Magnetization Dynamics of Current- and Field-Driven Domain Walls and Vortices

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4.9.2008

- time evolution of the magnetization is given by the extended Landau-Lifshitz-Gilbert equation[1]

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_{\text{eff}} + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt} - \frac{b_j}{M_s^2}\vec{M}\times\left(\vec{M}\times(\vec{j}\cdot\vec{\nabla})\vec{M}\right) - \xi\frac{b_j}{M_s}\vec{M}\times(\vec{j}\cdot\vec{\nabla})\vec{M}$$

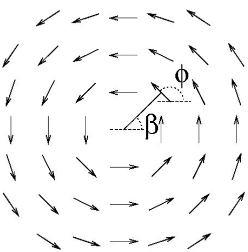
- exact numerical solution
- analytical solution using some approximations

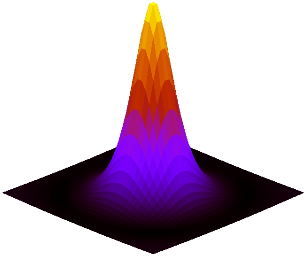
[1] S. Zhang and Z. Li, Phys. Rev. Lett. **93**, 127204 (2004)

Experiments

- experiments at the Advanced Light Source in Berkeley
- dynamics of vortices imaged at the scanning transmission X-ray Microscope STXM
- dynamics of domain walls investigated at the full-field soft X-ray transmission microscope XM-1
- sub 100 ps time resolution

Magnetic Vortices



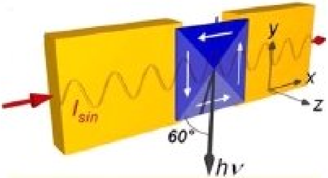


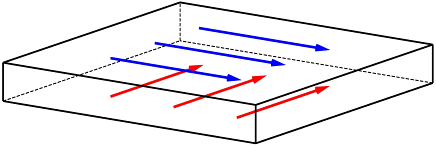
- the magnetization curls around a center region

$$\phi = \beta + \frac{\pi c}{2}$$

- c is the chirality
- in the center region the magnetization points out-of-plane

Vortex Excitation





- a vortex can be excited by current or magnetic field
- in experiments inhomogeneous current flow in the sample[1]
- ⇒ Oersted field which also excites the core
- experimental discrimination between the influence of
  - the spin torque
  - the Oersted field
- the Oersted field is included by a homogeneous magnetic field perpendicular to the current

[1] M. Bolte, G. Meier, B. Krüger, A. Drews, R. Eiselt, L. Bocklage, S. Bohlens, T. Tyliszczak, A. Vansteenkiste, B. Van Waeyenberge, K. W. Chou, A. Puzic, and H. Stoll, Phys. Rev. Lett. **100**, 176601 (2008)

Analytical Results

- parabolic confining potential
- harmonic excitation

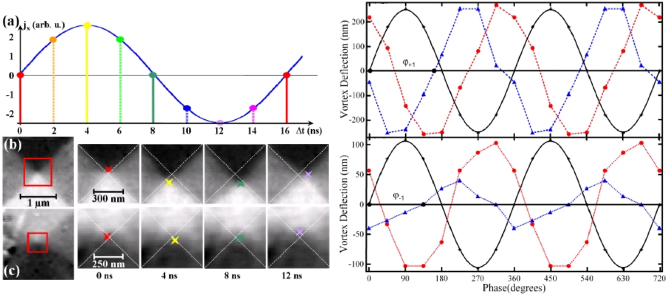
$$\begin{pmatrix} X \\ Y \end{pmatrix} = -\frac{e^{i\Omega t}\omega}{\omega^2 + (i\Omega + \Gamma)^2} \begin{pmatrix} \tilde{H} c \\ \tilde{j} p \end{pmatrix} - \frac{e^{i\Omega t} i\Omega}{\omega^2 + (i\Omega + \Gamma)^2} \begin{pmatrix} \tilde{j} \\ -\tilde{H} cp \end{pmatrix}$$

with $\tilde{H} = \gamma H_0 l/(2\pi)$ and $\tilde{j} = b_j j_0$[1]

- motion on ellipses
- the semi axes and the phases depend on the frequency and the source of excitation
- changing of c
  - spin-torque driven motion ⇒ same phase
  - Oersted-field driven motion ⇒ 180° phase shift

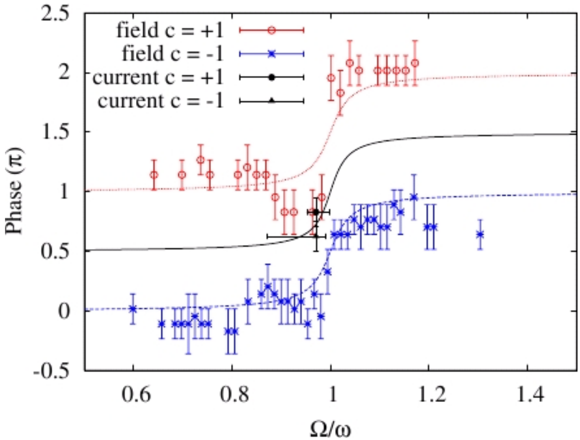
[1] B. Krüger, A. Drews, M. Bolte, U. Merkt, D. Pfannkuche, and G. Meier, Phys. Rev. B **76**, 224426 (2007)

Phase Shift



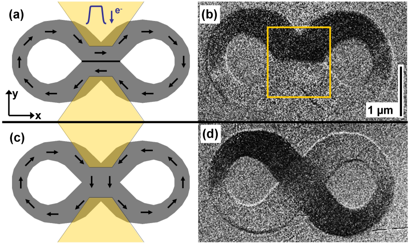
- the sample is imaged at different phases of the applied current
- vortices with both chiralities $c = +1$ (b) and $c = -1$ (c)
- 45° phase shift between vortices with different chiralities
  $\Rightarrow$ 70% of the excitation is driven by spin-transfer torque
- good accordance with numerical calculations

Phases of Current- and Field-Driven Vortices



- phase of field-driven vortices measured at permalloy squares deposited on a gold stripline
- good accordance with the theory

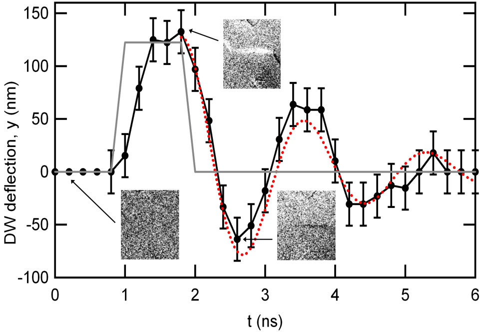
Experimental Setup



- ∞-shaped samples with two gold contacts[1]
- initial magnetization in -x direction
- two different magnetization patterns in remanence
  - globally curling magnetization with domain wall (a)
  - different curling direction in both rings without domain wall (c)
- corresponding X-ray images (b) and (d)

[1] L. Bocklage, B. Krüger, R. Eiselt, M. Bolte, P. Fischer, and G. Meier, submitted

Harmonic Oscillations



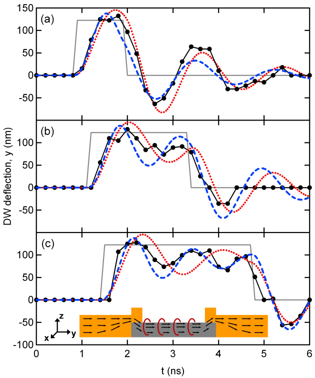
- excitation using a current pulse
- the subsequent small oscillation can be fitted by a harmonic oscillator
- assuming spin-torque driven excitation the initial motion should be downwards in the direction of the electron flow
  $\Rightarrow$ Oersted-field driven excitation

Analytical and Numerical Calculations

- equation of motion in an external potential E[1]

$$\ddot{Y} = -\frac{\dot{Y}}{\tau_d} - \frac{\lambda\gamma H_{\text{ext}}}{\alpha\tau_d} - \frac{\lambda\gamma\alpha\dot{H}_{\text{ext}}}{1+\alpha^2} - \frac{1}{m}\frac{dE}{dY}$$

- solved by numerical integration
  - using a harmonic potential $E = \frac{m\omega^2}{2}Y^2$
  - including a fourth order term $E = \frac{m\omega^2}{2}Y^2 + \frac{mk}{4}Y^4$
- $\omega = 3.6$ GHz
- $k = 4.5 \cdot 10^{-4}$ $\text{ns}^{-2}\text{nm}^{-2}$
- $B = -3.3$ mT at $j = 5 \cdot 10^{11}$ A/m^2



[1] B. Krüger, D. Pfannkuche, M. Bolte, G. Meier, and U. Merkt, Phys. Rev. B **75**, 054421 (2007)

Conclusion

- analytical expression for the current- and field-driven trajectory of vortices
- analytical result compared with micromagnetic simulations
- X-ray microscopy of current- and field-driven vortex gyration
- 70% of the excitation is driven by spin-transfer torque

- X-ray microscopy of current-induced domain-wall dynamics
- compared with an analytical model
- fourth order pinning potential
- the wall is mainly driven by the Oersted field

Acknowledgment

René Eiselt	Bartel Van Waeyenberge
Tolek Tyliszczak	Kang Wei Chou
Peter Fischer	Aleksandar Puzic
Arne Vansteenkiste	Herman Stoll

Financial support by the Deutsche Forschungsgemeinschaft via SFB 668 "Magnetismus vom Einzelatom zur Nanostruktur" and via Graduiertenkolleg 1286 "Functional metal-semiconductor hybrid systems" is gratefully acknowledged.

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