TECHNISCHE UNIVERSITÄT CHEMNITZ

Gastvorlesung „Magnetische Funktionsmaterialien“ im Rahmen der Vorlesung „Komplexe Materialien“

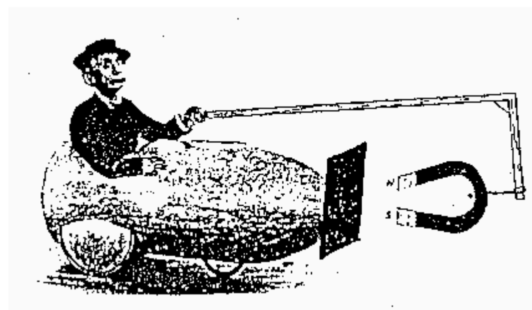
Feedback Session (all)

Prof. Dr. Olav Hellwig

Lehrstuhl für Magnetische Funktionsmaterialien

Sommersemester 2022

Tuesdays
9:15 – 10:45 Uhr



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)**

Ferromagnetische (Funktionale) Materialien

- Guest-lecture “Komplexe Materialien” part 1: FM functional materials for data storage (some basics) (1:36:31)
- Guest-lecture “Komplexe Materialien” part 2: FM functional materials for data storage (applications) (1:32:24)

- Total lecture time 3:08:55

Lecture Review (part 1)

Some questions for discussion …

Do you remember?

Question 1

Which elements are ferromagnetic at room temperature?

A: Fe, Cr, Mn

B: Co, Fe, Cr

C: Ni, Fe, Co

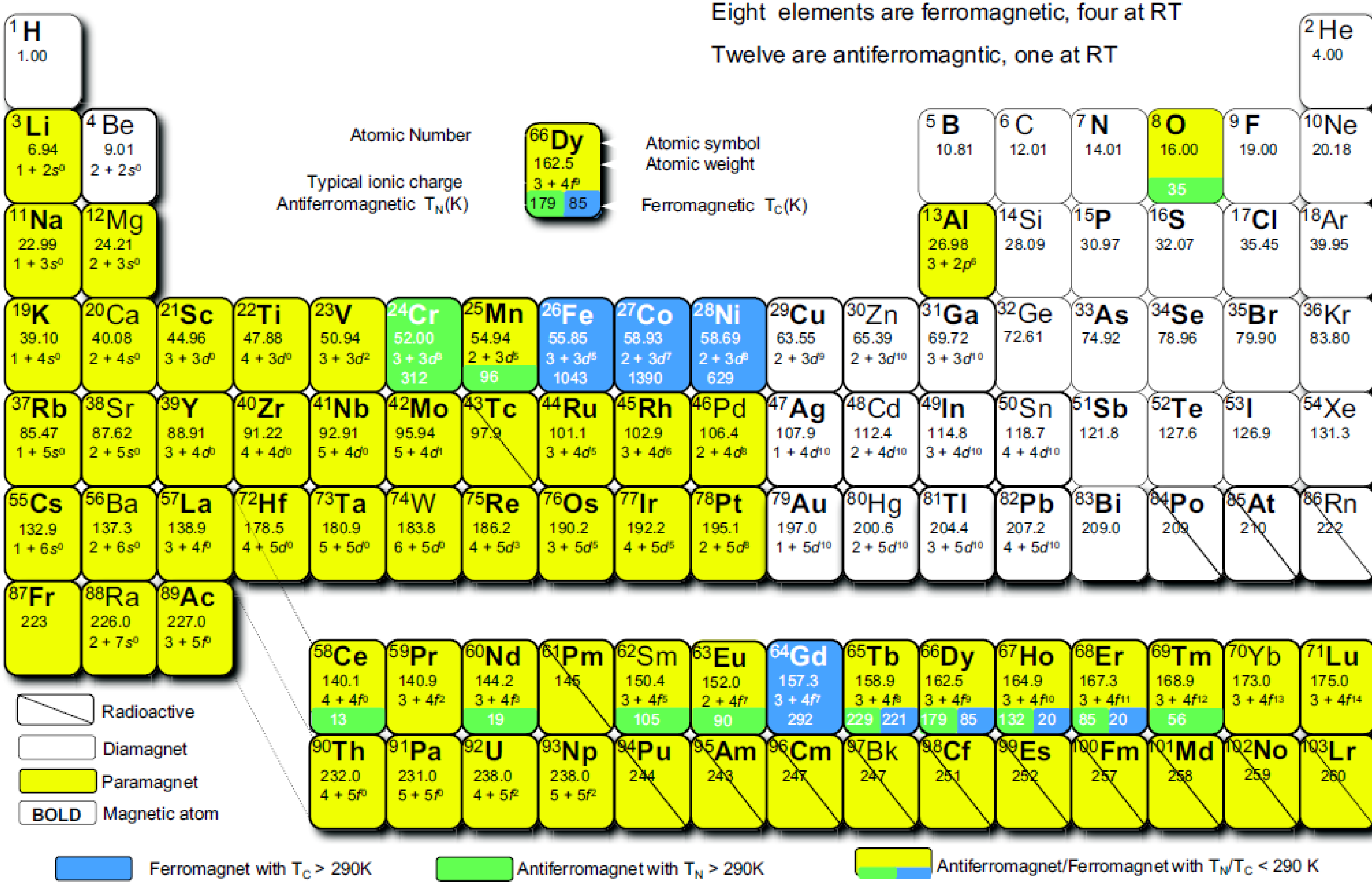
D: Co, Ni, Fe, Tb

E: Gd, Fe, Co, Ni

The Magnetic Periodic Table

Eight elements are ferromagnetic, four at RT

Twelve are antiferromagntic, one at RT



Question 2

Which material has the highest Curie Temperature T_C?

A: Fe

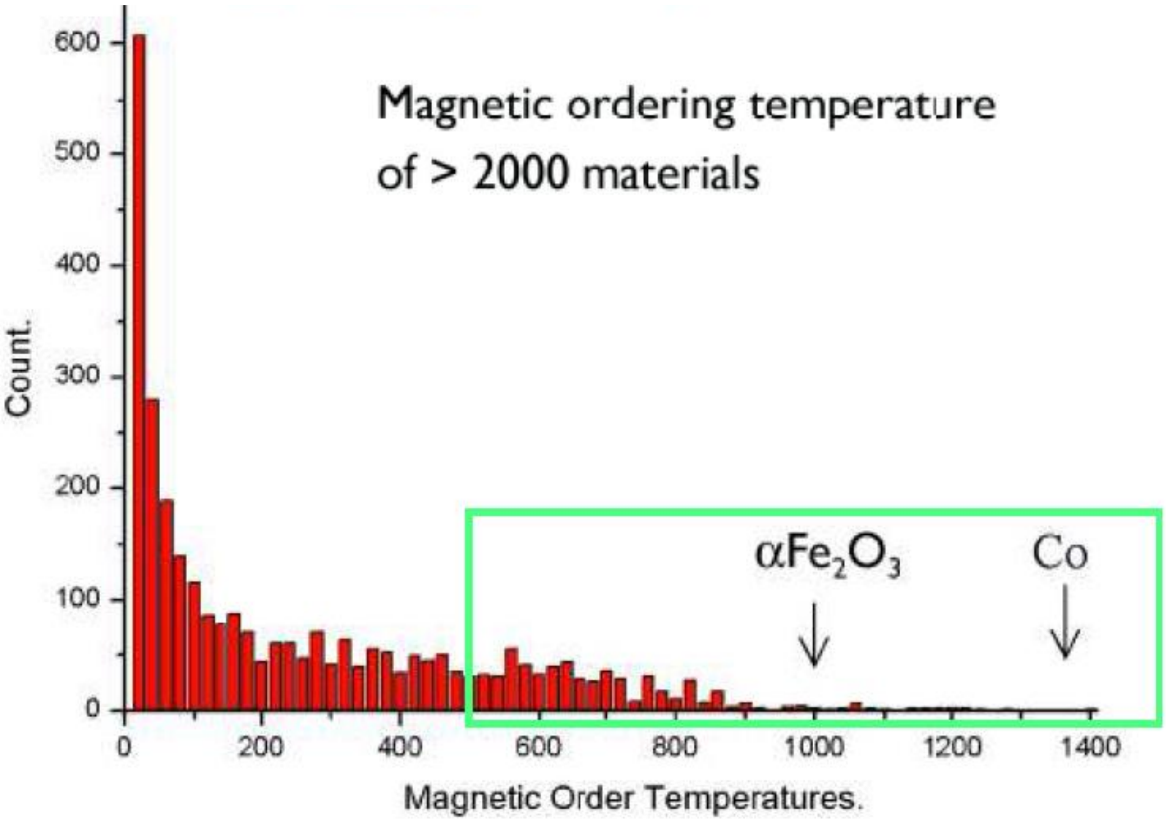
B: Co

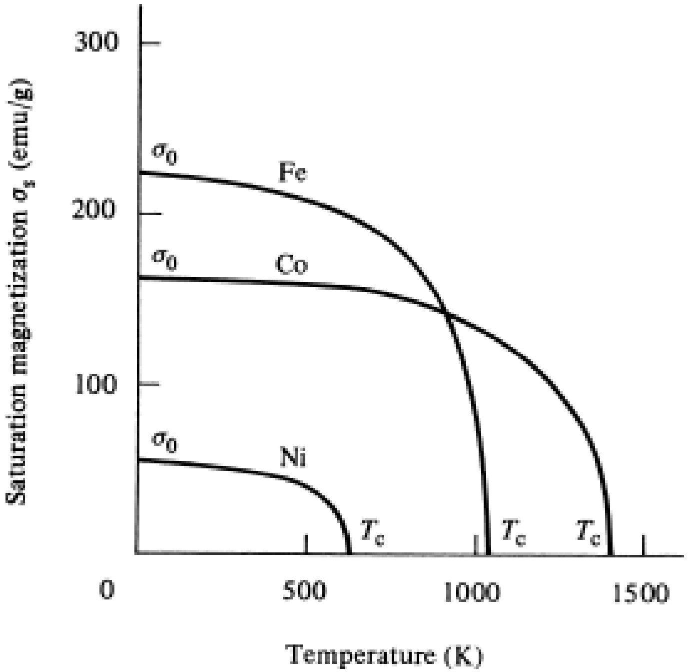
C: Ni

D: Fe_2O_3

E: $Co_{75\%}Fe_{25\%}$

T_C of magnetic materials





A useful magnetic material needs to be able to operate from -50 C to 120 C.

The Curie temperature needs to be > 500 K

Co has the highest T_C of all magnetic materials

Question 3

Which magnetic energy is the most short range?

A: Zeeman energy

B: Anisotropy Energy

C: Demagnetization energy

D: Exchange energy

E: Stray field energy

Question 4

Which magnetic energy is the most long range?

A: Shape anisotropy energy

B: Stray field energy

C: Demagnetization energy

D: all of the above

E: none of the above

Question 5

Which magnetic energy varies the most in strength across ferromagnetic materials?

A: Zeeman energy

B: Anisotropy Energy

C: Demagnetization energy

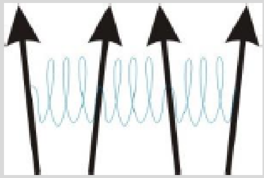
D: Exchange energy

E: Stray field energy

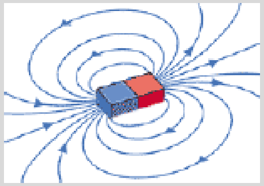
How much vary stray fields, exchange and ansiotropy across useful magnetic materials?

	M_s stray/demag $(\mathrm{MA\ m^{-1}})$	A exchange $(\mathrm{pJ\ m^{-1}})$	K_1 anisotropy $(\mathrm{kJ\ m^{-3}})$
$Ni_{80}Fe_{20}$	0.84	10	0.15
Fe	1.71	21	48
Co	1.44	31	410
CoPt	0.81	10	4900
$Nd_2Fe_{14}B$	1.28	8	4900
$SmCo_5$	0.86	12	17 200
CrO_2	0.39	4	25
Fe_3O_4	0.48	7	−13
$BaFe_{12}O_{19}$	0.38	6	330

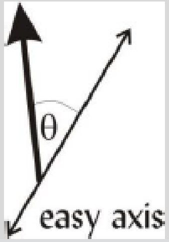
$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$



$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = K_U \sin\theta^2$$



	magnetization	exchange stiffness	anisotropy (energy density)
Variation across materials	less than 5	less than 10	up to 100 000

$$E_{magnetostatics} = -\frac{1}{2}\int_{sample}\vec{H}_d \cdot \vec{M}dV = -\frac{1}{2}\int_{sample}N\vec{M}^2 dV = -\frac{1}{2}N\vec{M}^2 V$$

largest variations in anisotropy

Question 6

Which ferromagnetic 3d element has in its single crystal ground state uniaxial magnetic anisotropy?

A: Fe

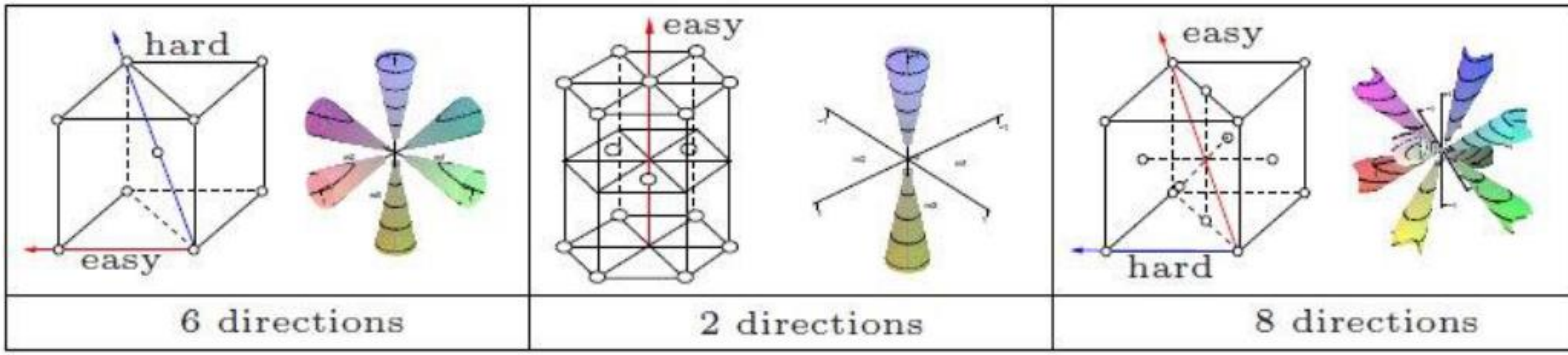
B: Co

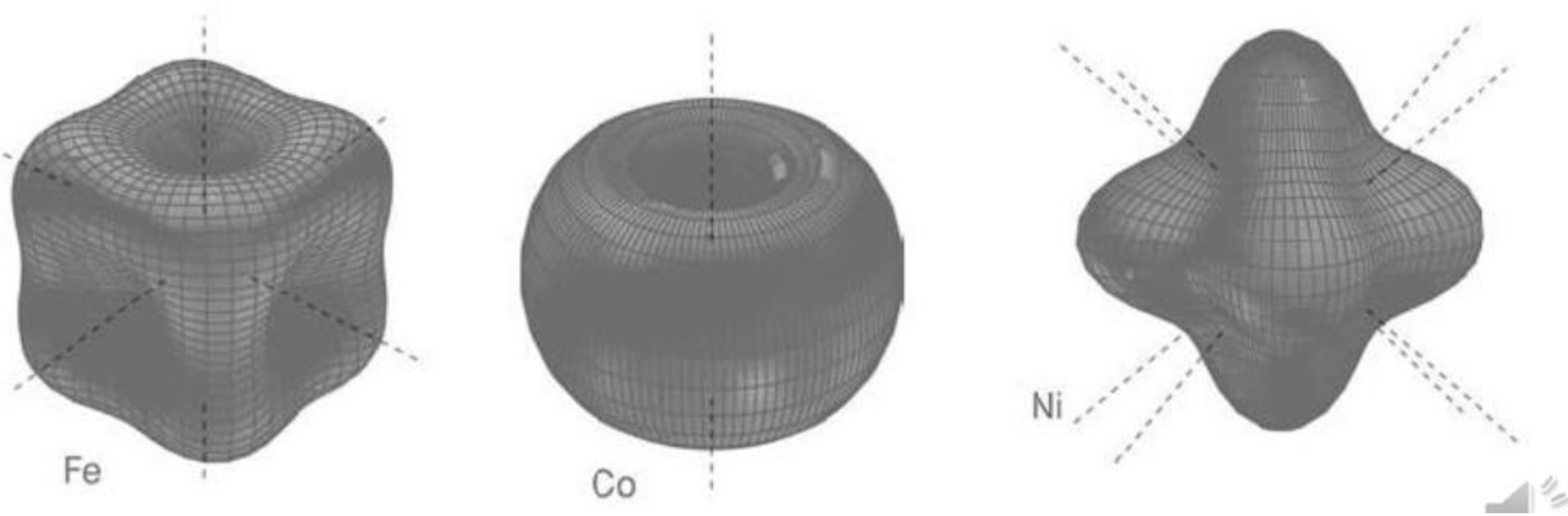
C: Ni

D: all of the above

E: None of the above

Fe bulk | Co bulk | Ni bulk





Question

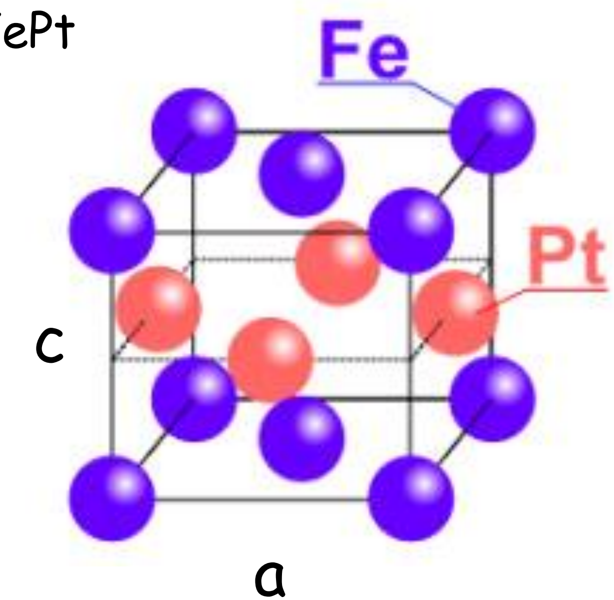
Give an example for a very hard magnetic material?

Why is this material particularly hard?
What is special about it?

Magneto-crystalline anisotropy energy

Simple hard magnetic structure

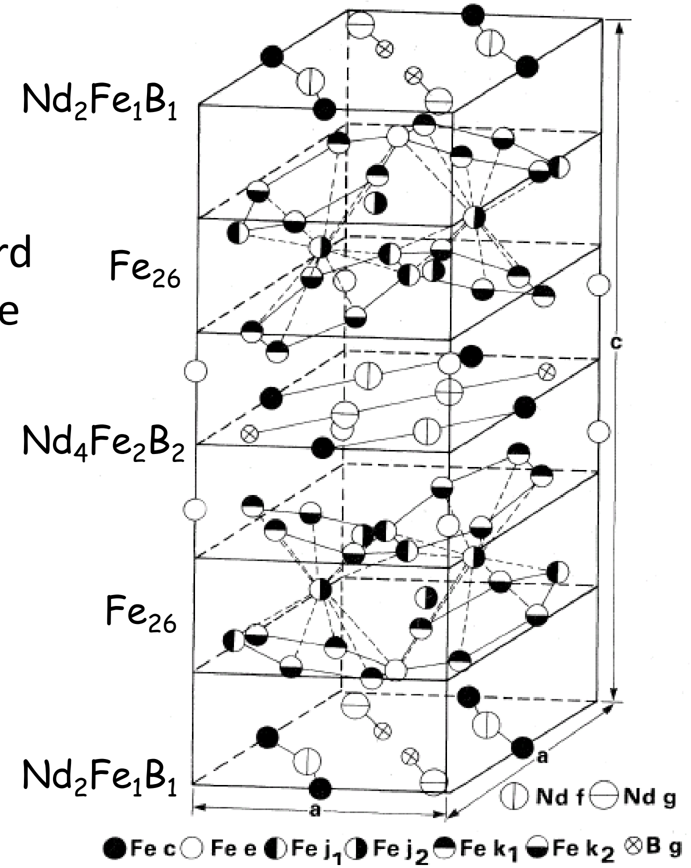
FePt



$Nd_2Fe_{14}B$

More complex hard magnetic structure

Cuboid unit cell: $Nd_8Fe_{56}B_4$



Alloy system	Material	K_1 (10^7erg/cm^3)	M_S (emu/cm^3)	H_K (kOe)	T_C (K)
Co-alloys	CoPtCr	0.20	298	13.7	—
$L1_0$ phases	FePt	6.6–10	1140	116	750
Rare-earth	$Fe_{14}Nd_2B$	4.6	1270	73	585
Transition metals	$SmCo_5$	11–20	910	240–400	1000

Energy term summary again, relative variation: exchange, demag, anisotropy

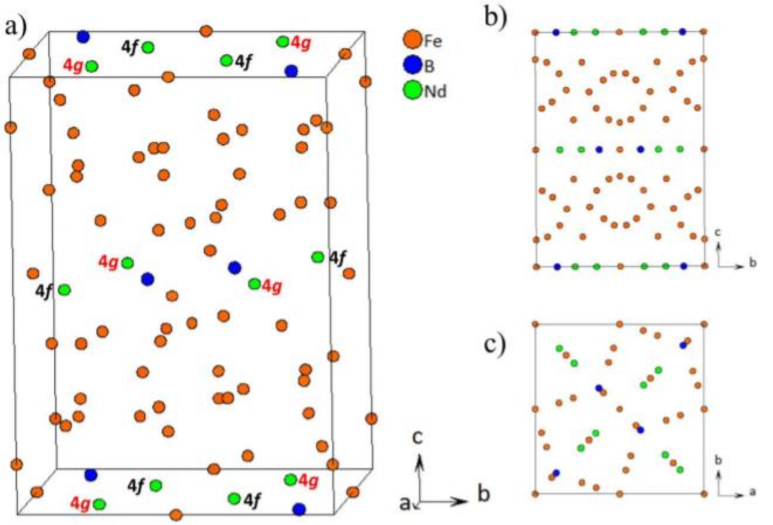


FIG. 3: 250 K structural refinement of sample $(Nd_{0.78}Ce_{0.22})_2Fe_{14}B$: a) isometric view showing the positions of the two different RE sites: $4g$ and $4f$ (the larger $4g$ site is denoted by a red label); b) view along a axis; c) view along c axis.

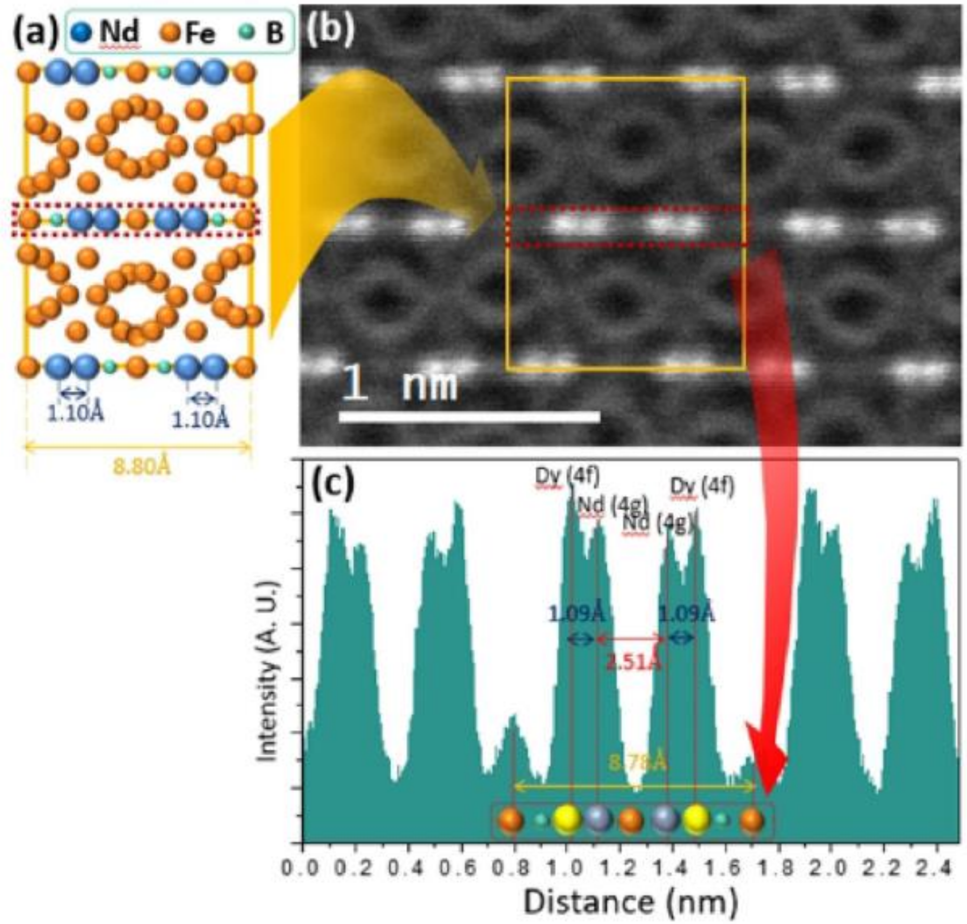
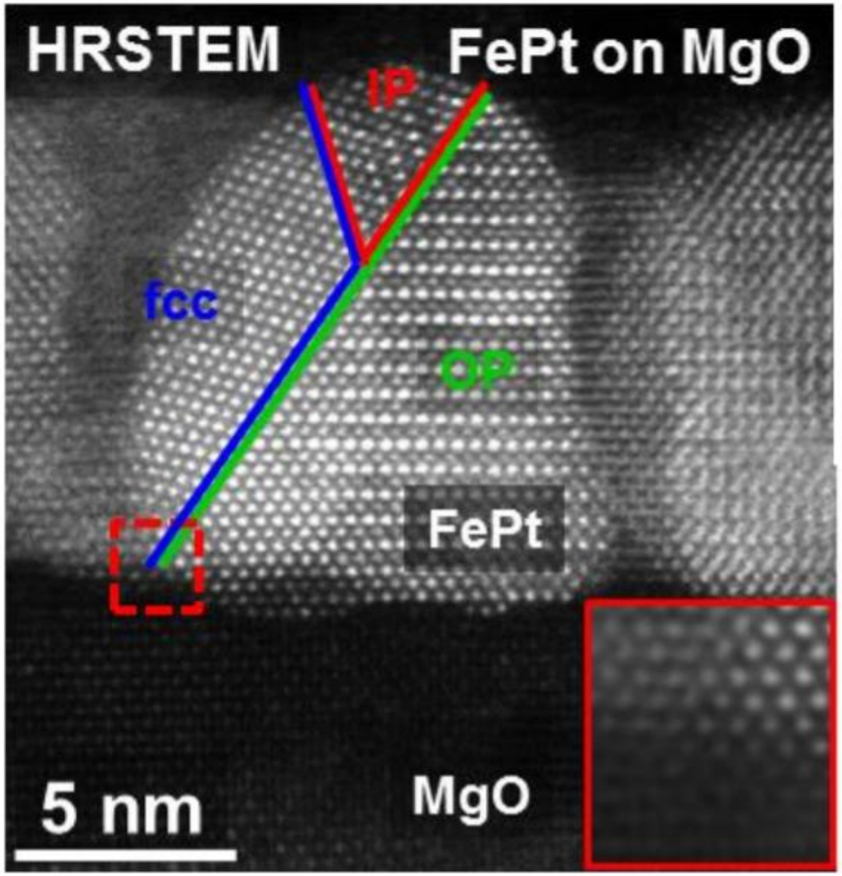


Figure 4. (**a**) Standard $Nd_2Fe_{14}B$ unit cell with [100] zone axis (**b**) HADDF-STEM image of $Nd_{1.5}Dy_{0.5}Fe_{14}B$ at [100] zone axis, (**c**) intensity histogram for the atoms in the red dotted panel in (**b**).

Sci Rep **11,** 6347 (2021)
https://doi.org/10.1038/s41598-021-85713-5

Microsc. Microanal. 22 (Suppl 3), 2016

Simple hard
magnetic structure



FePt

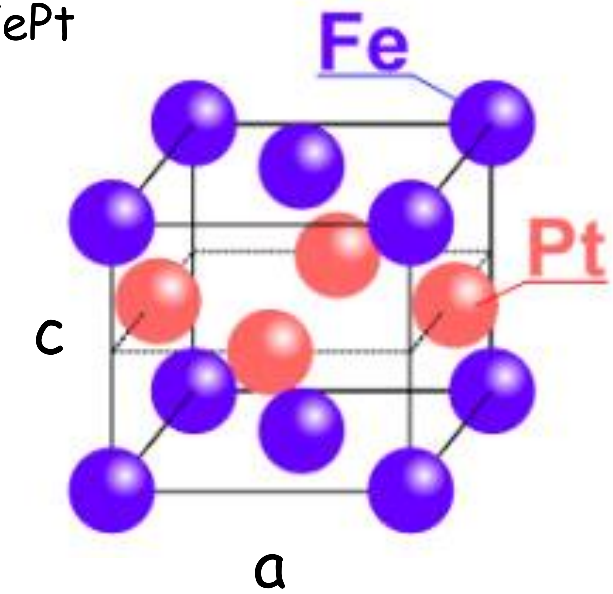


Figure 1. Cross-sectional high-resolution HAADF-STEM image of a defective $L1_0$ FePt grain grown on poly-crystalline (001)-textured MgO underlayer. Out-of-plane (OP) texture as highlighted with green is desired. In-plane (IP) (red segment) and non-ordered fcc (blue segment) sub-grains are defined as defective.

Question 7

Which of the following statements is true?

A: The larger the exchange energy, the larger the domain wall width

B: The larger the exchange energy, the shorter the domain wall width

C: The larger the anisotropy energy, the larger the domain wall width

D: The larger the stray field energy, the larger the domain wall width

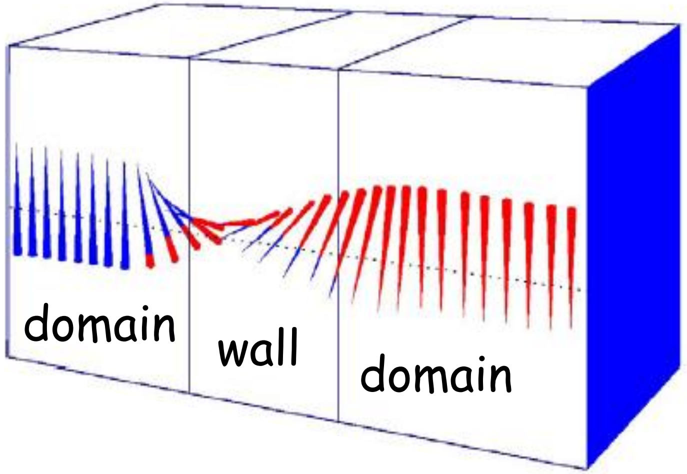
E: The larger the stray field energy, the shorter the domain wall width

Domain wall width and energy

walls $\sigma_w = exchange + anisotropy$

$$= \int_{-\infty}^{\infty} A\left(\frac{\partial\theta}{\partial x}\right)^2 + K\sin^2(\theta)dx$$

How do we define where the domain wall ends?



Minimize the energy (exchange+anisotropy),
No demag energy included in the domain wall

$$\theta(x) = \arctan[\sinh(\pi x/\delta_w)] + \pi/2$$

$\sigma_w = 4\sqrt{AK}$ domain wall energy density *and* $\delta_w = \pi\sqrt{A/K}$ domain wall width

anisotropy K
(energy density)
up to 100 000

exchange
stiffness A
less than 10

The domain wall does not have a precisely defined width, since the direction of magnetization only approaches the easy axis asymptotically. Anisotropy of some sort is necessary for finite domain wall width.

Stray field or demagnetization energy triggers domain formation ➔ domain wall formation
Exchange wants infinitely thick DW, anisotropy wants infinitely thin DW ➔ compromise

Some open discussion …

Compare magnetic data processing and storage in

A) Magnetic HDDs (read/write, mechanics …)
   a) Coil (read/write)
   b) Coil (write), GMR (read)

B) MRAM
   a) Toggle
   b) STT
   c) SOT

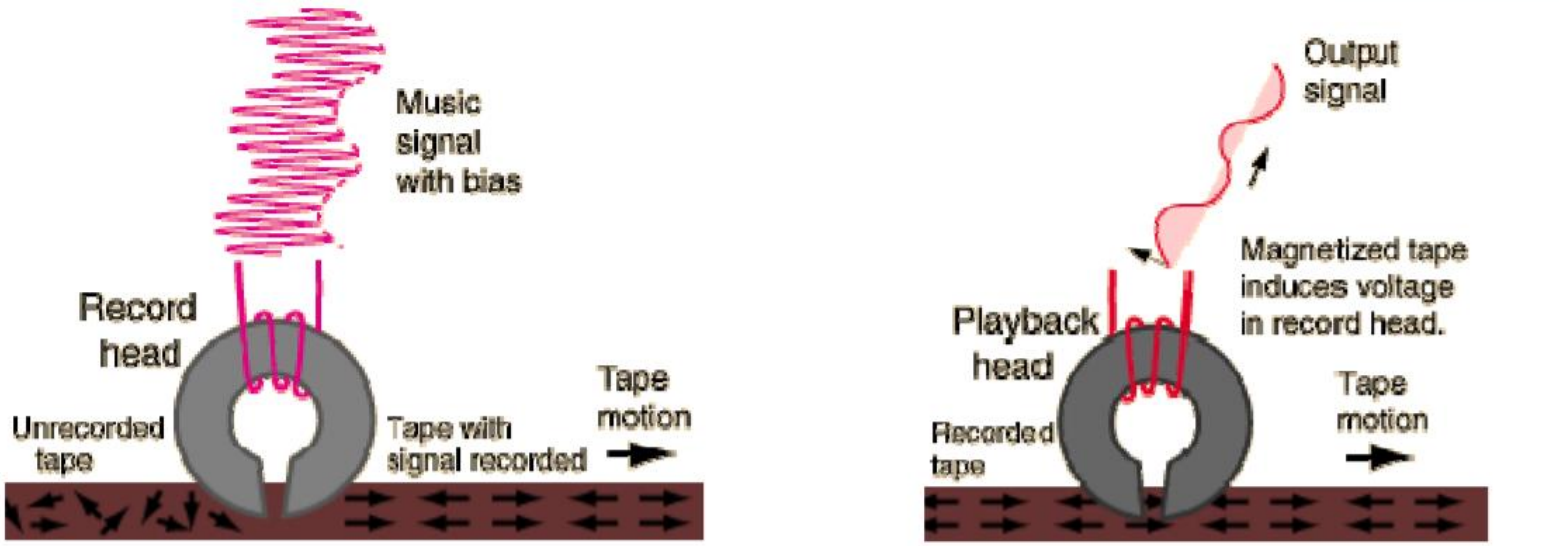
C) Spin Waves / Magnons

Shortly explain how and in which way each technology is superior to the previous one …

Read/Write process in early HDDs

Read/write – simple picture

HITACHI Inspire the Next

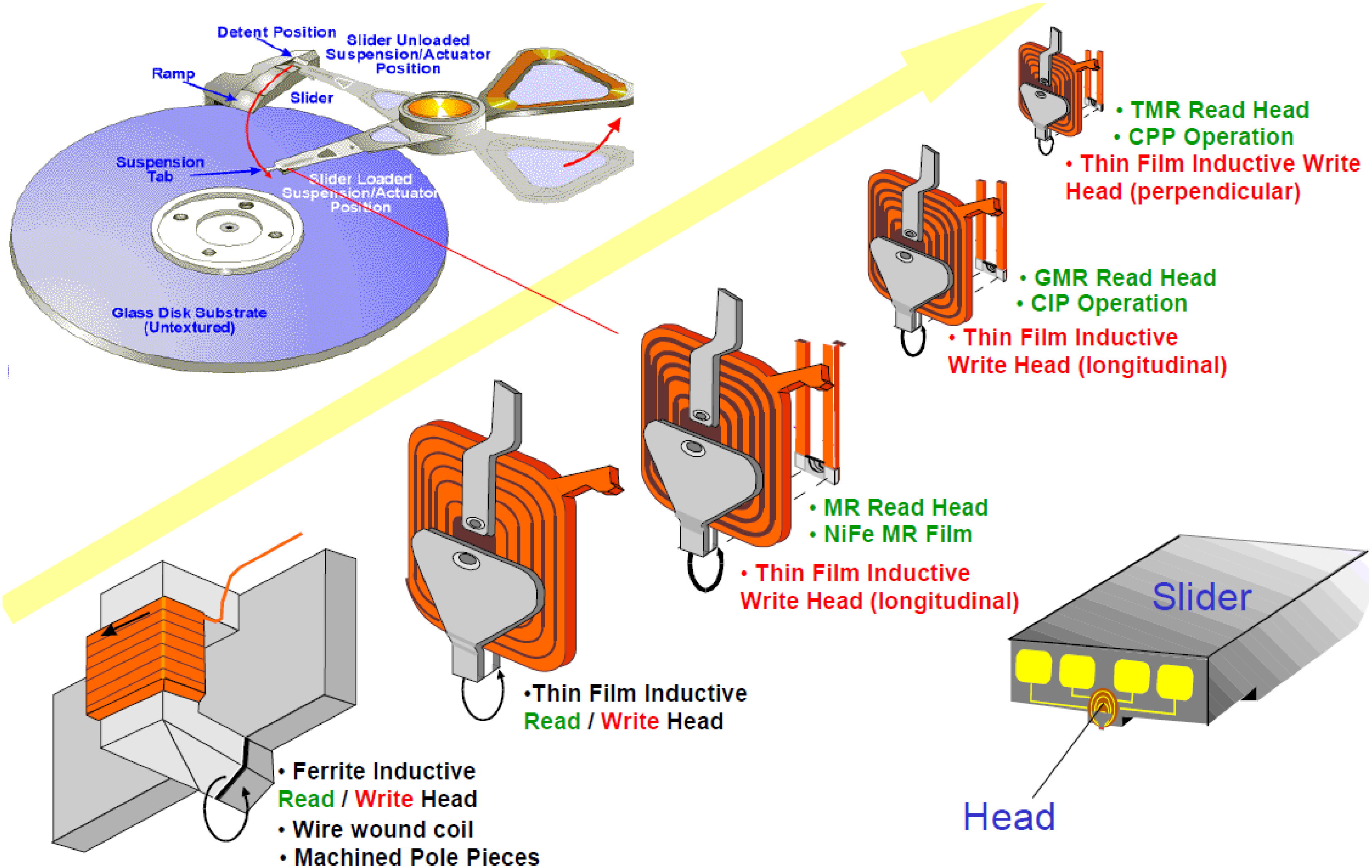


Recording electrical signals **written** onto magnetic media using split-gap electromagnet

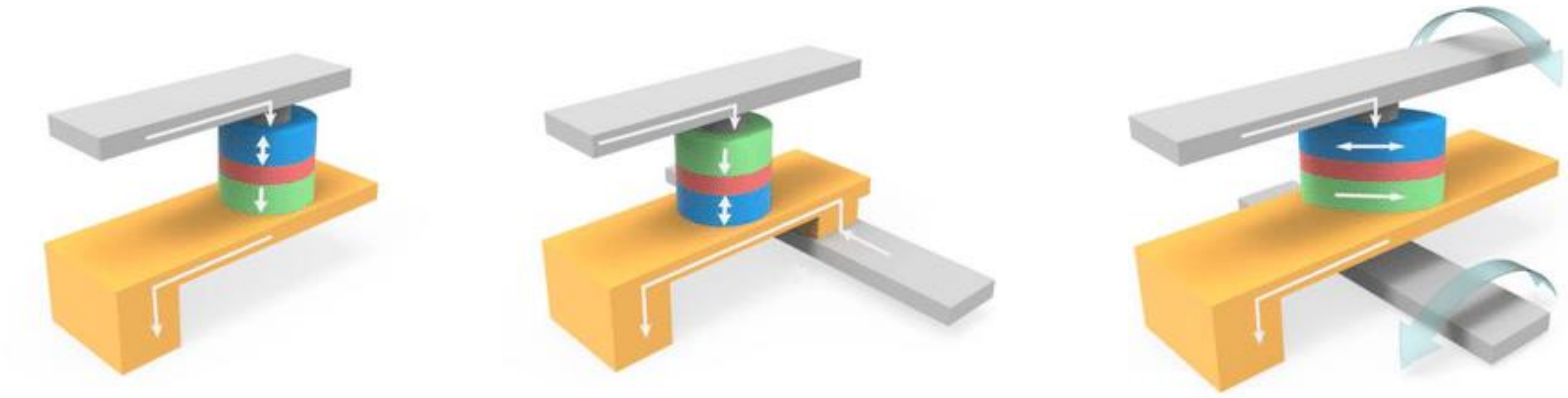
Playback (**Read**) of magnetic signals from magnetic media using (same) split-gap electromagnet

→ *today's* Read and Write components are completely different

Evolution of read/write heads in HDDs



Toggle- versus STT- versus SOT-MRAM

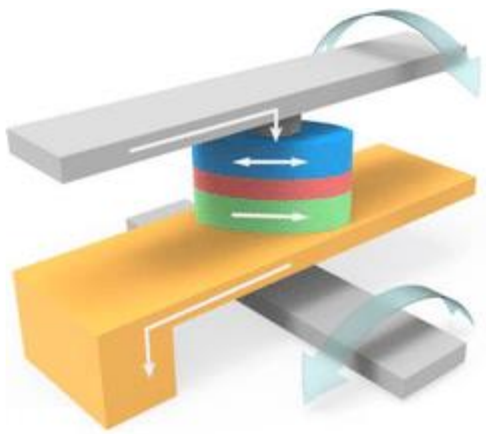


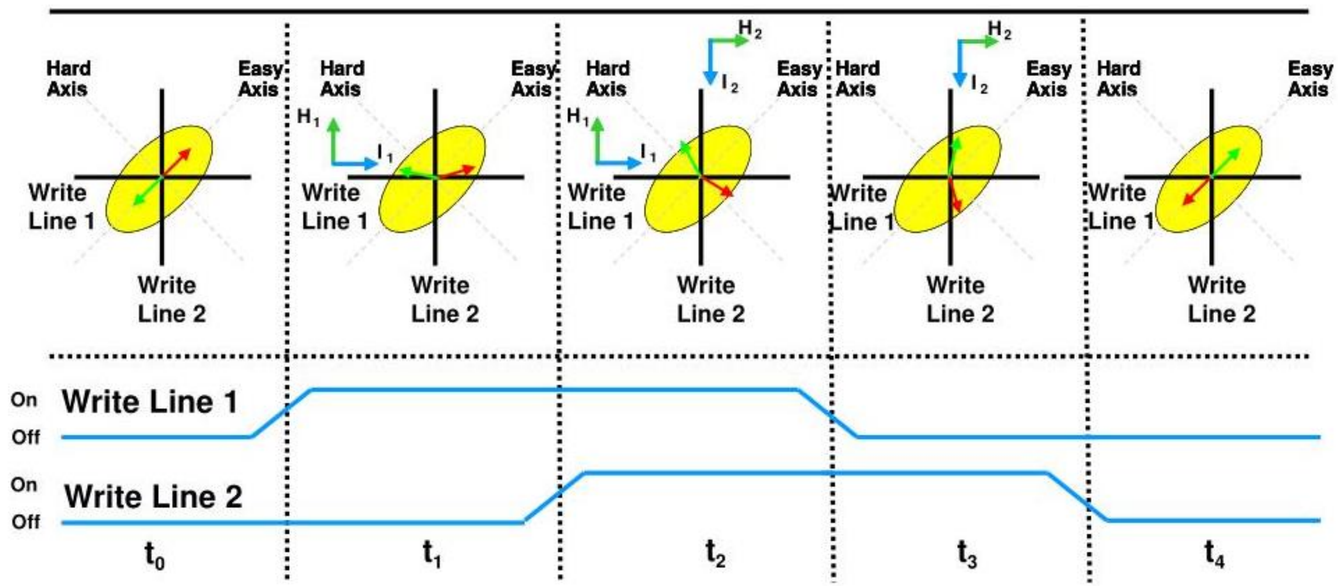
Memristors, Spintronics and 2D Materials for Future Computing Systems

D. Joksas[1], A. AlMutairi[2], O. Lee[3], M. Cubukcu[3,4],
A. Lombardo[3,1], H. Kurebayashi[3], A. J. Kenyon[1], and A. Mehonic[1]

[1]Department of Electronic and Electrical Engineering, University College London, UK
[2]Department of Engineering, University of Cambridge, UK
[3]London Centre for Nanotechnology, University College London, UK
[4]National Physical Laboratory, UK

Toggle-MRAM





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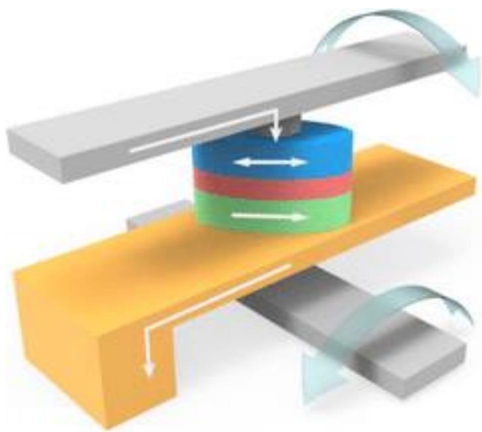
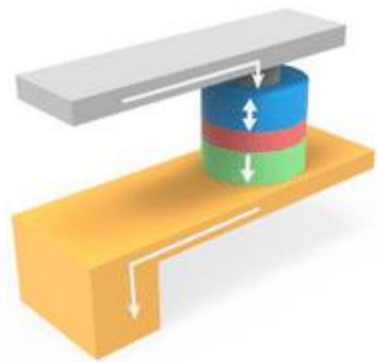
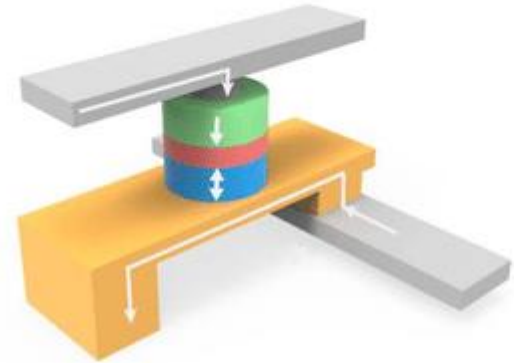
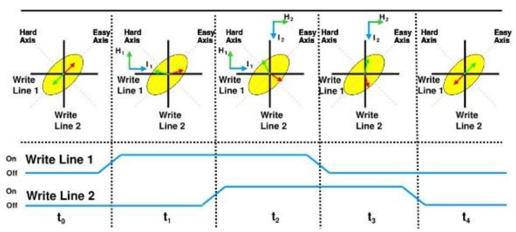
Toggle- versus STT- versus SOT-MRAM









$$I_c = \left(\frac{2e}{\hbar}\right)\left(\frac{\alpha}{\eta}\right) M_s V \left(H + H_{k\perp} - 4\pi M_s\right)$$

The spin Hall angle is a relationship between ***current densities***.

$$\theta_{SH} = \frac{J_S/(\hbar/2)}{J/e}$$

Memristors, Spintronics and 2D Materials for Future Computing Systems

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TECHNISCHE UNIVERSITÄT
IN DER KULTURHAUPTSTADT EUROPAS
CHEMNITZ

Institut für Physik

Physikalisches Kolloquium

- Online-Veranstaltung -

Mittwoch, 18.05.2022, um 11:15 Uhr

Dr. Lucian Prejbeanu
(SPINTEC, Grenoble)

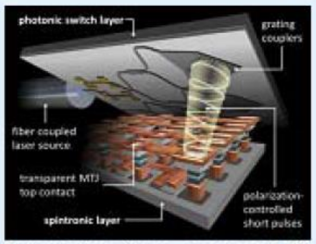
MRAM concepts for sub-nanosecond switching and ultimate scalability

MRAM concepts for sub-nanosecond switching and ultimate scalability

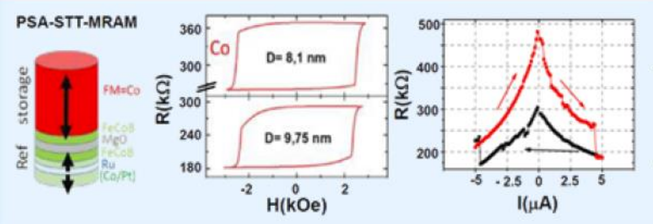
The development of magnetic-tunnel-junctions-based MRAM memories calls for technological breakthroughs intended to go well above the GHz operation speed, to match the speed of the processor. A very promising solution combines the spin-photon interaction, which enables the ultrafast reversal of the storage layer magnetization under the action of a laser pulse of few tens of fs duration. In the framework of the H2020 project called SPICE, SPINTEC demonstrated a conceptually new spintronic-photonic memory chip demonstrator with faster speed and lower energy consumption, as a cornerstone of a novel integration platform that combines photonic, magnetic and electronic components.

In conventional spin-transfer-torque (STT) magnetic random access memory (MRAM), lateral size reductions lead to limited storage retention. We proposed and validated a new MRAM cell concept using shape anisotropy suitable to achieve high retention at sub-10nm critical dimensions. In this concept, the thickness of the storage layer is significantly increased to values comparable to the cell diameter. A further advantage of perpendicular shape anisotropy is to be a robust source of bulk anisotropy less sensitive to temperature, while in conventional MRAM, the thermal sensitivity of the interfacial anisotropy is a limitation to MRAM applications requiring a wide range of operating temperatures.

Why not multilayering?



Schematic view of a hybrid spintronic-photonic demonstrator for ultrafast magnetic memories.



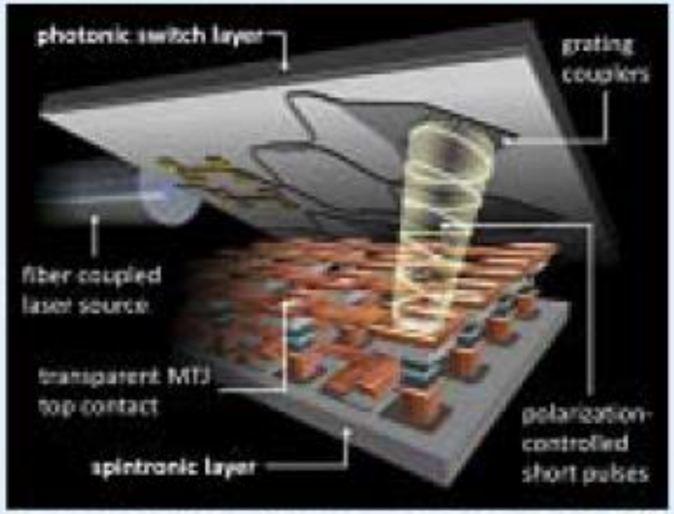
Quasi-static measurements demonstrate the stability, as well as field- and current-induced switching by spin transfer torque for PSA stacks based on a 60 nm thick Co storage layer. The cell diameter is estimated from the electrical resistance of the tunnel junction.

ZOOM-Link:
https://us02web.zoom.us/j/82310833626

Informationen zum Vortrag erteilt:

Prof. Dr. Georgeta Salvan, Tel.: 0371 531 33137

www.tu-chemnitz.de/physik



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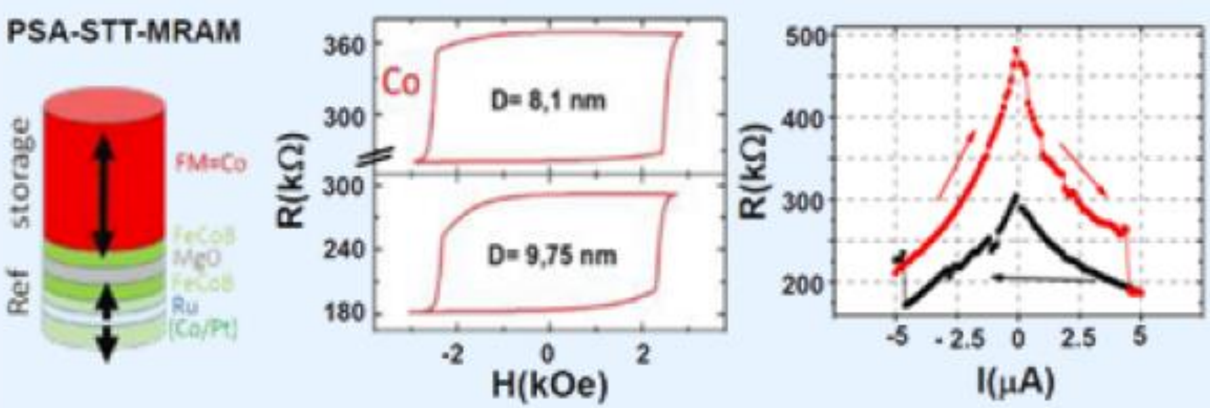

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Institut für Physik
Physikalisches Kolloquium

Mittwoch, 22.06.2022, um 11:15 Uhr

HS 013, Hörsaalgebäude, Reichenhainer Str. 90 und online via ZOOM

Dr. Tiffany S. Santos

Western Digital Corporation, San José, USA

Spins, Bits, and Flips: Essentials for High-Density Magnetic Random-Access Memory

Biography

Tiffany S. Santos received her S.B. and Ph.D. degrees in Materials Science and Engineering from MIT. Her Ph.D. thesis was on thin-film magnetism and spin-polarized tunneling in magnetic tunnel junctions under the supervision of Jagadeesh Moodera at the Francis Bitter Magnet Laboratory, MIT. She is the Director of Non-Volatile Memory Materials Research in the research division of Western Digital Corporation in San Jose, California where she leads a team working on materials for magnetic random access memory technology and other exploratory projects. She first joined the company in 2011, when it was previously known as Hitachi Global Storage Technologies, to work on research of granular FePt media for heat-assisted magnetic recording. Prior to working in industry, she was a Distinguished Post-Doctoral Fellow, and later an Assistant Scientist, at the Center for Nanoscale Materials in Argonne National Laboratory, where she studied emergent phenomena at the interfaces of complex oxide heterostuctures. Dr. Santos has an active role in professional societies in the magnetism community. She is a 2022 Distinguished Lecturer of the IEEE Magnetics Society. She was the Program Co-Chair of the 2020 INTERMAG Conference, and she will be the General Chair of the 2025 Magnetism and Magnetic Materials (MMM) Conference in Palm Beach, Florida. In 2009, she was awarded the prestigious L'Oréal USA Fellowship for Women in Science.

ZOOM-Link:
https://us02web.zoom.us/j/82310833626

Informationen zum Vortrag erteilt:
Prof. Dr. Olav Hellwig, Tel.: 0371 531 30521

www.tu-chemnitz.de/physik

Spins, Bits, and Flips: Essentials for High-Density Magnetic Random-Access Memory

Tiffany S. Santos, PhD
Western Digital Corporation
2022 IEEE Magnetics Society Distinguished Lecturer

The magnetic tunnel junction (MTJ), a device comprised of two ferromagnetic electrodes with a thin (about 1 nm) insulating tunnel barrier in between, was first proposed in a Ph.D. thesis by Michel Jullière in 1975 [1] and reached widespread commercialization nearly 30 years later as the read sensor in hard disk drives. MTJs became essential for data storage in consumer laptop and desktop computers, early-generation iPods, and now in data centers that store the information in "the Cloud." The application of MTJs has expanded even further, becoming the storage element in non-volatile memory, first in toggle magnetic random access memory (MRAM) used in automotive applications and outer space, and now in the production of spin-transfer torque MRAM as a replacement for embedded flash memory. As computing capabilities advance and drive demand for high-performance memory, innovation in MTJ continues in order to deliver faster, high-density MRAM that can support last-level cache, in-memory computing, and artificial intelligence.

In this talk, I will describe the seminal discoveries [2] that enabled MTJs for pervasive use in hard disk drives, MRAM, and magnetic sensors, such as the discovery of tunnel magneto-resistance (TMR) at room temperature, the invention of spin-transfer torque as the means to flip magnetization without a magnetic field, and the prediction and realization of high TMR using MgO tunnel barriers. As the demand for faster and higher density memory persists, still more breakthroughs are needed for MTJs contained in device pillars (or bits) just tens of nanometers in diameter. These advances require tuning of material properties at the atomic scale as well as across arrays of millions of bits in a memory chip. I will describe the magnetic properties of MTJs that are essential for high-performance MRAM, including perpendicular magnetic anisotropy, damping parameter, exchange constant, thermal stability factor, and TMR, and how to engineer these properties to deliver high spin-transfer torque efficiency and high data retention in spin-transfer torque MRAM devices [3,4]. In addition, I will describe an innovative nanofabrication process for achieving dense arrays of MRAM bits with 50 nm full pitch [5].

[1] M. Jullière, Ph.D. thesis, Rennes University, No. B368/217, Rennes, France, 1975; M. Jullière, Phys. Lett. A 54, 225-226 (1975).

[2] J. S. Moodera, G.-X. Miao, T. S. Santos, Physics Today 63, 46-51 (2010).

[3] T. S. Santos, G. Mihajlović, N. Smith, J.-L. Li, M. Carey, J. A. Katine, B. D. Terris, J. Appl. Phys. 128, 113904 (2020).

[4] G. Mihajlović, N. Smith, T. Santos, J. Li, B. D. Terris, J. A. Katine, Appl. Phys. Lett. 117, 242404 (2020).

[5] L. Wan, T.-W. Wu, N. Smith, T. Santos, G. Mihajlović, J.-L. Li, K. Patel, N.D. Melendez, B. Terris, J.A. Katine, IEEE Trans. Magn. 58(5), 3400406 (2022).

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.

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Discussion about and feedback on the lecture recordings