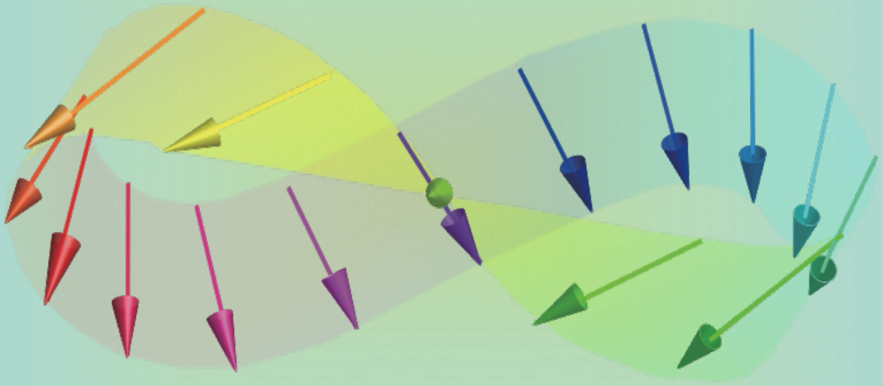
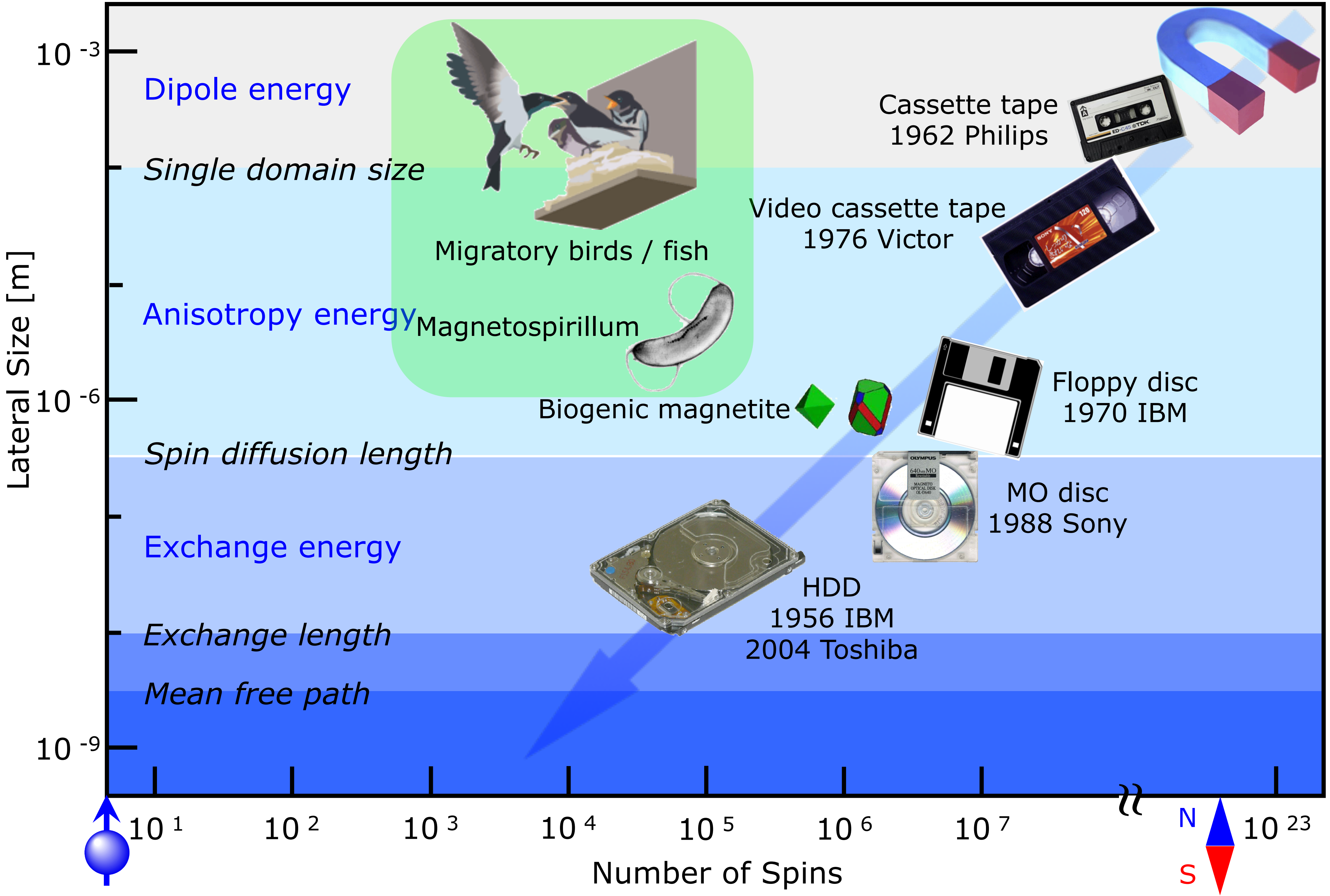
Tutorial on Spintronics and Its Device Applications



Atsufumi Hirohata

THE UNIVERSITY *of York*

Go into Nano-Scale



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

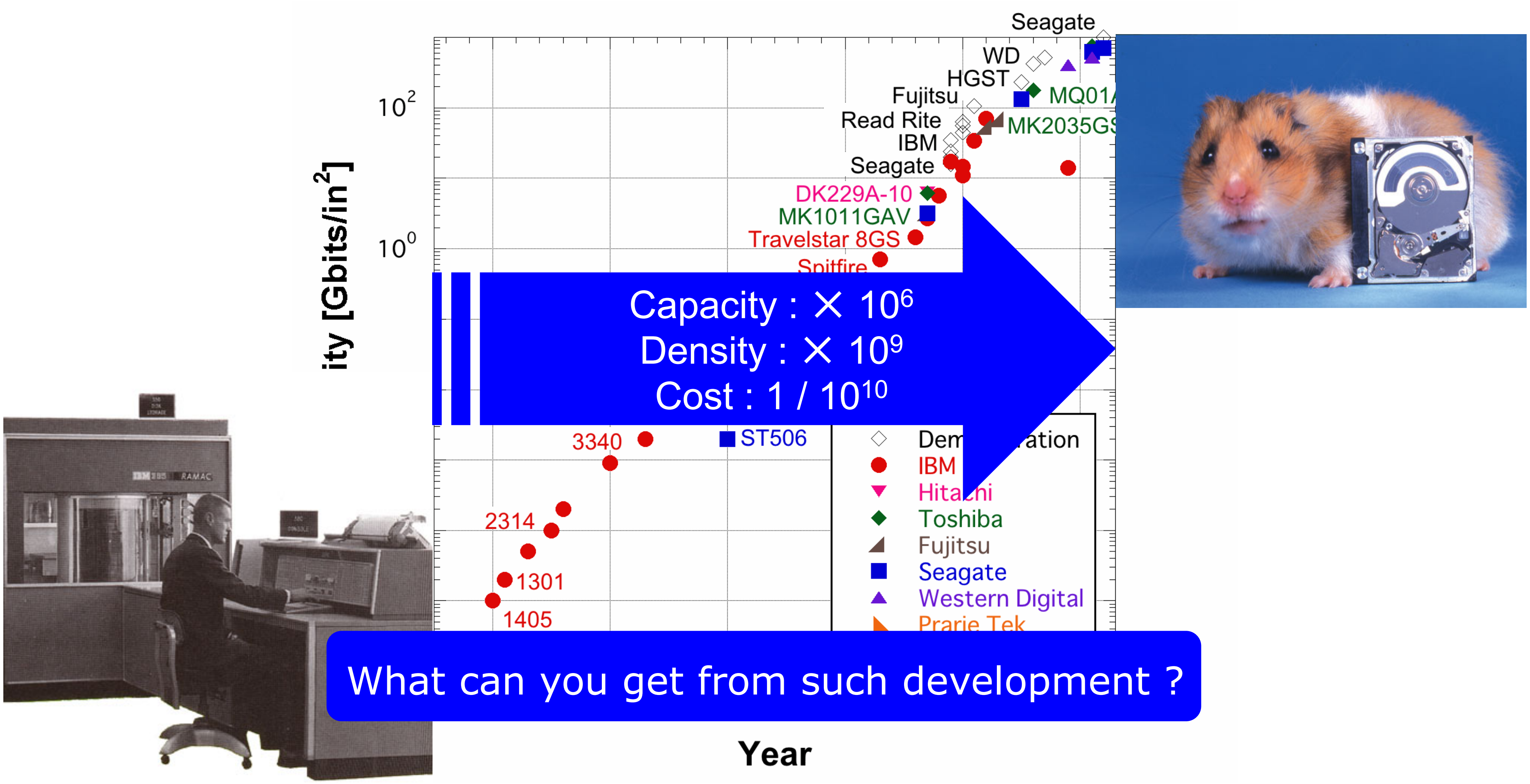
Increase in Recording Density of Hard Disc Drives

Similar to Moore's law :

Areal density in a hard disc drive (HDD) doubles every 36 months. (~ 1992)

After giant magnetoresistance (GMR) implementation,

it doubles less than every 20 months. (1992 ~)



Capacity : × 10^6
Density : × 10^9
Cost : 1 / 10^{10}

What can you get from such development ?

Nobel Prize in Physics 2007

naturenews

News

The physics prize inside the iPod

Giant magnetoresistance secures Nobel.

Geoff Brumfiel (/news/author/Geoff+Brumfiel/index.html)

Two researchers who discovered an effect that has dramatically shrunk the size of magnetic storage devices have won the 2007 Nobel Prize in Physics.

Albert Fert of the University of Paris-South in France and Peter Grünberg of Jülich Research Centre in Germany split the prize for their 1988 discovery of an effect called giant magnetoresistance (GMR). The Royal Swedish Academy of Sciences announced the award on 9 October in Stockholm.

The effect has been heralded as one of the first major applications of the fields of nanotechnology and 'spintronics'.

"I am so proud and so happy," Fert said in a press conference via telephone from France. "Science is something marvellous."

At the heart of GMR are the spins of electrons, which generate a magnetic field and can be aligned either up or down. An electron can easily pass through a material whose electrons are similarly aligned, but will encounter resistance when it passes through one with electrons aligned in the opposite direction.

Spin doctors: Peter Grünberg (left) and Albert Fert.

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physicsworld.com

NEWS

Oct 9, 2007

Nobel prize recognizes GMR pioneers

The 2007 Nobel Prize in Physics has been awarded jointly to Albert Fert of the Université Paris-Sud in France and Peter Grünberg of the Forschungszentrum Jülich in Germany "for the discovery of giant magnetoresistance". Their discovery, which both physicists made independently in 1988, led to a dramatic rise in the amount of data that can be stored on computer hard-disk drives. Fert and Grünberg share prize money totalling 10 million Swedish krone (about $1.5m).

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

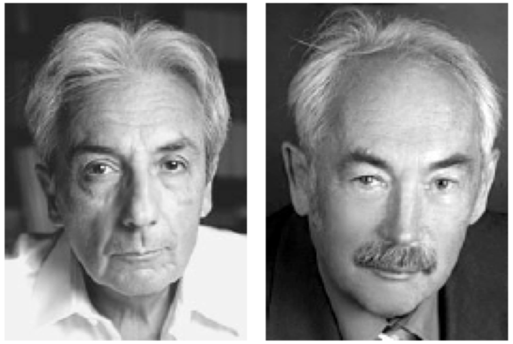


Photo: © Forschungszentrum

NOBEL PRIZES

Effect that Revolutionized Hard Drives Nets a Nobel

If you work at a computer, play video games, or listen to music on an iPod, you've benefited directly from the efforts of the winners of the 2007 Nobel Prize in Physics. Albert Fert of France's national research agency, CNRS, in Orsay, France, and Peter Grünberg of the Jülich Research Center in Germany independently discovered an effect known as giant magnetoresistance (GMR) that fueled a dramatic increase in the capacity of computer hard drives. The discovery also laid the cornerstone of a new field known as spintronics, in which researchers try to exploit the fact that electrons spin like little tops to make novel devices.

"It's a physics discovery that has had real consequences," says Robert Buhrman, an applied physicist at

ity. "Without
d not be able
le life around
drive."
the discovery
hers knew that
etic field to a
iron or nickel
conductivity.
t would flow
rallel to the
h the material
ed and more
Technologists
ffect to make
" that sensed
e magnetized
er hard drive.
, known as
agnetoresis-
the resistance

varied by a few percent.

In 1988, Grünberg and Fert found that they could greatly increase the change in resistance if they made layer-cake films with layers of iron separated by layers of nonmagnetic chromium only a few atoms thick. If two adjacent iron layers are magnetized in the same direction, then electrons spinning in one direction will pass along the film readily, whereas electrons spinning in the other direction will not. If, however, the iron layers are magnetized in opposite directions, then all electrons run into greater resistance, regardless of how they are spinning. That makes a GMR film an extremely sensitive magnetic field detector. As a result, all the bits and hardware in a disk drive can be made much smaller.

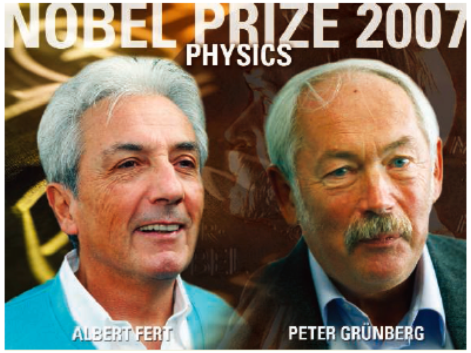
The basic quantum mechanical concepts behind GMR were understood in the 1970s, but at the time technology was not available to exploit them, Fert says. "I put this idea in the fridge," he says. "Then in the 1980s, it became possible to fabricate these materials." Grünberg could not be reached for comment when *Science* went to press.

Although Fert and Grünberg discovered the effect, Stuart Parkin of IBM's Almaden Research Center in San Jose, California, did much of the work to make GMR technologically useful. Stuart Wolf, a physicist at the University of Virginia, Charlottesville, says he was surprised that Parkin was not honored as well. But Tony Bland of the University of Cambridge, U.K., says that the Nobel committee apparently distinguished between the discovery and its cultivation. "This is properly a physics prize for a truly extraordinary and novel effect."

The advent of GMR helped launch the emerging field of spintronics, Wolf says. "This particular discovery seemed to crystallize a lot of people's interest in working in this area," he says. Their efforts may someday lead to myriad other devices, such as computer memory that can hold information even when it loses power and microchips that exploit spin to perform computations.

–ADRIAN CHO

With reporting by Daniel Clery.



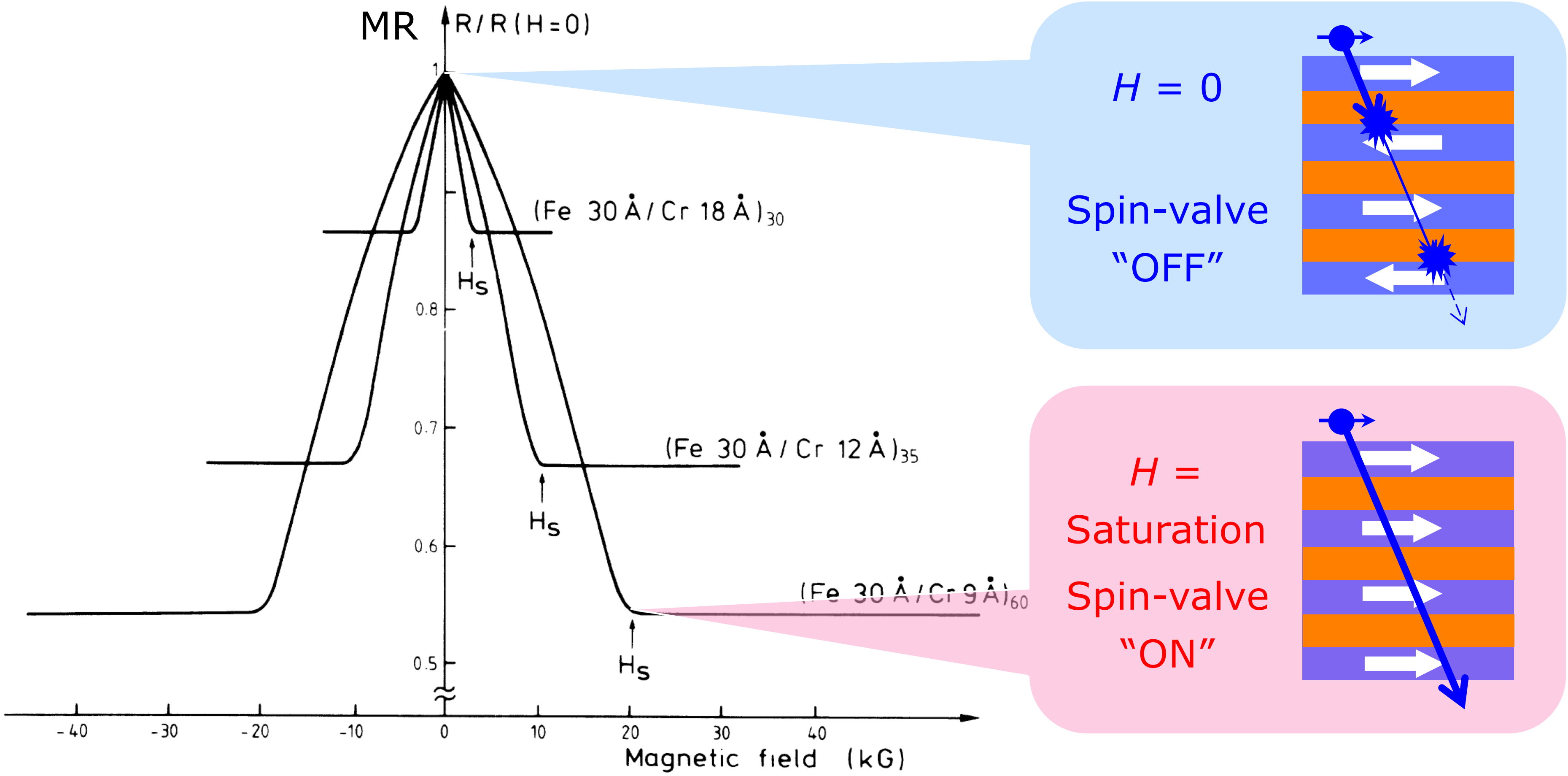
Thanks for the memories. Physicists Albert Fert (*left*) and Peter Grünberg independently discovered an effect that vastly increased the capacity of computer drives.

Published by AAAS

Discovery of Giant Magnetoresistance

Giant magnetoresistance (GMR) :

[3 nm Fe / 0.9 nm Cr] × 60 *



50 % resistance change at 4.2 K

* M. N. Baibich *et al.*, *Phys. Rev. Lett.* 61, 2472 (1988); P. Grünberg *et al.*, *Phys. Rev. Lett.* 57, 2442 (1986).

HDD in Cloud

In this lecture theatre,

30 Smart Phones = 1/4 Cloud server

81 % (2016, UK)

cloudServices online

20 Tablet PCs = 1/4 Cloud server

71 % (2016, UK)

3 Cloud servers used

Google for Education

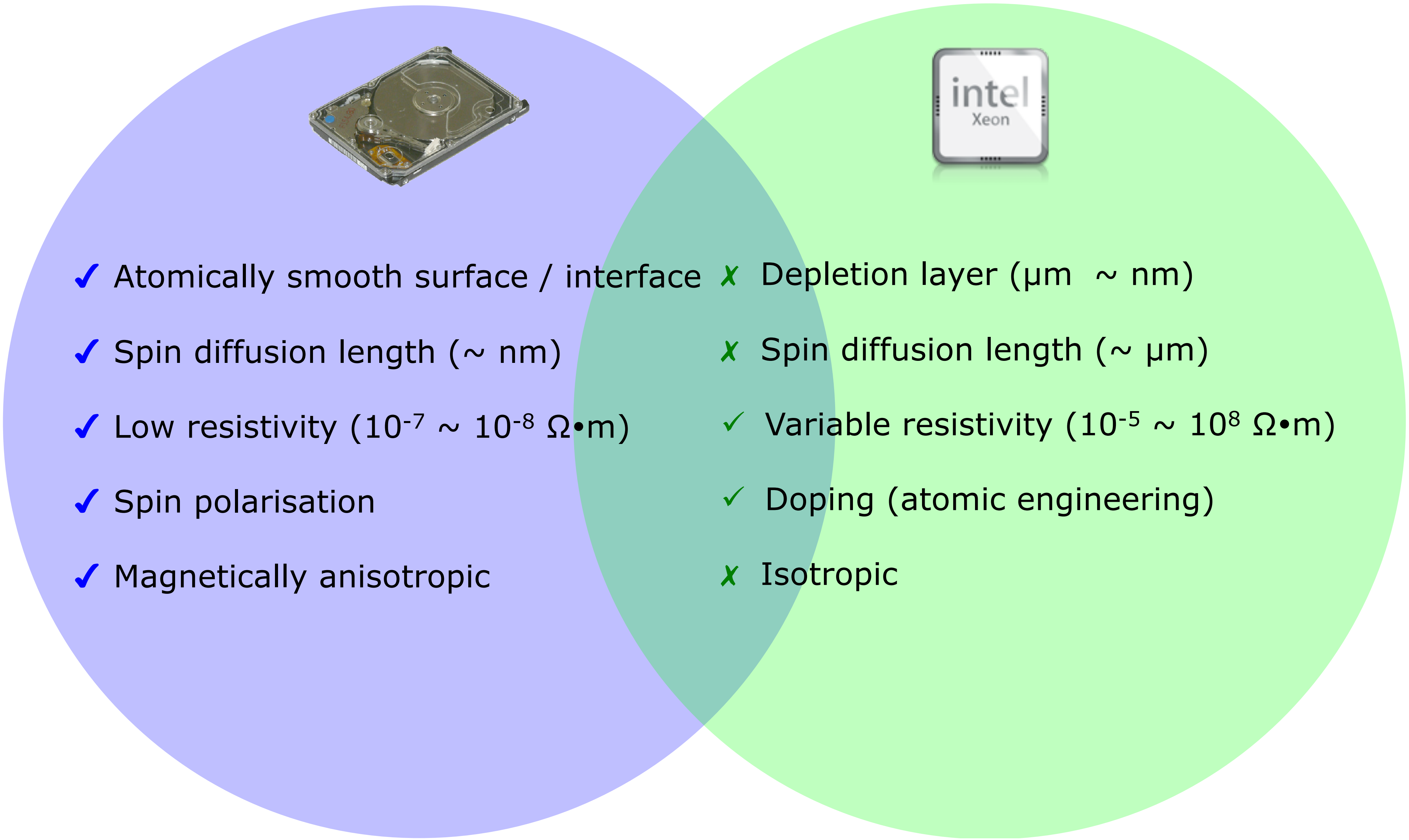
1 TB max. / person = 2.5 Cloud servers

Microsoft Azure

amazon web services

Magnetism + Electronics

By taking advantages from both magnetism and semiconductor physics,



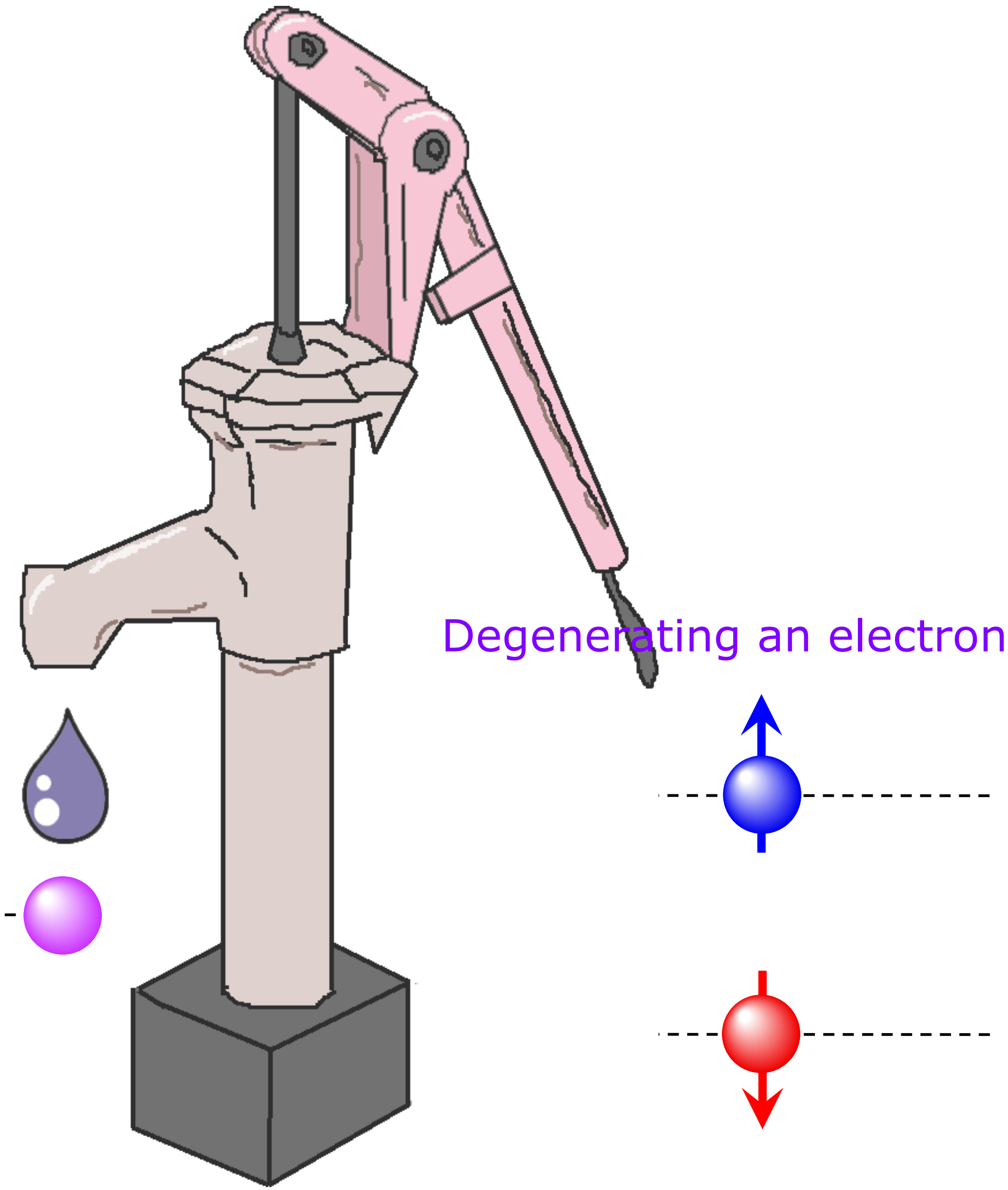
Magnetism

Semiconductor physics

- ✓ Atomically smooth surface / interface
- ✓ Spin diffusion length (~ nm)
- ✓ Low resistivity (10^{-7} ~ 10^{-8} Ω•m)
- ✓ Spin polarisation
- ✓ Magnetically anisotropic

- ✗ Depletion layer (μm ~ nm)
- ✗ Spin diffusion length (~ μm)
- ✓ Variable resistivity (10^{-5} ~ 10^{8} Ω•m)
- ✓ Doping (atomic engineering)
- ✗ Isotropic

Conventional Electronics

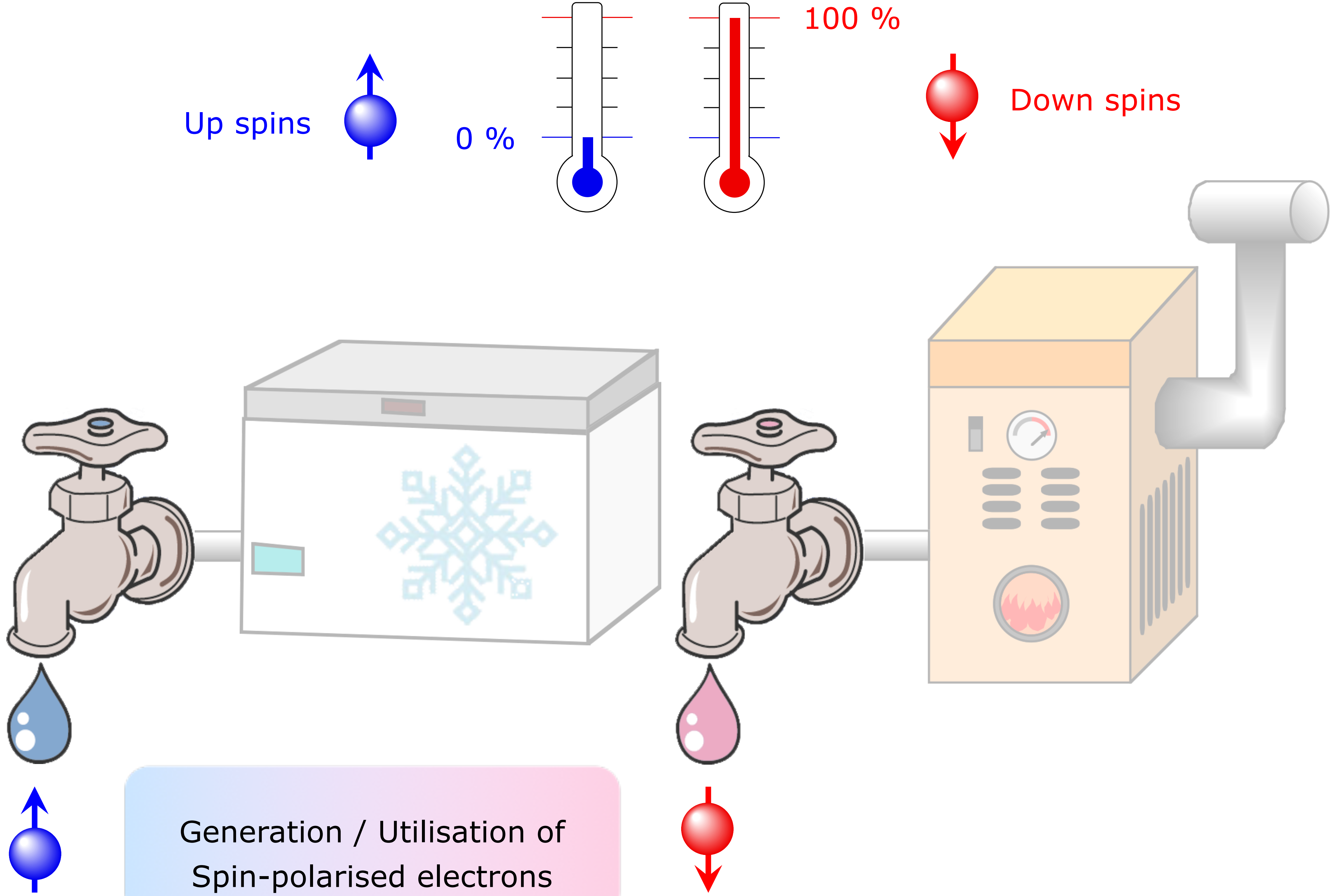


Electrical current e^-

Degenerating an electron state ...

New degree of freedom : Spin

Magnetoelectronics



Up spins

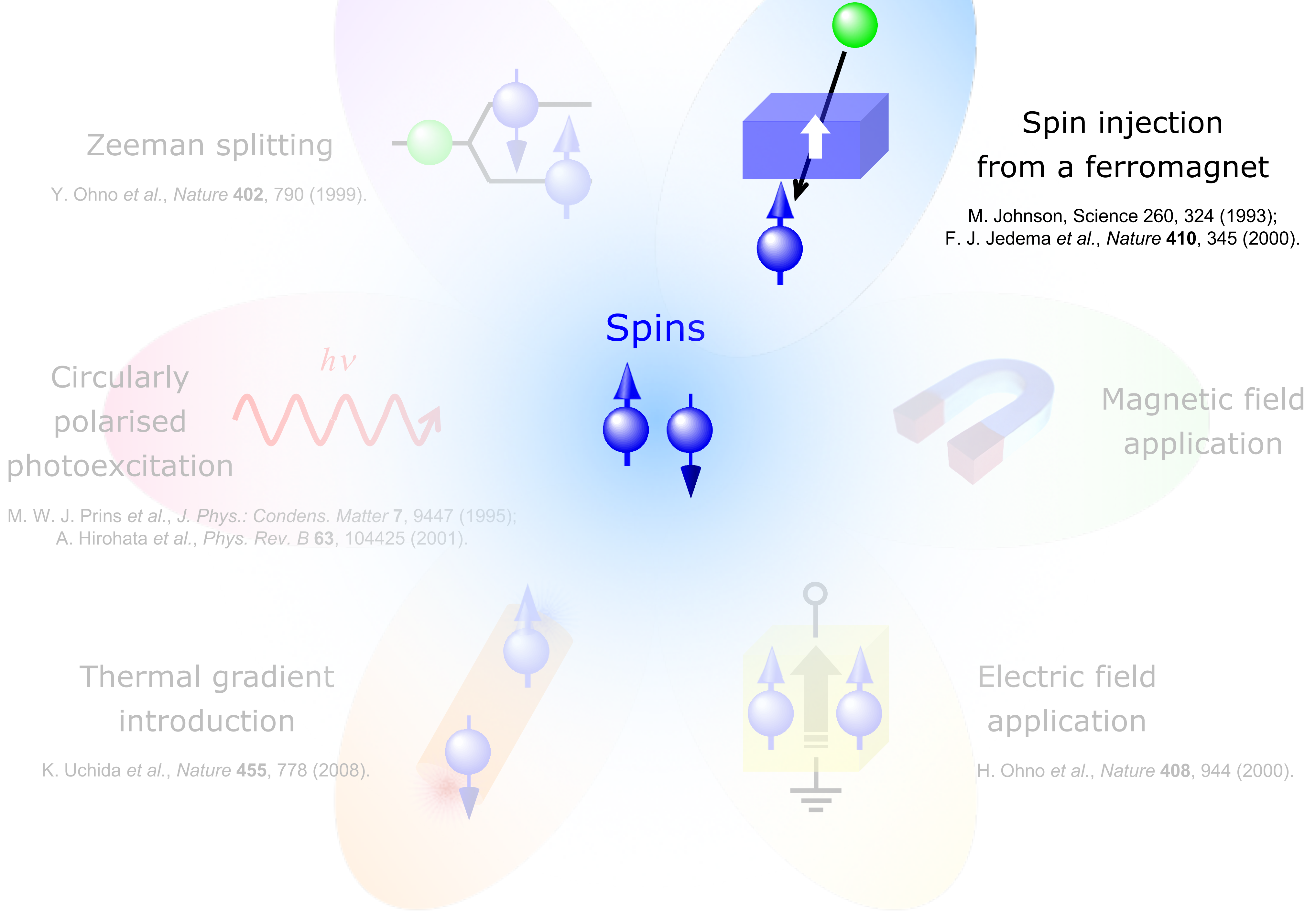
0 %

100 %

Down spins

Generation / Utilisation of
Spin-polarised electrons

Generation of Spin-Polarised Electrons



Zeeman splitting

Y. Ohno *et al.*, *Nature* **402**, 790 (1999).

Spin injection
from a ferromagnet

M. Johnson, Science 260, 324 (1993);
F. J. Jedema *et al.*, *Nature* **410**, 345 (2000).

Spins

Circularly
polarised
photoexcitation

M. W. J. Prins *et al.*, *J. Phys.: Condens. Matter* **7**, 9447 (1995);
A. Hirohata *et al.*, *Phys. Rev. B* **63**, 104425 (2001).

Magnetic field
application

Thermal gradient
introduction

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

Electric field
application

H. Ohno *et al.*, *Nature* **408**, 944 (2000).

Theoretical Models for GMR

Interlayer exchange coupling model :

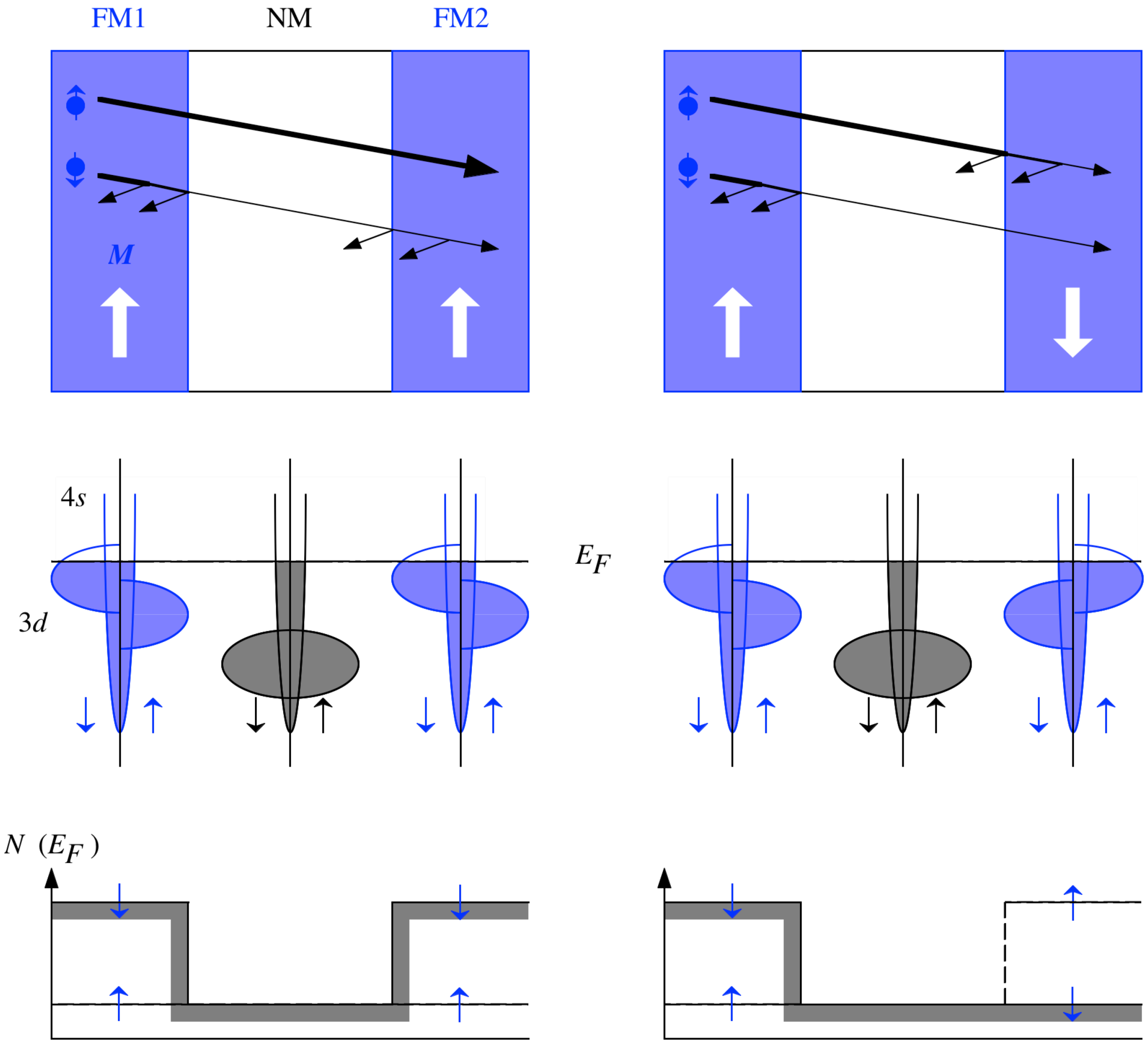
- RKKY-like oscillation *

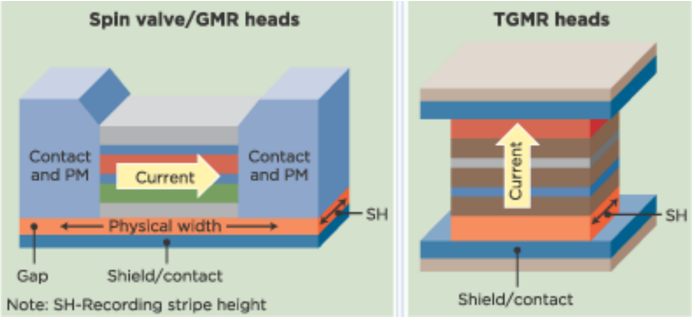
Two current model :

- 3*d* ferromagnets (FM) carry
  - up spin current
  - down spin current
- independently with different scattering rates at
  - the FM layers
  - the FM / NM interfaces. **

Current orientation :

- Current in the plane (CIP)
- Current perpendicular to the plane (CPP)





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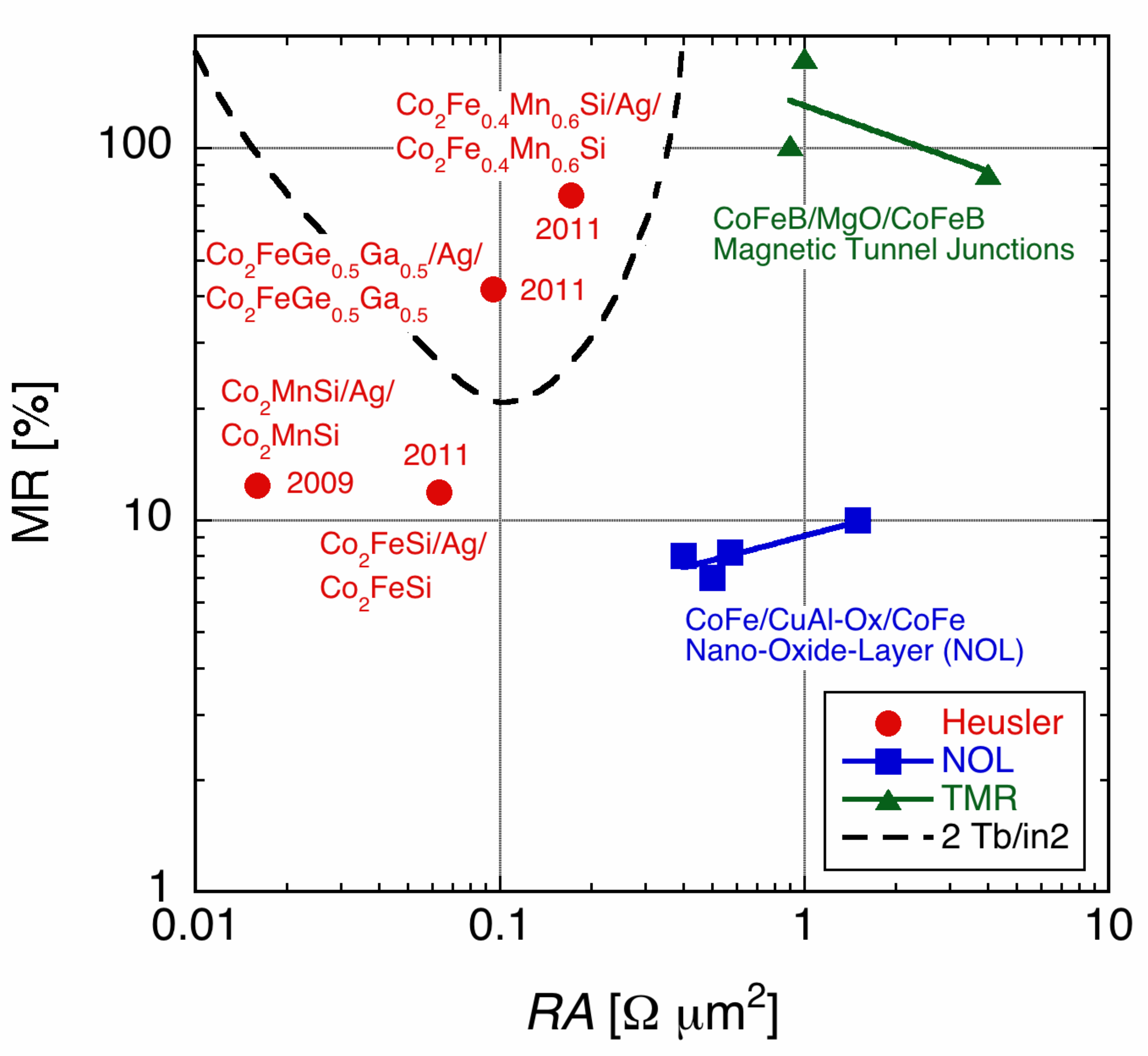
* K. B. Hathaway, *Ultrathin Magnetic Structures II*, B. Heinrich and J. A. C. Bland (Eds.) (Springer, Berlin, 1994), p. 45-72;

** J. Mathon, *Spin Electronics*, M. Ziese and M. J. Thornton (Eds.) (Springer, Berlin, 2001), p. 71-88.

Larger GMR Ratios

For > 2 Tb/in^2 recording :

Larger GMR ratios and smaller resistance-area product (*RA*) are required.

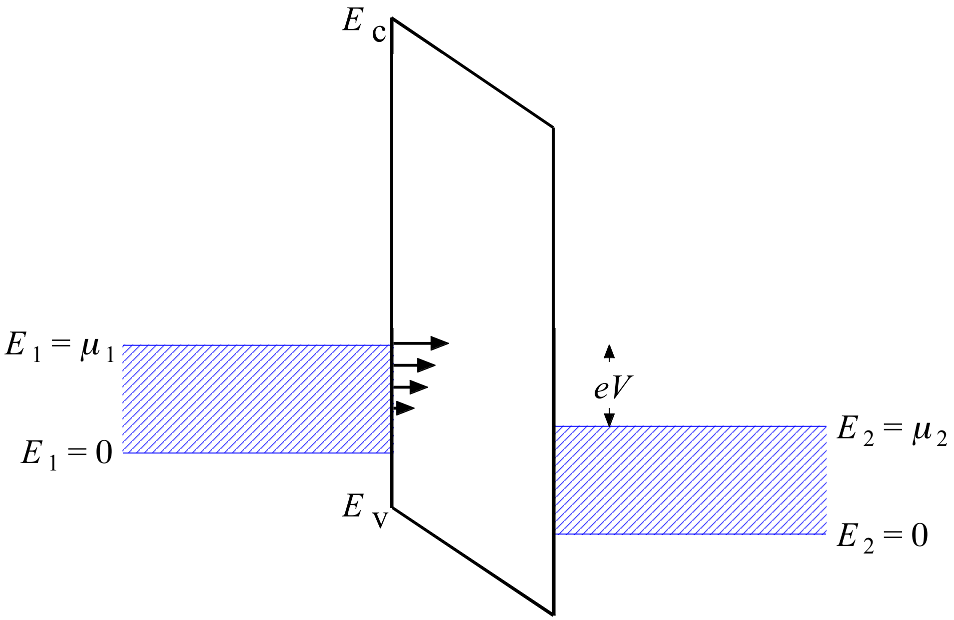


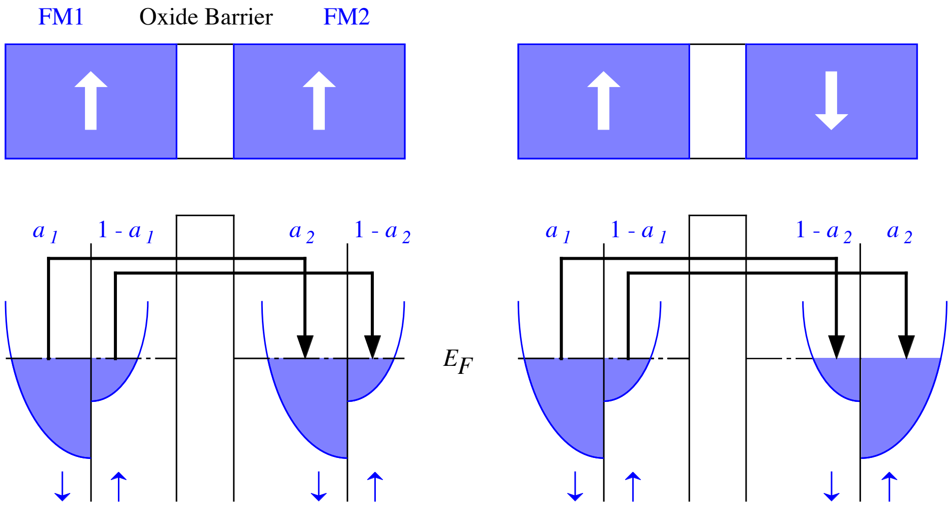
* A. Hirohata *et al.*, *Appl. Phys. A* **111**, 423 (2013).

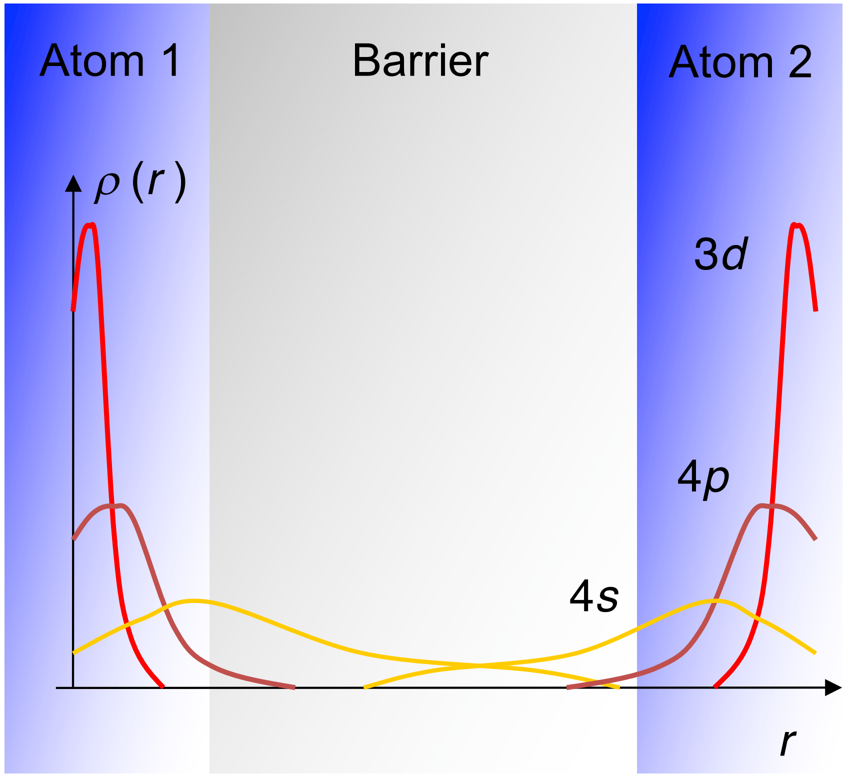
Spin-Dependent Electron Tunneling

Jullière's model :

FM / insulator / FM junctions *







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* M. Jullière., *Phys. Rep.* **54A**, 225 (1975).

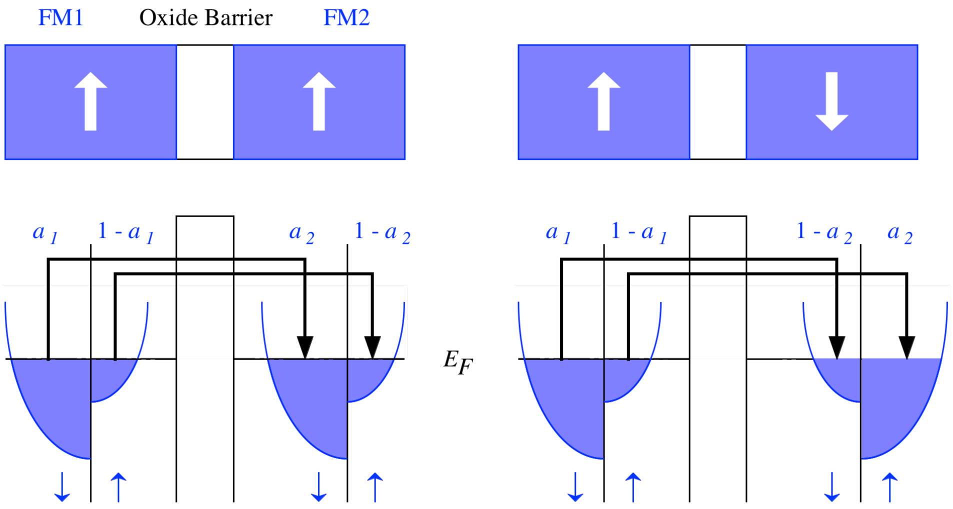
Theoretical Models for TMR

Free electron models :

Juliere's model :

$$\begin{cases} G^{p} \propto a_1 a_2 + (1-a_1)(1-a_2) \\ G^{a} \propto a_1(1-a_2) + (1-a_1)a_2 \end{cases}$$

$$\frac{R^{a}-R^{p}}{R^{p}} = \frac{2P_1P_2}{1-P_1P_2}$$



Slonczewski's model * :

spin split free electron band

→ for large energy gap in a barrier, spin polarization :

$$P = \frac{N_{\uparrow}(E_F) - N_{\downarrow}(E_F)}{N_{\uparrow}(E_F) + N_{\downarrow}(E_F)}$$

WKB approximation **

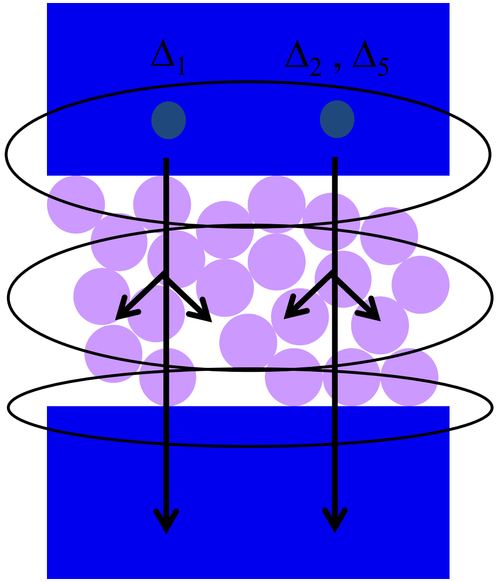
Transfer Hamiltonian approach

Ab initio calculations

J. C. Slonczewski, *Phys. Rev. B* **39**, 6995 (1989);
** W. F. Brinkman *et al.*, *J. Appl. Phys.* **41**, 1915 (1970).

Improved Tunnel Barriers

Conventional amorphous barriers : *

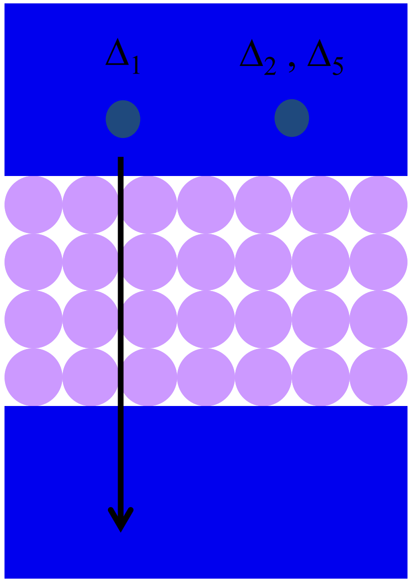


Defects in the barrier

Disorder at the interface :
- FM over-oxidation
- lattice defects

Disorder at the interface :
- FM over-oxidation
- lattice defects
- island growth of the barrier

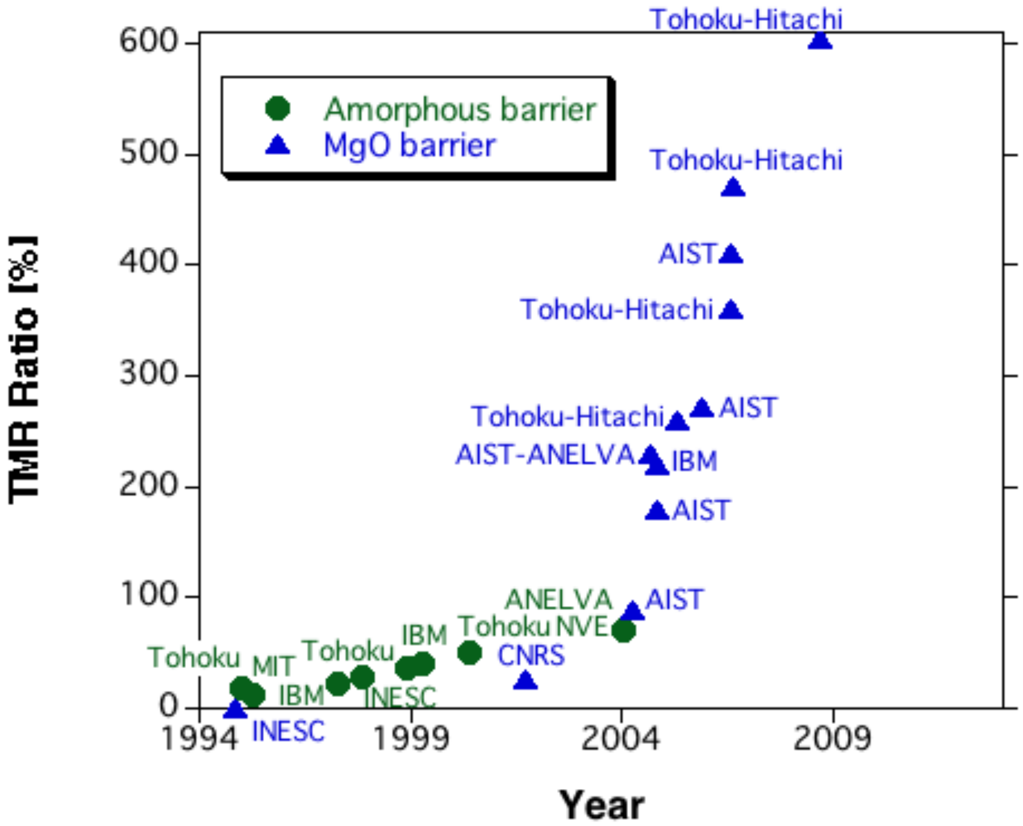
Epitaxial (oriented) barriers : *



* *After* S. Yuasa *et al.*, *28th Annual Conference on Magnetics*, Sep. 21-24, 2004 (Okinawa, Japan).

TMR for Device Applications

Recent progress in TMR ratios :



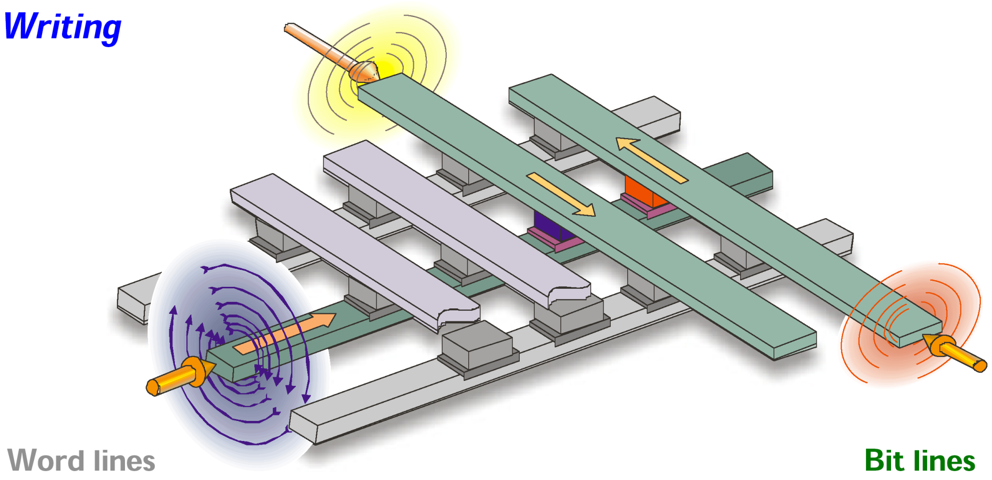
> *600 % TMR ratio* has been achieved !

↓

> Gbit MRAM can be realised.

NOT following Jullière's model : *

$$\text{TMR} = 2P_1P_2 \,/\, (\, 1 - P_1P_2 \,)$$



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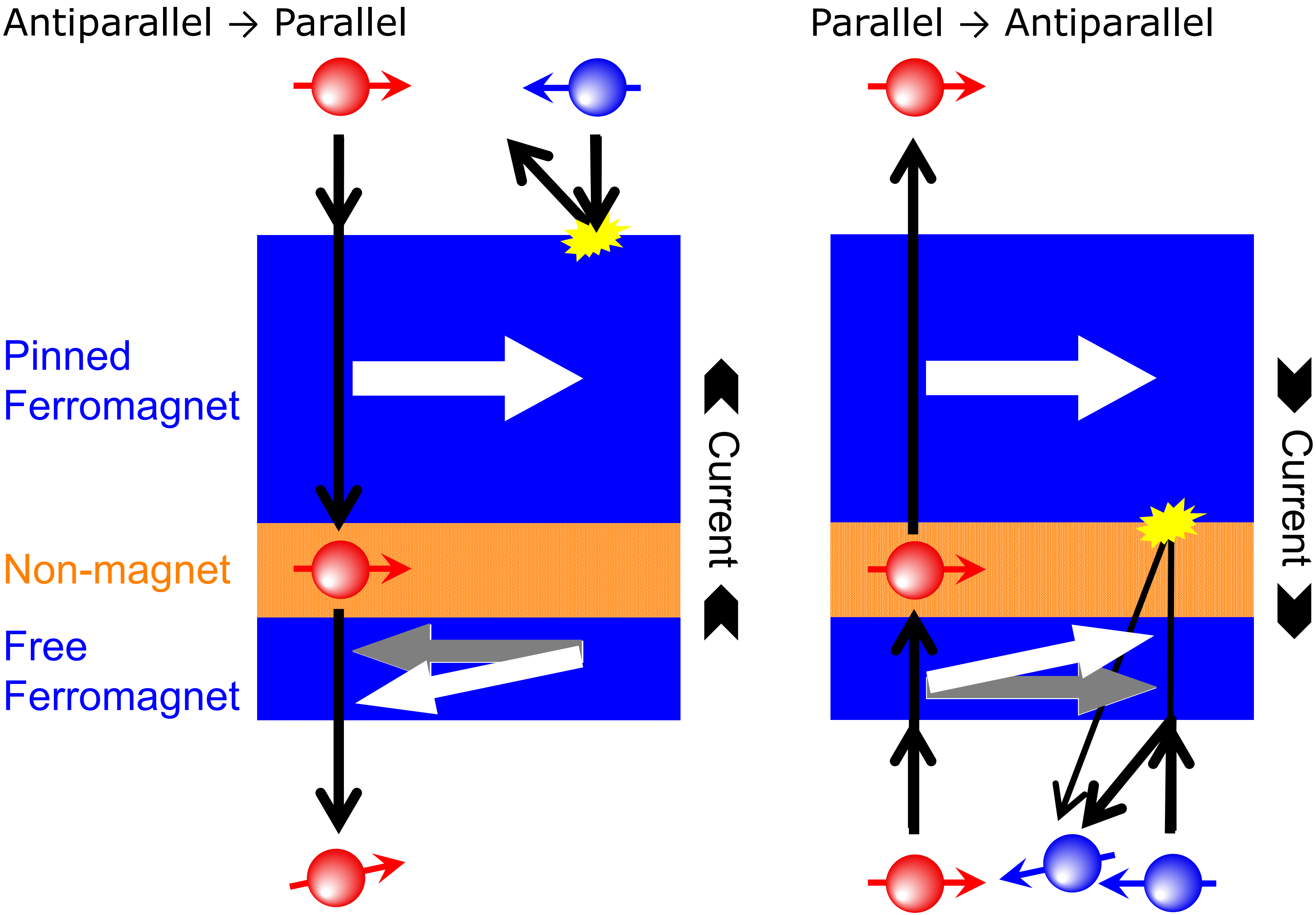
* M. Jullière., *Phys. Rep.* **54A**, 225 (1975).

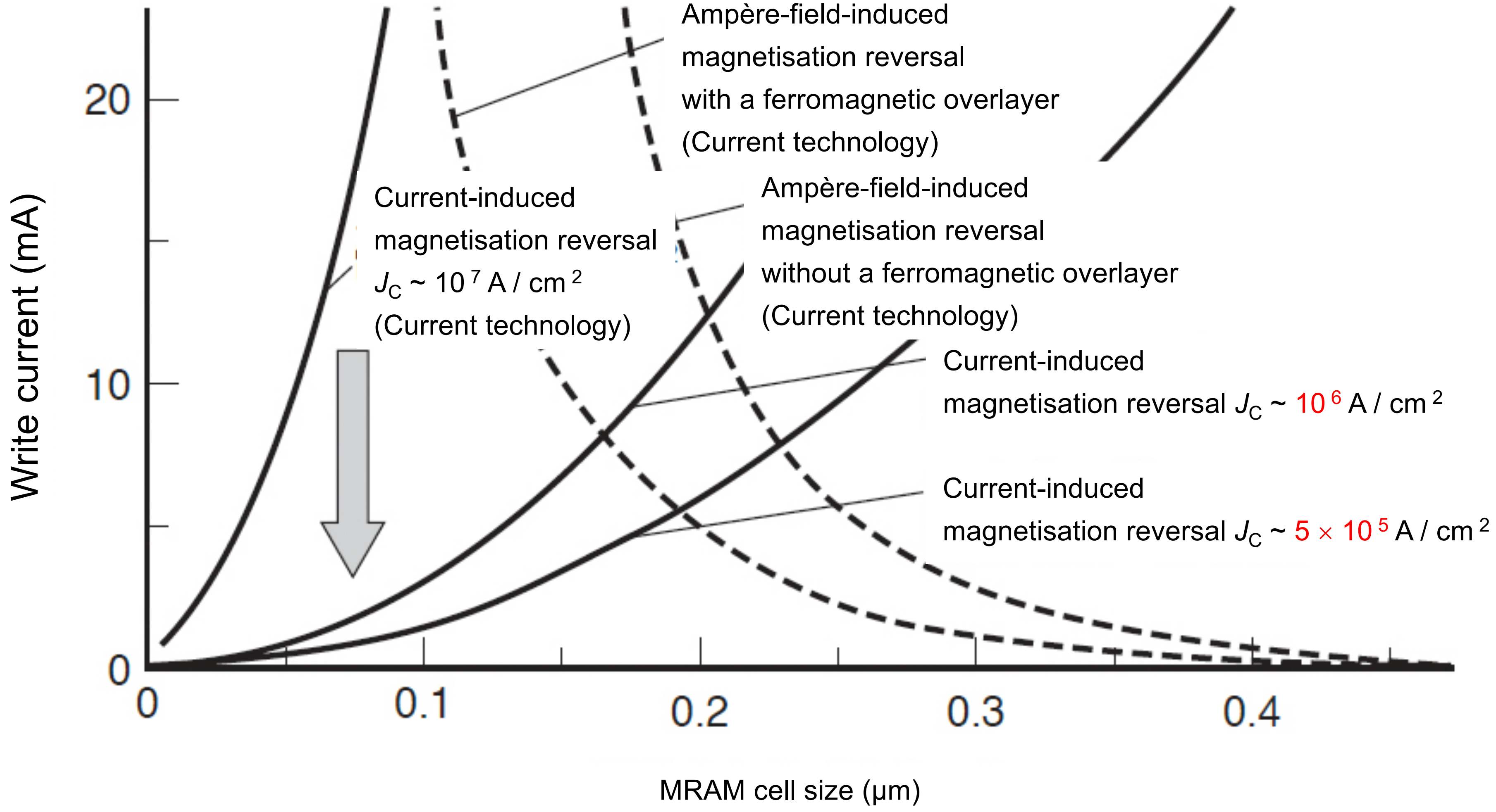
** S. S. P. Parkin, *1st Int'l Sch. on Spintronics and Quantum Info. Tech.*, May 13-15, 2001 (Maui, HI, USA).

Current-Induced Magnetisation Switching



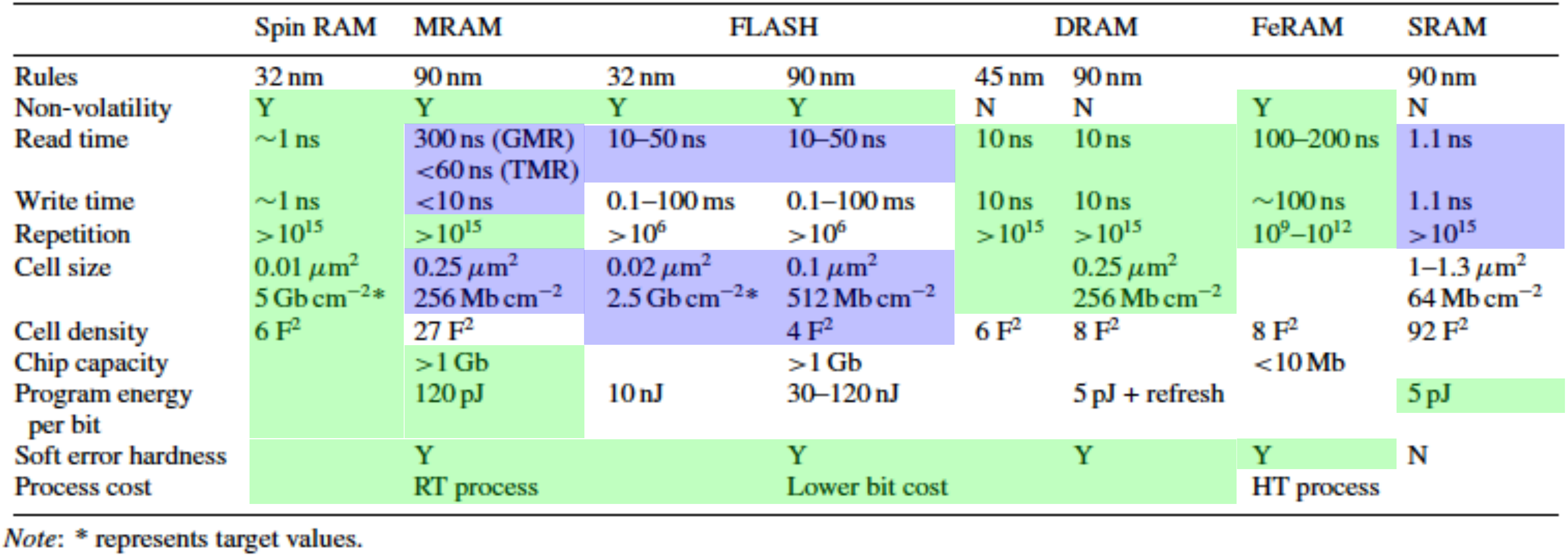
Improved MRAM Operation (Spin RAM)

Required writing currents for several techniques dependent upon cell size :



* S. Nakamura, Y. Saito and H. Morise, *Toshiba Rev.* **61**, 40 (2006).

Advantages of MRAM / Spin RAM

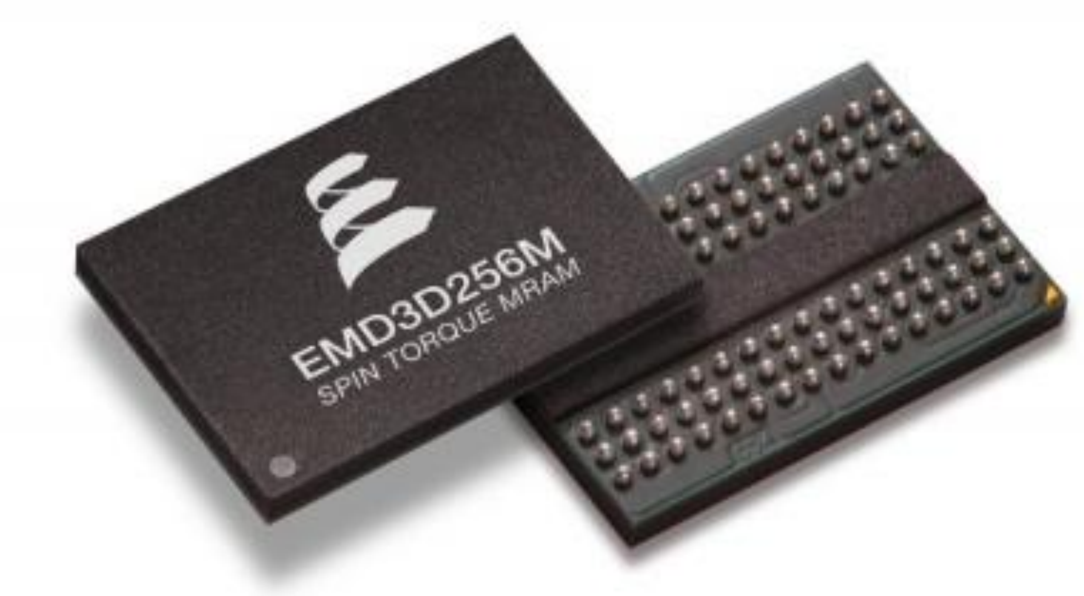


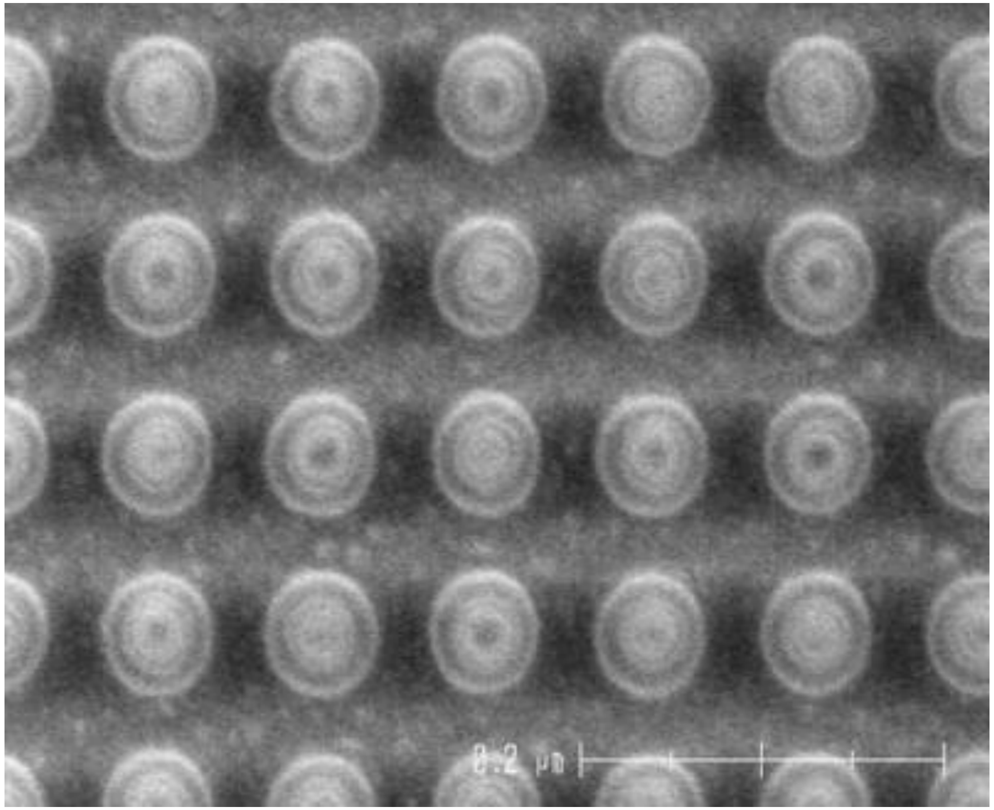
	Spin RAM	MRAM	FLASH		DRAM		FeRAM	SRAM
Rules	32 nm	90 nm	32 nm	90 nm	45 nm	90 nm		90 nm
Non-volatility	Y	Y	Y	Y	N	N	Y	N
Read time	~1 ns	300 ns (GMR) <60 ns (TMR)	10–50 ns	10–50 ns	10 ns	10 ns	100–200 ns	1.1 ns
Write time	~1 ns	<10 ns	0.1–100 ms	0.1–100 ms	10 ns	10 ns	~100 ns	1.1 ns
Repetition	$>10^{15}$	$>10^{15}$	$>10^{6}$	$>10^{6}$	$>10^{15}$	$>10^{15}$	10^{9}–10^{12}	$>10^{15}$
Cell size	0.01 μm^2 5 Gb cm^{-2}*	0.25 μm^2 256 Mb cm^{-2}	0.02 μm^2 2.5 Gb cm^{-2}*	0.1 μm^2 512 Mb cm^{-2}		0.25 μm^2 256 Mb cm^{-2}		1–1.3 μm^2 64 Mb cm^{-2}
Cell density	6 F^2	27 F^2		4 F^2	6 F^2	8 F^2	8 F^2	92 F^2
Chip capacity		>1 Gb		>1 Gb			<10 Mb	
Program energy per bit		120 pJ	10 nJ	30–120 nJ		5 pJ + refresh		5 pJ
Soft error hardness		Y		Y		Y	Y	N
Process cost		RT process		Lower bit cost			HT process	

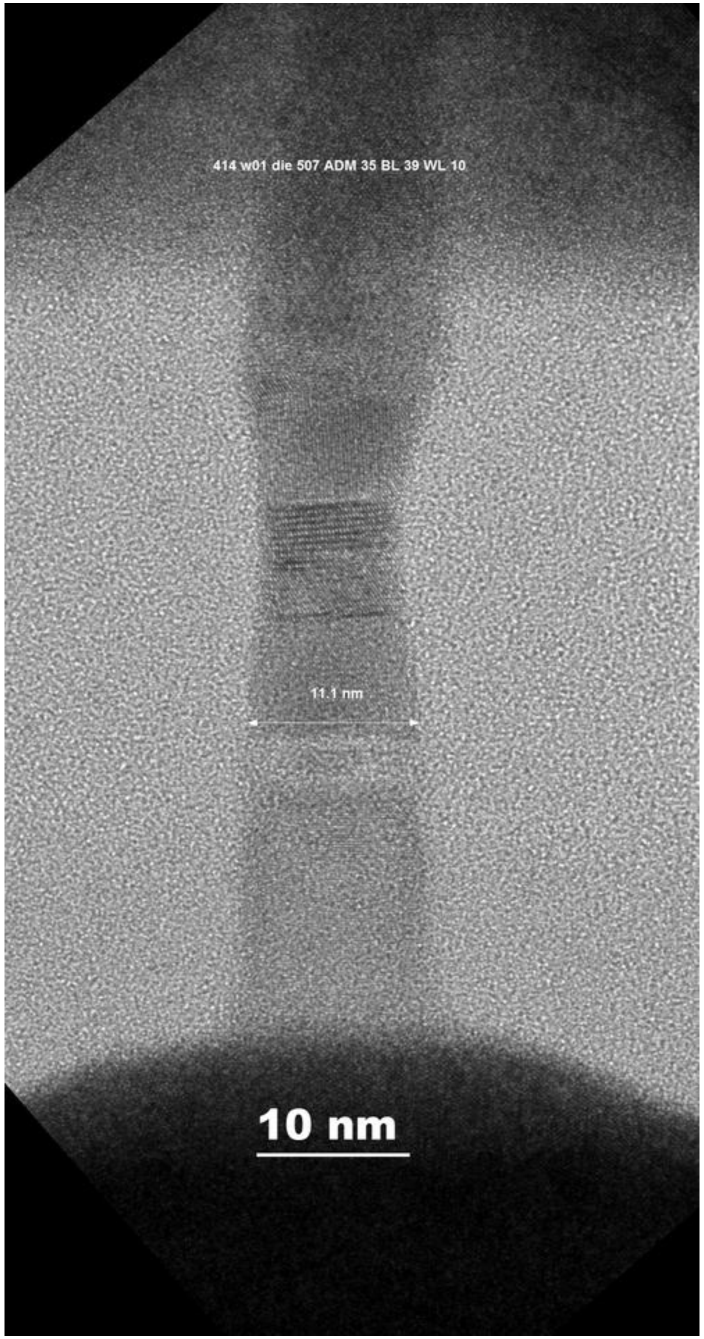
Note: * represents target values.

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

Latest Spin RAM



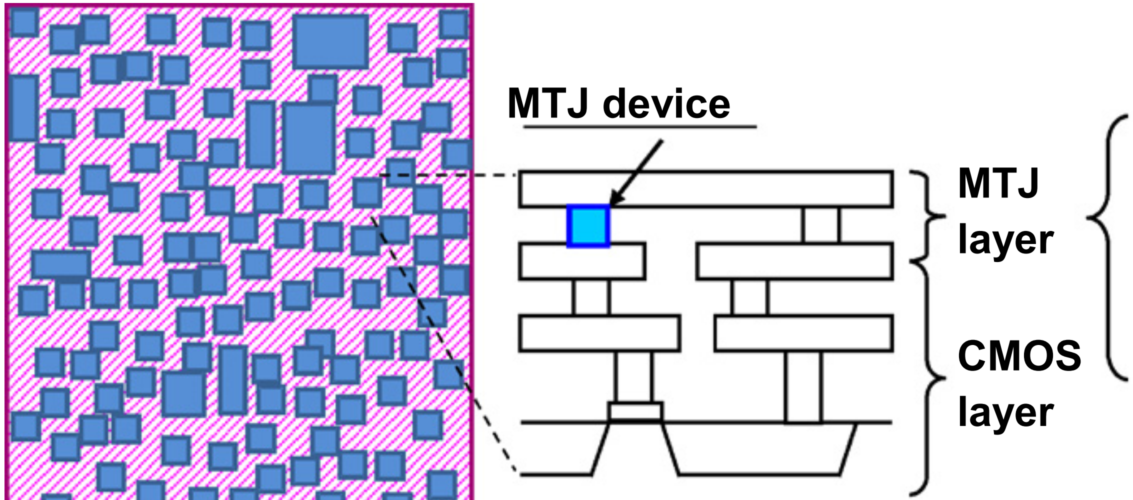




* News from EverSpin, IBM and Toshiba.

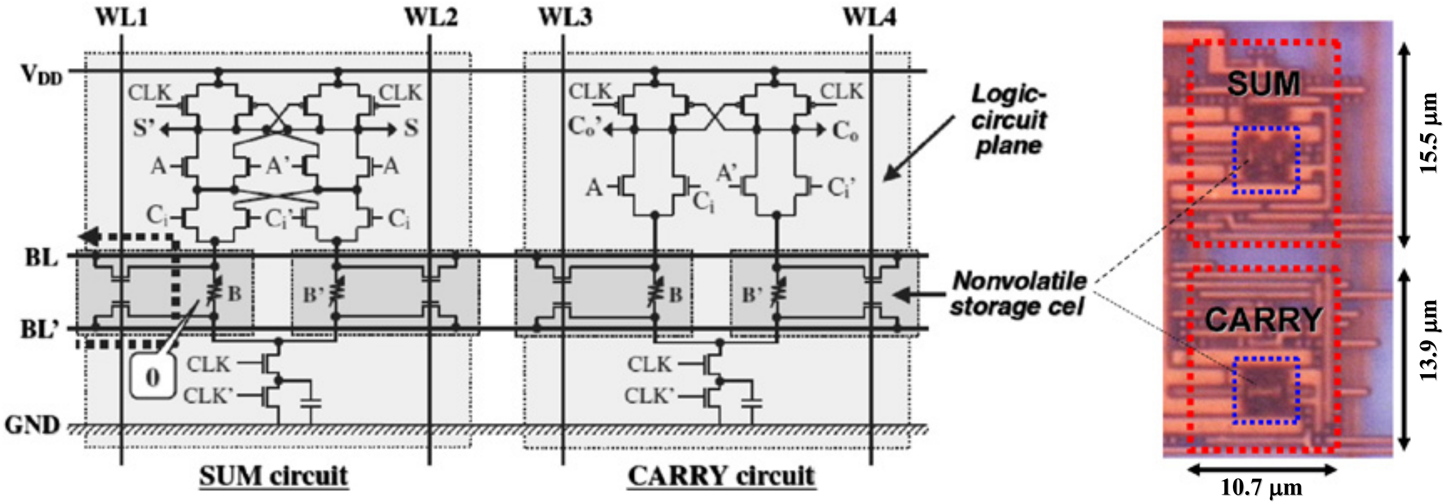
MRAM / Spin RAM Implementation

As a non-volatile universal memory, MRAM / Spin RAM can replace SRAM :



- Non-volatile
- Unlimited endurance
- Fast write
- Scalable
- CMOS compatible
- 3-D stack capable

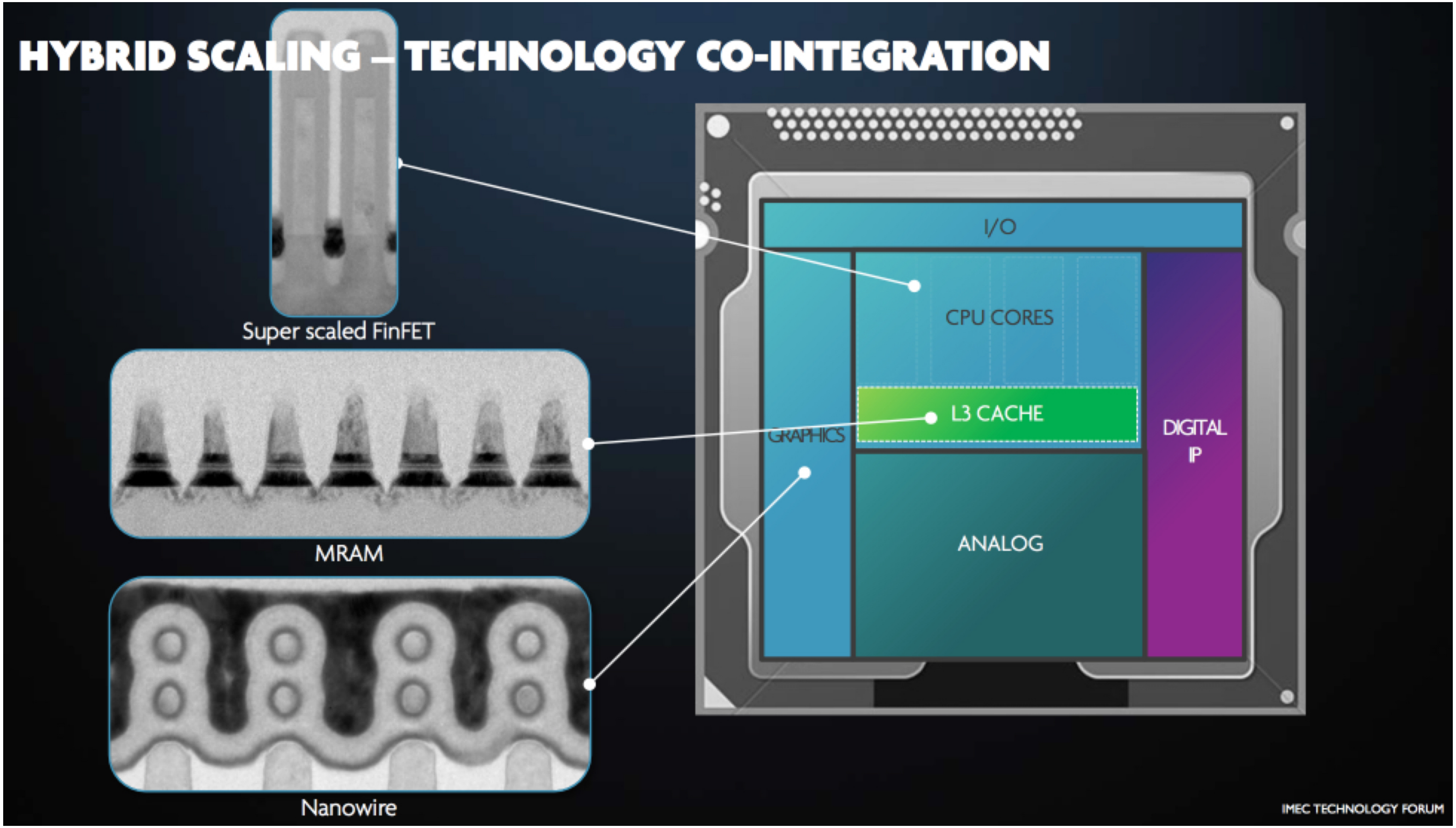
(a) Nonvolatile Logic-in-Memory Architecture



(b) Design example of nonvolatile full adder

* T. Kawahara *et al.*, *Microelectronics Reliability* **52**, 613 (2012).

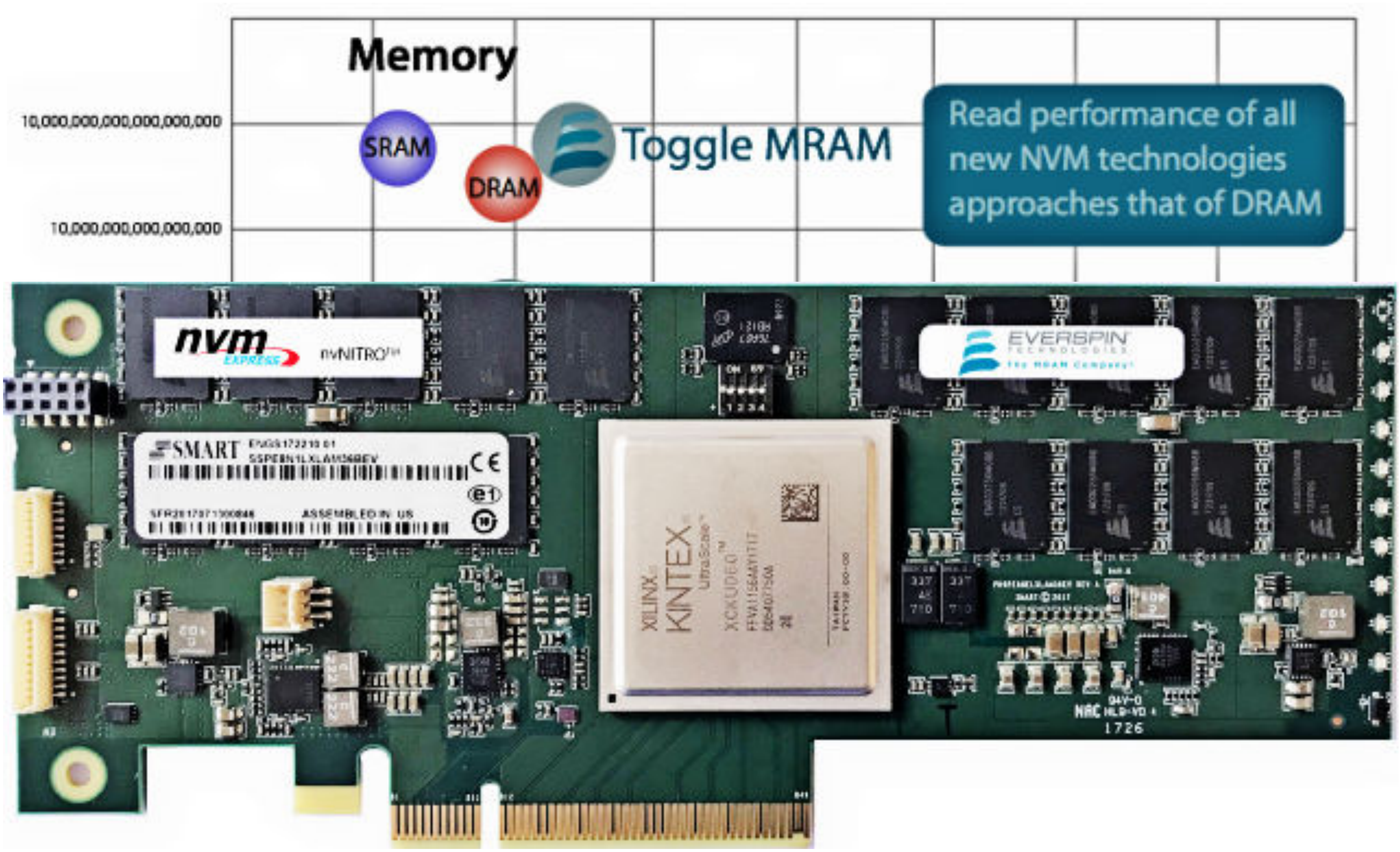
MRAM / Spin RAM and CPU Integration



HYBRID SCALING – TECHNOLOGY CO-INTEGRATION

* http://electroiq.com/blog/2017/07/how-low-can-we-go/

MRAM for SRAM / DRAM Replacement



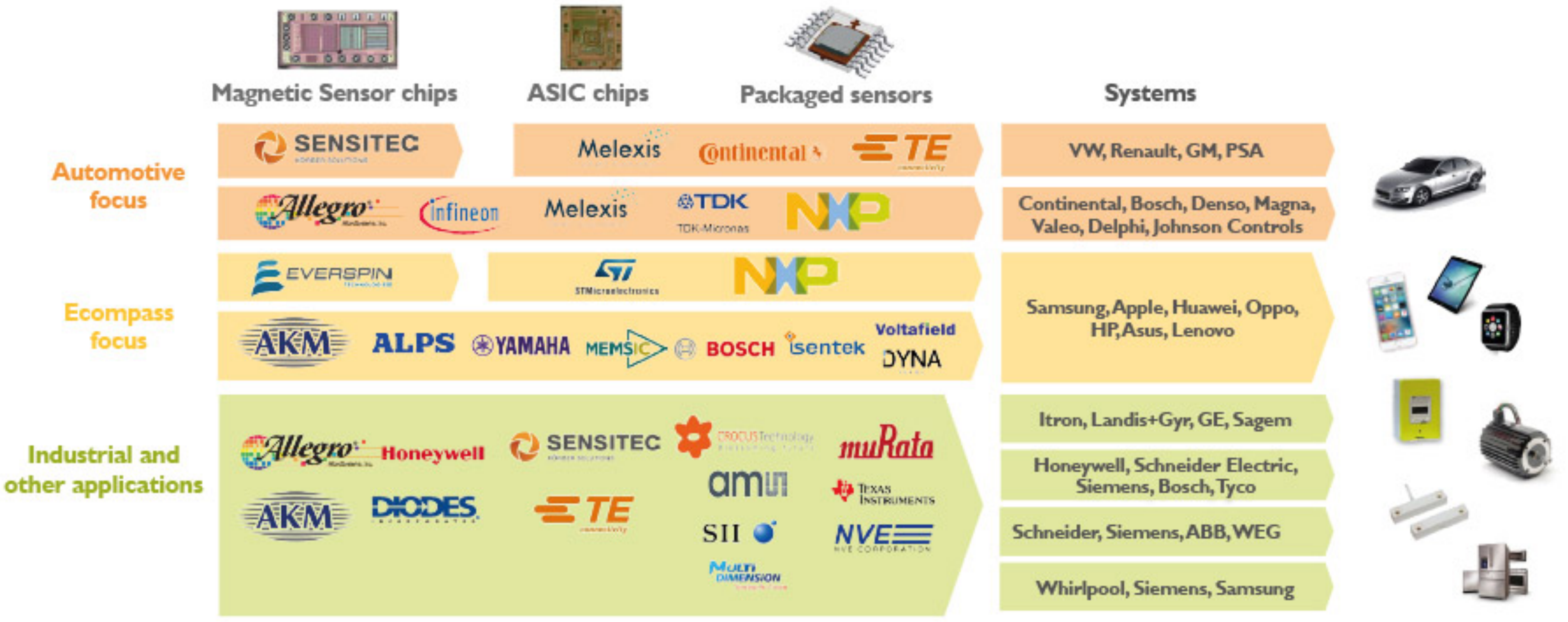
Read performance of all new NVM technologies approaches that of DRAM

* https://forums.xilinx.com/t5/Xcell-Daily-Blog/Everspin-s-new-MRAM-based-nvNITRO-NVMe-card-delivers-Optane/ba-p/785194

MRAM Manufacturers

Magnetic sensor supply chain and key players*

(Source: Magnetic Sensor Market and Technologies 2017 report, Yole Développement, November 2017)



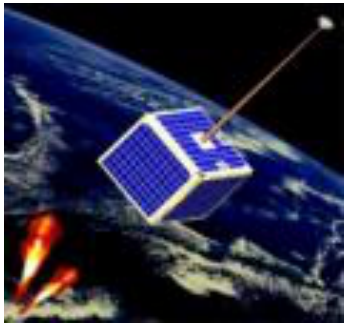
Systems:

- VW, Renault, GM, PSA
- Continental, Bosch, Denso, Magna, Valeo, Delphi, Johnson Controls
- Samsung, Apple, Huawei, Oppo, HP, Asus, Lenovo
- Itron, Landis+Gyr, GE, Sagem
- Honeywell, Schneider Electric, Siemens, Bosch, Tyco
- Schneider, Siemens, ABB, WEG
- Whirlpool, Siemens, Samsung

*Non-exhaustive list of the magnetic sensor supply chain and its key players

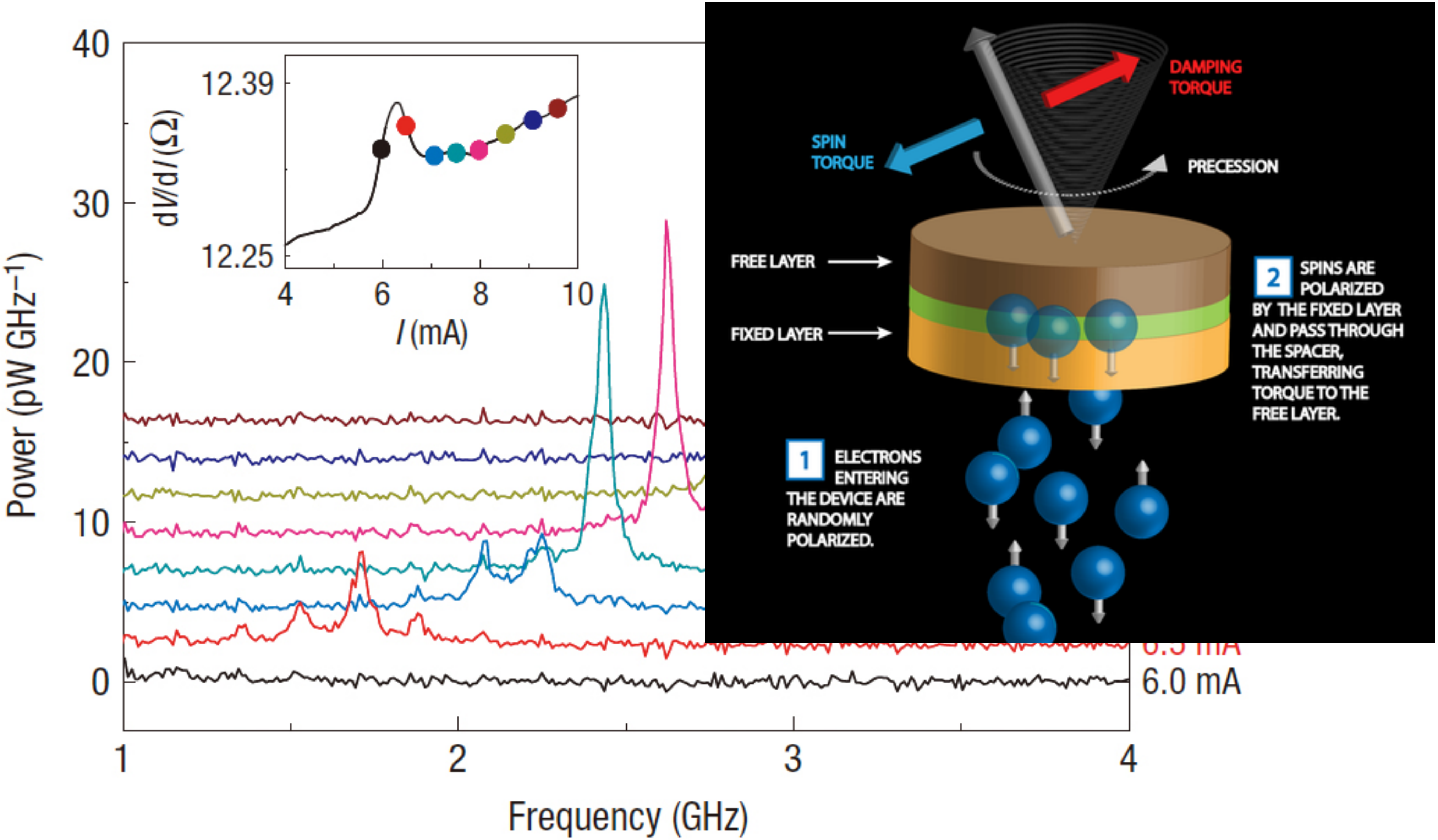
* https://www.i-micronews.com/

MRAM Applications



Spin Torque Oscillator

Magnetisation oscillates by spin-transfer torque : *



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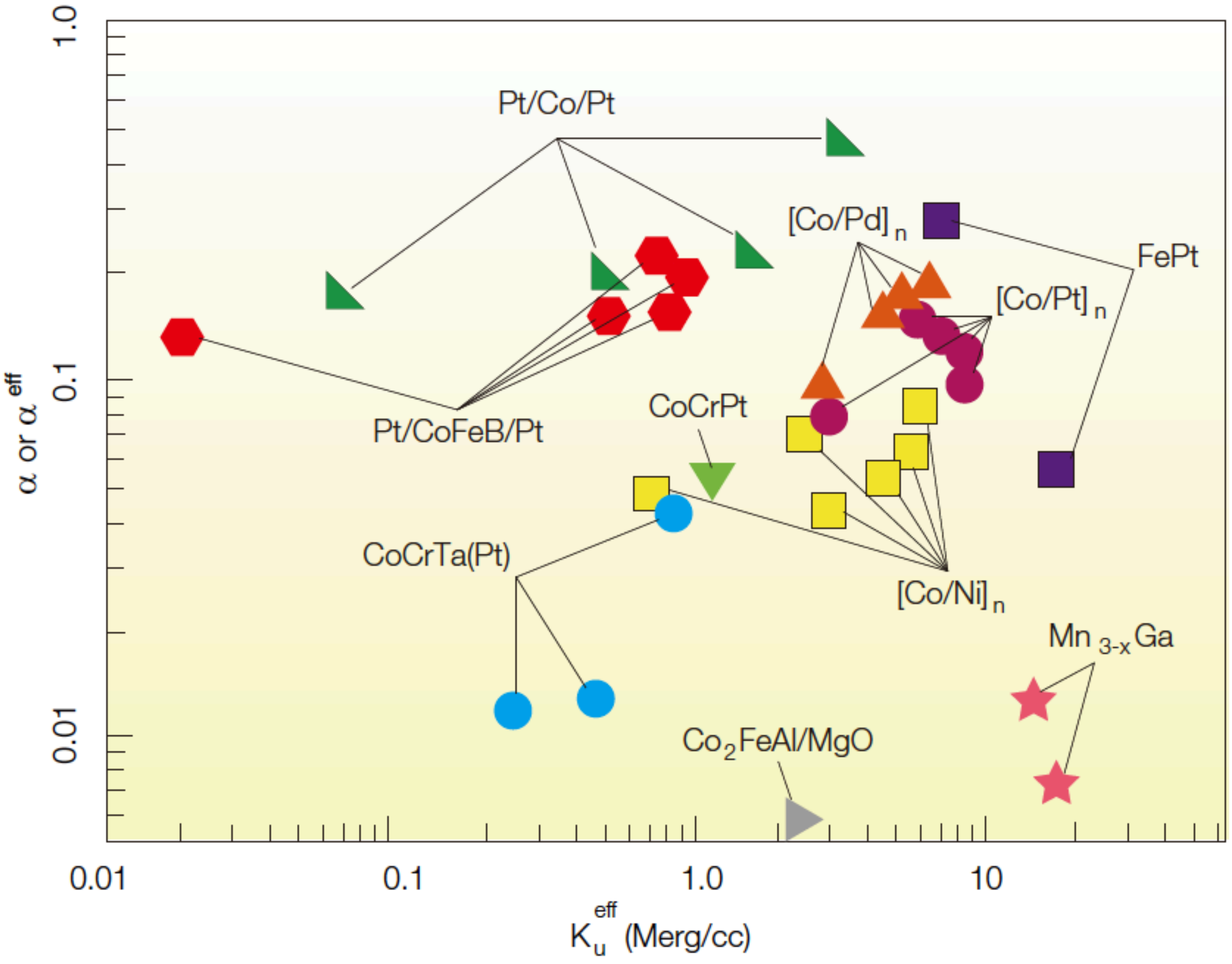
* O. Boulle *et al.*, *Nature Phys.* **3**, 492 (2007);

** https://www.nist.gov/news-events/news/2013/04/unprecedented-view-spintronic-switching.

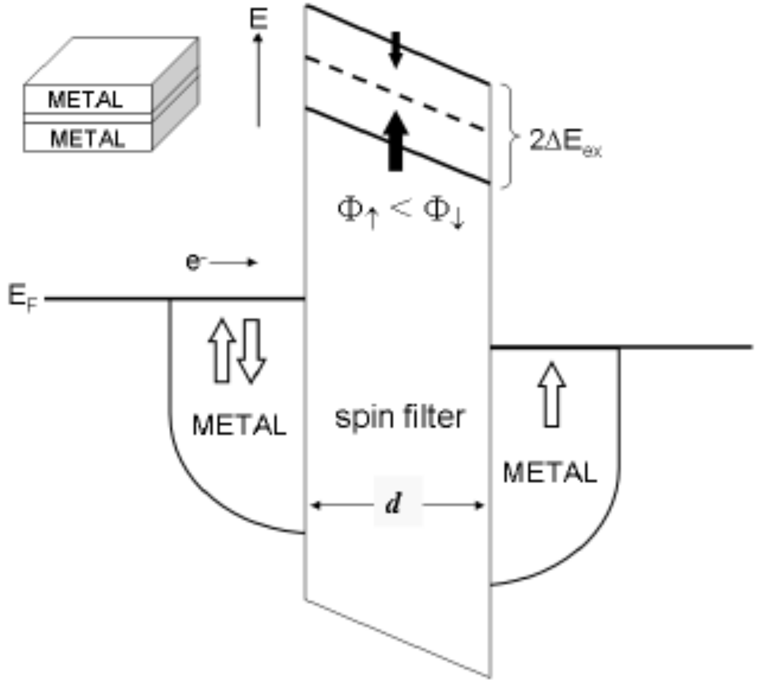
Damping Constants

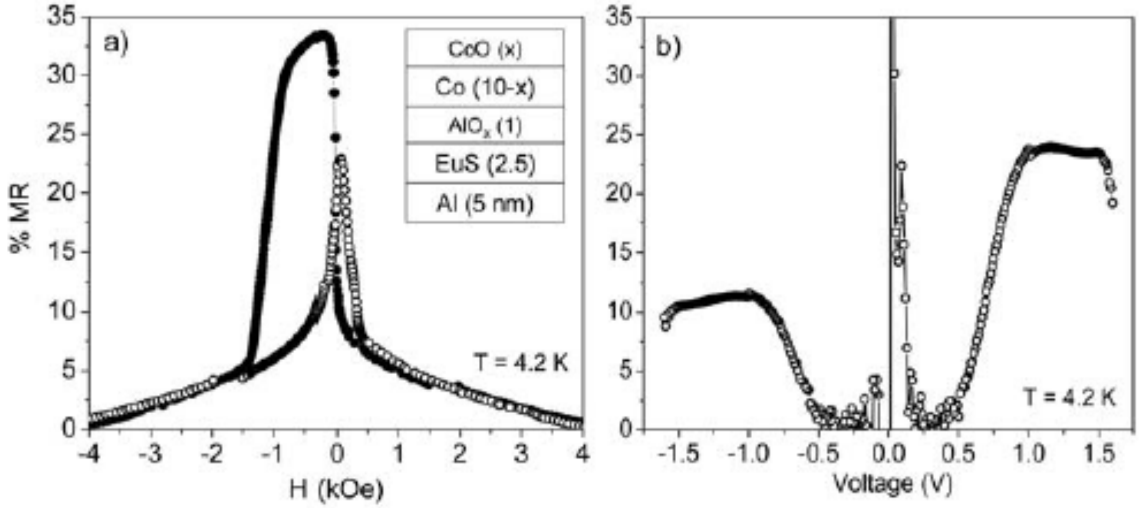


* Z. Bai *et al.*, *Spin* **2**, 1230006 (2012).

Spin Filtering

Band splitting in a tunnel barrier can filter only one spin orientation :





Material	Magnetic Behavior	Tc (K)	Moment (μ_B)	Structure, a(nm)	E_g (eV)	$2\Delta E_{ex}$ (eV)	P (%)	Spin Filter Reference
EuO	FM	69.3	7.0	Fcc, 0.514	1.12	0.54	29	Santos[23]
EuS	FM	16.6	7.0	Fcc, 0.596	1.65	0.36	86	Moodera[21]
EuSe	AFM	4.6	7.0	Fcc, 0.619	1.80		100	Moodera[22]
$BiMnO_3$	FM	105	3.6	perovskite			22	Gajek[26]
$NiFe_2O_4$	ferri-M	850	2	spinel	1.2		22	Lüders[27]
$CoFe_2O_4$	ferri-M	796	3	spinel	0.80		25	Ramos[28]

* J. S. Moodera *et al.*, *Epitaxial Ferromagnetic Films and Spintronic Applications*, A. Hirohata and Y. Otani (Eds.) (Research Signpost, Kerala, 2009) p. 111-143.

Rebranding ...

REVIEW

Spintronics: A Spin-Based Electronics Vision for the Future

S. A. Wolf,[1,2]* D. D. Awschalom,[3] R. A. Buhrman,[4] J. M. Daughton,[5] S. von Molnár,[6]
M. L. Roukes,[7] A. Y. Chtchelkanova,[8] D. M. Treger[8]

This review describes a new paradigm of electronics based on the spin degree of freedom of the electron. Either adding the spin degree of freedom to conventional charge-based electronic devices or using the spin alone has the potential advantages of nonvolatility, increased data processing speed, decreased electric power consumption, and increased integration densities compared with conventional semiconductor devices. To successfully incorporate spins into existing semiconductor technology, one has to resolve technical issues such as efficient injection, transport, control and manipulation, and detection of spin polarization as well as spin-polarized currents. Recent advances in new materials engineering hold the promise of realizing spintronic devices in the near future. We review the current state of the spin-based devices, efforts in new materials fabrication, issues in spin transport, and optical spin manipulation.

Until recently, the spin of the electron was ignored in mainstream charge-based electronics. A technology has emerged called spintronics (spin transport electronics or spin-based electronics), where it is not the electron charge but the electron spin that carries information, and this offers opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects that arise from the interaction between spin of the carrier and the magnetic properties of the material.

Traditional approaches to using spin are based on the alignment of a spin (either "up" or "down") relative to a reference (an applied magnetic field or magnetization orientation of the ferromagnetic film). Device operations then proceed with some quantity (electrical current) that depends in a predictable way on the degree of alignment. Adding the spin degree of freedom to conventional semiconductor charge-based electronics or using the spin degree of freedom alone will add substantially more capability and performance to electronic products. The advantages of these new devices would be nonvolatility, increased data processing speed, decreased electric power consumption, and increased integration densities compared with conventional semiconductor devices.

Major challenges in this field of spintronics that are addressed by experiment and theory include the optimization of electron spin lifetimes, the detection of spin coherence in nanoscale structures, transport of spin-polarized carriers across relevant length scales and heterointerfaces, and the manipulation of both electron and nuclear spins on sufficiently fast time scales. In response, recent experiments suggest that the storage time of quantum information encoded in electron spins may be extended through their strong interplay with nuclear spins in the solid state. Moreover, optical methods for spin injection, detection, and manipulation have been developed that exploit the ability to precisely engineer the coupling between electron spin and optical photons. It is envisioned that the merging of electronics, photonics, and magnetics will ultimately lead to new spin-based multifunctional devices such as spin-FET (field effect transistor), spin-LED (light-emitting diode), spin RTD (resonant tunneling device), optical switches operating at terahertz frequency, modulators, encoders, decoders, and quantum bits for quantum computation and communication. The success of these ventures depends on a deeper understanding of fundamental spin interactions in solid state materials as well as the roles of dimensionality, defects, and semiconductor band structure in modifying these dynamics. If we can understand and control the spin

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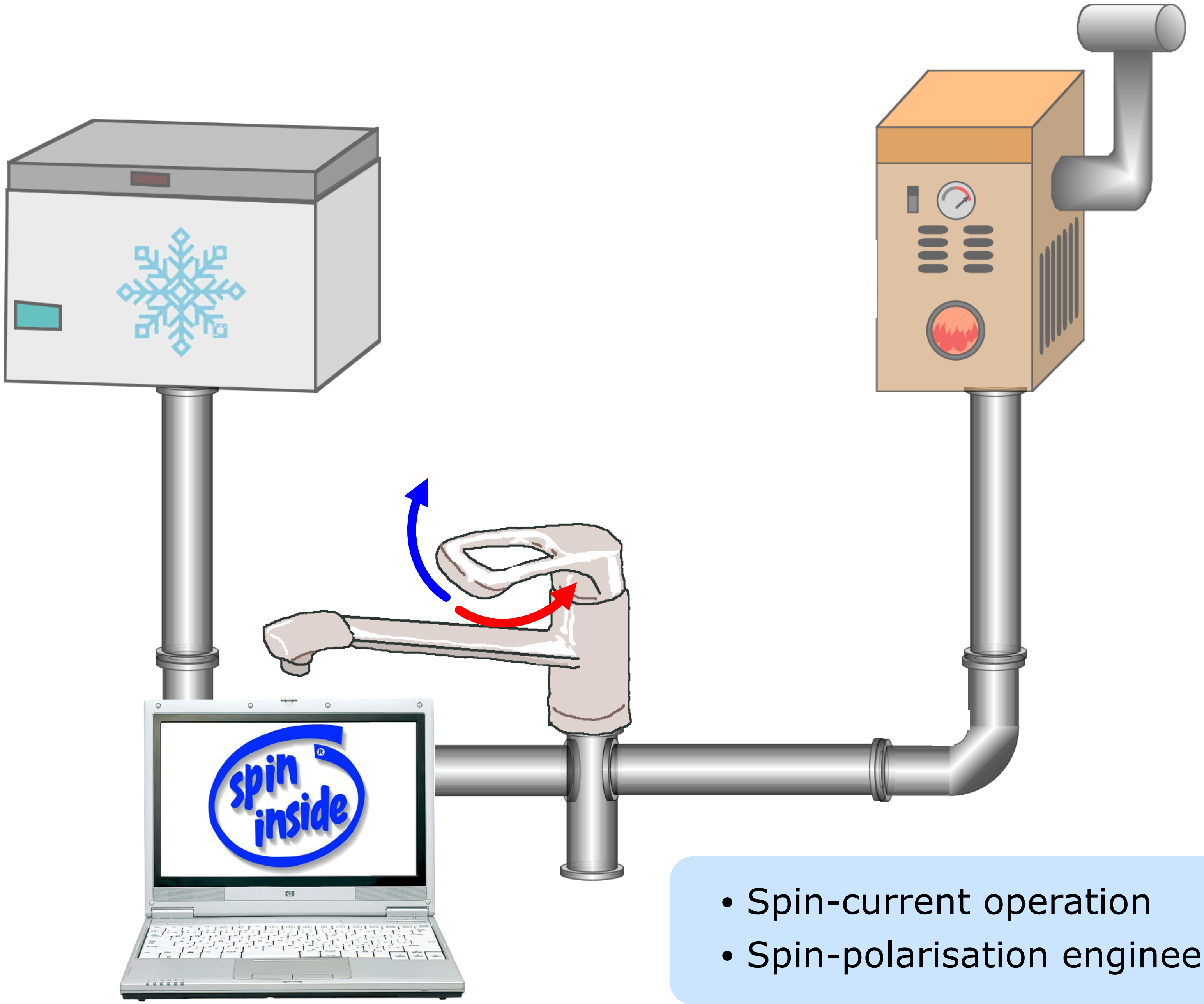
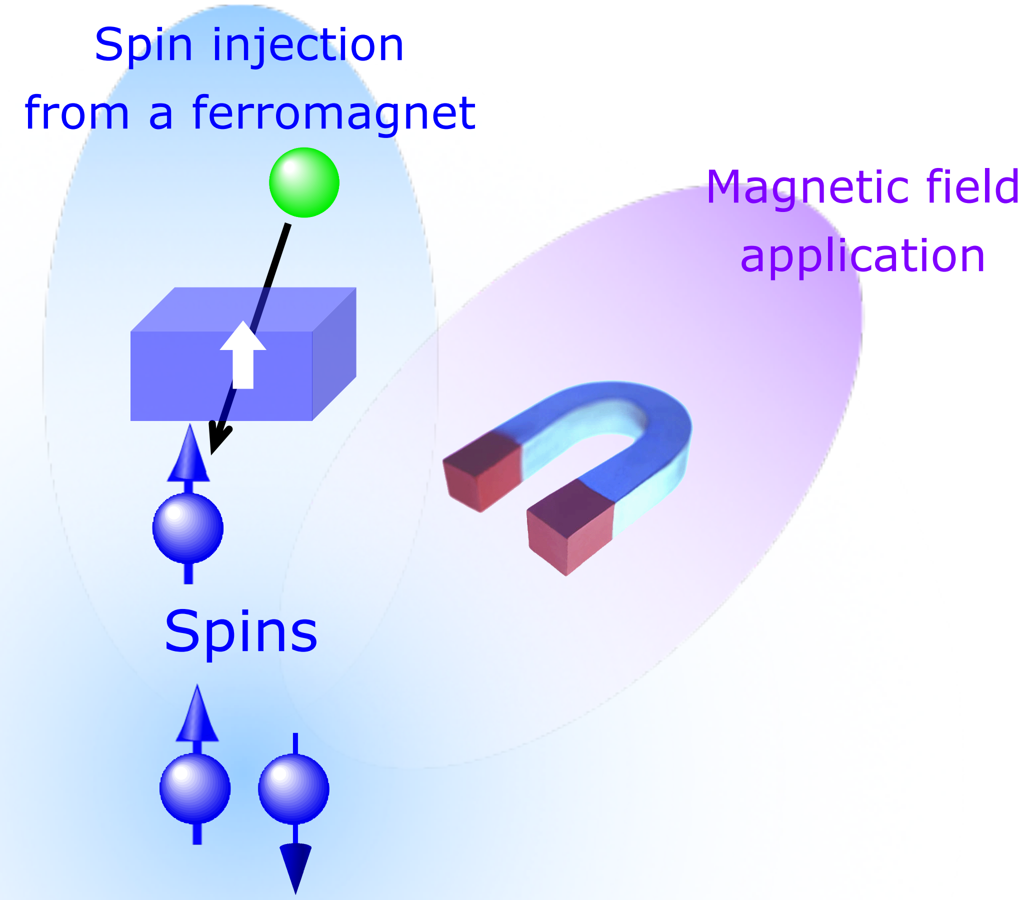
[1] Defense Advanced Research Projects Agency (DARPA), 3701 North Fairfax Drive, Arlington, VA 22203, USA. [2] Naval Research Laboratory, Washington, DC 20375, USA. [3] University of California, Department of Physics, Santa Barbara, CA 93106, USA. [4] Cornell University, Applied and Engineering Physics, 211 Clark Hall, Ithaca, NY 14853, USA. [5] NVE, 11409 Valley View Road, Eden Prairie, MN 55344, USA. [6] Florida State University, MARTECH, 406 Keen Building, Tallahassee, FL 32306, USA. [7] California Institute of Technology, Department of Physics, MS-114-36, Pasadena, CA 91125, USA. [8] Strategic Analysis, 3601 Wilson Boulevard, Suite 500, Arlington, VA 22201, USA.

*To whom correspondence should be addressed. E-mail: swolf@darpa.mil

Next-Generation Spintronic Applications

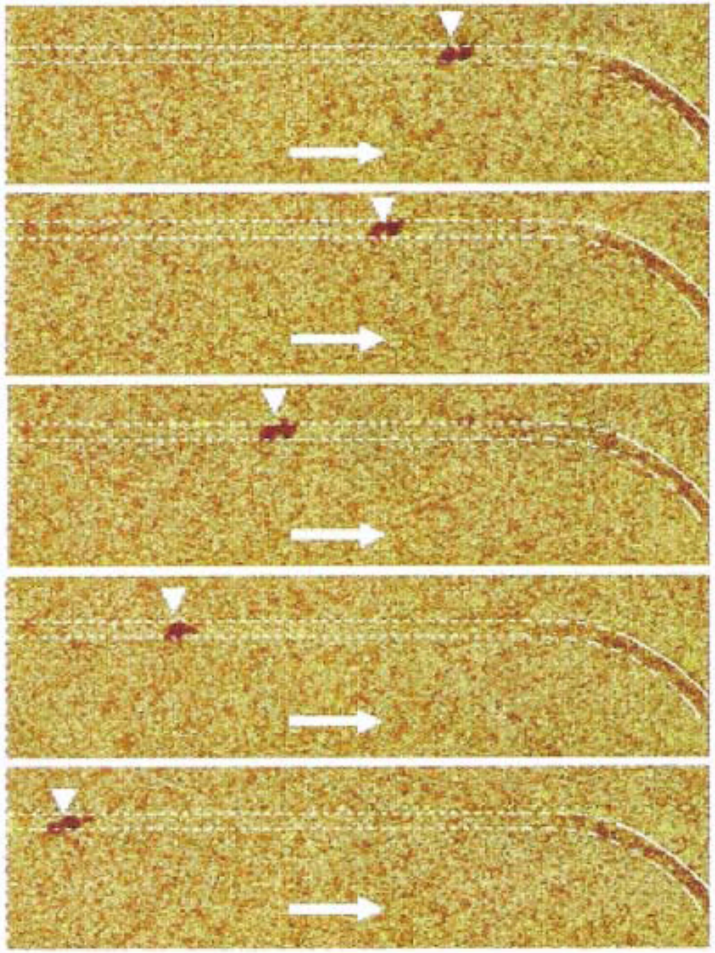


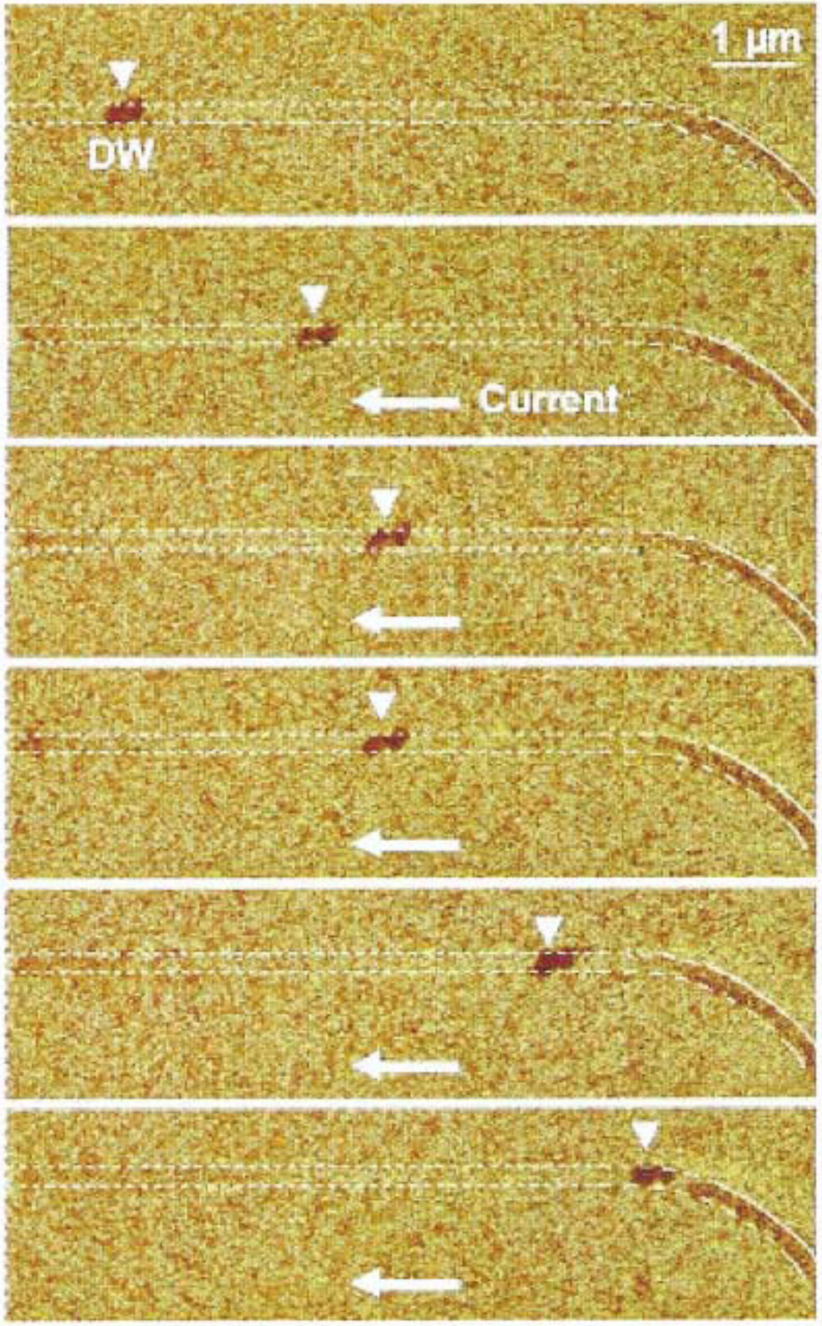
- Spin-current operation
- Spin-polarisation engineering


Spin injection
from a ferromagnet
Magnetic field
application
Spins

Domain Wall Displacement

- For fast operation spin transfer torque (STT) will be used to move the walls.
- This requires a narrow track, possibly down to 100 nm, so that the STT dominates the Lorentz field.





* A. Yamaguchi *et al.*, *Science* **97**, 077205 (2004).

Racetrack memory

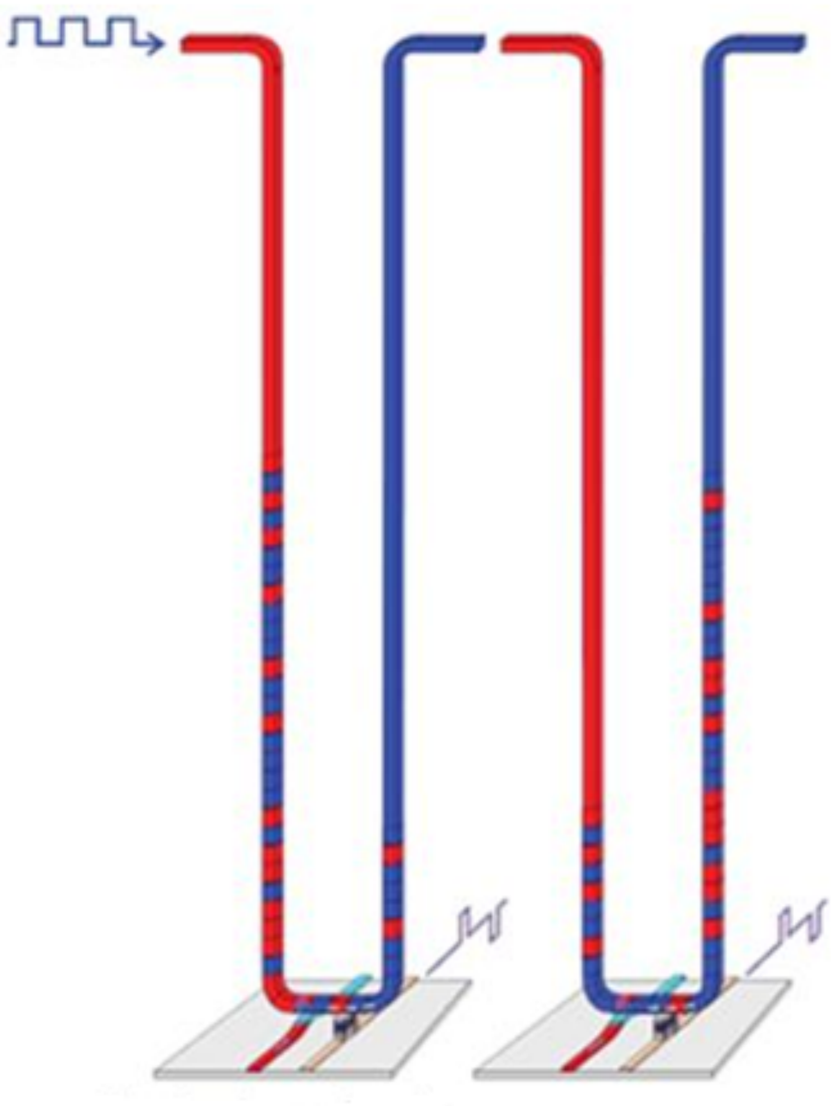
- Racetrack memory has been originally proposed by Parkin of IBM.*

- The principle is to use domain walls (DWs) as a shift register or storage system.

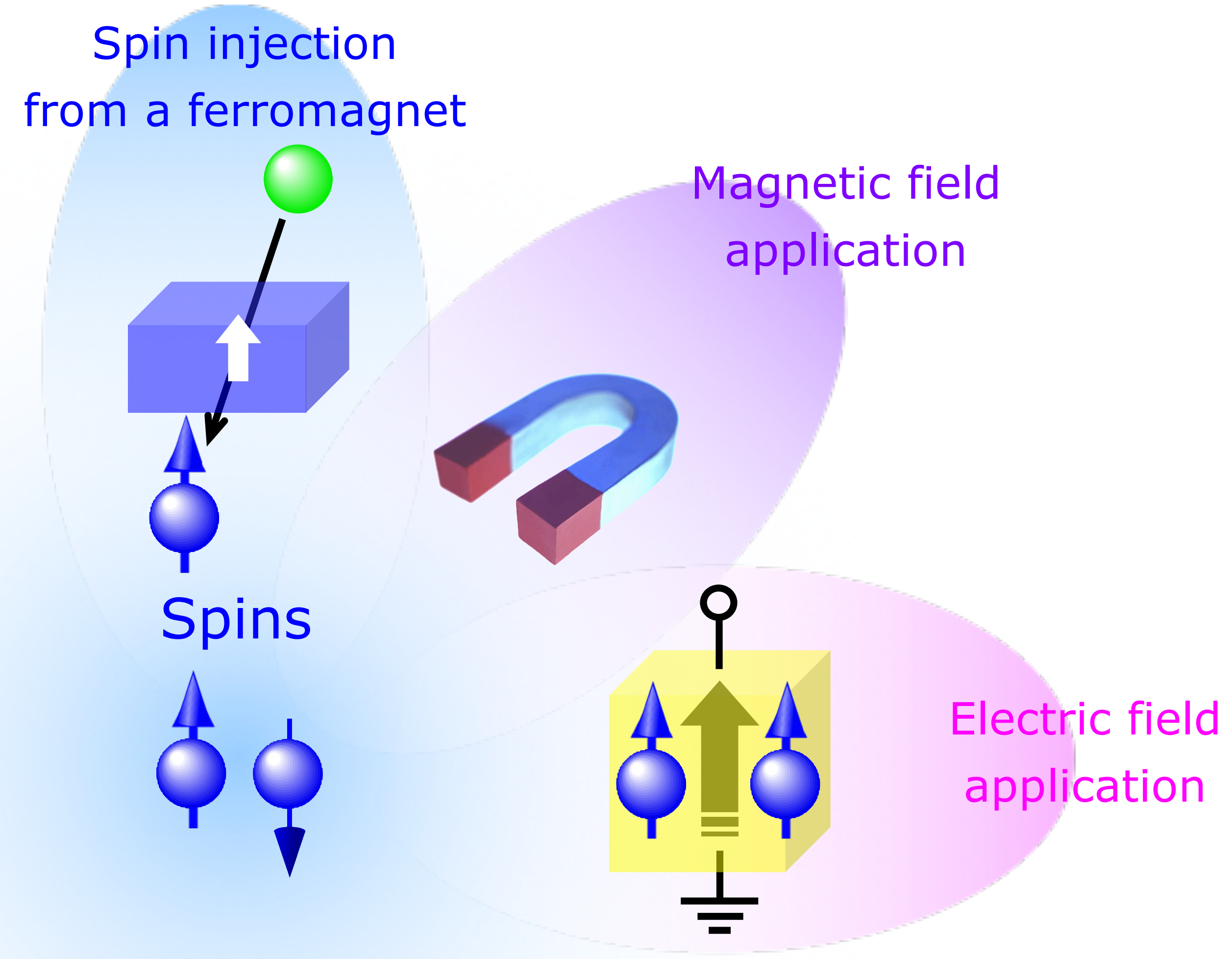
- This can lead to a new storage architecture.

- Racetrack systems may be cheaper to fabricate than MRAM for low cost storage.

- The vertical orientation is impractical due to the demagnetising effects.

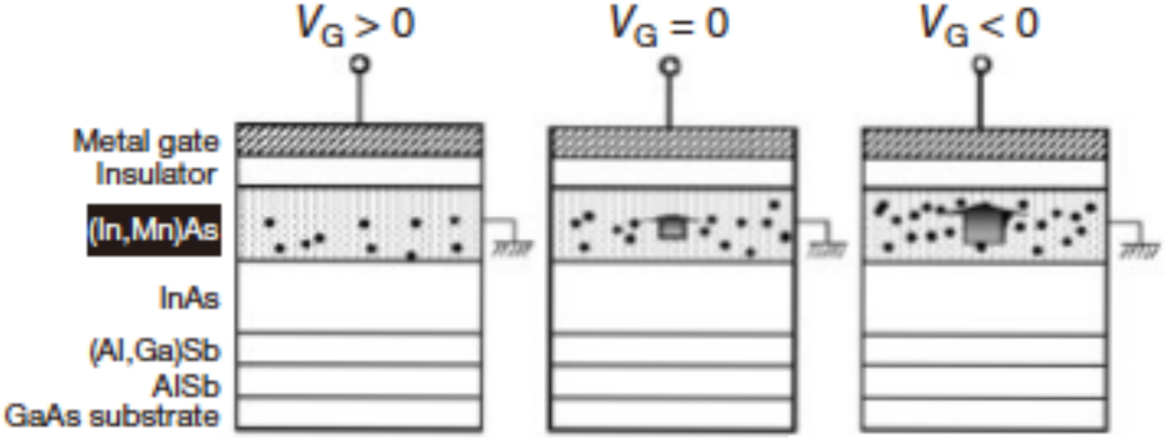


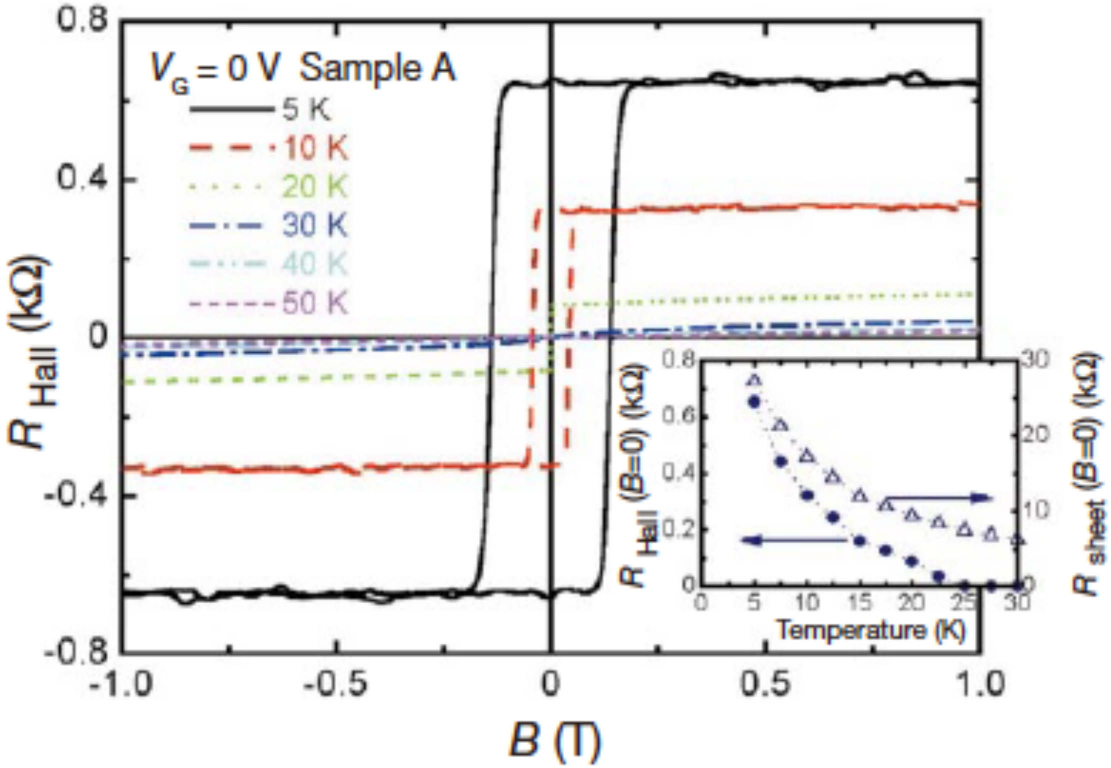
* S. S. P. Parkin *et al.*, *Science* **320**, 190 (2008).


Spin injection
from a ferromagnet
Magnetic field
application
Spins
Electric field
application

Electric Field Control of Magnetism - *Semiconductors*

Dilute magnetic semiconductor (GaMnAs) : *

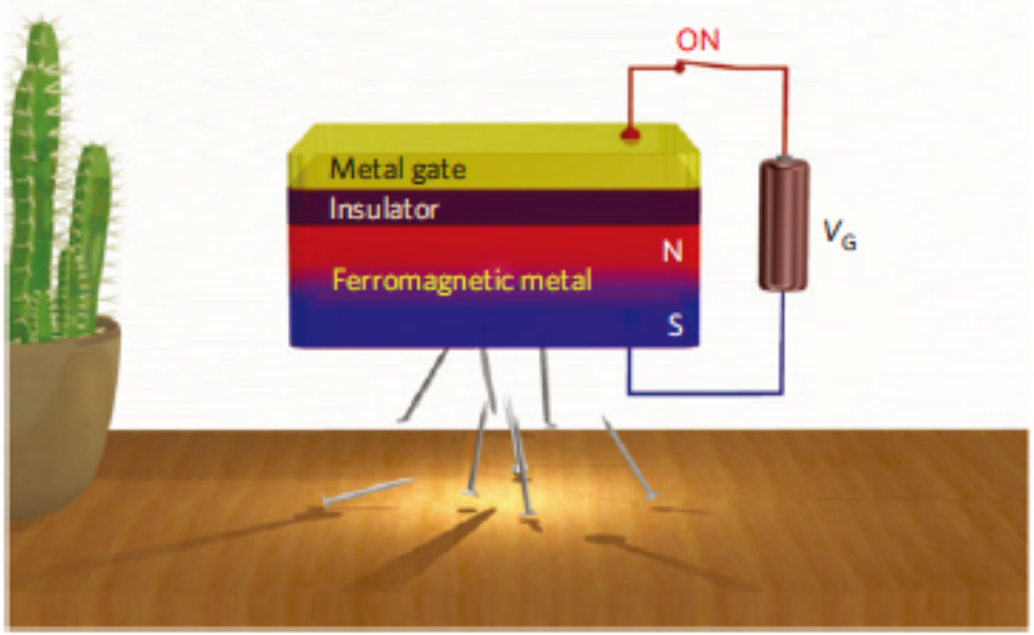


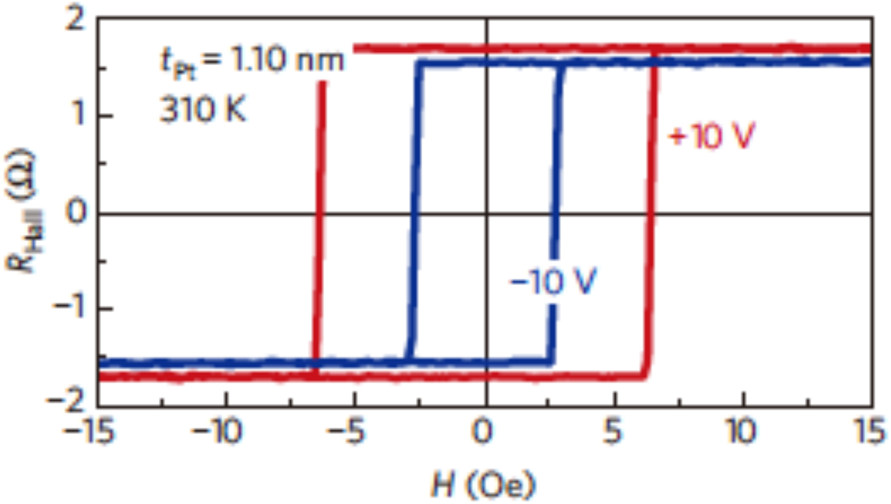


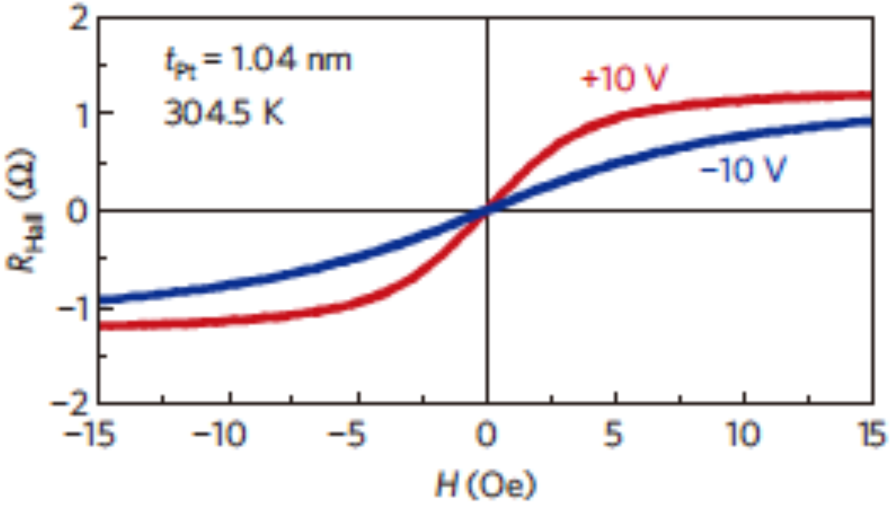
* H. Ohno *et al.*, *Nature* **408**, 944 (2000).

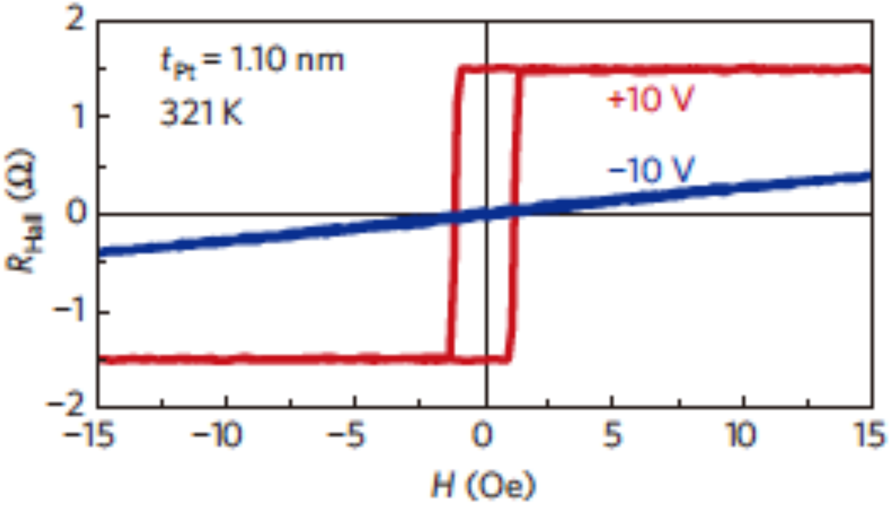
Electric Field Control of Magnetism - *Metals*

Ferromagnetic metal (Co) : *

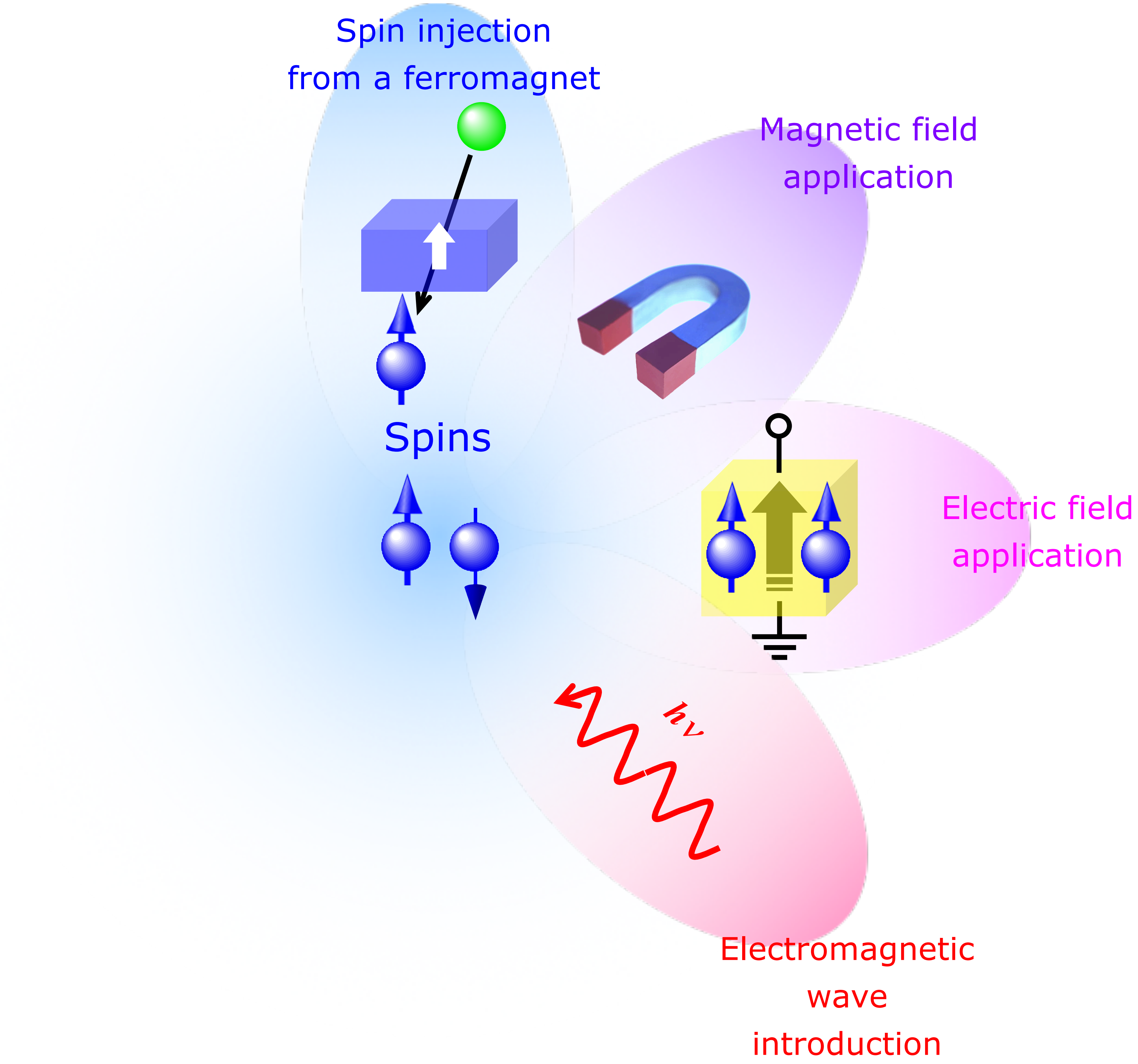






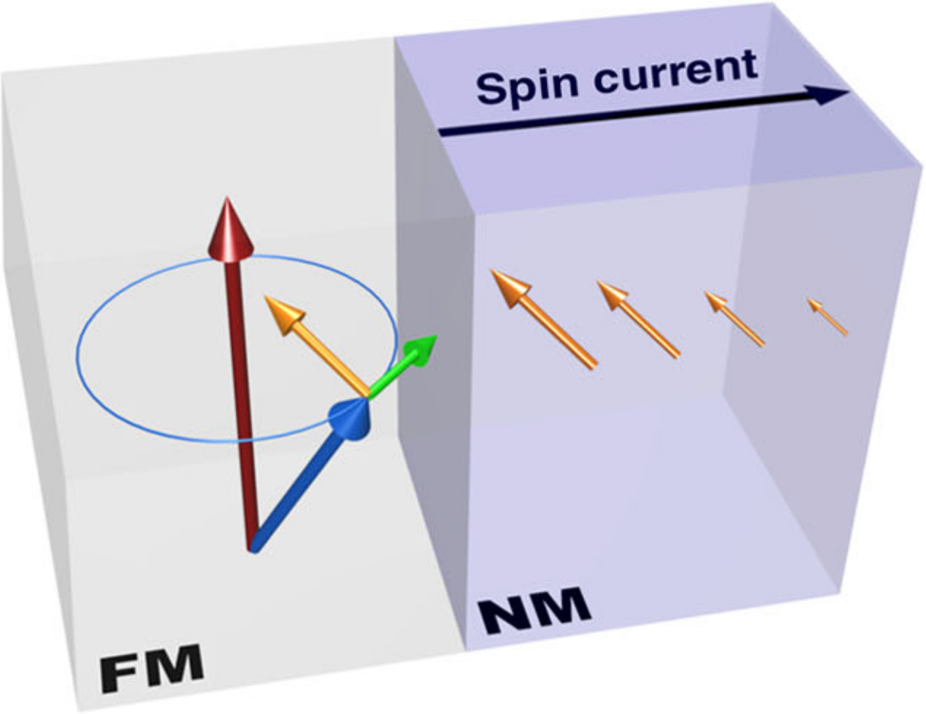


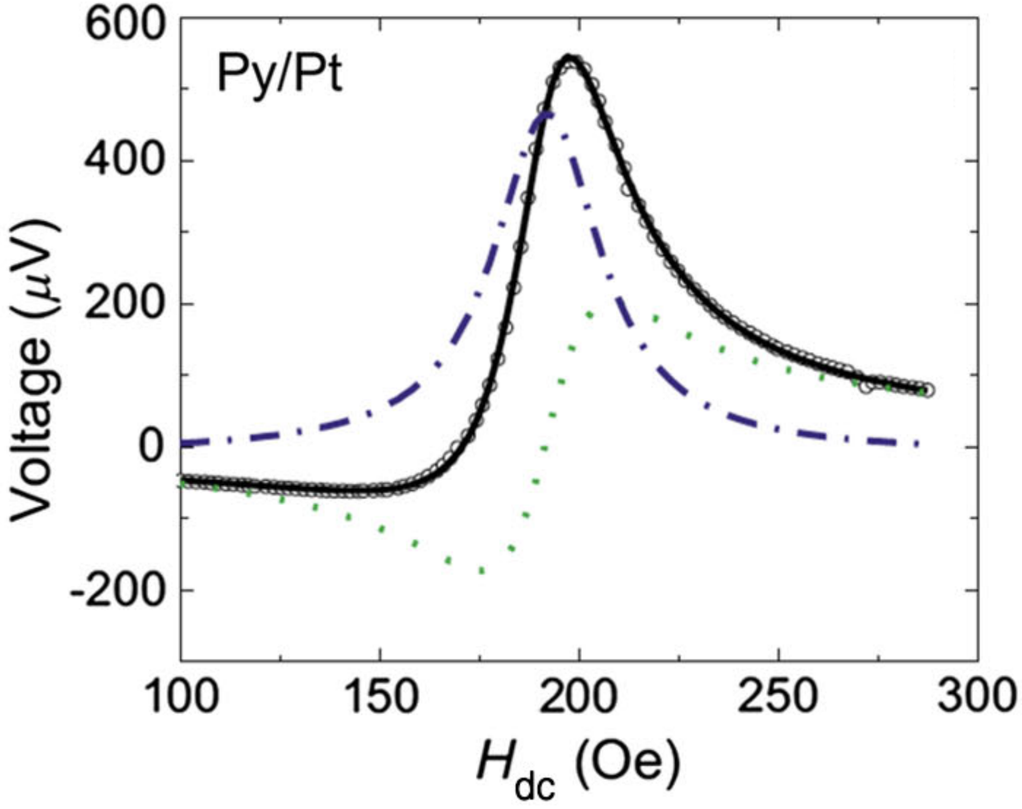
* D. Chiba *et al.*, *Nature Mater.* **10**, 853 (2011).


Spin injection
from a ferromagnet
Magnetic field
application
Spins
Electric field
application
hν
Electromagnetic
wave
introduction

Microwave-Induced Spin Currents

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





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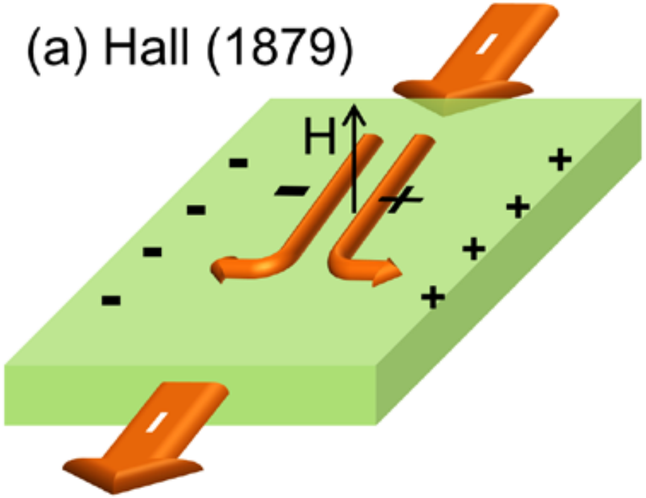
* O. Mosendz *et al.*, *Phys. Rev. B* **82**, 214403 (2010);
A. Hoffmann and S. Bader, *Phys. Rev. Appl.* **4**, 047001 (2015).

Spin Hall Effect

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



Edwin Herbert Hall
(1855-1938)

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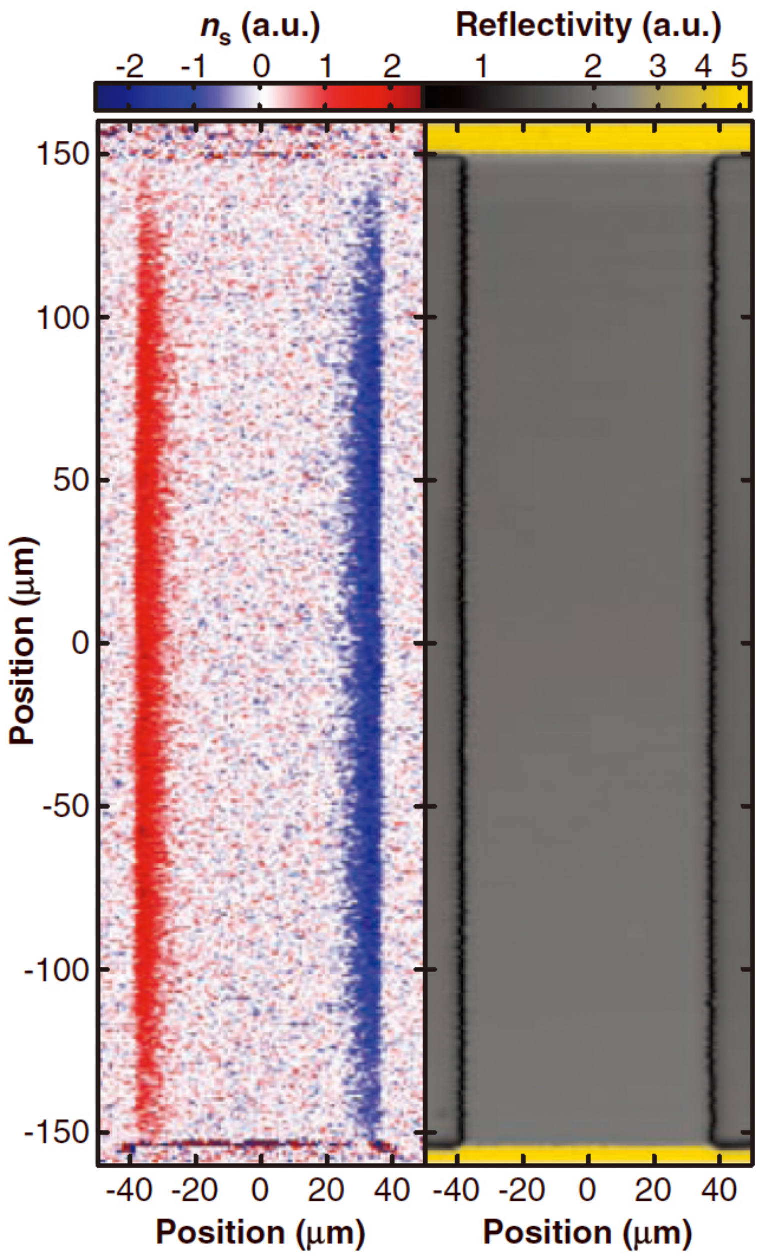
* C.-Z. Chang and M. Li, *J. Phys.: Condens. Matter* **28**, 123002 (2016).

Spin Hall Effect in GaAs

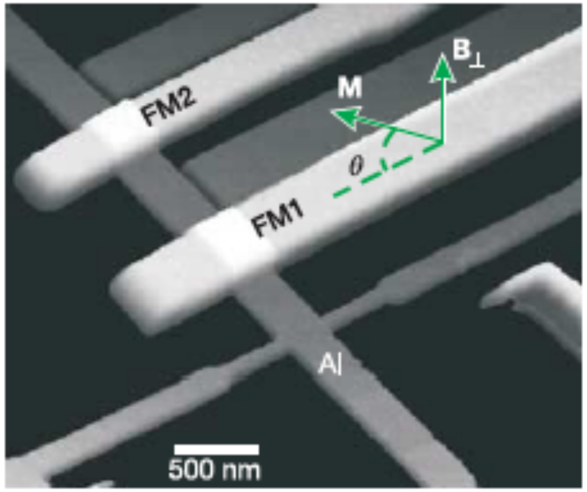
MOKE detection of spins generated by the spin Hall effect : *

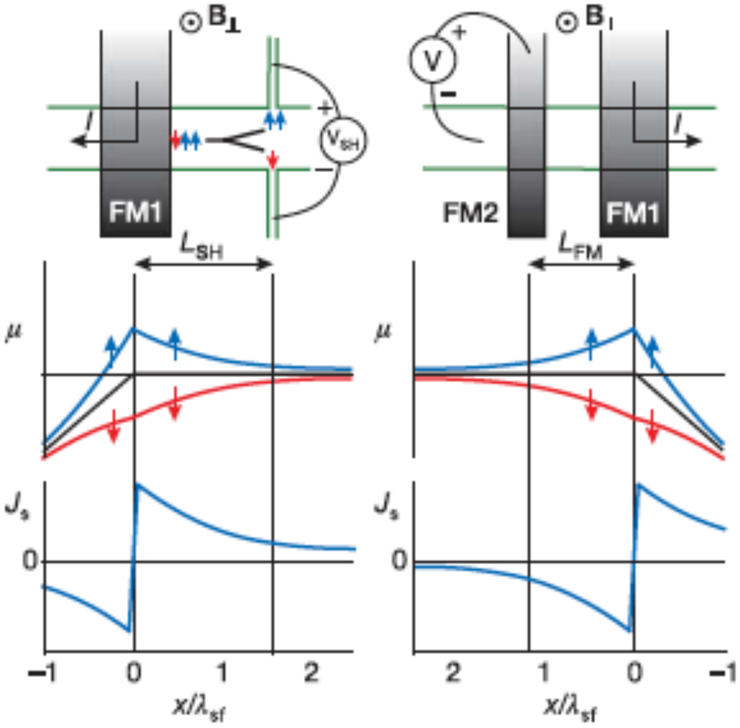


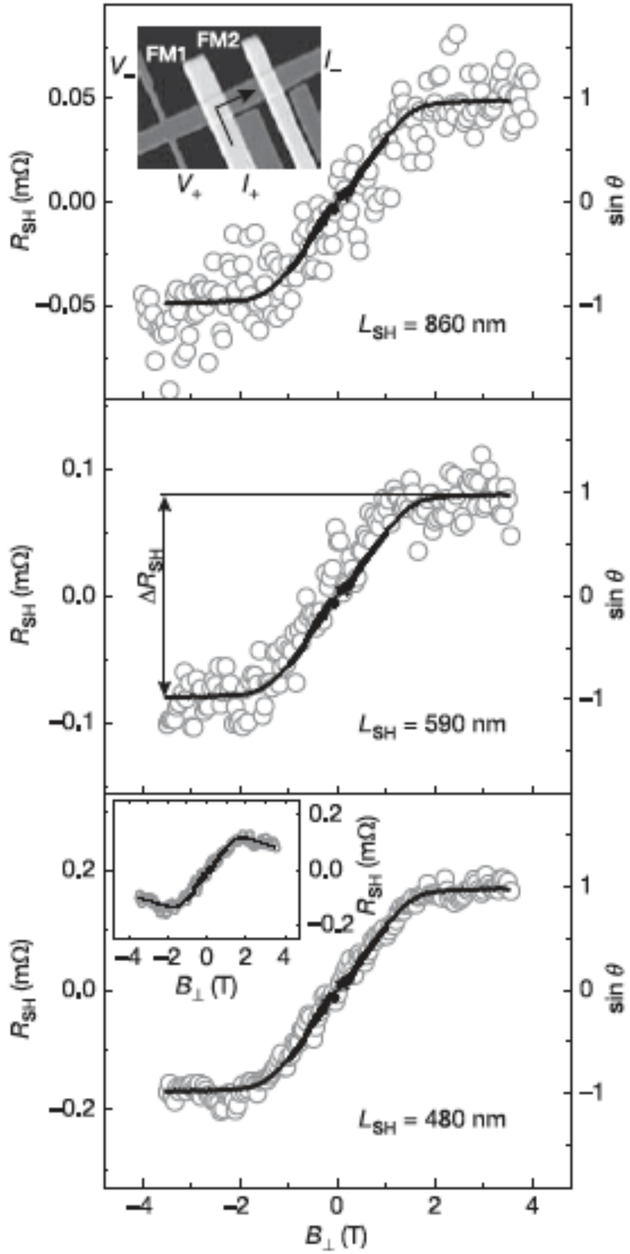
* Y. K. Kato *et* al., *Science* **306**, 1910 (2004).

Lateral Spin-Valve with the Spin Hall Effect

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



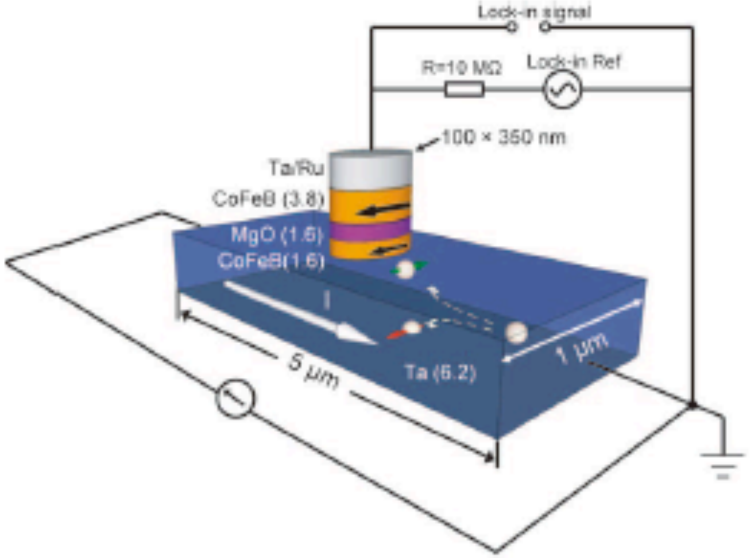


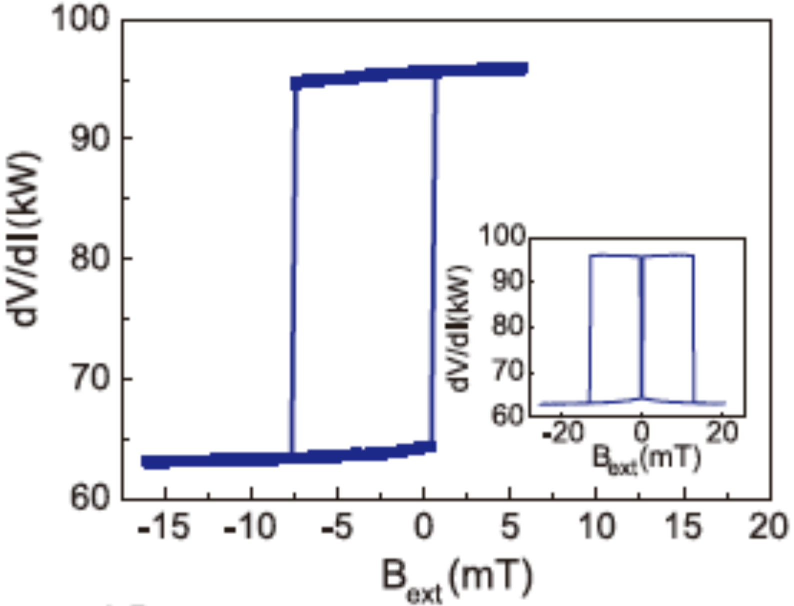


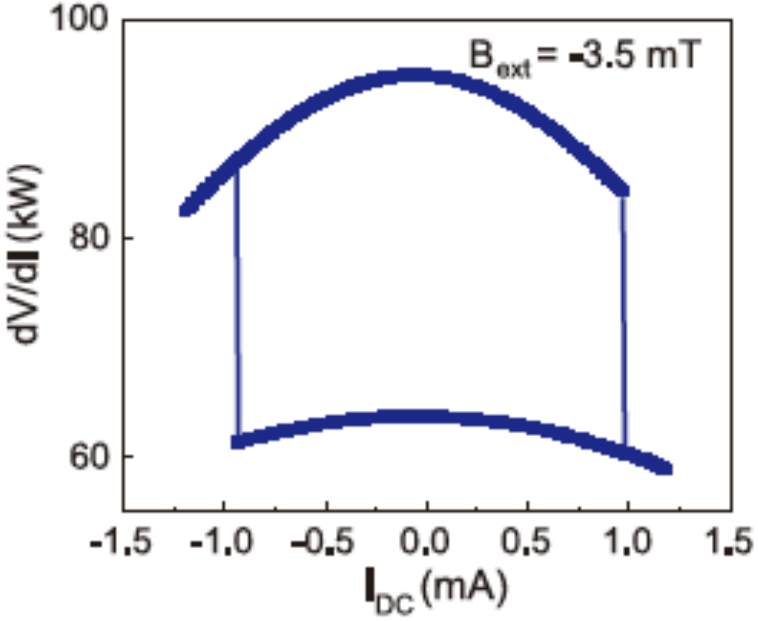
* S. O. Valenzuela and M. Tinkham, *Nature* **442**, 176 (2006).

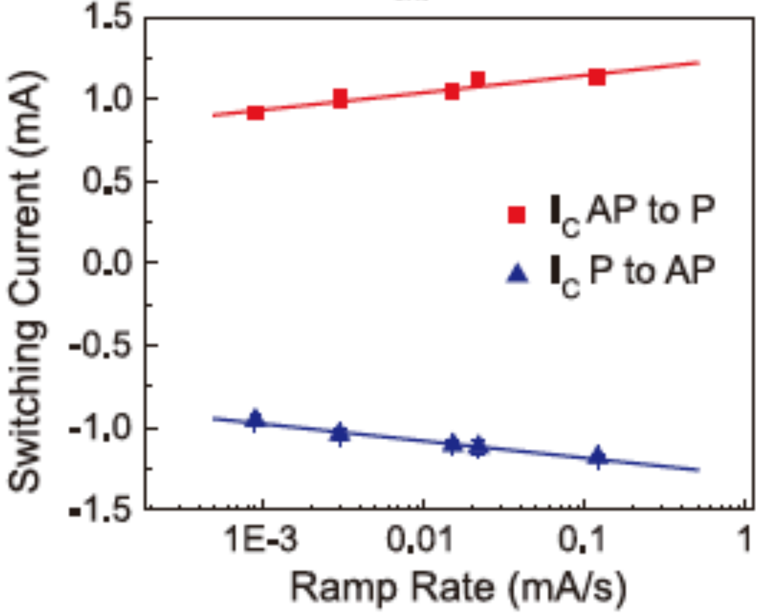
Magnetisation Reversal by the Spin Hall Effect

CoFeB / MgO / CoFeB nanopillar on Ta : *

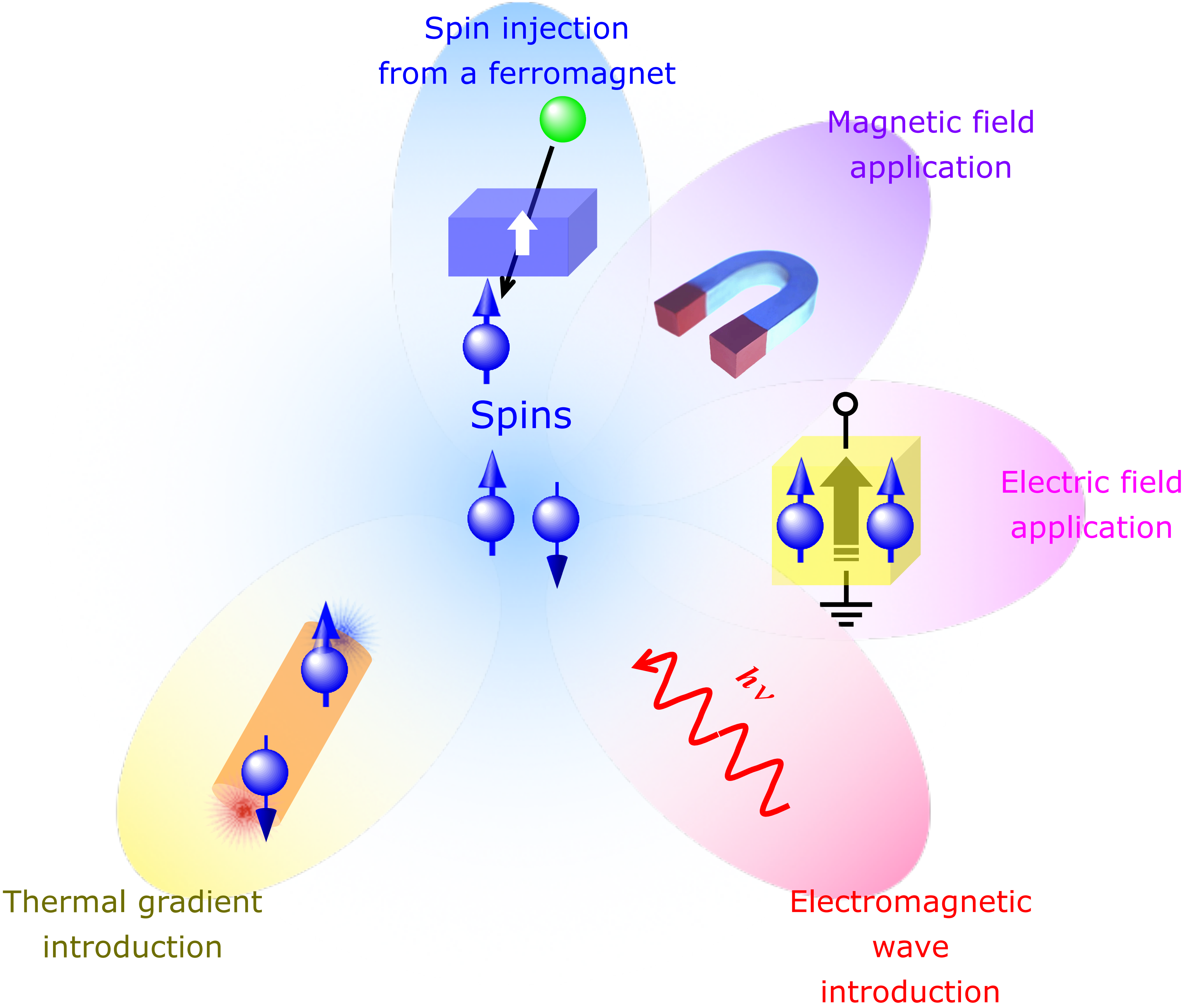




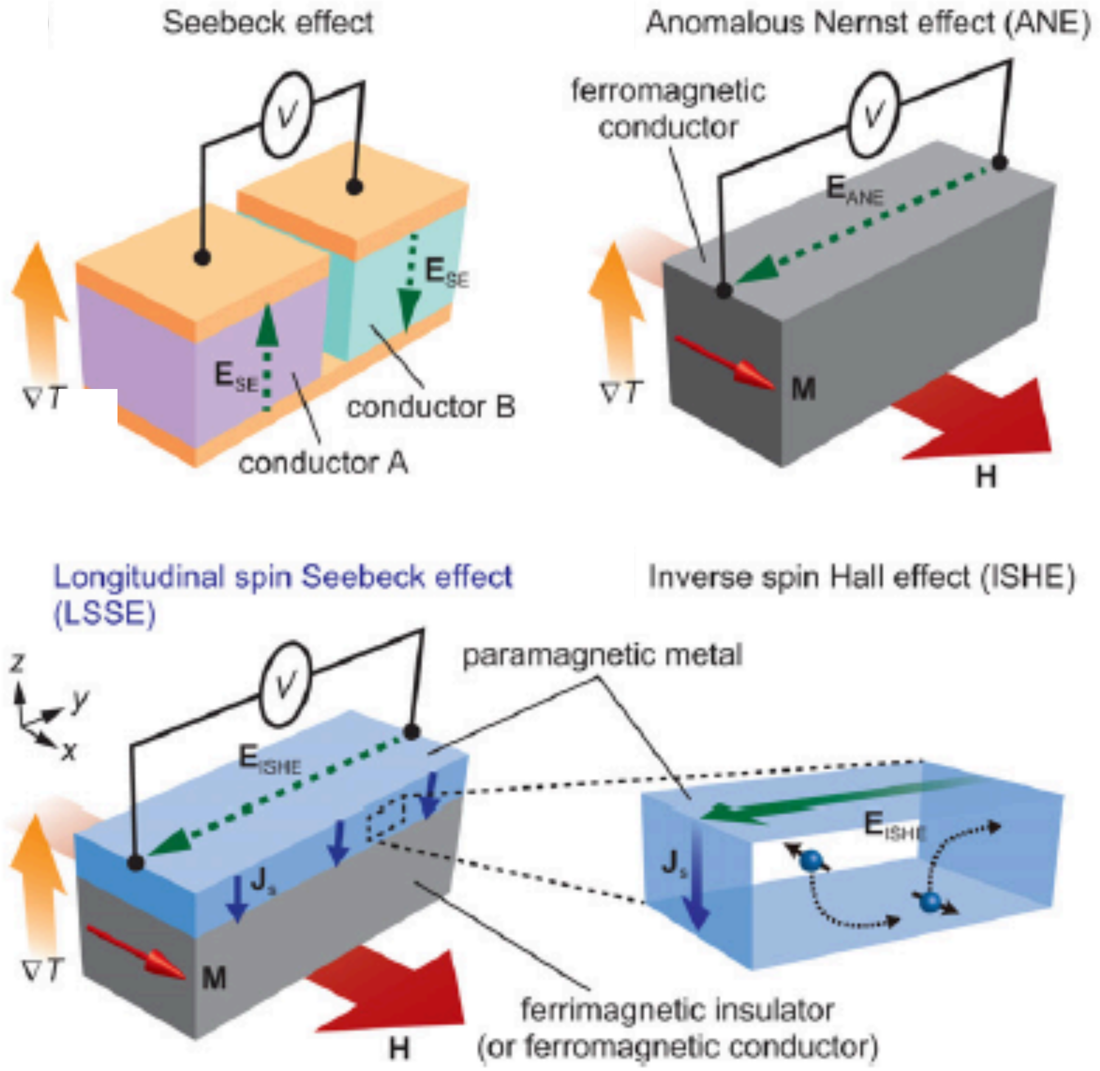


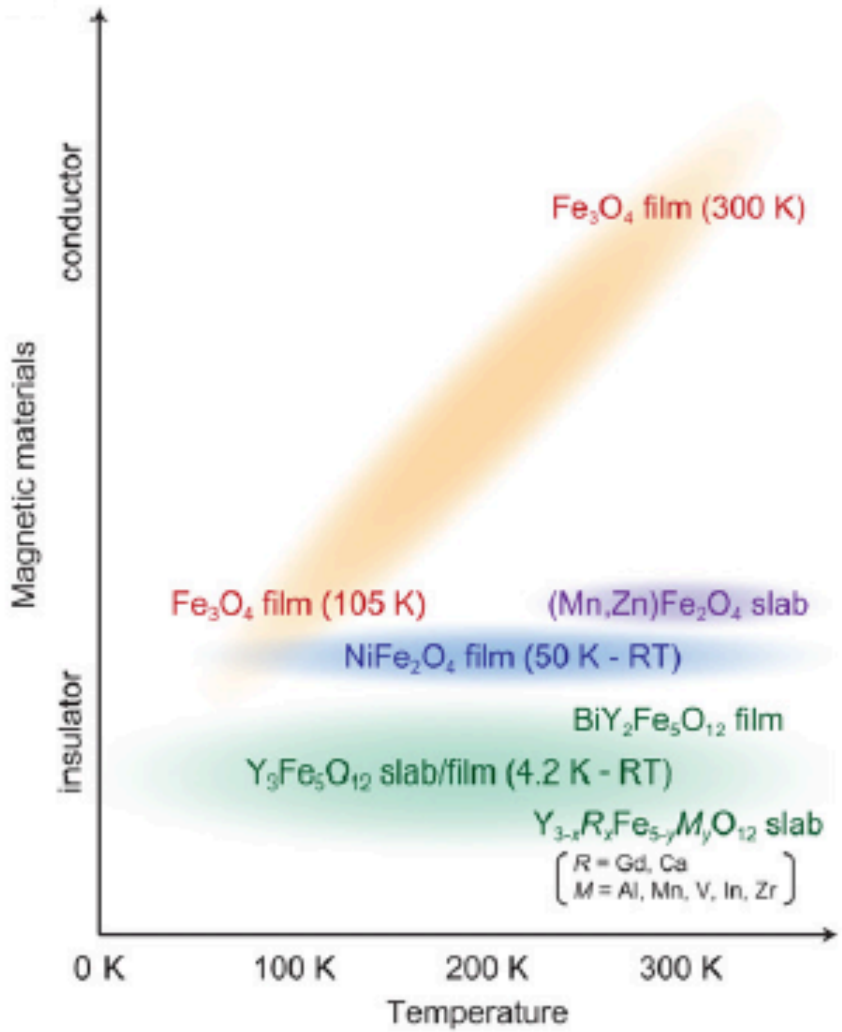


* L. Liu *et al.*, *Science* **336**, 555 (2012).


Spin injection
from a ferromagnet
Magnetic field
application
Spins
Electric field
application
$h\nu$
Thermal gradient
introduction
Electromagnetic
wave
introduction

Spin Seebeck Effect

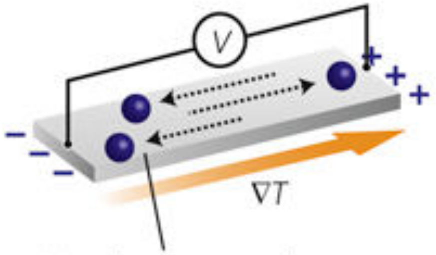
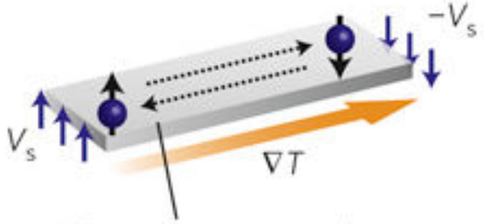
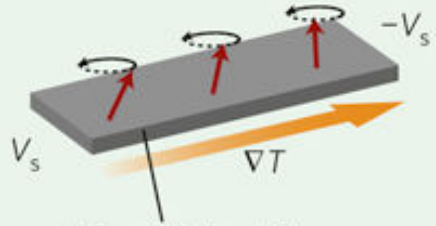


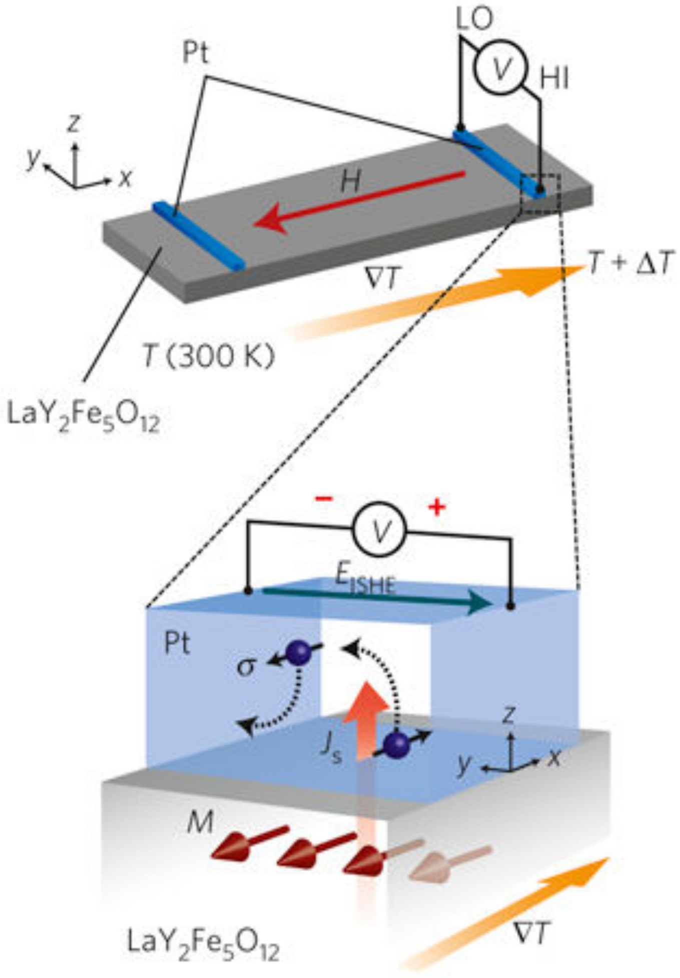


* K. Uchida *et al.*, *Nature* **455**, 778 (2008);

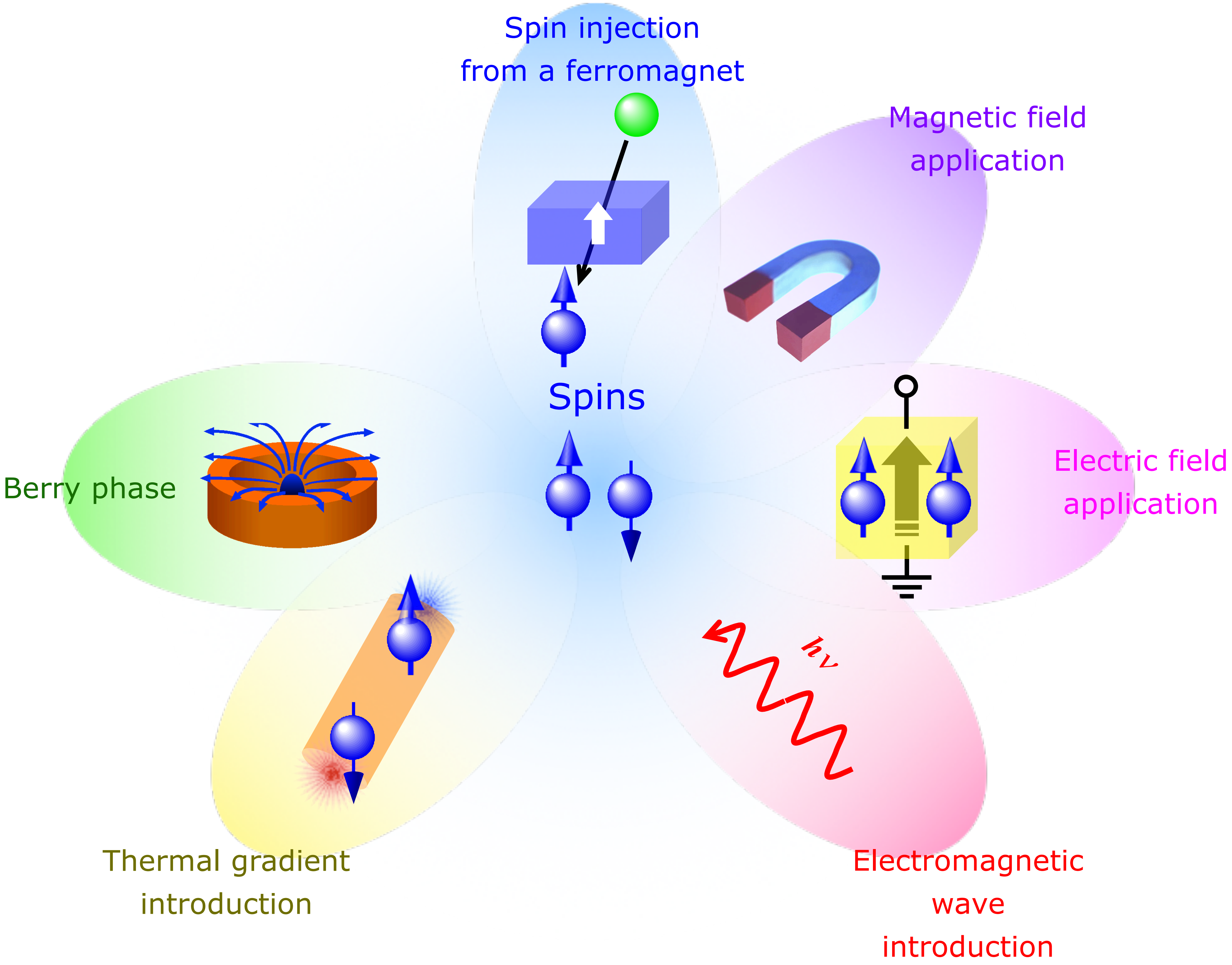
** K Uchida *et al.*, *J. Phys.: Condens. Matter* **26**, 343202 (2014).

Spin Seebeck Effect

Output / Material	Electricity	Magnetism
Conductor	Seebeck effect  Metal or semiconductor	Spin Seebeck effect  Ferromagnetic metal
Insulator	×	Spin Seebeck effect  Magnetic insulator



* K. Uchida *et al.*, *Nature Mater.* **9**, 894 (2010).


Spin injection
from a ferromagnet
Magnetic field
application
Spins
Berry phase
Electric field
application
Thermal gradient
introduction
hν
Electromagnetic
wave
introduction

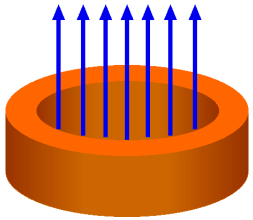
Theoretical Prediction on a Persistent Current

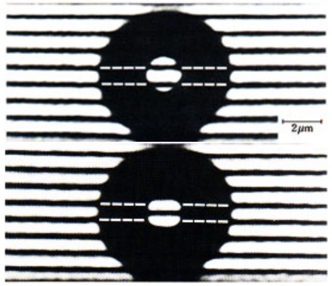
Persistent current :

induced by a magnetic flux threading a mesoscopic ring

→ *Aharonov-Bohm effect* *

- The persistent current oscillates with the flux.

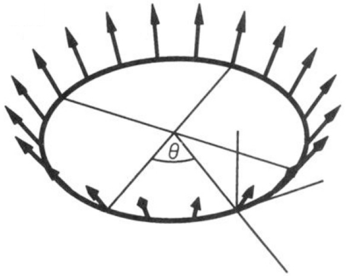


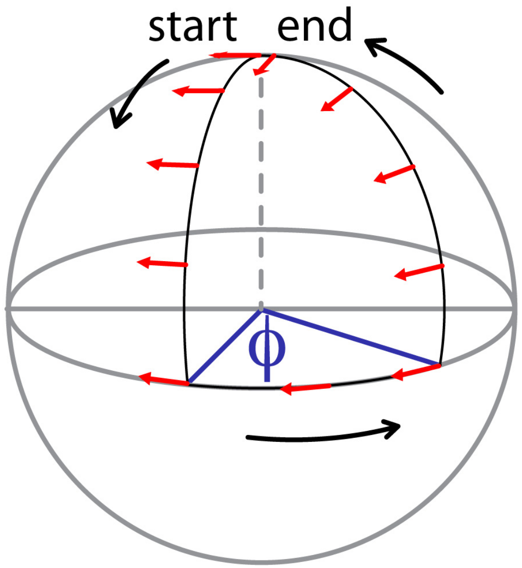


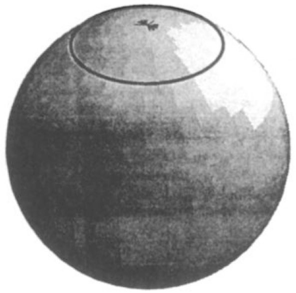
induced by a magnetic field rotating slowly in time **

→ *Berry (geometrical) phase*

- Non-uniform external magnetic fields are required.
- Spin-polarised persistent current can be generated.







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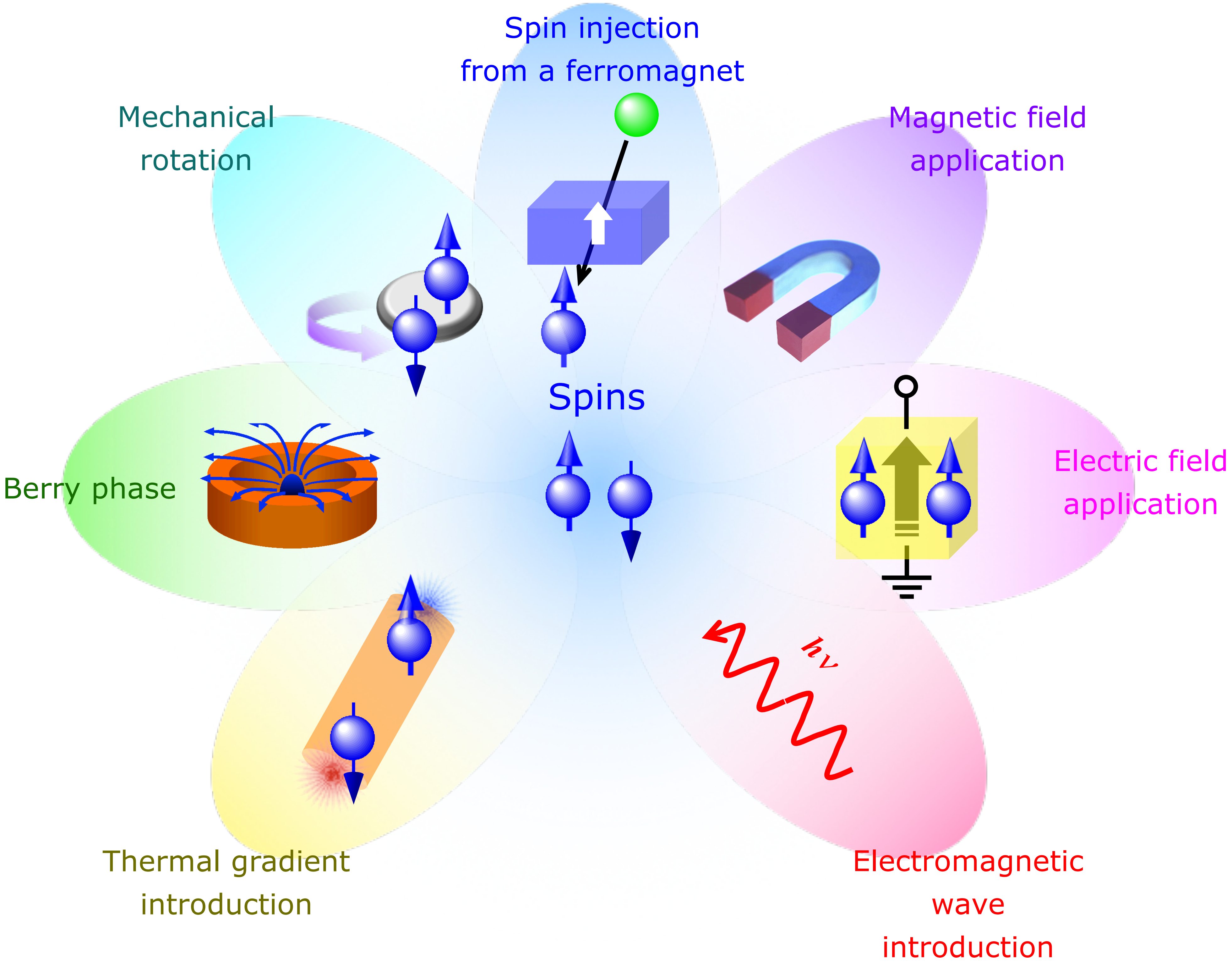
* Y. Aharonov and D. Bohm, *Phys. Rev.* 115, 485 (1959); A. Tonomura *et al.*, *Phys. Rev. Lett*. 56, 792 (1986);
** D. Loss and P. M. Goldbart, *Phys. Rev. B* 45, 13544 (1992).

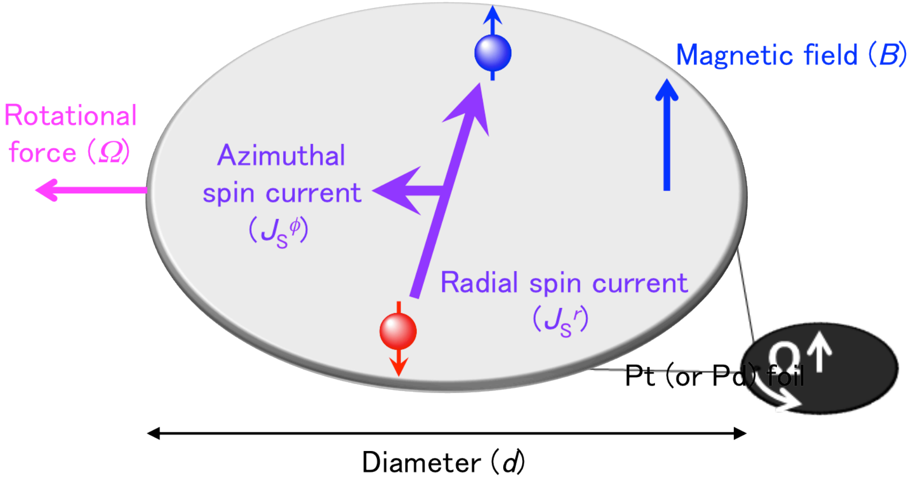

Spin injection
from a ferromagnet
Mechanical
rotation
Magnetic field
application
Spins
Berry phase
Electric field
application
hν
Thermal gradient
introduction
Electromagnetic
wave
introduction

Spin Current in a Rotating Body

- The Einstein de Haas effect describes the rotation of a magnetised body due to the conservation of angular momentum, by the application of a magnetic field.*
- The Barnett effect describes the inverse effect, where a body exhibits an increased magnetisation due to mechanical rotation.**
- The coupling between rotation and magnetisation and magnetisation and spin currents is well established.
- In 2011 Matsuo *et al.* proposed a new method for the direct generation of a *spin current* via mechanical rotation.***

$$J_S = 2enR\eta_{SO}\frac{\hbar 2\pi f}{2\epsilon_F}\omega_C$$

J_S = spin current density
e = electron charge
n = electron density
R = radius of rotation
η_{SO} = spin orbit coupling strength, 0.59
f = frequency
ε_F = Fermi energy
$\omega_C = qB/m$ for electron wave packet



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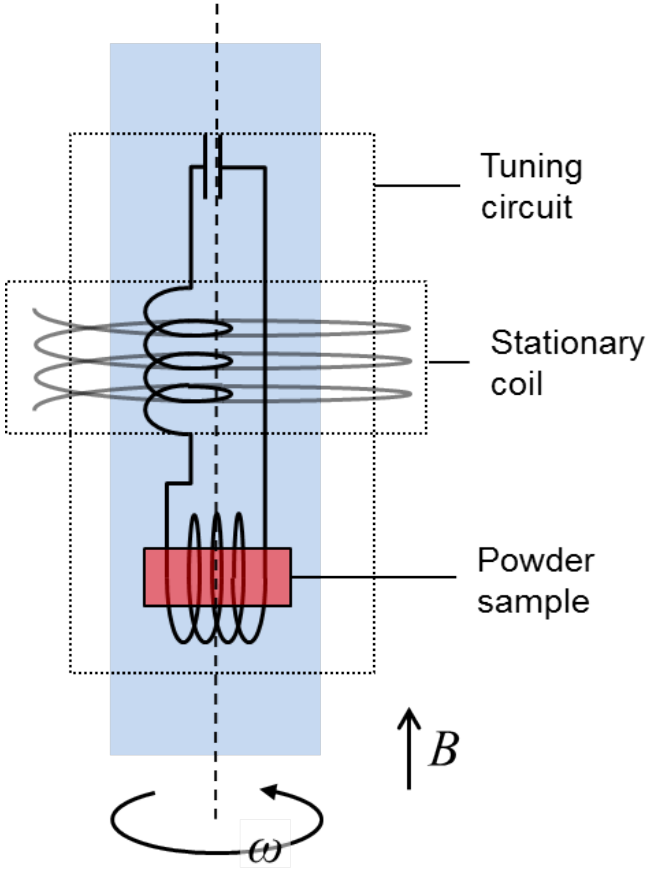
* A. Einstein and W. J. de Haas, *KNAW Proc.* **18**, 696 (1915);
** S. J. Barnett, *Phys. Rev.* **6**, 239 (1915);
*** M. Matsuo *et al.*, *Phys. Rev. Lett.* **106**, 076601 (2011).

Spin Mechatronics Measurement

- In a similar vein, one can observe the Barnett field in a rotating body observing a shift in the NMR.
- The nuclear *g* factor dependence of the NMR shift is observed to measure the Barnett field.*
- The presence of a spin current may be detected by the magneto-optical Kerr effect (MOKE).
- This allows for direct probing of the conduction electrons.



Schematic of the NMR measurement setup for the Barnett effect [6]

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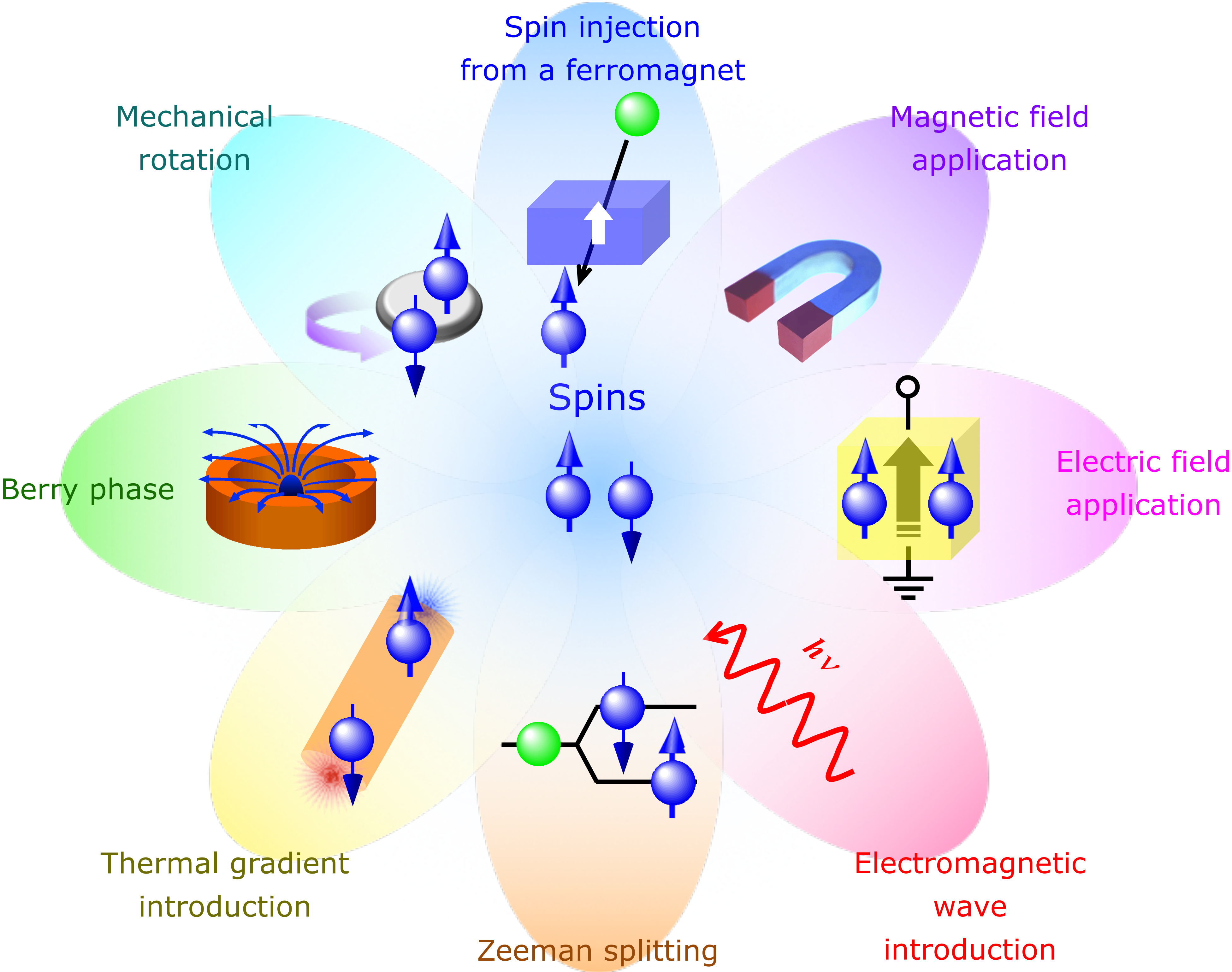
* H. Chudo *et al.*, *Appl. Phys. Exp.* **7**, 063004 (2014).


Spin injection
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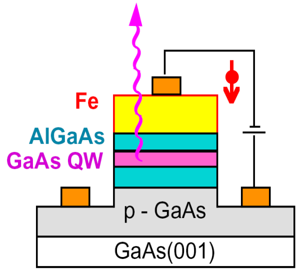
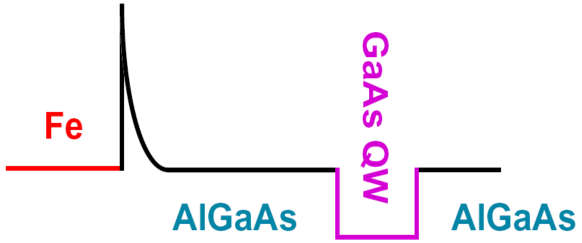
application
$h\nu$
Thermal gradient
introduction
Zeeman splitting
Electromagnetic
wave
introduction

Spin Transport - *Spin-pol'd electrons / holes* → *SC* → *Circ.-pol'd photons*

Spin LED structure



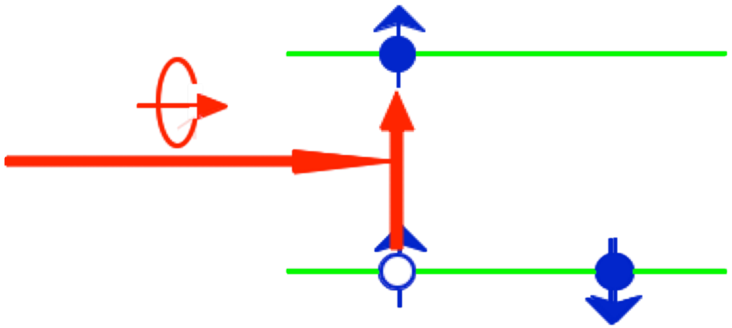


Structures	Spin polarisation	Refs.
Spin-polarised *electron* injection :		
300 nm BeMgZnSe + BeMnZnSe / 100 nm *n*-AlGaAs / 15 nm *i*-GaAs QW / … / *p*-GaAs	~ 42% @ <5 K	R. Fiederling *et al.*, *Nature* **402**, 787 (1999).
360 nm CdMnTe / 1400 nm CdTe	~ 30% @ 5 K	M. Oestreich *et al.*, *Appl. Phys. Lett.* **74**, 1251 (1999).
n-ZnMnSe / AlGaAs / 10-15 nm GaAs QW / AlGaAs	~ 83% @ 4.5 K	B. T. Jonker *et al.*, *Phys. Rev. B* **62**, 8180 (2000); *Appl. Phys. Lett.* **81**, 265 (2002).
20 nm Fe / GaAs / InGaAs QW / GaAs	~ 2% @ 25 K	H. J. Zhu *et al.*, *Phys. Rev. Lett.* **87**, 016601 (2001).
12.5 nm Fe / AlGaAs / GaAs QW / GaAs	~ 13% @ 4.5 K ~ 8% @ 240 K	A. T. Hanbicki *et al.*, *Appl. Phys. Lett.* **80**, 1240 (2002).
8 nm NiFe + 2 nm CoFe / 1.4 nm **AlO$_x$** / 15 nm AlGaAs / 100 nm GaAs QW / GaAs	>9.2% @ 80 K	V. F. Motsnyi *et al.*, *Appl. Phys. Lett.* **81**, 265 (2002).
20 nm (Co, Fe & NiFe) / 2 nm **Al$_2$O$_3$** / 50 nm *n*-AlGaAs / 50 nm si-AlGaAs / 20 nm si-GaAs QW / … / GaAs	0.8%, 0.5% & 0.2% @ RT	T. Manago *et al.*, *Appl. Phys. Lett.* **81**, 694 (2002).
Spin-polarised *hole* injection :		
300 nm *p*-GaMnAs / 20-220 nm GaAs / 10 nm InGaAs QW	~ 1% @ <31 K	Y. Ohno *et al.*, *Nature* **402**, 790 (1999).

Optically-Induced Spin-Polarised Electrons

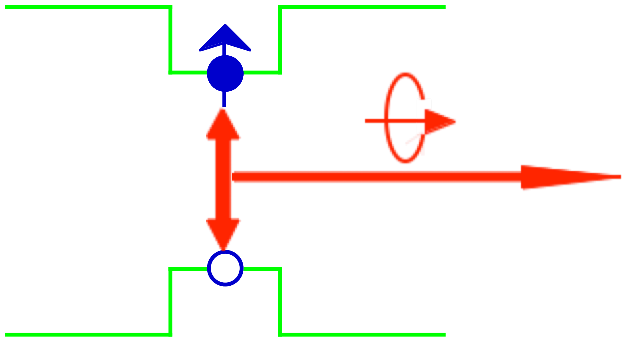
Photoexcitation :

Electrons spin-polarised by introducing circularly polarised light

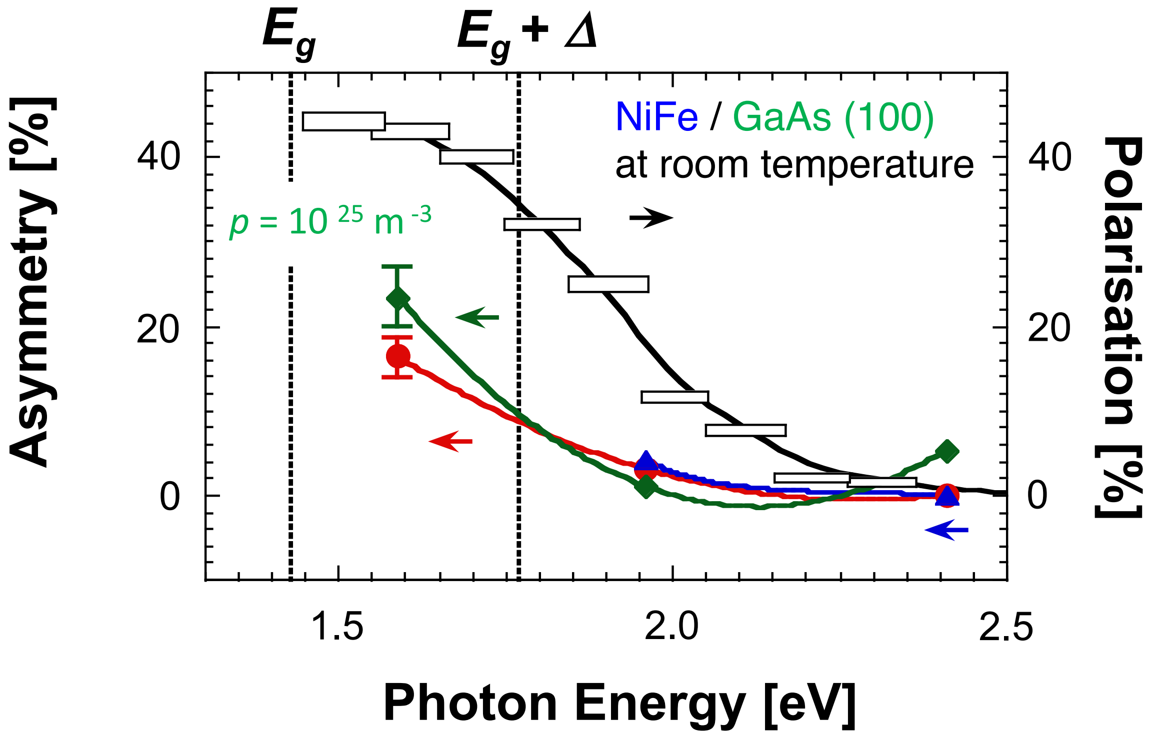


Circularly polarised electroluminescence (EL) :

Circularly polarised light generated by spin-polarised electrons at a quantum well (QW)



Photon Energy Dependence

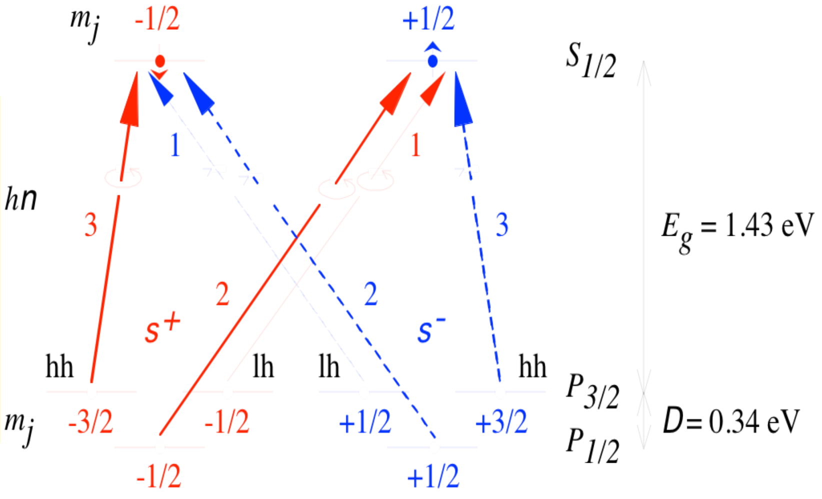


Spin polarisation ∝ asymmetry in spin transport effect :

$$A = (I^{n} - I^{0}) / (I^{n} + I^{0})$$

A decreases with increasing photon energy.

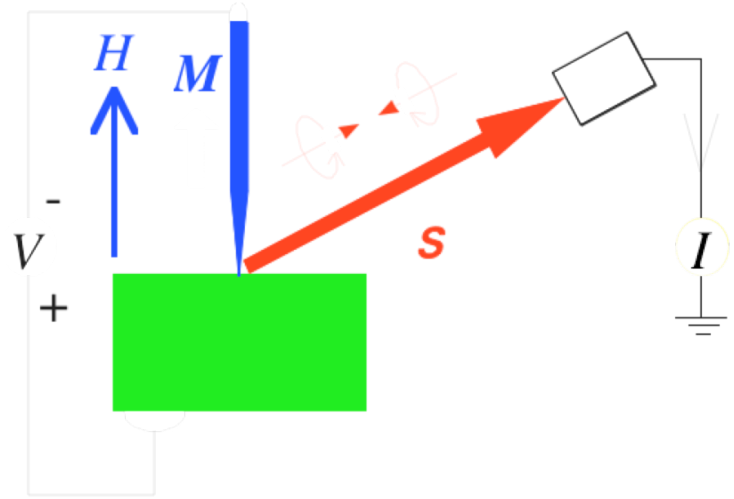
∝ spin polarisation in GaAs



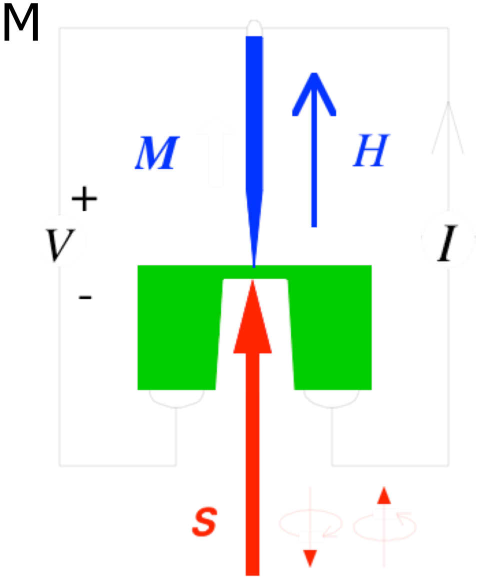
* D. T. Pierce *et al.*, *Phys. Lett.* **51A**, 465 (1975); A.Hirohata *et al.*, *Phys. Rev. B* **63**, 104425 (2001).

Spin Electronics with Optical Methods

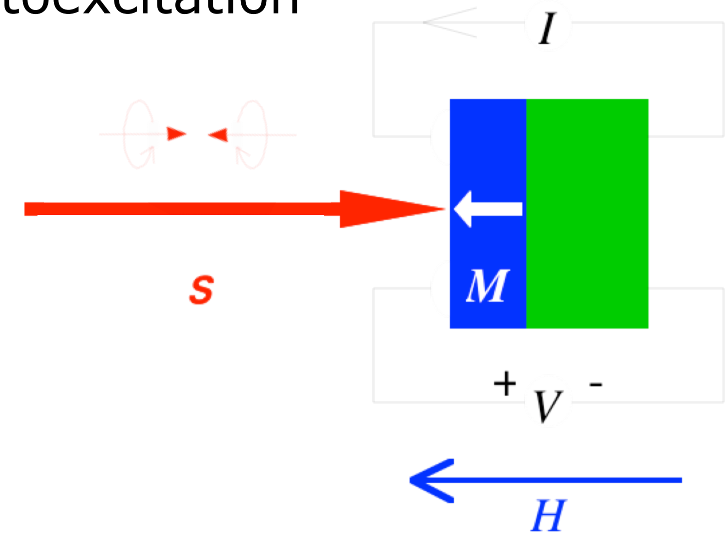
Spin-polarised inverse photoemission



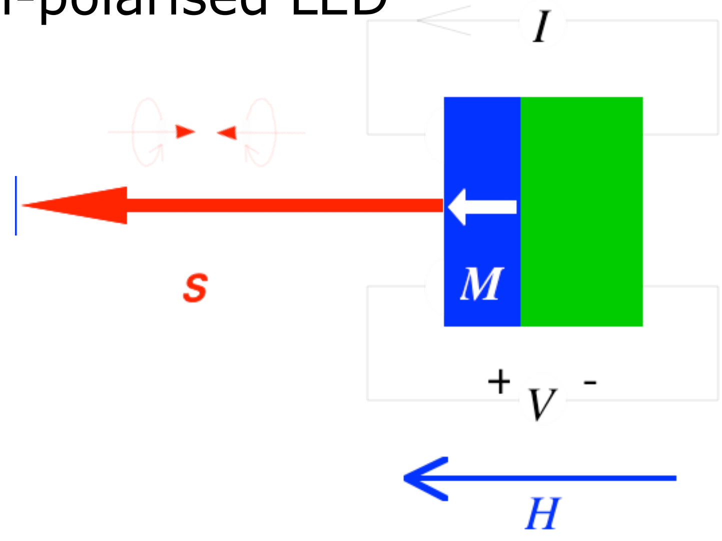
Spin-polarised STM



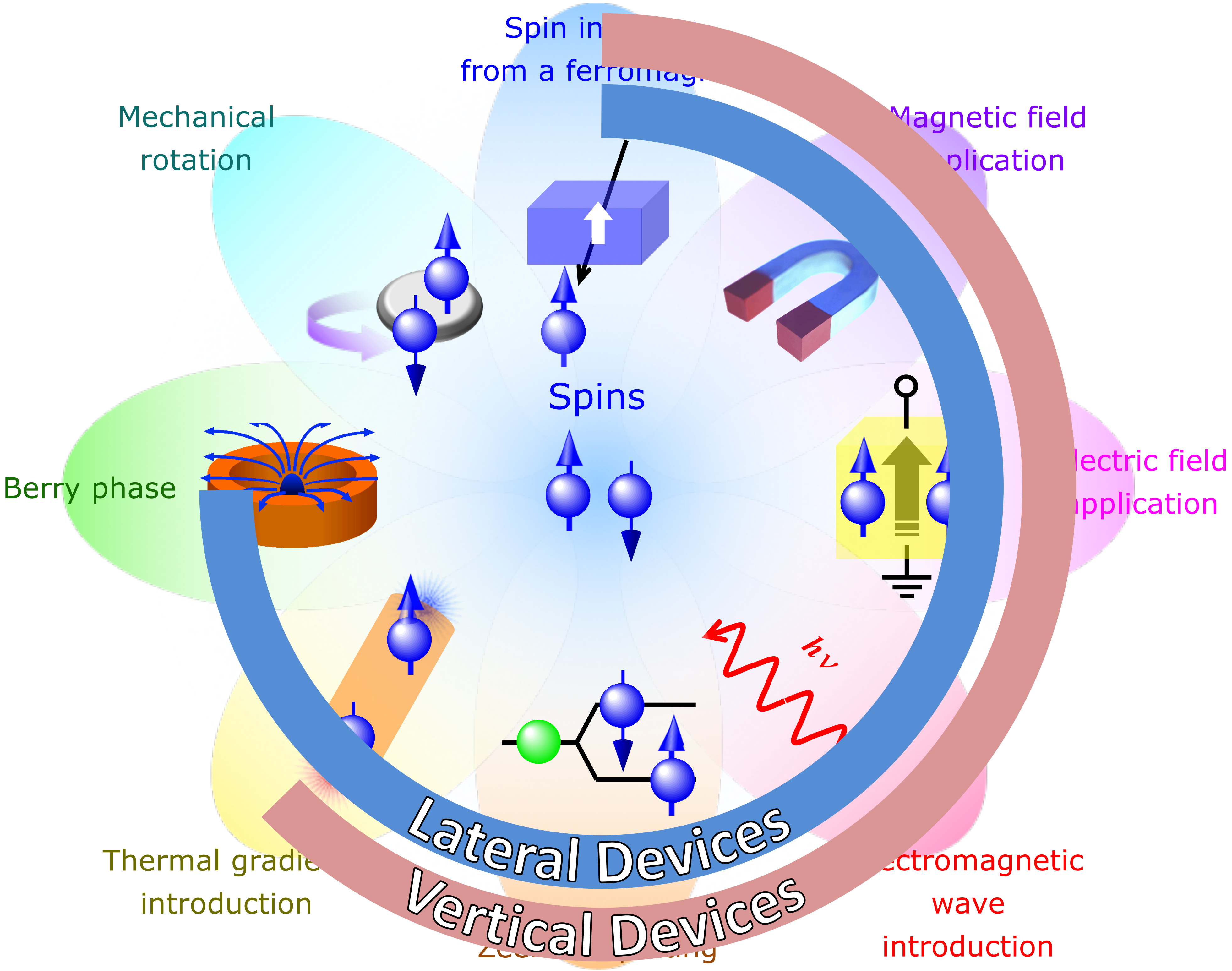
Photoexcitation



Spin-polarised LED



* A. Hirohata, "Optically induced and detected spin current," in S. Maekawa *et al.* (Eds.) *Spin Current* (Oxford University Press, Oxford, 2012) pp. 49-64.


Spin in
from a ferromag
Mechanical
rotation
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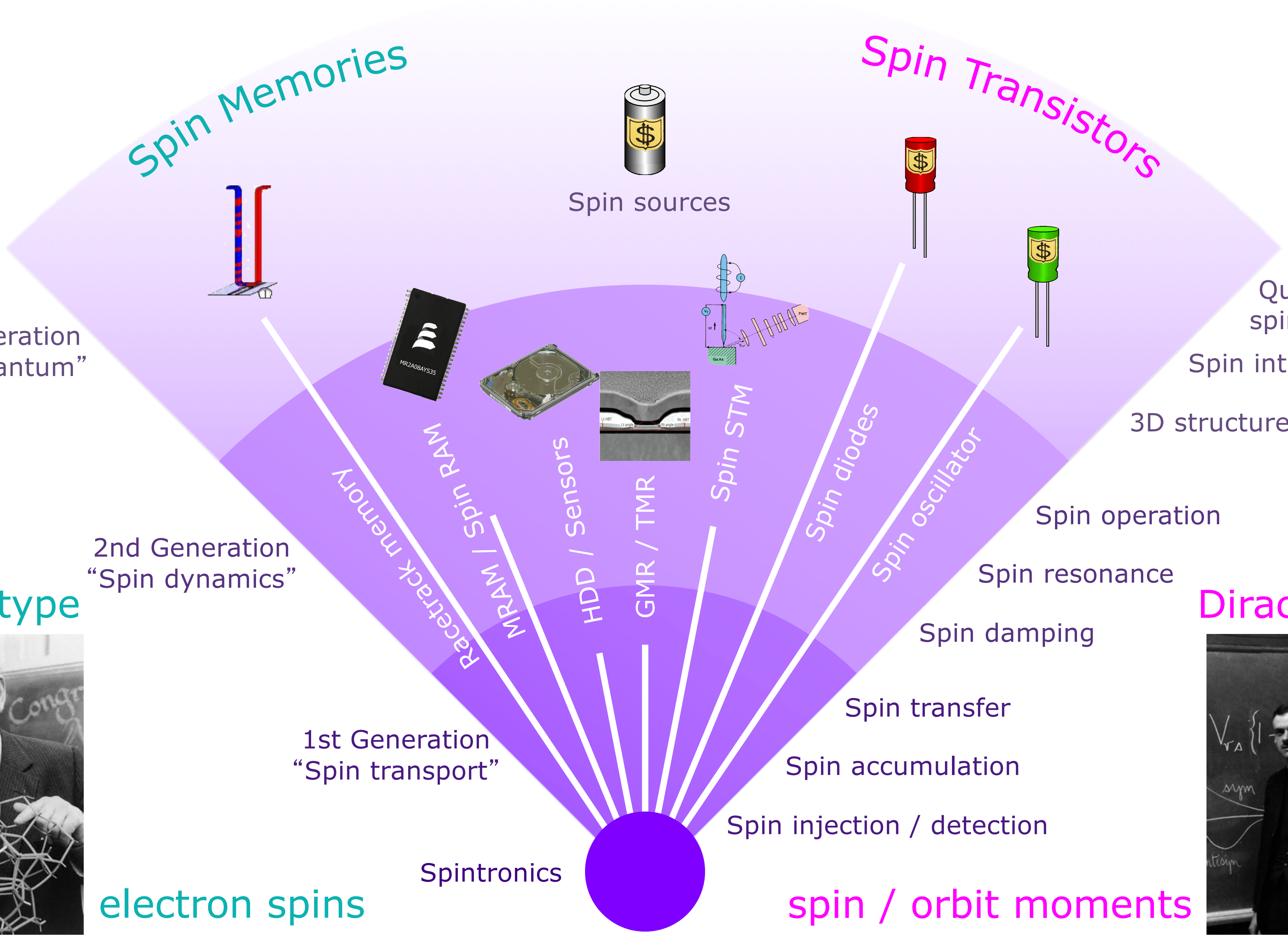
introduction
ctromagnetic
wave
introduction
Lateral Devices
Vertical Devices

Nano-Spintronic Devices

Development of nano-spintronic devices : *



Spin Memories

Spin sources

Spin Transistors

Racetrack memory

MRAM / Spin RAM

HDD / Sensors

GMR / TMR

Spin STM

Spin diodes

Spin oscillator

3rd Generation
"3D / quantum"

2nd Generation
"Spin dynamics"

1st Generation
"Spin transport"

Spintronics

Quantum spintronics

Spin interference

3D structures

Spin operation

Spin resonance

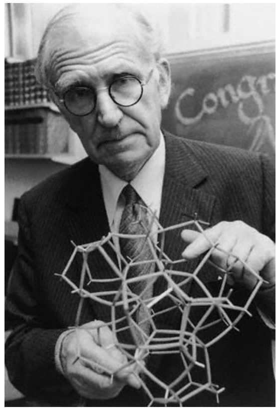
Spin damping

Spin transfer

Spin accumulation

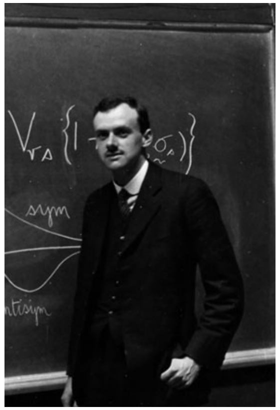
Spin injection / detection

Mott type



electron spins

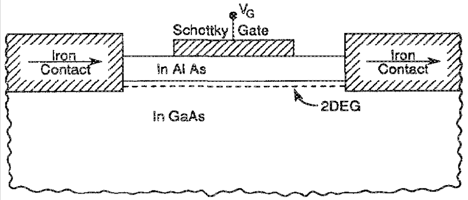
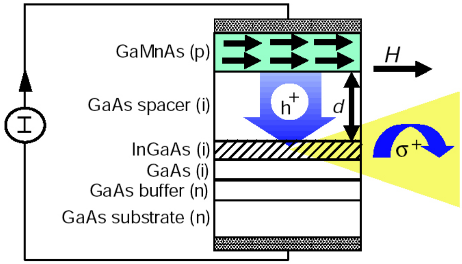
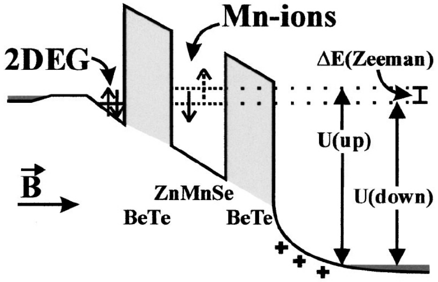
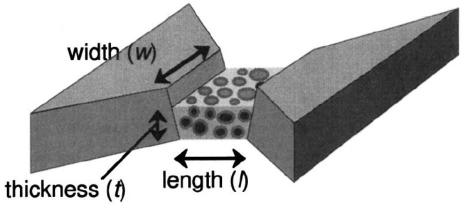
Dirac type



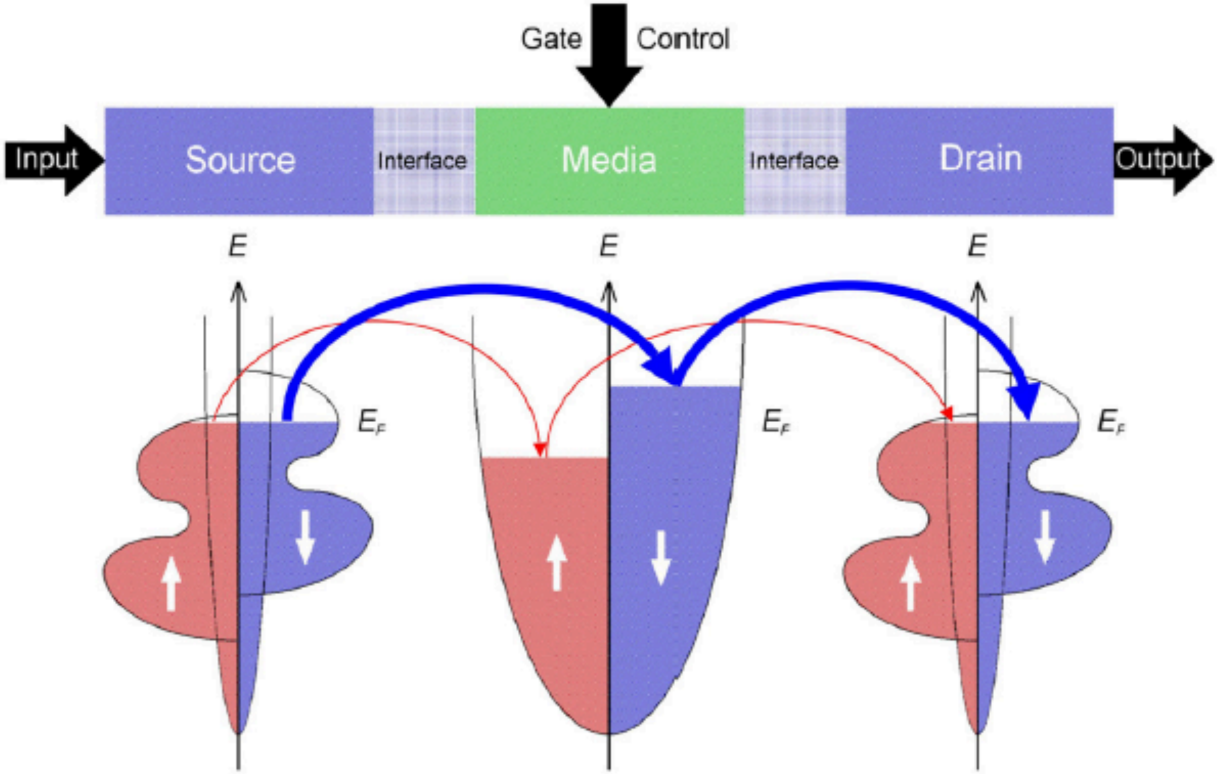
spin / orbit moments

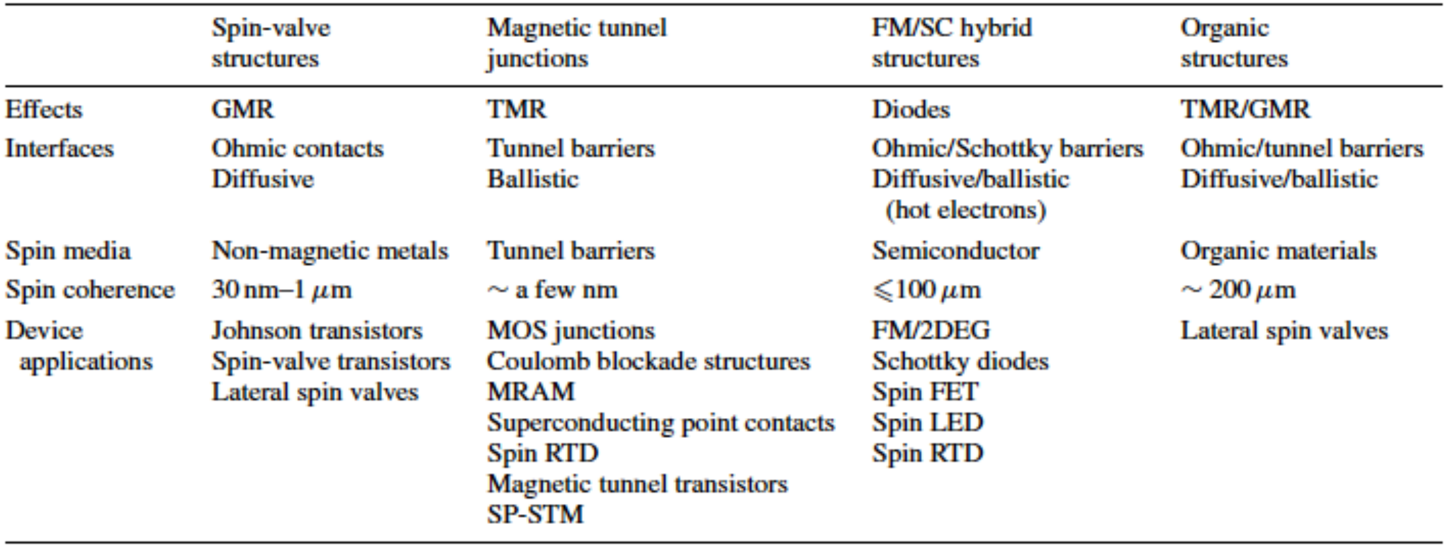
* A. Hirohata and K. Takanashi, *J. Phys. D: Appl. Phys.* **47**, 1930001 (2014).

Major Spin-Polarised Three-Terminal Devices

	Spin FET	Spin LED	Spin RTD	Coulomb blockade
				
Input	Spin-polarised electrons / holes	Spin-polarised electrons / holes	Spin-polarised electrons / holes	Spin-polarised electrons
Source	Ferromagnets (FM)	Dilute magnetic semiconductors (DMS)	Double tunnel barriers	Ferromagnets (FM)
Gate	Bias voltage	Bias voltage	Bias voltage	Bias voltage
Drain	Ferromagnets (FM)	Quantum wells (QW)	Quantum wells (QW)	Ferromagnets (FM)
Output	Electrical signals - Spin-polarised electrons / holes	Circularly polarised electroluminescence (EL)	Circularly polarised electroluminescence (EL)	Electrical signals
Notes		• Low temperature • High magnetic field	• Low temperature	• Low temperature
Refs.	S. Datta and B. Das, *Appl. Phys. Lett.* **56**, 665 (1990).	Y. Ohno *et al.*, *Nature* **402**, 790 (1999).	T. Gruber *et al.*, *Appl. Phys. Lett.* **78**, 1101 (2001).	K. Yakushiji *et al.*, *Appl. Phys. Lett.* **78**, 515 (2001).

Nano-Spintronic Devices



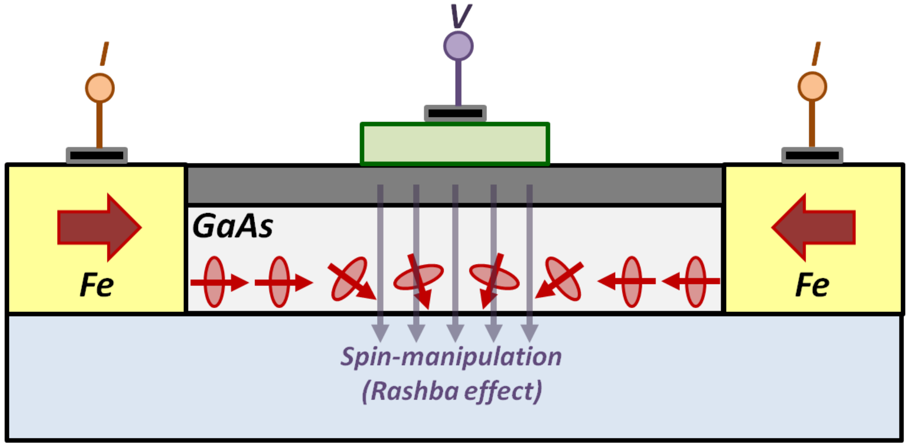


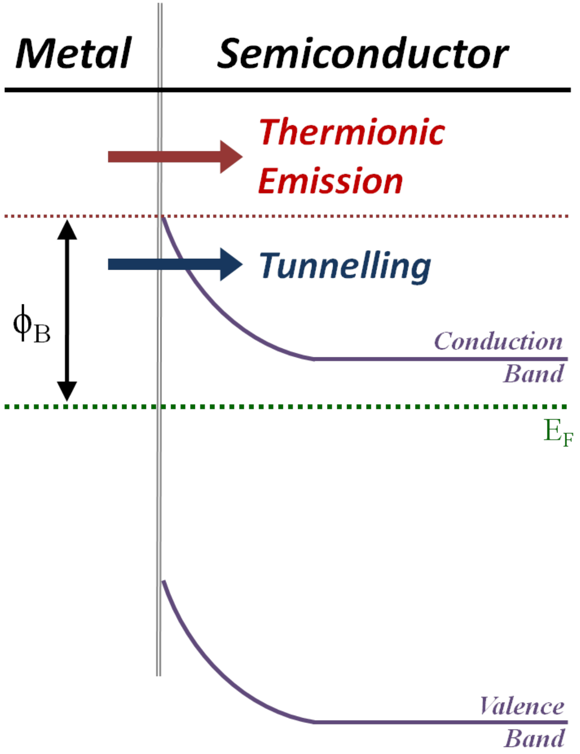
	Spin-valve structures	Magnetic tunnel junctions	FM/SC hybrid structures	Organic structures
Effects	GMR	TMR	Diodes	TMR/GMR
Interfaces	Ohmic contacts Diffusive	Tunnel barriers Ballistic	Ohmic/Schottky barriers Diffusive/ballistic (hot electrons)	Ohmic/tunnel barriers Diffusive/ballistic
Spin media	Non-magnetic metals	Tunnel barriers	Semiconductor	Organic materials
Spin coherence	30 nm–1 μm	$\sim$ a few nm	$\leqslant$100 μm	$\sim$ 200 μm
Device applications	Johnson transistors Spin-valve transistors Lateral spin valves	MOS junctions Coulomb blockade structures MRAM Superconducting point contacts Spin RTD Magnetic tunnel transistors SP-STM	FM/2DEG Schottky diodes Spin FET Spin LED Spin RTD	Lateral spin valves

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

Spin-Polarised Field Effect Transistor

- Spin transistor was originally proposed by Datta and Das.
- Fe/GaAs is one of the leading systems for obtaining efficient spin-polarised injection into a semiconductor (SC). **
- GaAs has long carrier spin lifetimes and large spin diffusion lengths.
- Fe is an ideal injector as it has:
  - high Curie temperature
  - low coercivity
  - good lattice matching with GaAs
- The intrinsic Schottky barrier that forms at the Fe/SC interface overcomes the limitations due to the conductivity mismatch.





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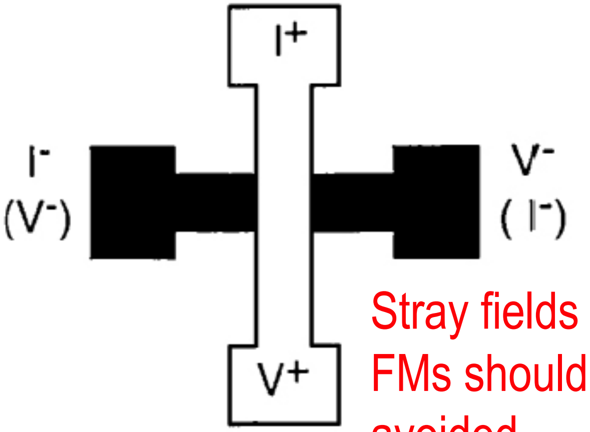
* S. Datta and S. Das, *Appl. Phys. Lett.* **56**, 665 (1990);
** G. Wastlbauer and J. A. C. Bland, *Adv. Phys.* **54**, 137 (2005); D. Hagele *et al.*, *Appl. Phys. Lett.* **73**, 1580 (1998);
J. M. Kikkawa and D.D. Awschalom, *Nature* **397**,139 (1999); E. I. Rashba, *Phys. Rev. B* **62**, R16267 (2000).

Spin Transport - *Spin-pol'd electrons → SC → Spin-pol'd electrons*

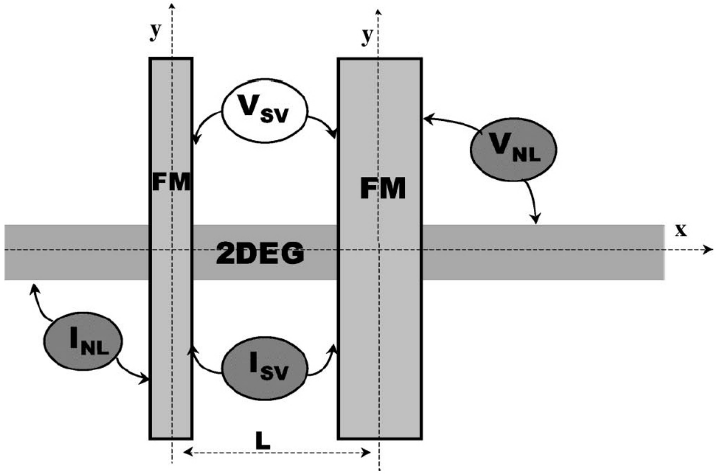
Spin FET structures :

Hall bar geometry



Stray fields from FMs should be avoided.

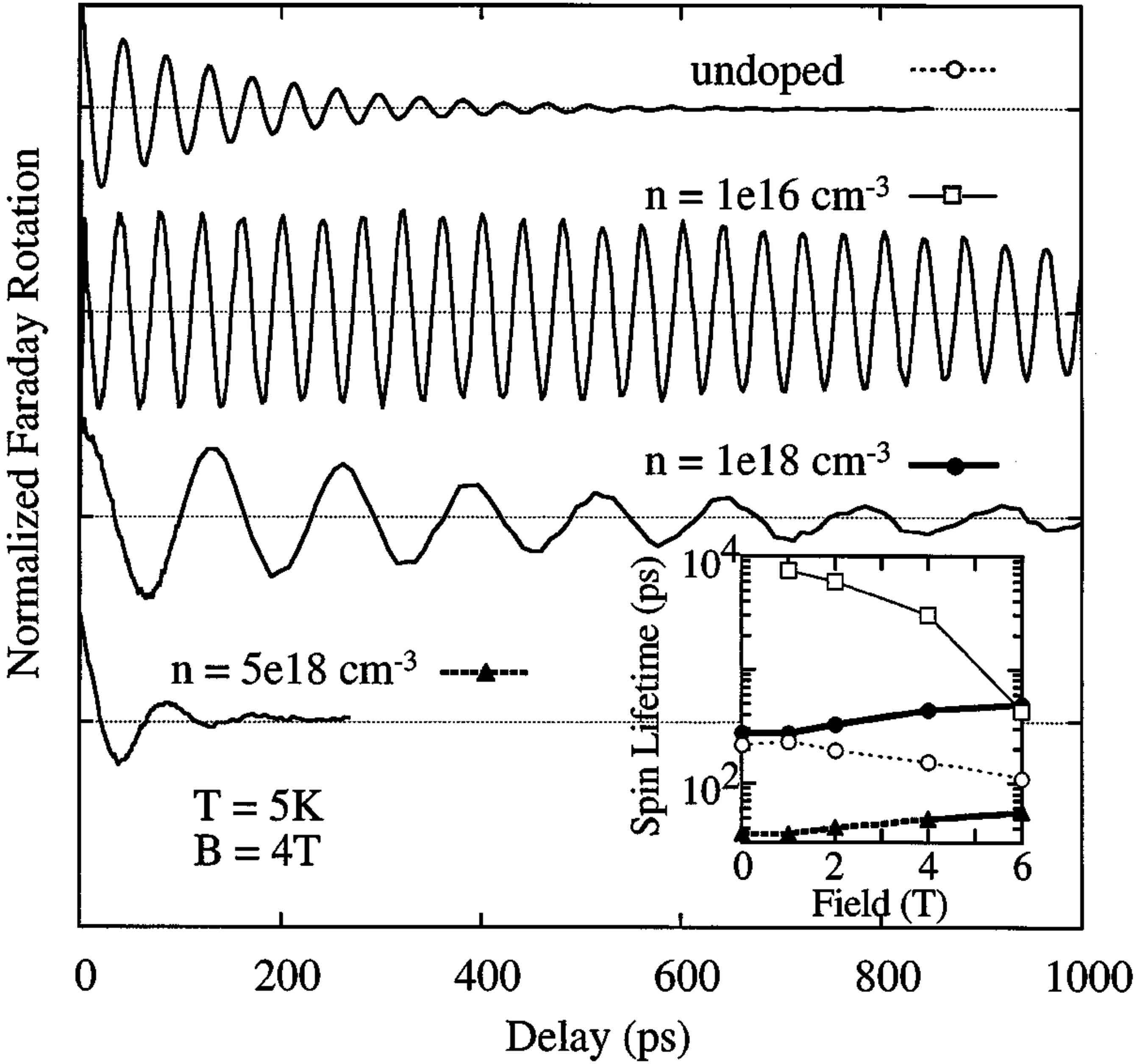
Asymmetric multi-terminal geometry



Structures	Spin polarization	Refs.
FM / 2DEG Hall-bar-type structures :		
86 nm NiFe / 25 nm AlGaSb / 15 nm InAs 2DEG / … / GaAs	~ 1% @ 75 K	P. R. Hammar *et al.*, *Phys. Rev. Lett.* **83**, 203 (1999); *Phys. Rev. B* **61**, 7207 (2000).
NiFe / 750-6400 nm InAs QW / NiFe	Hall effect @ 4.2 K	F. G. Monzon and M. L. Roukes, *J. Magn. Magn, Mater.* **198-199**, 632 (1999).
FM / 2DEG asymmetric structures :		
NiFe & Co / InAs 2DEG / NiFe & Co	AMR @ 4.5 K	A. T. Filip *et al.*, *Phys. Rev. B* **62**, 9996 (2000).
60 nm NiFe / InAs 2DEG / GaAs	~ 0.2% @ < 10 K	C.-M. Hu *et al.*, *Phys. Rev. B* **63**, 125333 (2001).
Schottky (tunnel) diodes (FM / SC) :		
3.5 nm Fe / 2 nm **Oxide** / *n*-GaAs	~ 5% @ <RT	A. Filipe *et al.*, *Phys. Rev. Lett.* **80**, 2425 (1998).

Spin-Polarised Electrons in GaAs

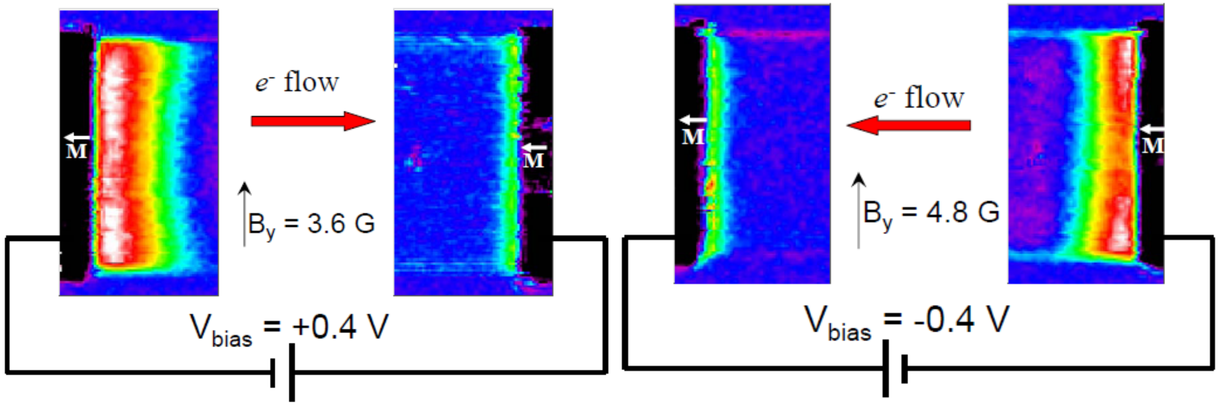
> 100 μm spin diffusion length : *

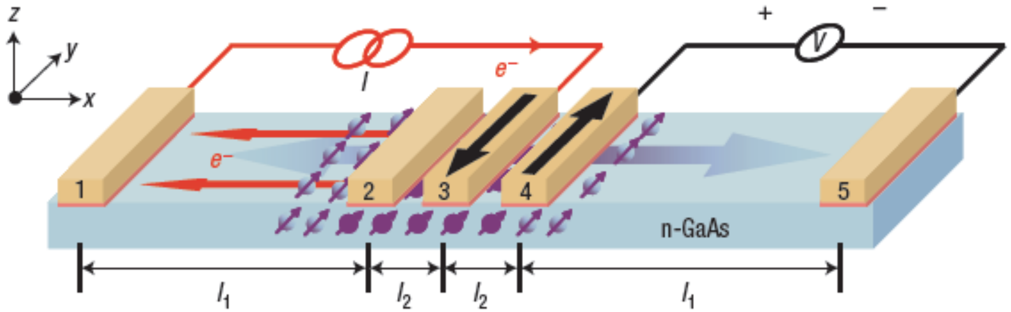


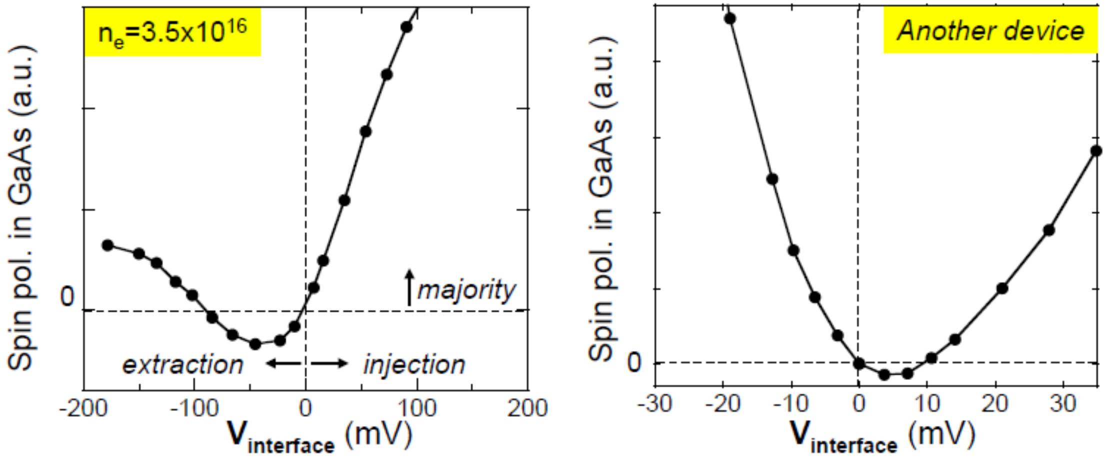
* J. M. Kikkawa and D. D. Awschalom, *Phys. Rev. Lett.* **80**, 4313 (1998).

Spin Transport Measurements in GaAs

- Experimental studies have shown that spin injection can be achieved leading to a majority spin accumulation.
- Spin injection / extraction has been observed using both optical * and electrical ** techniques.
- A bias dependant polarisation inversion has been observed, the origin of which remains unknown.
- Knowledge of the mechanism(s) responsible for the polarisation inversion required for the development of future devices.



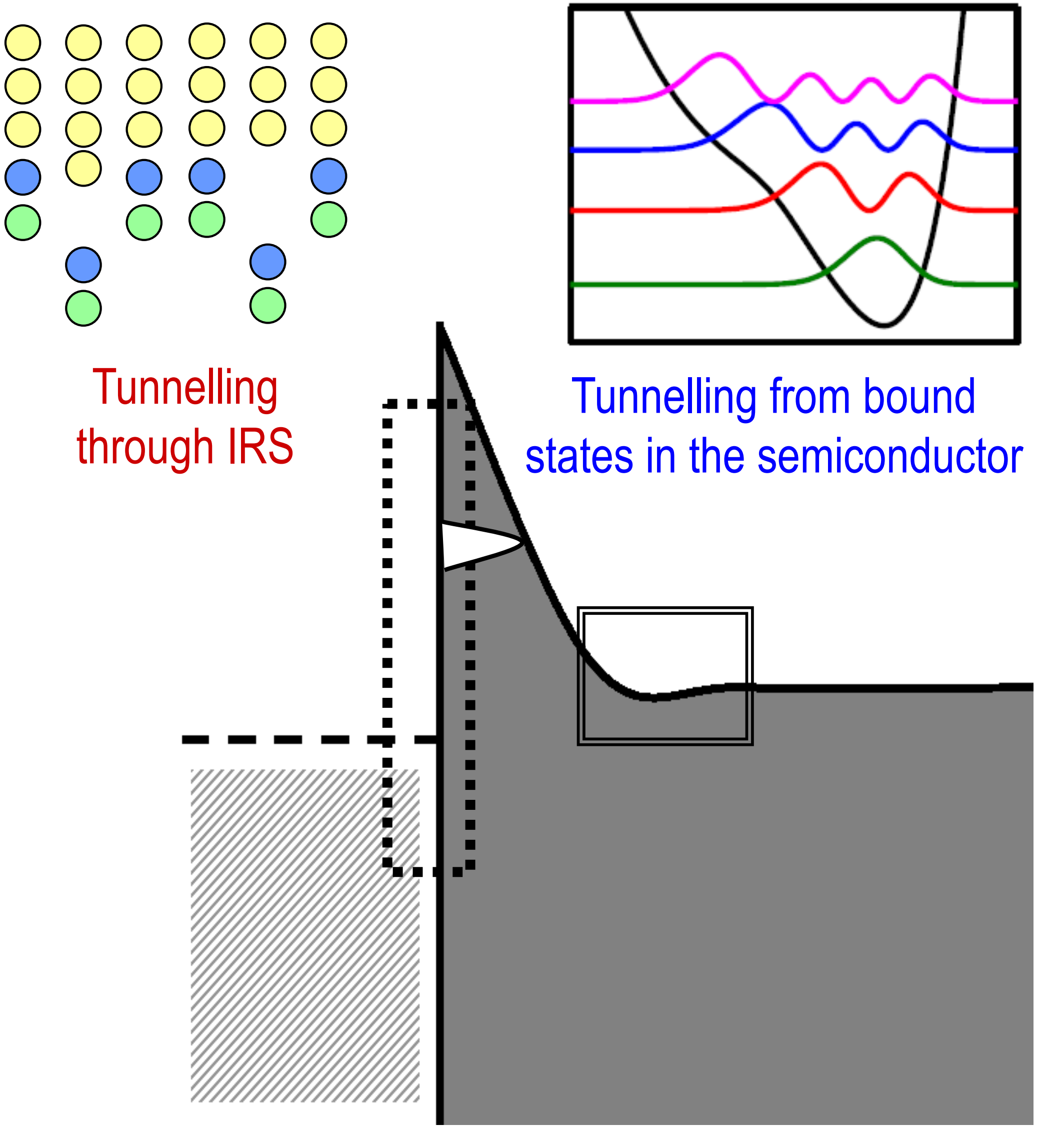




* S.A. Crooker *et al.*, *Science* **309**, 2191 (2005);
** X. Lou *et al.*, *Nature Phys.* **3**, 197 (2007).

Possible Origins of Spin Polarisation Reversal

- There are two promising candidates to explain the polarisation inversion**:**
  - Tunnelling through interface resonance states (IRS). *
  - Tunnelling from bound states in the semiconductor. **
- It has been shown that the contribution arising from bound states can be varied through control of the doping profile.
- The strength and position of IRS is sensitive to the atomic interface structure. *



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* S Honda *et al.*, *J. Phys. D: Appl. Phys.* **43**, 135002 (2010);
** H. Dery and L.J. Sham, *Phys. Rev. Lett.* **98**, 046602 (2007).

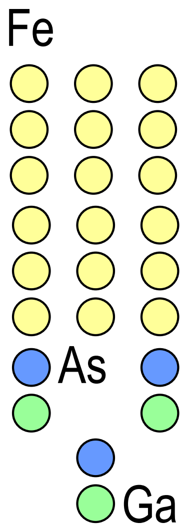
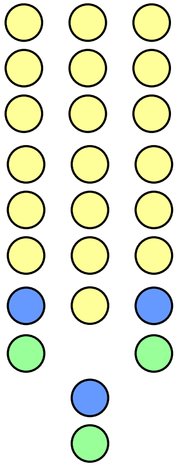
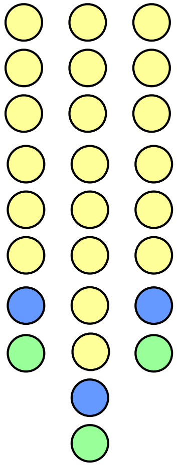
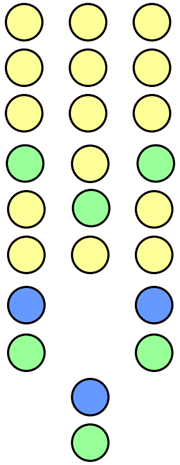
Fe / GaAs (001) Interface Structures

- There are several proposals for the interface structure of Fe / GaAs (001) films.

- Calculations suggest that the abrupt interface is energetically favourable for As-terminated surfaces (often used to limit diffusion).

- Previous calculations predict that minority carrier interface states lie 0.3 eV below the top of the Schottky barrier.
  - *- These are yet to be observed experimentally*.

- Calculations are yet to be performed for inter-atomic spacings measured experimentally.

			
Abrupt	***Partially intermixed***	***Fully intermixed***	***Fe_3Ga***
As-rich	*Ga-rich*, ***	*Least favourable*	*After over-annealing*

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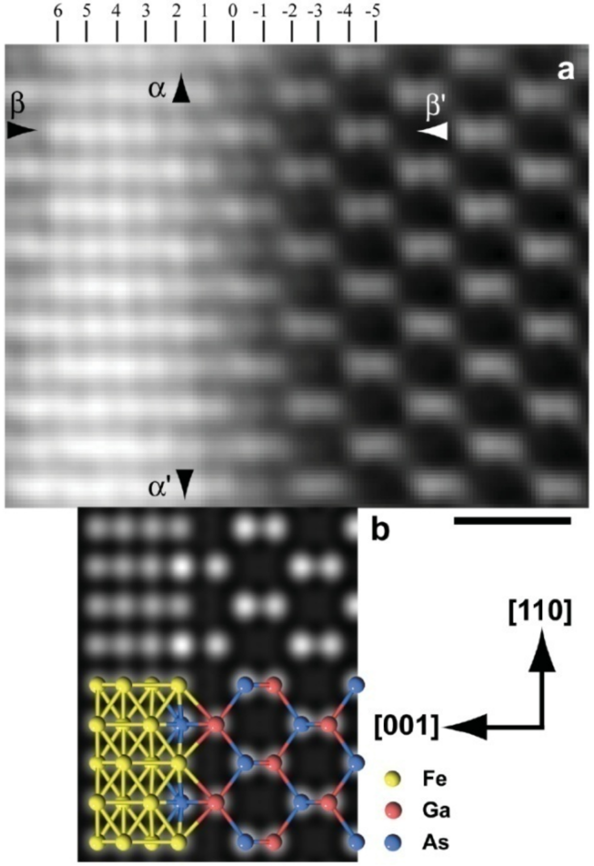
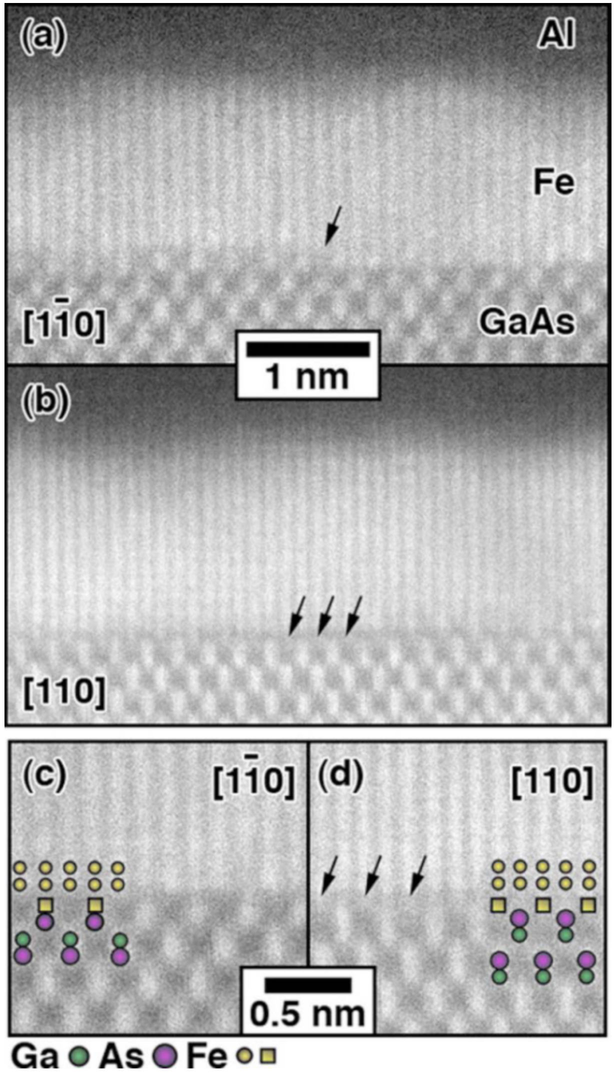
* T. J. Zega *et al.*, *Phys. Rev. Lett.* **96**, 196101 (2006);

** J. M. LeBau *et al.*, *Appl. Phys. Lett.* **93**, 121909 (2008).

Previous Experimental Observations

- There have been two previous reports on experimental observations of the Fe/GaAs interface. *,**
- The two studies reported different interfacial structures.
- Both reports did not observed the abrupt interface.
- Experimental values for the Schottky barrier height range from 0.2 to 0.8 eV. ***, ****





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* T. J. Zega *et al.*, *Phys. Rev. Lett.* **96**,196101 (2006);
** J. M. LeBau *et al.*, *Appl. Phys. Lett.* **93**, 121909 (2008);
*** H. Kurebayashi *et al.*, *Appl. Phys. Lett.* **91**, 102114 (2007);
**** B. T. Jonker *et al.*, *J. Appl. Phys.* **81**, 4362 (1997).

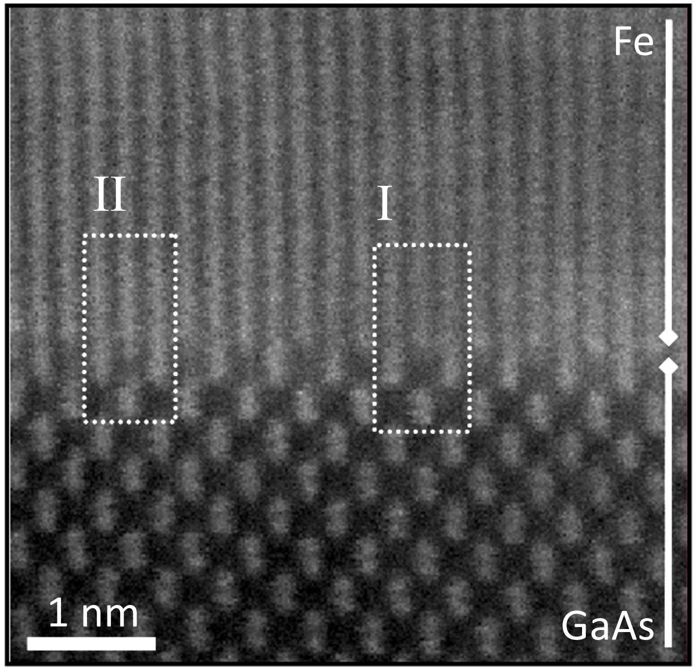
HAADF STEM Observation on Fe/GaAs Interfaces

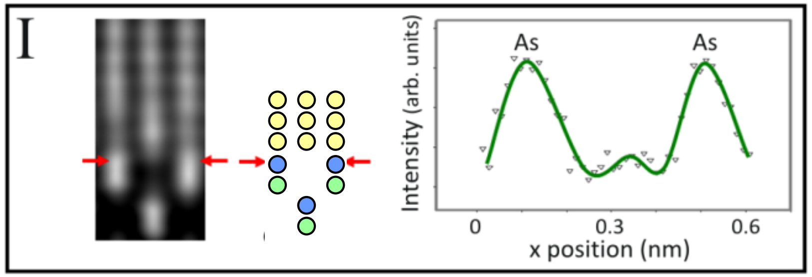
- The figure shows an unfiltered HAADF-STEM image the Fe / GaAs interface.

- Two different interfacial structures are observed.
  - Abrupt (first report) **
  - Partially mixed (as reported previously) *

- Analysis of the intensity profiles (z-contrast) taken across the interfaces suggest that Fe is responsible for the partially mixing.

- From the areas observed the film is ~ 95% abrupt.





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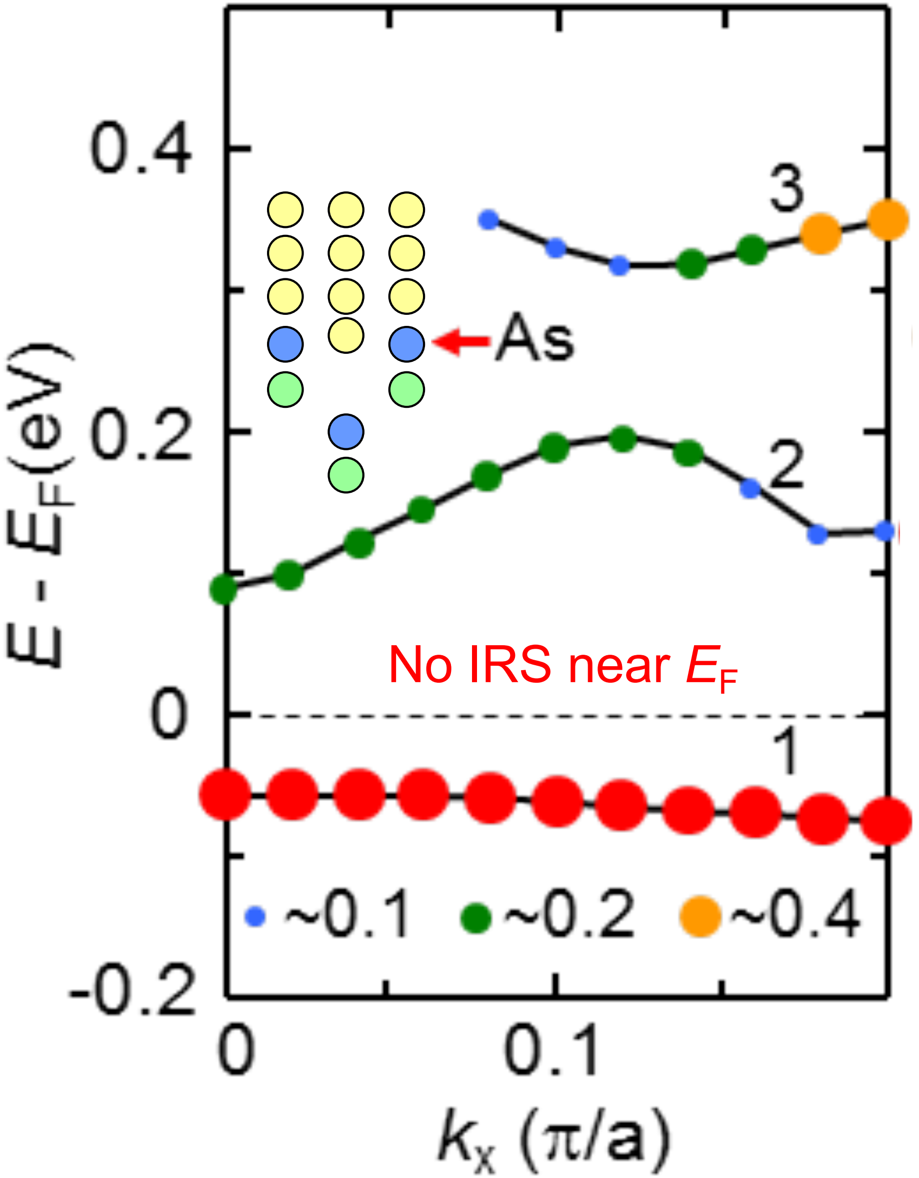
* L. R. Fleet *et al.*, *IEEE Trans. Magn.*, **47**, 2756 (2011);
** L. R. Fleet *et al.*, *Phys. Rev. B* **87**, 024401 (2012).

Peak Positions of IRSs

Interface I



No IRS near E_F

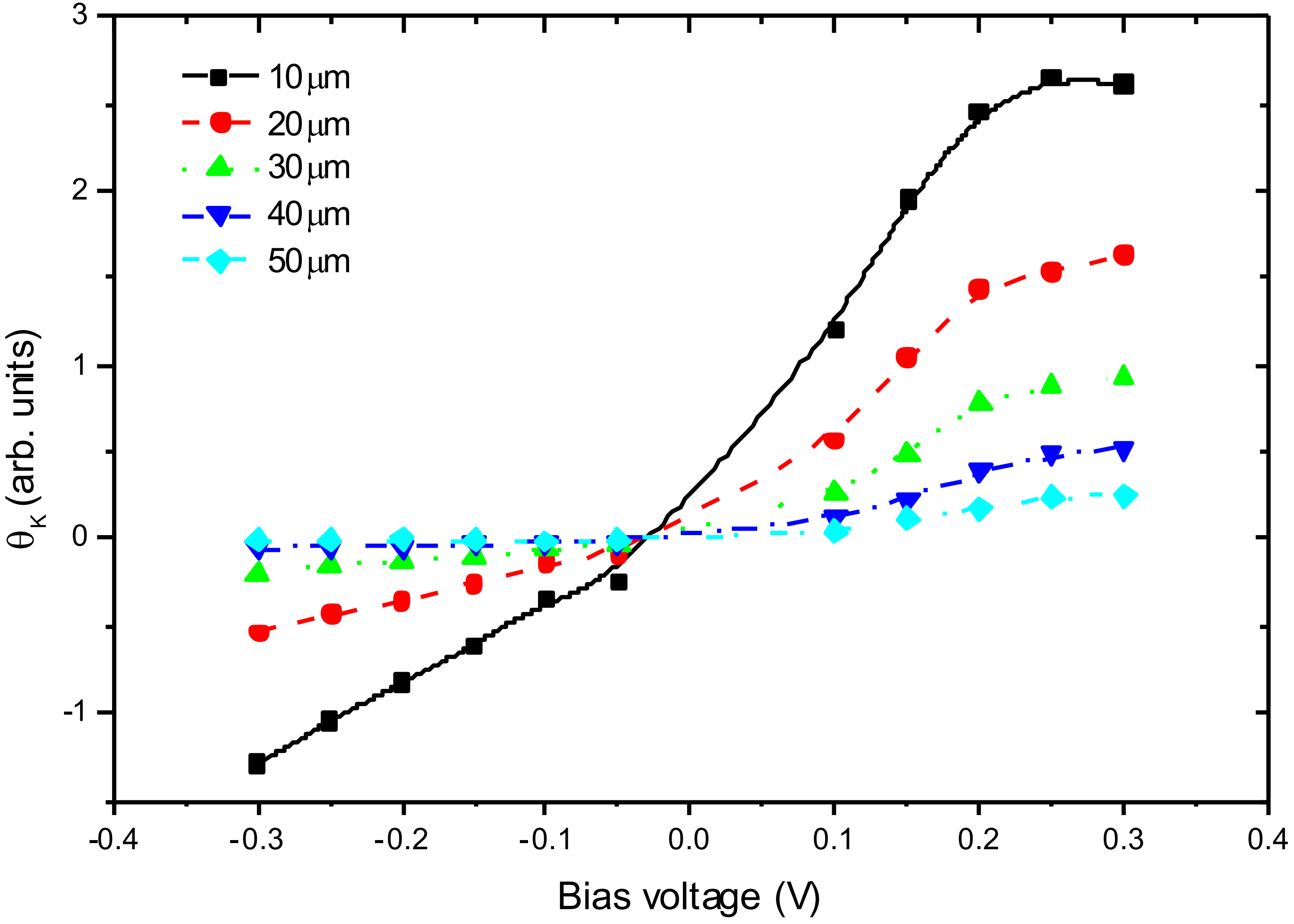
No spin polarisation reversal

* L. R. Fleet *et al.*, *Phys. Rev. B* **87**, 024401 (2012).

Bias Dependence

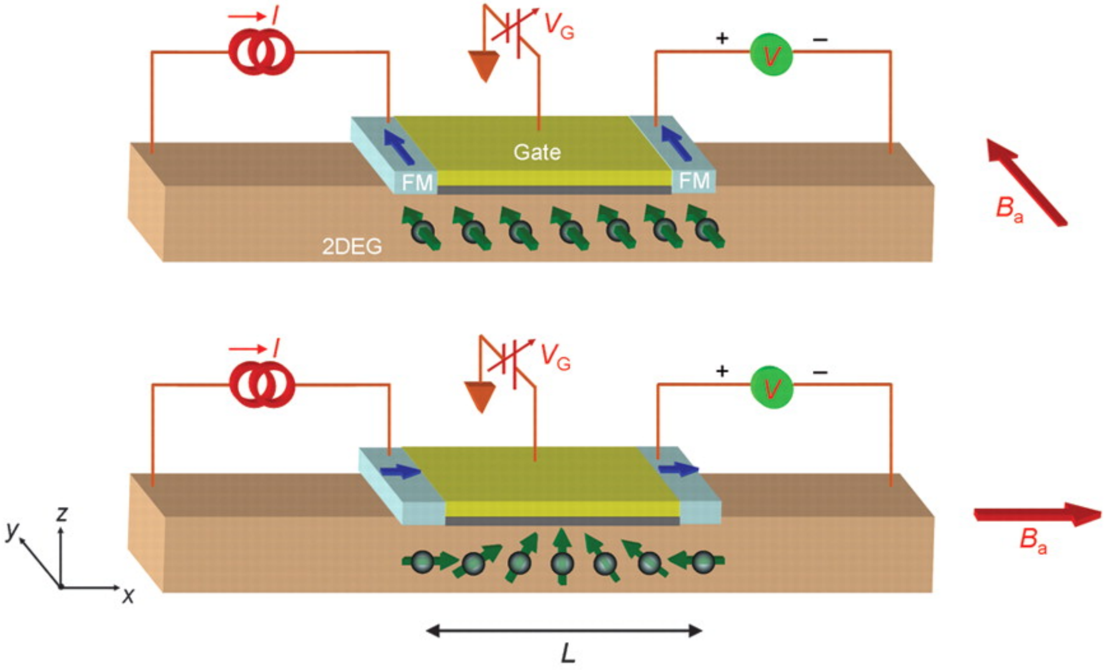
- No spin polarisation reversal induced by a bias voltage.

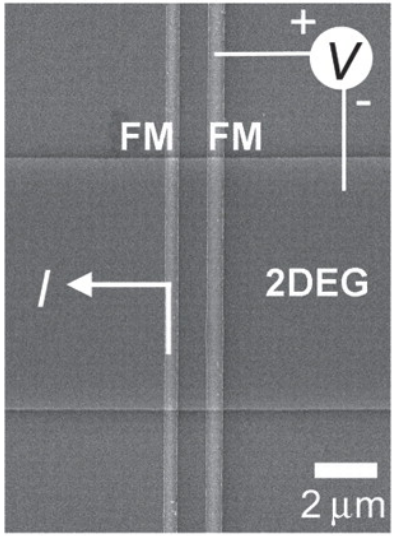
 → Agrees with calculations.

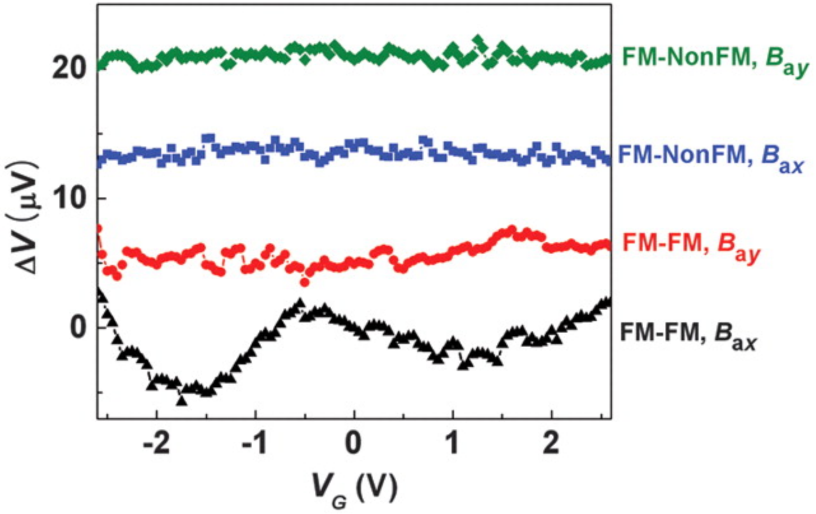


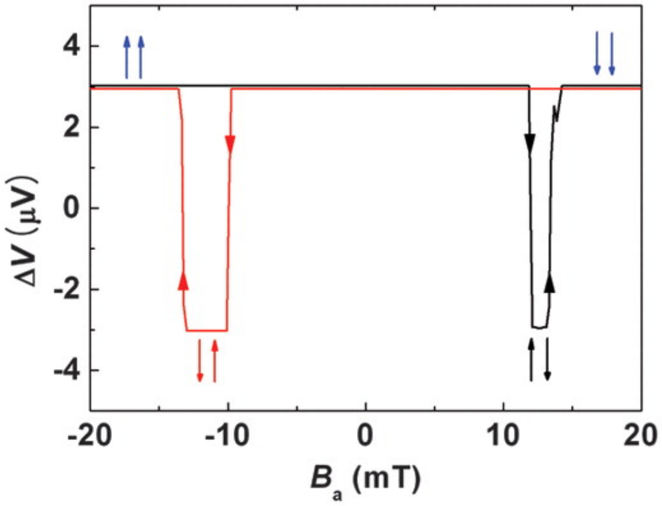
Recent Demonstration of Spin FET Operation

Gate operation in a NiFe / InGaAs / NiFe spin FET : *









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* H. C. Koo *et al.*, *Science* **325**, 1515 (2009).

Theoretical Studies - *FM* → *SC*

FM / SC Interfaces :

Ohmic contacts :

- Diffusive process : 100 % spin polarisation in FM is crucial.

→ DMS, Heusler compounds and half-metallic FM as FM

G. Schmidt *et al.*, *Phys. Rev. B* **62**, R4790 (2000).

Schottky / tunnel barrier contacts :

- Ballistic process : $R_{SC} << R_{tunnel}$

E. I. Rashba, *Phys. Rev. B* **62**, 16267 (2000).

P. Mavropoulos *et al.*, *Phys. Rev. B* **66**, 024416 (2002).

Spin coherence length :

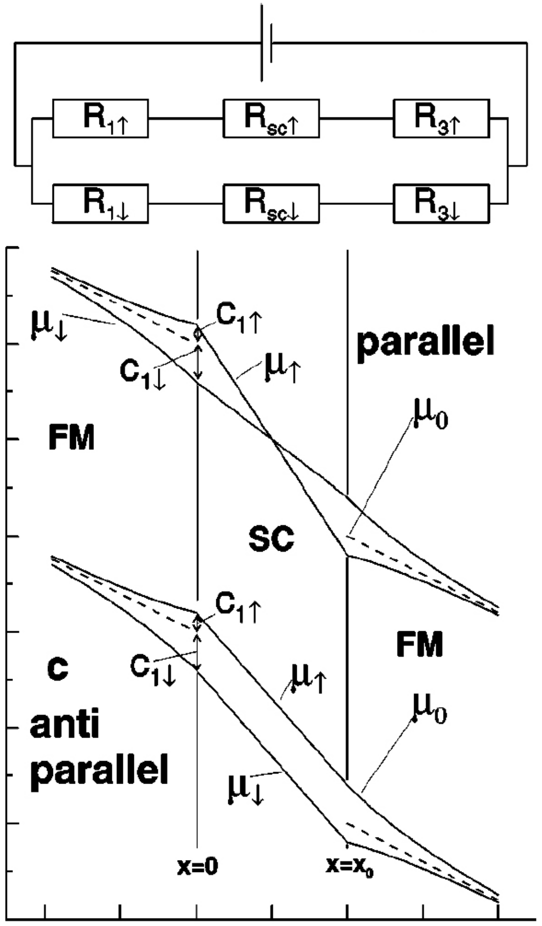
- Spin life time : electrons >> holes

M. E. Flatté and G. Vignale, *Appl. Phys. Lett.* **78**, 1273 (2001).

Spin modulation :

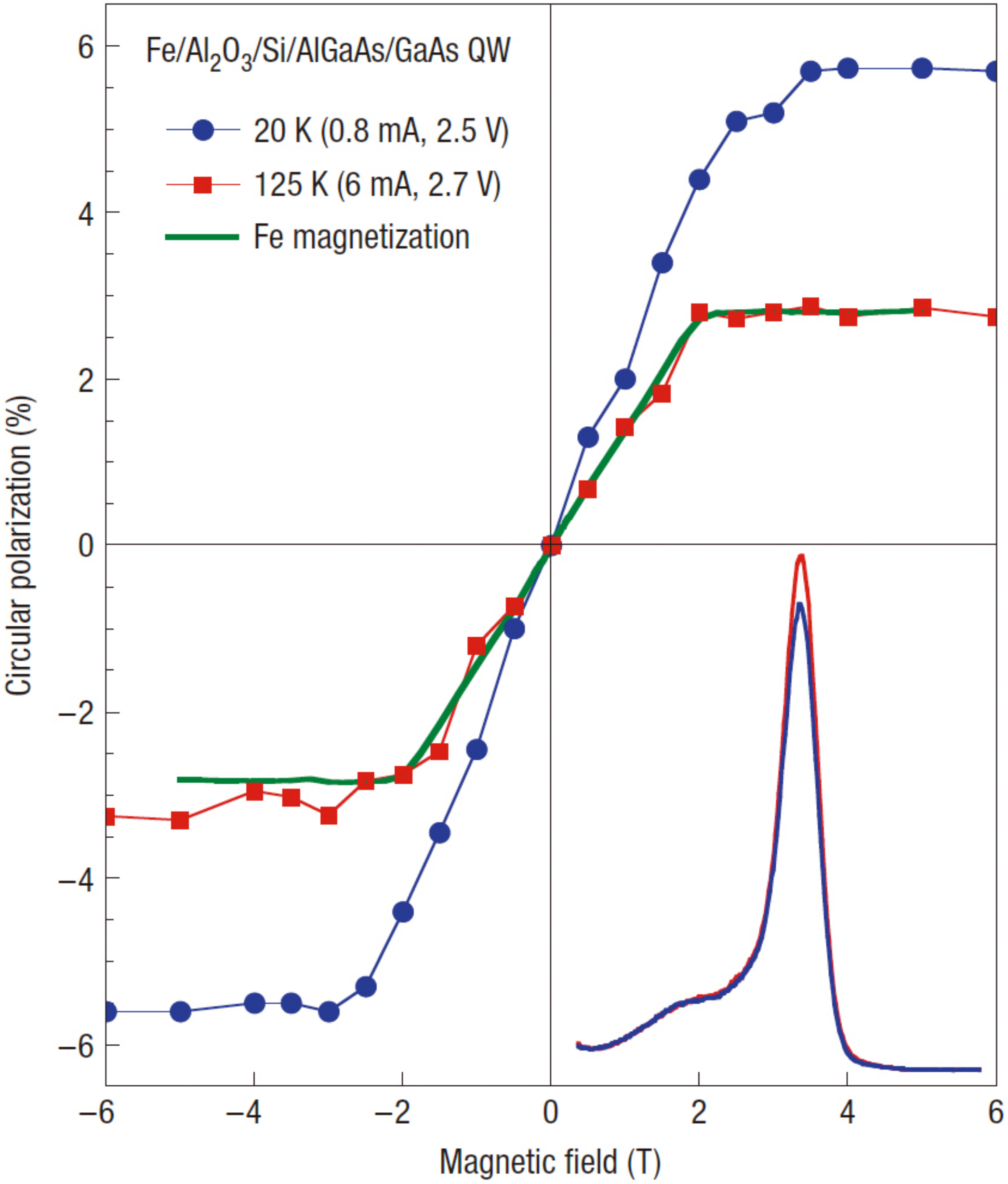
- Spin orientation ∝ gate voltage

A. Bournel *et al.*, *Mater. Sci. Forum* **297**, 205 (1999).



Spin Injection into Si

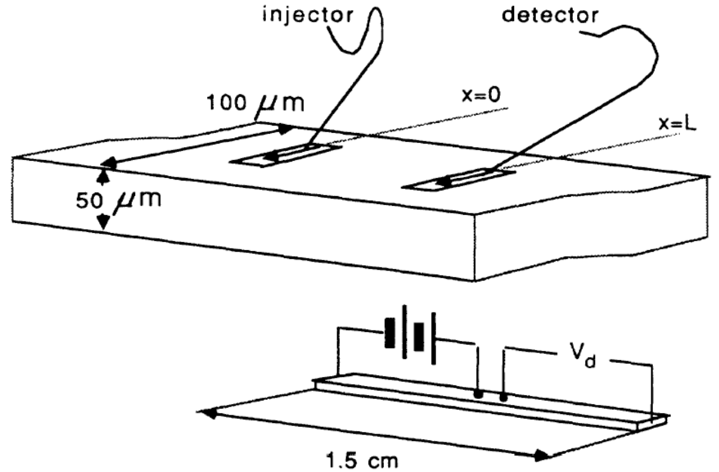
Ballistic spin injection into Si : *

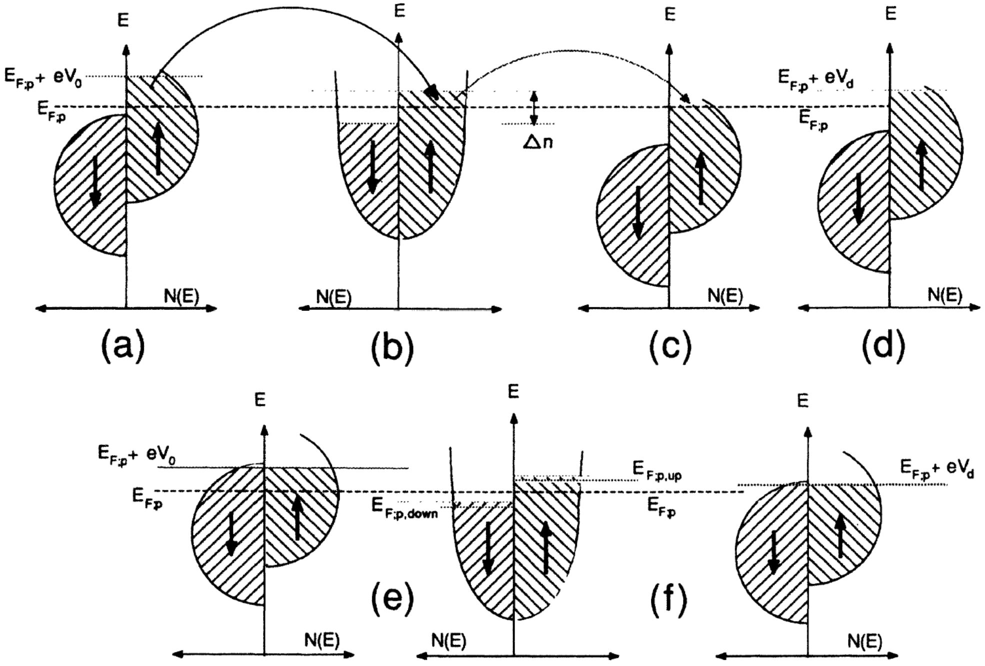


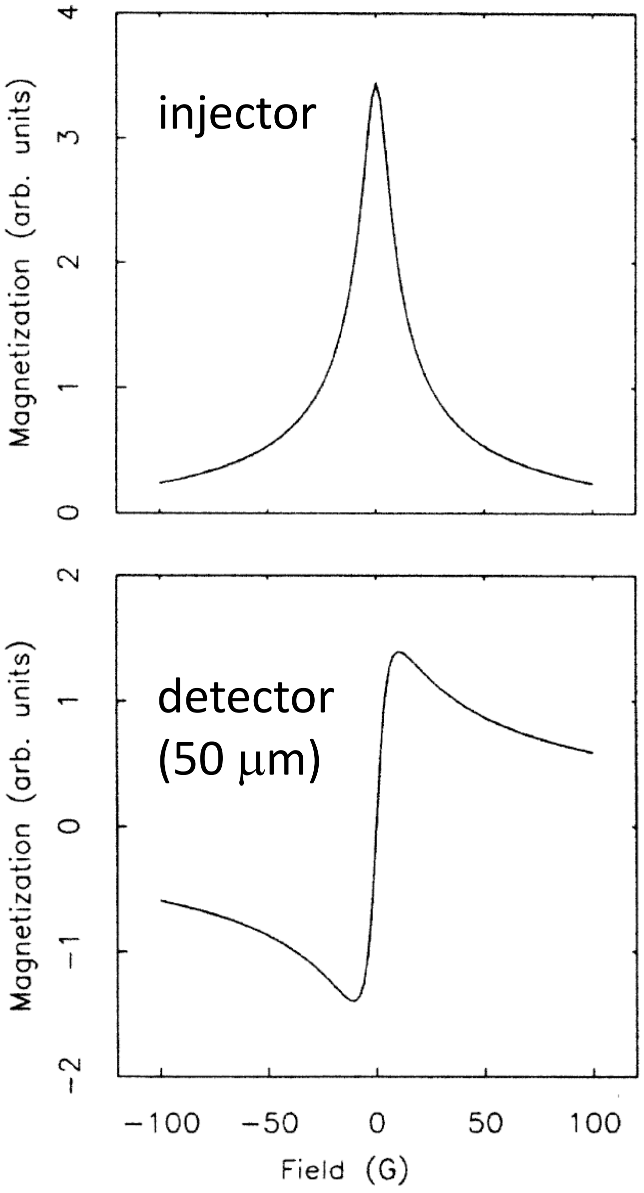
* B. T. Jonker *et al.*, *Nature Phys.* **3**, 542 (2007).

Johnson Transistors

All-metallic transistors : *







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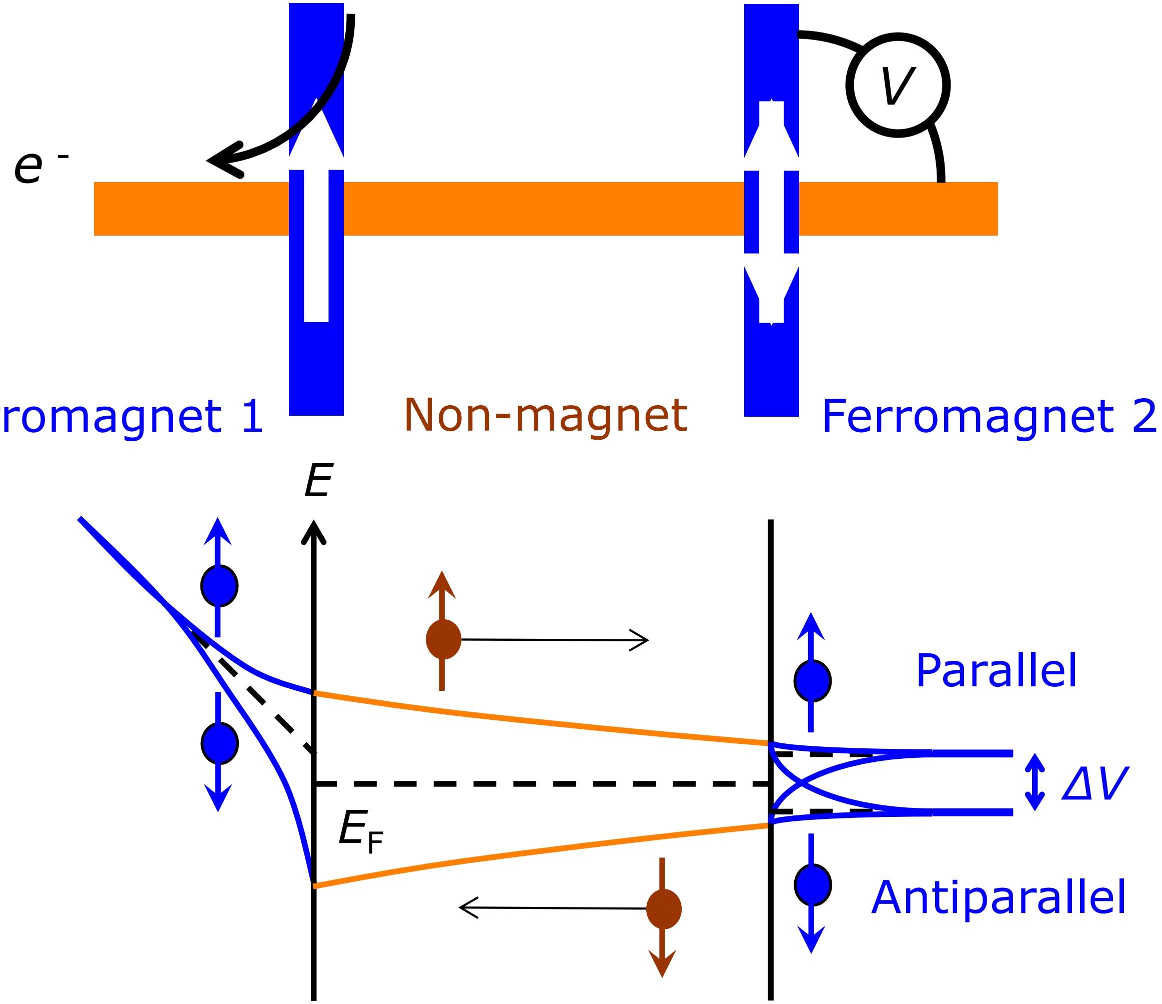
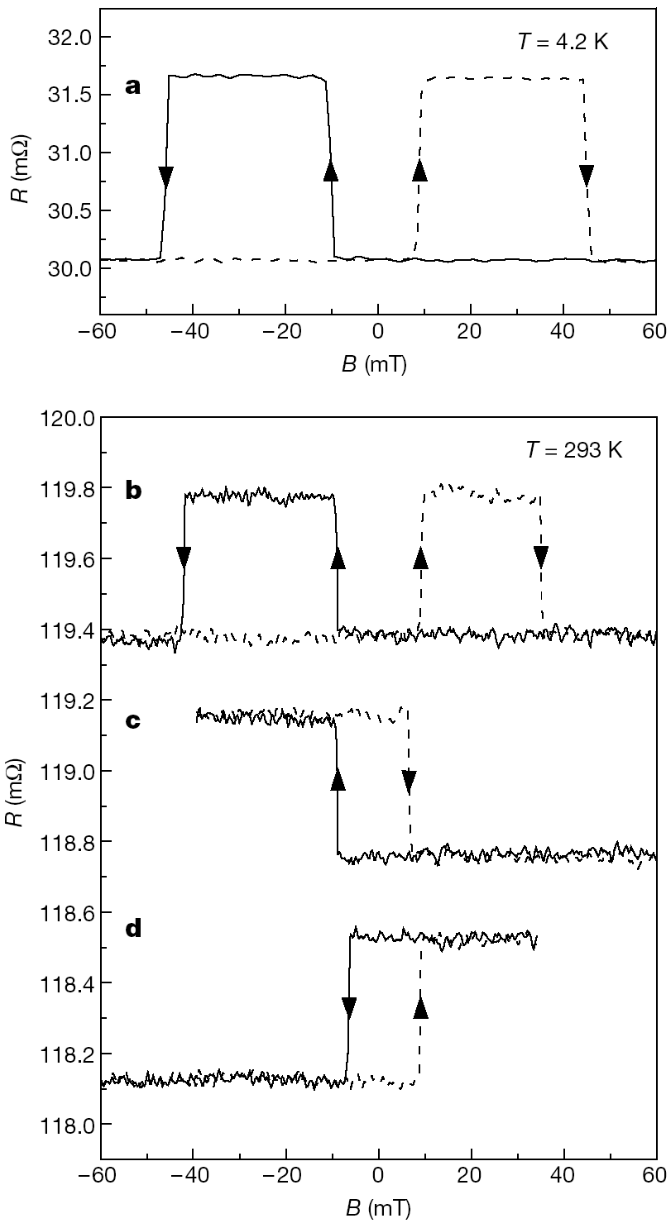
* M. Johnson and R. H. Silsbee, *Phys. Rev. Lett.* **56**, 1790 (1985), *Phys. Rev. B* **37**, 5312 (1988).

Recent Improvement

Lateral spin-valve structures with Co / Al / Co nano-wires : *

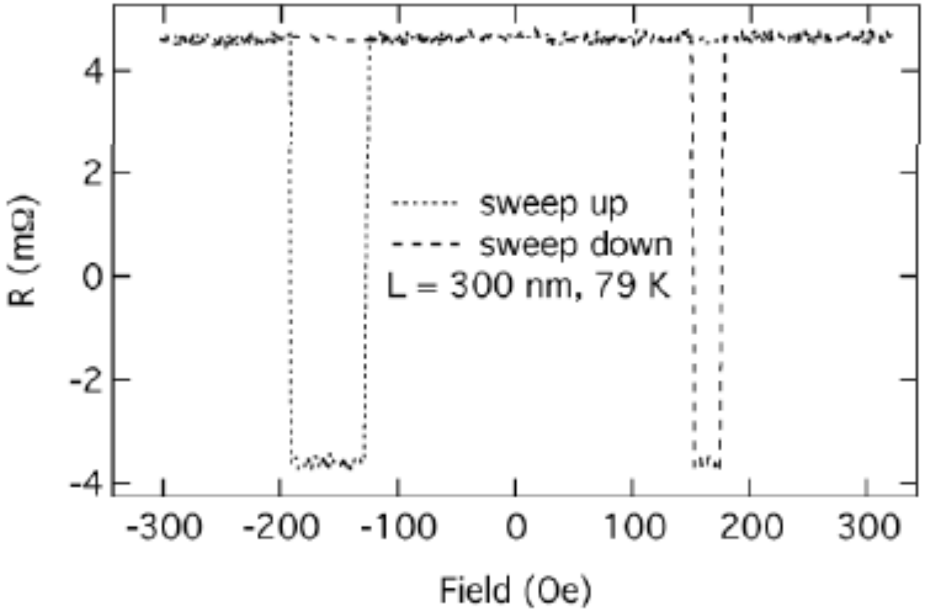




* F. J. Jedema *et al.*, *Nature* **410**, 345 (2001).

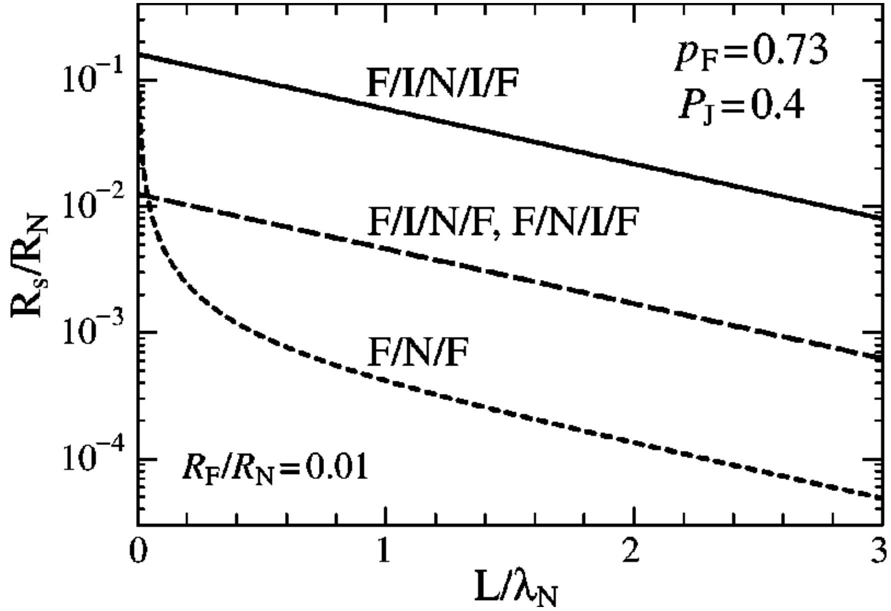
Further Enhancement in Spin-Valve Signals

Spin injection into Ag : *



Increase by one order of magnitude.

Interfacial control : **



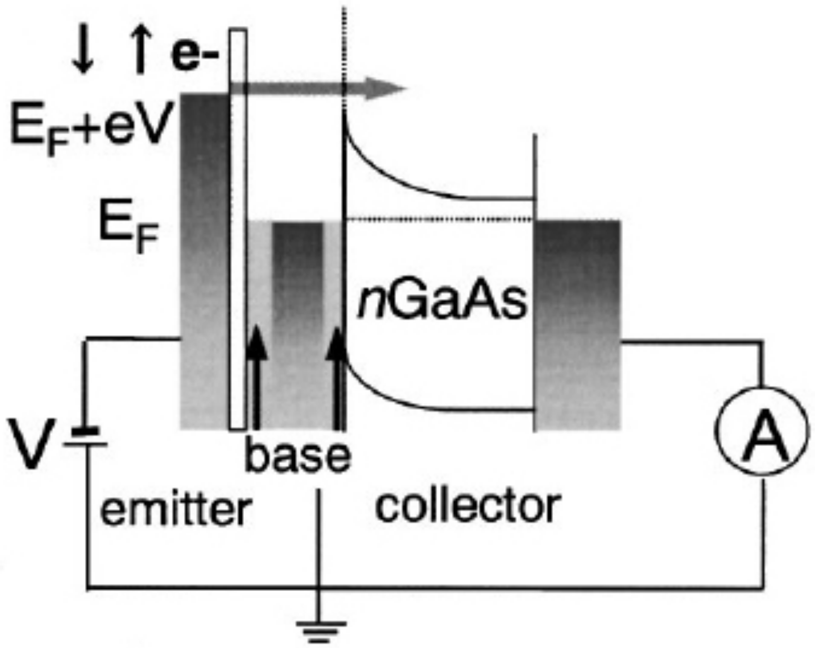
Increase spin injection efficiency
by insulator insertion (ballistic injection).

Increase spin detection efficeincy
by insulator insertion (spin voltage).
by Ohmic contact (spin current).

* R. Godfrey and M. Johnson, *Phys. Rev. Lett.* **96**, 136601 (2006);
** S. Takahashi and S. Maekawa, *Phys. Rev. B* **67**, 052409 (2003).

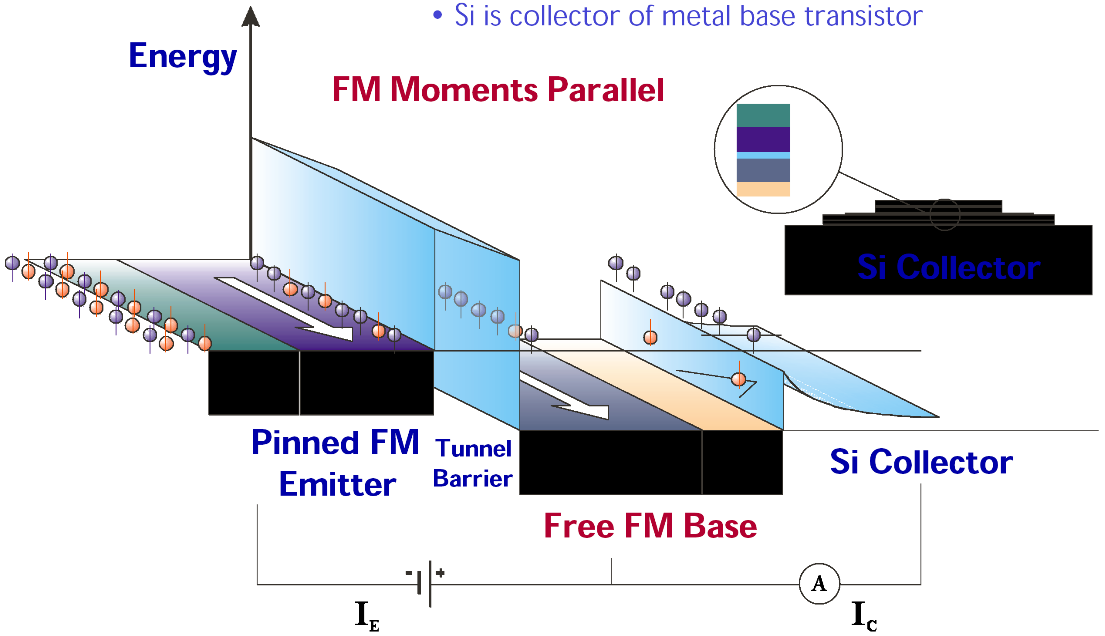
Spin Valve / Magnetic Tunnel Transistors

Spin valve transistor : *



Magnetic tunnel transistor : **

- MTJ prepared on H-terminated n doped Si
- MTJ forms emitter and base of metal base transistor
- Si is collector of metal base transistor



Combining semiconductor with GMR / TMR devices :

→ First step towards all metal devices

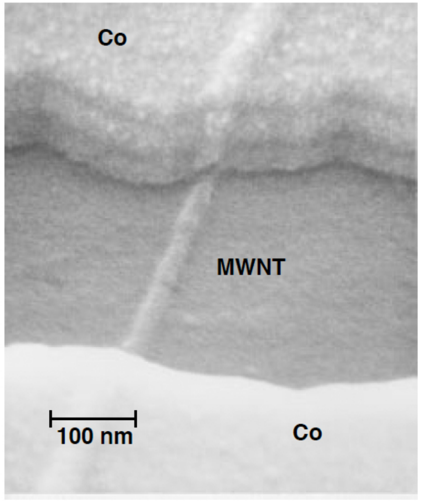
---

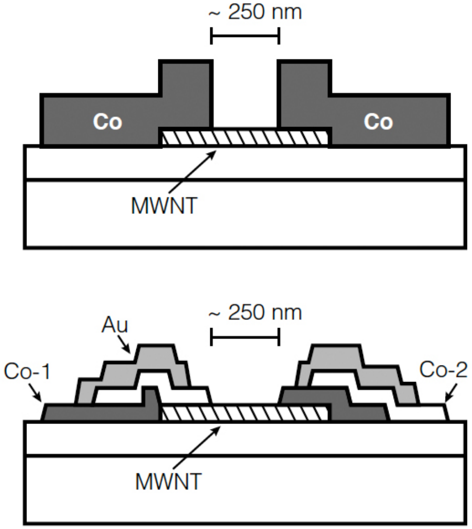
* R. Sato and K. Mizushima, *Appl. Phys. Lett.* **79**, 1157 (2001); D. J. Monsma *et al.*, *Science* **281**, 407 (1998);

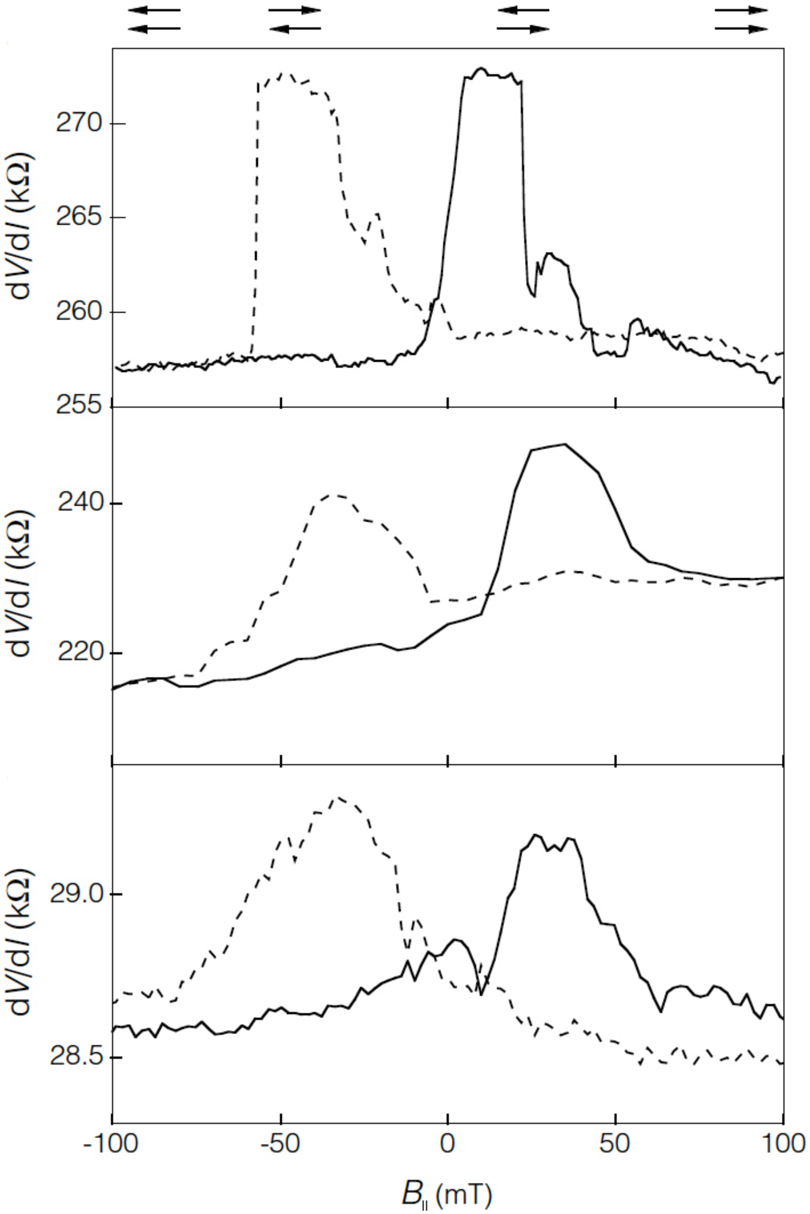
** S. S. P. Parkin, *1st Int'l Sch. on Spintronics and Quantum Info. Tech.*, May 13-15, 2001 (Maui, HI, USA).

Spin Transport in a CNT

Magnetoresistance in a multi-wall (MW) CNT :





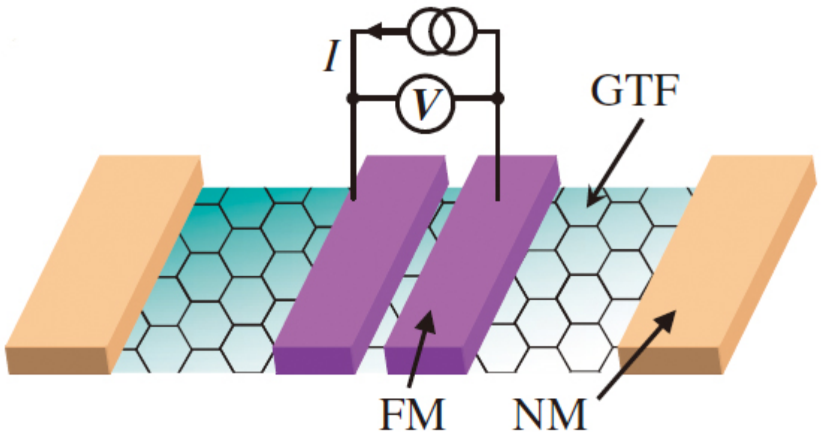


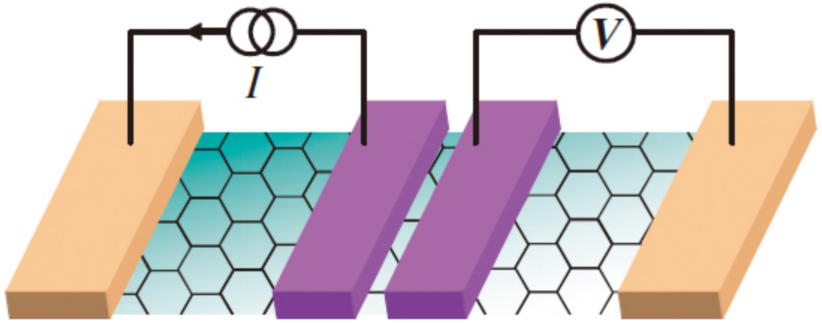
* K. Tsukagoshi *et al.*, *Nature* **401**, 572 (1999).

Spin Transport in Graphene

Spin transport in graphene at room temperature :

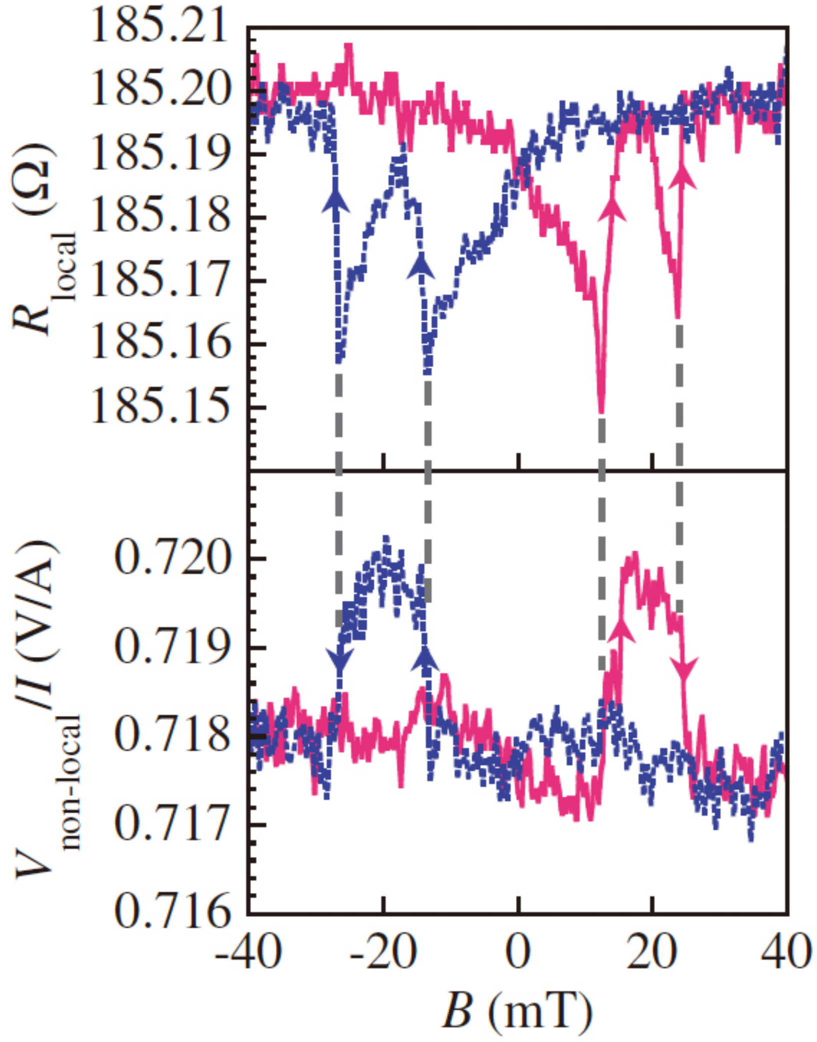
Local 2-terminal measurement





Non-local 4-terminal measurement

Anisotropic magnetoresistance (AMR)

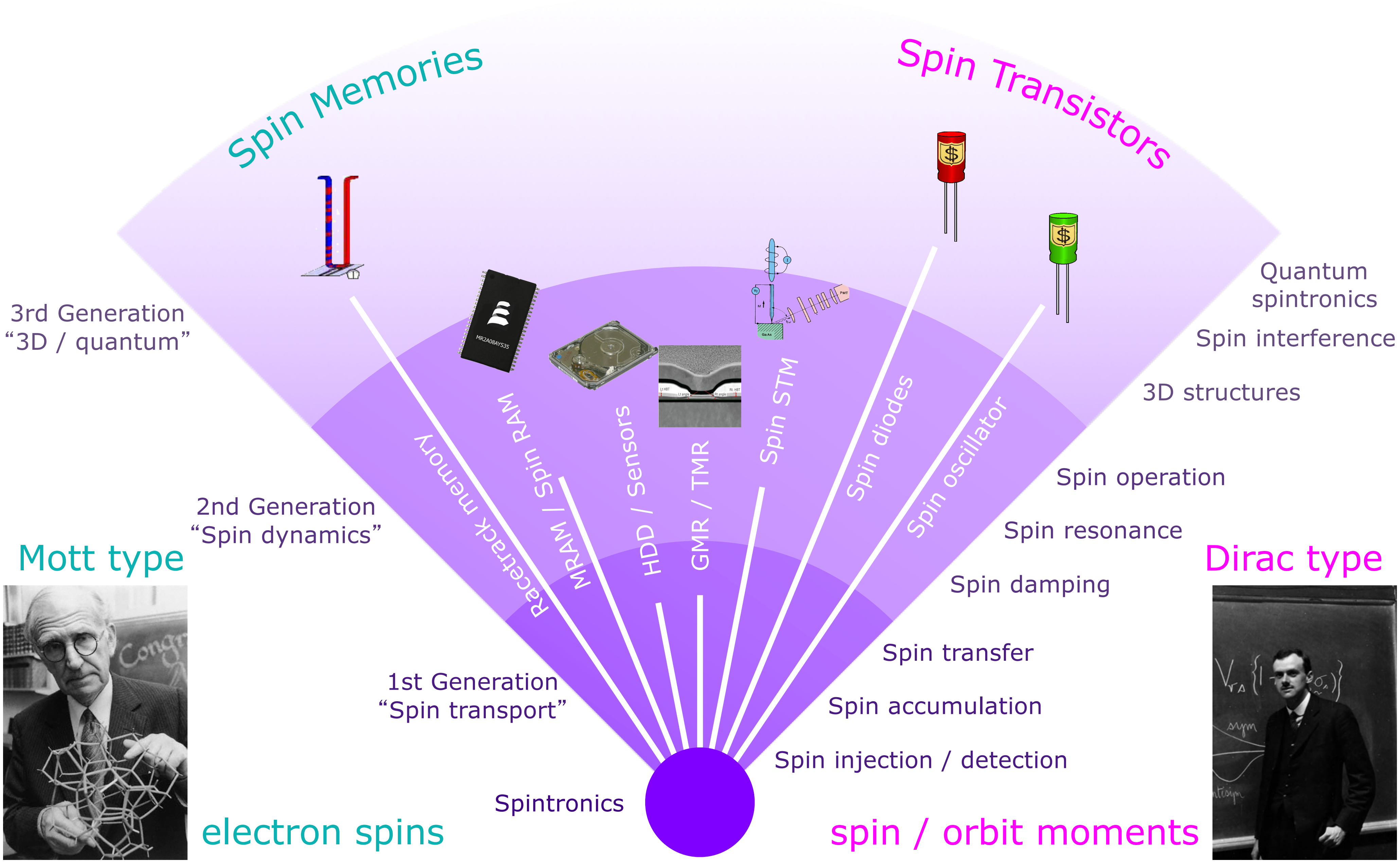


Spin transport signals

* M. Ohishi *et al.*, *Jpn. J. Appl. Phys.* **46**, L605 (2007).

Nano-Spintronic Devices

Development of nano-spintronic devices : *



Spin Memories

Spin Transistors

Racetrack memory

MRAM / Spin RAM

HDD / Sensors

GMR / TMR

Spin STM

Spin diodes

Spin oscillator

3rd Generation
"3D / quantum"

Quantum spintronics

Spin interference

3D structures

2nd Generation
"Spin dynamics"

Spin operation

Spin resonance

Spin damping

1st Generation
"Spin transport"

Spin transfer

Spin accumulation

Spin injection / detection

Spintronics

Mott type

electron spins

Dirac type

spin / orbit moments

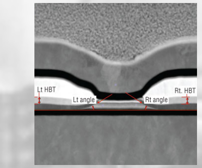
---

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

Two Categories for Spintronic Devices

Mott-type

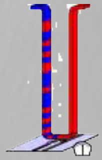
Electron (hole) spins



GMR / TMR

HDD / Sensors

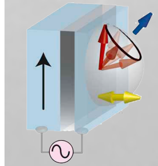
MRAM / Spin RAM



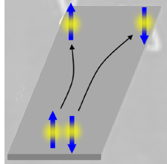
Racetrack memory

Dirac-type

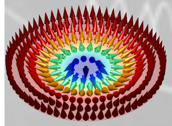
Spin and orbital moments



TAMR

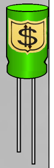


Spin Hall

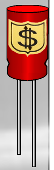


Skyrmions

Spin transistor



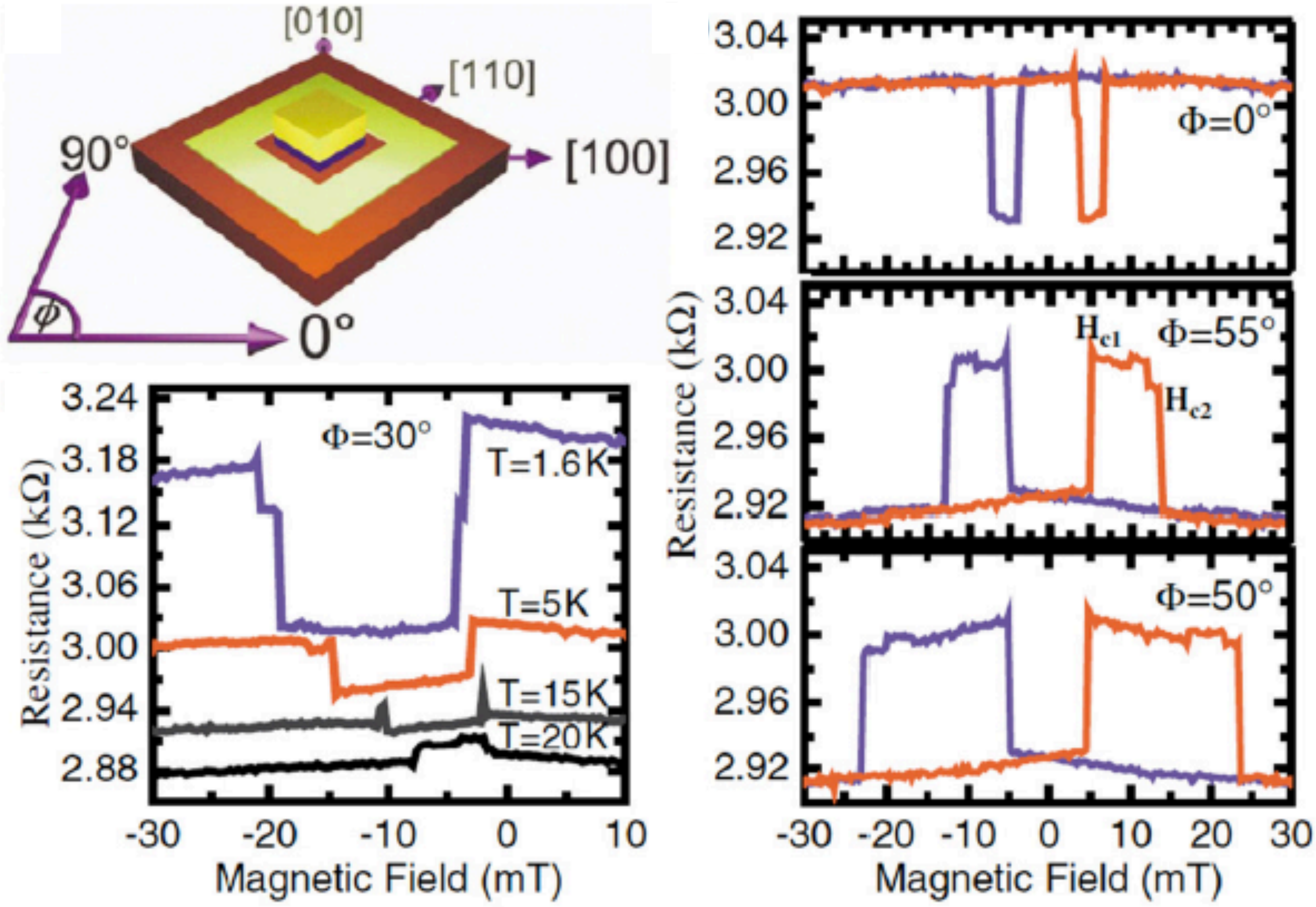
Spin LED



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

Tunnelling Anisotropic Magnetoresistance

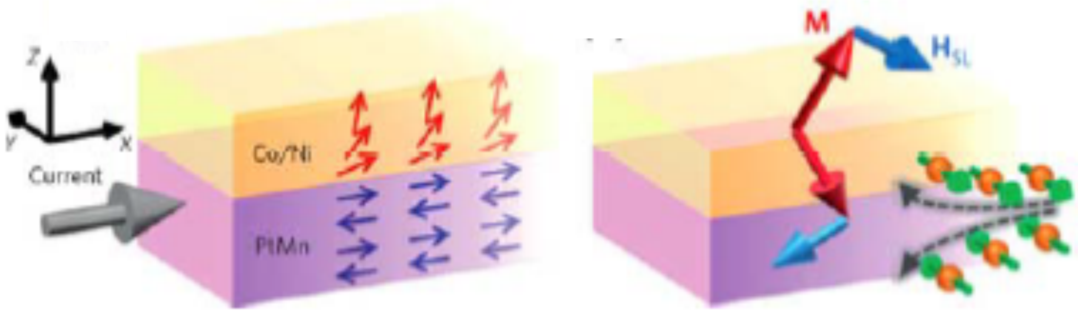
70 nm GaMnAs / GaAs (001) : *

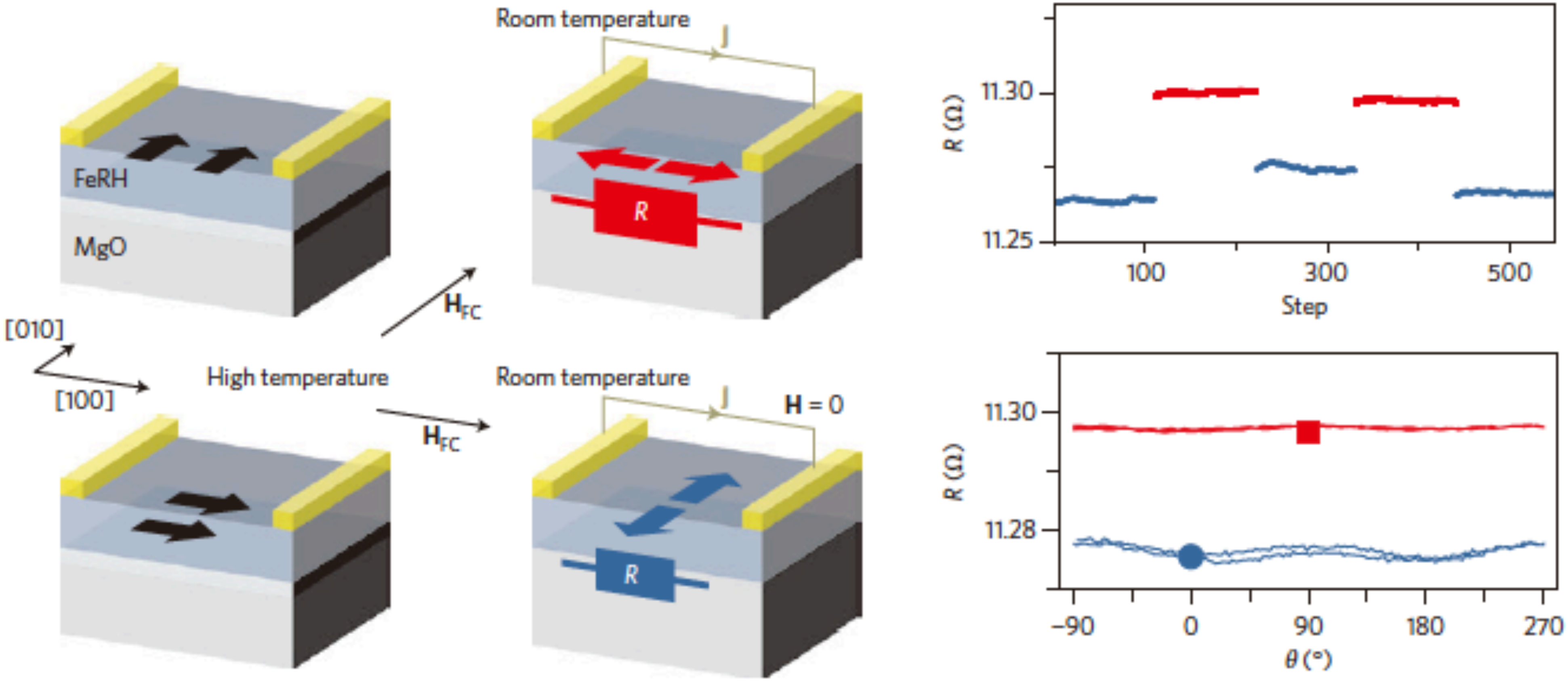


* C. Gould *et al.*, *Phys. Rev. Lett.* **93**, 117203 (2004).

Antiferromagnetic Spintronics

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

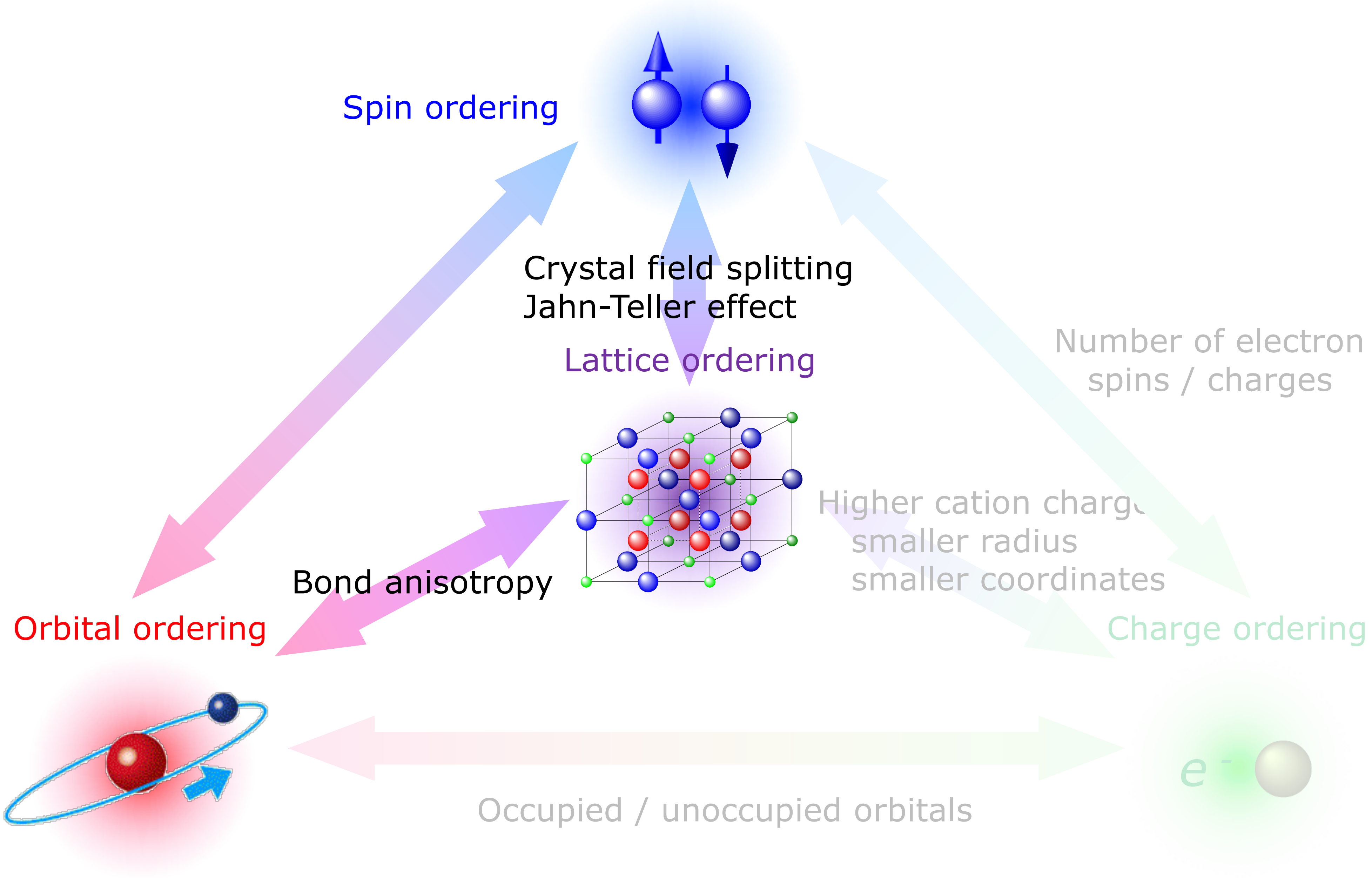




* O. Gomonay *et al.*, *Phys. Status Solidi* **11**, 1700022 (2017);
** T. Jungwirth et al., *Nature Nanotechnol.* **11**, 231 (2016).

Spin-Orbit Interaction

In strongly correlated systems : *



Spin ordering

Crystal field splitting
Jahn-Teller effect

Lattice ordering

Number of electron
spins / charges

Higher cation charge
smaller radius
smaller coordinates

Bond anisotropy

Orbital ordering

Charge ordering

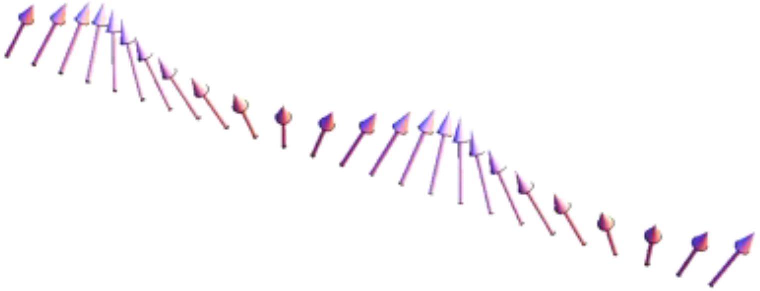
Occupied / unoccupied orbitals

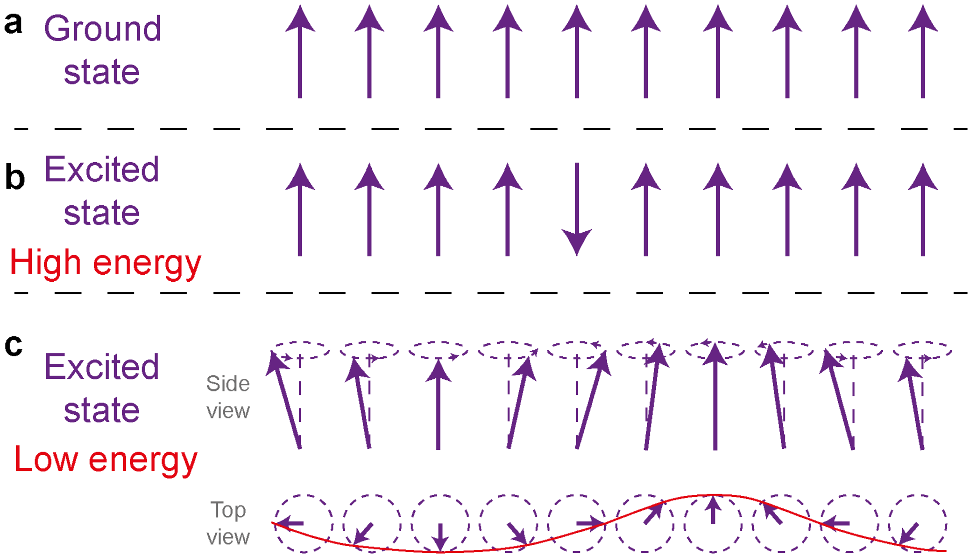
---

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

Spin Wave

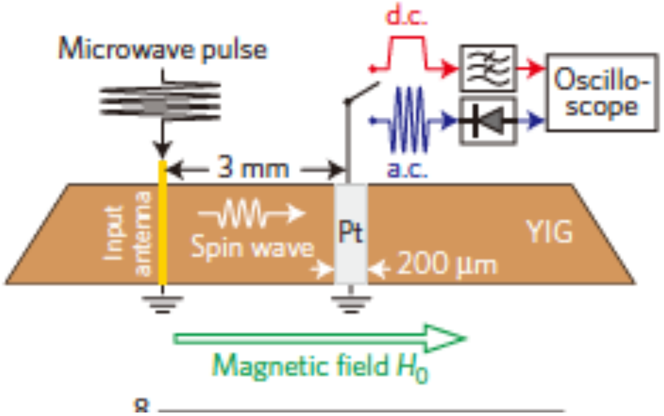
Spin wave (magnon) : *

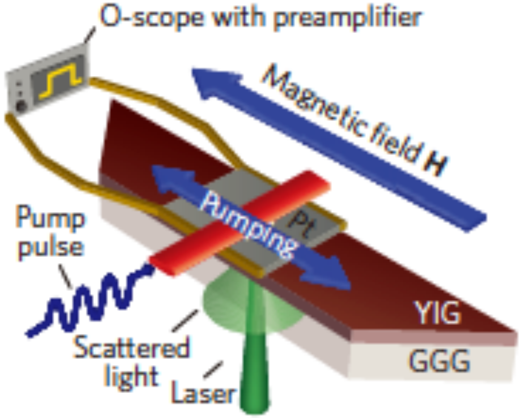


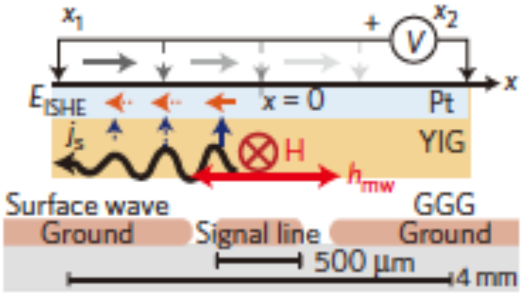


Analogous to phonon, quantised crystalline lattice.

Magnon introduction : **





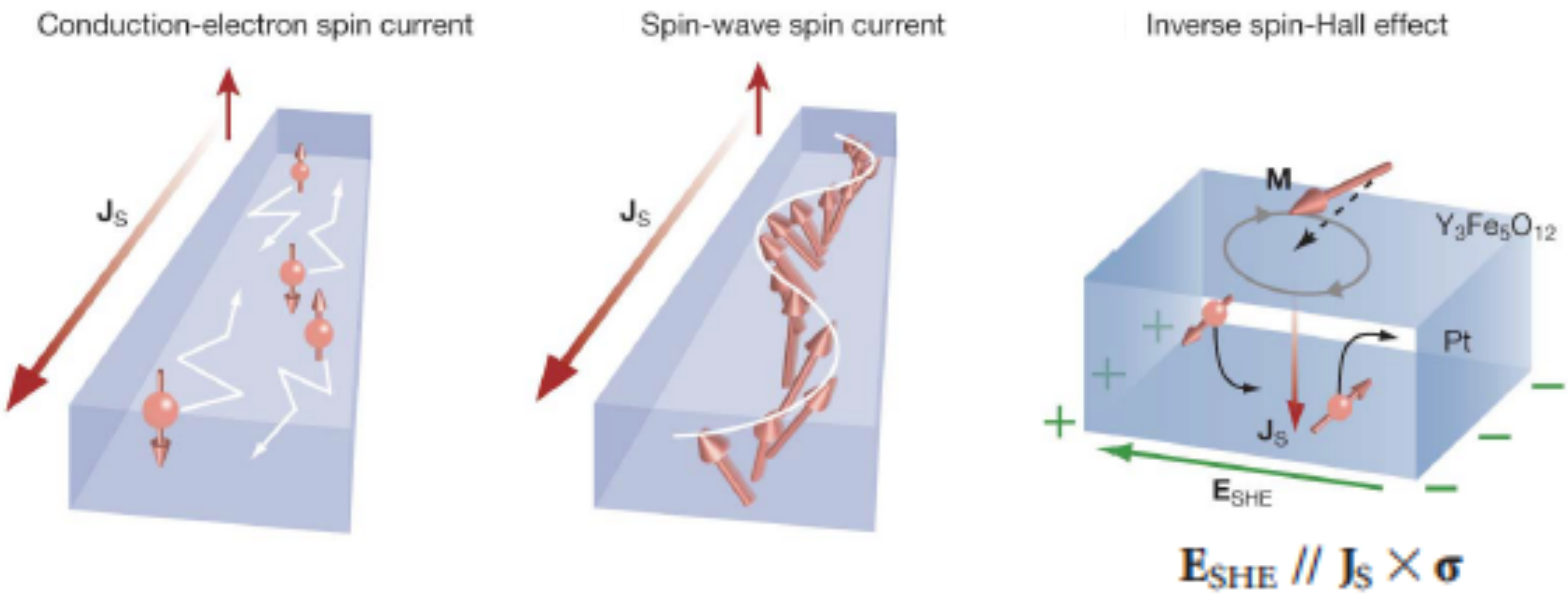


* https://www.youtube.com/watch?v=pWQ3r-2Xjeo

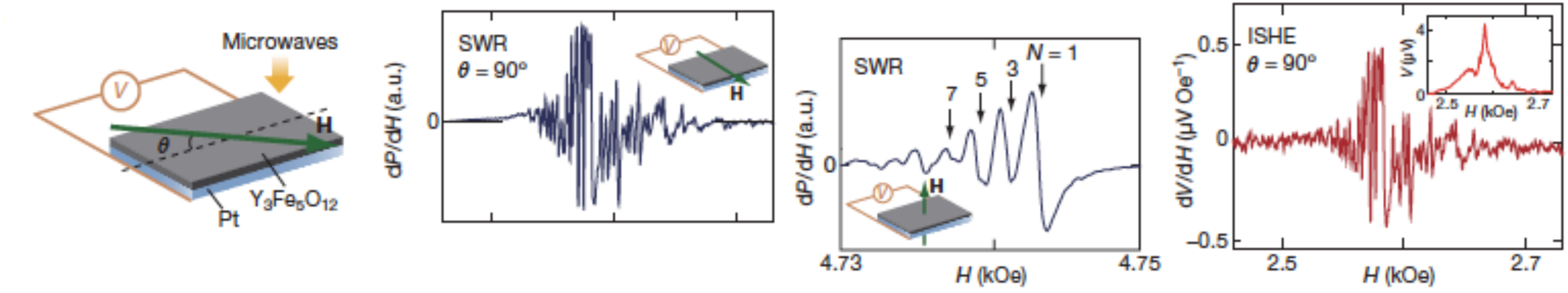
** A. V. Chumak *et al.*, *Nature Phys.* **11**, 453 (2015).

Microwave-Induced Spin Currents

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



$$\mathbf{E}_{\mathrm{SHE}} \,/\!/\, \mathbf{J}_S \times \boldsymbol{\sigma}$$



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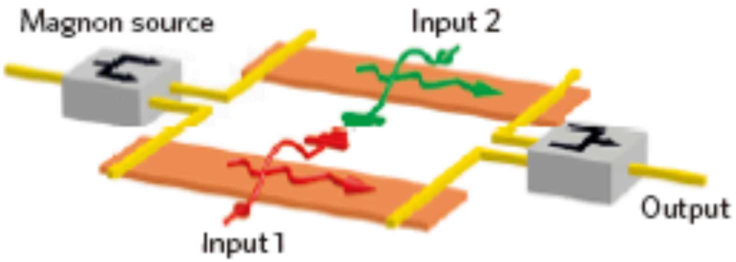
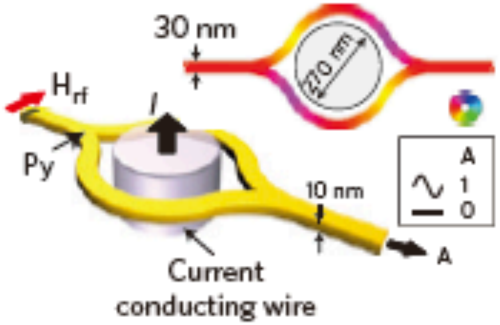
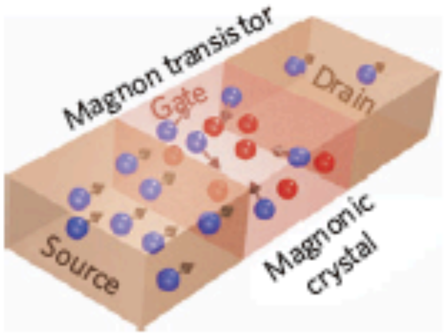
* Y. Kajiwara *et al.*, *Nature* **464**, 262 (2010).

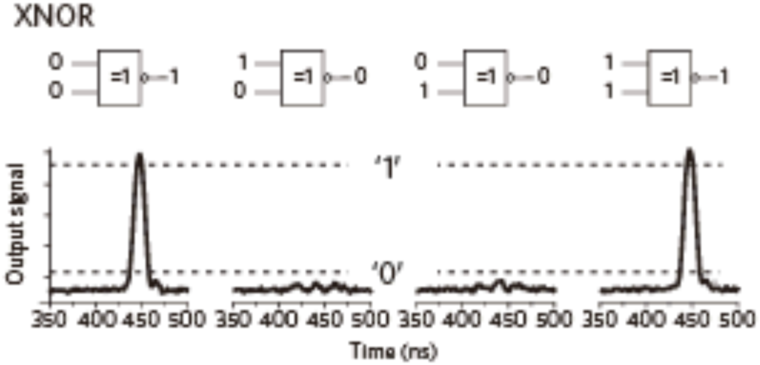
Spin Wave Logics

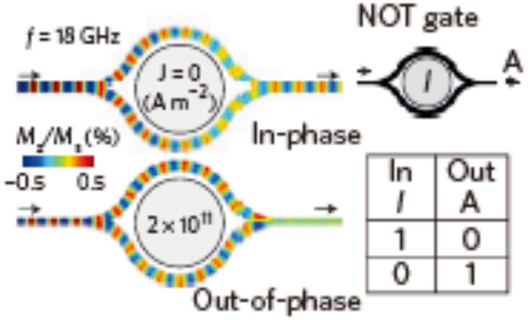
Magnonics : *



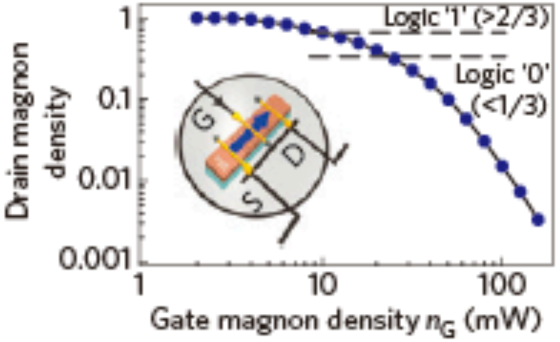


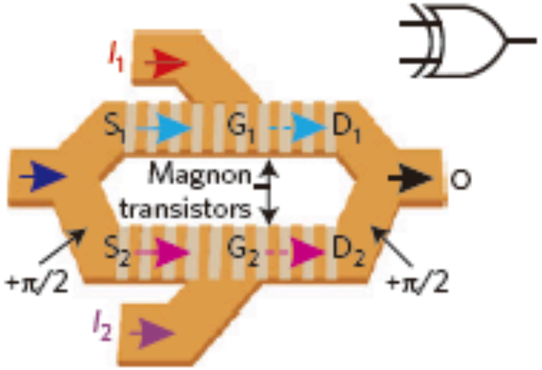






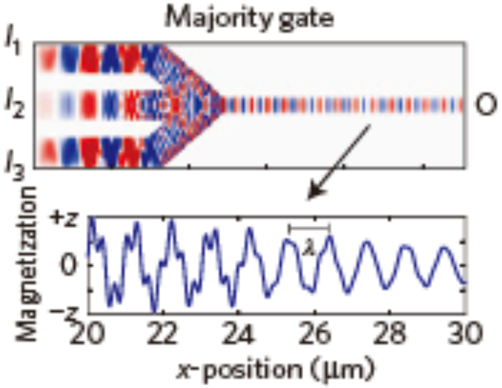
In	Out
I	A
1	0
0	1





XOR

I_1	I_2	O
0	0	0
0	1	1
1	0	1
1	1	0



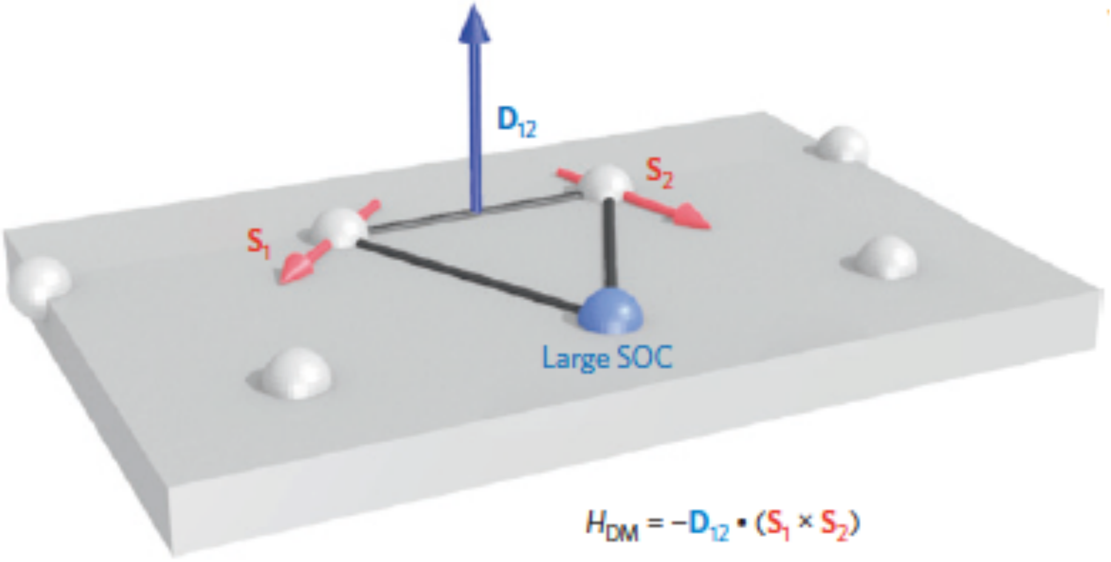
I_1	I_2	$I_3 = I_c$	O	
0	0	0	0	AND
1	0	0	0	
0	1	0	0	
1	1	0	1	
0	0	1	0	OR
1	0	1	1	
0	1	1	1	
1	1	1	1	

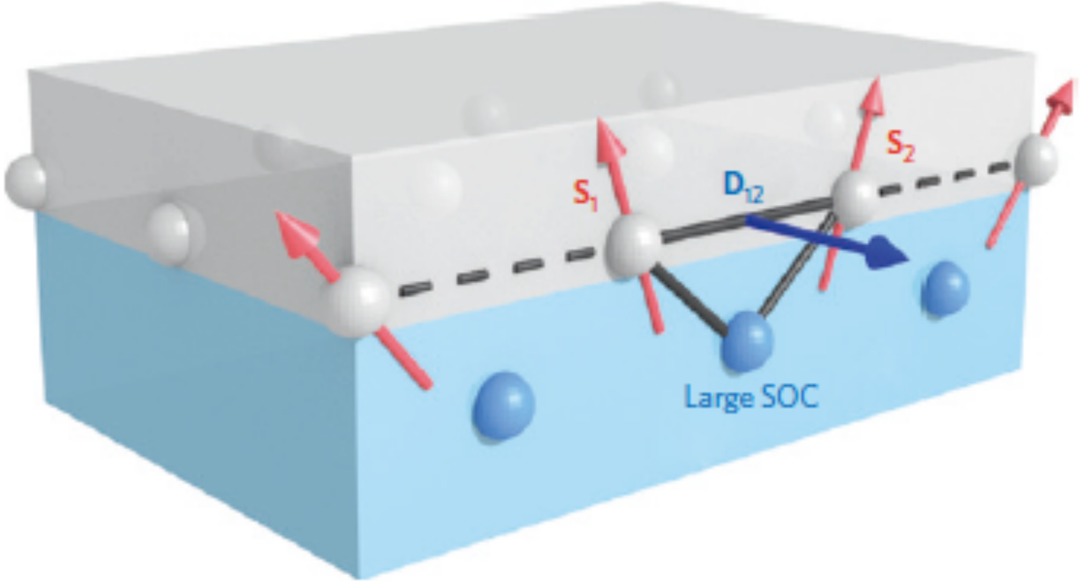
---

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

Dzyaloshinskii-Moriya Interactions

Dzaloshinskii-Moriya interactions (DMI) between canted spins : *

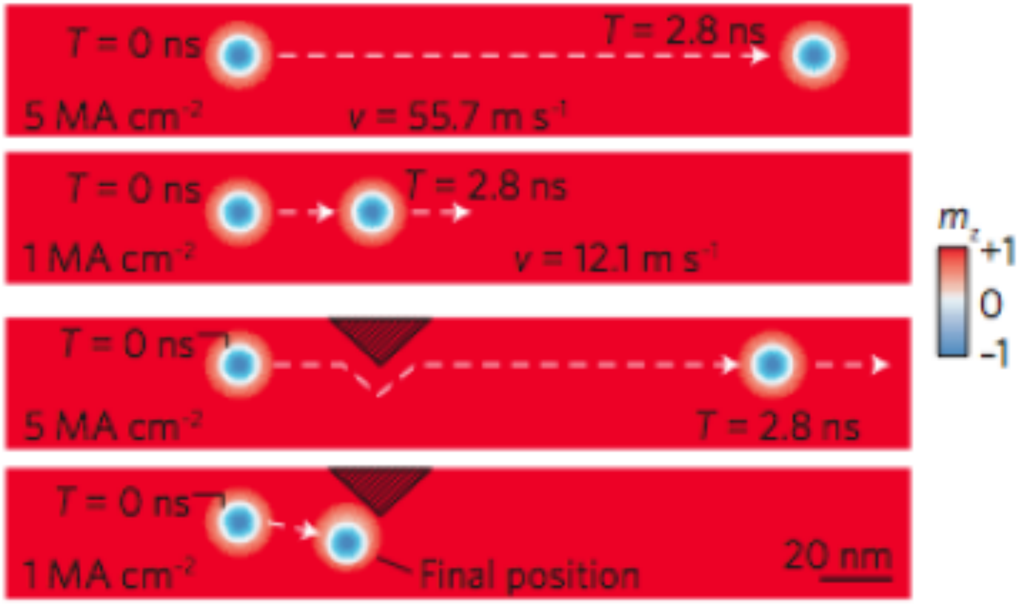


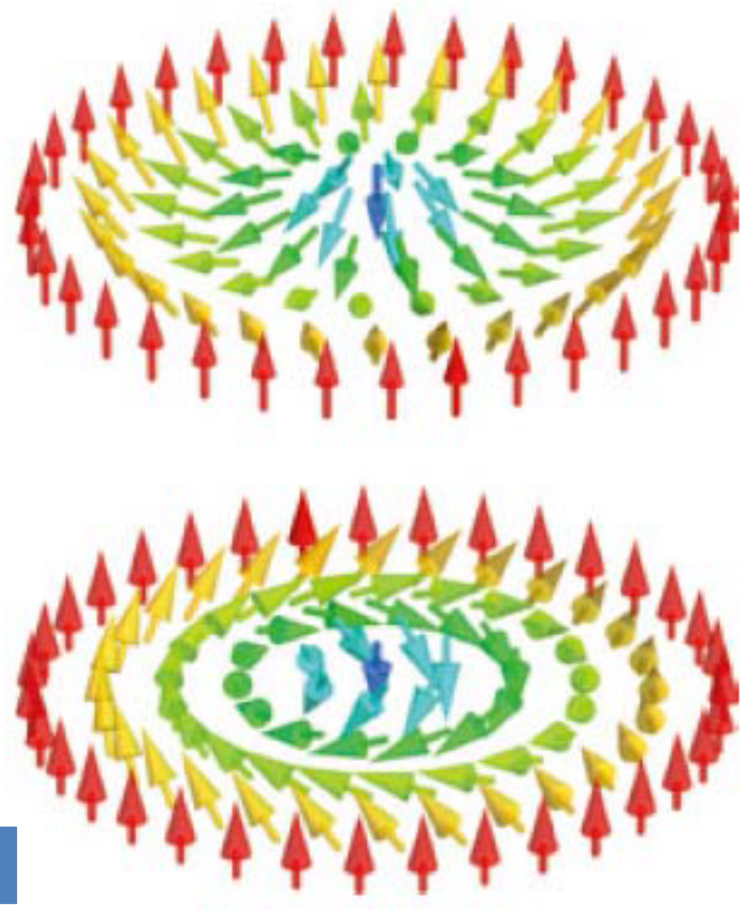


* I. Dzyaloshinskii, *J. Phys. Chem. Solids* **4**, 241 (1958); T. Moriya, *Phys. Rev.* **120**, 91 (1960);
** A. Fert *et al.*, *Nature Nanotechnol.* **8**,152 (2013).

Skyrmion Motion by a Current

500 × 40 × 0.4 nm^3 Co stripes with DMI of 1.4 meV per atom : *

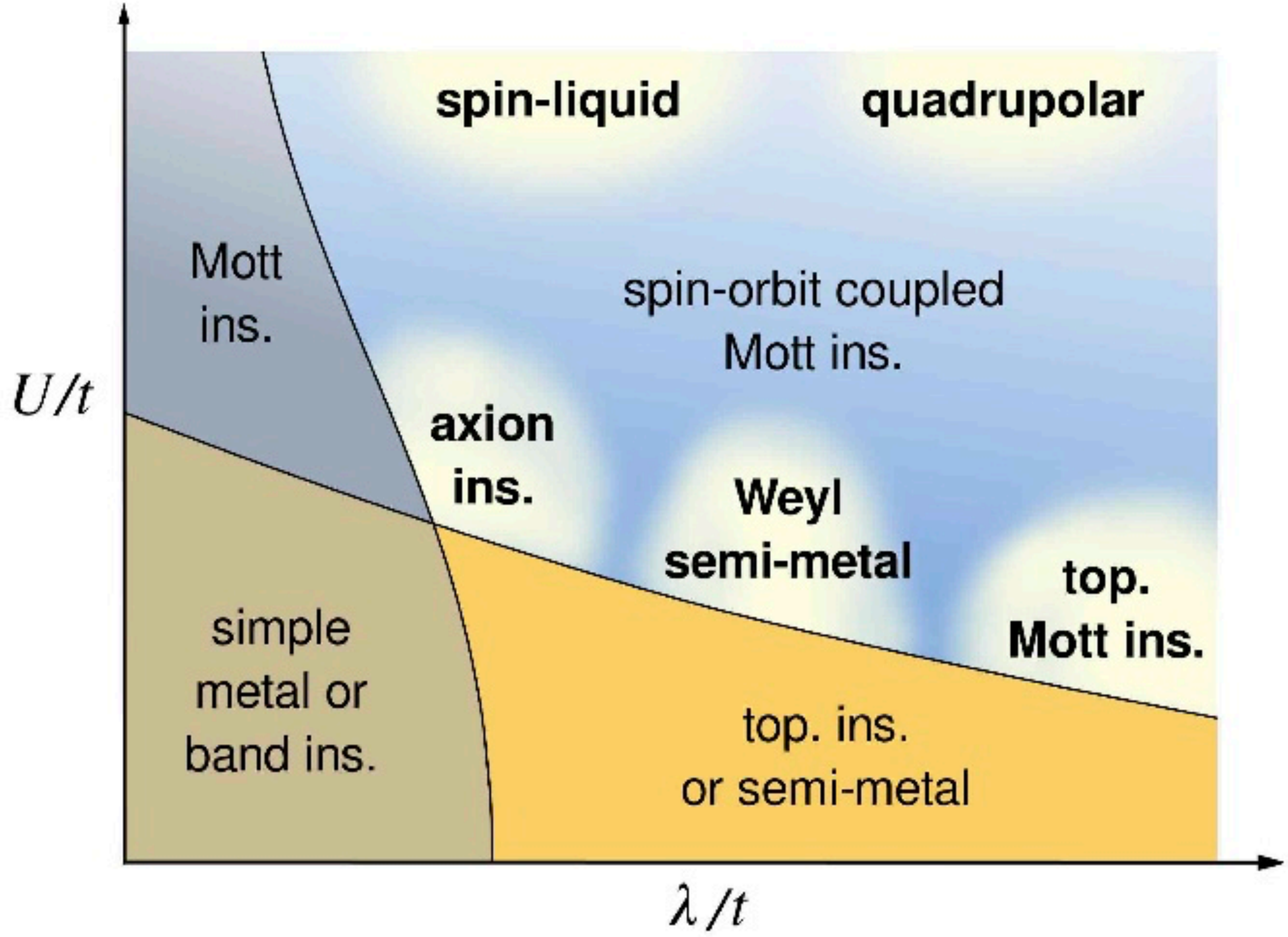




	Skyrmions	Domain walls
Size [nm]	1~10	100~1,000
Velocity [m/s]	~100	~500
Critical current density [A/cm]	10^2	~10^7

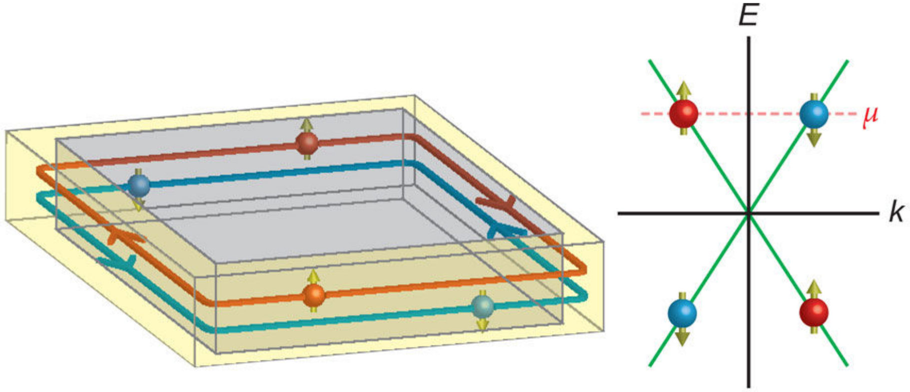
* A. Fert *et al.*, *Nature Nanotechnol.* **8**,152 (2013);
** N. Romming *et al.*, *Phys. Rev. Lett.* **114**, 177203 (2015).

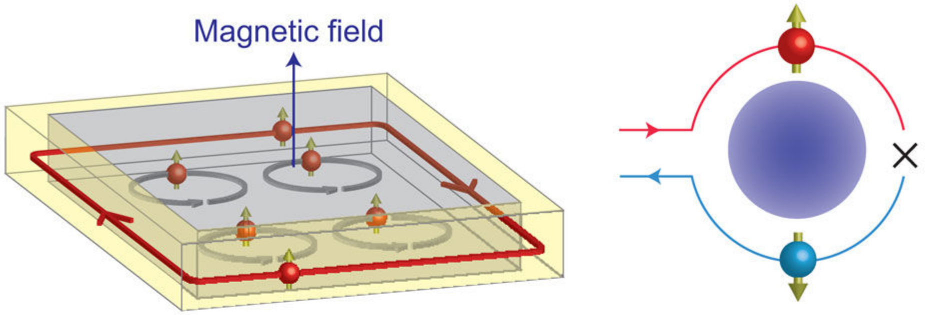
Spin-Orbit Coupling Energy

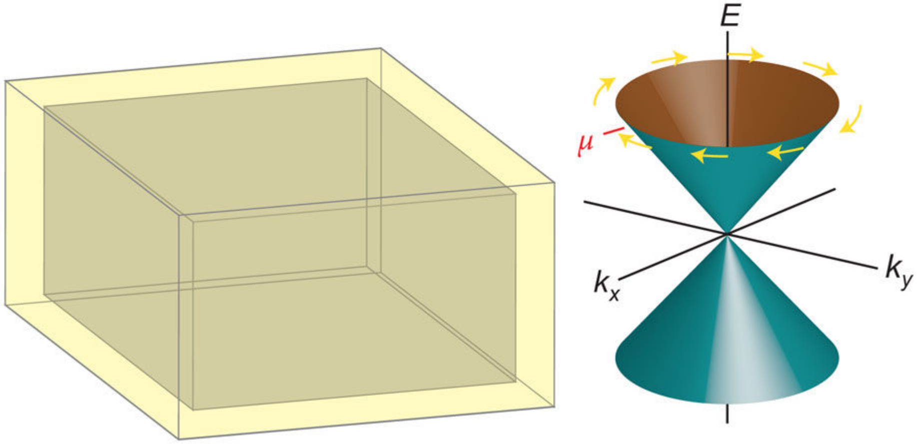


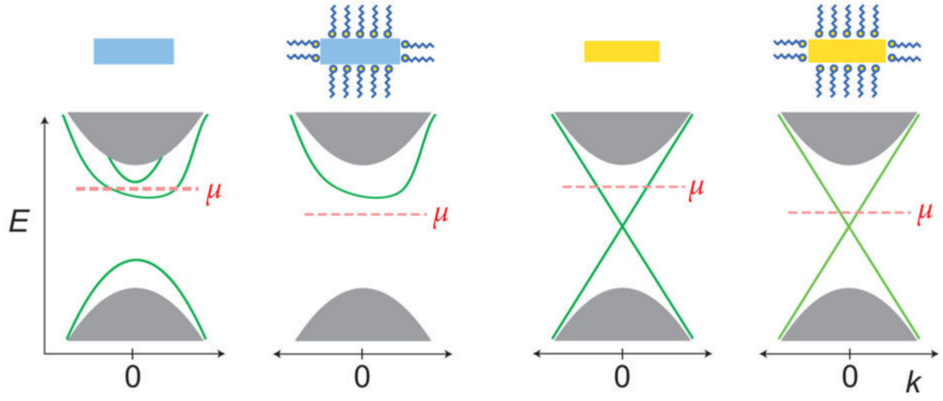
* http://condensedconcepts.blogspot.co.uk/2013/05/mott-physics-with-spin-orbit-coupling.html.

Topological Insulators



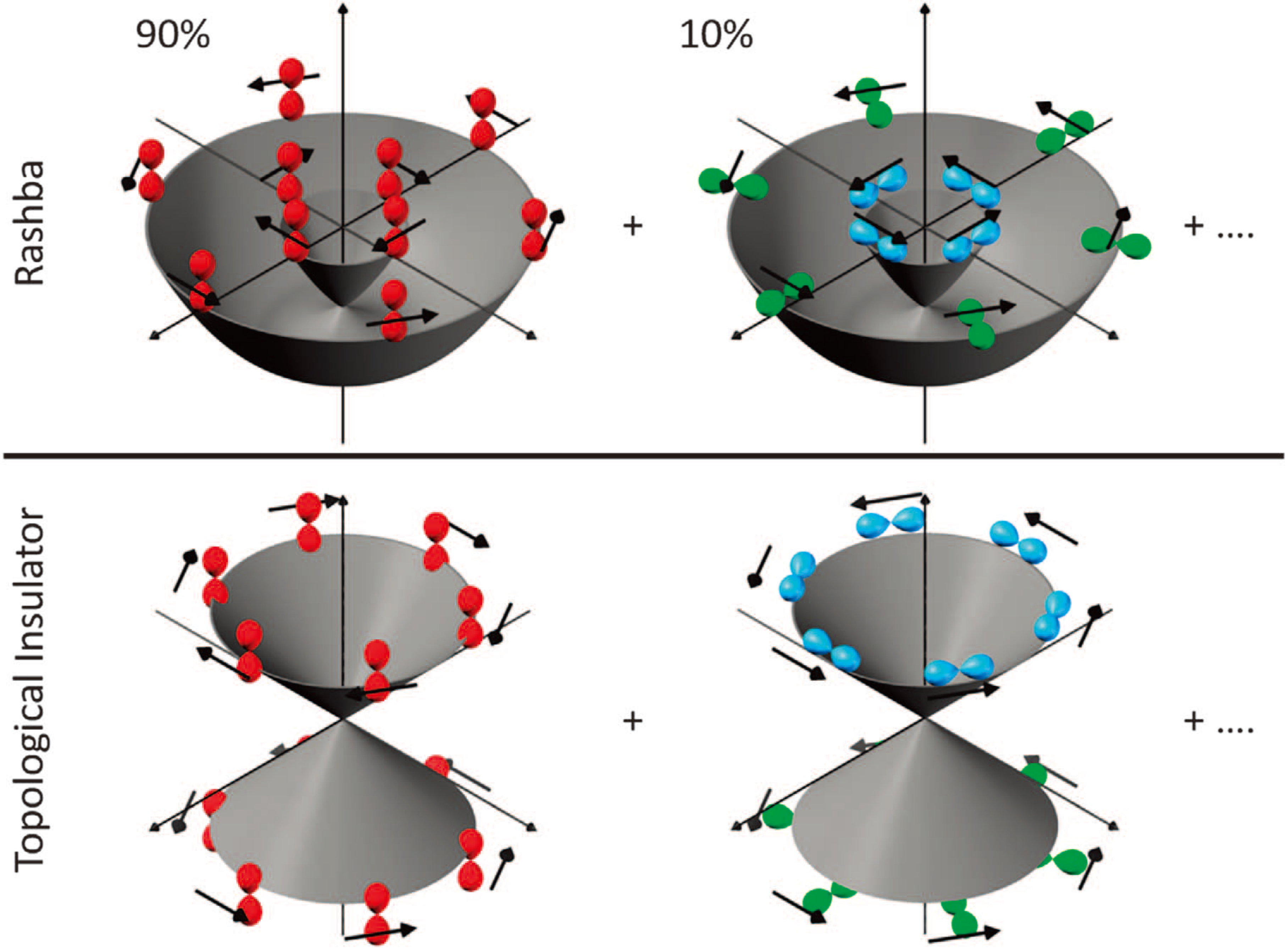






* D. Kong and Y. Cui, *Nature Chem.* **3**, 845 (2011).

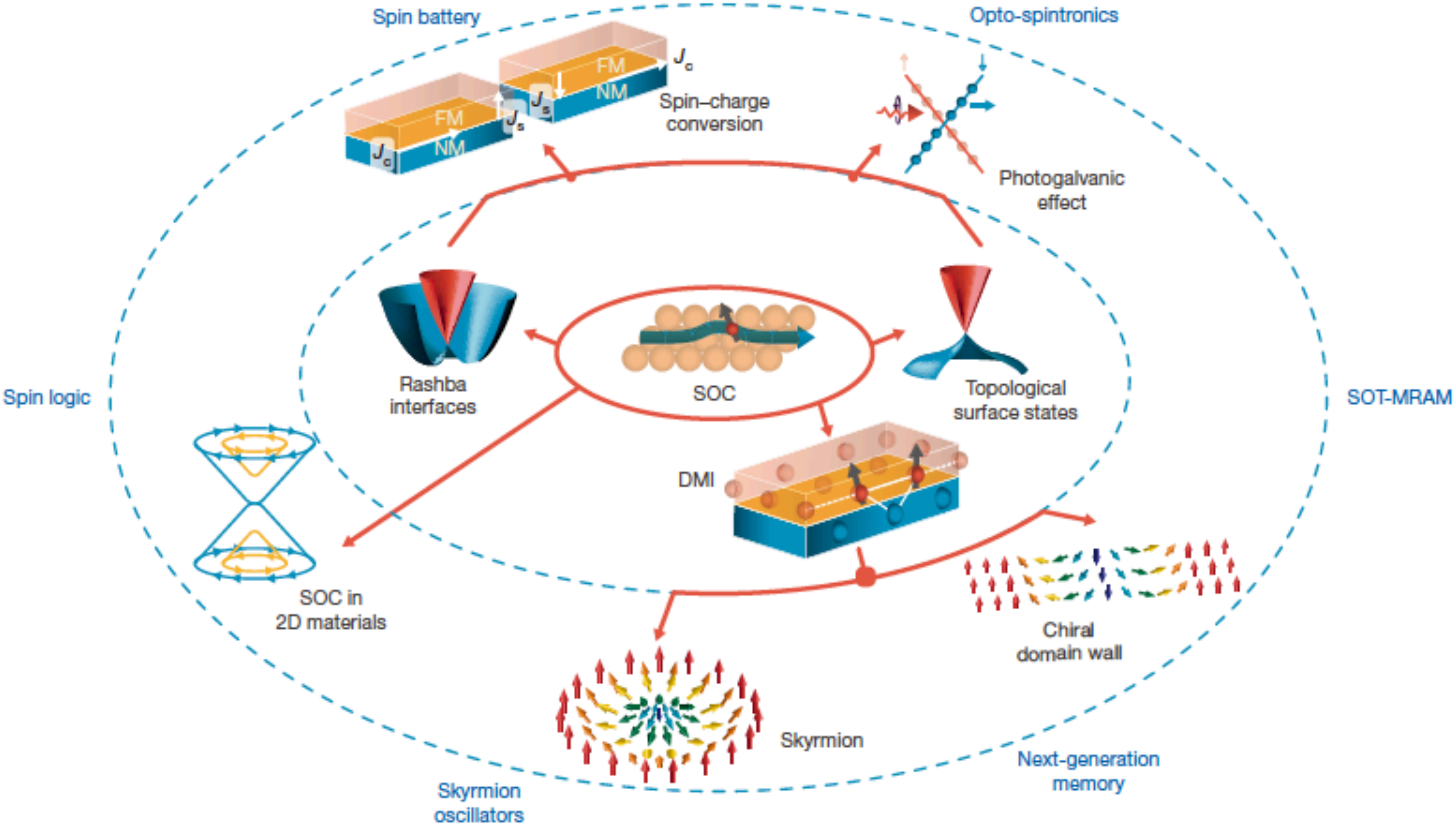
Spin Coupled to In-Plane Orbit



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

Phenomena with the Spin-Orbit Coupling

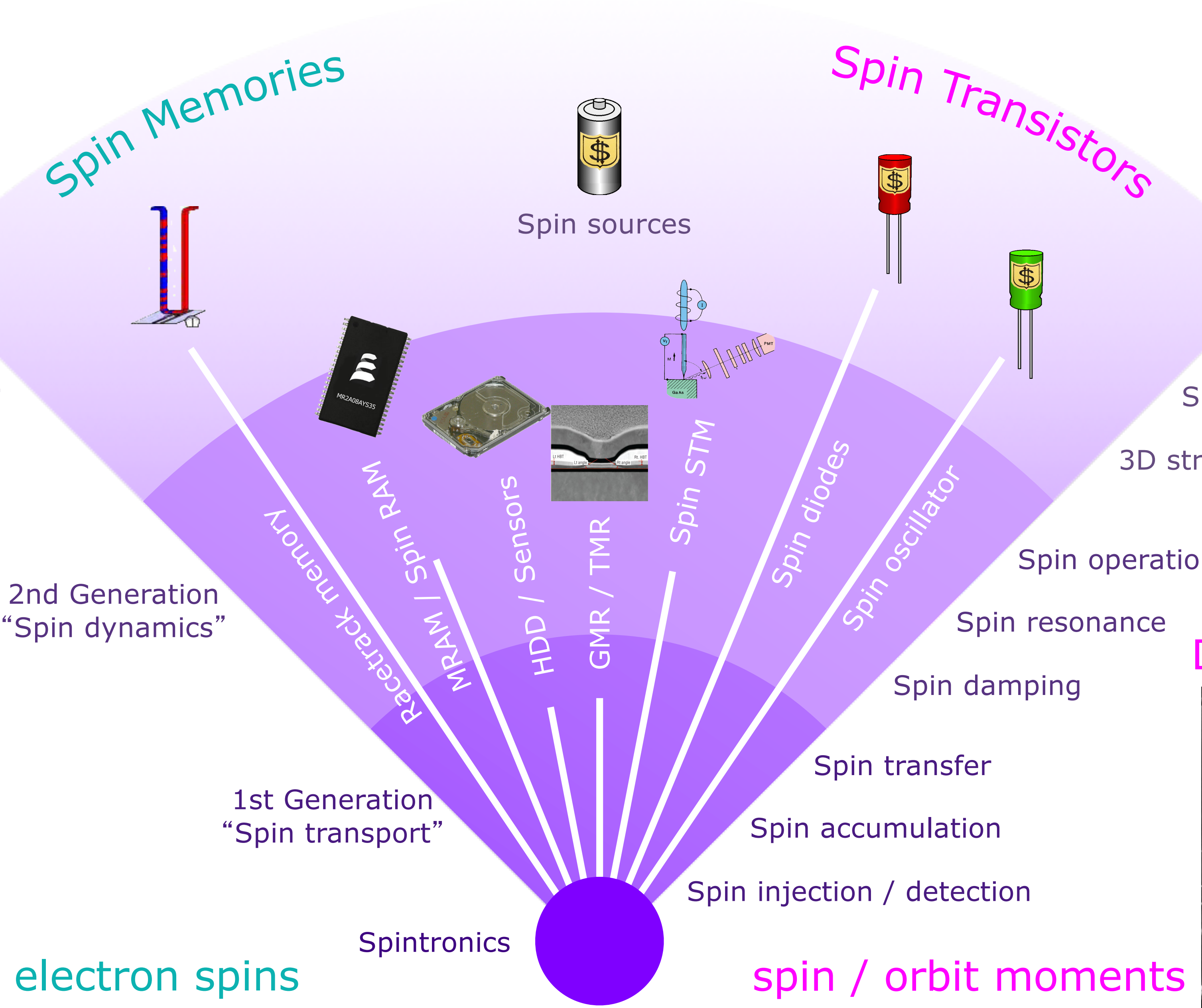
Spin-orbitronics : *



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

Nano-Spintronic Devices

Development of nano-spintronic devices : *



Spin Memories

Spin sources

Spin Transistors

Racetrack memory

MRAM / Spin RAM

HDD / Sensors

GMR / TMR

Spin STM

Spin diodes

Spin oscillator

3rd Generation
"3D / quantum"

Quantum spintronics

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3D structures

2nd Generation
"Spin dynamics"

Spin operation

Spin resonance

Spin damping

1st Generation
"Spin transport"

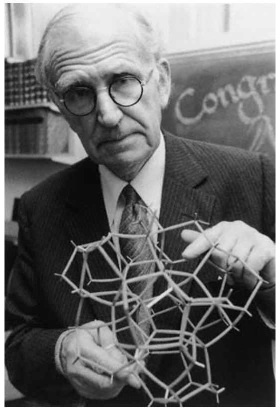
Spin transfer

Spin accumulation

Spin injection / detection

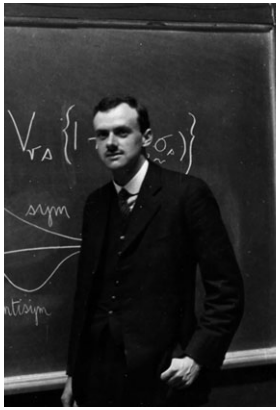
Spintronics

Mott type



electron spins

Dirac type



spin / orbit moments

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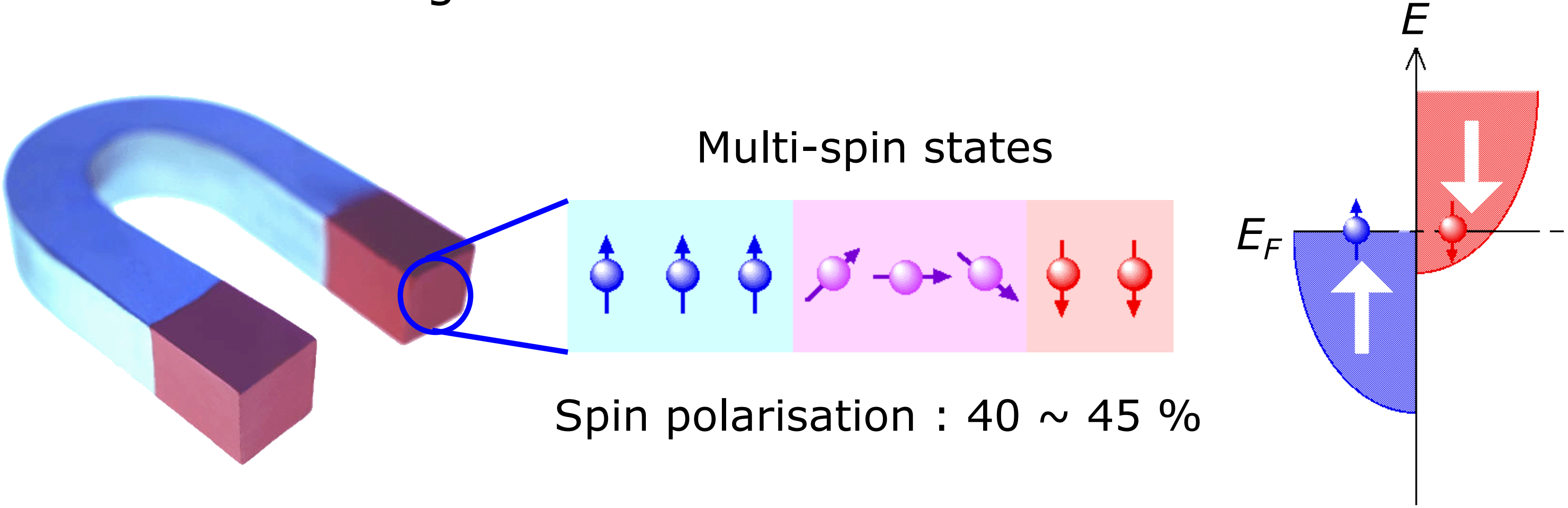
* A. Hirohata and K. Takanashi, *J. Phys. D: Appl. Phys.* **47**, 1930001 (2014).

Half-Metallic Feromagnet

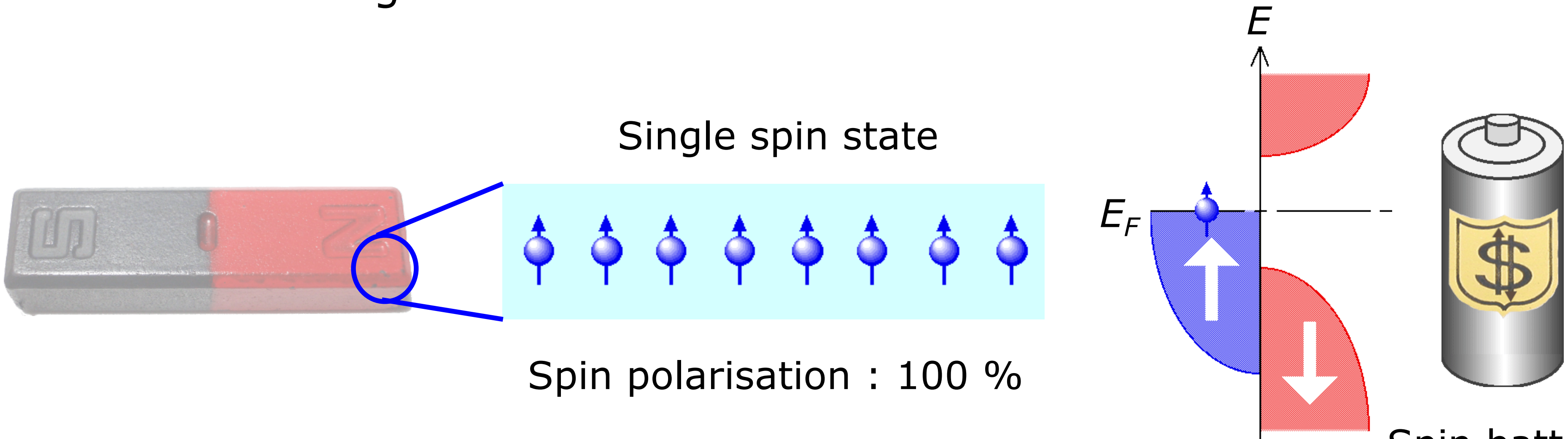
Conventional ferromagnet :



Multi-spin states

Spin polarisation : 40 ~ 45 %

Half-metallic ferromagnet :



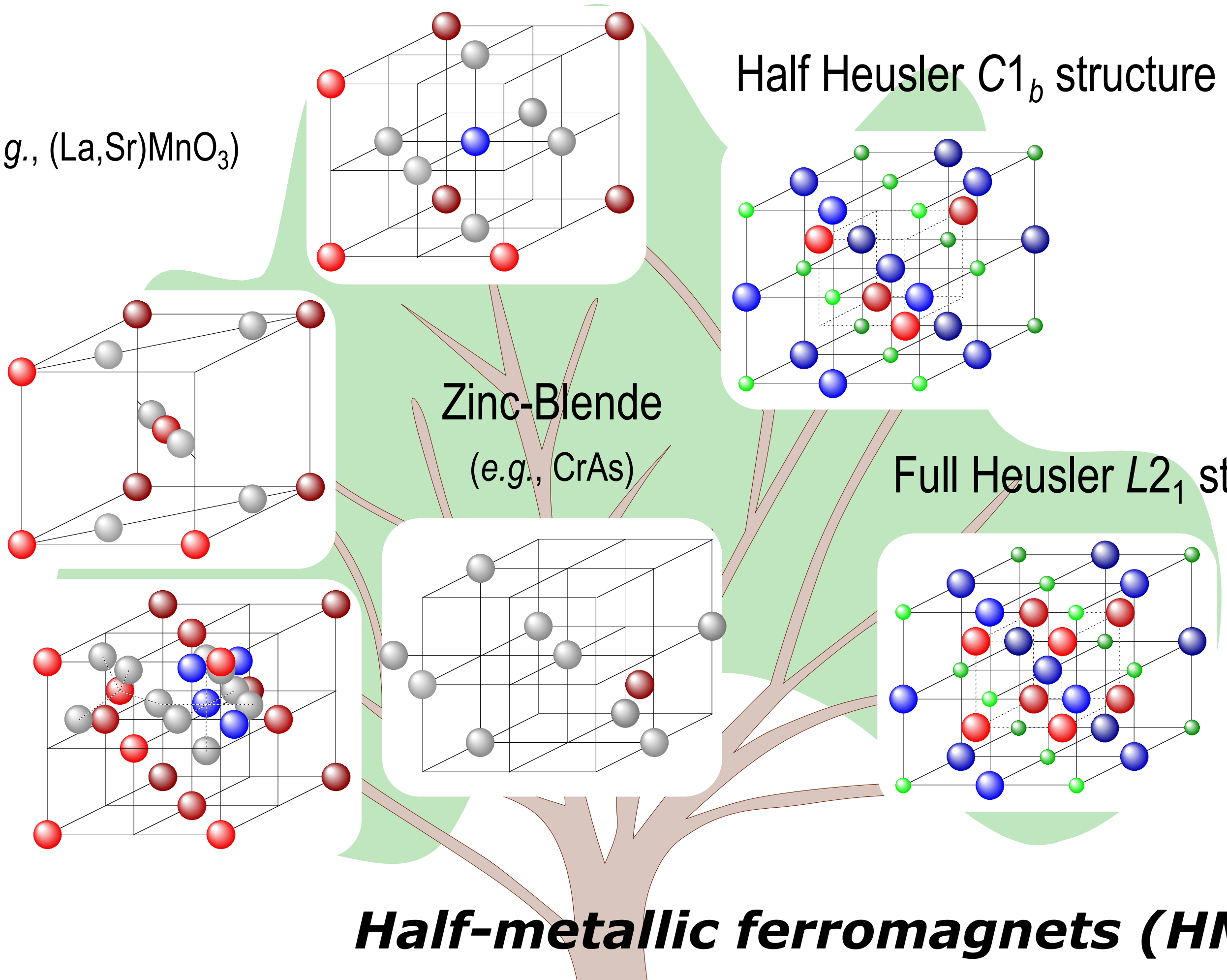
Single spin state

Spin polarisation : 100 %

Spin battery

R. A. de Groot *et al.*, *Phys. Rev. Lett.* 50, 2024 (1983).

Half-Metallic Ferromagnets



Perovskite (*e.g.*, (La,Sr)MnO_3)

Half Heusler $C1_b$ structure (*e.g.*, NiMnSb)

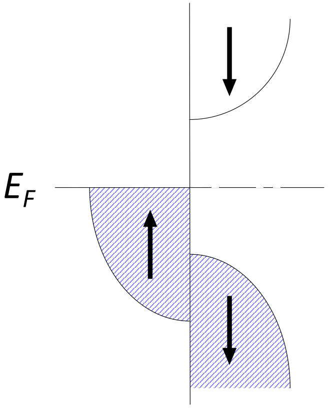
Rutile (*e.g.*, CrO_2)

Zinc-Blende (*e.g.*, CrAs)

Full Heusler $L2_1$ structure (*e.g.*, Co_2MnGe)

Spinel (*e.g.*, Fe_3O_4)

Half-metallic ferromagnets (HMF)



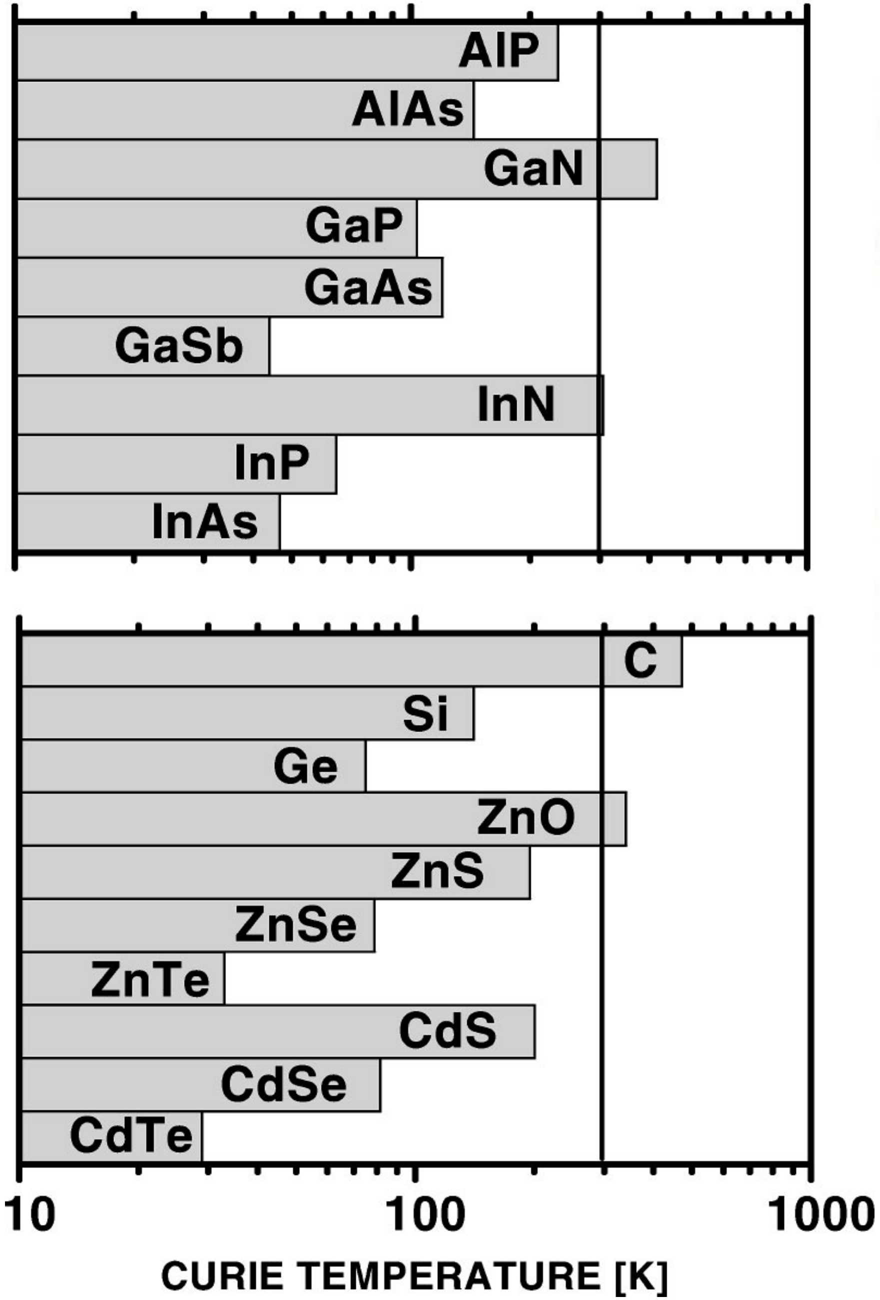
Conduction electrons at the E_F is *100% spin-polarised*.

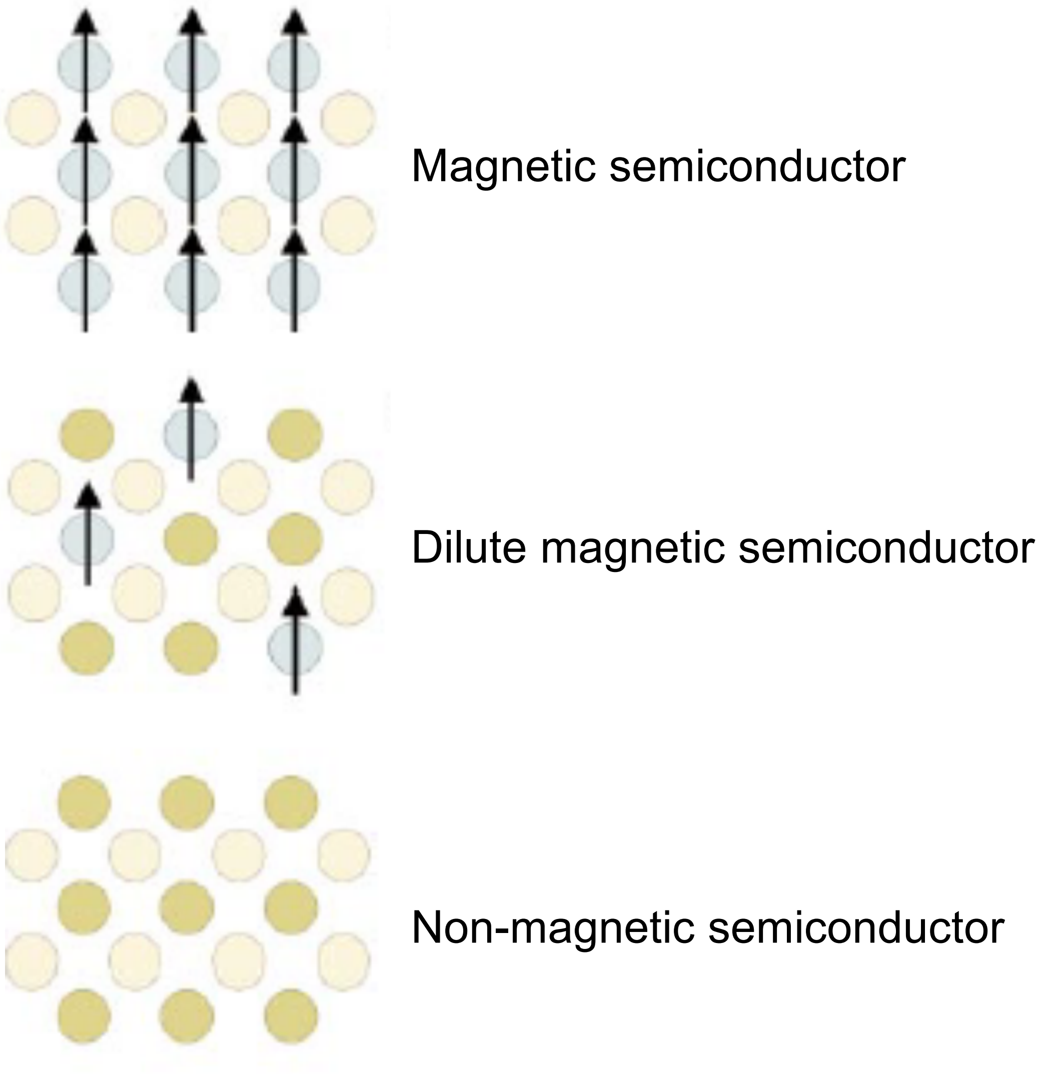
Obstacles to realisation of HMF devices :

- *Curie temperature below room temperature*
- *atomic disorder / unstable phases*

* R. A. de Groot *et al.*, *Phys. Rev. Lett.* **50**, 2024 (1983).

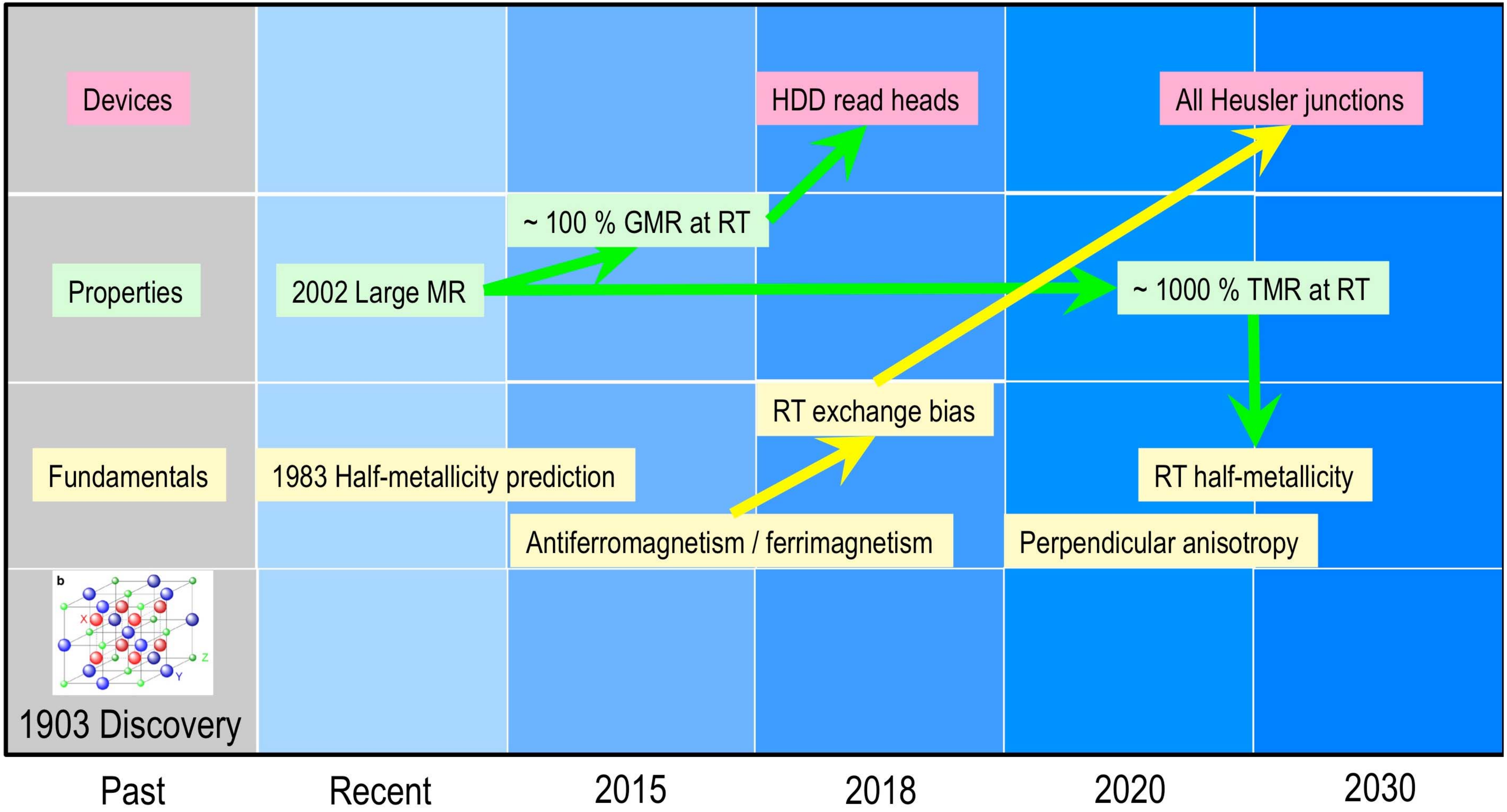
Dilute Magnetic Semiconductors





* H. Munekata *et al.*, *Phys. Rev. Lett.* **63**, 1849 (1989); H. Ohno, *Science* **281**, 951 (1998);
* T. Dietl *et al.*, *Phys. Rev. B* **63**, 195205 (2001).

Roadmap on Heusler Alloys



Devices

HDD read heads

All Heusler junctions

Properties

2002 Large MR

~ 100 % GMR at RT

~ 1000 % TMR at RT

Fundamentals

1983 Half-metallicity prediction

RT exchange bias

Antiferromagnetism / ferrimagnetism

RT half-metallicity

Perpendicular anisotropy

1903 Discovery

Past

Recent

2015

2018

2020

2030

* A. Hirohata *et al.*, *IEEE Trans. Magn.* **51**, 07160747 (2015).

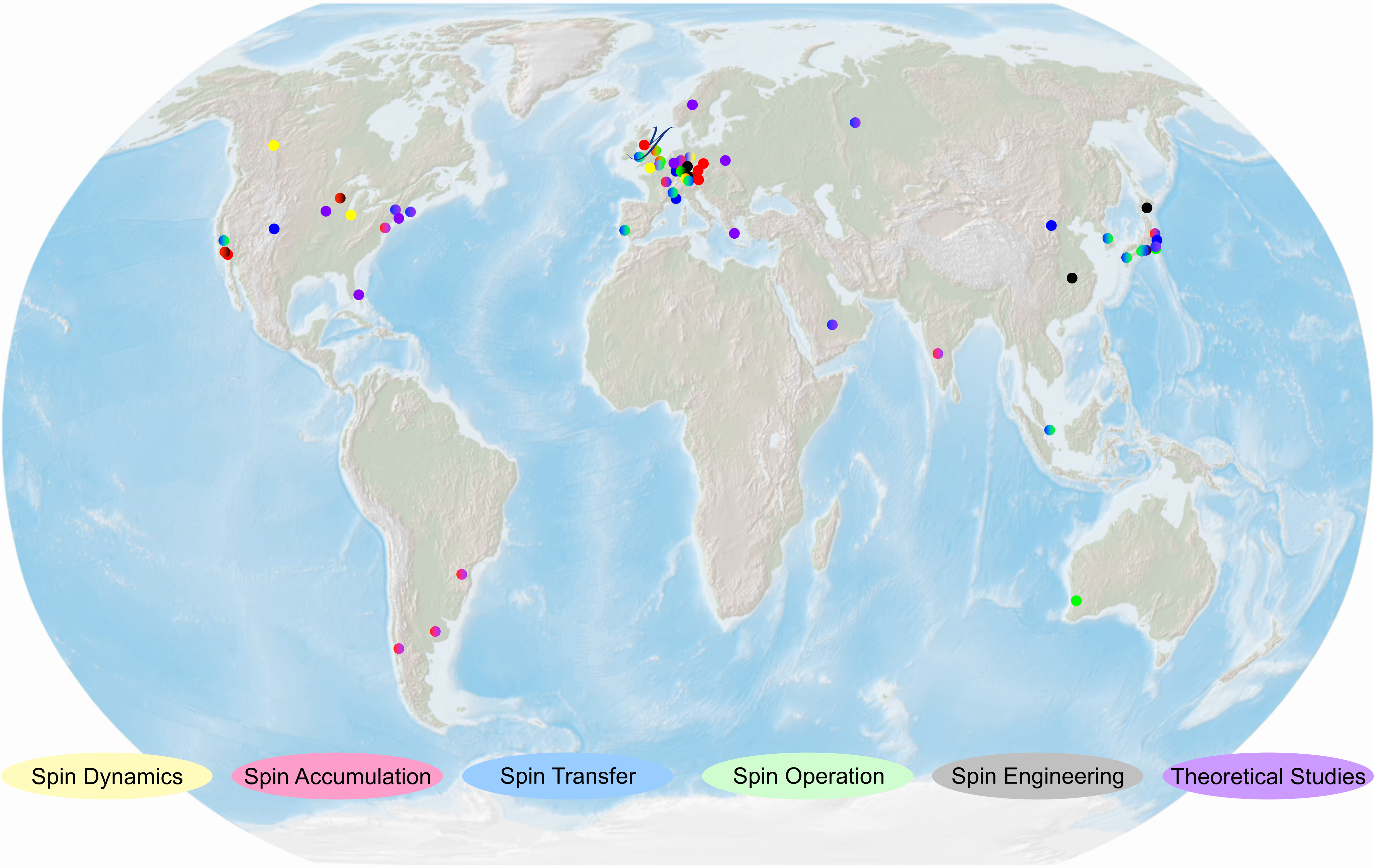
Summary

In spintronics, the following contributions need to be considered :

- Spin-current generation
  e.g., spin injection, electric fields, spin Hall, spin Seebeck, ...
- Stray fields
  e.g., spin injector design, edge/surface roughness, ...
- Volume effects
  e.g., epitaxial/poly, edge/surface roughness, activation volume, ...
- Interfacial effects
  e.g., spin Hall effects, skyrmions, DMI, exchange bias, ...
- Operation temperatures
  e.g., Curie temperature, Néel temperature, ...
- Time dependency
  e.g., damping, spin wave, spin pumping, interfacial relaxation, ...
- Transport
  e.g., ballistic, diffusive (Ohmic), hot electrons, ...
- Media
  e.g., semiconductor, non-magnetic metal, organic material, ...

Spintonics Studies in the World

Spintronics is one of the *most exciting subject in nano-electronics* :



Group Members

Thank you very much for your attention.

Atsufumi Hirohata

Department of Electronic Engineering
University of York
+44 (0)1904 32 3245
atsufumi.hirohata@york.ac.uk

york spintronics

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