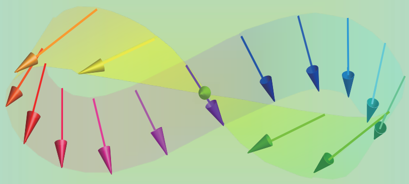
Information Storage and Spintronics 15



Atsufumi Hirohata

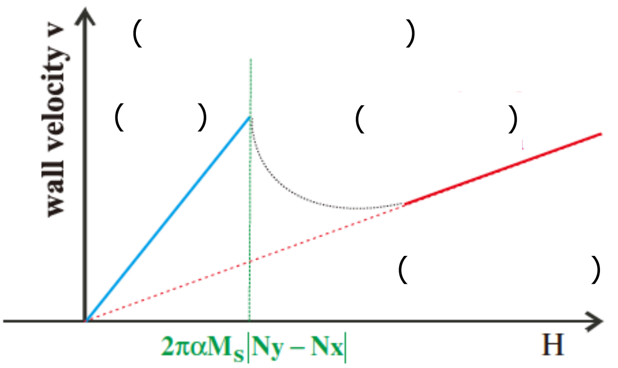
Department of Electronic Engineering

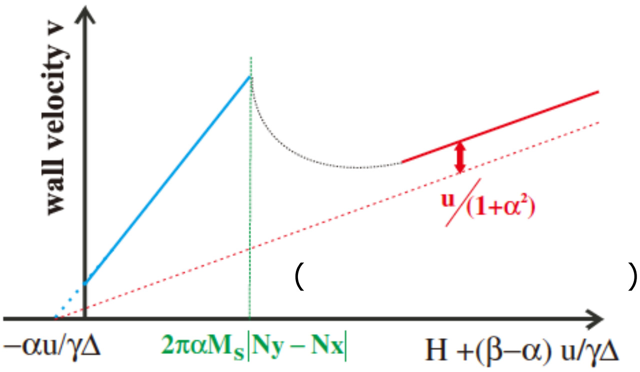
THE UNIVERSITY *of York*

14:00 Thursday, 24/November/2022 (SLB 101)

Quick Review over the Last Lecture

Domain wall motion by a magnetic field or electrical current : *





* A. Mougin *et al.*, *Euro. Phys. Lett.* 78, 57007 (2007).

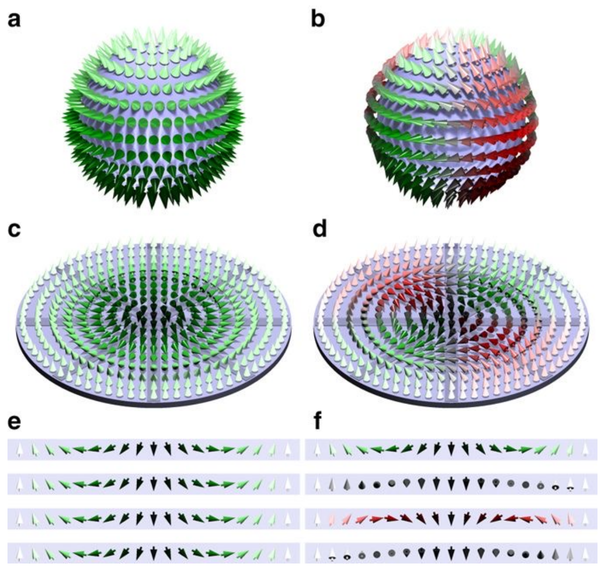
15 Skyrmions and Voltage Control

- Magnetic skyrmions
- Dzyaloshinskii-Moriya interactions
- Spin generation efficiency
- Voltage-controlled magnetism

Skyrmion

Topological transformation : *

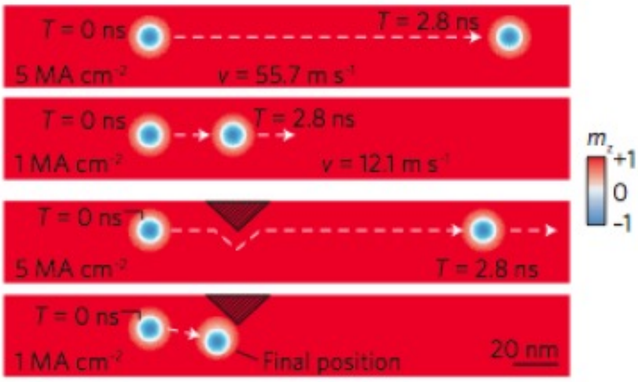
Nucleon model proposed by Tony Skyrme in 1962 : **

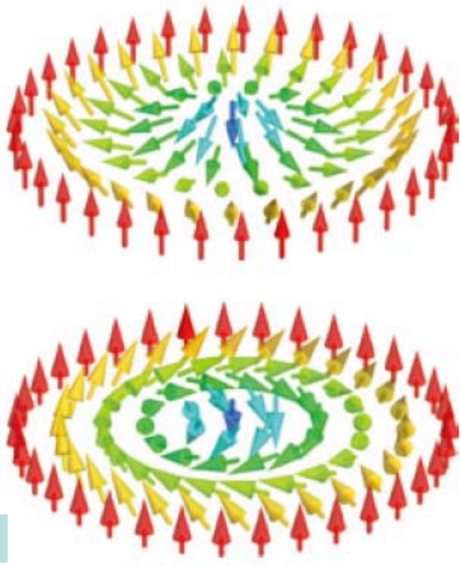


* http://www.Wikipedia.org;
** T. Skyrme, *Nucl. Phys.* **31**, 556 (1962).

Skyrmion Motion by a Current

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



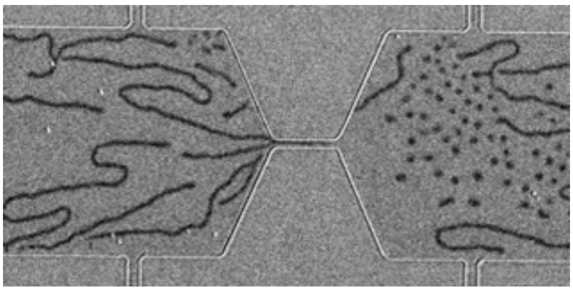


	Skyrmions	Domain walls
Size [nm]		
Velocity [m/s]		
Critical current density [A/cm^2]		

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

Skyrmion Motion by a Current

Skyrmion motion demonstrated by the Argonne National Laboratory : *

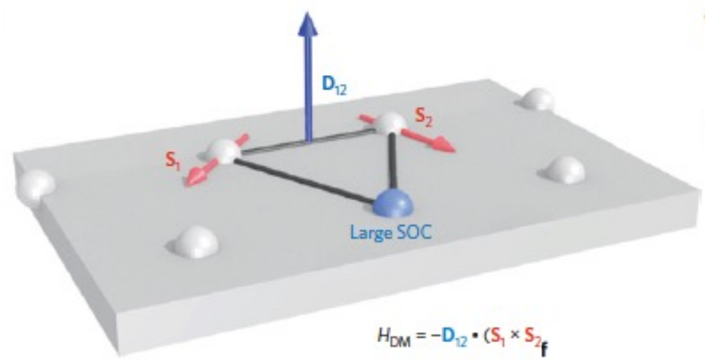


Magnetic skyrmion : **

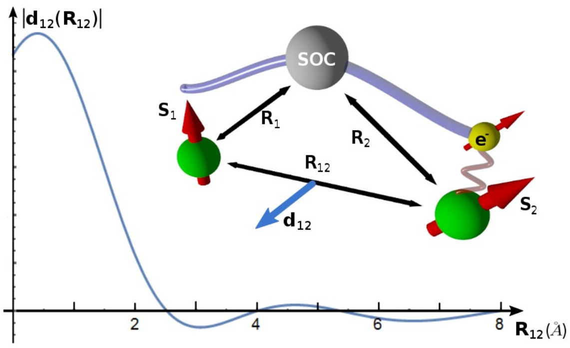
* https://www.eurekalert.org/multimedia/pub/media/93588_web.mp4
** https://www.youtube.com/watch?v=3s3cmGjxPVc

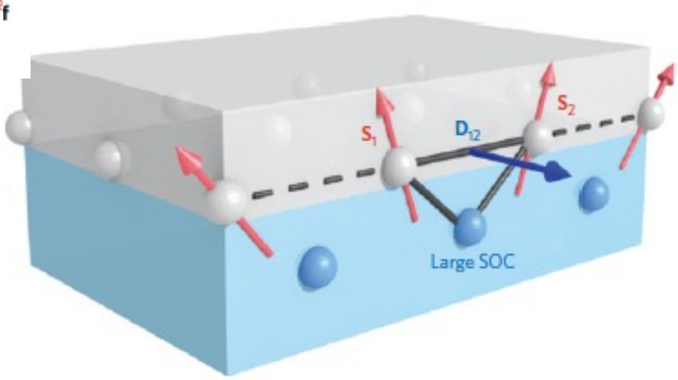
Dzyaloshinskii-Moriya Interactions

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



$H_{SO} =$

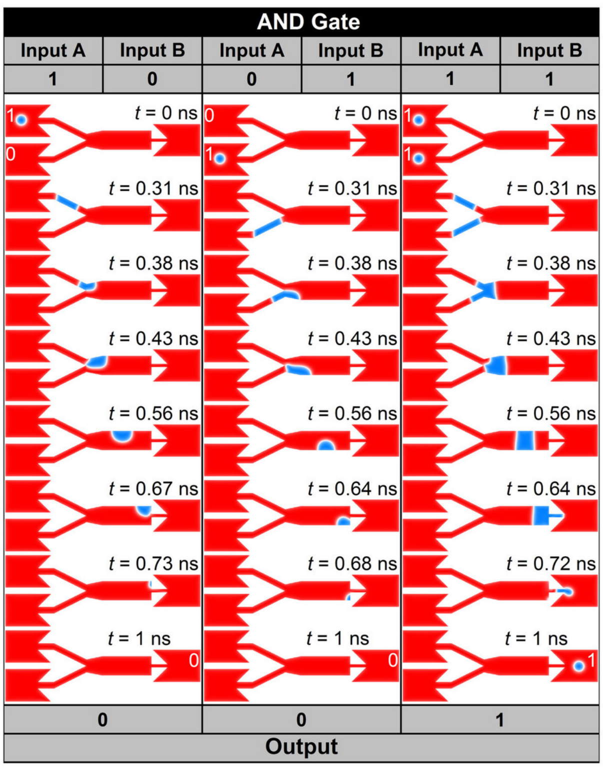


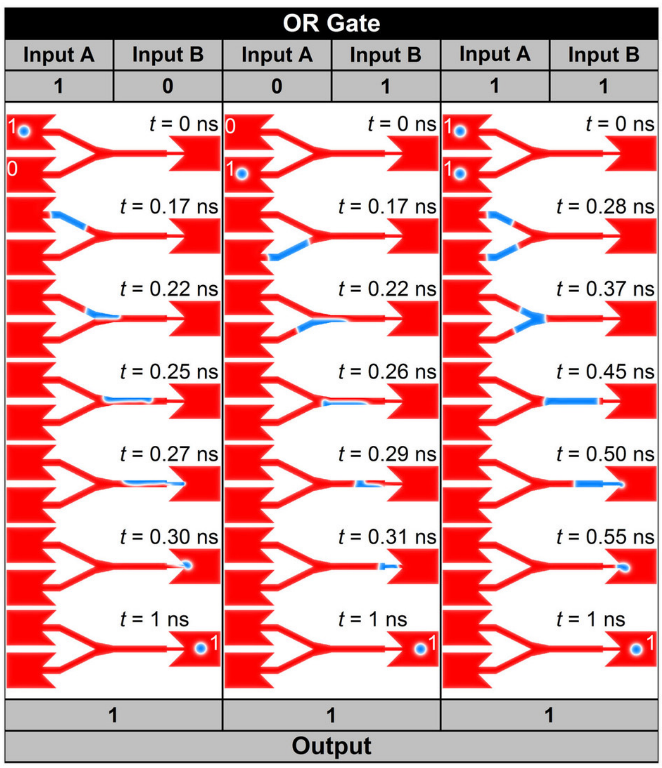


* I. Dzyaloshinskii, *J. Phys. Chem. Solids* 4, 241 (1958); T. Moriya, *Phys. Rev.* 120, 91 (1960);
** A. Fert *et al.*, *Nature Nanotechnol.* 8,152 (2013);
*** https://hal.archives-ouvertes.fr/hal-01426434v2

Skyrmion Logic

Skyrmion logic for AND and OR operations : *

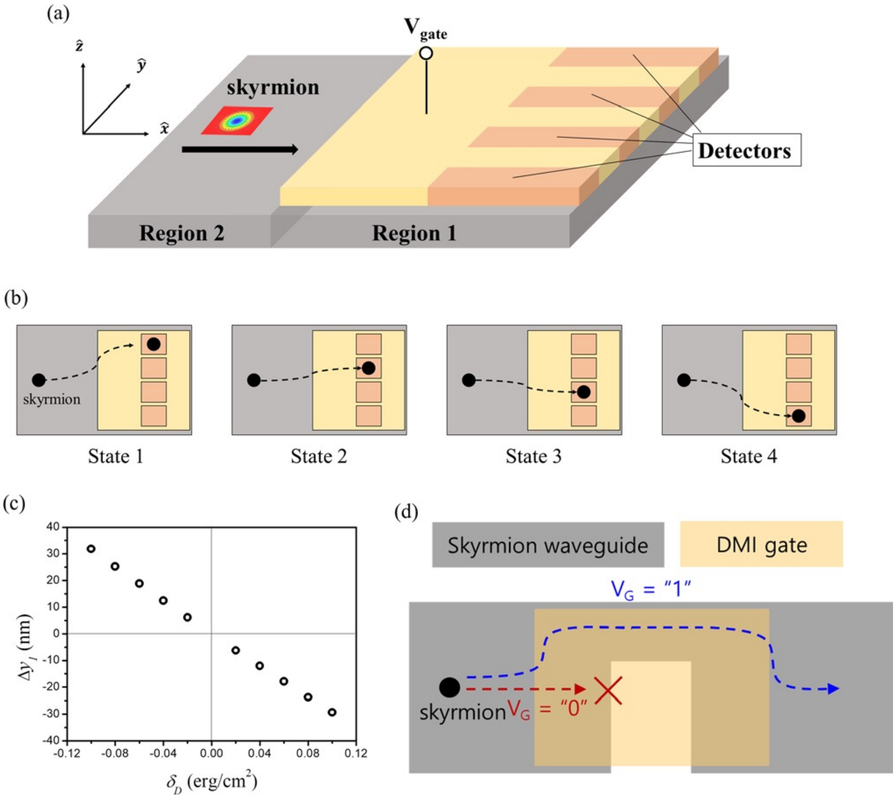




* Ihttp://www.wikipedia.org/

Skyrmion Logic

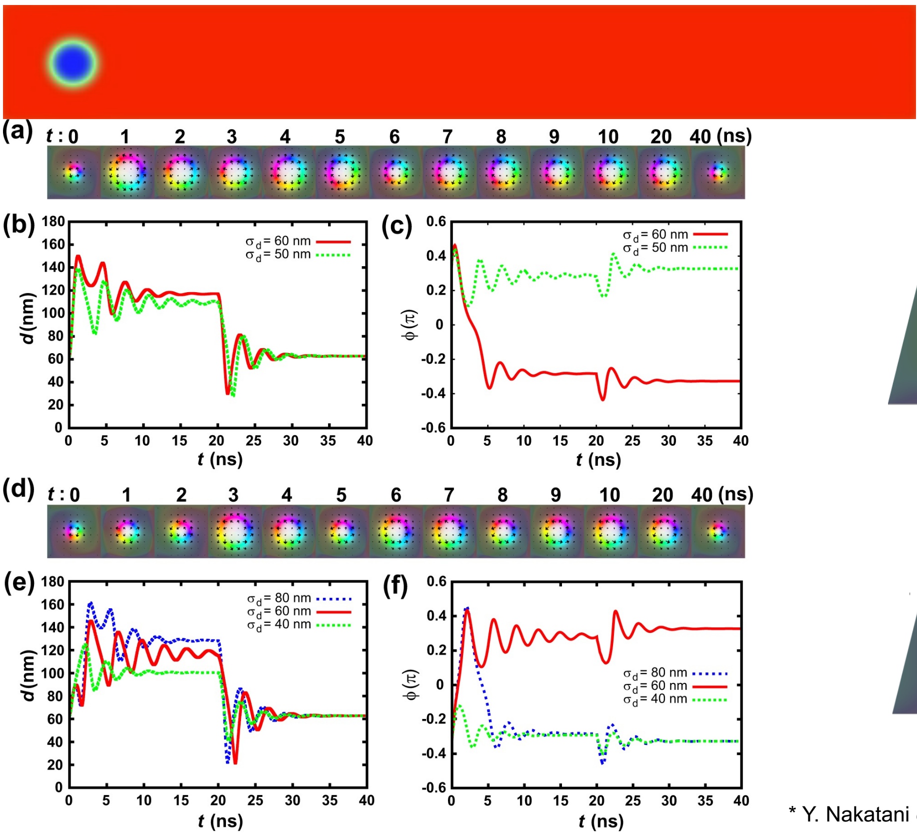
Skyrmion motion can be controlled by an electric field : *

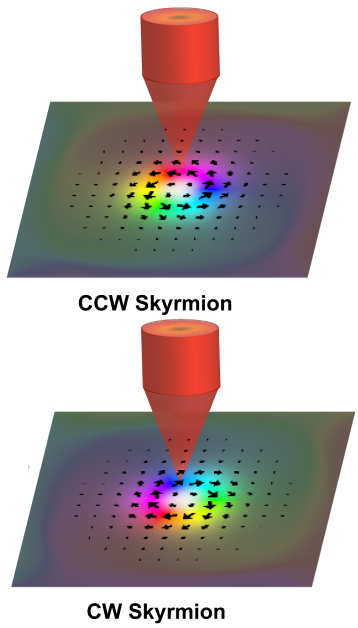


* I.-S. Hong *et al.*, *Appl. Phys. Lett.* **115**, 072406 (2019).

Skyrmion Control by Local Heating

Skyrmion motion and chirality reversal can be achieved by local heating : *



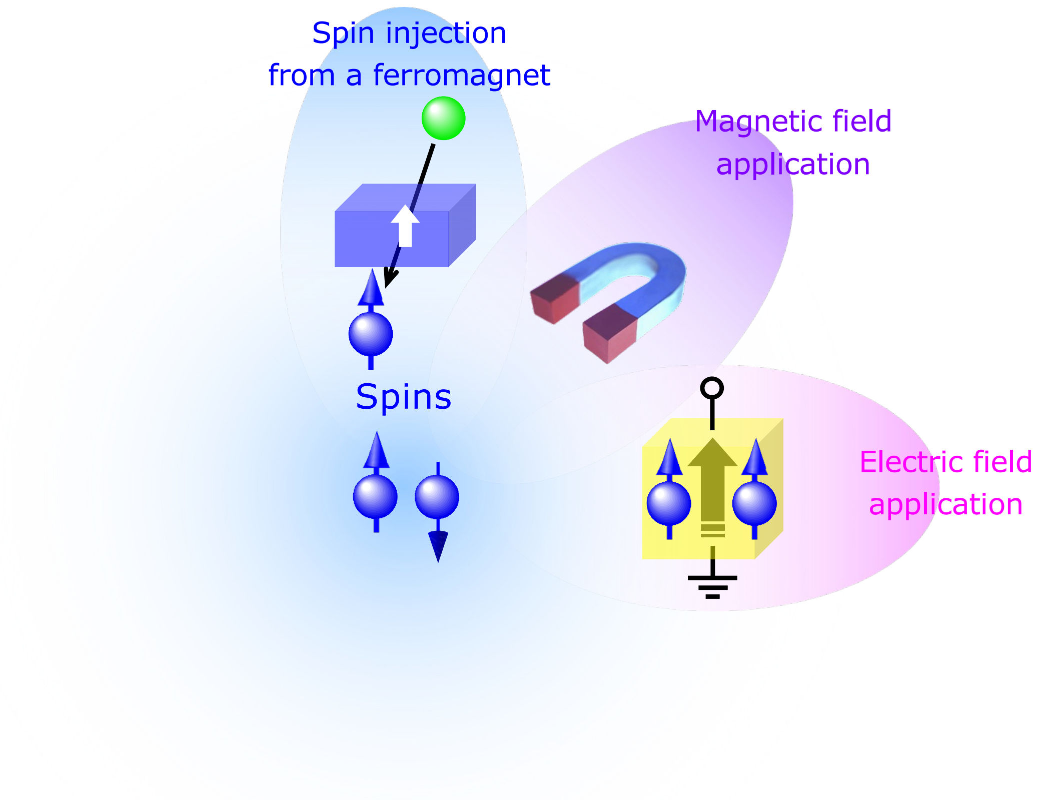


* Y. Nakatani *et al.*, *Sci. Rep.* **9**, 13475 (2019).

Spin Generation Efficiency

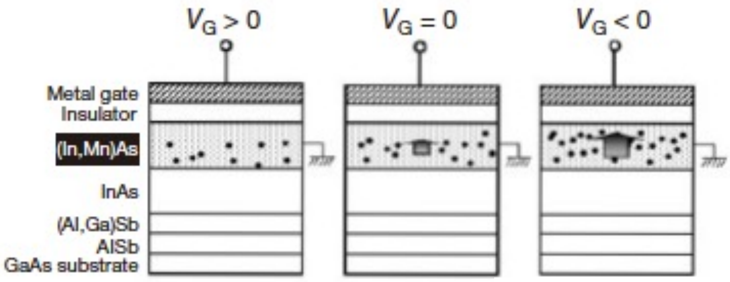
Method	System	Efficiency (η)	Ref.
Spin injection	Lateral spin-valve: $Co_2FeSi/Cu/Co_2FeSi$	27%	[1]
	Spin Hall: $Pt_{0.85}Hf_{0.15}$ (5.5)/Pt (0.5)/Co (1) (nm)	(23±2)%	[2]
	Topological insulator: $(Bi_{1-x}Sb_x)_2Te_3$ thin films	45~57% (max)	[3]
Magnetic field	(Stray field from a ferromagnet)	N/A	[4]
Electric field application	(Interfacial band changes under a field)	N/A	[5]
Electromagnetic wave	Spin pumping: $Y_3Fe_5O_{12}$/Pt	~20%	[6]
Zeeman splitting	(Intrinsic Zeeman splitting at low temperature)	N/A	[7]
Thermal gradient	$Pt/Ni_{0.2}Zn_{0.3}Fe_{2.5}O_4$ film	10^{-3}%	[8]
Berry phase	(Geometrical phase introduced by a field)	100% (theory)	[9]
Mechanical rotation	(Electrical motor for mechanical rotation)	100% (theory)	[10]

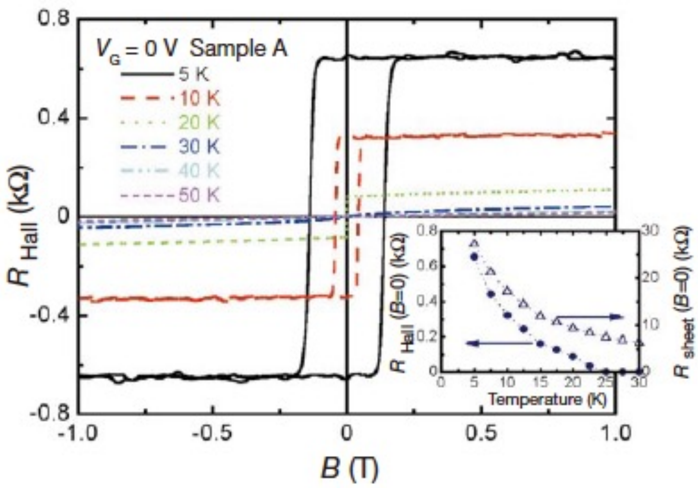
[1] T. Kimura *et al.*, *NPG Asia Mater.* 4, e9 (2012).
[2] M.-H. Nguyen *et al.*, *Appl. Phys. Lett.* 108, 242407 (2016).
[3] K. Kondou *et al.*, *Nature Phys.* 12, 1027 (2016).
[4] A. Hirohata, PhD thesis (University of Cambridge, 2000).
[5] H. Ohno *et al.*, *Nature* 408, 944 (2000).
[6] T. Tashiro *et al.*, *Sci. Rep.* 5, 15158 (2015).
[7] H. Munekata *et al.*, *Phys. Rev. Lett.* 63, 1849 (1989).
[8] A. Kirihara *et al.*, *Sci. Rep.* 6, 23114 (2016).
[9] D. Loss and P. M. Goldbart, *Phys. Rev. B* 45, 13544 (1992).
[10] S. Maekawa *et al.* (Eds.), *Spin Current* (Oxford University Press, Oxford, 2017).



Electric Field Control of Magnetism - *Semiconductors*

Dilute magnetic semiconductor [(In,Mn)As] : *

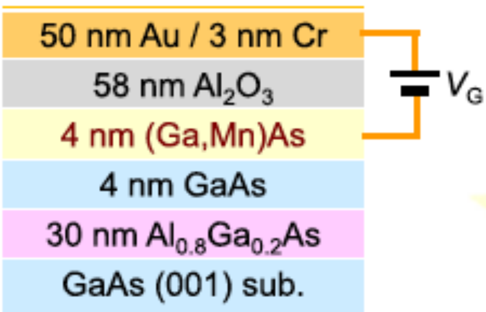


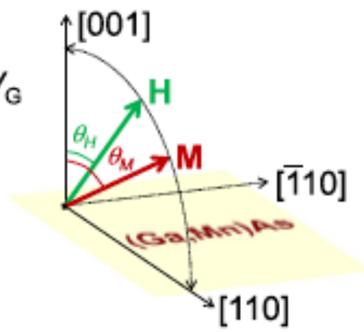


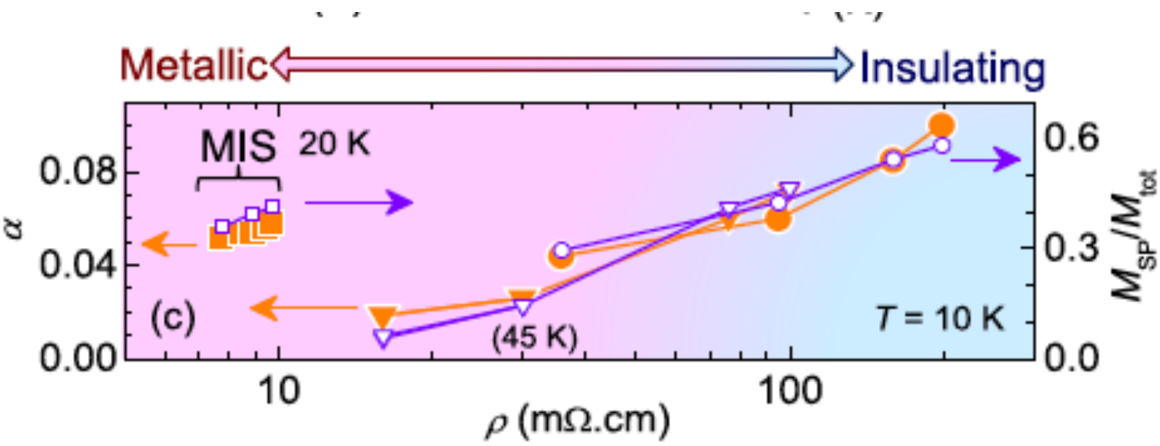
* H. Ohno *et al.*, *Nature* **408**, 944 (2000).

Electric Field Control of Magnetism - *Semiconductors*

Dilute magnetic semiconductor (GaMnAs) : *



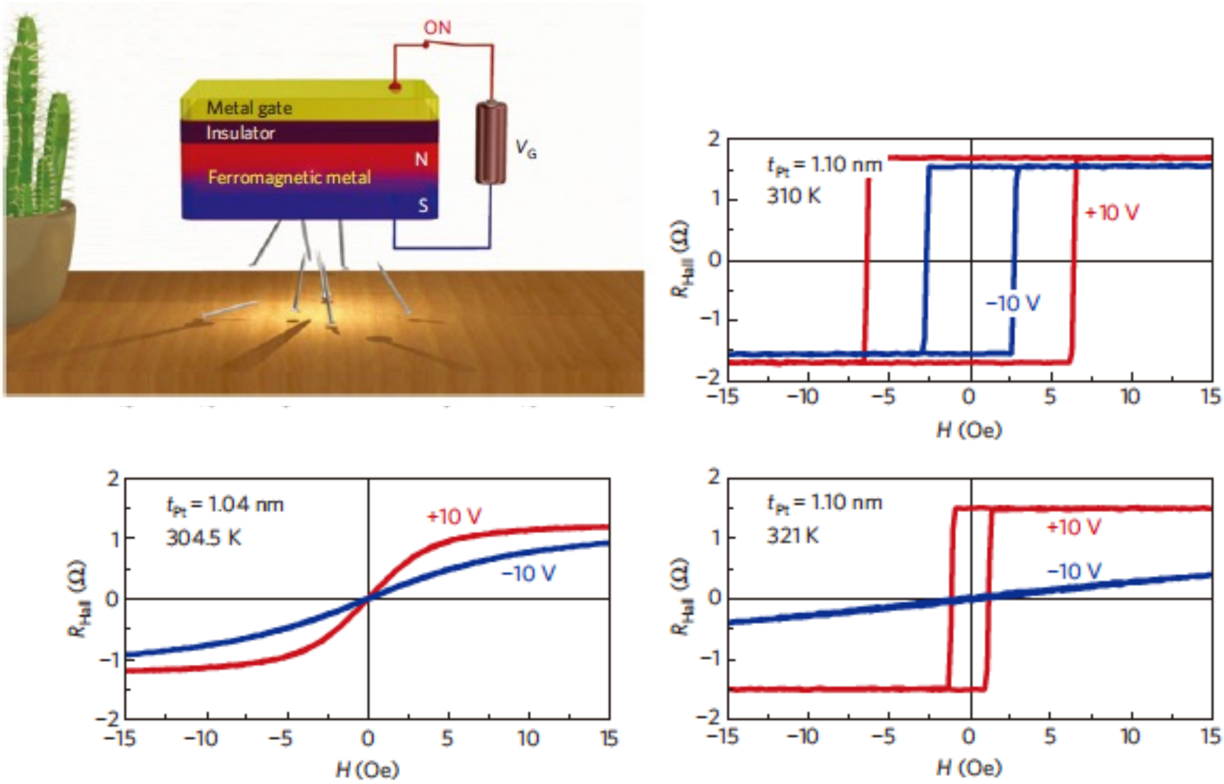




* L. Chen *et al.*, *Phys. Rev. Lett.* **115**, 057204 (2015).

Electric Field Control of Magnetism - *Metals*

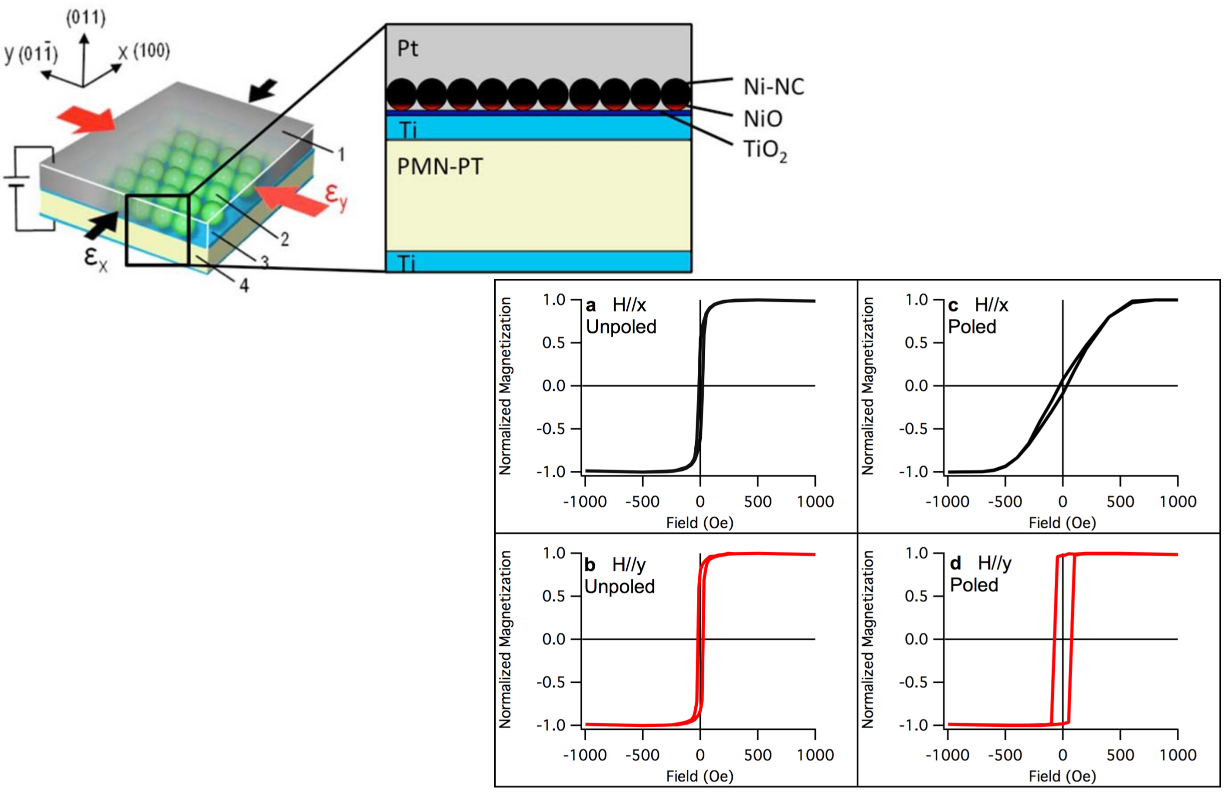
Ferromagnetic metal (Co) : *



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

Electric Field Control of Magnetism - *Superparamagnetism*

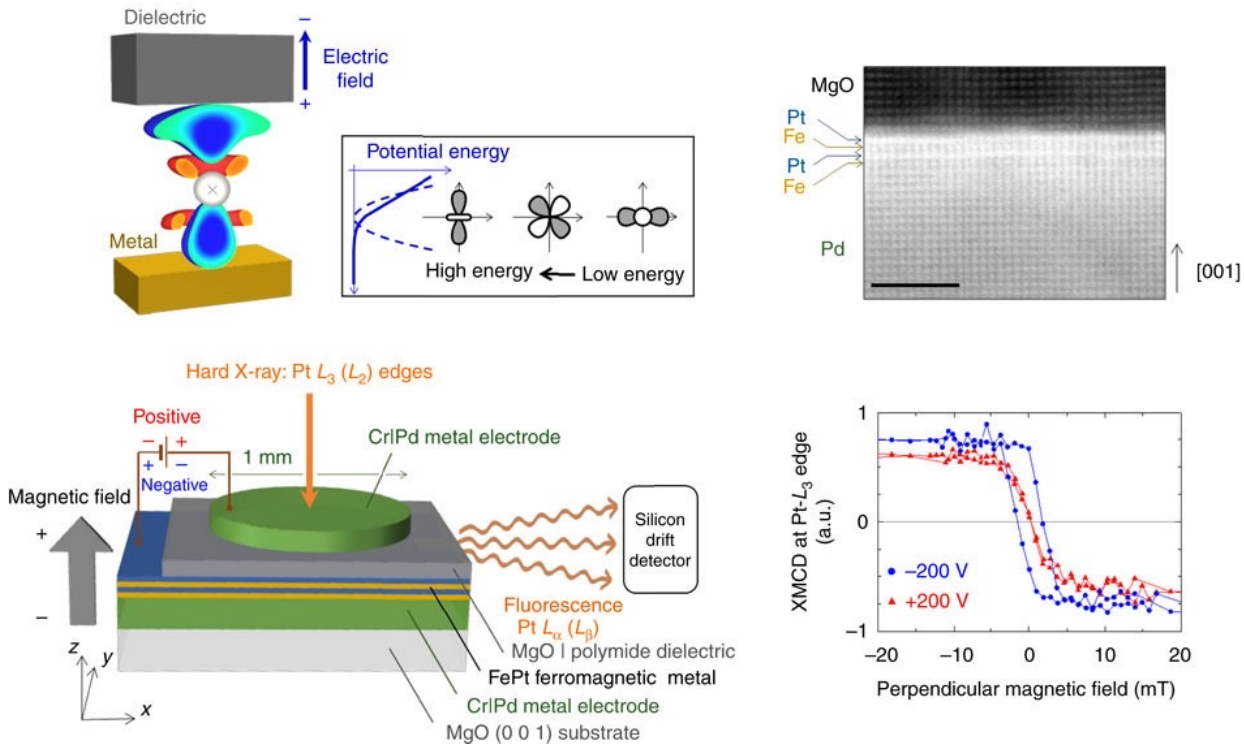
Array of NiO nanoparticles : *



* H. K. D. Kim *et al.*, *Nano Lett.* **13**, 884 (2013).

Band Structures by Voltage Control

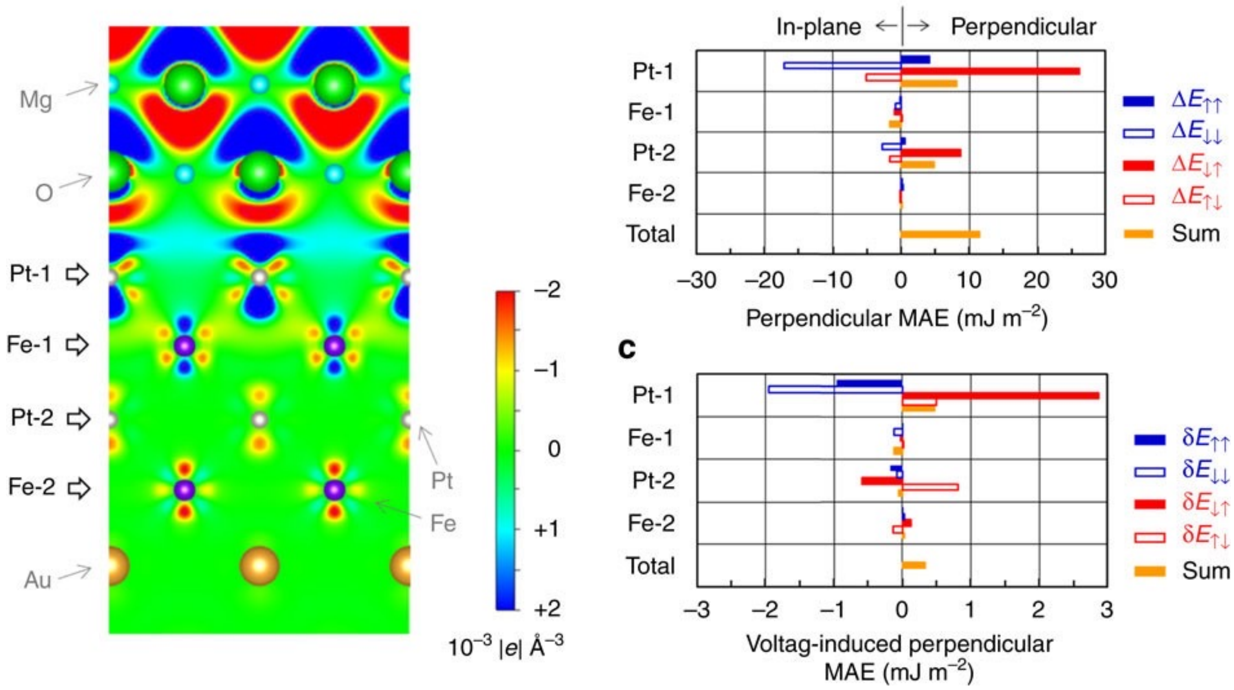
Voltage-controlled magnetic tunnelling junction : *



* S. Miwa *et al.*, *Nature Commun.* **8**, 15848 (2017).

Band Structures by Voltage Control

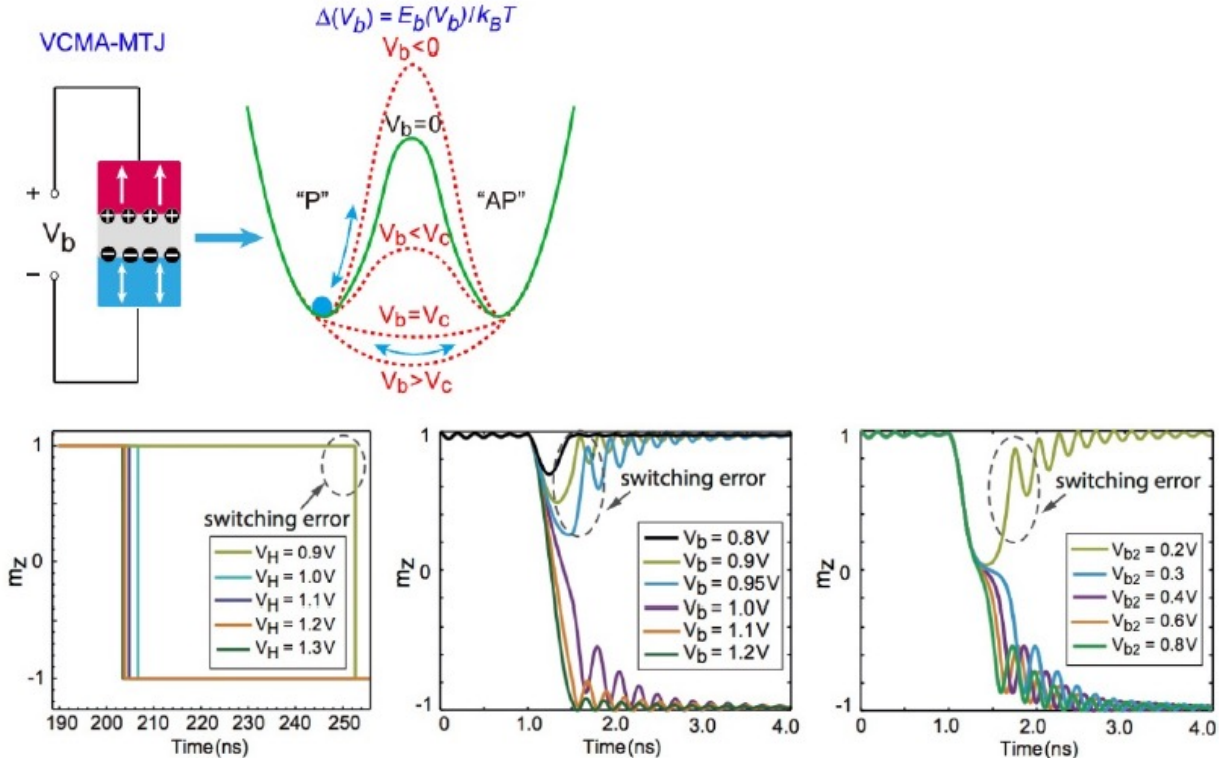
Voltage-controlled magnetic tunnelling junction : *



* S. Miwa *et al.*, *Nature Commun.* **8**, 15848 (2017).

Voltage Control of MRAM Switching

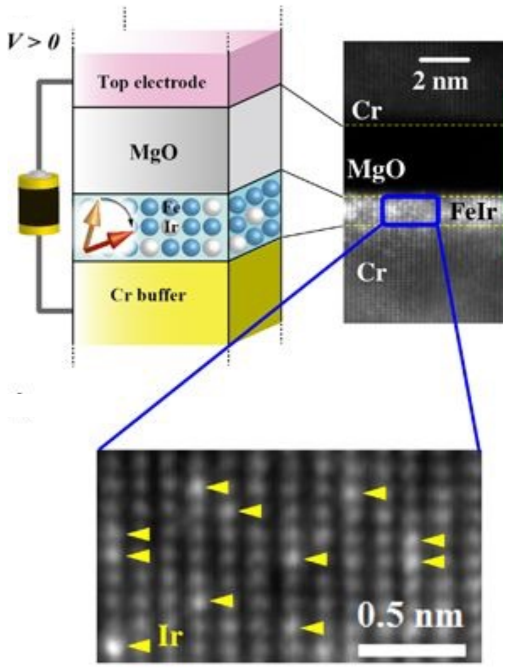
Voltage-controlled magnetic tunnelling junction : *

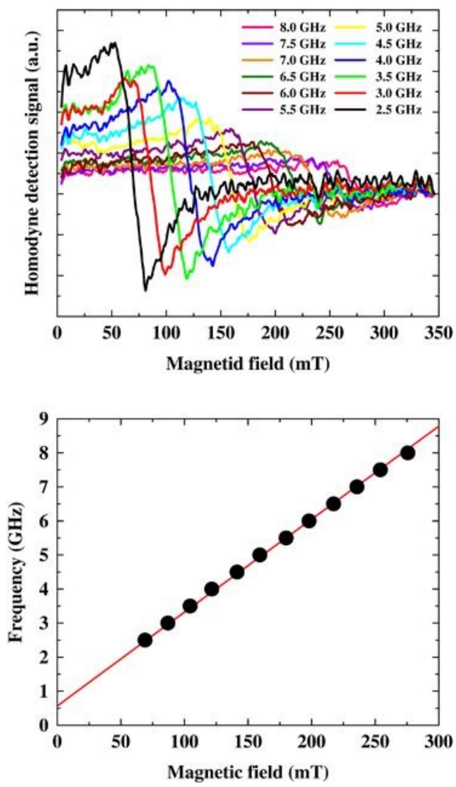


* H. Cai *et al.*, *Appl. Sci.* **7**, 929 (2017).

Voltage Control of MRAM Frequency

Voltage-controlled magnetic tunnelling junction : *





* T. Nozaki *et al.*, *NPG Asia Mater.* **9**, e451 (2017).

Voltage Controlled MRAM Operation

Writing power can be reduced by 1 / 60 as compared with STT : *

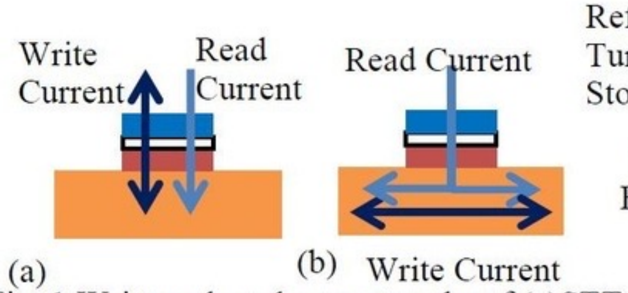


Fig. 1 Write and read current paths of (a)STT MRAM and (b)VoCSM, respectively.

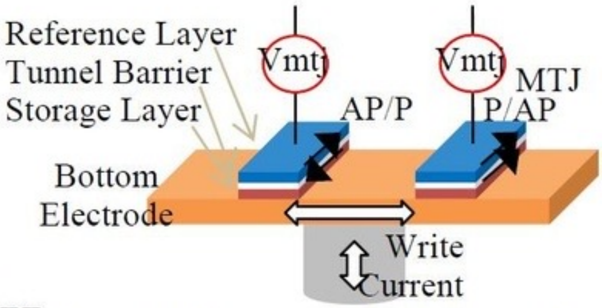
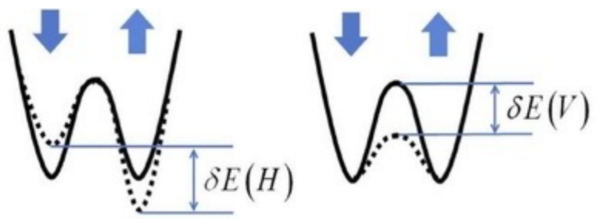


Fig. 2 A diagram of the high-speed VoCSM memory cell.



External Magnetic Field (H)   VCMA(V)

Effective Perpendicular Anisotropy, K_i

$K_i(V) = K_i(0) - \varepsilon V/d$, where d is free layer thickness, and ε is the VCMA coefficient.
For standard PMA CoFeB/MgO tunnel junctions, $K_i(0) \sim$ 1-2 mJ/m^2 and $\varepsilon \sim$ 30-50 fJ/Vm

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

MRAM Generations

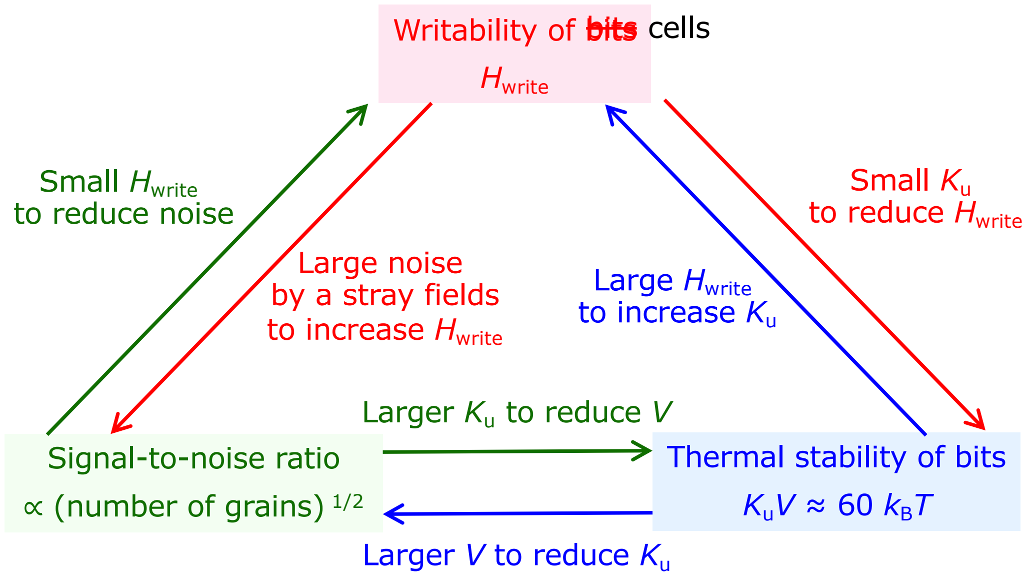
Recent development in MRAM : *

Generation	Name	Recording operation	Writing operation	Fabrication rule	Storage capacity
1st	(Field) MRAM	In-plane		nm	Mbit
2nd	STT-MRAM	In-plane		nm	Mbit
3rd	STT-pMRAM	Perpendicular		nm	Mbit

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

Tri-Lemma in ~~HDD~~ MRAM

Requirements for ~~higher-density recording :~~
reliable MRAM operation :



Current Issues on STT-MRAM

Operation cycles : *

Current introduction to a MTJ memory cell is needed for both writing and reading operations.

- Data writing by STT with a current density of ~ 10^8 A/cm^2, inducing permanent damage on a tunnel barrier.
- Data reading by a sending current, which may rewrite a data by accident.

Possible solutions

- 1T1MTJ →
- Alternative phenomena to be used for a writing operation :
    - Voltage-controlled magnetic anisotropy (   )
    - Spin-orbit torque (   )

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

Current Technology of STT-MRAM

Expectations against current technology : *

Expectations to MRAM :

- Reduction in stand-by power consumption by eliminating a leakage current generated by DRAM etc.

  →

- Increase in storage density by reducing a unit memory area.
- Increase in operation speed for the replacement of SRAM.

  →

  →

- Improvement in radiation resistance by reducing soft error in a transistor etc.

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

4th Generation MRAM Options

For longer operation cycle and lower power consumption : *

	Memory cell unit	Memory cell size	Writing speed	Writing energy	Operation cycle
STT-MRAM	2T MTJ	F^2	ns	fJ	(SRAM)
VoC-MRAM	2T MTJ	F^2	ns	fJ	(SRAM)
SOT-MRAM	2T MTJ	F^2	ns	fJ	(SRAM)

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