Magnetic semiconductor spintronics

Tomas Jungwirth

D. Fang, H. Kurebayashi, J. Wunderlich, K. Vyborny, Liviu P. Zarbo, R.P. Campion, A. Casiraghi, B.L. Gallagher, T. Jungwirth, A. J. Ferguson, *Nature Nanotech. 6 (2011) 413 – 417*

T. Jungwirth, J. Wunderlich, K. Olejník, *Nature Mater. 11 (2012), 382-390.*

P. Němec, E. Rozkotová, N. Tesařová, F. Trojánek, E. De Ranieri, K. Olejník, J. Zemen, V. Novák, M. Cukr, P. Malý, T. Jungwirth, *Nature Phys. 8 (2012) 411 - 415*.

P. Němec, V. Novák, N. Tesařová, E. Rozkotová, H. Reichlová, D. Butkovičová, F. Trojánek, K. Olejník, P. Malý, R. P. Campion, B. L. Gallagher, Jairo Sinova, and T. Jungwirth, *Nature Commun. 4 (2013) 1422(1) - 1422(8).*

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E. De Ranieri, P. E. Roy, D. Fang, E. K. Vehsthedt, A. C. Irvine, D. Heiss, A. Casiraghi, R. P. Campion, B. L. Gallagher, T. Jungwirth, J. Wunderlich , *Nature Mater. 12 (2013) 808 – 814*

P. Wadley, V. Novak, R. P. Campion, C. Rinaldi, X. Marti, H. Reichlova, J. Zelezny, J. Gazquez, M. A. Roldan, M. Varela, D. Khalyavin, S. Langridge, D. Kriegner, F. Maca, J. Masek, R. Bertacco, V. Holy, A. W. Rushforth, K. W. Edmonds, B. L. Gallagher, C. T. Foxon, J. Wunderlich, and T. Jungwirth *, Nature. Commun. 4 (2013) 2322(1) - 2322(6)*

H. Kurebayashi, Jairo Sinova, D. Fang, A. C. Irvine, J. Wunderlich, V. Novak, R. P. Campion, B. L. Gallagher, E. K. Vehstedt, L. P. Zarbo, K. Vyborny, A. J. Ferguson, T. Jungwirth, *arXiv:1306.1893*

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T. Jungwirth, J. Wunderlich, V. Novak, K. Olejnik, B. L. Gallagher, R. P. Campion, K. W. Edmonds, A. W. Rushforth, A. J. Ferguson, P. Nemec, *arXiv:1310.1944*

Magnetic semiconductor spintronics

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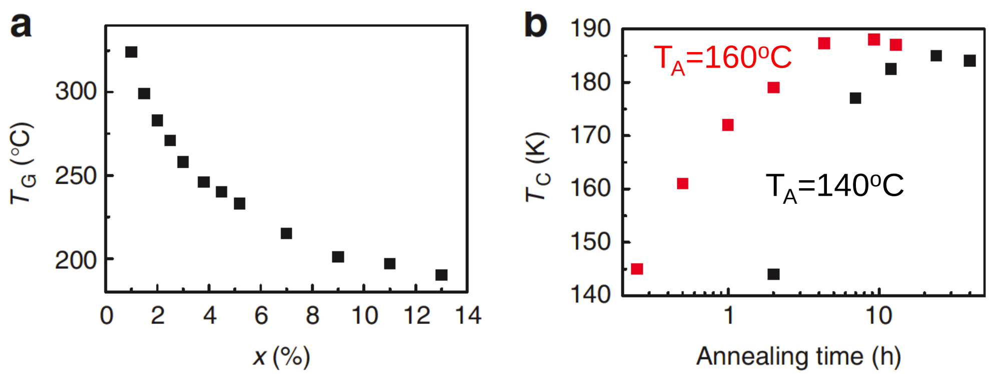
Institut de Ciencia de Materials de Barcelona, Spain

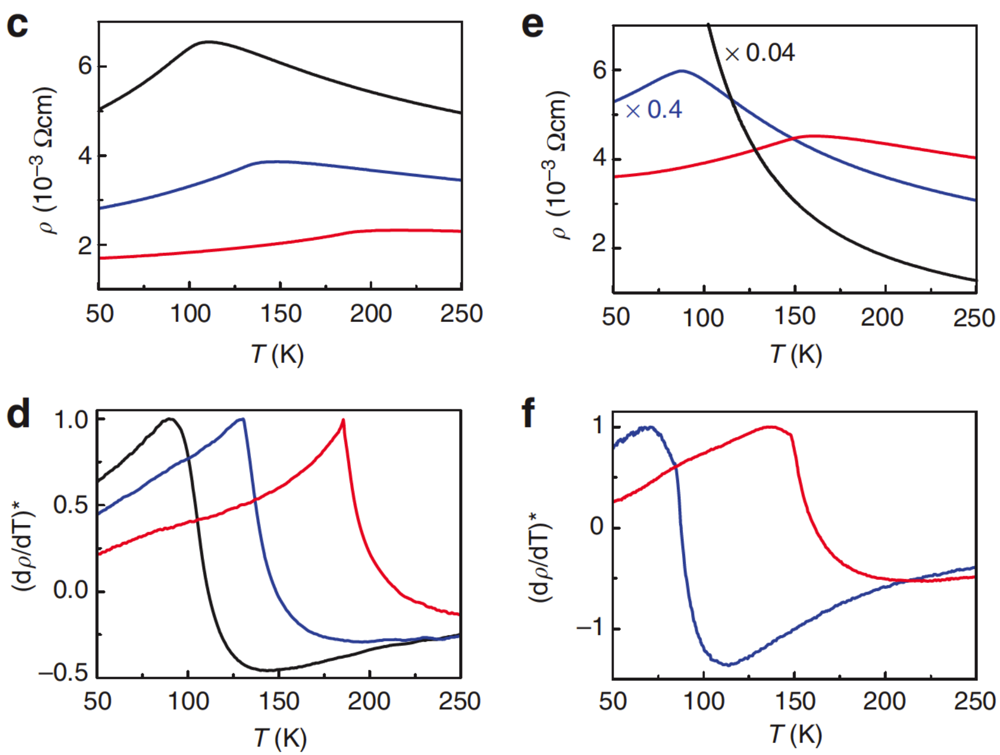
Univ. of California, Berkeley

Optimizing MBE growth and post-growth annealing of (Ga,Mn)As



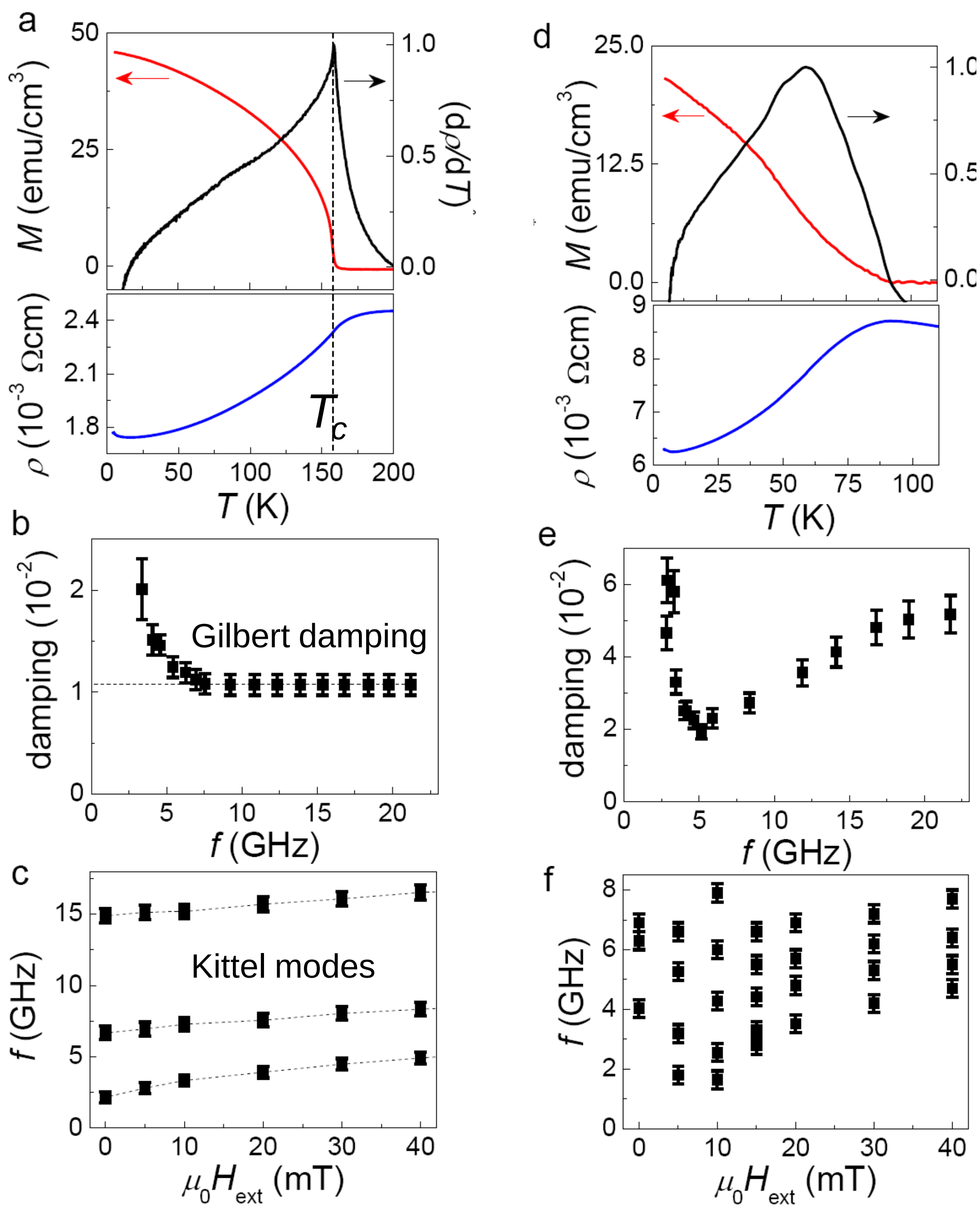
Optimized (Ga,Mn)As

Not optimized (Ga,Mn)As (10°C lower T_G)



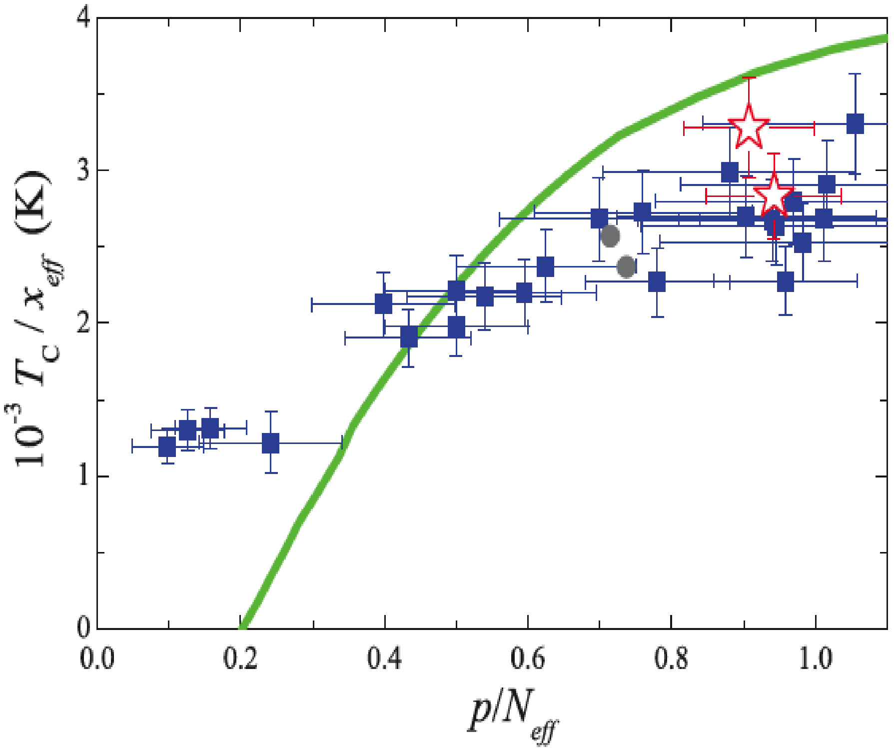
Němec, Novák, TJ et al.
Nature Commun. '13

Optimized (Ga,Mn)As **Not optimized (Ga,Mn)As (thicker films)**

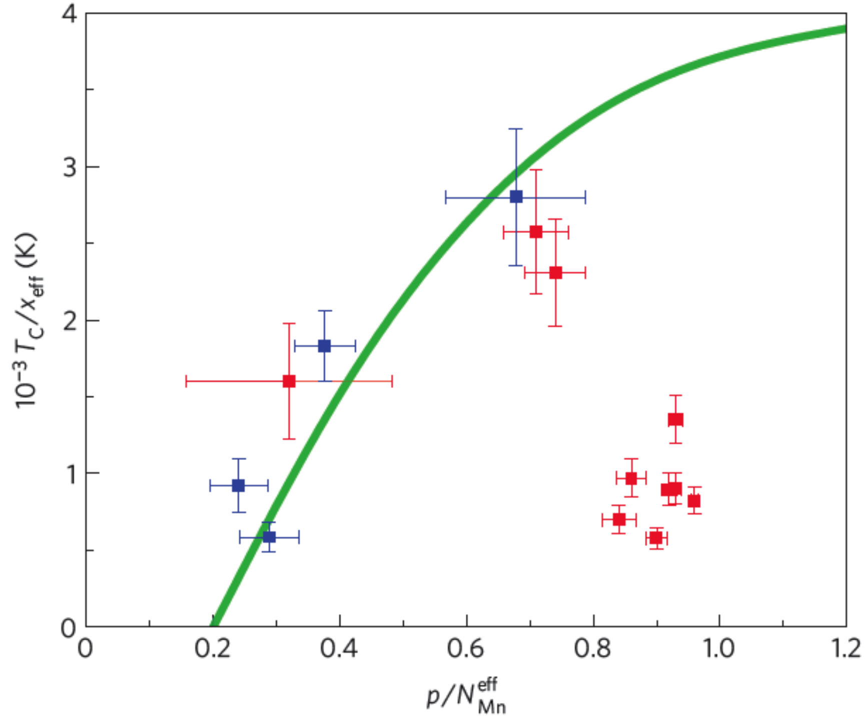


Němec, Novák, TJ et al.
Nature Commun. ‘13

Optimized (Ga,Mn)As



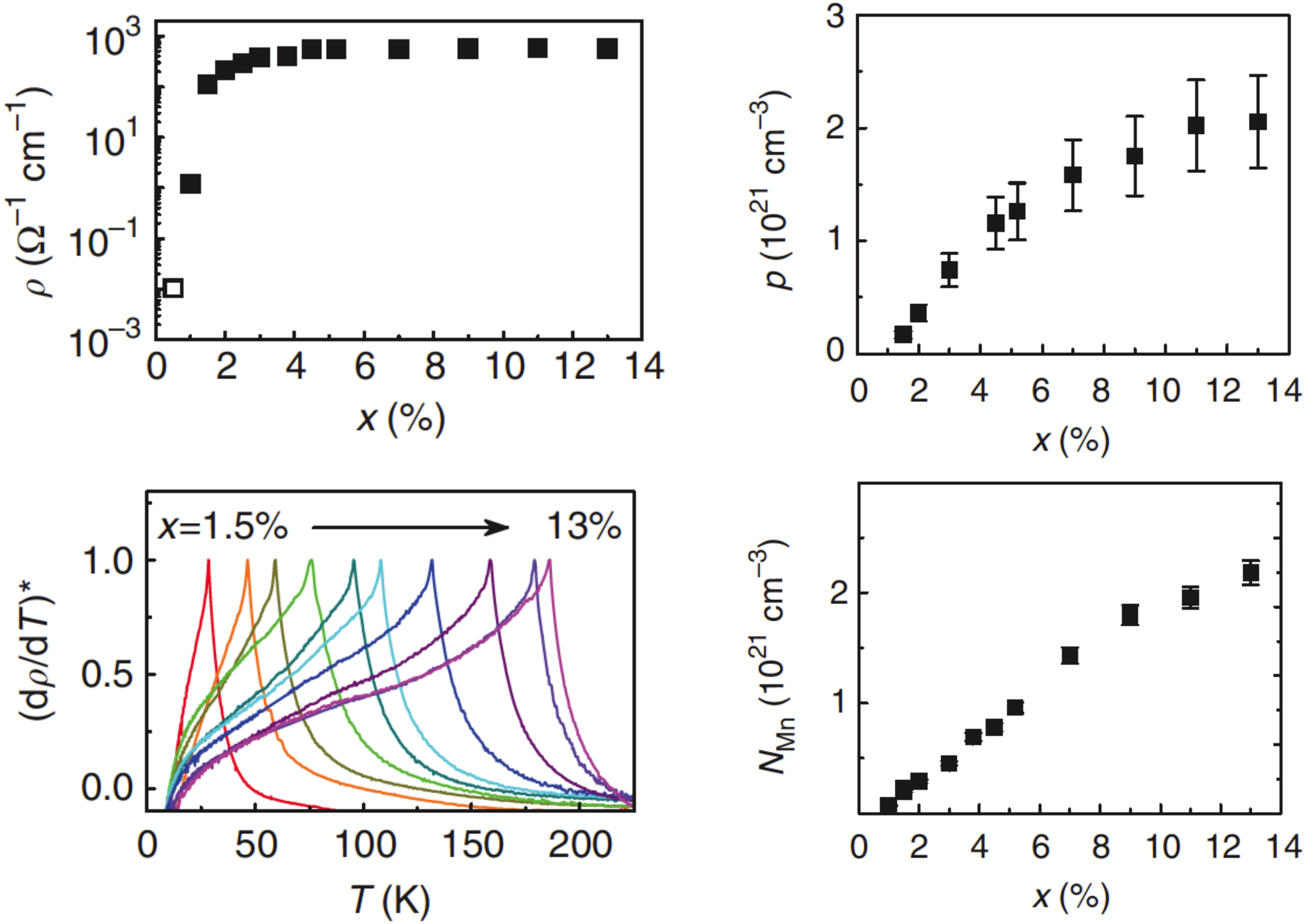
Wang et al. PRB '13



Dobrowolska et al. Nature Mater '12

Series of optimized $Ga_{1-x}Mn_xAs$

Fully reproducible and well behaved FM and degenerate semiconductor



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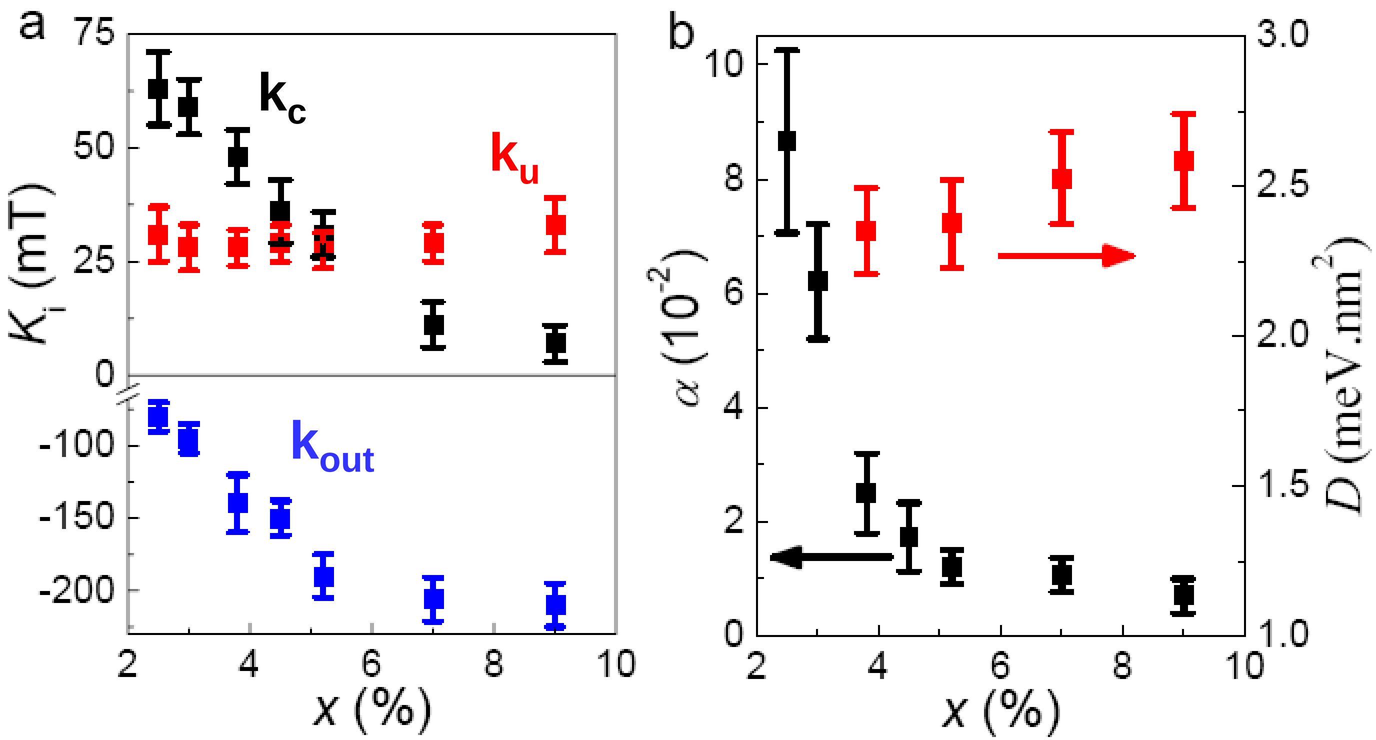


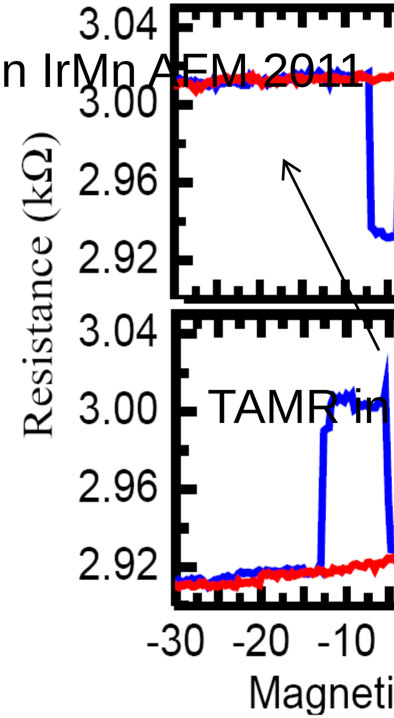
.. and tuneable, and compatible with III-V heterostructure and fabrication techniques

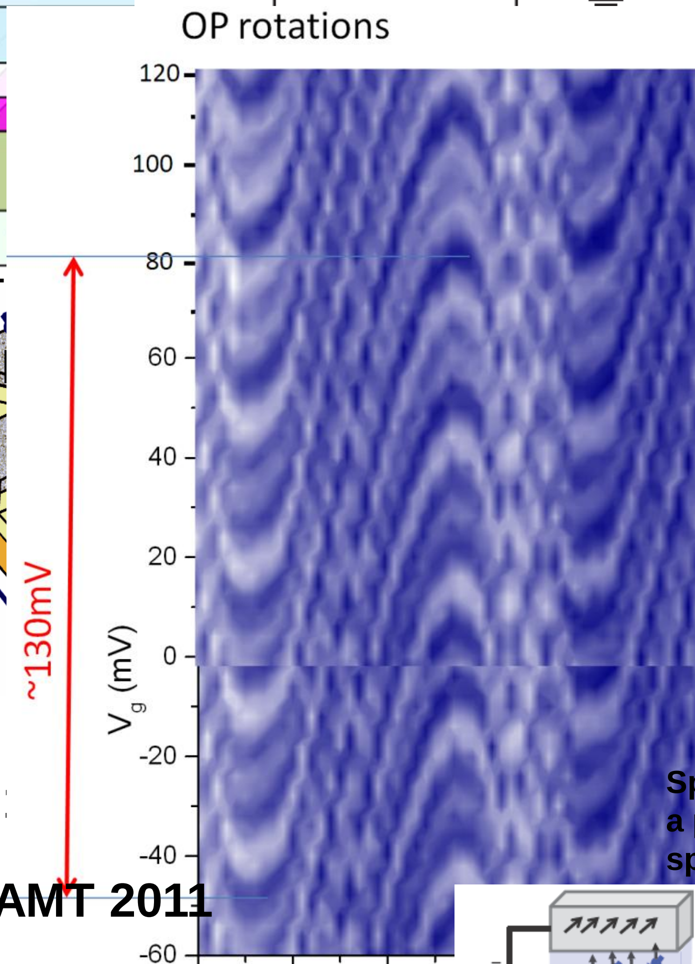
... and strong exchange and spin-orbit ~ 100s meV → strong disorder (even unintentional) is not detrimental to spintronics in (Ga,Mn)As

.. and the full range of spintronic effects described qualitatively or semiquantitatively by mutually consistent DFT, TB-Anderson, kinetic-exchange **k.p** models

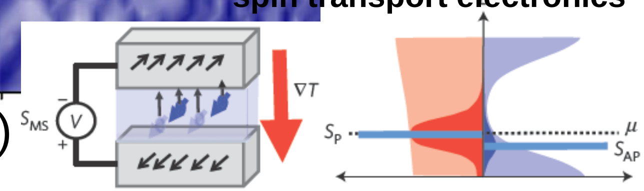
>100meV chem. pot. AMR in IrMn/MgO/Pt 2013

>100%TAMR in IrMn AFM 2011





Spintronics :
a pormanteau meaning
spin transport electronics



GaMnAs

Ohmic AMR 1856 ↔ TAMR 2004 ↔

AMT 2006 ↔ TAMT 2011

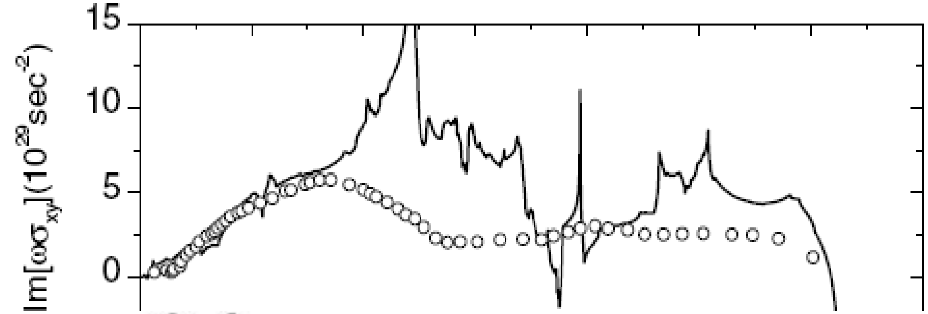
(TMT in TM FMs 2011)

AMT in TM FMs 2012

→shift in gate voltage corresponds to 7 gate voltage periods

GaMnAs in spintronics: *arXiv:1310.1944*

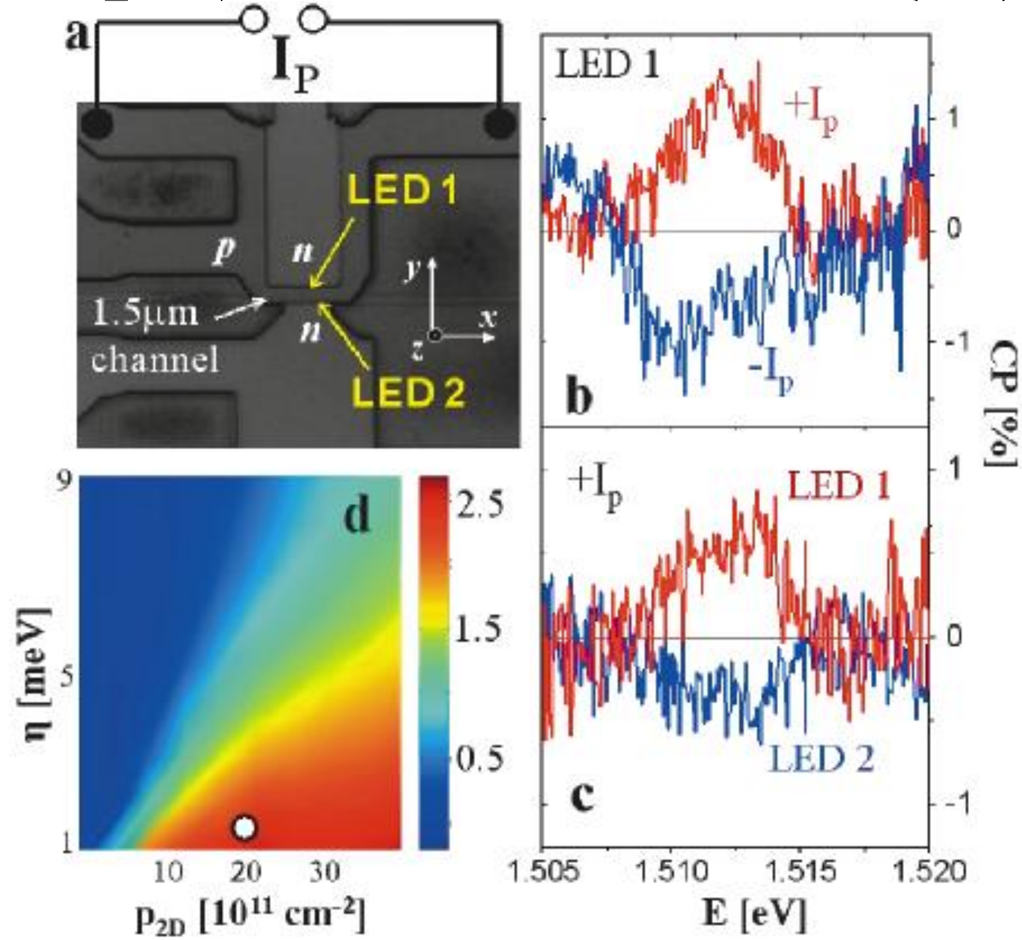
Intrinsic AHE in TM FMs 2004



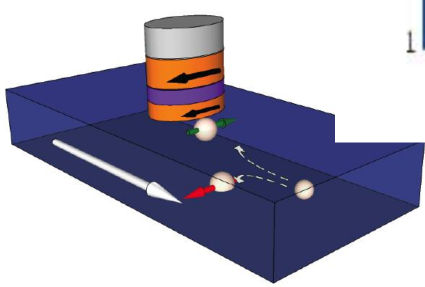
GaMnAs

AHE 1881 ↔ intrinsic AHE 2002

intrinsic SHE in p-GaAs 2004

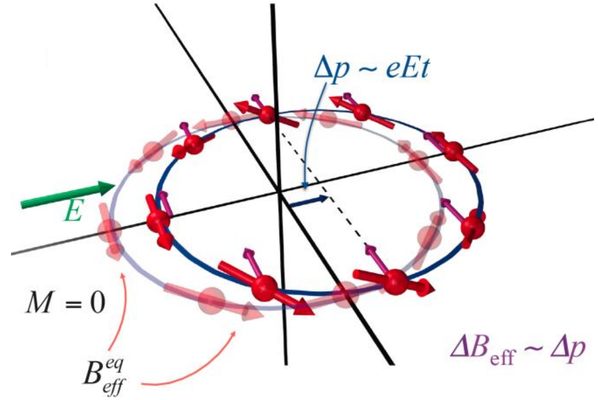


intrinsic SHE in m



SHE-STT MTJ 2012

GaMnAs in spintronics: *arXiv:1310.1944*

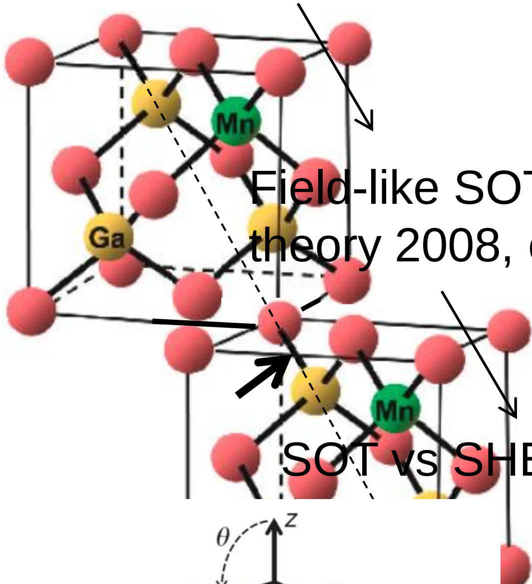


intrinsic AHE/SHE

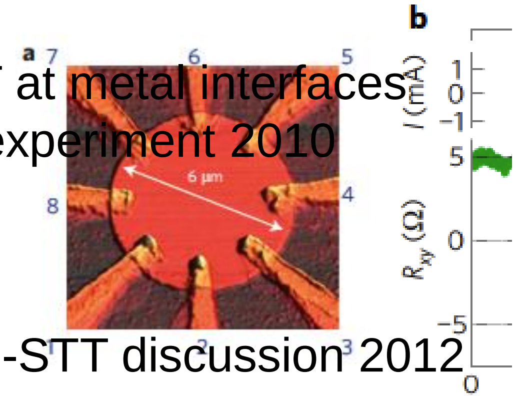
↓

GaMnAs

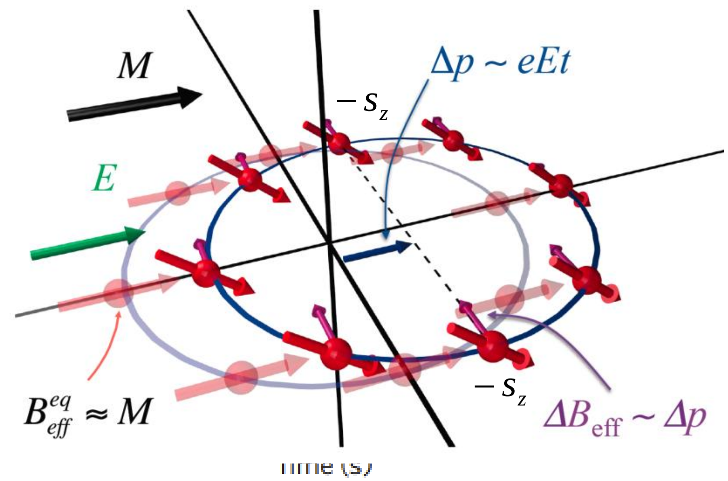
Field-like SOT theory 2005 ↔ experiment 2009 ↔ intrinsic anti-damping SOT

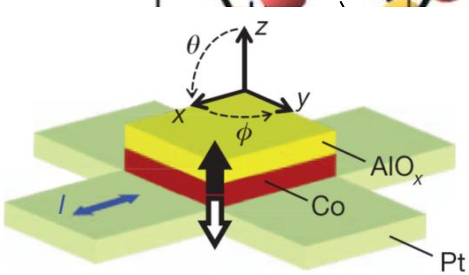


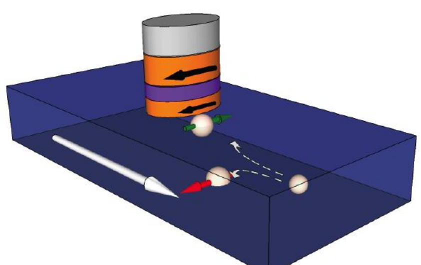
Field-like SOT at metal interfaces
theory 2008, experiment 2010



SOT vs SHE-STT discussion 2012

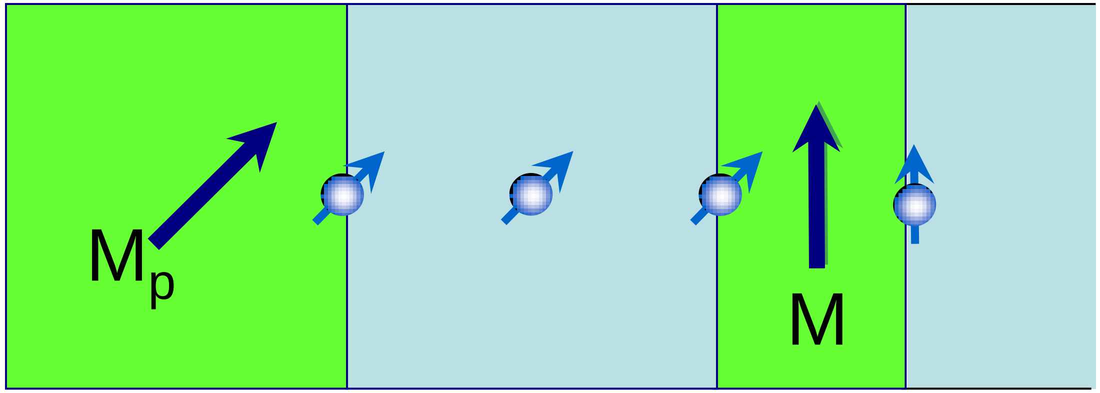




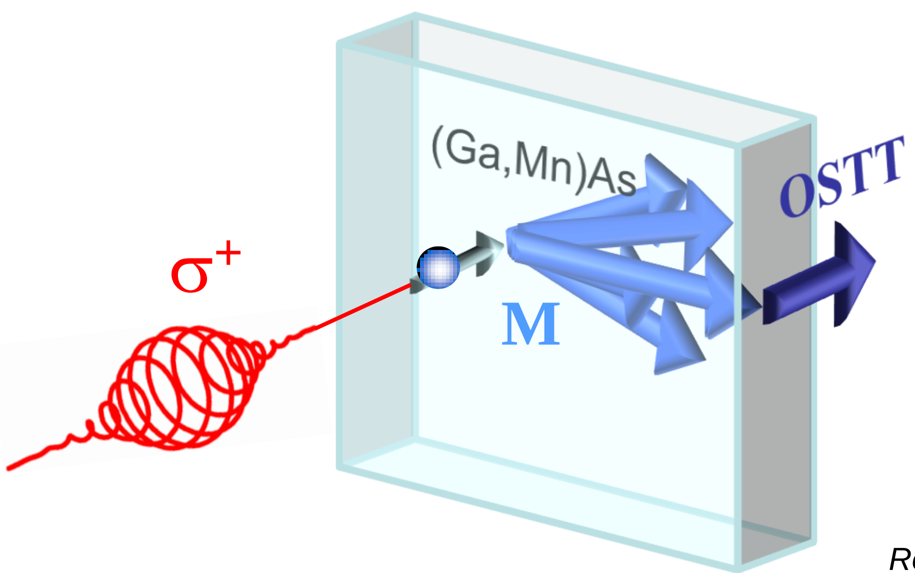


GaMnAs in spintronics: *arXiv:1310.1944*

Electrical spin-tranfer torque

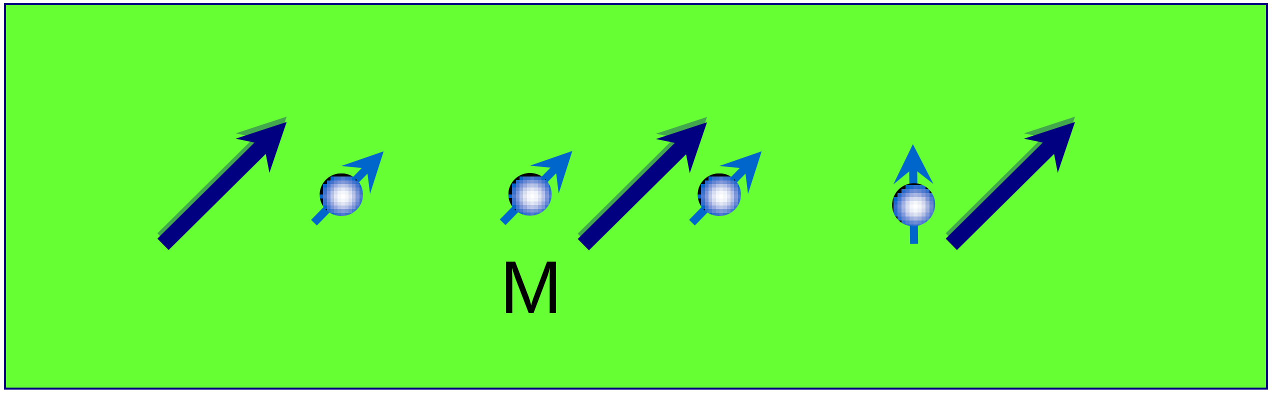


Optical spin-tranfer torque

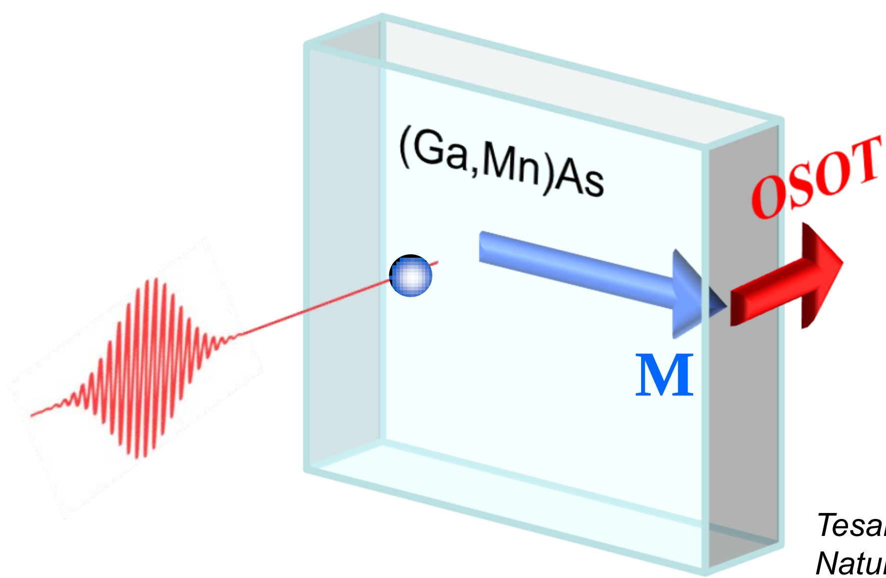


Rossier, MacDonald, et al. ‘03
Němec, Novák, TJ et al. Nature Phys.‘12

Electrical spin-orbit torque



Optical spin-orbit torque



Tesařová, Němec, Novák, TJ et al.
Nature Photonics '13

Steady-state carrier spin polarization $\vec{s} \rightarrow$ torque $\frac{d\vec{M}}{dt}$

$$\frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H]\rangle \qquad \vec{s} = \langle\vec{\sigma}\rangle_{\text{QM averaging in non-equilibrium}}$$

Spin-transfer torque

$$H = H_0 + H_{ex}$$

$$\downarrow \; H_{ex} = J\vec{M}\cdot\vec{\sigma}$$

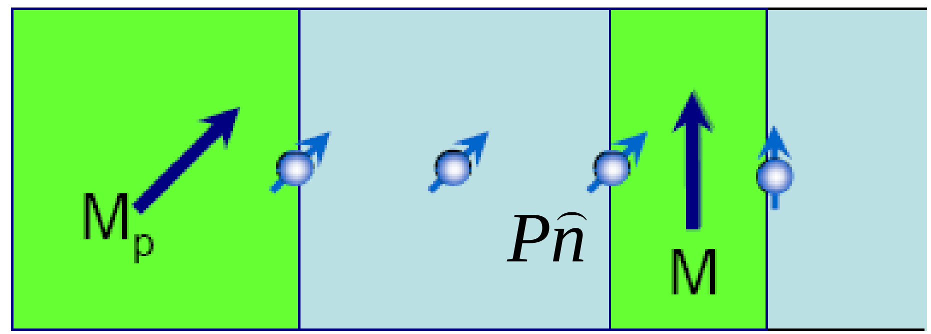
Steady state

$$0 = \frac{d\vec{s}}{dt} = \frac{J}{\hbar}\vec{s}\times\vec{M} + P\hat{n}$$

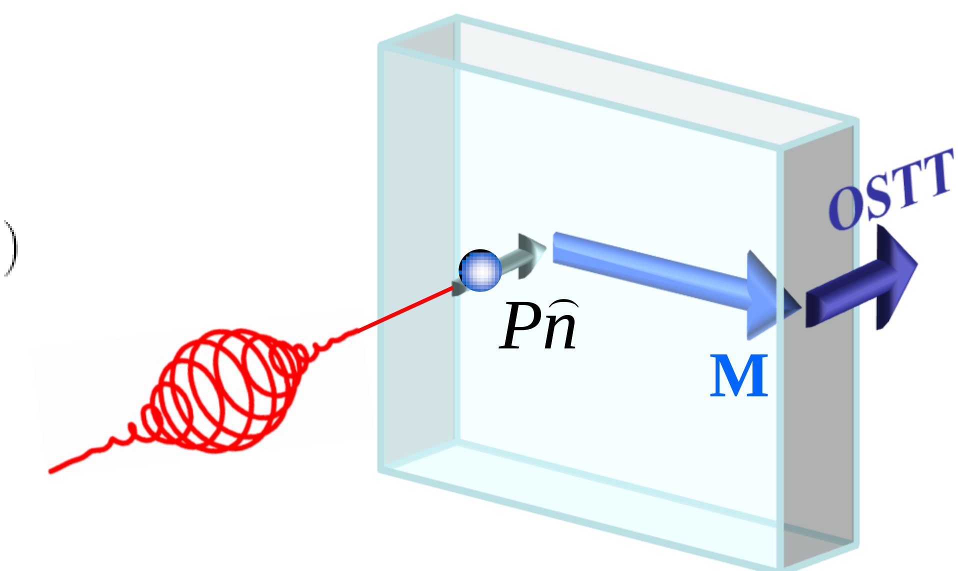
External

$$\frac{d\vec{M}}{dt} = \frac{J}{\hbar}\vec{M}\times\vec{s} = P\hat{M}\times(\hat{n}\times\hat{M})$$

Electrical spin injection



Optical spin injection

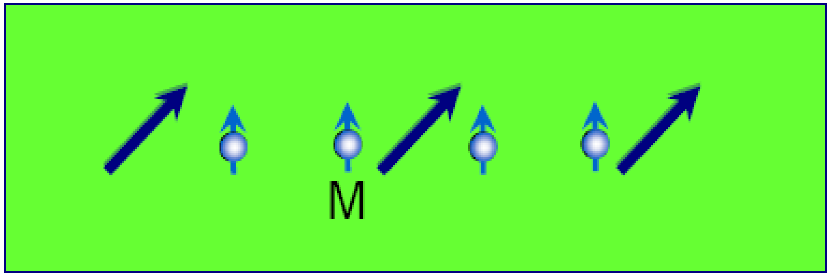


Steady-state carrier spin polarization $\vec{s} \rightarrow$ torque $\frac{d\vec{M}}{dt}$

$$\frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H]\rangle \qquad \vec{s} = \langle\vec{\sigma}\rangle$$

QM averaging in non-equilibrium

Electrical spin injection



Spin-orbit torque

$$H = H_0 + H_{ex} + H_{so}$$

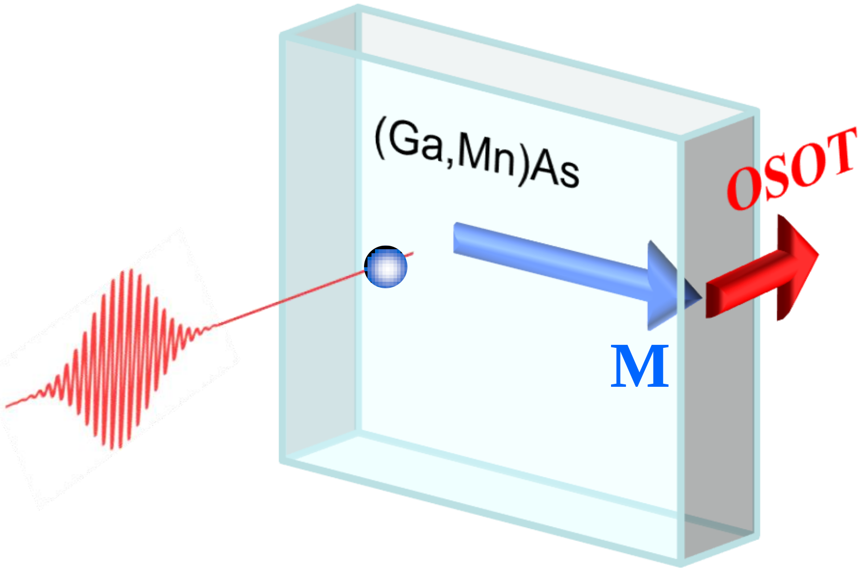
Internal

Steady state

$$0 = \frac{d\vec{s}}{dt} = \frac{J}{\hbar}\vec{s} \times \vec{M} + \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{so}]\rangle$$

$$\frac{d\vec{M}}{dt} = \frac{J}{\hbar}\vec{M} \times \vec{s} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{so}]\rangle$$

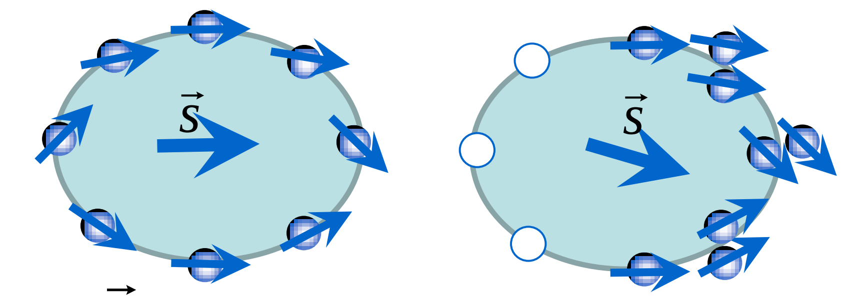
Optical spin injection



Steady-state carrier spin polarization $\vec{s} \rightarrow$ torque $\frac{d\vec{M}}{dt}$

$$\frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H]\rangle \qquad \vec{s} = \langle\vec{\sigma}\rangle$$

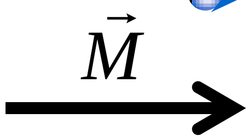
Linear response: eigenstates of H
& non-equilibrium distribution
Electrical drift and relaxation



Spin-orbit torque

$$H = H_0 + H_{ex} + H_{so}$$

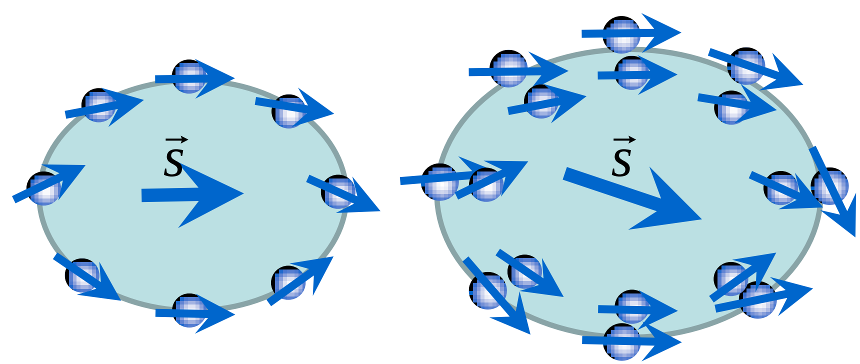
Internal



Steady state

$$0 = \frac{d\vec{s}}{dt} = \frac{J}{\hbar}\vec{s} \times \vec{M} + \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{so}]\rangle$$

Optical generation and relaxation



$$\frac{d\vec{M}}{dt} = \frac{J}{\hbar}\vec{M} \times \vec{s} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{so}]\rangle$$

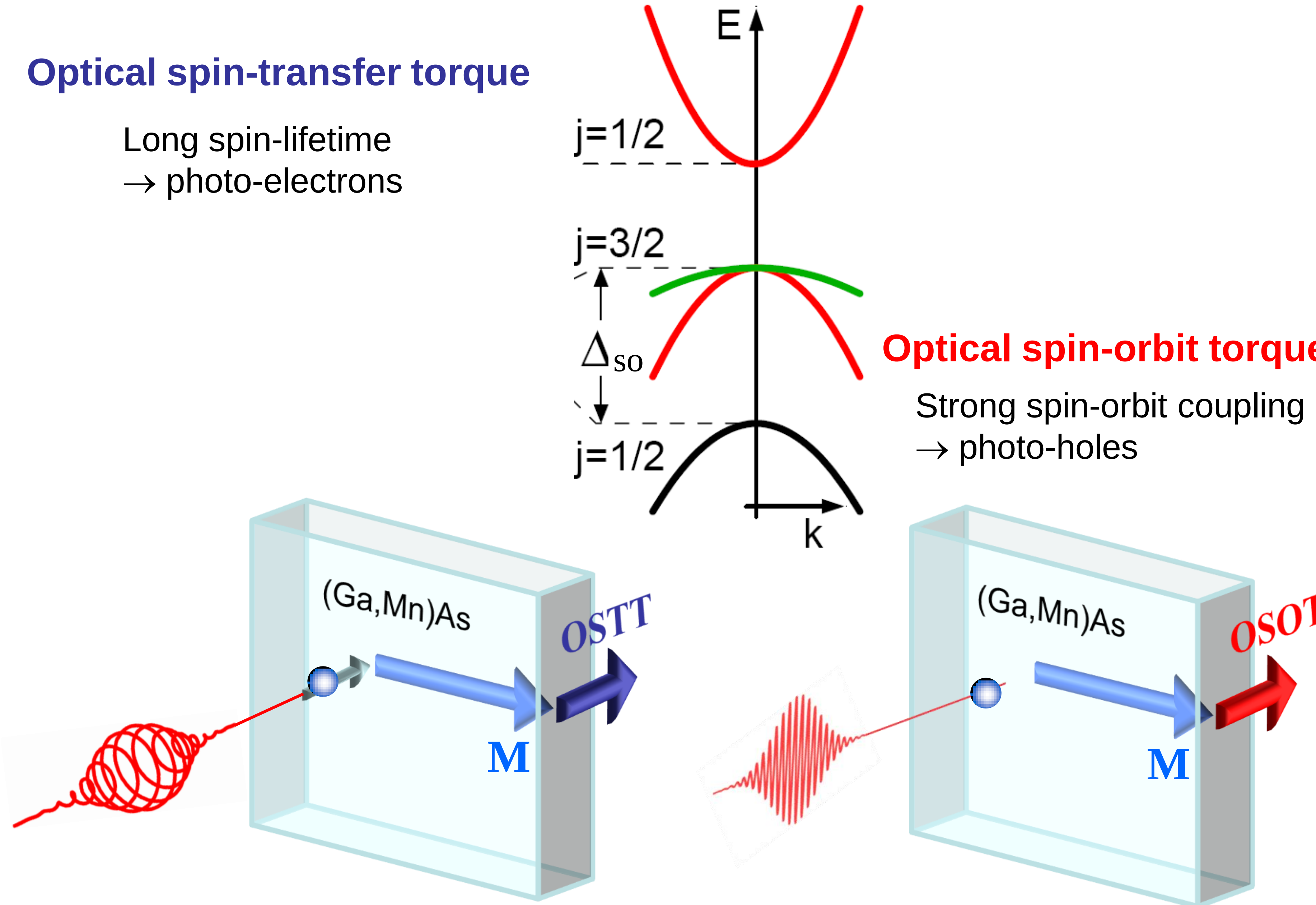
Optical spin torques in ferromagnetic semiconductor (Ga,Mn)As

Optical spin-transfer torque

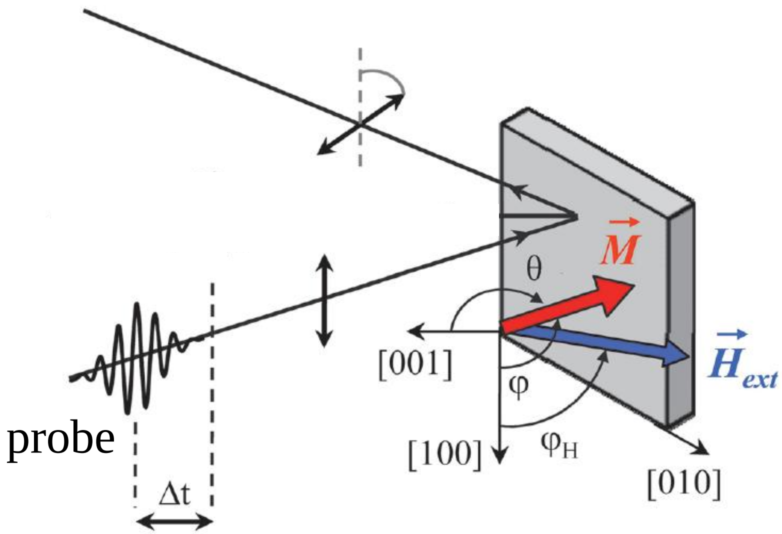
Long spin-lifetime
→ photo-electrons

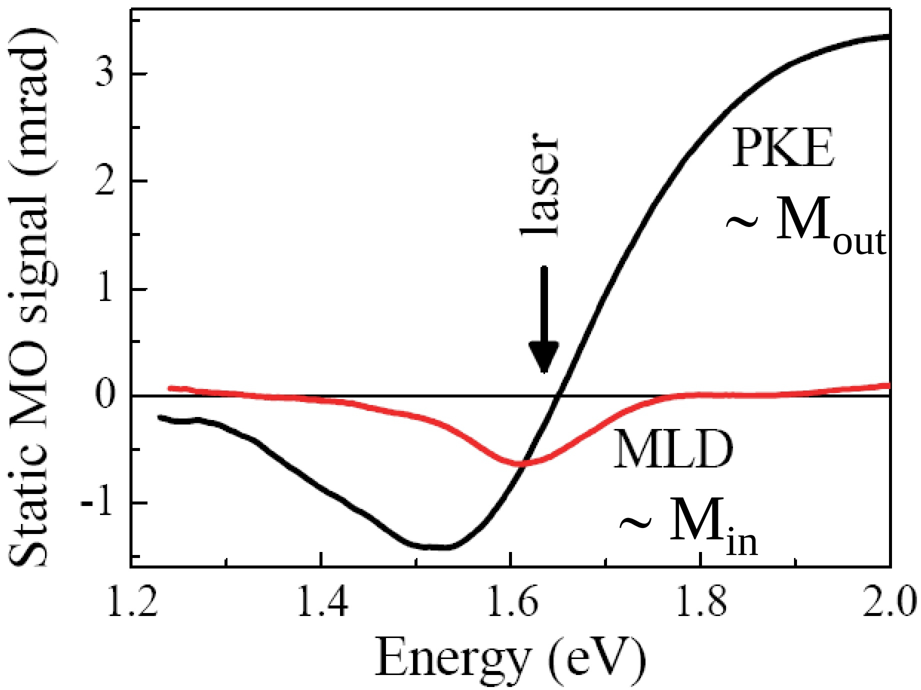
Optical spin-orbit torque

Strong spin-orbit coupling
→ photo-holes



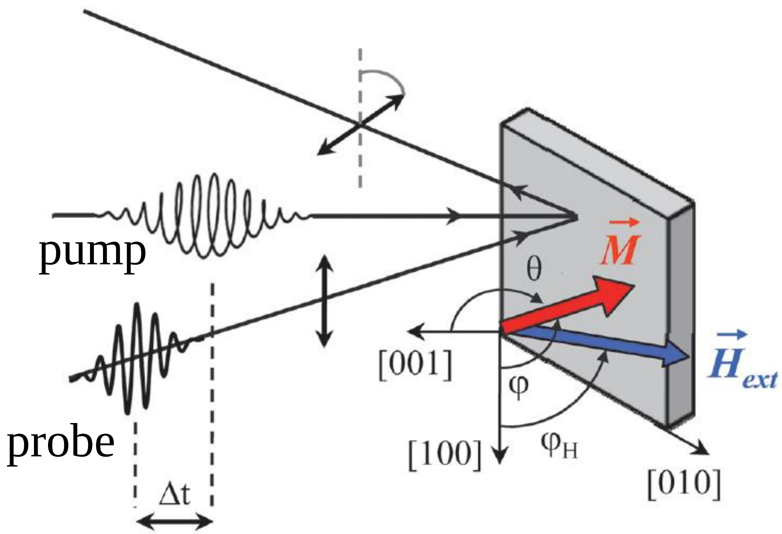
Magneto-optical parameters of (Ga,Mn)As

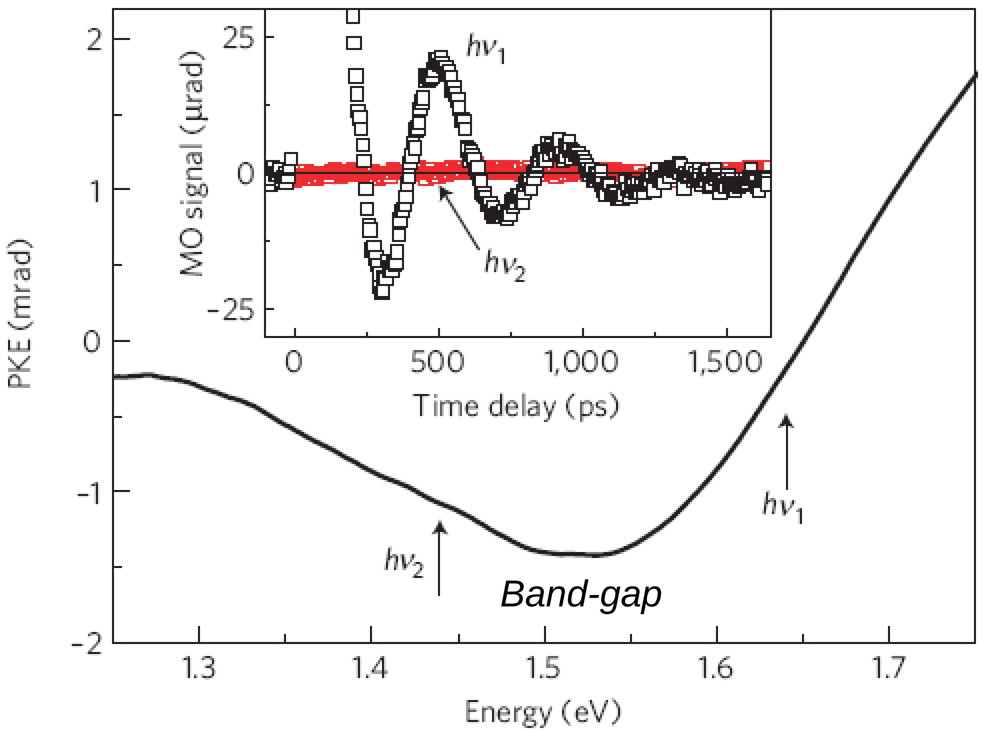




Tesařová, Němec, Novák, TJ et al. Appl. Phys. Lett.'12

Pump-and-probe magneto-optical signals in (Ga,Mn)As





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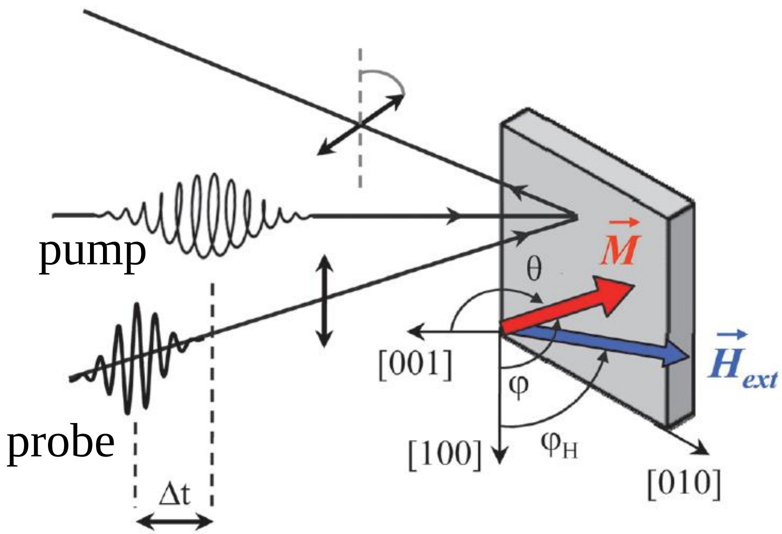
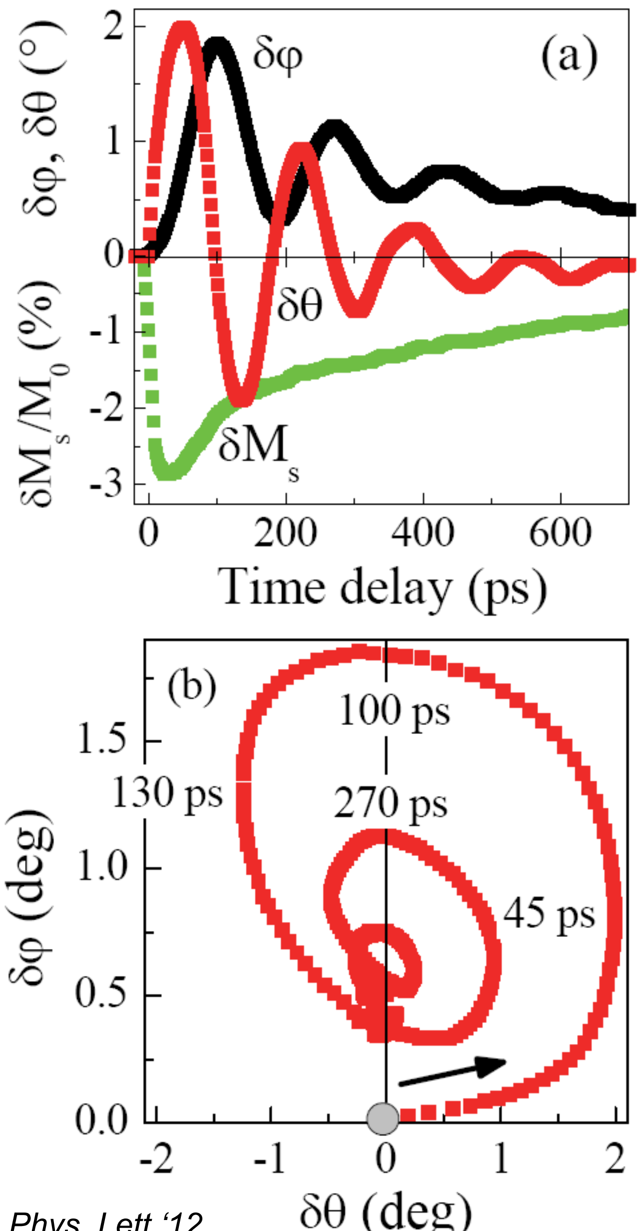
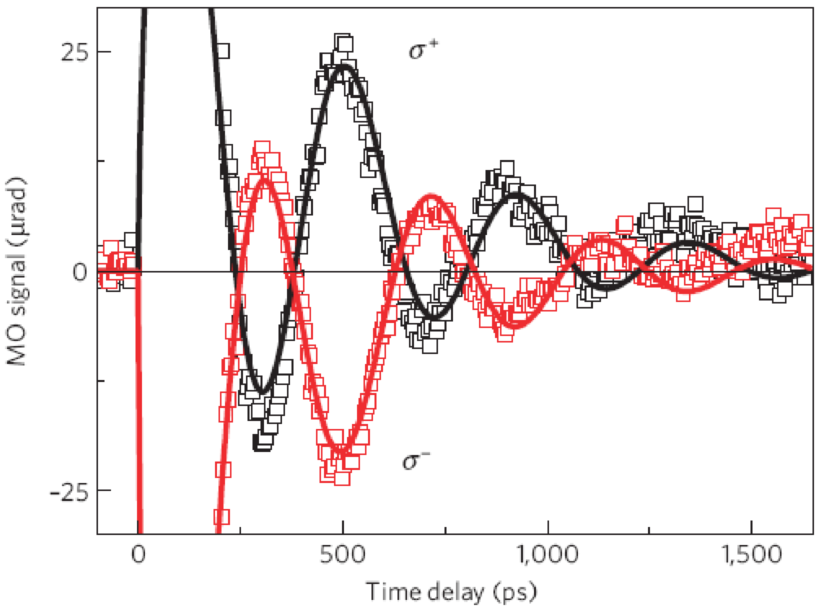
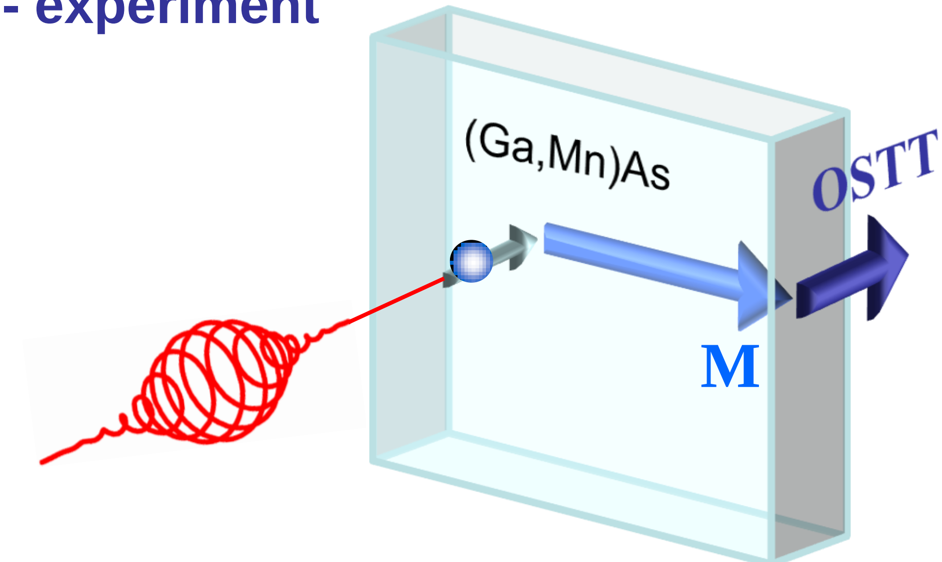


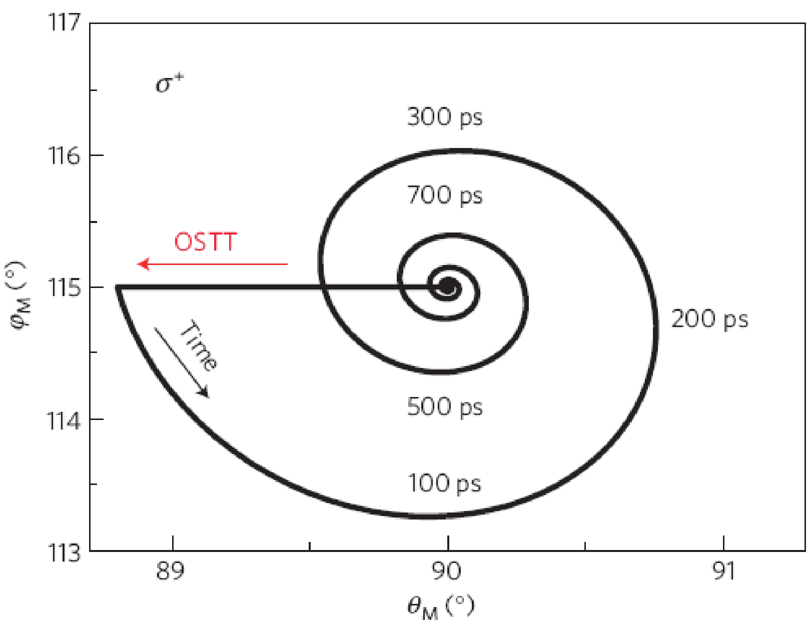


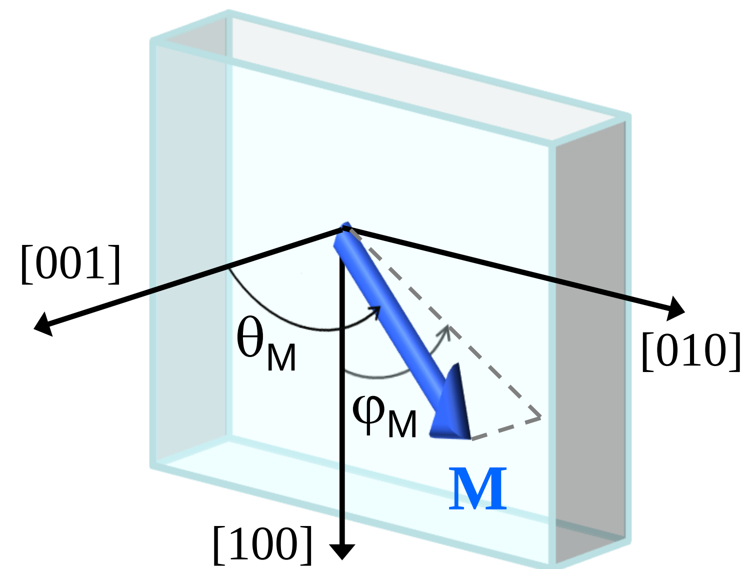
Tesařová, Němec, Novák, TJ et al. Appl. Phys. Lett.'12

Optical spin-transfer torque - experiment



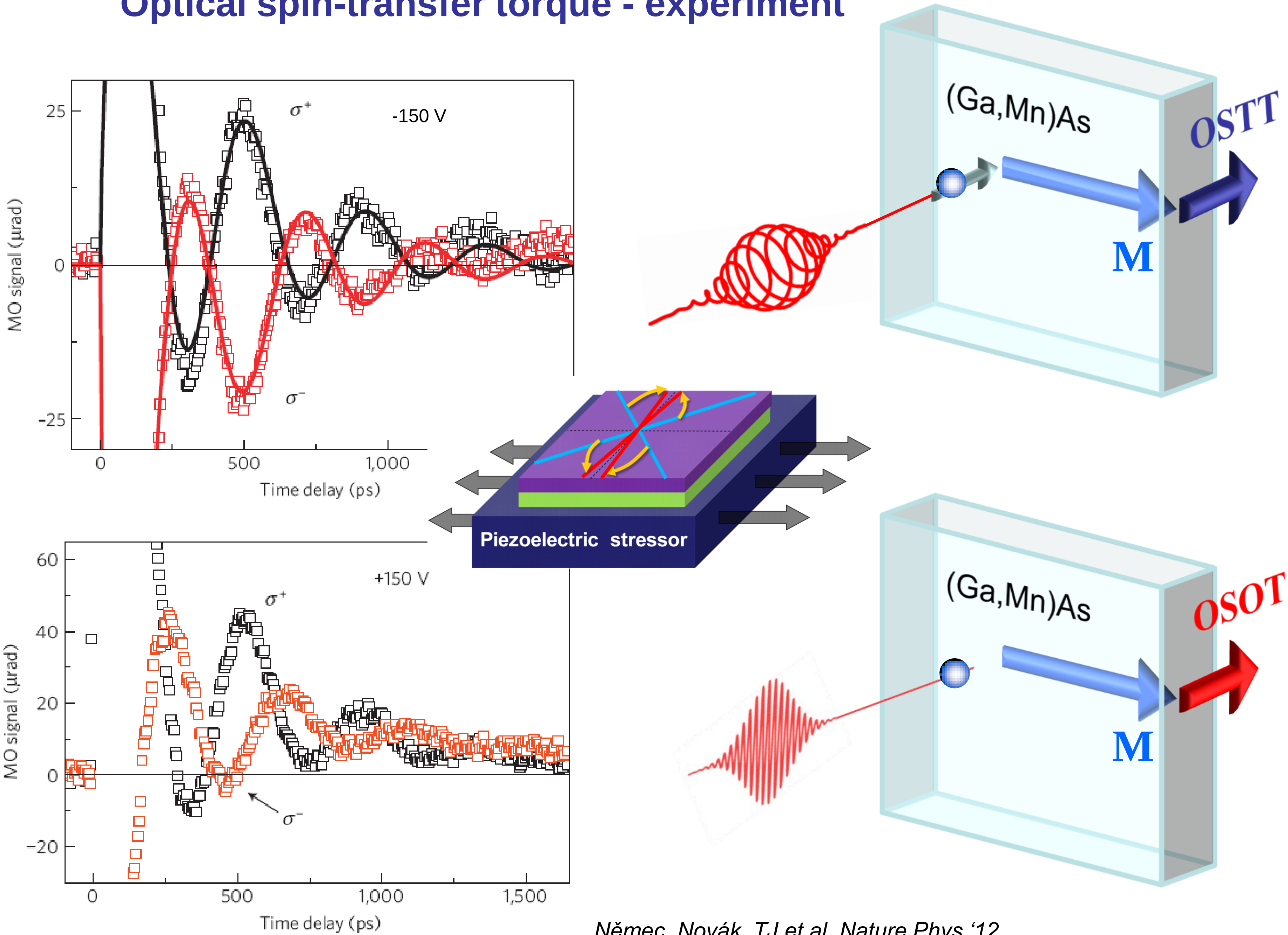






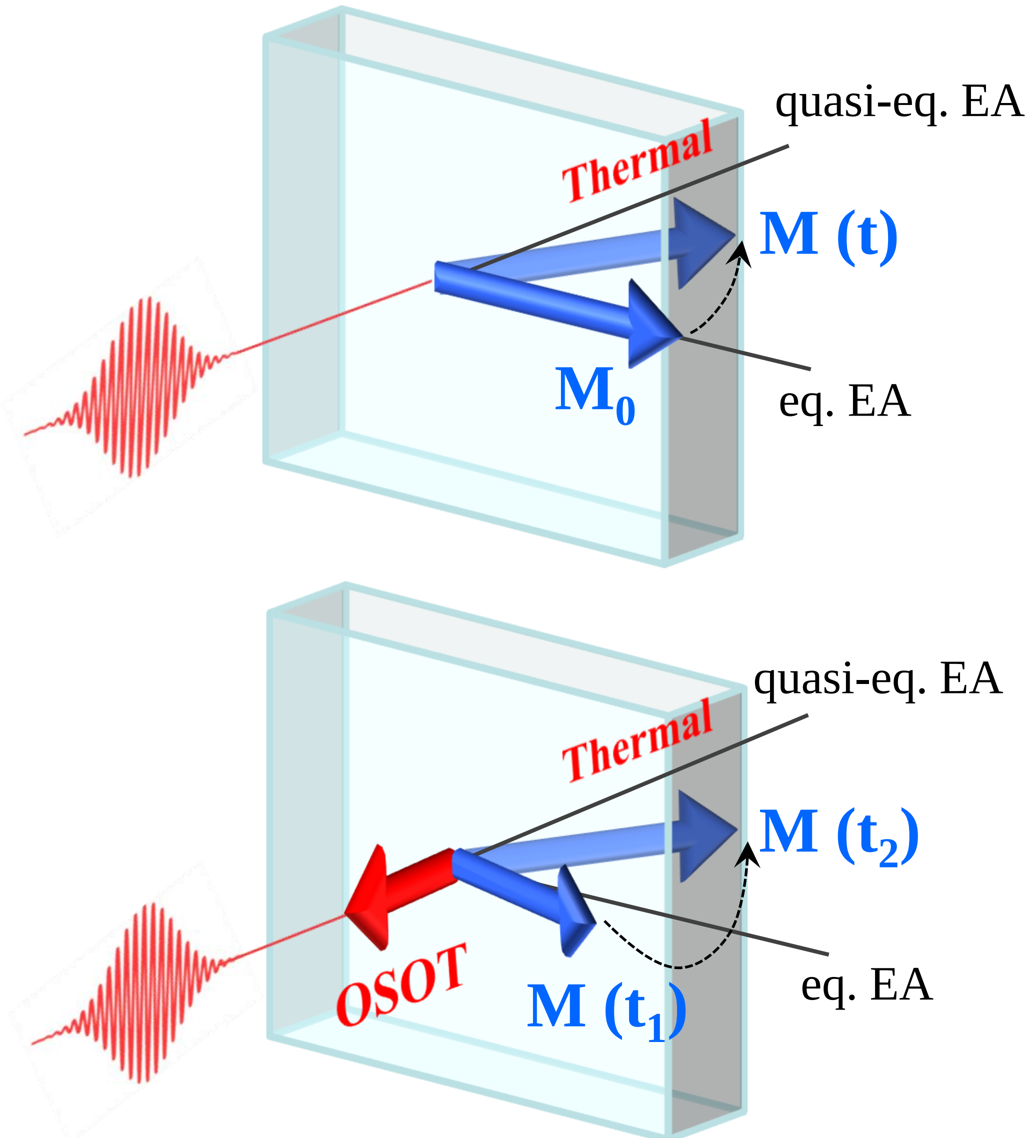
Němec, Novák, TJ et al. Nature Phys.'12

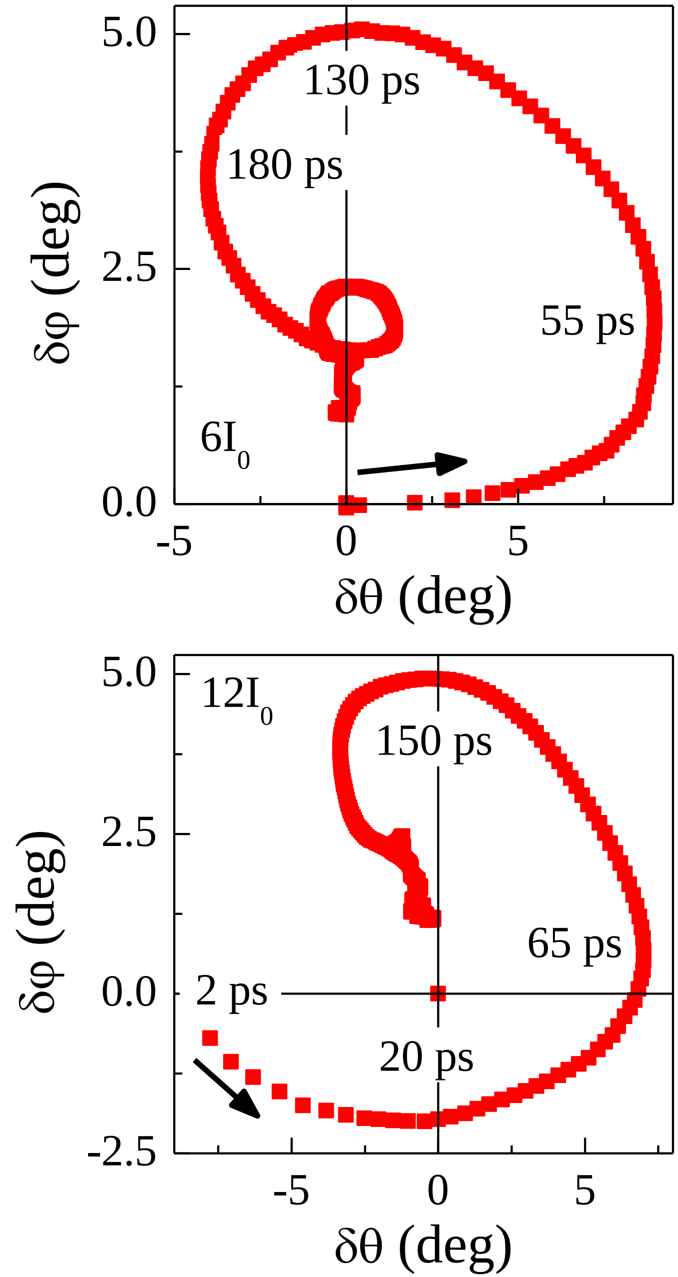
Optical spin-transfer torque - experiment



Němec, Novák, TJ et al. Nature Phys.'12

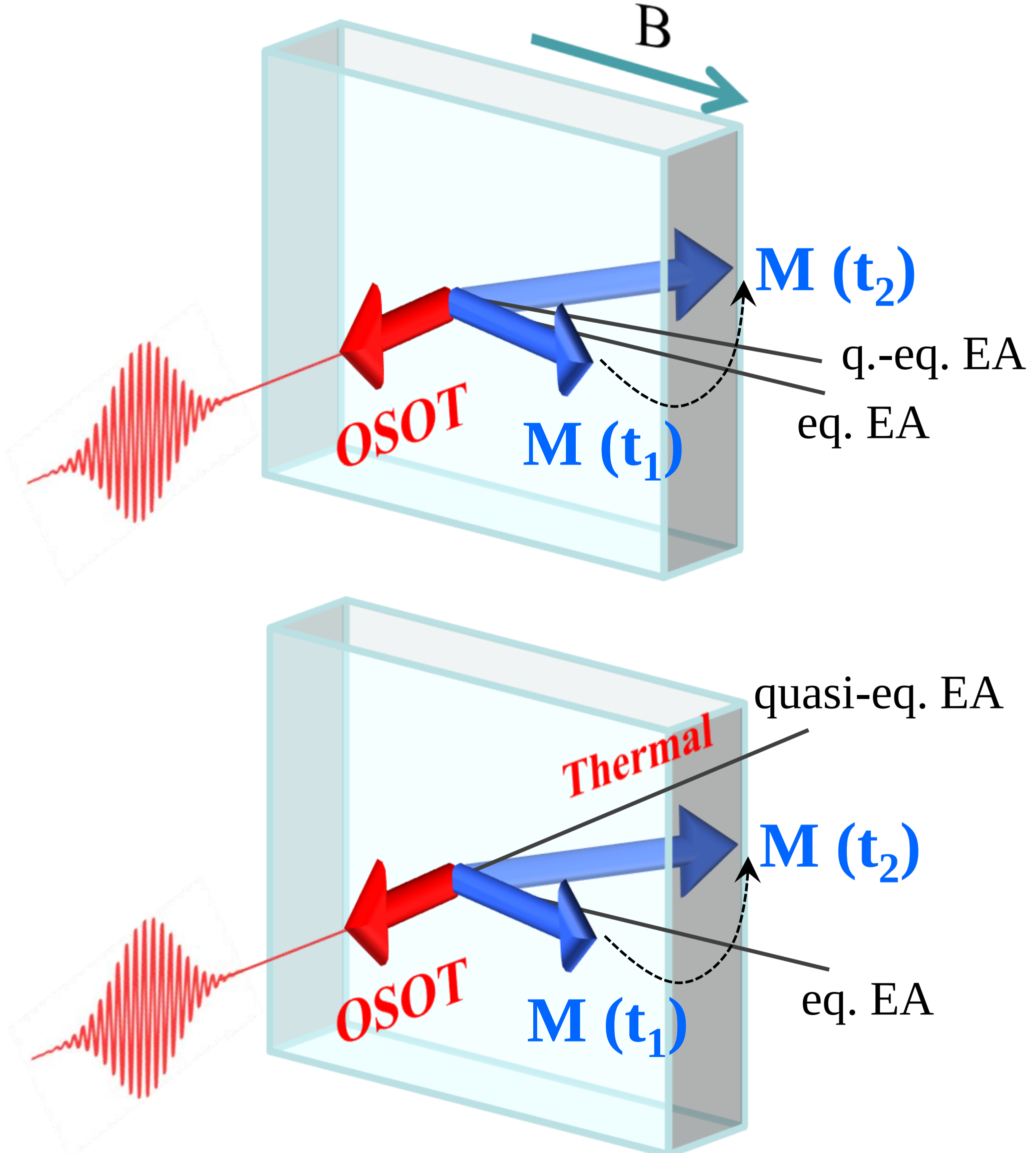
Optical spin-orbit torque - experiment

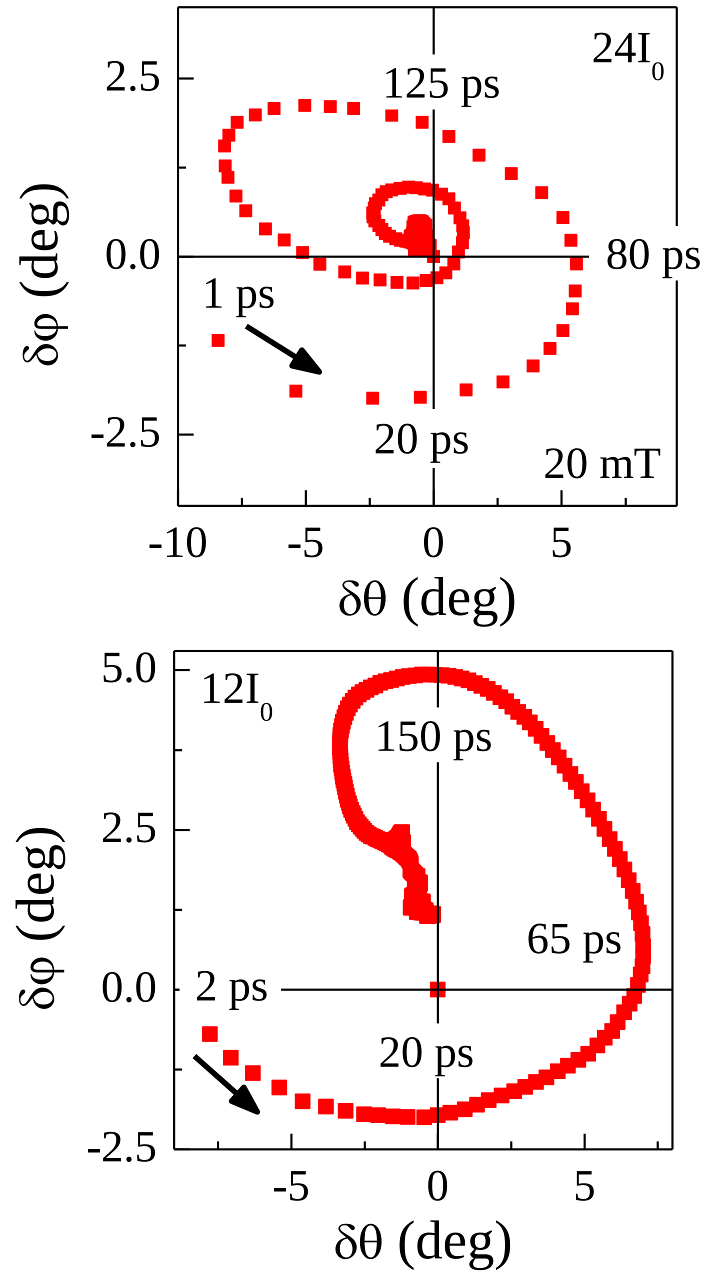




Tesařová, Němec, Novák, TJ et al., Nature Photonics '13

Optical spin-orbit torque - experiment

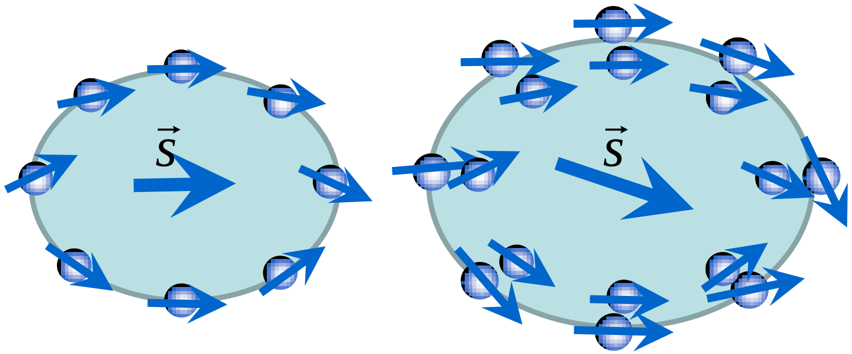




Tesařová, Němec, Novák, TJ et al., Nature Photonics '13

Optical spin-orbit torque - theory

Optical generation and relaxation

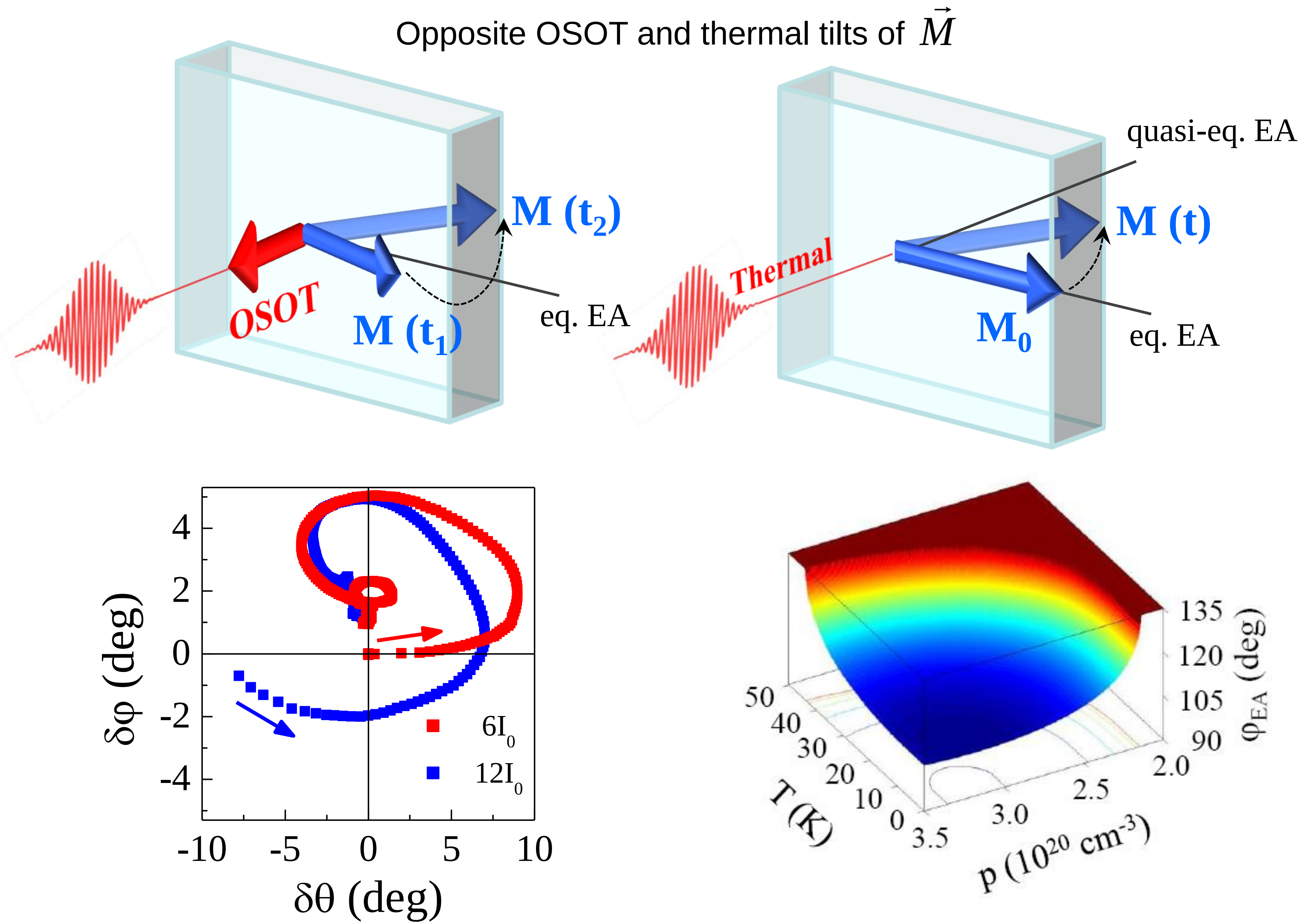


$$\frac{d\vec{M}}{dt} = \frac{J}{\hbar}\vec{M}\times\vec{s} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{so}]\rangle \qquad H_{ex} = J\vec{M}\cdot\vec{\sigma}$$

$$\vec{H}_{an} = -\frac{\partial}{\partial\vec{M}}\sum_a\int d\mathbf{k}\,\epsilon_{a,\vec{k}} f_{a,\vec{k}} = -\sum_a\int d\vec{k}\langle a,\vec{k}|\frac{\partial H}{\partial\vec{M}}|a,\vec{k}\rangle f_{a,\vec{k}}$$

$$= -\sum_a\int d\vec{k}\langle a,\vec{k}|J\vec{\sigma}|a,\vec{k}\rangle f_{a,\vec{k}} = -J\vec{s}\,.$$

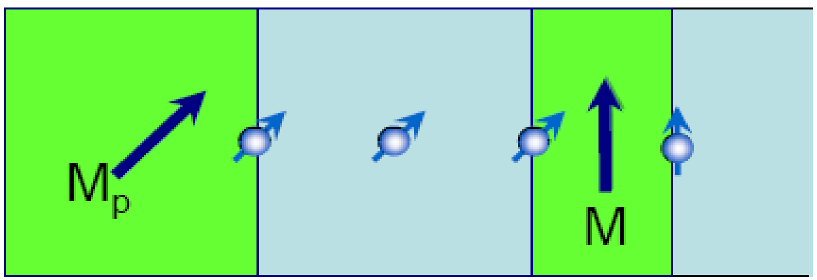
Photo-hole spin-density ↔ hole-density-dependent magnetic anisotropy field



Opposite OSOT and thermal tilts of $\vec{M}$
M (t2)
M (t1)
OSOT
eq. EA
quasi-eq. EA
M (t)
Thermal
M0
eq. EA
δφ (deg)
δθ (deg)
6I0
12I0
T (K)
p (10^{20} cm^{-3})
φ_{EA} (deg)

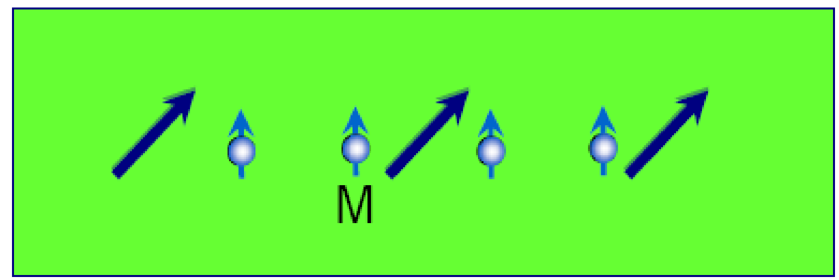
Electrical spin-tranfer torque

Non-uniform magnetic structure



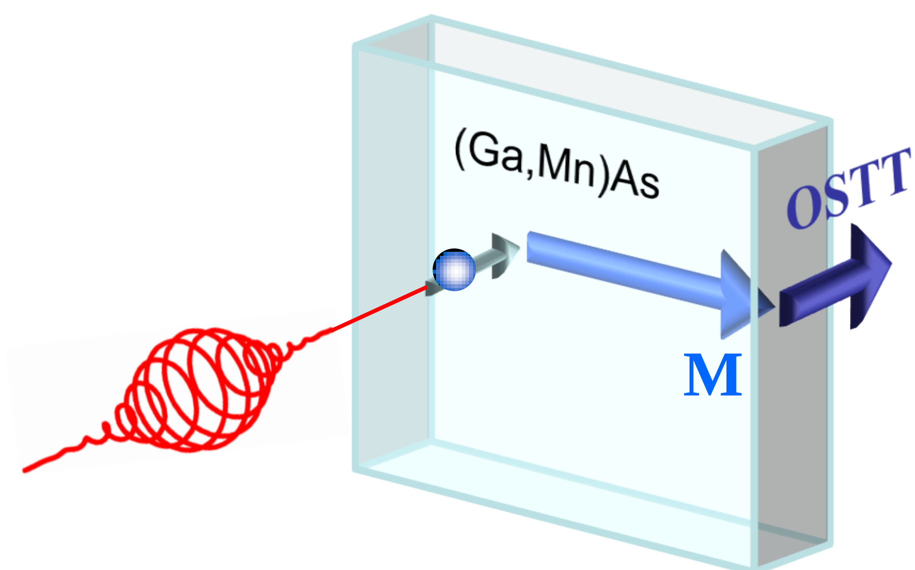
Electrical spin-orbit torque

Broken inversion-symmetry magnet



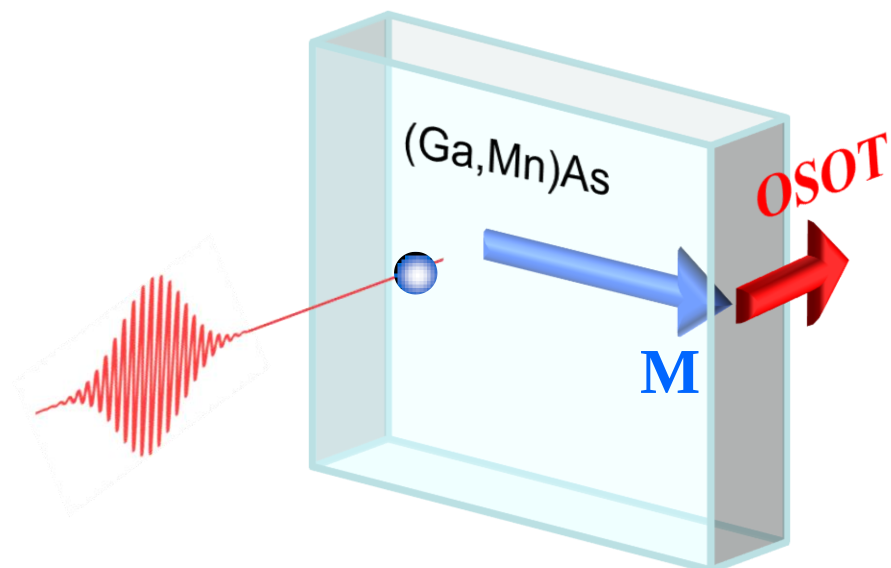
Optical spin-tranfer torque

Uniform magnet



Optical spin-orbit torque

Inversion-symmetric magnet



AFM semiconductors: prospect for room-T magnetic-semiconductor spintronics

TJ, Novák, et al. PRB ’11, Cava Viewpoint, Physics ’11, Máca, TJ et al. JMMM ’12, Wadley, TJ, et al. Nature Commun. ‘13

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

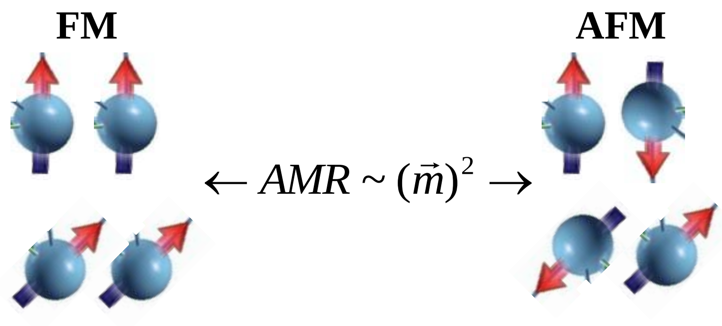
III-V	FM T_C (K)	AFM T_N (K)
FeN		100
FeP		115
FeAs		77
FeSb		100-220
GdN	72	
GdP		15
GdAs		19
GdSb		27

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**

Beleanu et al. arxiv:13076404

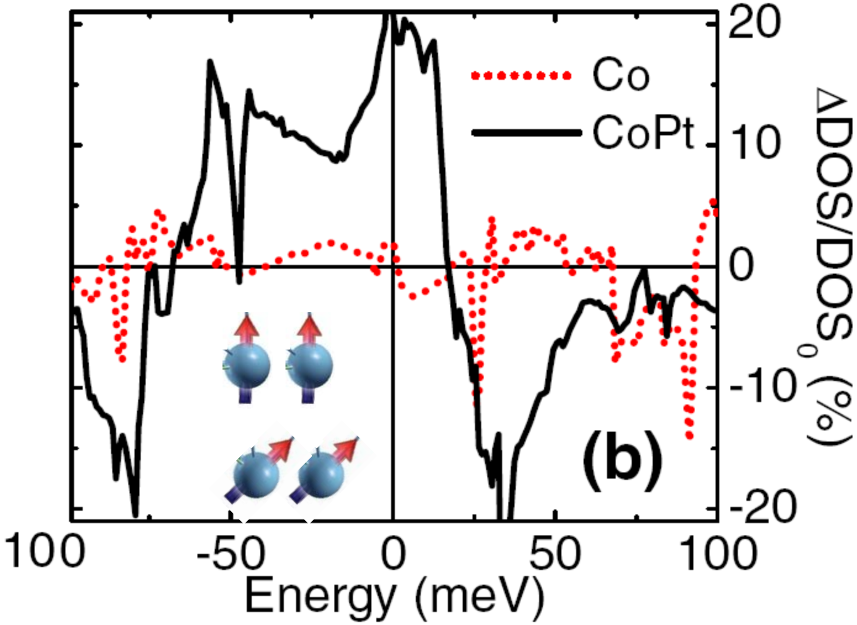
Antiferromagnetic metals



$$\leftarrow AMR \sim (\vec{m})^2 \rightarrow$$

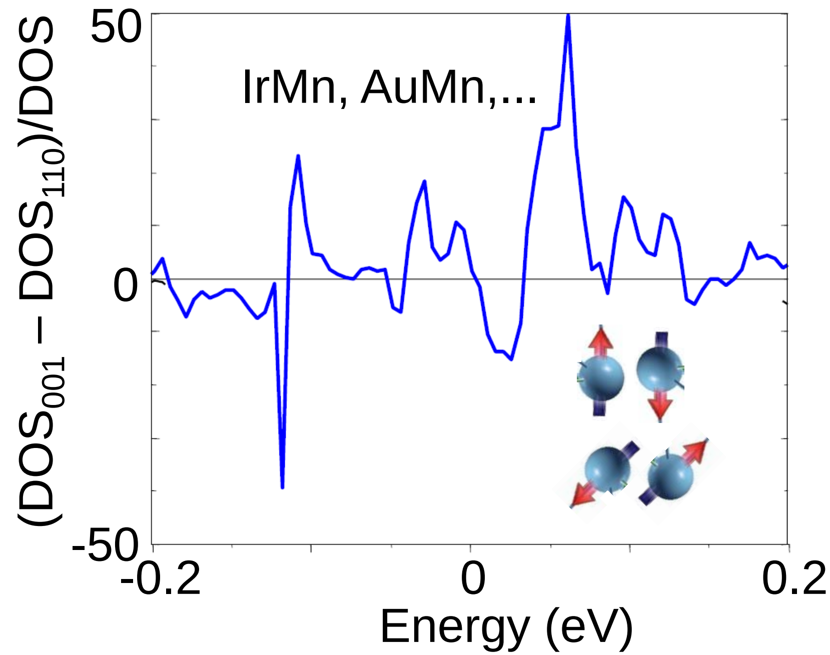
Spin-orbit induced anisoropic electronic structure: DFT calculations

Ferromagnets



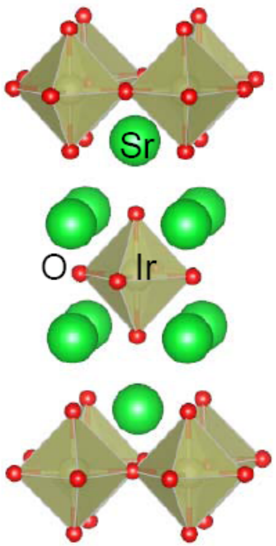
Park, TJ et al. PRL'08

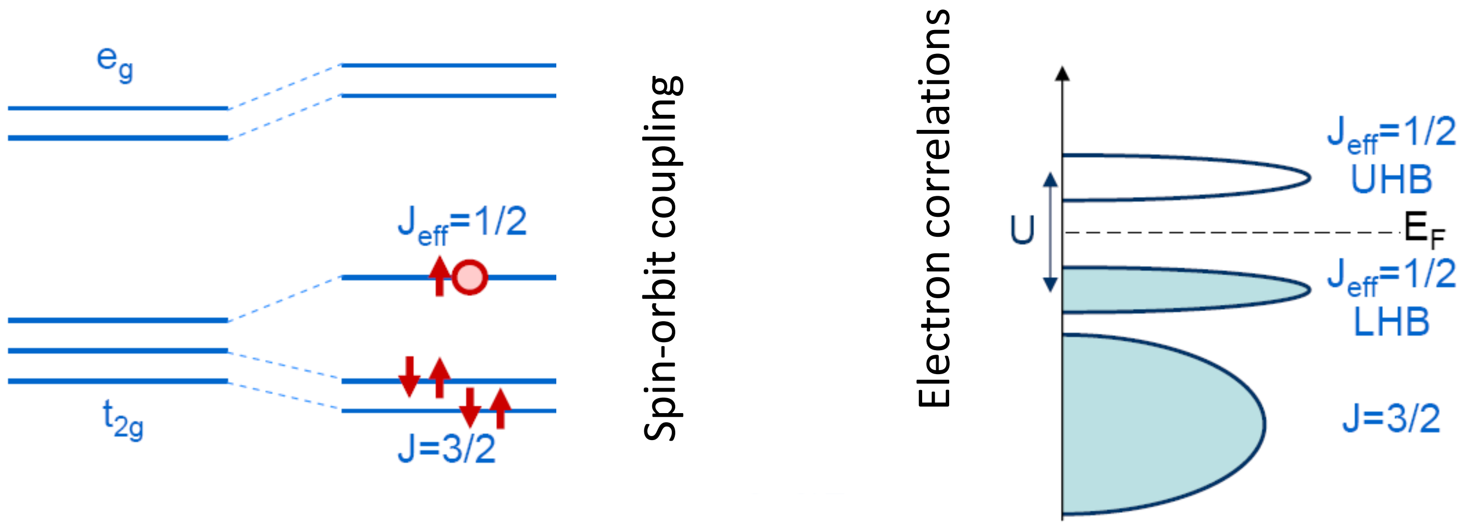
Antiferromagnets

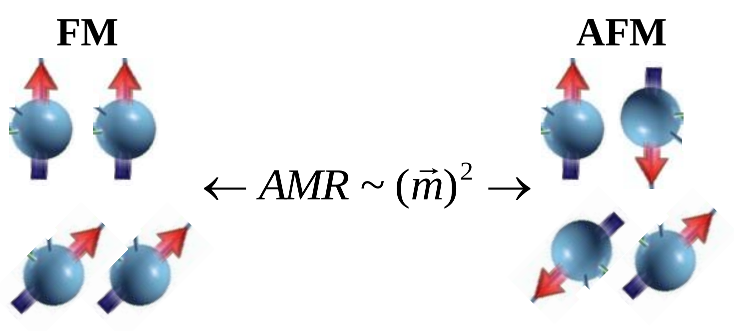


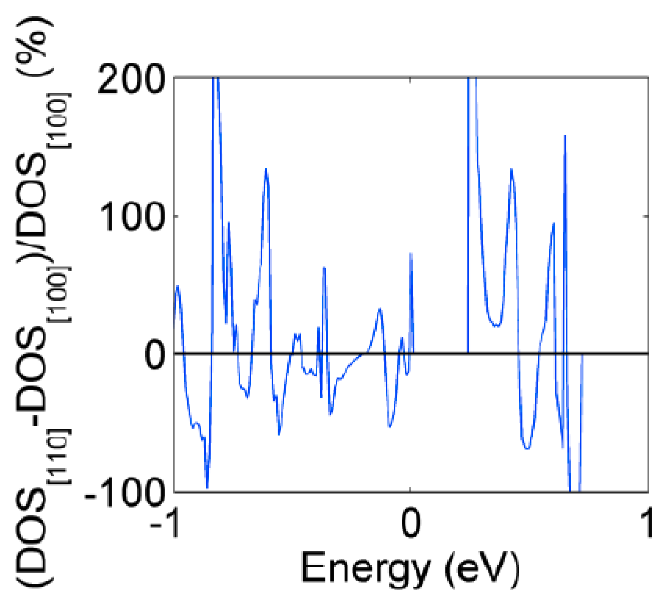
Shick, Khmelevskyi,TJ, et al., PRB'10

Spin-orbit-coupled Mott AFM semiconductor Sr_2IrO_4



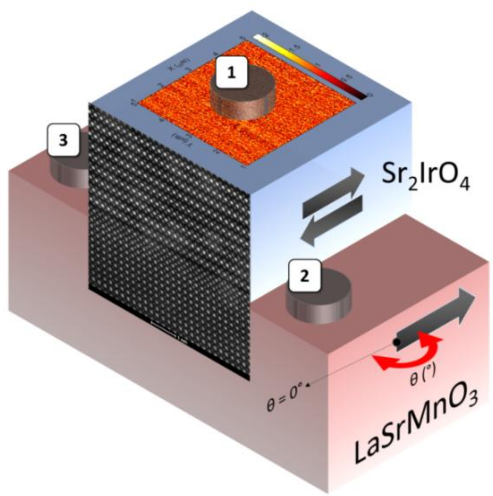


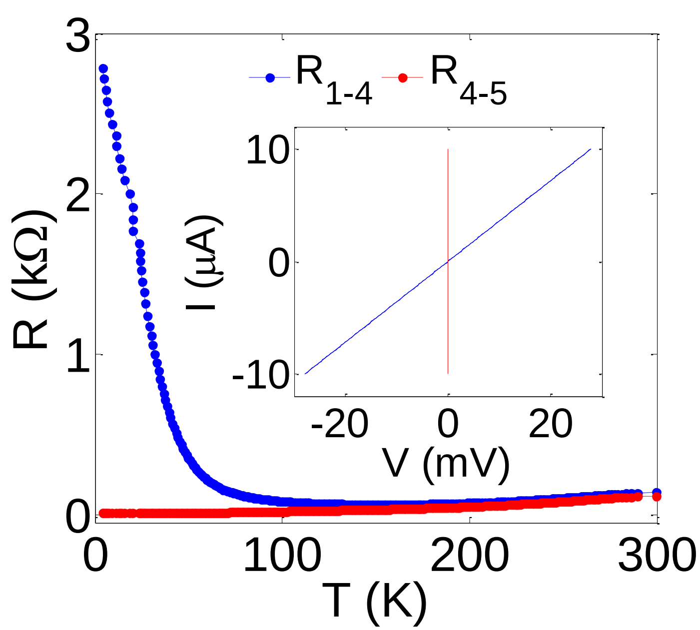


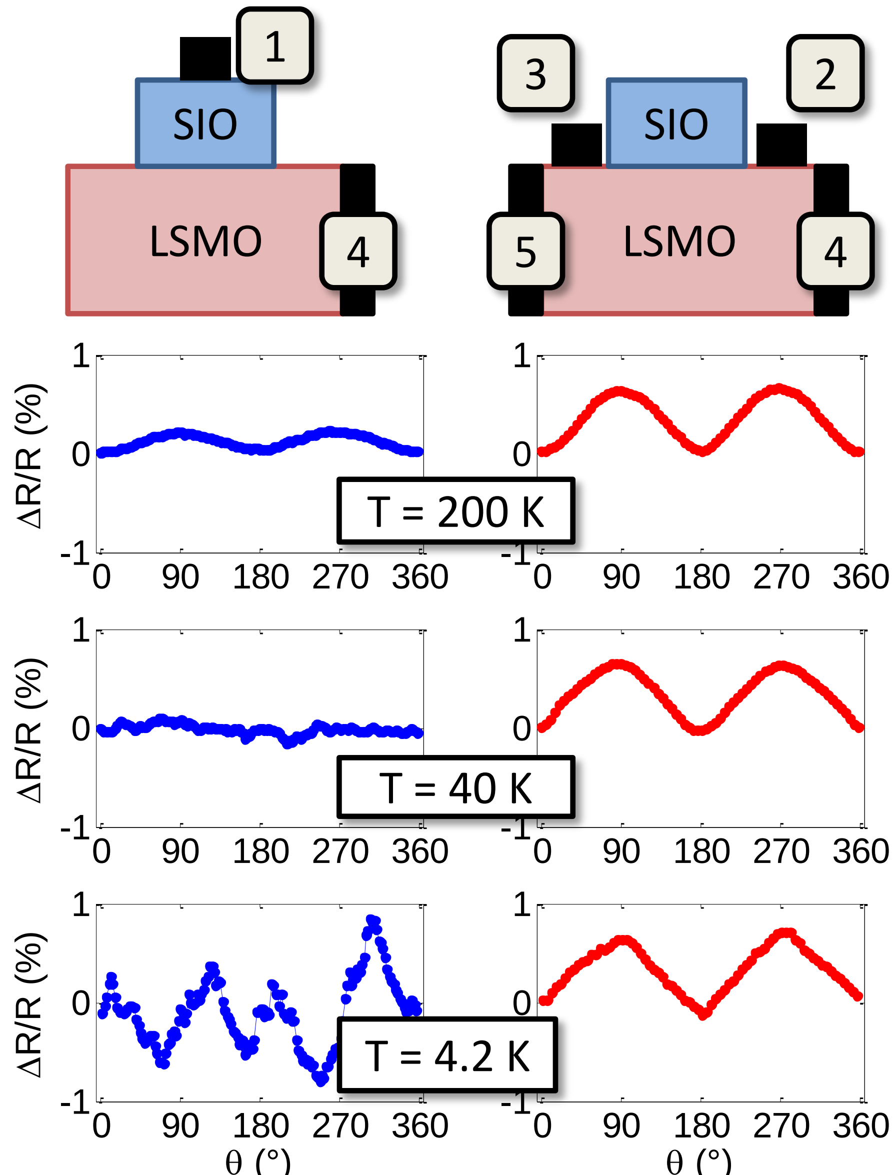


Marti,TJ et al. arXiv:13034704

Field-rotation Ohmic AMR of Sr_2IrO_4 AFM semiconductor

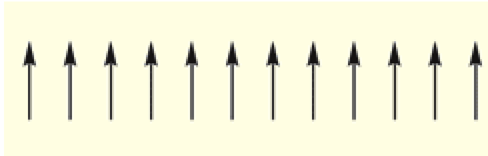






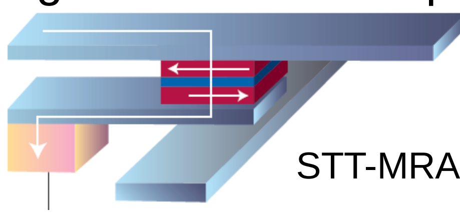
Marti,TJ et al. arXiv:13034704

Ferromagnets:

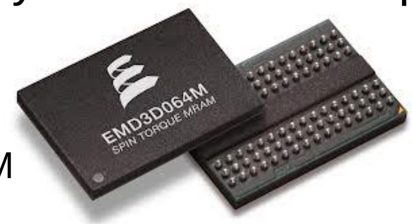


Ordered M≠0: good for manipulation by magnetic field and detection by stray fields,

Magnetic field not employed in advanced spintronics



STT-MRAM

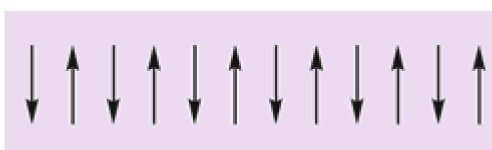


perturbed by <~T

produces <~T nearby stray field perturbation

High T_C not well compatible with semiconductor band structure

Antiferromagnets:



Ordered M=0: bad for manipulation by magnetic field and detection by stray fields,

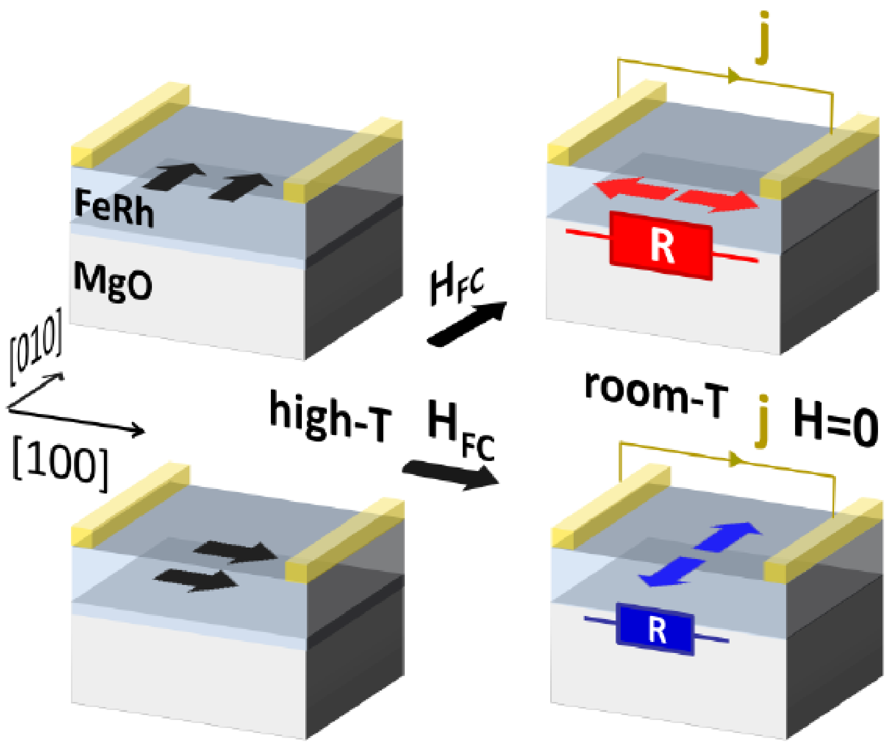
insensitive to <~100T perturbation

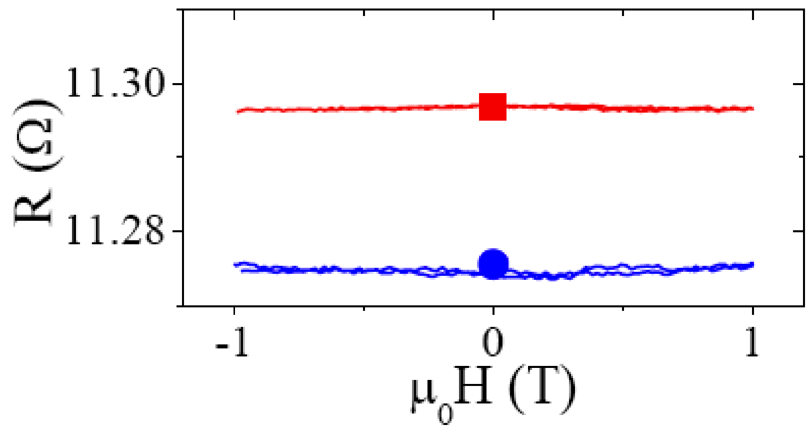
produces no stray field perturbation

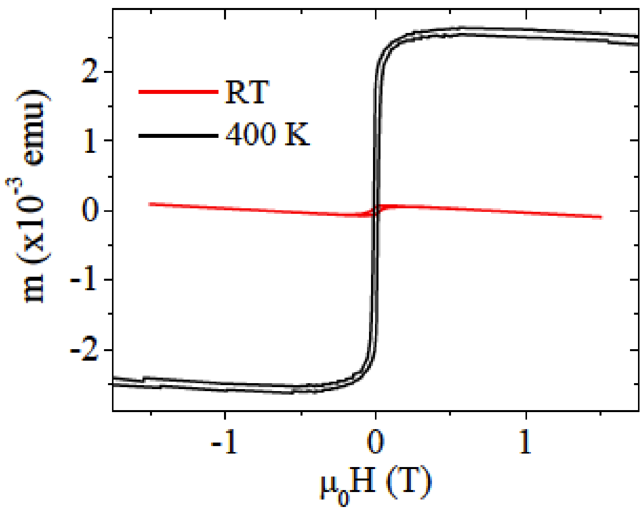
High T_N well compatible with semiconductor band structure

AFM-alone room-T memory resistor

Insensitive to magnetic field and no stray field





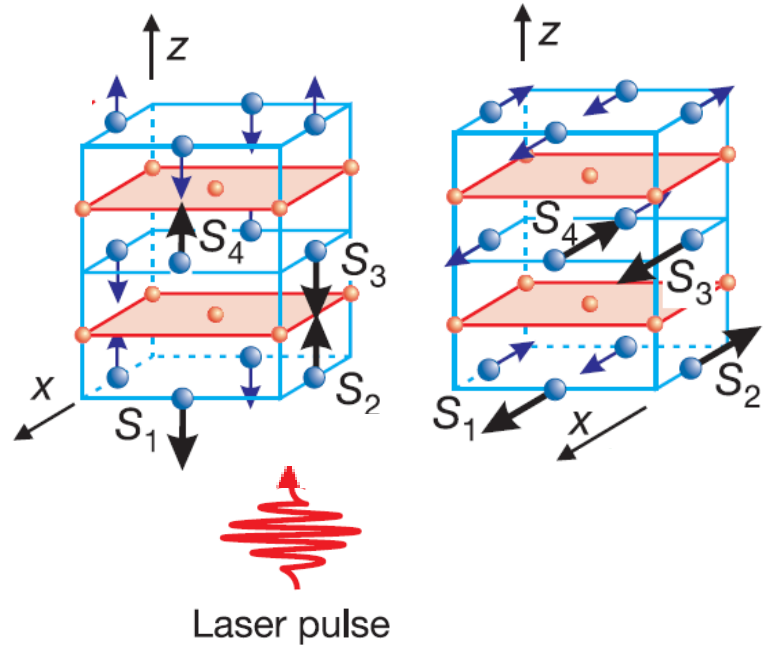


Marti, TJ et al. preprint '13

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, ***Th. Rasing Plenary Wed 16:15***



VOLUME 93, NUMBER 11 PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2004

Ultrafast Manipulation of Antiferromagnetism of NiO

N. P. Duong,[1] T. Satoh,[1,2] and M. Fiebig[1,*]