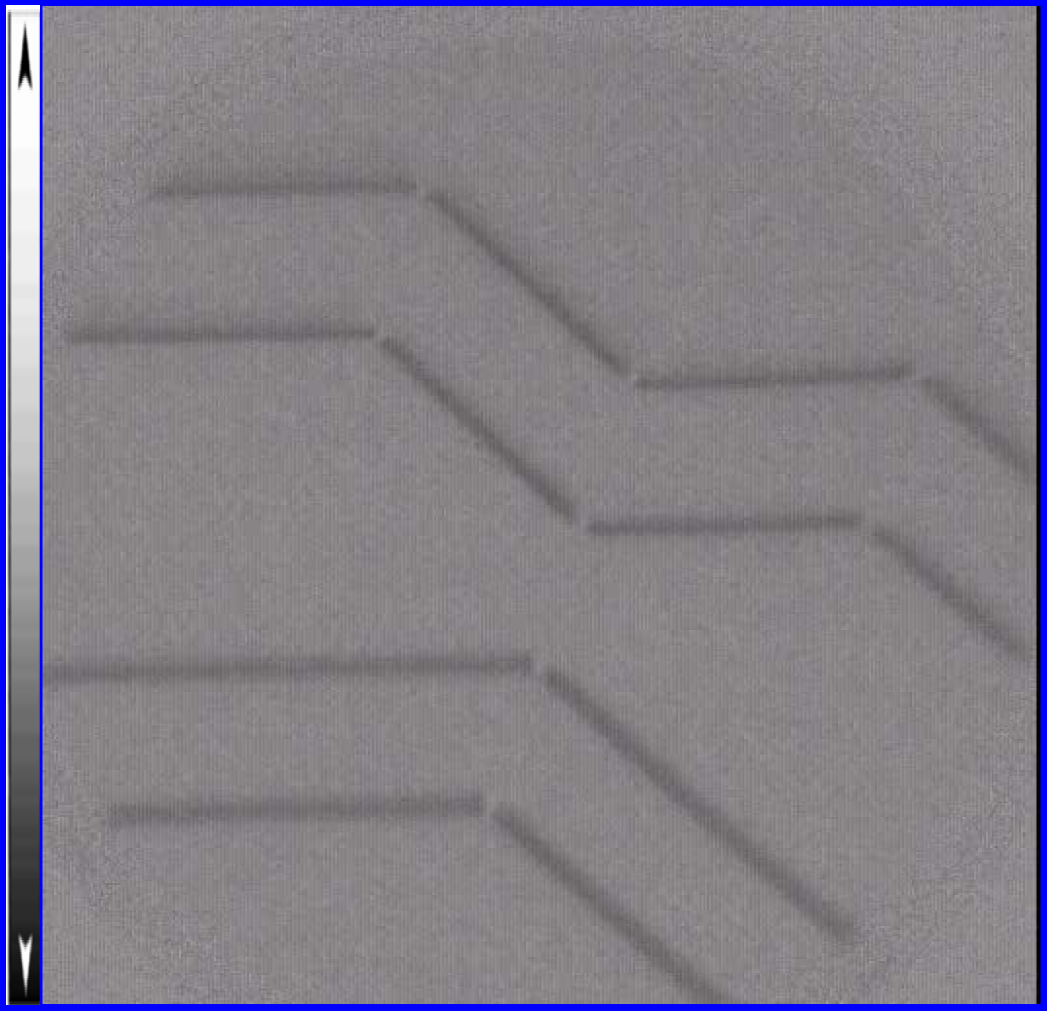
Direct CIDP Observations with XMCD-PEEM



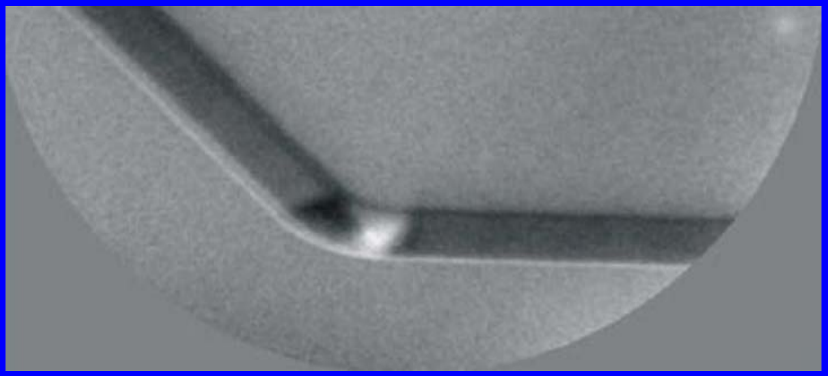


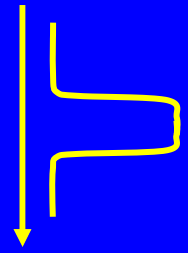
- Domain walls move in the direction of the electron flow.
- High-resolution imaging reveals the domain wall spin structures (vortex, transverse).

The Stochastic Nature of CIDP (XMCD-PEEM)

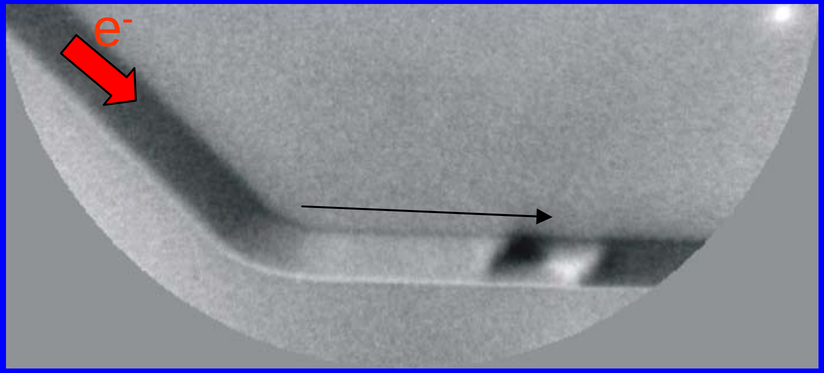


Pulses with 146V-156V, 150µs





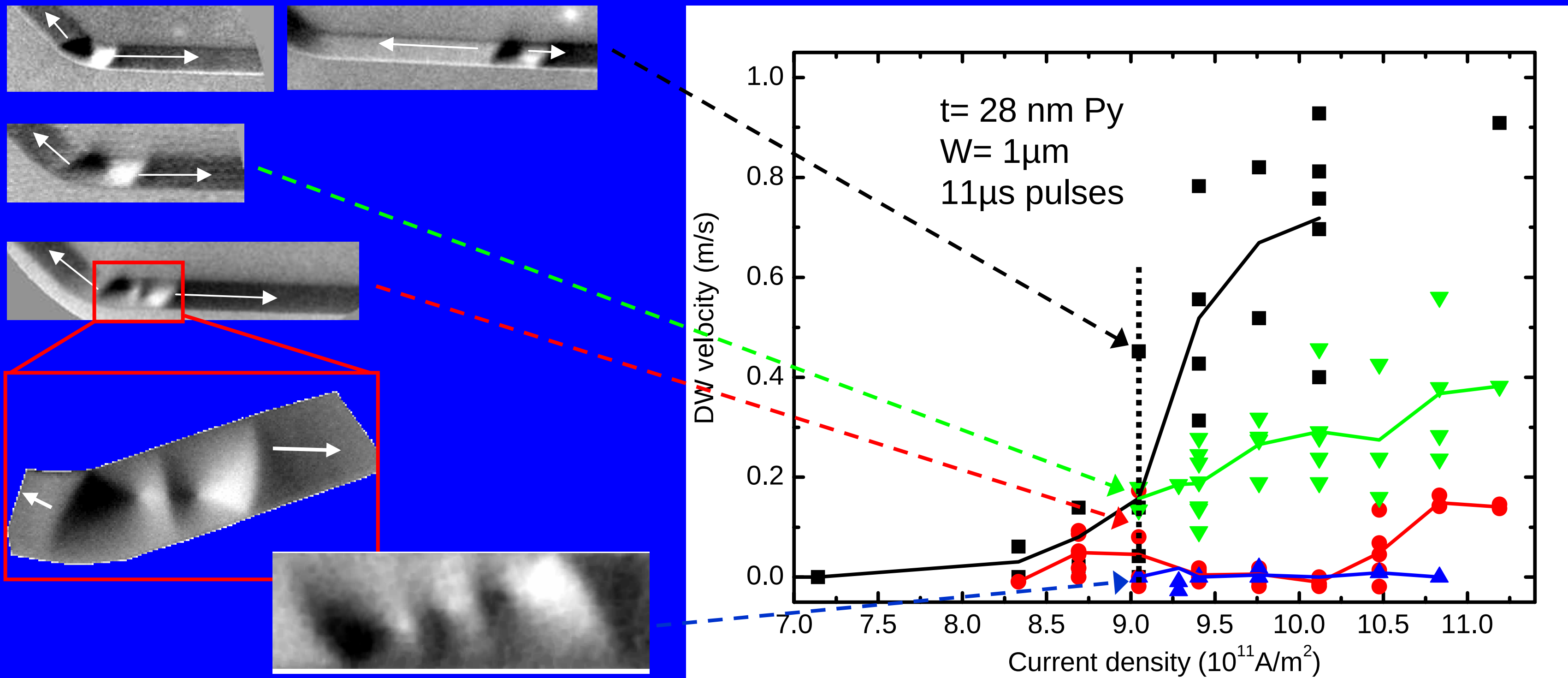
Current pulse
25µs, 10^{12}A/m^2



Py; 1µm wide, 28nm thick

Current-induced DW Transformations

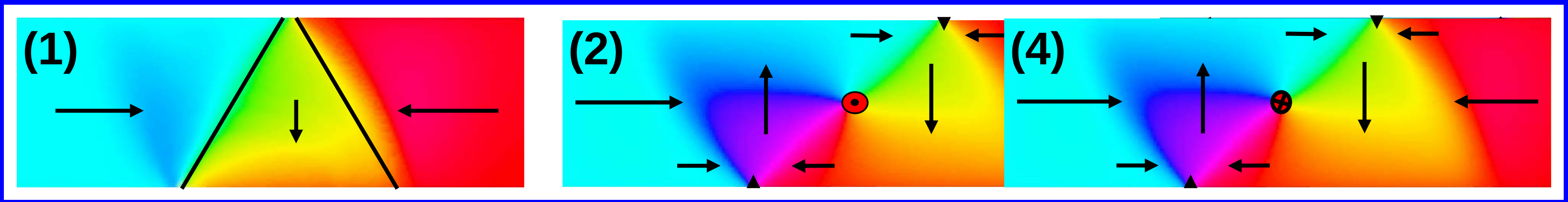
The Stochastic Nature of CIDP: Vortex Core Nucleation and Annihilation



APL **88**, *232507 (2006).*

- 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

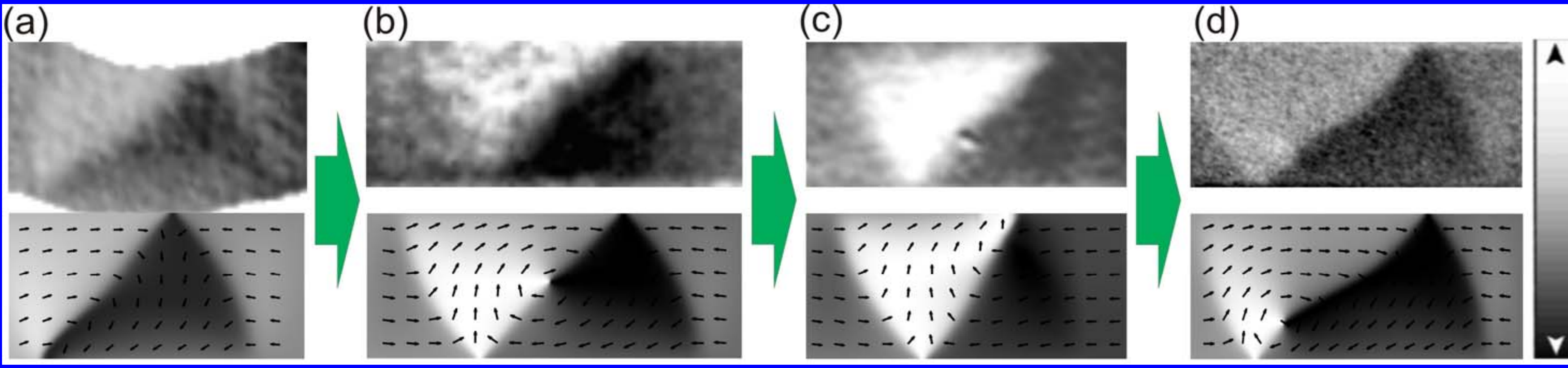


*A. Thiaville et al., EPL **69**, 990 (2005).*

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

W = 1.5 µm, t = 7 nm, close to TW-VW phase boundary

Appears in PRL 2008



Transverse wall (**down**)

Vortex wall (**clockwise**) after pulse injection (10^{12}A/m^{2}, 25 µs)

Transverse wall (**up**) after pulse injection

Displaced vortex core gives direct evidence of transformation mechanism!

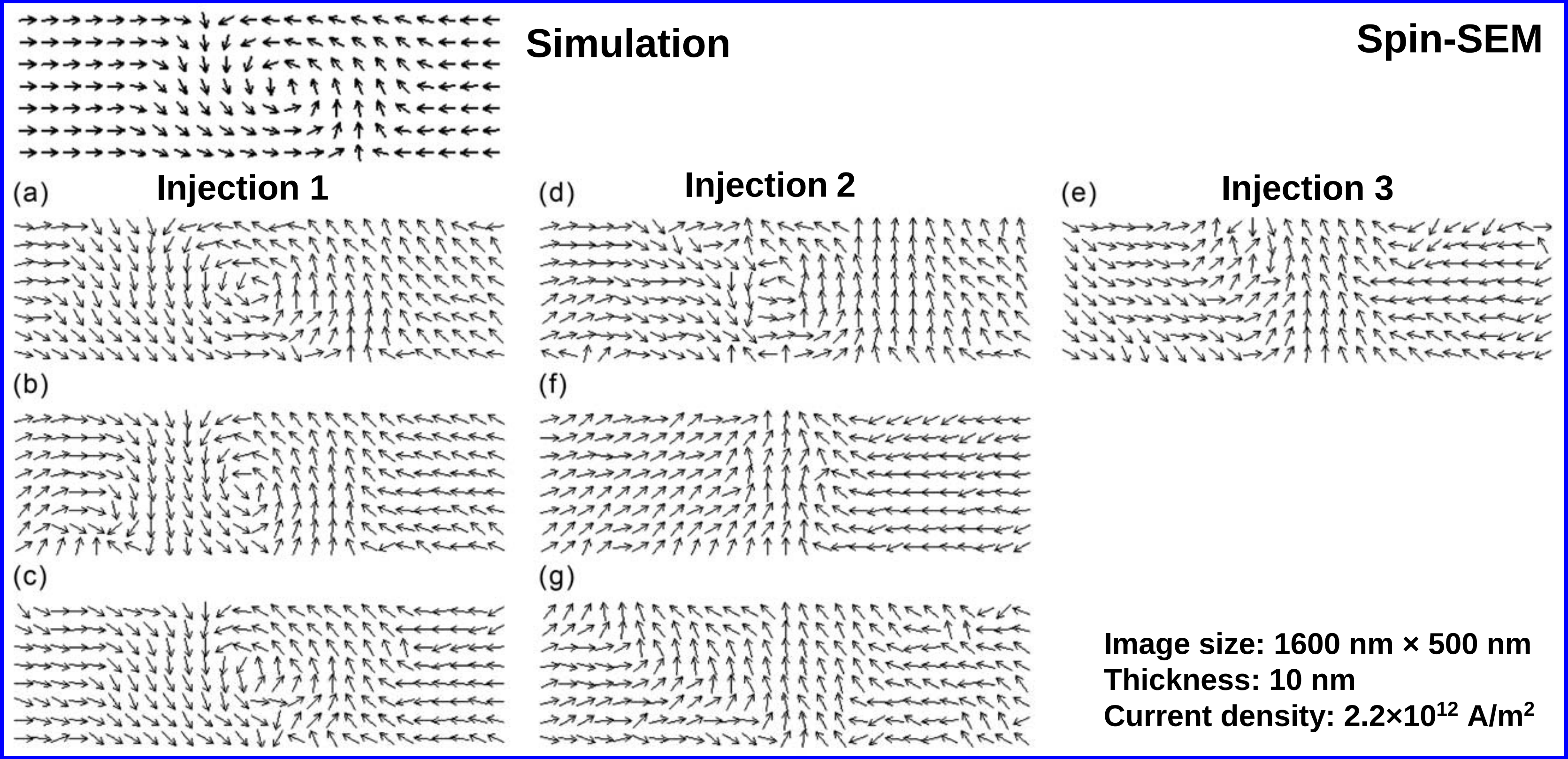
Direct Observation of CIDP in „Zig-Zag“ Lines

- 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 (α-β) (see: *He et al., PRB 73, 184408 (2006)*).

$$\underline{v} = -\frac{u_x}{1+\alpha^2}\left(\left(1+\beta\alpha\right)\frac{\partial \underline{S}}{\partial x} + (\alpha-\beta)\,\underline{S}\times\frac{\partial \underline{S}}{\partial x}\right)$$

- 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

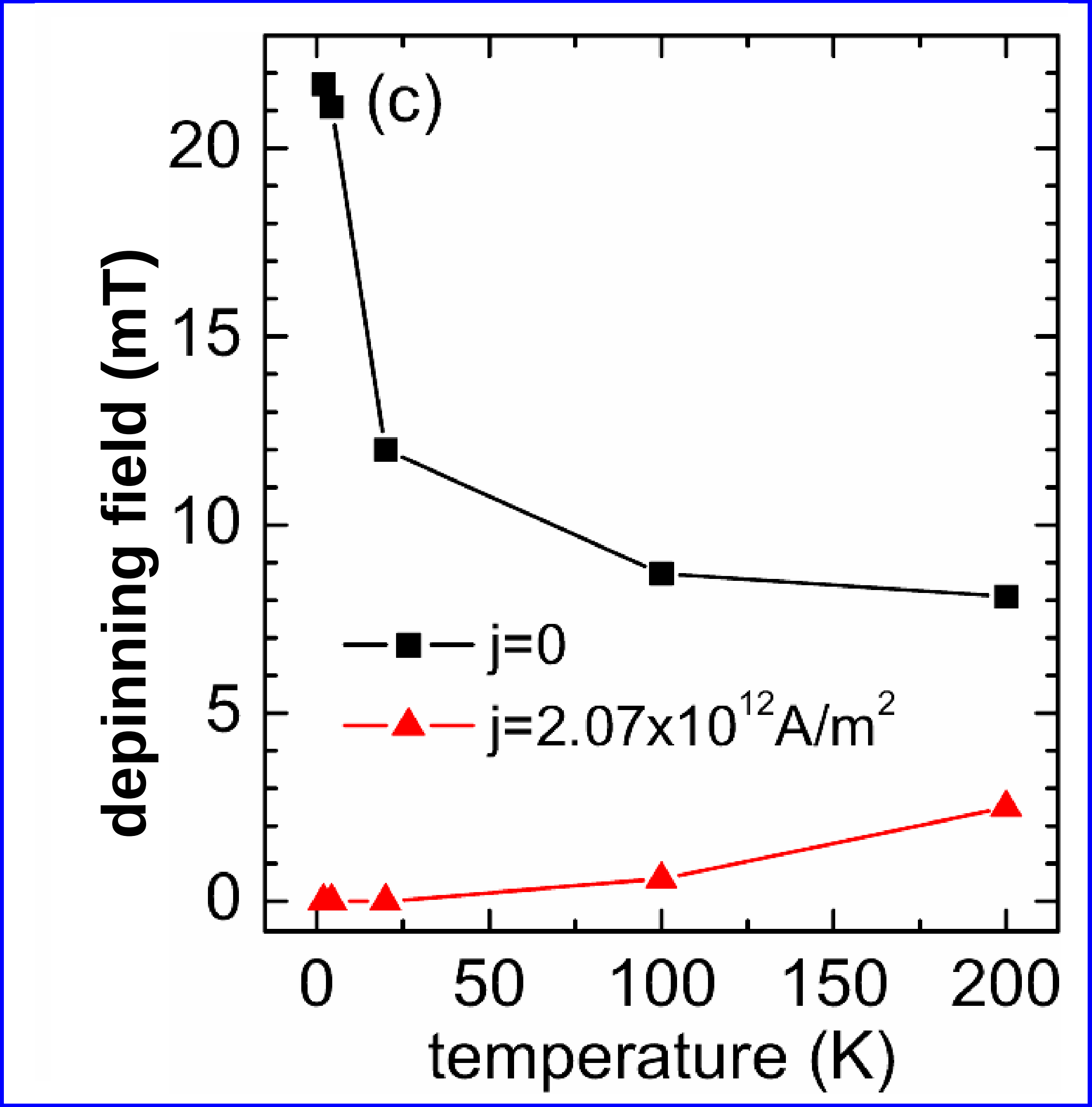


PRL **95**, *026601 (2005).*

- 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



PRL ***97****, 046602 (2006).*

- 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 tempera-tures!
- 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 temperatur (spin wave generation?).

Deutsche Forschungsgemeinschaft DFG

SFB 767

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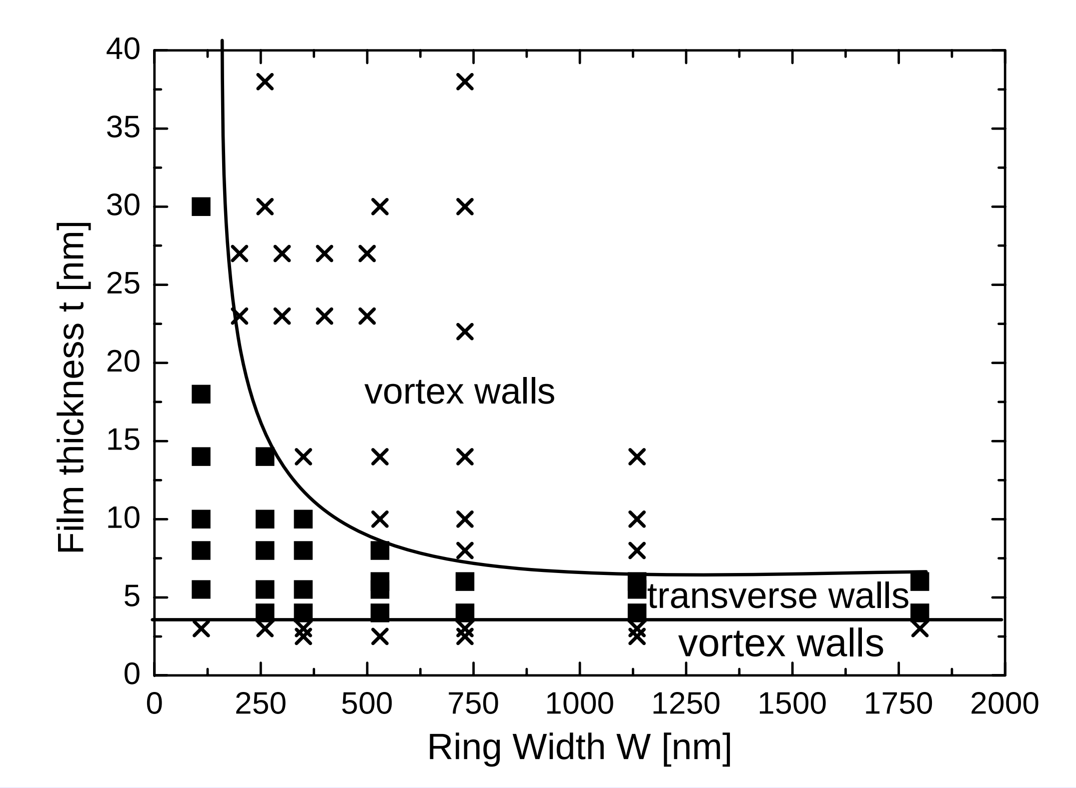
Domain Wall Phase Diagram for Permalloy Rings



*APL **88**, 52507 (2006).*