Spin-orbit effects in transport and magnetism:

Relativistic spintronics with ferro, antiferro, and paramagnets

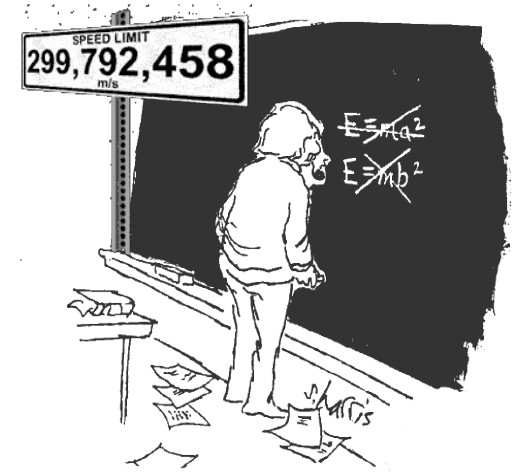
Tomas Jungwirth

Inst. of Physics, Prague Czech Rep. *Univ. of Nottingham, UK*

Outline

1. Relativistic QM, magnetism, and spintronics with ferro, antiferro, and paramagnets
2. Reading spin information
3. Writing spin information

Relativistic quantum mechanics



Dirac equation (limit $v \rightarrow c$)

$$E = c\hbar\vec{k}\cdot\vec{\sigma}$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

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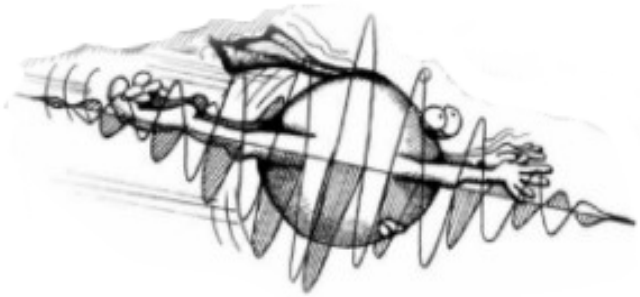
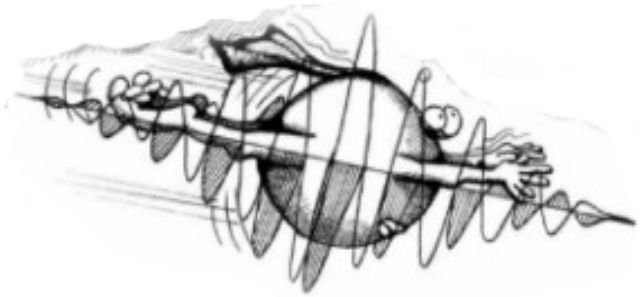


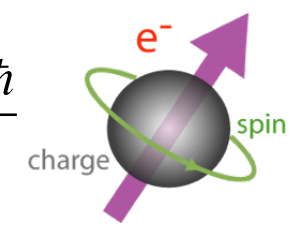


Spin = angular momentum

$$s_i = \frac{\hbar}{2}\sigma_i$$

Spin & charge → magnetic moment

$$\vec{m} = \mu_B\vec{\sigma} \qquad \mu_B = \frac{|e|\hbar}{2m}$$



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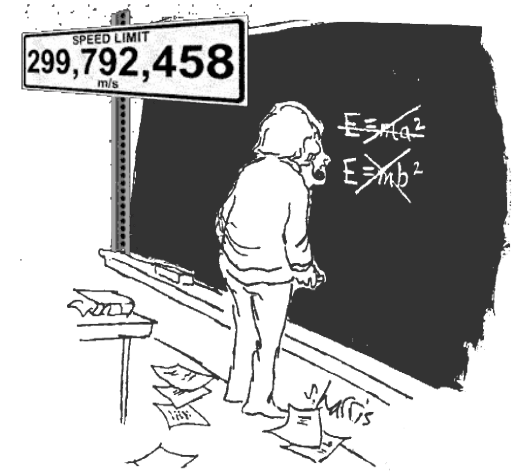

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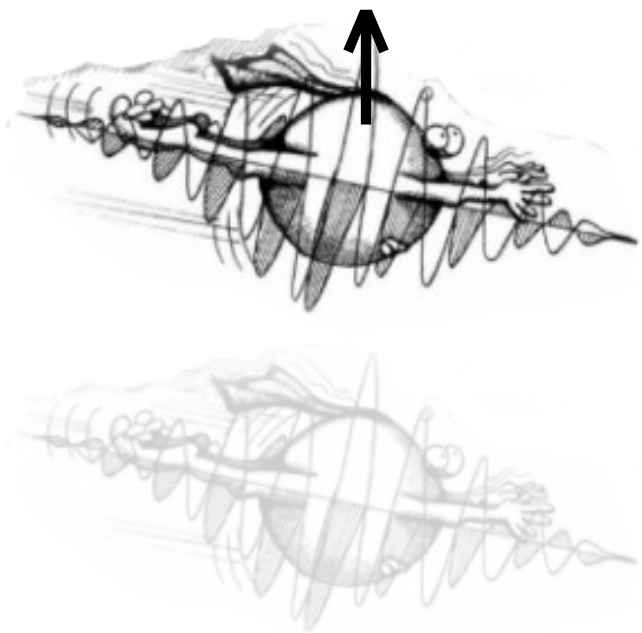
Spin-orbit coupling



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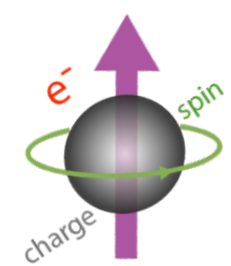

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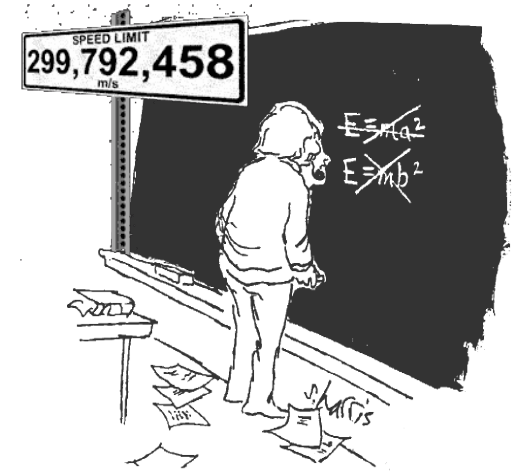

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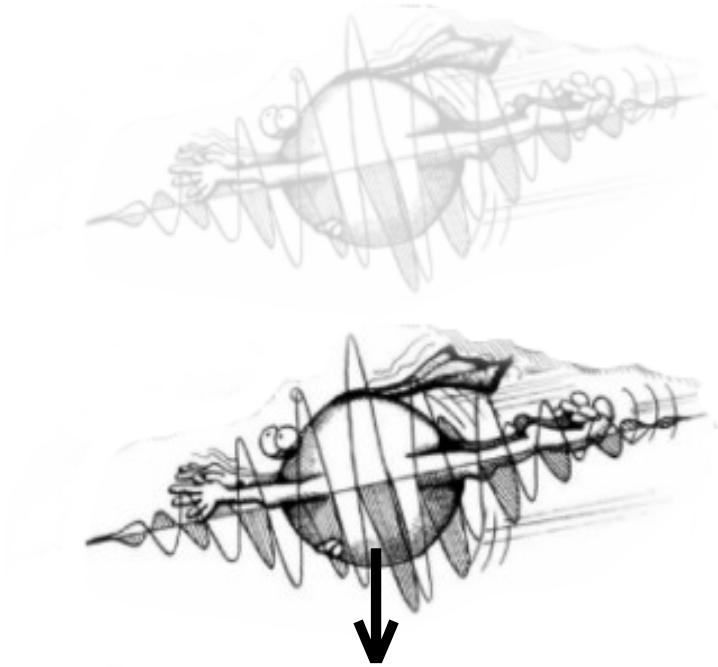

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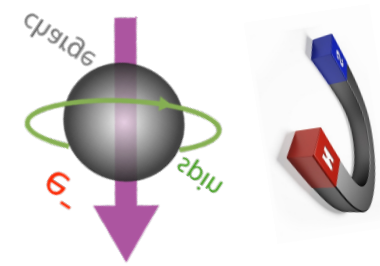
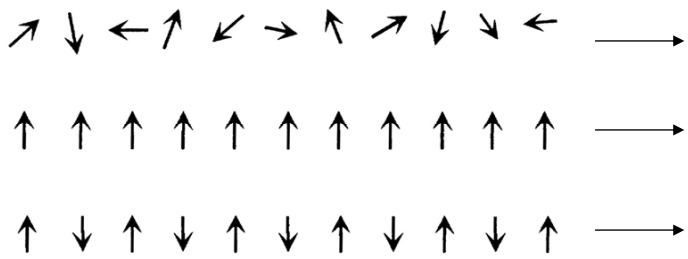


Magnetism

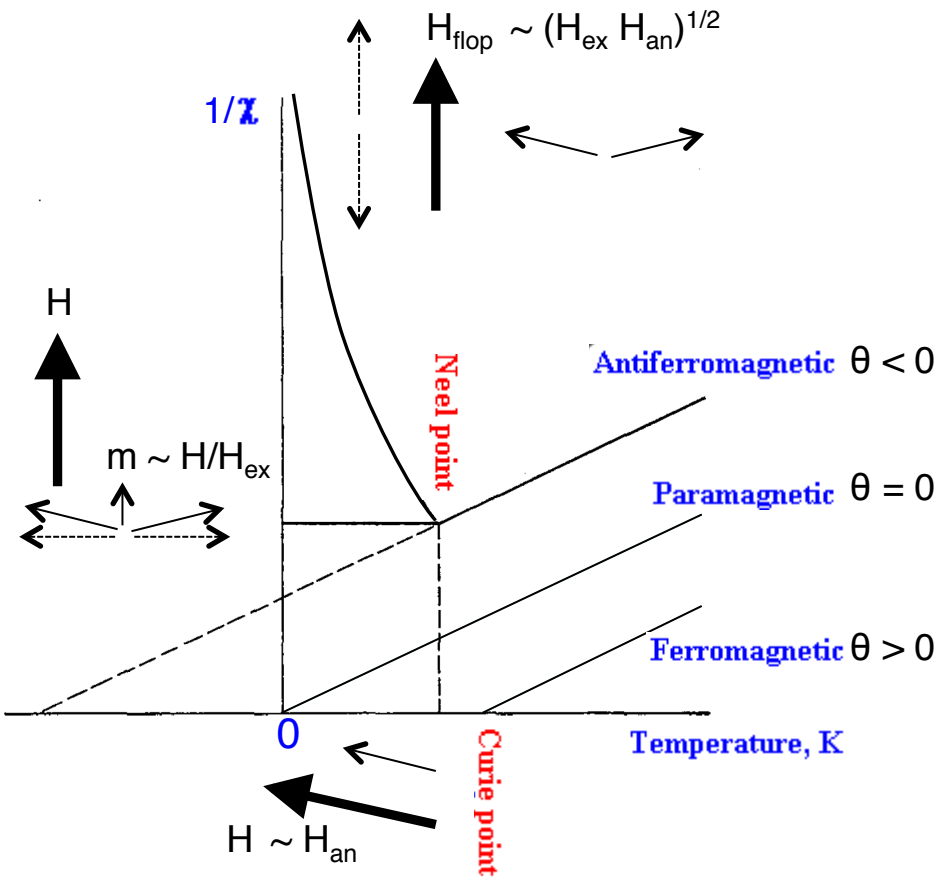


Paramagnetic no spontaneous order

Ferromagnetic exchange coupling, order by **global** uniform molecular field

Antiferromagnetic exchange coupling, order by **local** (atomistic) molecular field

Curie-Weiss law $1/\chi \sim T - \theta$



Nobel Lecture, December 11, 1970

LOUIS NÉEL

Magnetism

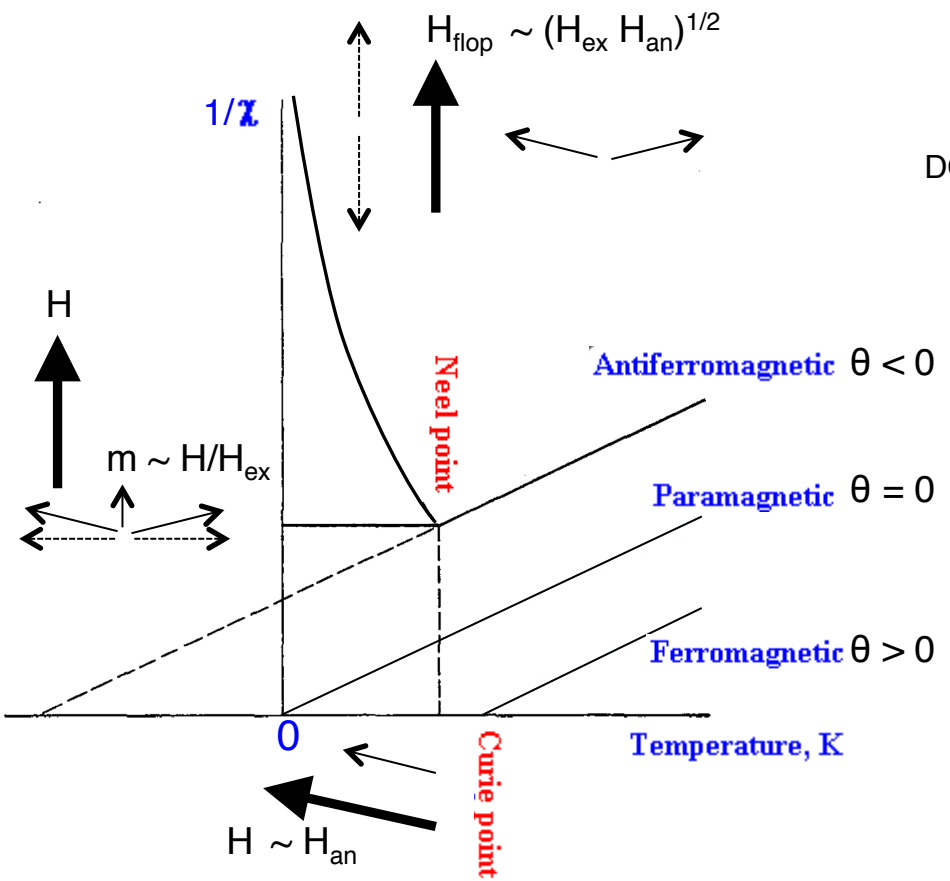
↗ ↓ ← ↑ ↙ → ↖ ↗ ↓ ↘ ← ⟶ Paramagnetic no spontaneous order

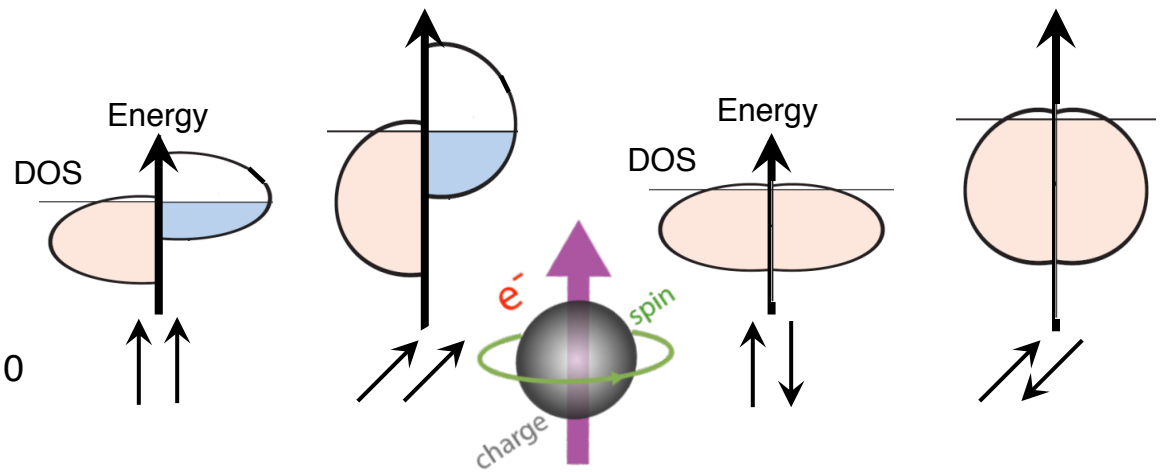
↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ⟶ Ferromagnetic exchange coupling, order by **global** uniform molecular field

↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓ ↑ ⟶ Antiferromagnetic exchange coupling, order by **local** (atomistic) molecular field

Curie-Weiss law $1/\chi \sim T - \theta$

Ferromagnetic & Antiferromagnetic: **Relativistic** coupling between spin and lattice orbitals ⟶ magnetic anisotropy ⟶ magnetic memory



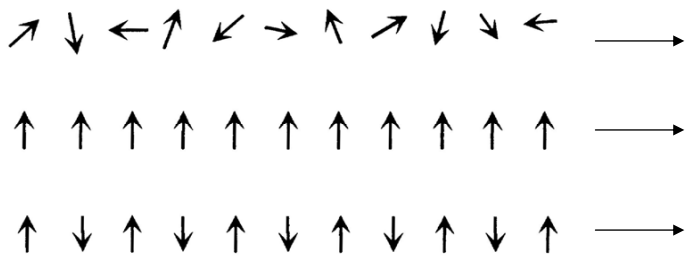


Ferromagnets ⇔ Antiferromagnets for ~ M^2 - effects

Nobel Lecture, December 11, 1970

LOUIS NÉEL

Magnetism



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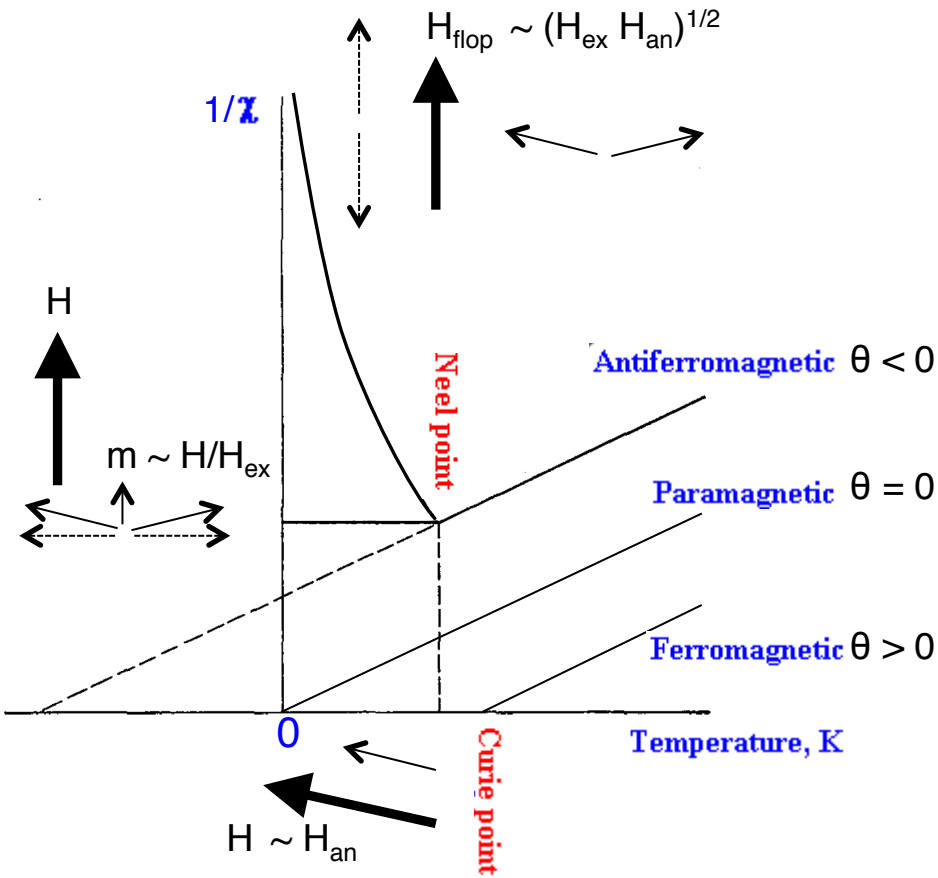


Ferromagnetic: Memory, large net magnetic moment sensitive to magnetic fields

⟶ many applications, **spintronics** one of them

Antiferromagnetic: Memory but zero net magnetic moment insensitive to magnetic fields

Paramagnetic: No memory, not very sensitive to magnetic fields

Magnetism

Paramagnetic no spontaneous order

Ferromagnetic exchange coupling, order by **global** uniform molecular field

Antiferromagnetic exchange coupling, order by **local** (atomistic) molecular field

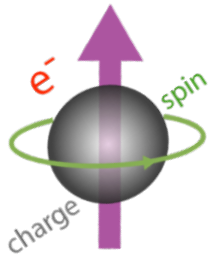
Antiferromagnets are interesting and useless

Nobel Lecture, December 11, 1970

LOUIS NÉEL

Antiferromagnetic (paramagnetic) spintronics:
Makes antiferromagnets (paramagnets) useful and spintronics more interesting

Let electrons with their spins move and relativistic spin-orbit coupling will take care of the rest….



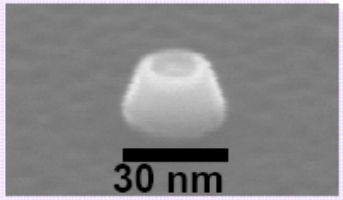
Spintronics: ferromagnets

MRAM: universal memory

Radiation-hard
Spin not charge-based

Non-volatile
as Flash

Dense
as DRAM
10nm possible

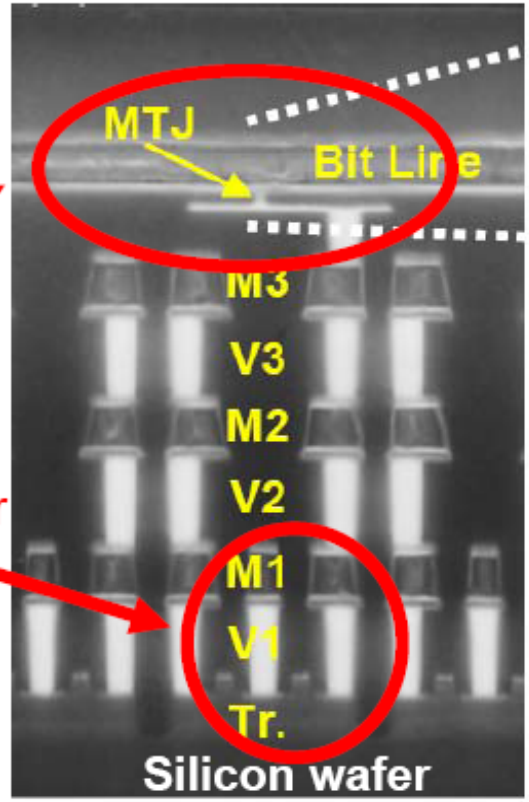


Cyclability
(nb write cycles>10^{16})
as DRAM

Speed (~1-10ns)
as SRAM Cache L3-L2

Compatible with CMOS

Cross sectional view
of a MRAM cell



Magnetic
element level

CMOS Transistor

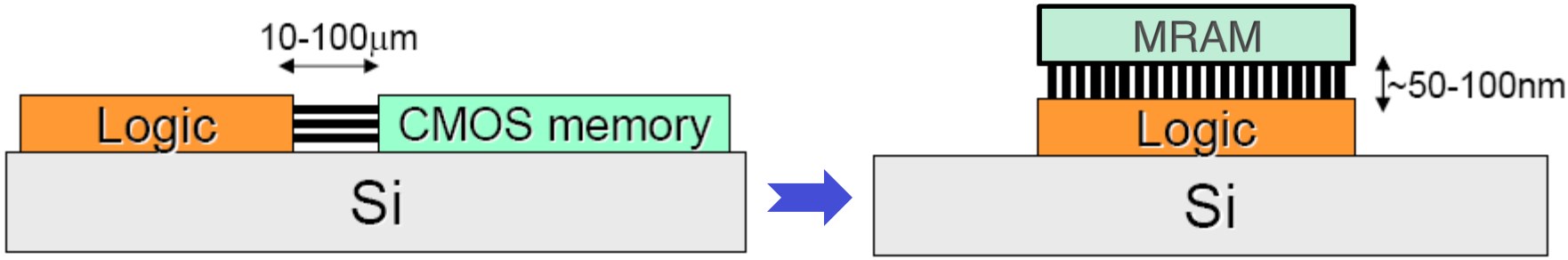
GB MRAMs: few years prospect

Spintronics: ferromagnets

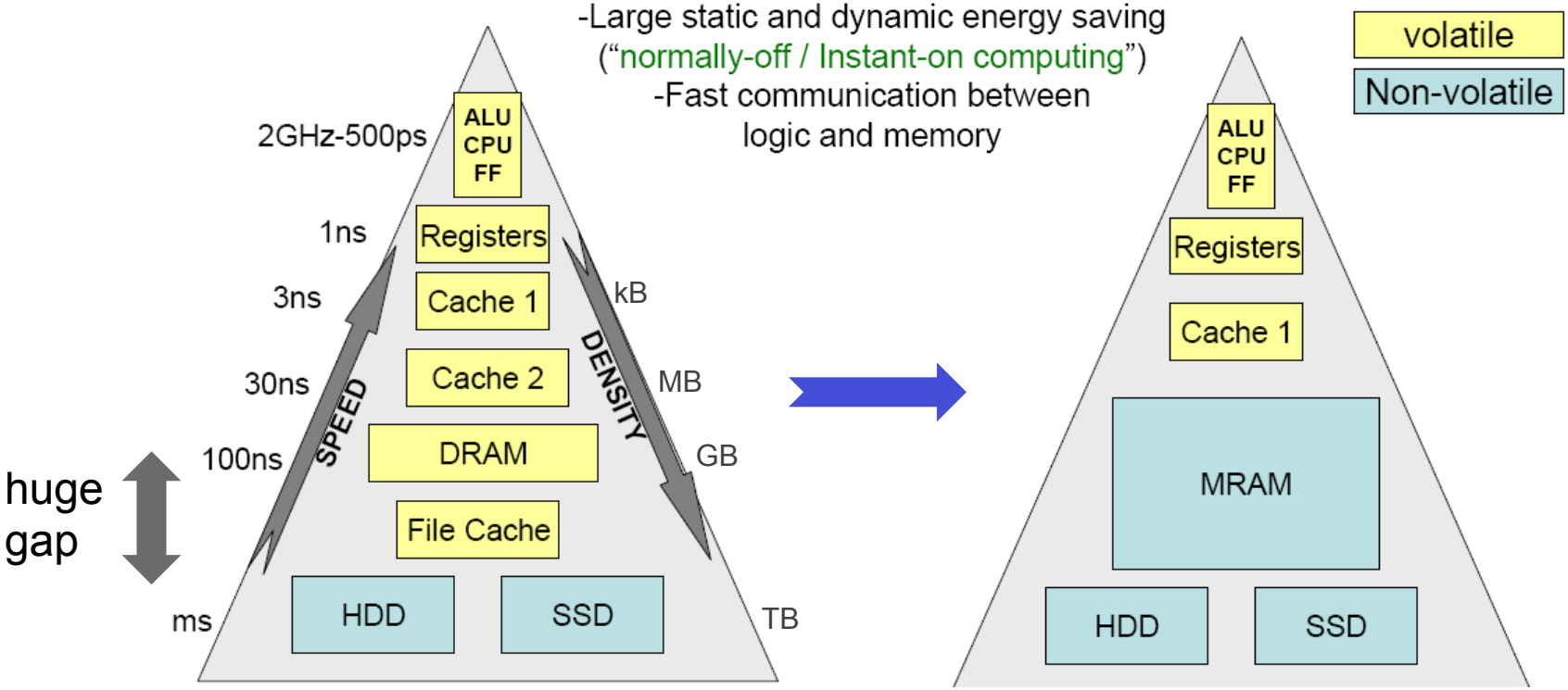
Conventional architecture with CMOS

New architectuture with MRAM

"Logic-in memory"



-Memory much closer to logic
-Large static and dynamic energy saving
("normally-off / Instant-on computing")
-Fast communication between
logic and memory



Spintronics: ferromagnets

Conventional architecture with CMOS

New architectuture with MRAM

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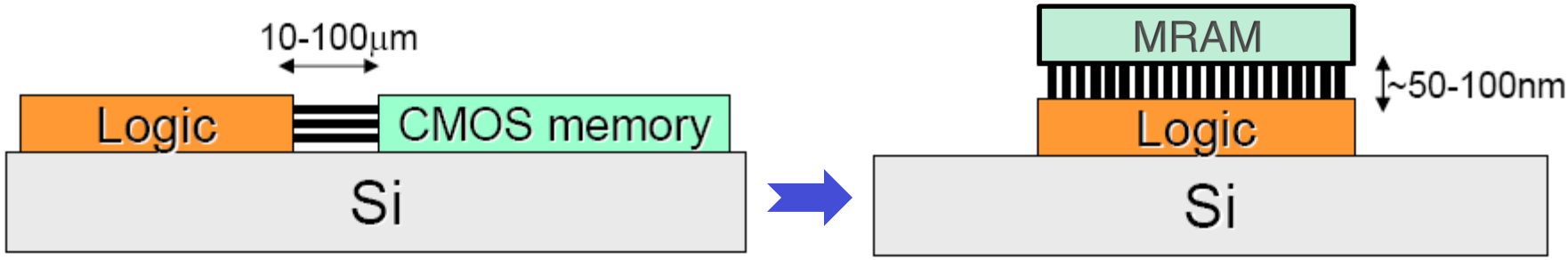
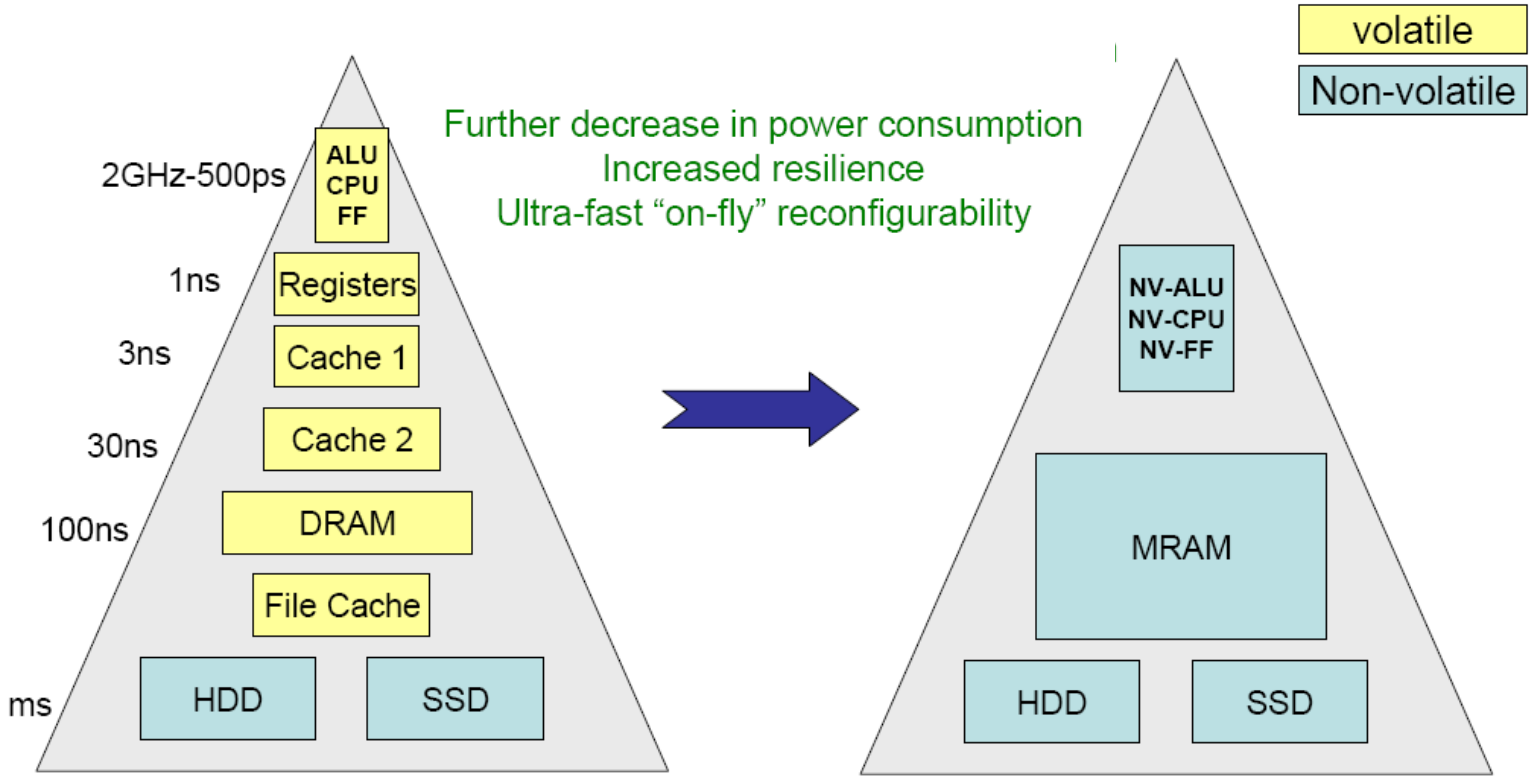
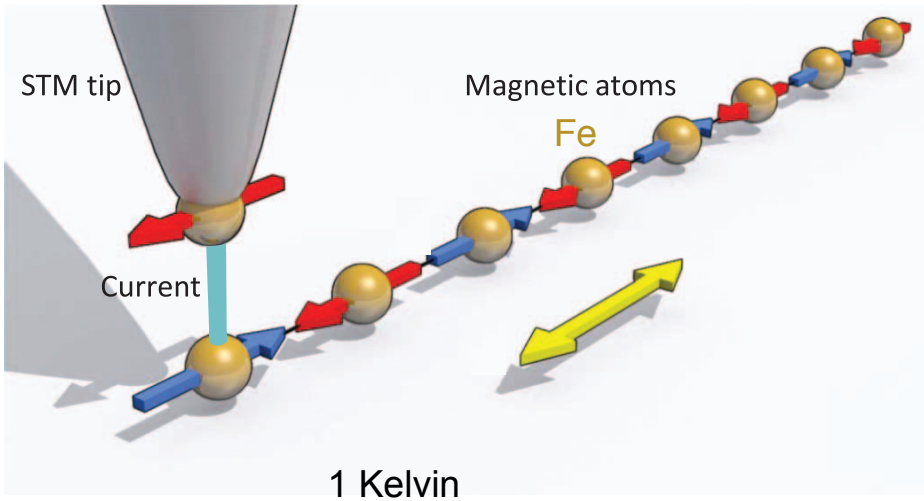


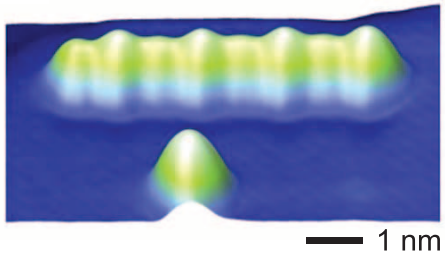


Spintronics: antiferromagnets

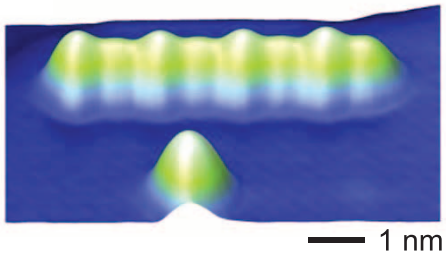
Local (atomistic) control by local current



Néel State '0'



Néel State '1'



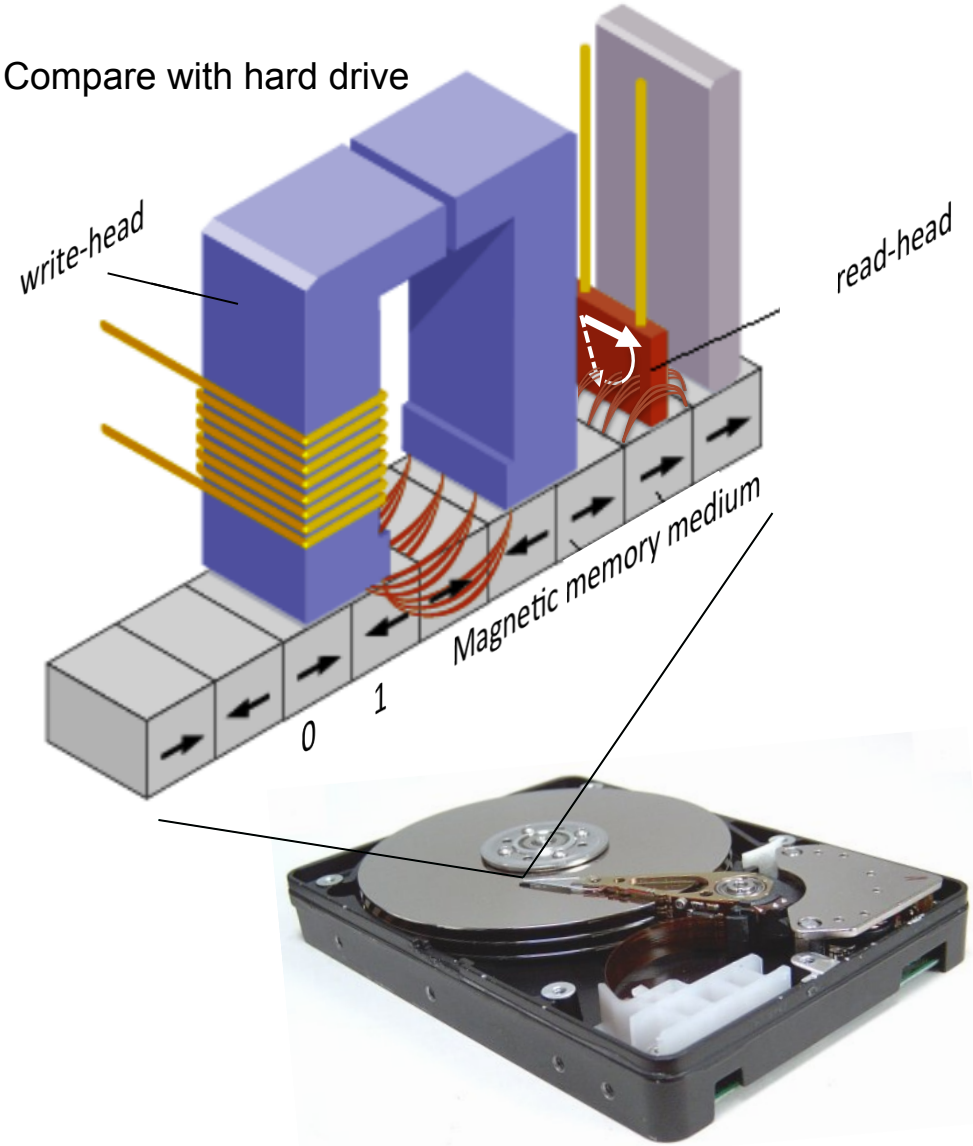
Mechanical "atomistic HD"
→ only in labs

Incompatible with
microelectronic chips

Only few magnetic atoms
→ $E_{an} * V << \text{room-T}$

Loth et al. Science '12

Compare with hard drive



Spintronics: antiferromagnets

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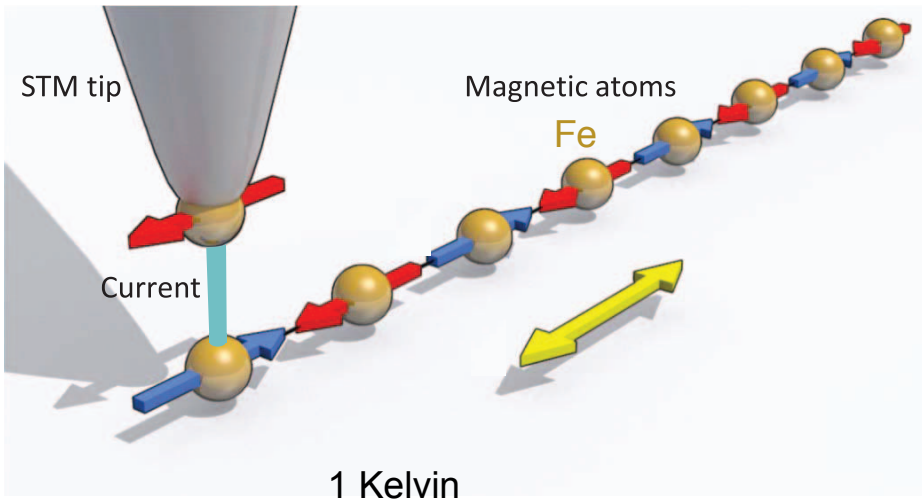

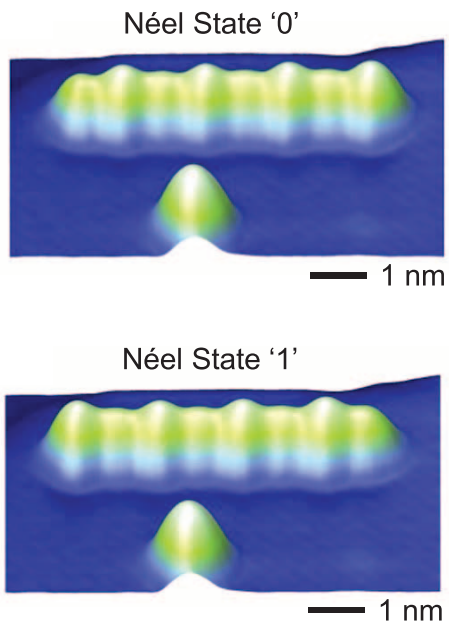

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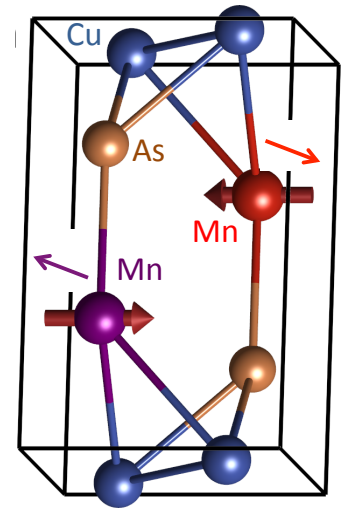
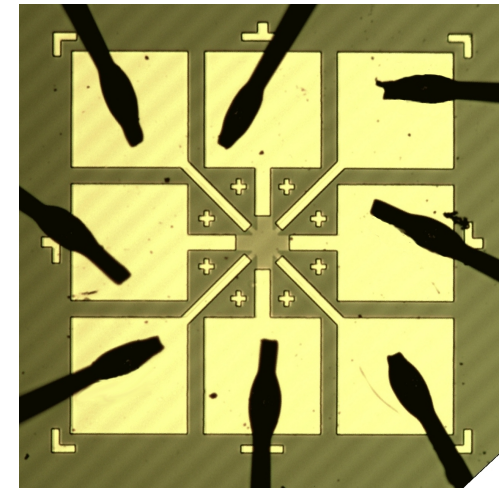
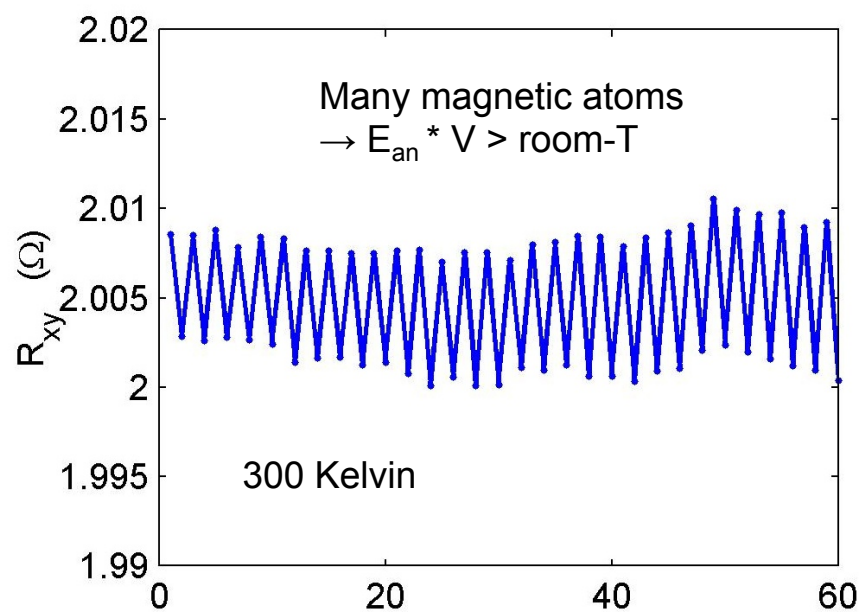
Loth et al. Science '12

Local (atomistic) control by global current

Microelectronic solid-state chip







Wadley et al. arXiv '15

Spintronics: antiferromagnets

Radiation-hard
Spin not charge-based

Magetic-field-hard
Not ferromagnetic

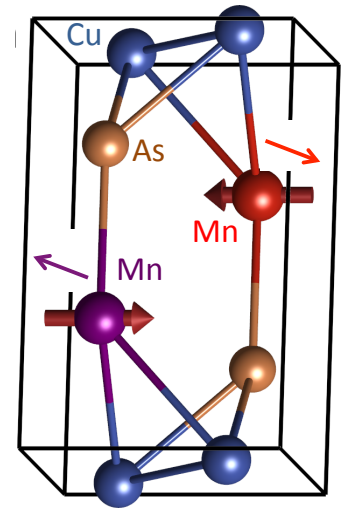
No stray field cross-talk
Not ferromagnetic

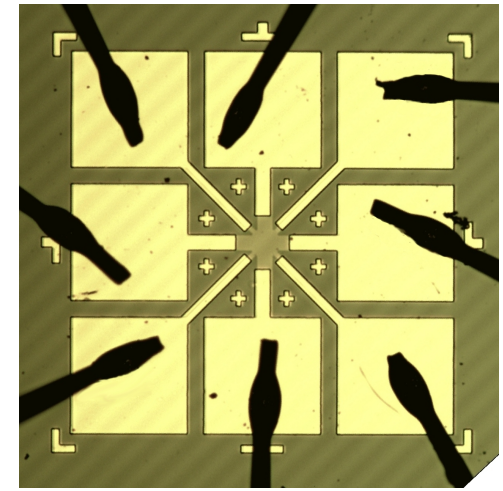
THz dynamics
GHz in ferromagnets

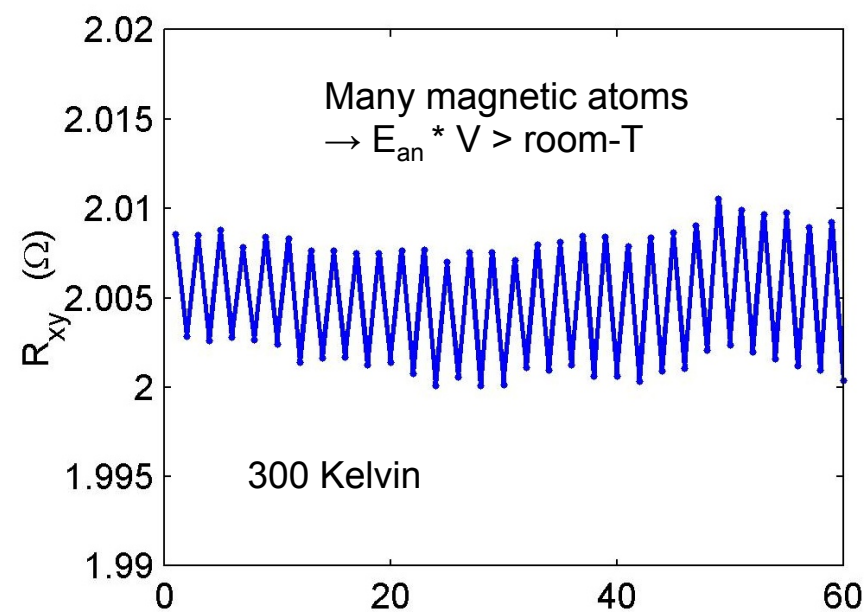
Many insulators, semiconductors, metals, superconductors
Ferromagnets mostly metals

Local (atomistic) control by global current

Microelectronic solid-state chip







Wadley et al. arXiv '15

Ferromagnetic and antiferromagnetic semiconductors

II-VI	FM T_C (K)	AFM T_N (K)
MnO		122
MnS		152
MnSe		173
MnTe		**323**
EuO	67	
EuS	16	
EuSe		5
EuTe		10

I-VI-III-VI	FM T_C (K)	AFM T_N (K)
$CuFeO_2$		11
$CuFeS_2$		**825**
$CuFeSe_2$		70
$CuFeTe_2$		254

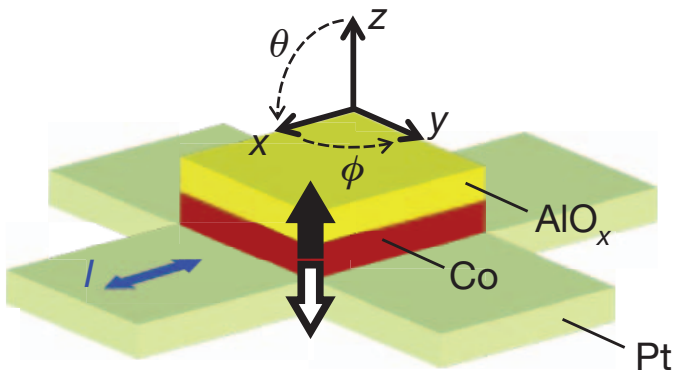
III-V	FM T_C (K)	AFM T_N (K)
FeN		100
FeP		115
FeAs		77
FeSb		100-220
GdN	72	
GdP		15
GdAs		19
GdSb		27

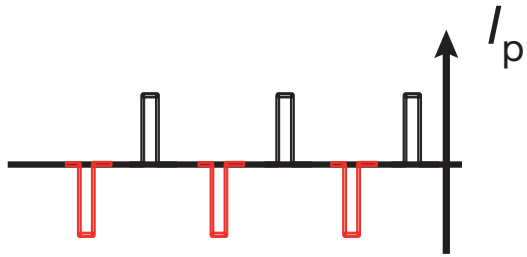
II-V-IV-V	FM T_C (K)	AFM T_N (K)
$MnSiN_2$		**490**

I-II-V	FM T_C (K)	AFM T_N (K)
Ia=Li, Na,.. Ib=Cu II=Mn V=Sb,As, P		**> room T**

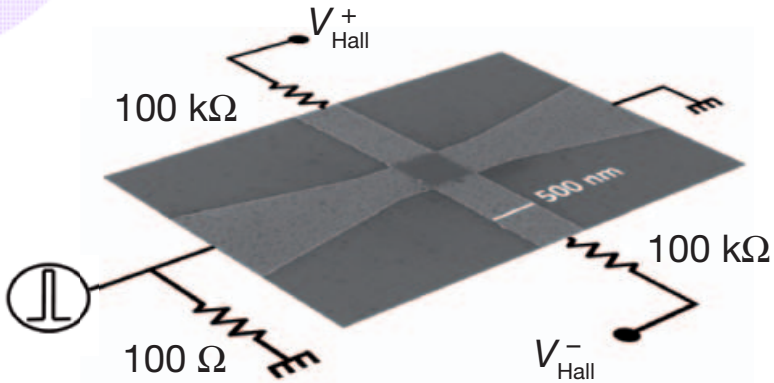
Spintronics: paramagnets

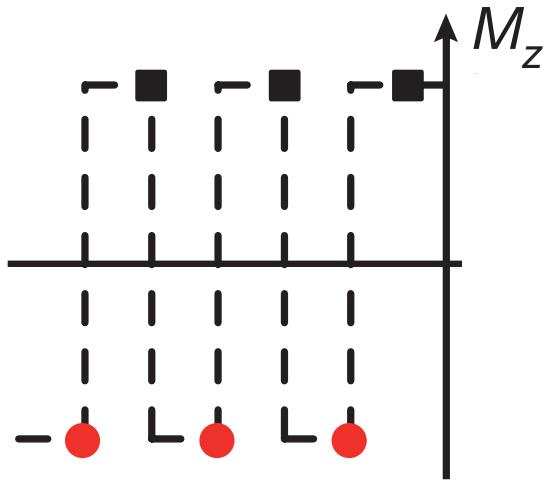
Ferromagnet switched by electrically generated spin-polarization in paramagnet





New efficient writing schemes





Miron et al. Nature '11, Liu et al. Science '12

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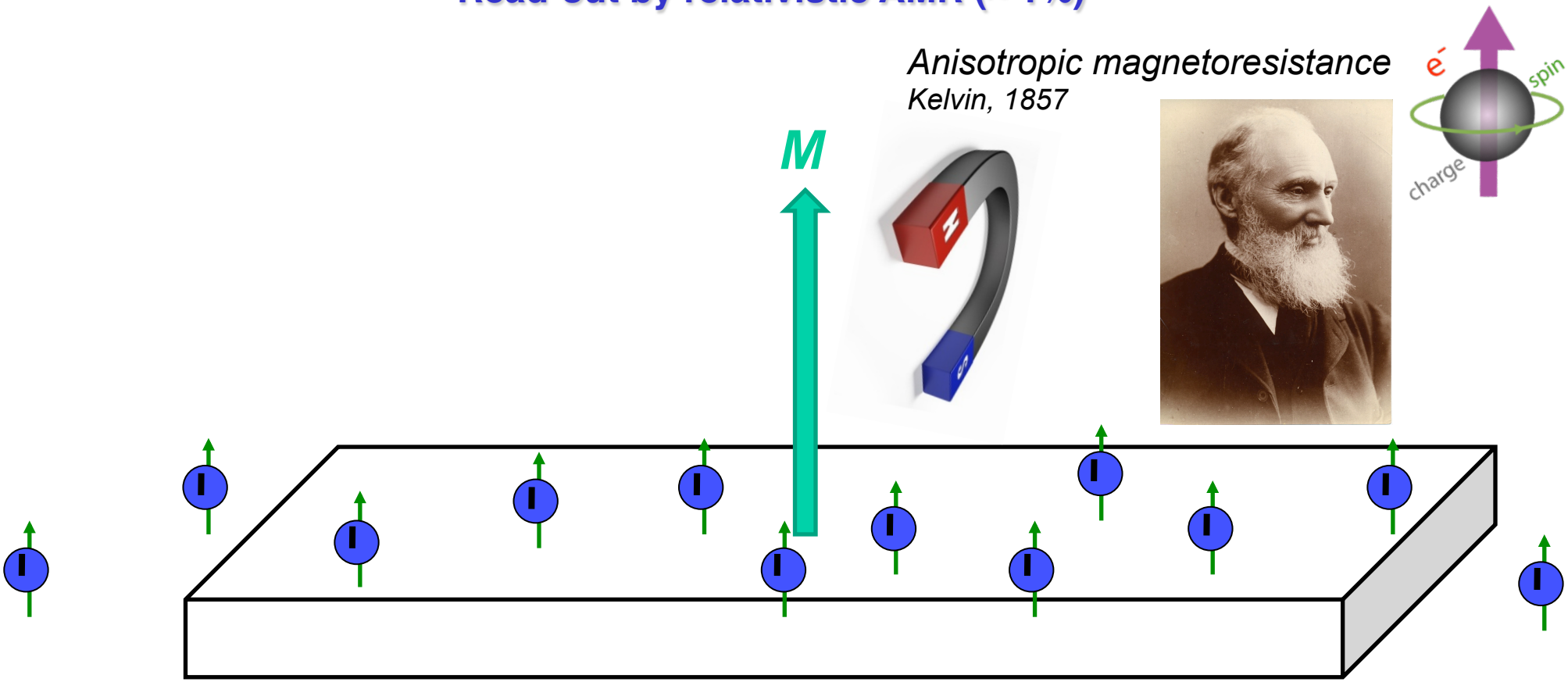
3. Writing spin information

Read-out by relativistic AMR (~ 1%)

Anisotropic magnetoresistance
Kelvin, 1857



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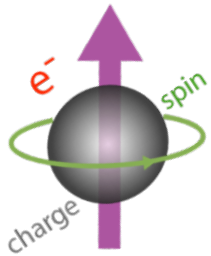

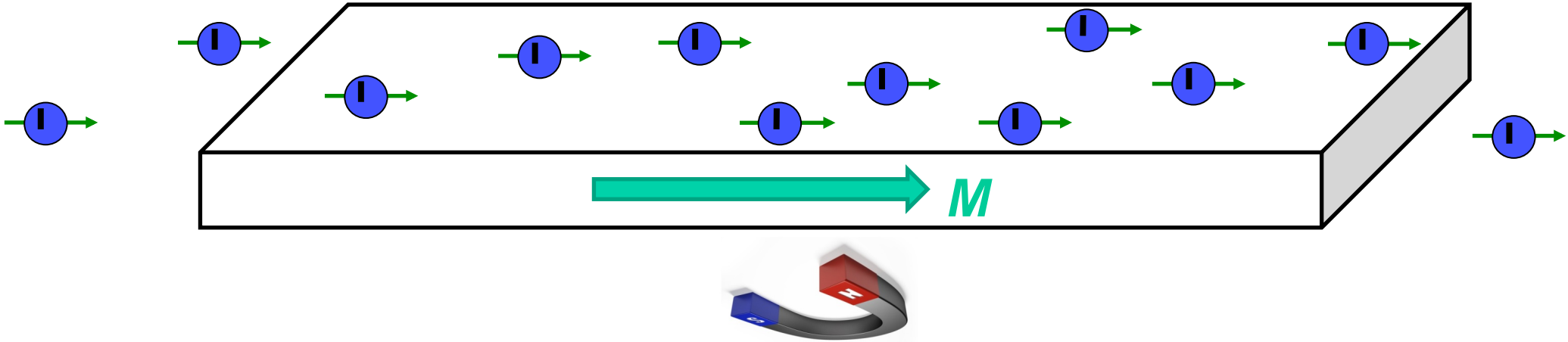

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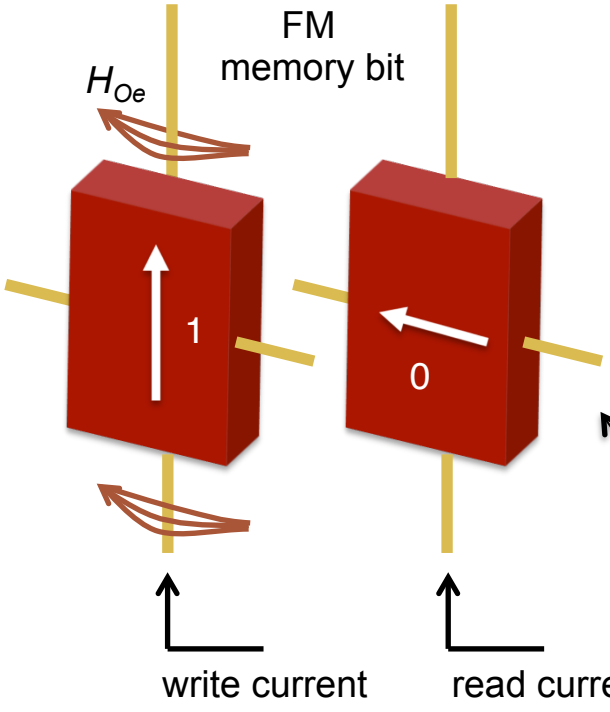

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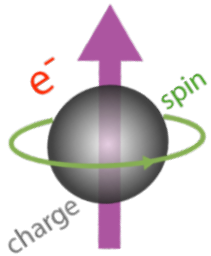
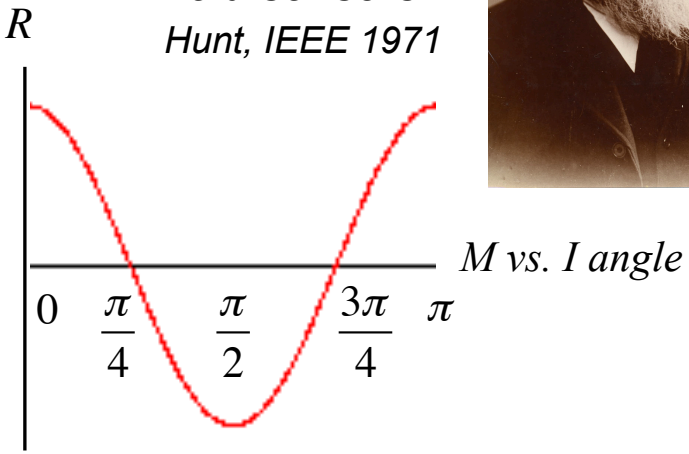
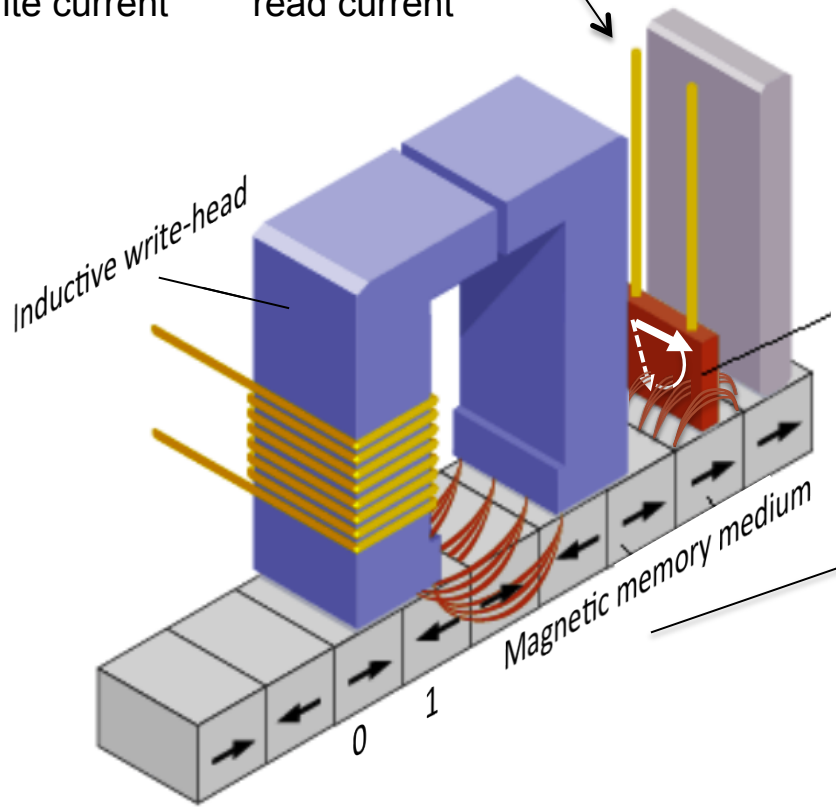


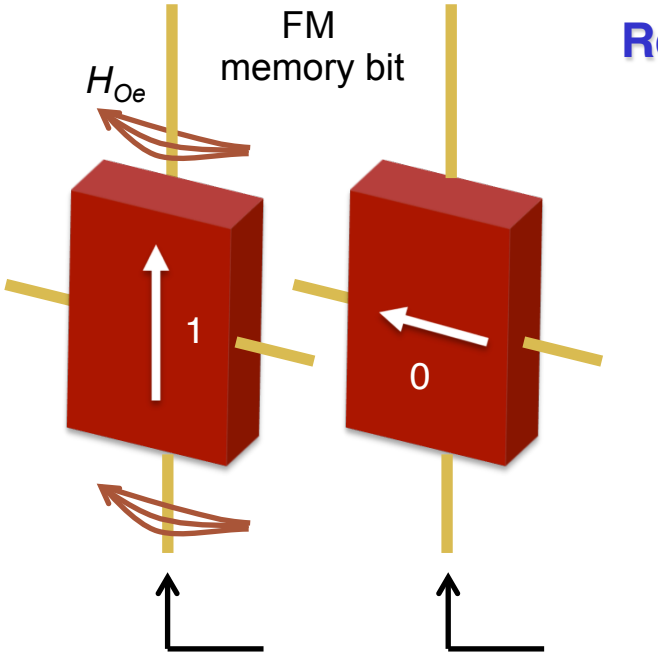
field sensors
Hunt, IEEE 1971



1980's



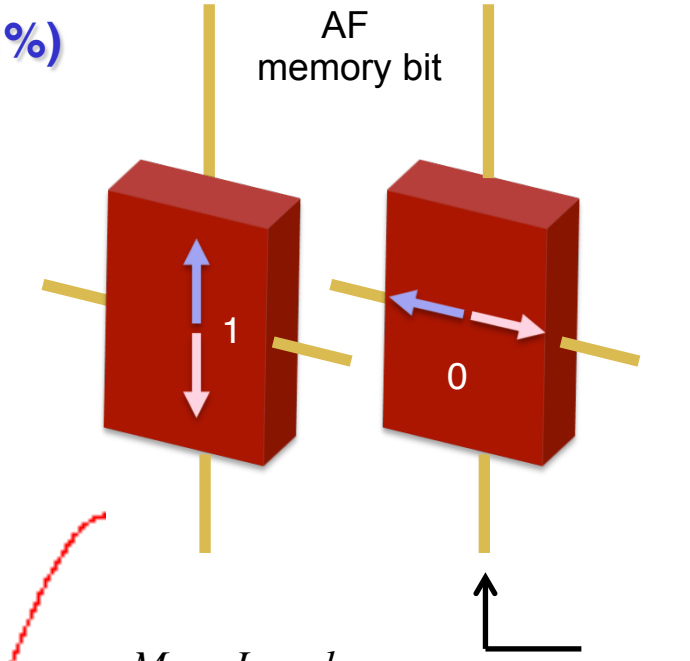
Read-out by relativistic AMR (~ 1%)

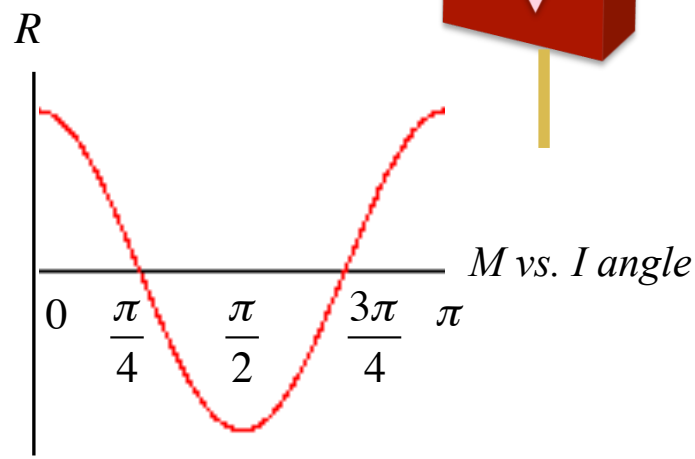


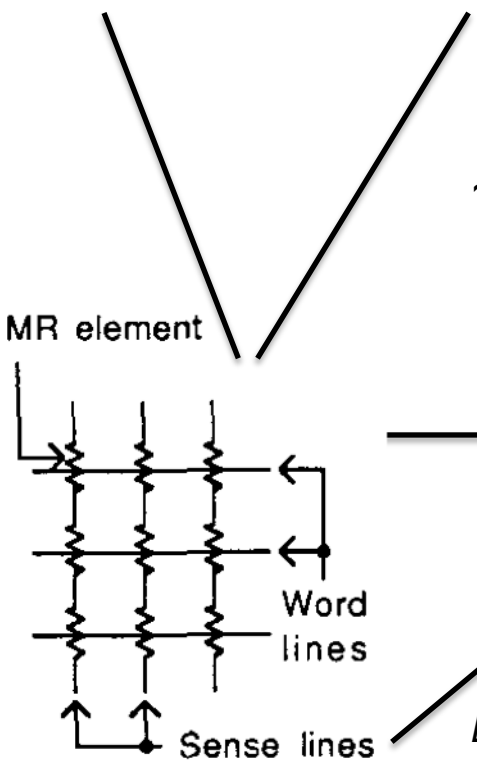
Storage: Magnetic anisotropy

Read-out: AMR

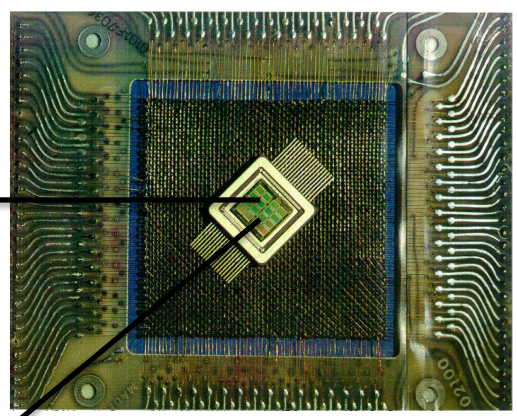
Even in M (L. Néel)





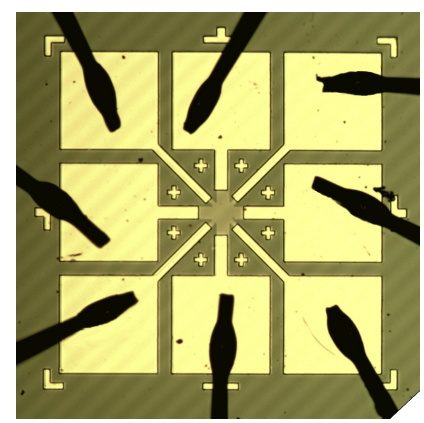


~ 100 kB FM AMR-MRAM



Daughton, Thin Solid Films '92

AF AMR- bits

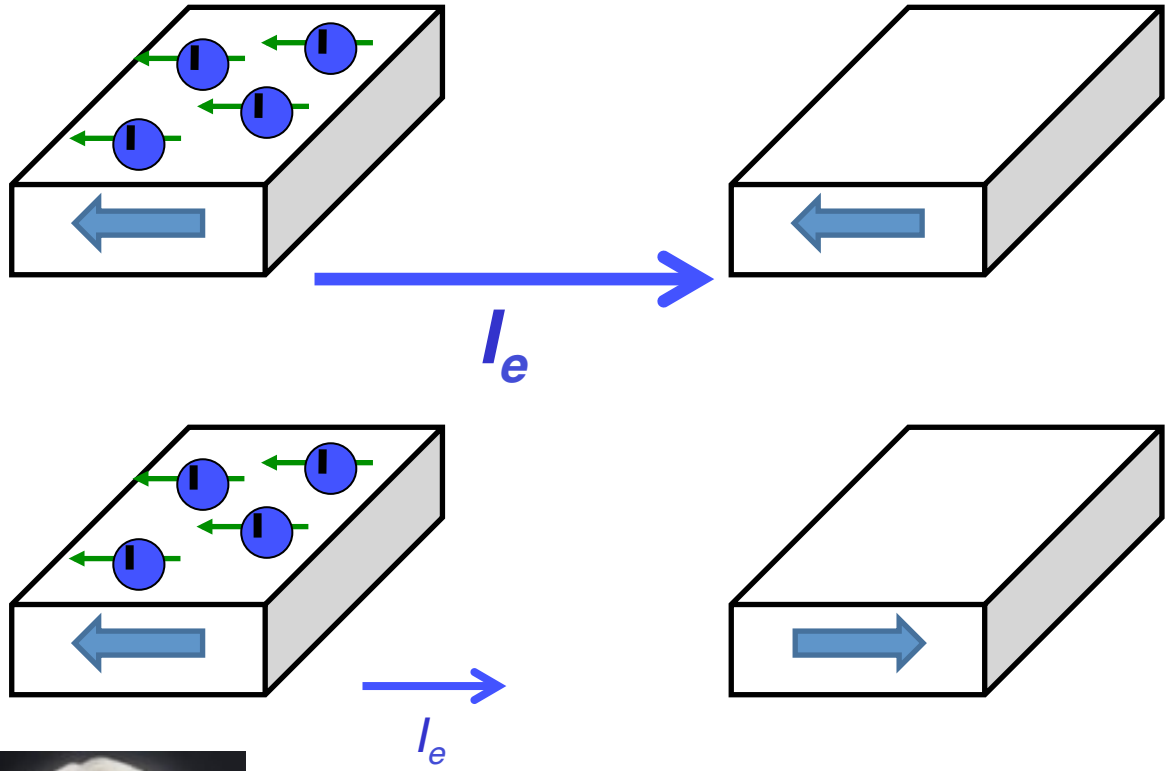


Marti et al. Nature Mater. '14, Wadley arXiv '15

Small MR and low reistance

→ unfavorable for high density and fast readout

Read-out by giant (~10%) or tunneling (~ 100%) magnetoresistance relies on spin but the rest is non-relativistic



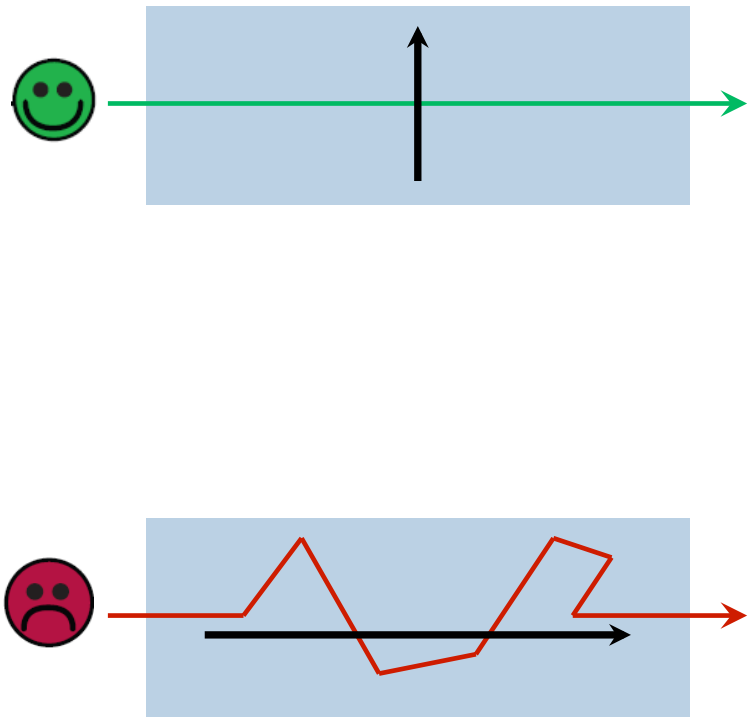
Giant magnetoresistance
Fert, Grünberg, et al. 1988

Read-out by giant (~10%) or tunneling (~ 100%) magnetoresistance relies on spin but the rest is non-relativistic

~1% anisotropic magnetoresistance

Kelvin, 1857

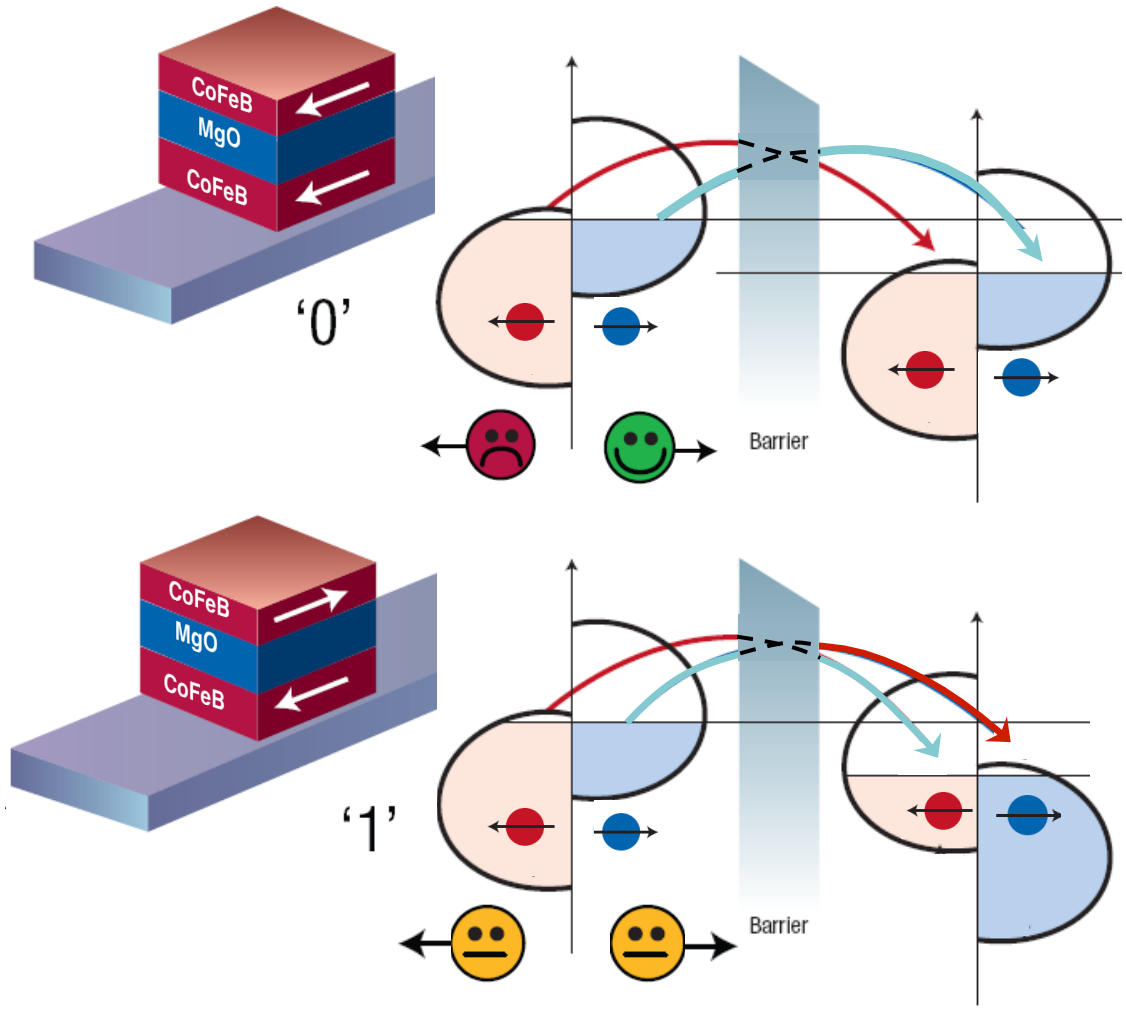
Spin-dependent scattering



~100% tunneling magnetoresistance

Julliere 1975, Moodera et al., Miyazaki & Tezuka 1995

Spin-dependent tunneling DOS

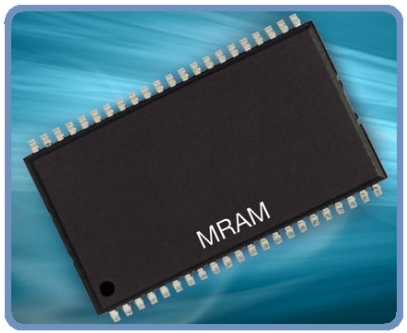


Read-out by giant (~10%) or tunneling (~ 100%) magnetoresistance relies on spin but the rest is non-relativistic

~100% tunneling magnetoresistance

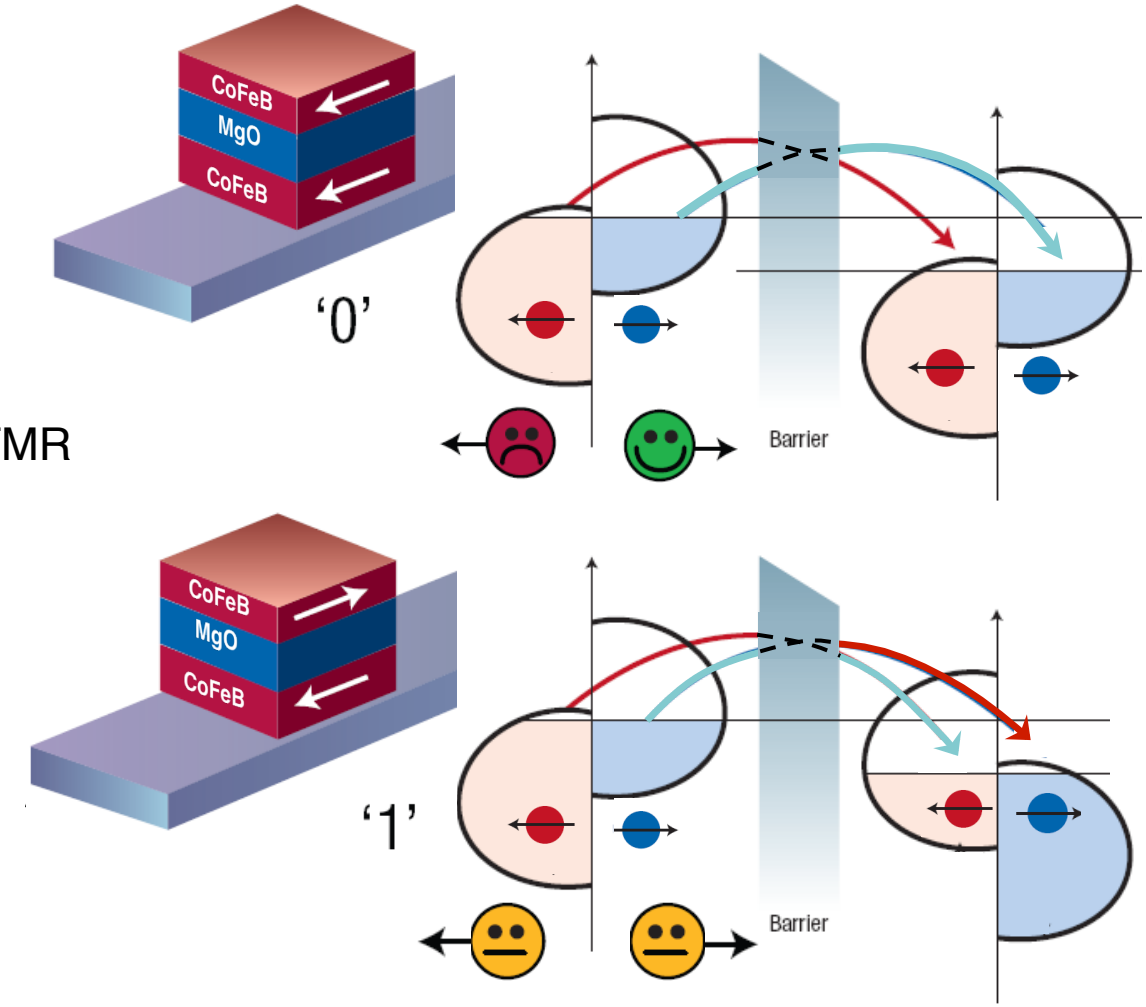
Julliere 1975, Moodera et al., Miyazaki & Tezuka 1995

TMR-MRAM
2006



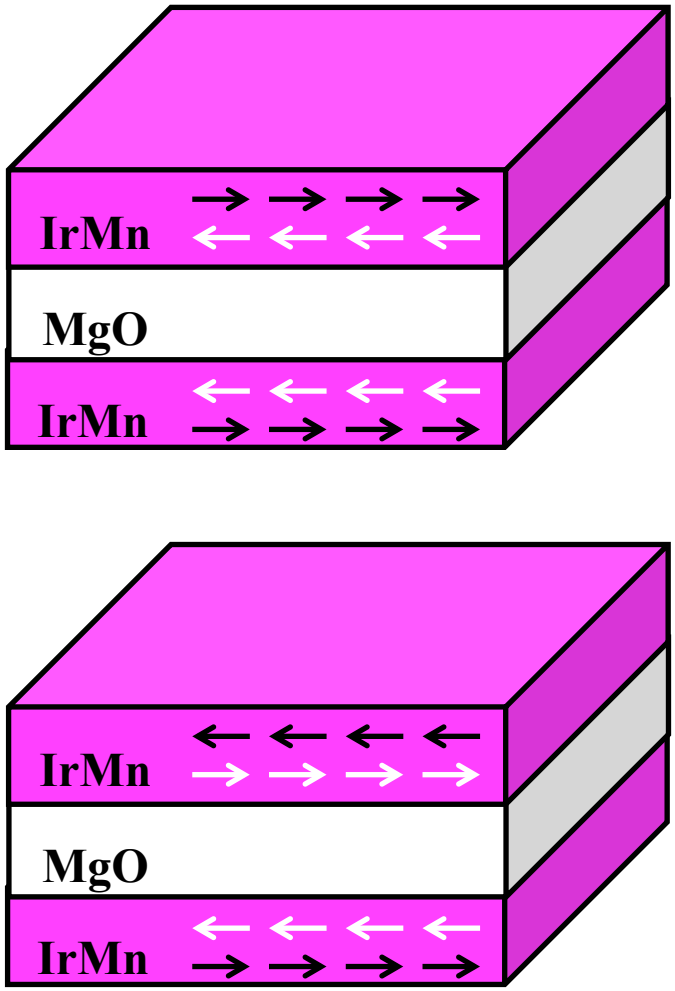
Enhanced Scalability due to large TMR

Spin-dependent tunneling DOS



Read-out by giant (~10%) or tunneling (~ 100%) magnetoresistance relies on spin but the rest is non-relativistic

Antiferromagnetic GMR/TMR



Relies on coherence at perfectly epitaxial interfaces

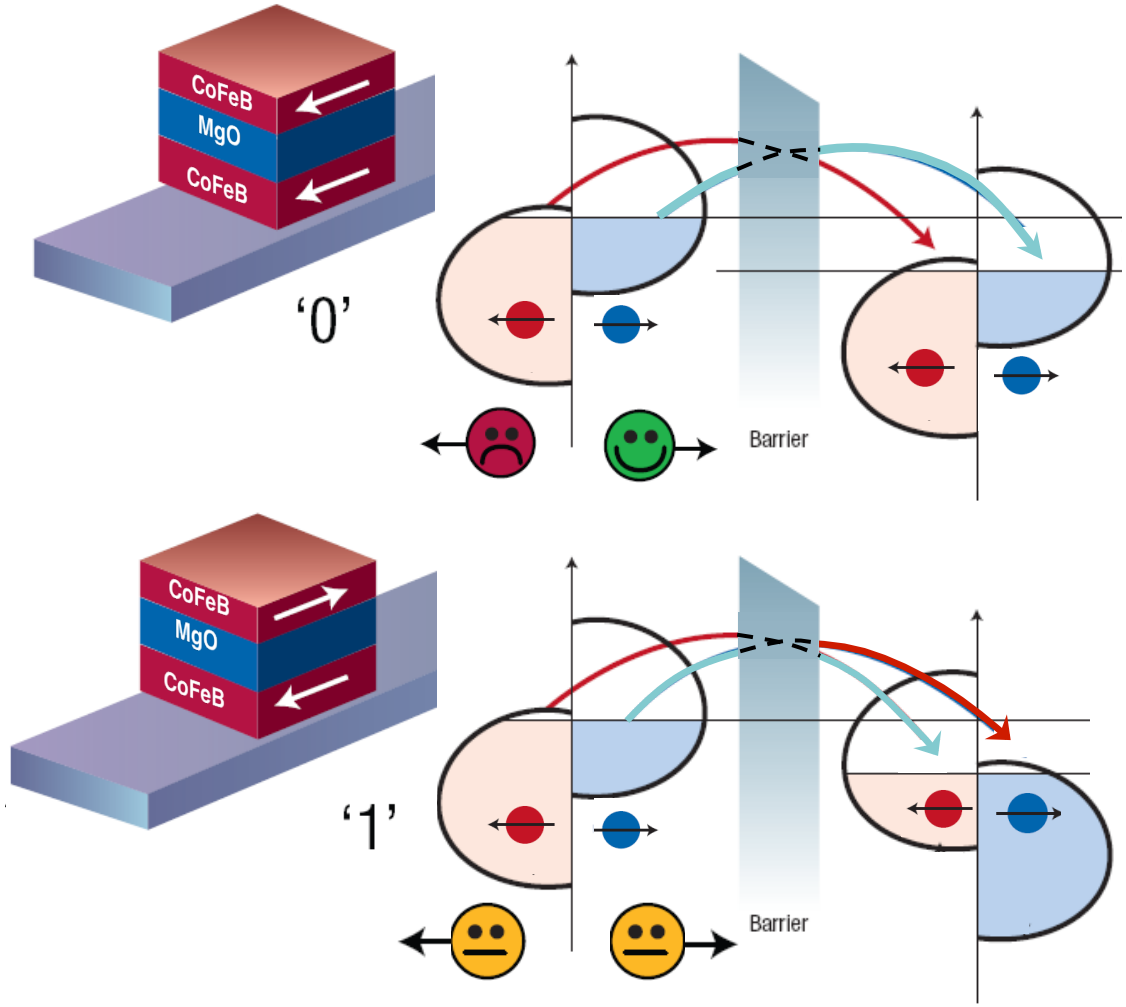
→ not yet observed

MacDonald & Tsoi, Philos. Trans. A PRL '11

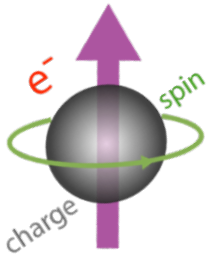
~100% tunneling magnetoresistance

Julliere 1975, Moodera et al., Miyazaki & Tezuka 1995

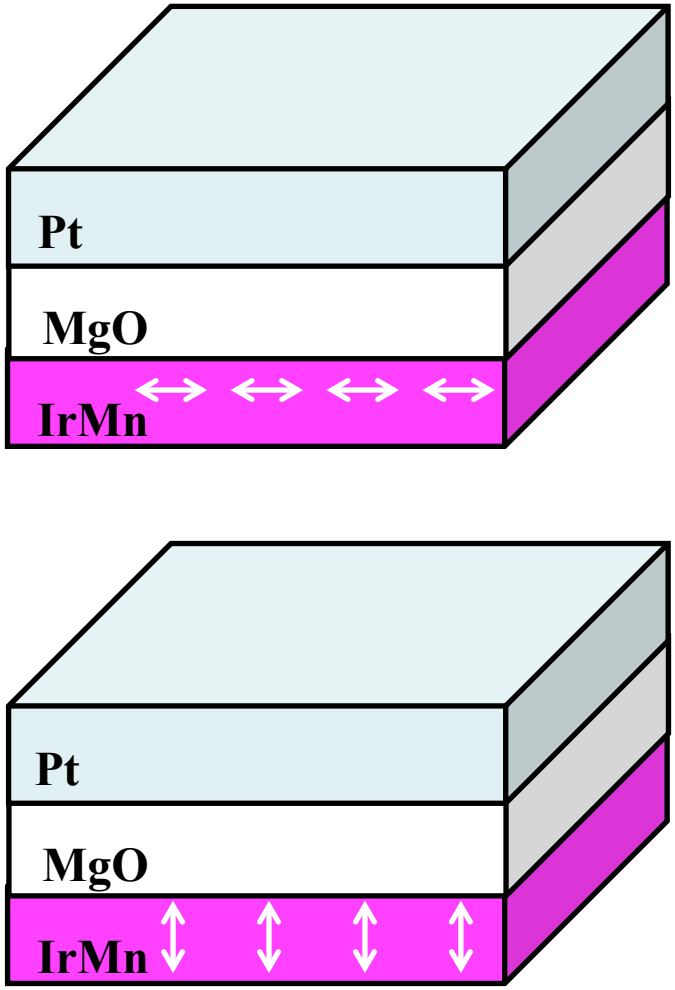
Spin-dependent tunneling DOS



Read-out by relativistic tunneling/transistor AMR (can be << 100%)



Antiferromagnetic GMR/TMR

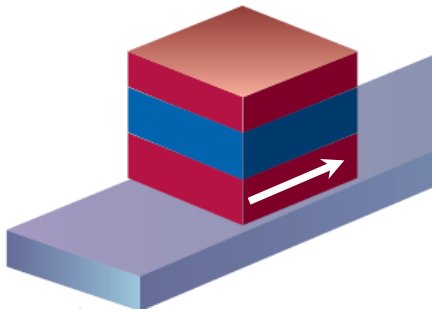


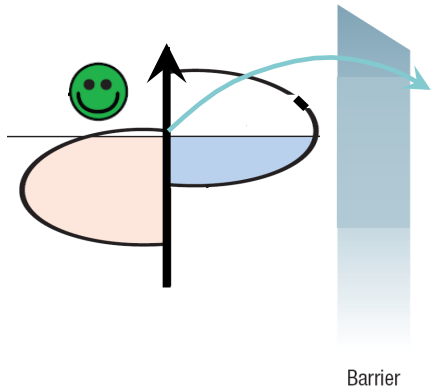
Tunneling AMR in ferromagnet

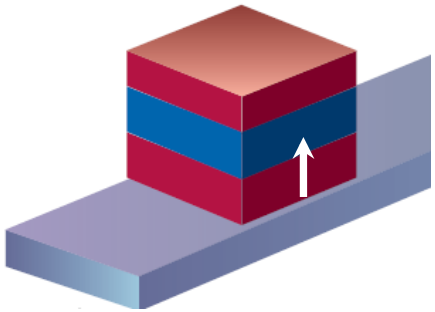
Gould et al. PRL '04

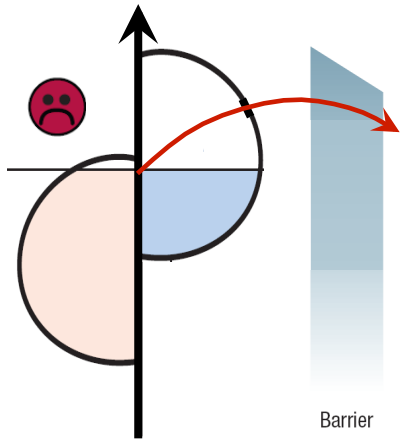
Spin-dependent tunneling DOS

Even in M (L. Néel)





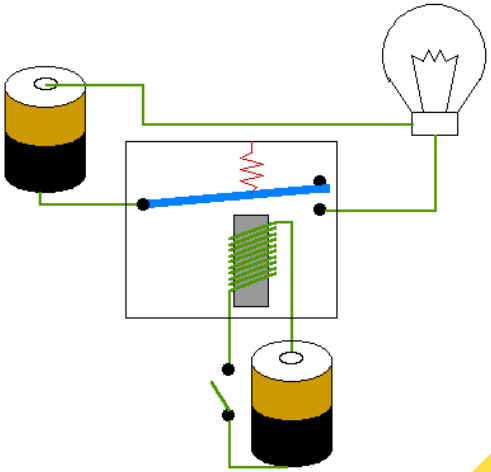




Does not rely on coherence at perfectly epitaxial interfaces

→ TAMR > 100 % observed

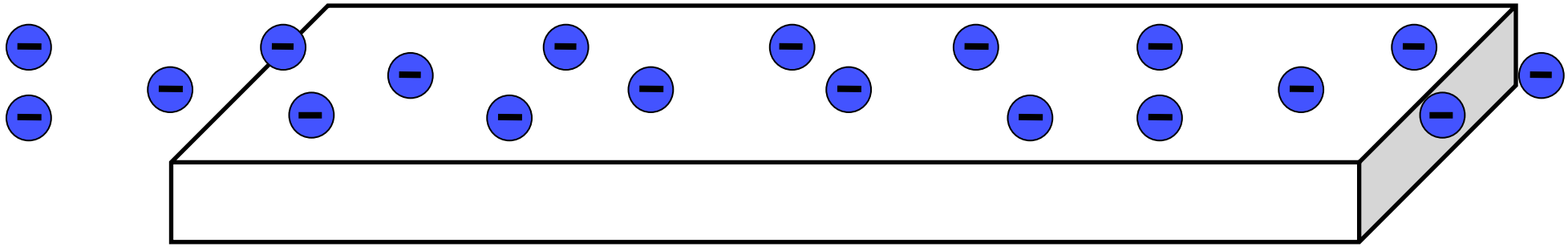
Park et al., Nature Mater. '11

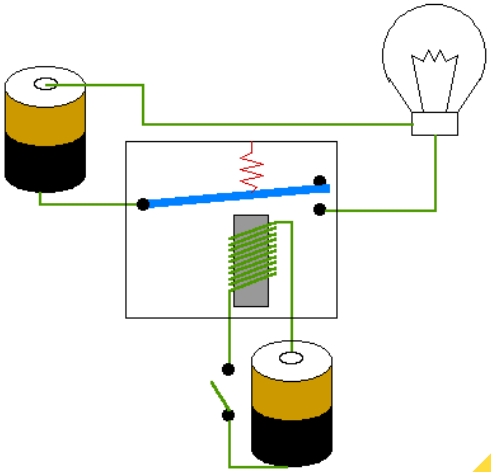


Read-out by relativistic tunneling/transistor AMR (can be << 100%)

Transistor AMR in ferromagnet

Wunderlich et al. PRL '06, APL '12





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Transistor AMR in ferromagnet

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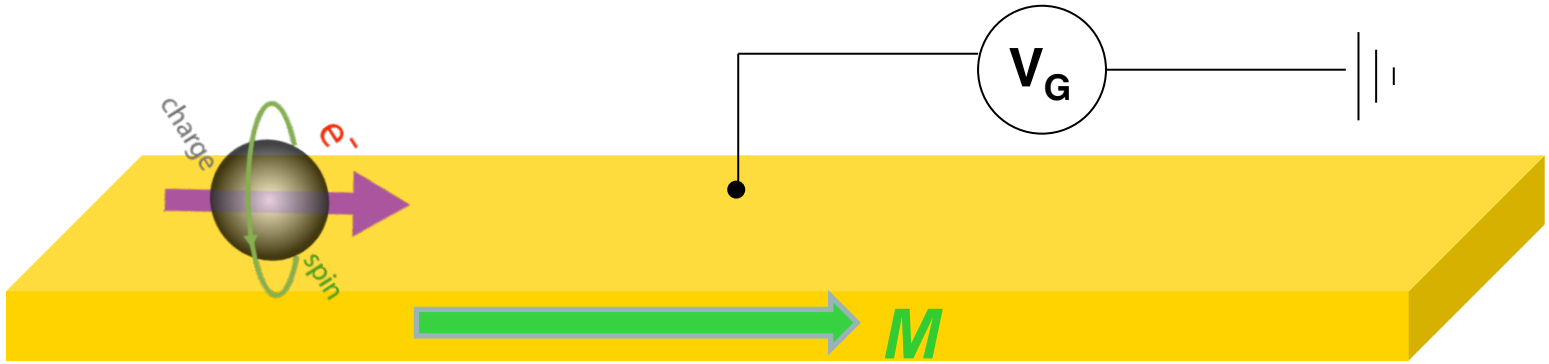
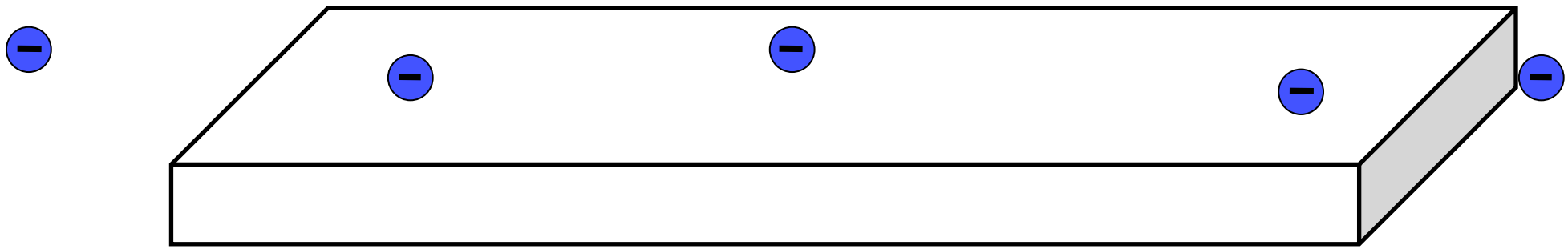
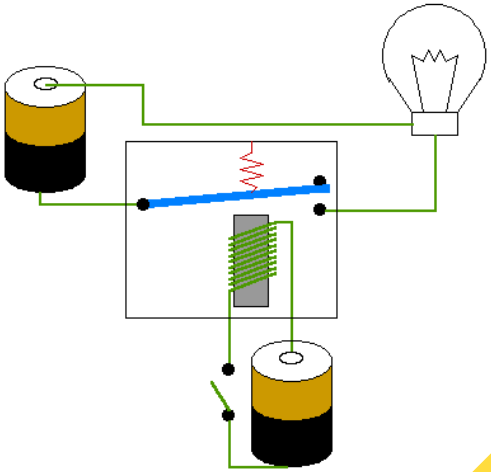


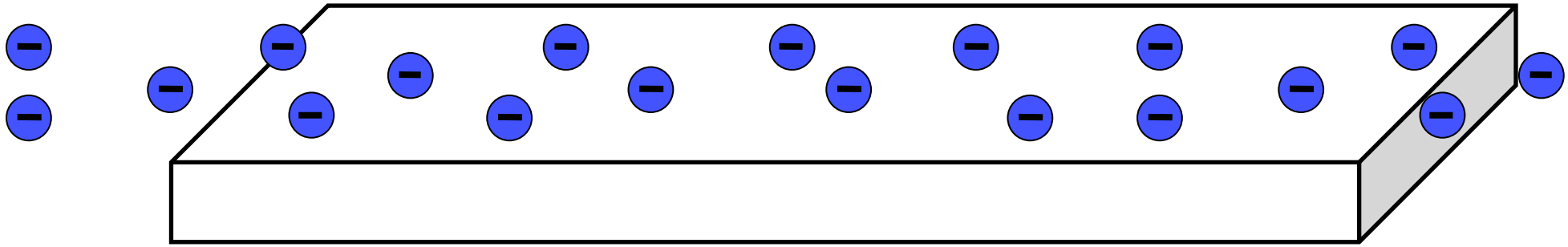




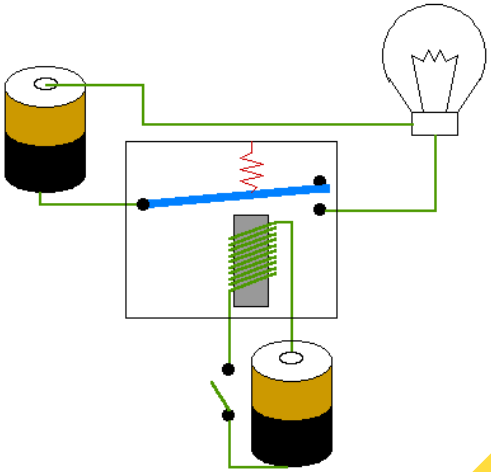
Read-out by relativistic tunneling/transistor AMR (can be << 100%)

Transistor AMR in ferromagnet

Wunderlich et al. PRL '06, APL '12

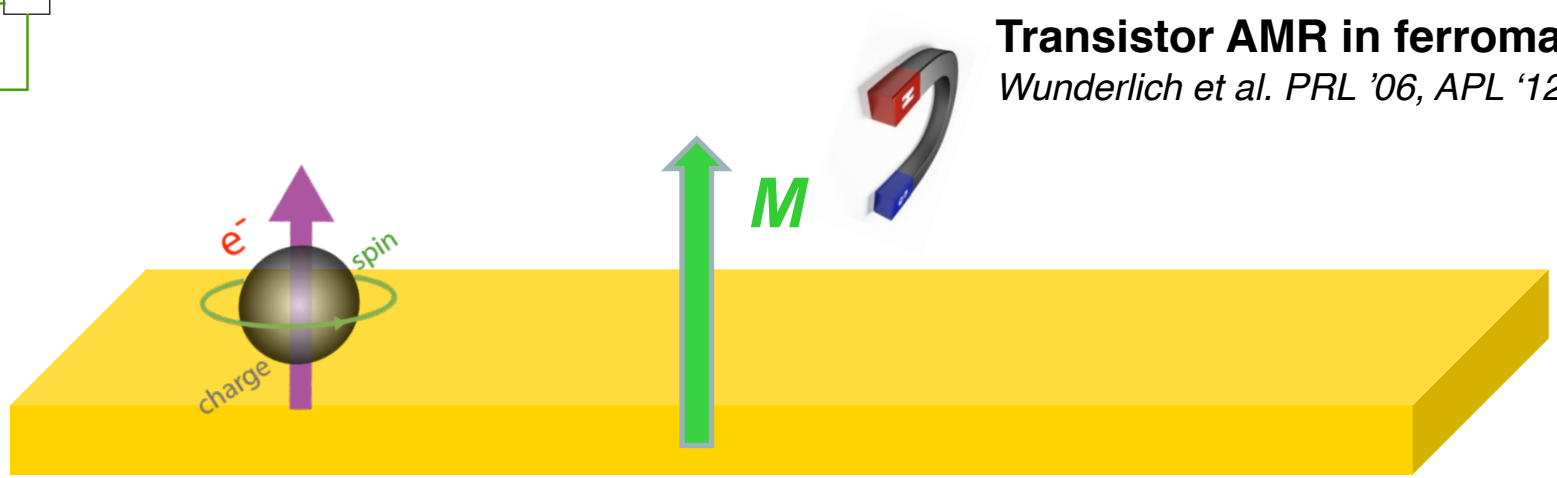


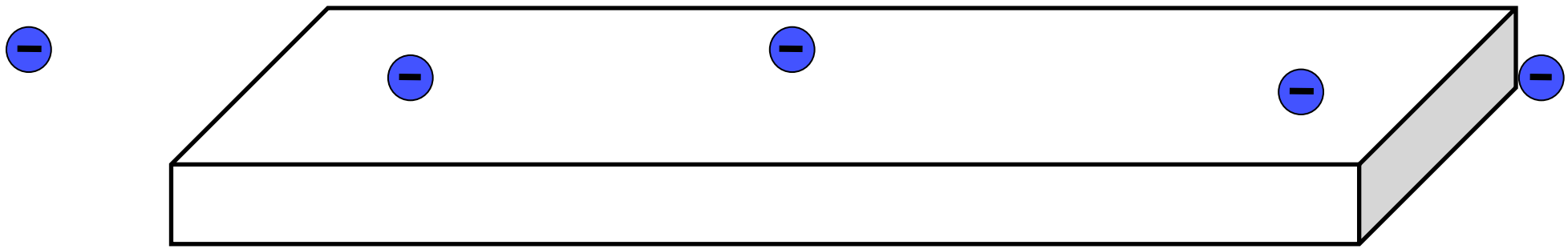
Read-out by relativistic tunneling/transistor AMR (can be << 100%)



Transistor AMR in ferromagnet

Wunderlich et al. PRL '06, APL '12





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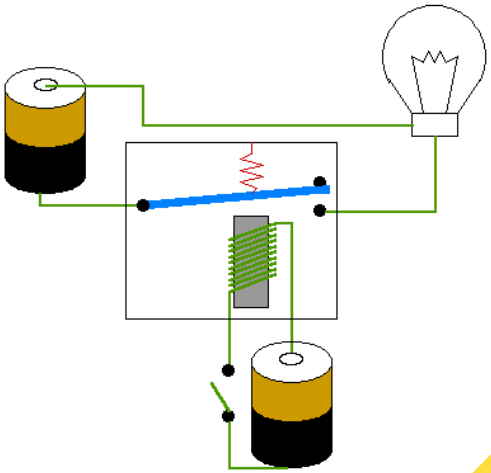
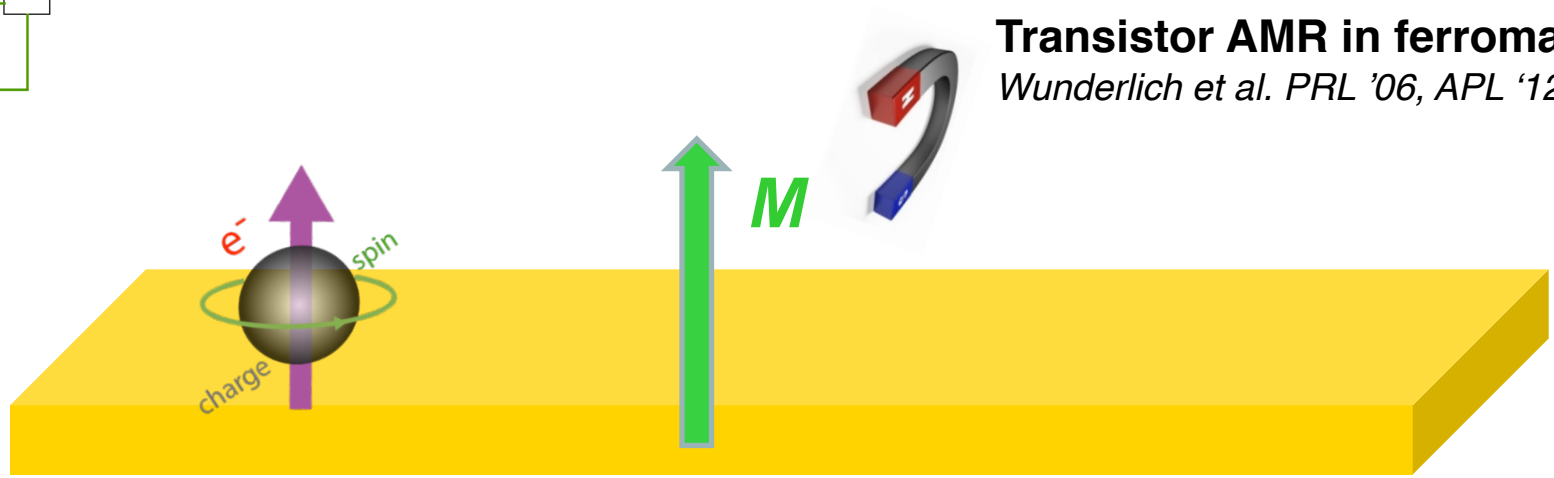
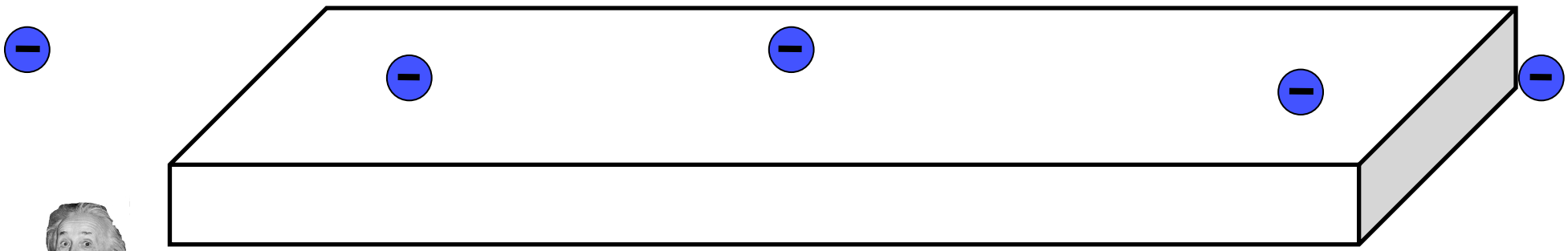
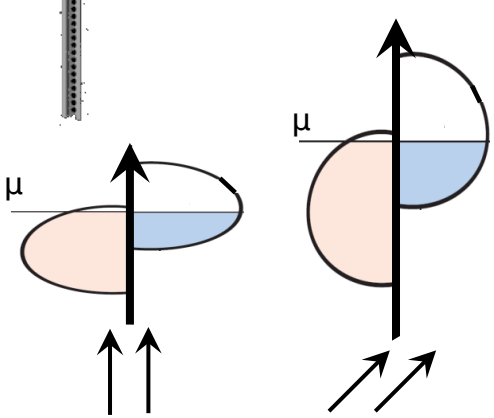


Transistor AMR in ferromagnet

Wunderlich et al. PRL '06, APL '12





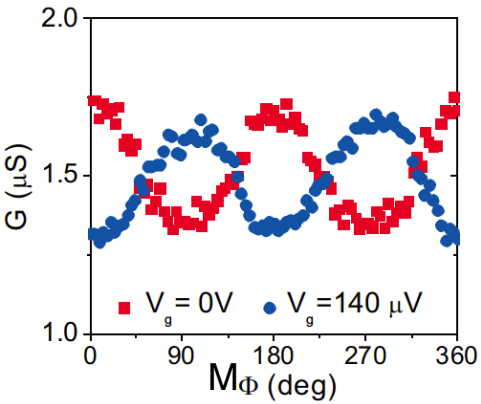


Article Talk

Spintronics

From Wikipedia, the free encyclopedia

Spintronics (a portmanteau meaning "spin transport electronics"[1][2][3])

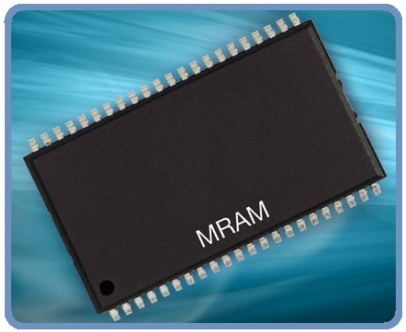


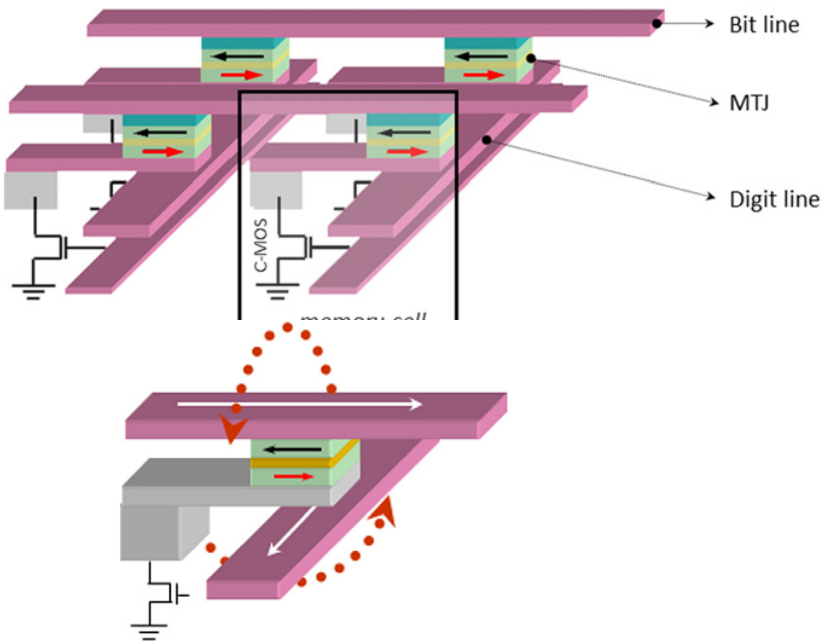
Outline

1. Relativistic QM, magnetism, and spintronics with ferro, antiferro, and paramagnets
2. Reading spin information
3. Writing spin information

Writing by magnetic field

Ferromagnetic AMR/TMR-MRAMs

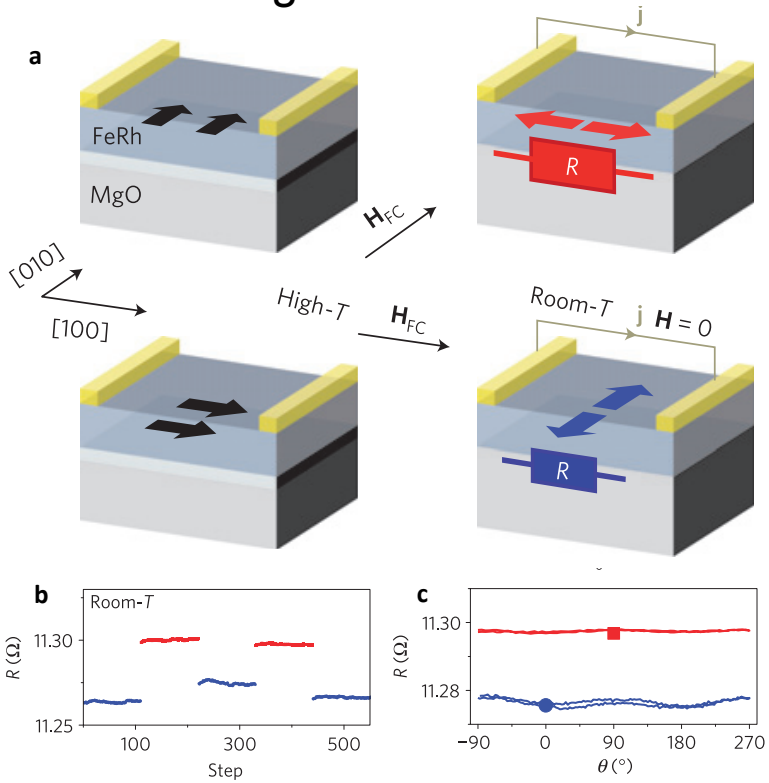




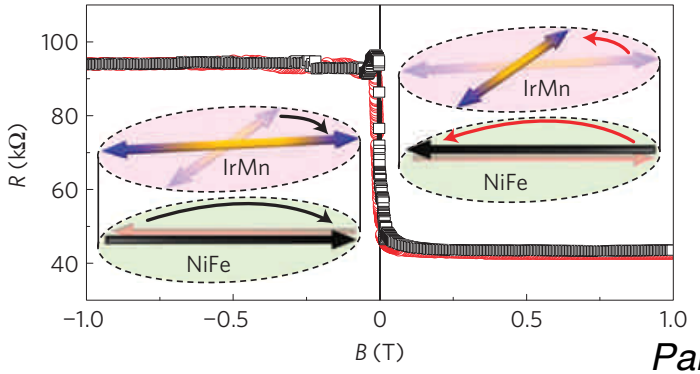
Magnetic field scales with current

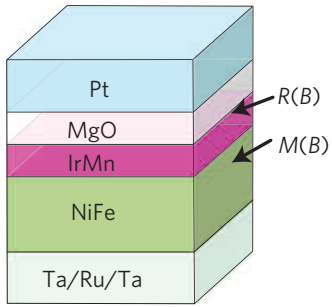
→ not scalable for high-density MRAM

Antiferromagnetic AMR/TAMR bits



Marti et al. Nature Mater. '14

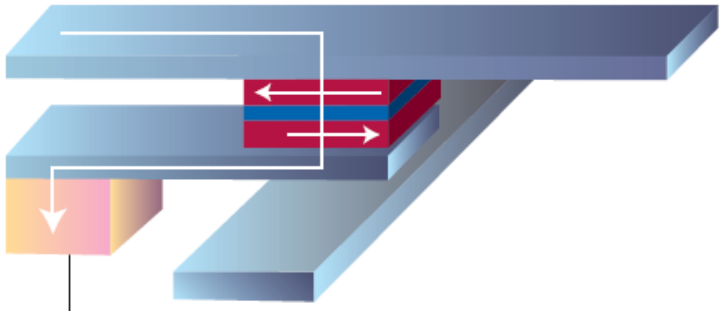




Park et al. Nature Mater '11

Writing by spin torque

Ferromagnetic TMR-ST-MRAMs

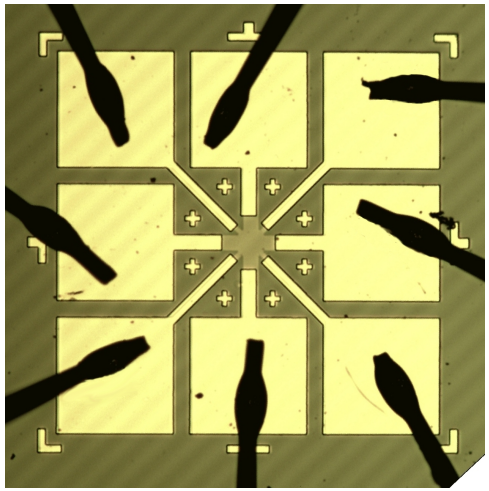


ST scales with current density

→ high-density MRAMs

Chappert et al. Nature Mater. '07

Antiferromagnetic AMR bits



ST in principle as efficient as in ferromagnets

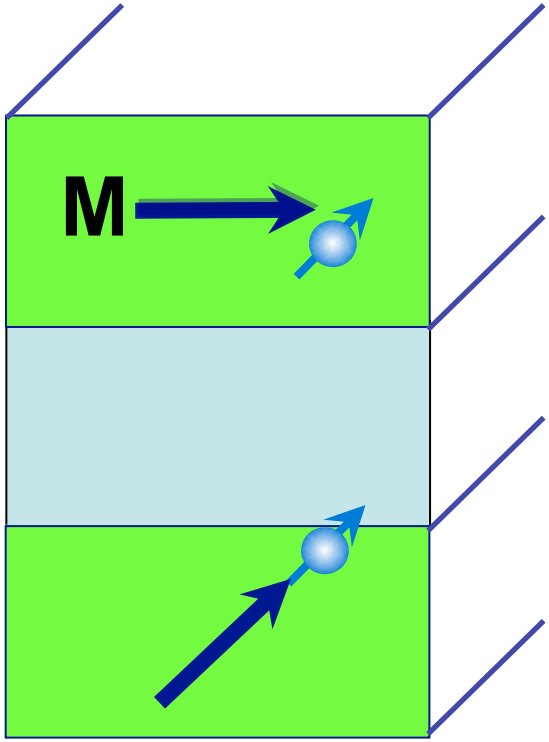
No auxiliary ferromagnets needed

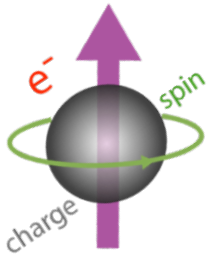
Zelezny et al. PRL'14, Wadley et al. arXiv '15

Writing by non-relativistic spin-transfer torque

Transfer between carrier spin **angular momentum** and magnetization **angular momentum**

Slonczewski, Berger, 1996

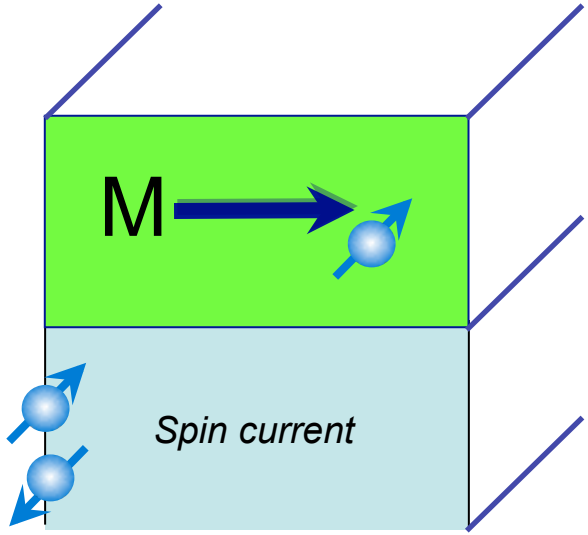


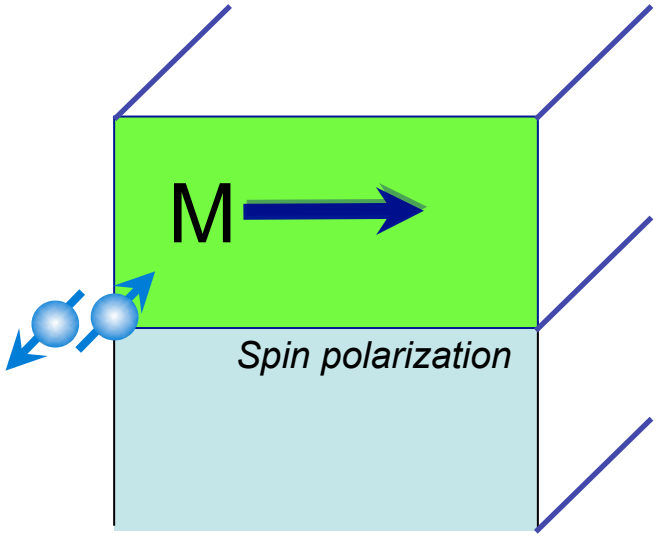


Writing by relativistic spin-orbit torque

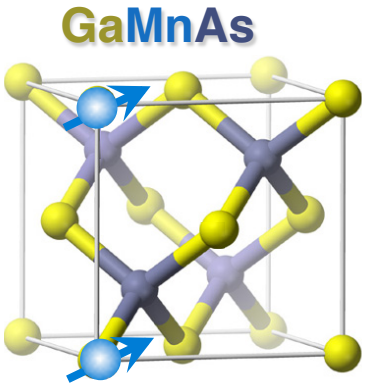
Transfer between carrier **linear momentum** and spin **angular momentum**

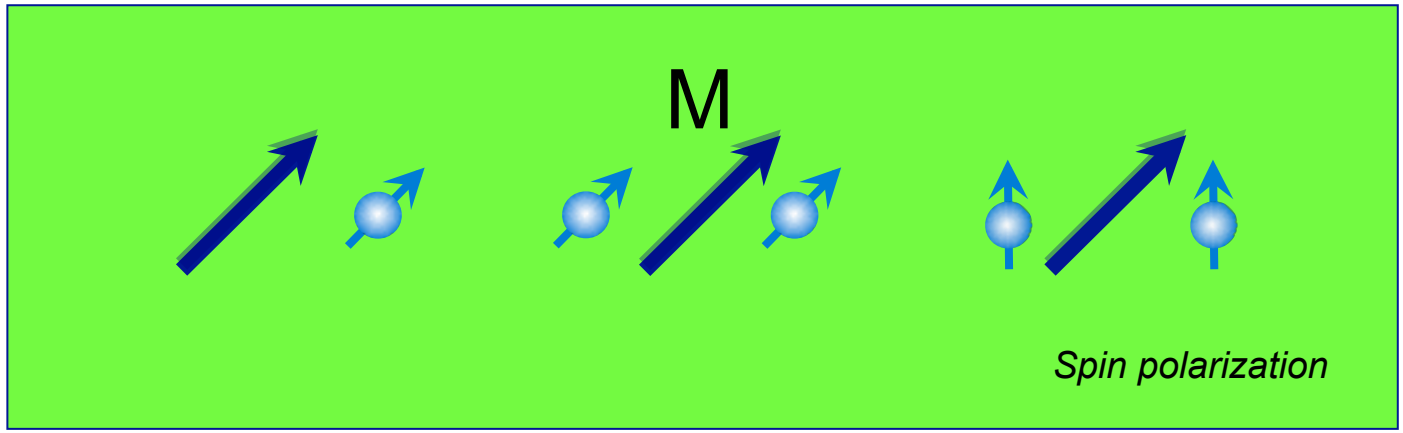
Spin Hall effect 2004
Wunderlich et at., Awschalom et al., 2004





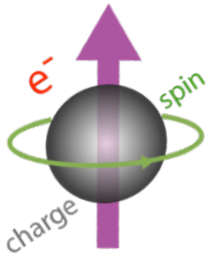
Inverse spin galvanic (Edelstein) effect 2004



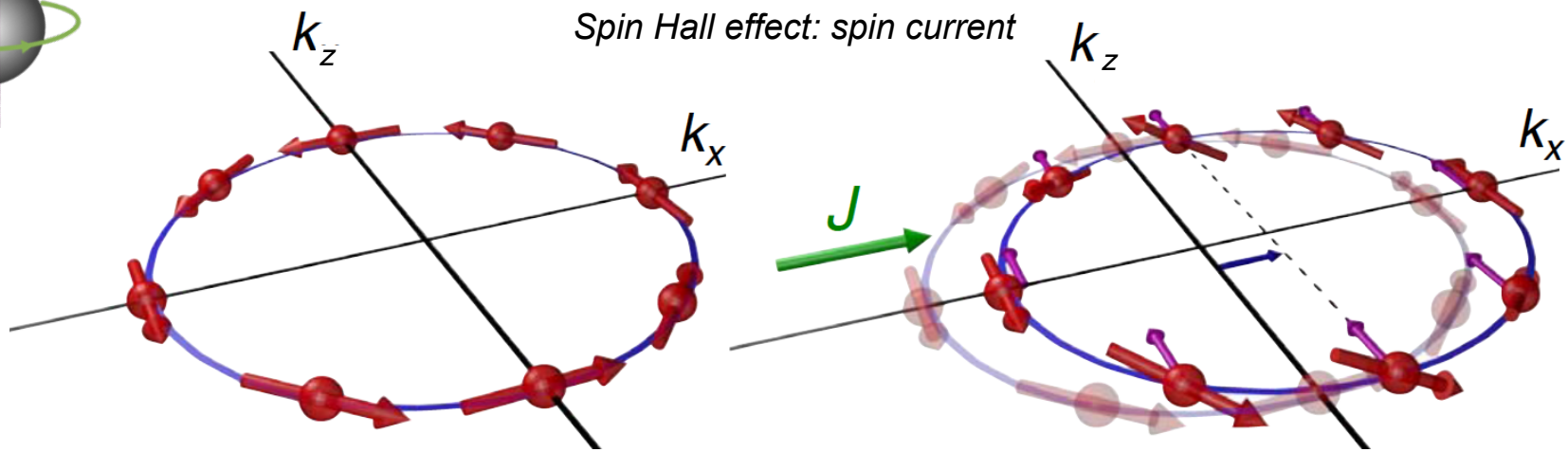


Silov et al. APL '04, Ganichev et al. arXiv '04, Bernevig & Vafek, PRB '05, Manchon & Zhang, PRB '08, Chernyshev et al. Nature Phys.'09

Writing by relativistic spin-orbit torque



Spin Hall effect: spin current



Linear response I. (quantum mechanics class)

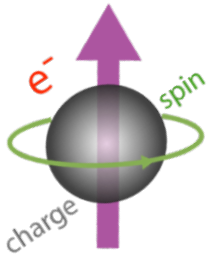
Perturbation theory: equilibrium distribution function and non-equilibrium states

$$J_y^z = \sum_l \langle \psi_l(t) | \hat{j}_y^z | \psi_l(t) \rangle f_0(\varepsilon_l)$$

Sinova et at., RMP '15
arXiv: 1411.3249

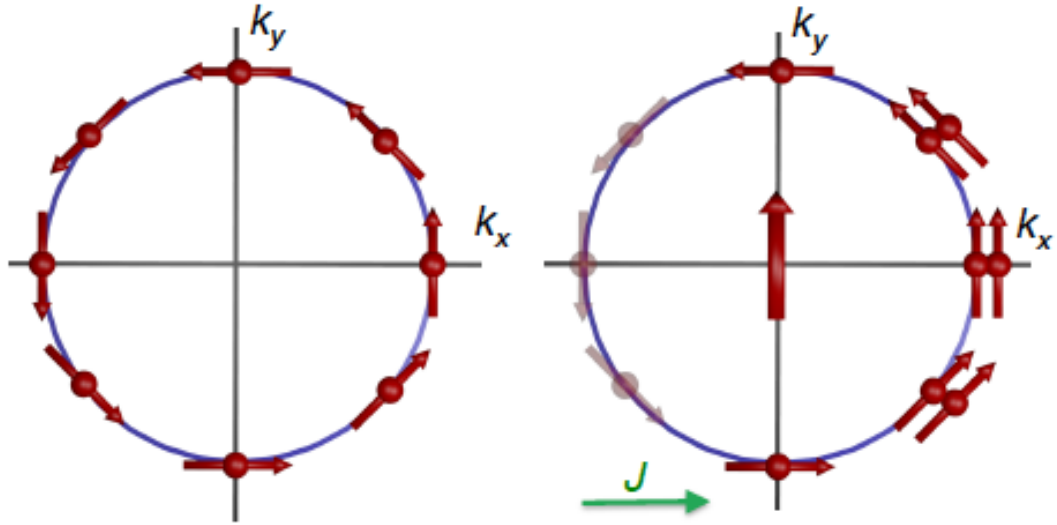
$$|\psi_l(t)\rangle = |l\rangle e^{-i\varepsilon_l t/\hbar} + \frac{e}{i\omega} \sum_{l' \neq l} |l'\rangle \frac{\langle l' | \vec{E} \cdot \hat{v} | l \rangle e^{-i\omega t}}{\varepsilon_l - \varepsilon_{l'} + \hbar\omega} e^{-i\varepsilon_{l'} t/\hbar} + \cdots$$

$$J_y^z = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} (f^0_{\vec{k},n'} - f^0_{\vec{k},n}) \frac{\mathrm{Im}[\langle k, n' | \hat{j}_y^z | \vec{k}, n \rangle \langle \vec{k}, n | \vec{v} \cdot \vec{E} | \vec{k}, n' \rangle]}{(\varepsilon_{\vec{k},n'} - \varepsilon_{\vec{k},n})^2}$$



Writing by relativistic spin-orbit torque

Inverse spin galvanic effect: spin polarization – requires inversion asymmetry



Linear response II. (condensed matter class)

Boltzmann theory : non-equilibrium distribution function and equilibrium states

Sinova et at., RMP '15
arXiv: 1411.3249

$$\vec{S} = \frac{1}{V}\sum_{k,n} \vec{s}_{0n,\vec{k}}\, g_{n,\vec{k}}(E_j)$$

$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(\varepsilon_{n,\vec{k}})$$

$$e\vec{E}\cdot\vec{v}_{0n,\vec{k}}\frac{\partial f_0(\varepsilon_{n,\vec{k}})}{\partial \varepsilon_{n,\vec{k}}} = -\frac{1}{V}\sum_{k,n} W_{n,\vec{k},n',\vec{k}'}(f_{n,\vec{k}} - f_{n',\vec{k}'})$$

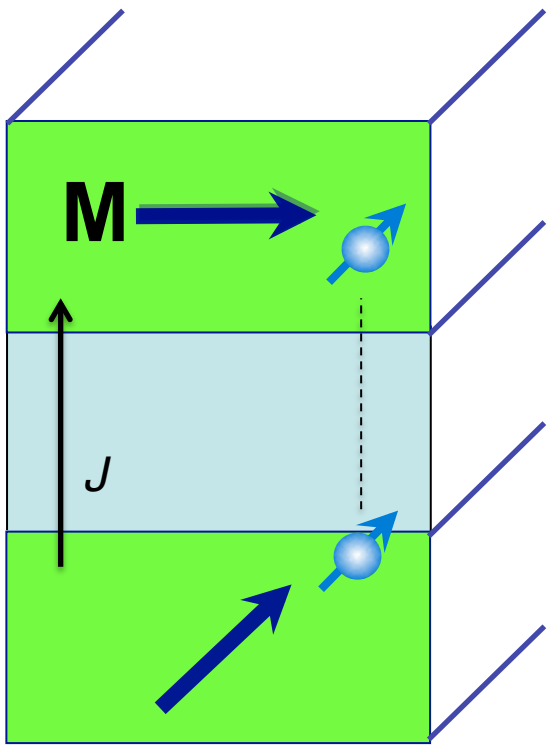
Spin torques in ferromagnets and antiferromagnets

Spins injected by out-of-plane current from FM polarizer

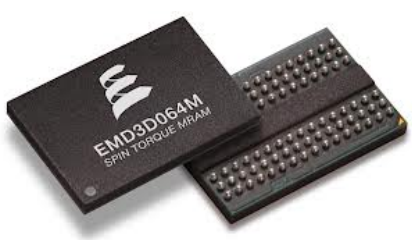
- spin angular momentum transfer $\vec{p}_{curr} \sim J$

- spin precession $\frac{d\vec{s}}{dt} = \frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{ex}]\rangle \qquad H_{ex} = J_{ex}\vec{M}\cdot\vec{\sigma} \qquad \tau_{ex} = \frac{\hbar}{J_{ex}M}$

- spin decay τ_s



Ralph & Stiles, JMMM '08



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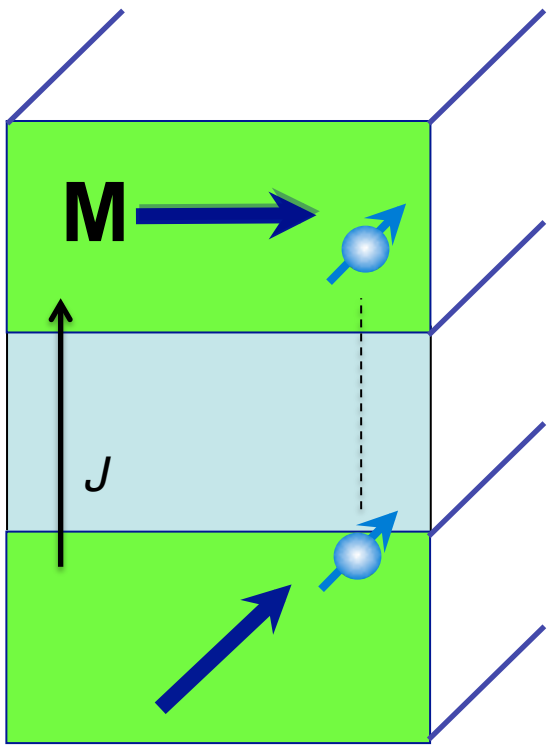
Spins injected by out-of-plane current from FM polarizer



Ralph & Stiles, JMMM '08

- spin angular momentum transfer $\vec{p}_{curr} \sim J$

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- spin decay τ_s

$$\tau_s << \tau_{ex}: \; 0 = \frac{d\vec{s}}{dt} = \vec{p}_{curr} - \frac{\vec{s}}{\tau_s}$$

$$\tau_s >> \tau_{ex}: \; 0 = \frac{d\vec{s}}{dt} = \vec{p}_{curr} + \frac{J_{ex}}{\hbar}\vec{s}\times\vec{M}$$

$$\vec{T} = \frac{d\vec{M}}{dt} = \frac{J_{ex}}{\hbar}\vec{M}\times\vec{s}$$

Field-like torque

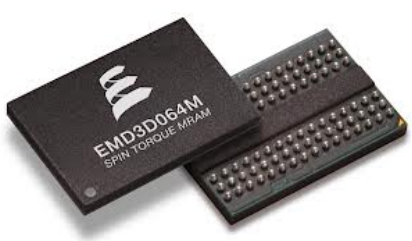
$$\vec{T} = \frac{\tau_s}{\tau_{ex}}\vec{M}\times\vec{p}_{curr}$$

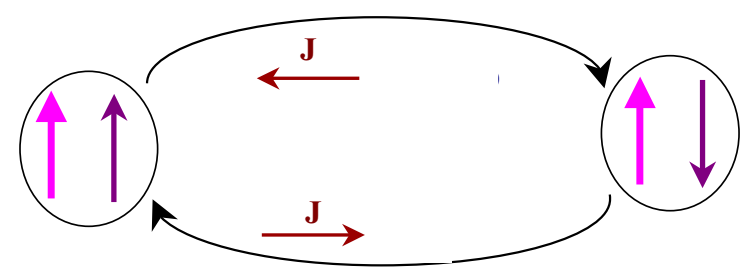
$$J_{crit} \sim H_{aniso}$$

Antidamping-like torque

$$\vec{T} = \vec{M}\times[\vec{p}_{curr}\times\vec{M}]$$

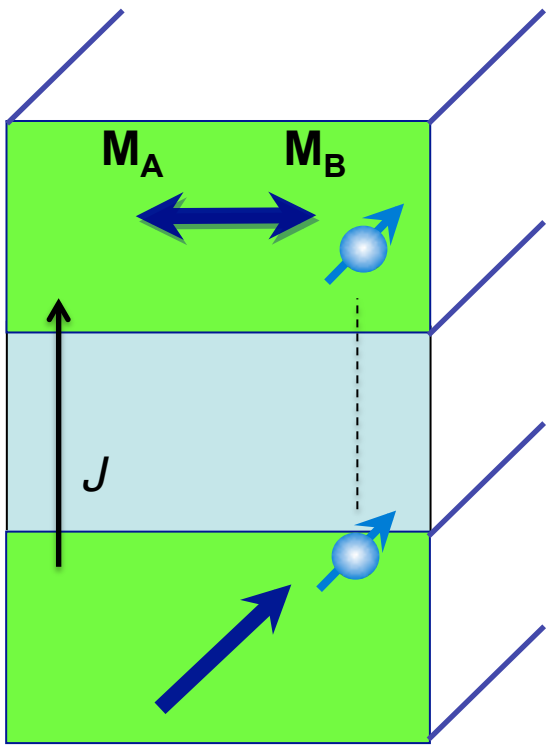
$$J_{crit} \sim \alpha_{Gilbert} H_{aniso}$$





Spin torques in ferromagnets and antiferromagnets

Spins injected by out-of-plane current from FM polarizer



Gomonay & Loktev, Low Temp. Phys. '14
MacDonald & Tsoi, Philos. Trans. A PRL '11

Field-like torque

$$\vec{T}_A \sim \vec{M}_A \times \vec{p}_{curr}$$

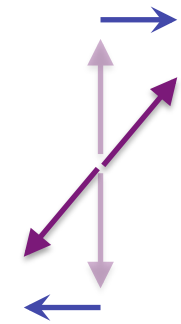
$$\vec{M}_A = -\vec{M}_B$$

$$\vec{T}_B \sim \vec{M}_B \times \vec{p}_{curr}$$

$$J_{crit} \sim \sqrt{H_{exch} H_{aniso}}$$

Antidamping-like torque

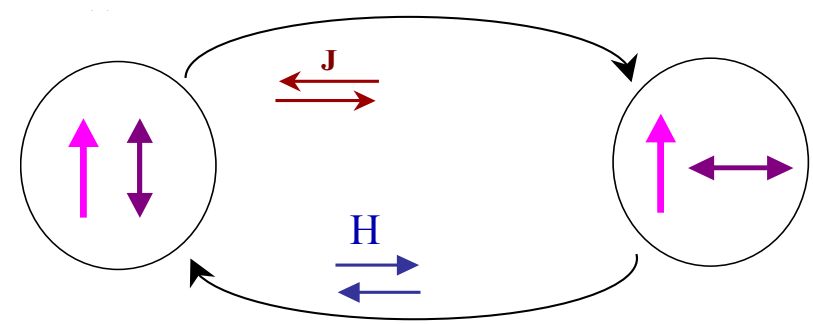
$$\vec{T}_A \sim \vec{M}_A \times [\vec{p}_{curr} \times \vec{M}_A]$$



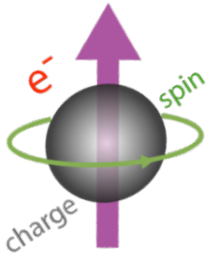
$$\vec{T}_B \sim \vec{M}_B \times [\vec{p}_{curr} \times \vec{M}_B]$$

$$J_{crit} \sim \alpha_{Gilbert} H_{aniso}$$

Even torque works (L. Néel)

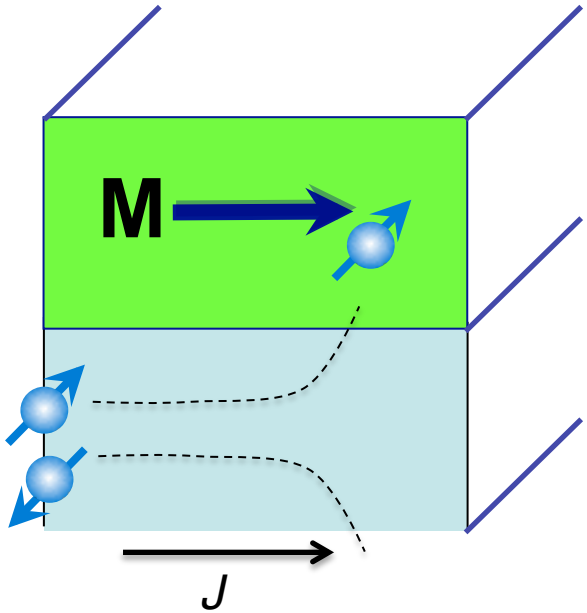


Requires magnetic field to switch back

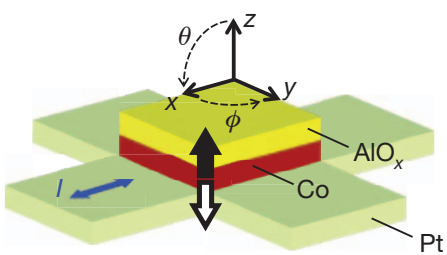


Spin torques in ferromagnets and antiferromagnets

Spins injected by in-plane current via spin Hall effect



Miron et al. Nature '11
Liu et al. Science '12

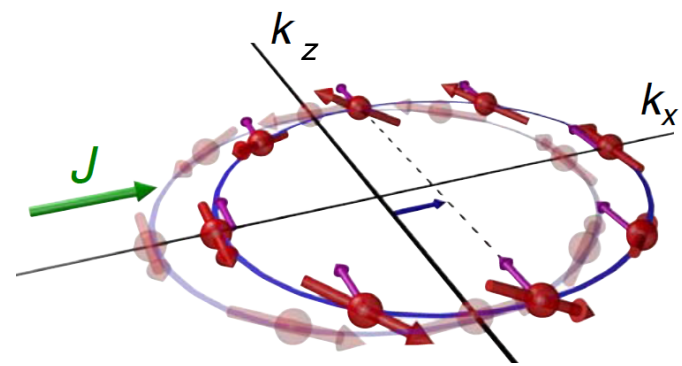


Field-like torque

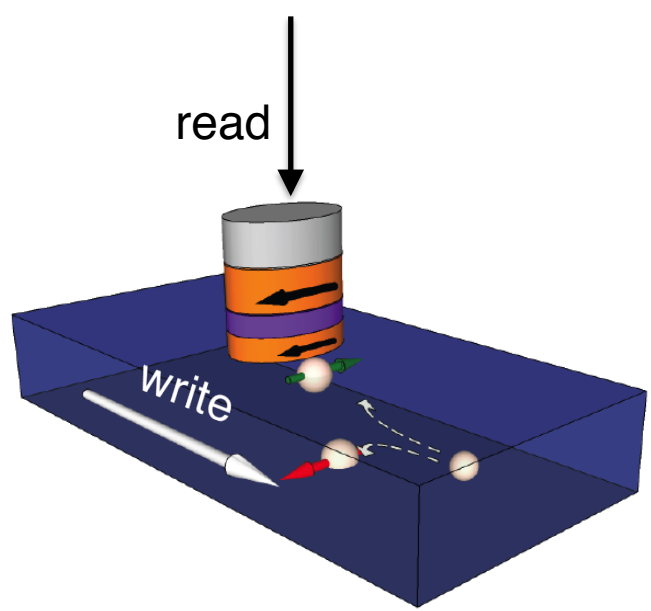
$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$

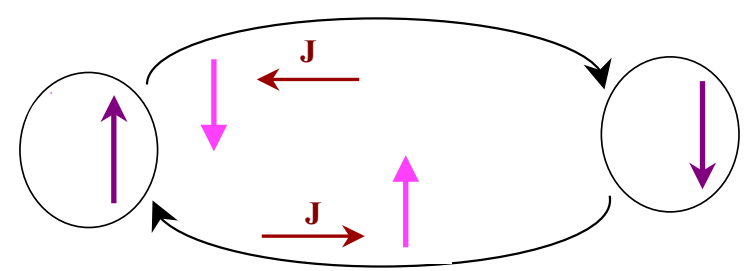
Antidamping-like torque

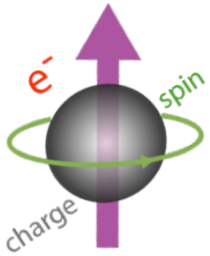
$$\vec{T} \sim \vec{M} \times [\vec{p}_{curr} \times \vec{M}]$$



$$\mathrm{sgn}(\vec{p}_{curr}) \sim \mathrm{sgn}(\vec{J})$$







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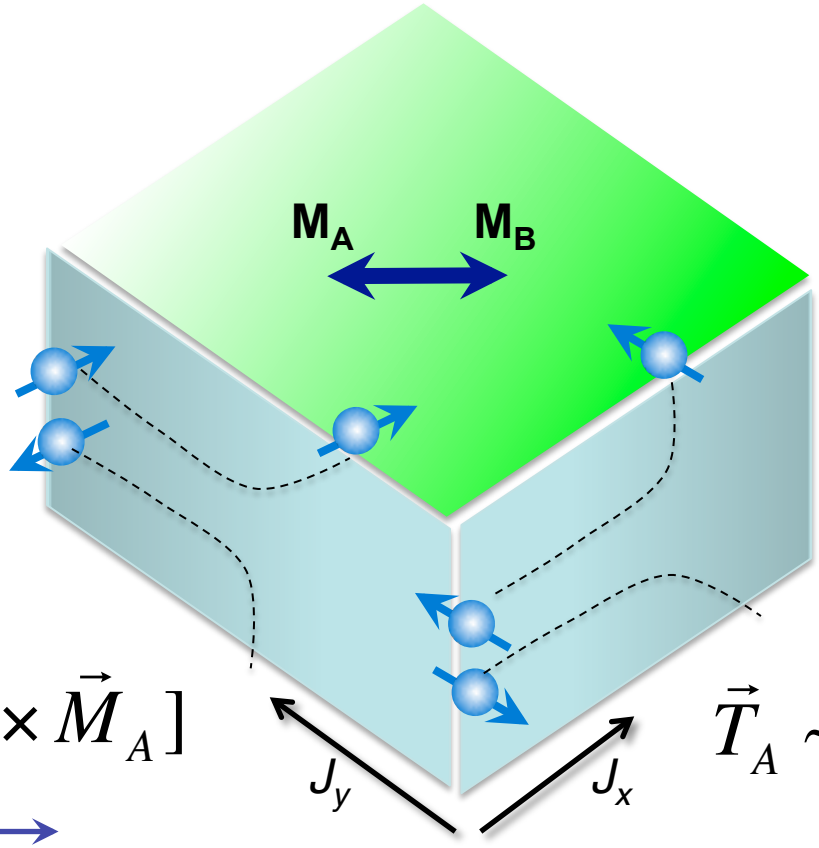
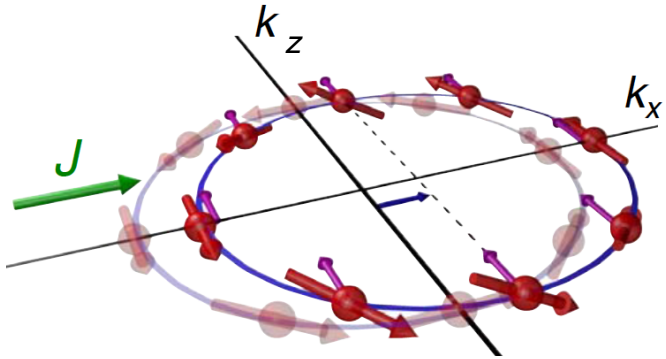




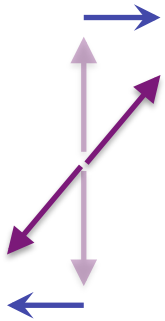
$$\vec{p}_{curr} \perp \vec{J}$$

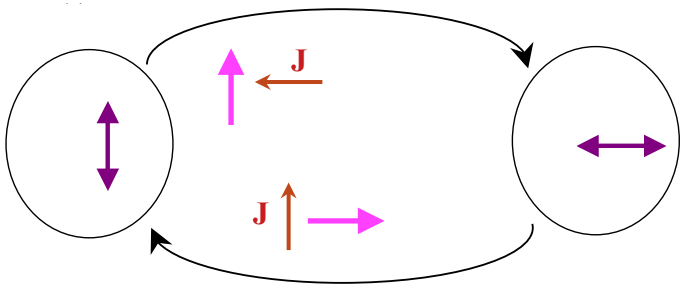
Antidamping-like torque

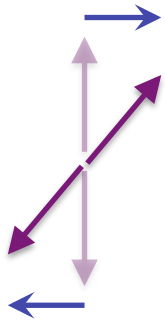
$$\vec{T}_A \sim \vec{M}_A \times [\vec{p}_{curr\|y} \times \vec{M}_A]$$

Antidamping-like torque

$$\vec{T}_A \sim \vec{M}_A \times [\vec{p}_{curr\|x} \times \vec{M}_A]$$

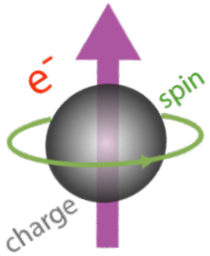






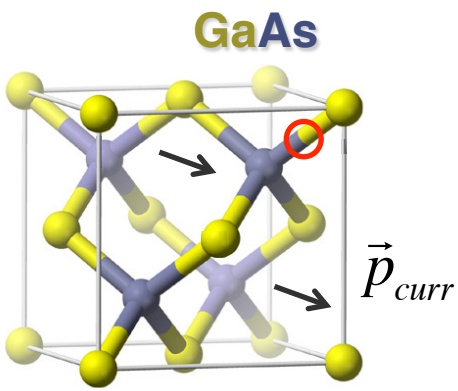
$$\vec{T}_B \sim \vec{M}_B \times [\vec{p}_{curr\|y} \times \vec{M}_B]$$

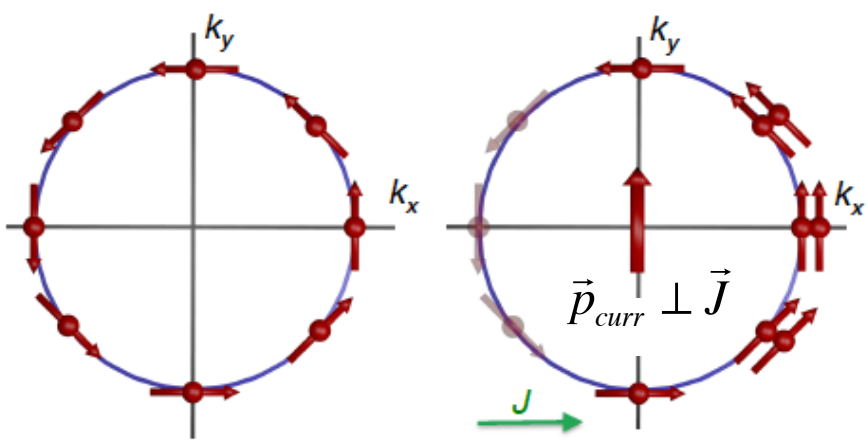
$$\vec{T}_B \sim \vec{M}_B \times [\vec{p}_{curr\|x} \times \vec{M}_B]$$

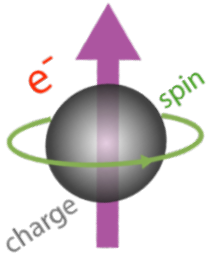


Spin torques in ferromagnets and antiferromagnets

Spin polarization due to inversion asymmetry and current via ISGE



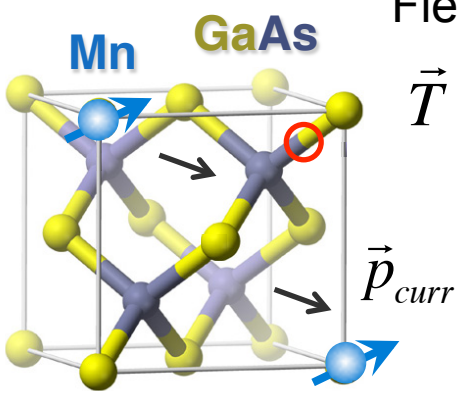




Spin torques in ferromagnets and antiferromagnets

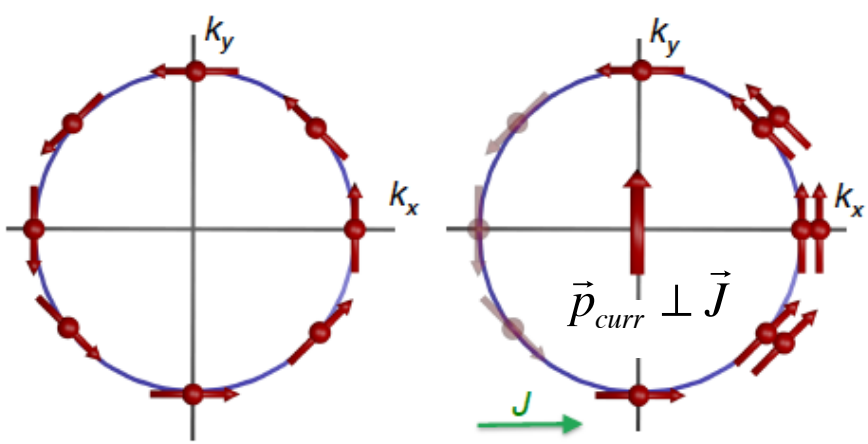
Spin polarization due to inversion asymmetry and current via ISGE

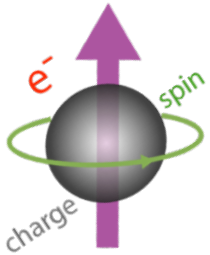
FM with global inversion asymmetry



Field-like torque

$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$

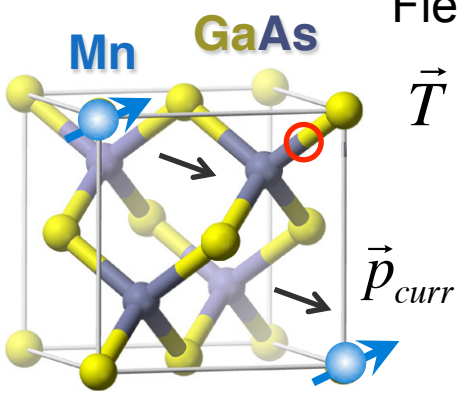




Spin torques in ferromagnets and antiferromagnets

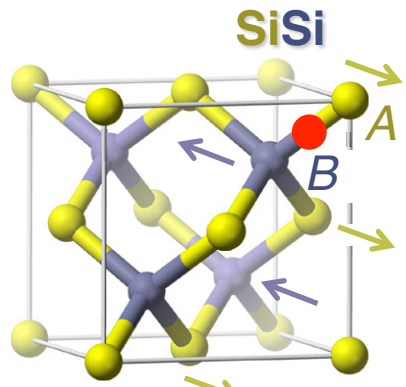
Spin polarization due to inversion asymmetry and current via ISGE

FM with global inversion asymmetry

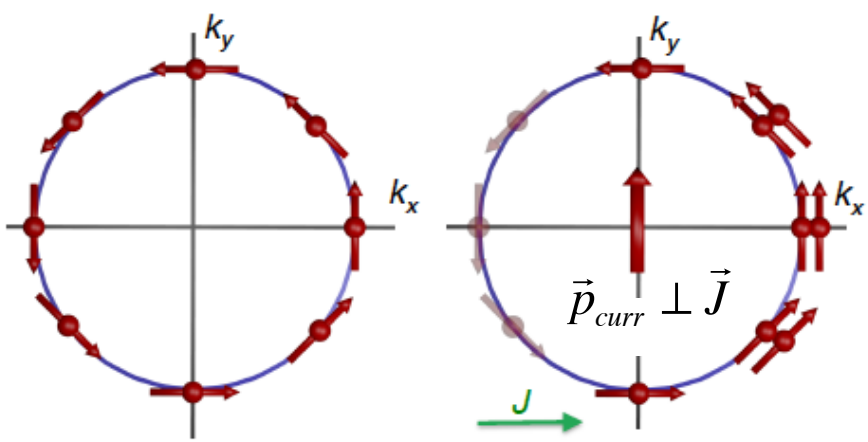


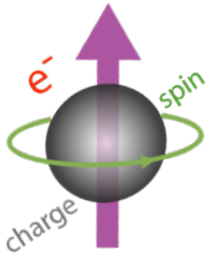
Field-like torque

$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$



$$\vec{p}_{curr,A} = -\vec{p}_{curr,B}$$





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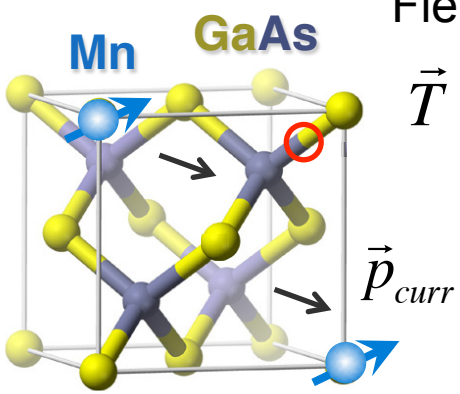
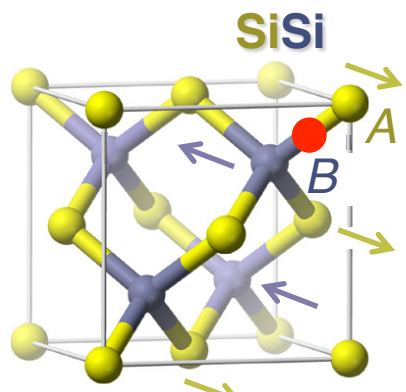


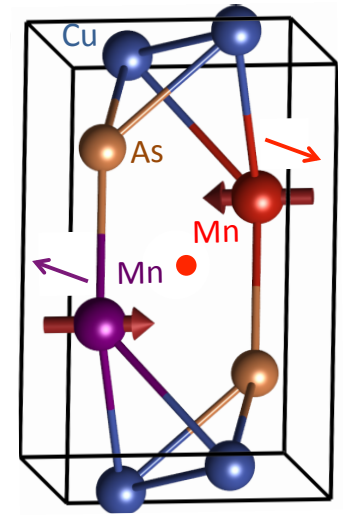
Field-like torque

$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$

AF with local inversion asymmetry



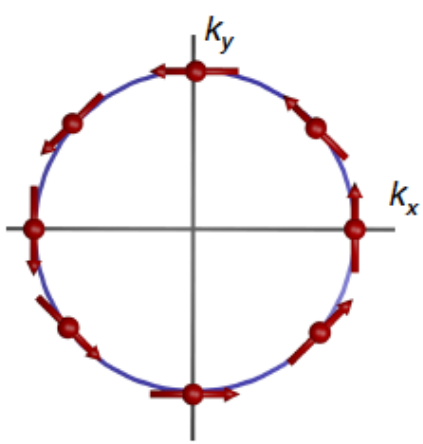
$$\vec{p}_{curr,A} = -\vec{p}_{curr,B}$$

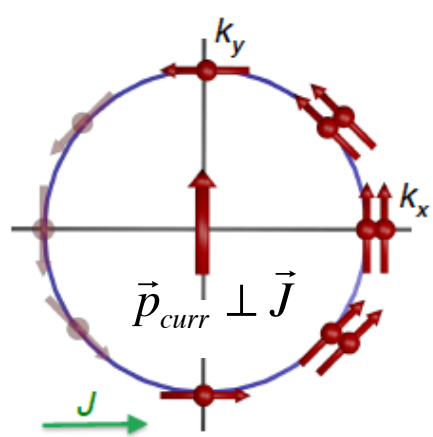


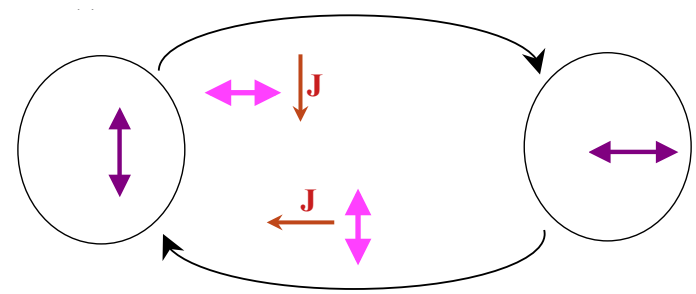
Field-like torque

$$\vec{T}_A \sim \vec{M}_A \times \vec{p}_{curr,A}$$

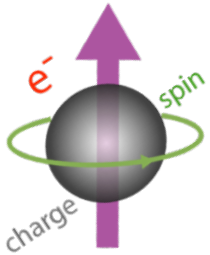
$$\vec{T}_B \sim \vec{M}_B \times \vec{p}_{curr,B}$$







Zelezny et al. PRL '14



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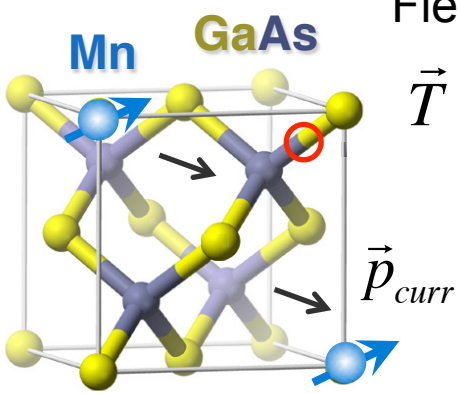
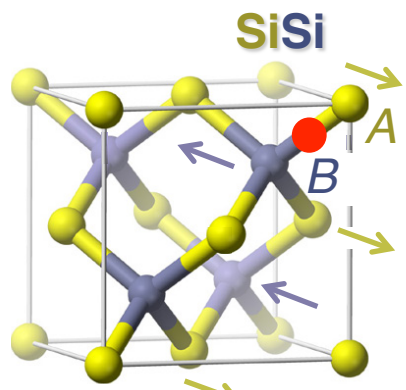
FM with global inversion asymmetry

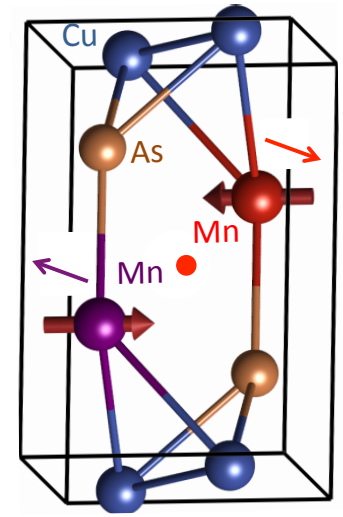


Field-like torque

$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$

AF with local inversion asymmetry



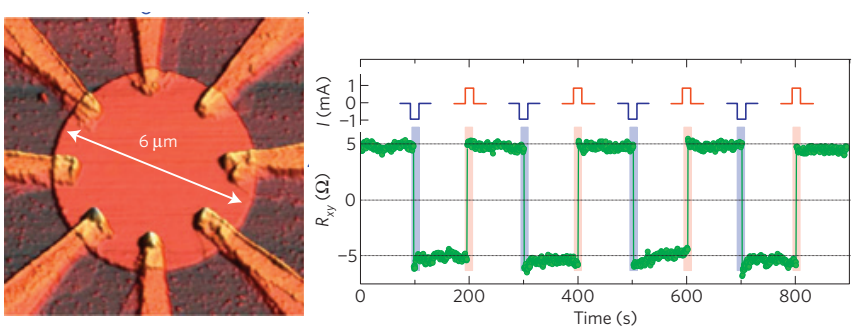


$$\vec{p}_{curr,A} = -\vec{p}_{curr,B}$$

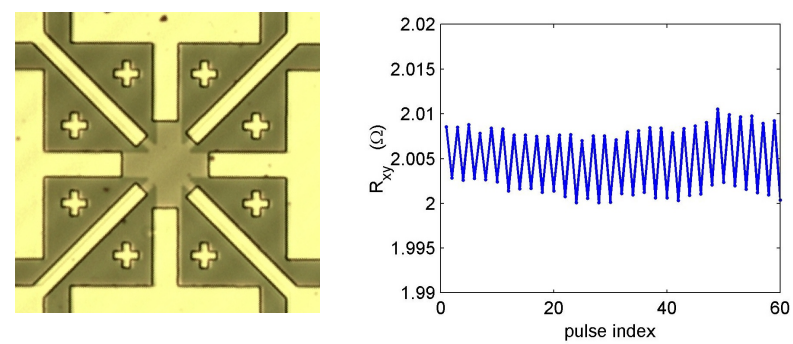
Field-like torque

$$\vec{T}_A \sim \vec{M}_A \times \vec{p}_{curr,A}$$

$$\vec{T}_B \sim \vec{M}_B \times \vec{p}_{curr,B}$$



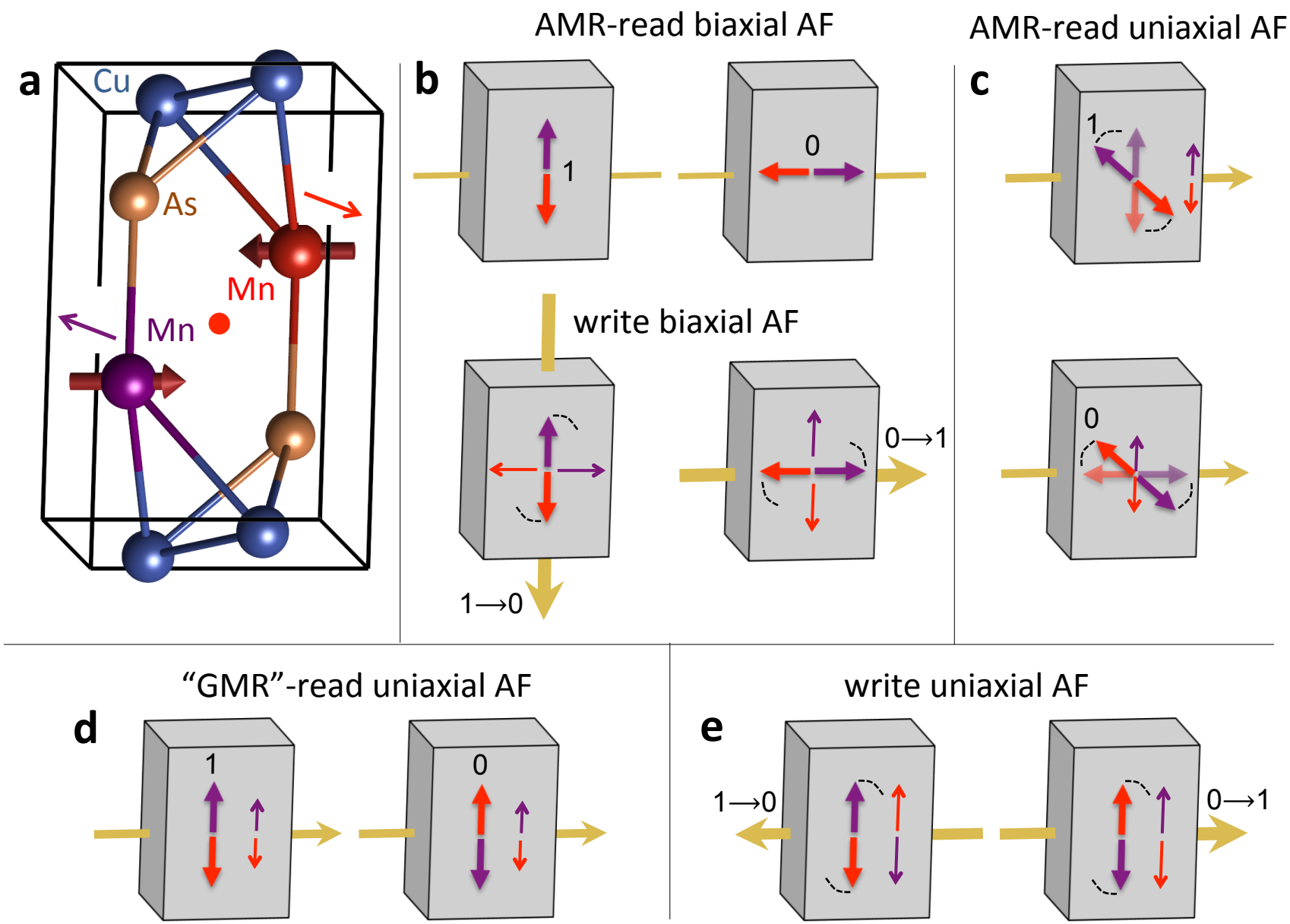
Chernyshov et al. Nature Phys. '09



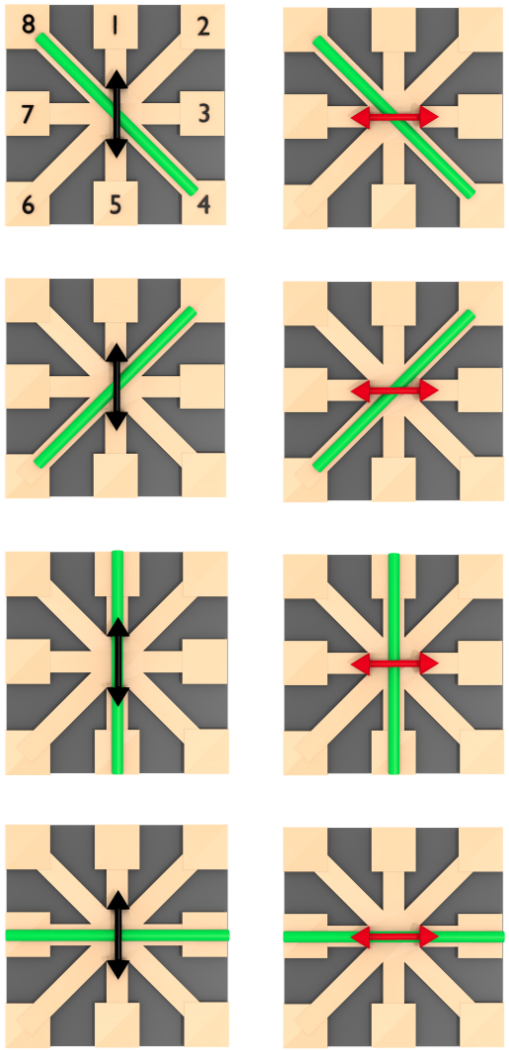
Wadley arXiv '15

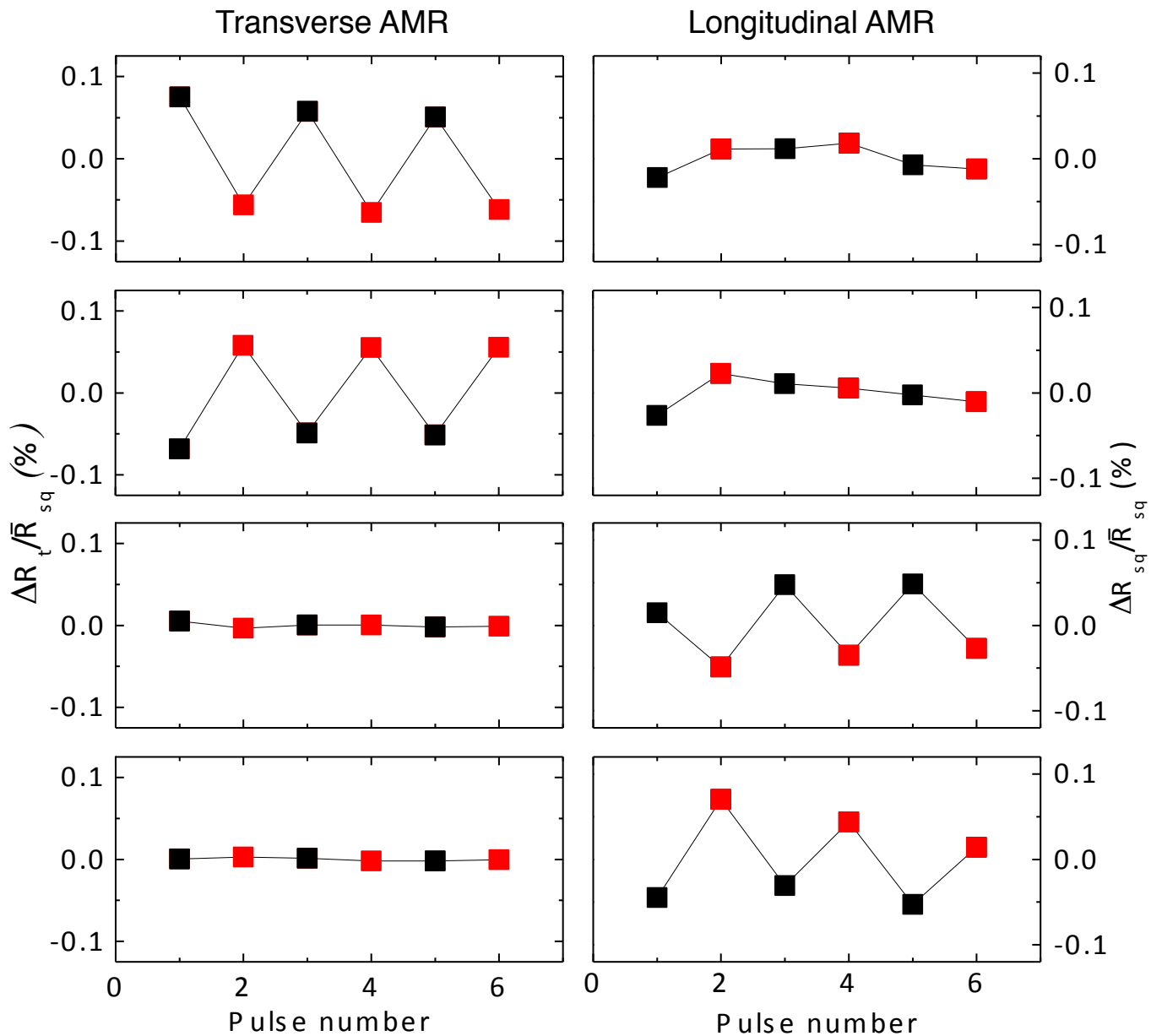
Summary

1. Relativistic QM, magnetism, and spintronics with ferro, antiferro, and paramagnets
2. Reading spin information
3. Writing spin information


a
Cu
As
Mn
Mn
b
AMR-read biaxial AF
1
0
write biaxial AF
0⟶1
1⟶0
c
AMR-read uniaxial AF
1
0
d
"GMR"-read uniaxial AF
1
0
e
write uniaxial AF
1⟶0
0⟶1

Electrical switching of an antiferromagnet





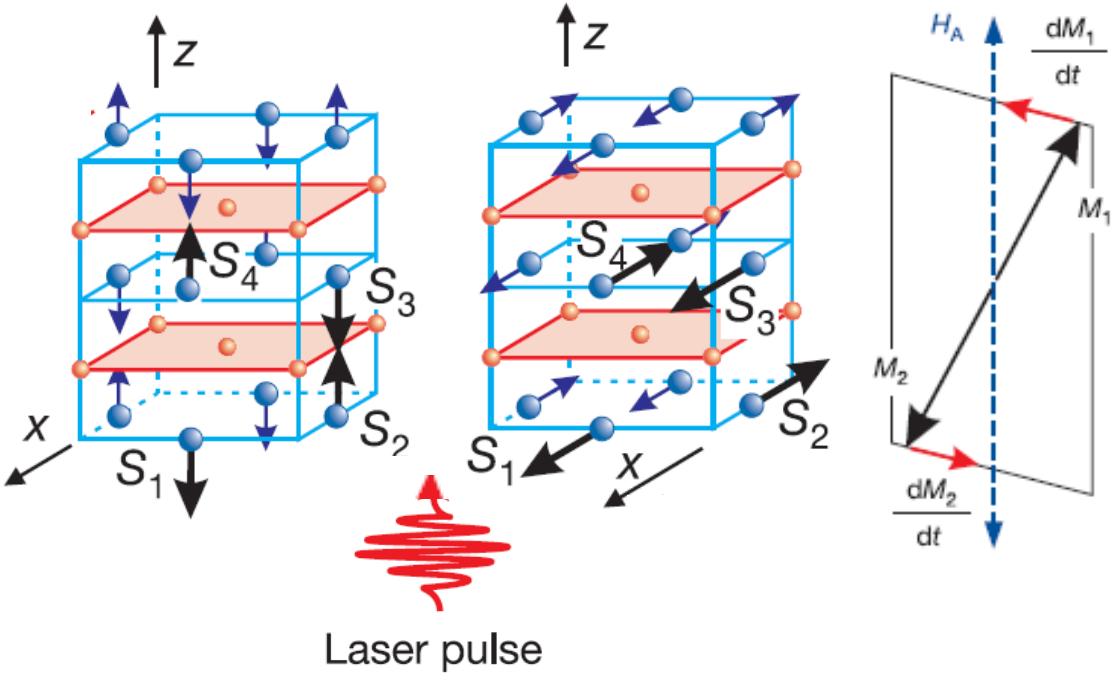
Wadley, TJ et al. arXiv '15

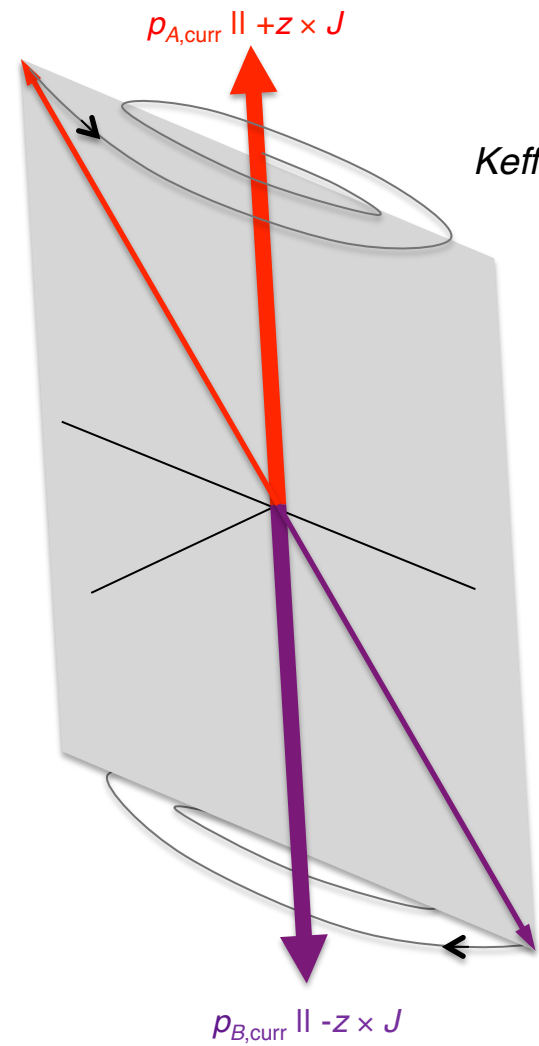
Field-like ISGE torque in antiferromagnets

Laser-induced ultrafast spin reorientation in the antiferromagnet $TmFeO_3$

A. V. Kimel[1], A. Kirilyuk[1], A. Tsvetkov[1], R. V. Pisarev[2] & Th. Rasing[1]

Nature '04



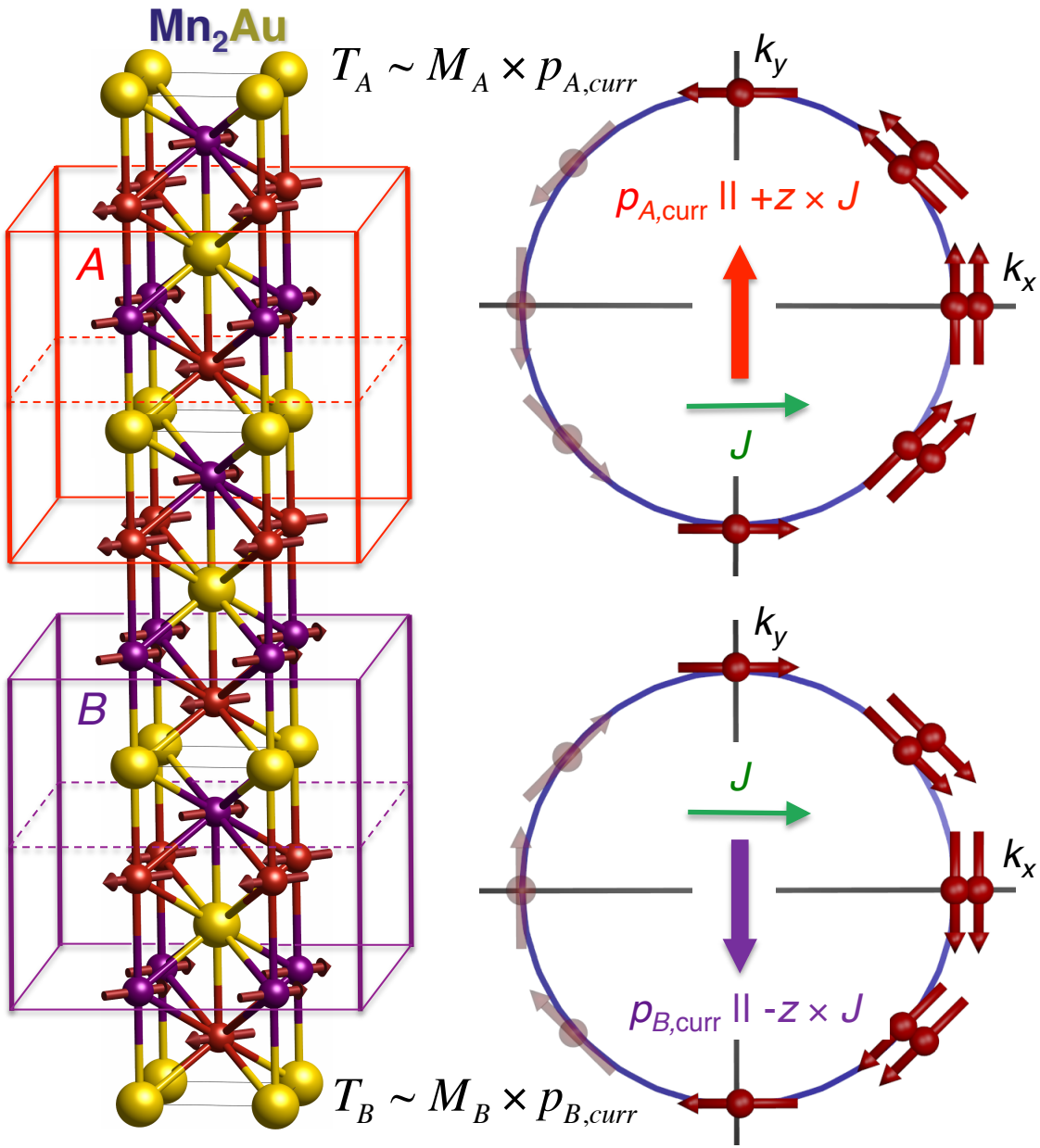


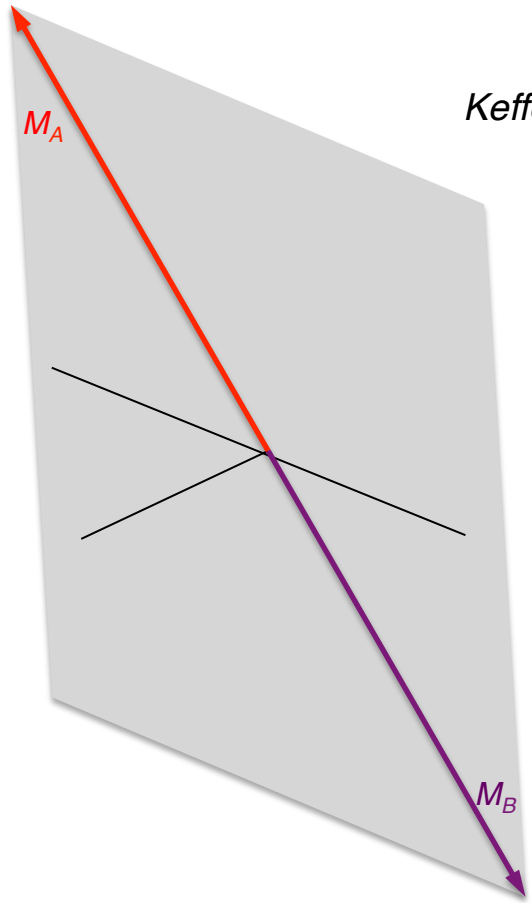
Keffer, Kittel,PR'52

Non-centro-symmetric sublattices ➔ Néel-order (alternating-sign) $p_{A/B,curr}$

Zelezny, TJ et al. PRL '14

Field-like spin-orbit torque in antiferromagnets





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Fast in-plane AFM dynamics

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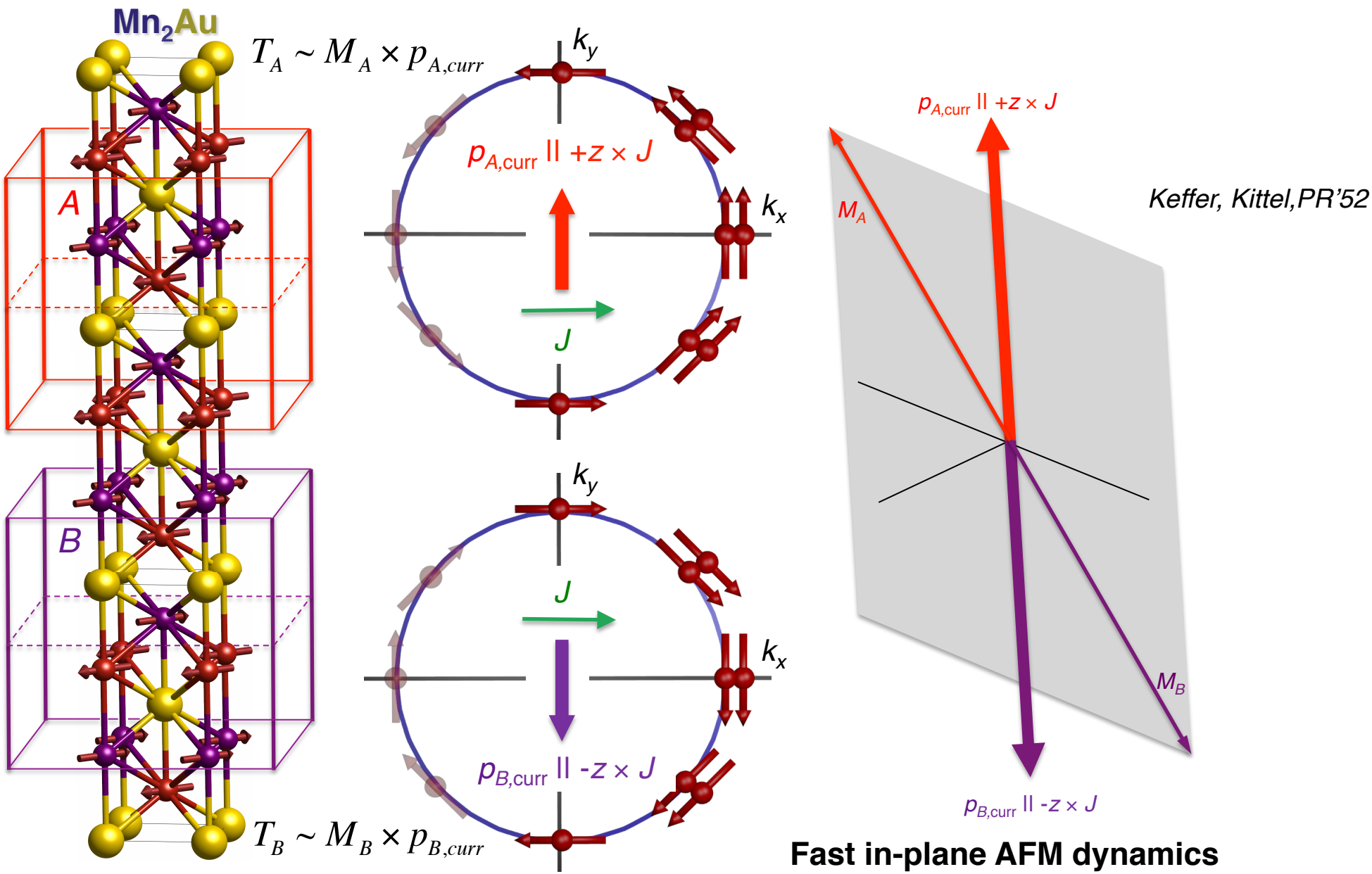

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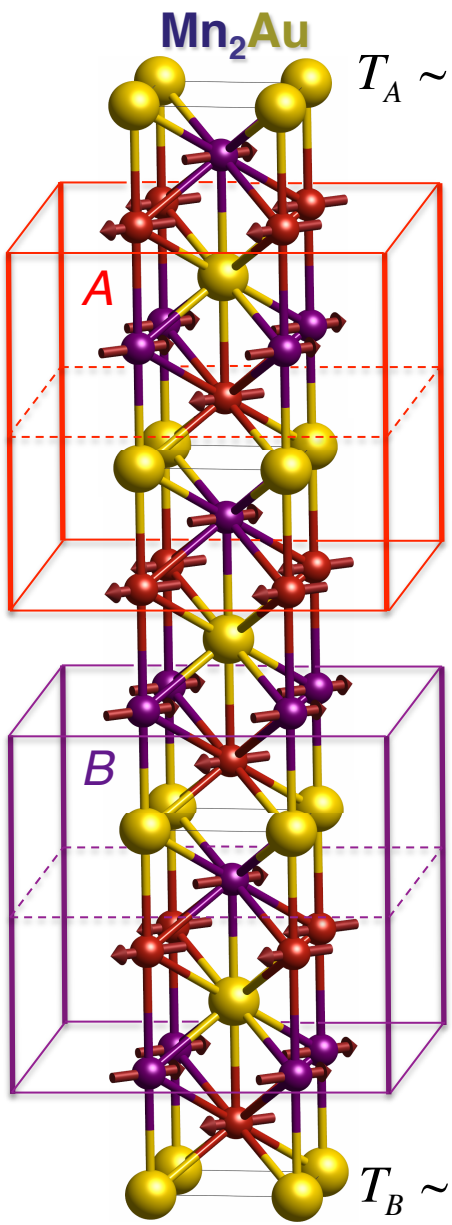
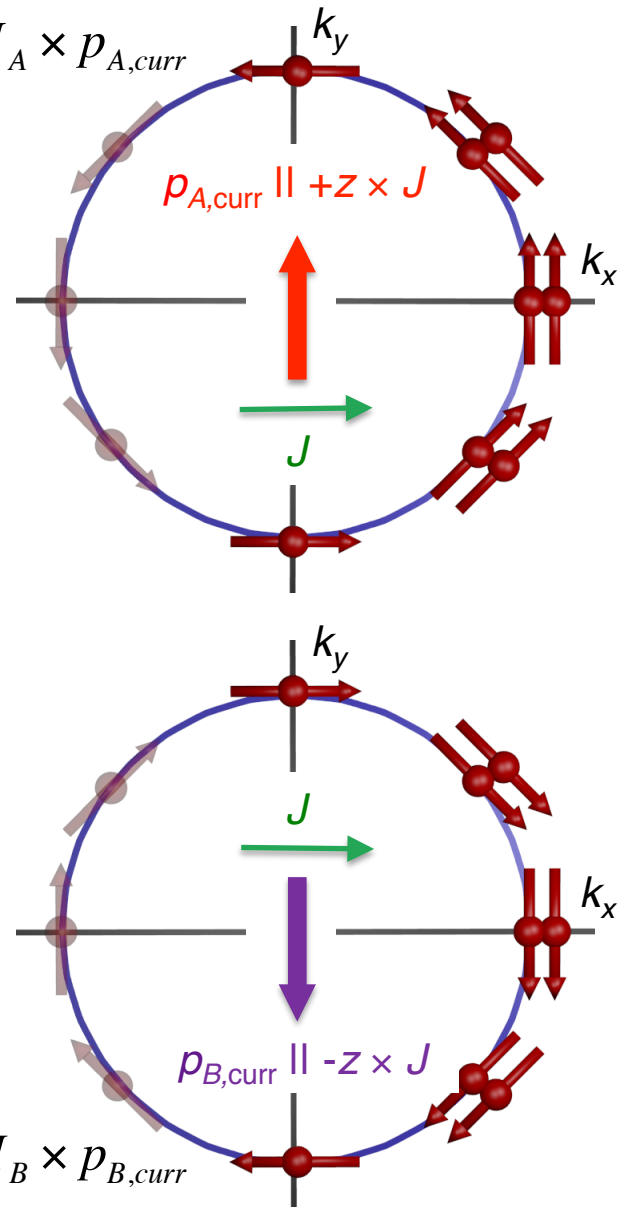
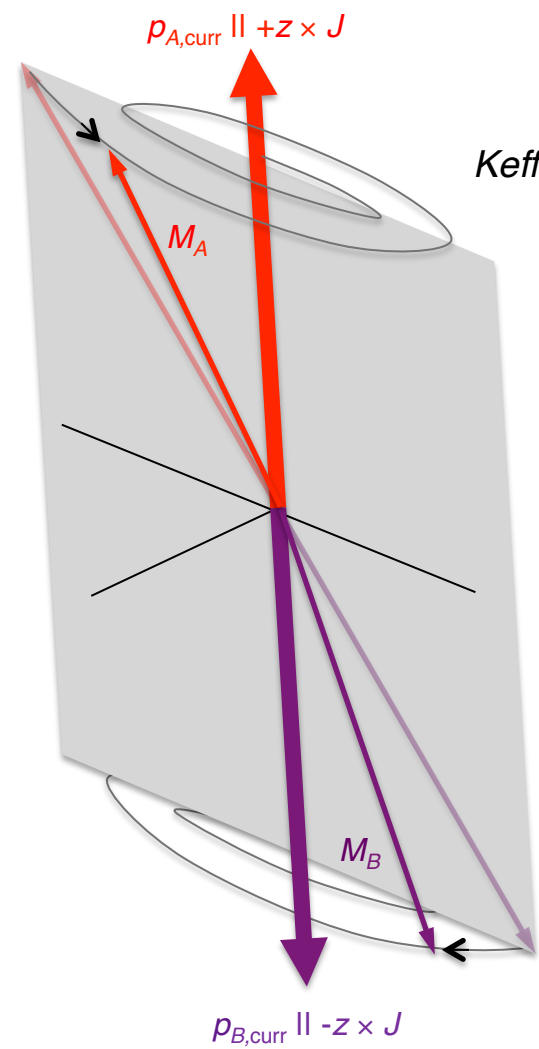


$T_A \sim M_A \times p_{A,curr}$



$T_B \sim M_B \times p_{B,curr}$



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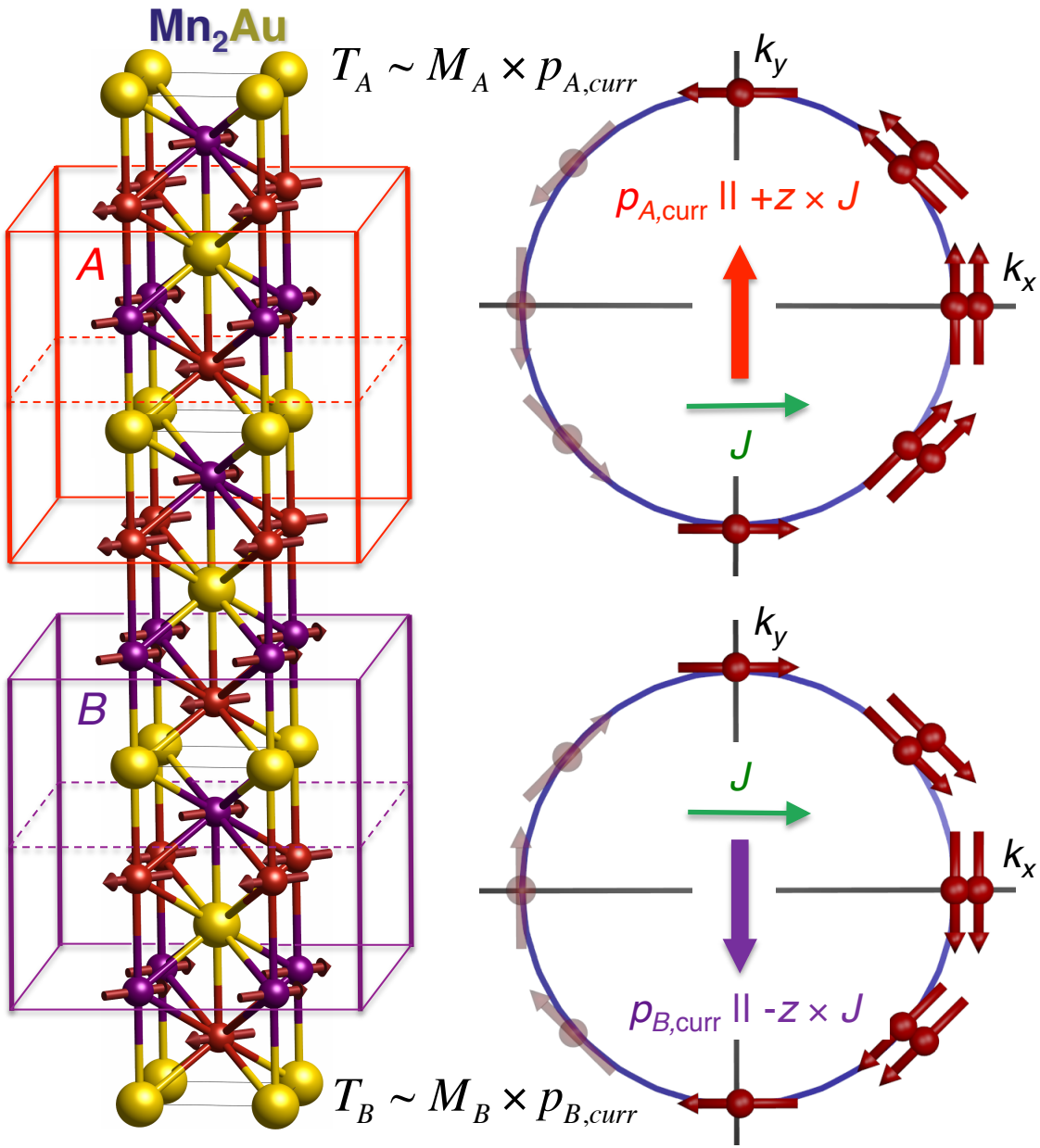

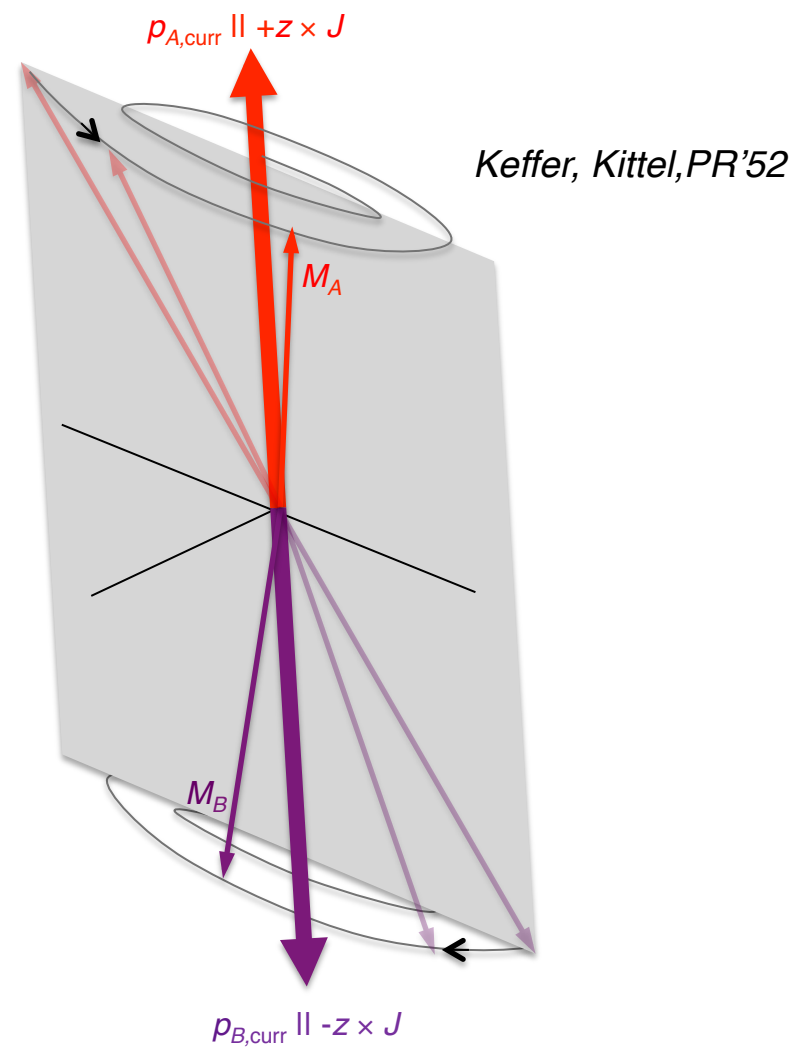

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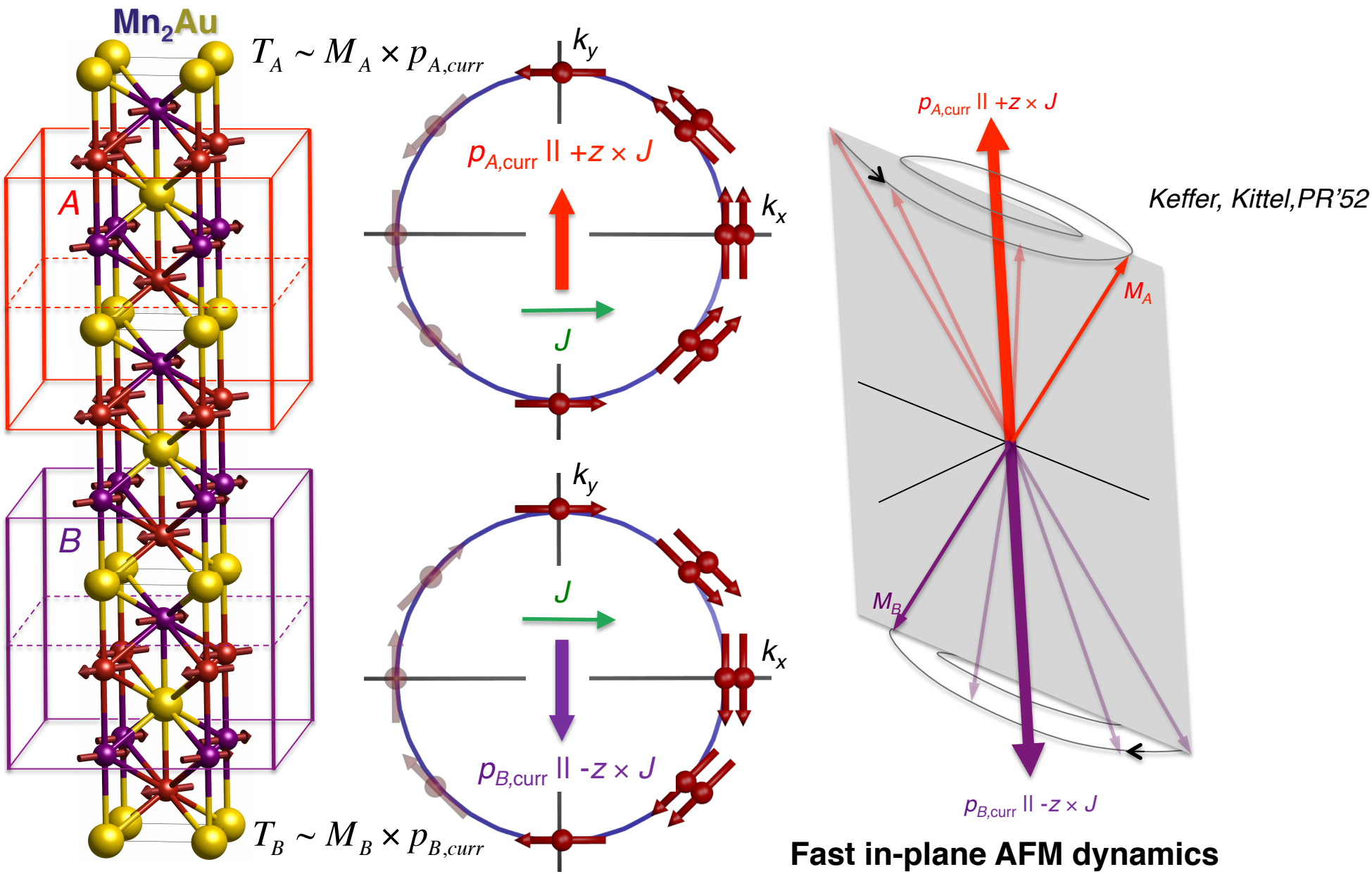

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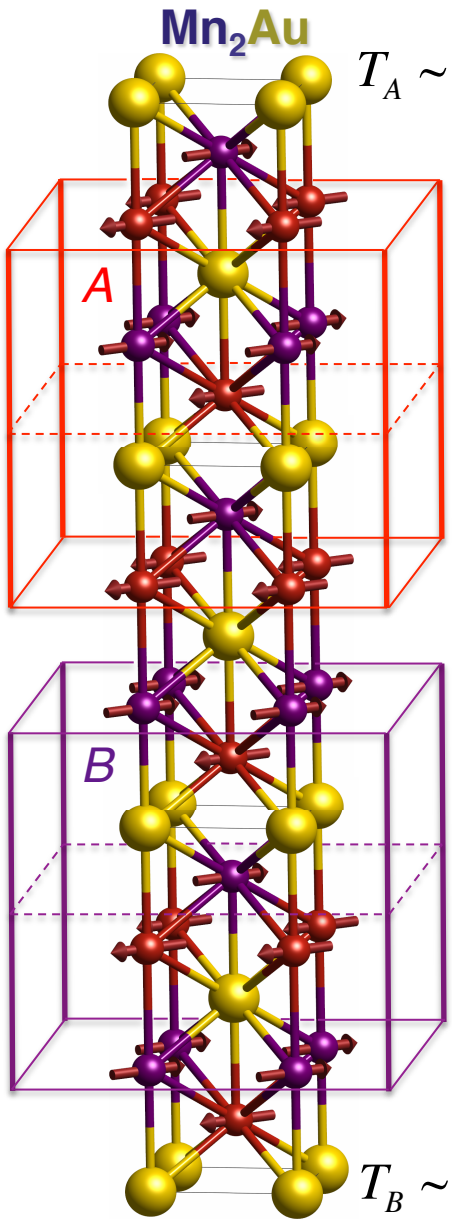
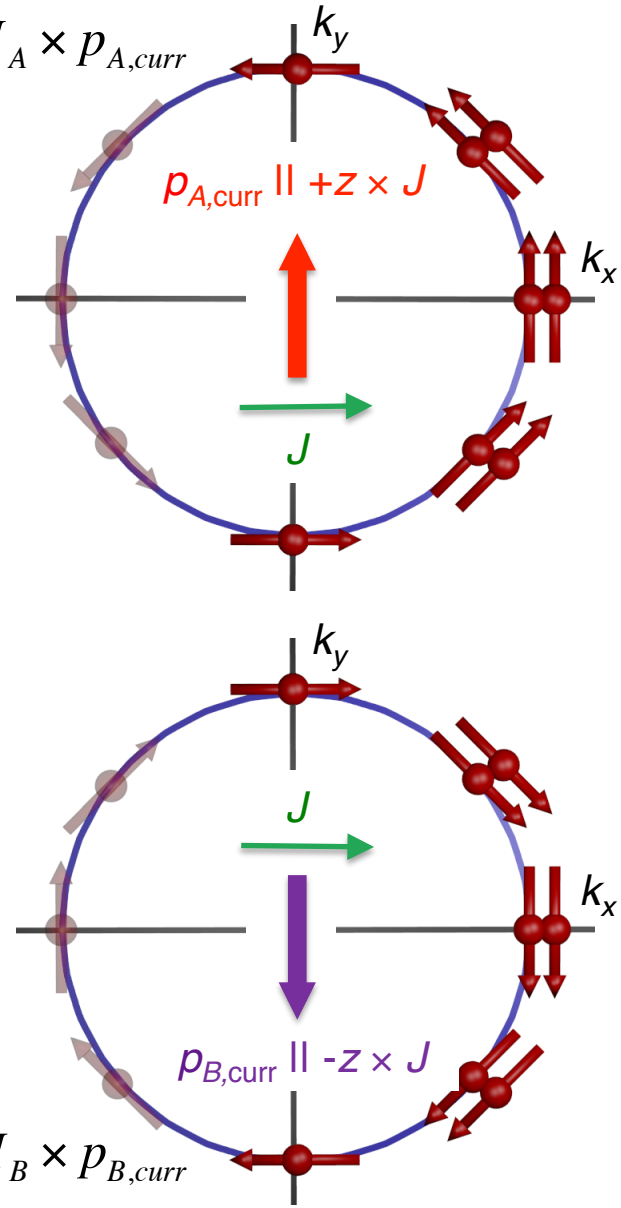
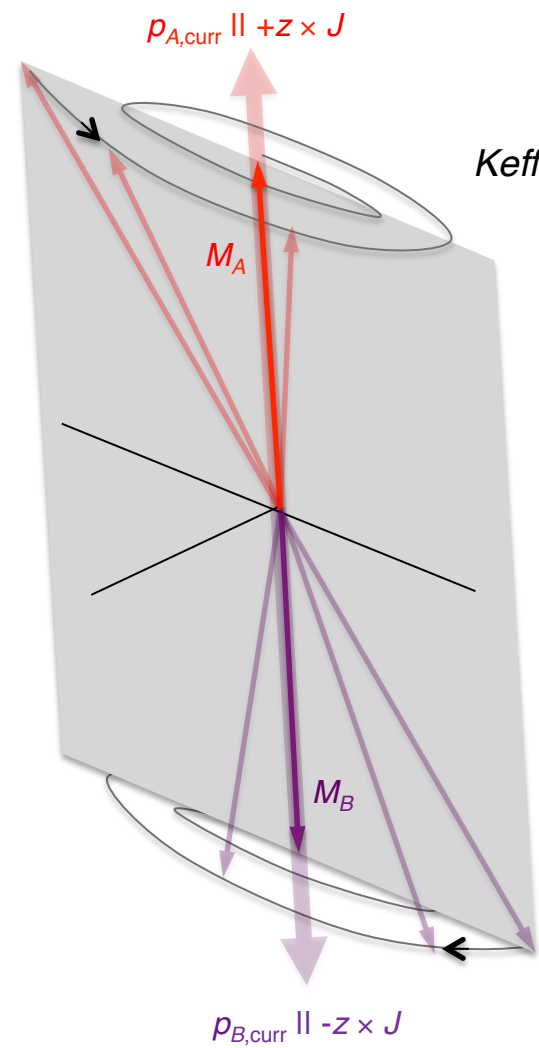


$T_A \sim M_A \times p_{A,curr}$



$T_B \sim M_B \times p_{B,curr}$



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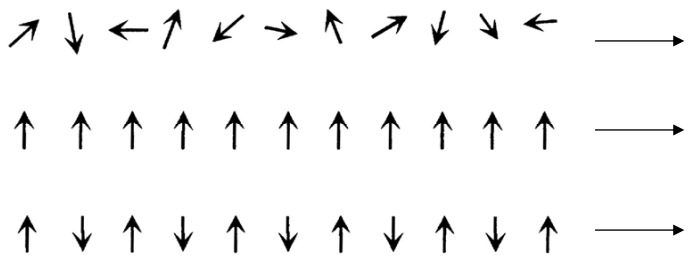
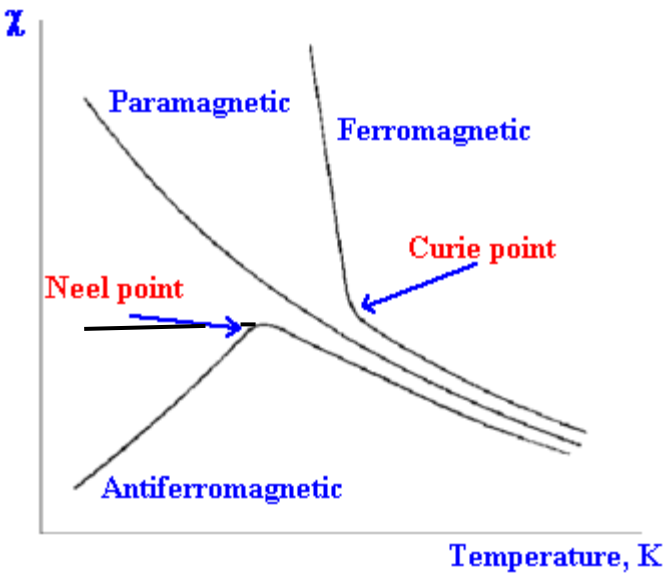
Magnetism



Paramagnetic no spontaneous order

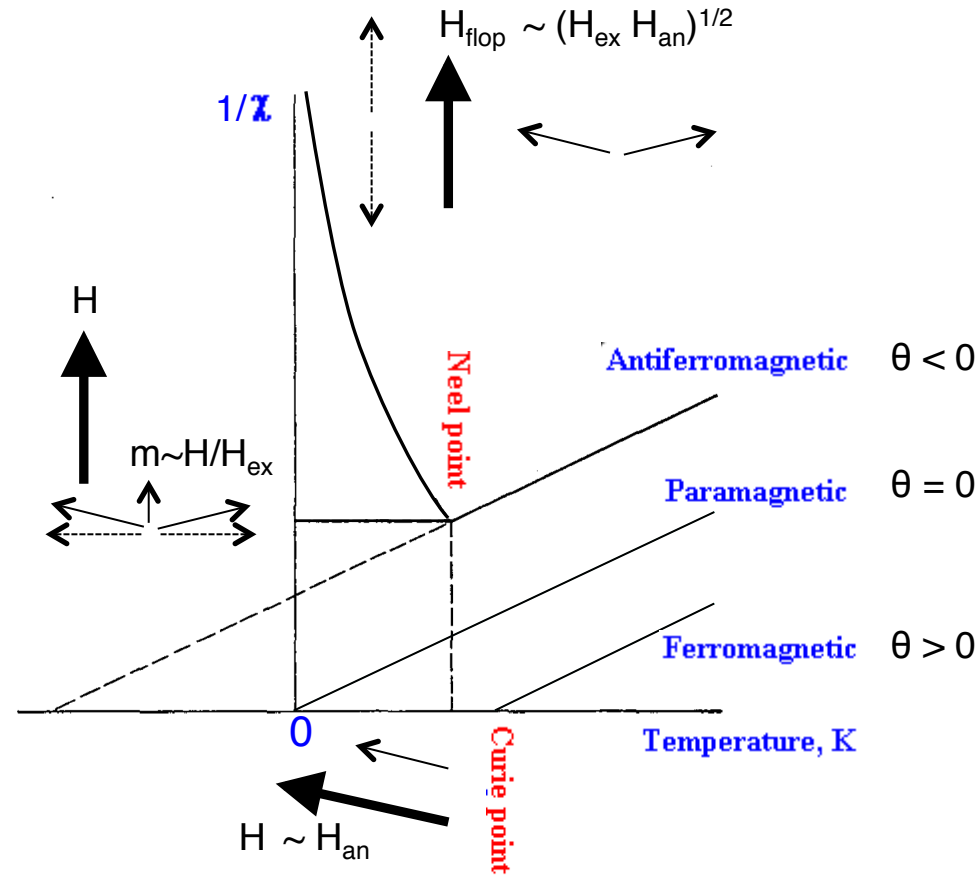
Ferromagnetic exchange coupling, order by global uniform molecular field

Antiferromagnetic exchange coupling, order by local (atomistic) molecular field



Curie-Weiss law

$$1/\chi \sim T - \theta$$



Ferromagnetic: Large net magnetic moment (stray fields), sensitive to magnetic fields, slower dynamics $\omega \sim H_{an} \sim$GHz

Antiferromagnetic: Zero net magnetic moment (no stray fields), insensitive to magnetic fields, fast dynamics $\omega \sim H_{flop} \sim$THz