A flavor of Nanomagnetism and Spintronics (2)

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1. Magnetoresistance

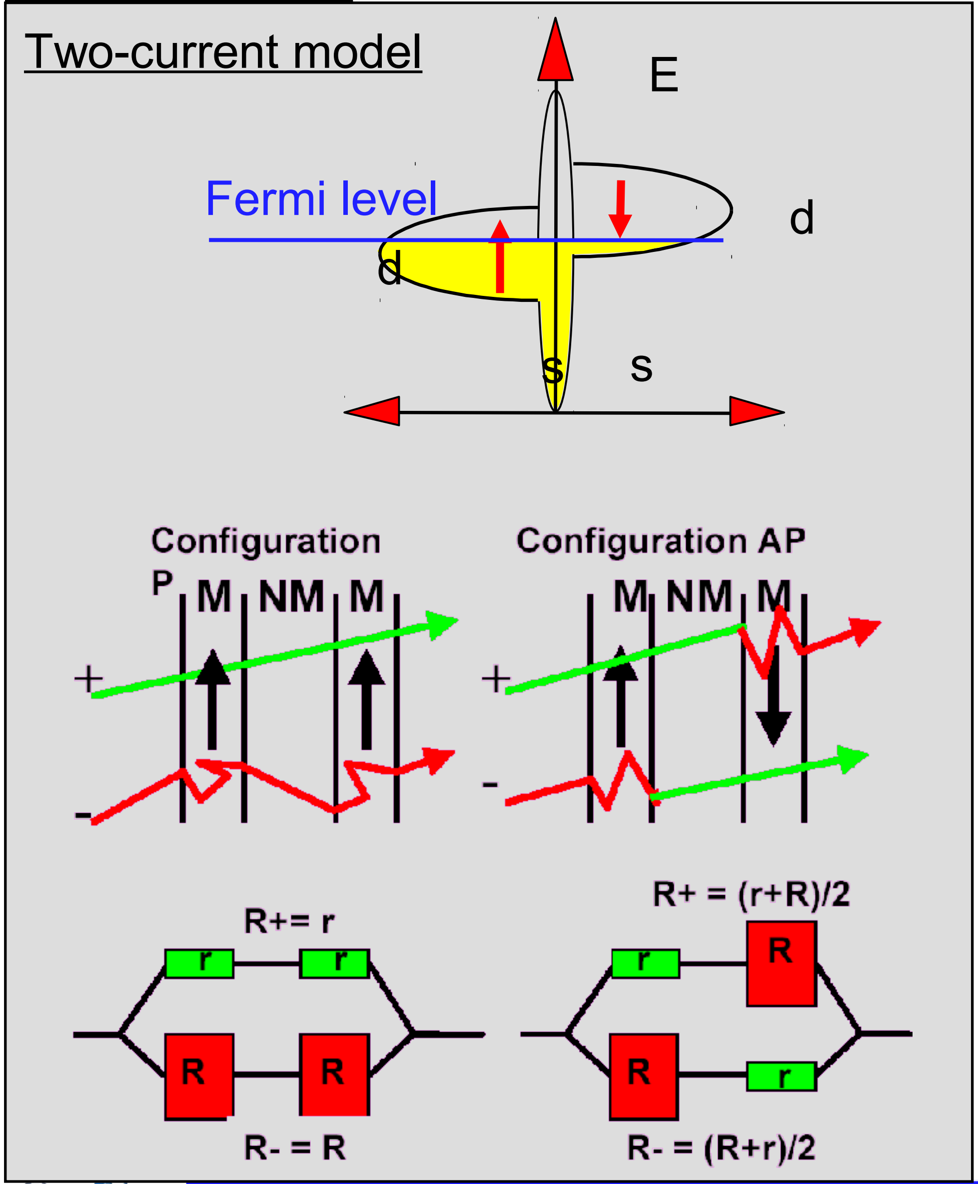
2. Spin transfer for magnetization switching

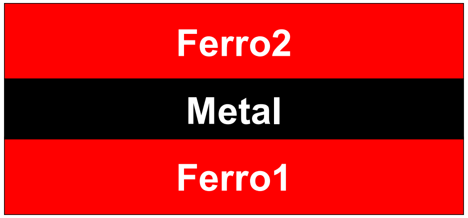
3. Spin transfer for domain wall motion

4. Other simuli : electric field, light, temperature etc.

Principle of GMR

Discovery: 1988, groups of A. Fert (CNRS-Thalès) and P. Grünberg (Jülich)





Features

$$\Delta R \propto \cos(\theta)$$

Geometry: multilayers

Magnitude: ≤ 40-50%

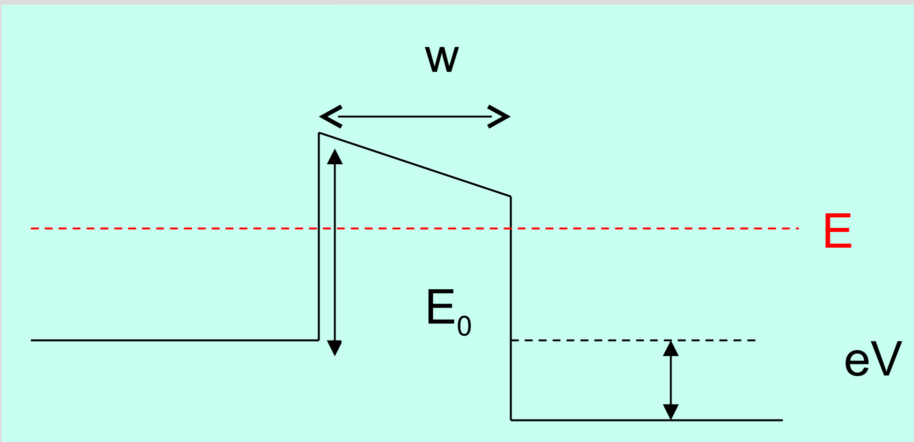
Applications

- Magnetic sensors: compass, read heads
- Magnetic memory direct reading

Principle of TMR

Discovery: 1975 (Jullière); 'rehabilitated' 1995, Moodera et coll.

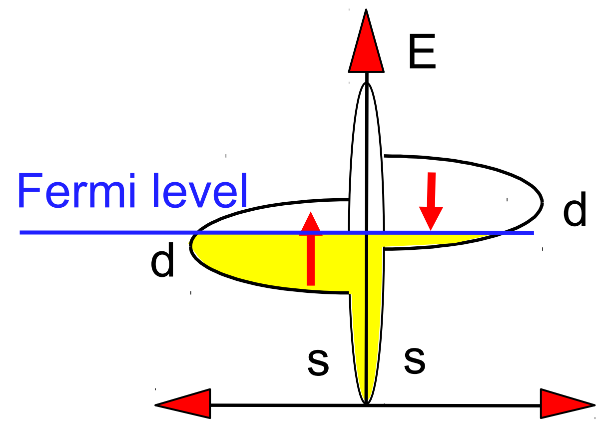
- Electron tunnelling between electrodes



- Classical machanics: no current
- Quantum mechanics: tunneling current

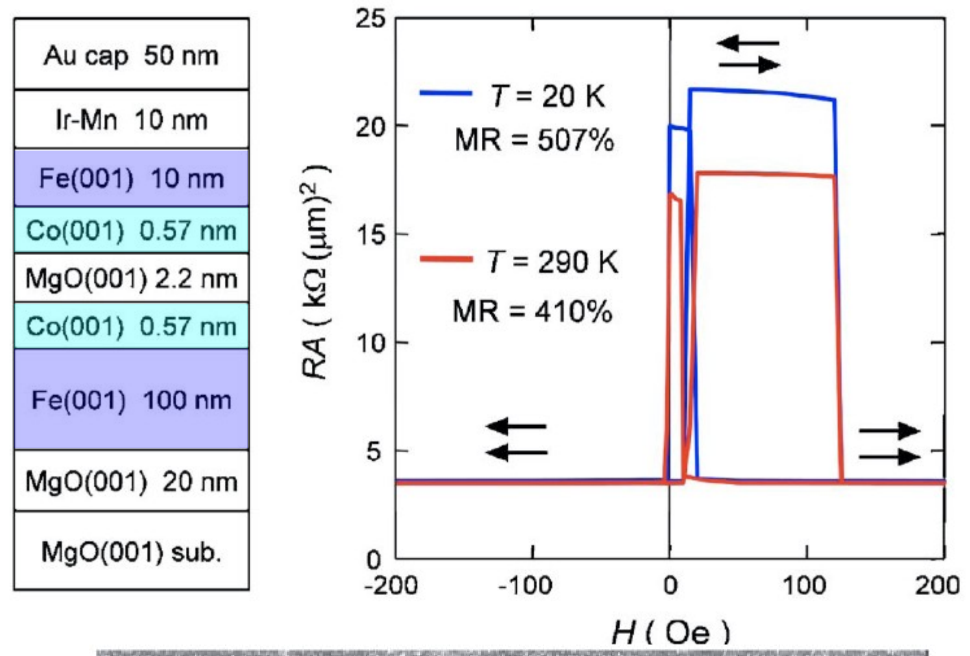
Schrödinger's equation:

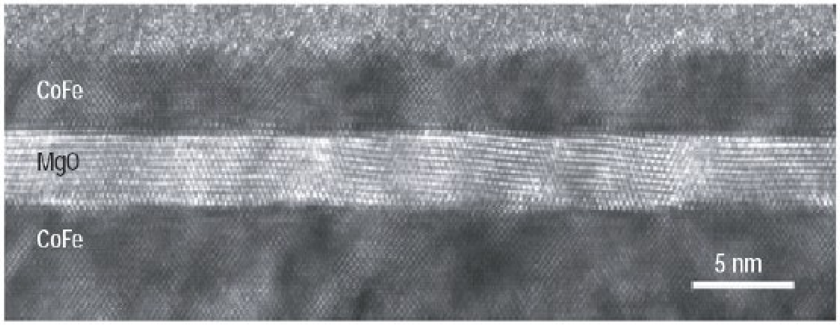
$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\left|\psi\right\rangle + V(x)\left|\psi\right\rangle = E\left|\psi\right\rangle$$



Beyond Jullière's model

Spin filtering in textured Mg(001)





S. Yuasa et al., Appl. Phys. Lett. 89, 042506 (2006)

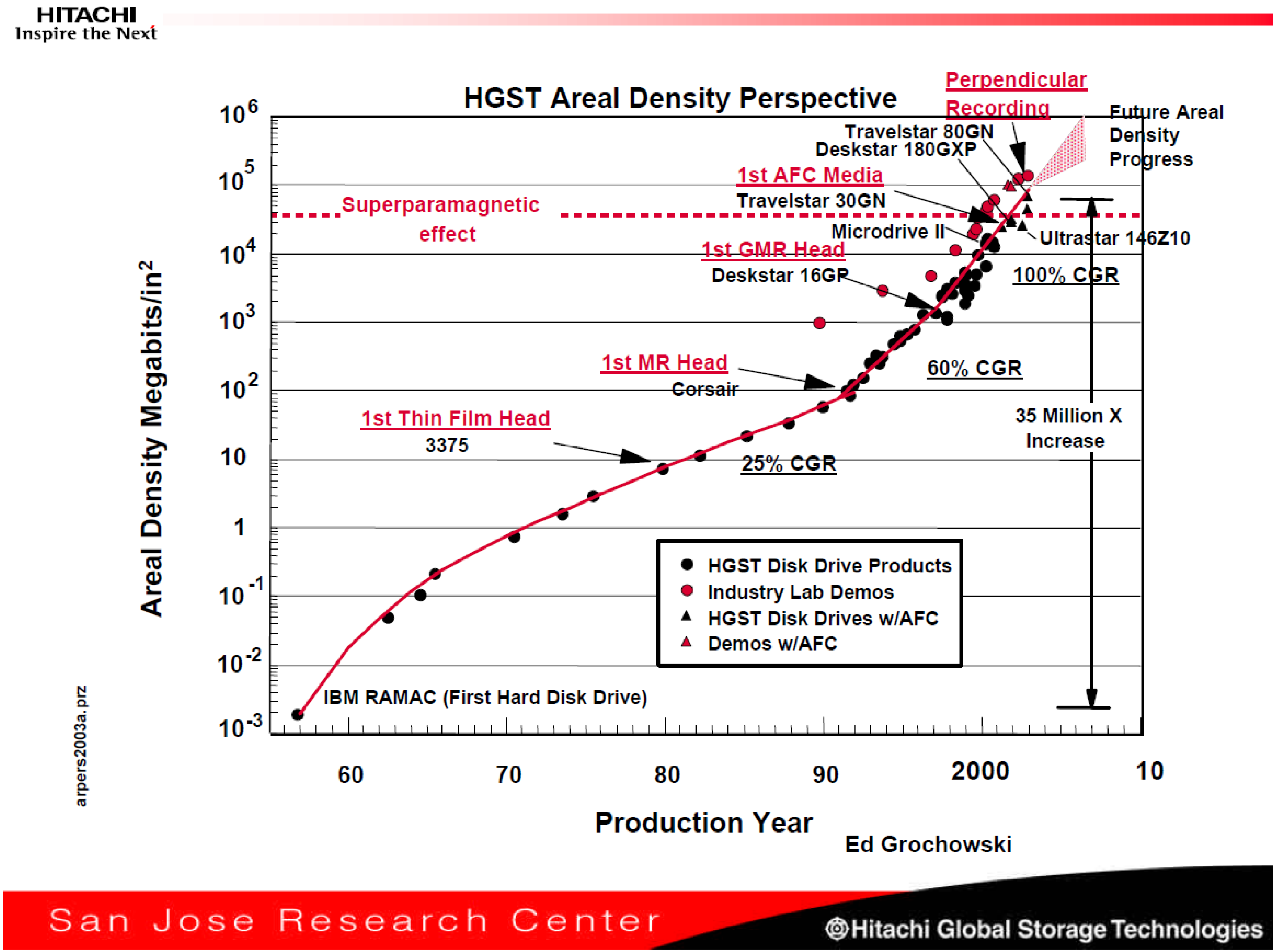
Features

$$\Delta R \propto \cos(\theta)$$

Geometry: multilayers
Magnitude: up to 400% at RT
High resistance
Ultrathin oxyde layer

Applications

- Direct reading of memory cells
- Magnetic field sensors
- Reprogrammable magnetic logic


HITACHI
Inspire the Next
HGST Areal Density Perspective
Areal Density Megabits/in²
Production Year
Perpendicular Recording
Future Areal Density Progress
Travelstar 80GN
Deskstar 180GXP
1st AFC Media
Travelstar 30GN
Superparamagnetic effect
Microdrive II
Ultrastar 146Z10
1st GMR Head
Deskstar 16GP
100% CGR
60% CGR
1st MR Head
Corsair
35 Million X Increase
1st Thin Film Head
3375
25% CGR
HGST Disk Drive Products
Industry Lab Demos
HGST Disk Drives w/AFC
Demos w/AFC
IBM RAMAC (First Hard Disk Drive)
arpers2003a.prz
Ed Grochowski
San Jose Research Center
Hitachi Global Storage Technologies

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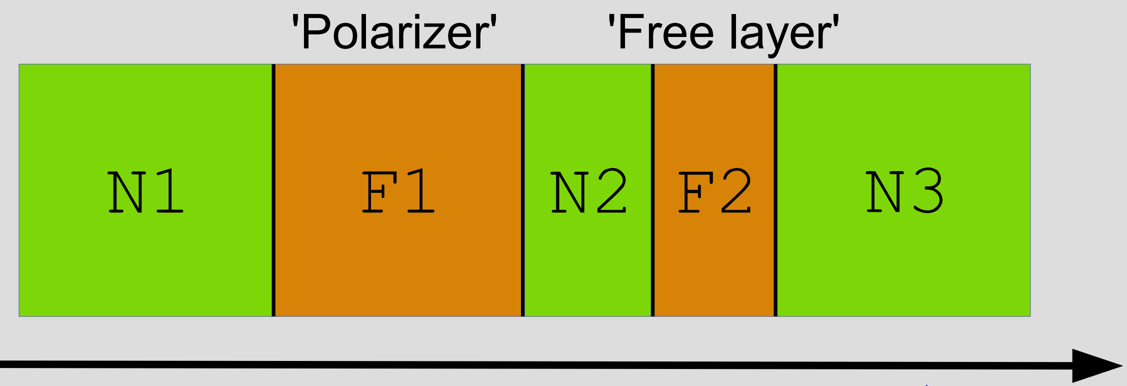
Spin transfer effect

Can be viewed as
the GMR-reversed effect

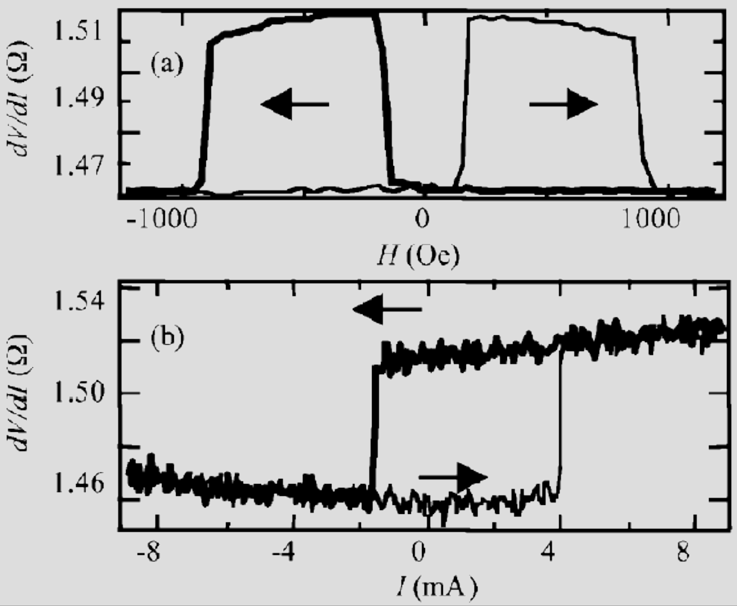
J. C. Slonczewski (1996)
L. Berger (1996)



Electron flow – Carrying magnetic moment $\mathbf{u}=(P g \mu_B / 2 e M_S)\,\mathbf{j}$

Example

Myers & Ralph, Cornell (2000)



Field switching

Current switching

Motivations

- Simplified architectures for writting bits (MRAMs etc.)
- Fully electronic read/write
- Devices with domain wall motion (memory, logic)
- Devices for GHz oscillators

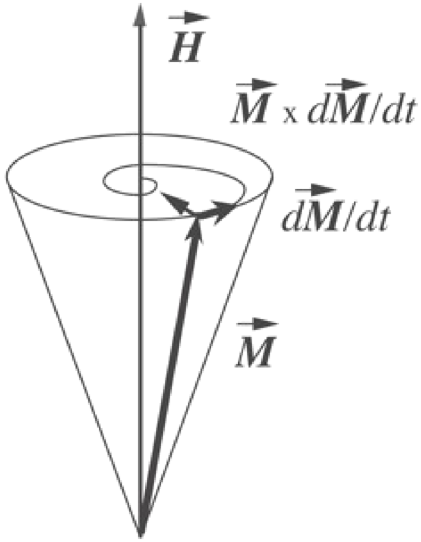
Physics : torques and precession

$$\dot{m} = \gamma_0 \left(\mathbf{H} + \boxed{b\, I\, \mathbf{m}_\mathbf{p}} \right) \times \mathbf{m} + \alpha\, \mathbf{m} \times \dot{\mathbf{m}} - \boxed{\gamma\, a\, I\, \mathbf{m} \times [\mathbf{m} \times \mathbf{m}_\mathbf{p}]}$$

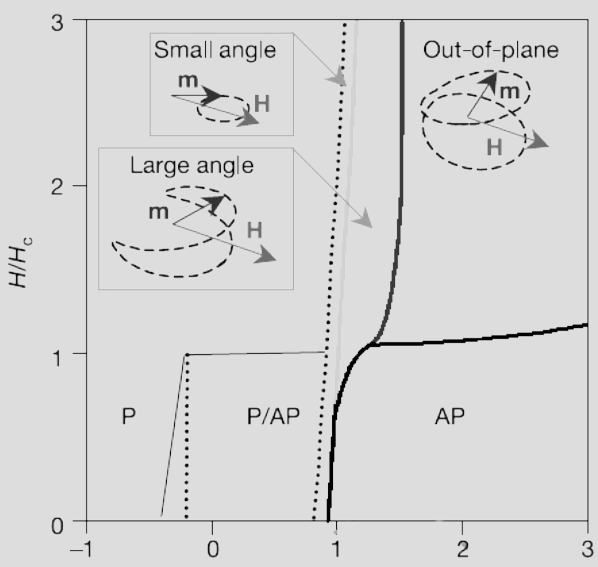
Field-like
(preserves energy)

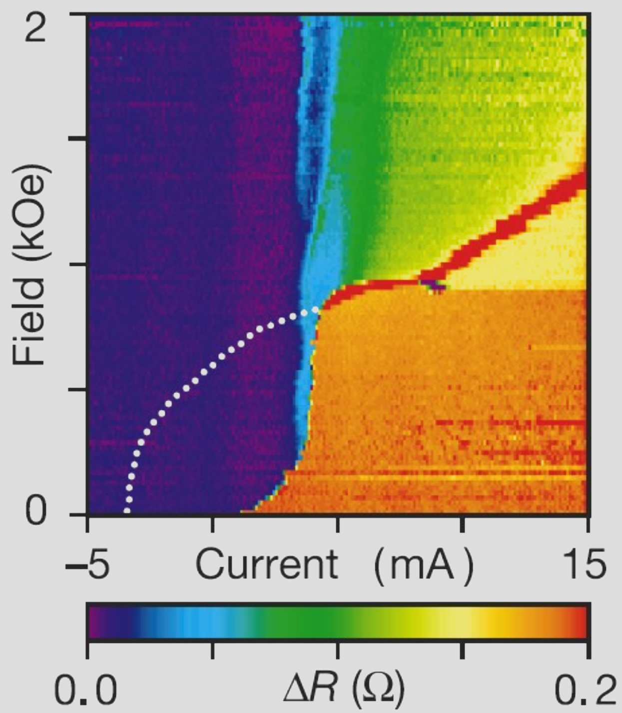
Spin-transfer
(brings or removes energy)

a and b depend on $\mathbf{u} = (P g \mu_B / 2 e M_S)\, \mathbf{j}$



Switching and oscillators





S. I. Kiselev, Nature 425, 380 (2003)

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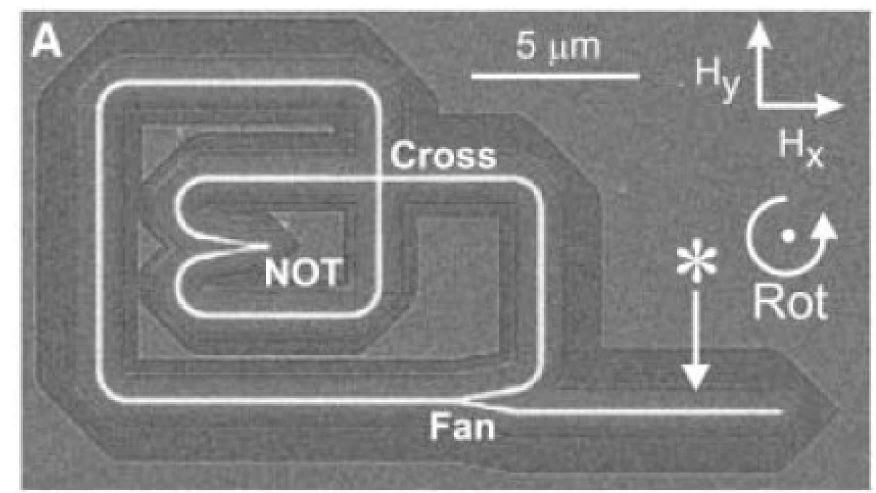
Magnetic logic with domain walls (Field driven)

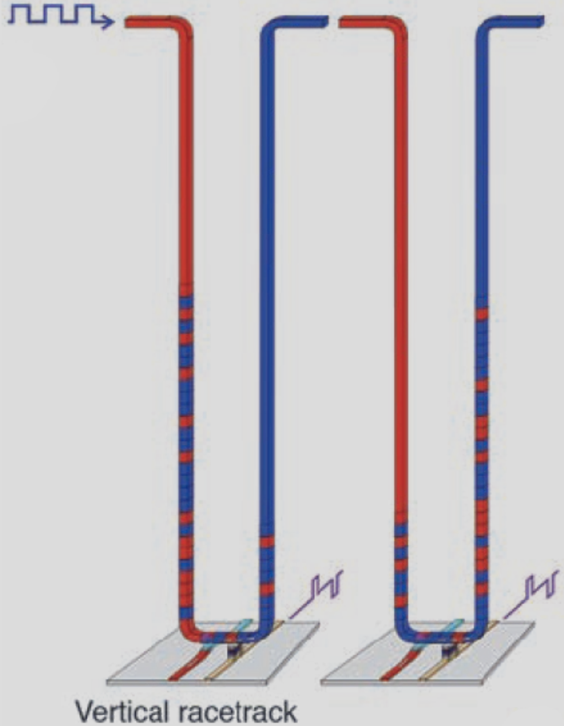


D. A. Allwood et al., Science 309, 1688 (2005)

Limitation:

Requires homogeneous rotating field

Magnetic memories with domain walls (Current driven)



S. S. P. Parkin, IBM-Almaden
U.S. patents 6834005, 6898132, 6920062

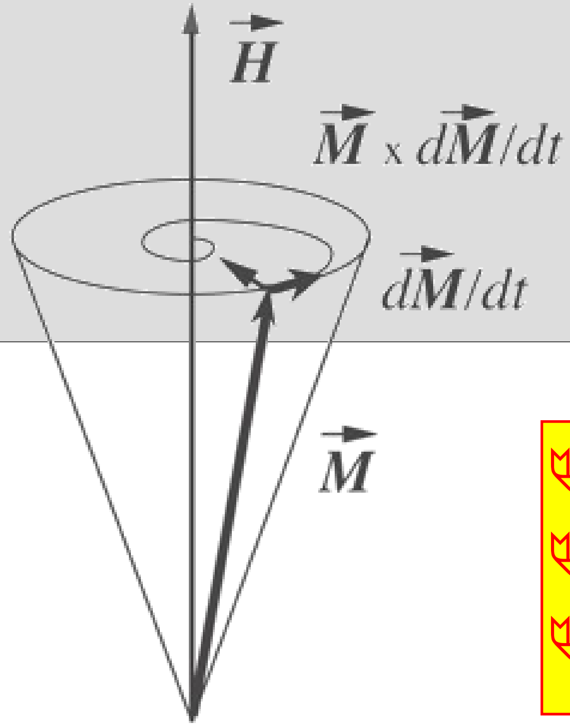
- Makes use of spin transfer effect
- Potentially 3D storage, however technologically challenging

Modified Landau-Lifshitz equation

Landau Lifshitz Gilbert equation + two "spin transfer torque" terms

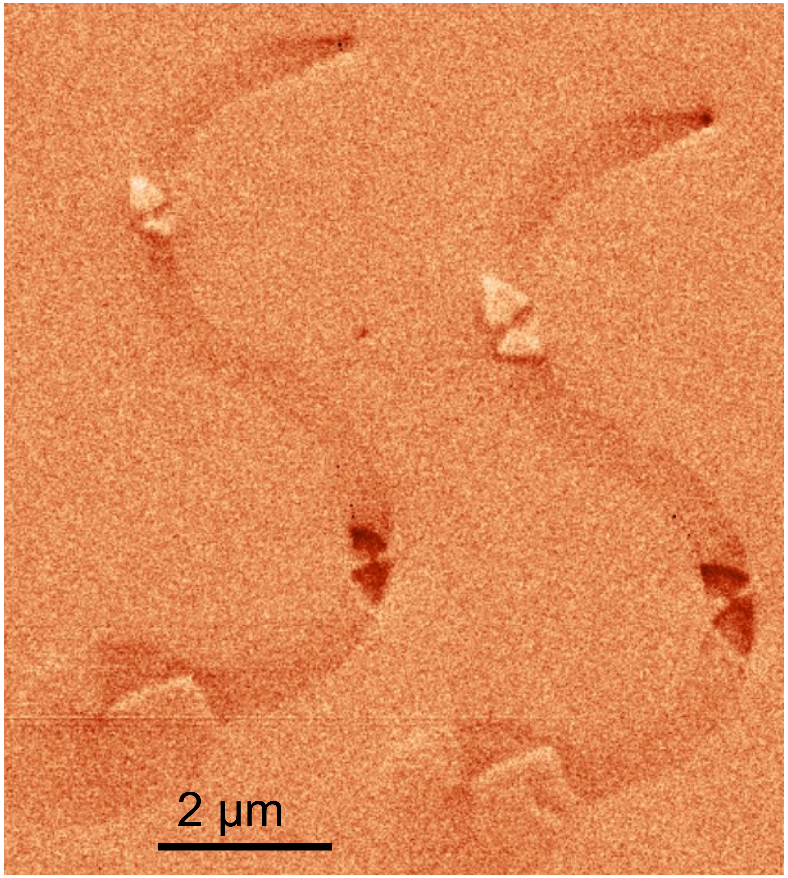
$$\dot{m} = \underbrace{\gamma_o \mathbf{H}\times\mathbf{m}}_{\text{precession}} + \underbrace{\alpha\,\mathbf{m}\times\dot{\mathbf{m}}}_{\text{damping}} - \underbrace{(\mathbf{u}.\nabla)\mathbf{m}}_{\text{adiabatic}} + \underbrace{\beta\,\mathbf{m}\times[(\mathbf{u}.\nabla)\mathbf{m}]}_{\text{non-adiabatic}}$$

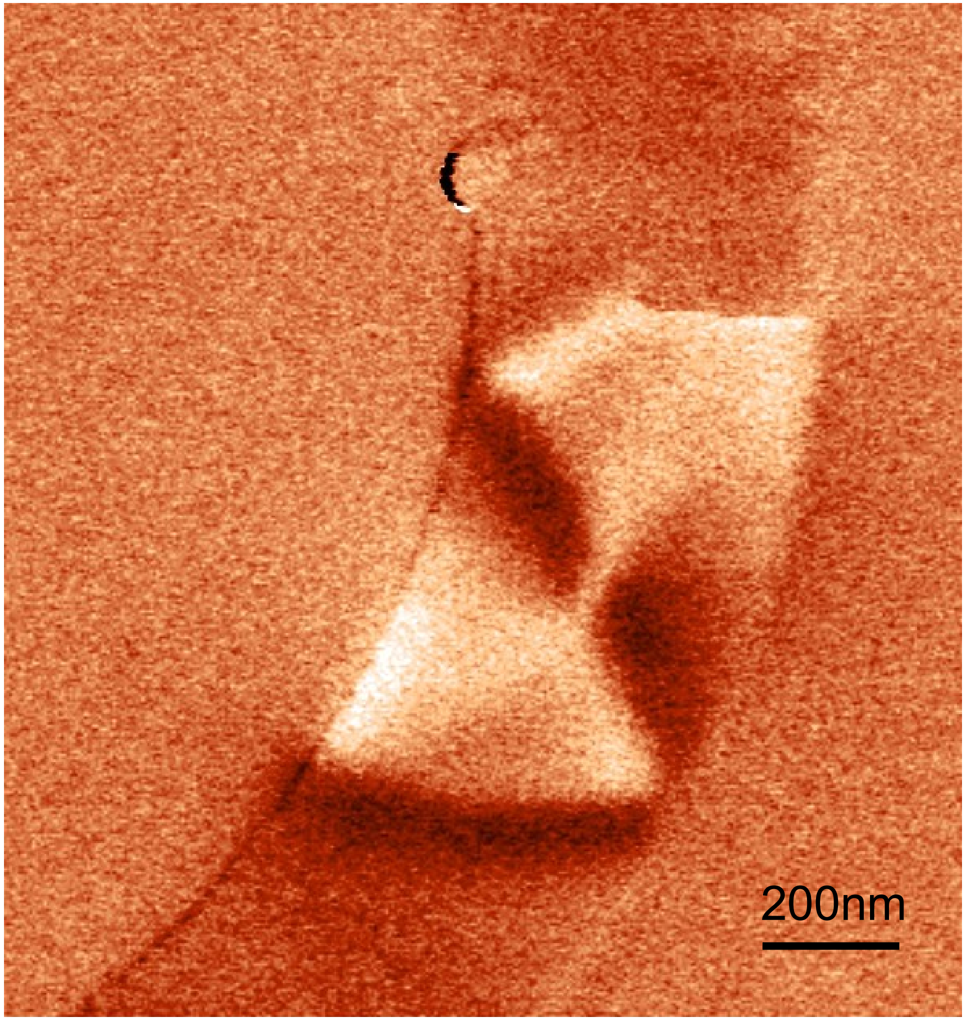
Flow of magnetic moment: $\mathbf{u} = (P g \mu_B / 2 e M_S)\,\mathbf{j}$



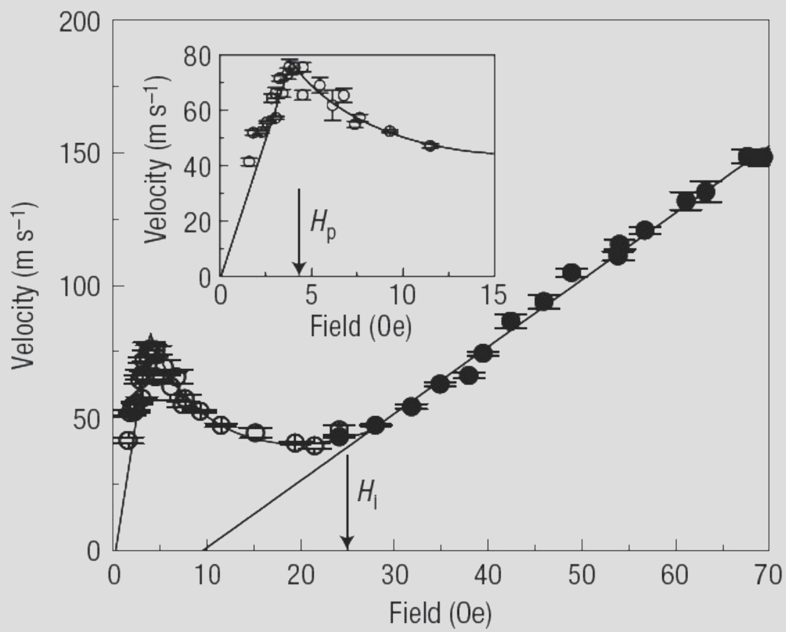
Zhang and Li, PRL 93, 127204 (2004)
Thiaville et al., EPL 69, 990 (2005)
Tatara et al., JPSJ 75, 064708 (2006)

- Fundamental physics: origin and magnitude of β unclear
- Experimental determination of β necessary
- Stripes and wires are different


2 µm

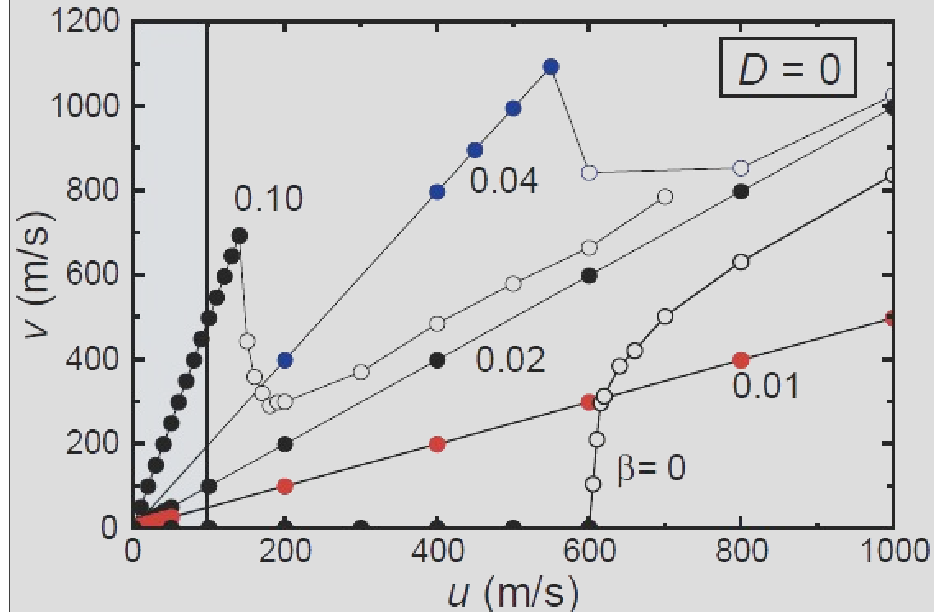

200nm

Propagation in field



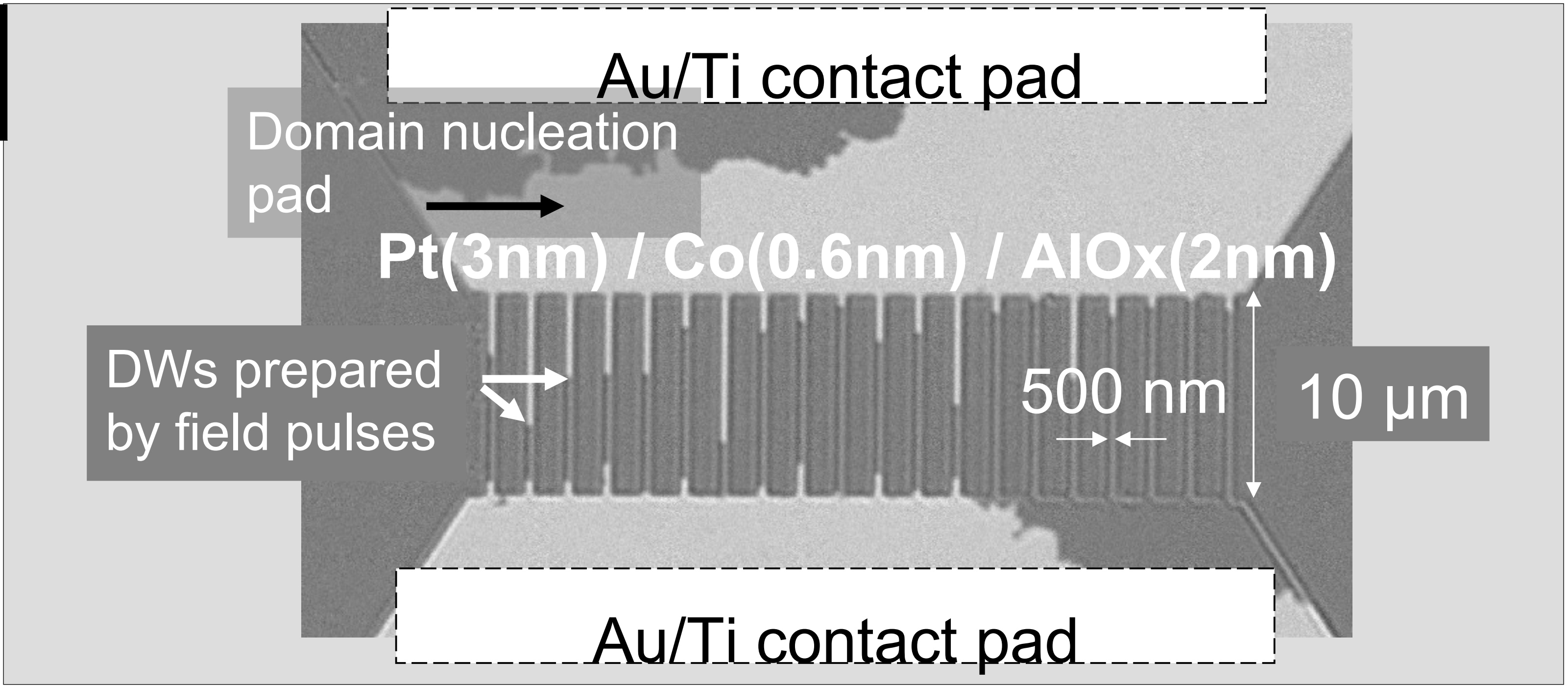
G. S. D. Beach et al., Nature. Mater. 4, 741 (2005)

Propagation in current

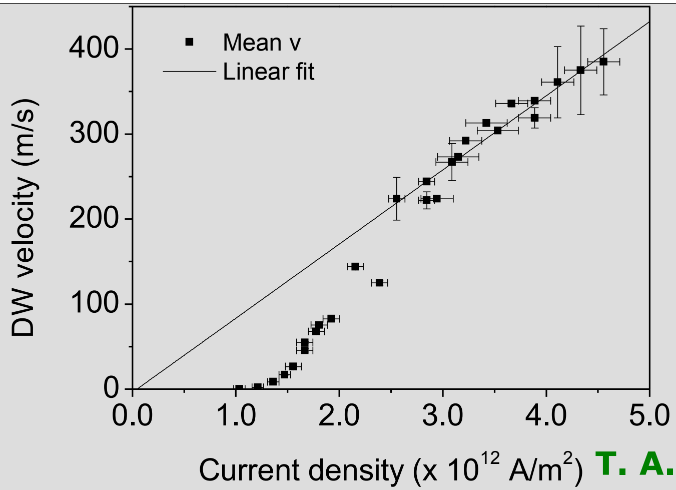


A. Thiaville et al., Europhys. Lett. 69, 990 (2005)

Measuring device



Results



- First, non-linear regime (DW creep)
- Second, linear regime (flow)
- High DW mobility
- Rashba-like effect for high β ?

T. A. Moore et al., Appl. Phys. Lett. 93, 262504 (2008)
M. Miron, Nature. Phys. 9, 230 (2010)

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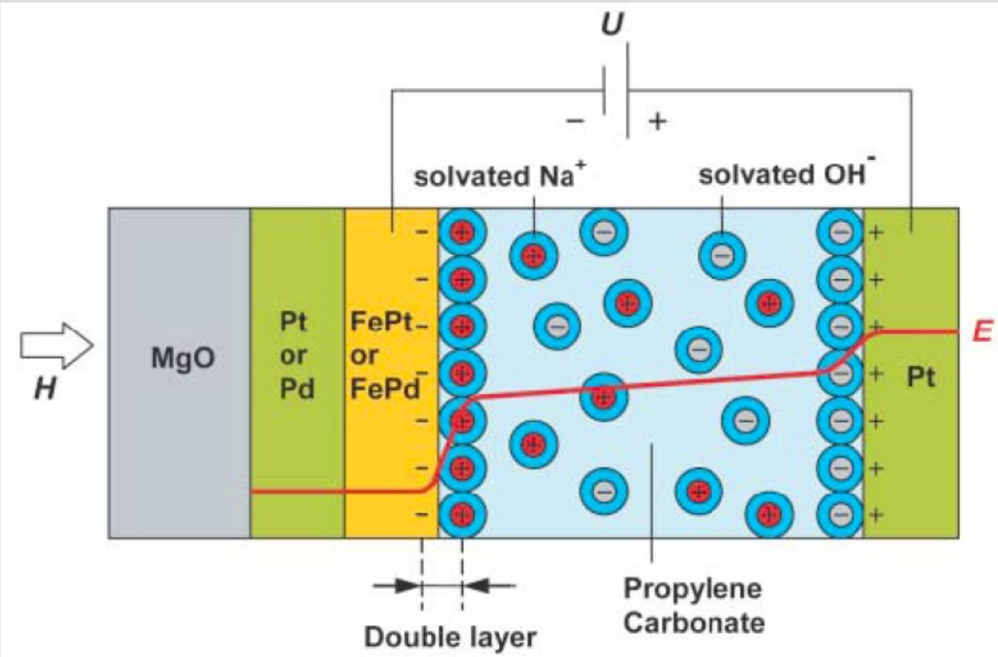
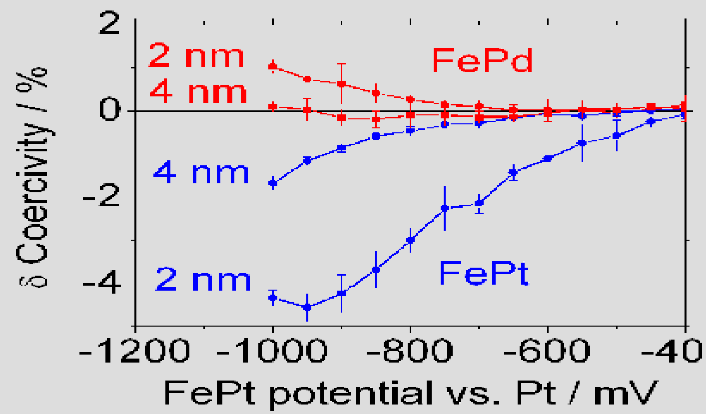
Electric modification of intrinsic properties





M. Weisheit et al., Science 315, 349 (2007)

See also: magnetic semiconductors, multiferroics etc.

See follow-up : reversal with electric field :

T. Nozaki et al., Appl. Phys. Lett. 96022506, (2010).

M. Weiler et al., New J. Phys. 11, 013021 (2009)

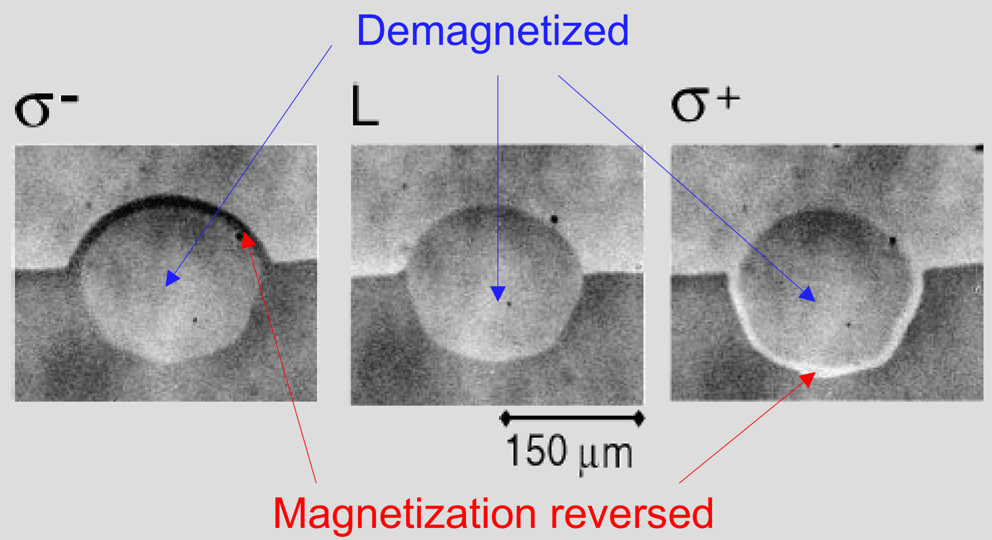
Principle

Combined heating
+ inverse Faraday effect

Magneto-optical material. Tc=500K
Gd22Fe74.6Co3.4

Ti:S laser:
λ=800nm; $\Delta\tau$=40fs.

Preliminary: one shot with large power

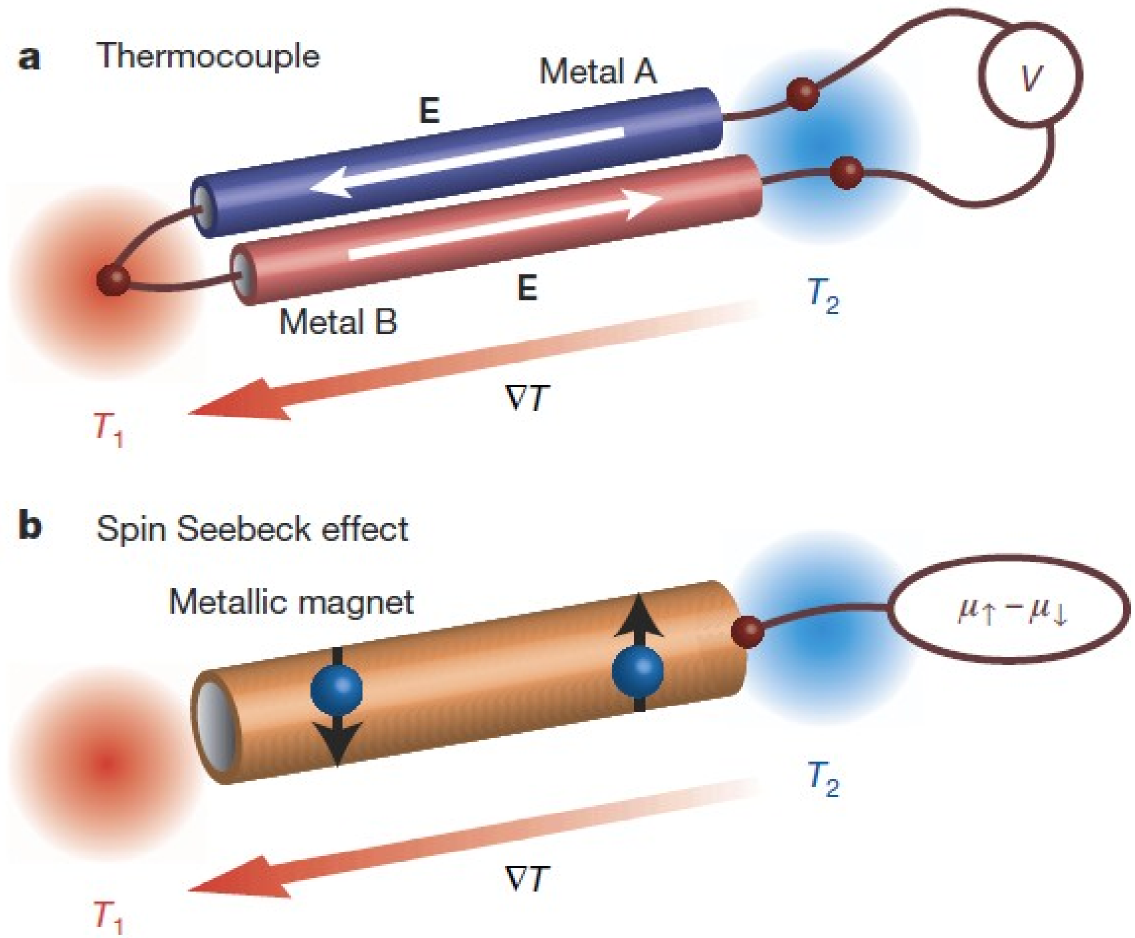


Local reversal with controlled power

C. D. Stanciu et al.,
Phys. Rev. Lett. 99, 047601 (2007)

Similar to thermoelectricity, however with spin-dependant chemical potential

- Spin Seebeck coefficient
- Generation of pure spin currents



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


Thank you and bye-bye !