Opportunities and challenges for nanomagnetism and spintronics

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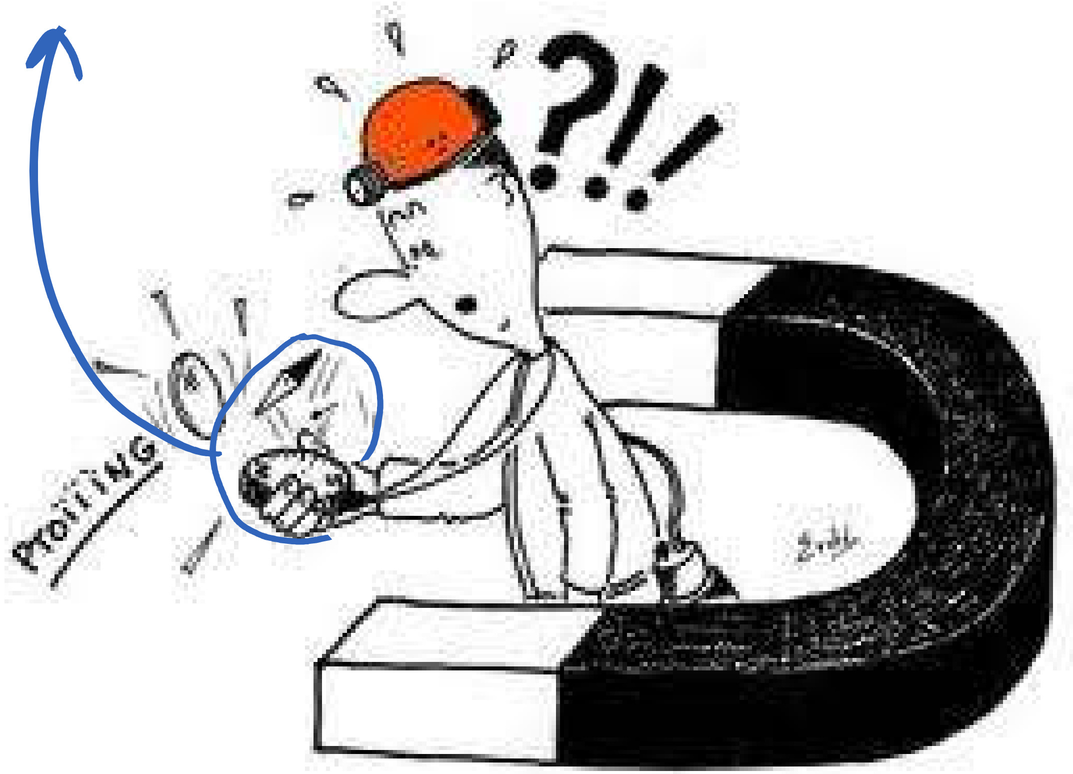
Slides: http://fruchart.eu/slides

Opportunities and challenges for nanomagnetism and spintronics

NANOSENSOR



For the scientist

SPINS

For society

NEPTUNE - POSEIDON

SPIN !

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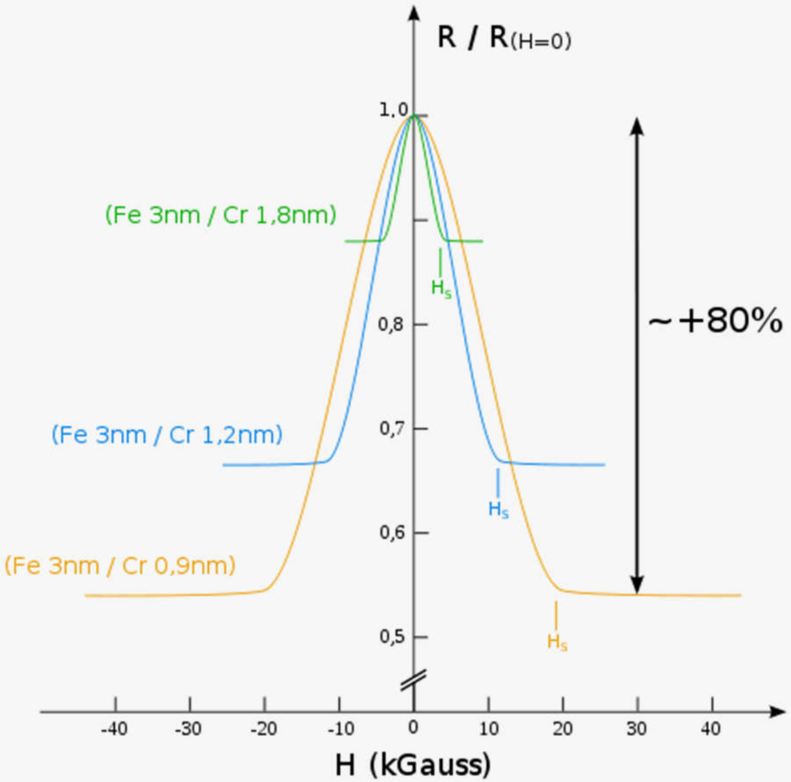
- Decades of nanomagnetism

Giant magneto-resistance



A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

The Nobel Prize in Physics 2007

Photo: U. Montan
Albert Fert
Prize share: 1/2

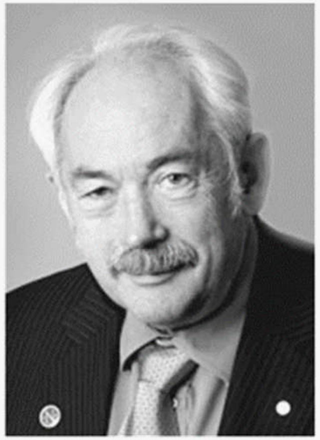
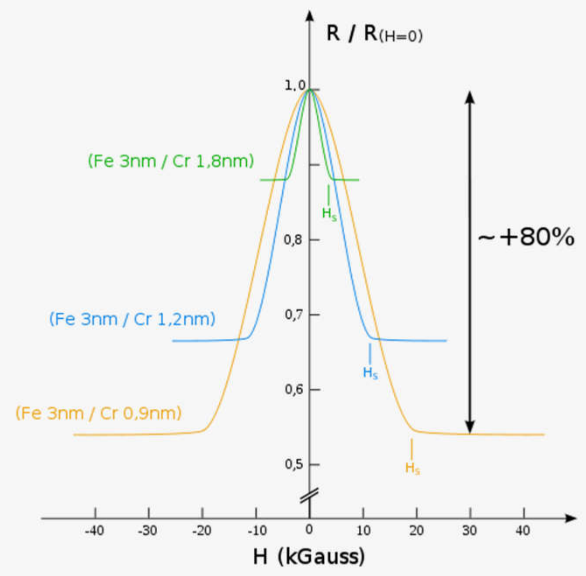


Photo: U. Montan
Peter Grünberg
Prize share: 1/2

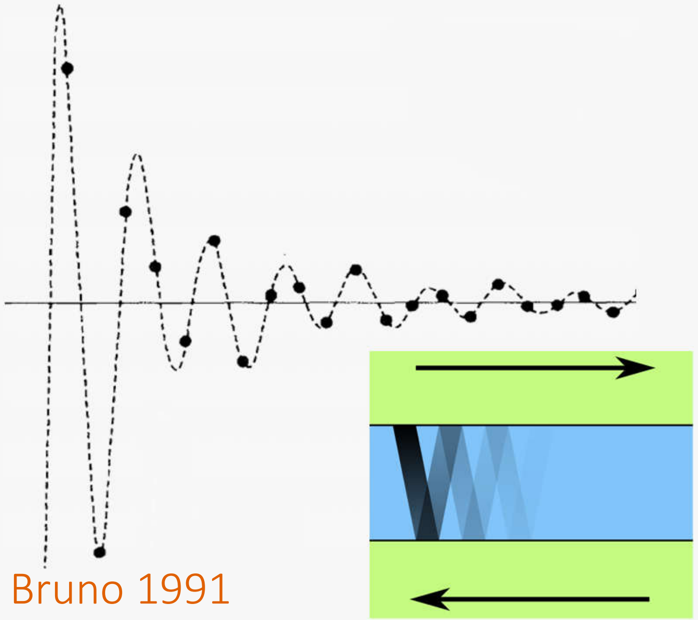
The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

Giant magneto-resistance



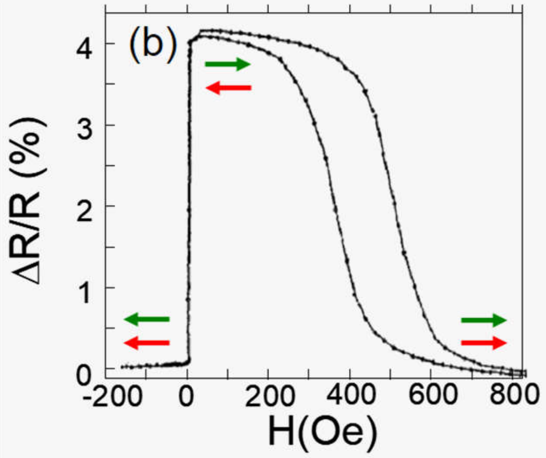
1988

RKKY coupling



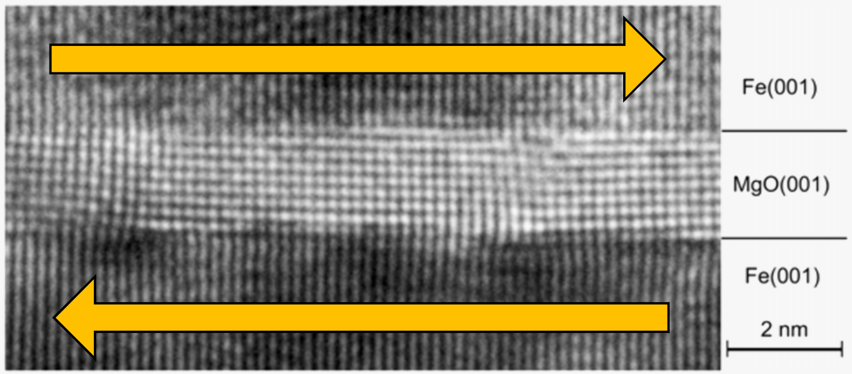
Bruno 1991

Spin-valve concept



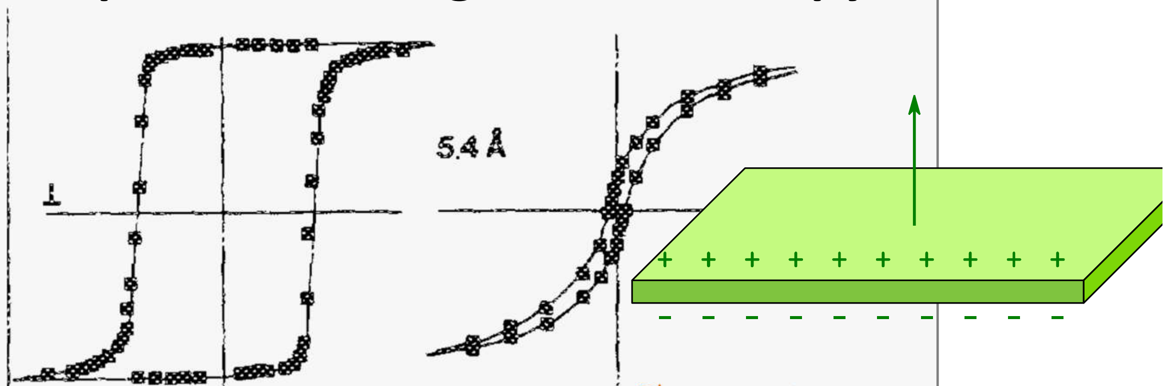
Diény 1991

Tunneling magneto-resistance



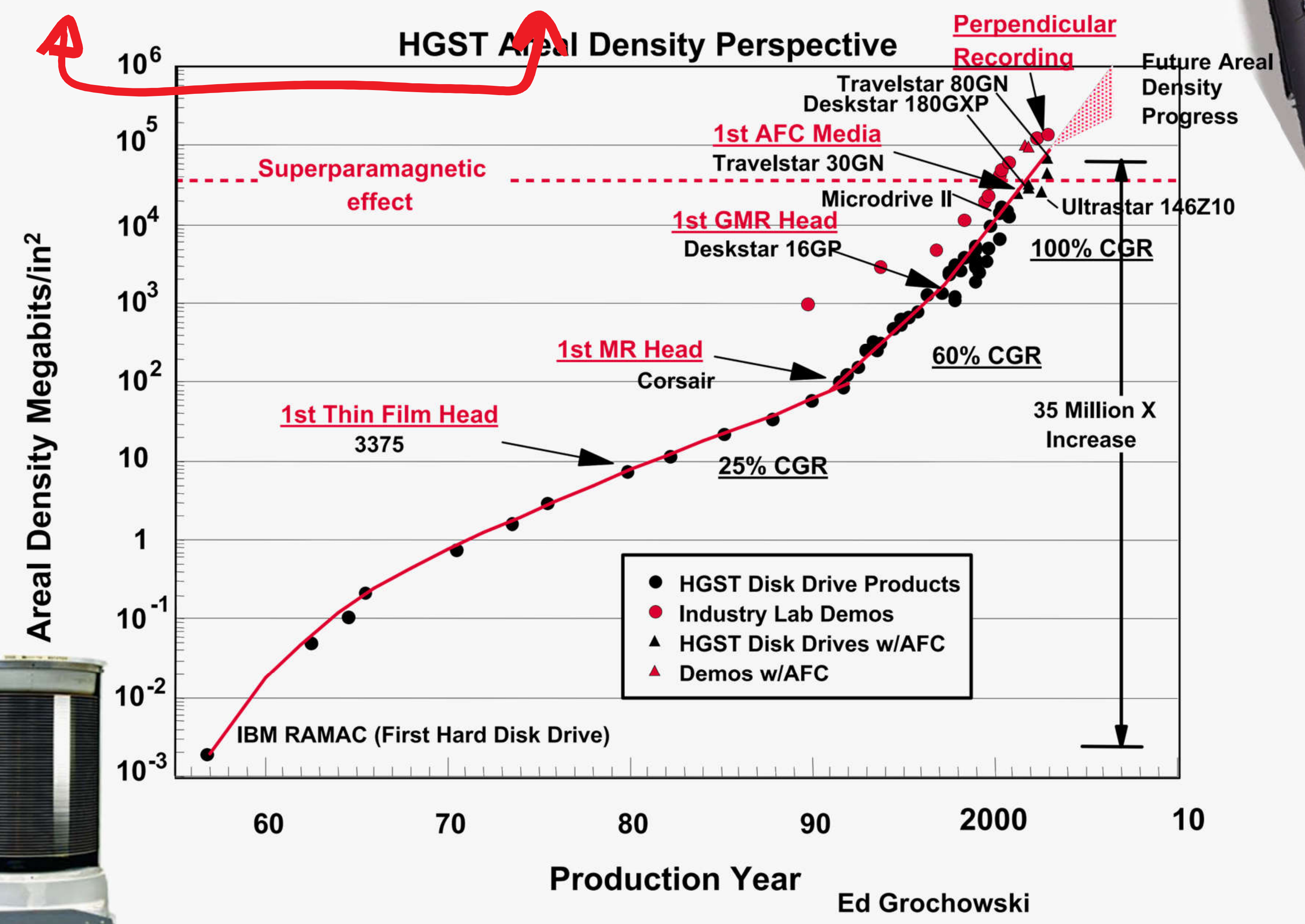
Moodera 1995 (Yuasa 2007)

Perpendicular magnetic anisotropy



Chappert 1988

Technology pushing science: hard disk drives

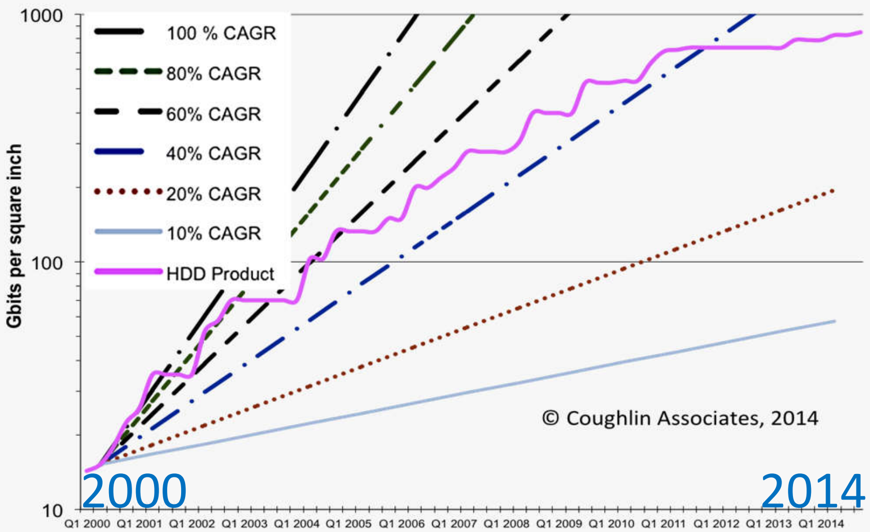


**Steady progress of HDD, however:
incremental, keeping the design**

1956

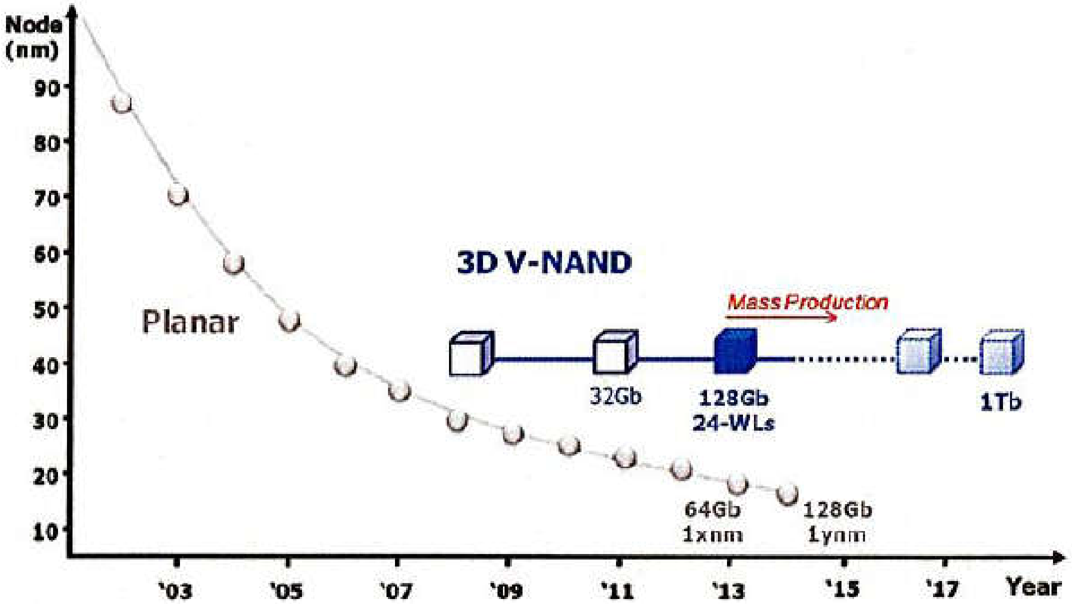
Today

Staggering areal density

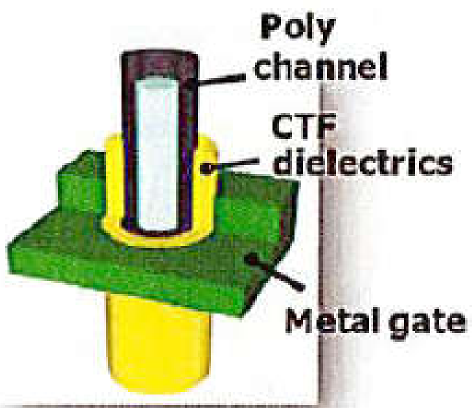


- **Increasing fundamental and technological bottlenecks**
- **Any 2D-based technology is bound to face an end**

Competing technologies go 3D



24-layer 3D NAND Flash



Cross-over in 2016

- 1Gb/mm2 → 600Gb/in2...
- Magnetic mass storage may only remain for niche applications

K. T. Park et al., IEEE J. Sol. State Circuits 50 (1), 204 (2015)

Technology hitting science: precessional dynamics

Basics of precessional dynamics

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = |\gamma_0|\mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha\mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

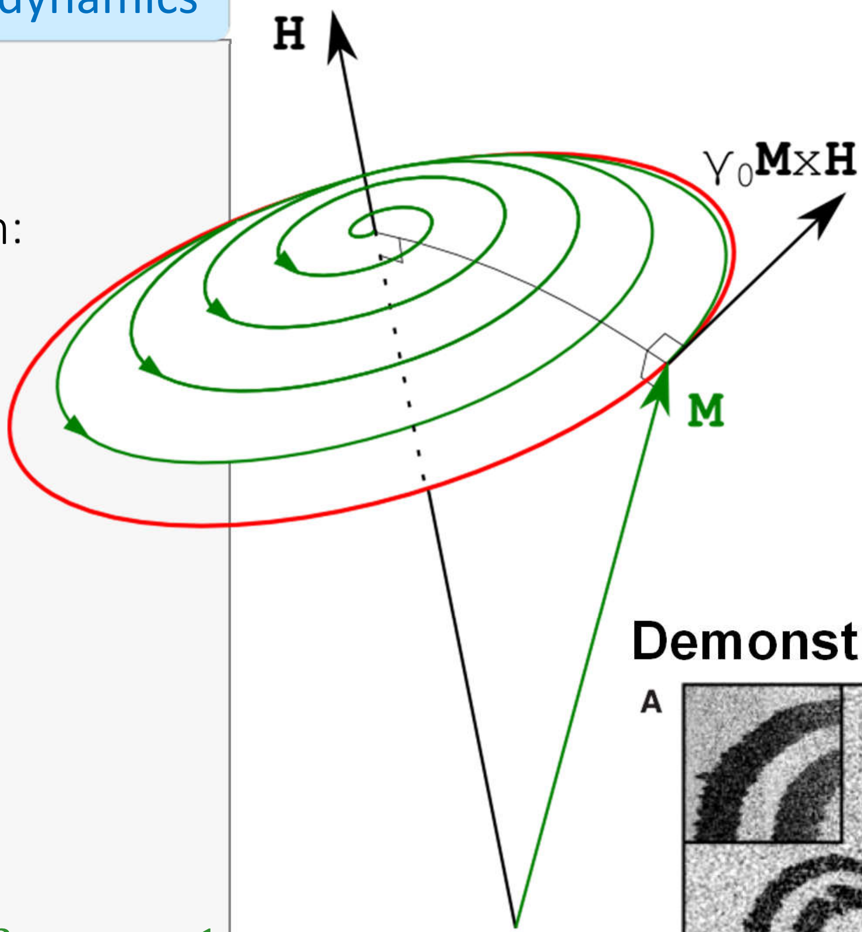
Gyromagnetic ratio

$$\gamma_0 = \mu_0\gamma \qquad \gamma = \frac{gq}{2m}$$

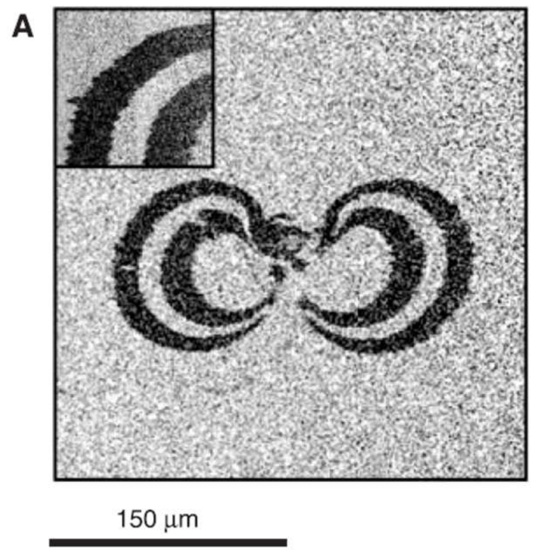
$$\frac{\gamma}{2\pi} = 28\ \mathrm{GHz/T}$$

$\mathbf{H}_{\mathrm{eff}}$ Effective field (including applied)

α Damping coefficient $\approx 10^{-3} \to 10^{-1}$



Demonstration: 1999

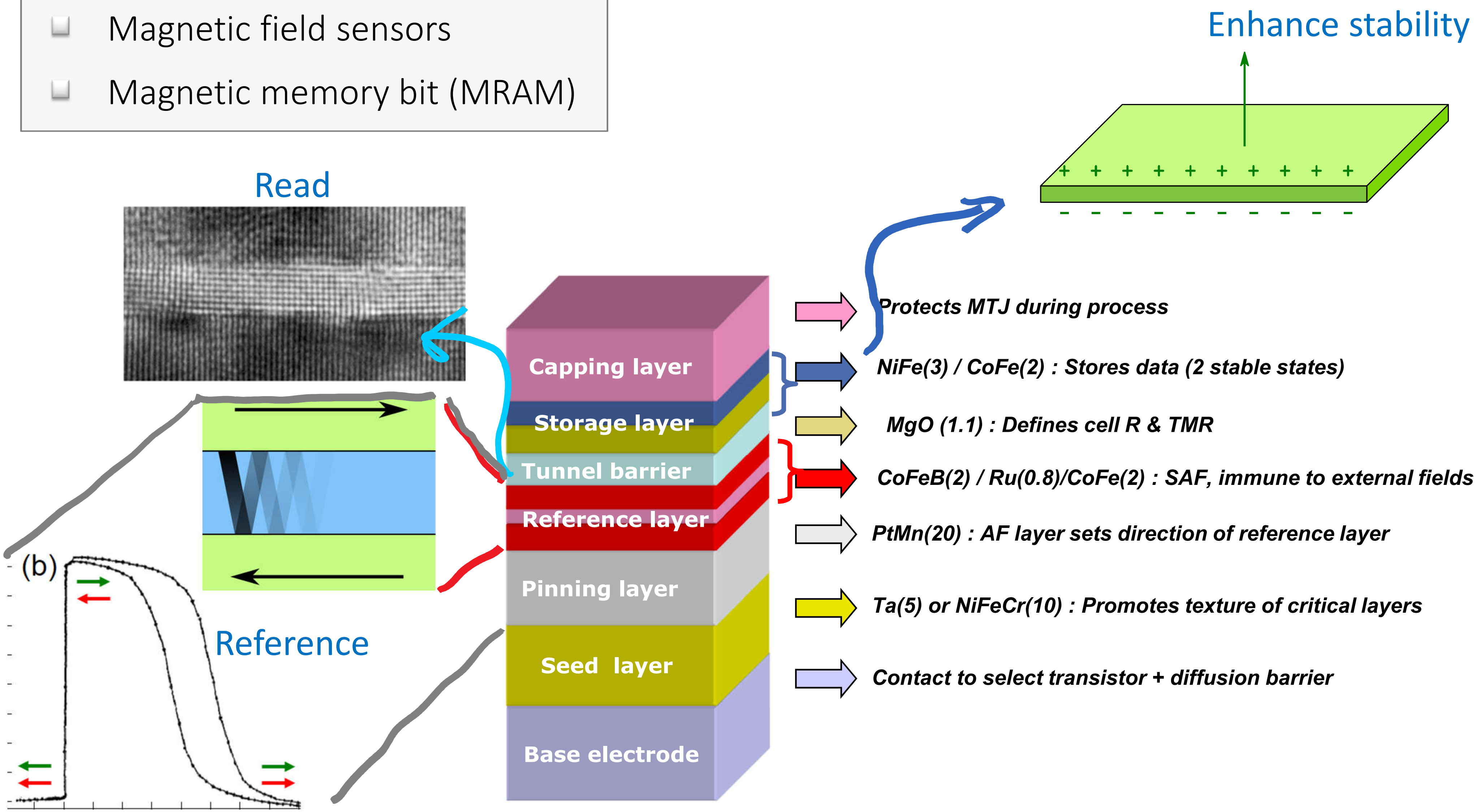


- All magnetization processes are intrinsically precessional
- Change of paradigm from quasistatics to precessional

C. Back et al., Science 285, 864 (1999)

Solid-state magnetic cells

- Magnetic field sensors
- Magnetic memory bit (MRAM)



Spin-transfer torque: theoretical prediction

$$P_{\mathrm{trans}} = P \frac{J}{|e|} \mu_{\mathrm{B}}$$

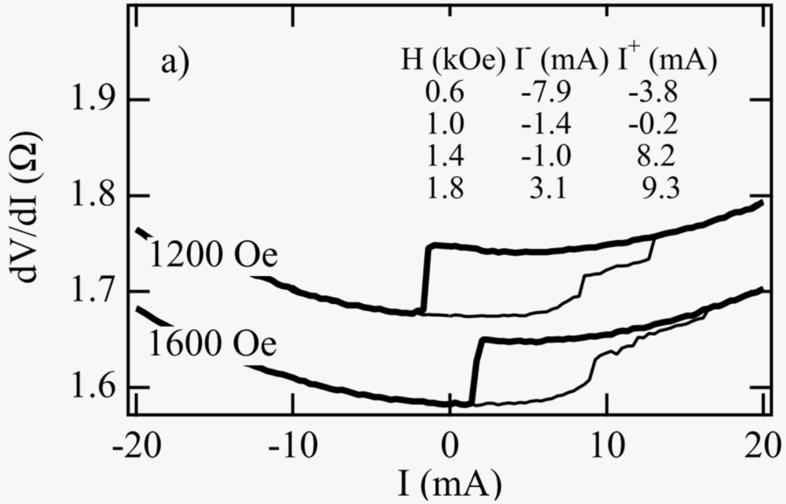
$$\frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} = \quad |\gamma_0| \mathbf{m}_2 \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m}_2 \times \frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} \quad \frac{P_{\mathrm{trans}}}{M_2} \mathbf{m}_2 \times (\mathbf{m}_2 \times \mathbf{m}_1)$$

J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1-7(1996)

Would anybody still publish ground-breaking science in a focused journal ?

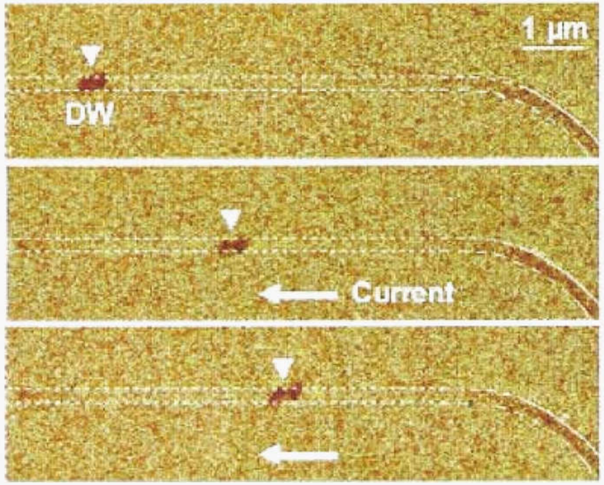
Spin-transfer torque: experiments

Magnetization switching



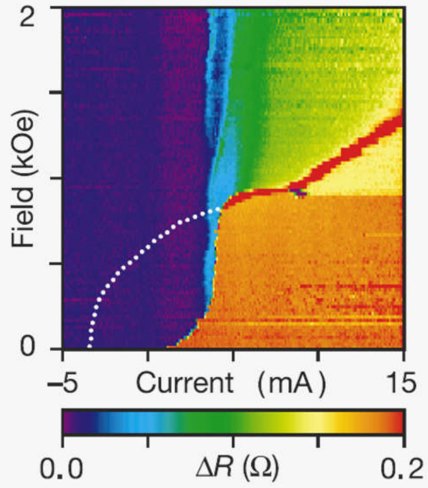
Katine 2000

Domain-wall motion



Yamaguchi 2004

Oscillator

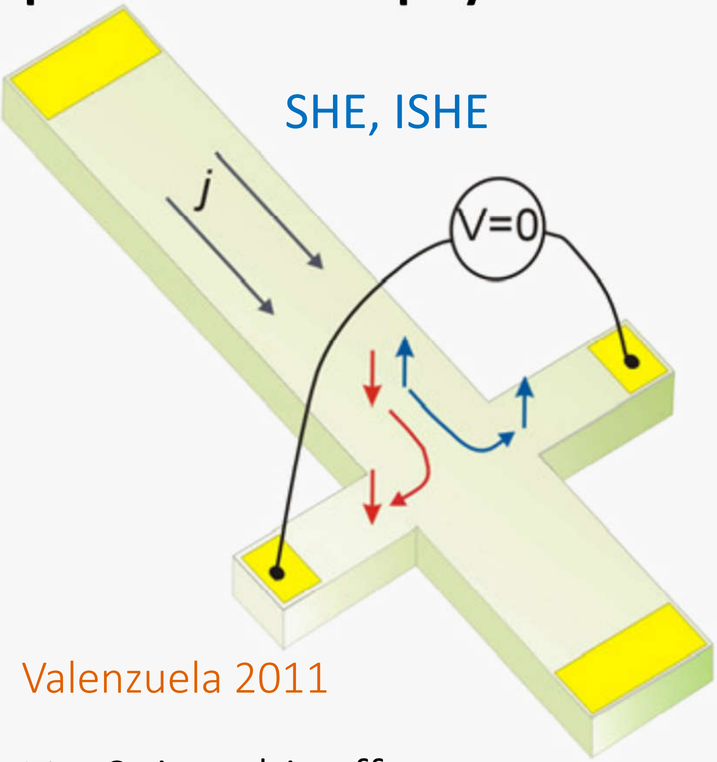


Kiselev 2003

New physics!

- Magnetization switching with charge current
- Domain-wall motion with charge current
- Precessional dynamics with charge current
- … all with deep roots in condensed matter magnetism

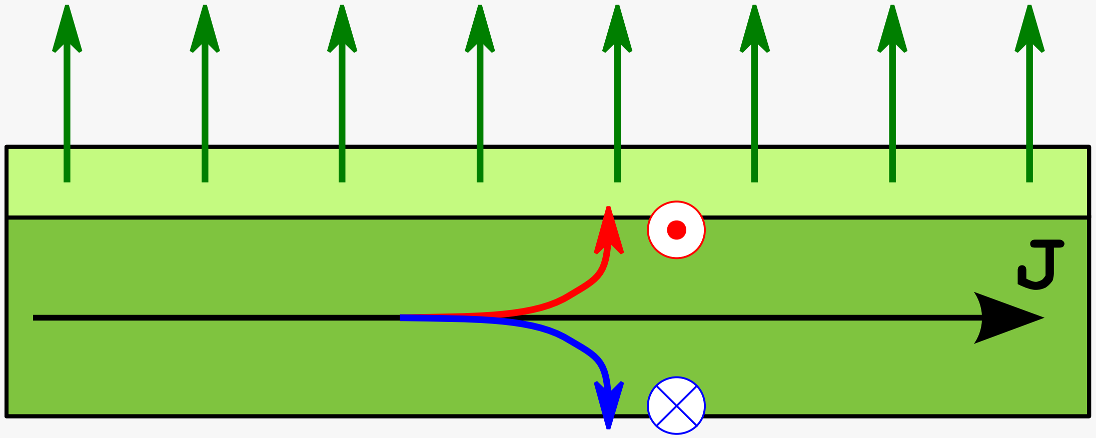
Spin-Hall effect: physics



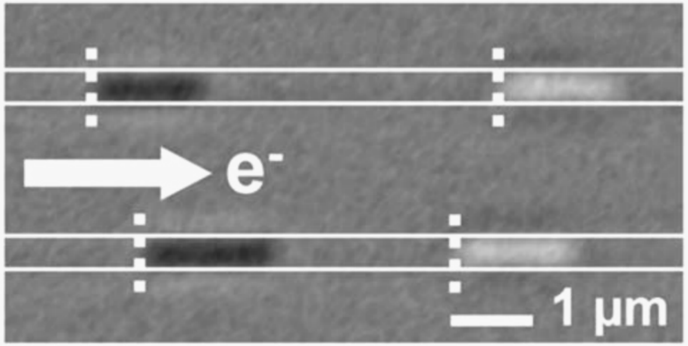
Valenzuela 2011

- Spin-orbit effect
- Analogous to Mott detectors
- Generate pure spin currents from non-magnetic materials

Spin-Hall effect: drive magnetization dynamics



Domain wall motion, magnetization switching …

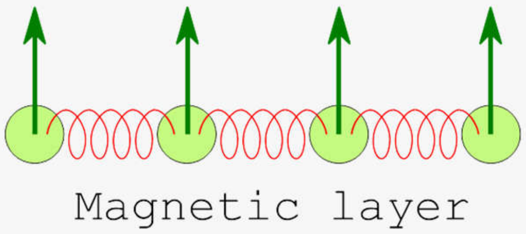


Moore 2008

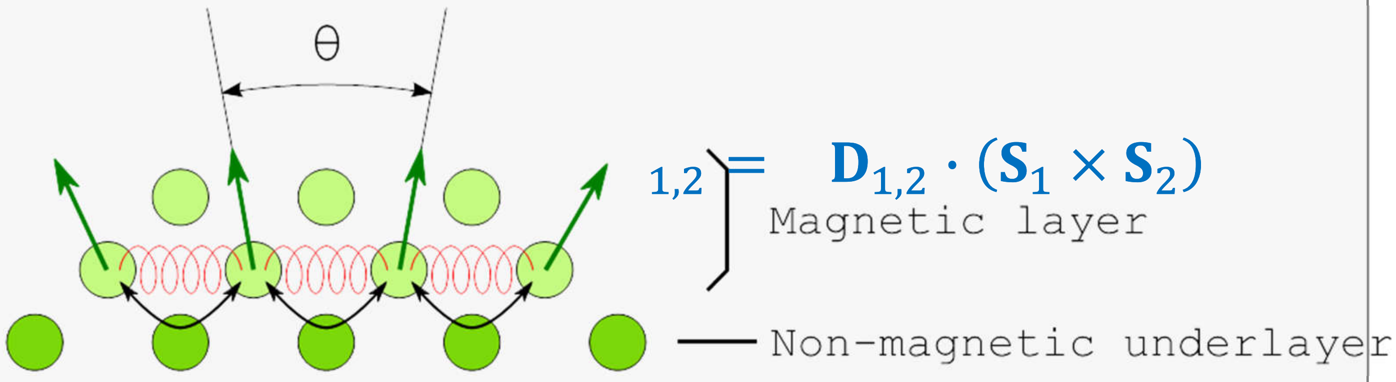
- New physics, increased efficiency, new materials…

Magnetic exchange

$$_{1,2} = \quad J_{1,2}\,\mathbf{S}_1 \quad \mathbf{S}_2$$

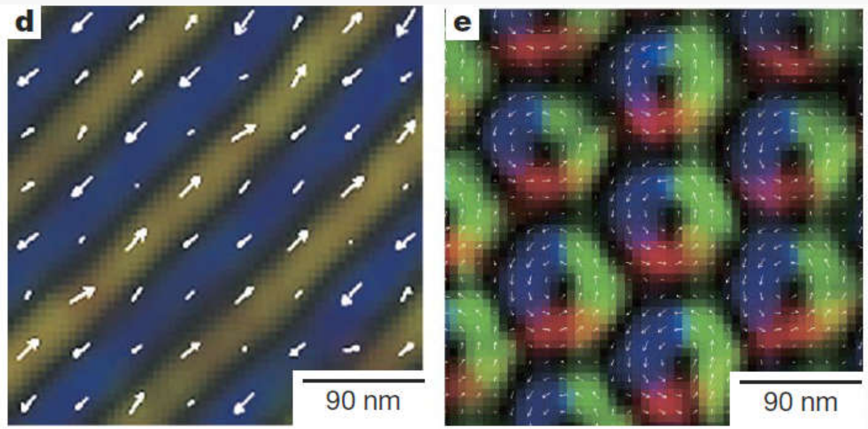


The Dzyaloshiinski-Moriha interaction (DMI)

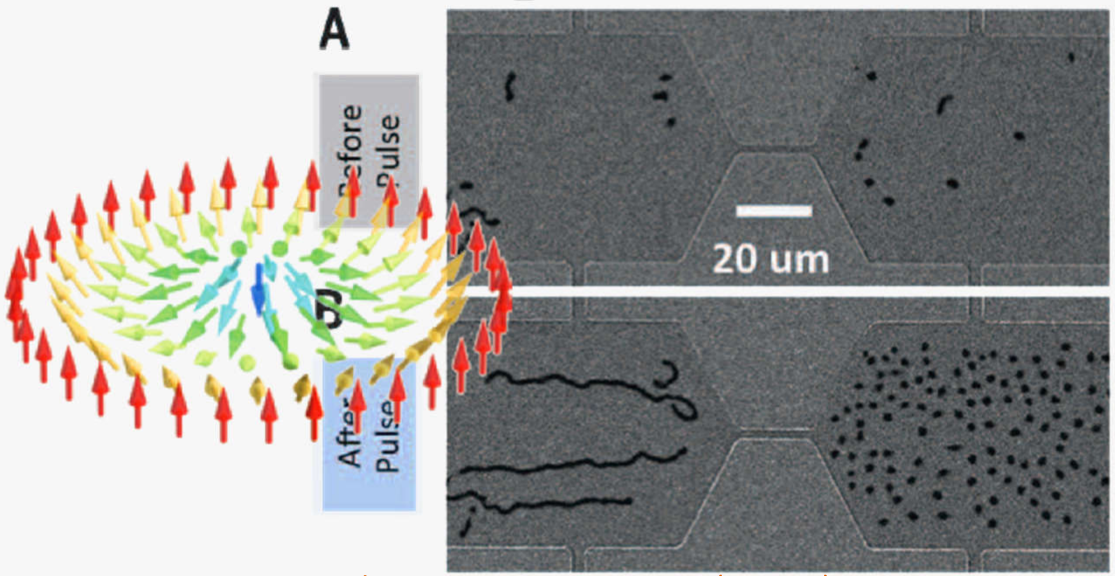


$$_{1,2} = \quad \mathbf{D}_{1,2} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$$

Chiral magnetization textures: spirals and skyrmions



X. Z. Yu et al., Nature 465, 901 (2010)



W. Jiang et al.,Science 349,283 (2015)

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- Decades of nanomagnetism

- Societal challenges

Frontier backgrounds for nanomagnetism

Societal requests and challenges

- Energy consumption – Pollution, global warming
- Communication: more, faster, cheaper
- Intelligent systems: comfort, safer, less energy
- Sustainability: energy, material criticality
- Health
- …

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- Decades of nanomagnetism

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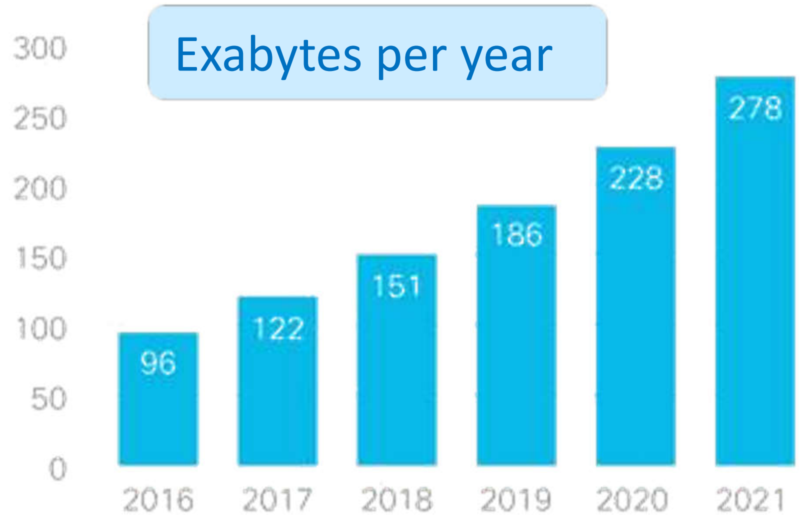
- Energy consumption in ICT

Continuous growth of data handling

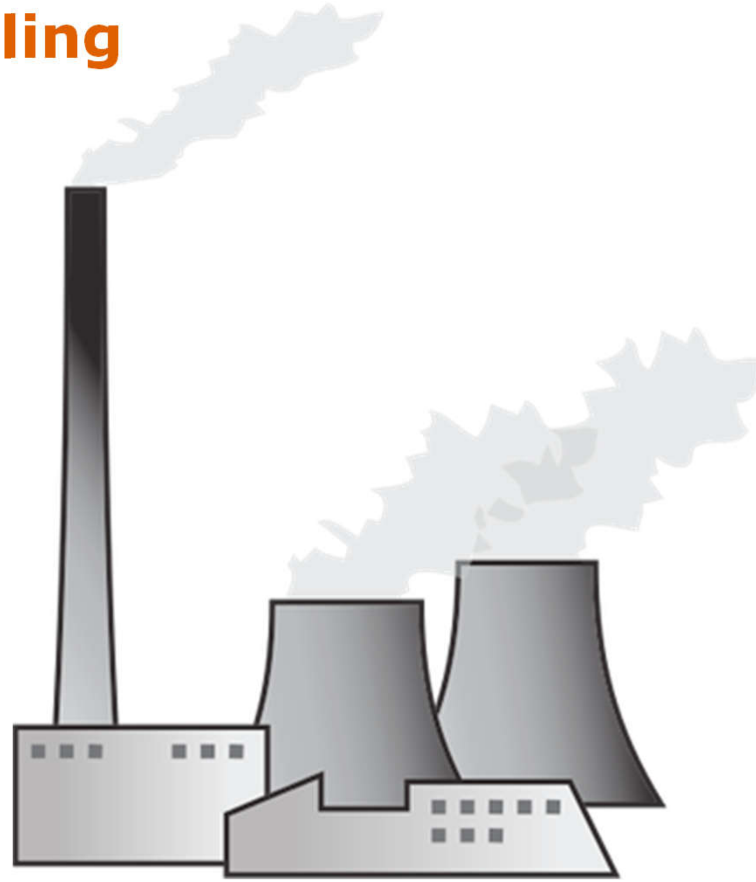


CISCO

https://www.smartinsights.com

1 Farm = Multi-MW operating power

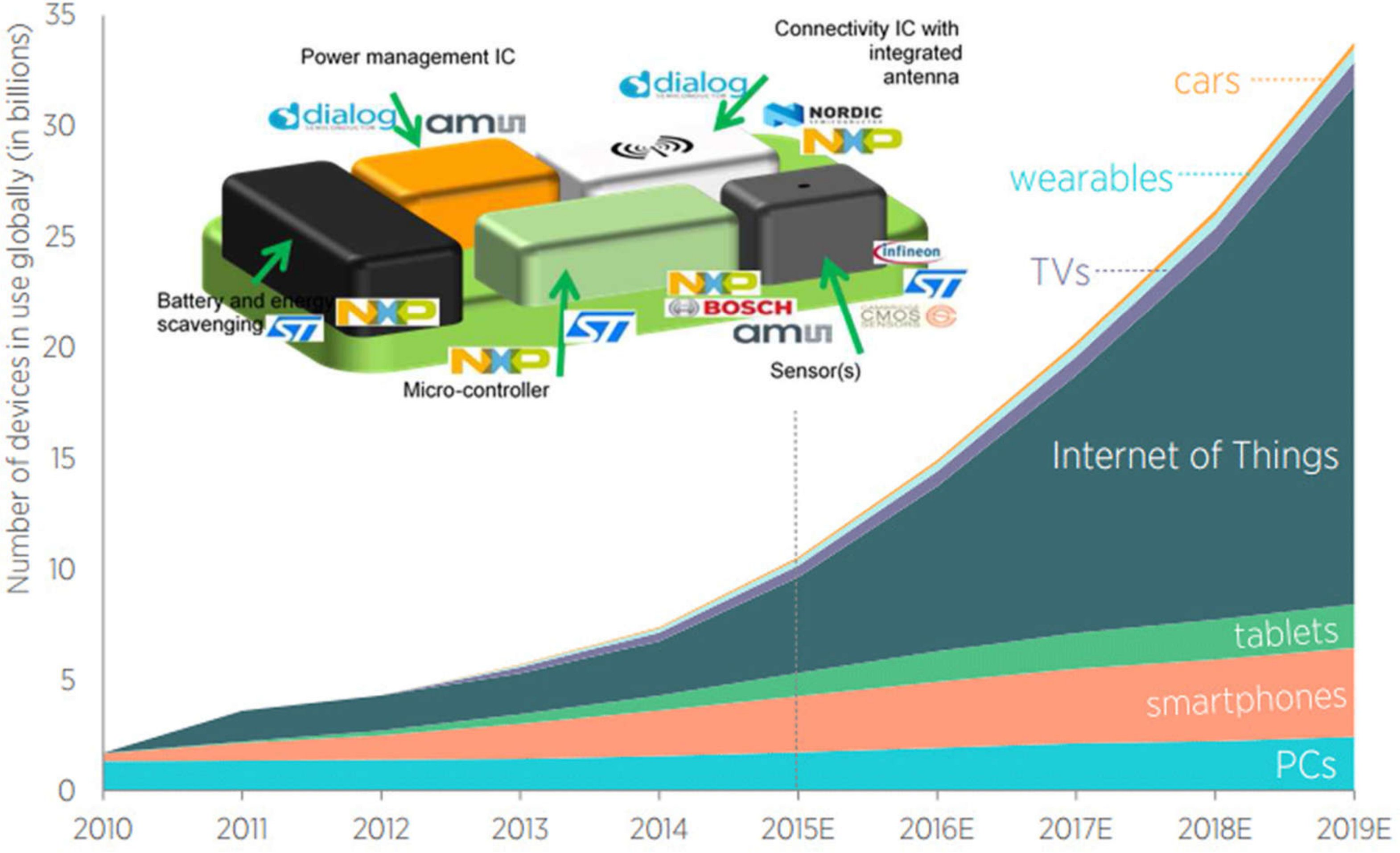
+ Same amount for cooling



Requirements

- Cost
- Environment

Internet of Things: a booming market

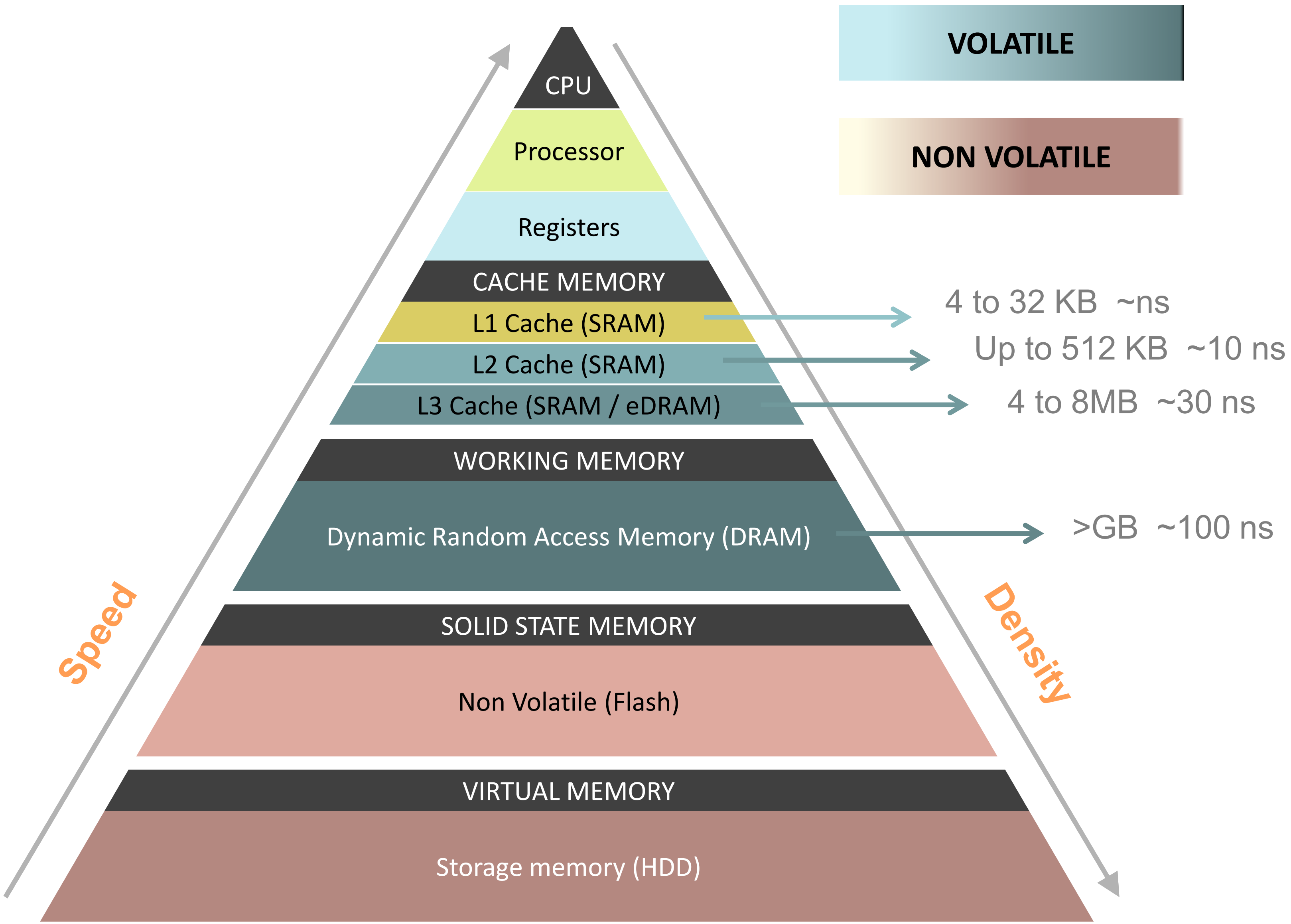


Source: John Greenough, "The Internet of Everything 2015," *Business Insider Intelligence*. Produced by Adam Thierer and Andrea Castillo, Mercatus Center at George Mason University, 2015.

Requirements

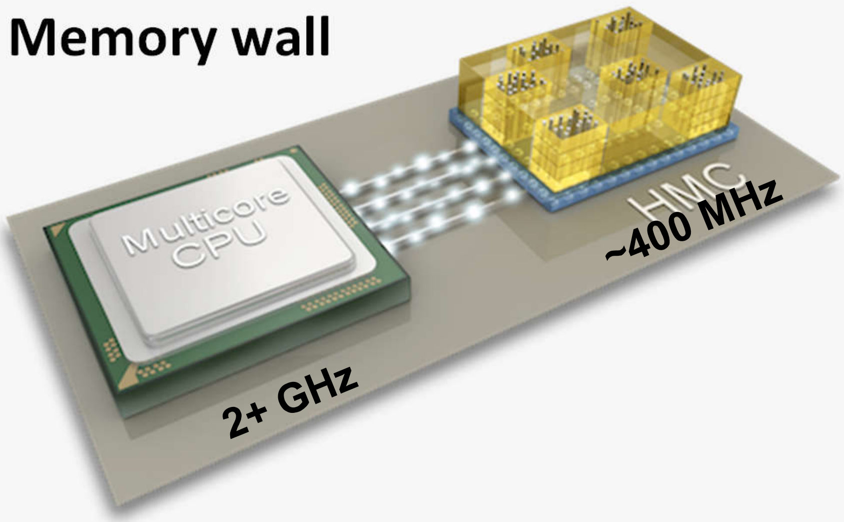
- Cost, weight, material
- Low-power

Memory challenges to address



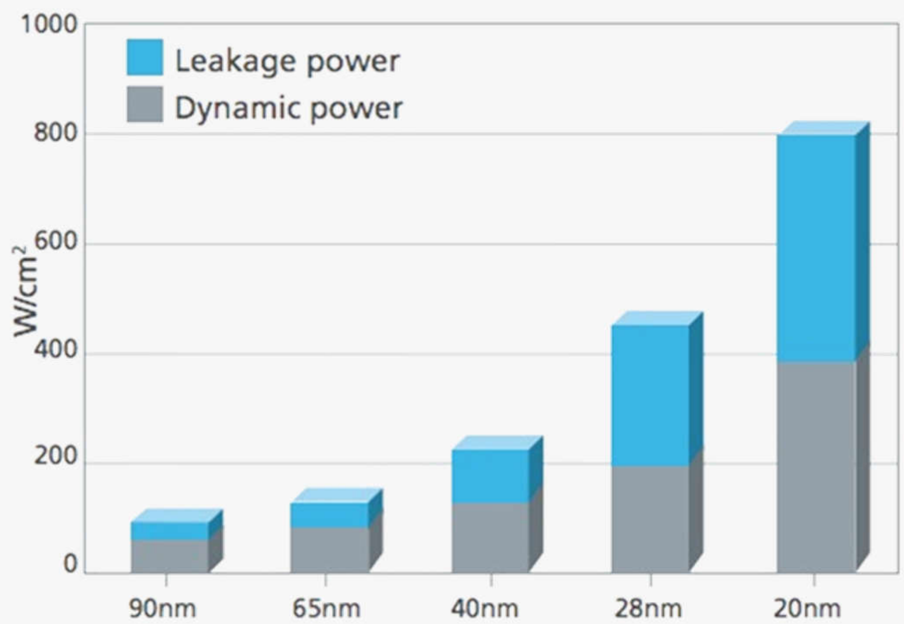
Memory challenges to address

Memory wall



- Logic keeps awaiting data
- Limits speed
- Increases power consumption

SRAM leakage



Challenges

- Embed memory
- (Leakage) power

Non-volatile
like Flash
10+ years retention

Dense
like DRAM
$10F^2$, small overheads

Fast
Like SRAM
~10ns in normal mode

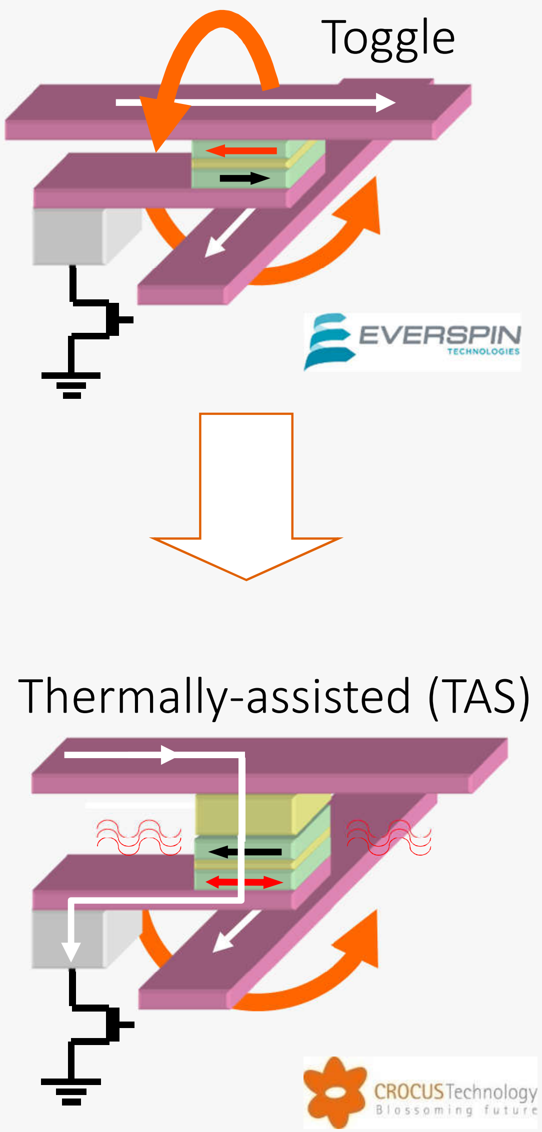
High Endurance
like SRAM / DRAM
10^{12} cycles, up to 10^{16}

MRAM is not the best but …

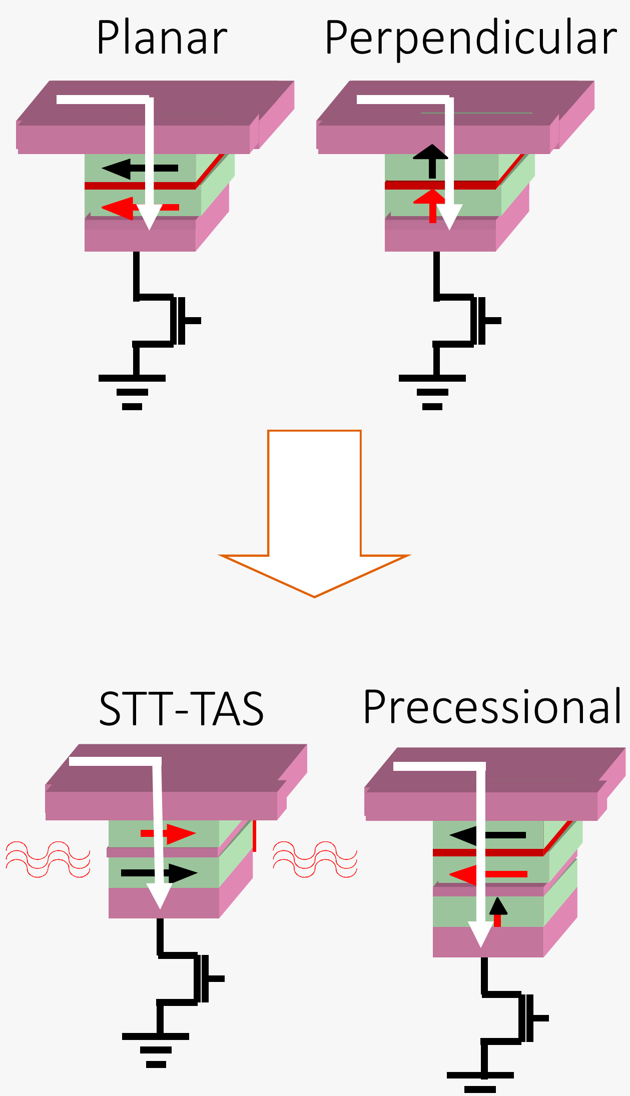
- Can replace SRAM at 1/6th of size, zero leakage
- Can replace e-Flash at $>10^5$x speed, lower power
- Can replace DRAM (if running out of steam)

Generations of MRAM

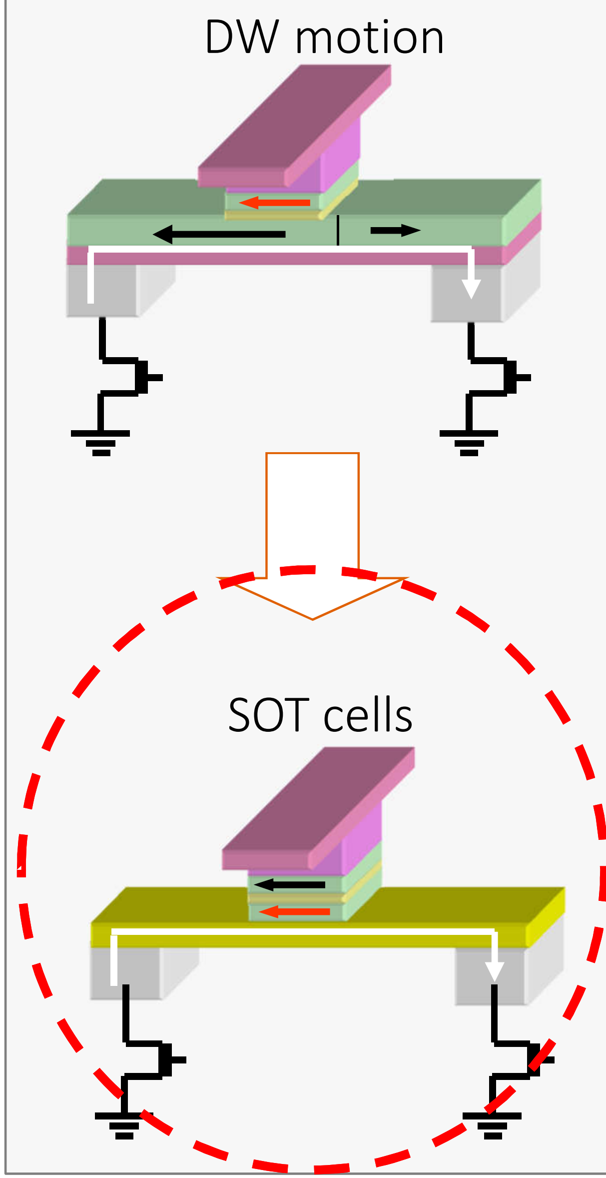
Field driven



STT



SOT (spin-orbit torque)



MRAM players

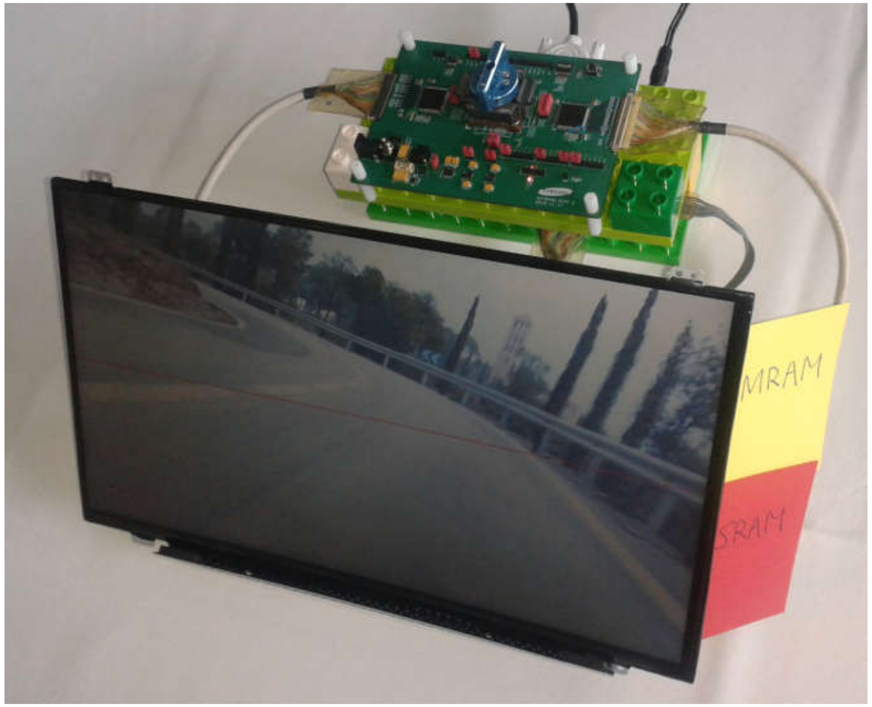
EVERSPIN TECHNOLOGIES
NEC
intel
TDK
Avalanche Technology
tsmc
RENESAS Everywhere you imagine.
IBM
GLOBALFOUNDRIES
Spin Transfer Technologies
Micron
CROCUS Technology Blossoming future
SAMSUNG
SONY
FUJITSU
TOWERJAZZ
GRANDIS
TEL
QUALCOMM
TOSHIBA
Hprobe
KEYSIGHT TECHNOLOGIES
SINGULUS
APPLIED MATERIALS
hynix
Canon CANON ANELVA CORPORATION
CAPRES A/S COPENHAGEN APPLIED RESEARCH

MRAM coming to reality

EVERSPIN
TECHNOLOGIES

256Gb in production. 1Tb in the pipes.

SAMSUNG



Demo at the 7th MRAM
Global Innovation Forum (Zurich, June 2016)

https://www.linkedin.com/company/mram-info/

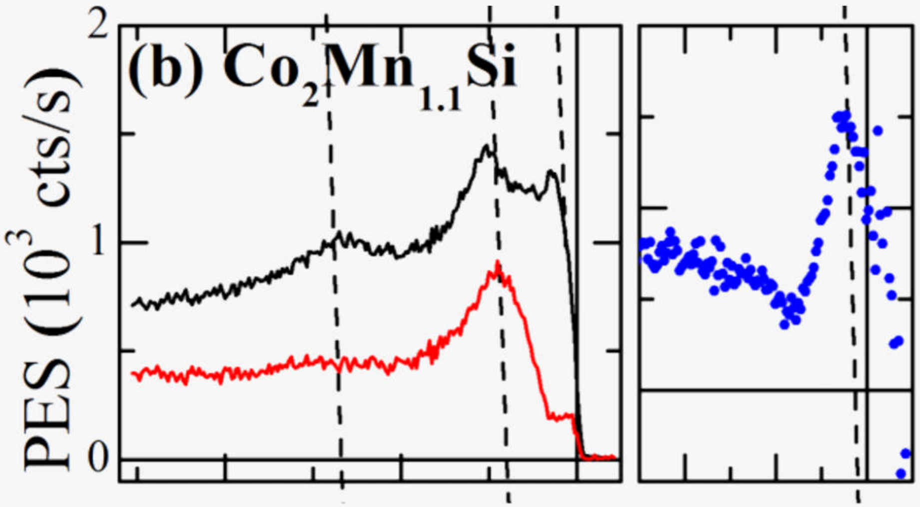
https://www.mram-info.com

Fundamental frontiers and challenges: efficiency

Efficiency of writing

- Spin-Hall, three-terminal?
- Spin-Hall efficiency, topological insulators?
- Electric field effects
- Low damping: heusler etc.

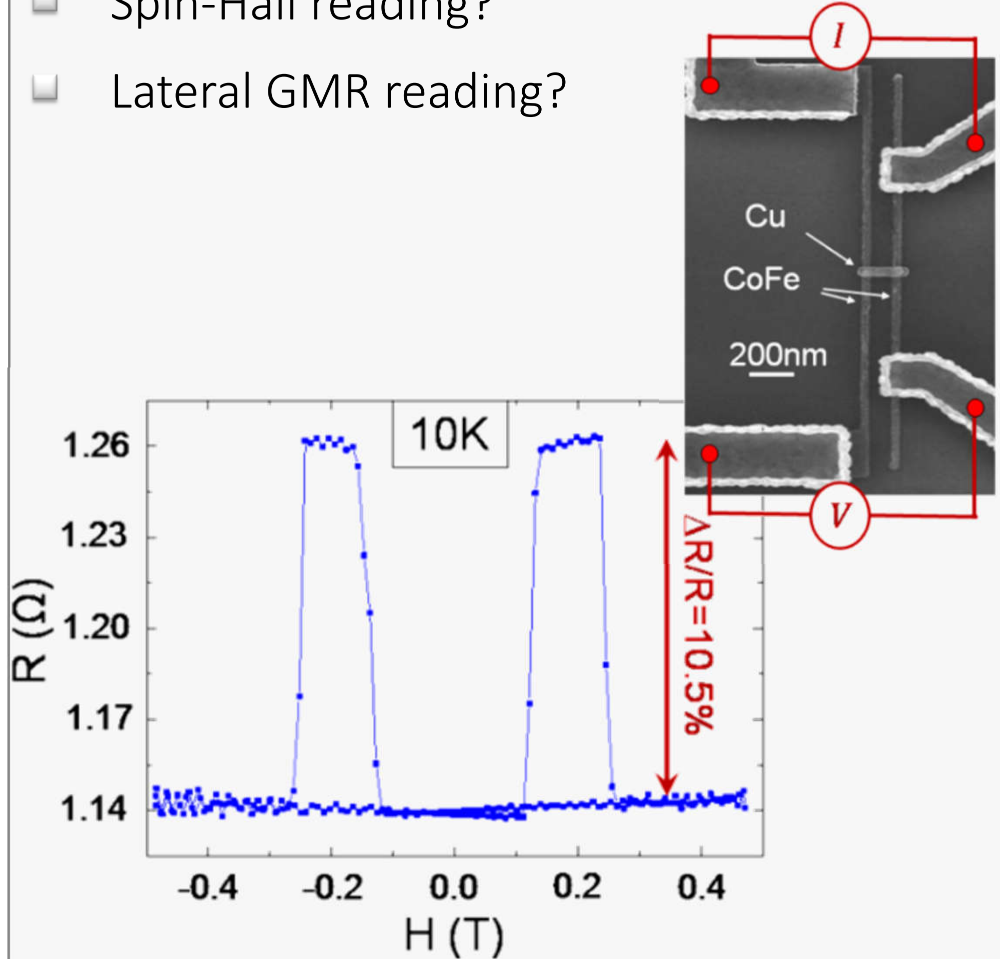
Co_2MnSi Heusler alloy
Damping $\alpha < 7 \cdot 10^{-4}$



S. Andrieu et al., PRB93, 094417 (2016)

Efficiency of reading

- Electric field, multiferroics
- Spin-Hall reading?
- Lateral GMR reading?

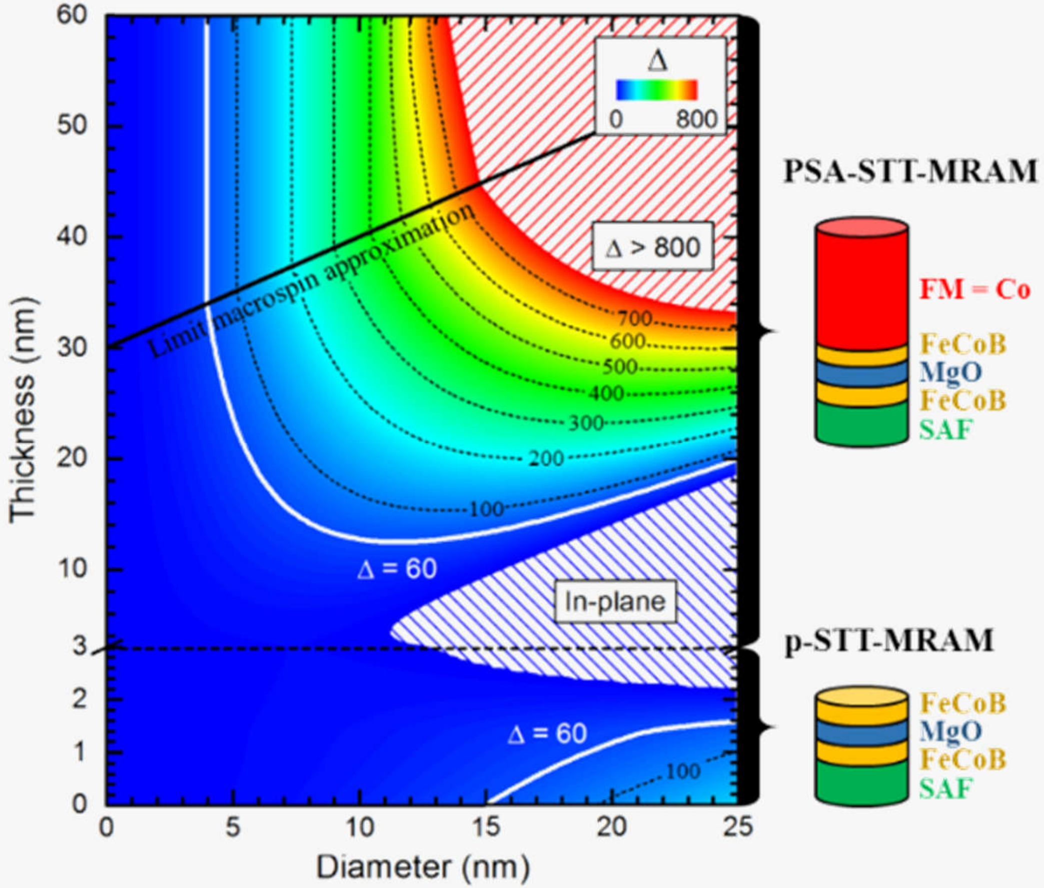


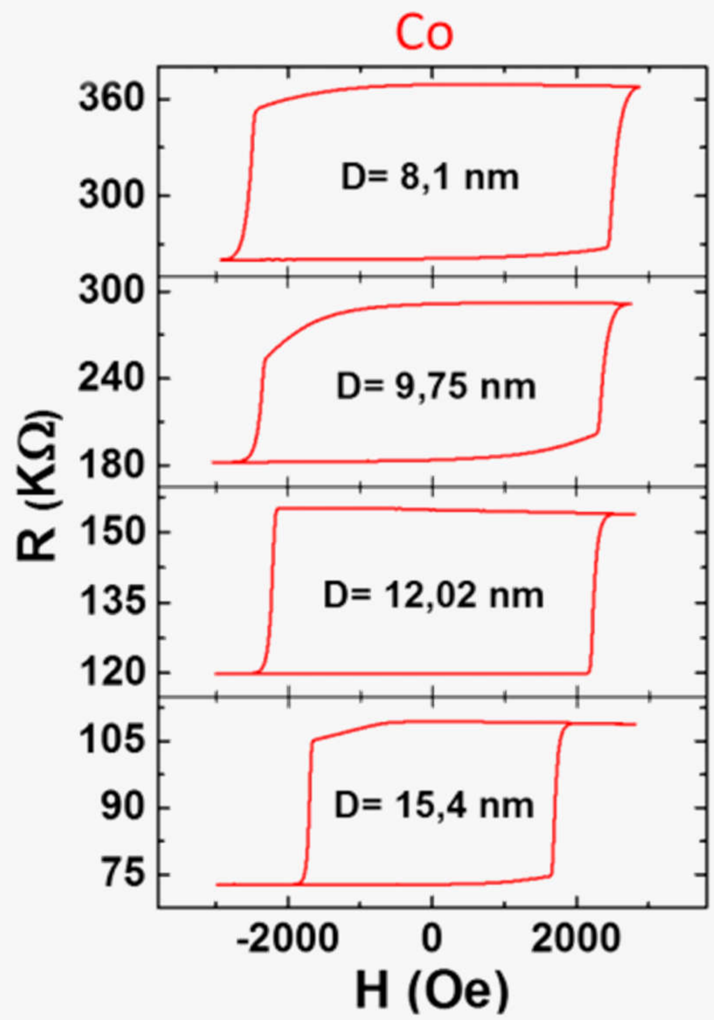
G. Zahnd, Sci. Rep. 7.1 9553 (2017)

Bit size & retention

- 3D design
- Patterning challenges

PSA STT-MRAM
Perpendicular Shape Anisotropy



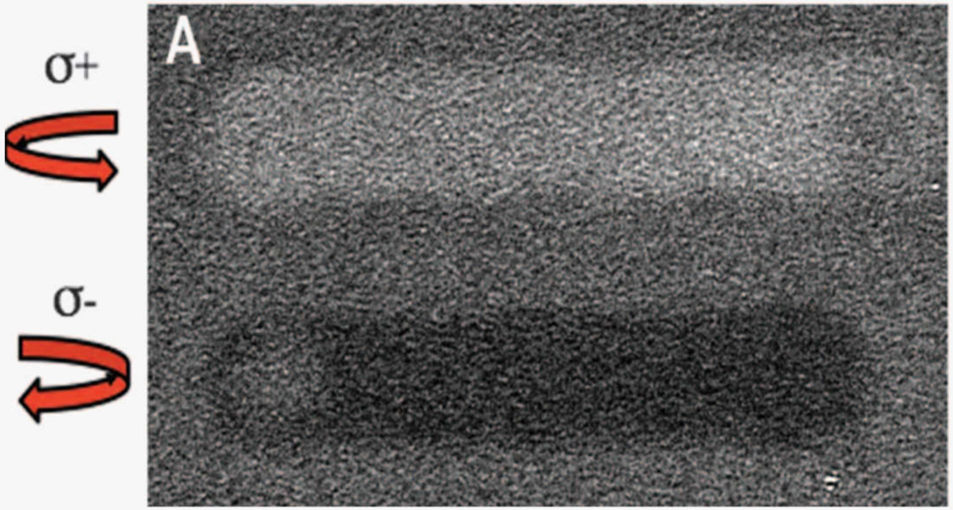


Watanabe et al, Nat.Com. 9, 663 (2018)
N. Perrissin et al., Nanosacale 10, 12187 (2018)

Fast optical switching

$Gd_{22}Fe_{74.6}Co_{3.4}$
λ=800nm, 40fs

C. D. Stanciu, PRL99, 047601 (2007)



C. H. Lambert, Science 345, 1337 (2014)

Physics

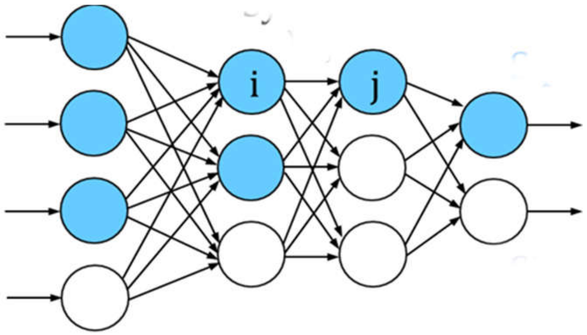
- Three-temperature model
- Superdiffusive hot electrons
- Multiphysics and multiscale modeling

Technology

- All-optical or not?
- One shot or stochastic?
- Material versatility?

- Decades of nanomagnetism

- Neuromorphic computing



- Societal challenges

- Energy consumption in ICT

New computing scheme: neuromorphic

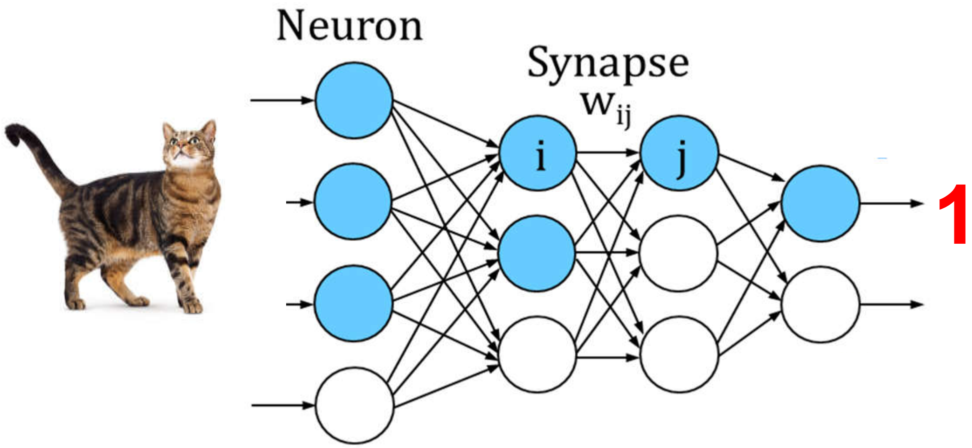
Brain 20 W

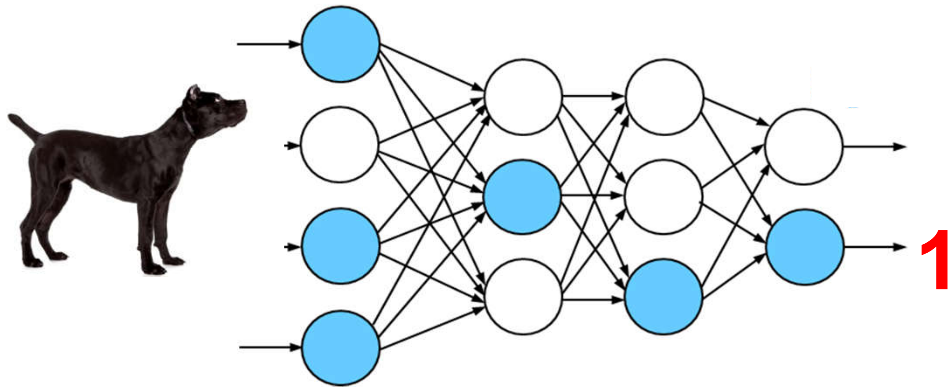
- Low power
- Non-linear, stochastic

High-performance computing 10 MW

- High power
- Deterministic

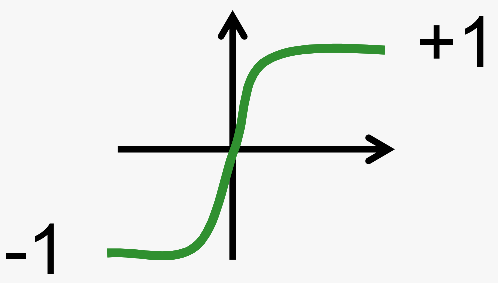
How do neurons and synapses work?





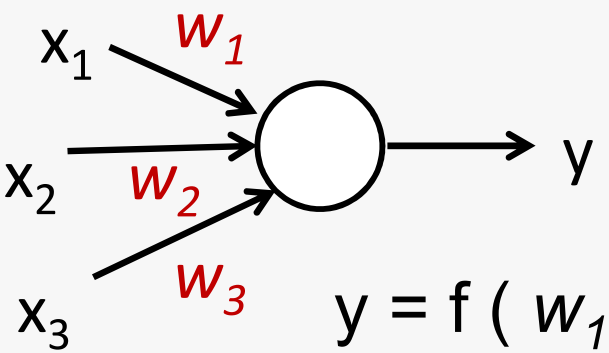
Neurons

- Non-linear



Synapses

- Analog valves (weighs w)



$$y = f\,(w_1 x_1 + w_2 x_2 + w_3 x_3)$$

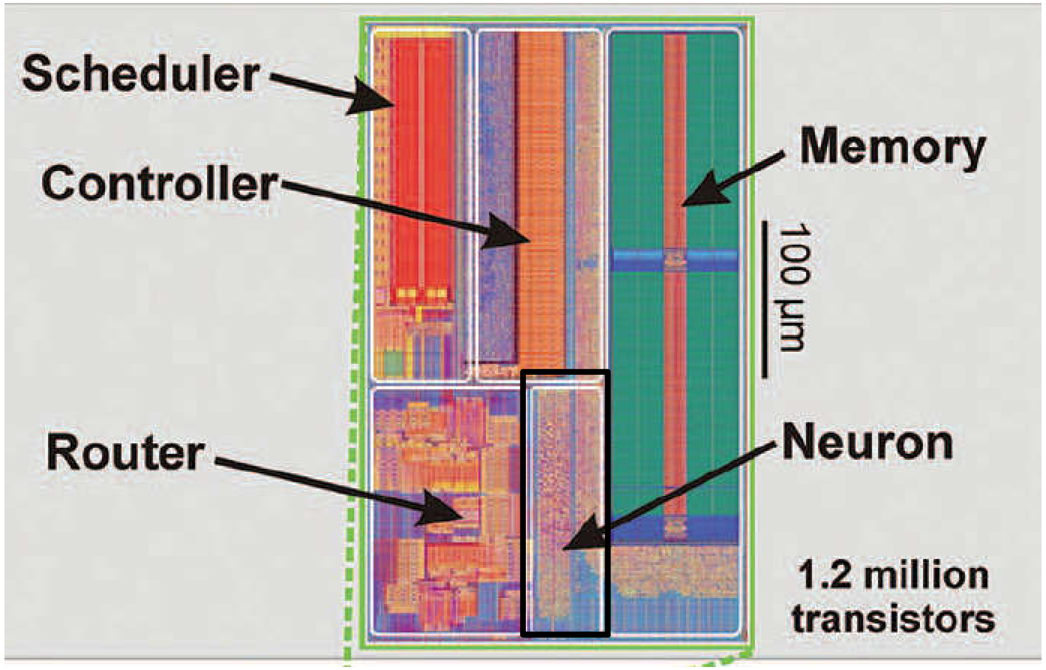
- **Ingredients for neural networks: non-linearity, memory and plasticity**

CMOS emulated circuits

- A transistor is nanoscale but it is just a switch
- CMOS does not provide memory (volatile)

CMOS neuron 10-100 µm

CMOS synapse 10 µm



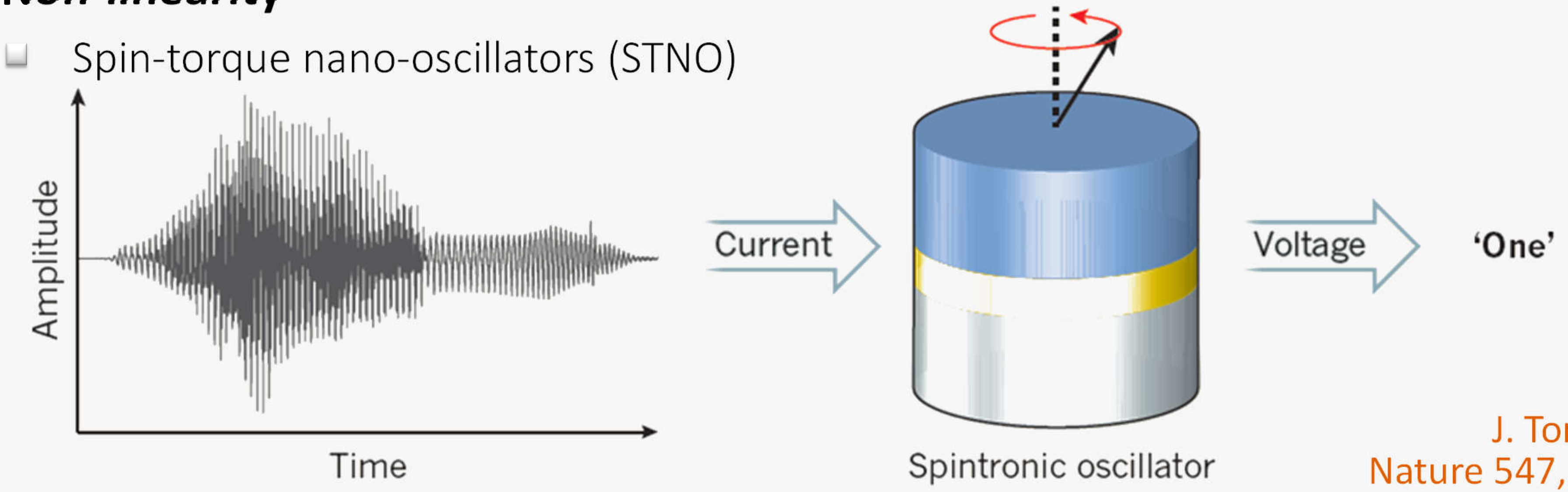
Merolla et al, Science 345, 668 (2014)

Brainscales 20 wafer machine.
4M neurons, 1B synapses

- **May neurons and synapses be produced as hardware components ?**

Non-linearity

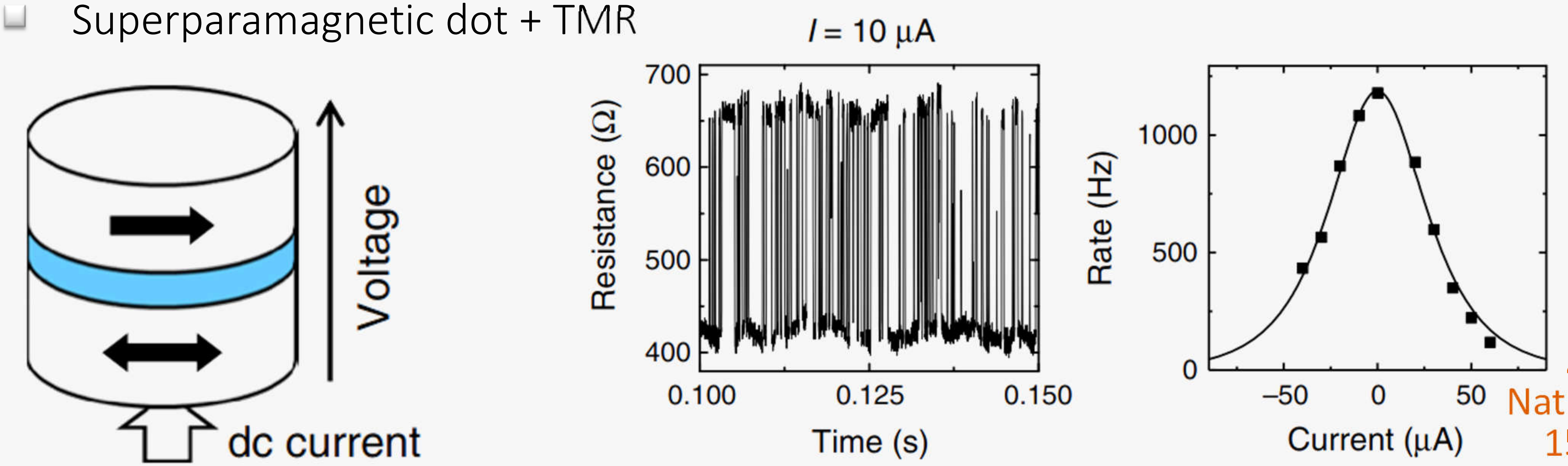
- Spin-torque nano-oscillators (STNO)



J. Torrejon et al, Nature 547, 428 (2017)

Stochasticity

- Superparamagnetic dot + TMR



A. Mizrahi, Nat. Comm. 9, 1533 (2018)

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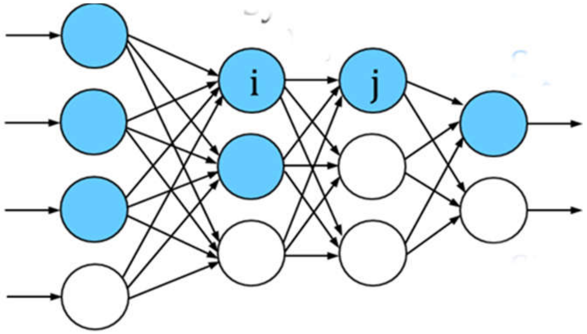
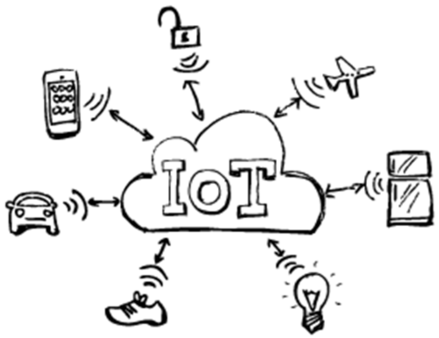
- Energy consumption in ICT

- Neuromorphic computing



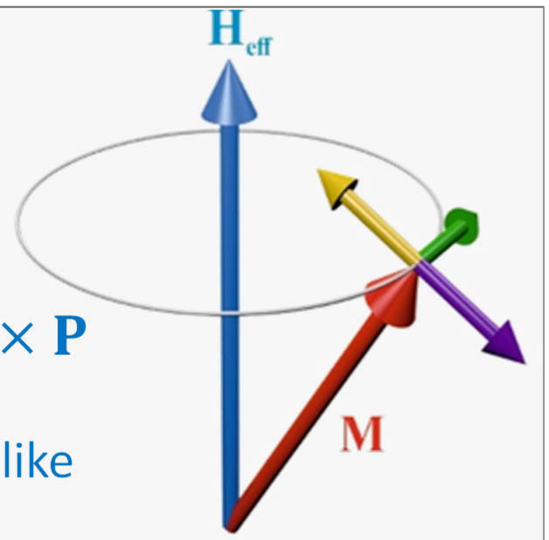
- Wireless communication



Current-driven precession of magnetization

$$\frac{d\mathbf{m}}{dt} = |\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt} + |\gamma_0|a_j\mathbf{m}\times(\mathbf{m}\times\mathbf{P}) + b_j\mathbf{m}\times\mathbf{P}$$

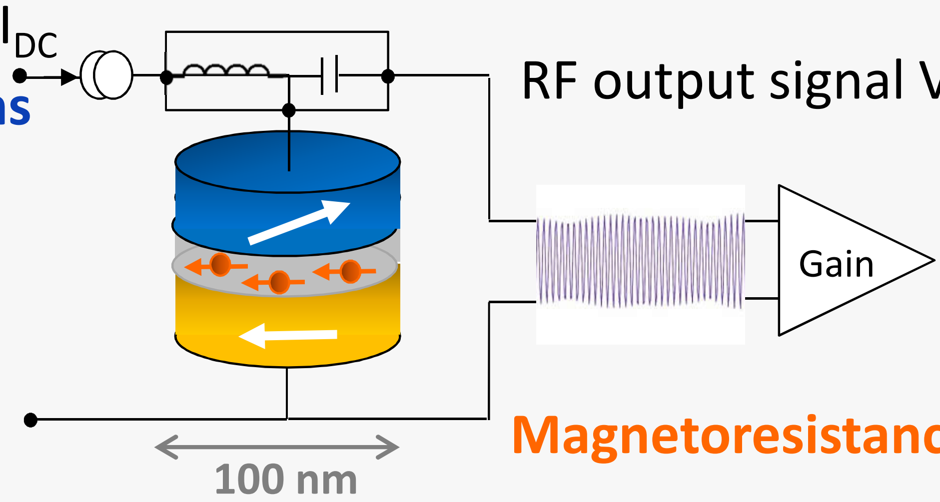
Damping-like Field-like



Implementation in spin-torque nano-oscillators (STNO)

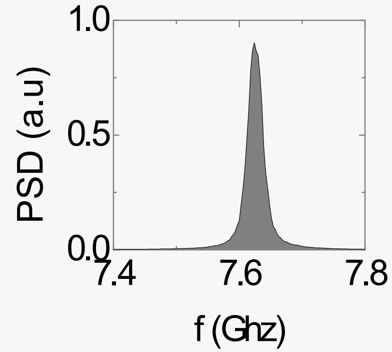
Steady state oscillations

Spin momentum transfer



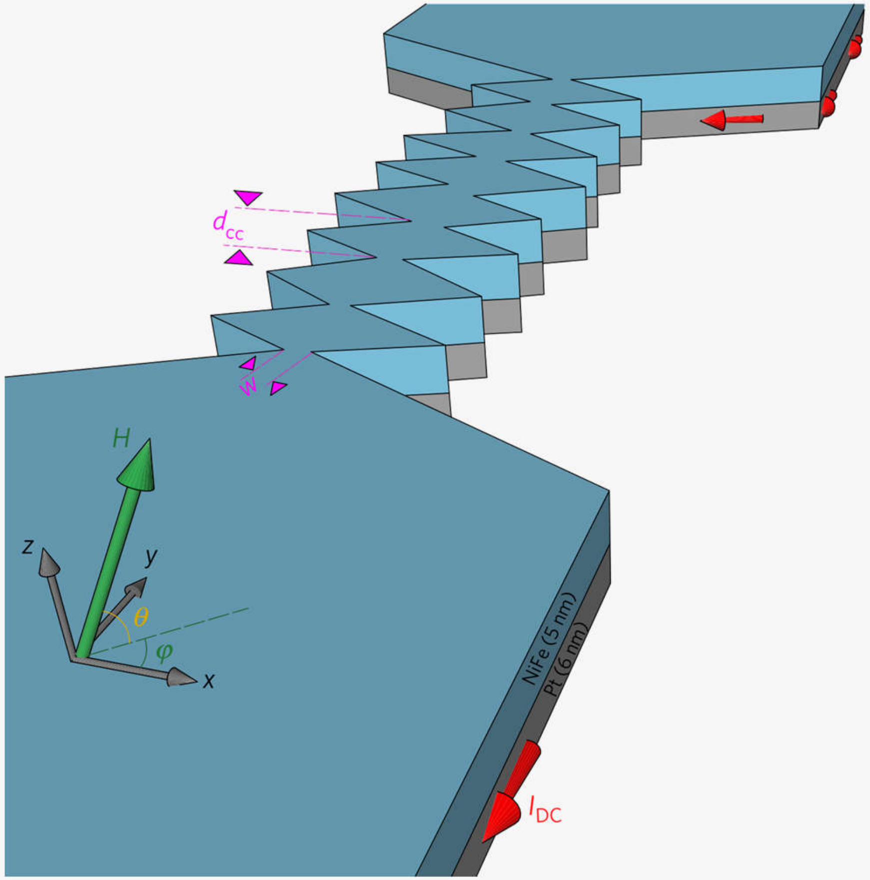
RF output signal V(t)

Magnetoresistance

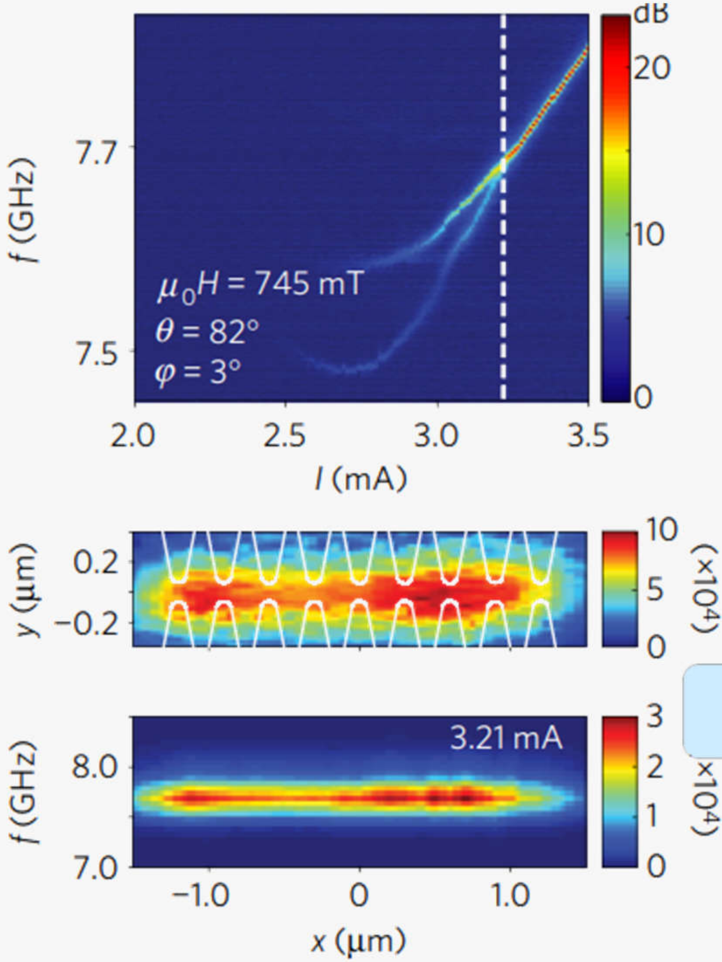


Goal: increase power, increase frequency and phase coherence

Mutual synchronization



Spin-Hall Nano-Oscillator (SHNO)

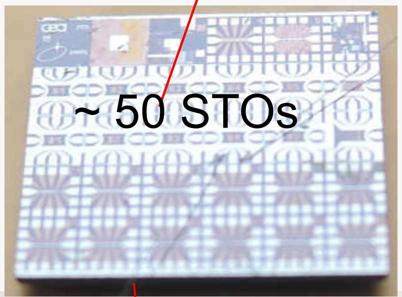


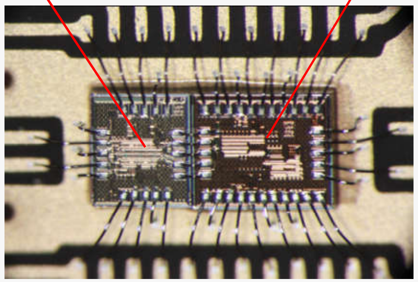
μ-BLS

A. A. Awad, Nat. Phys. 13, 292 (2016)

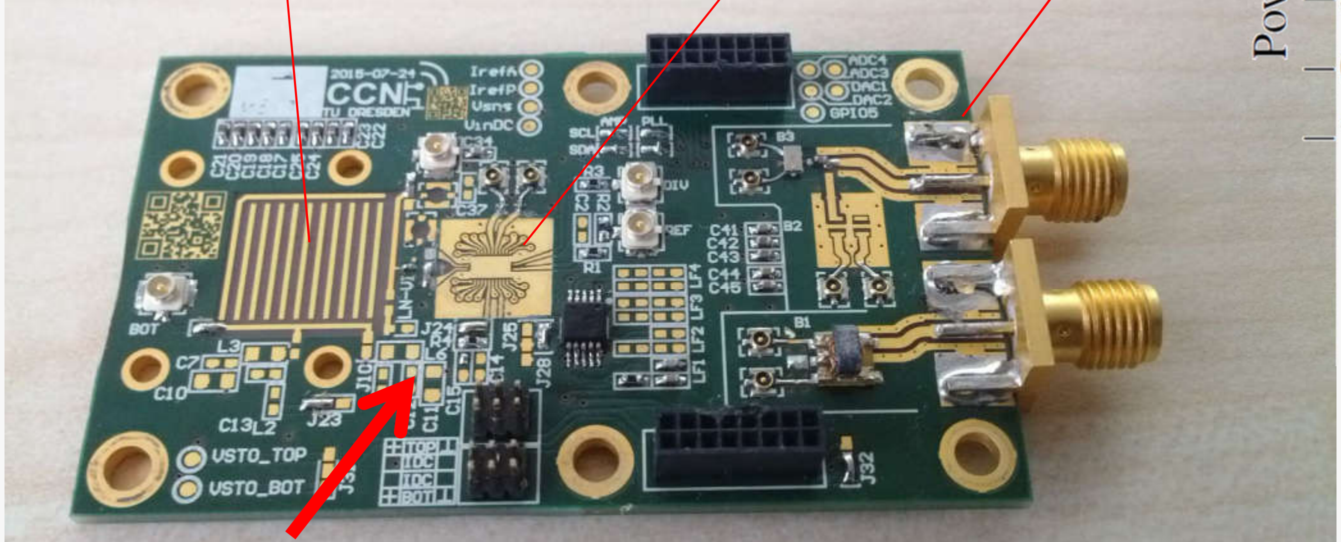
External synchronization through PLL

PLL = STO chip + Amp-IC + PLL-IC + PCB card

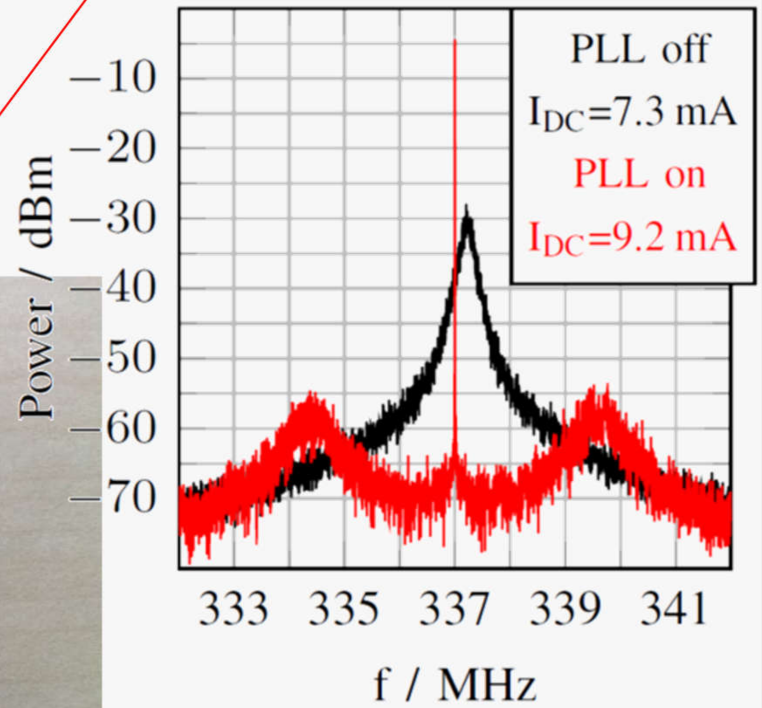




Wideband, hybrid PLL



Bias network to STO (SMD components)



M. Kreissig, AIP Adv. 7, 056653 (2017)

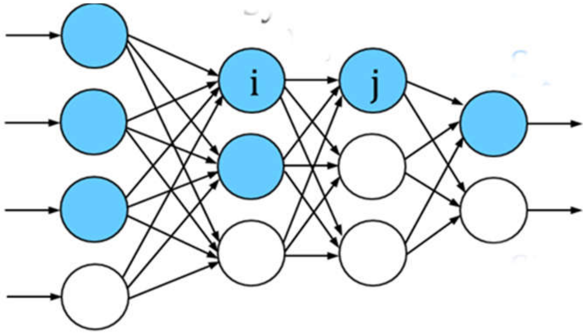
Table of content

- Decades of nanomagnetism

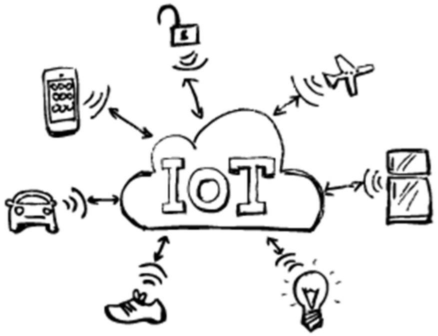
- Societal challenges

- Energy consumption in ICT

- Neuromorphic computing

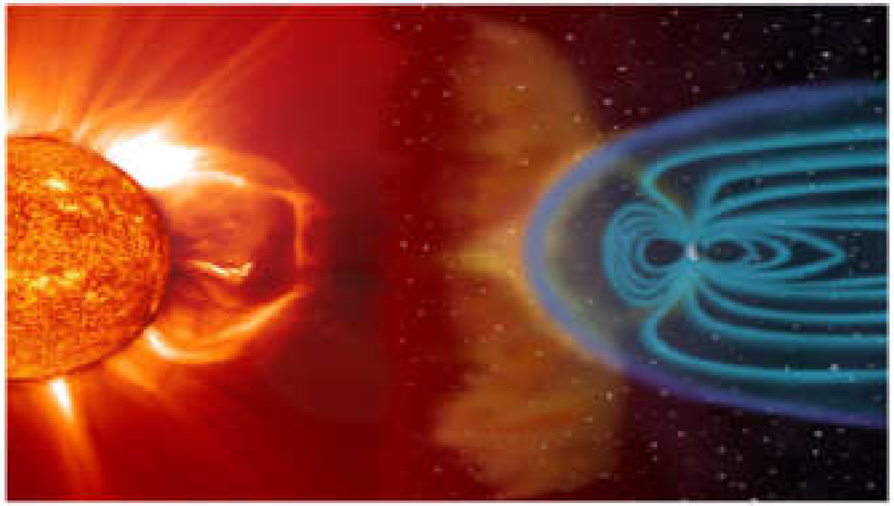


- Wireless communication



- Radiation hardness

Space applications



- Solar particles
- Cosmic rays

Nuclear industry

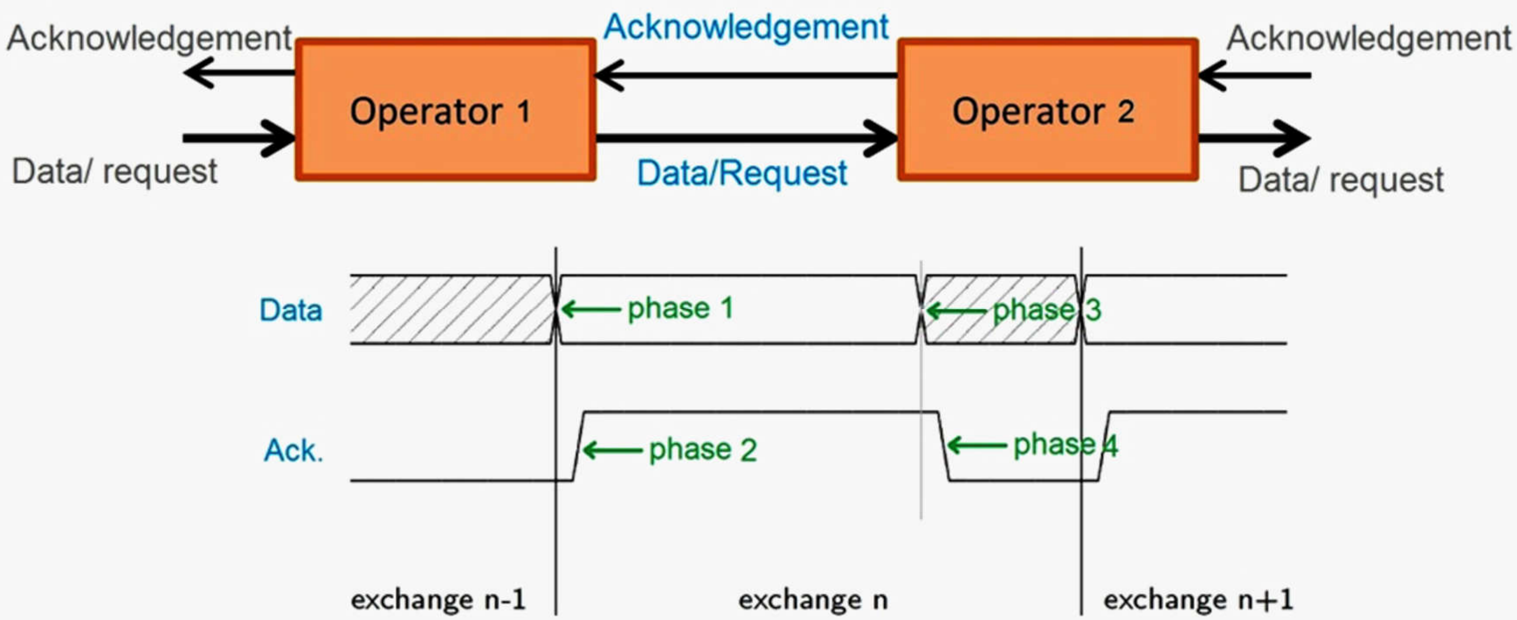
- Accidents
- Decommissioning

Consequences

- SSE: Single-Event Effects (digital damage)
- TID: Total Ionizing Dose

MRAM and asynchronous communication

- Combine DRAM and MRAM
- In case of SEE, refresh DRAM with MRAM content
- Redundancy reduced, cost lowered



Context

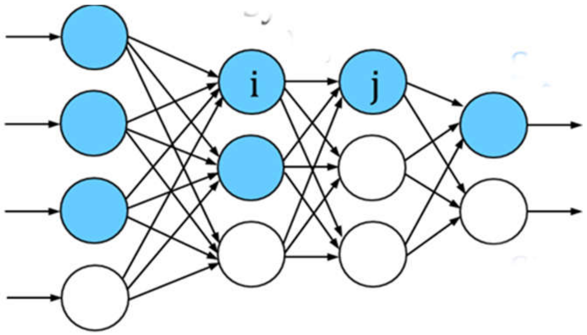
- Spintronics hardware and IC design experts

- Decades of nanomagnetism

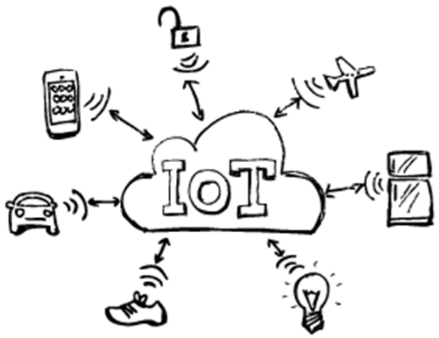
- Societal challenges

- Energy consumption in ICT

- Neuromorphic computing



- Wireless communication



- Radiation hardness

- Material criticality

Co Cr Cu Fe Ga Ge
In K Li Mg Mn Mo
Nb Ni P Pb Pt Re
REE Rh Ru Si Sn Ta

Material criticality

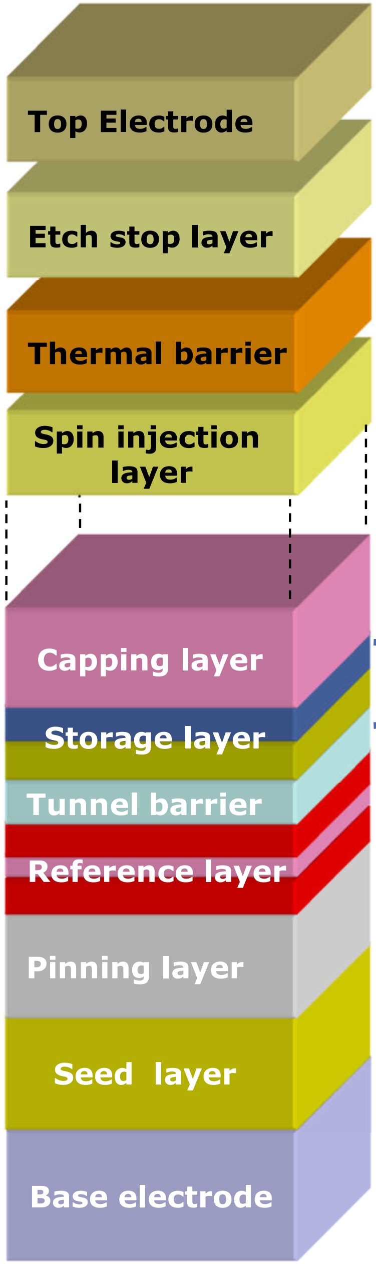
TOULON = 165 000 INHABITANTS

EVERY DAY: WORLD POPULATION

INCREASES BY 250 000

⇒ CONCERN ABOUT RESSOURCES

Materials for spintronics



Spintronics requires an increasing number of materials and elements in stacks

- Price
- Material criticality

Protects MTJ during process

NiFe(3) / CoFe(2) : Stores data (2 stable states)

MgO (1.1) : Defines cell R & TMR

CoFeB(2) / Ru(0.8)/CoFe(2) : SAF, immune to external fields

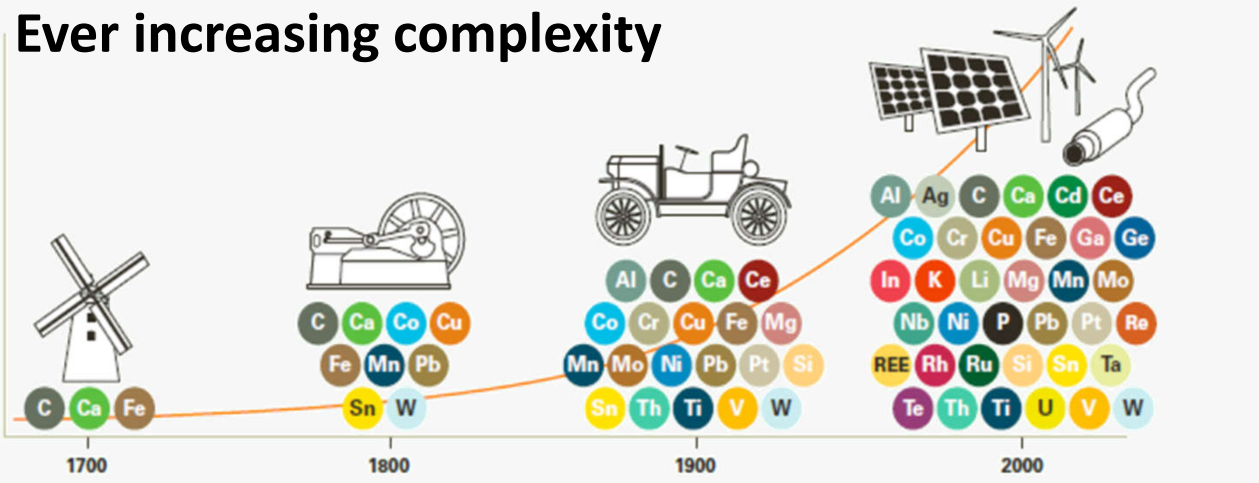
PtMn(20) : AF layer sets direction of reference layer

Ta(5) or NiFeCr(10) : Promotes texture of critical layers

Contact to select transistor + diffusion barrier

Material criticality: context

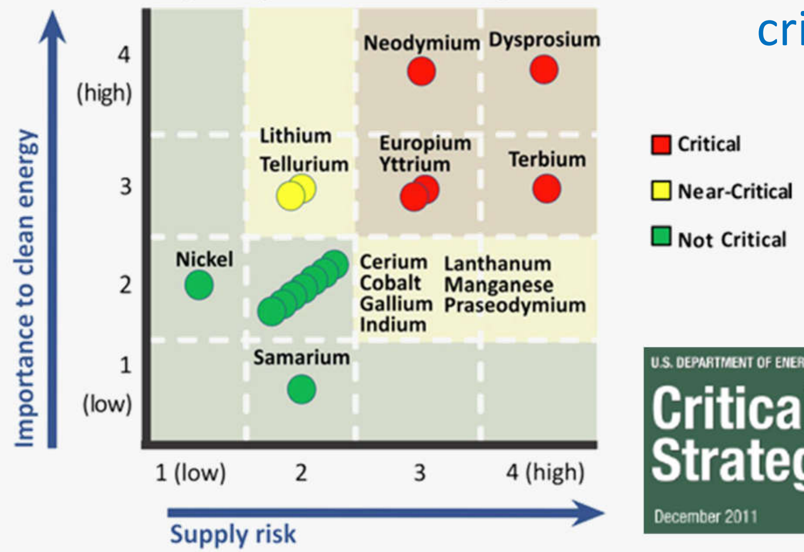
Ever increasing complexity

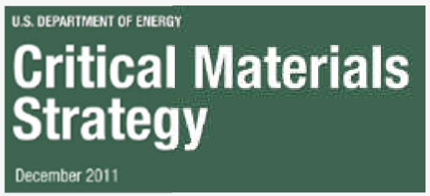


© Fraunhofer IWKS, Armin Reller

Quantifying criticality

Mid-term (2015-2025) criticality matrix





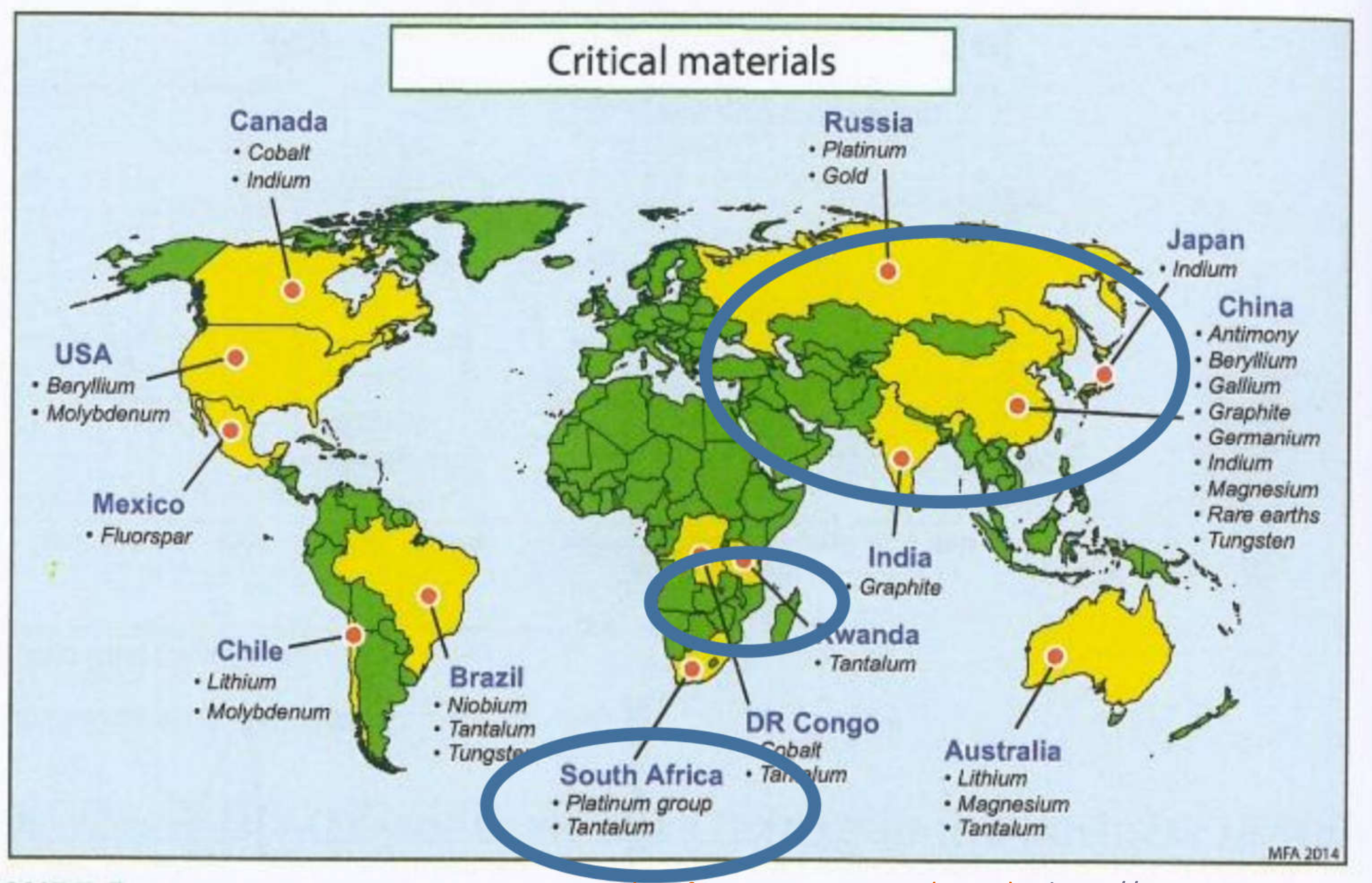
Criticality

- Geopolitical
- Limited resources
- Environmental regulations
- Ethics
- Cost

Actions

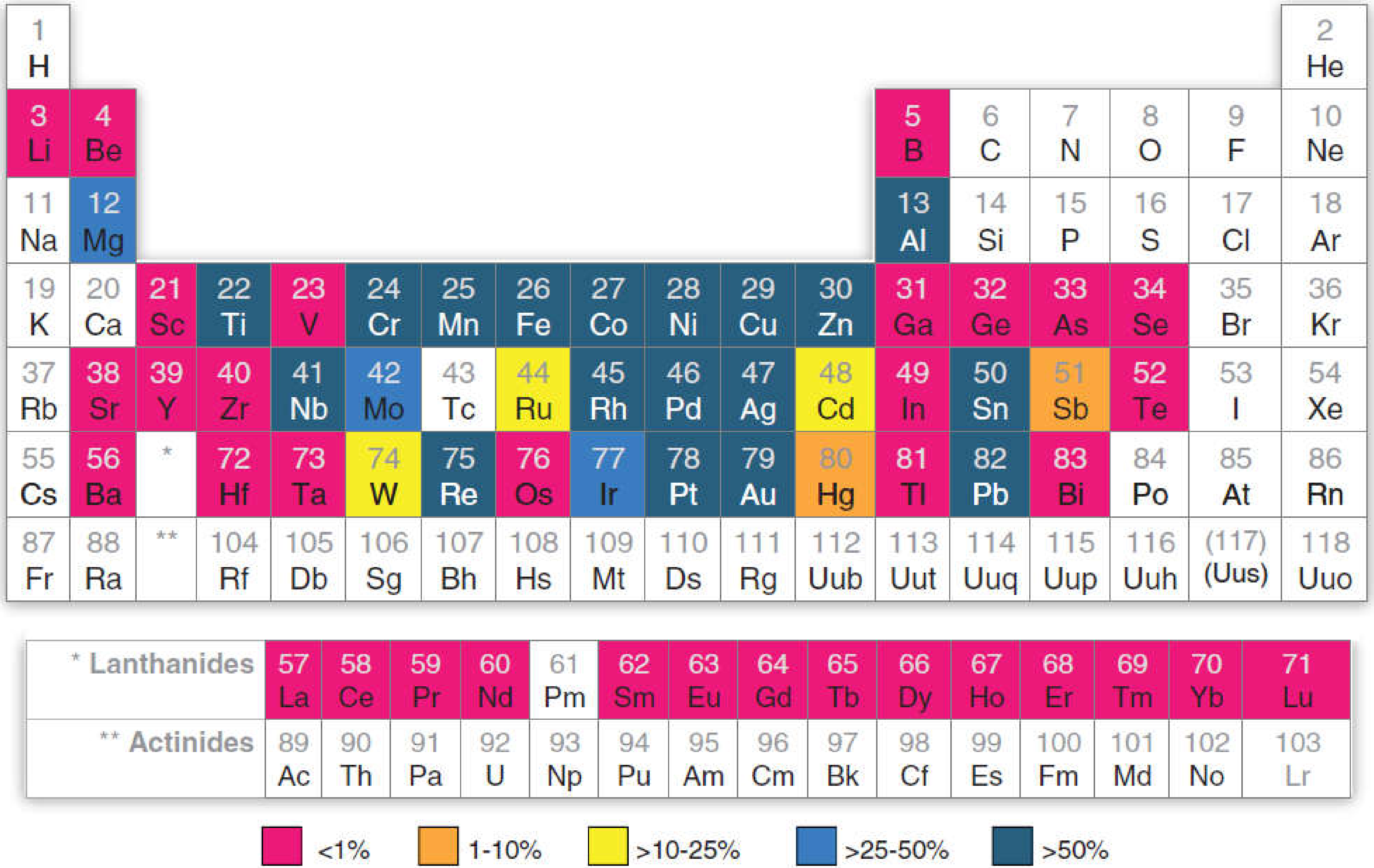
- Replace
- Reduce
- Reuse

Material criticality: mining



EU: Raw Materials Information System (RMIS) – http://rmis.jrc.ec.europa.eu

Material criticality: recycling



T. E. Graedel et al., J. Ind. Ecol. 15, 355 (2011)

Reference layers

- Antiferromagnets
  - PtMn, IrMn
- Synthetic antiferromagnets
  - Ru, Ir

Writing

- Spin-Hall effect
  - Pt, W …
- Dzyaloshiinski-Moriya
  - Pt, Ir, W …

Perpendicular magnetic anisotropy

- Interfacial anisotropy
  - Pt, Pd…

Note

- Often related to high spin-orbit
- Heavy (and rare) elements

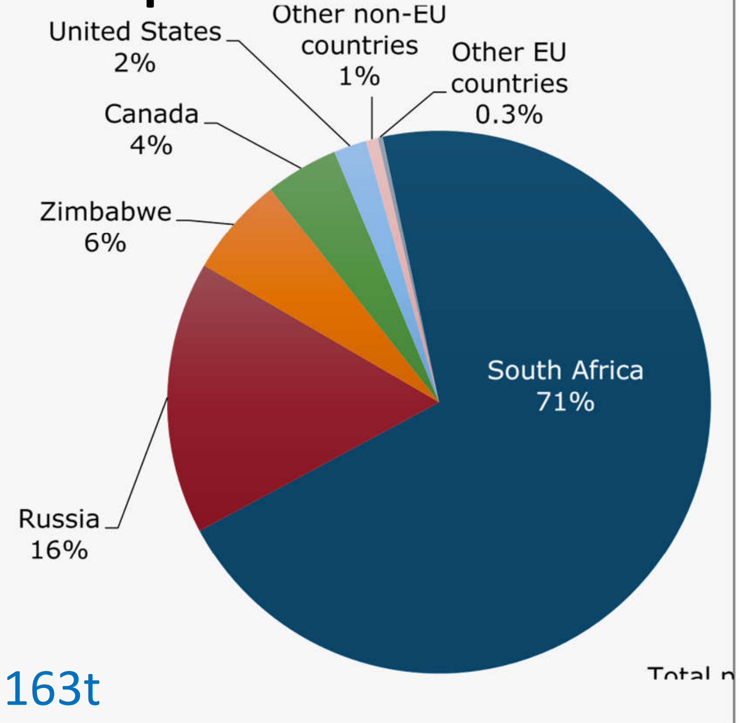
Material criticality in spintronics: case of Pt

Study on the review of the list of Critical Raw Materials

European Commission

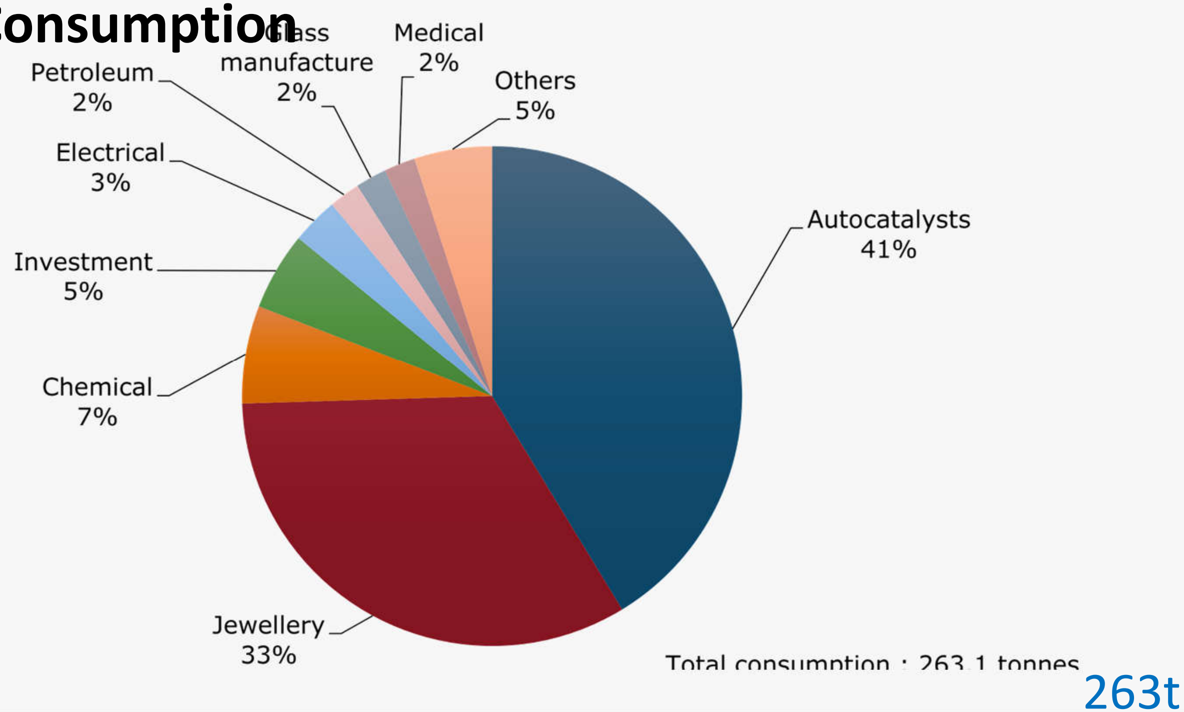
Critical Raw Materials Factsheets

Mine production



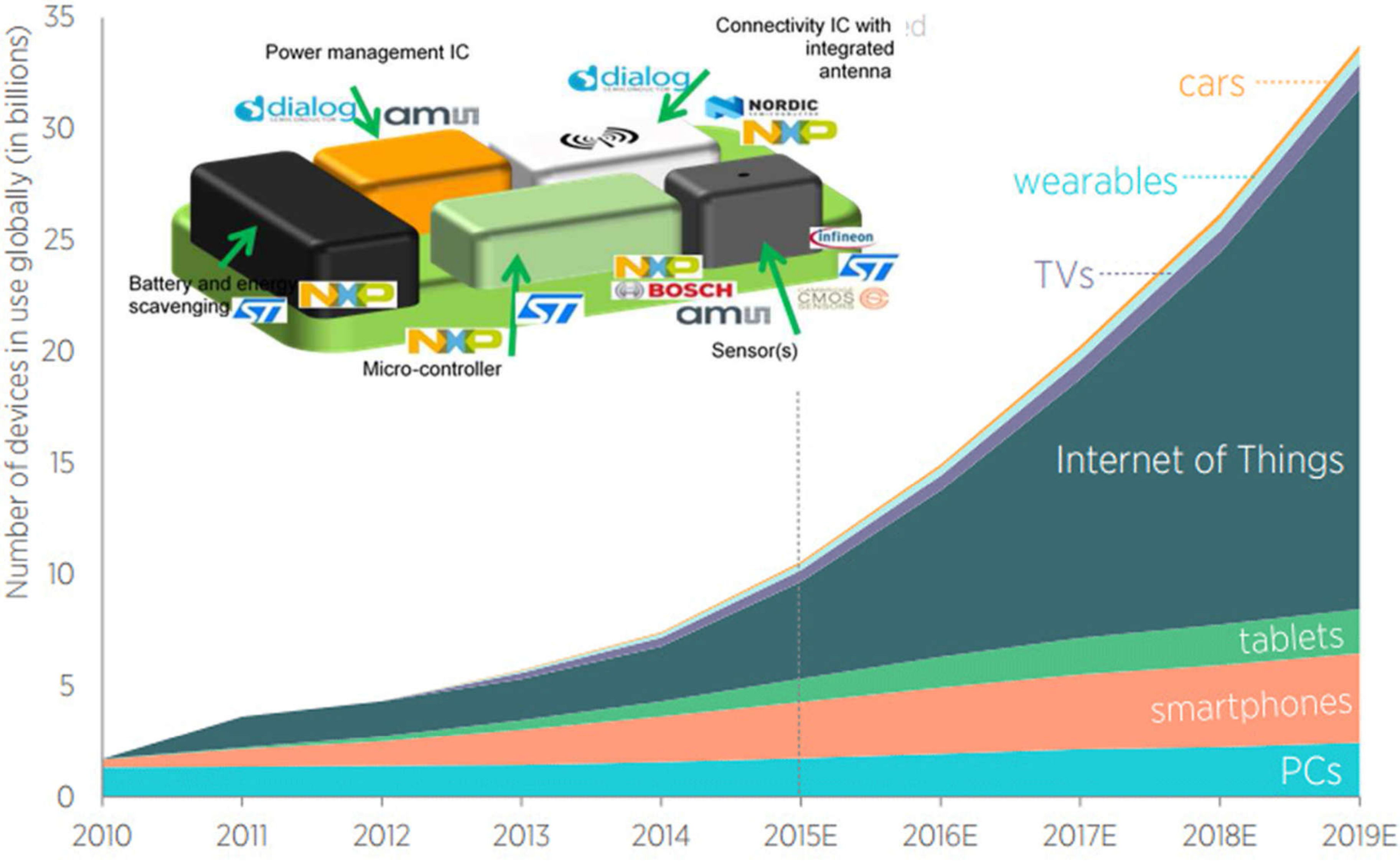
Price

Consumption



Raw Materials Information System (RMIS) – http://rmis.jrc.ec.europa.eu

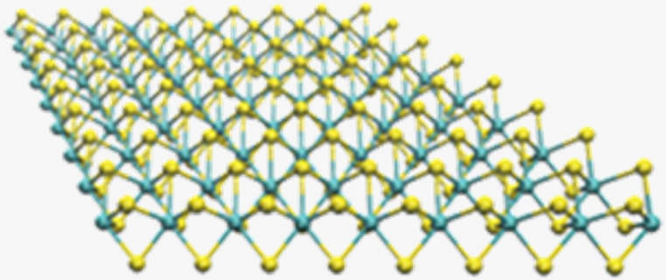
Serious issue for massive production



Source: John Greenough, “The Internet of Everything 2015,” *Business Insider Intelligence*. Produced by Adam Thierer and Andrea Castillo, Mercatus Center at George Mason University, 2015.

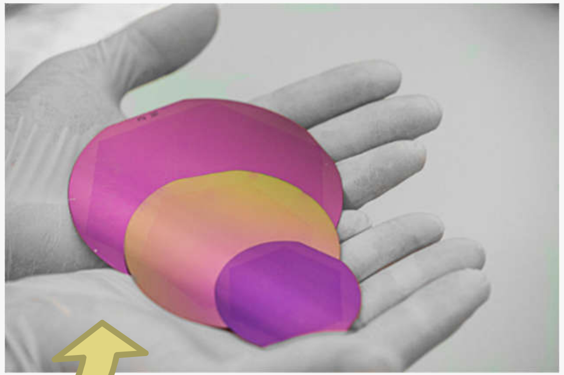
Replace, Reduce

2D materials



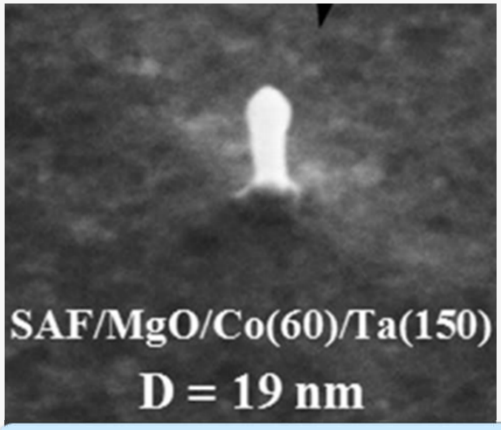
2D materials: graphene, WSe_2, $MoSe_2$, MoS_2

Need for upscaled production



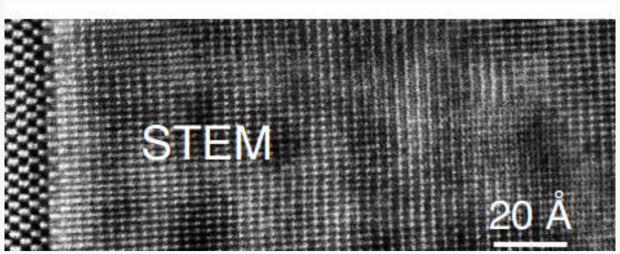
Anisotropy, interconversion, RKKY

3D structures



Anisotropy, stacks on wafer

Heusler alloys



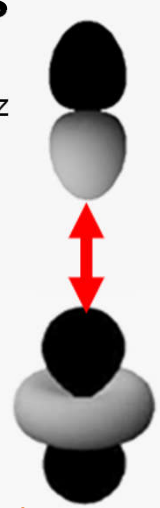
Antiferromagnets, anisotropy, polarizers

Oxide interfaces

O-p_z

Anisotropy

Co-dz^2



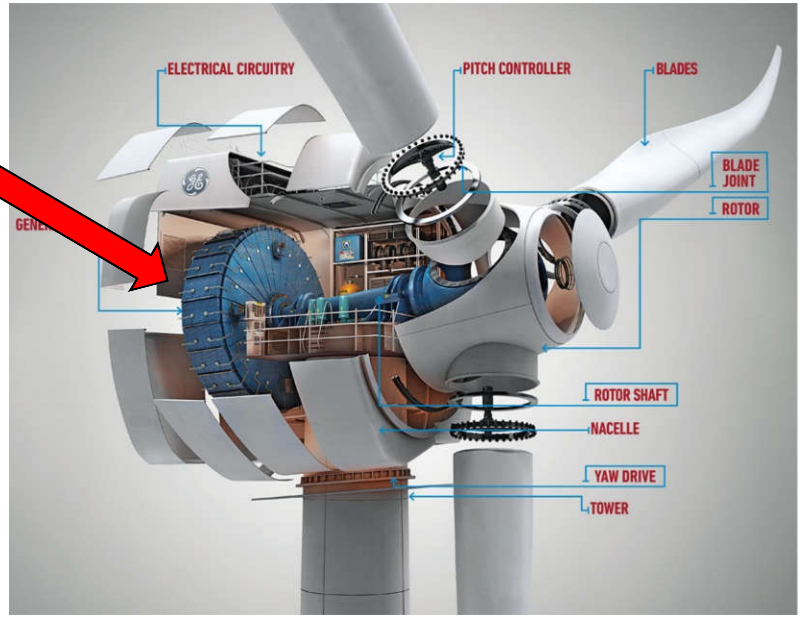
B. Diény, M. Chshiev, Rev. Mod. Phys. (2017)

Material criticality: magnets for energy

(image Renault)

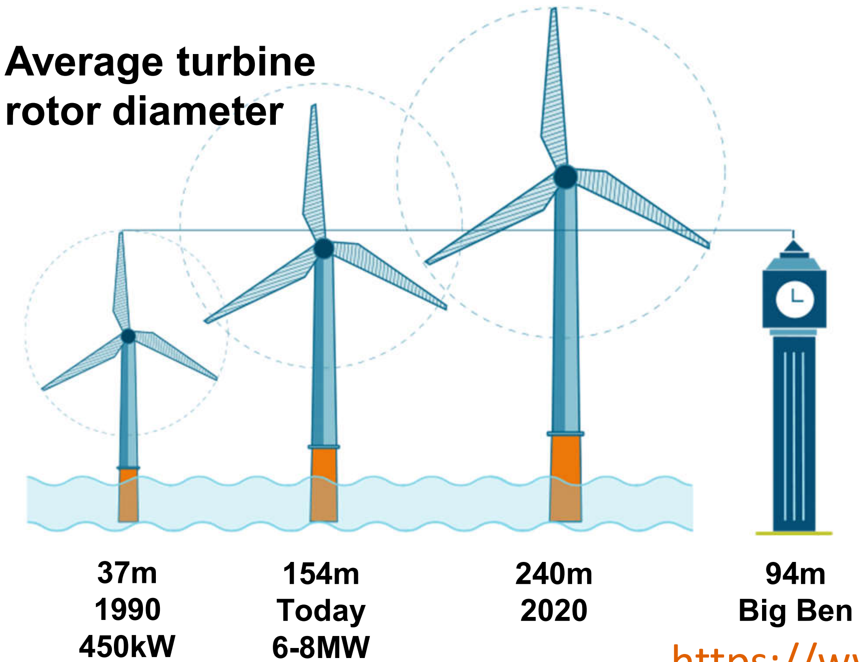
per 1 MW windpower

- **+/- 600 kg Nd-Dy-Fe-B**
- 4% Dy = 24 kg
- 28% Nd = 168 kg



(image General Electric, Data: US DOE)

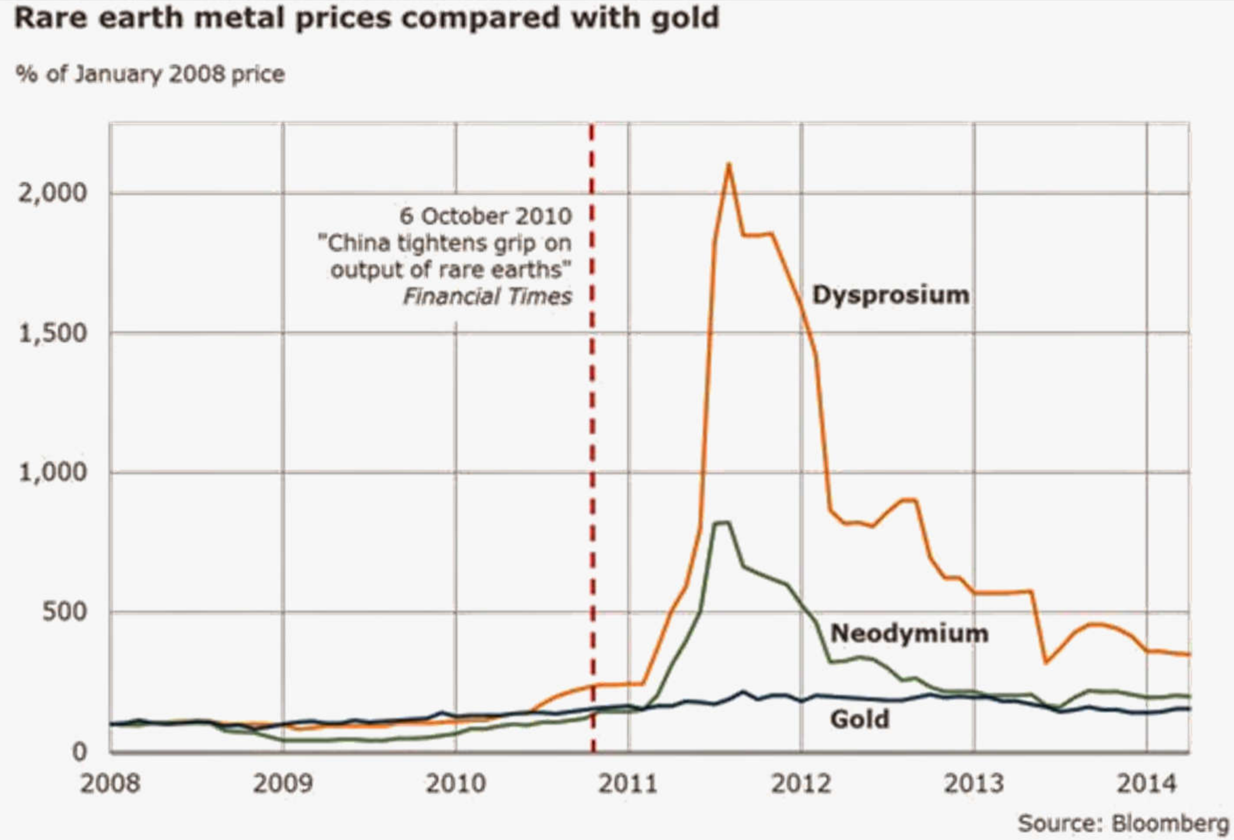
Average turbine rotor diameter



https://www.siemens.com/global/en/home/markets/wind/offshore.html

Material criticality: rare earth

China triggers the 2011 crisis



Never safe again…

Impact on permanent magnets

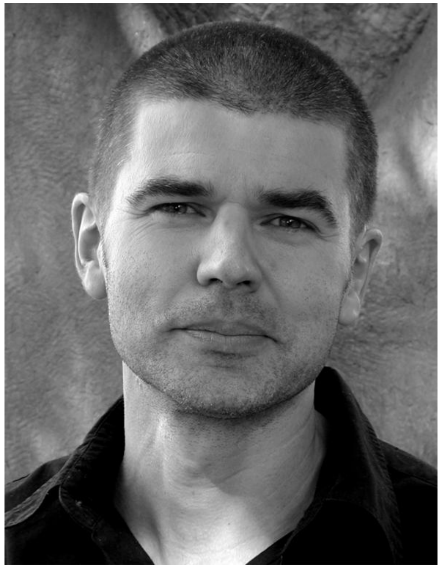
- Markets: wind mills, electric cars, magnetic refrigeration…
- New material research programs launched: materials and microstructure

Special thanks for sharing material

Bernard DIENY
Grenoble

Ursula EBELS
Grenoble

Julie GROLLIER
Paris



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