Domain Wall Dynamics

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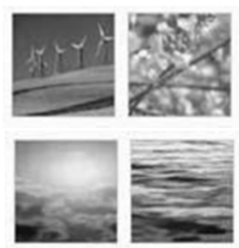
- **Motivation: Physics & Applications**
- **Head-to-head Domain Wall (DW) spin structures**
- **DW manipulation by magnetic fields**
- **DW manipulation by spin-polarized currents – spin torque**
- **DW manipulation by using pure diffusive spin currents**
- **DW manipulation by temperatures - Spin Seebeck effect**
- **Magnetization manipulation by photons - fs demagnetization**

Motivation – why do we need low power electronics?

- Rising energy consumption
  → Rising CO_2 emission
  → Global warming:
- 6 °C by 2100 will lead to catatstropic consequences costing billions[1]
- Even an ambitious 2°C target[2] will be challenging.
- Two approaches:
  CO_2 – neutral energy production
  Reduction to energy consumption
  → How about IT?



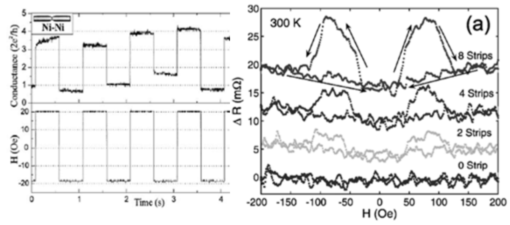
More in our Policy Paper[3]:
"Sustainable Technology Leadership – mit Technologie und Energie in die Zukunft"

[1]IPCC Report 2009; [2]G8 summit 2009; [3]http://www.stiftung-nv.de/THINK-TANK/Themenschwerpunkte/Publikationen/140882

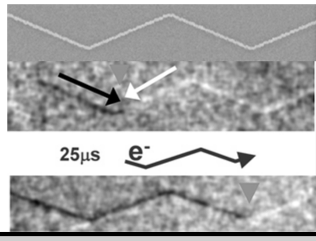
Domain walls & currents – exciting physics & applications

DW Magnetoresistance effects:

A. Aziz et al., PRL **97**, 206602 (2006); A. Patra et al., PRB **82**, 134427 (2010).

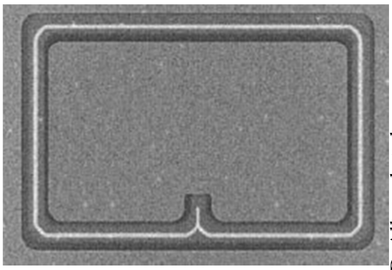


Current-induced domain wall motion (CIDM)



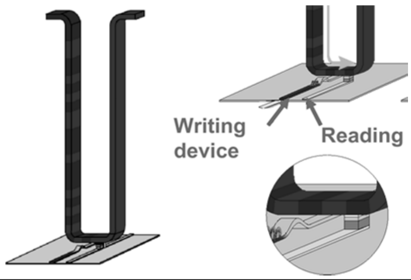
-A. Yamaguchi PRL **92**, 77205('04)
-J. Grollier et al., APL 83, 509 ('03)
-N. Vernier et al., EPL **65**, 526 ('04)
-M. Tsoi et al., APL **83**, 2617 ('03)
-M. Kläui, et al. APL **83**, 105 (2003)

Magnetic Logic – NOT gate



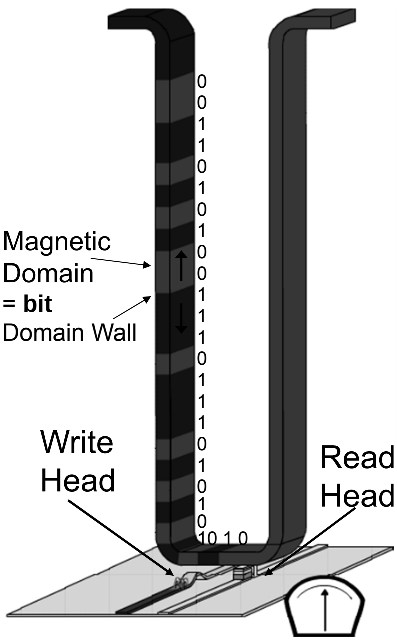
D. Allwood et al., Science **296**, 2003 (2002)

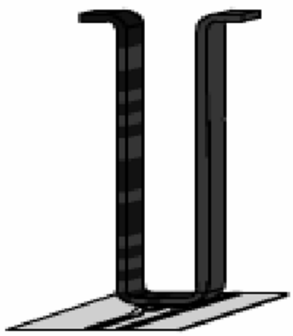
Storage – Racetrack memory



S. S. P. Parkin, Science **320**, 190 , (2008); Patent 6834005.

Prologue: Storage based on Domain Walls: Racetrack Memory





- Each domain acts as 1 bit (>100 bits per cell)
- High capacity by using a 3D design!
- Select: move domain of interest to read-out
- Read: read sensor (head) at read-out position
- Write: strip line generates a localized field

S. S. P. Parkin, Science **320**, 190 (2008); Patent US2006/0221677; M. Kläui, Physik in unserer Zeit (3/2009)

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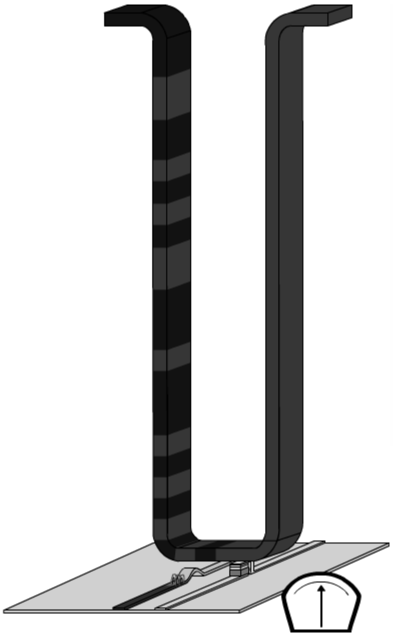

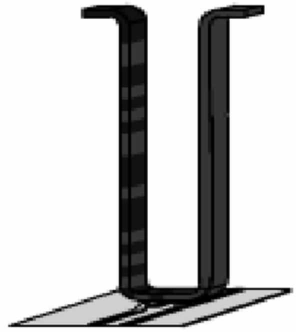

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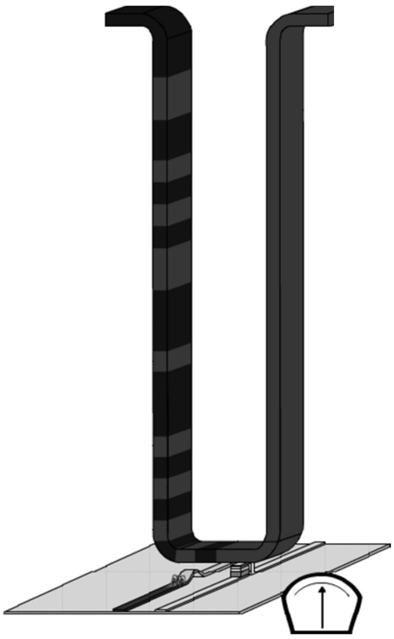

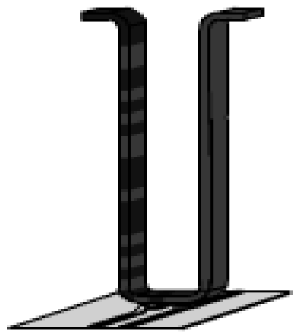

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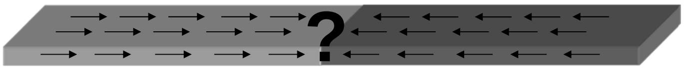
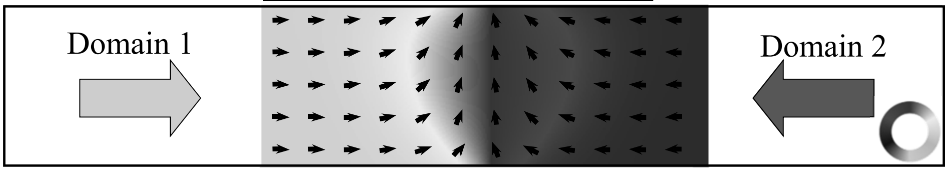
S. S. P. Parkin, Science **320**, 190 (2008); Patent US2006/0221677; M. Kläui, Physik in unserer Zeit (3/2009)

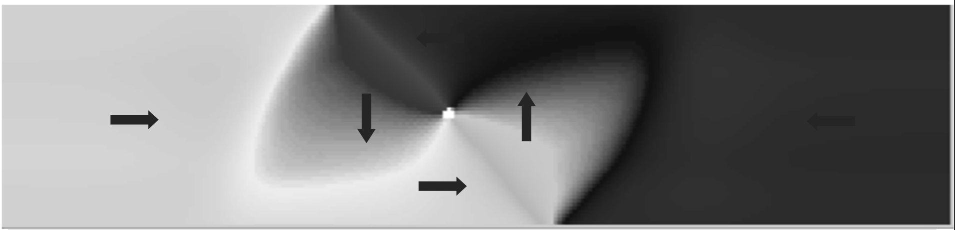
1. Domain Wall spin structures - Theory



Transverse Walls



- Large stray field → energetically favourable in thin and narrow structures.



- Large exchange energy → energetically favourable in thick and wide structures.

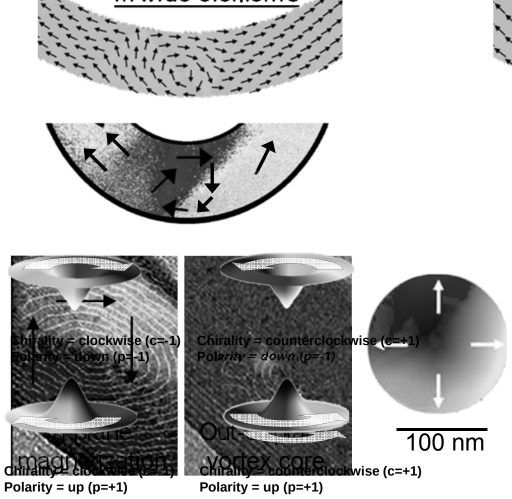
[1]R.D. McMichael et al., IEEE Trans. Mag. **33**, 4167 ('97), [2]Y. Nakatani JMMM **290**, 750 ('05); [3] M. Kläui, J. Phys. C. **20**, 313001 ('08)

1. Domain Wall spin structures - Experiment

Co Rings, D=1.7µm; W=0.4 µm, 0.25 µm; t=34 nm; Spin-SEM & Holography, STXM

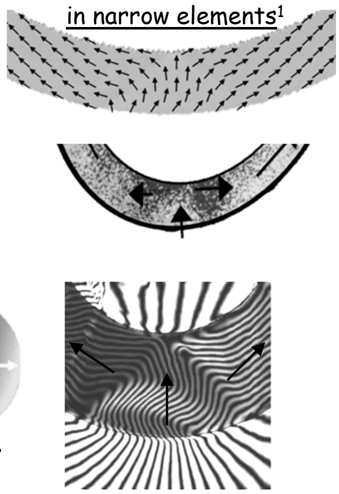
Vortex Walls

in wide elements[1]



Transverse Walls

in narrow elements[1]



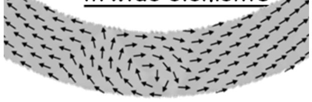
[1]M. Kläui et al., PRL **86**, 1098 ('01), PRB **68**, 134426 ('03); APL **86**, 32504 ('05); APL **92**, 112502 ('08)

1. Domain Wall spin structures - Experiment

$La_{0.7}Sr_{0.3}MnO_3$, $Co_2FeAl_{0.4}Si_{0.6}$ D=200-2000 nm; t=10-50 nm; XPEEM

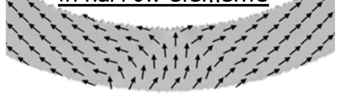
Vortex Walls

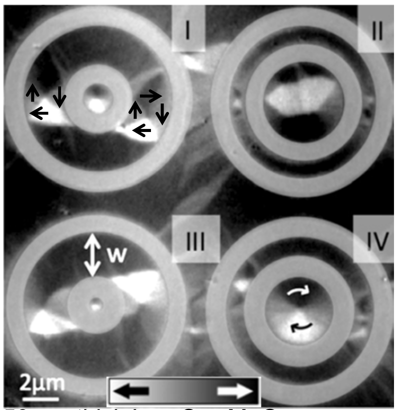
in wide elements



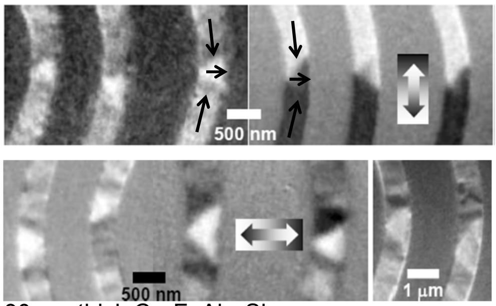
Transverse Walls

in narrow elements[1,2]





50 nm thick $La_{0.7}Sr_{0.3}MnO_3$



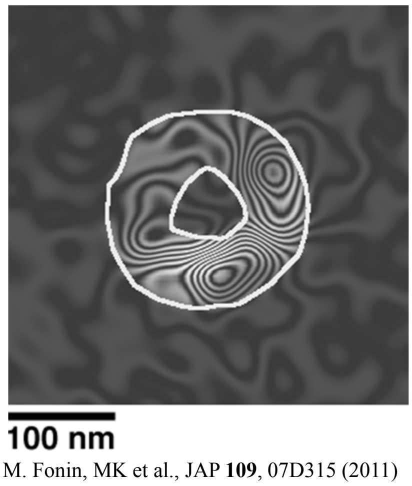
30 nm thick $Co_2FeAl_{0.4}Si_{0.6}$

- More exciting highly spin-polarized materials exhibit also well-defined domain wall spin structures that can be tune by the geometry.[1]

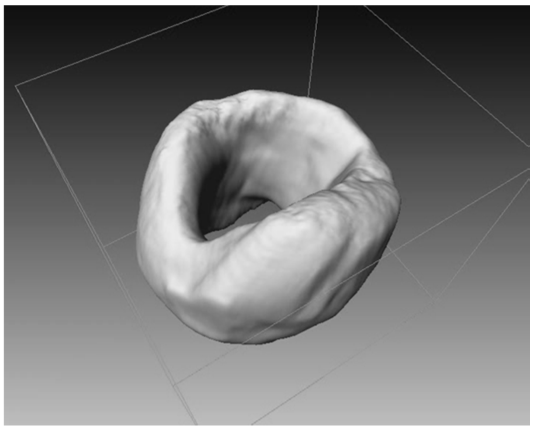
[1]J. Rhensius, MK et al., Appl. Phys. Lett. **99**, 062508 (2011); C. A. Vaz, MK et al., Appl. Phys. Lett.

1. Domain Wall spin structures - Experiment

Fe_3O_4 Rings, D=10µm; W=0.4 µm, 0.25 µm; t=34 nm; XPEEM & electron holography



M. Fonin, MK et al., JAP **109**, 07D315 (2011)

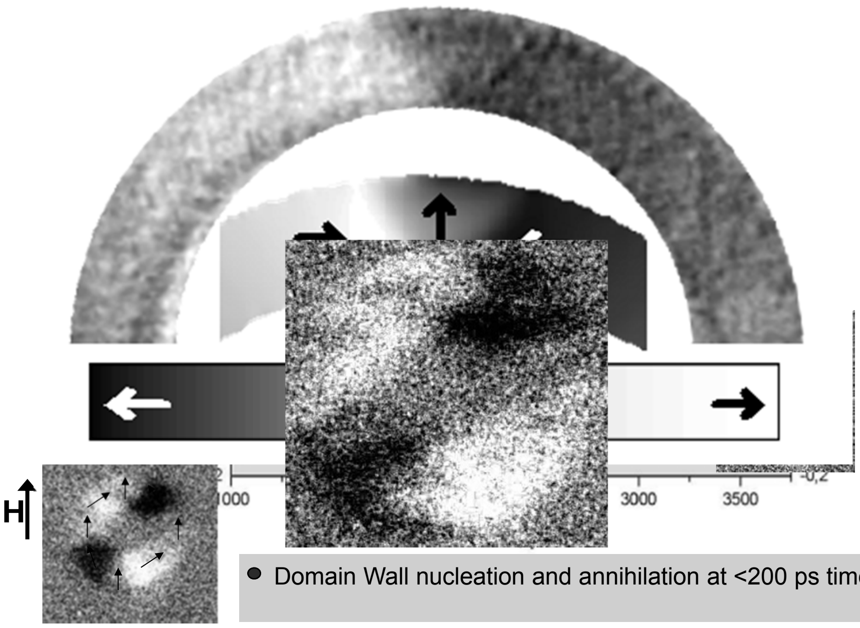


M. Eltschka, MK et al., Appl. Phys. Lett. **92**, 222508 (2008)
C. Jie, MK et al., J. Am. Chem. Soc. **130**, 16968 (2008)

- Magnetite is a highly spin-polarized half – metallic ferromagnet.
  → promising for spintronics applications and current-induced wall motion.
- Magnetite exhibits a cubic anisotropy. → Zig-zag domain walls spin structure

2. Magnetization dynamics induced by magnetic fields

NiFe and Co, D=3 µm, t=5 nm, W=800 nm, time-resolved X-PEEM & MOKE



- Domain Wall nucleation and annihilation at <200 ps timescale

I. Neudecker, MK et al., Phys. Rev. Lett. **96**, 057207 (2006)

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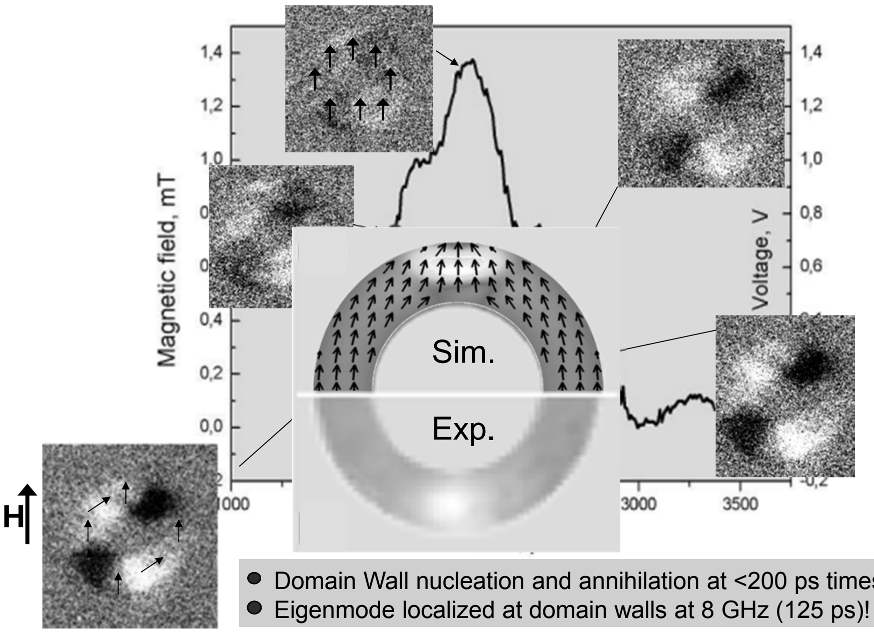
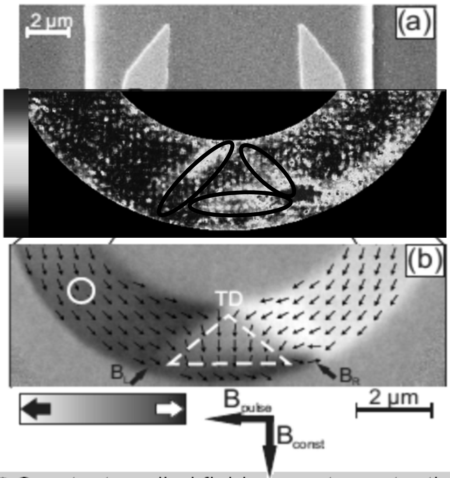


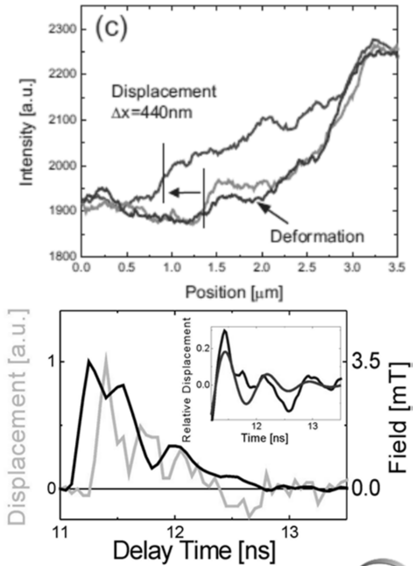
- Domain Wall nucleation and annihilation at <200 ps timescale
- Eigenmode localized at domain walls at 8 GHz (125 ps)!

I. Neudecker, MK et al., Phys. Rev. Lett. **96**, 057207 (2006)

2. Conventional field-induced domain wall motion

Permalloy rings, D=3 μm, t=25 nm, W=600 nm, time-resolved XPEEM & STXM

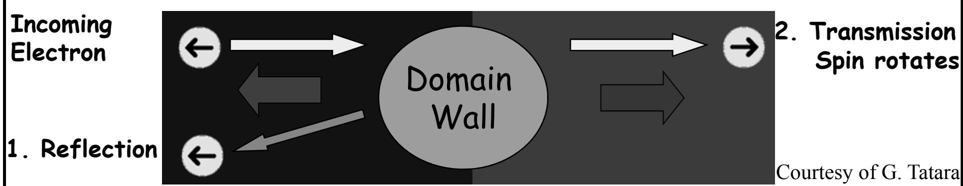




- Constant applied field generates potential well.
- Wall displacement by a 1ns pulsed perp. field.
- Wall moves 440 nm in 200ps: speed >2000 m/s
- Displacement exhibits delay → inertia & mass
- Mechanism: exchange energy stored in DW!

J. Rhensius, MK et al., Phys. Rev. Lett. **104**, 67201 (2010)

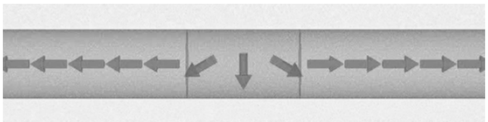
3. Interaction between spin currents and magnetization



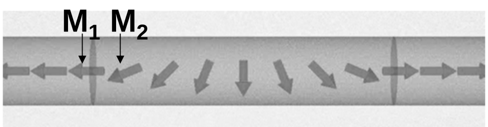
Courtesy of G. Tatara

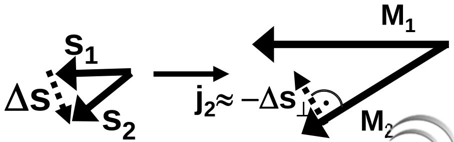
Two possible Mechanisms:

1. Narrow Wall: Non-adiabatic Transport – Domain Wall Magnetoresistance



2. Wide Wall: Adiabatic Transport





[1]G. Tatara et al., PRL **92**, 86601 ('04); O. Boulle, MK et al., Mat. Sci. Eng. Rep. doi.org/10.1016/j.mser.2011.04.001

3. Current-induced domain wall propagation - Theory

- Magnetization Dynamics: Landau Lifschitz Gilbert equation:

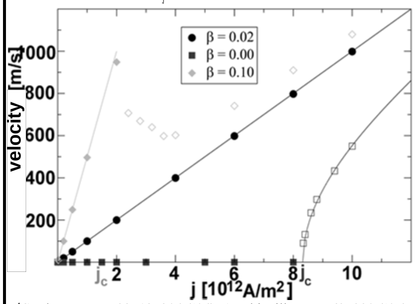
$$\dot{\vec{m}} = \gamma_0 \vec{H} \times \vec{m} + \alpha \vec{m} \times \dot{\vec{m}}$$

- Spin-transfer torque model[1]

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

$\vec{u} = \vec{j} g P \mu_B / (2eM_s)$ $\beta = \beta_{sr} + \beta_{na}$ spin relaxation & non-adiabatic transport

- Adiabatic term: proportional to j, P; Non-adiabatic term: proportional to β
- Theoretical models: $\beta_{sr} \cong \alpha$, β_{na} large for large magnetization gradients[2]



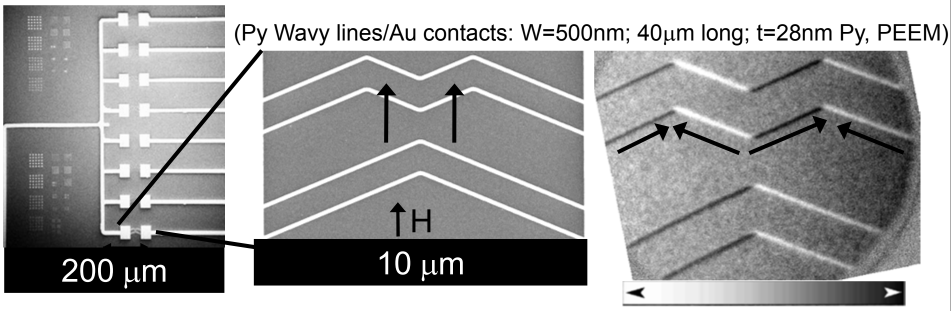
- **For β=0:** No DW motion for **$j < j_c$**.
- **For $\beta \neq 0$:** DW motion at small **j**.
- DW velocity: **$v \approx (\beta/\alpha) \cdot u$** (below Walker)
  $v \approx u$ (above Walker)
- Simulation shows periodic wall type transformations at $j > j_c$ if $\beta \neq \alpha$.
- Theory so far 0K → atomistic model[3].

[1]S. Zhang, PRL 93, 127204 ('04), A. Thiaville, EPL 69, 990 ('05);
[2]J. Xiao et al., PRB 73, 54428 ('06); JMMM 320, 1282 ('08)
[3]C. Schieback et al., Eur. J. Phys. B **59**, 429 (2007)

3. Current-induced domain wall motion – Experiment

Permalloy ($Ni_{80}Fe_{20}$) Wires W=50-500nm, t=5-50 nm, Spin-SEM and X-PEEM

(Py Wavy lines/Au contacts: W=500nm; 40μm long; t=28nm Py, PEEM)

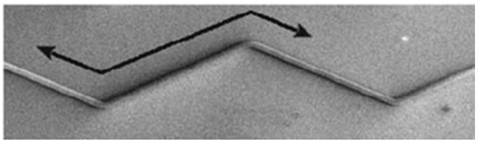


- Contacted zig-zag permalloy ($Ni_{80}Fe_{20}$) wires with variable geometries.
- Depending on the geometry, **vortex** or **transverse** walls are present.
- Domain walls are created at the kinks → magnetization is pointing in opposite directions in adjacent branches of the wire.
- The kinks are ¼ ring elements with a radius >> wire width
  → wires magnetically smooth.

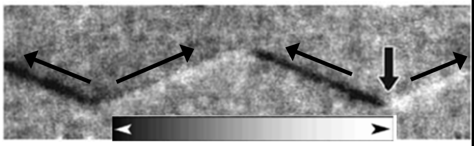
M. Kläui et al., PRL **94**, 106601 (2005); APL **88**, 232507 (2006);

3. Current-induced domain wall motion – Experiment

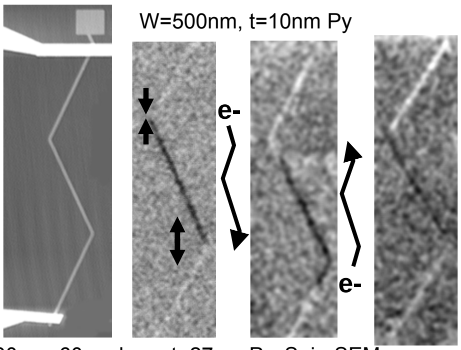
Permalloy ($Ni_{80}Fe_{20}$) Wires W=50-500nm, t=5-50 nm, Spin-SEM and X-PEEM



SEM topography image



Spin-SEM magnetization image



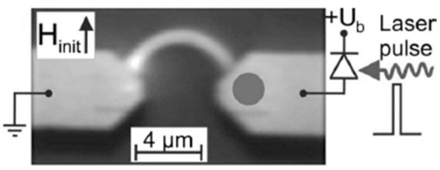
W=300nm; 60μm long; t=27nm Py, Spin-SEM measurement

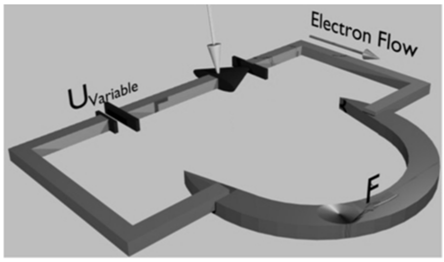
- Head-to-head vortex walls are formed at kinks.
- j_{crit}=2,3×10^{12} A/m^2
- Walls move in the direction of the electron flow.
- Velocity is independent of the pulse length: 1 m/s
- Walls move beyond kinks.
- Head-to-head and tail-to-tail walls move in the same direction → **spin torque effect, no** field effect.

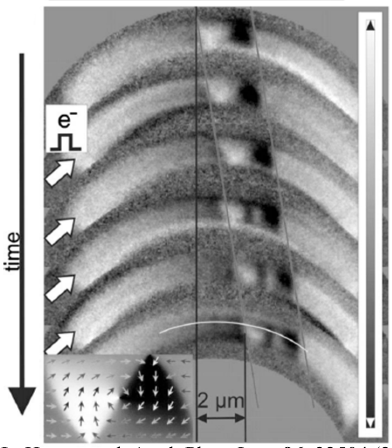
M. Kläui et al., PRL **95**, 026601 (2005); PRL **94**, 106601 (‘05); P.-O. Jubert et al., JAP **99,** 08G523 (‘06).
Other experiments: PRL **92**, 77205 (‘04) MFM; APL **83**, 509 (‘03) MR; Nature **428**, 539 (‘04) MOKE; PRL **98**, 187202 (2007) TXM; PRB **81**, 60402R (2010) Spin-SEM; PRB **81**, 224418 (2010) PEEM;

3. Imaging of fast current-induced motion– Experiment

Permalloy ($Ni_{80}Fe_{20}$) Wires W=50-500nm, t=5-50 nm, Spin-SEM and XPEEM





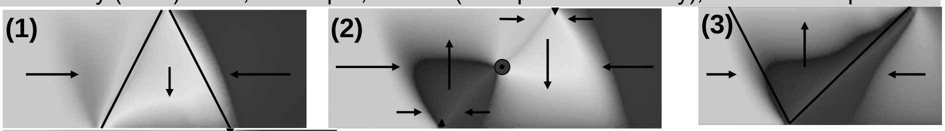


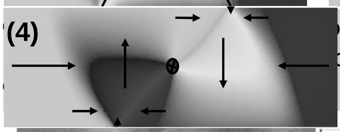
- Pulse injection using a fs laser and a diode to generate short pulses.[1]
- Fast rise time < 50ps, pulse length 3ns
- j = 2 - 4 * 10^{12} A/m^2
- Domain wall transformations occur: → above Walker breakdown
- Velocity: **130 m/s** (u=120 m/s)
- →v ≅ u (above Walker breakdown)[1] ☑
- Walker breakdown indicates $\beta \neq \alpha$ [2]

[1]L. Heyne et al. Appl. Phys. Lett. **96**, 32504 (2010); [2]L. Heyne et al., PRL **100**, 66603 (2008)

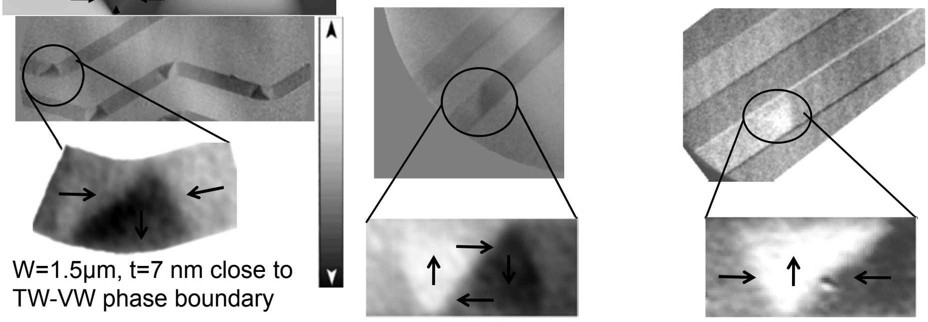
4. Imaging of periodic wall transformations

Permalloy (NiFe) wires, W=1.5μm, t=7 nm (near phase boundary), X-PEEM & Spin-SEM





eriodic transformation of DW type by the nucleation
core: TW (down) → VW (CW) → TW (up) → VW (CW).
but VW with the same circulation direction (CW).



1. Transverse Wall (down) after remagnetization.

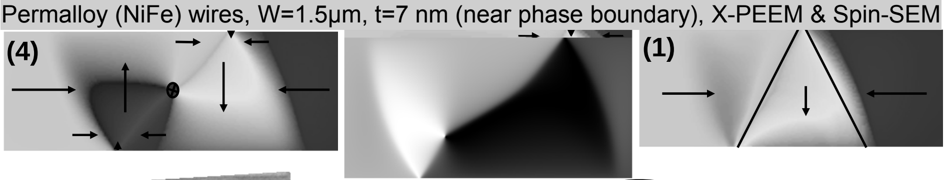
2. Vortex Wall (clockwise) after pulse injection 10^{12}A/m^2

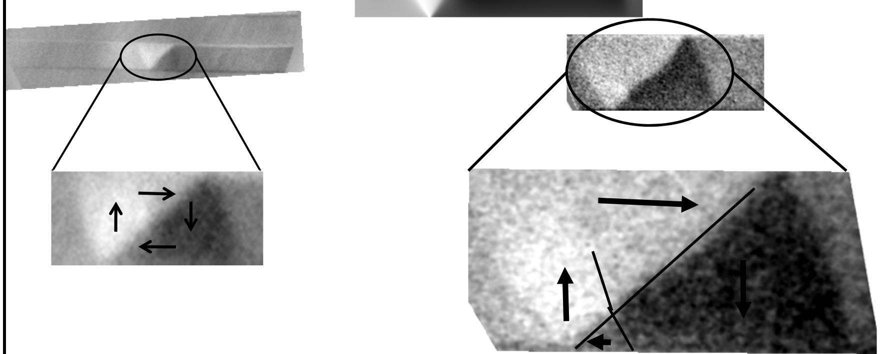
3. Transverse Wall up after pulse injection

L. Heyne, M. Kläui et al., PRL **100**, 66603 (2008)

4. Imaging of periodic wall transformations

Permalloy (NiFe) wires, W=1.5μm, t=7 nm (near phase boundary), X-PEEM & Spin-SEM





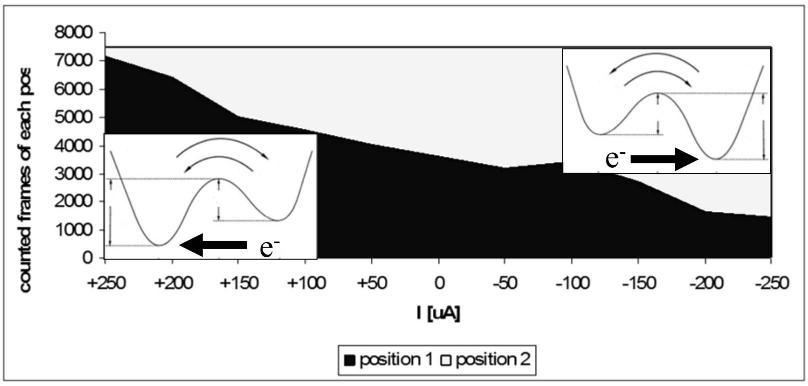
4. Vortex Wall (clockwise) after pulse injection 10^{12}A/m^2. Periodic transformation→ $\beta \neq \alpha$

DW during transformation from VW (CW) to TW (down). Displaced vortex core gives direct evidence of transformation mechanism!

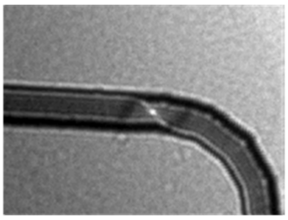
L. Heyne, M. Kläui et al., PRL **100**, 66603 (2008)

4. Thermally activated hopping biased by currents

Permalloy (NiFe) wires, W=150nm, t=15 nm, Lorentz Microscopy



- At finite temperature, a wall can move between
- different pinning sites (thermally activated hopping). Injecting a current, the potential landscale is tilted.
- Analysis using rate theory[1] yields non-adiabaticity:
- β_{VW} = 0.1±0.02; β_{TW} = 0.01±0.004 ≈α
- → Dependence of β on the wall spin structure![2]



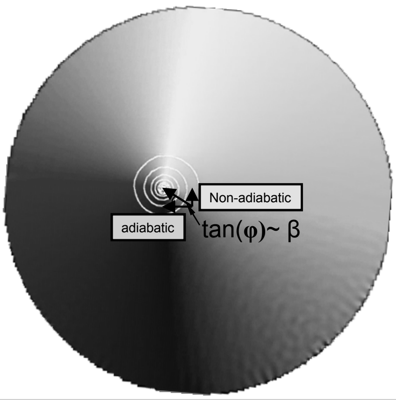
[1]P. Hänggi et al., Rev. Mod. Phys. **62**, 251 (1990); [2]M. Eltschka, MK et al., PRL **105**, 56601 (2010)

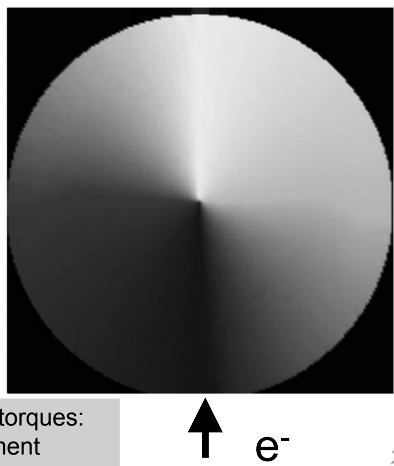
4. Quantitative determination of Torque Terms

Py discs, W=200-500 nm, t=30 nm, Micromagnetic simulations

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

3 torque terms: H (Oersted field), adiabatic torque and non-adiabatic torque





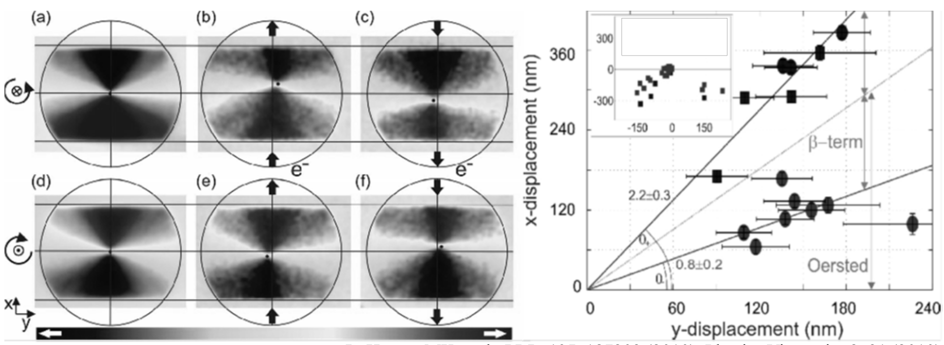
- Dynamics of adiabatic and non-adiabatic torques:
- Elliptical trajectory with the final displacement direction being a direct measure for β (β ∝ tan(φ)) !

4. Determination of Torque Terms

Py wires, W=200-500 nm, t=30 nm, Micromagnetic simulations

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

3 torque terms: H (Oersted field), adiabatic torque and non-adiabatict torque



L. Heyne, MK et al., PRL **105**, 187203 (2010); Physics Viewpoint **3**, 91 (2010)

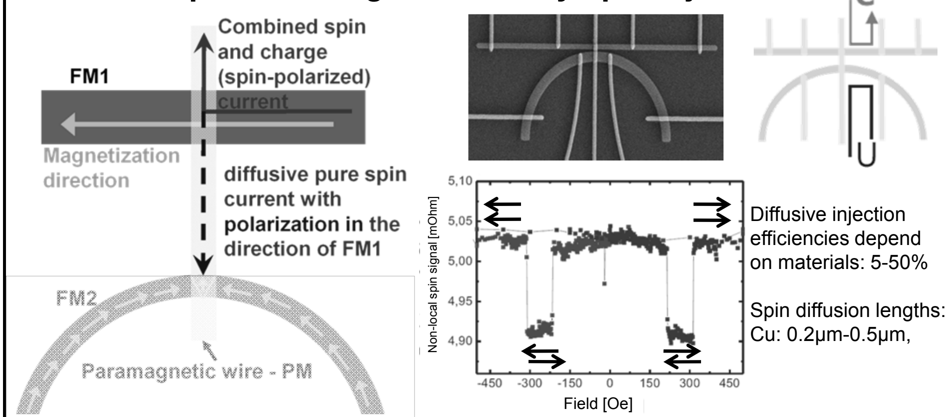
- We set the polarity and chirality and determine the displacement direction.
- Deduce the torque terms from the various combinations: Oersted Field: $\mathbf{H_{oe}=5Oe}$, Non-adiabaticity β **= 0.15±0.07** → β **/**α **≈ 15**
- β **>>**α →non-adiabatic transport across high magnetization gradient at the vortex core

5. Domain wall motion by pure diffusive spin currents

[Py/Cu/Py], W=100-300 nm, t=10-50 nm, Magnetotransport

Combined spin and charge currents → Spin torque but also Joule Heating → Separating charge and spin effects: Pure diffusive spin currents → no heating

Spin current generation by spin injection:

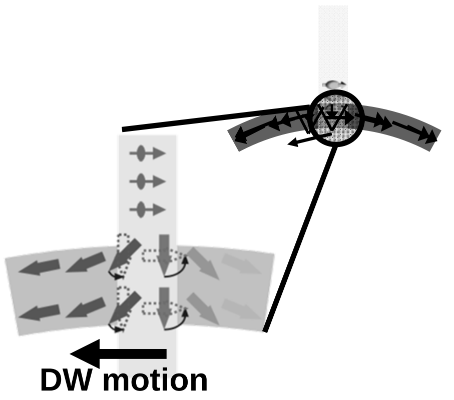


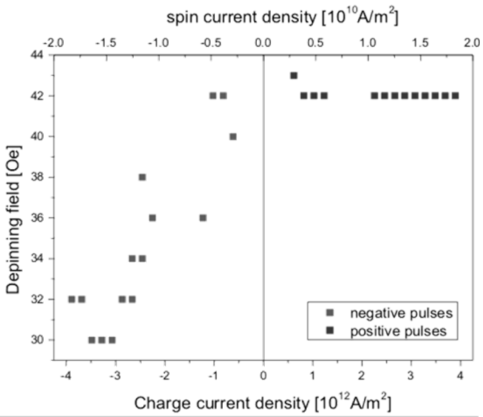
- Spin injection from FM1 into PM generates spin accumulation, which diffuses up/down.
- Spin current is detected by FM2 by measuring the voltage in a non-local geometry.

M. Johnson et al., PRB **37**, 5326 ('88); F. Jedema et al., Nature **410**, 345 ('01); D. Ilgaz, MK et al., PRL **105**, 76601 ('10)

5. Domain wall motion by pure diffusive spin currents

[Py/Cu/Py], W=100-300 nm, t=10-50 nm, Magnetotransport



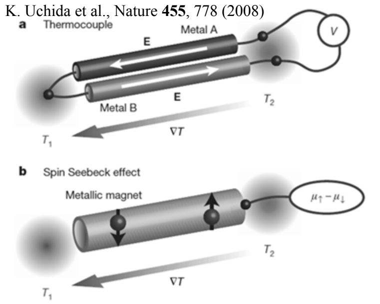


- Spin current is absorbed by second ferromagnet FM2 with a domain wall.
- The absorbed spins exert a torque on the magnetization (DW) in FM2.
- Negative current densities: spin-accumulation support domain wall motion.
  $\rightarrow$ The depinning field is reduced for negative spin currents.
- Efficiency: 10^{-13} T/A/m^2 > 100X larger than for spin torque with spin-polarized current!

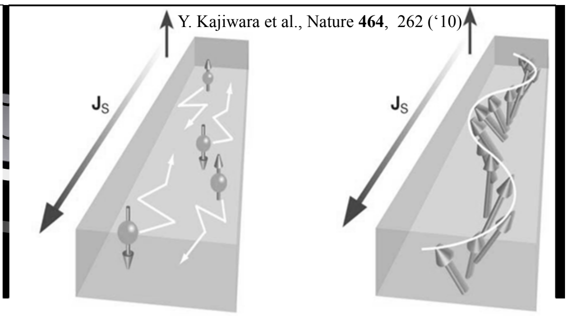
D. Ilgaz, MK et al., PRL **105**, 76601 (2010); Y. Tserkovnyak et al., Rev. Mod. Phys. 77, 1375 (2005)

6. Thermal spin currents - Spin Caloritronics

K. Uchida et al., Nature **455**, 778 (2008)



Y. Kajiwara et al., Nature **464**, 262 ('10)

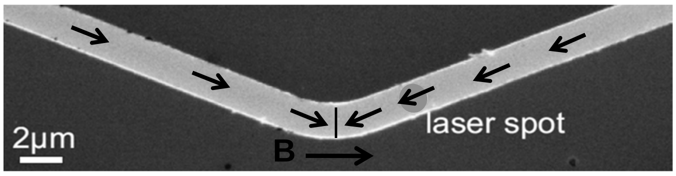


- Temperature gradients are predicted to generate spin currents due to the different Seebeck coefficients for majority and minority electrons (Spin Seebeck Effect).[1]
- Different theories have been put forward:
  Metallic Systems: Spin current torques[2]
  Magnetic Insulators: Magnonic spin currents[3]
- $\rightarrow$ Depending on the model, temperature of electron, spin or lattice system is important
  $\rightarrow$ use optical laser pulses

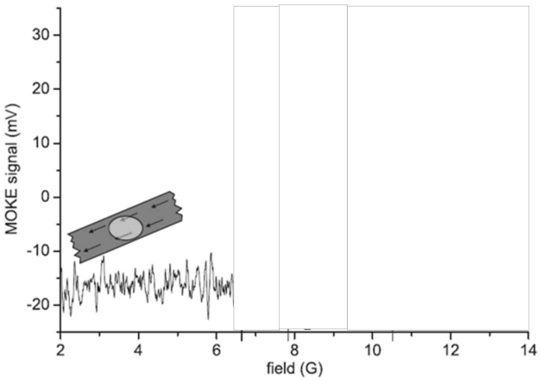
[1]K. Uchida et al., Nature **455**, 778 (2008); [2]M. Hatami et al., PRL **99**, 66603 ('07); [3]D. Hinzke et al., PRL **105**, 27205 (2011)

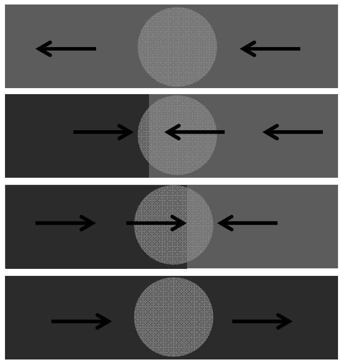
6. Effects of thermal spin currents on DW pinning

25 nm Py, Magneto-optical Kerr microscopy



J. Franken, MK et al., APL **95**, 212502 (2009); P. Möhrke, MK et al., SSC **150**, 489 (2010)

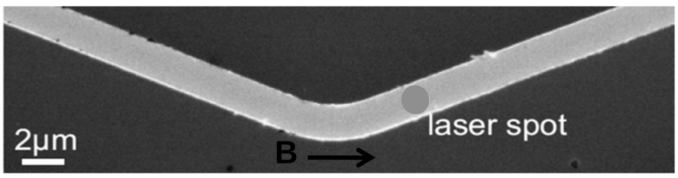




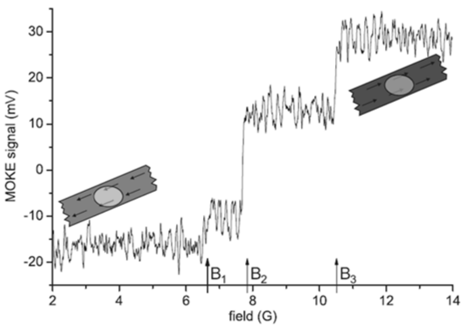
- Measure domain wall depinning fields in the laser spot. Influence of laser power?

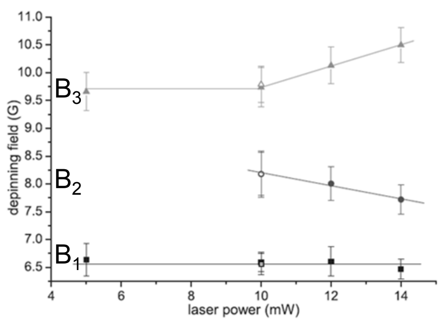
6. Effects of thermal spin currents on DW pinning

25 nm Py, Magneto-optical Kerr microscopy



J. Franken, MK et al., APL **95**, 212502 (2009); P. Möhrke, MK et al., SSC **150**, 489 (2010)





- Depending on direction of temperature gradient and domain wall motion the depinning field is increased or decreased → potential well deepens with increasing laser power!
- → not just thermally activated depinning → effect of spin currents!

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1. Great people in my groups:

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erc

Review on DWs: O. Boulle, MK et al., Current-induced domain wall motion
In Materials Science and Engineering Reports 72, 159 (2011)

Summary

1. **Geometrically – confined domain walls in new materials exhibit exciting physical properties**
   (geometry - dependent wall spin structures, fast field-induced wall motion >2000 m/s, inertia due to transfer of energy,…)
2. **Spin-polarized currents induce DW & vortex core motion, which yields the non-adiabatic torque (β)**
   (wall displacement >130m/s; spin structure transformations yield $\beta \neq \alpha$, vortex core displacement yields β=0.015, thermal domain wall hopping yields spin structure dependence of β,…)
3. **Efficient DW manipulation due to diffusive spin currents by spin injection and Spin Seebeck effect**
   (spin current generated by spin injection is absorbed by DW, efficiency for DW depinning 100X larger, temperature grad. generate spin currents, flexible domain wall pinning,…)

Review on DWs: O. Boulle, MK et al., Current-induced domain wall motion
In Materials Science and Engineering Reports 72, 159 (2011)