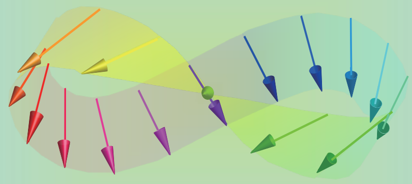
Information Storage and Spintronics 18



Atsufumi Hirohata

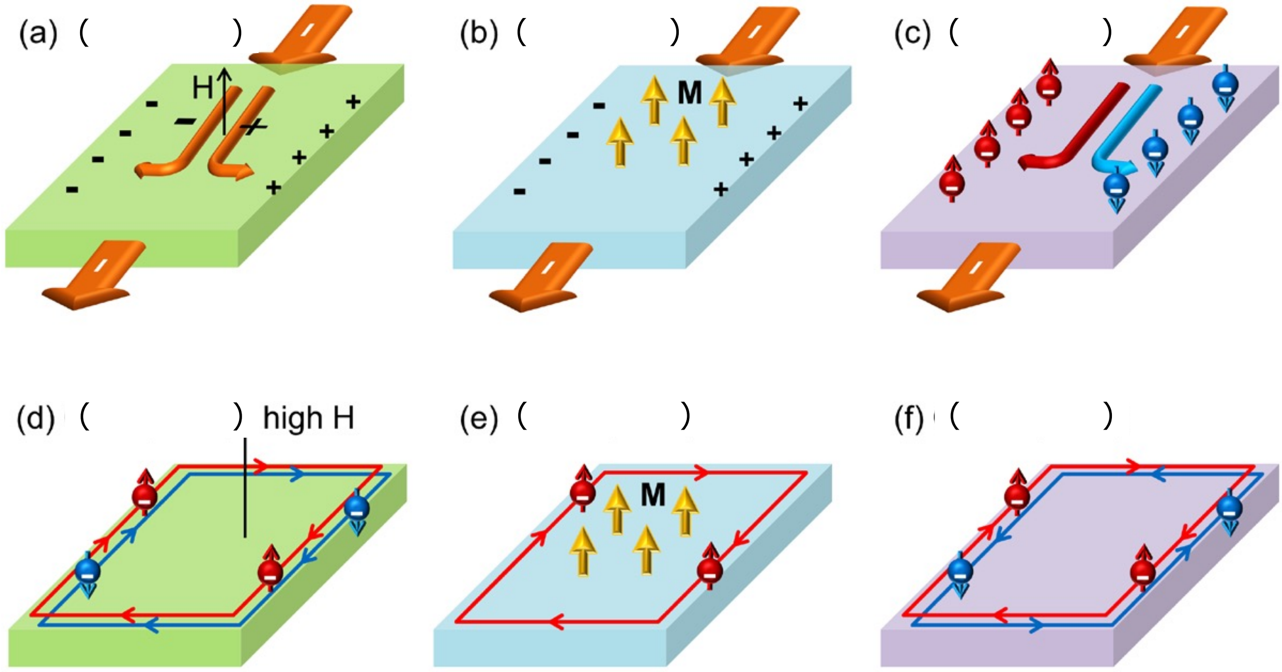
Department of Electronic Engineering

THE UNIVERSITY *of York*

14:00 Thursday, 01/December/2022 (SLB 101)

Quick Review over the Last Lecture

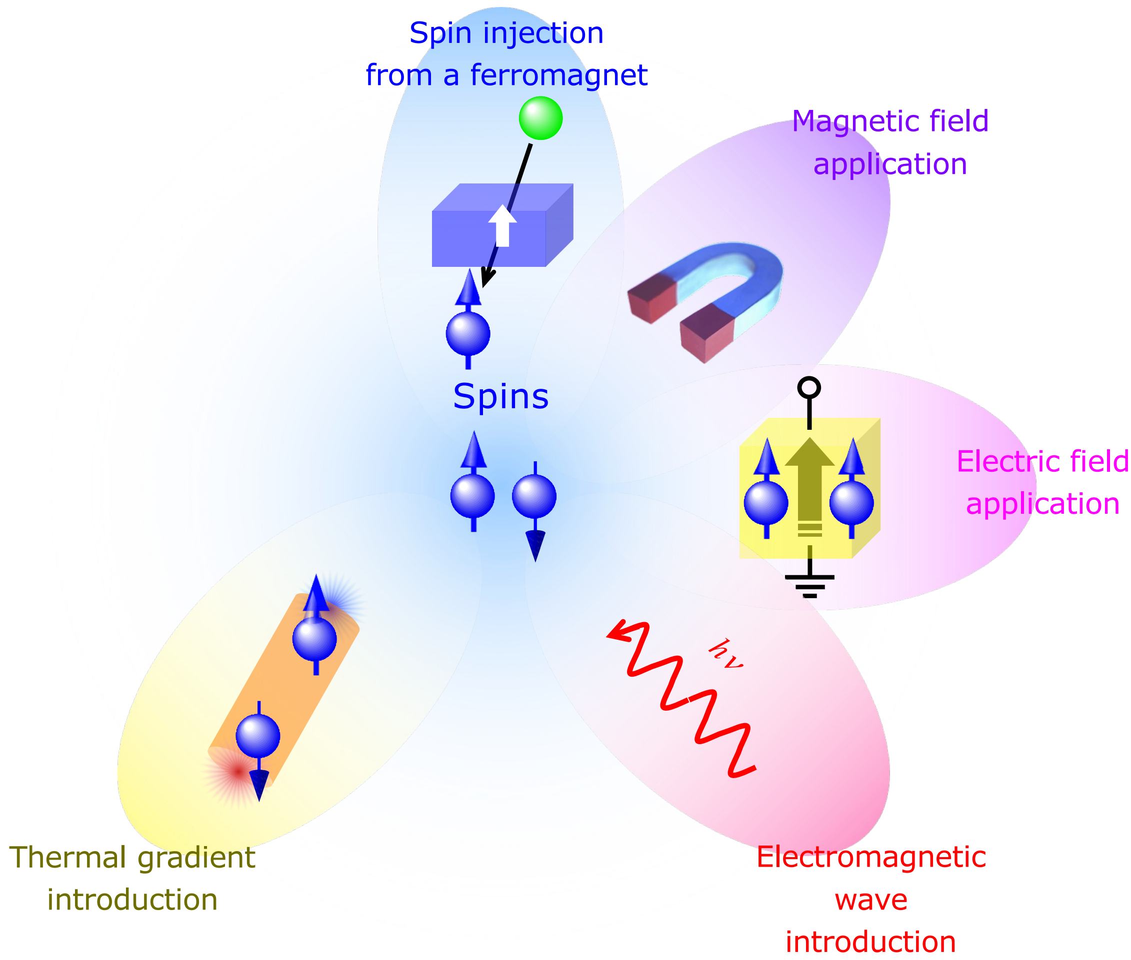
Family of Hall effects : *



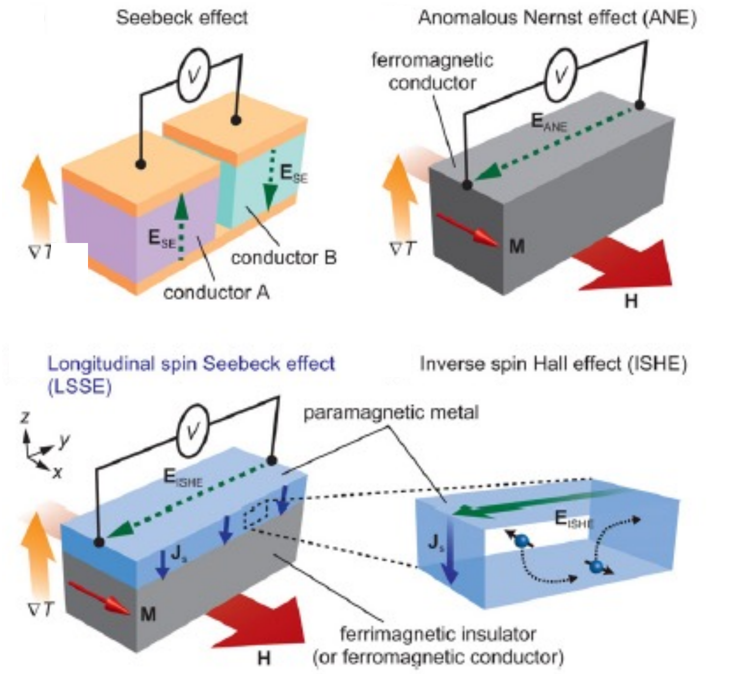
* C.-Z. Chang and M. Li, *J. Phys.: Condens. Matter* **28**, 123002 (2016).

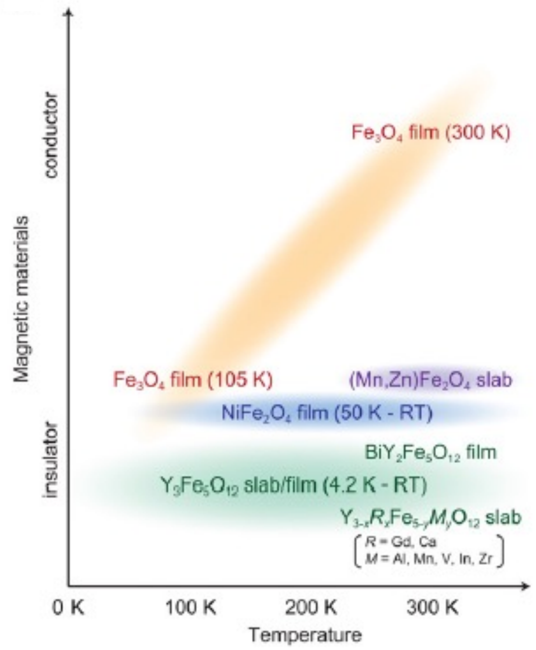
18 Other Spintronic Devices

- Spin caloritronics
- Berry's phase
- Spin mechatronics
- Zeeman splitting
- Spin optics



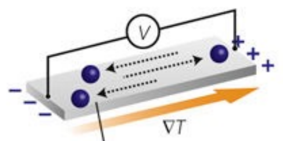
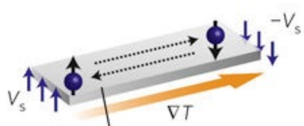
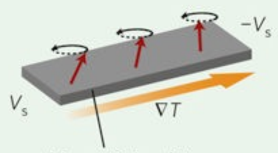
Spin Seebeck Effect

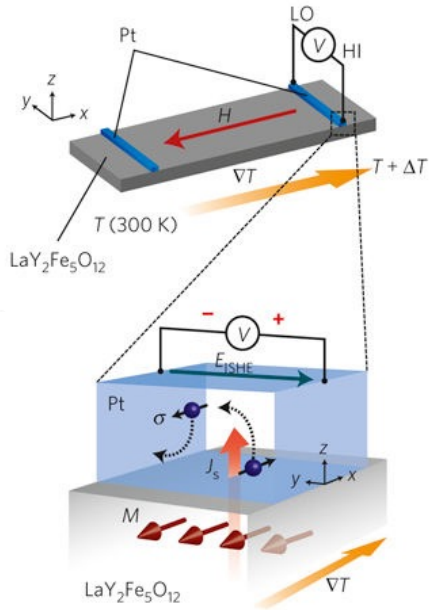




* K. Uchida *et al.*, *Nature* **455**, 778 (2008);
** K Uchida *et al.*, *J. Phys.: Condens. Matter* **26**, 343202 (2014).

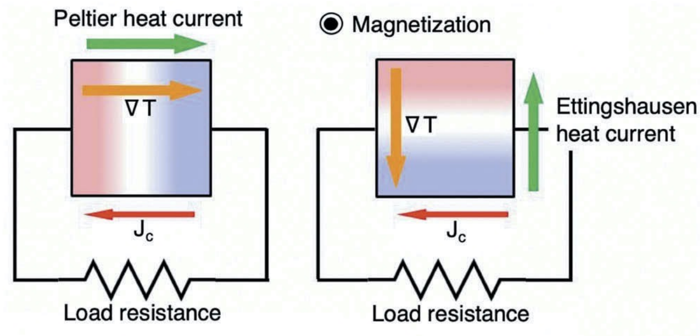
Spin Seebeck Effect

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).

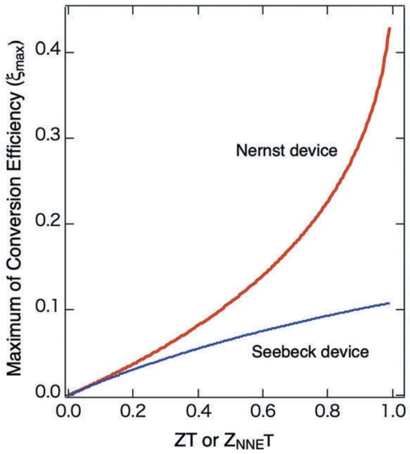
Spin Seebeck and Nernst Effects



Seebeck device (p-type)　　Nernst device

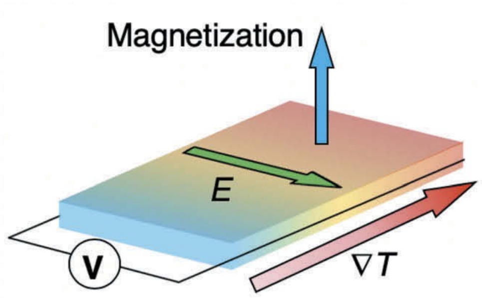
Figure of merit *ZT* :

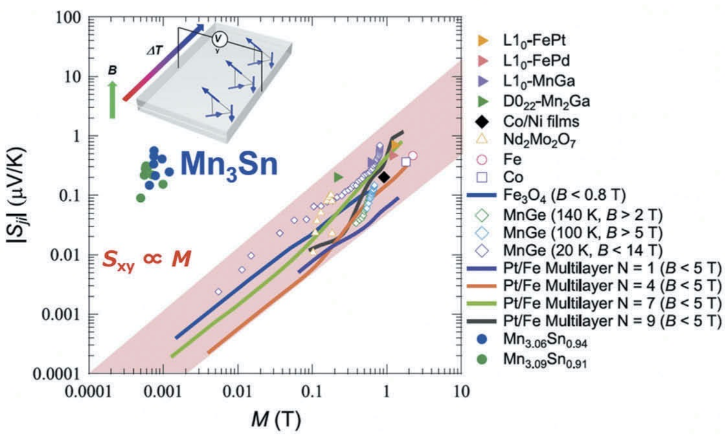
where *T* : temperature, σ : electrical conductivity and κ : thermal conductivity.

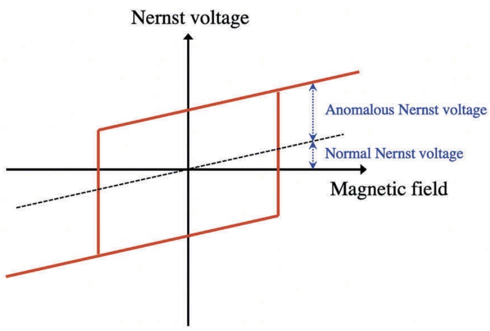


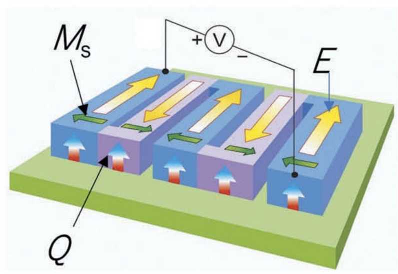
* M. Mizuguchi and S. Nakatsuji, *Sci. Technol. Adv. Mater.* **20**, 262 (2019).

Spin Nernst Effect

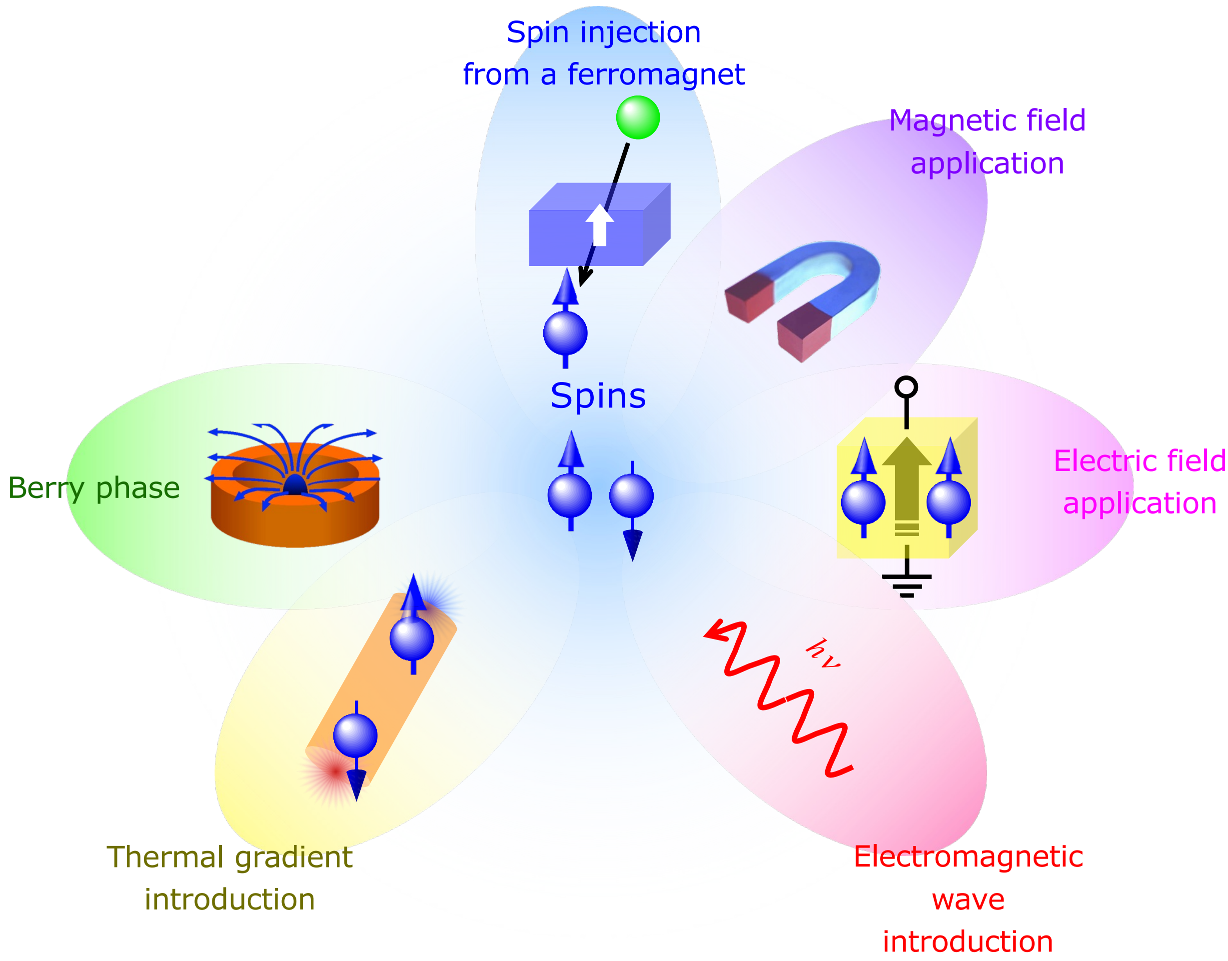








* M. Mizuguchi and S. Nakatsuji, *Sci. Technol. Adv. Mater.* **20**, 262 (2019).



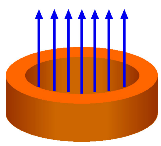
Theoretical Prediction on a Persistent Current

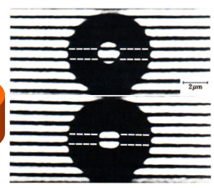
Persistent current :

induced by a magnetic flux threading a mesoscopic ring

→ *Aharonov-Bohm effect* *

- The persistent current oscillates with the flux.

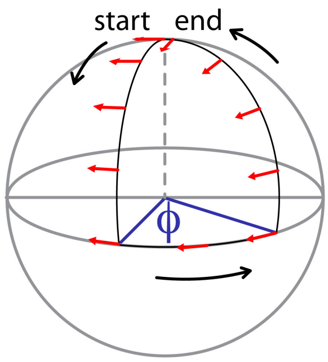


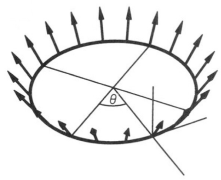


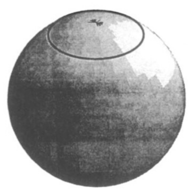
induced by a magnetic field rotating slowly in time **

→ *Berry (geometrical) phase*

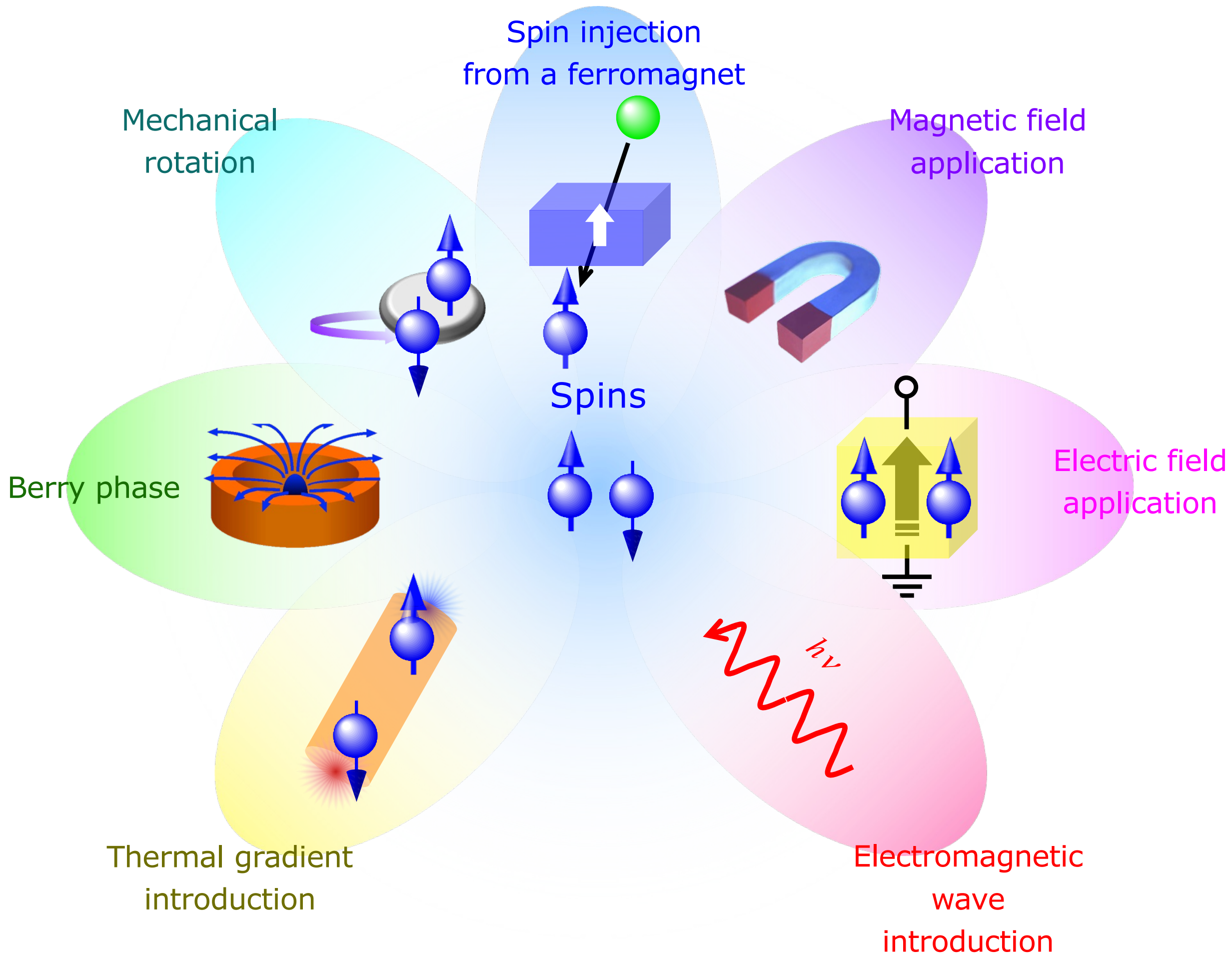
- Non-uniform external magnetic fields are required.
- Spin-polarised persistent current can be generated.







* 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).

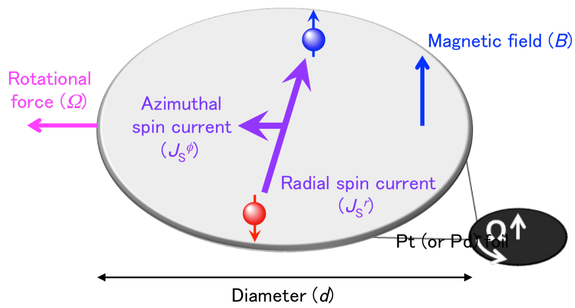


Spin Current in a Rotating Body

- 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.***

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

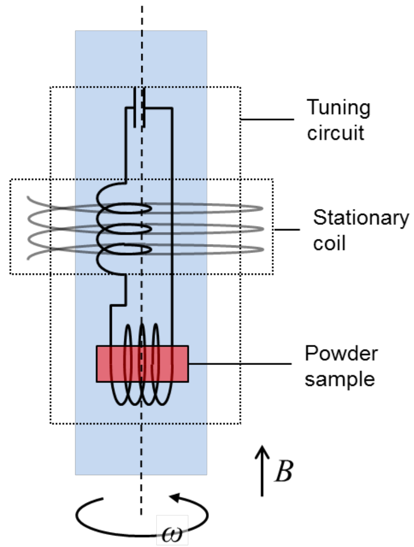
J_S = spin current density
e = electron charge
n = electron density
R = radius of rotation
η_{SO} = spin orbit coupling strength, 0.59
f = frequency
ε_F = Fermi energy
$\omega_C = qB/m$ for electron wave packet



* 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).

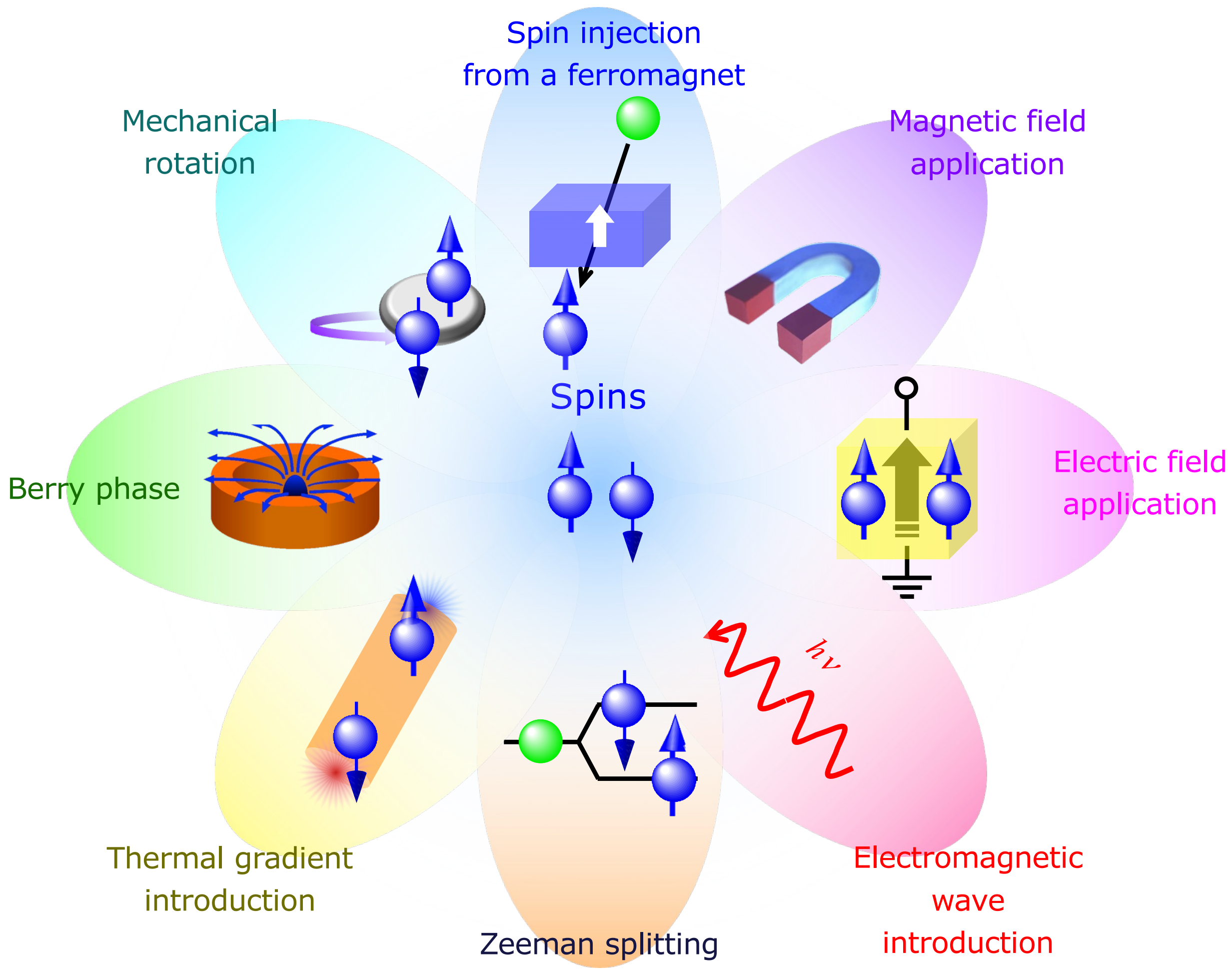
Spin Mechatronics Measurement

- 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.



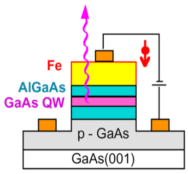
Schematic of the NMR measurement setup for the Barnett effect [6]

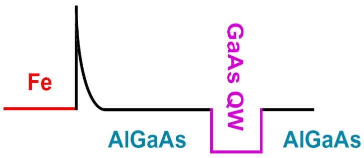
* H. Chudo *et al.*, *Appl. Phys. Exp.* **7**, 063004 (2014).



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

Spin LED structures :



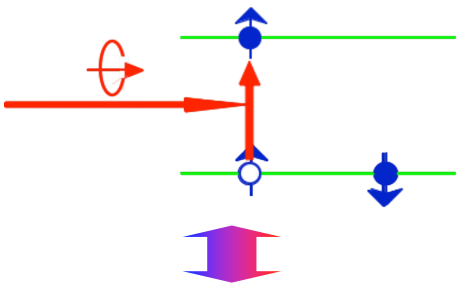


Structures	Spin polarisation	Refs.
Spin-polarised *electron* injection :		
300 nm BeMgZnSe + BeMnZnSe / 100 nm *n*-AlGaAs / 15 nm *i*-GaAs QW / … / *p*-GaAs	~ 42% @ <5 K	R. Fiederling *et al.*, *Nature* **402**, 787 (1999).
360 nm CdMnTe / 1400 nm CdTe	~ 30% @ 5 K	M. Oestreich *et al.*, *Appl. Phys. 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_2O_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

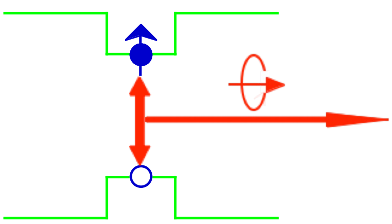
Photoexcitation :

Electrons spin-polarised by introducing circularly polarised light

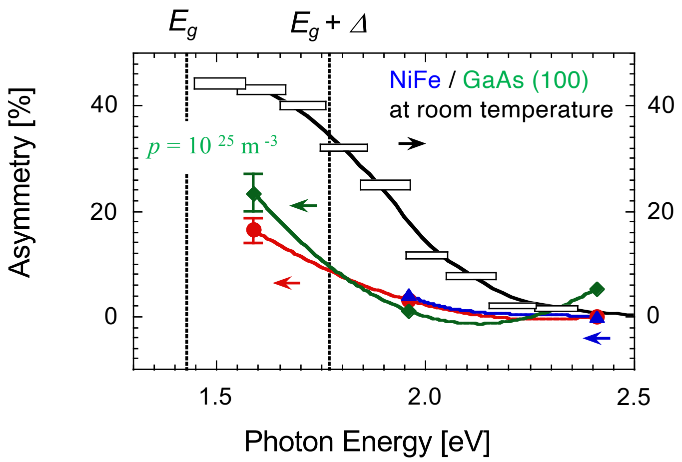


Circularly polarised electroluminescence (EL) :

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



Photon Energy Dependence

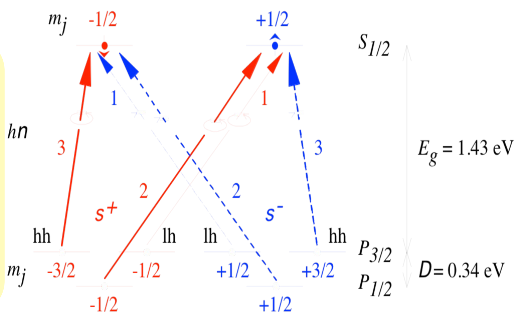


Spin polarisation ∝ asymmetry in spin transport effect :

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

A decreases with increasing photon energy.

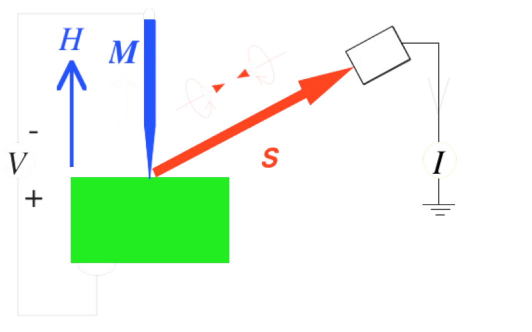
∝ spin polarisation in GaAs



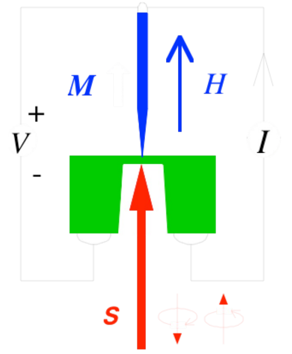
* D. T. Pierce *et al.*, *Phys. Lett.* 51A, 465 (1975); A.Hirohata *et al.*, *Phys. Rev. B* **63**, 104425 (2001).

Spin Electronics with Optical Methods

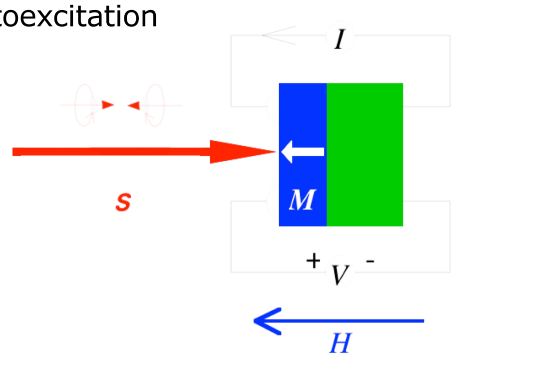
Spin-polarised inverse photoemission



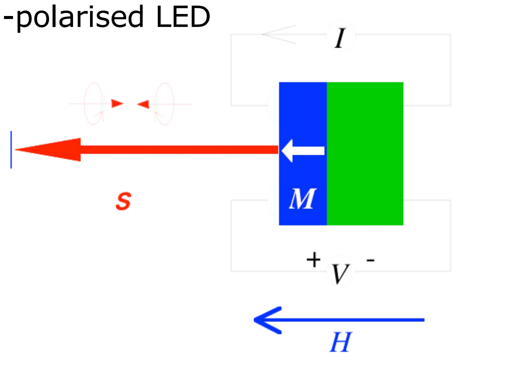
Spin-polarised STM



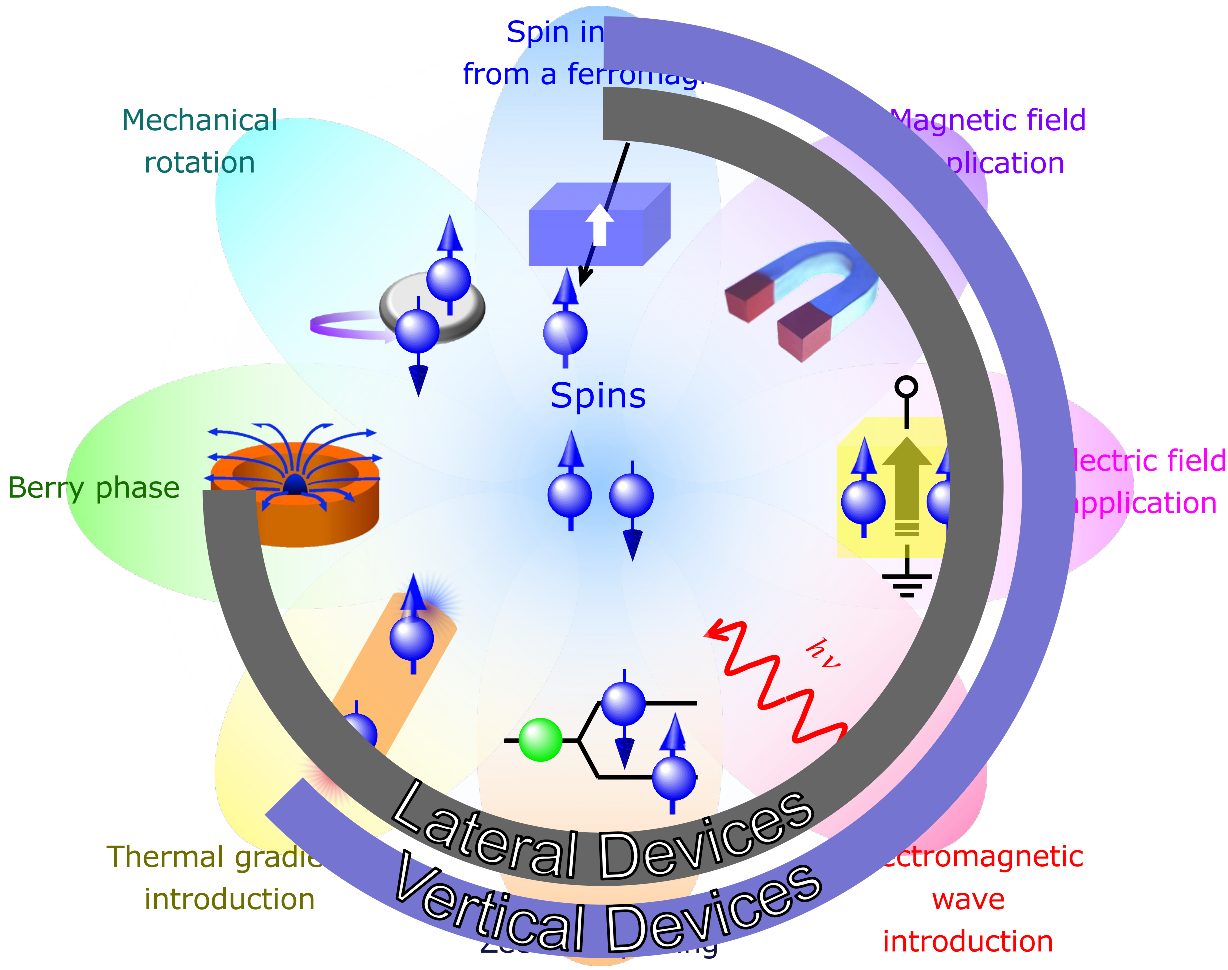
Photoexcitation



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.

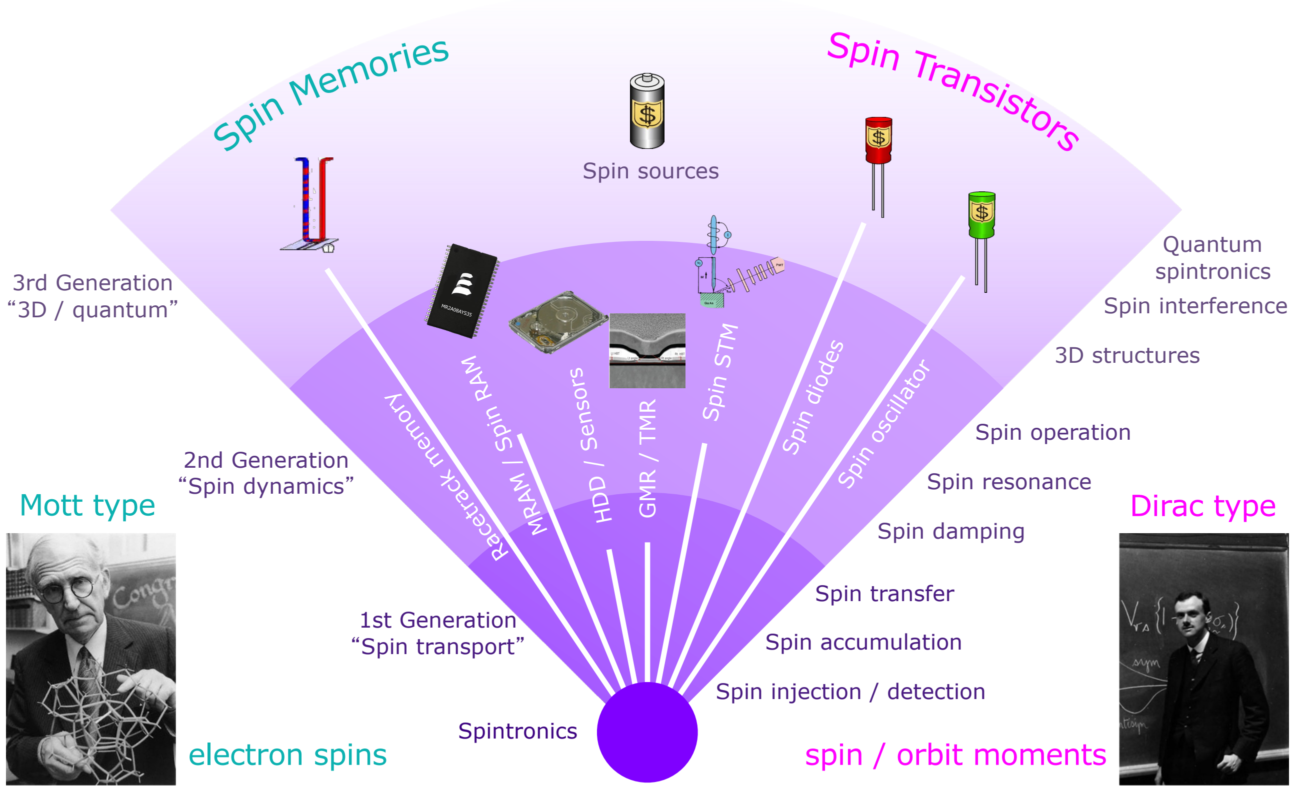


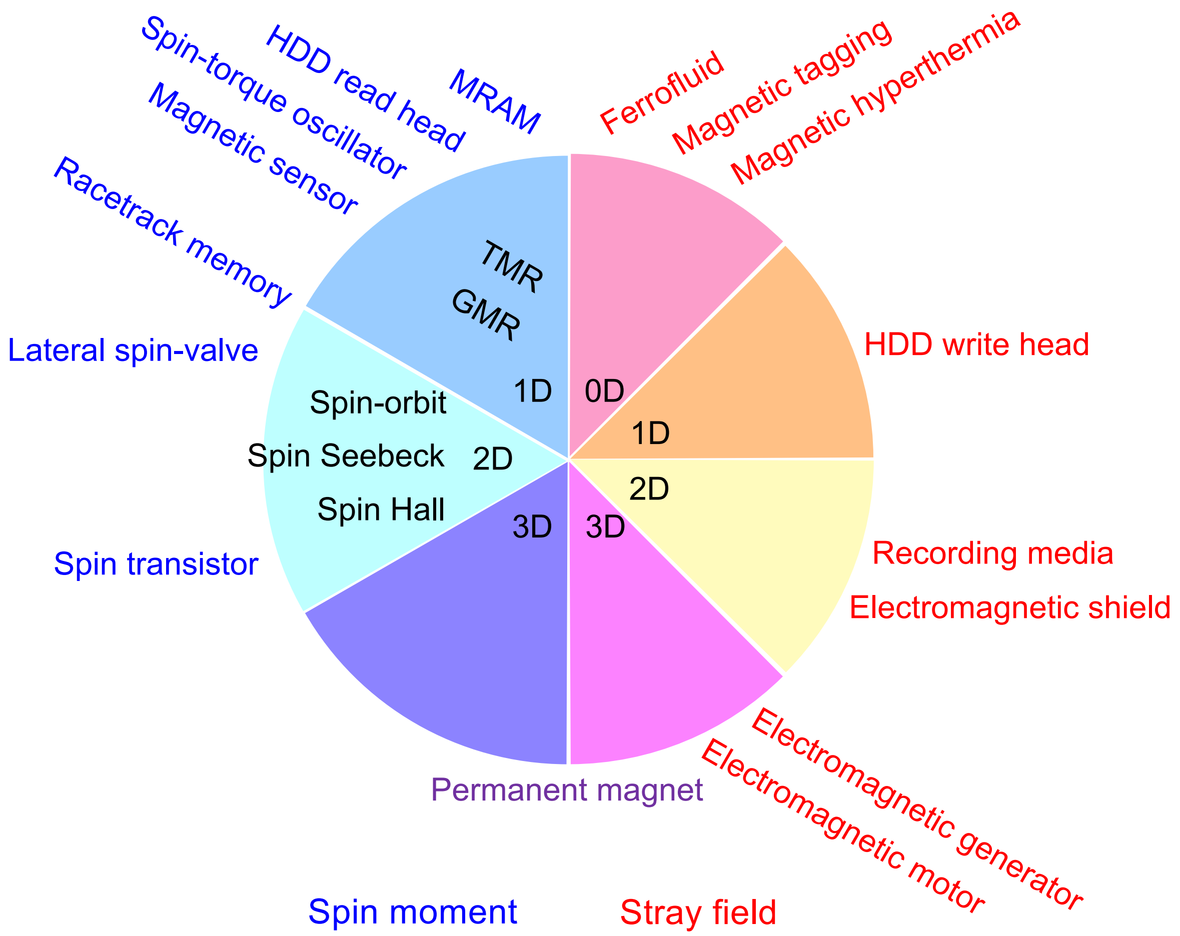
Quick Review over this Module

Electrical spin generation	1957 RKKY	1975 Jullière	1988 GMR 1999 Spin injection	1995 RT-TMR 2001 Giant TMR theory Spin-valve 1996 STT theory 1999 STT experiment 2000 Conductance mismatch	2004 Giant TMR 2003 Spin oscillator 2004 LLG equation	2016 Neuromorphic operation	
Spin-orbit effects	1960 DMI theory 1958 SOT theory 1958 Skyrmionl theory	1971 Spin Hall theory		2004 Spin Hall experiment	2004 Domain motion by a current 2006 Inverse spin Hall 2009 Skyrmions		
Electric field application			1989 FM DMS	1990 Spin FET concept	2000 Voltage-control FM		
Electromagnetic wave application				1995 Photoexcitation 1998 Spin STM	2002 Spin pumping 2002 FMR	2010 Magnonics	
Spin-band splitting				1993 Spin injection 1999 Spin LED			
Influence of thermal gradient					2008 Spin Seebeck	2017 Spin Nernst	
Geometrical phase	1959 AB effect		1981 AAS effect 1984 Berry phase	1992 Persistent current theory 1999 Ballistic MR			
Mechanical rotation	1015 Barnett effect					2011 Spin mechatronics theory 2016 Hydrodynamic spin current 2018 MOKE detection	
Materials	1903 Heusler alloy discovery		1983 Half-metallic Heusler alloy 1988 DMS		2005 Topological insulator		
Products	1956 HDD	1972 MRAM concept		1997 GMR-HDD 1995 GMR sensors	2002 MRAM 2008 TMR-HDD	2016 TMR sensors 2011 Racetrack memory prototype 2019 STT-MRAM	
		1970	1980	1990 1G	2000 2G	2010 3G	2020

* A. Hirohata *et al.*, *J. Magn. Magn. Mater.* **509**, 166711 (2020).

Summary of Spintronic Devices





Spintonics Studies in the World

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