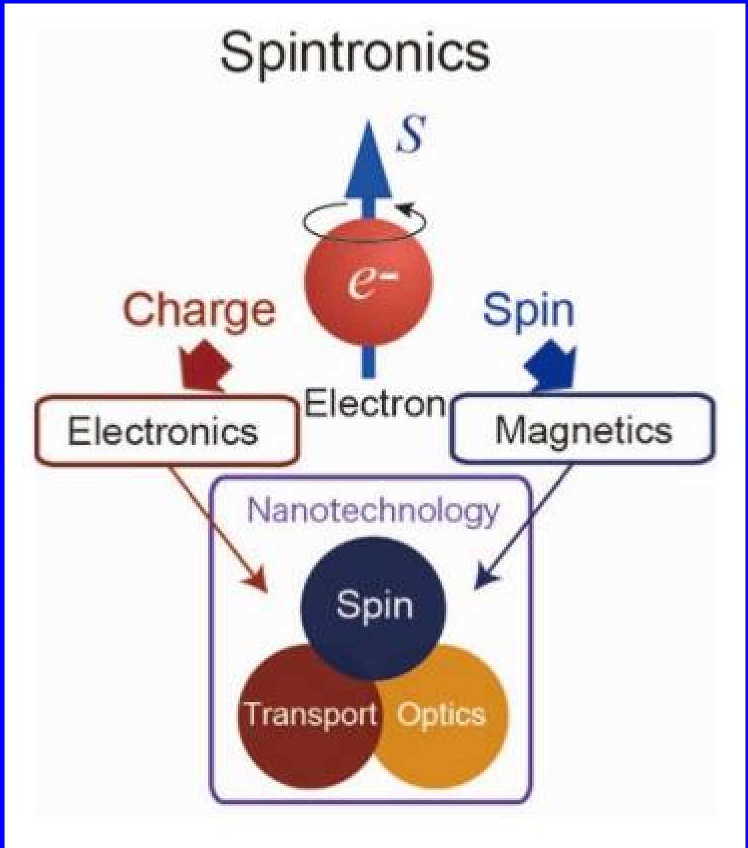
Spintronics = Spin Electronics

P. Němec

Charles University, Prague, Czech Republic

Wikipedia:

"Spintronics is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices."



http://www.rpip.tohoku.ac.jp

Outline

- Introduction to spintronics
- Spintronic applications:
  - existing
  - developed
  - envisioned
- Antiferromagnetic spintronic

Charles University, Prague, Czech Republic (**P. Němec**,V. Saidl, T. Janda, L. Horák …)

Academy of Sciences CR, Prague, Czech Republic (**T. Jungwirth**, V. Novák, K.Olejník, …)

University of Nottingham, United Kingdom (**P. Wadley**, K. Edmonds, R. Campion, …)

Hitachi Cambridge Laboratory, United Kingdom (**J. Wunderlich**, P. Roy, …)

Electronics

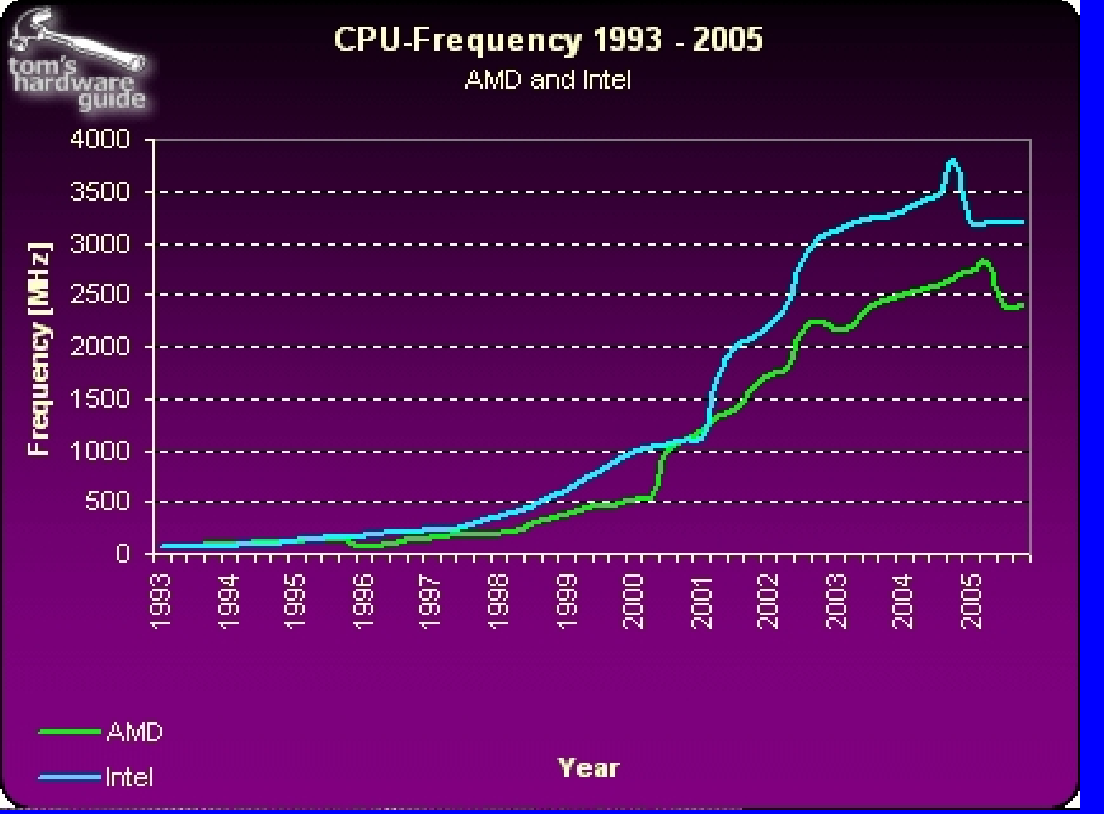
• **CPU** (central processing unit) **speed** = instructions per second

- determined by a) **clock rate**

b) **instructions per clock**

a) clock rate

• does not increase since 2005 <= **heat dissipation**

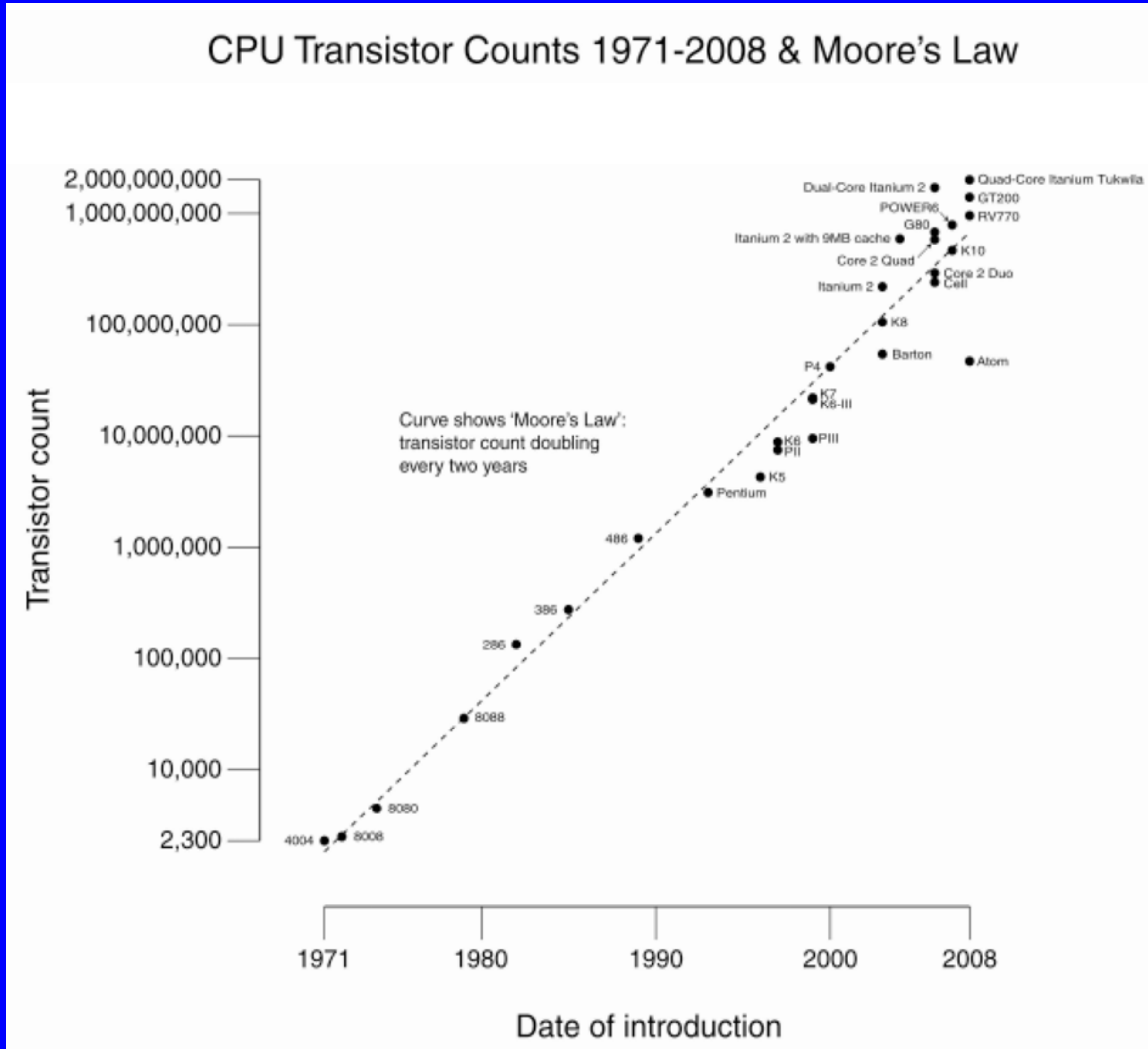


b) instructions per clock

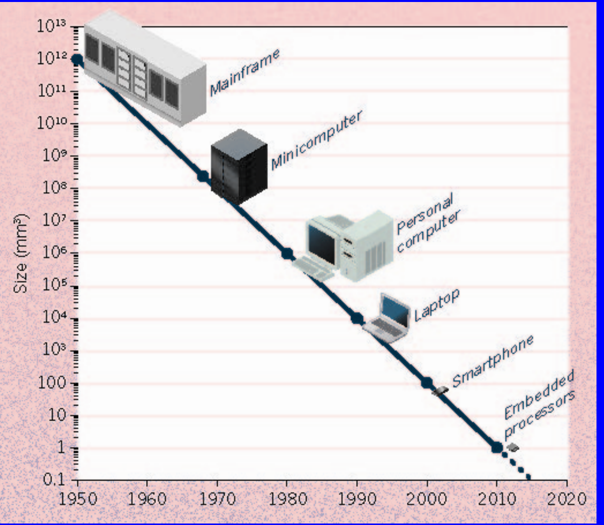
- scales as a square root of number of transistors on a chip=> **miniaturization of transistors**

- described by **Moore's Law**:

  "Number of transistors per chip is doubling every two years."



- **Moore's Law: self-fulfilling prophecy**
  - new chips followed the law because the industry made sure that they did



- February 2016: M.M. Waldrop: "*More than Moore*", Nature **530**, 144–147.

THE SEMICONDUCTOR INDUSTRY WILL SOON ABANDON ITS PURSUIT OF MOORE'S LAW.

NOW THINGS COULD GET A LOT MORE INTERESTING.

Next month, the worldwide semiconductor industry will formally acknowledge what has become increasingly obvious to everyone involved: Moore's law, the principle that has powered the information-technology revolution since the 1960s, is nearing its end.

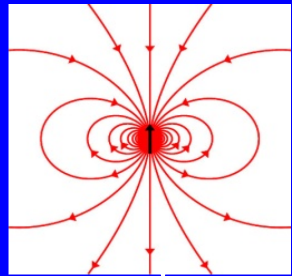
A different approach, which does stay in the digital realm, is the quest to find a 'millivolt switch': a material that could be used for devices at least as fast as their silicon counterparts, but that would generate much less heat. There are many candidates, ranging from 2D graphene-like compounds to spintronic materials that would compute by flipping electron spins rather than by moving electrons. "There is an enormous research space to be explored once you step outside the confines of the established technology," says Thomas Theis, a physicist who directs the nanoelectronics initiative at the Semiconductor Research Corporation (SRC), a research-funding consortium in Durham, North Carolina.

Spin

spin = ***intrinsic angular momentum*** which has associated **magnetic moment**

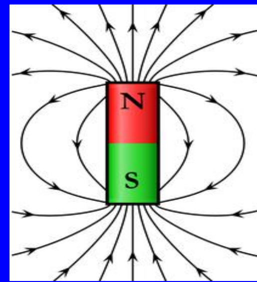
- it has **magnitude**: for electron $\frac{1}{2}\hbar$

direction: depicted by an arrow



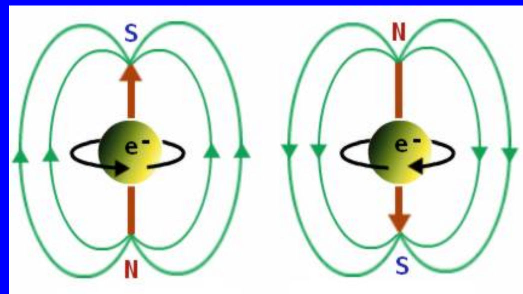
spin

⇔

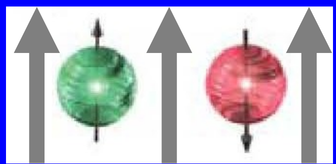


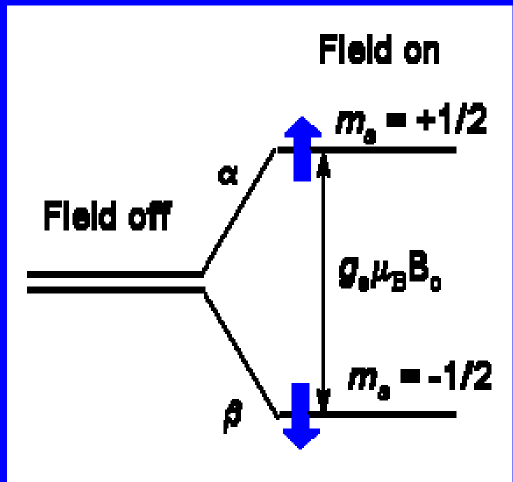
bar magnet

- frequently depicted as a spinning ball



- in external **magnetic field** $\boldsymbol{B_0}$ electrons with opposite spins have **different energy**



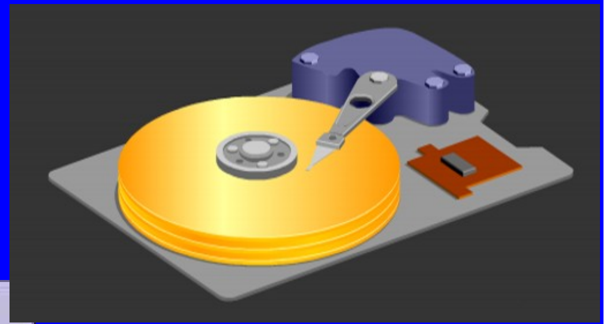


μ_B … Bohr magneton $\mu_B \equiv \frac{e\hbar}{2m}$

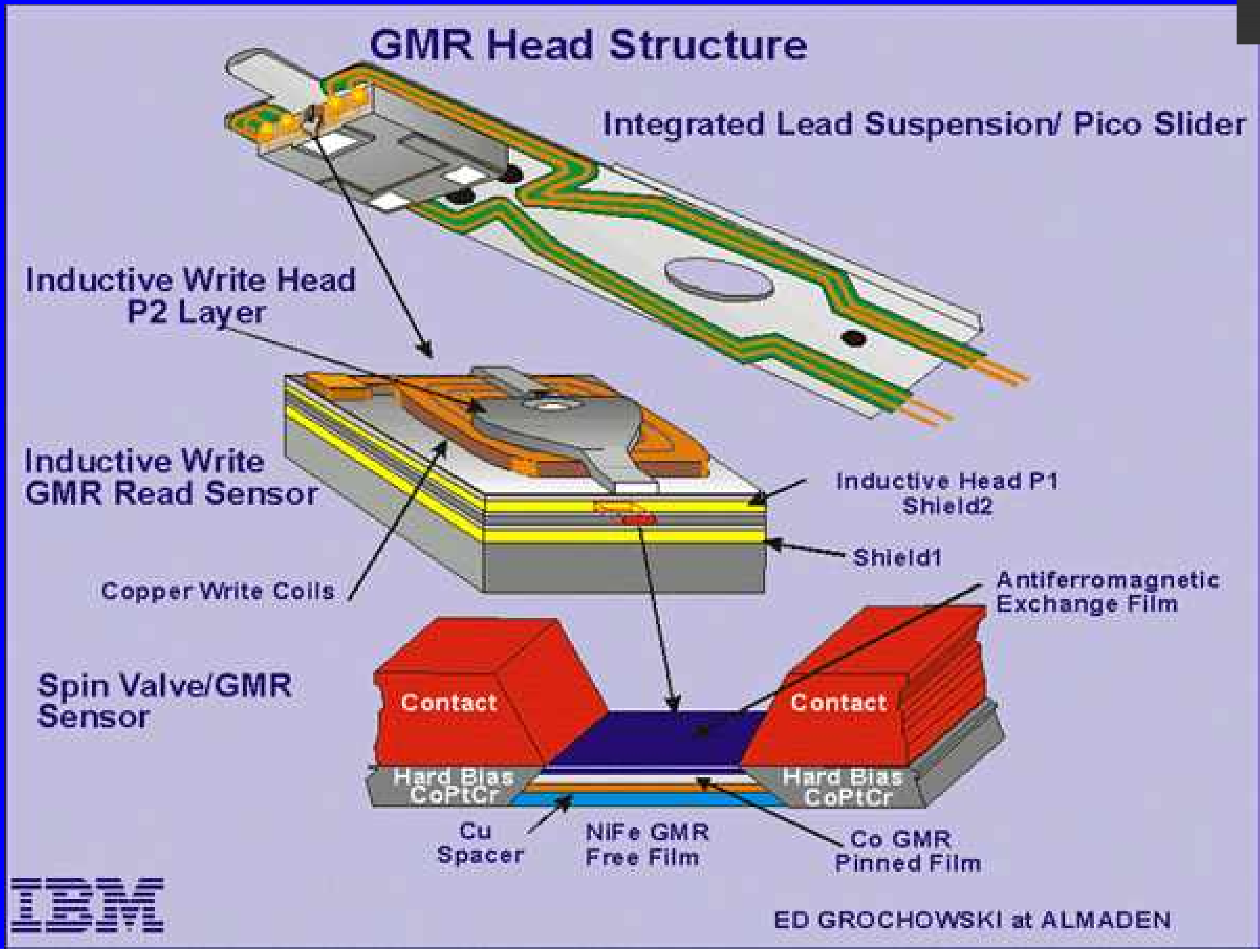
g_e … g-factor of electron

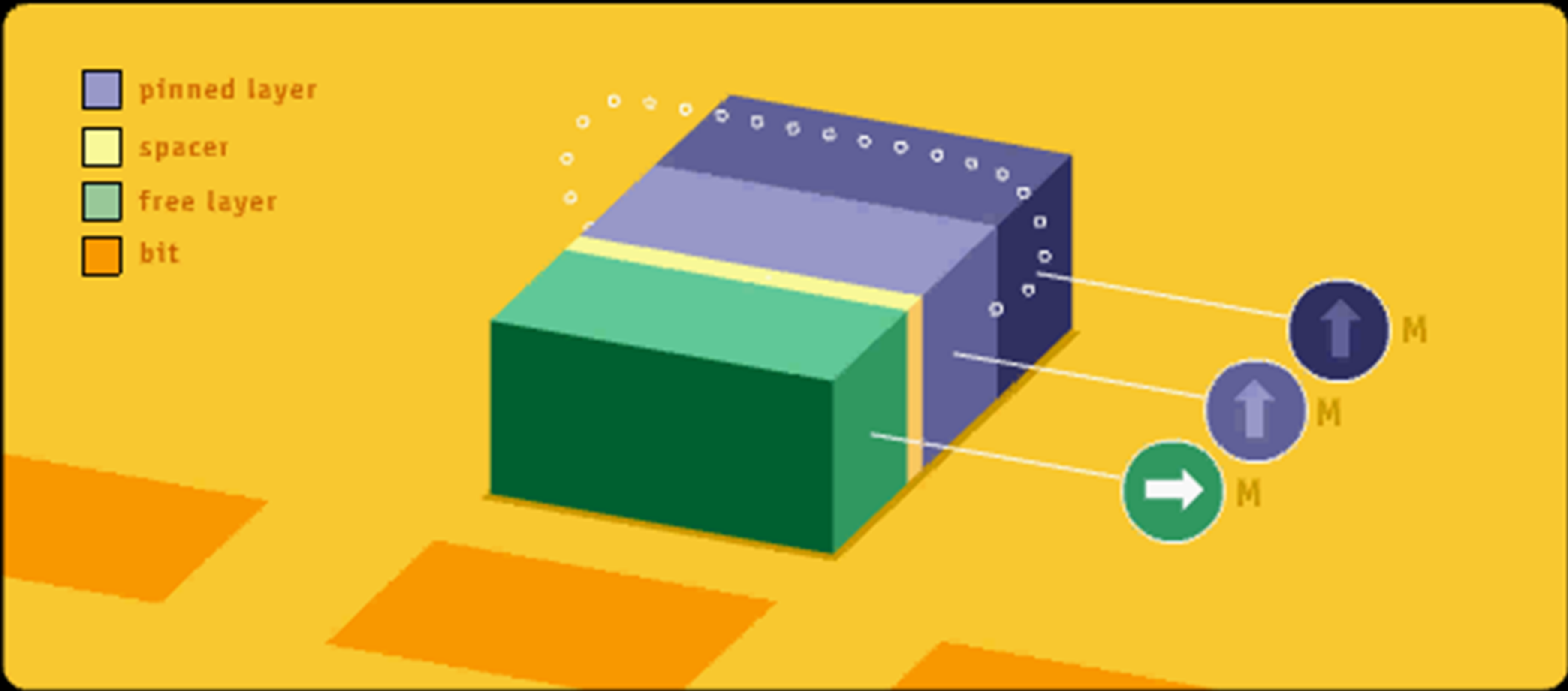
Spintronic applications: Commercially available

HDD read heads

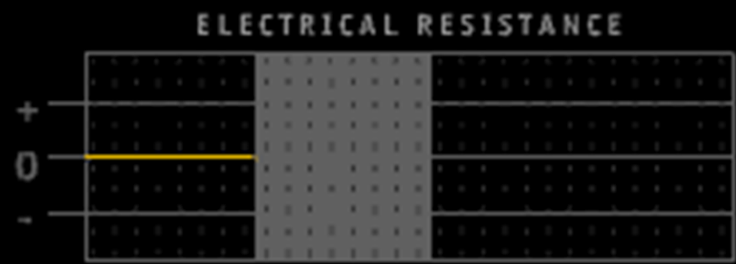


- introduced by IBM in 1997
  => data storage density increase by 100 % annually





GMR READ SENSOR / SPIN VALVE 1 2 3 4 5 6



The GMR sensor structure resembles the MR sensor, but as you can see by the movement of the arrow on the free layer, and the electrical resistance read-out, the signal is much stronger in the GMR sensor. [NEXT]

HDD read heads (1997)

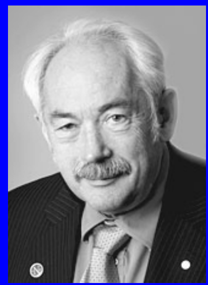
- based on **Giant Magnetoresistence** (GMR)
  - Nobel Prize in Physics in 2007

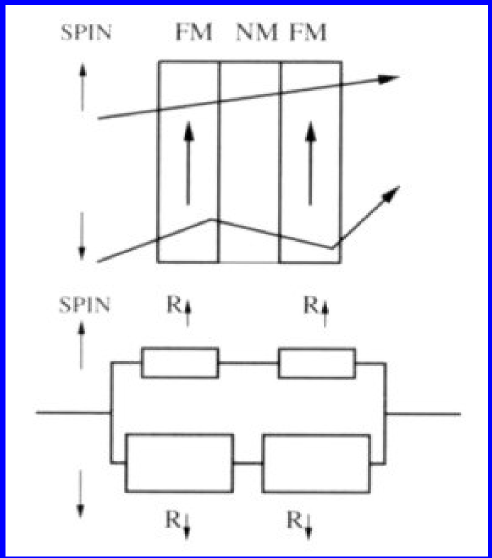
Albert Fert (France)

Phys. Rev. Lett. ***61****, 2472 (1988).*

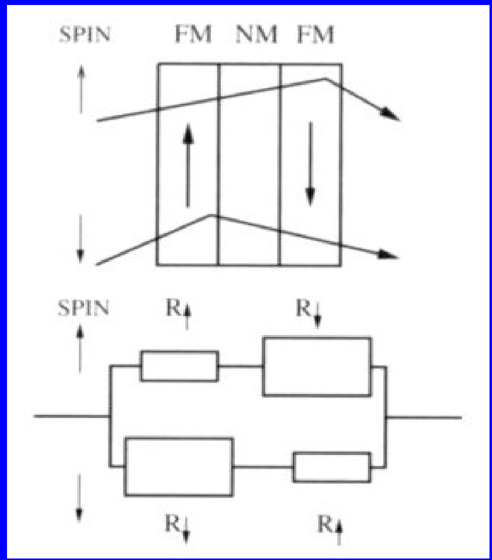
Peter Grünberg (Germany)

Phys. Rev. B ***39****, 4828 (1989).*





small resistance

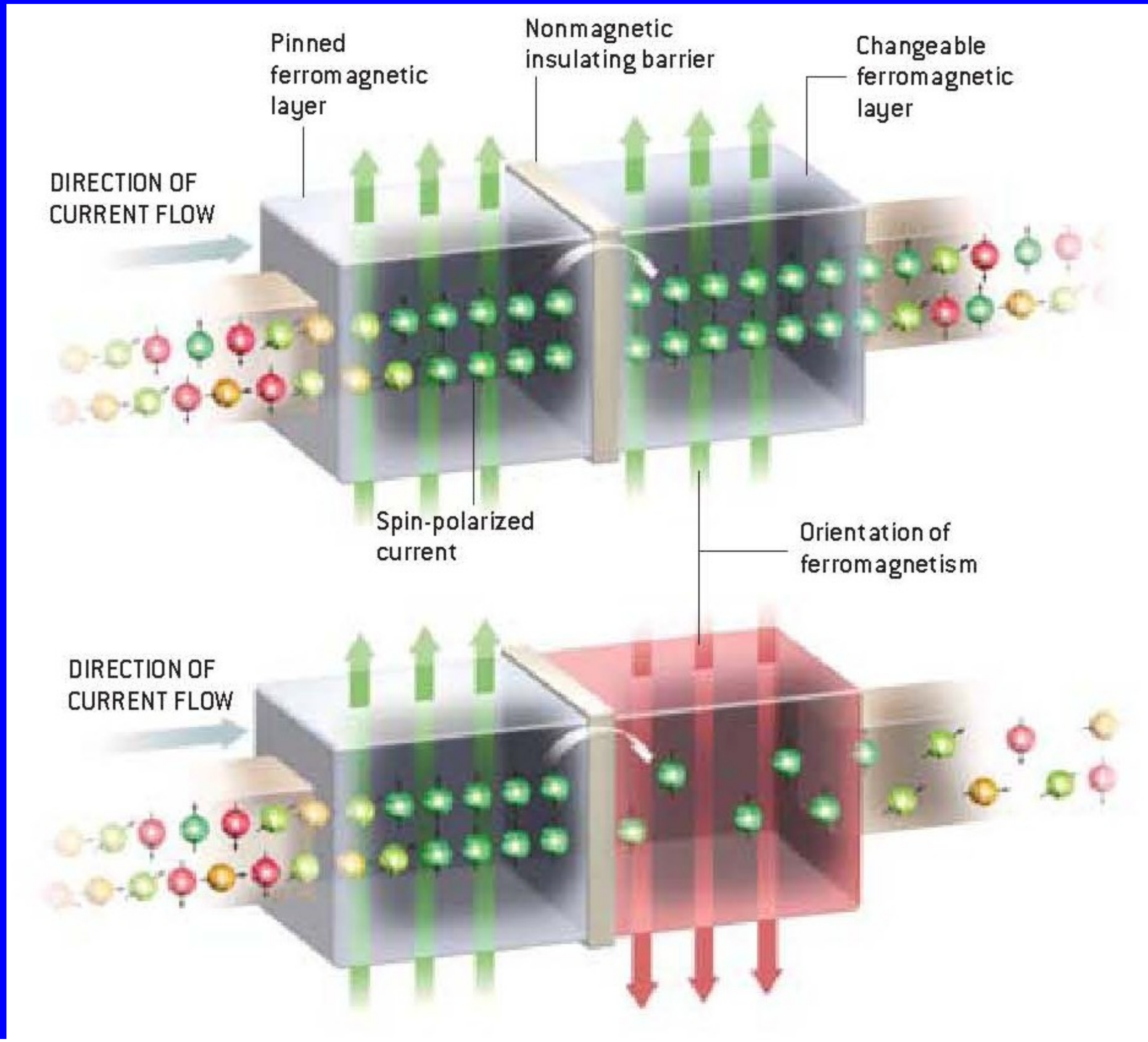


large resistance

Spintronic applications: Commercially available

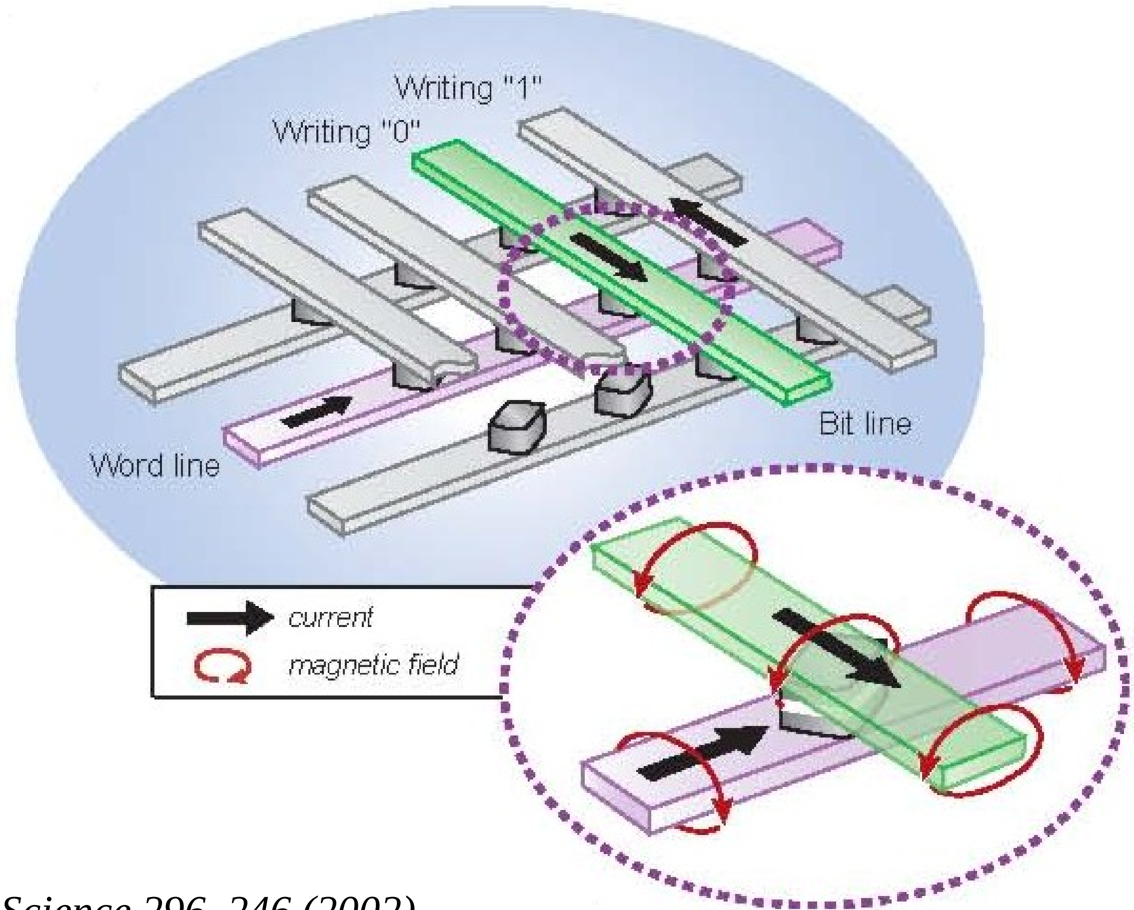
Magnetic random-access memory (MRAM)

- magnetic tunnel junction: **fast and nonvolatile**
- <u>data readout</u>: tunneling anisotropic magnetoresistance

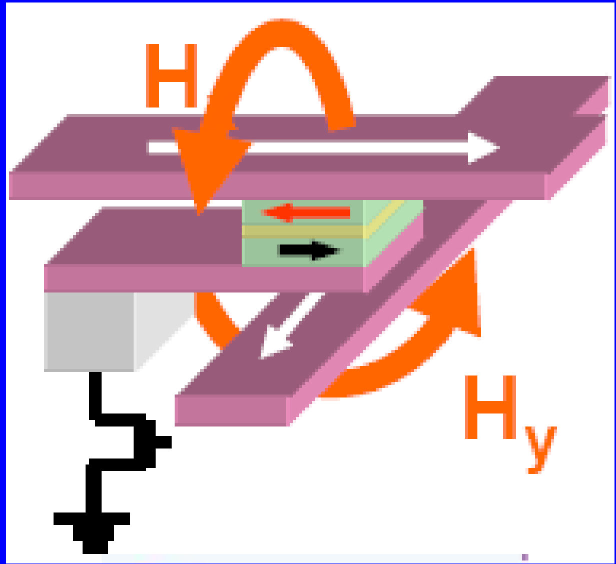


Magnetic random-access memory (MRAM)

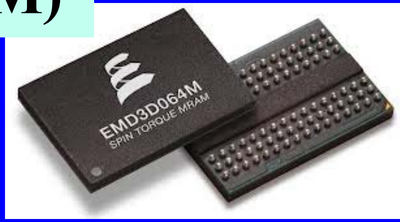
- data readout: tunneling anisotropic magnetoresistance
- data writing: ***first* generation: magnetic field**
  - March 2007: Freescale Semiconductor, **4 MB** chip MR2A16A



Science 296, 246 (2002).



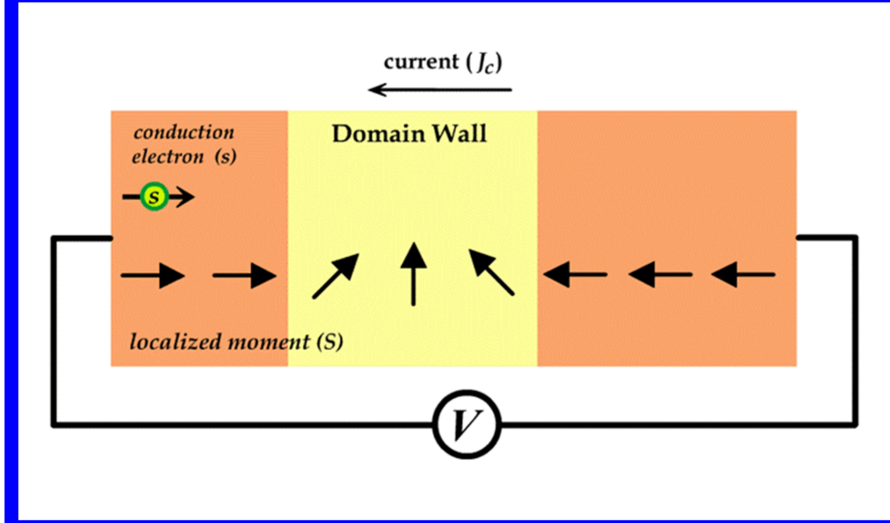
Magnetic random-access memory (STT-MRAM)

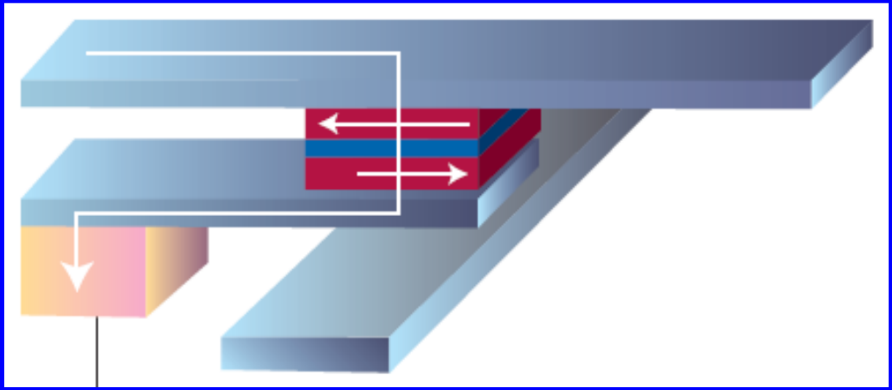


- data readout: tunneling anisotropic magnetoresistance
- data writing: ***second* generation: ST-MRAM**
  - November 2012: Everspin Technologies, **64 MB** chip EMD3D064M (August 2016: **256 MB** chip)

spin-transfer torque (STT)

- STT: non-relativistic effect
- angular momentum of a **spin-polarized electrical current** entering ferromagnet **from external polarizer** is transferred to the magnetization





http://www.klaeui-lab.de

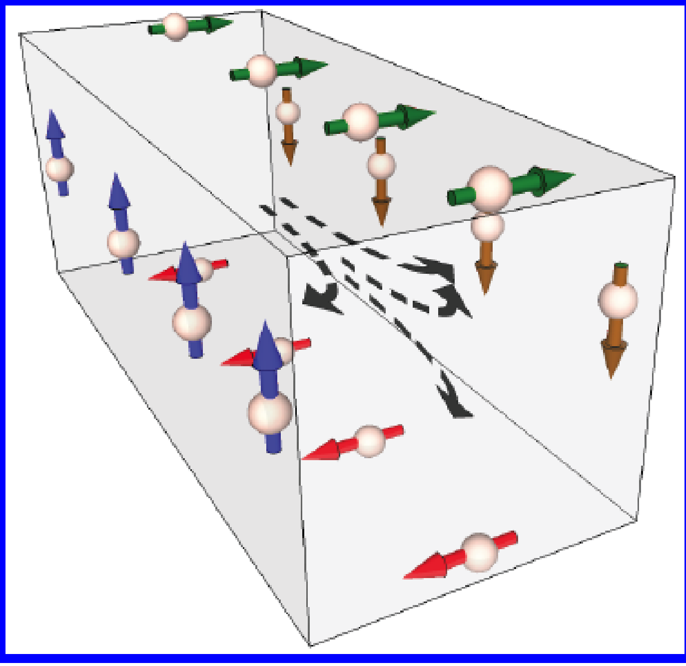
Spintronic applications: Under development

Magnetic random-access memory (MRAM)

- data readout: tunneling anisotropic magnetoresistance
- data writing: ***third* generation: spin Hall effect**

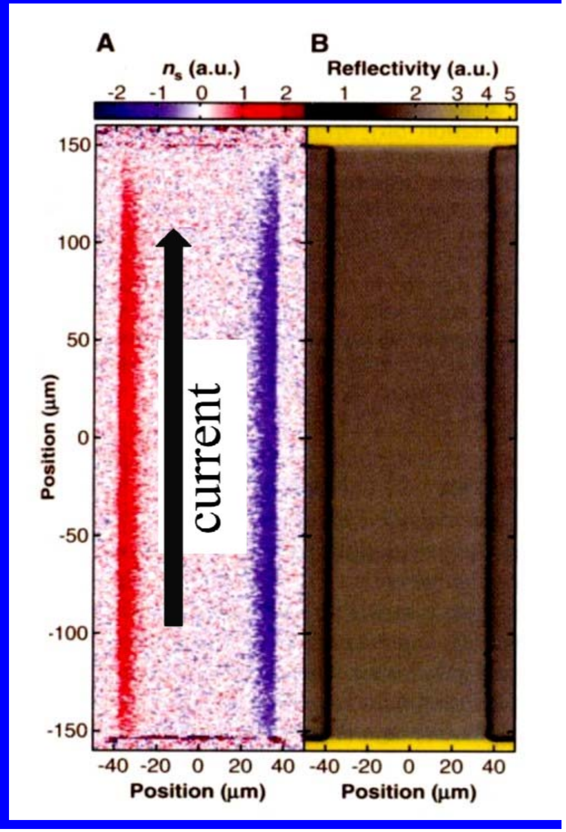
spin Hall effect (SHE)

- accumulation of spin polarization on edges of **paramagnetic** sample (due to spin-orbit interaction)
- observed in 2004 in semiconductors and later in metals



- **very strong effective magnetic fields**

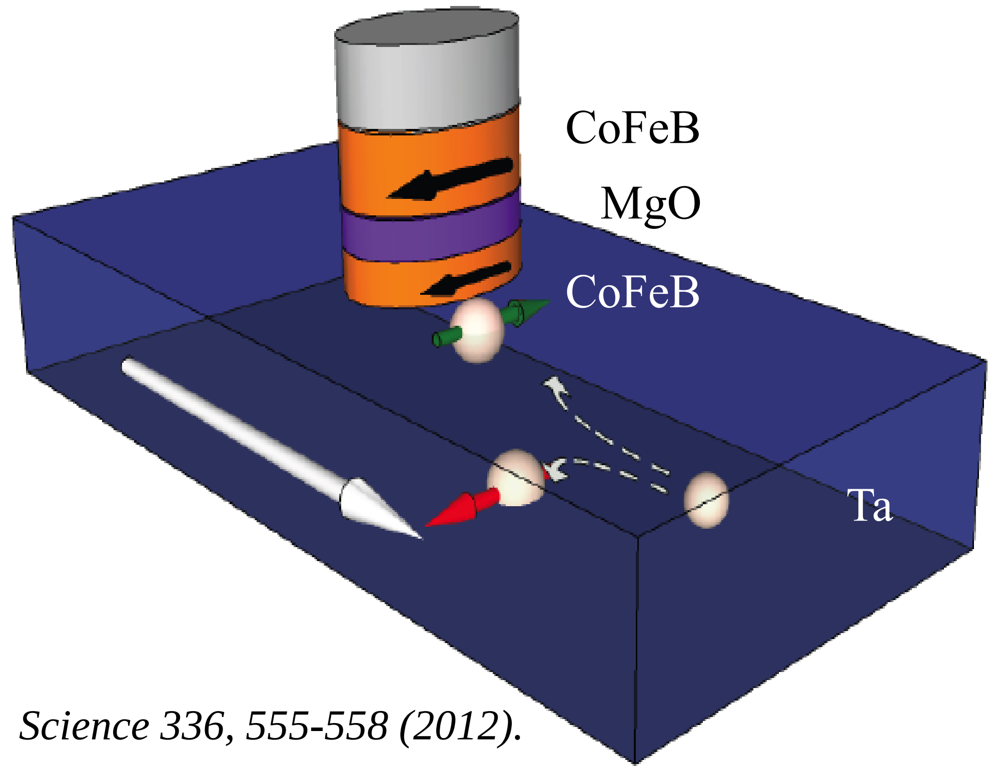
Science 306, 1910 (2004).



Magnetic random-access memory (SHE-MRAM)

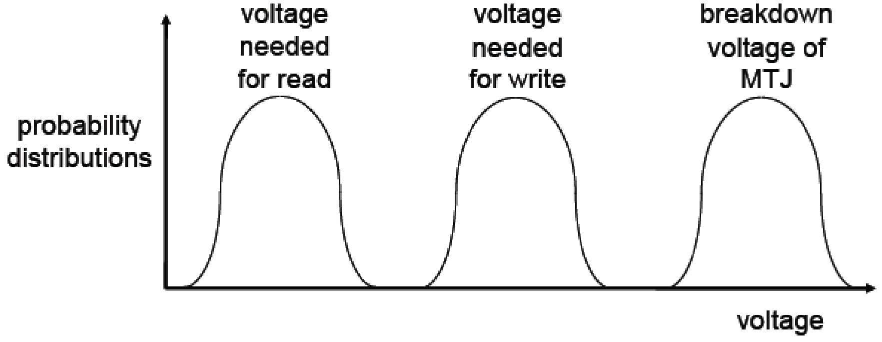
- data readout: tunneling anisotropic magnetoresistance
- data writing: ***third* generation: spin Hall effect**

- MRAM switching by a combination of SHE a STT:
  - in-plane current in the film → perpendicular spin-current due to SHE →
  → switching of MRAM due to STT

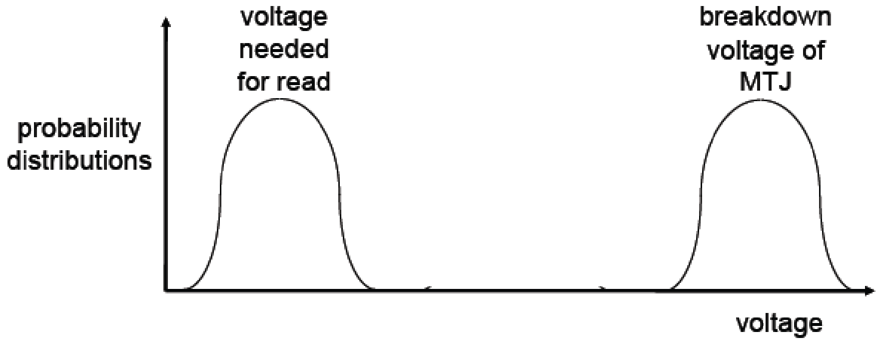


Science 336, 555-558 (2012).

STT-MRAM



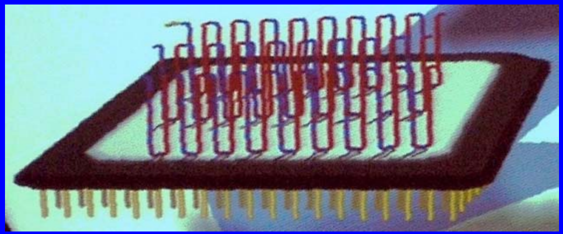
SHE-MRAM

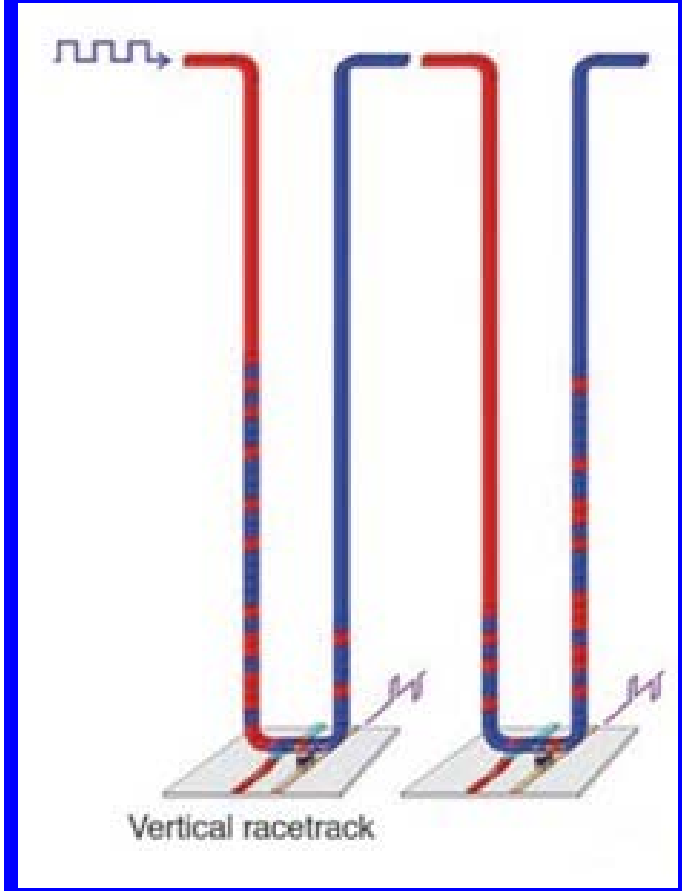


Spintronic applications: Under development

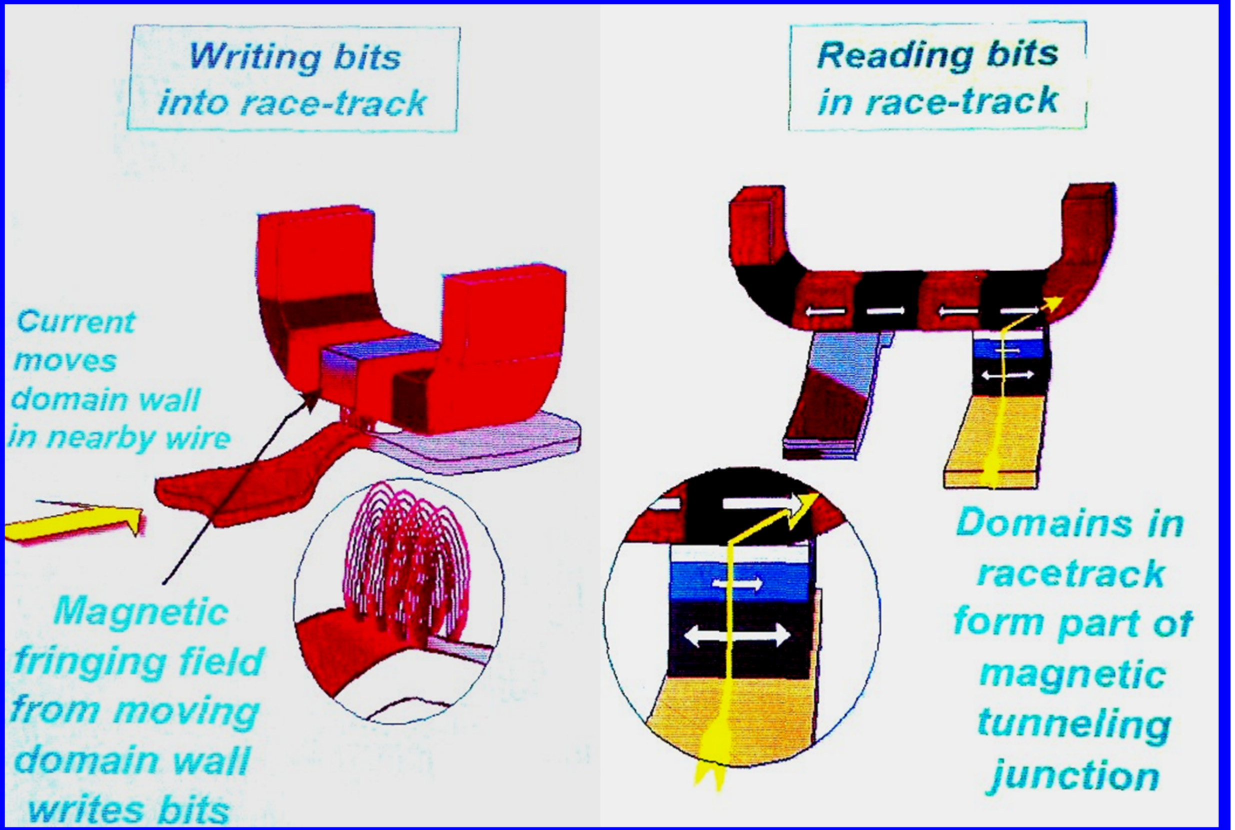
Race-track memory

- domain walls are moved by STT (v > 100 m/s)
- developed by IBM (S. S. P. Parkin)





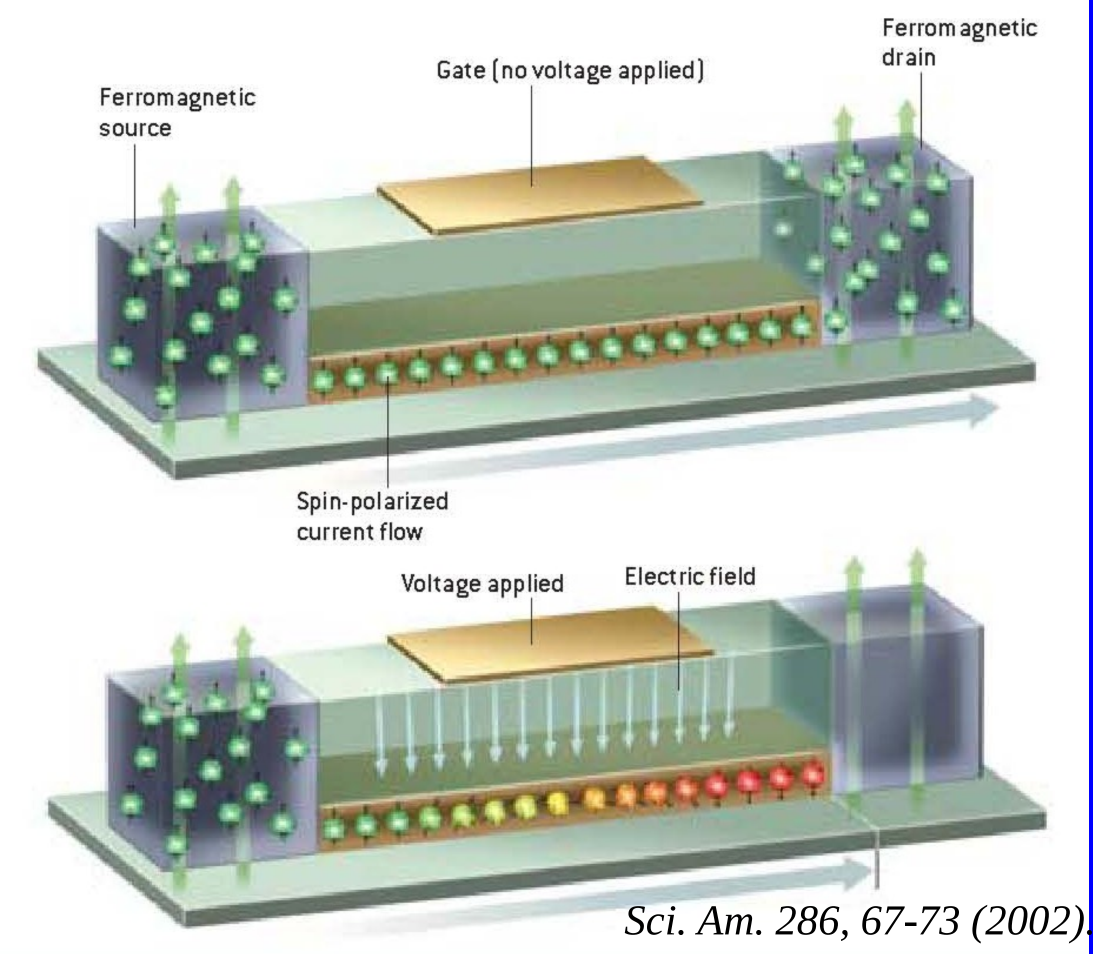
Science 320, 190 (2008).



Spintronic applications: Under development

Spin transistor: proposal

- **spin field effect transistor** (spin-FET): Appl. Phys. Lett. **56**, 665 (1990).
  - rotation of electron spin due to spin-orbit interaction (voltage controlled)



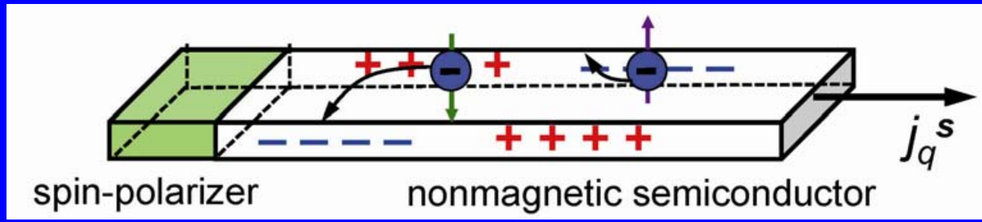
Sci. Am. 286, 67-73 (2002).

- faster
- less energy needed
- **reconfigurable**

Spintronic applications: Under development

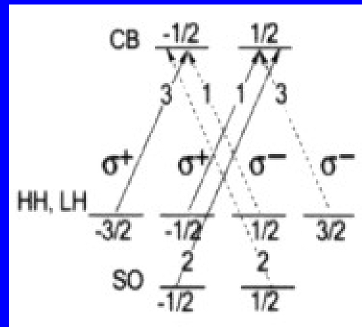
Spin transistor: demonstration

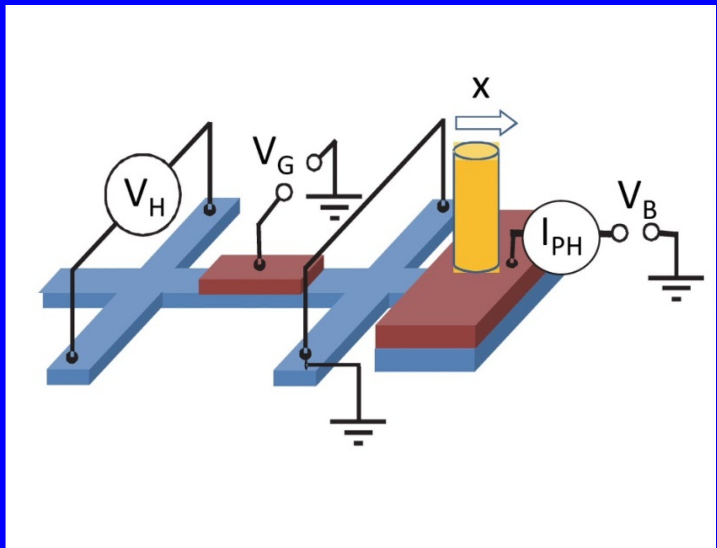
- **spin-injection Hall effect (SIHE)**:
  - rotation of electron spin due to spin-orbit interaction
    - can be measured by electrodes

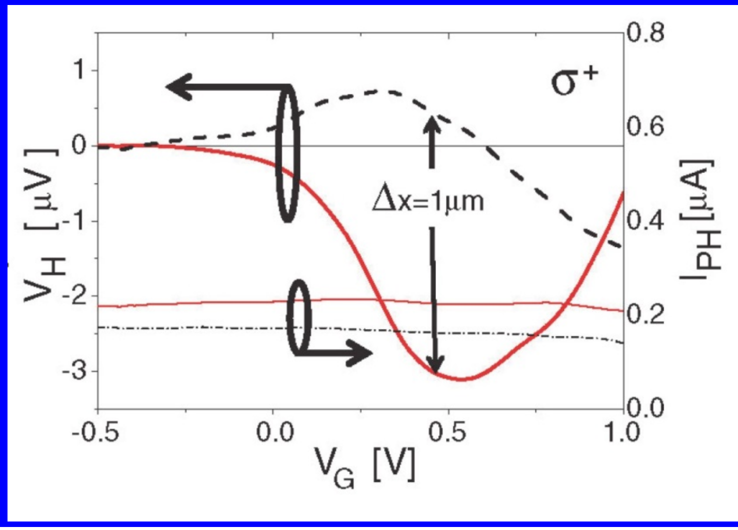


J. Wunderlich a kol., Nat. Phys. 6, 675 (2009).

- **optical injection** of spin-polarized electrons in GaAs:
  - due to selection rules
- **gate** changes the precession period







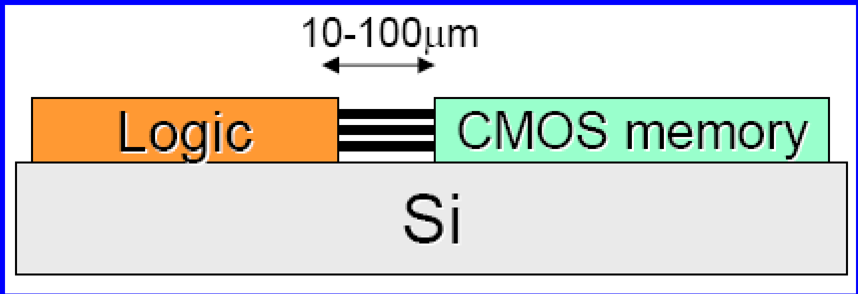
J. Wunderlich a kol., Science 330, 1801 (2010).

Spintronic applications: Under development

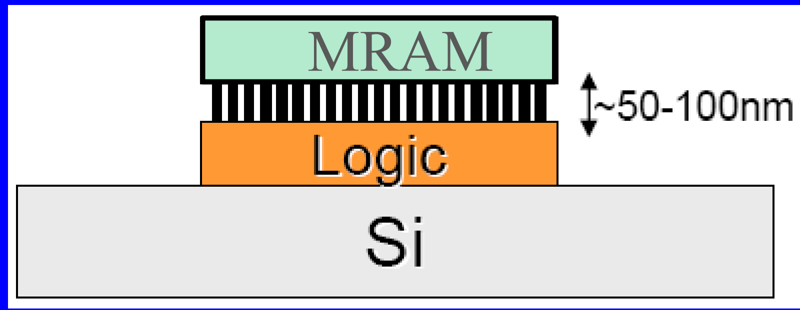
(pseudo)spin MOSFET

• **combination of Si-based MOSFET transistors with MRAM technology**:

conventional CMOS architecture



"logic in memory" architecture

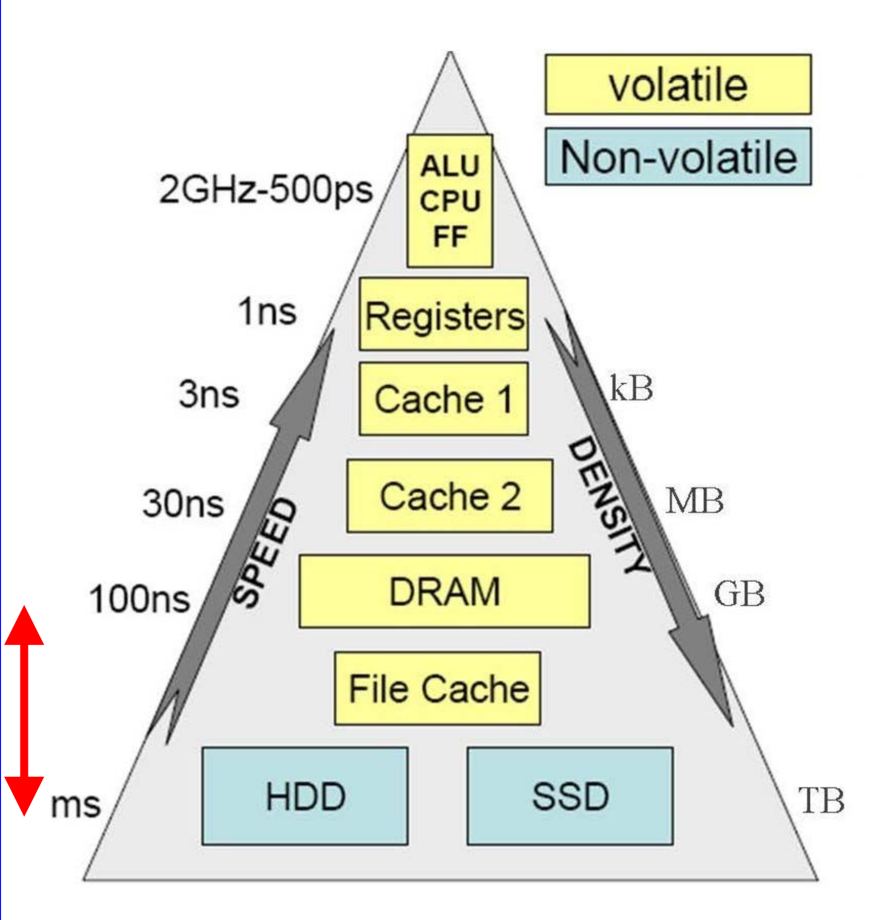


- memory much closer to logic
  → **fast communication** between logic and memory
  → large static and dynamic **energy saving**
  ("normally-off / instant-on computing")

Spintronic applications: Research directions

Fast nonvolatile data storage

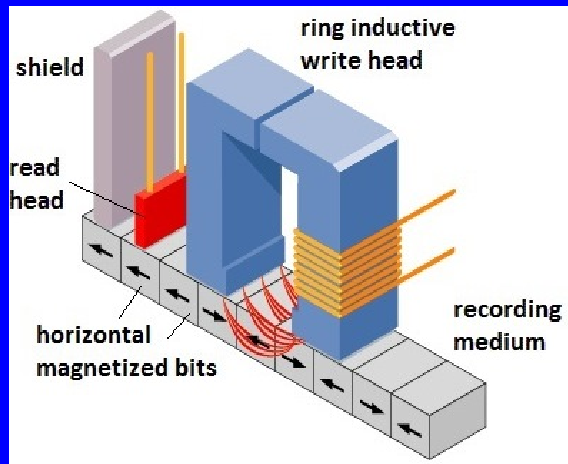
- **ultrafast technology gap** (for permanent data storage):
  - CPU: produces data at frequency ~2 GHz ⇔ 500 **ps**
  - HDD: data storage ~ **ns - ms**

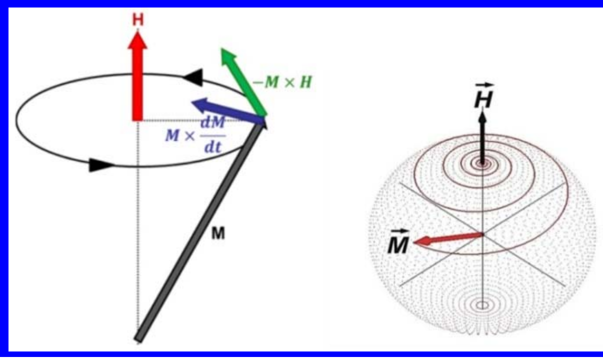


gap

HDD

- data stored by magnetic field

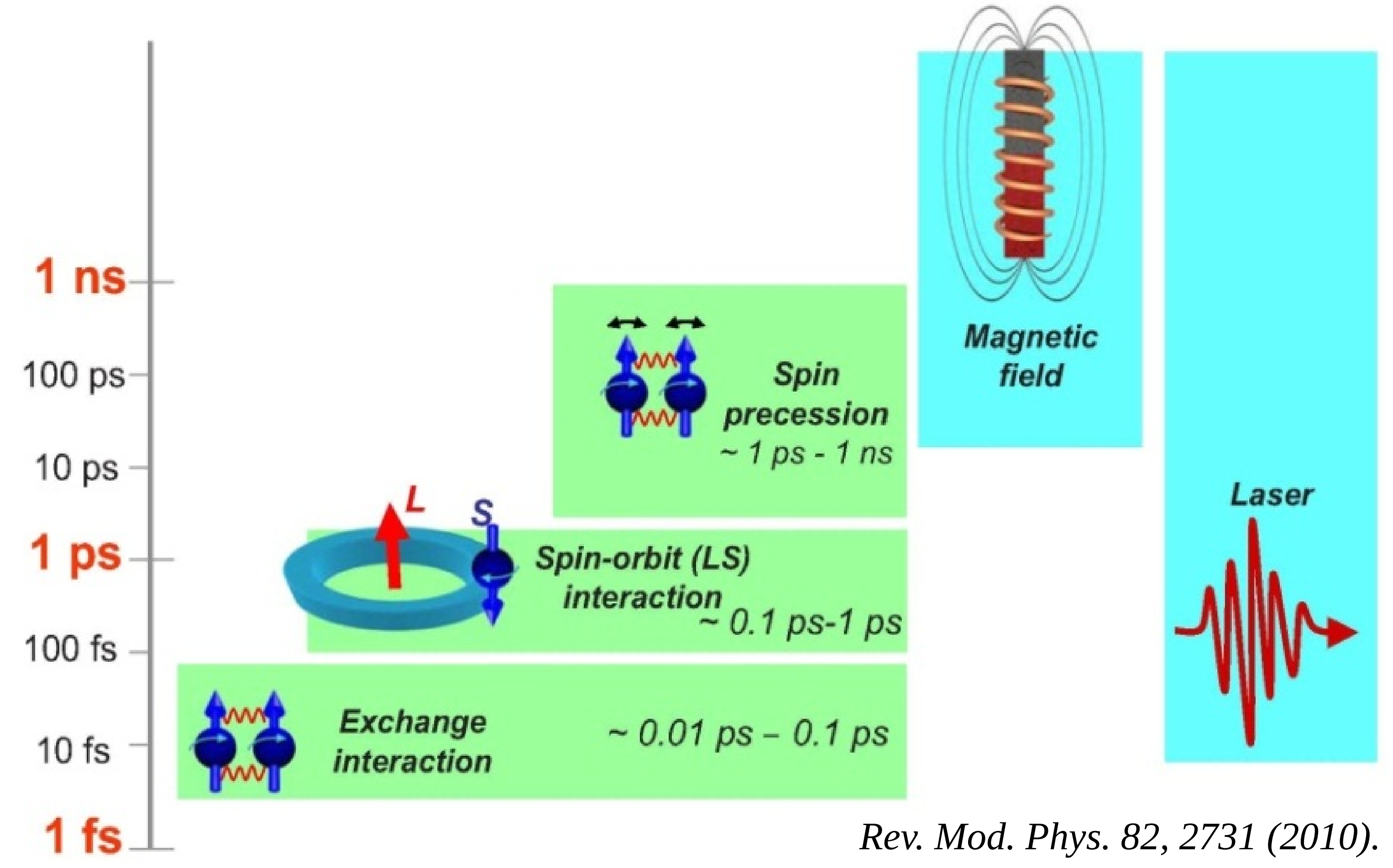




Femtomagnetism

• ultrafast (sub-ps) manipulation with magnetization by **femtosecond laser pulses:**

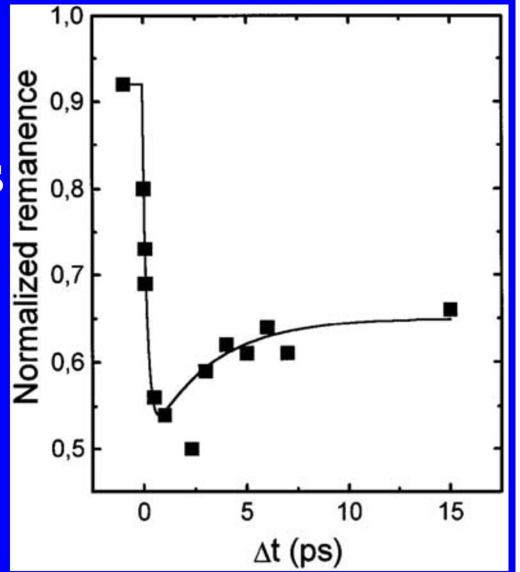
- investigation/modification of magnetic materials on a time scale shorter than that of exchange or spin-orbit interactions



Rev. Mod. Phys. 82, 2731 (2010).

Femtomagnetism

1. Modification of magnetization magnitude



1996 – **demagnetisation in nickel induced by** 60 fs pulses

- **sub-ps** reduction of magnetic moment

=> **femtomagnetism**

- various mechanisms responsible …

Phys. Rev. Lett. 76, 4250 (1996).

2. Modification of magnetization direction

2005- **inverse Faraday effect**

$$\mathbf{M}(0) = \frac{\chi}{16\pi}[\mathbf{E}(\omega)\times\mathbf{E}^*(\omega)]$$

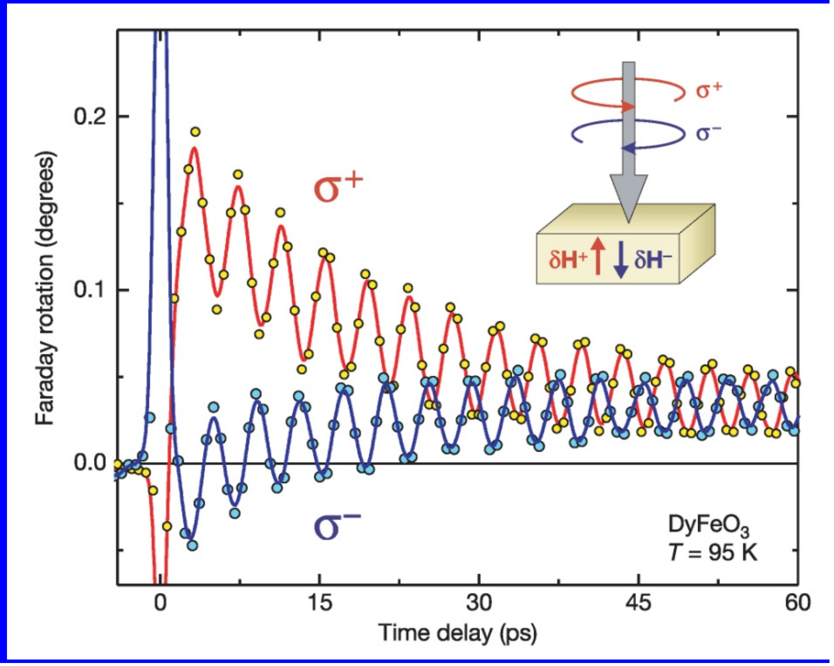
Faraday rotation: $\alpha_F = \frac{\chi}{n}\mathbf{M}\cdot\mathbf{k}$

χ … magneto-optical susceptibility

=> light acts as **effective magnetic field**

- direction determined by light helicity

Nature 435, 655 (2005).



Femtomagnetism

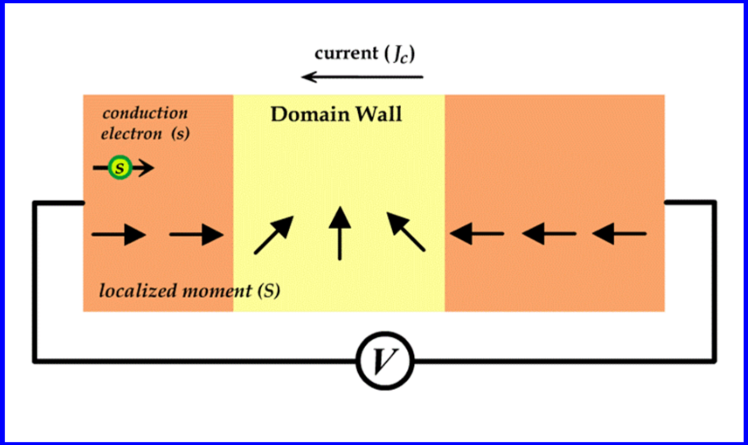
Search for optical analogues of electrical torques

spin-transfer torque (STT):

- non-relativistic effect
- angular momentum of a **spin-polarized electrical current** entering ferromagnet **from external polarizer** is transferred to the magnetization

spin-orbit torque (SOT):

- relativistic (spin-orbit) effect
- **no external polarizer** is needed (present in uniform ferromagnet)
- initially unpolarized current is **spin-polarized due to spin-orbit interaction** => torque on magnetization



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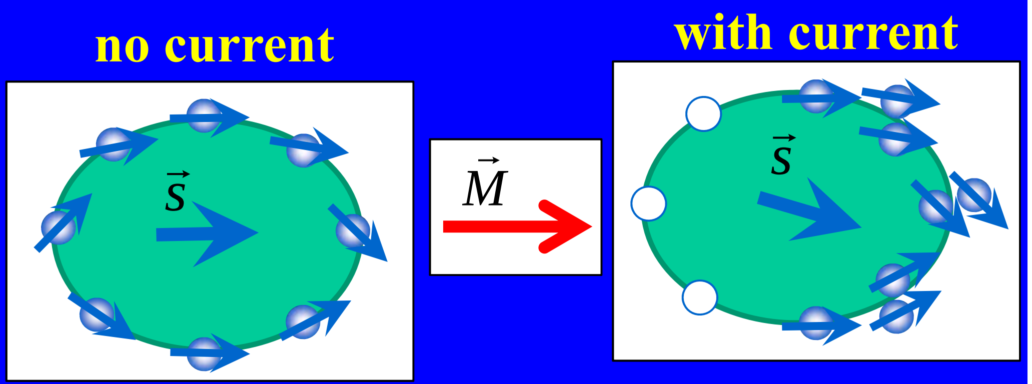
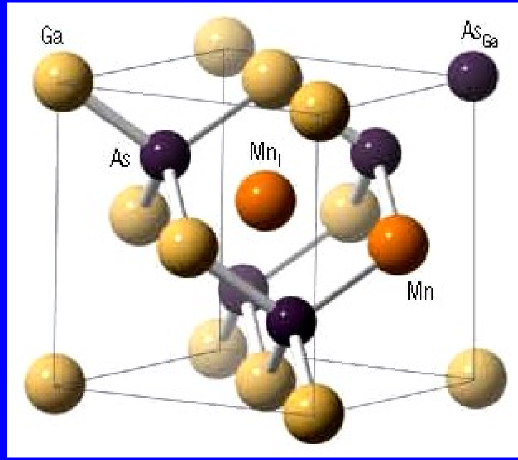


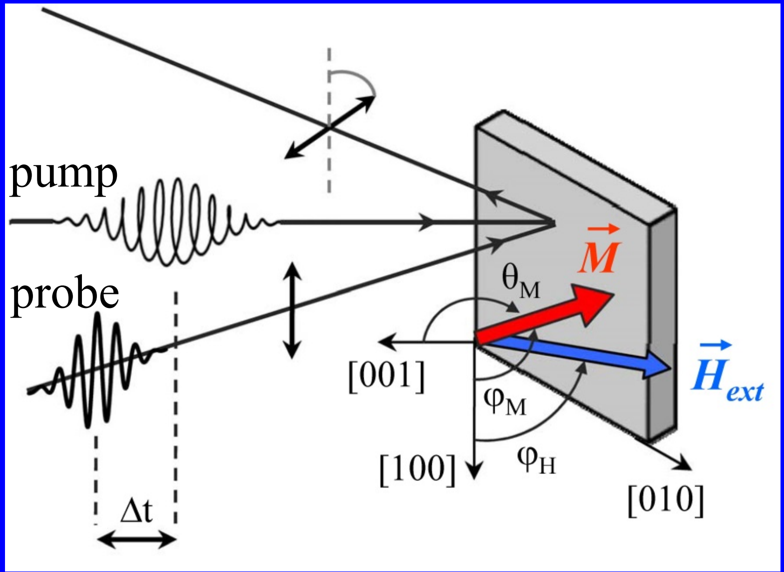
Why use optical pulses? **Same physics but much faster!**

Optical torques: experimental observation

- **material**: **ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$**
  - partial replacement of non-magnetic atoms by magnetic ones
  - **direct-gap** semiconductor => photoinjection of cariers
  - strong **exchange coupling** between carriers and Mn
  - large **magneto-optical activity**
  - Curie temperature $T_c \leq 200$ K



- **method**: **time-resolved magneto-optical experiment**



- strong circularly-polarized **pump pulse**
  => photo-injection of spin-polarized electrons
- weak **probe pulse** with linear polarization
  - rotation of polarization plane
- **time delay** between pump and probe pulses
  => **dynamics of pump-induced magnetization change**

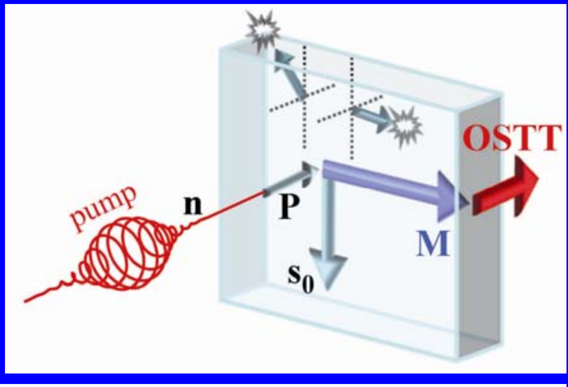
P. Nemec et al., Nature Physics 8, 411 (2012).

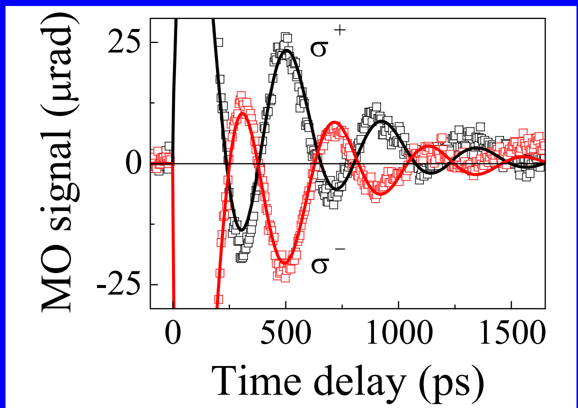
N. Tesarova et al., Nature Photonics 7, 492 (2013).

Optical torques: experimental observation

<u>**optical spin-transfer torque**</u>

- absorption of **circularly-polarized** pulse => **spin-polarized electrons**
- **coupled precession dynamics** of magnetization M and carrier spin s





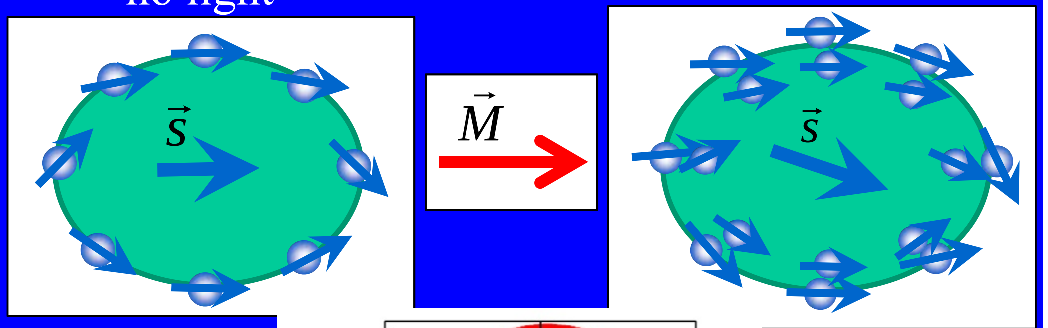
Nature Physics 8, 411 (2012).

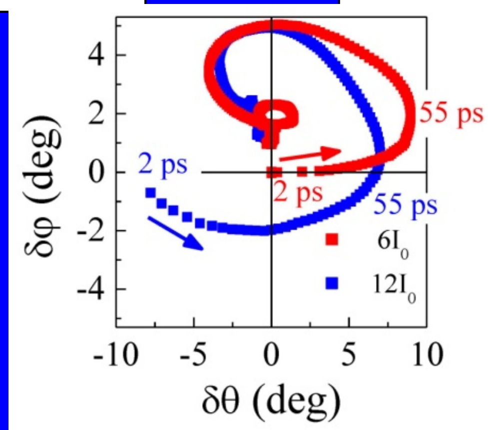
<u>**optical spin-orbit torque**</u>

- absorption of pulse => non-equilibrium concentration of holes

spin-orbit interaction=> **non-equilibrium spin-polarization** - misaligned relative to M

no light   illuminated



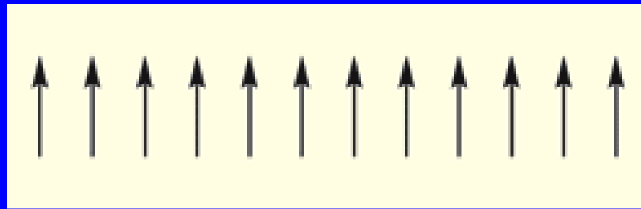


Nature Photonics 7, 492 (2013).

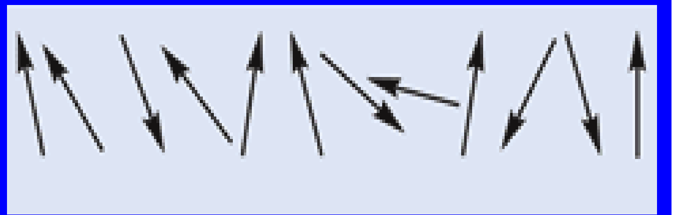
Spintronics from material perspective

Ferromagnets - rare

- ordered materials with **M≠0**
- **good** for direct manipulation by magnetic field
- **bad** for retention with magnetic field around
- **not well** compatible with semiconductors

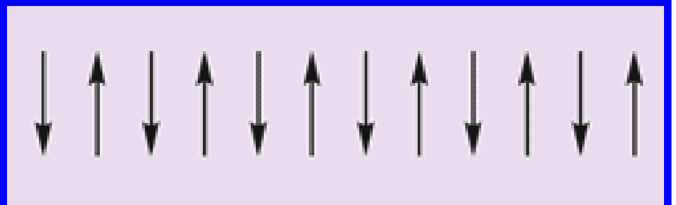


Paramagnets - very frequent



- disordered materials with **M=0**
- **bad** for direct manipulation by magnetic field
- **no** magnetic memory
- **compatible** with semiconductors; transitsors & photonics

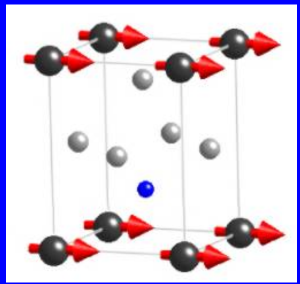
Antiferromagnets - frequent



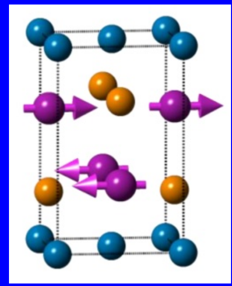
- ordered materials with **M=0**
- **bad** for direct manipulation by magnetic field
- **good** for retention with magnetic field around
- **compatible** with semiconductors; transitsors & photonics

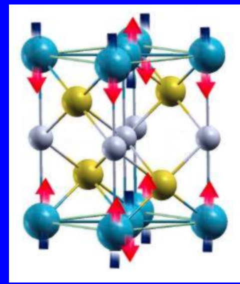
Spintronics with antiferromagnets

ferromagnets (FM)



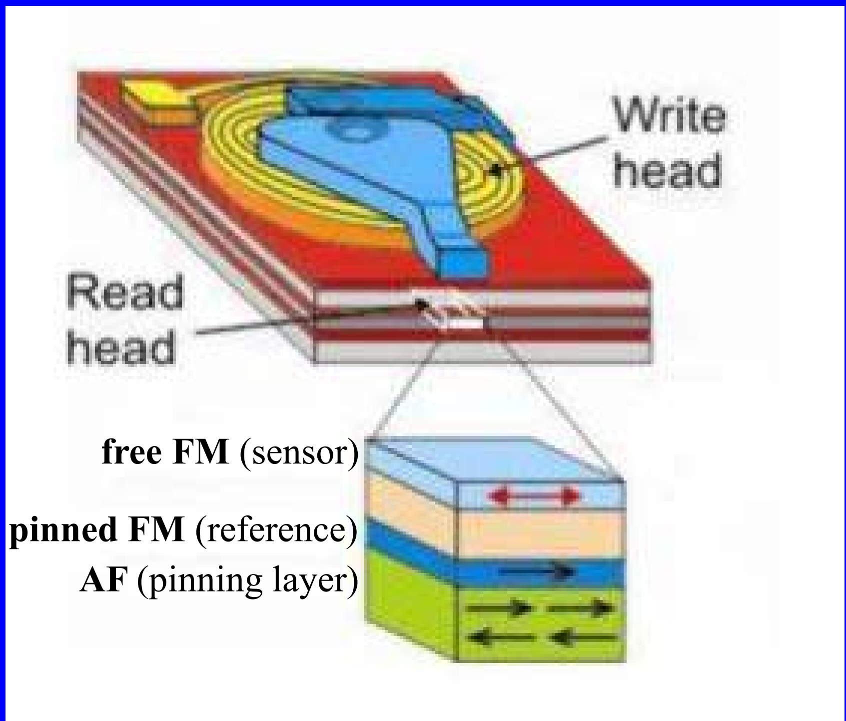
antiferromagnets (AF)





• AF are used quite frequently as pinning layers for FM:

exchange bias spin valve: read head for HDD



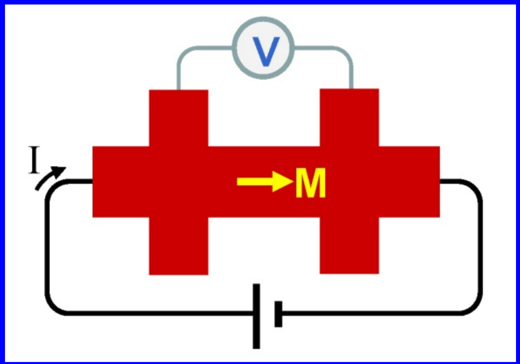
Antiferromagnetic spintronics

• antiferromagnets: "**Interesting, but without application**"

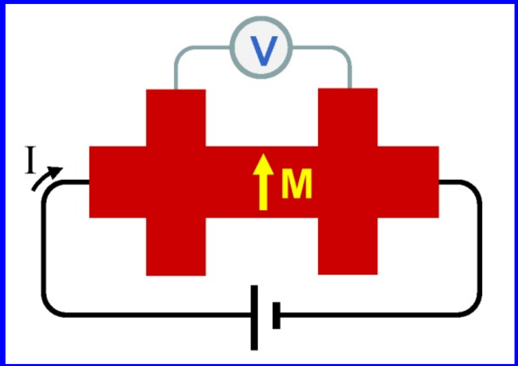
Louis Néel, Nobel Lecture, December 11, 1970

• effects even in magnetization should be equally present in FM and AF:

Anisotropic Magnetoresistence

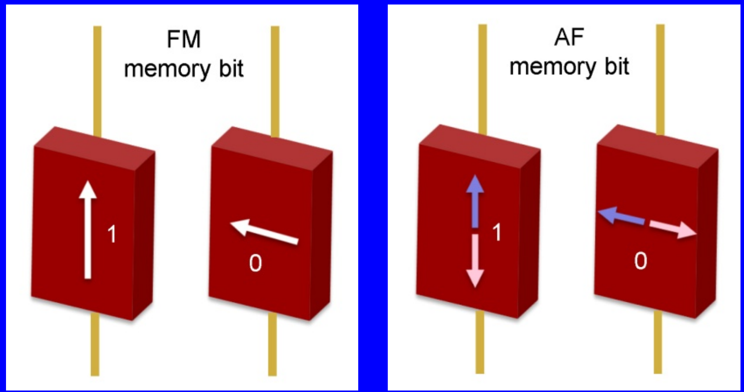


high resistance



low resistance

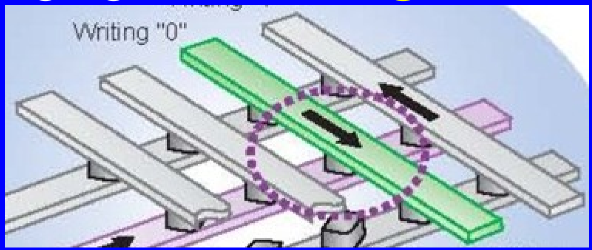
=> realization of **magnetic memory**



• review: T. Jungwirth *et al.*, Nature Nanotechnol. **11**, 231 (2016).

Antiferromagnetic spintronics: Potential advantages

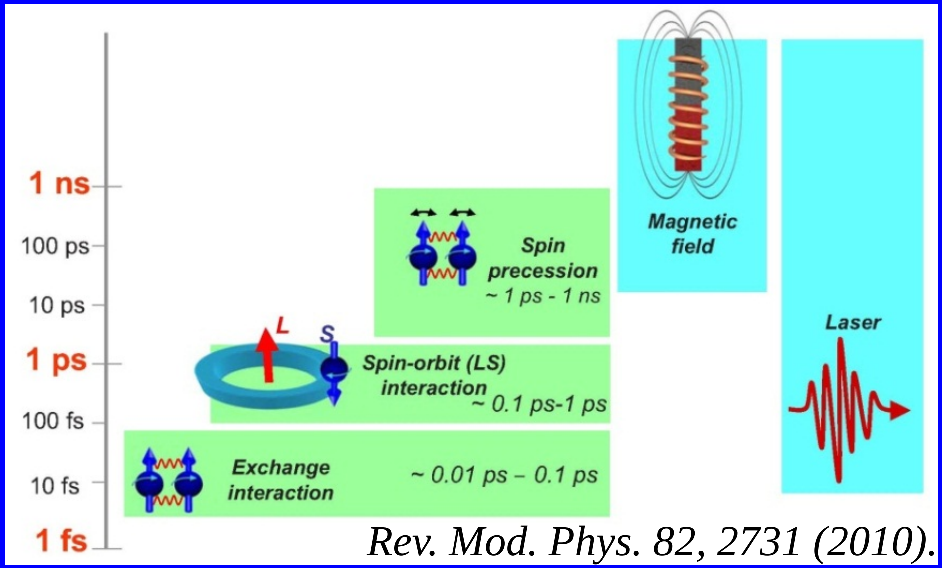
- wide range of AF materials (oxides, semiconductors, metals, semimetals, …)
- **advantages for a construction of *non-volatile* memory devices:**
  - **robust** against external magnetic fields (like charge-based memory) and against radiation (like ferromagnetic memory)
  - no stray fringing fields => **high density** of memory elements is possible



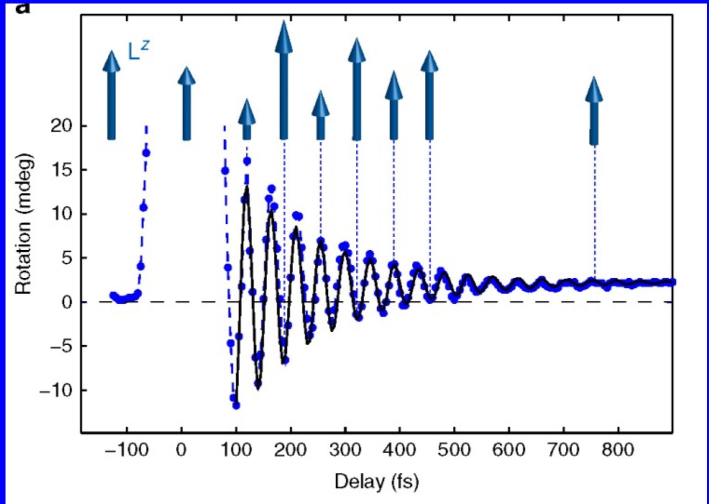
MRAM: 64 MB

DDRAM: 1 GB

- **ultrafast dynamics** (THz instead of GHz for ferromagnets)



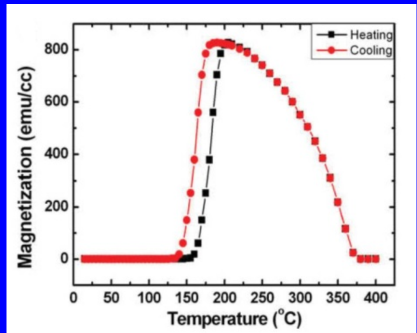
Rev. Mod. Phys. 82, 2731 (2010).



Nature Commun. 7, 10645 (2016).

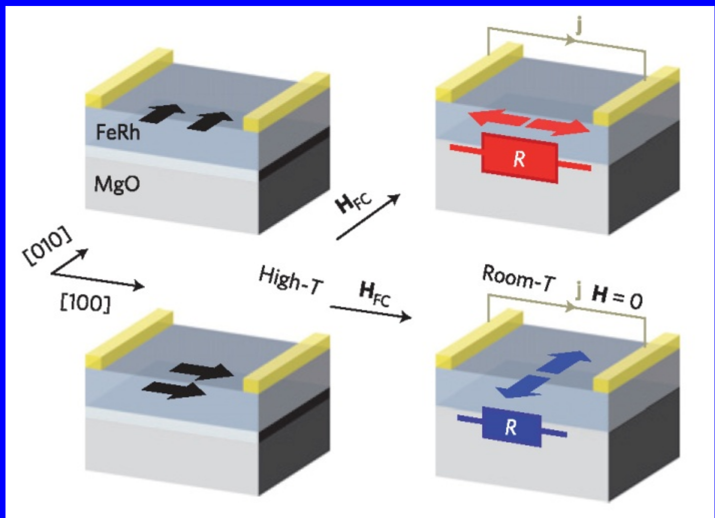
Antiferromagnetic spintronics: FeRh device

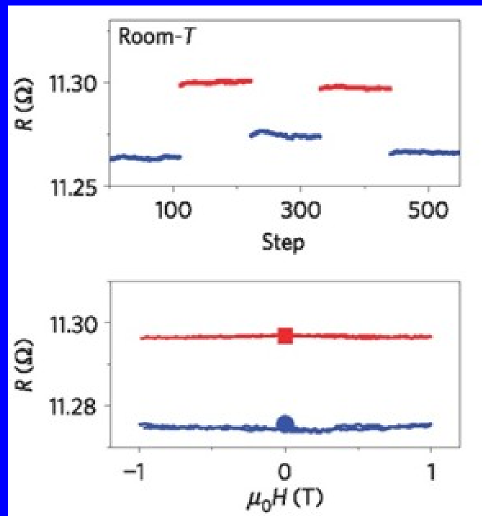
- **FeRh**: 1st order magneto-structural **phase transition** at $T_{tr} \approx 400$ K:
  - FM at high temperature, AF at low (e.g., room) temperature



Scripta Materialia 61, 851 (2009).

- **antiferromagnetic memory device at 300K**:
  - magnetic moments oriented at $T > T_{tr}$ (in FM state) by magnetic field
  - information stored after cooling to 300 K (in AF state)





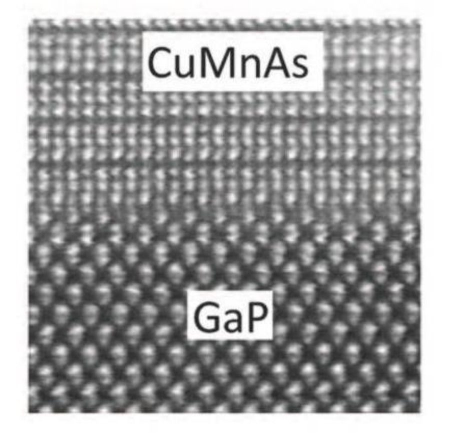
- robust against magnetic field

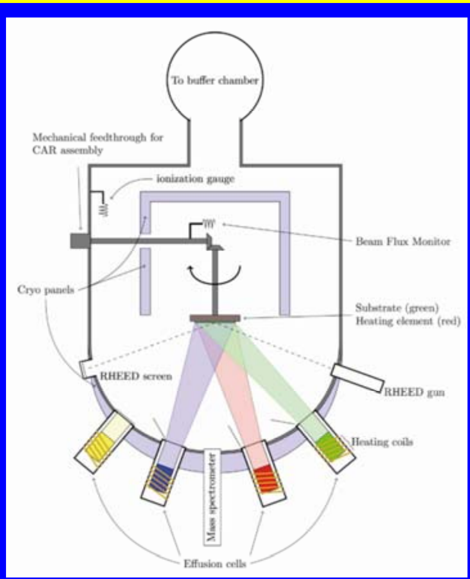
X. Marti et al., Nature Materials 13, 367–374 (2014).

Antiferromagnetic spintronics: CuMnAs device

- **CuMnAs**: antiferromagnetic semi-metal with $T_N \approx 450$ K
  - epitaxial films prepared by MBE

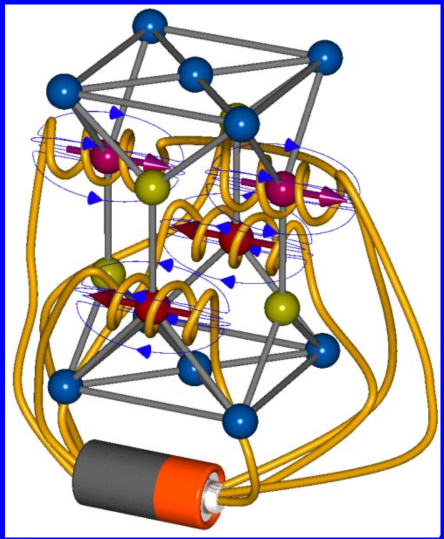
HRTEM:

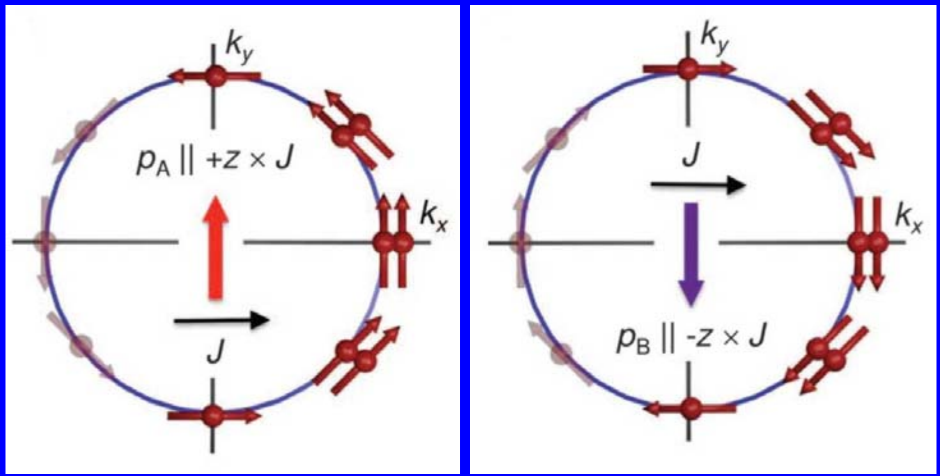




P. Wadley et al. Nature Commun. 4, 2322 (2013).

- **electrical** manipulation with orientation of spins: **staggered current-induced field**

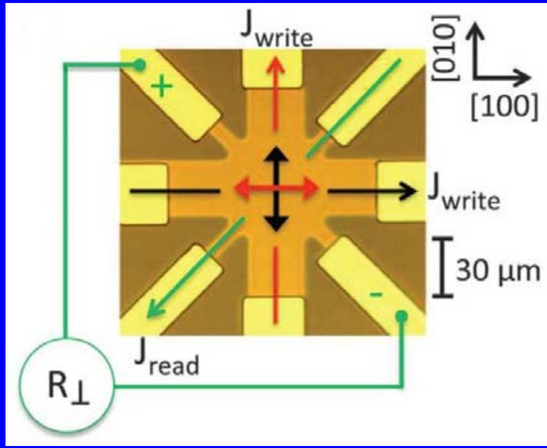




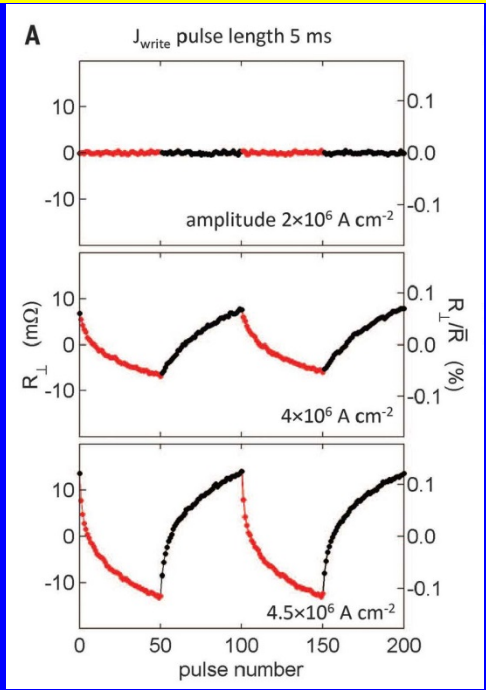
J. Zelezny et al., Phys. Rev. Lett. 113, 157201 (2014).

Antiferromagnetic spintronics: CuMnAs device

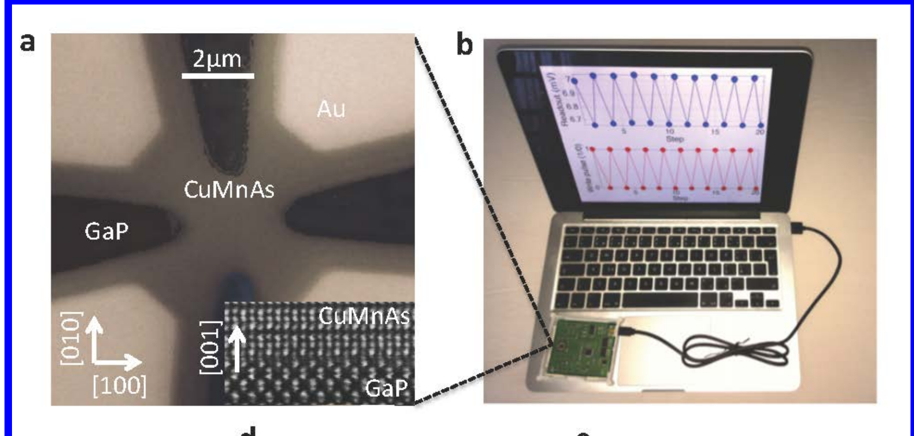
• room-temperature **all electrical switching and readout**:

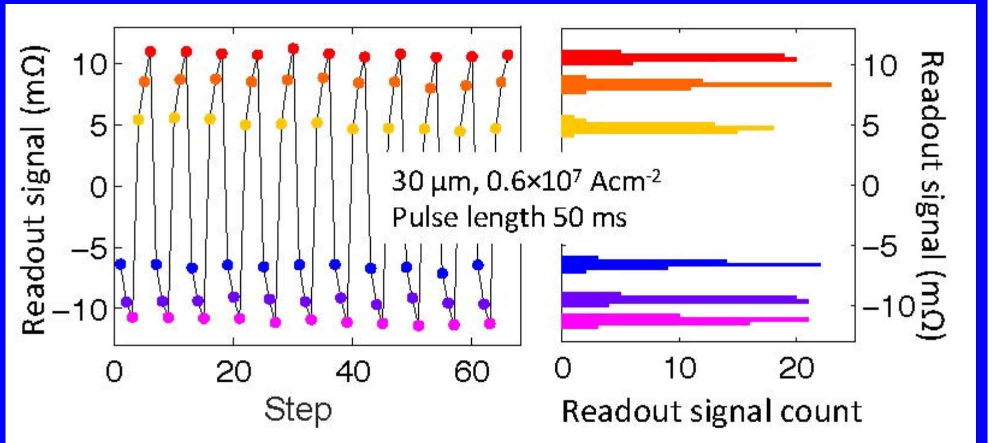


P. Wadley et al. Science 351, 587-590 (2016).



• **USB-operated** memory device: multi-level switching





V. Schuler et al., Nature Commun. in press; https://arxiv.org/abs/1608.03238.

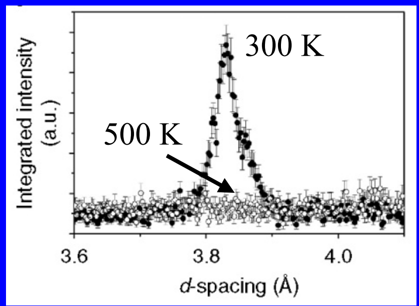
Material research of antiferromagnets

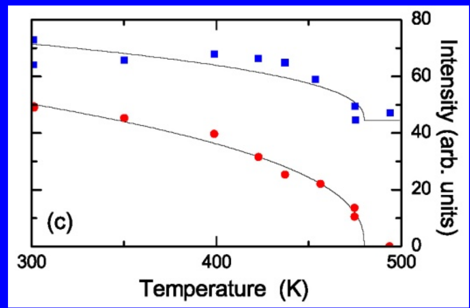
- **zero net magnetic moments** in compensated antiferromagnets limits considerably the portfolio of methods applicable for their research
- spintronic devices are formed by **nanometer-thick (metallic) films**

=> information about magnetic ordering can be obtained by:

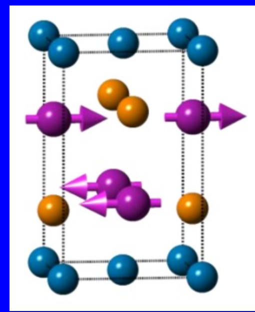
1) neutron diffraction: for films thicker than ≈ 500 nm

CuMnAs:



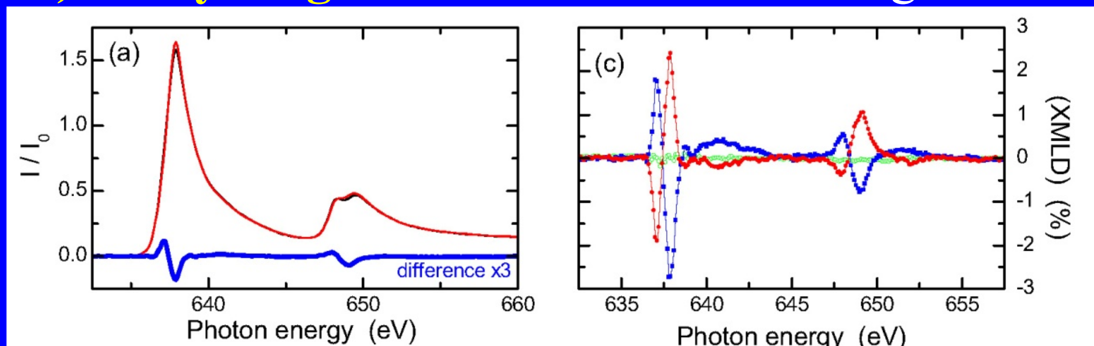


=>



T_N = 480 K

2) X-ray magnetic linear dichroism: sign has to be determined by theory



=> uniaxial magnetic anisotropy

- **these experiments require large scale facilities** ☹

=> new <u>table-top</u> experimental techniques are needed

Nat. Comm. 4, 2322 (2013).
Sci. Rep. 5, 17079 (2015).

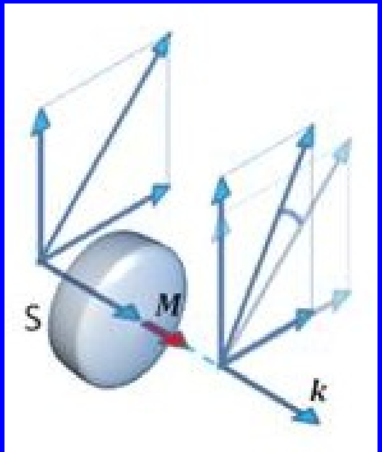
Magneto-optics in ferromagnets

• rotation of light polarization due to magneto-optical effects:

1) **odd** in magnetization: MO ~ M

Kerr effect

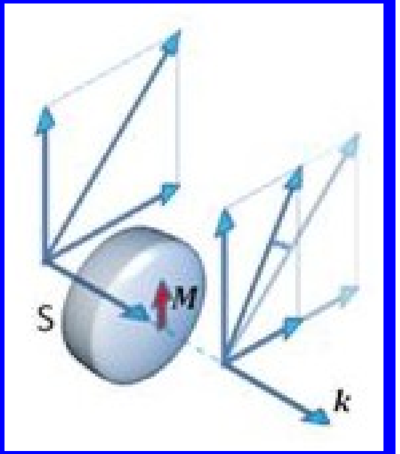
different index of refraction for σ^+ and σ^- **circularly** polarized light

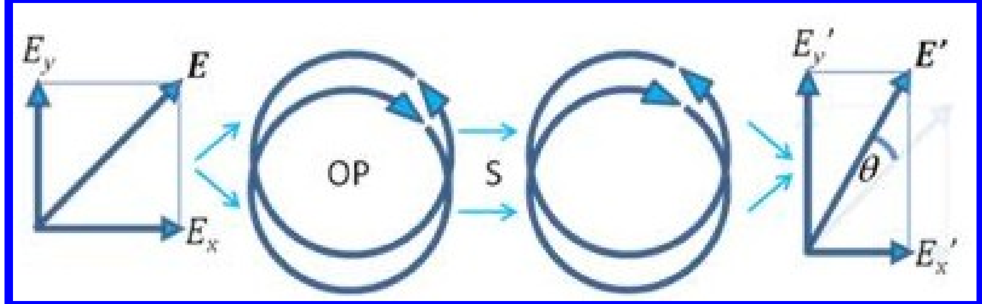


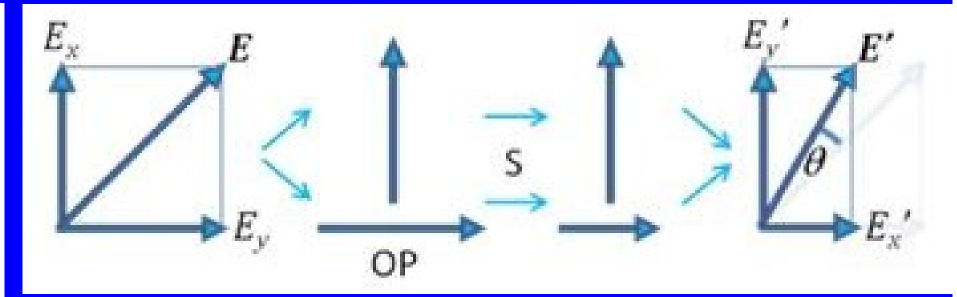
2) **even** in magnetization: MO ~ M^2

Voigt effect (magnetic linear dichroism)

different absorption for $E^{//}$ and $E^{\perp}$ **linearly** polarized light







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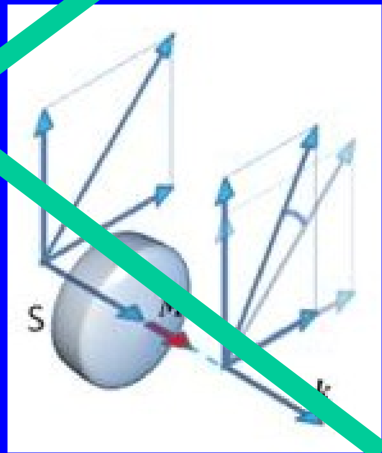

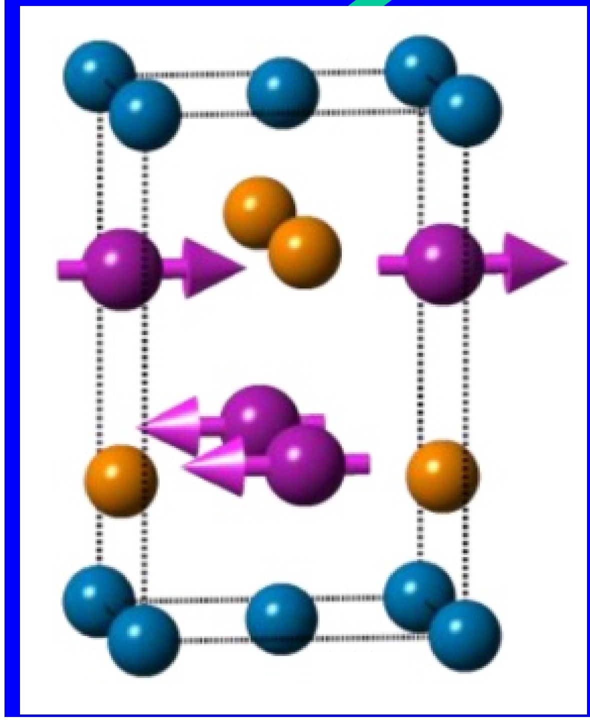

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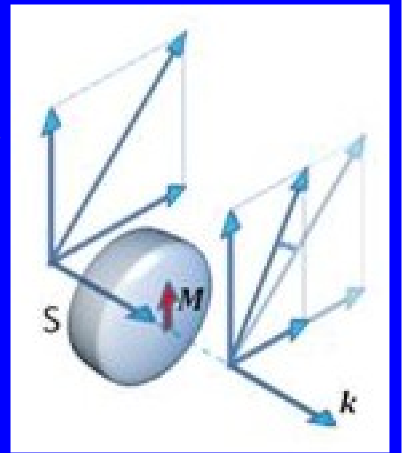
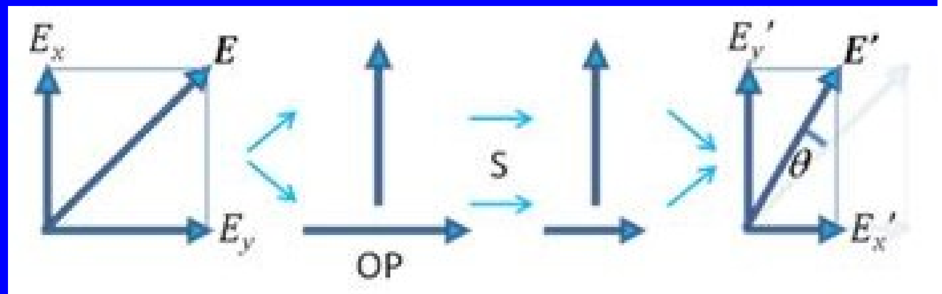
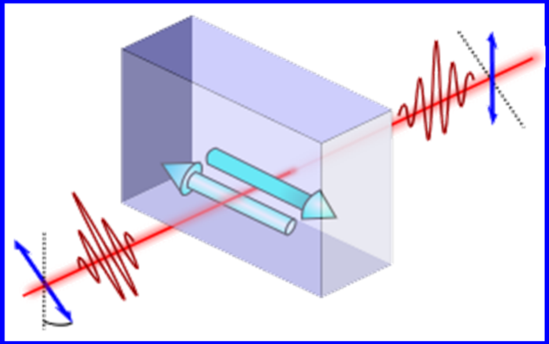


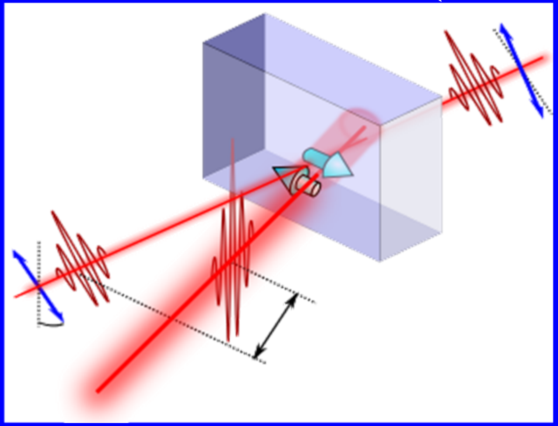


Magneto-optical studies of CuMnAs

- problem with Voigt effect in **antiferromagnets**:
  - difficult to separate from other sources of polarization rotation (anisotropies)

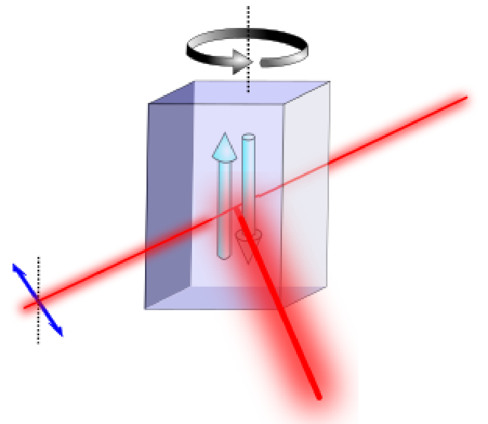


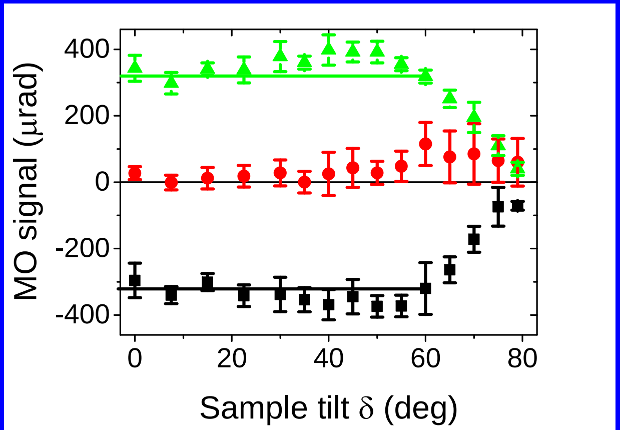
MO ~ M^2

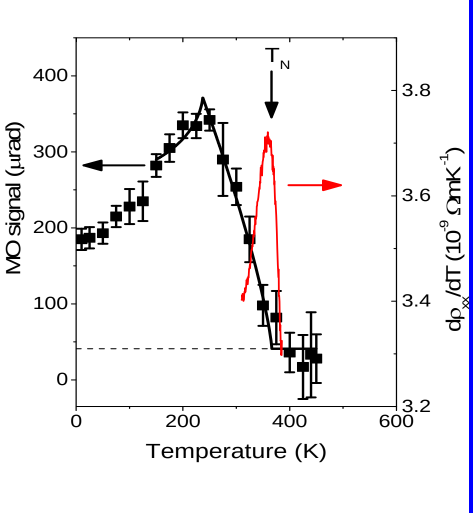


  - solution: **local heating** by pump pulses

- determination of: **easy axis position** and **Néel temperature**:







V. Saidl et al., Nature Photonics, online 9 January 2017