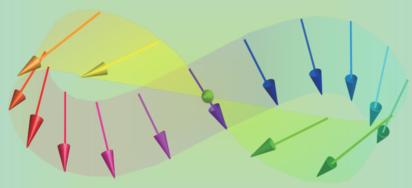
Information Storage and Spintronics 13



Atsufumi Hirohata

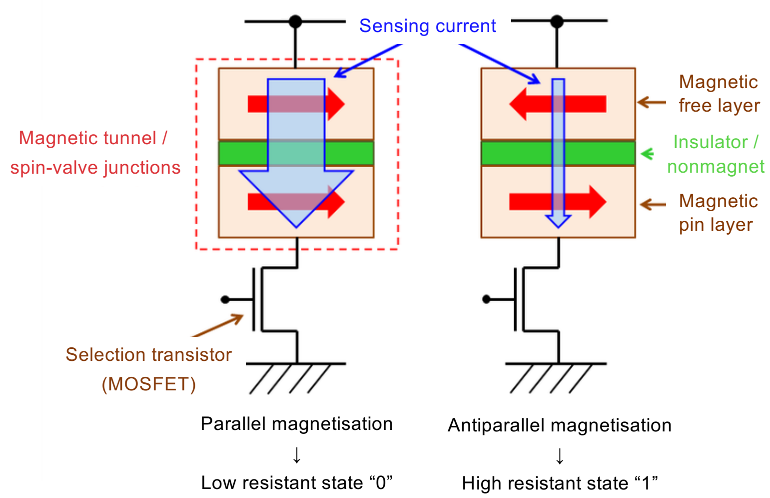
Department of Electronic Engineering

THE UNIVERSITY *of York*

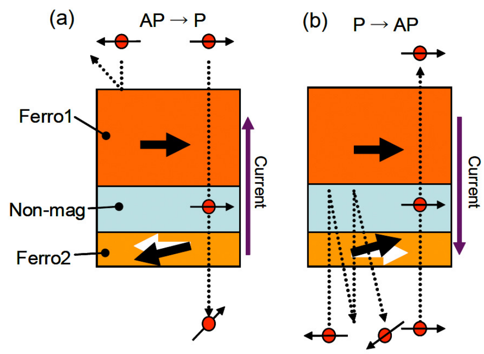
14:00 Monday, 14/November/2022 (SLB 101)

Quick Review over the Last Lecture

MRAM read-out :



MRAM STT write-in :



* http://www.wikipedia.org/;

** M. Oogane and T. Miyazaki, "Magnetic Random Access Memory," in *Epitaxial Ferromagnetic Films and Spintronic Applications*, A. Hirohata and Y. Otani (Eds.) (Research Signpost, Kerala, 2009) p. 335;

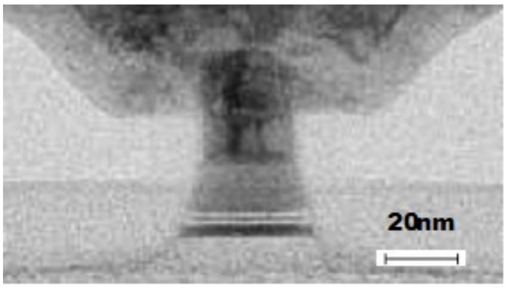
*** http://www.toshiba.co.jp/

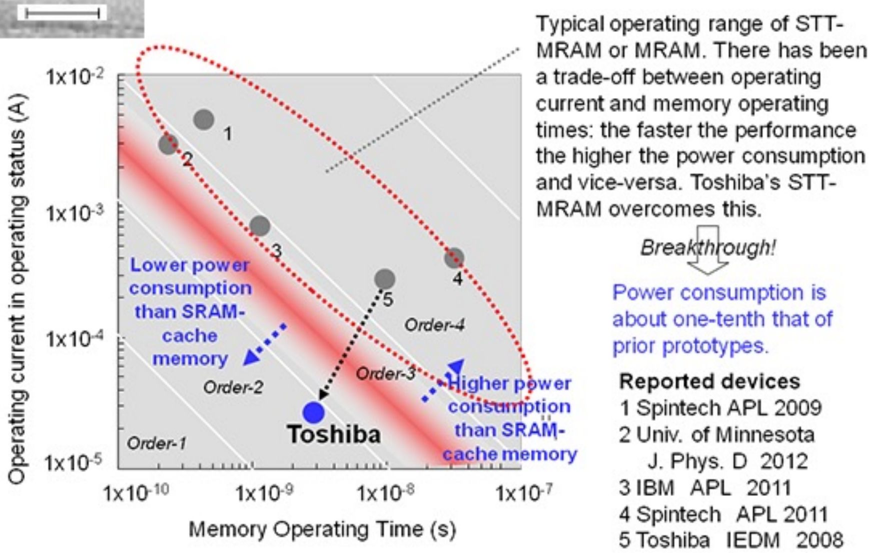
13 Spin-Transfer Torque

- Spin-transfer torque
- Gilbert damping

Perpendicular MTJ

In 2007, Toshiba demonstrated STT operation with perpendicular magnetisation : *

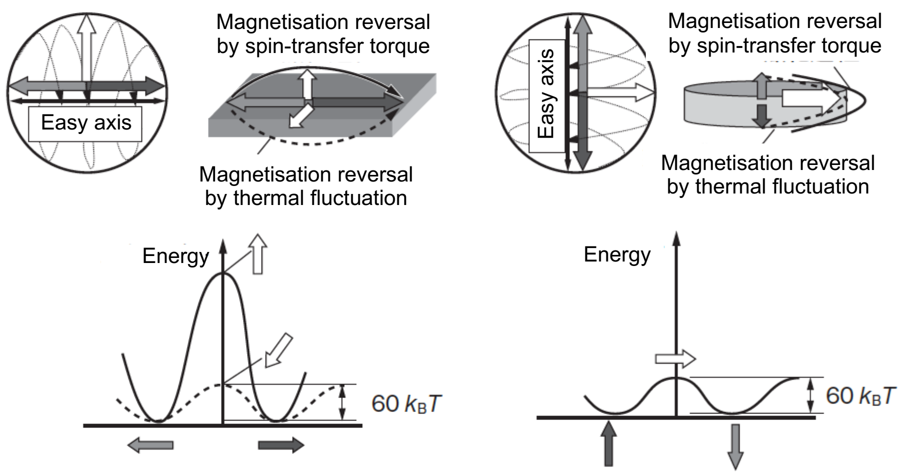


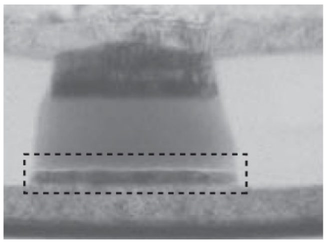


* http://www.toshiba.co.jp/

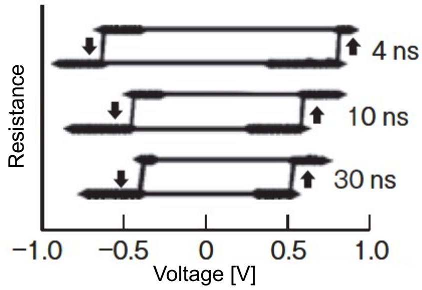
Advantages of Perpendicular MTJ

Energy barrier can be lowered using perpendicular magnetisation : *





50-nm perpendicular MTJ

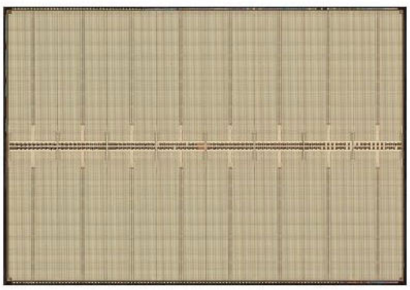


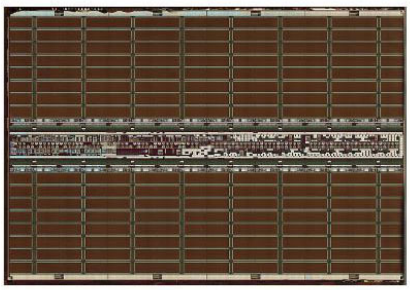
* http://www.toshiba.co.jp/

p-MRAM Products

- ✓ Aupera Technologies AUP-AXL-M128 M.2 Module
- ✓ 256 Mb, pMTJ DDR3
- ✓ EMD3D256M08G1-150CBS1
- ✓ IBM FLASH System (FLASH Core)
- ✓ Standalone Product

EVERSPIN TECHNOLOGIES

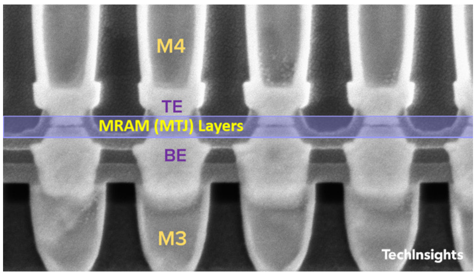




TechInsights

* https://www.techinsights.com/blog/techinsights-memory-technology-update-iedm18

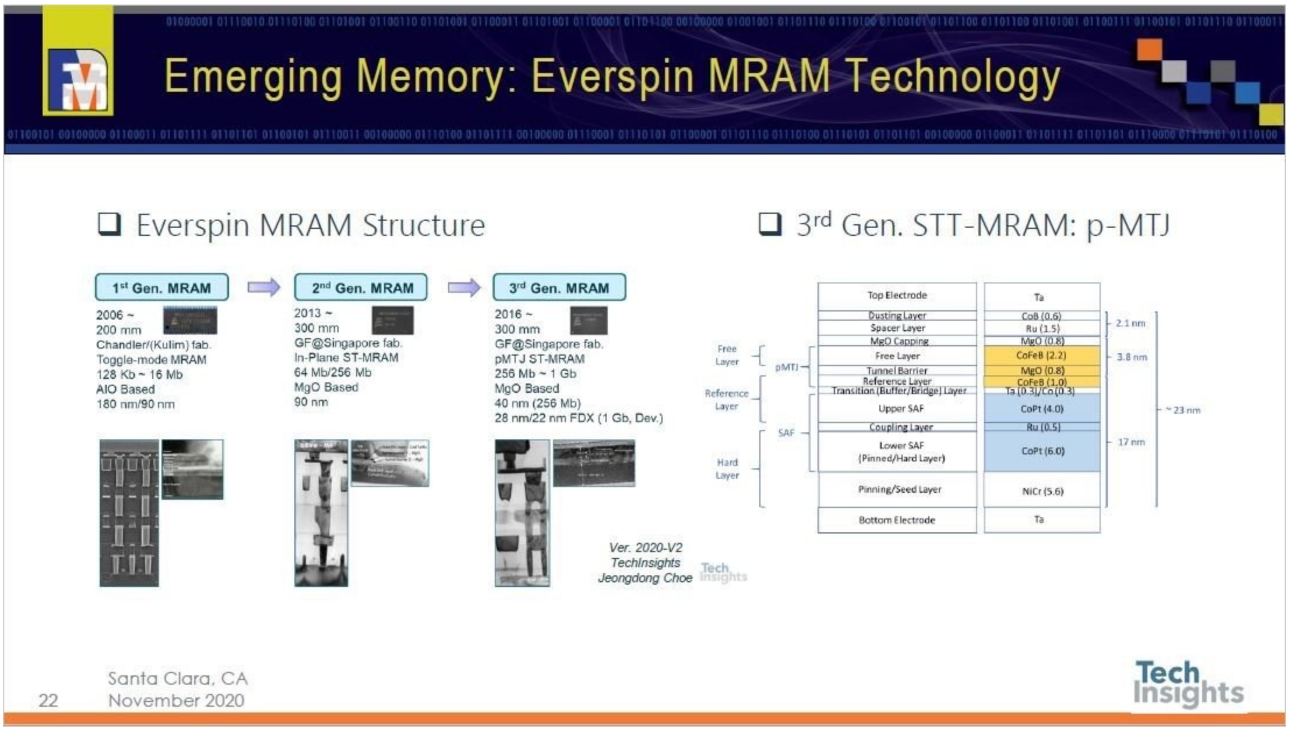
p-MRAM Products



Items	Everspin 2nd Gen. MRAM (DDR3)	Everspin 3rd Gen. MRAM (DDR3)	Everspin 4th Gen. MRAM (DDR4)
Product Example	EMD3D064M DDR3 ST-MRAM	EMD3D256M DDR3 ST-MRAM	EMD4E001G DDR4 ST-MRAM
Die Size	65.3 mm^2 (11.15 mm x 5.86 mm)	100.1 mm^2 (12.12 mm x 8.26 mm)	105.1 mm^2 (12.29 mm x 8.55 mm)
Technology Node	90 nm	40 nm	28 nm
Memory / Die	64 Mb	256 Mb	1,024 Mb (1 Gb)
Bit Density	0.98 Mb/mm^2	2.56 Mb/mm^2	9.75 Mb/mm^2
Cell Size	0.387 μm^2	0.156 μm^2	0.0396 μm^2
Pitch (WL/BL)	530 nm / 730 nm	150 nm / 520 nm	110 nm / 180 nm
MTJ	In-plane MTJ	pMTJ	pMTJ
MRAM Integration	Between M3 and M4	Between M3 and M4	Between M3 and M4
# Metals	5	5	7

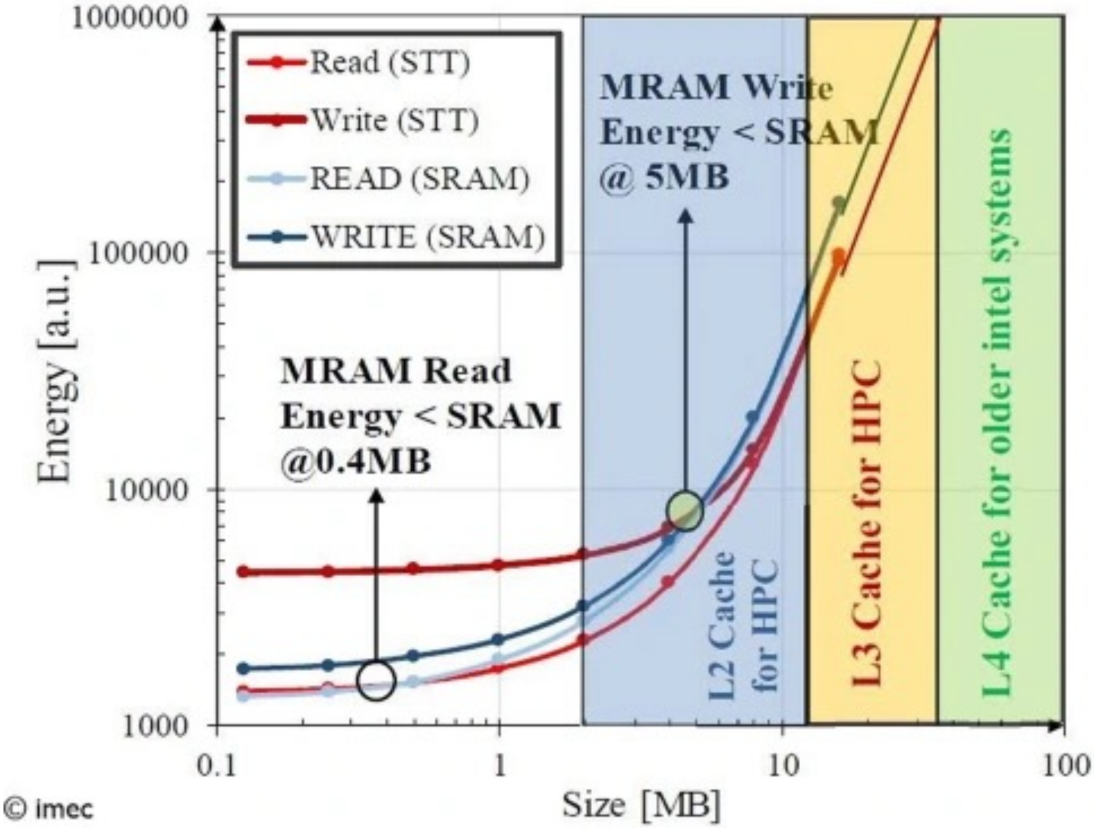
* https://www.techinsights.com/blog/memory/worlds-first-1-gb-28-nm-stt-mram-product-everspin

3rd Generation MRAM



* https://eetimes.jp/ee/articles/2104/27/news030.html?fbclid=IwAR2PFG-O-i2wNUHV0-qFjWmZ0LPPUgY1tVo0NsNd9LvMYf84u9-1LyaQxGo

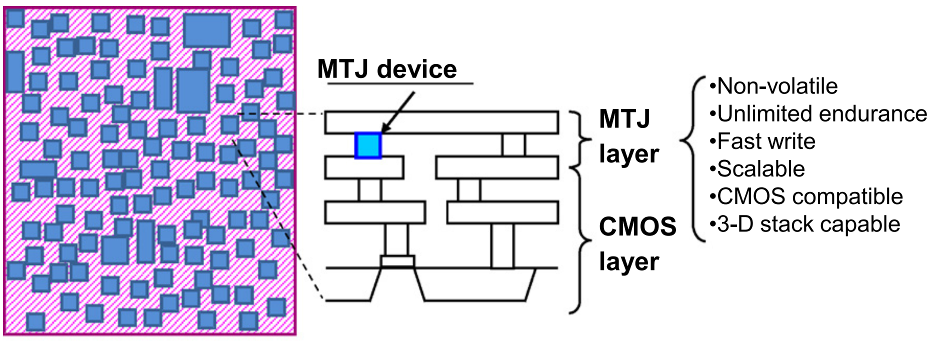
Energy Consumption



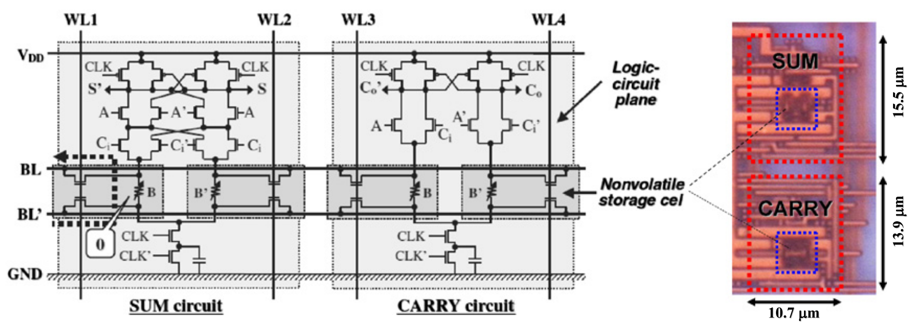
* https://www.eeweb.com/mram-technologies-from-space-applications-to-unified-cache-memory/

MRAM / Spin RAM Implementation

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



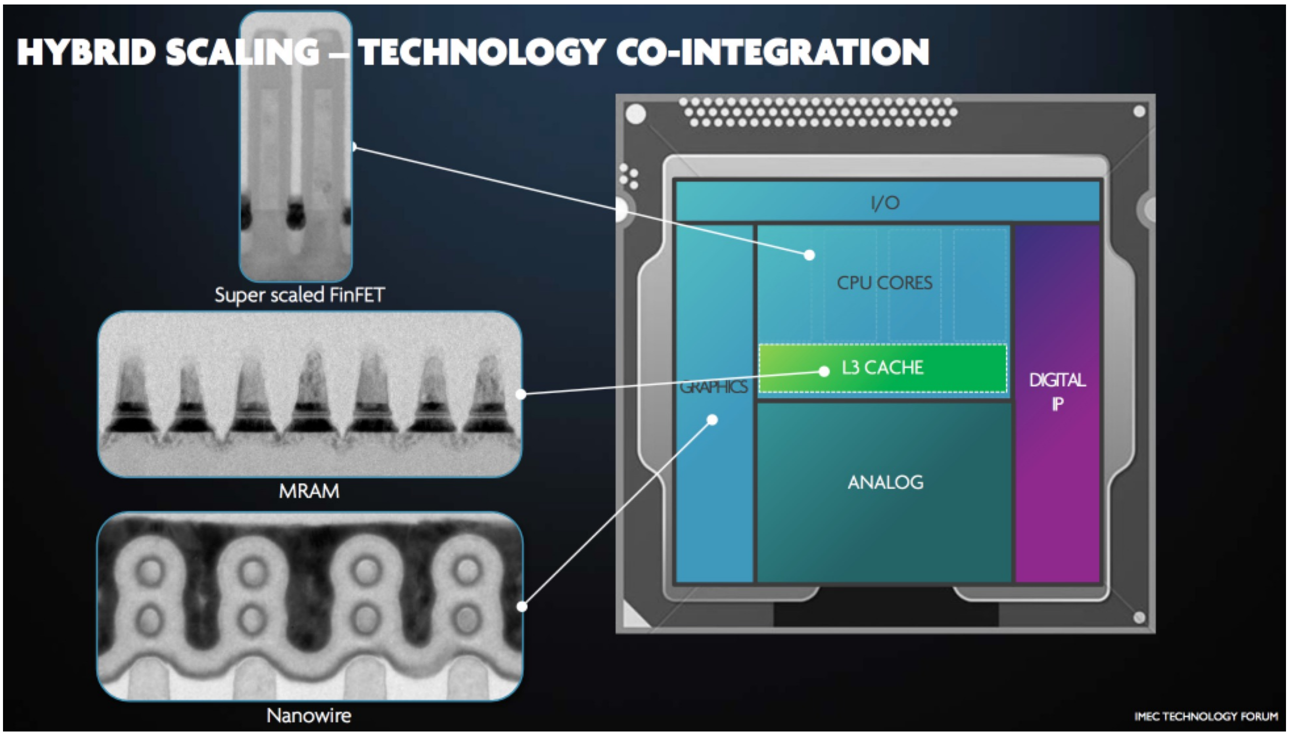
(a) Nonvolatile Logic-in-Memory Architecture



(b) Design example of nonvolatile full adder

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

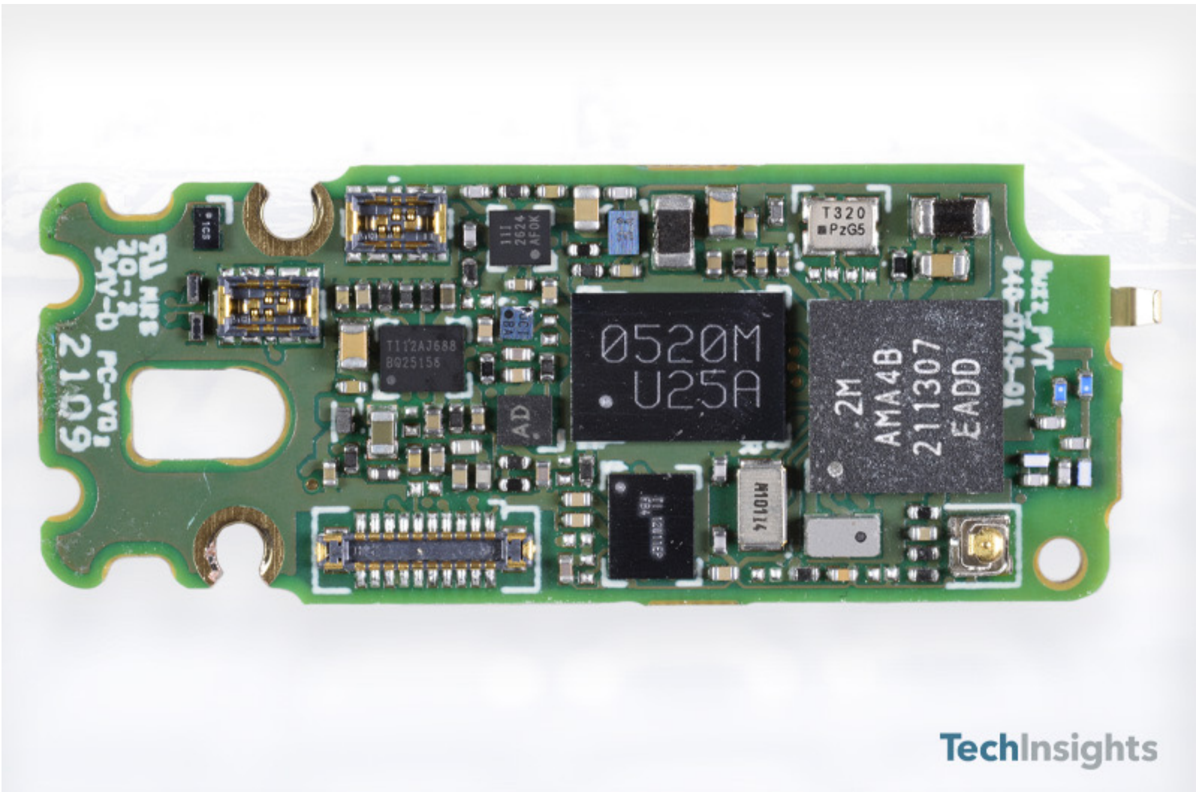
MRAM / Spin RAM and CPU Integration



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

Embedded MRAM Products

Ambiq Apollo4 Blue, which a new ARM Cortex-M4 SoC : *

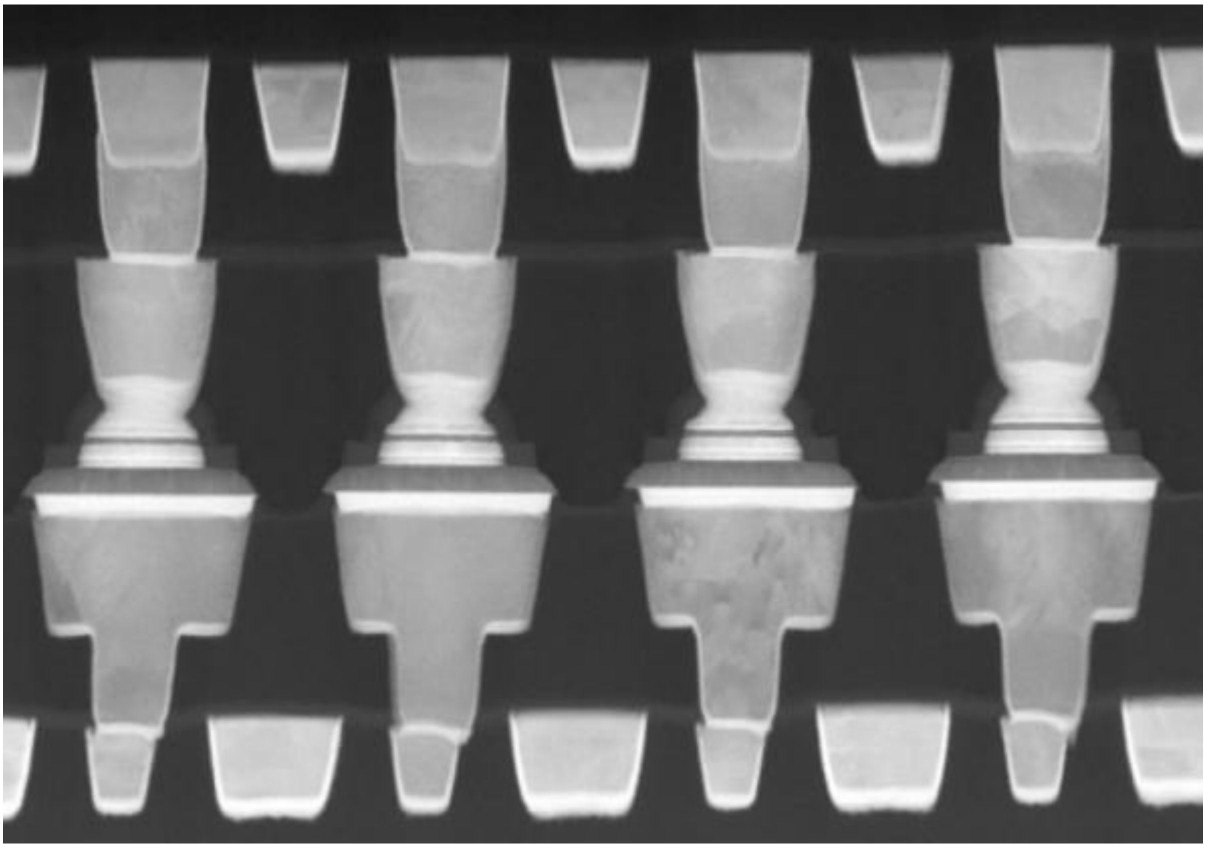


* https://semiengineering.com/will-the-fitbit-charge-5-outshine-the-fitbit-luxe/

Embedded MRAM

* https://www.youtube.com/watch?v=DlKRpXRudL8

Intel embeds MRAM in FinFET process

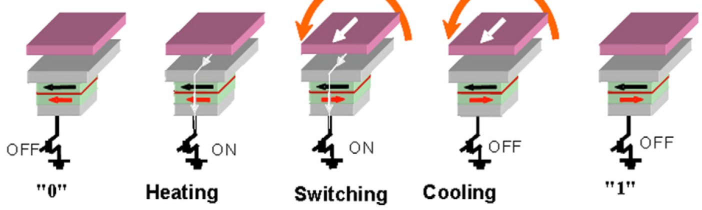


* http://www.eenewsanalog.com/news/iedm-intel-embeds-mram-finfet-process/page/0/1

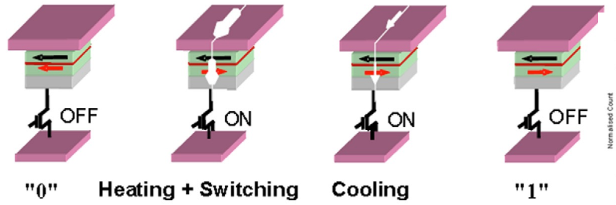
Thermally Assisted (TA)-MRAM

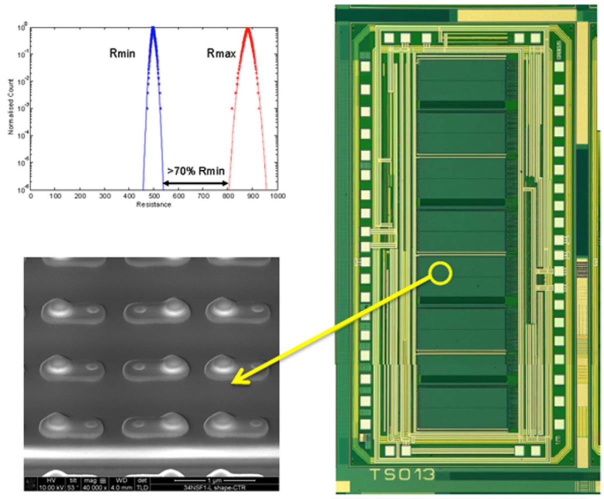
Crocus demonstrated 1-Mbit MRAM with thermally assisted STT operation : *

TAS-FIMS :



TAS-STT :

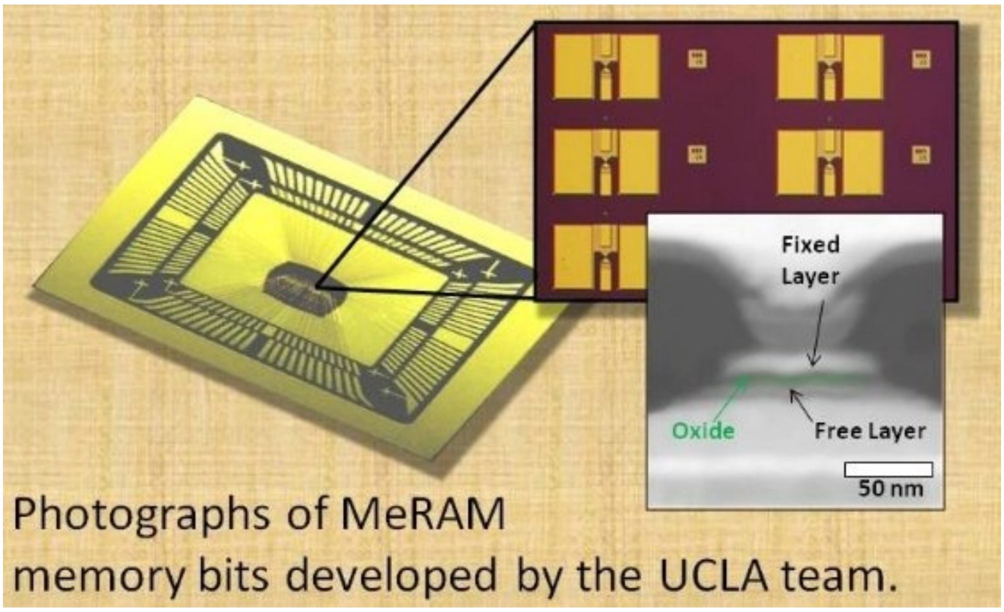




* I. L. Prejbeanu *et al.*, *J. Phys. D: Appl. Phys.* **46**, 074002 (2013).

Reduced Energy Consumption

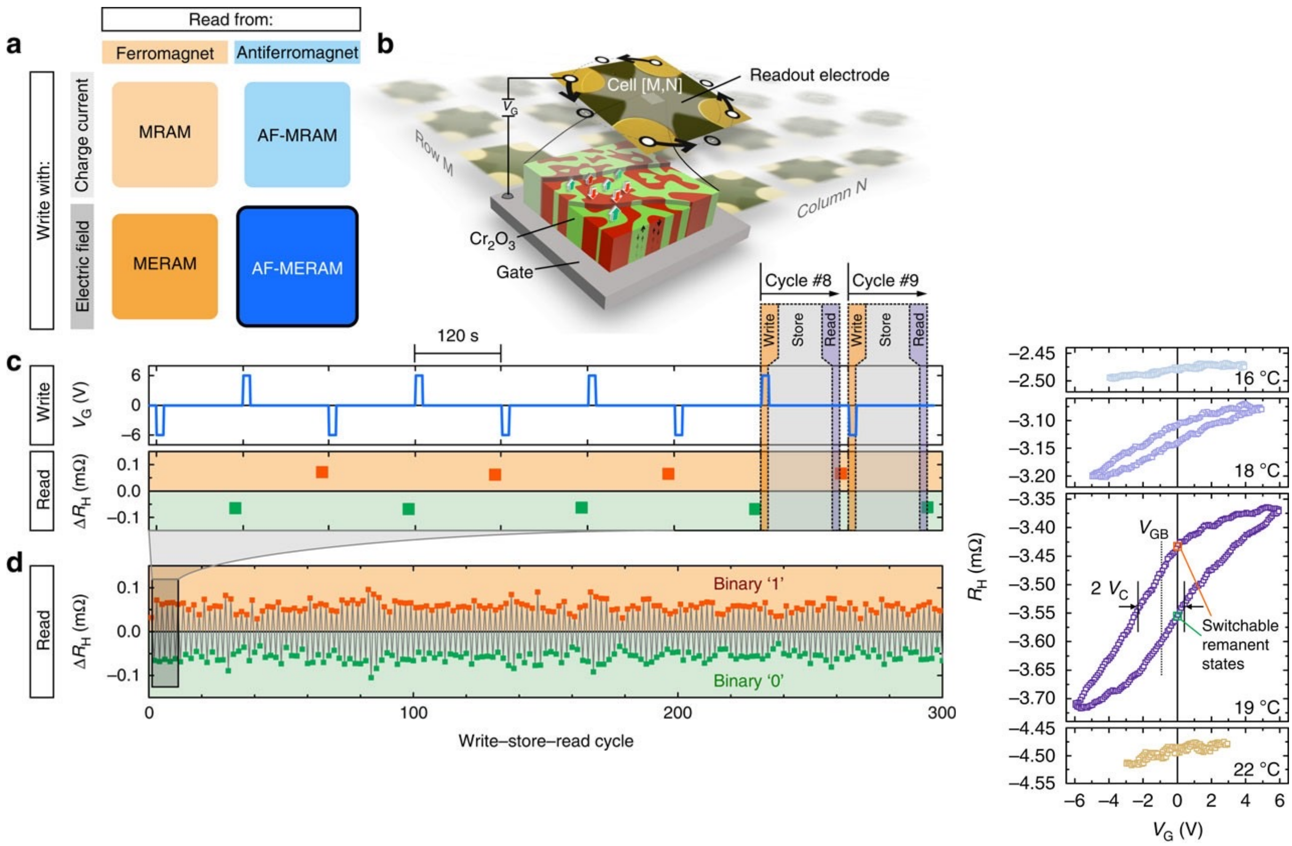
3-orders of reduction in energy consumption was demonstrated by UCLA team : *



Voltage-induced magnetisation reversal was used.

* http://newsroom.ucla.edu/portal/ucla/ucla-engineers-have-developed-241538.aspx

Magnetoelectric Random Access Memory (MeRAM)



* T. Kosub *et al.*, *Nat. Commun.* **8**, 13985 (2017).

MRAM Production

Home (/) > Manufacturing & Process Technology (/category-main-page-manufacturing/) > Four Foundries Back MRAM

MANUFACTURING & PROCESS TECHNOLOGY (/CATEGORY-MAIN-PAGE-MANUFACTURING/)

Four Foundries Back MRAM

53 155

Next-gen embedded memory technology ramps up in wake of flash scaling issues.

AUGUST 23RD, 2017 - BY: **MARK LAPEDUS (HTTPS://SEMIENGINEERING.COM/AUTHOR/MARK-LAPEDUS/)**

Four major foundries plan to offer MRAM as an embedded memory solution by this year or next, setting the stage for what finally could prove to be a game-changer for this next-generation memory technology.

GlobalFoundries, Samsung, TSMC and UMC plan to start offering spin-transfer torque magnetoresistive RAM (ST-MRAM or STT-MRAM) as an alternative or a replacement to NOR flash, possibly starting later this year. This represents a big shift in the market, because until now only Everspin has shipped MRAM (https://semiengineering.com/kc/knowledge_center.php?kcid=95) for various applications, such as a battery-backed SRAM replacement, write-cache and others.

The next big opportunity for STT-MRAM is the embedded memory IP market. NOR flash, the traditional embedded memory, is running into an

TECHNICAL PAPERS

Machine Learning Based Prediction: Health Behavior On BP (Https://Semiengineering.com/Machine-Learning-Based-Prediction-Health-Behavior-On-Bp/)

OCTOBER 12, 2018 BY TECHNICAL PAPER LINK

Autonomous Vehicle Navigation In Rural Environments Without Detailed Prior Maps (MIT) (Https://Semiengineering.com/Autonomous-Vehicle-Navigation-In-Rural-Environments-Without-Detailed-Prior-Maps-Mit/)

MAY 15, 2018 BY TECHNICAL PAPER LINK

Silicon CMOS Architecture For A Spin-Based Quantum Computer (Https://Semiengineering.com/Silicon-Cmos-Architecture-For-A-Spin-Based-Quantum-

Overall site Searc

SPONSORS

(http://appliedmaterials.com/) (ht

(http://www.kla-tencor.com/) (ht

(http://globalfoundries.com/) (ht

(http://www.umc.com/English/) (ht

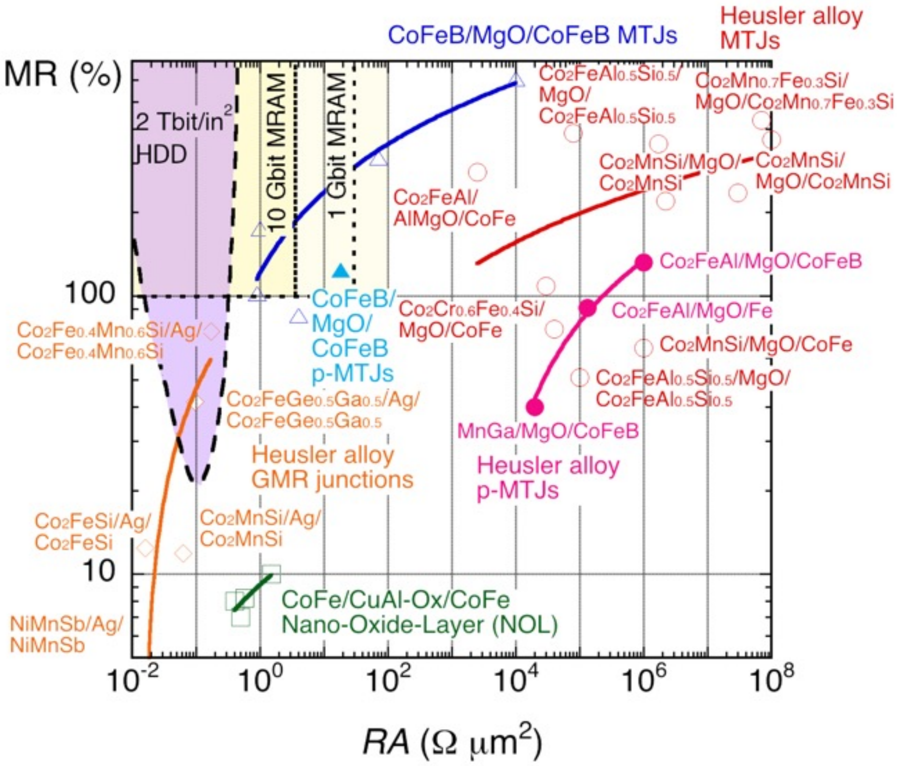
(http://www.semi.org/) (ht

NEWSLETTER SIGNUP

Email:

* https://semiengineering.com/four-foundries-back-mram/

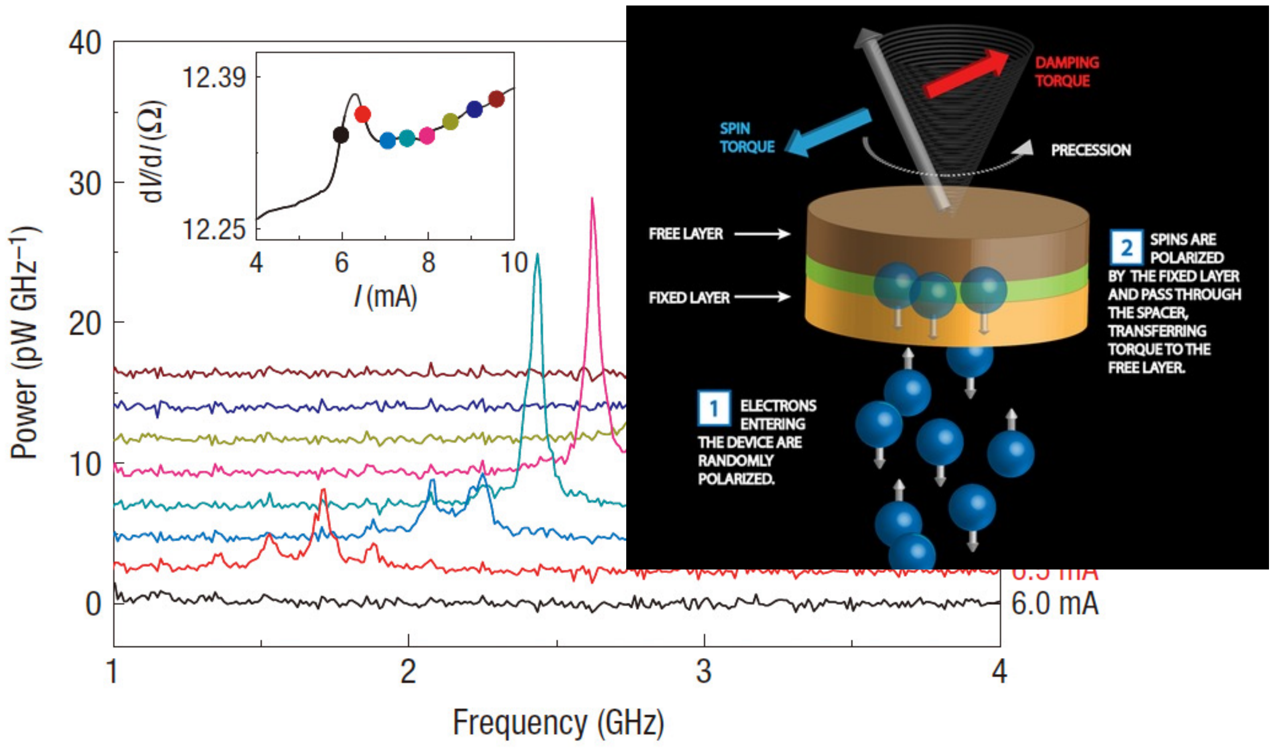
MRAM Targets



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

Spin Torque Oscillator

Magnetisation oscillates by spin-transfer torque : *



* O. Boulle *et al.*, *Nature Phys.* **3**, 492 (2007);
** https://www.nist.gov/news-events/news/2013/04/unprecedented-view-spintronic-switching.

Spin-Transfer Torque

Landau-Lifschits-Gilbert equation : *

$$\frac{\partial \vec{M}}{\partial t} = \boxed{-\gamma \vec{m} \times \overrightarrow{H_{\text{eff}}}} + \boxed{\alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}} - \boxed{\frac{\gamma}{d} \vec{m} \times (\vec{m} \times \Delta \vec{J_S})}$$

where H_{eff} : an effective magnetic field, γ : the gyromagnetic ratio and α : the Gilbert damping constant.

$$|\gamma| = \frac{g\mu_B}{h}$$

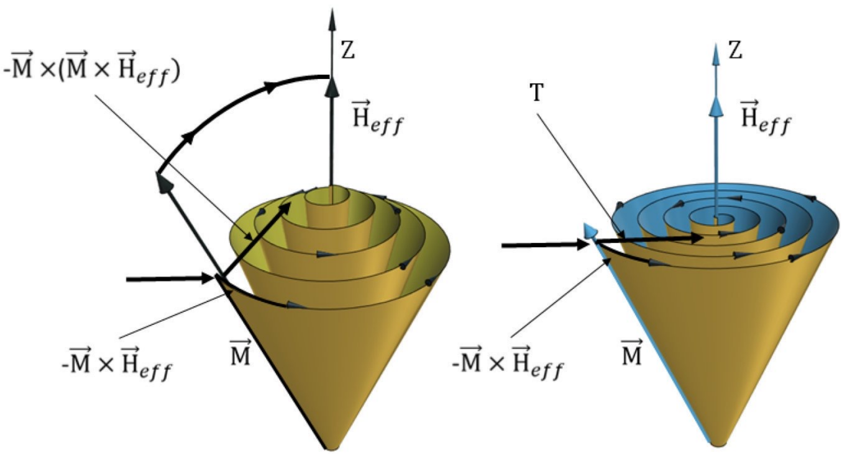
where g : Lange's g-factor, μ_B : the Bohr magneton and h : the Planck constant.

$$\alpha = \frac{|\gamma|\Delta H}{2\omega}$$

where ΔH : the full width half maximum of a ferromagnetic resonance ω : the resonant frequency.

* A. Hirohata (Guest Editor), *J. Phys. D: Appl. Phys.* **44,** 380301 (2011).

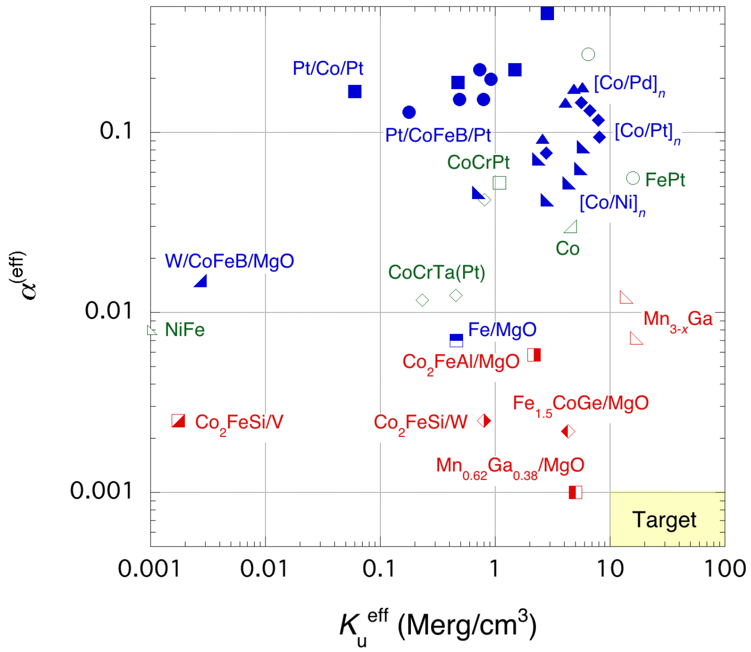
Advantages of MRAM / Spin RAM



* S Azzawi *et al.*, *J. Phys. D: Appl. Phys.* **50,** 473001 (2017).

Damping Constants

For faster magnetisation reversal in a data bit of MRAM, a low damping constant is required : *

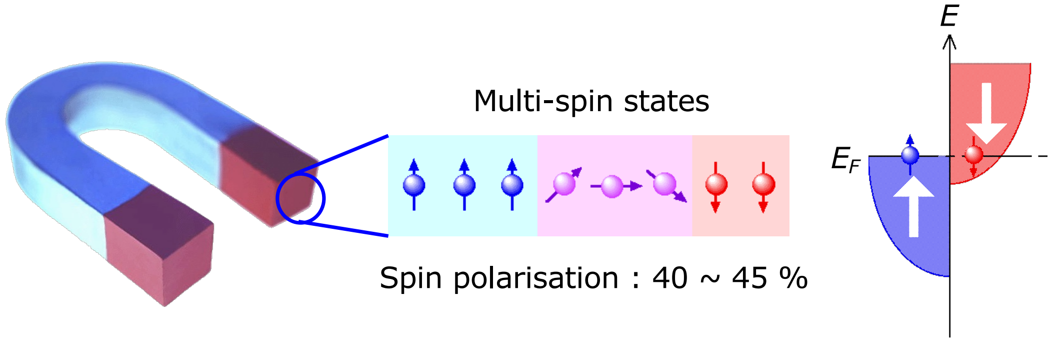


Theoretically, the damping constant α , ensuring the to exhibit a small α (<0.01).

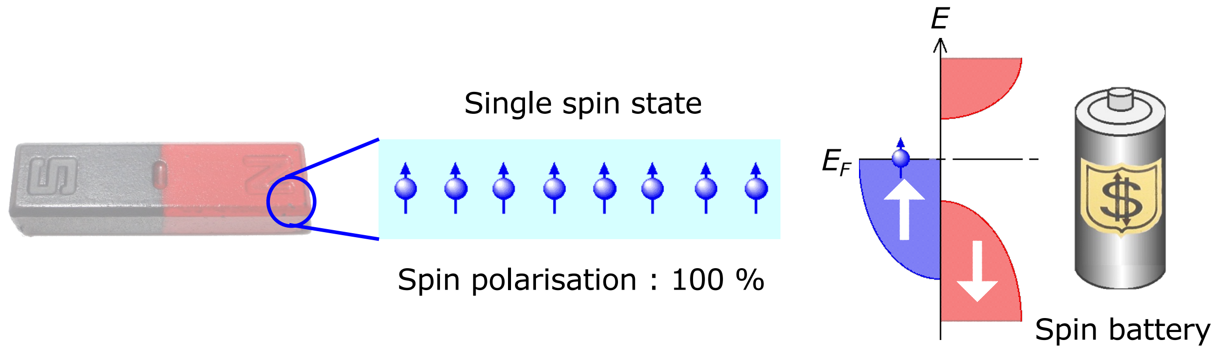
* A. Hirohata *et al.*, *J. Magn. Magn. Mater.* **509**, 166711 (2020).

Half-Metallic Feromagnet

Conventional ferromagnet :

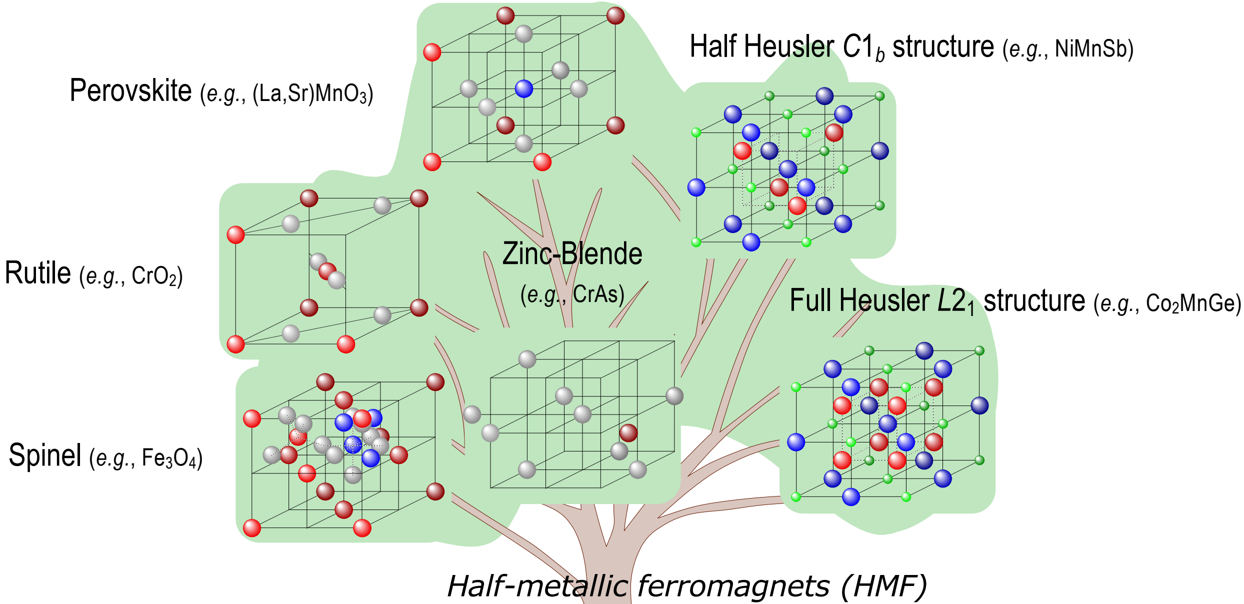


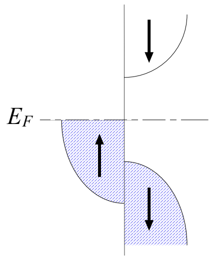
Half-metallic ferromagnet :



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

Half-Metallic Ferromagnets



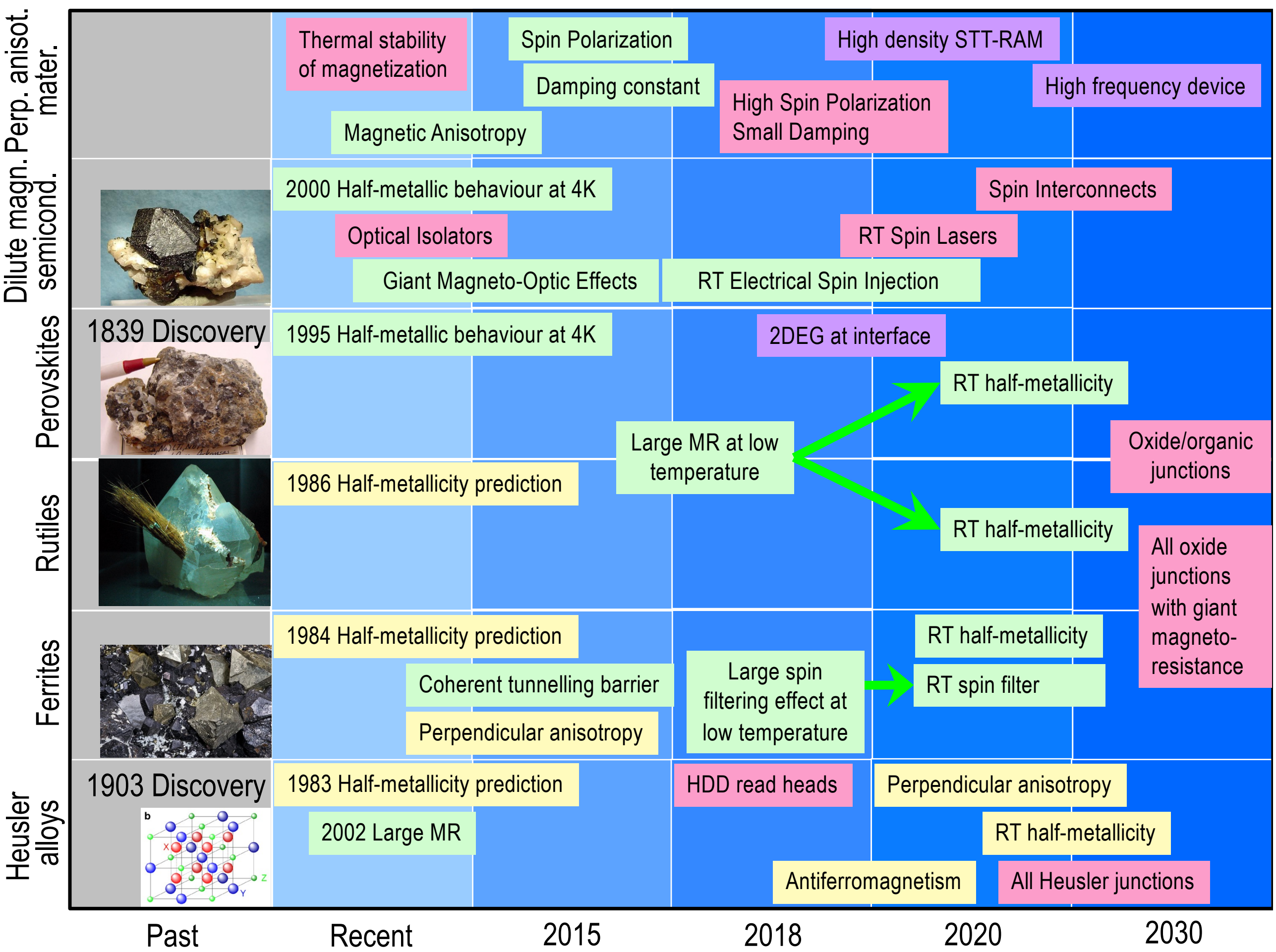


Conduction electrons at the E_F is.

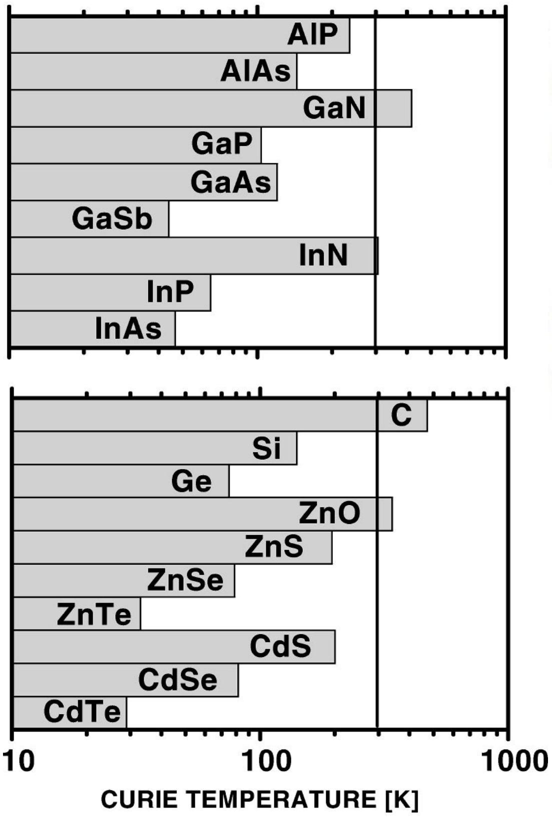
Obstacles to realisation of HMF devices :

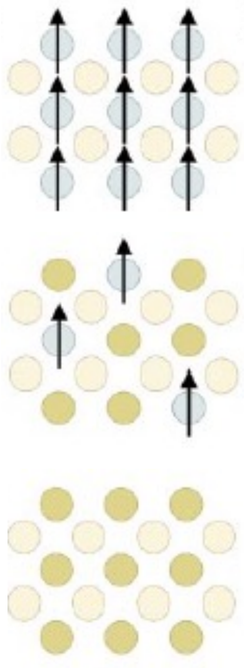
- *Curie temperature below room temperature*
- *atomic disorder / unstable phases*

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



Dilute Magnetic Semiconductors





Magnetic semiconductor

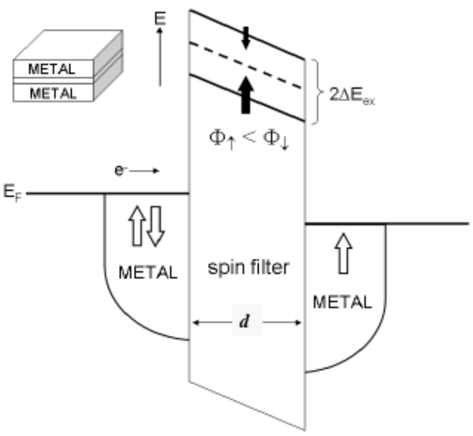
Dilute magnetic semiconductor

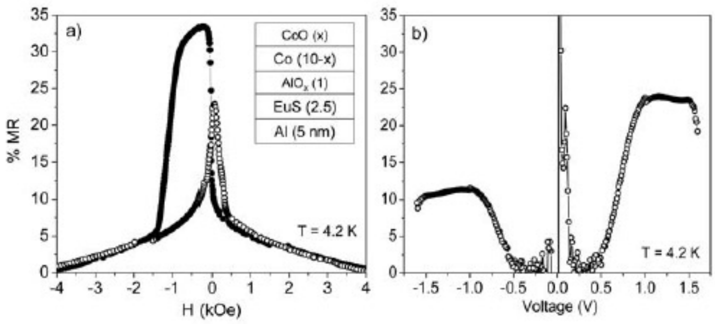
Non-magnetic semiconductor

* 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).

Spin Filtering

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



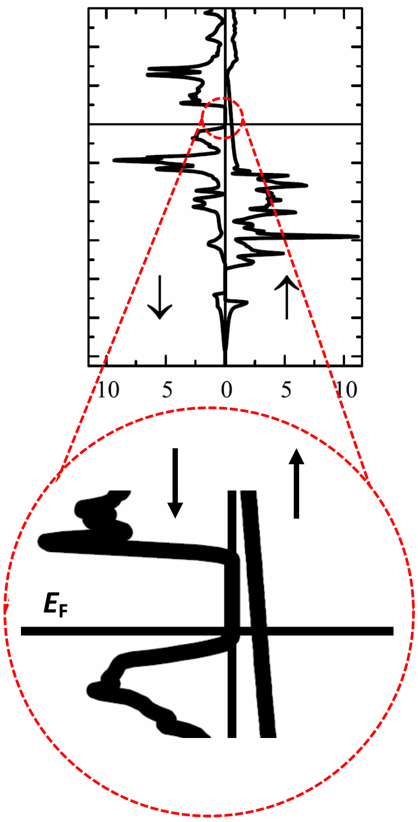


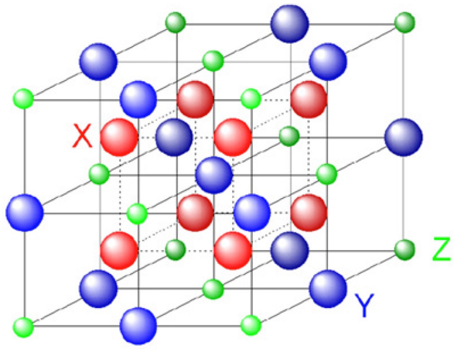
Material	Magnetic Behavior	Tc (K)	Moment (μ_B)	Structure, a(nm)	E_g (eV)	$2\Delta E_{ex}$ (eV)	P (%)	Spin Filter Reference
EuO	FM	69.3	7.0	Fcc, 0.514	1.12	0.54	29	Santos[23]
EuS	FM	16.6	7.0	Fcc, 0.596	1.65	0.36	86	Moodera[21]
EuSe	AFM	4.6	7.0	Fcc, 0.619	1.80		100	Moodera[22]
$BiMnO_3$	FM	105	3.6	perovskite			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.

Half-Metallic Heusler Alloys

Band gap is formed only for a minority spin density of states :

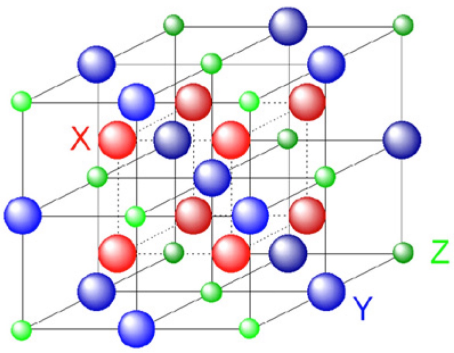




* A. Hirohata, *Curr. Opin. Solid. Stat. Mater. Sci.* **10**, 93 (2006)..

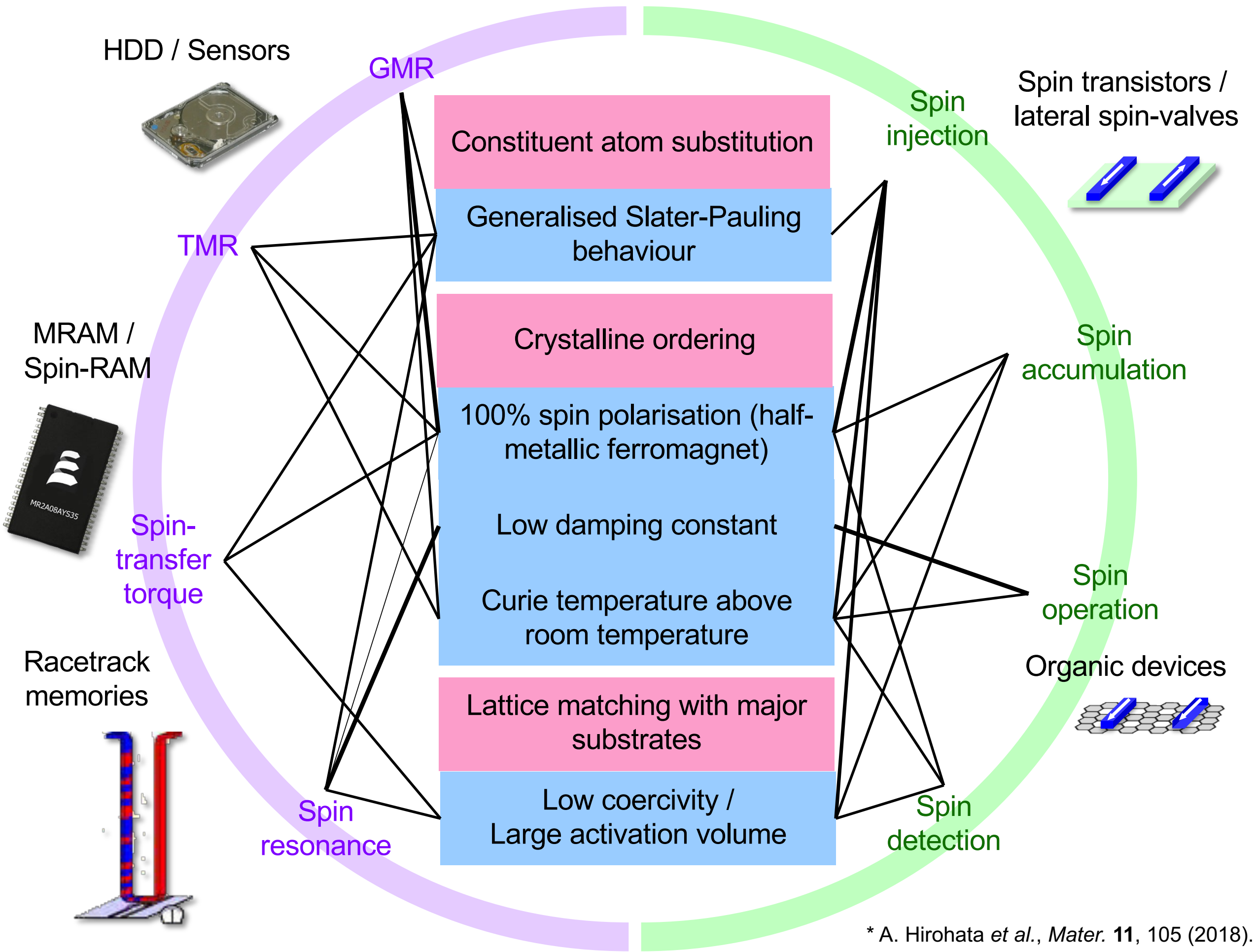
Heusler Alloy Combinations

Typical Heusler alloys have the form of X_2YZ :



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

* K. Elphick *et al.*, *Sci. Techol. Adc. Mater.* (https://doi.org/10.1080/14686996.2020.1812364 , in press).



* A. Hirohata *et al.*, *Mater.* **11**, 105 (2018).

Recent Development on Heusler Alloy Devices