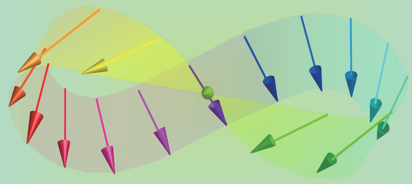
Information Storage and Spintronics 17



Atsufumi Hirohata

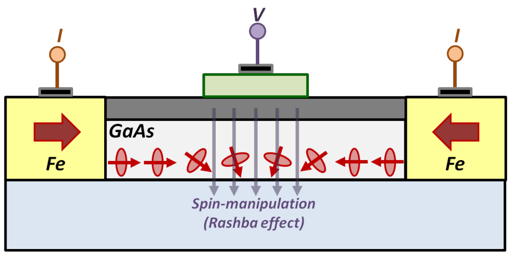
Department of Electronic Engineering

THE UNIVERSITY of York

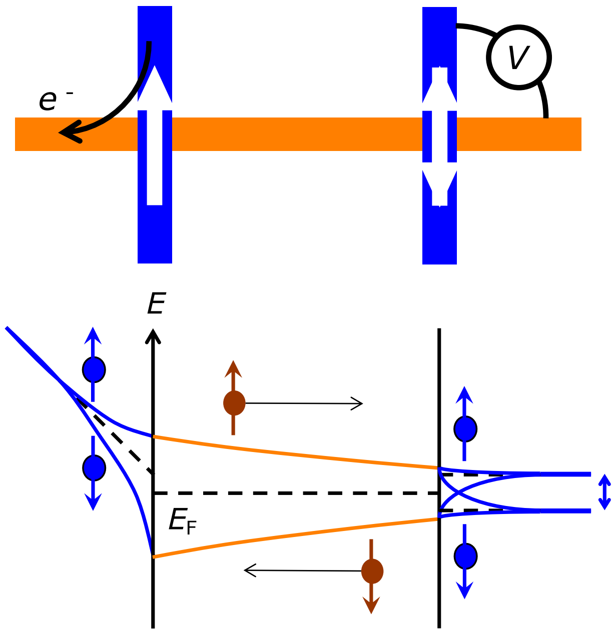
14:00 Monday, 28/November/2022 (SLB 101)

Quick Review over the Last Lecture

Spin-polarised transistor : *



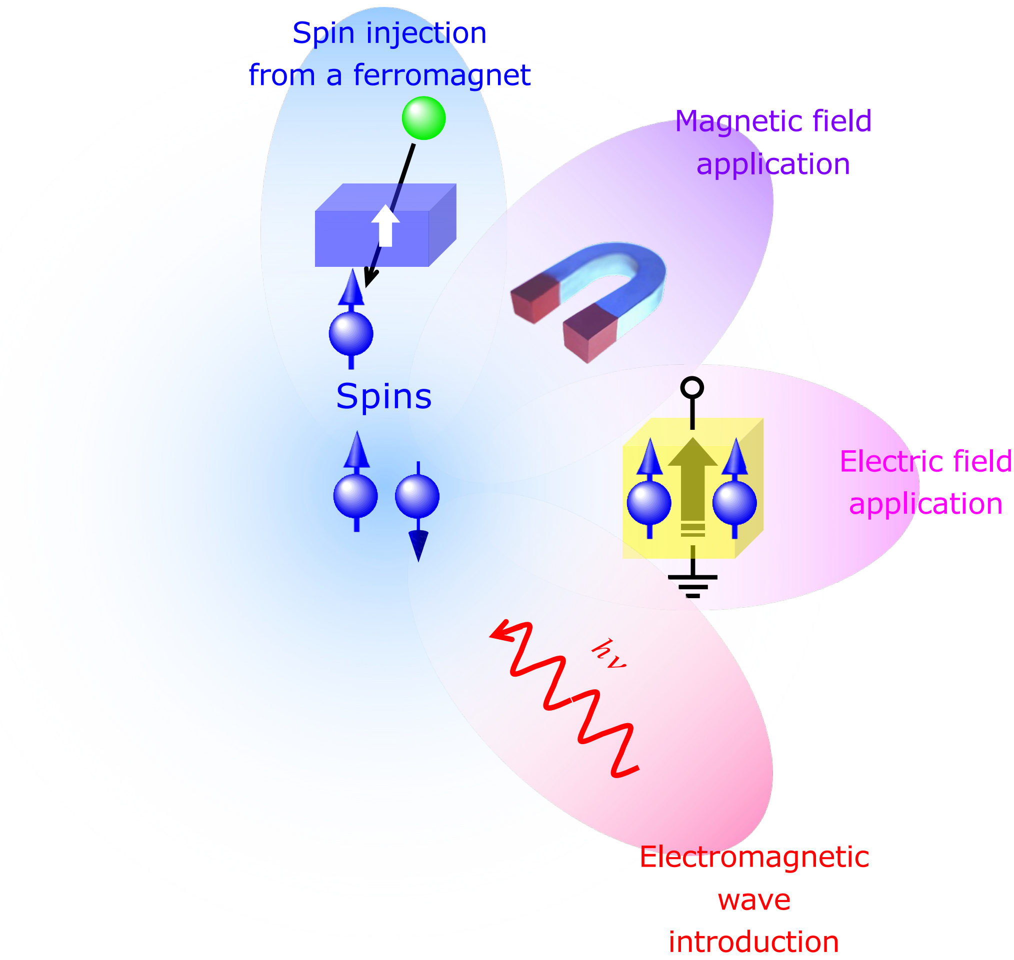
Lateral spin-valve : *



* S. Datta and S. Das, *Appl. Phys. Lett.* **56**, 665 (1990).

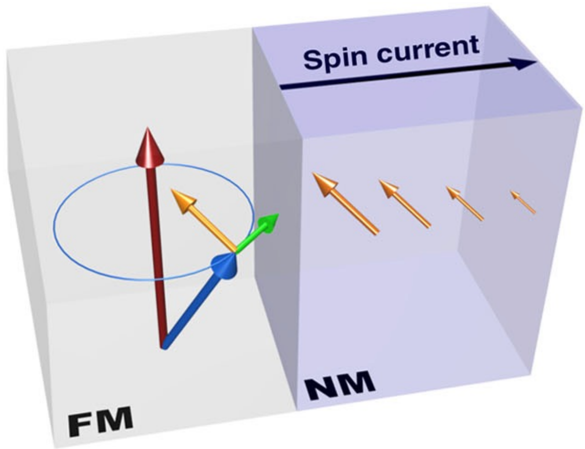
17 Spin-Orbit Devices

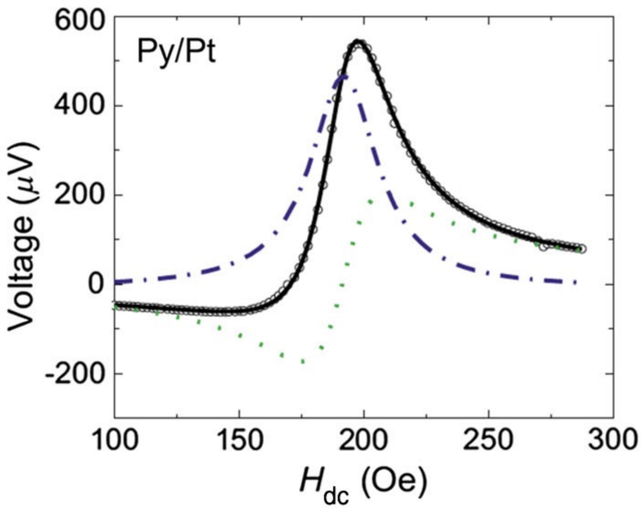
- Microwave introduction
- Spin Hall effects
- Spin-orbit interactions
- Tunnelling anisotropic magnetoresistance
- Topological insulators



Microwave-Induced Spin Currents

Spin-polarised currents can be introduced by electromagnetic wave : *

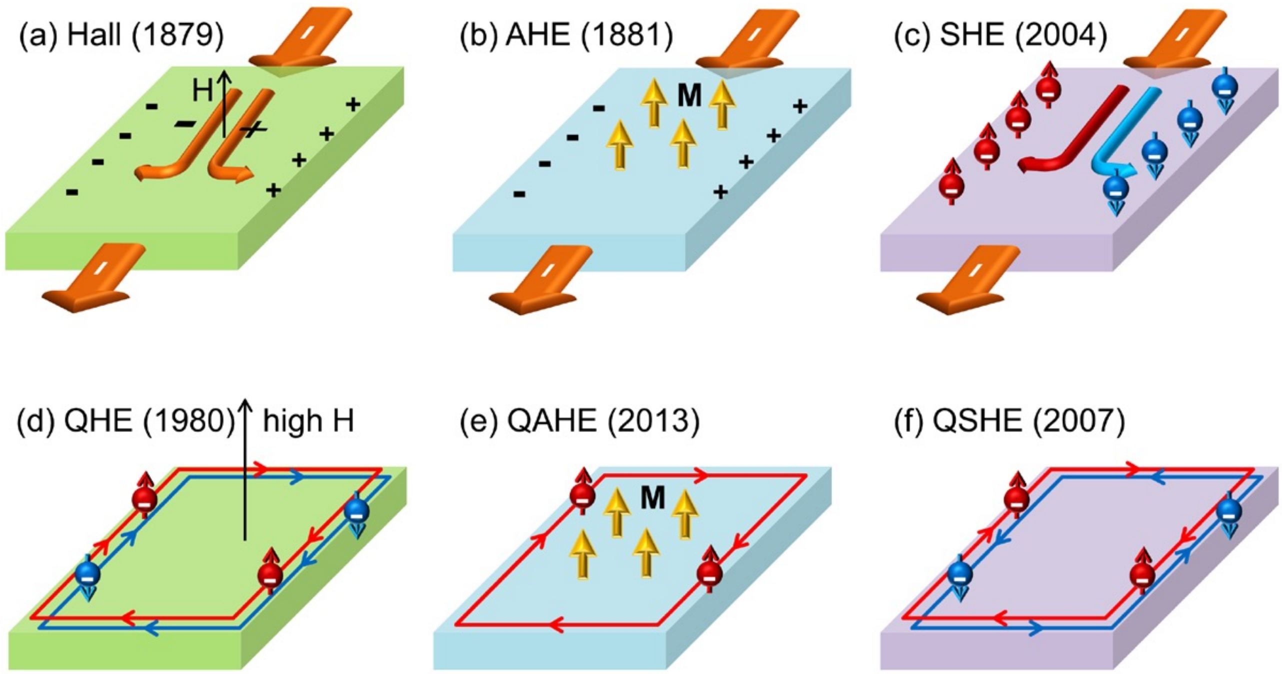




* O. Mosendz *et al.*, *Phys. Rev. B* **82**, 214403 (2010);
A. Hoffmann and S. Bader, *Phys. Rev. Appl.* **4**, 047001 (2015).

Spin Hall Effect

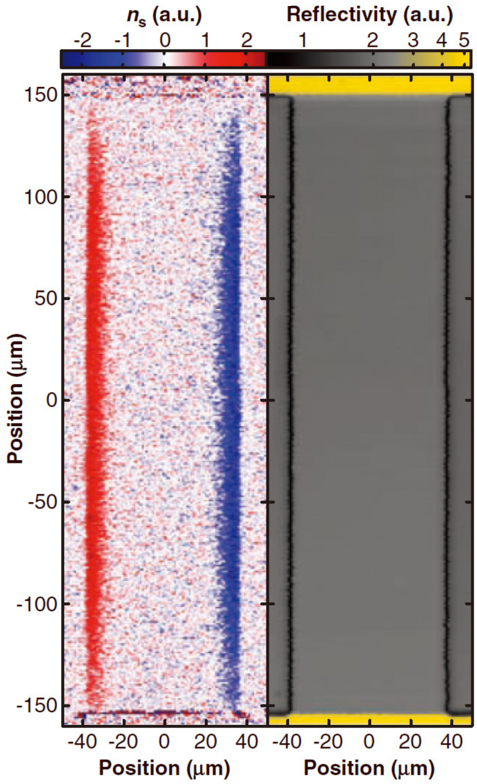
Spin Hall / inverse spin Hall / anomalous spin Hall effects etc. : *

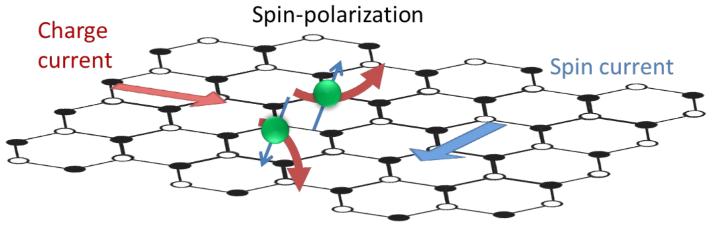


* C.-Z. Chang and M. Li, *J. Phys.: Condens. Matter* **28**, 123002 (2016).

Spin Hall Effect in GaAs

MOKE detection of spins generated by the spin Hall effect : *





$(\quad\quad\quad\quad\quad) = \theta_{SH} \times (\quad\quad\quad\quad\quad)$

Hamiltonian can be determined as

$$H = \frac{\hbar^2 k^2}{2m} + \lambda_{SO}(\boldsymbol{\sigma} \times \boldsymbol{k})$$

$\hbar$: Planck constant / 2π

k : wave vector

m : electron mass

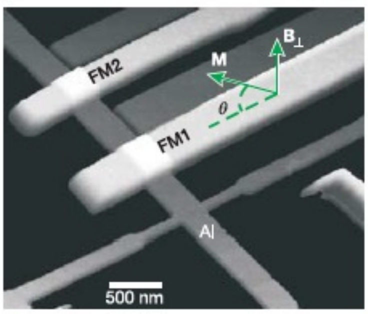
λ_{SO} : spin-orbit coupling constant

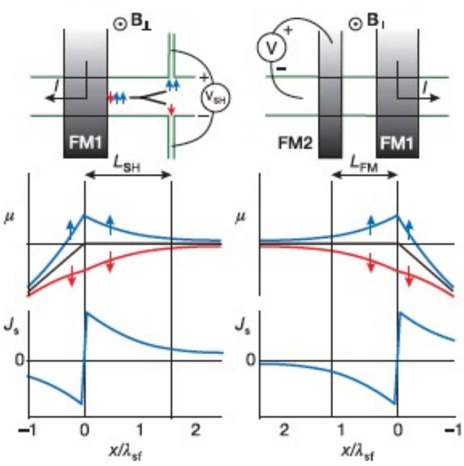
$\boldsymbol{\sigma}$: spin matrix

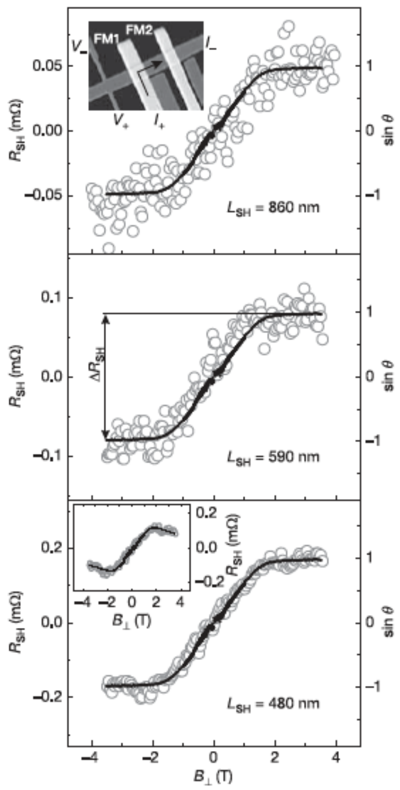
* Y. K. Kato *et al.*, *Science* **306**, 1910 (2004);
** http://www.wikipedia.org/

Lateral Spin-Valve with the Spin Hall Effect

$Co_{0.8}Fe_{0.2}$ / Al_2O_3 / Al nanowires : *



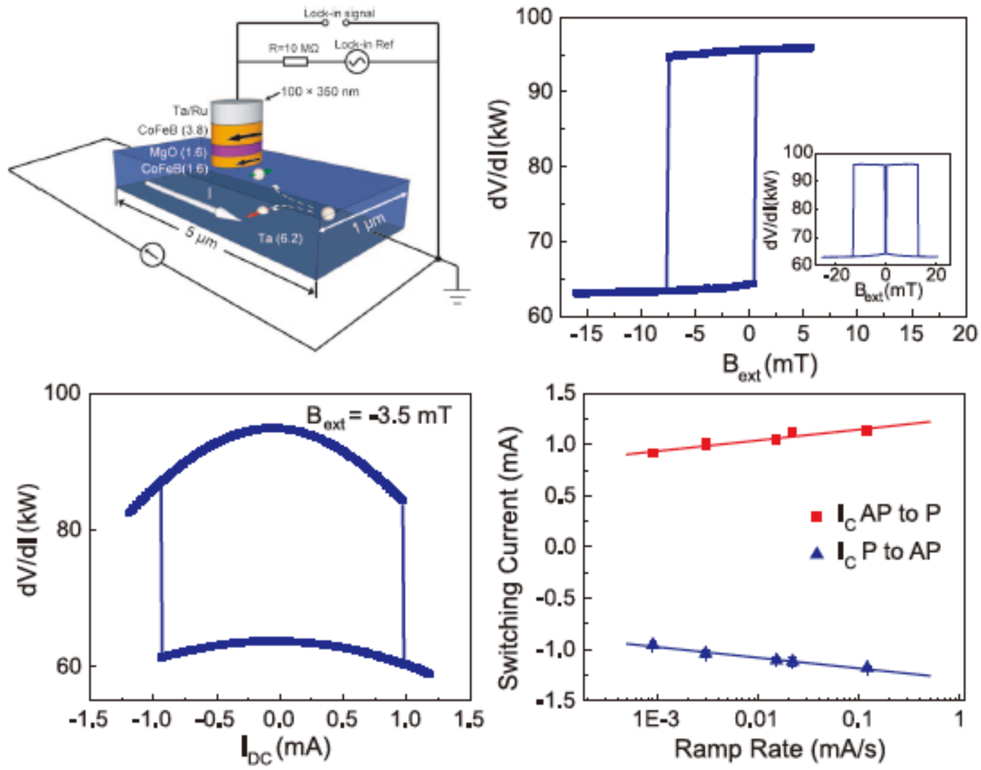




* S. O. Valenzuela and M. Tinkham, *Nature* **442**, 176 (2006).

Magnetisation Reversal by the Spin Hall Effect

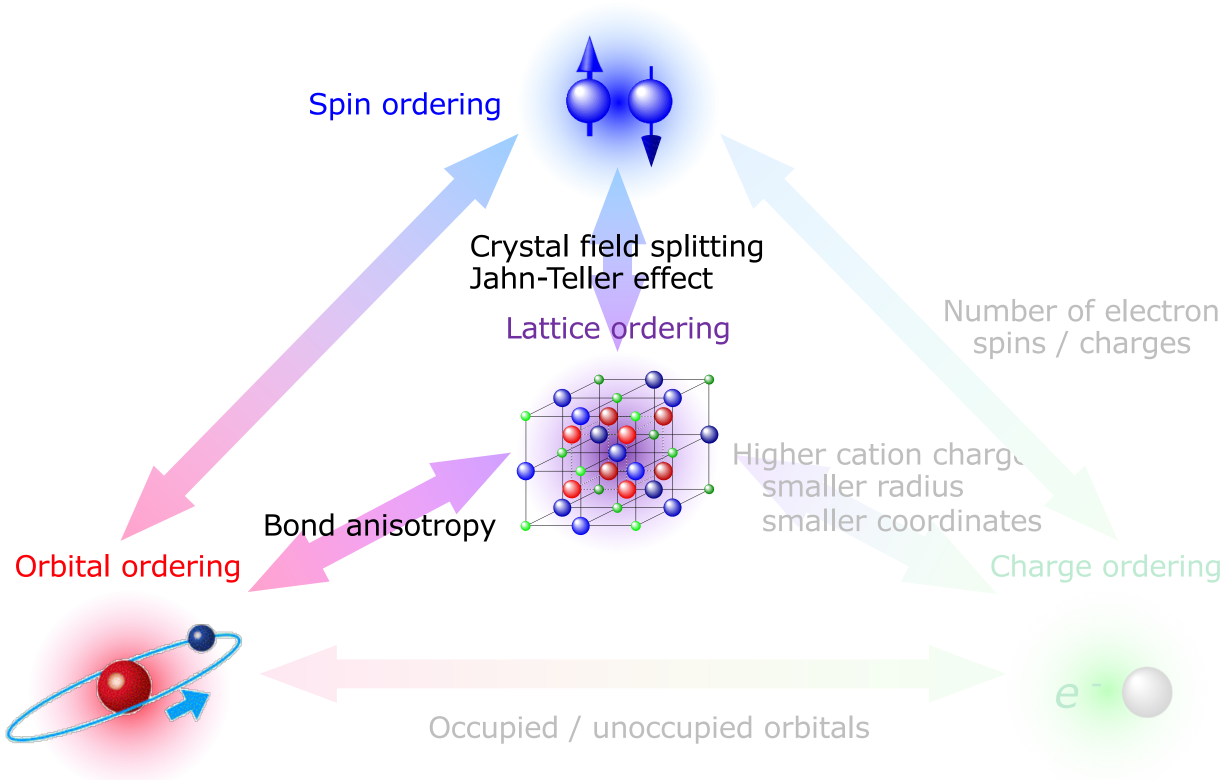
CoFeB / MgO / CoFeB nanopillar on Ta : *



* L. Liu *et al.*, *Science* **336**, 555 (2012).

Spin-Orbit Interaction

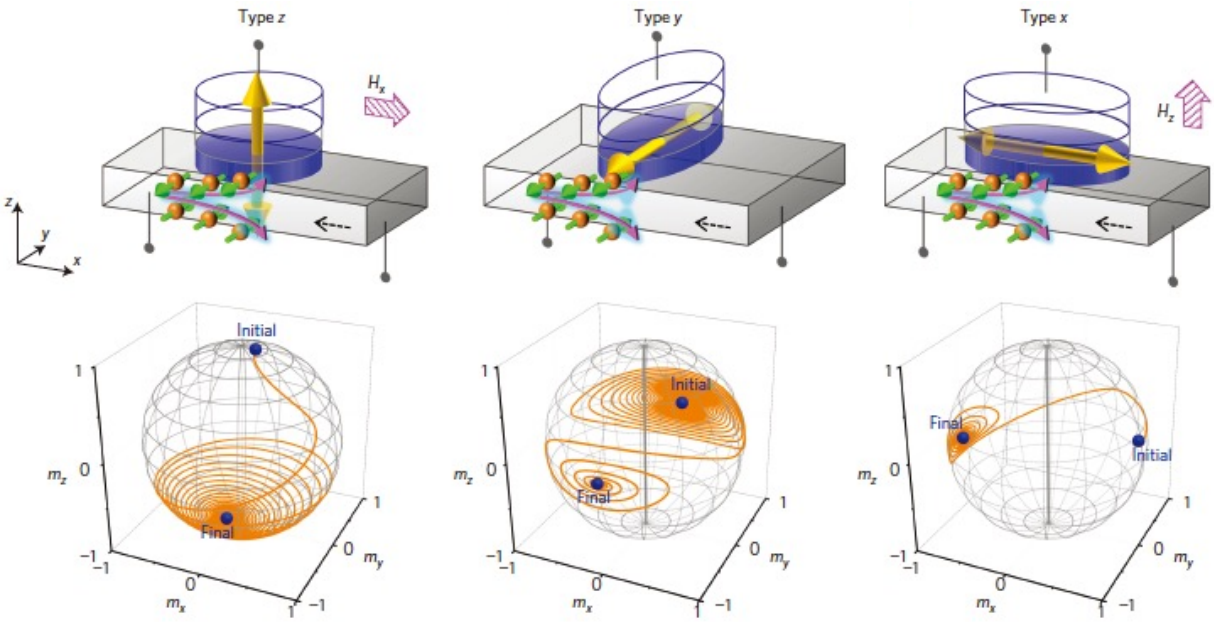
In strongly correlated systems : *



* *After* https://www.slideshare.net/algerien1970/electrical-transport-and-magnetic-interactions-in-3d-and-5d-transition-metal-oxides.

Spin-Orbit Torque for MRAM

Switching current can be reduced by 1 / 20 : *

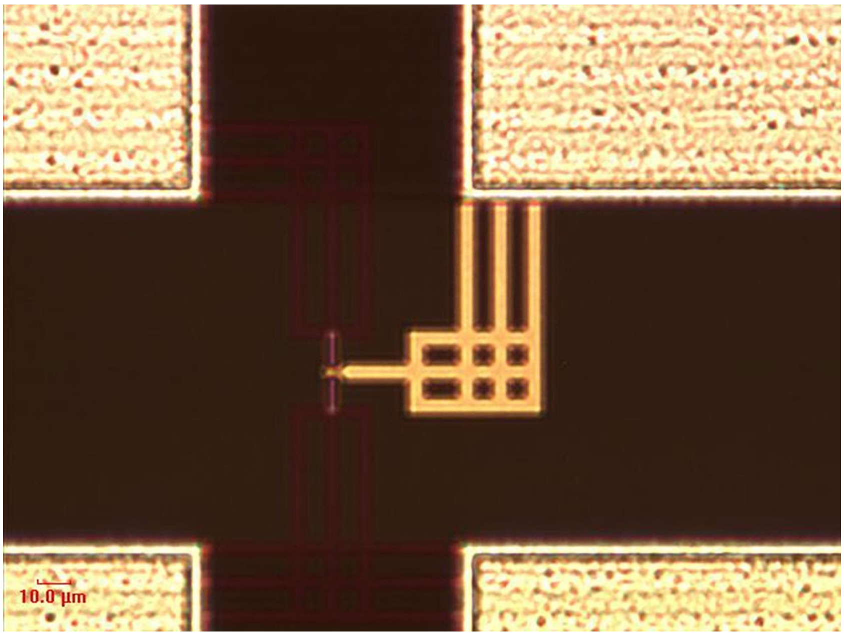


	Type z	Type y	Type x
$\mu_0 H_K^{eff}$ (mT)	260 ± 10	4.2 ± 0.5	4.04 ± 0.01
$E/k_B T$	42 ± 2	46 ± 4	45.5 ± 0.2
J_C^0 (10^{11} A m^{-2})	20 ± 1	1.0	4.3 ± 0.2
c_J^{th} (mT)	130	1.58	19.95
θ_{SH}^{eff}	−0.25 ± 0.02	−0.08	−0.22 ± 0.01

* S. Fukami *et al.*, *Nat. Nanotechnol.* **11**, 621 (2016).

Spin-Orbit Torque for MRAM

Switching speed can be reduced by 1 / 25 : *



The switching speed of the SOT-MRAM reached 210 picoseconds while the STT-MRAM, created on the same wafer, clocked a speed of 5 nanoseconds.

* https://spectrum-ieee-org.cdn.ampproject.org/c/s/spectrum.ieee.org/nanoclast/computing/hardware/sotmram-escapes-from-the-lab.amp.html

Spin-Orbit Torque MRAM

As a SRAM replacement, MRAM needs faster operation, lower power consumption and longer life : *

Generation	Type	Recording method	Writing method	Writing speed [ns]	Writing energy [fJ/bit]	Writing life time	Fabrication rule [nm]	Recording capacity [Mbit]	Cell configuration	Cell size [F^2]
1st	Field MRAM	In-plane magnetisation	Magnetic field				90 ~ 130	< 16		
2nd	STT-MRAM	In-plane magnetisation	Spin-transfer torgue (STT)				40 ~ 65	< 256		
3rd	pSTT-MRAM	Perpendicular magnetisation	STT	< 10	~ a few 100	10^{12}	16 ~ 28	> 256	2 transistors (T) + 2 MTJ	~ 80
4th	SOT-MRAM	Perpendicular magnetisation	Spin-orbit torque		~ 10		16 ~ 28	> 256	2T + 1MTJ	~ 40
5th?	VCM	Perpendicular magnetisation	Voltage-controlled magnetic anisotropy (VCMA)		~ 3		16 ~ 28	> 256	2T + ~ 10MTJ	4 ~ 8

* https://pc.watch.impress.co.jp/docs/column/semicon/1145577.html

Spin-Orbit Torque MRAM

Writing power can be reduced by   as compared with STT : *

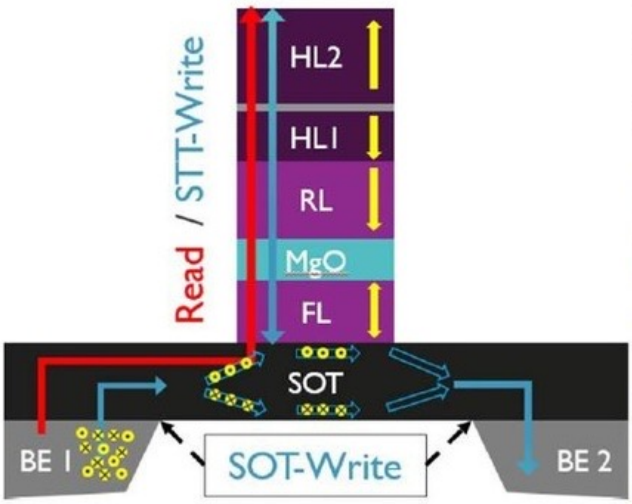


Fig. 1: Schematic of MTJ stack with top-pinned SAF design and following composition: W(SOT) / CoFeB(FL) / MgO (10 $\Omega.\mu m^2$) / CoFeB(RL) / SAF (HL1-HL2). Compared to STT, SOT writing is decoupled from TMR reading using 3 terminal geometry, which allows larger cell endurance. SOT converts charge into spin current, perpendicular to the FL, which enables ultra-fast switching.

* https://pc.watch.impress.co.jp/docs/column/semicon/1145577.html

Spin-Orbit Torque MRAM towards Production

MRAM-info

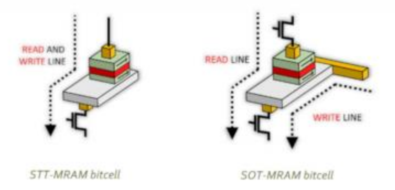
Graphene-catalog

Home About us What is MRAM? STT-MRAM MRAM companies Conferences Spintronics Advertise h

Home » SOT-MRAM developer Antaios raises $11 million

SOT-MRAM developer Antaios raises $11 million

SOT-MRAM developer Antaios raised $11 million from VCs and Applied Ventures, to accelerate its next-generation memory development and develop new strategic partnerships.



SOT-MRAM devices feature switching of the free magnetic layer done by injecting an in-plane current in an adjacent SOT layer, unlike STT-MRAM where the current is injected perpendicularly into the magnetic tunnel junction and the read and write operation is performed through the same path.

Antaios, established in 2017 in France, is developing SOT-MRAM technology based on research performed at SPINTEC. Other groups around the world are also developing SOT-MRAM technologies, including IMEC, ITRI, NTU and others.

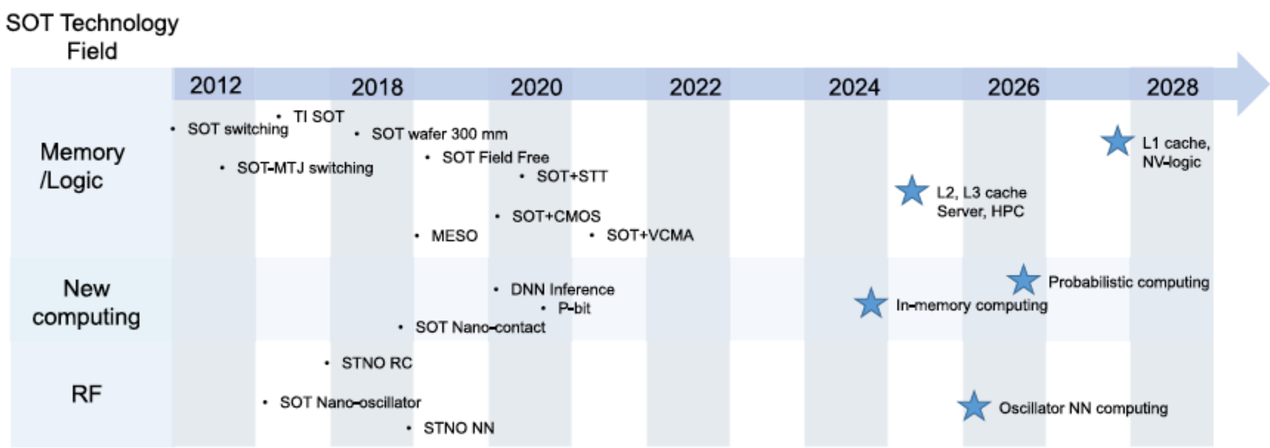
Tags: Investment SOT-MRAM

Posted: Sep 17, 2020 by Ron Mertens

Log in to post comments

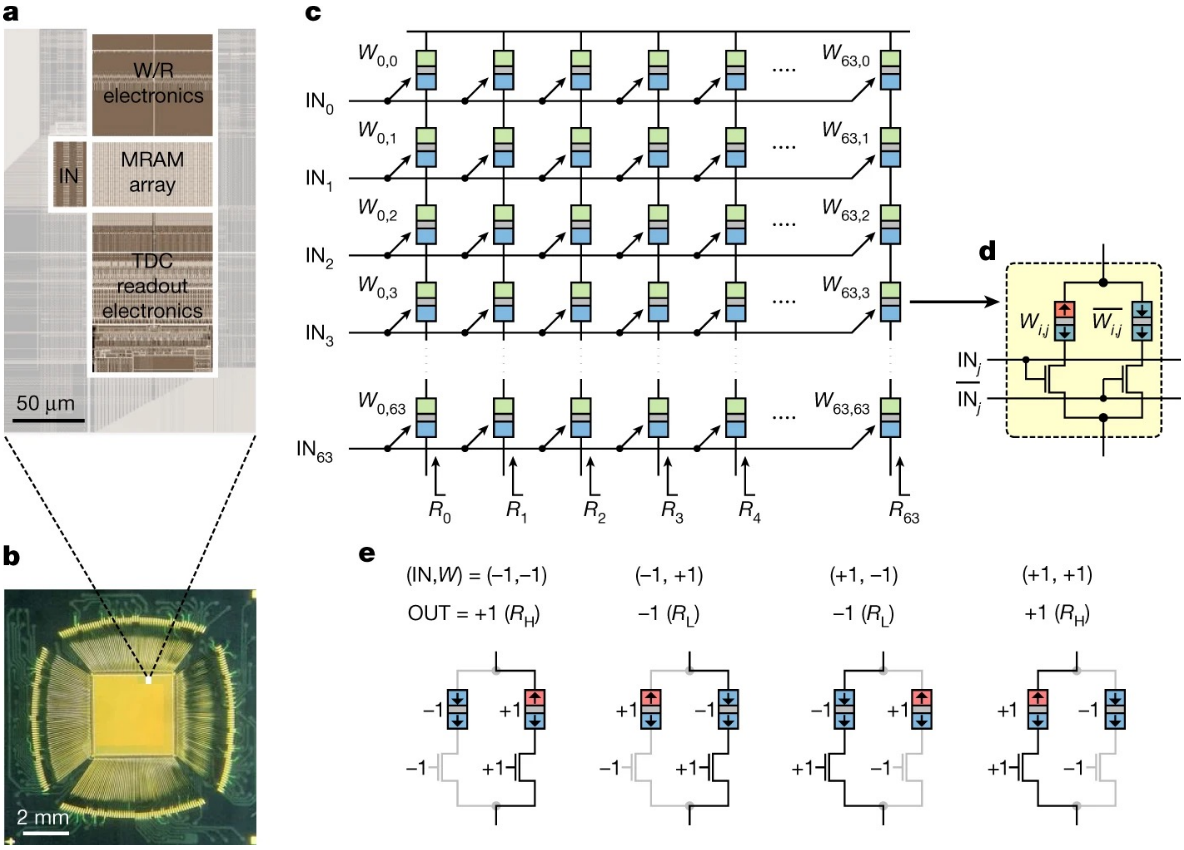
* https://www.mram-info.com/sot-mram-developer-antaios-raises-11-million

MRAM Roadmap



* Q. Shao *et al.*, *IEEE Trans. Magn.* **57**, 800439 (2021).

In MRAM Computation



* S. Jung *et al.*, *Nature* **601**, 211 (2022).

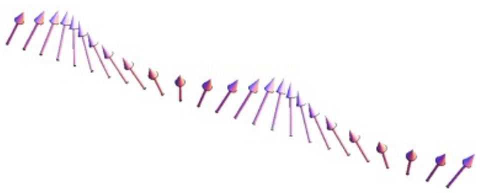
Spin Waves

Spin wave (magnon) : *

The magnon flow can be determined as

$$\overrightarrow{J_m} = \hbar \sum_k \overrightarrow{v_k} \overrightarrow{n_k},$$

where $\overrightarrow{v_k}$ is the group velocity of the spin wave ($=\partial\omega_k/\partial\vec{k}$) and n_k is the distribution function of the spin wave.

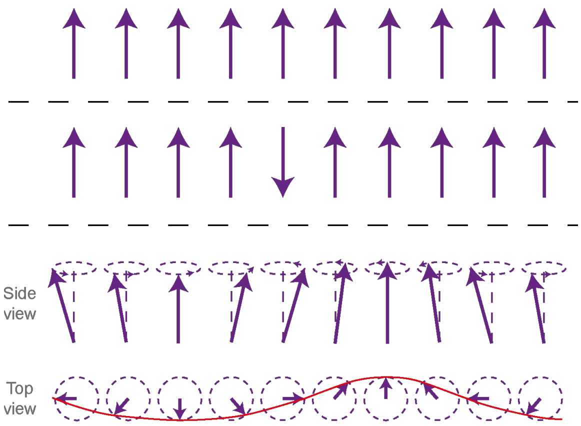


Analogous .

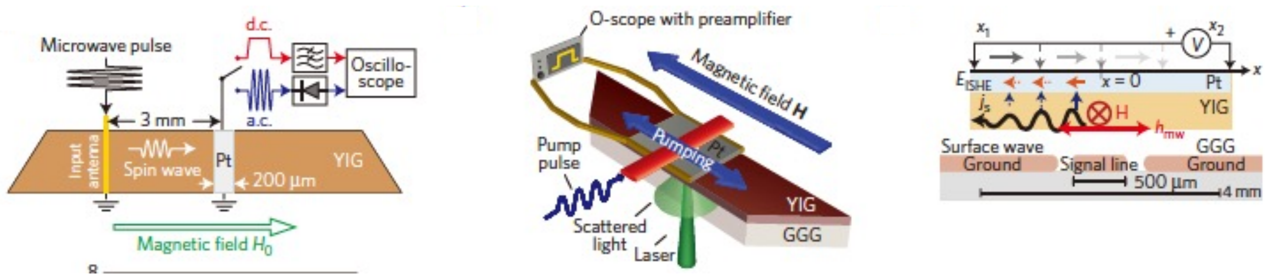
* https://www.youtube.com/watch?v=pWQ3r-2Xjeo

Spin Wave

Spin wave (magnon) : *



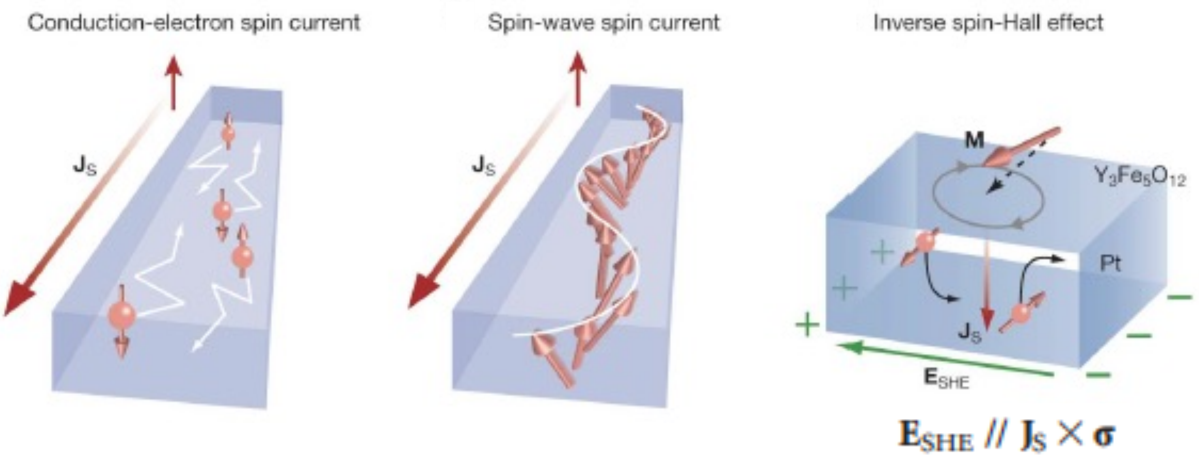
Magnon introduction : *

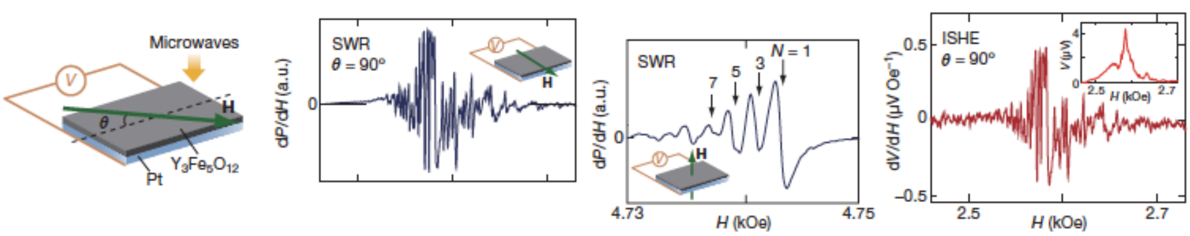


* A. V. Chumak *et al.*, *Nature Phys.* **11**, 453 (2015).

Microwave-Induced Spin Currents

Spin-polarised currents can be introduced by electromagnetic wave : *

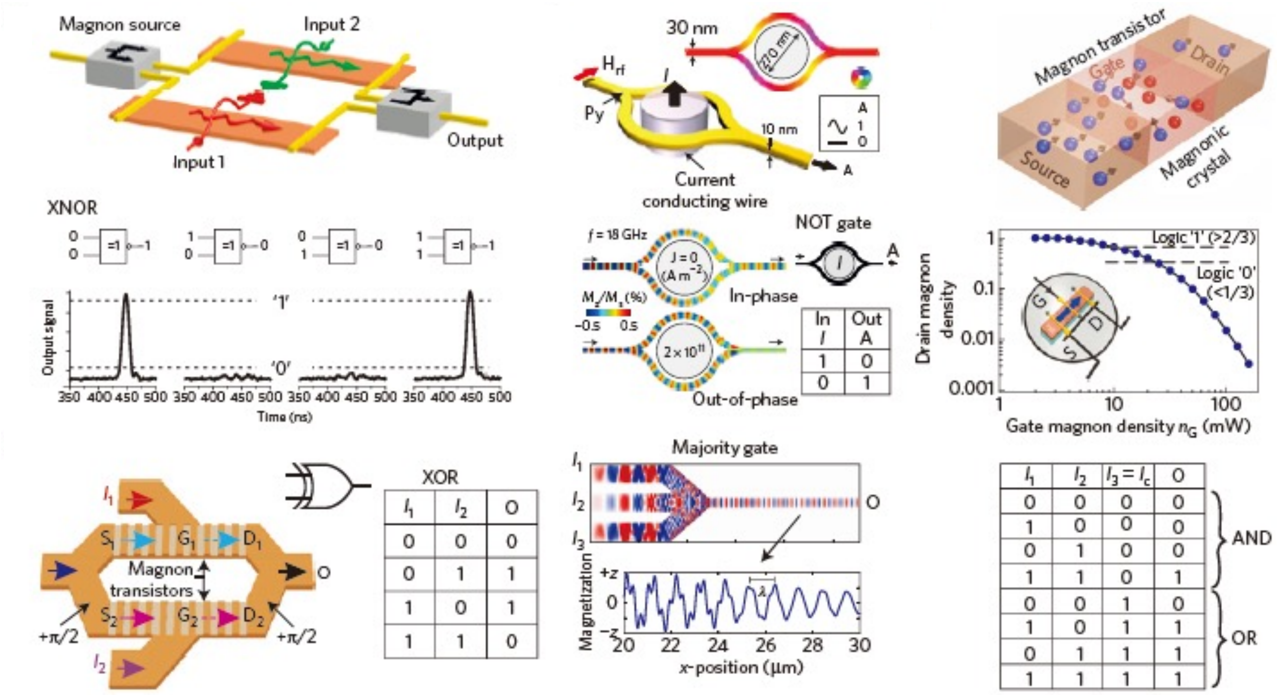




* Y. Kajiwara *et al.*, *Nature* **464**, 262 (2010).

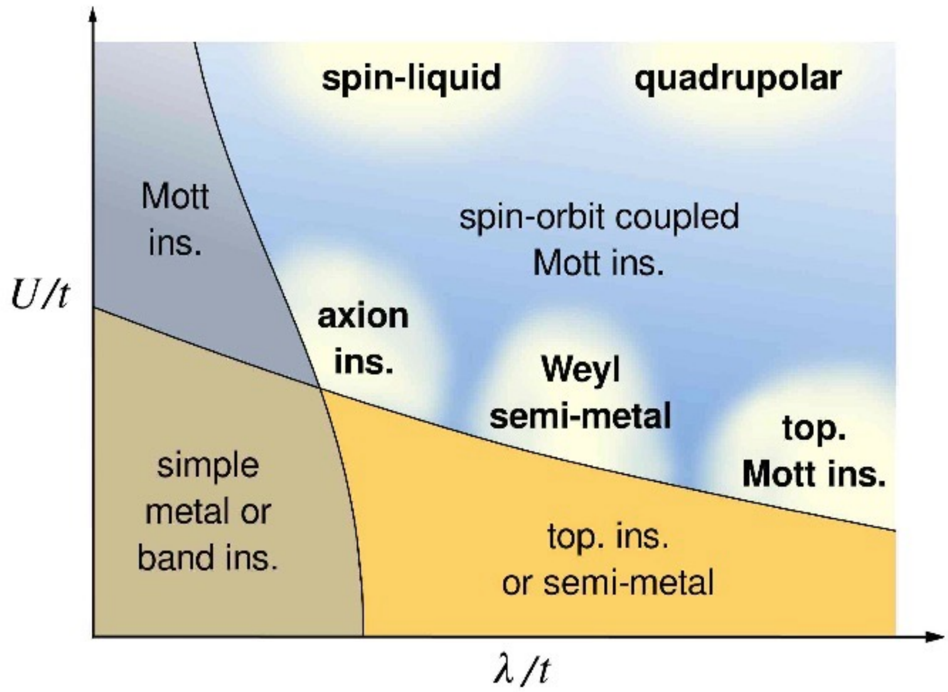
Spin Wave Logics

Magnonics : *



* A. V. Chumak *et al.*, *Nature Phys.* **11**, 453 (2015).

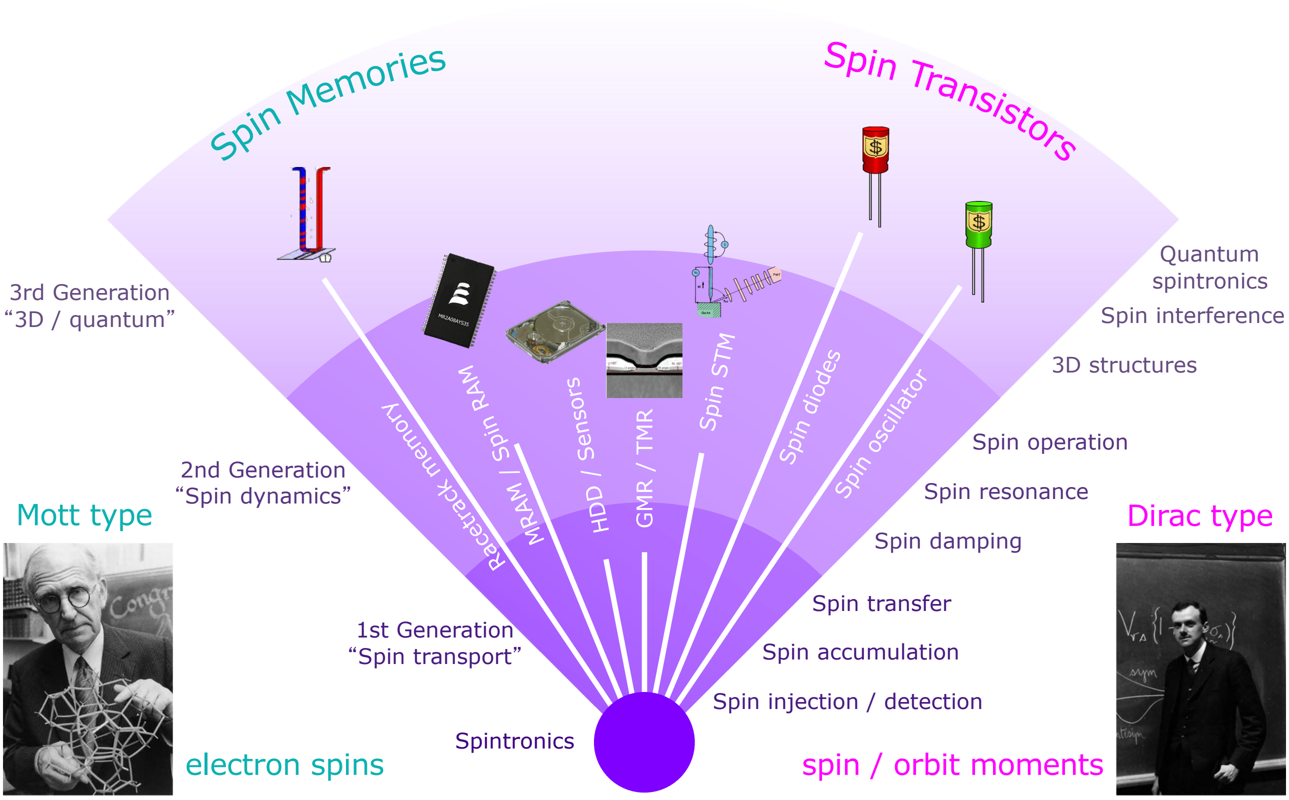
Spin-Orbit Coupling Energy



* http://condensedconcepts.blogspot.co.uk/2013/05/mott-physics-with-spin-orbit-coupling.html.

Nano-Spintronic Devices

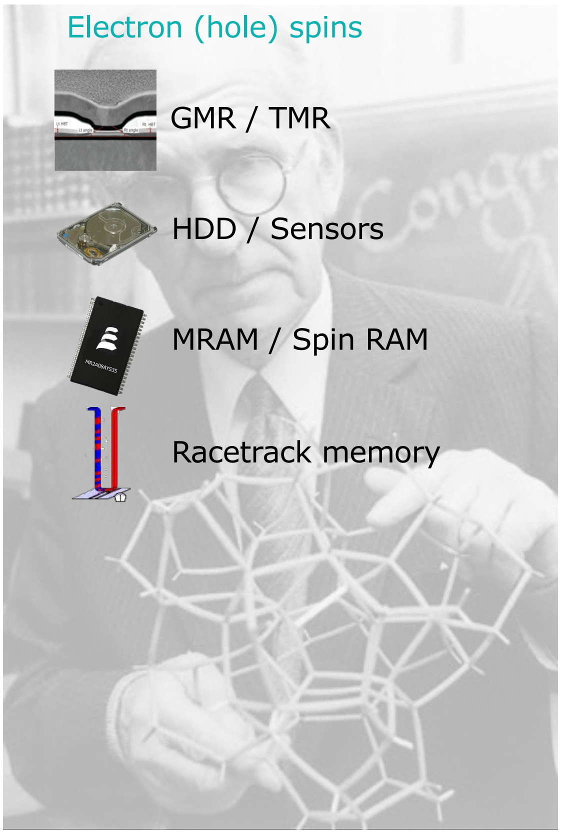
Development of nano-spintronic devices : *



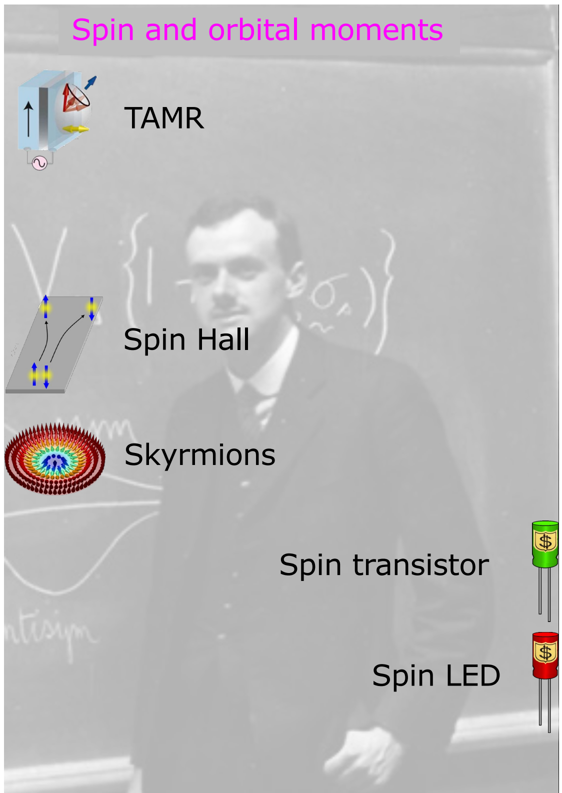
* A. Hirohata and K. Takanashi, *J. Phys. D: Appl. Phys.* **47**, 1930001 (2014).

Two Categories for Spintronic Devices

Mott-type



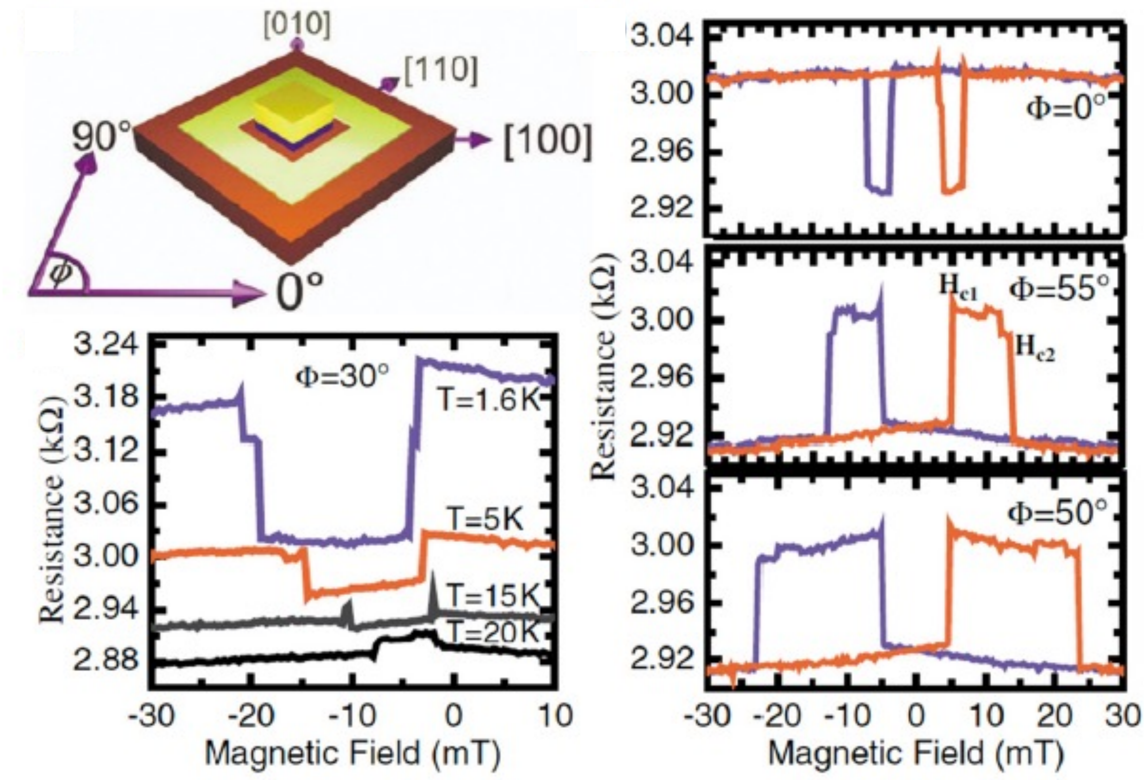
Dirac-type



* *After* J. Sinova and I. Zutic, *Nature Mater.* **11**, 368 (2012).

Tunnelling Anisotropic Magnetoresistance

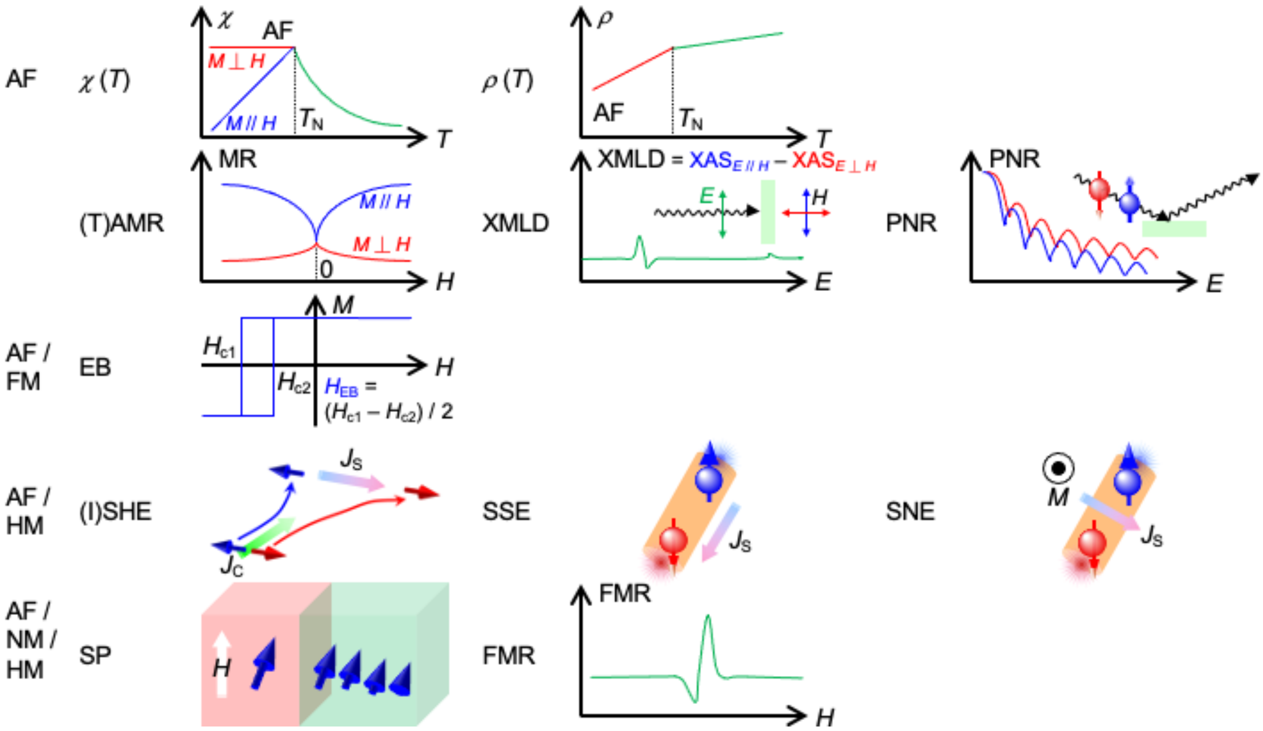
70 nm GaMnAs / GaAs (001) : *



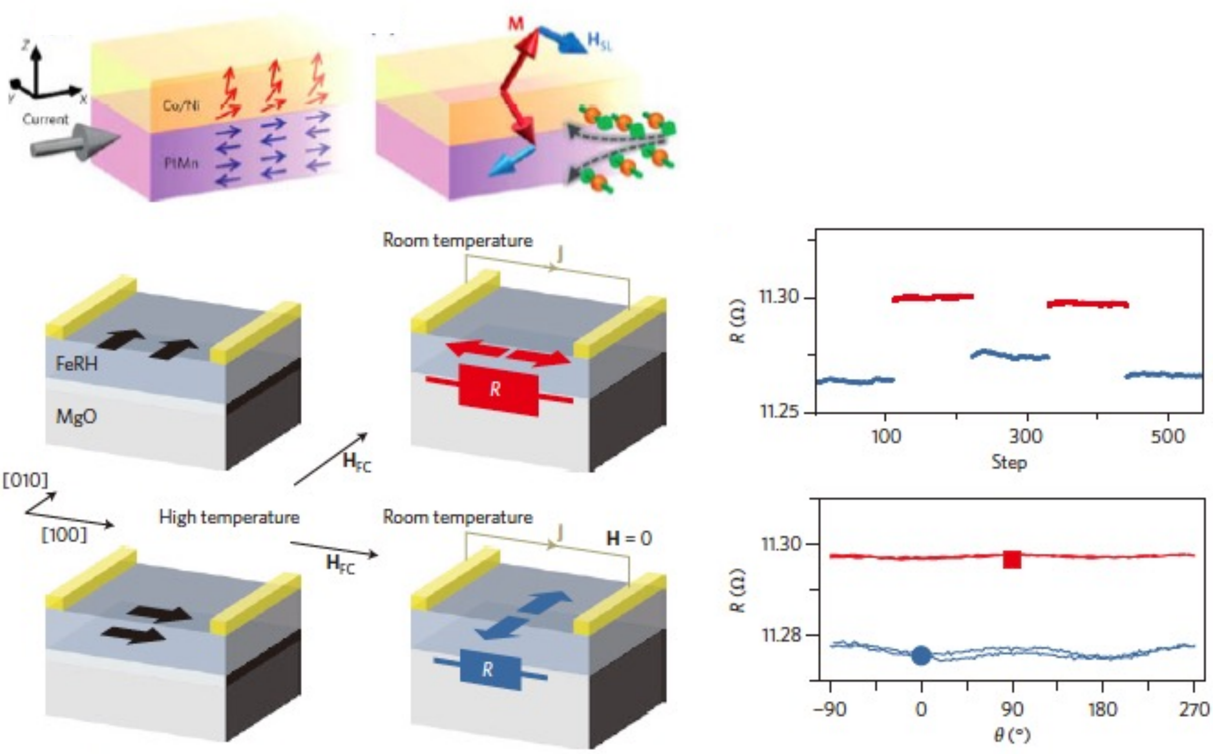
* C. Gould *et al.*, *Phys. Rev. Lett.* **93**, 117203 (2004).

Antiferromagnetic Spintronics

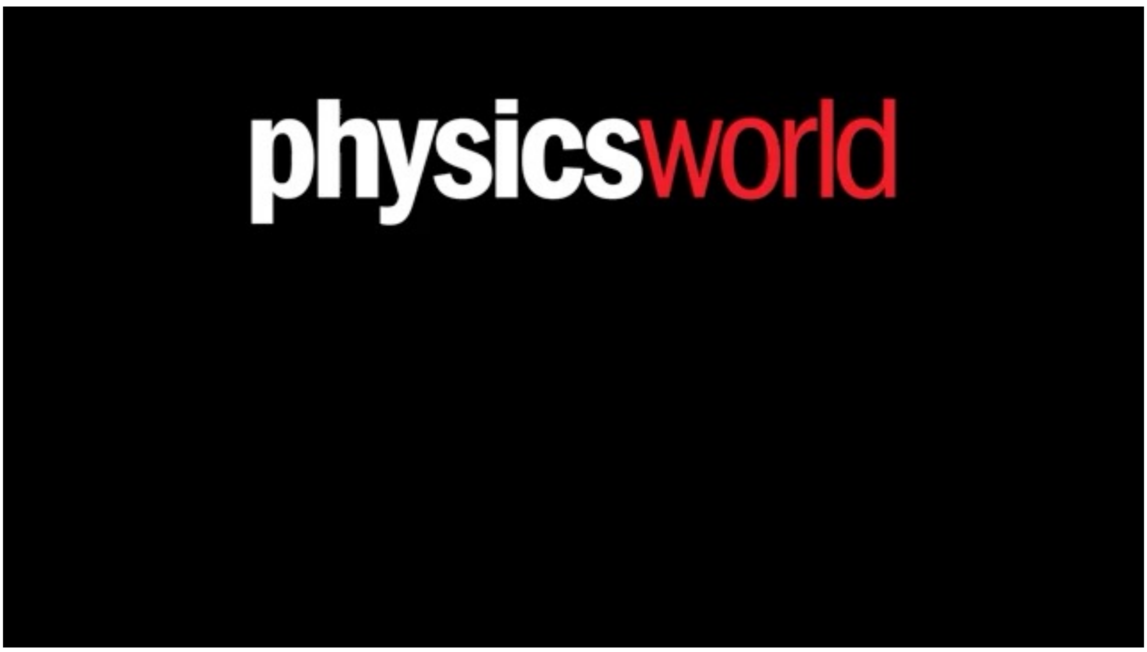
A series of applications have been demonstrated using antiferromagnets : *



Similar spin-current generation can be achieved with an antiferromagnet : *

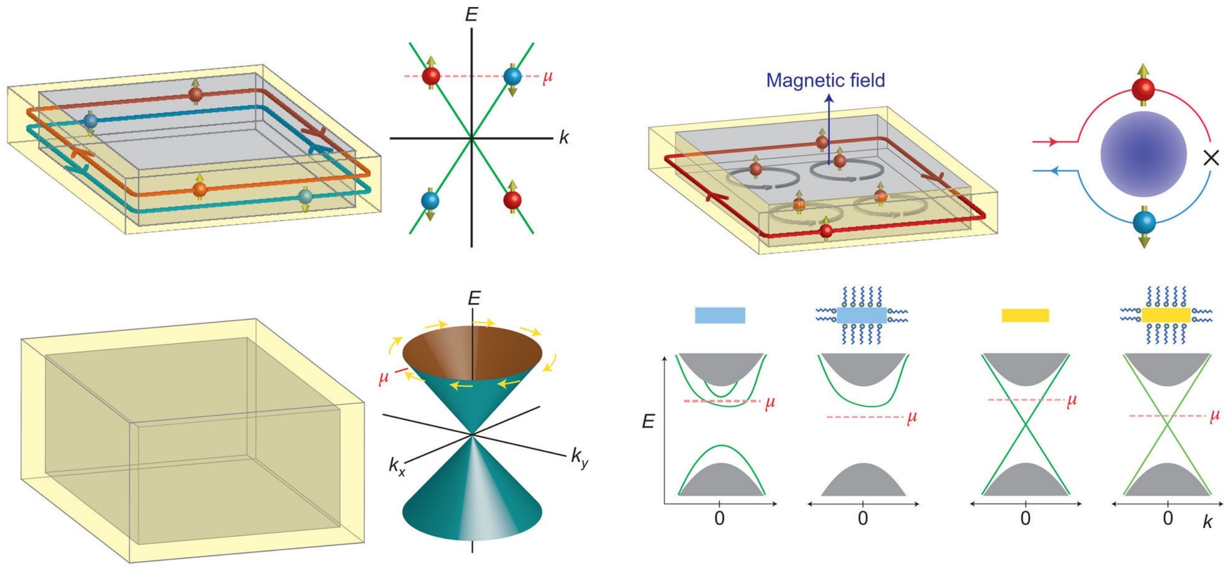


* O. Gomonay *et al.*, *Phys. Status Solidi* **11**, 1700022 (2017);
** T. Jungwirth et al., *Nature Nanotechnol.* **11**, 231 (2016).



* https://www.youtube.com/watch?v=zJ0-5oCc1rU

Topological Insulators

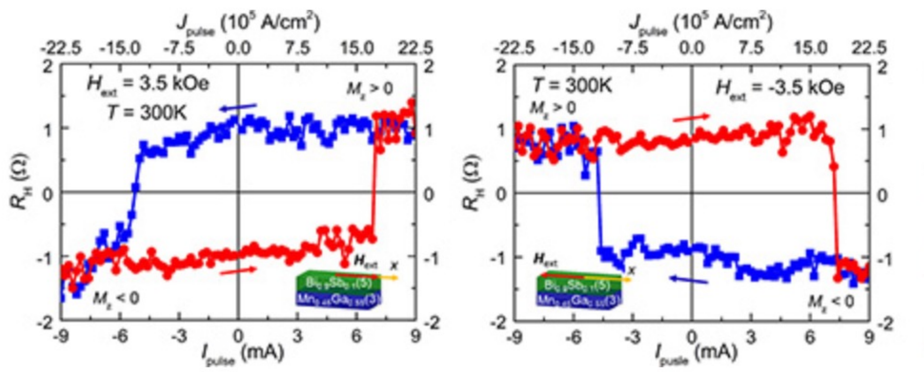


* D. Kong and Y. Cui, *Nature Chem.* **3**, 845 (2011).

Topological Insulators

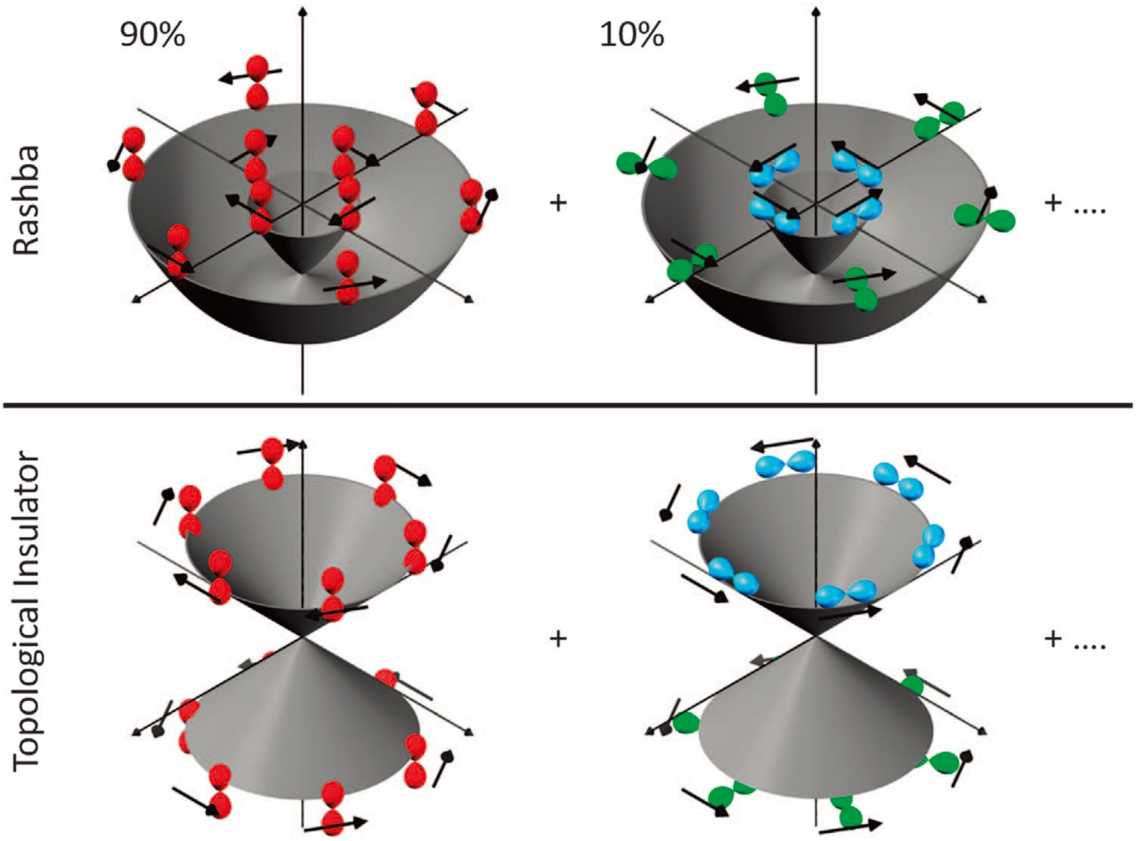
Spin-Hall measurements using topological insulators : *

	Spin-Hall Materials	θ_{SH}	$\sigma(\Omega^{-1}m^{-1})$	$\sigma_{SH}\ (\frac{\hbar}{2e}\ \Omega^{-1}m^{-1})$
Heavy metals	Ta (Science '12)	0.15(△)	5.2×10^5 (◎)	0.8×10^5
Heavy metals	Pt (PRL '12)	0.08(×)	4.2×10^6 (◎)	3.4×10^5
Heavy metals	W (APL '12)	0.4(△)	4.7×10^5 (◎)	1.9×10^5
Topological insulators	Bi_3Se_2 (Nature '14)	2〜3.5(○)	5.5×10^4(△)	$1.1\text{-}2.0\times10^5$
Topological insulators	**BiSb (Nature Mat.'18)**	**52**(◎)	**2.5×10^5** (◎)	**1.3×10^7**



* N. H. D. Khang *et al.*, *Nat. Mater.* **17**, 808 (2019).

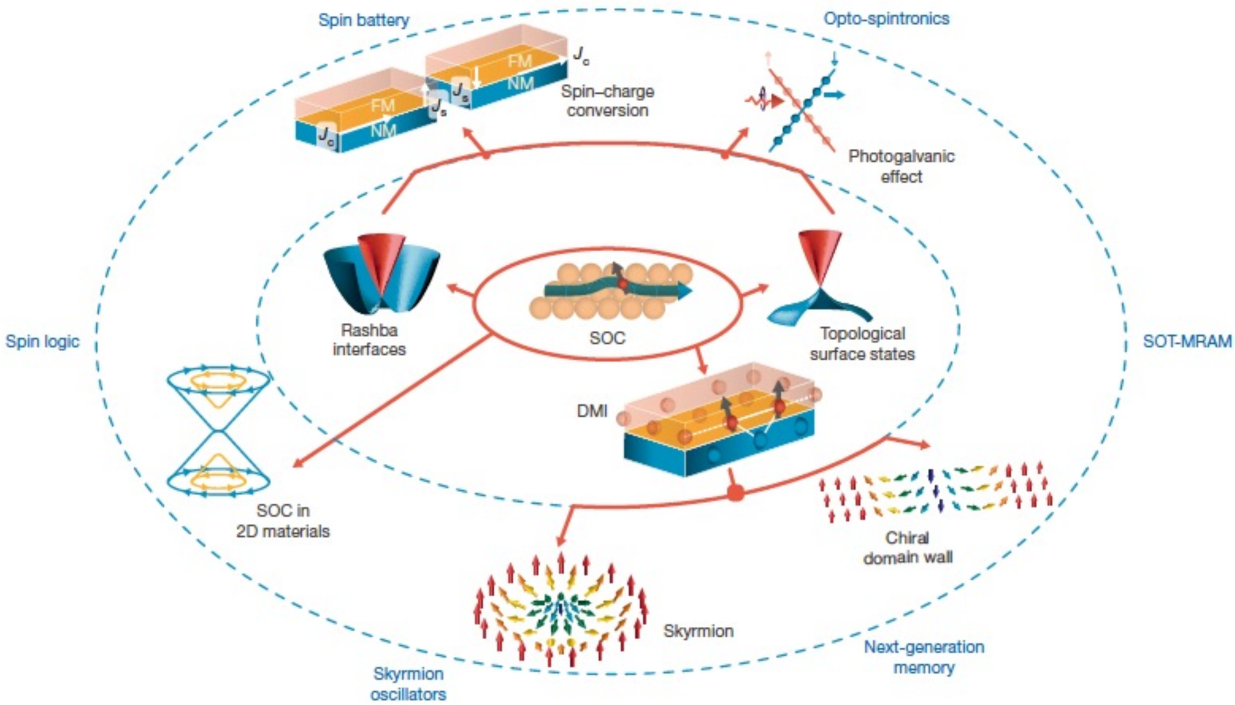
Spin Coupled to In-Plane Orbit



* J. A. Waugh *et al.*, *npj Quantum Mater.* **1**, 16025 (2016).

Phenomena with the Spin-Orbit Coupling

Spin-orbitronics : *



* A. Soumyanarayanan et al., Nature **539**, 509 (2016).