TECHNISCHE UNIVERSITÄT
CHEMNITZ

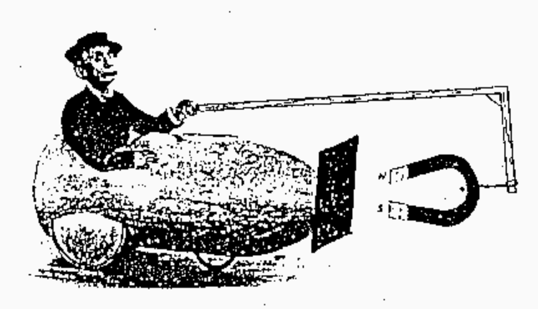
Gastvorlesung „Magnetischen Funktionsmaterialien“ im Rahmen der Vorlesung

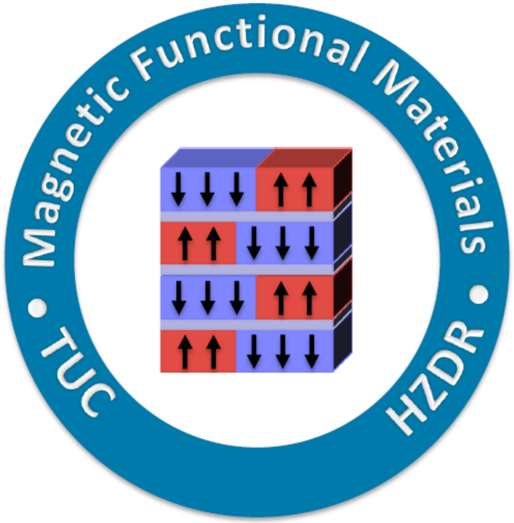
„Komplexe Materialien“ (Prof. Deibel)

Prof. Dr. Olav Hellwig

7.5.2020

Magnetische Funktionsmaterialien
SS 2020





Inhalt

Ferromagnetische (Funktionale) Materialien

- Einordung und Einleitung
- Energien und Energiedichten einer ferromagnetischen Probe
  - Austauschwechselwirkung
  - Streufeld- oder Demagnetisierungsenergie, Formanisotropie
  - Anisotropie (außer Formanisotropie = Demagnetisierungsenergiedichte)
  - Zeemann Energie, äußeres Feld
- Wechselseitige Konkurrenz verschiedener magnetischer Energieterme
- Hysterese-Effekte, Stoner-Wohlfarth Modell, Basis für binäre magn. Datenspeicher
- **Magnetische Funktionsmaterialien zur Datenspeicherung**
  - **Entwicklung der Festplatte: Von magnetischen Mikrosystemen zu Nanosystemen**
  - **GMR (Riesenmagnetwiderstand) und TMR Effekte für empfindlichere Leseköpfe**
  - **Zukünftige Festplattentechnologien**
  - **Neue Effekte in der Nanowelt: Spin tranfer torque in Nanokontakten**
  - **Separation von Ladungs und Spinströmen: Spin orbit torque in Dünnschichtsystemen**
  - **Anwendungen im Magnetic Random Access Memory (MRAM)**
  - **Die Spinwelle als Informationsträger (HZDR-movie)**

Data processing and data storage in the old days …

FBI- data storage facility 1942

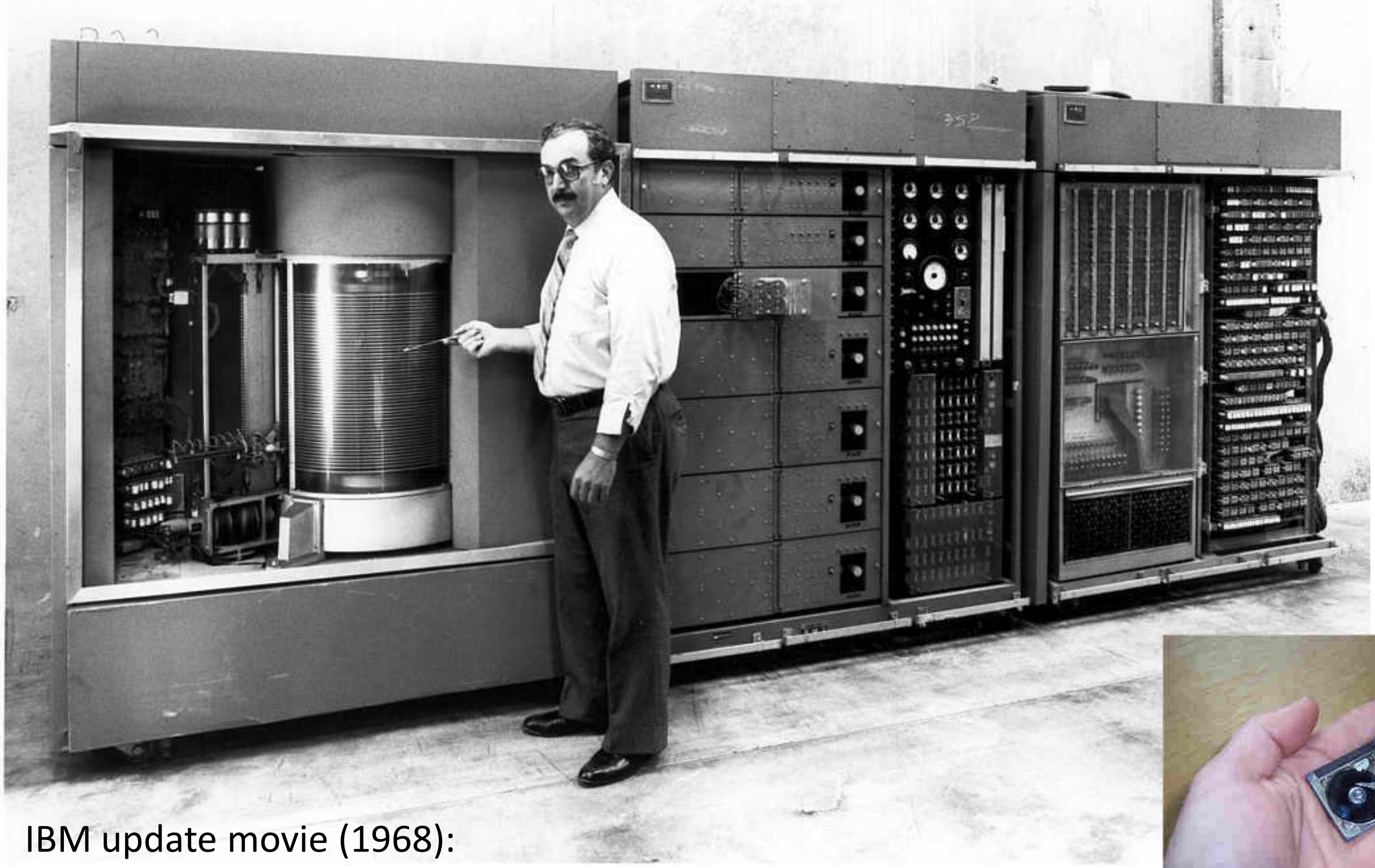
FBI

Data processing and data storage in the old days …

Data storage back then: FBI facility from World War II, Source: Google LIFE image archive.
By 1942 the FBI was adding 400,000 file cards a month to its archives, and were receiving 110,000 requests for "name checks" per month. By 1944 the agency contained some 23 million card records, as well as 10 million fingerprint records.

Largest and smalles HDD ever built …

IBM RAMAC movie (1956): https://www.youtube.com/watch?v=6coKh7vtpsY



IBM update movie (1968):

https://www.youtube.com/watch?v=PQwCMDRajJo

History of the Hard Disk Drive and related technologies

First Magnetic Recording System
(V. Poulsen) 1898

Wire recording

magnetic tape

Video magnetic tape

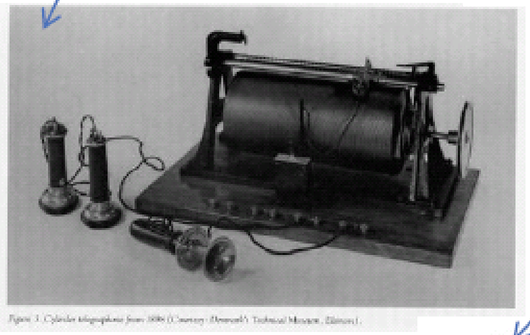
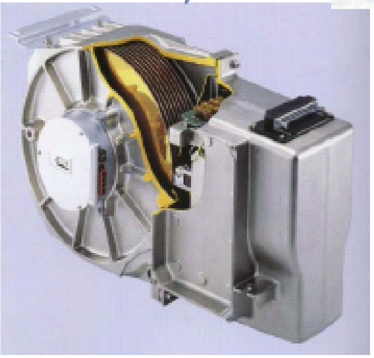


Figure 1. Cylinder telegraphone from 1898 (Courtesy Denmark's Technical Museum, Elsinore).

Hard Disk Drive
IBM, 1956

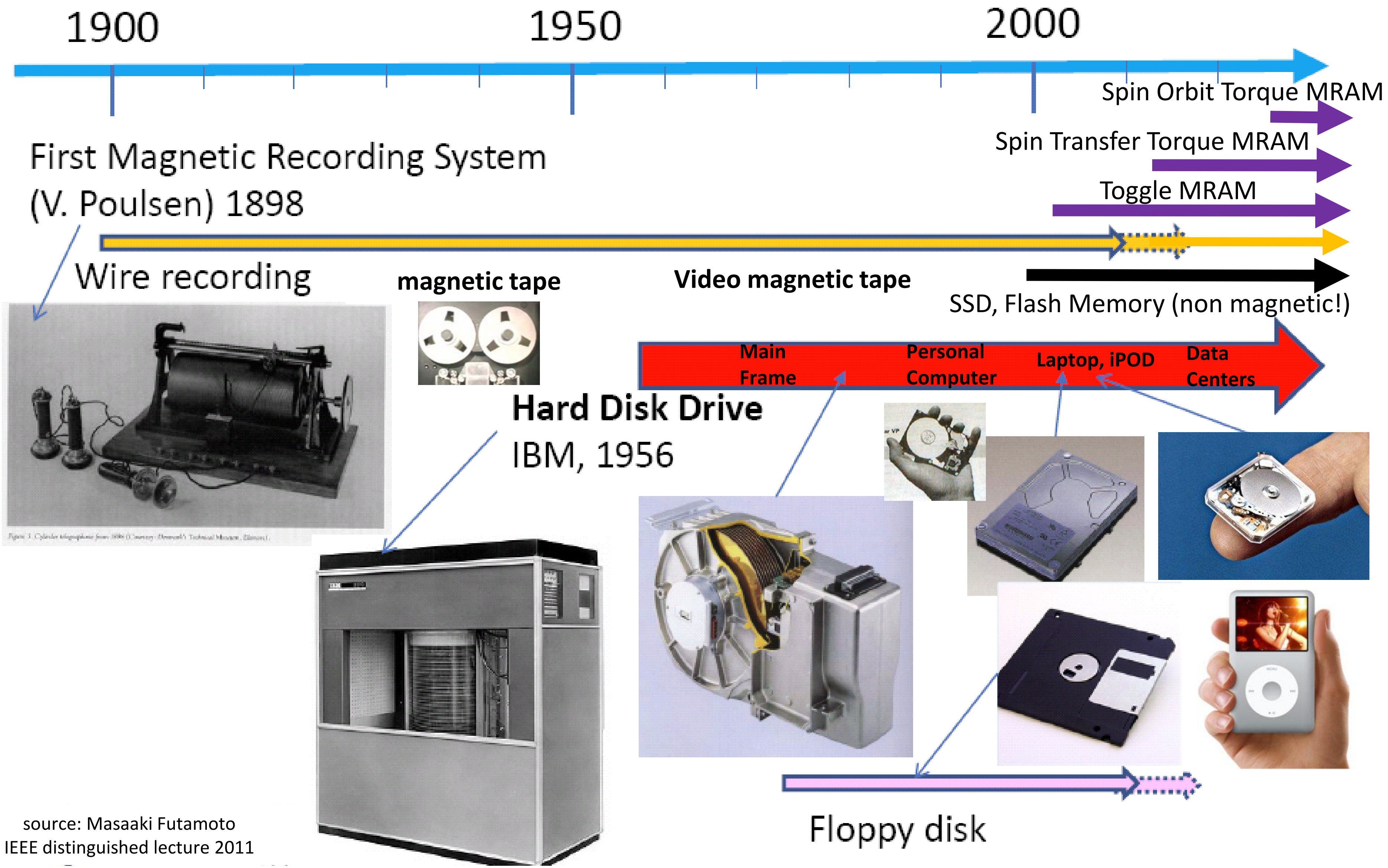


Floppy disk

source: Masaaki Futamoto
IEEE distinguished lecture 2011

Add new technologies

History of the Hard Disk Drive and related technologies



1900
1950
2000

Spin Orbit Torque MRAM

Spin Transfer Torque MRAM

Toggle MRAM

First Magnetic Recording System
(V. Poulsen) 1898

Wire recording

magnetic tape

Video magnetic tape

SSD, Flash Memory (non magnetic!)

Main Frame

Personal Computer

Laptop, iPOD

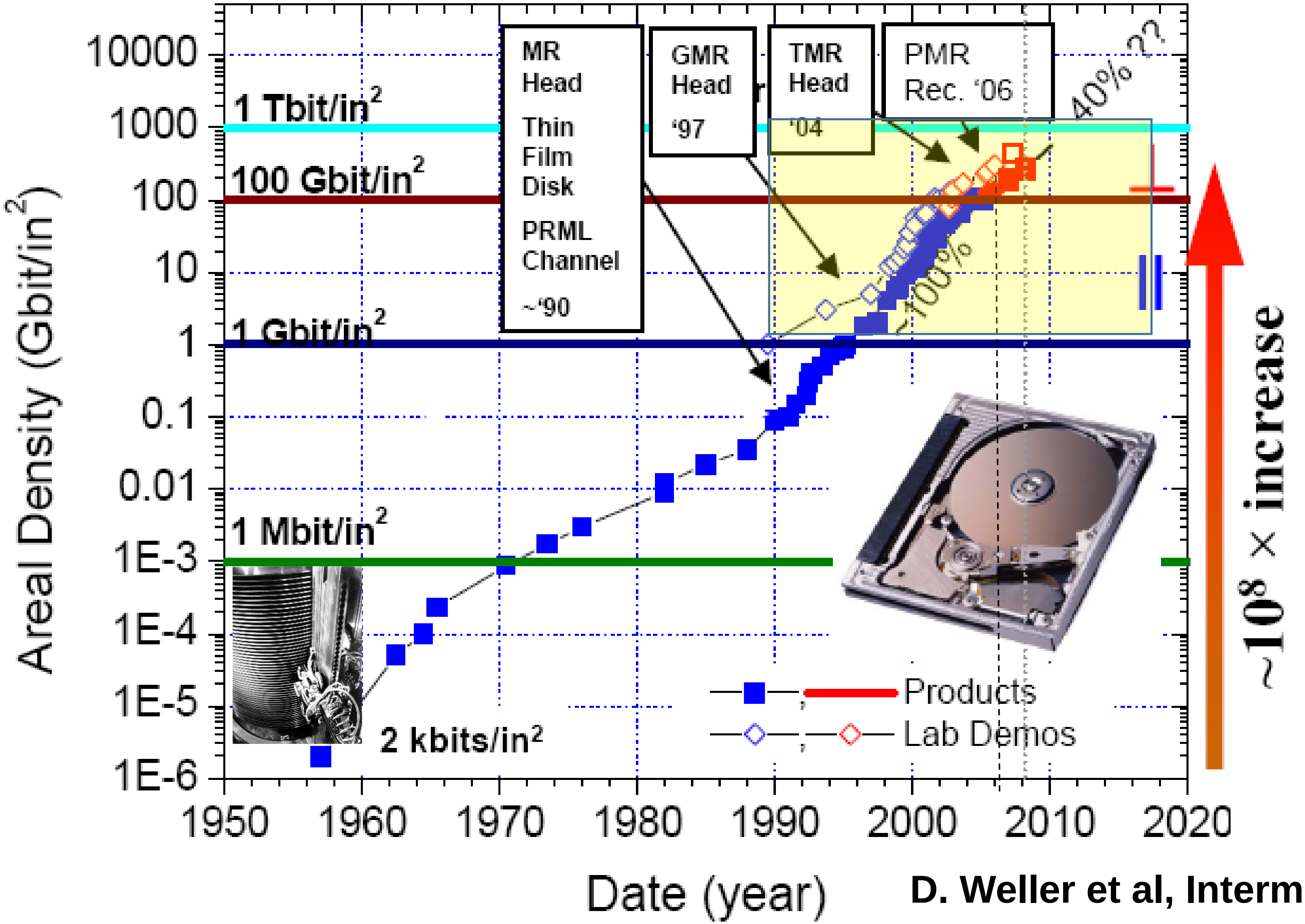
Data Centers

Hard Disk Drive
IBM, 1956

Floppy disk

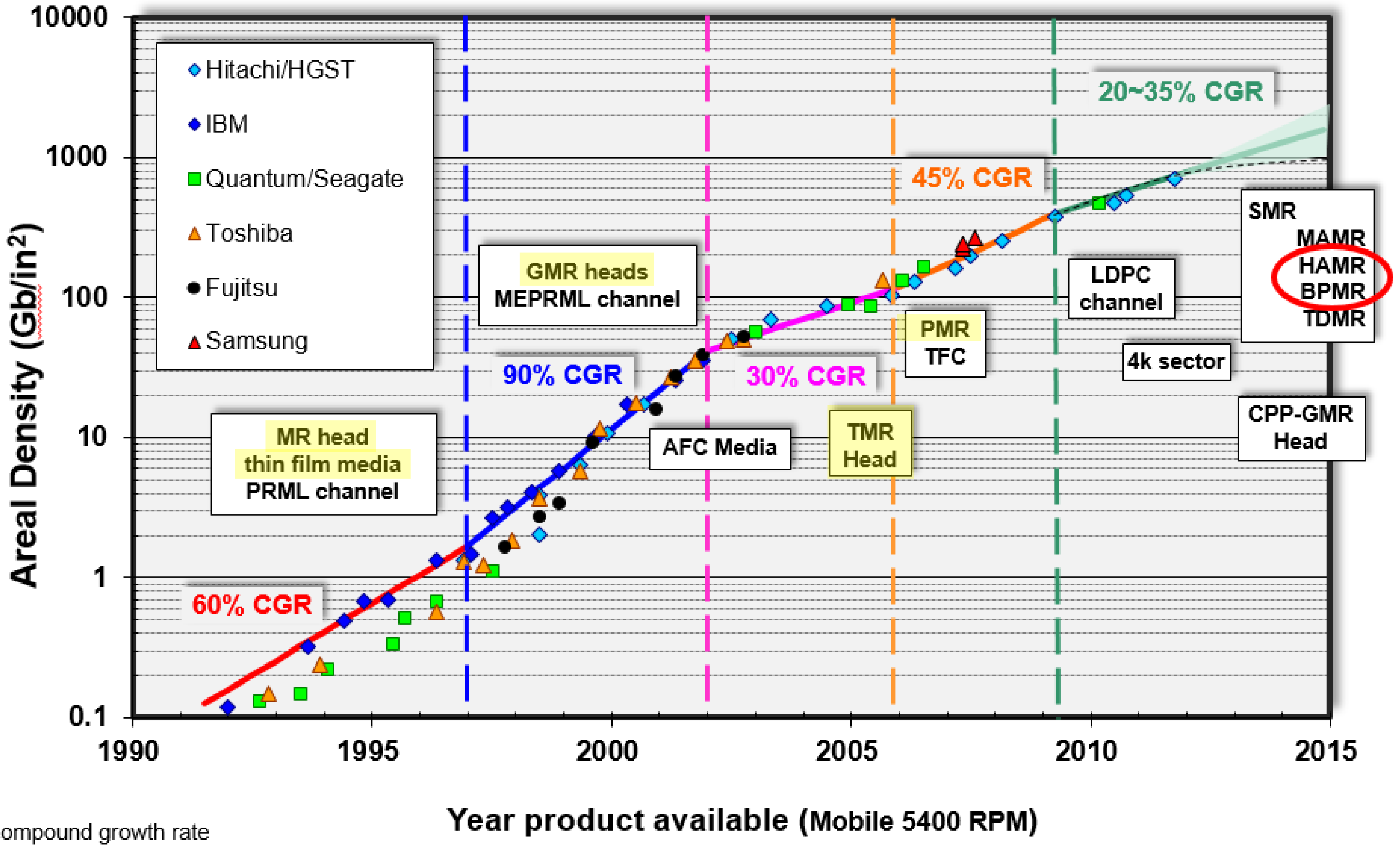
source: Masaaki Futamoto
IEEE distinguished lecture 2011

HDD areal density progress



D. Weller et al, Intermag 2008

Magnetic recording density development

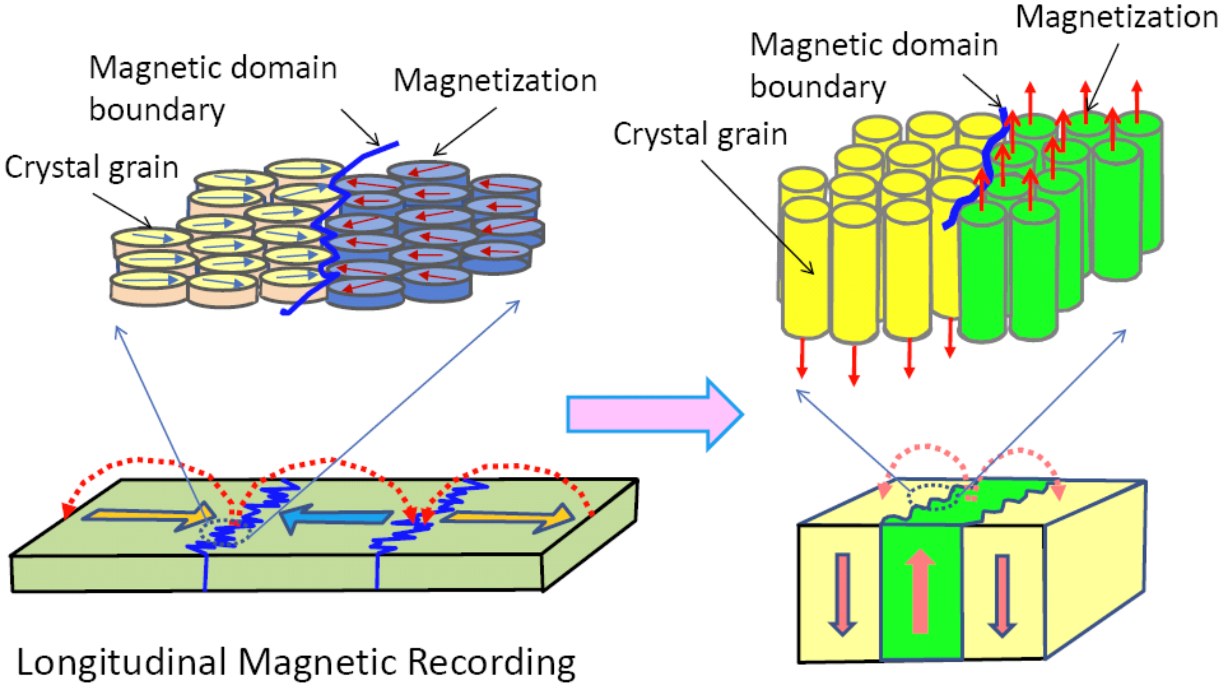


CGR = compound growth rate
LDPC = Low Density Parity Check
TFC = Thermal Flight Control
AFC = Anti-Ferromagnetically Coupled
MEPRML = Modified E Partial Response Maximum Likelihood
TMR = Tunneling Magneto Resistance
CPP-GMR = Current Perpendicular to Plane – Giant Magneto Resistance

PMR = Perpendicular Magnetic Recording
SMR = Shingled Magnetic Recording
MAMR = Microwave Assisted Magnetic Recording
HAMR = Heat Assisted Magnetic Recording
BPMR = Bit Patterned Magnetic Recording
TDMR = Two-Dimensional Magnetic Recording

From Longitudinal to Perpendicular Media

Shift from LMR to PMR



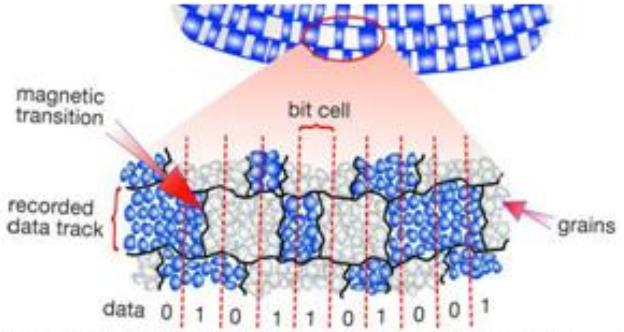
Longitudinal Magnetic Recording (LMR)

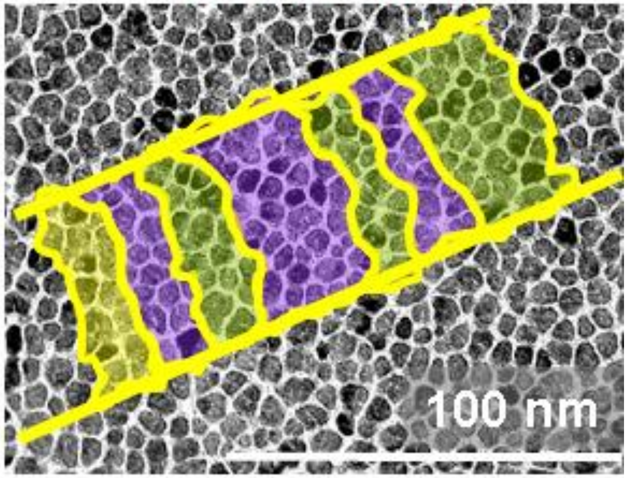
Perpendicular Magnetic Recording (PMR)

highest demag fields
at bit transitions

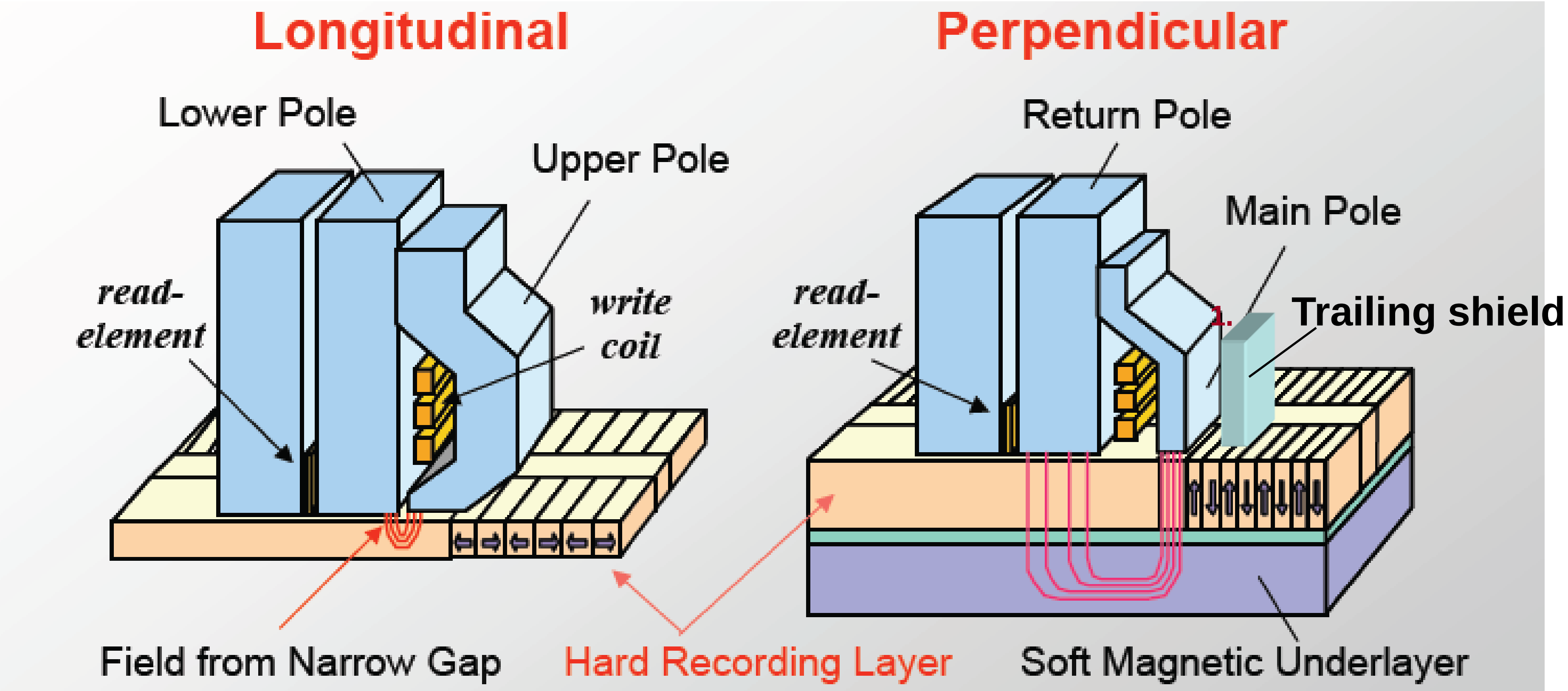
highest demag fields
in bit center
➔ intergranular exchange
counteracts demag fields

Conventional granular media





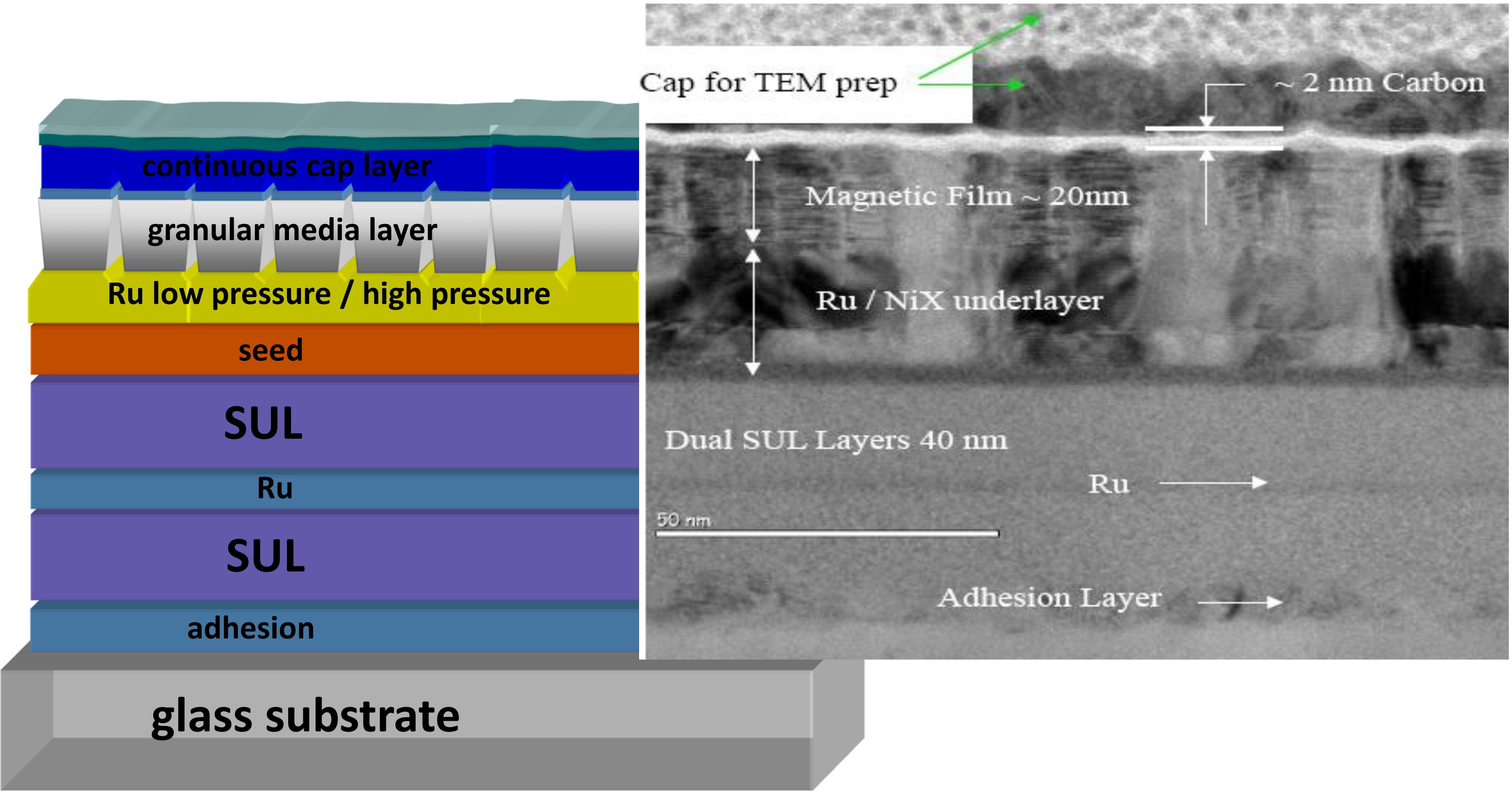
From Longitudinal to Perpendicular Media



- **Part of the head structure must be built into the disk!**
  - **magnetically soft layer placed immediately under recording medium**
  - **strong field concentrated under main pole writes on medium**

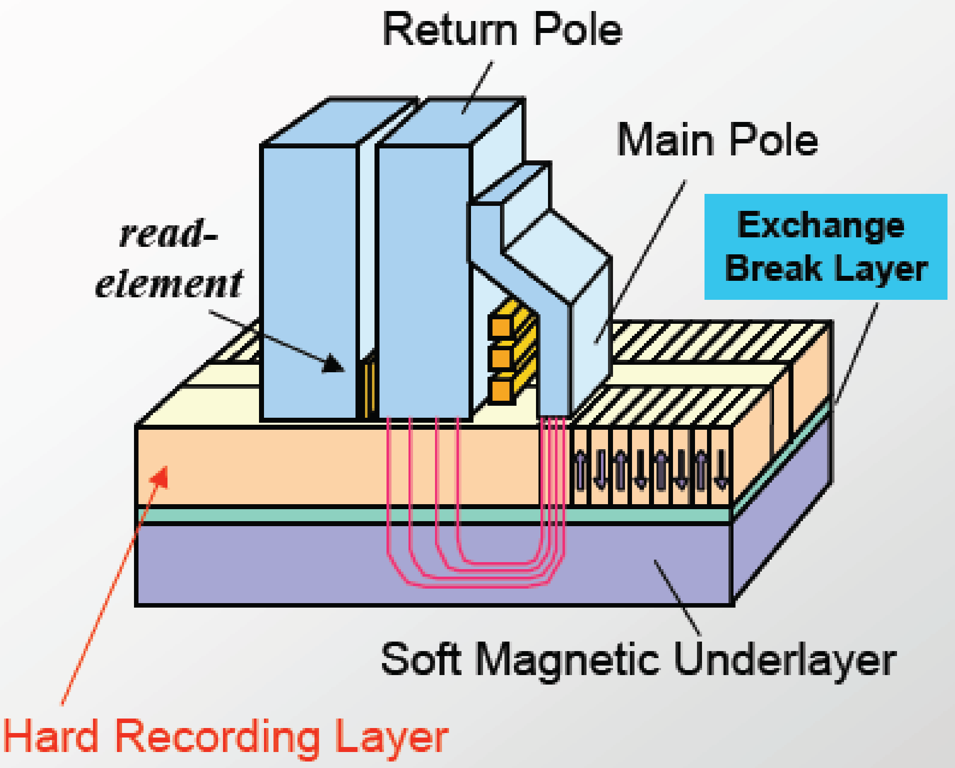
  (diffuse ‘return field’ under return pole is too weak to affect medium)

Basic PMR Media structure



From Longitudinal to Perpendicular Media

Perpendicular recording:



Advantages:

- higher write fields
- better high density stability
- smaller read-back spacing
- better grain orientation

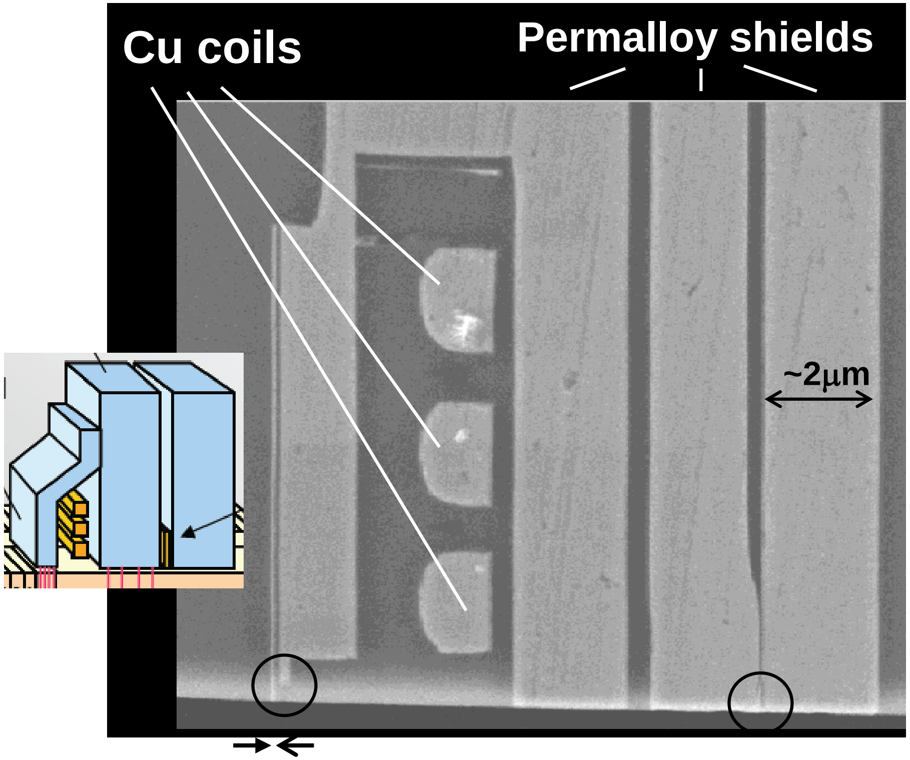
Disadvantages:

- much thicker structure
  (surface roughness)
- more layers / complex processing
  (new tooling? - investment)
- exchange break (between HRL and SUL)
- SUL magnetization
- new materials needed

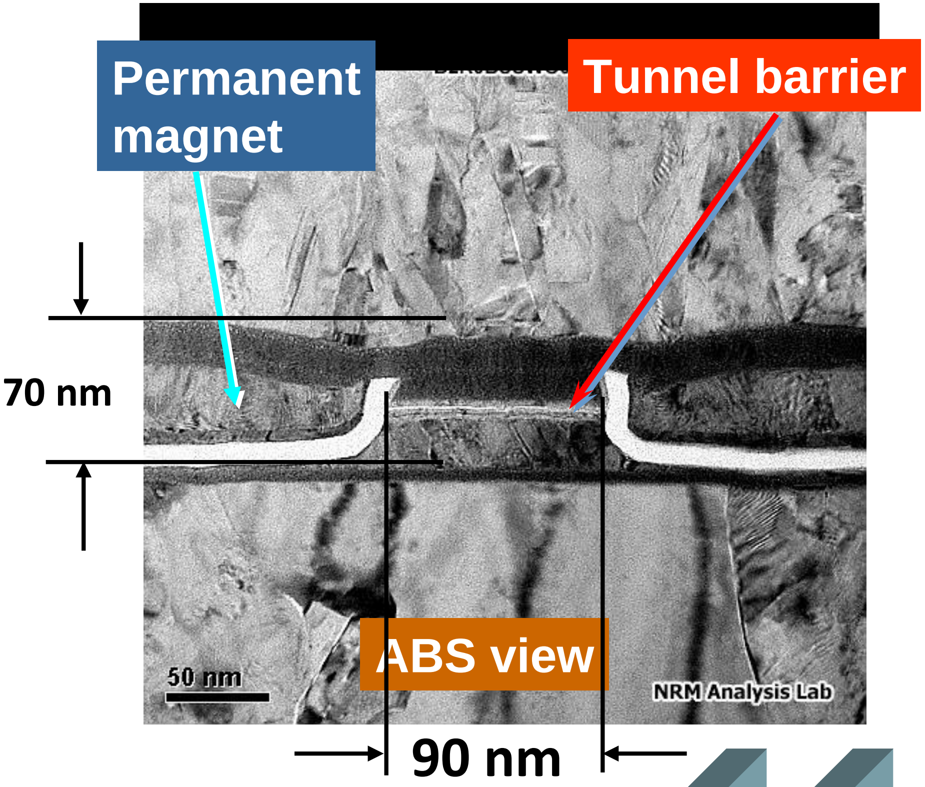
TEM write and read-head for PMR

Perpendicular Write-Read Head

Single Pole Writer with 2.4 T Pole



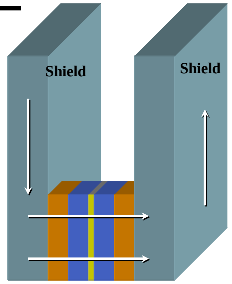
TMR Reader with ΔR/R=18%



Writer:
~ 170 nm thick
~ 100 nm wide

Reader:
~ 70 nm gap
~ 90 nm wide

170 Gbit/in^2 dimensions



Read resolution down track given by layer thickness (90 degree tilt), cross track by lithography ➔ magnetic recording ahead of Moore‘s law …

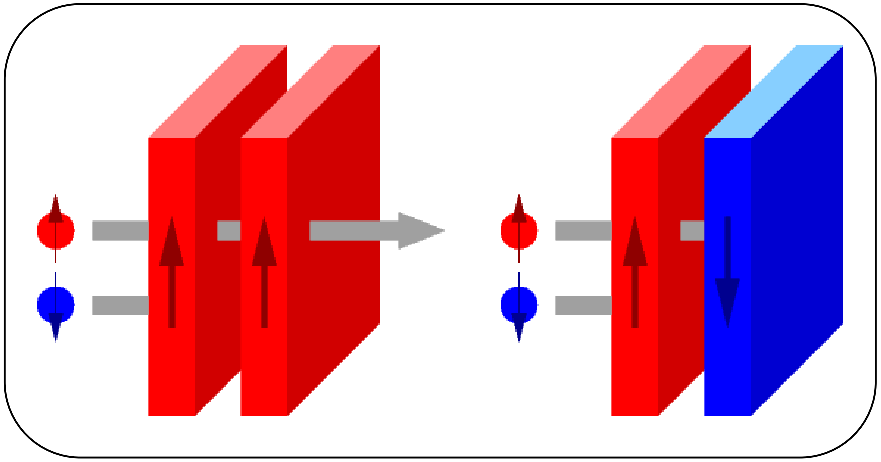
Giant Magnetoresistance (GMR)

What is Magnetoresistance?

Change of electrical resistivity of the material under the application of magnetic field

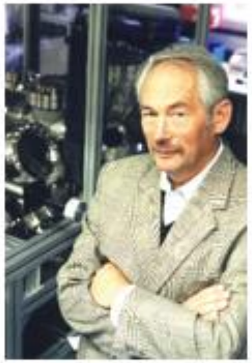
Magnetoresistance converts magnetic signal into electrical signal

GMR, Nobel prize in physics (2007)



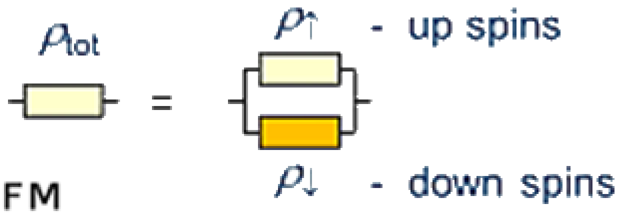
Baibich *et al*. *PRL* **61**, 2472 (1988)
Grünberg *et al*. *PRB* **39**, 4828 (1989)

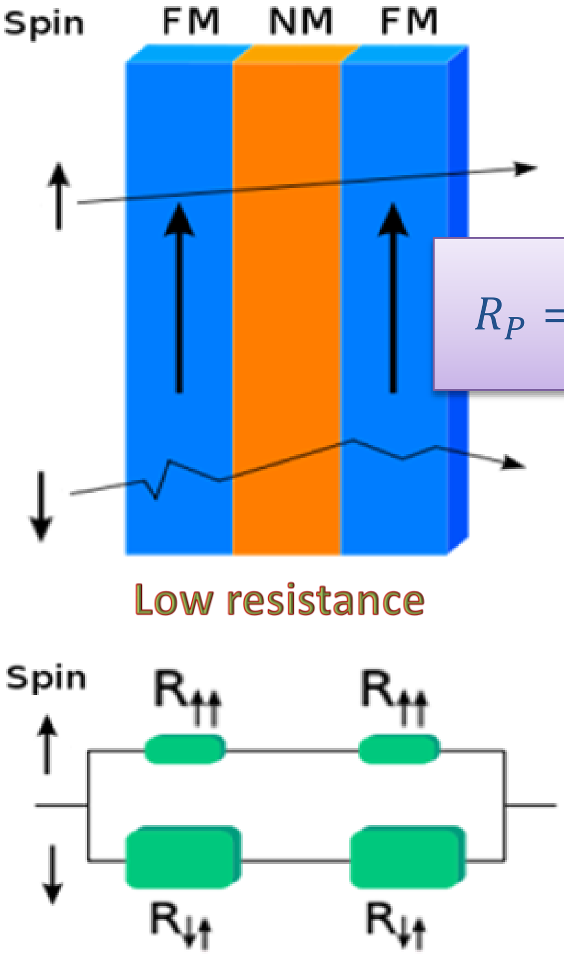
Albert Fert
Université Paris-Sud,
Orsay, France



Peter Grünberg
Institut für Festkörperforschung,
Forschungszentrum Jülich,
Germany

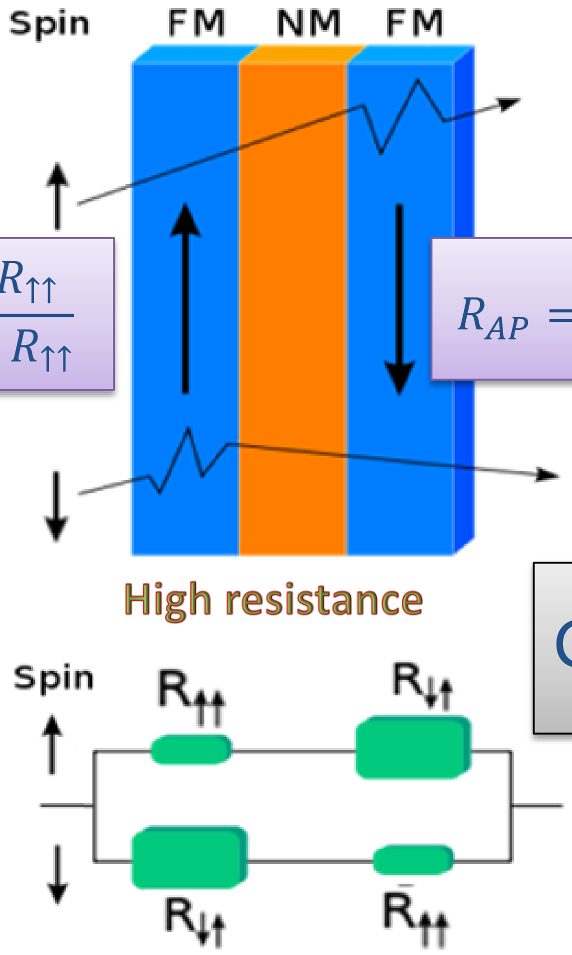
GMR – equivalent circuits for multilayer





Low resistance

$$R_P = \frac{2R_{\downarrow\uparrow}R_{\uparrow\uparrow}}{R_{\downarrow\uparrow}+R_{\uparrow\uparrow}}$$



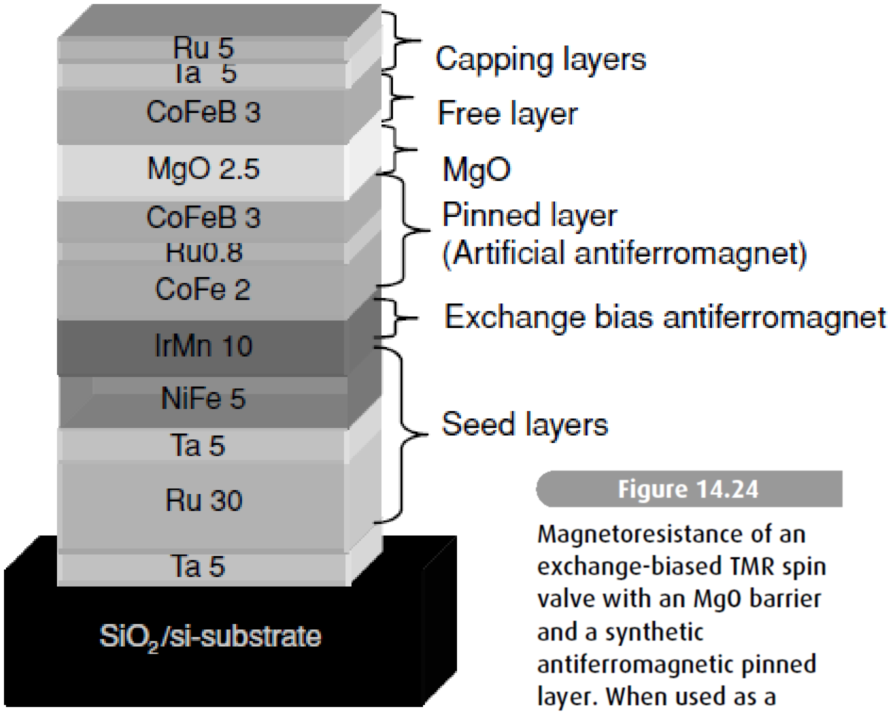
High resistance

$$R_{AP} = \frac{R_{\downarrow\uparrow}+R_{\uparrow\uparrow}}{2}$$

$$\mathrm{GMR} = \frac{R_{AP} - R_P}{R_P}$$

Spin valve head, Coey

Basic Read Head Structure



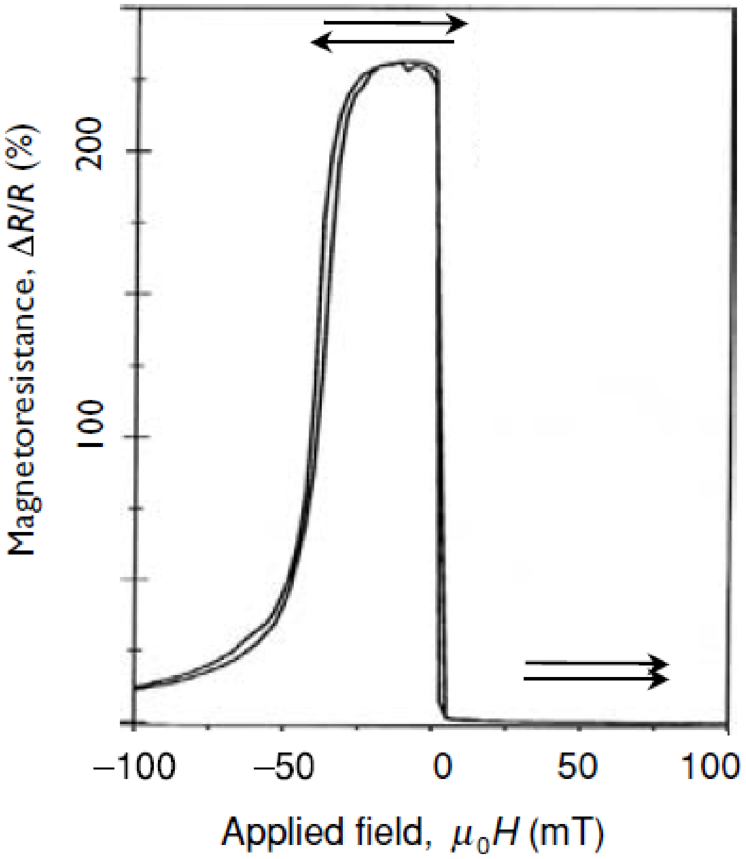


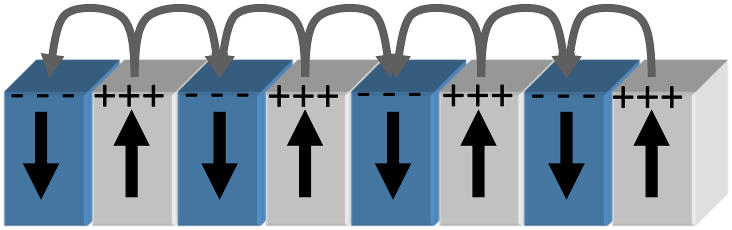
Figure 14.24

Magnetoresistance of an exchange-biased TMR spin valve with an MgO barrier and a synthetic antiferromagnetic pinned layer. When used as a memory element, the axes of the free and pinned layers are parallel, giving an abrupt switch near zero field, as shown. When the device is used as a sensor, these axes are perpendicular, leading to a linear $R(B)$ transfer curve, as the free layer rotates coherently in the applied field. (Data courtesy of Gen Feng.)

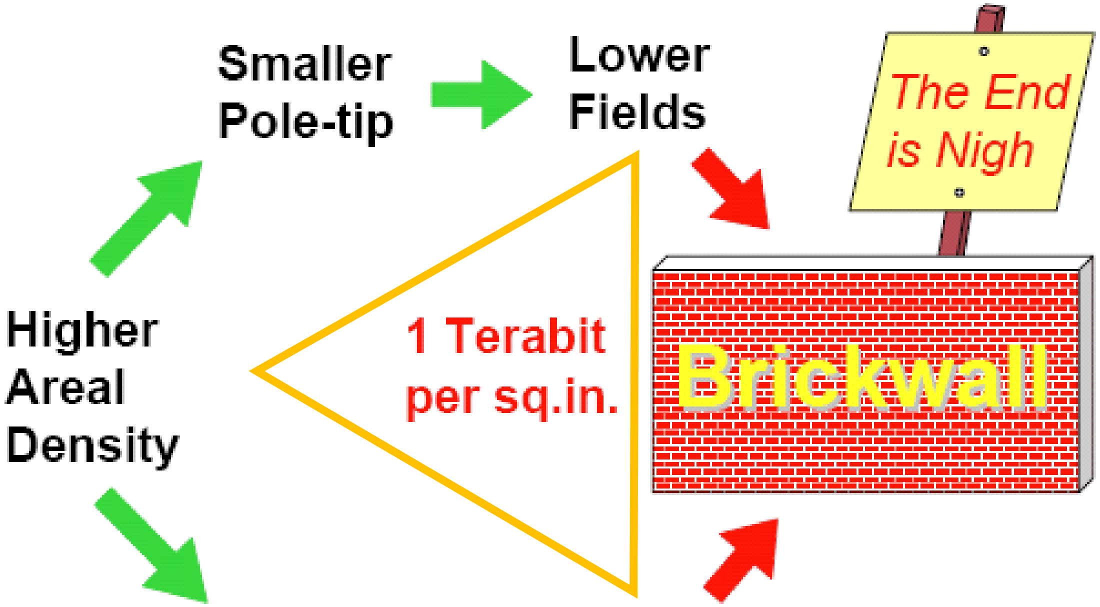
What effects are used here?

- Interlayer exchange coupling
- Exchange bias
- Tunneling magnetoresistance

PMR geometry



"Superparamagnetic Brickwall" – J. Judy

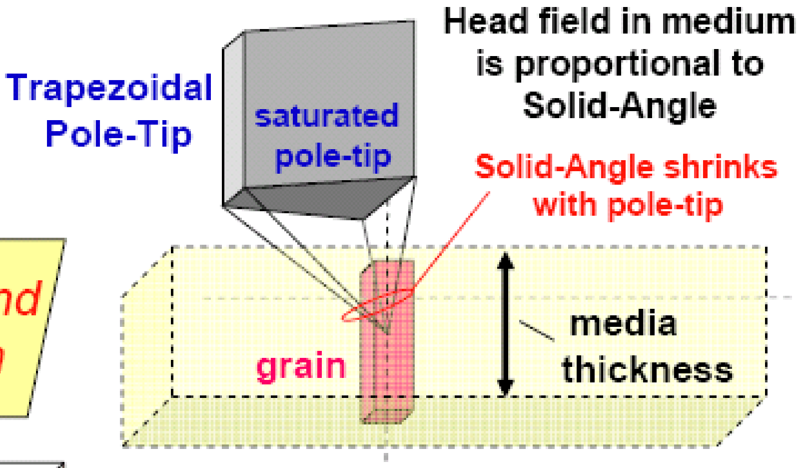


Higher Areal Density

Smaller Pole-tip → Lower Fields

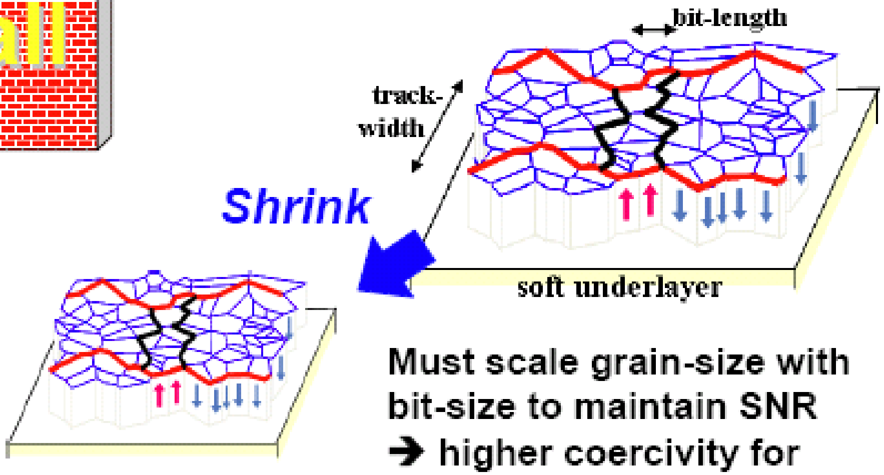
Smaller Grains → Higher Coercivity

1 Terabit per sq.in.



Head field in medium is proportional to Solid-Angle

Solid-Angle shrinks with pole-tip



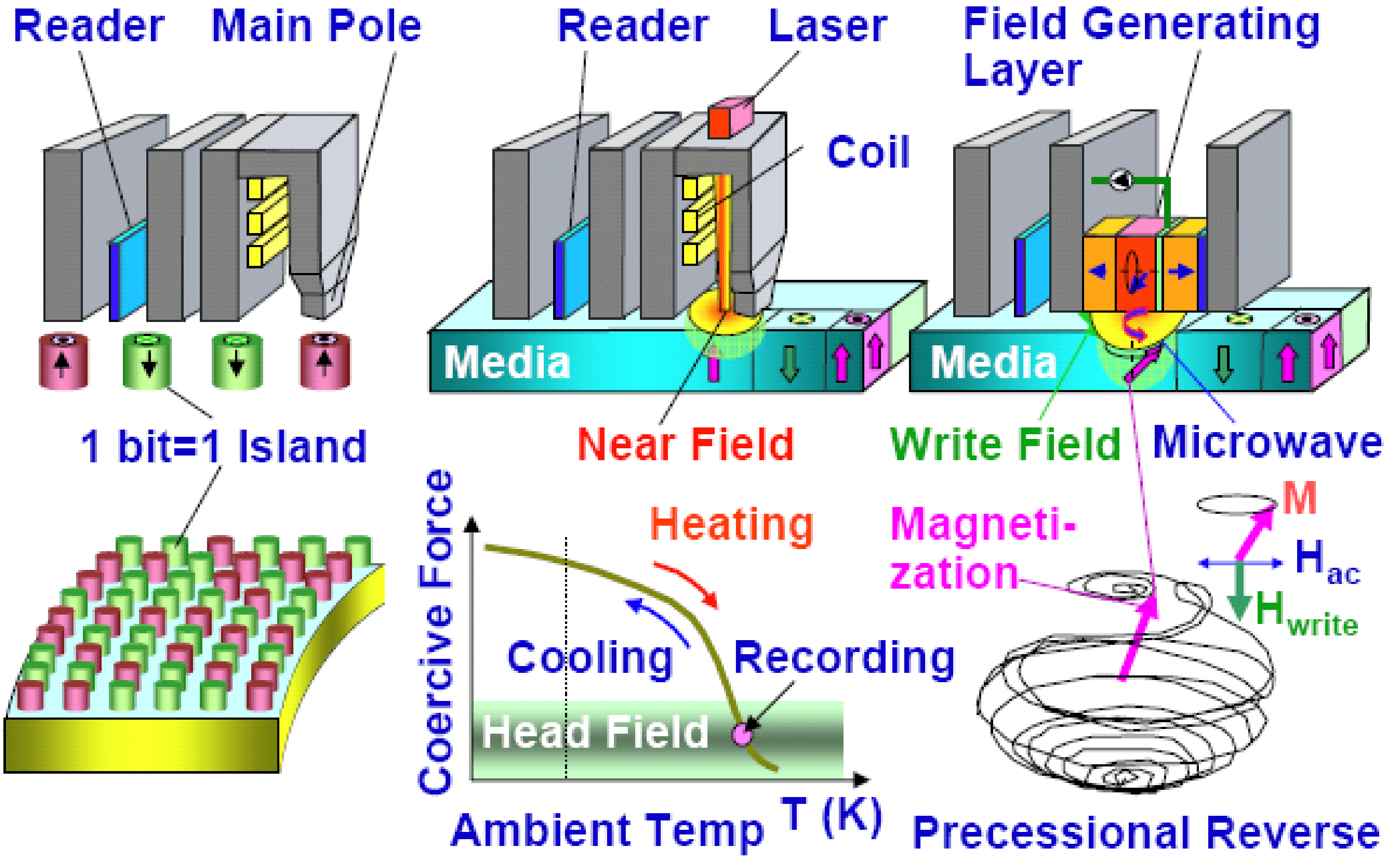
Must scale grain-size with bit-size to maintain SNR
➔ higher coercivity for thermal stability

Grain volumes shrink faster than scaling

- halving 'grain-pitch' leaves only 19% of core area
  (9 ➔ 4.5 nm pitch, assuming 1nm grain-boundary required)

Bit Patterned
Magnetic nano-islands w/ exchange coupled grains

Heat/Microwave Assisted
Energy assisted writing to thermally stable & hard-to-write media



(a) Bit Patterned (b) Heat Assisted (c) Microwave Assisted

Spin and its journey

4th century, China
Loadstone

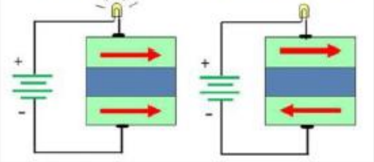
Uhlenbeck
and Goudsmit

W. Pauli

1925 – 1927
Theory of electron spin

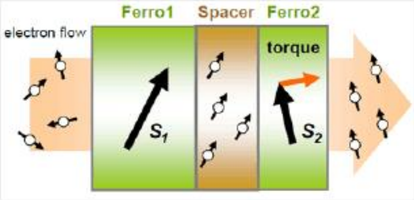
1956 – IBM 350
Magnetic storage
(5 MB)

Grunberg and Fert

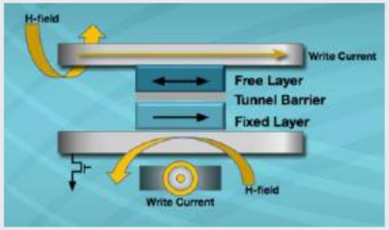


1987-88 Giant
magnetoresistance
(GMR)

Data storage
Since 1990's

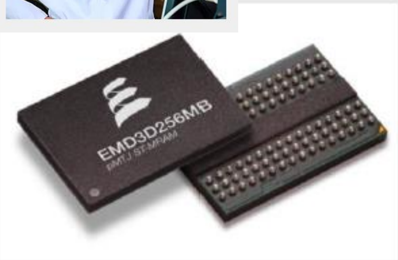


2001
Spin transfer torque
(STT)



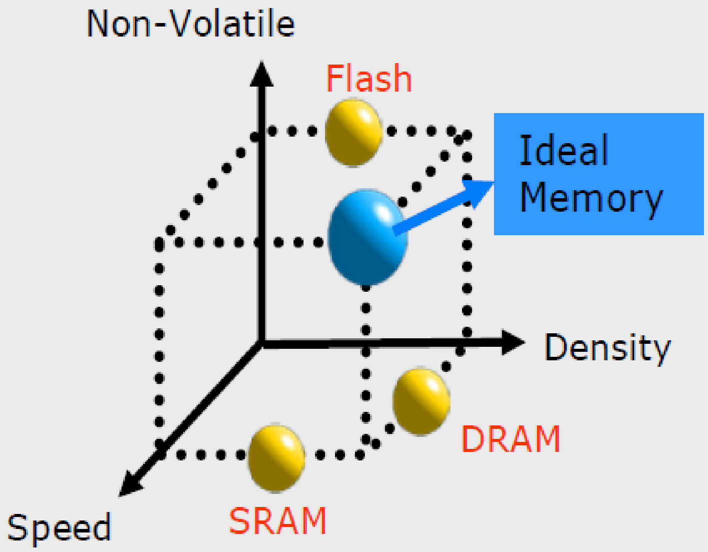
2002
Toggle MRAM

Prof. Hyunsoo Yang



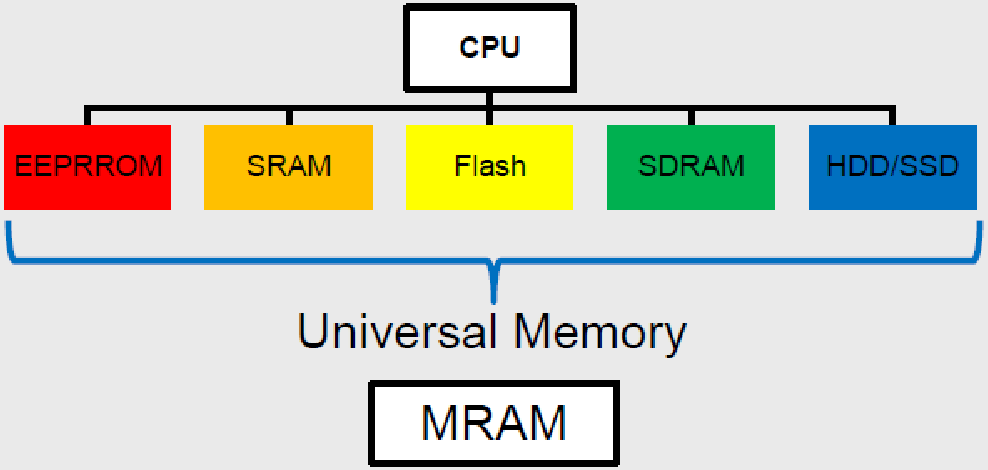
2012-
STT MRAM

The power of the MRAM



Wanted Attributes!

- High endurance
  - > 20 years lifetime
  - > 10^{15} cycles
- Fast random access
  - \- Read time ~ 1-10 ns
  - \- Write time ~ 1-10 ns
- High density
- Integration with conventional CMOS
- Low power (zero stand-by current)
- Cheap!



CPU

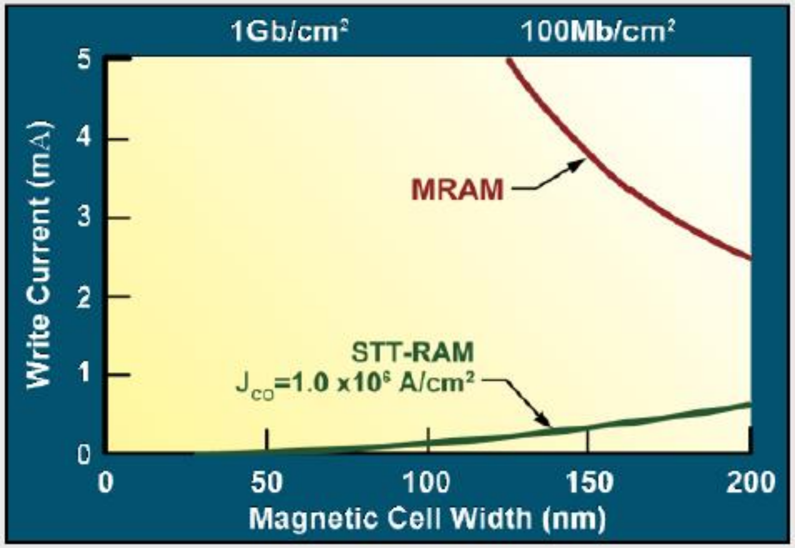
EEPRROM | SRAM | Flash | SDRAM | HDD/SSD

Universal Memory

MRAM

Future Computer:
CPU+MRAM

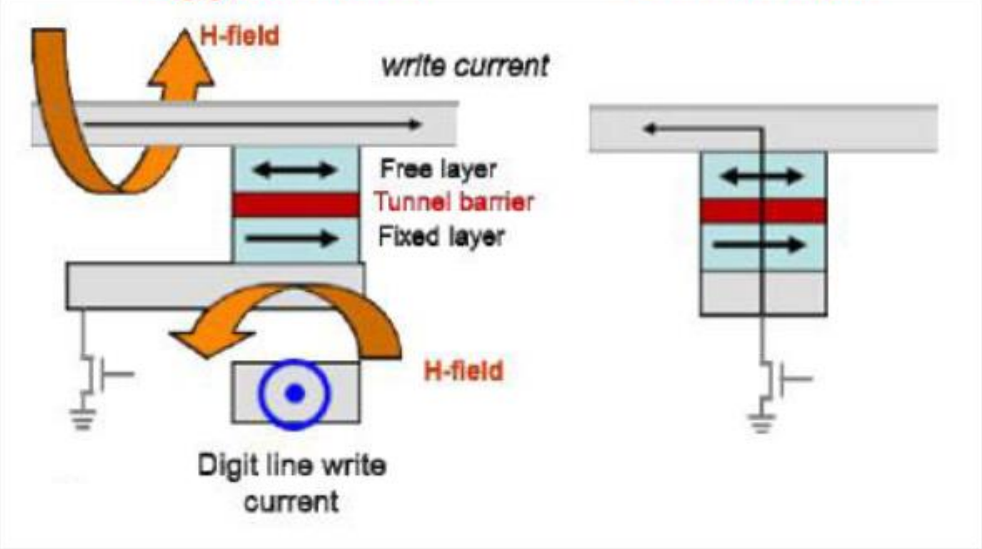
Spin torque MRAM



-Present STT-MRAM (Everspin) uses 90 nm node
-GF started to use 40, 28, 14 nm node
-TSMC, IBM, Samsung, TDK, Hynix, Sony, Avalanche, Toshiba, Intel, Qualcomm…

2019 March
Samsung
28 nm FD-SOI
embedded

Toggle-MRAM STT-MRAM

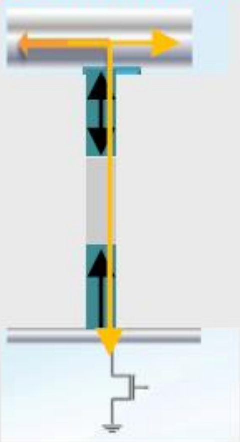


16 Mb 256 Mb

Everspin STT-MRAM benefits realized in IBM's FlashCoreModule™

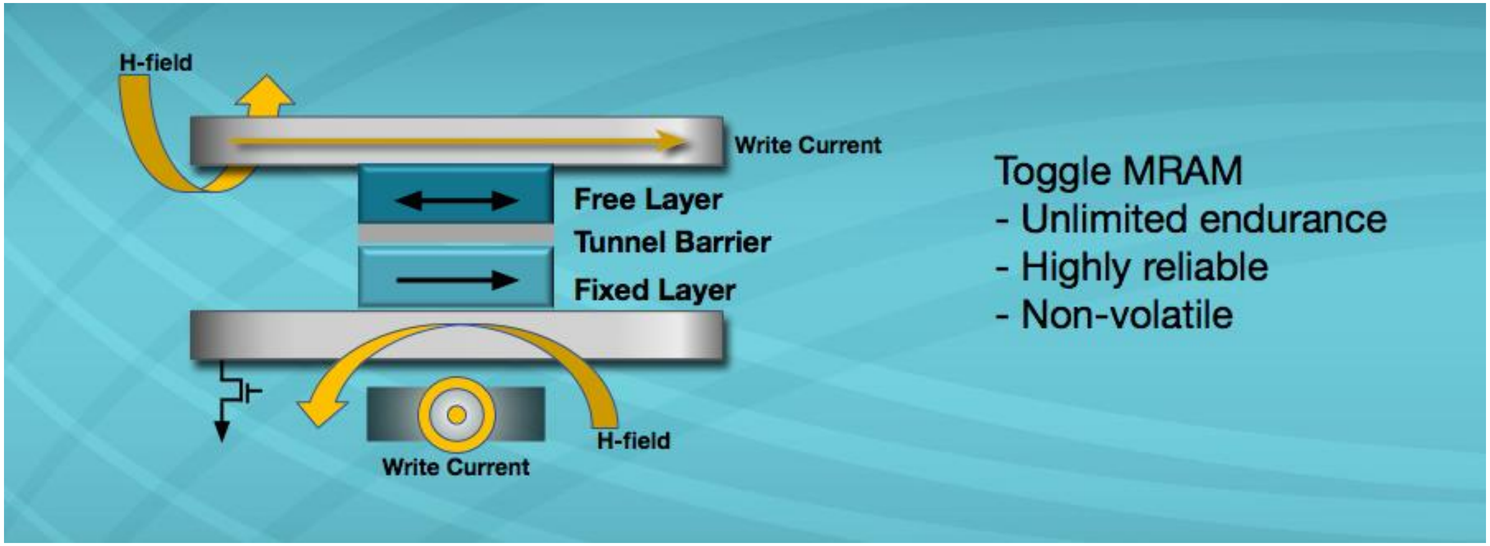
Everspin with GlobalFoundries

SOT-MRAM

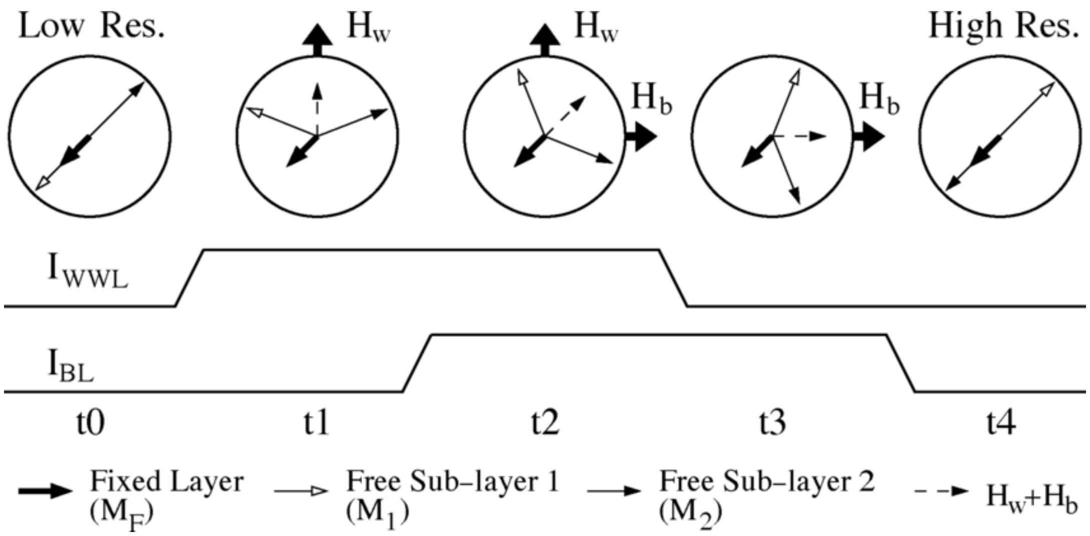


Future

Toggle MRAM

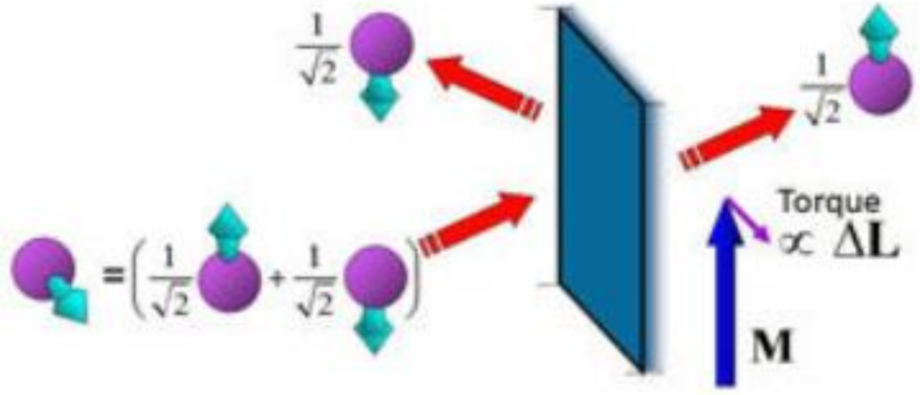


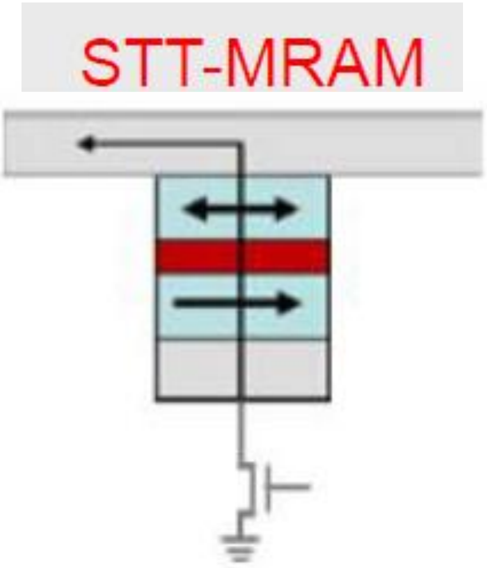
Toggle MRAM
- Unlimited endurance
- Highly reliable
- Non-volatile



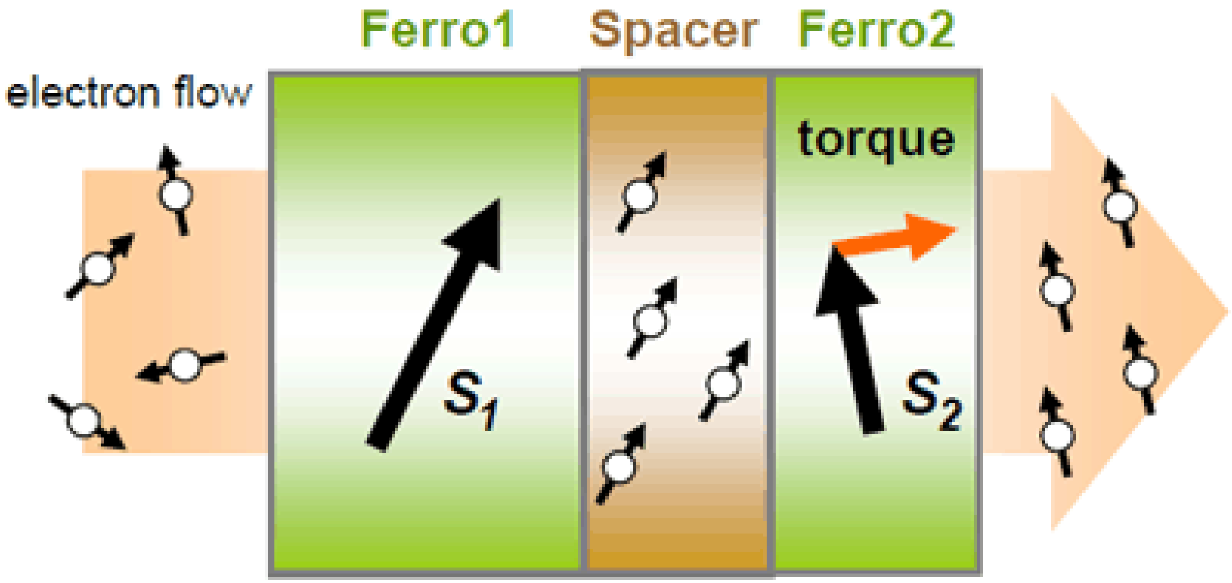
Spin-Transfer-Torque

A ferromagnetic material such as iron takes on permanent magnetization when the magnetic properties of its atoms all line up in the same way. Because individual electrons also have an intrinsic magnetic alignment, defined by their so-called spin direction, they can interact with ferromagnets in some unusual ways. For example, an electric current flows more easily through a ferromagnet if electron spins line up with, rather than opposite to, the magnetization.





Spin diffusion length across spacer layer on the 10-100 nm range

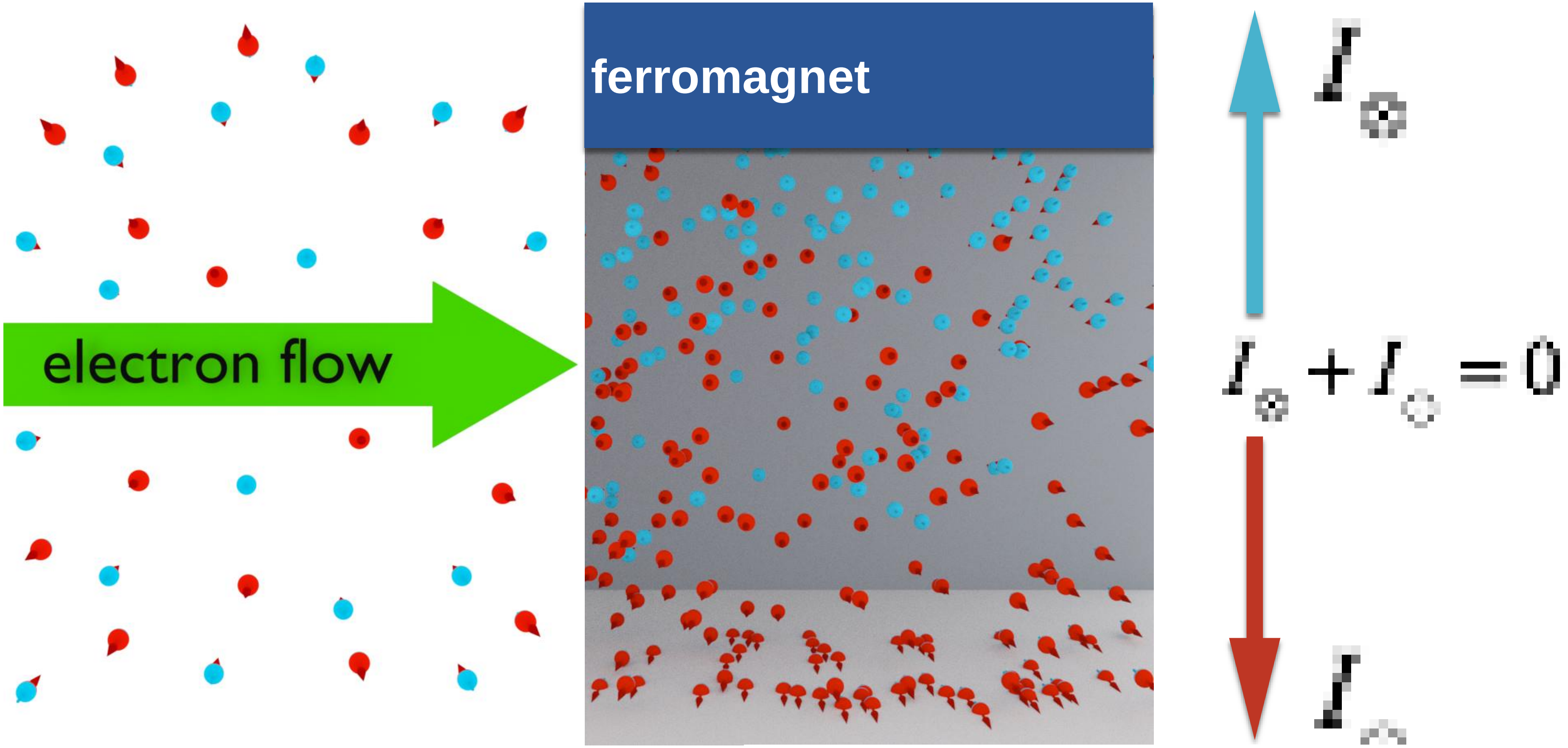


Necessary critical current densities of the order 10^6 - 10^7 A/cm^2 are only achieved in nanostructures

Spin-Orbit-Torque

animation by Helmut Schultheiss and Toni Hache

- transport of angular momentum without transport of electric charge



M.Dyakonov: *Sov. Phys. JETP Lett*. **13**: 467, 1971

J.E.Hirsch: Phys. Rev. Lett. ***83*** *(9),1999*

L. Berger: Phys. Rev. B. 54, 9353: 1996; J. Appl. Phys. **90**, 4632: 2001

J.C. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996); **195,** L261(1999)

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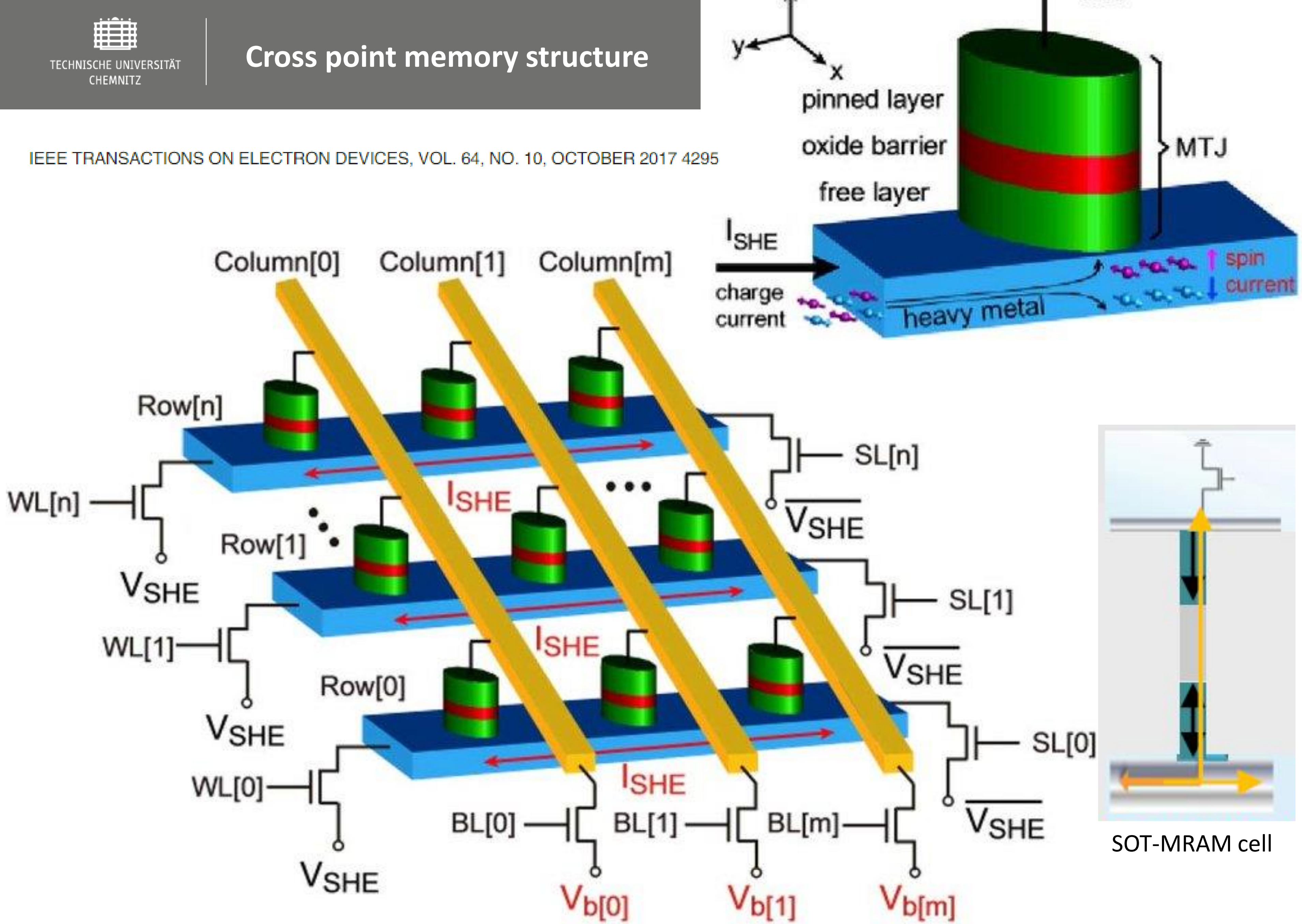
Cross point memory structure

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 64, NO. 10, OCTOBER 2017 4295



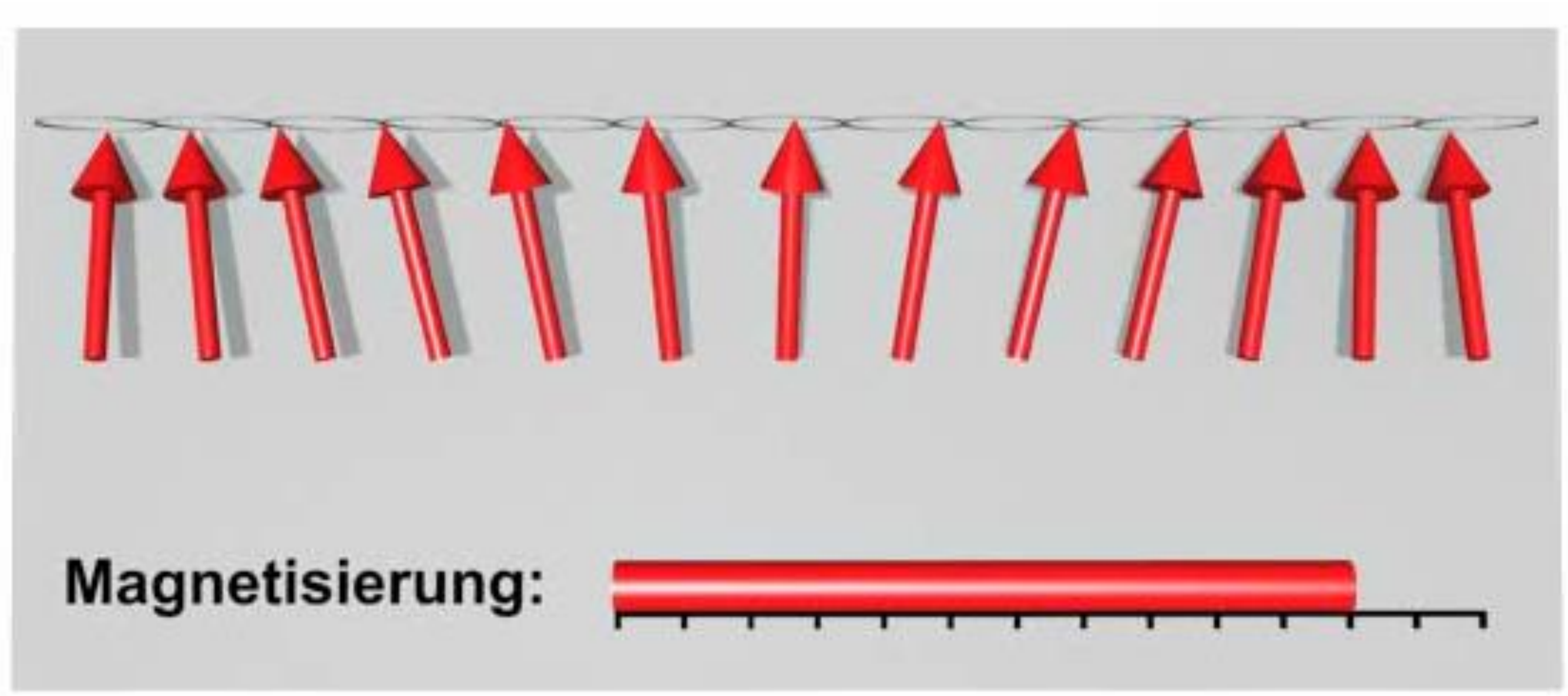
SOT-MRAM cell

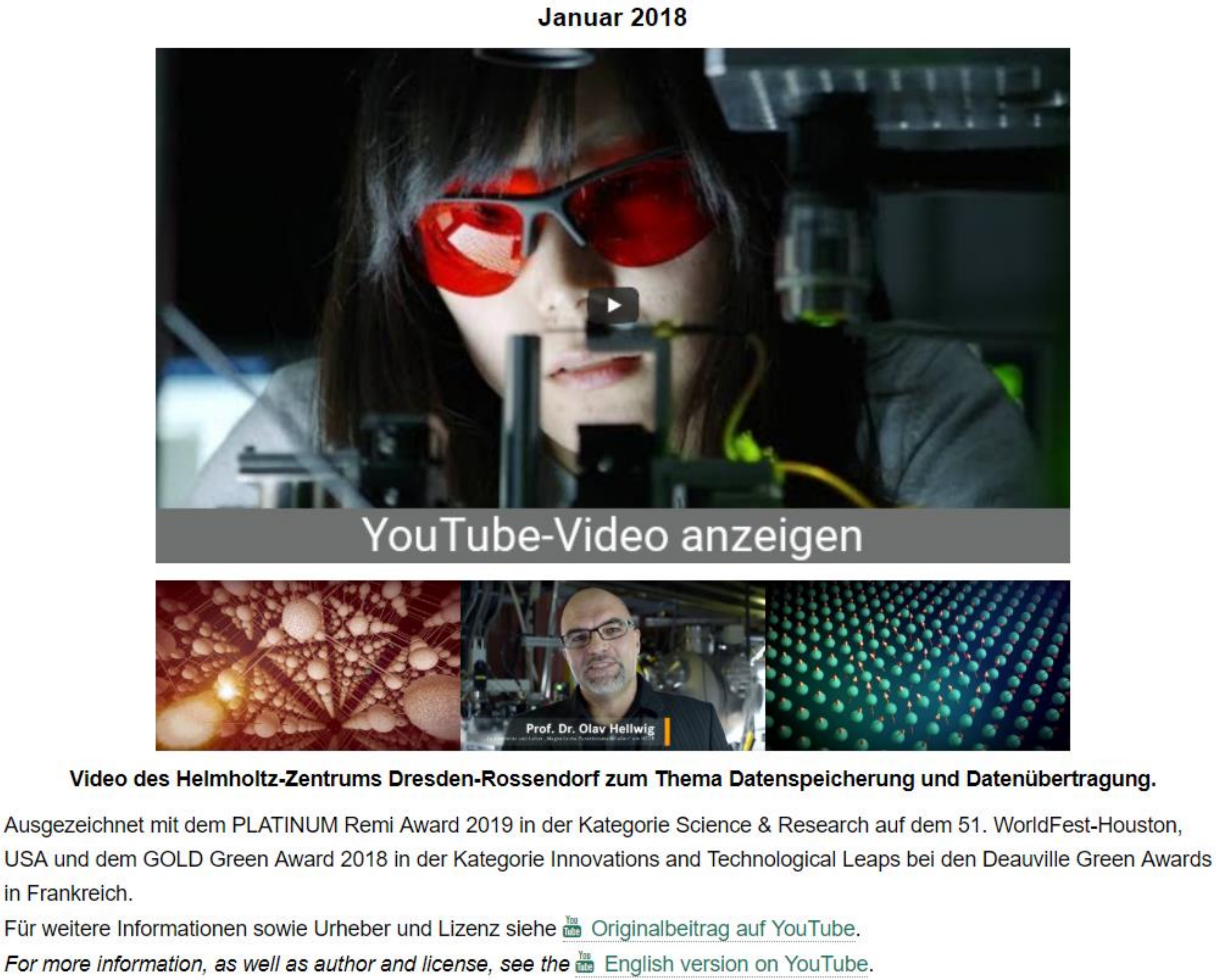
Magnons and spin waves

Concept

- Instead of flipping a single spin, readjust all spins slightly

➡ **Spin wave**





Januar 2018

Video des Helmholtz-Zentrums Dresden-Rossendorf zum Thema Datenspeicherung und Datenübertragung.

Ausgezeichnet mit dem PLATINUM Remi Award 2019 in der Kategorie Science & Research auf dem 51. WorldFest-Houston, USA und dem GOLD Green Award 2018 in der Kategorie Innovations and Technological Leaps bei den Deauville Green Awards in Frankreich.

Für weitere Informationen sowie Urheber und Lizenz siehe Originalbeitrag auf YouTube.

For more information, as well as author and license, see the English version on YouTube.

https://www.tu-chemnitz.de/physik/MAGFUN/

Inhalt

Ferromagnetische (Funktionale) Materialien

- **Einordung und Einleitung**
- **Energien und Energiedichten einer ferromagnetischen Probe**
  - **Austauschwechselwirkung**
  - **Streufeld- oder Demagnetisierungsenergie, Formanisotropie**
  - **Anisotropie (außer Formanisotropie = Demagnetisierungsenergiedichte)**
  - **Zeemann Energie, äußeres Feld**
- **Wechselseitige Konkurrenz verschiedener magnetischer Energieterme**
- **Hysterese-Effekte, Stoner-Wohlfarth Modell, Basis für binäre magn. Datenspeicher**
- **Magnetische Funktionsmaterialien zur Datenspeicherung**
  - **Entwicklung der Festplatte: Von magnetischen Mikrosystemen zu Nanosystemen**
  - **GMR (Riesenmagnetwiderstand) und TMR Effekte für empfindlichere Leseköpfe**
  - **Zukünftige Festplattentechnologien**
  - **Neue Effekte in der Nanowelt: Spin tranfer torque in Nanokontakten**
  - **Separation von Ladungs und Spinströmen: Spin orbit torque in Dünnschichtsystemen**
  - **Anwendungen im Magnetic Random Access Memory (MRAM)**
  - **Die Spinwelle als Informationsträger (HZDR-movie)**