Current-induced Domain Wall Dynamics

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- Motivation: Physics & Applications
- Head-to-head domain wall spin structures
- Behaviour of domain walls at constrictions (pinning sites)
- Spin Torque Theory and simulations of CIDM
- Observation of CIDM in different materials (velocities, etc...)
- Current-induced domain wall quasiparticle excitations
- Magnetic Shift Register Device
1. Domain walls & currents – exciting physics & applications

**Current-induced domain wall motion (CIDM)**


M. Yamanouchi, Nature **428**, 539’04


**DW Magnetoresistance effects:**


**Magnetic Logic – NOT gate**


**Storage – Racetrack memory**

Large stray field $\rightarrow$ energetically favourable in thin and narrow structures.\textsuperscript{1,2}

Large exchange energy $\rightarrow$ energetically favourable in thick and wide structures.\textsuperscript{1,2}

\textsuperscript{1}R.D. McMichael et al., IEEE Trans. Mag. 33, 4167 (1997), \textsuperscript{2}Y. Nakatani JMMM 290, 750 (2005).
2. Head-to-head Domain Walls - Experiment

Co Rings, $D=1.7 \mu m$; $W=0.4 \mu m$, $0.25 \mu m$; $t=34 \text{ nm}$; Spin-SEM & Electron holography


$^1$M. Kläui et al., PRB 68, 134426 (2003); PRL 86, 1098 (2001), APL 84, 951 (2004); APL 86, 32504 (2005);
Transverse walls are attracted into the notch (single attractive potential well).

Vortex walls are repelled by the constriction but pinned adjacent to the constriction due to the reduced stray field (double potential well).

There is a definite sense of rotation of the vortex wall depending on the position.

M. Kläui et al., PRL 90, 97202 (2003); APL 87, 102509 (2005)
3. Pinning of TW and VW at constrictions - Experiment

Permalloy Rings, W=200 nm; t=27 nm; Electron holography and magnetotransport

- (a), (b) show transverse walls (<50nm)
- (c)-(g) show vortex walls (>50nm).
- (e), (g) show a head-to-head and a tail-to-tail wall after reversing H.

**Depinning field** (exp. black) increases as potential well **DEPTH** (red) with decreasing constriction width (factor 6).\(^1\)

**The WIDTH** of the potential well extends far beyond the physical size of the notch.\(^2\)

\(^1\)M. Kläui et al., APL 87, 102509 (2005); \(^2\)M. Kläui et al., PRL 90, 97202 (2003)
4. Current induced domain wall propagation

Two possible mechanisms:
1. Narrow wall: Linear momentum transfer
2. Wide wall: Angular momentum transfer

- Transmission
- Spin rotates

Description using the Landau – Lifshitz Gilbert equation:

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

- Adiabatic spin torque: proportional to \( \vec{u} = \frac{jgP\mu_B}{(2eM_s)} \)
- \( \beta \)-term torque (sources: spin relaxation and non-adiabatic transport): \( \beta = \alpha? \)

Zig-zag permalloy (Ni\textsubscript{80}Fe\textsubscript{20}) wires with variable geometries are used. Depending on the geometry, vortex or transverse walls are present. Zig-zag wires allow one to generate head-to-head domain walls at the kinks by applying the field in the direction indicated by the arrow. The magnetization is pointing in opposite directions in adjacent branches of the wire. The kinks are ¼ ring elements with a radius >> wire width (wires magnetically smooth).

M. Kläui et al., APL 88, 232507 (2006); PRL 94, 106601 (2005)
Head-to-head vortex walls are formed at kinks. $j_{\text{crit}} = 2,3 \times 10^{12} \text{ A/m}^2$

Walls move in the direction of the electron flow.

Pulse length $\Delta t$ is varied.

Velocity is independent of the pulse length: 1 m/s

Walls move beyond kinks.

Head-to-head and tail-to-tail walls move in the same direction $\rightarrow$ no field effect.

W=300nm; 60µm long; t=27nm Py, Spin-SEM measurement
M. Kläui et al., PRL 95, 026601 (2005), P.-O. Jubert, M. Kläui et al. JAP 99, 08G523 (2006);
Domain walls move in the direction of the electron flow and high-resolution imaging reveals the domain wall spin structures (vortex, transverse, etc.).

M. Klüui et al., PRL 94, 106601 (2005); PRL 95, 026601 (2005); PRL 100, 66603 (2008)
5. Resonant Domain Wall Dynamics
Permalloy (NiFe) Rings, W=200 nm; t=30 nm; Magnetotransport and Simulations

- Measurement of the depinning field as a function of μ-wave frequency.
- Depinning field is strongly reduced for certain μ-wave frequencies (resonance).
- TW has higher resonance frequency than VW; Narrow dip → high Q-factor.

D. Bedau, M. Kläui et al., PRL 99, 146601 (2007)
5. Electrical detection of domain wall oscillations
Py rings, W=200 nm, D=1.5 µm, t=30 nm, Magnetotransport

- Mixing of AC current (with frequency f=ω) and resistance change ΔR (with f=ω): → DC signal (and 2ω).
- Homodyne detection (DC signal): \( U_{DC} = I_{AC} \times ΔR \times \cos(φ) \) with φ the phase shift.¹
- For an undamped oscillation φ(ω)=90° at resonance → dispersion-like signal.
- For TW asymmetric dip (φ≠90° at \( ω=ω_{res} \) due to asymmetric potential or damping). → Independent check of the resonant frequencies possible (at variable fields!).

Using TEM electron holography, the size and the polarity (out-of-plane component) of the vortex core is determined.\(^3\)

Using current pulses with alternating polarity, the vortex core can be moved perpendicular to the current reproducibly between two positions.\(^2\)

The direction depends on the vortex core polarity.

The displacement direction and the total displacement is in agreement with theoretical predictions.\(^1\)

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H. Kohno et al., JMMM \textbf{310}, 2020 (‘07); \(^2\)L. Heyne, MK et al., PRL \textbf{100}, 66603 (‘08); \(^3\)APL \textbf{92}, 112502 (‘08)