HISTORICAL HINTS – LOOKING INTO THE FUTURE

B.Dieny

Magnetism ?

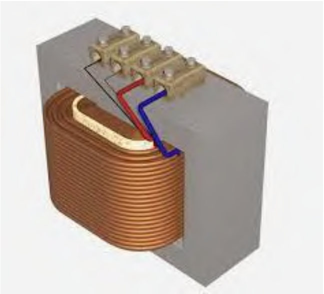
Magnetic spoon/compass (magnetite) from Han Dynasty (~1000BC)

19th-20th

Ampere, Biot, Coulomb, Faraday, Maxwell, Oersted, Savard, Tesla

compass

Hard magnets

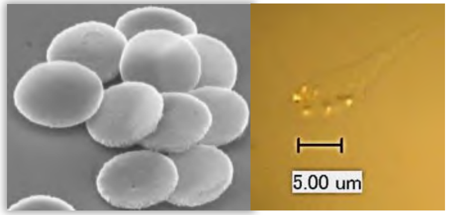


Soft magnets

Hard disk drives

Magnetic memory

Magnetic field sensors



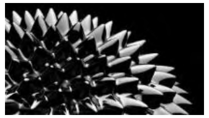
Magnetic nanoparticles

Magnetic imaging

Magnetism: a broad range of applications…

Permanent magnets

Magnets



ferrofluids

Motors

alternators

Robotics

Transportation

Soft magnets

Flux carriers in transformers

Magnetic core in electromagnets

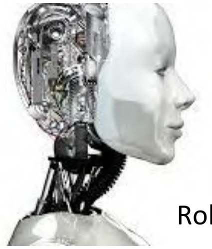
Sense layer in magnetic field sensors

Microwave devices

Magnetism in electronics

Memory, storage, RF

Wireless communication



Robotics, AI

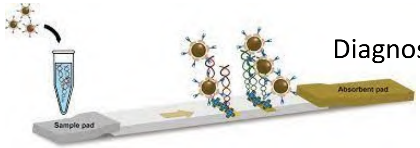
Data storage

Hard disk drives

Mag tapes recording

Biomedical

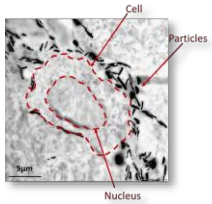
MRI



Diagnosis

Cell sorting

Drug delivery



Cancer, diabetes therapies based on mechanical stimulation of cells

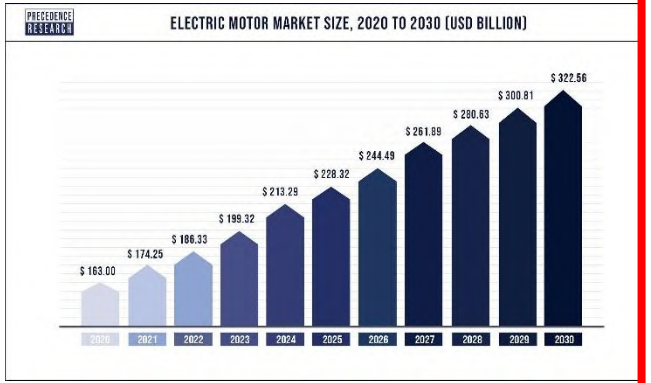
Magnetism: economic weight in industry

ENERGY/MOTORS

Electrical power generation and transmission

1,500B$ (2020)
(International Energy Agency)

Electrical motors



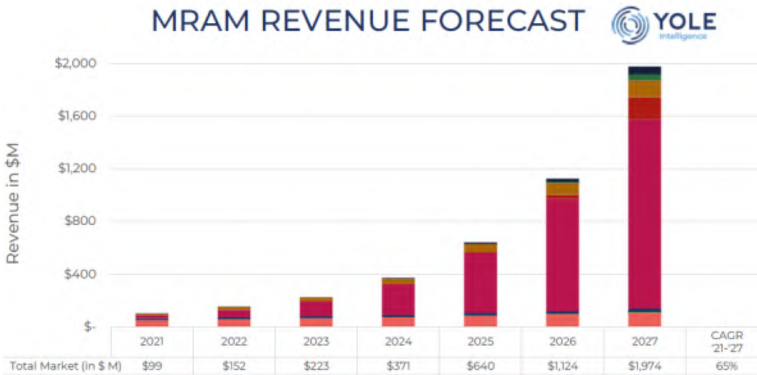
**163B$** (2020) -> 322B$ (2030)

INFORMATION-COMMUNICATION

Data storage

56B$ (2020) ↗↘↗

MRAM



1 B$ (2026) ↗

Magnetic field sensors for IoT

27B$ in 2022 ↗

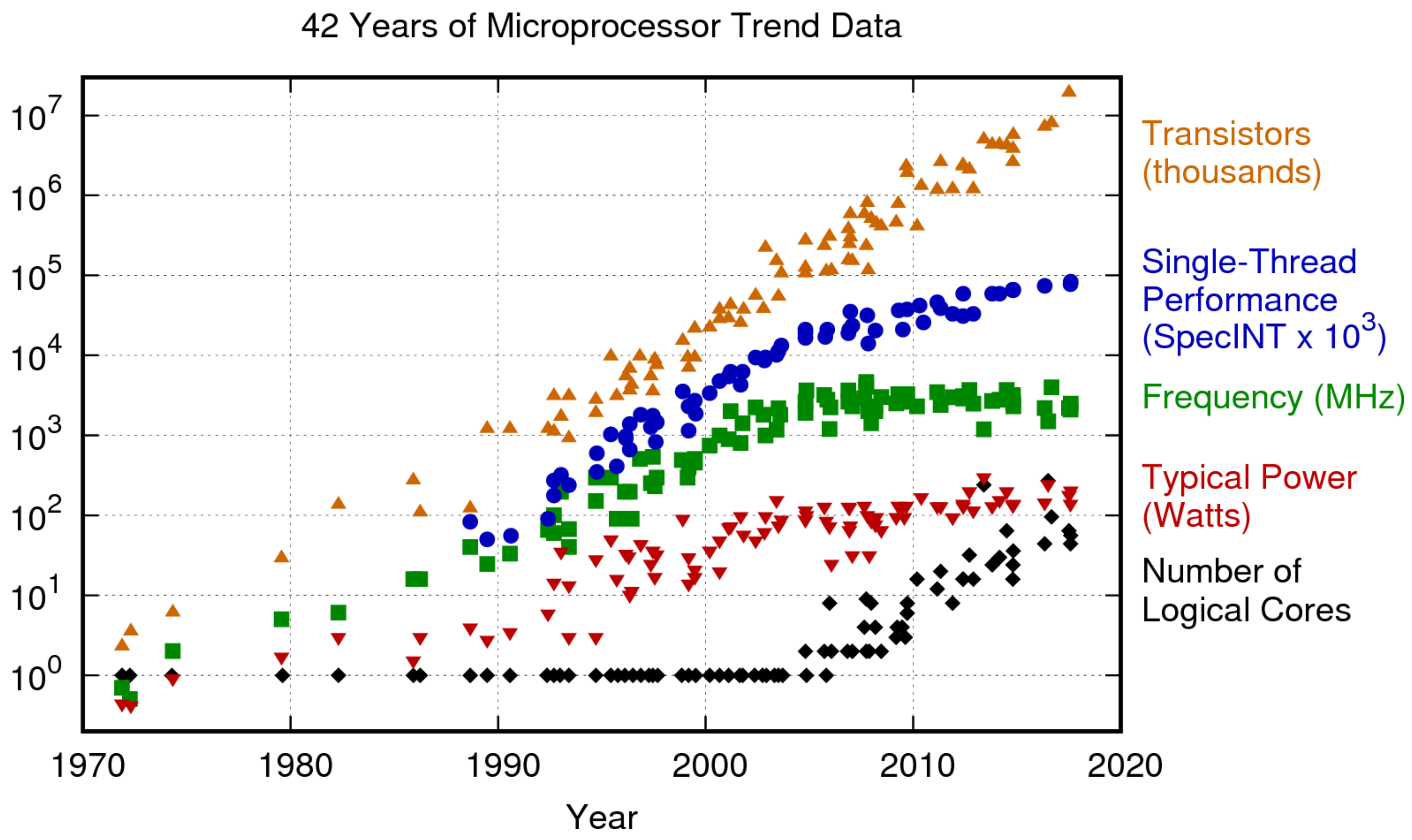
BIOMEDICAL

MRI

6,5B$ (2020) ↗

Place of magnetism in microelectronics

The number of transistors (MOSFET) per unit area has doubled every 2 years for 50 years ***(Moore's law).***



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

1980 **2020**

This trend is reaching physical limits : New paradigms are needed (Beyond CMOS)

Power consumption:

Static (Leakage)
+ Dynamic

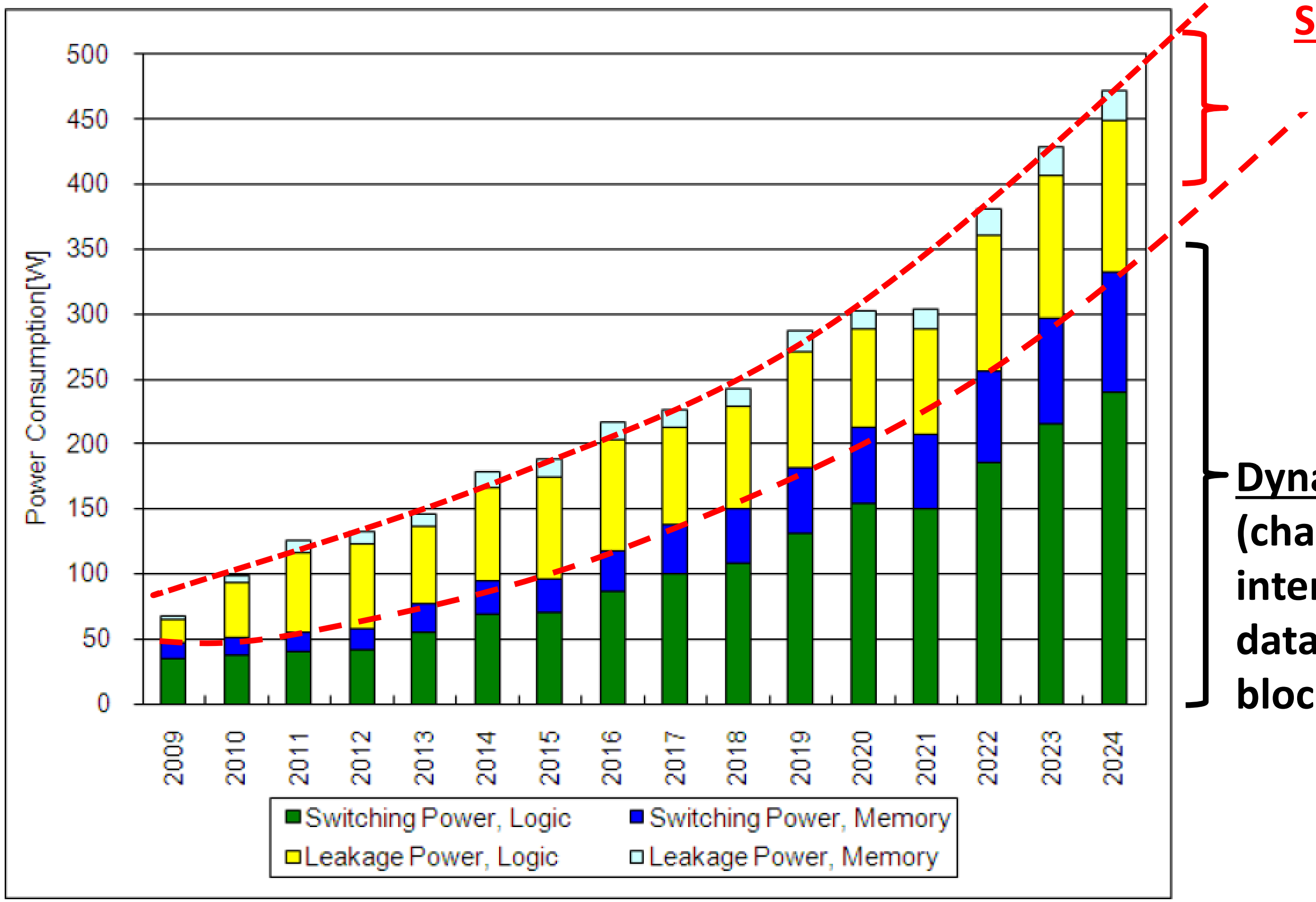


Figure SYSD11 SOC Consumer Stationary Power Consumption Trends—UPDATED

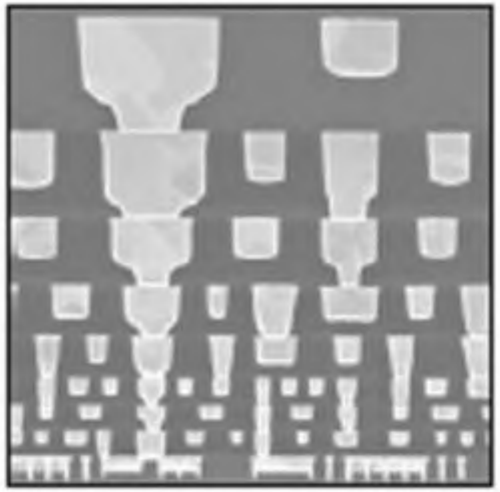
Static power consumption (leakage)

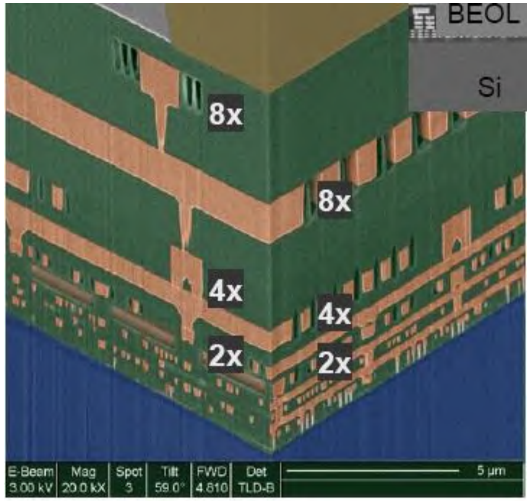
Dynamic power consumption (charging/discharging of interconnects when transferring data between memory and logic blocks)

Power consumption of electronic circuits (e.g. microprocessor) per cm²

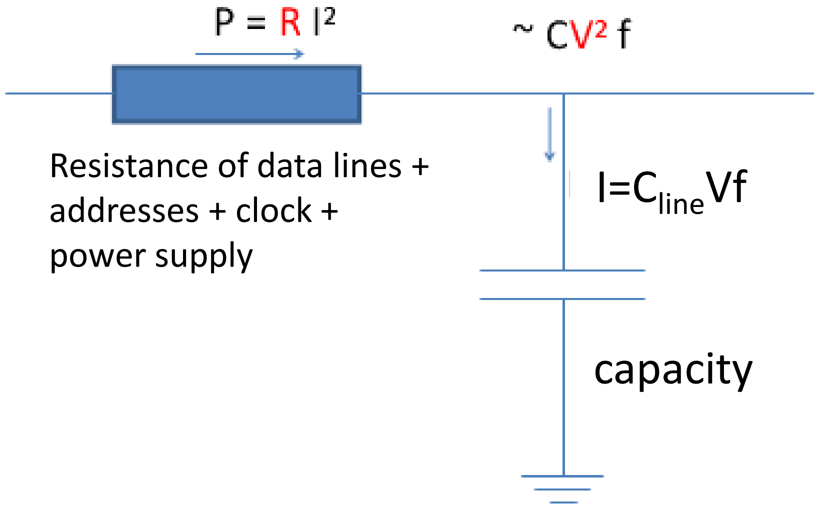
But this downsize scaling is increasingly difficult...

Dynamic power consumption mainly due to Joule dissipation in interconnects and capacitive losses





BEOL Technology



Capacity of lines and transistors

The interconnects length keeps on increasing and correlatively the dynamic losses

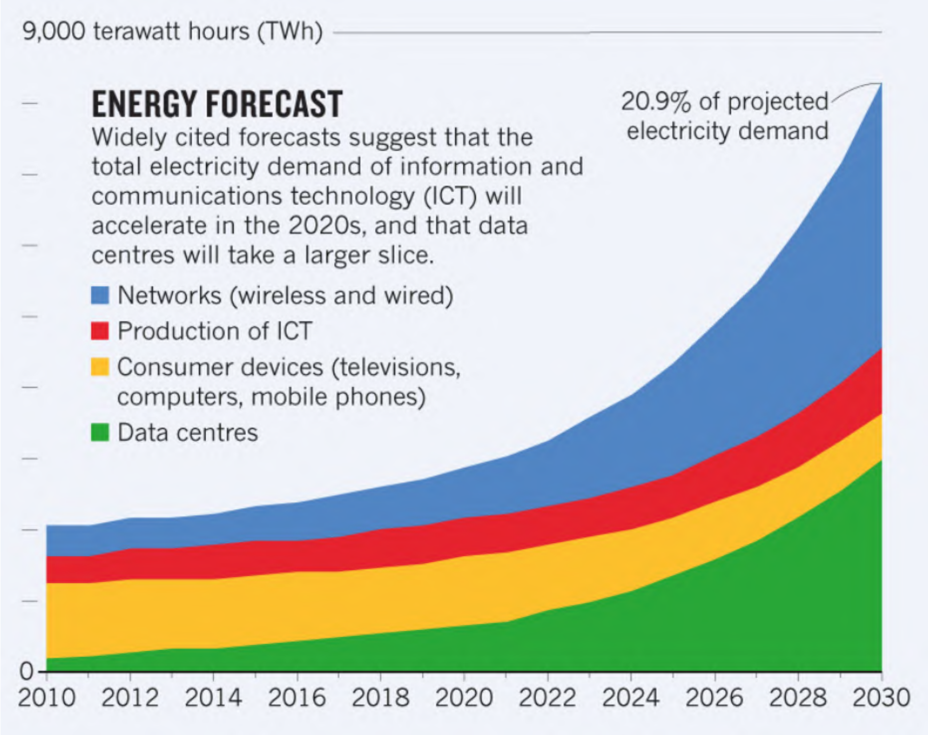
Technology node:	90 nm (2003)	→ 65nm (2005)	→ 45nm (2007)	→ 32 nm (2009)	→ 22 nm (2011-13)	→ 14 nm (2018)
Nb of transistors per chip	10^7 transistors	→ 10^8	→ 10^9	→ $3\ 10^9$	→ 10^{10}	→ $3.\ 10^{10}$
Total length of interconnects	**~10 km**	**→ ~ 30 km**	**→ ~ 100 km**	**→ 300 km**	**→ 900 km**	**→ 2500 km etc…**

Lot of energy is wasted in transferring data between memory and logic blocks

Steadily rising power consumption associated with ICT

In countries such as US, Europe etc, 15% of the overall electrical power consumption is due to ICT (21% expected in 2030).

• Increasing number of **data centers** for cloud computing (Facebook, Amazon, Google, Apple, bitcoin….) : > 100 MW to run the servers + 100 MW to cool them.



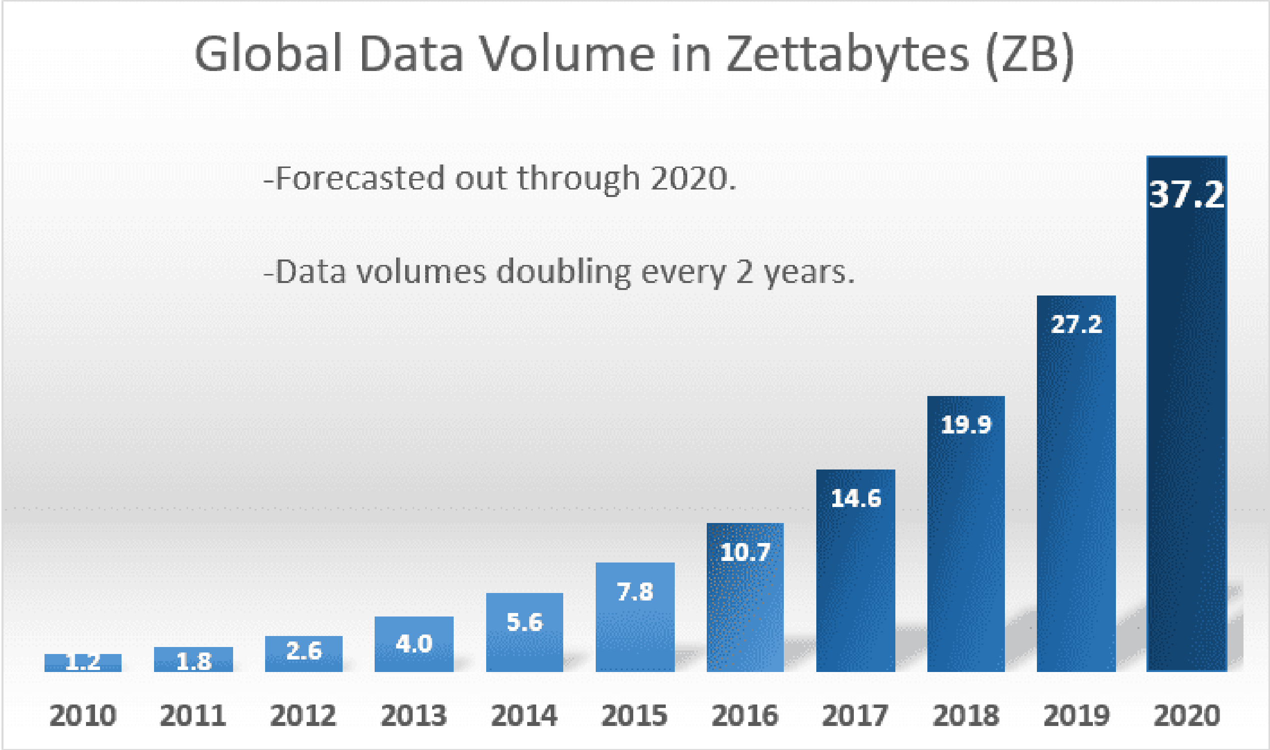
Nicola Jones, https://www.nature.com/articles/d41586-018-06610-y

• **High Performance Computers** (HPC) : from Petaflops (10^{15} flop/s) to Exaflops (10^{18} flop/s): Tens of MW of power consumption

• For **wearable applications** (Smart-phones, tablets etc), reducing power consumption increases battery autonomy.

It is mandatory to improve the energy efficiency of electronic systems
(… while avoiding creating new needs….)

Exponentially growing amount of data produced worldwide:
smartphones, internet of things (connected objects), autonomous vehicles…



90% of data are generated by machines

1 ZB = 1000^7bytes = 10^{21} bytes = 1000000000000000000000 bytes = 1000 exabytes = 1million petabytes = 1billion terabytes.

2 Billions of 10Tb hard disk drives required to store the data produced in 2018 !

Need to filter these data, sort them, store them

Spin-electronics brought solutions for data storage and low power electronics and will continue to do so.

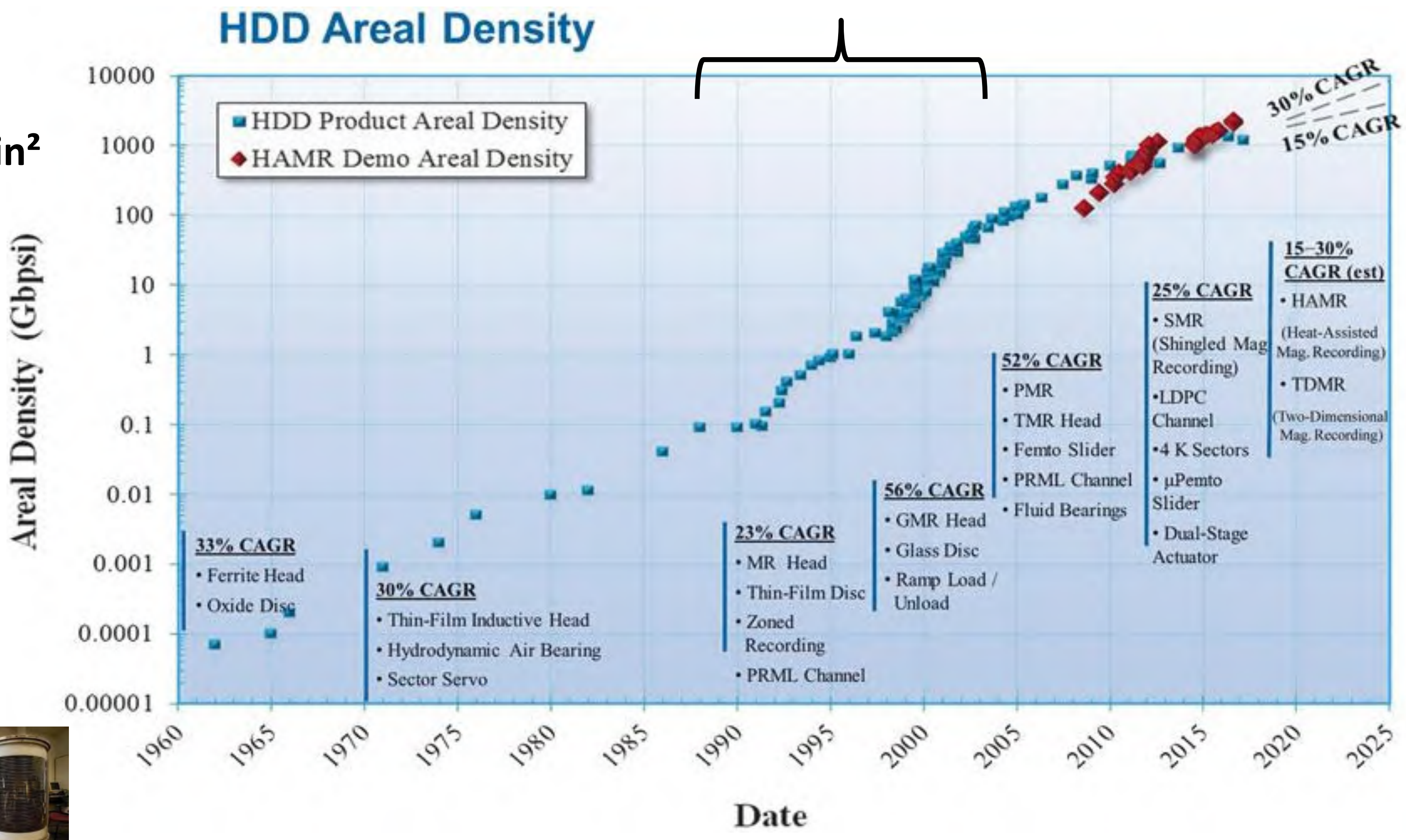
- **Hard disk drives**
- **Non-volatile electronics**

Spin-electronics brought solutions for data storage and low power electronics and will continue to do so.

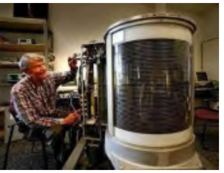
- **Hard disk drives**
- **Non-volatile electronics**

Golden times of GMR and TMR heads development

1Tb/in²



Progress in areal density is slowing down due to physical limits and lack of new cost effective solutions (Patterned media are too expensive)

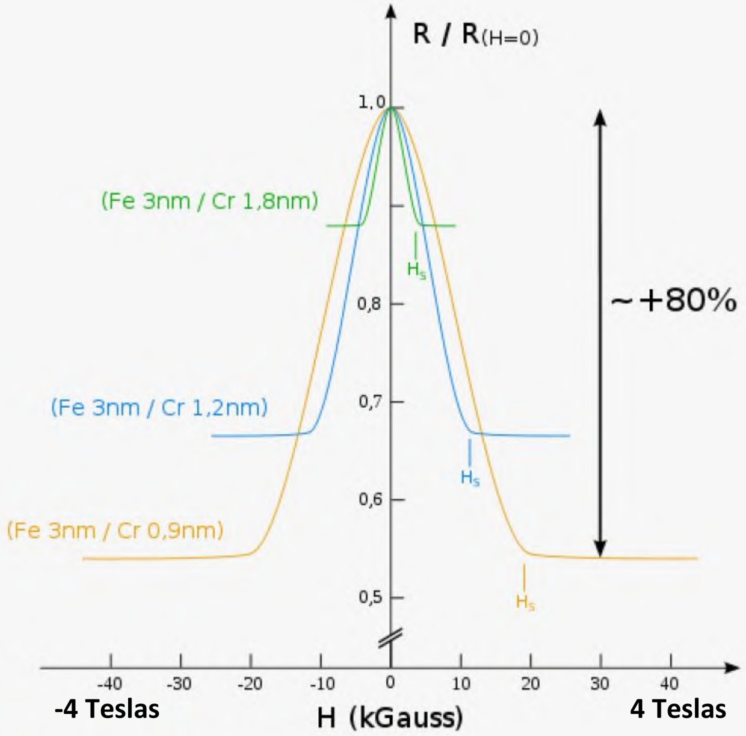


M.T. Kief, R.H. Victora, MRS Bulletin, 43, 87 (2018)

Golden times of GMR and TMR heads development (1989-2005)

GMR discovery (1988): the launch of spin-electronics

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

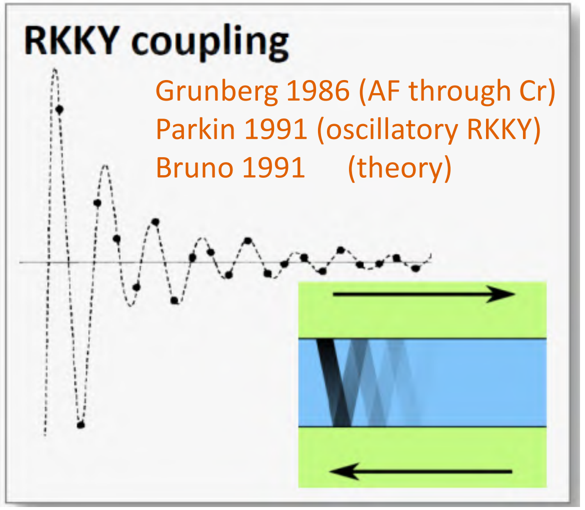
Photo: U. Montan
Peter Grünberg
Prize share: 1/2

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

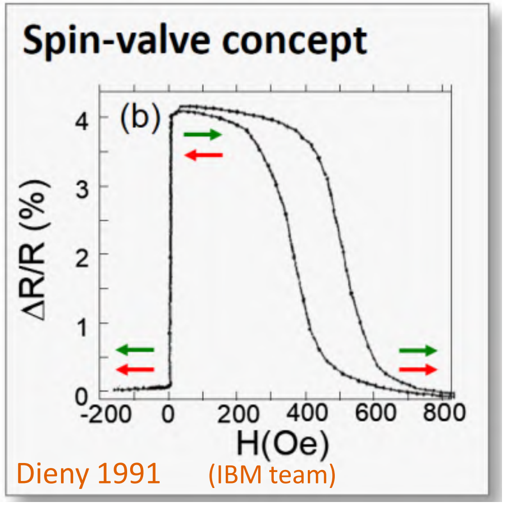
Golden times of GMR and TMR heads development (1989-2005)

Metallic SV used in MR heads between 1998 and 2004

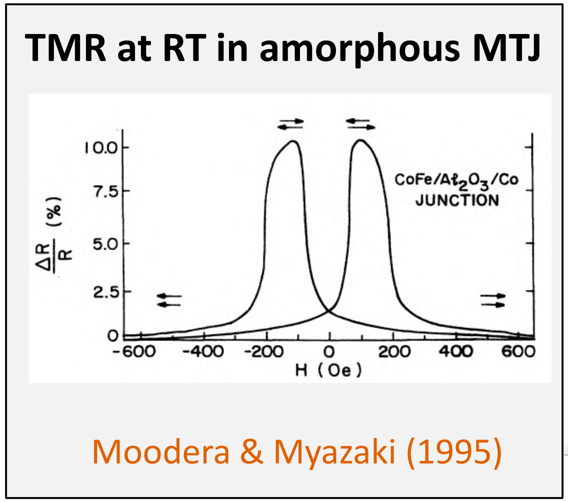
TMR introduced in MR heads in 2004 by Seagate with TiOx, gradually replaced by AlOx then MgO



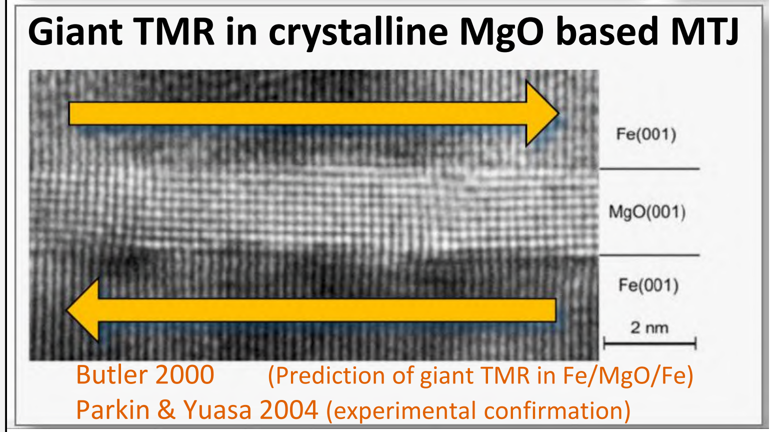
Synthetic antiferromagnetic pinned layer



Concept of low field GMR sensor based on free/spacer/pinned (exchange biased) stack.
Later also adopted for magnetic tunnel junctions.



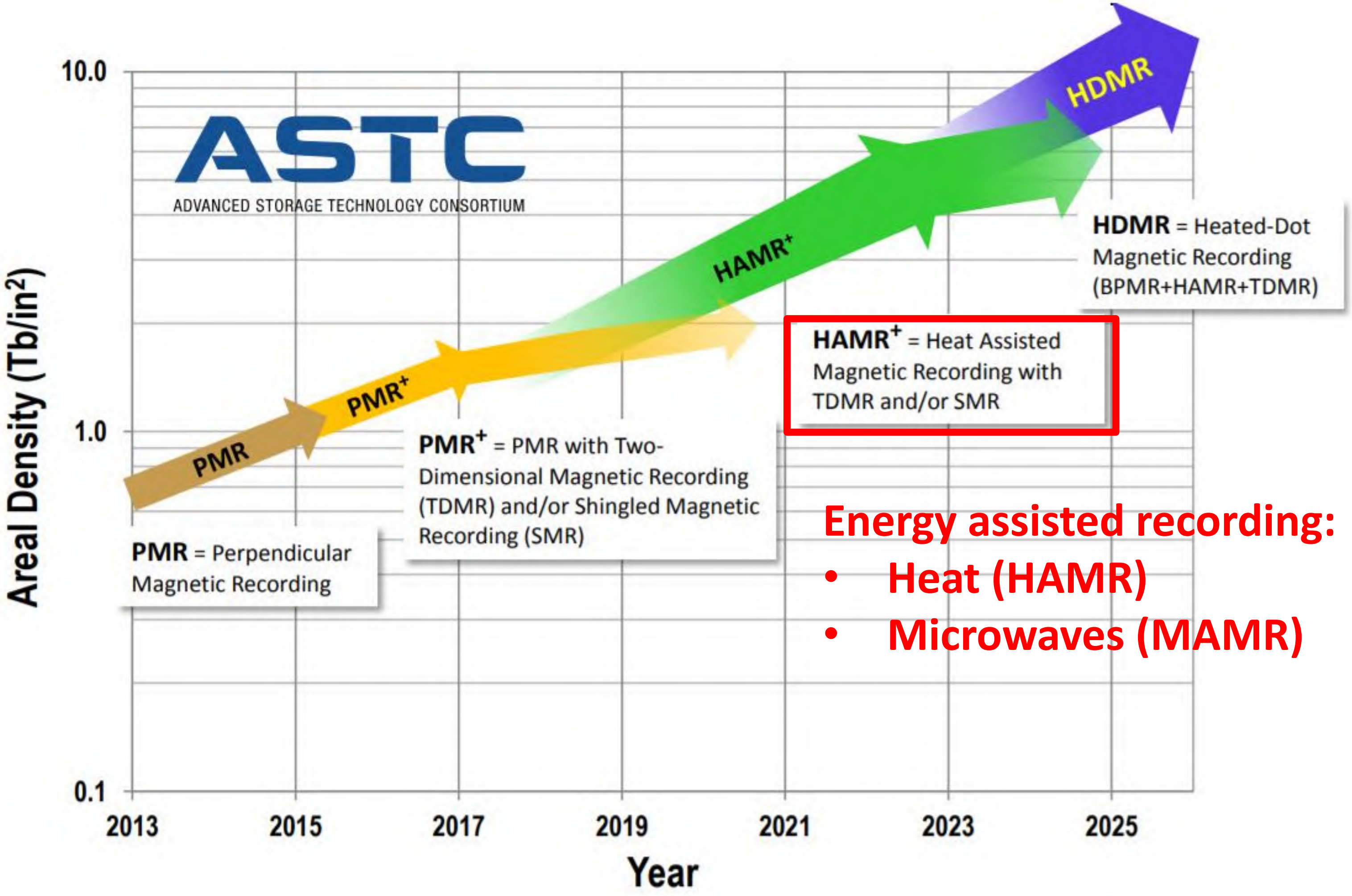
TMR first observed by Julliere in 1975 through Ge but only at low temperature.



Larger TMR ->Boosted readout signal
Later used in MRAM but much lower resistance x Area product needed for heads.

Hard disk drive technology

For more than 50 years, R&D in magnetism has been largely stimulated by the development of magnetic recording technology

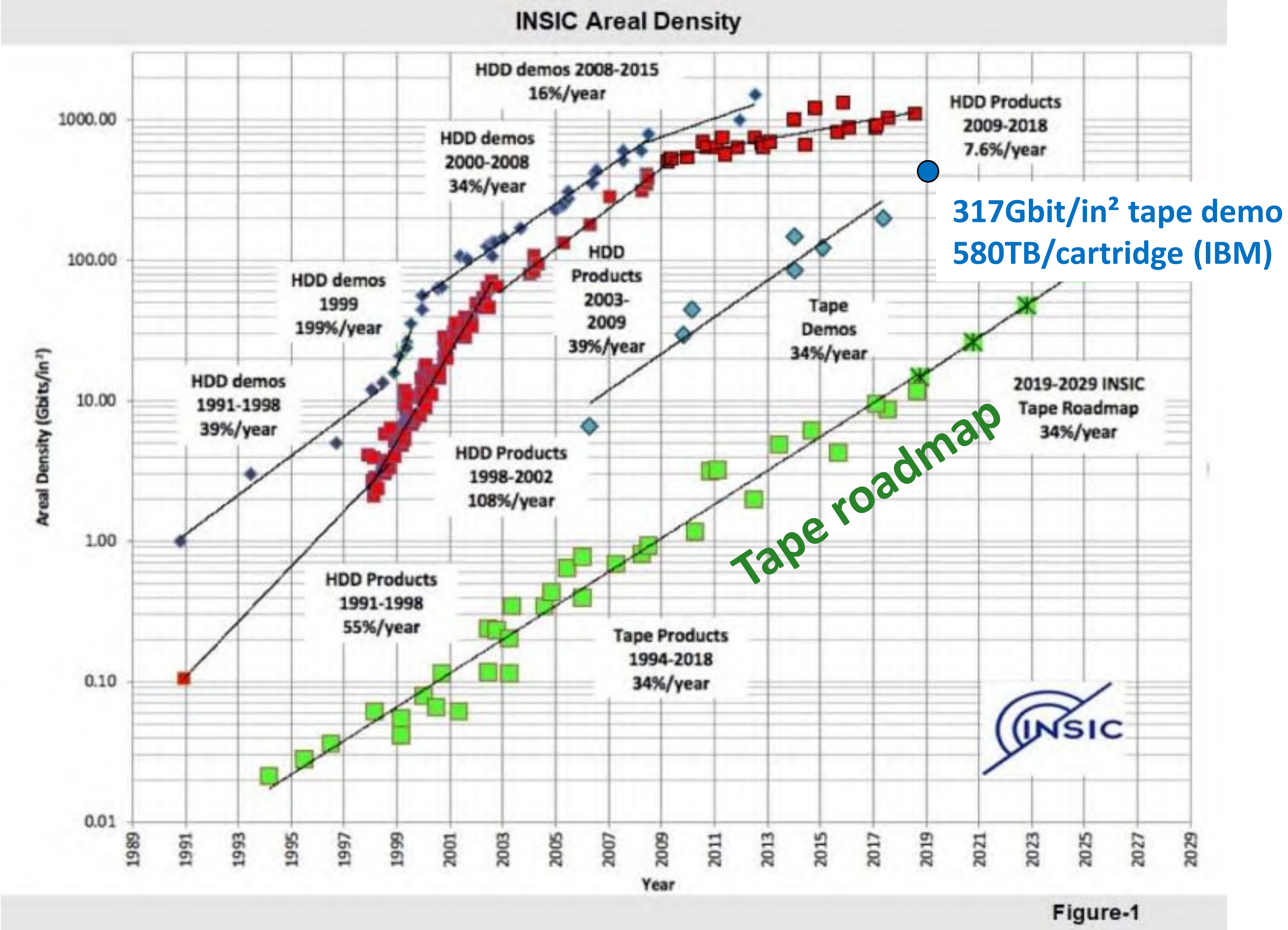


Energy assisted recording:

- **Heat (HAMR)**
- **Microwaves (MAMR)**

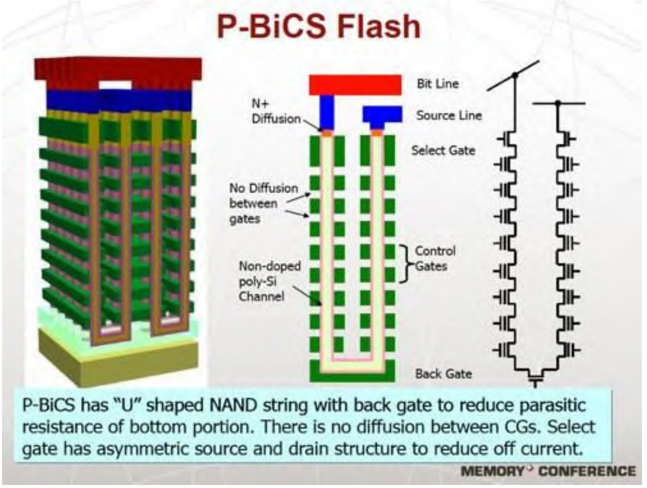
Magnetic tapes recording

Magnetic tapes extensively used in server farms as ultimate long term storage

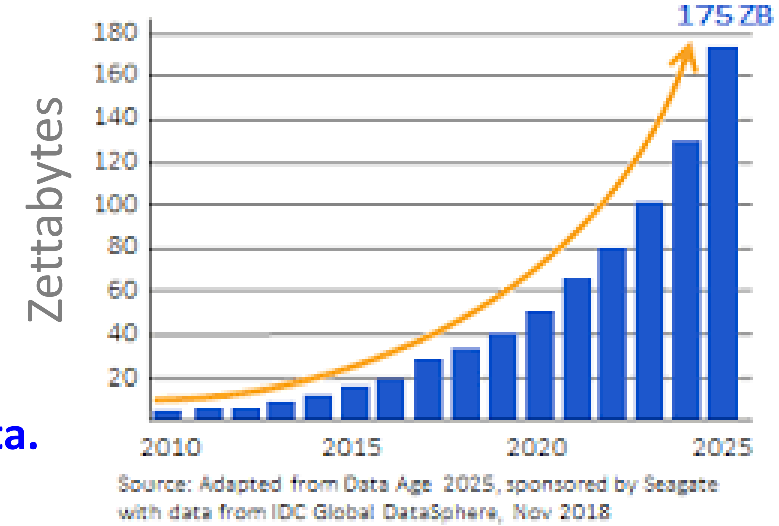


Coexistence of 3 storage technologies in server farms (cloud)

Flash SSD for hot storage	Magnetic HDD for cold storage	Magnetic tapes for archive storage



Annual Size of the global Datasphere



In 2020: 50 Zettabytes of data generated worldwide!

1 Zettabyte=10^{21}bytes= 1 billion Terabytes

10 billions (5Tb)-HDD needed to store the data produced in 2020

This coexistence allows to cope with the exponential growth of generated data.

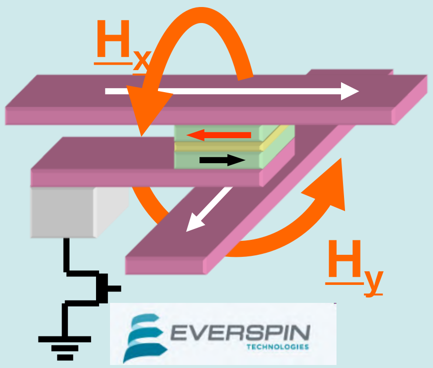
However, more and more market shares taken by Flash SSD storage

Spin-electronics brought solutions for data storage and low power electronics and will continue to do so.

- Hard disk drives
- **Non-volatile electronics**

spintec
SPIN IN ELECTRONICS

Field-driven MRAM

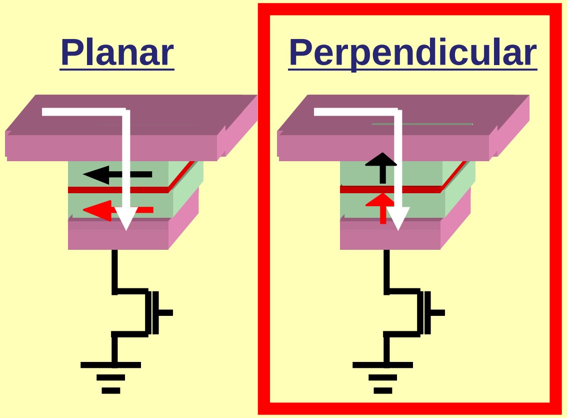


Toggle MRAM

Cell size=1.55μm²=(1.24μm)²
(4Mbit EVERSPIN, GE05, Intermag2004)

Commercialized since 2006 (1Mb, 2Mb, 4Mb, 8Mb, 16Mb) but not scalable. Large power consumption due to field writing.

STT (STT MRAM)

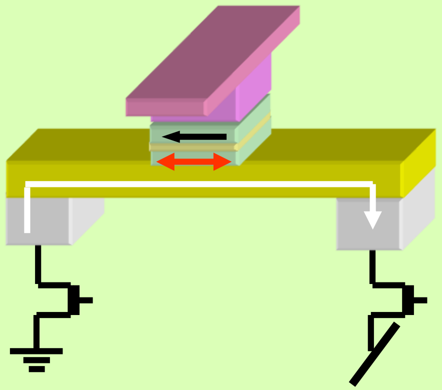


Cell size=0.0084μm²=(91nm)²
(demo IMEC, TMRC2020)
Cell size=0.036μm²=(189nm)²
(Production 1 Gbit Samsung, IEDM2019)

Commercialized since 2012. Now in production @ all major microelectronics foundries

Spin-orbit torque

(spin-Hall, Rashba)



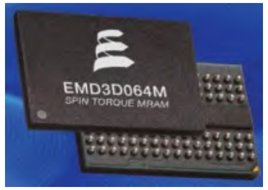
Cell size = 0.021μm²=(145nm)²
(demo IMEC, TMRC2020)

Still under R&D for fast, very endurant memory application.

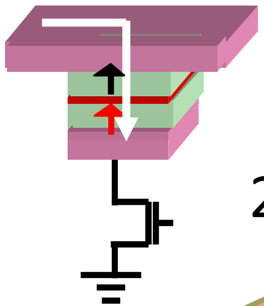
The out-of-plane magnetized MTJs offer better downsize scalability of STT-MRAM and better tradeoff between retention and writability than for in-plane magnetized MTJs

MRAM based on magnetic tunnel junctions: 23 years of R&D

spintec
SPIN IN ELECTRONICS



2018 **eMRAM foundry production**
(SAMSUNG, TSMC, GF, 2019)

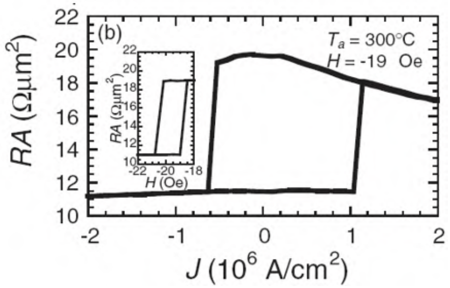


2013 SOT-MRAM

STT-MRAM 1st products
(EVERSPIN, 2012)

2010 STT switching in **pMTJ with iPMA**
(Tohoku Univ., 2010)

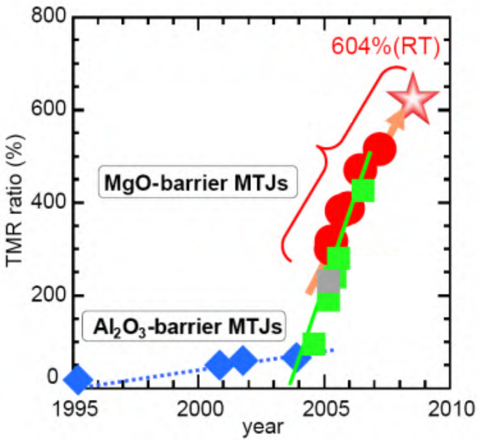
Spin orbit torque (SOT) switching *(SPINTEC, 2011)*



2006 **1st commercial MTJ-based MRAM products**
(field-written Toggle MRAM) *(Everspin, 2006)*

2004 **Giant tunnel magnetoresistance in MgO** based crystalline MTJs *(Parkin, Yuasa, 2004)*

1st **STT switching in MTJs** *(Grandis, Cornell Univ., Sony, 2004)*



2000 1st observation of STT magnetization switching in metallic pillars *(Cornell Univ., 2000)*

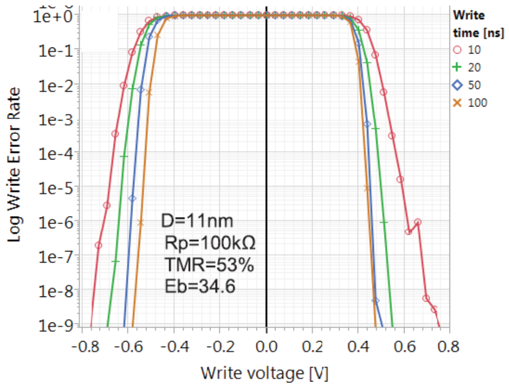
1996 Prediction of **spin transfer torque** (STT) *(Slonczewki, Berger, 1996)*

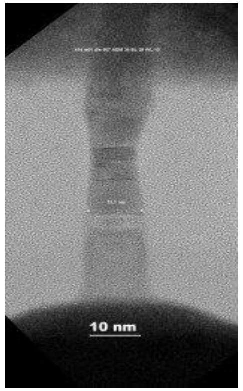
1995 Discovery of **tunnel magnetoresistance** (TMR) at RT in AlOx basd MTJ

STT-MRAM assets

- **Non-volatility**
- **Downsize scalability**
- **Write speed**
- **Write endurance**

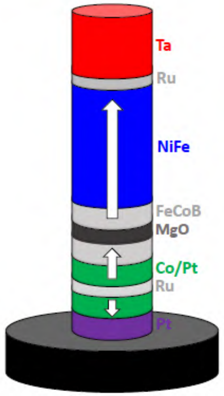
(for pulse duration >30ns)



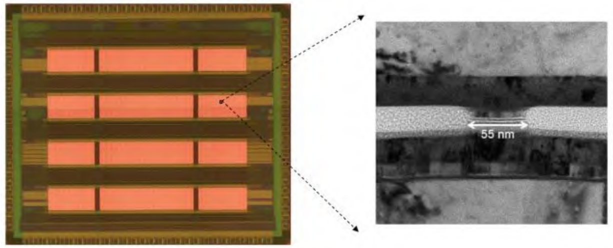


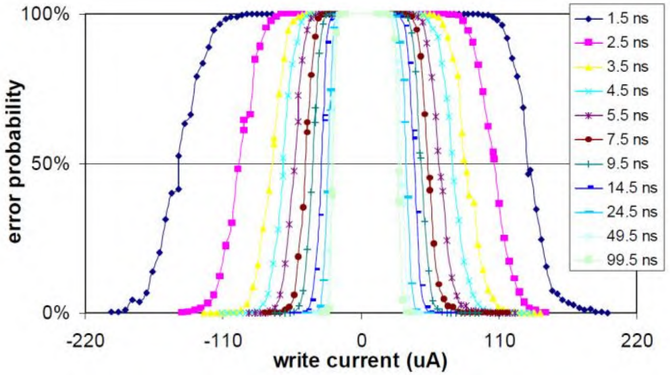
11nm STT-MRAM cell
(IBM)
Janusz et al, IEEE Mag.Lett.7, 3102604(2016)

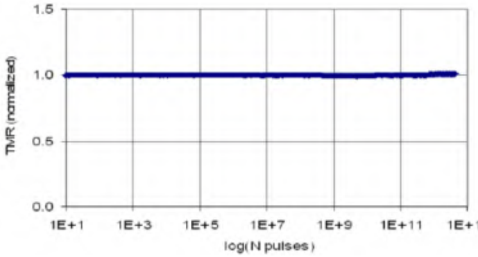
5nm PSA-STT-MRAM cell
(SPINTEC)

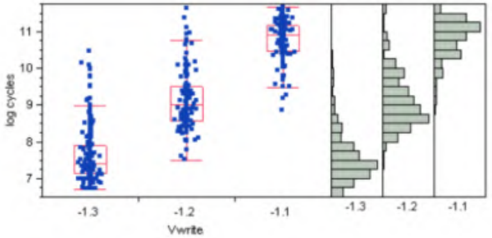


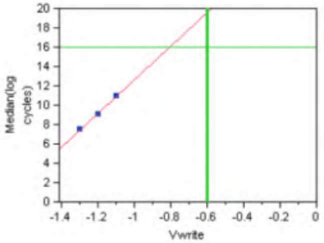
8 Mbit fully functional demo from TDK/Headway Techno now transfered to TSMC











10^{20} cycles à 0.6V

Grandis/Samsung

An increasing number of industrial actors active in the MRAM arena

EVERSPIN TECHNOLOGIES
NEC
intel
TDK
AvalancheTechnology
tsmc
GLOBAL FOUNDRIES
RENESAS
Everywhere you imagine.
IBM
SPIN MEMORY
Spin-ION TECHNOLOGIES
SONY
Micron
CROCUS Technology
Blossoming future
SAMSUNG
TOWERJazz
TEL
QUALCOMM
KEYSIGHT TECHNOLOGIES
TOSHIBA
Hprobe
SINGULUS
APPLIED MATERIALS
Canon CANON ANELVA CORPORATION
hynix

STT-MRAM in volume production

- 2012 : 64Mbit
- 2018 : 256Mbit
- 2019: 1Gbit

In collaboration with

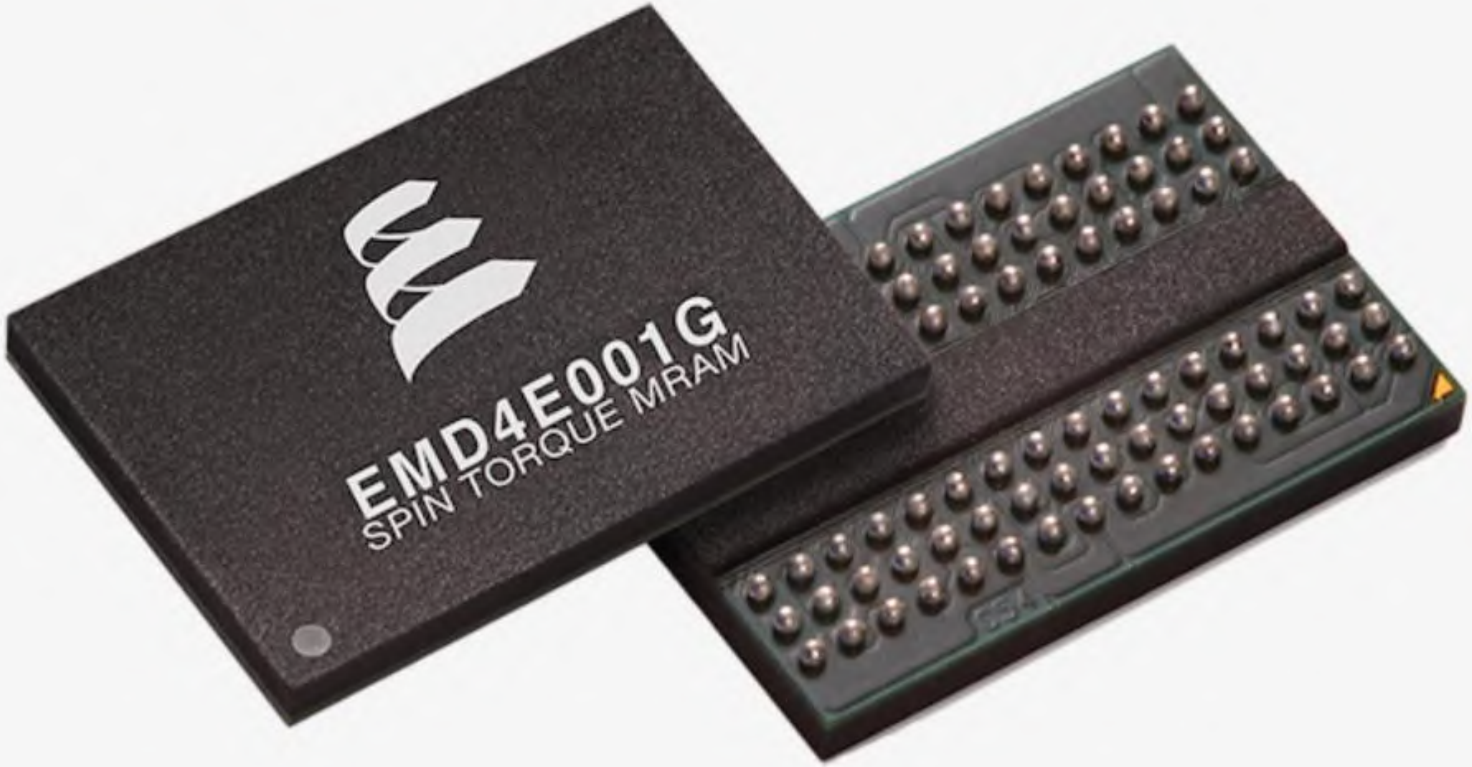
GLOBAL FOUNDRIES

anandtech.com/show/14580/everspin-begins-production-of-1gb-sttmram

Everspin Begins Production of 1Gb STT-MRAM

by Billy Tallis on June 24, 2019 4:30 PM EST

Posted in SSDs Storage GlobalFoundries Everspin MRAM

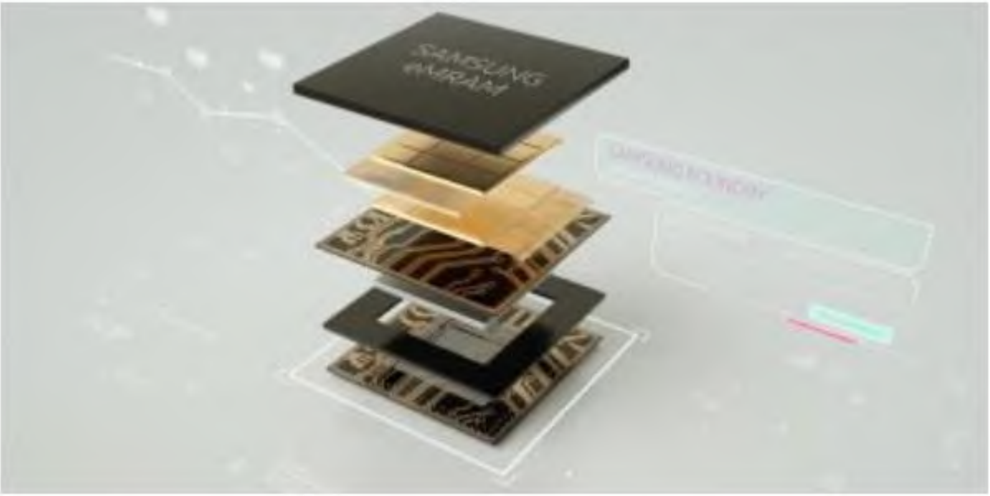


STT-MRAM in volume production

mram-info.com/samsung-starts-shipping-28nm-embedded-mram-memory

Samsung starts shipping 28nm embedded MRAM memory

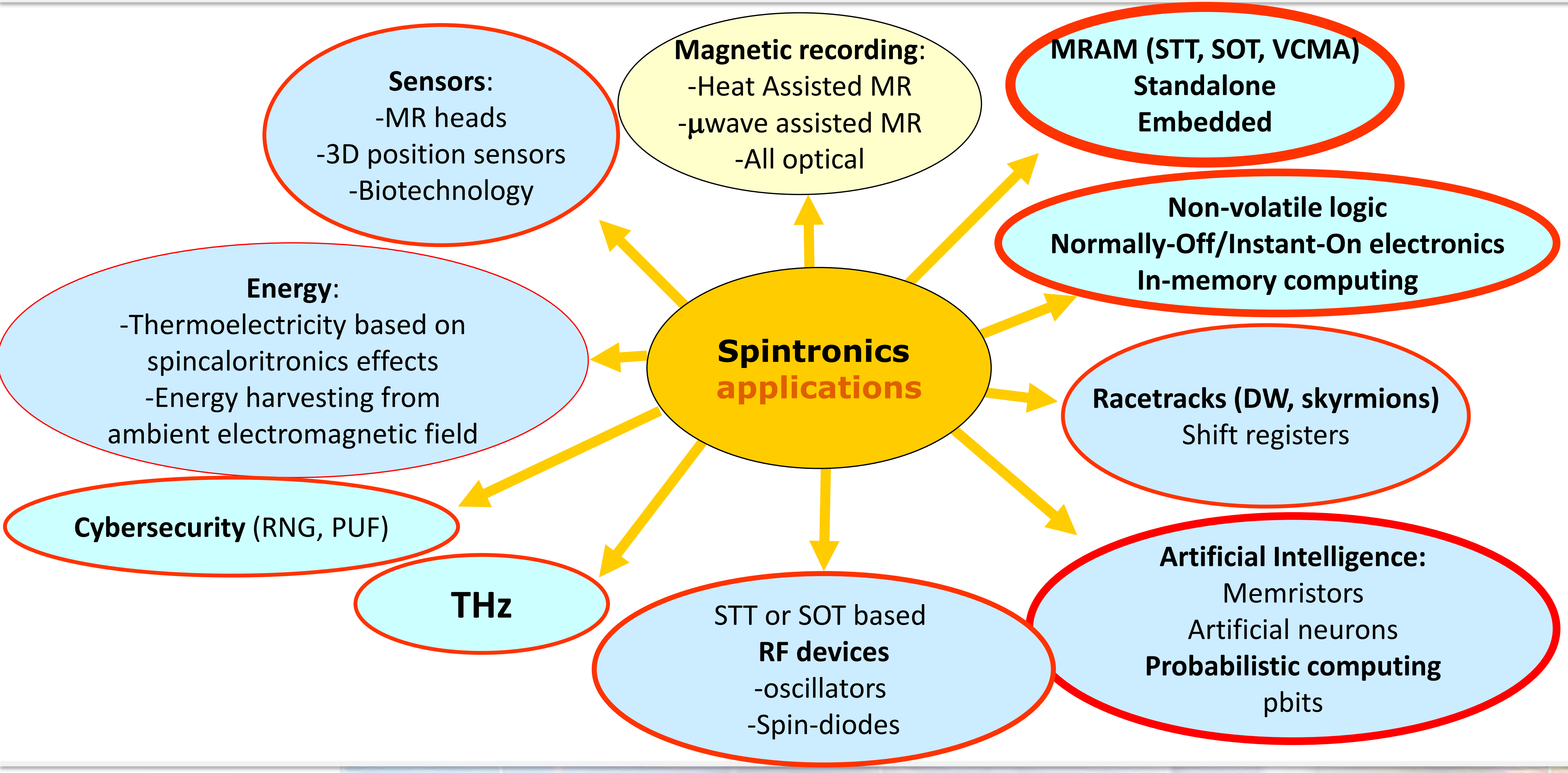
Samsung announced that it has started to mass produce its first embedded MRAM, made using the company's 28nm FD-SOI process. Samsung says that its eMRAM memory module offers higher performance and endurance when compared to eFlash, and can be integrated into existing chips.



Source: Anand Tech
Tags: Samsung Embedded MRAM MRAM production
Posted: Mar 08, 2019 by Ron Mertens

Samsung details that its eMRAM is 1,000 times faster than its eFlash memory, and it does not require an erase cycle before writing data (unlike Flash memory). The voltage used is also lower - and in total eMRAM consumes 1/400 the energy compared to eFlash for the writing process. Samsung's MRAM capacity, though, is lower than its 3D Xpoint, DRAM and NAND flash.

Spintronics broadening spectrum of interest



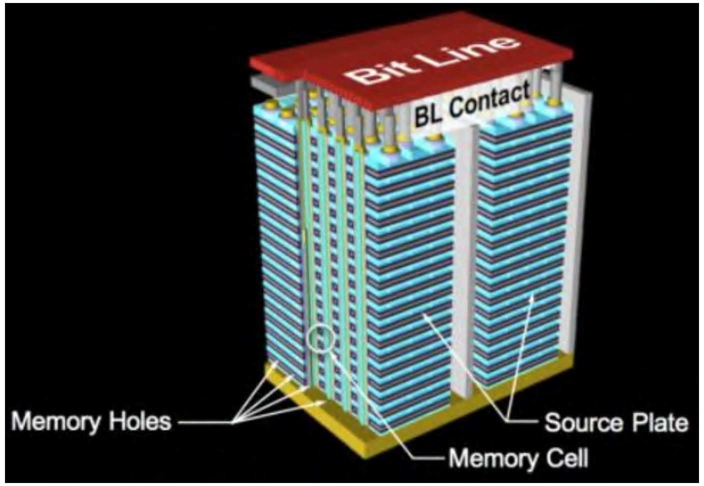
Looking into the future…

Rather than trying to guess what will be the main future topics of research…

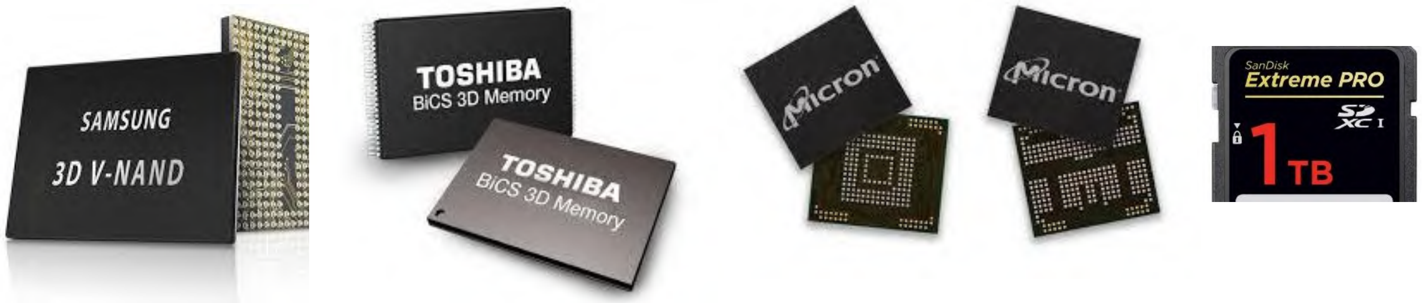
… a few messages on the methodology :

- Importance of benchmarking with other technologies
- Keep in mind industrial and economic constrains
- Care in moving up on the TRL scale
- As a community, keep a diversity of basic research topics
- Importance of transversality (multidisciplinarity), of opening-up to other fields and communities

3D NAND Flash



>Tbit NAND FLASH products



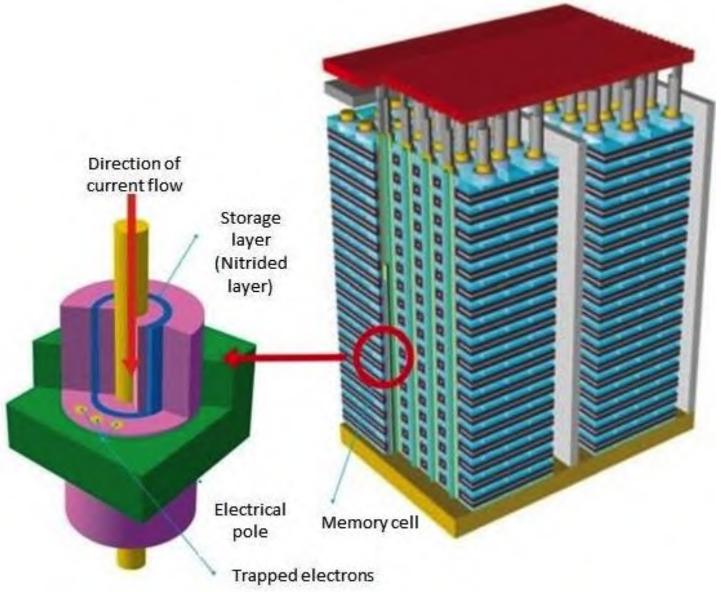
3 bit per cell + multiple stacked layers

Year	2016-2017		2018-2019		2020-2021	2022-2023
Generation 3D	L48	L64	L96	L128	L256	512
Die size (3b/cell)	256-512 Gb	512Gb – 1Tb	512Gb-2Tb	1-3Tb	2-6 Tb	4-12Tb
Hole CD	65-100	65-100	65-100	65-100	65-100	65-100
Slit pitch (# holes)	4	4	4-8	8	8	8
Vertical pitch	50-70nm	40-60	40-60	40-50	40-50	40-50
BL CD	20	20	20 - 40	~40	~40	~40
Multiple stacks	No	No	No	No	Yes (2-4)	Yes (4-8)

Magnetic hard disk drives (HDD)

10x advantage in cost/Gbit but gradually decreasing

3D NAND Solid State Drives



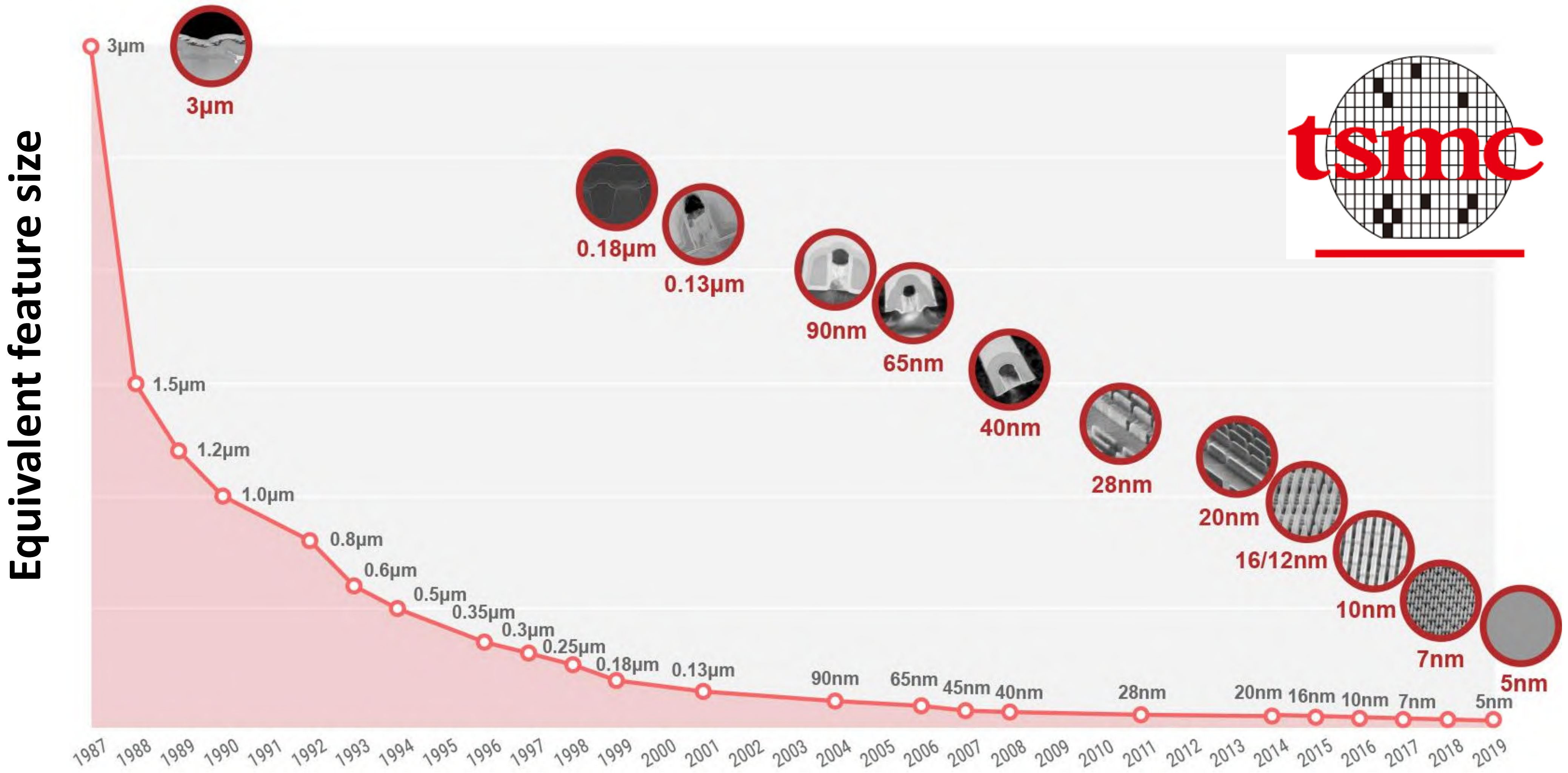
256 layers of memory cells, 3bit per cells.

In-plane pitch between cells ~150nm

Effective 2D pitch =150nm/sqrt(3x256)= 5.4nm !

Any storage concept that we may think about (e.g. DW or skyrmions based racetracks) should be benchmarked not to HDD but to 3D NAND FLASH. **Need to identify a « killer application ».**

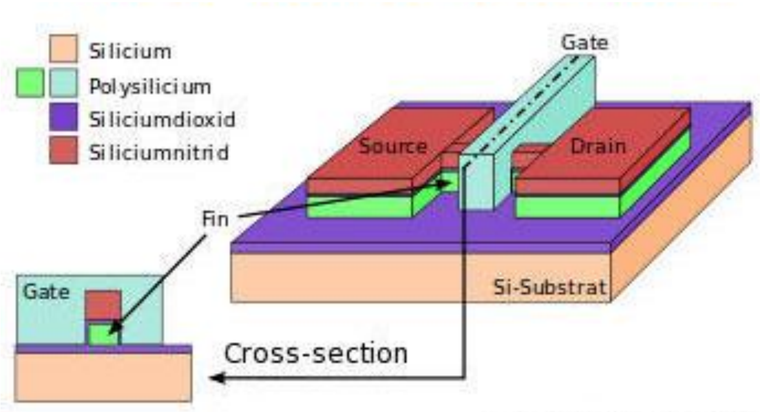
Steady evolution in microelectronics towards smaller footprint on wafer



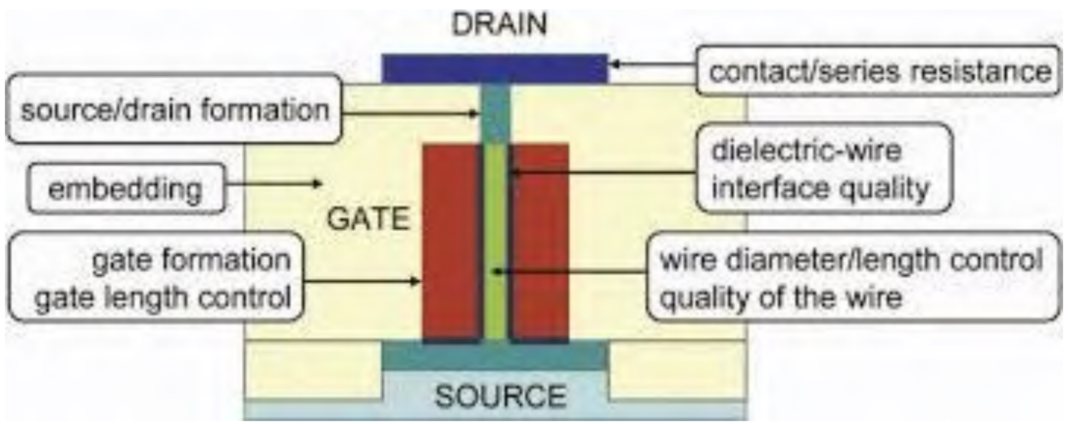
Smaller footprint means more devices per wafer and therefore reduced costs

Smaller footprint not only means smaller feature size but also going vertical, stacking several functionalities on top of each other , 3D wafer bonding

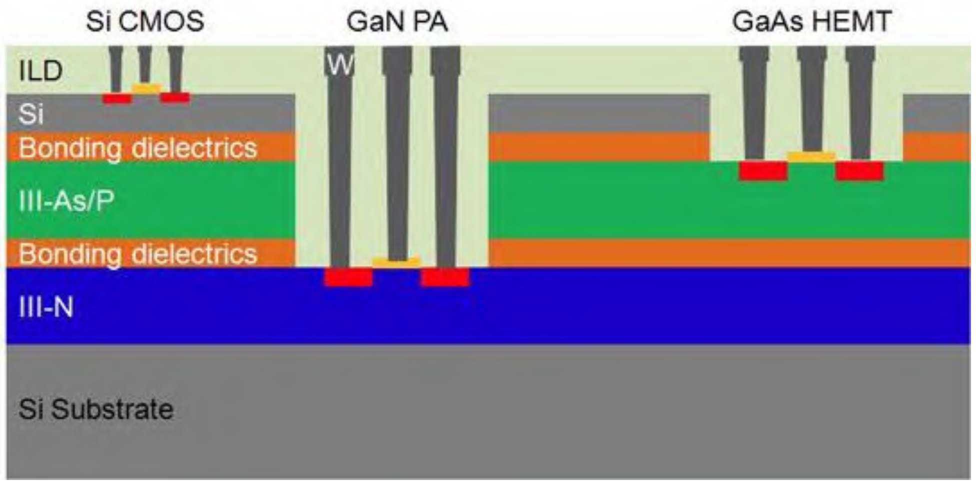
planar FinFET



Vertical FET



Wafer bonding



CMOS components

High frequency devices (GaAs)

Power devices (GaN)

Si substrate

- When possible, spintronics devices should extend vertically rather than horizontally
- e.g. Spintronics lateral devices. Can we make them vertical (ALD, deposition on sidewalls…)?
- Racetracks, can we make them vertical and reliable ? What about skyrmions racetracks? How to make them vertical ? If at the end we make them work, is there a « killer application » for them?

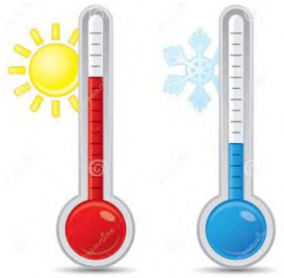
A key requirement for microelectronics applications : Reliability

- **Error rates (write, read, standby) must remain below device specifications**

- **Device must operate on a wide range of temperatures :**

  -Consumer electronics : 0°C – 85°C

  -Automotive : -40°C – 130°C



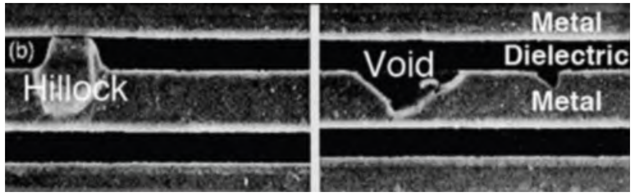
- **Must not fail under exposure to magnetic field**

  (still missing norms in this area).

  Magnetic shielding unpractical in numerous applications

- **No degradation in time over the device lifetime**

e.g. defects formation due to electromigration



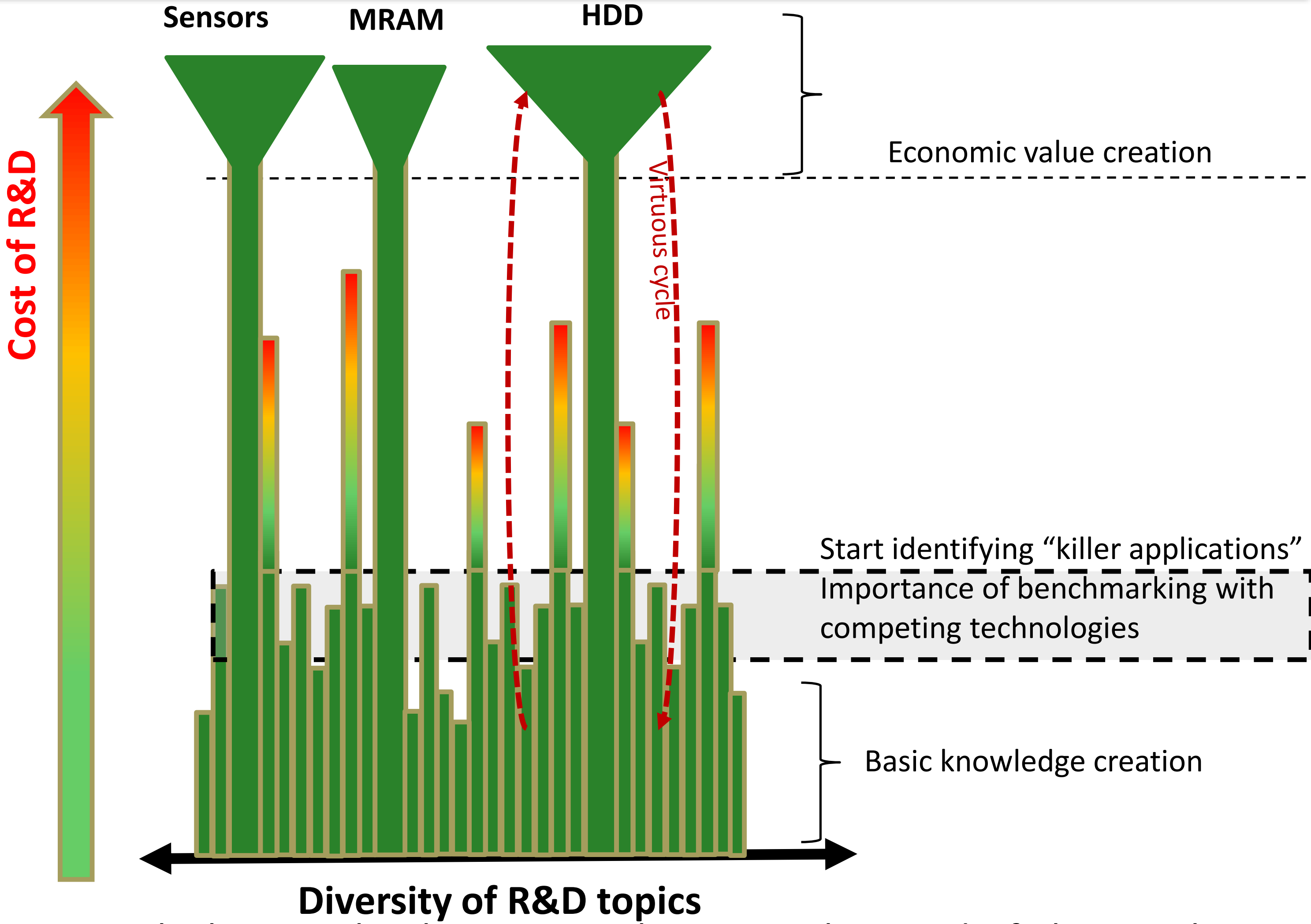
Samandari-Rad et al, IEEE Access, 2, 577 (2014)

Care in going up on the TRL scale / TRL and Cost of R&D

spintec SPIN IN ELECTRONICS

TECHNOLOGY READINESS LEVEL (TRL)

DEPLOYMENT	9	ACTUAL SYSTEM PROVEN IN OERATIONAL ENVIRONMENT
DEPLOYMENT	8	SYSTEM COMPLETE AND QUALIFIED
DEPLOYMENT	7	SYSTEM PROTOTYPE DEMONSTRATION IN OPERATIONAL ENVIRONMENT
DEVELOPMENT	6	TECHNOLOGY DEMONSTRATED IN RELEVANT ENVIRONMENT
DEVELOPMENT	5	TECHNOLOGY VALIDATED IN RELEVANT ENVIRONMENT
DEVELOPMENT	4	TECHNOLOGY VALIDATED IN LAB
RESEARCH	3	EXPERIMENTAL PROOF OF CONCEPT
RESEARCH	2	TECHNOLOGY CONCEPT FORMULATED
RESEARCH	1	BASIC PRINCIPLES OBSERVED



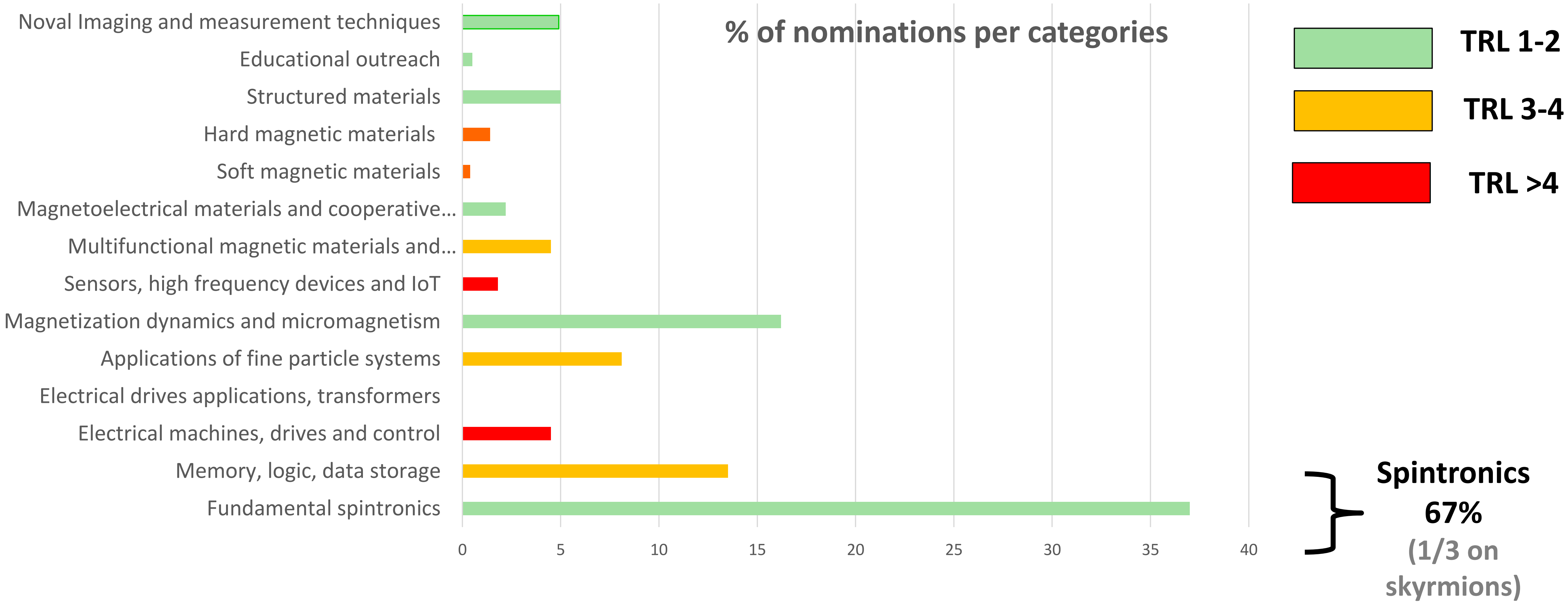
Examples : **Magnonics, race-tracks**... Lot of R&D effort to push these technology up on the TRL scale. Need of clear evaluation from system point of view and economic perspective considering the competing technologies.

MRAM : Insufficient academic support to help industry to broaden the range of applications of MRAM technology.

As a community, keep a diversity of R&D topics …

INTERMAG21

Nominations of invited speakers (Total 222)



- Need to keep large diversity in our basic research topics since we do not know ahead of time which ones will really lead to applications.

As a community, keep a balance between low and high TRL R&D…

INTERMAG21

TECHNOLOGY READINESS LEVEL (TRL)

DEPLOYMENT	9	ACTUAL SYSTEM PROVEN IN OERATIONAL ENVIRONMENT	13%
	8	SYSTEM COMPLETE AND QUALIFIED	
	7	SYSTEM PROTOTYPE DEMONSTRATION IN OPERATIONAL ENVIRONMENT	
DEVELOPMENT	6	TECHNOLOGY DEMONSTRATED IN RELEVANT ENVIRONMENT	
	5	TECHNOLOGY VALIDATED IN RELEVANT ENVIRONMENT	
	4	TECHNOLOGY VALIDATED IN LAB	22%
RESEARCH	3	EXPERIMENTAL PROOF OF CONCEPT	
	2	TECHNOLOGY CONCEPT FORMULATED	65%
	1	BASIC PRINCIPLES OBSERVED	

- Worldwide R&D effort in magnetism significantly **more weighted towards basic research than 10 years ago.**
- **Importance to keep a balance between low and high TRL levels since *in-fine*, the funding of our R&D** more or less **relates to the economic value that it generates.**

Importance of transversality

- Nowadays, **most of innovation comes from mixing expertise from different fields**, e.g. physics/chemistry, physics/biology, magnetism/microelectronics, spintronics/photonics… etc.

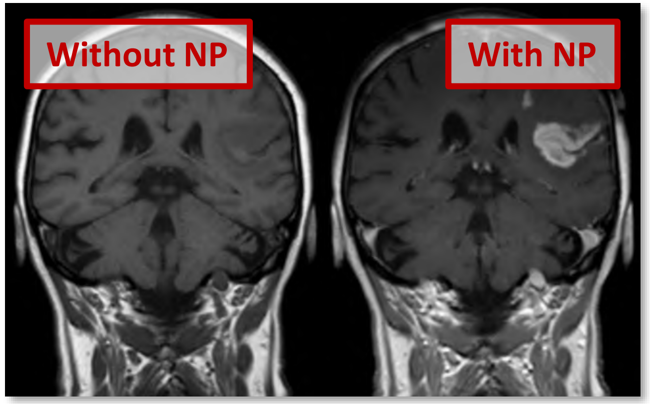
- More and more interdisciplinary institutes and R&D centers in the world.

- **Importance to open-up to other fields, to other R&D communities**, attend wide-audience seminar or read wide-readership articles out of our field of research, widen our scientific culture, keep our critical sense.

- **Example of transversality at the magnetism/biology interface**

spintec
SPIN IN ELECTRONICS

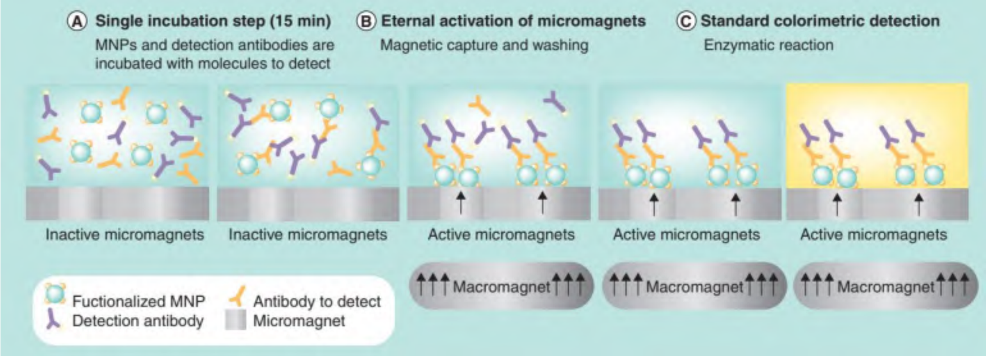
Contrast agent for magnetic resonance imaging



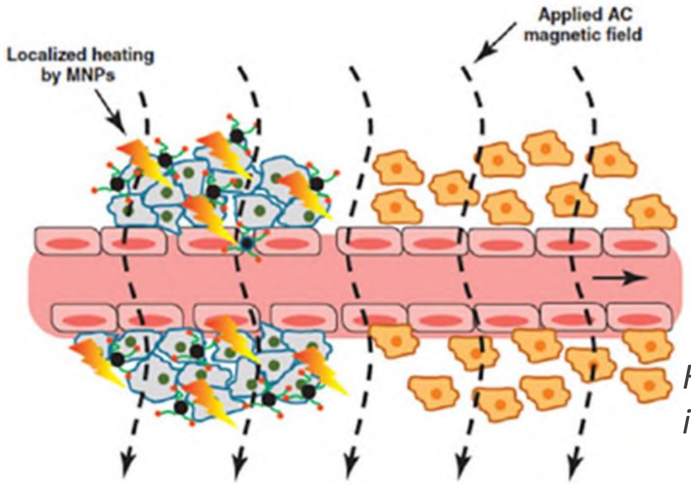
SPIONS: Superparamagnetic Iron Oxide particles – diameter: 5nm-25nm
Considered as biocompatible- Accepted by drug regulatory agencies

Microfluidic Device for Diagnosis / Cell Sorting

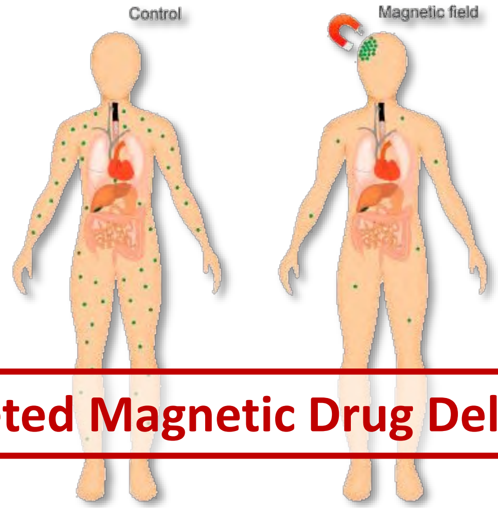
MagIA diagnostics



Magnetic Hyperthermia for Cancer Treatment



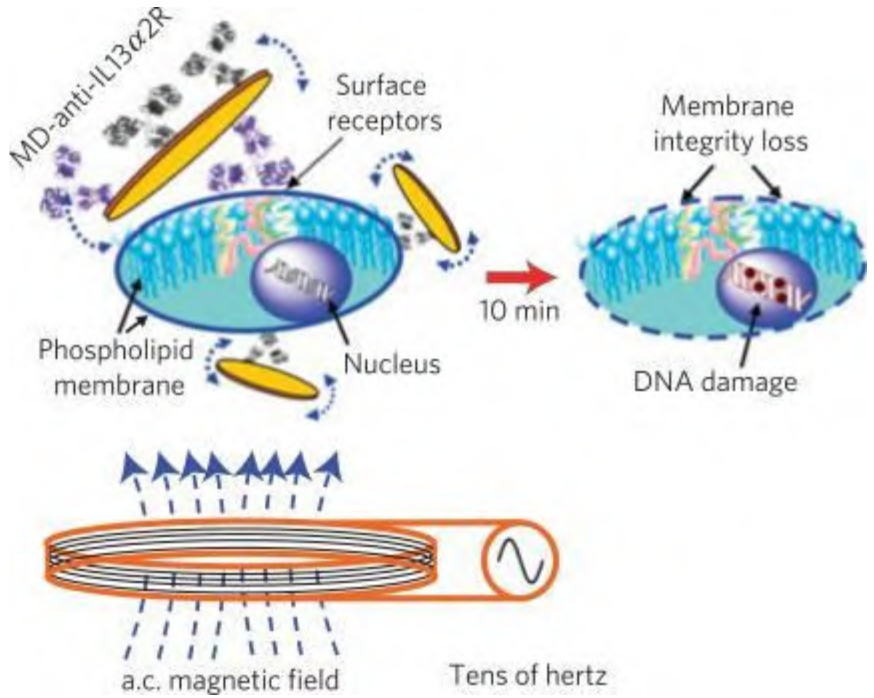
Heating at 44°C induces cell death



Targeted Magnetic Drug Delivery

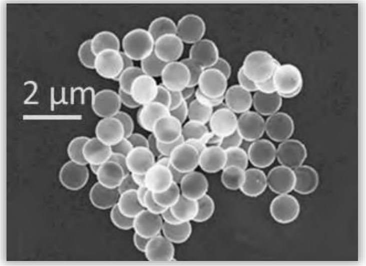
Magnetomechanical cancer cells destruction

- Destruction of cancer cells is observed following the vibration of magnetic particles in close contact



- **Micron-size particles**
- Rotating or AC magnetic field …
  - … *with low intensity (~0.1 T)*
  - … *with low frequency (≤ 20 Hz)*

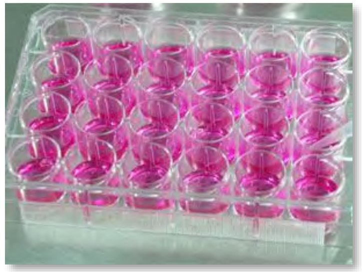
Renal carcinoma cells



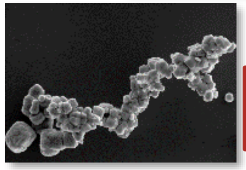
- *Purely mechanical effect*
- *No heating / no drug delivered…*

D.-H. Kim et al., Nature Mater. 9, 165 (2010); S. Leulmi *et al.*, Nanoscale 7, 15904 (2015).

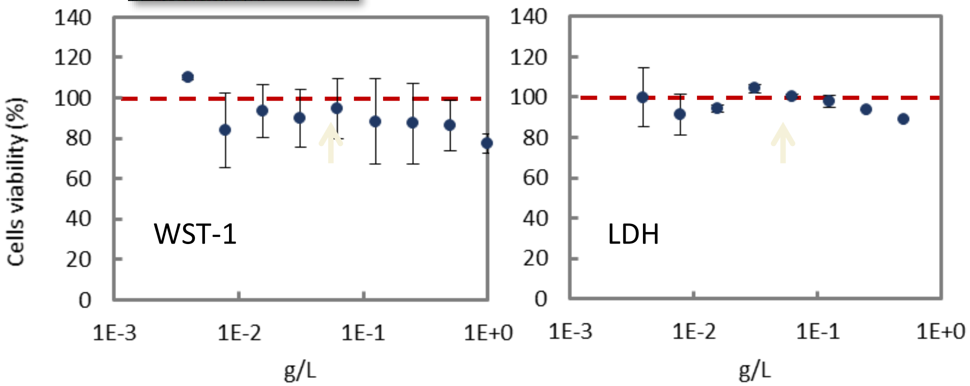
Non-toxicity of the magnetic particles

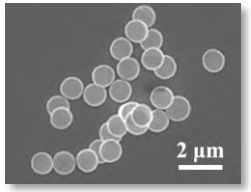


- Glioblastoma cells viability after 24h incubation with particles
- WST-1 measures cells metabolic activity
- LDH measures membrane permeability

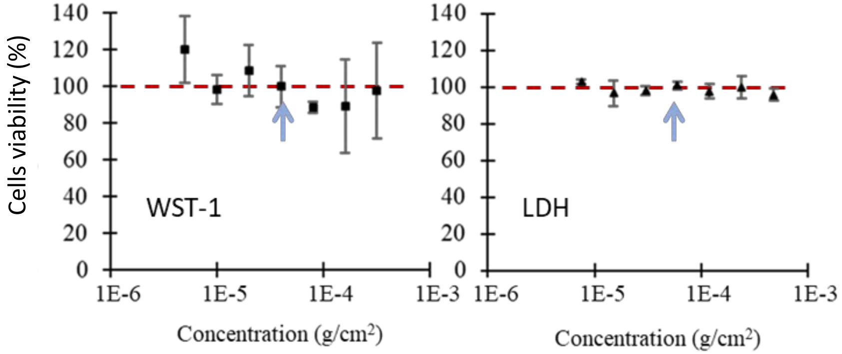


Magnetite

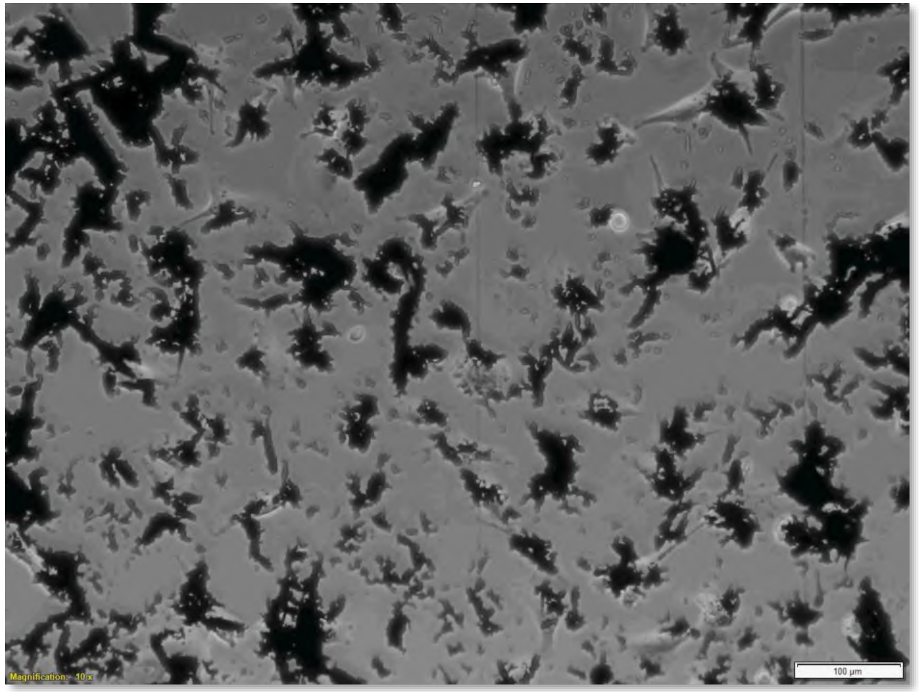




Vortex



- **No toxicity up to very high concentrations**
- **Cell division stopped for 24h**
- **Doses used in our experiments 0.05 - 0.1g/L**
- **Similar results with both types of particles**



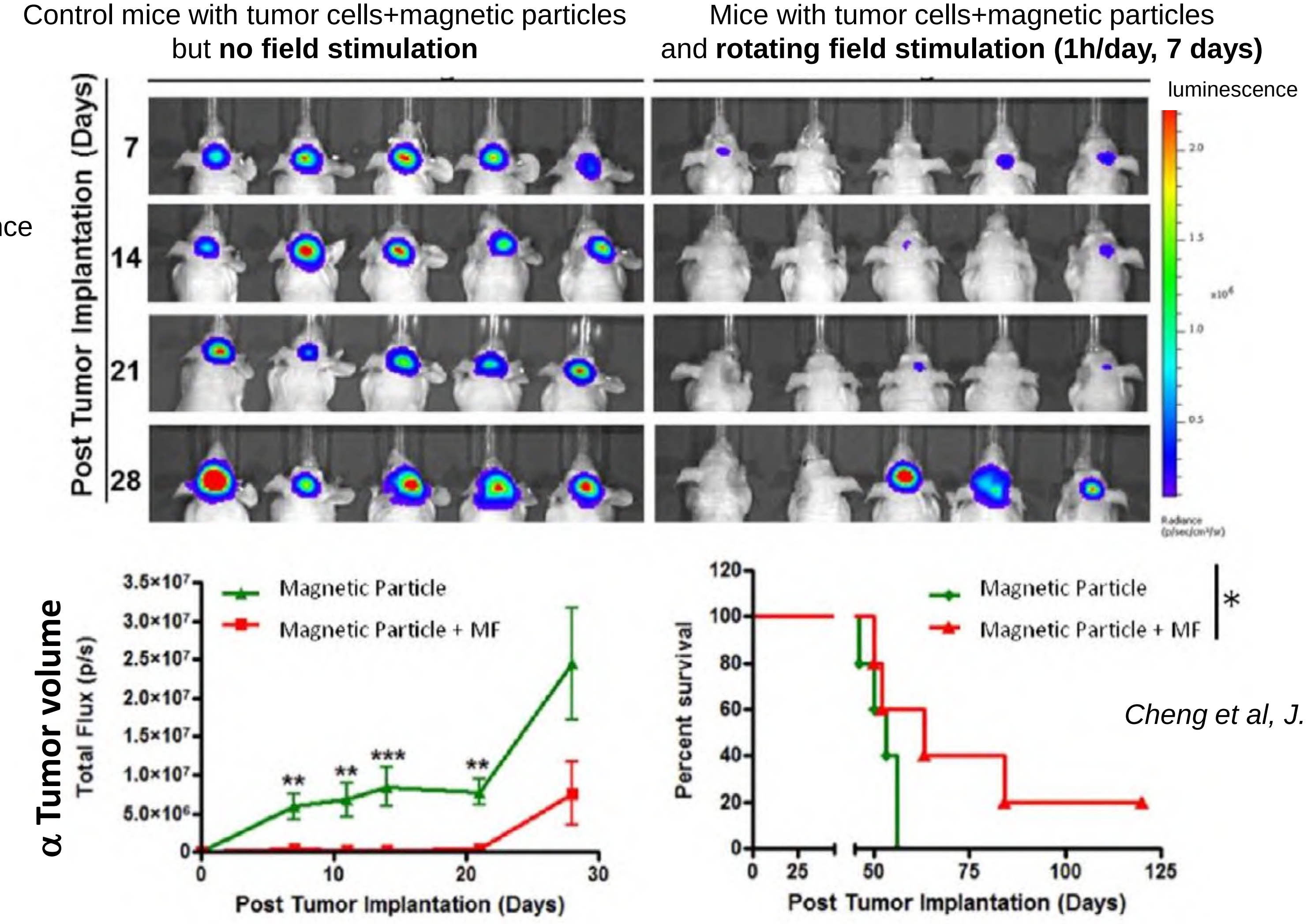
U87 Glioblastoma cells
Evolution over 48h

The cancer cells grab all magnetic particles !

Magnetomechanical cancer cells destruction – *in-vivo* study (chicago Univ.)

Magnetic particles injected in the mice brain at the same time as cancer cells

Bioluminescence imaging of glioblastoma tumor



Cheng et al, J. Controlled Release 223 (2016) 75

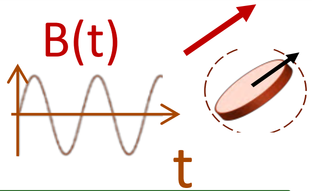
Significant increase in survival rate thanks to the magnetic treatment

Stimulation of insulin secretion from pancreatic cells

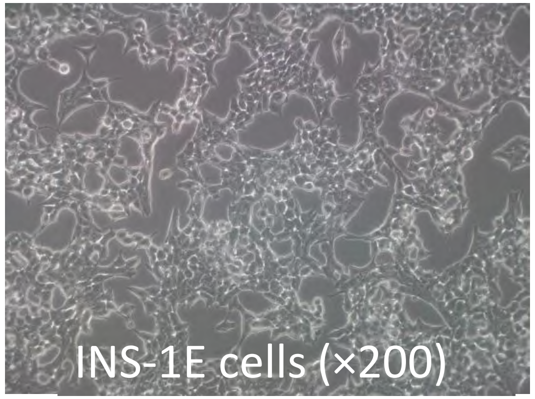
SyMMES — Systèmes moléculaires et nanomatériaux pour l'énergie et la santé

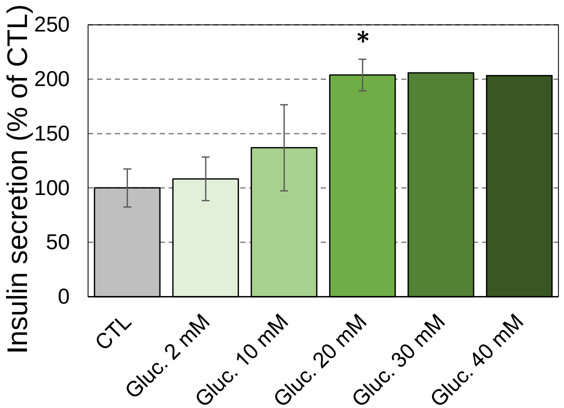
spintec — Spin in electronics

- Characterization of insulin secretion in β-islet pancreatic cells (INS-1E)
- → Cells mechanically stimulated by vibrating magnetic particles



Control: INS-1E cells without alternating magnetic field



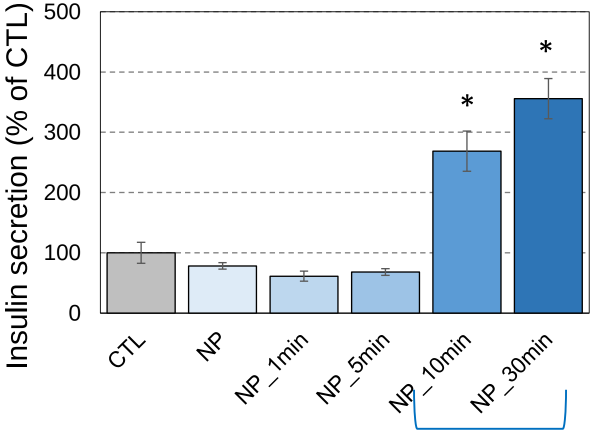


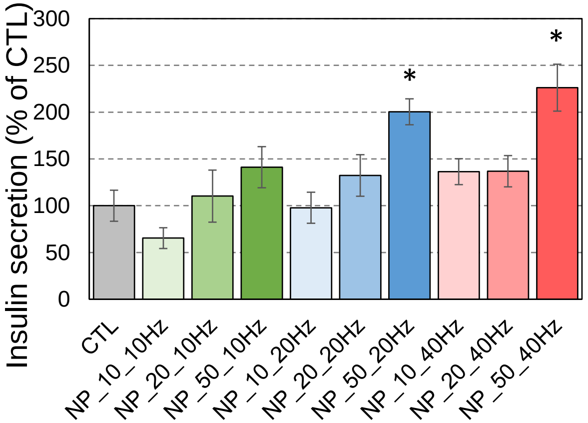
Reactivity of INS-1E cells to glucose stimulation :

insulin secretion via exposure to increasing concentration of **glucose** for 30 min.

→ Increase in insulin secretion vs glucose concentration as expected

INS1 cells on magnetic membrane + alternating field





Insulin secretion

vs B(t) duration,

For 1,5,10, or 30 min,

for 50 µg/mL of NPs, rotating B(t) of 10 Hz.

vs Mps concentration and vs B frequency,

Mps: 10; 20; or 50 µg/mL

B(t) at 10; 20; or 40 Hz

Duration 10 min.

MP + B(t) → insulin secretion is enhanced

May open innovative treatment of Type 2 Diabetes

S.Ponomareva et al, Nanoscale, 14, 13274 (2022)

CONCLUSION

- **Magnetism is present in numerous applications** that we use in our everyday life.
- Economic weight represented by **energy production and motors** far exceeds that of ICT applications.
- In ICT applications, **HDD and sensors have been the first major applications of spintronics.**
- MRAM technology now adopted by microelectronic industry but **need of help from academia to broaden the range of applications** (beyond eFLASH, to SRAM, non-volatile electronics, HPC, cryoelectronics, neuromorphic…).
- In our **R&D orientations**, need to pay attention to **benchmarking** with relevant competing technologies, **reduced footprint** on wafers (directly translate into costs), **reliability**
- As a community, **keep a wide diversity of basic research topics and a good balance between low and high TRL levels.**
- **Open-up to other fields and other communities.**
- **Importance of transversality** e.g magnetism/biology

Thank you !