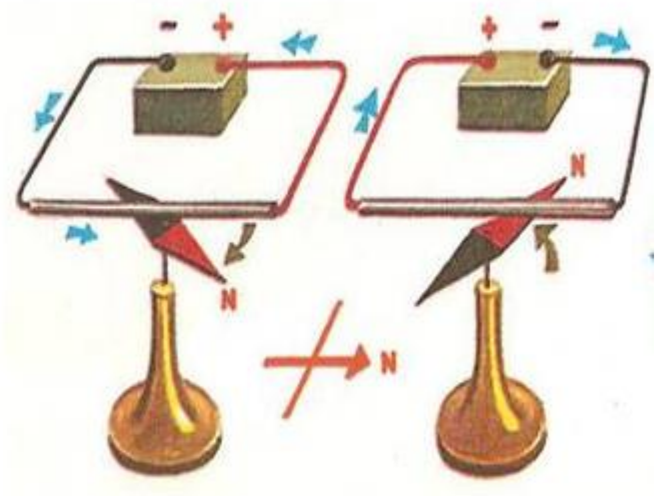
4. Magnetism

Repetition from the last lecture

- What is photonics?
- What is a surface plasmon?
- What are localised surface plasmons used for?
- Can light pass through a hole smaller than its wavelength? If so, what are the properties of transmitted light?
- What causes the brilliant color of opal, butterflies and peacock feathers?
- What kinds of chromic materials exist and what are they used for?

Introduction to Magnetism

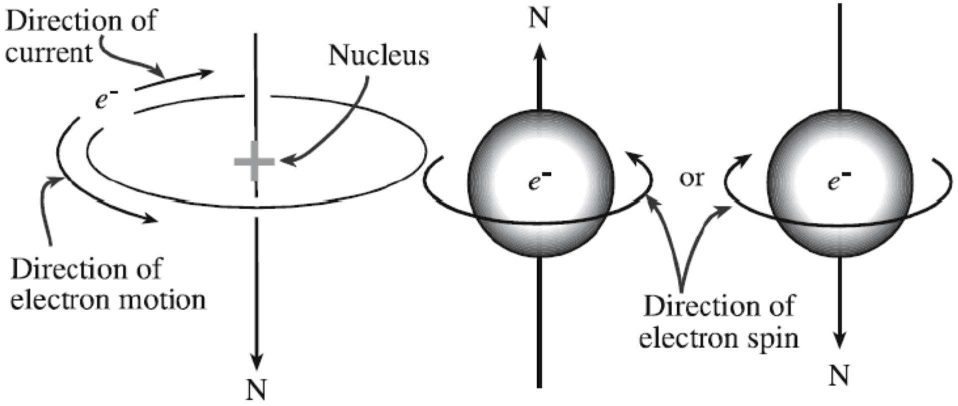
- In 1820 Hans Christian Oersted discovered that electric current (movement of electric charge) induces a magnetic field in its surroundings.
    - The mathematical description of this phenomenon is described by the Biot-Savart(-Laplace) law and Maxwell's equations



https://qsstudy.com/oersteds-idea-magnetic-field/

Magnetism of Matter

- Magnetism of matter is caused by the movement of electric charge in the matter. The main sources of this movement are:
  - The movement of an electron in an atomic orbital (orbital magnetic moment)
  - The rotation of the electron about its axis (spin magnetic moment)

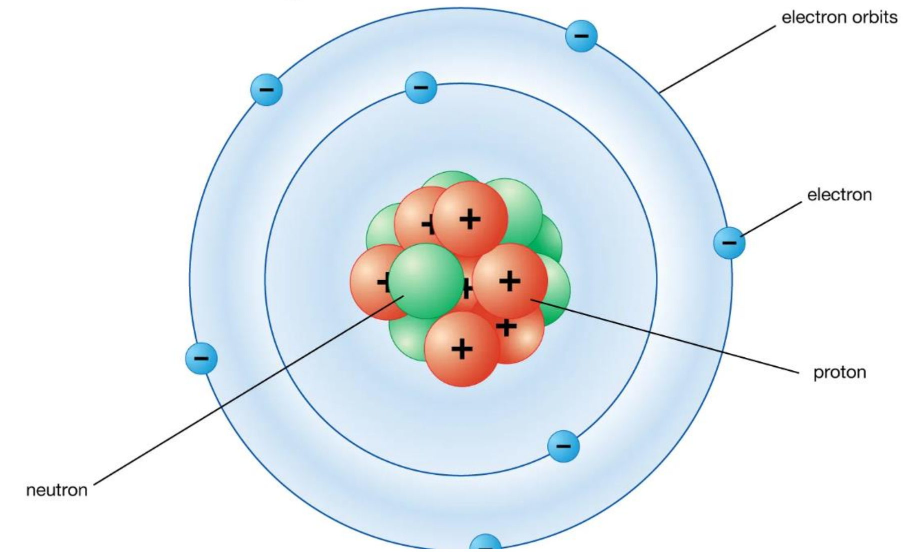


- Both contributions are added together (the contribution of spin is about 2x more significant).

Atom

- Bohr model from the 20th century does not describe the atom accurately enough

Bohr atomic model of a nitrogen atom



- It was not until quantum physics came up with a better description – electrons have a wave-particle nature and we only describe the probability of their occurrence – this is the highest in orbitals.

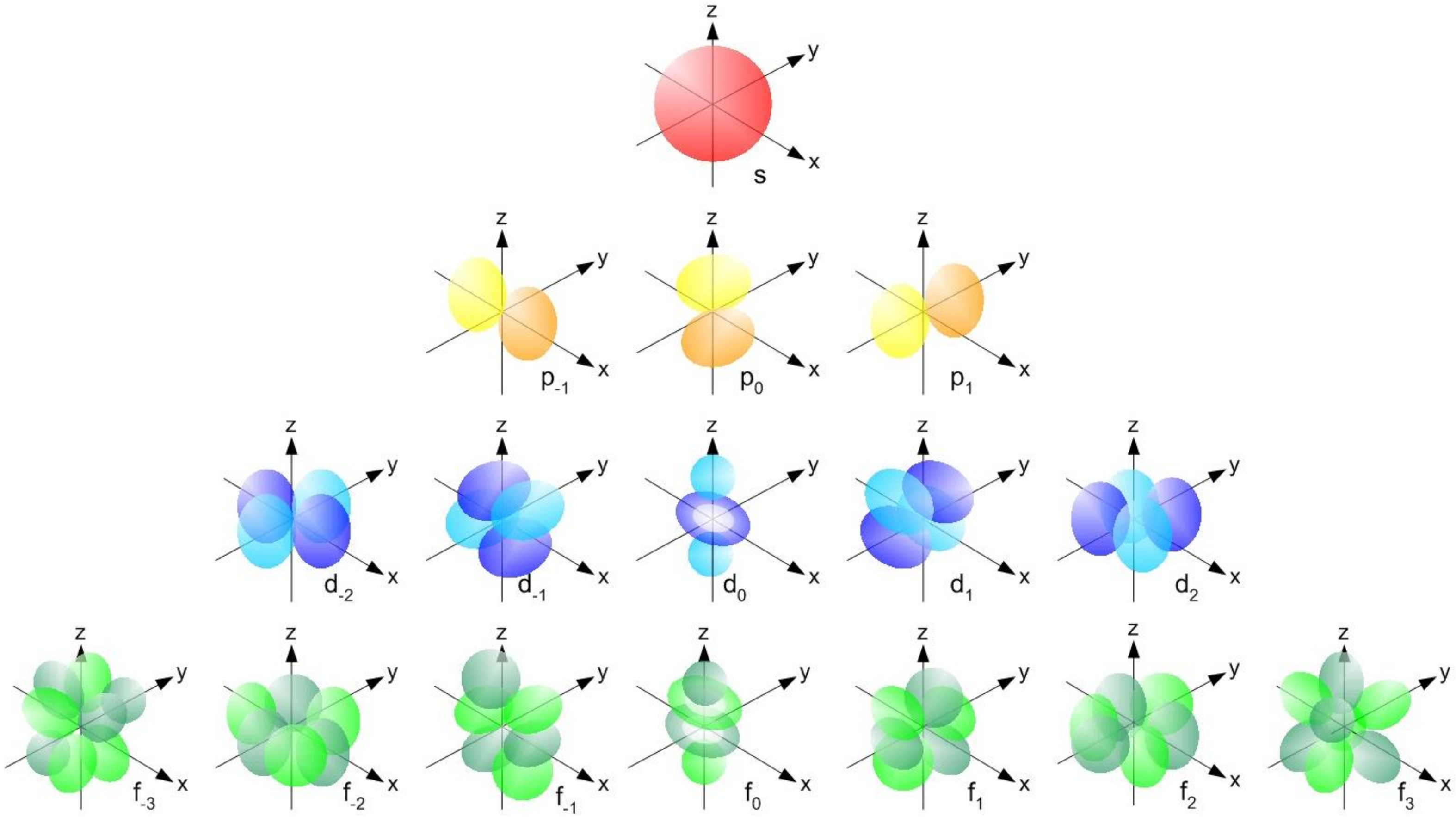
https://www.britannica.com/science/Bohr-model

Atom – Quantum Numbers

- If there are electrons in an electron shell, their stationary states are described by the quantum numbers n, l, m and m_s. No two electrons in an atom can have all quantum numbers the same (Pauli exclusion principle).

Quantum number	**Symbol**	**Allowed values**	**It describes**	**It determines**
Principal	n	1, 2, 3, 4,… (K, L, M, N, …)	energy and distance from the nucleus	energy and orbital size
Azimuthal (Orbital)	l	0, 1 , 2, 3, … n-1 (s, p, d, f)	orbital angular momentum	shape of the orbital
Magnetic	m	0, ±1, ±2, …, ±l	orbital magnetic moment	orbital orientation in space
Spin	m_s	±1/2	spin magnetic moment	internal angular momentum

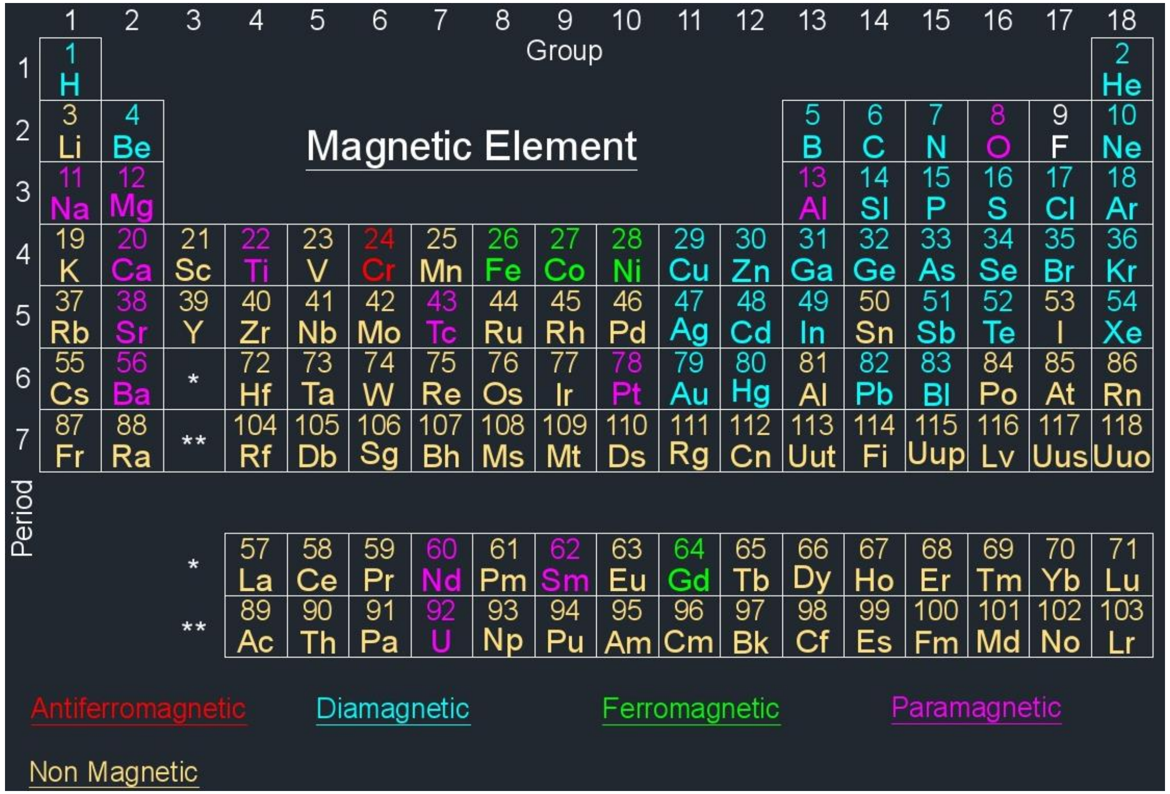
Orbitals



https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Quantum_Mechanics/09._The_Hydrogen_Atom/Atomic_Theory/Electrons_in_Atoms/Electronic_Orbitals

Magnetic Periodic Table

- In practice, we do not work with individual atoms, but with solids. Therefore, we work with bonding orbitals instead of atomic orbitals (those overlapping between atoms and forming bonds).



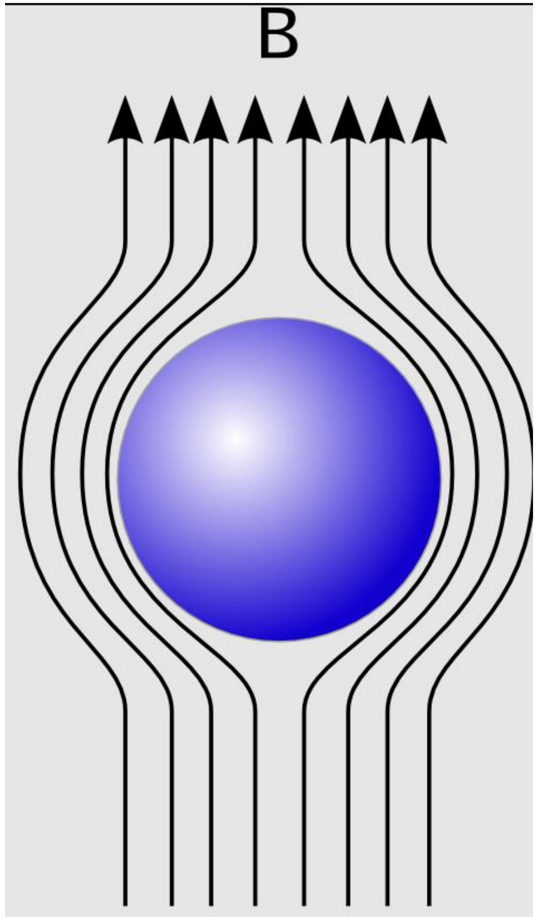
Magnetic Element

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Al	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Ms	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fi	115 Uup	116 Lv	117 Uus	118 Uuo
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

https://www.piping-designer.com/index.php/disciplines/chemical/chemical-elements/1875-magnetic-element

Basic Types of Matter – Diamagnetic Materials

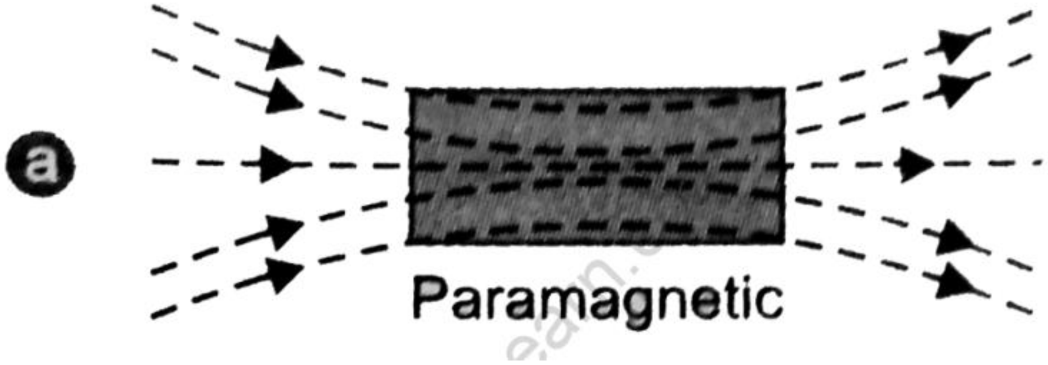
- Material with paired electrons – it dows not create a magnetic field on its own
- External magnetic field partially deforms the orbitals and the field is weakened inside the diamagnetic
- No significant industrial applications
- Al_20_3, B, C, Ge, Au, Pb, Si, Ag, NaCl, …



https://en.wikipedia.org/wiki/Diamagnetism

Basic Types of Matter – Paramagnetic Materials

- A material with unpaired electrons with mutually independent magnetic moments. These do not collectively interact with each other.
- Magnetic susceptibility is positive and hence by applying an external magnetic field, the spin moments are rotated and the field is amplified.
- When removed from the magnetic field, the magnetic moments will again randomly spin and lose magnetic properties.
- They have no significant industrial application.
- Al, Ca, Cr, Li, Mg, Na, Ti, FeO, …



https://infinitylearn.com/surge/blog/iit-jee/paramagnetic-materials/

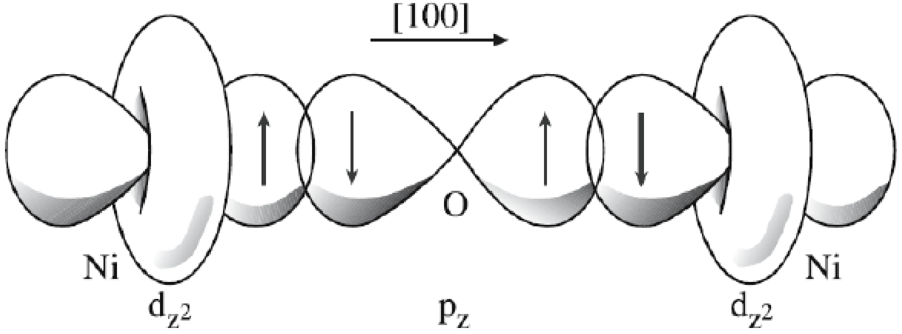
Basic Types of Matter – Ferromagnetic Materials

Ferromagnetic materials

- Magnetic spin moments are oriented in the same direction : ↑↑ ↑↑ ↑ ↑
- They show very strong magnetism
- Fe, Co, Ni, Gd, $Nd_2Fe_{14}B$ (neodymium magnet), …

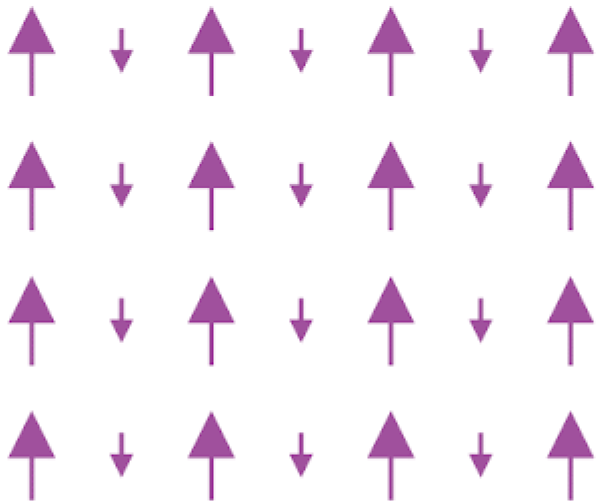
Antiferromagnetic materials

- Magnetic spin moments are oriented antiparallel: ↑↓ ↑↓ ↑↓
- They show weak magnetism
- CoO, NiCo, NiO, …



Basic Types of Matter – Ferrimagnetic Materials

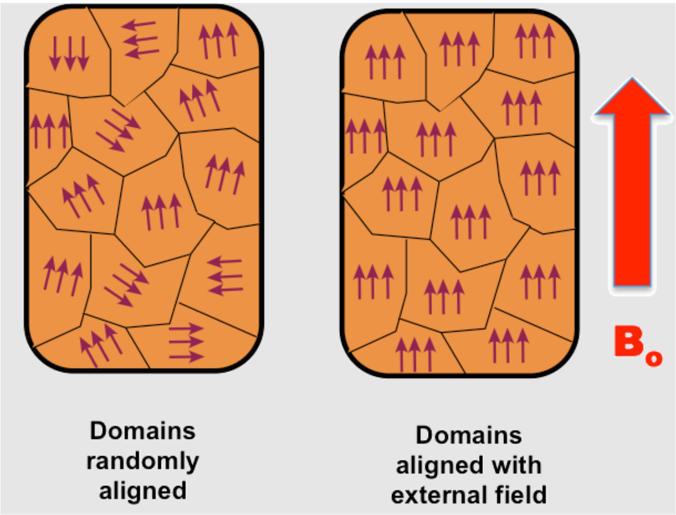
- The crystal contains 2 sublattices with antiparallel oriented magnetic moments of different sizes.
- The moments are only partially cancelled and the material is characterized by spatial magnetization.
- Ferrites - most are electrical insulators (use in high frequency electronics)
- Fe_3O_4, YFe_5O_{12}, $CoFe_2O_4$,…

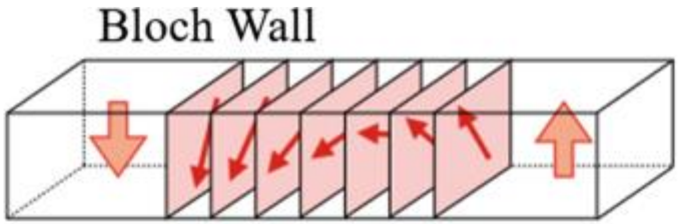


http://sciexplorer.blogspot.com/2011/10/magnetism-explained-4-other-kinds-of.html

Magnetic Domains

- Ferromagnetic and ferrimagnetic materials consist of small regions (domains) with the same direction of magnetization. In an unmagnetized material, the total magnetization is zero despite the magnetization of the individual domains.
- The interface between the domains is called the Bloch wall and has a thickness of ~ 100 nm
- When exposed to an external magnetic field, the domain boundaries shift and become larger. This is not simply a reversible process and a hysteresis loop is observed.

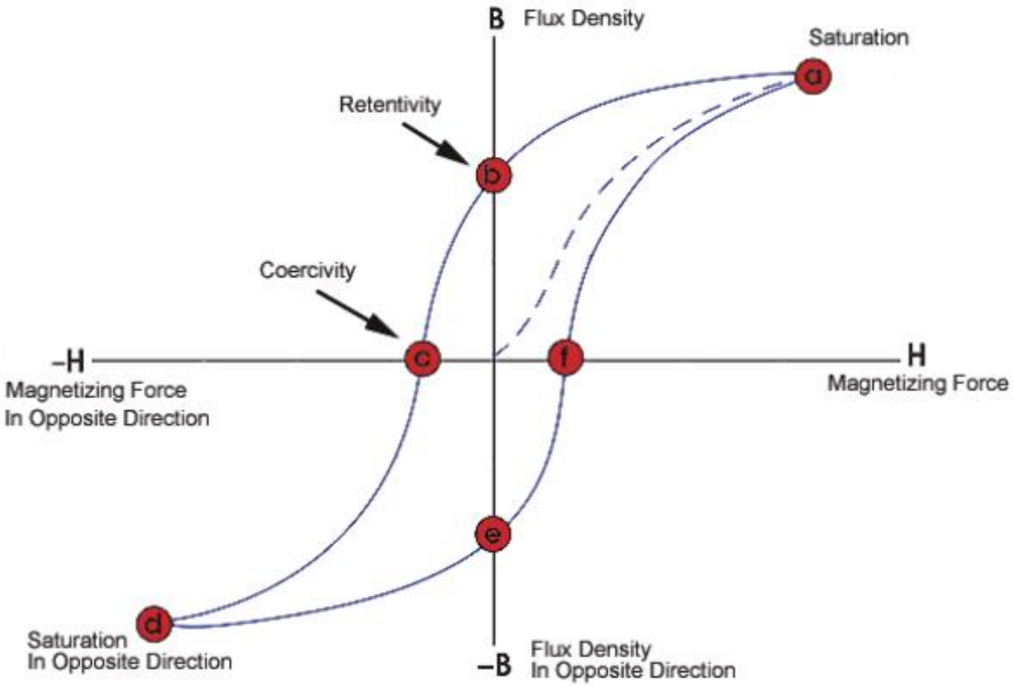




https://www.wenzelamerica.com/its-a-dogs-bark-its-a-barcalounger-its-barkhausen-noise-analysis/magnetic-domains/
http://cpb.iphy.ac.cn/article/2018/1941/cpb_27_6_066802/cpb_27_6_066802_f5.jpg.html

Magnetic Hysteresis Loop

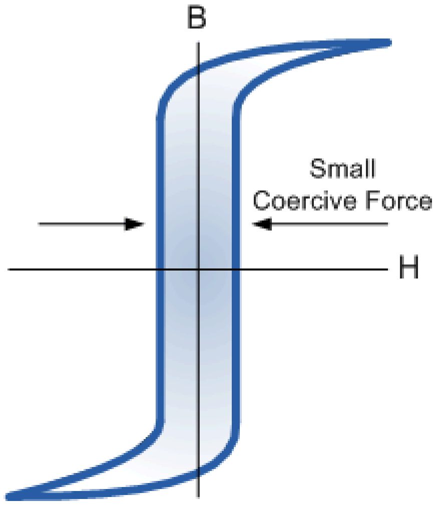
- b,e – remanence = permanent magnet
- c,f – coercivity – resistance of the magnet to external field against its demagnetization
- The material returns to 0,0 only when heated to the Curie temperature T_c



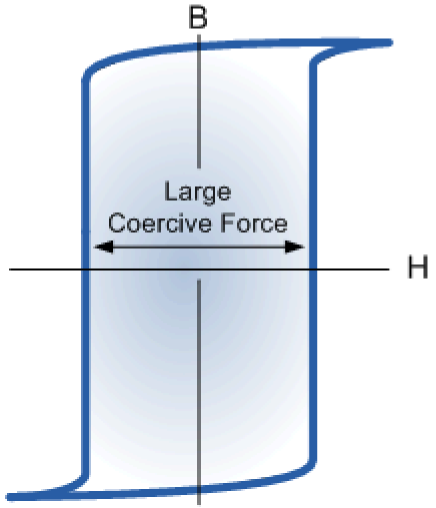
https://www.nde-ed.org/Physics/Magnetism/HysteresisLoop.xhtml

Magnetically Hard and Soft Materials

- Soft materials
  - Domains in the material respond rapidly to changes in the magnetic field.
  - The area of the hysteresis curve is relatively small = relatively little work required to change magnetization (small heat loss).
  - Transformer cores, magnetic recording media,...
- Hard materials
  - Permanent magnets (motors, locks,...)



“Soft” Ferromagnetic Material

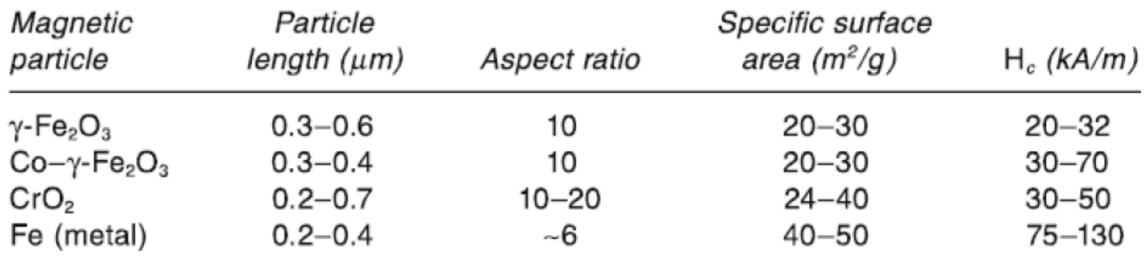


“Hard” Ferromagnetic Material

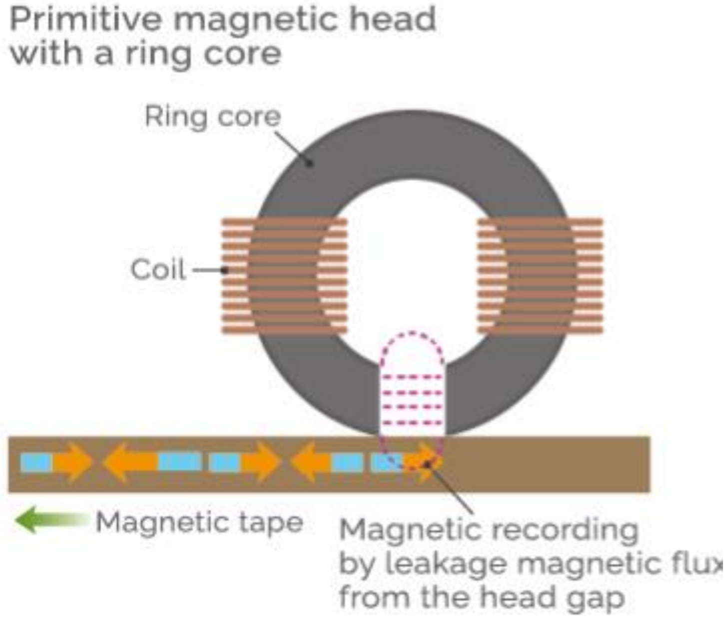
https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

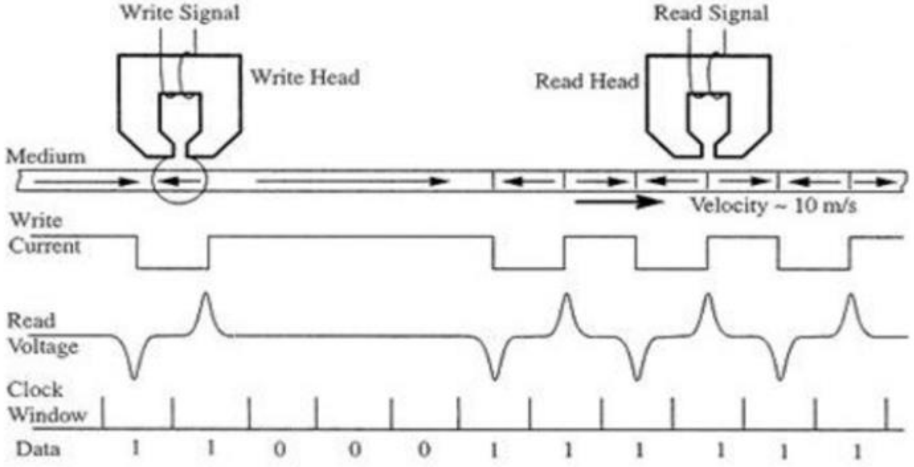
Magnetic Data Recording

- Coercivity large enough to preserve the data, but not too large that the data can be deleted
- Small and light – homogeneously distributed needle-like particles



Magnetic particle	*Particle length (μm)*	*Aspect ratio*	*Specific surface area (m^2/g)*	*H_c (kA/m)*
γ-Fe_2O_3	0.3–0.6	10	20–30	20–32
Co–γ-Fe_2O_3	0.3–0.4	10	20–30	30–70
CrO_2	0.2–0.7	10–20	24–40	30–50
Fe (metal)	0.2–0.4	~6	40–50	75–130

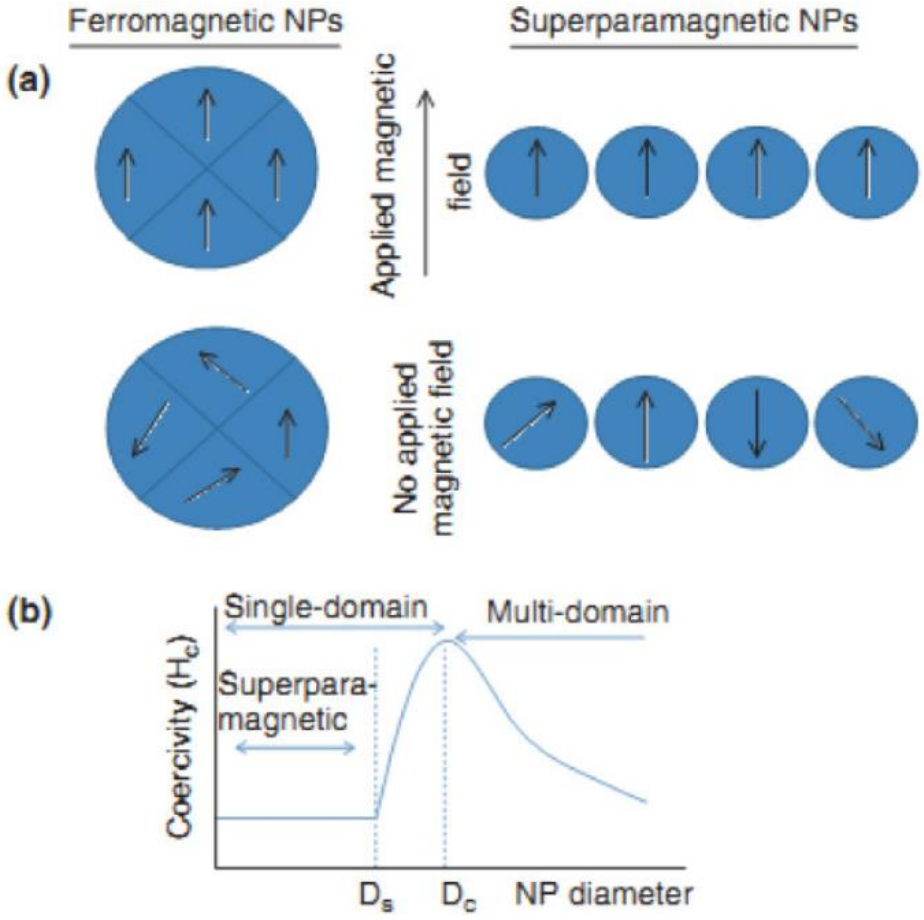




https://www.tdk.com/en/tech-mag/ferrite02/006
https://www.researchgate.net/figure/Magnetic-Recording-working-principle_fig2_290150099

Magnetic nanoparticles

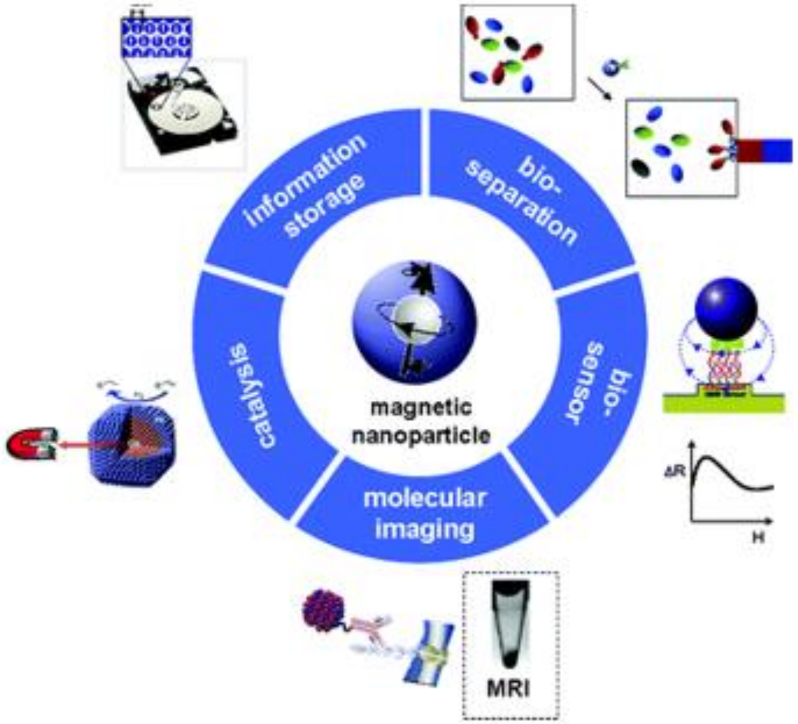
- By shrinking ferromagnetic to the size of a single domain, we observe different properties.
- Superparamagnetism – owing to the small size, the thermal energy is large enough to „turn“ the spin of an electron. The spins in the domain are no longer all aligned.



https://www.researchgate.net/publication/221846063_Magnetic_nanoparticles_Preparation_physical_properties_and_applications_in_biomedicine

Magnetic Nanostructures – Application

- Spintronics
- Bioapplications
- Imaging
- Catalysis
- …



https://www.cd-bioparticles.com/t/Properties-and-Applications-of-Magnetic-Nanoparticles_55.html

Magnetic Field Detection

- Photonic crystals with Fe_3O_4 core
- They change their band structure with different magnetic field - absorption/reflection of different colors

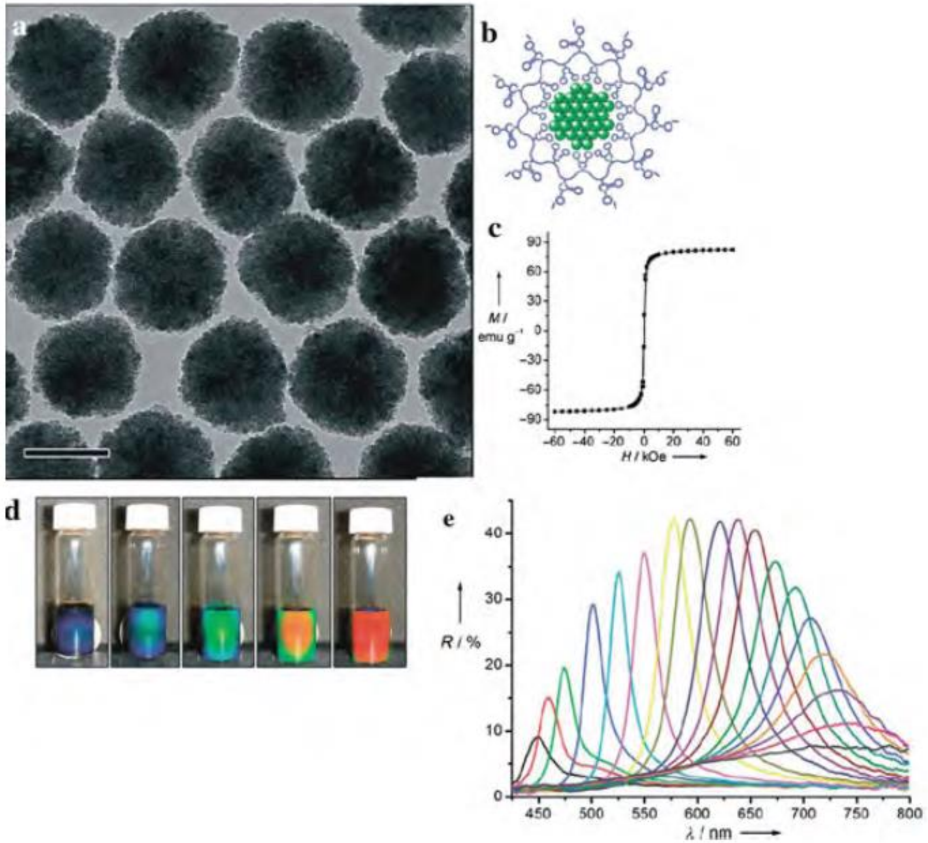
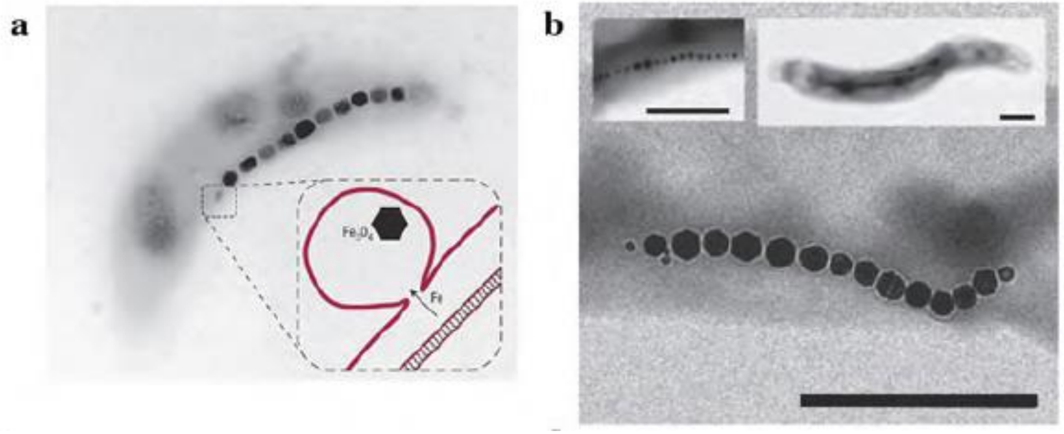


Fig. 8.40 (**a**) Transmission electron micrograph and (**b**) schematic illustration of polyacrylate-capped Fe_3O_4 colloidal nanocrystal clusters (CNCs) with a nanocrystal size of ∼ 10 nm; scale bar: 100 nm. (**c**) Magnetization curve of CNCs measured at room temperature exhibiting superparamagnetic behavior. (**d**) Photographs of solutions of colloidal photonic crystals formed in response to an external magnetic field; the magnet–sample distance decreases gradually from *right* to *left*.

H.E. Schaefer, Nanoscience: The Science of the Small in Physics, Engineering, Chemistry, Biology and Medicine, Springer, 2010

Medical Imaging

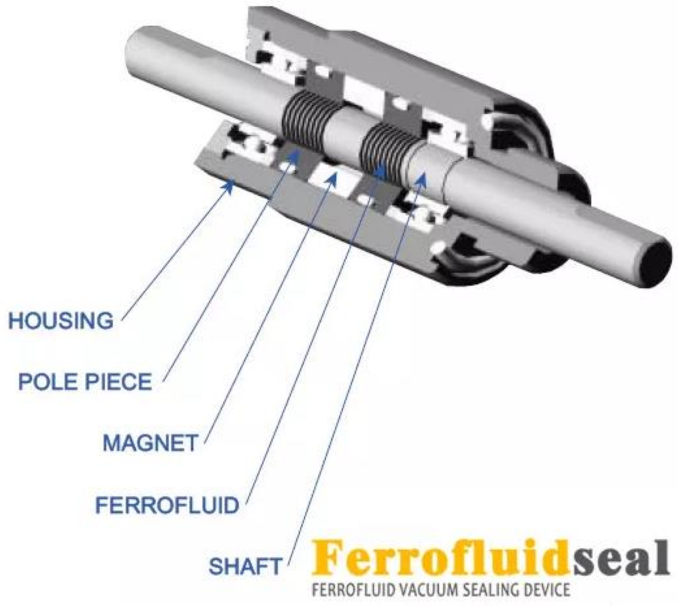
- Magnetic nanoparticles coated with a specific antibody bind to a virus under investigation and form clusters large enough for imaging, e.g. in NMR
- Obtaining magnetic nanoparticles, for example from magnetotactic bacteria (e.g. Magnetospirillum magnetotacticum) – these biomaterialize magnetosomes (magnetic Fe_3O_4 nanoparticles) from iron

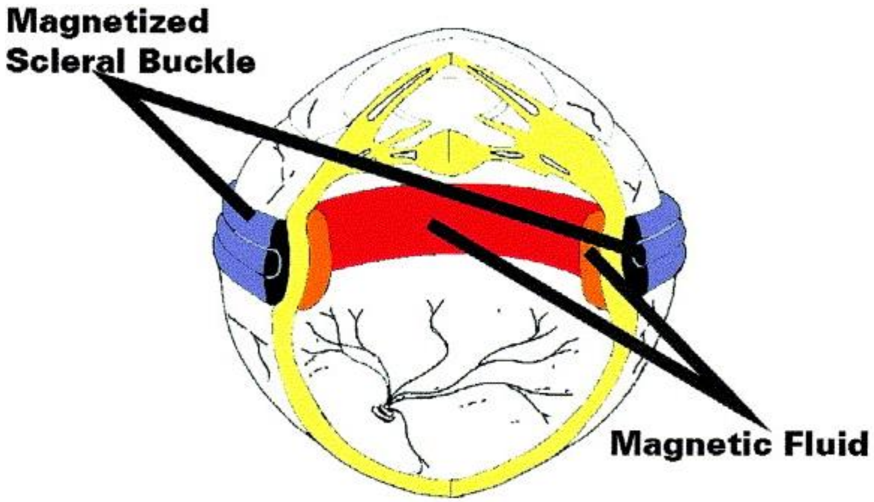


H.E. Schaefer, Nanoscience: The Science of the Small in Physics, Engineering, Chemistry, Biology and Medicine, Springer, 2010

Ferrofluid

- Stable colloidal systems of monodomain particles in a liquid carrier (water, oil,...).
- Application:
  - Sealing – oil ferrofluid and a suitable magnet seals the space (vacuum, bearings,...)
  - imaging
  - medicine

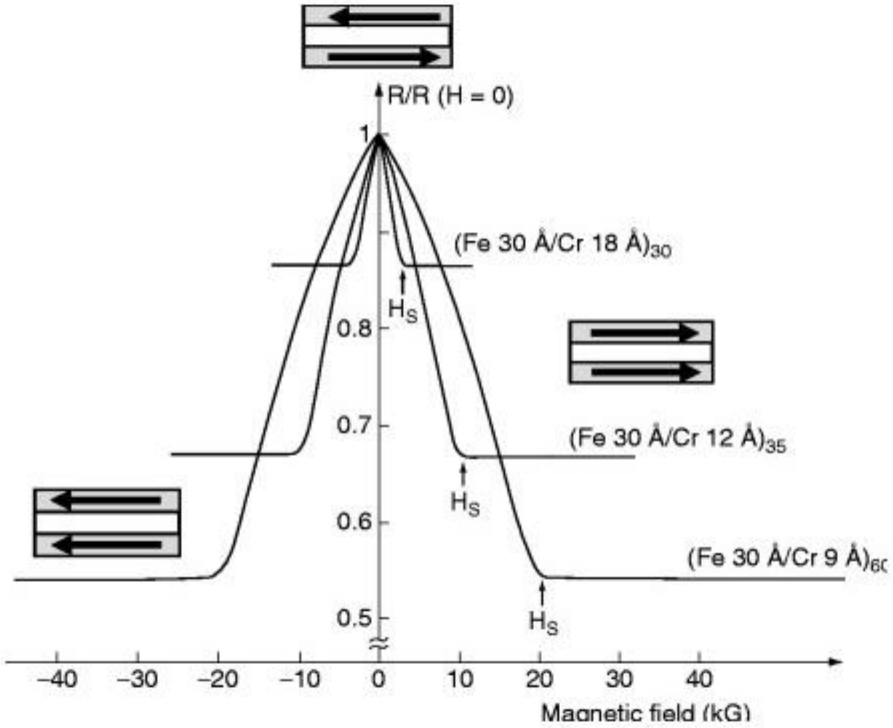




https://www.sciencedirect.com/science/article/abs/pii/S0304885398005629

Giant Magnetoresistance (GMR)

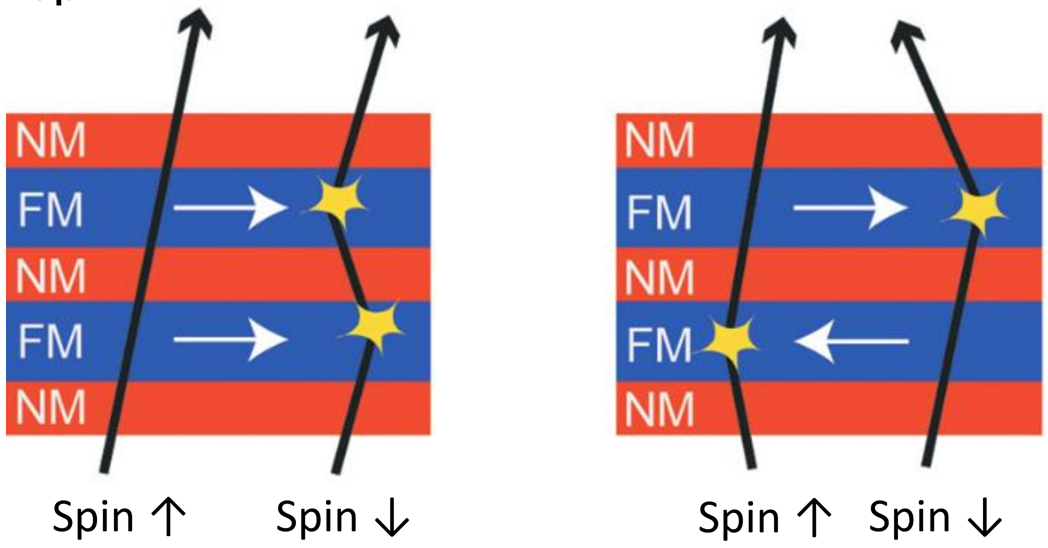
- Multilayer nanomagnetic structure
- Discovered in 1988, Nobel Prize 2007
- A thin layer of conducting material separates 2 ferromagnetic layers. The thickness of all layers is less than the mean free path of an electron in the conducting material (about 100 nm). Depending on the direction of magnetization, the electrical resistance across the layers changes significantly (> 80%),



https://www.sciencedirect.com/topics/chemistry/negative-magnetoresistance

GMR – Mott‘s Theory

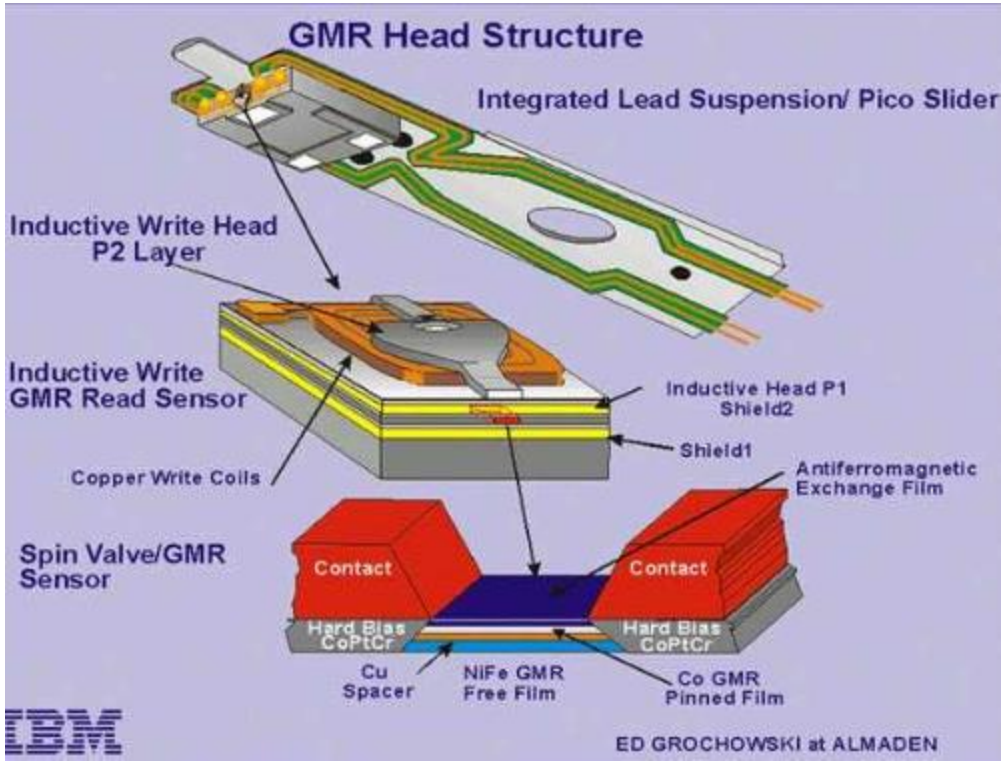
- The electric current in metals can be divided into the current conducted by electrons with spin ↑ and with spin ↓. Their motion can be characterized by resistance.
- Ferromagnetic material is characterized by an excess of one type of spin.
- A moving electron with spin with the same orientation as the ferromagnetic material does not have enough exergy levels to relax to, and therefore its collisions are elastic – it does not lose energy in them.
- An electron with the opposite spin orientation undergoes frequent inelastic collisions where it loses energy (higher resistance).
- Coincidentally oriented magnetizations allow one type of spin to pass without collisions
- Oppositely oriented will slow down both types of spin.



https://www.researchgate.net/publication/316839051_Magnetic_sensing_platform_technologies_for_biomedical_applications

Use of GMR

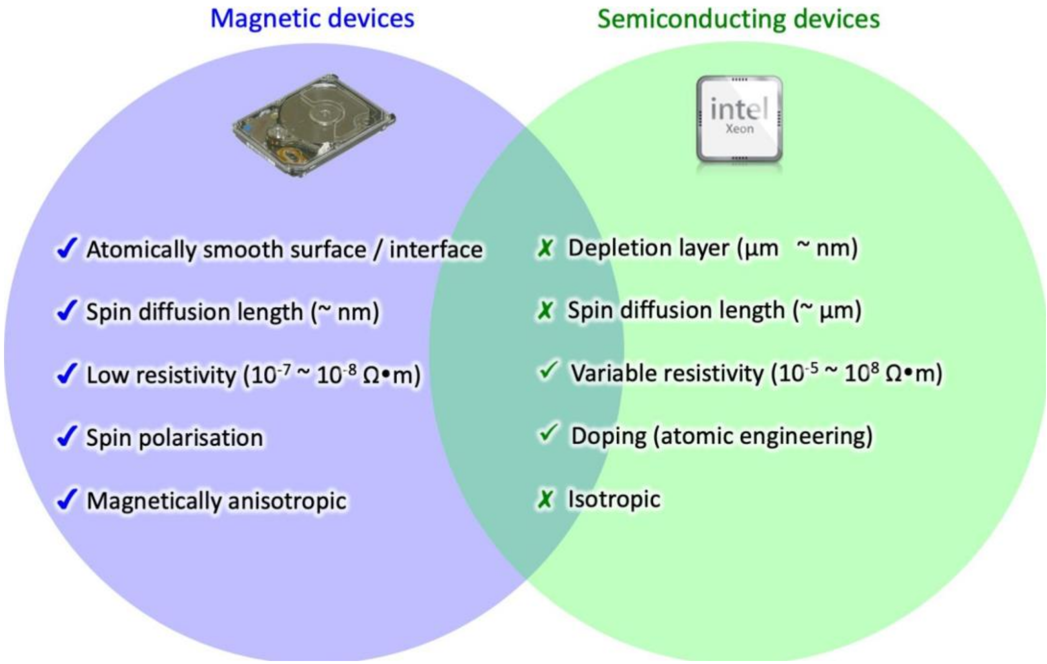
- HDD read-and-write head (10-100 Gb/inch)
- Antiferromagnetic exchange layer together with a permanent magnet (hard bias) maintains a constant direction of Co layer magnetization. The magnetization direction of magnetically soft NiFe depends on the magnetization direction written on the recording medium. The change in resistance is monitored by reading the current.



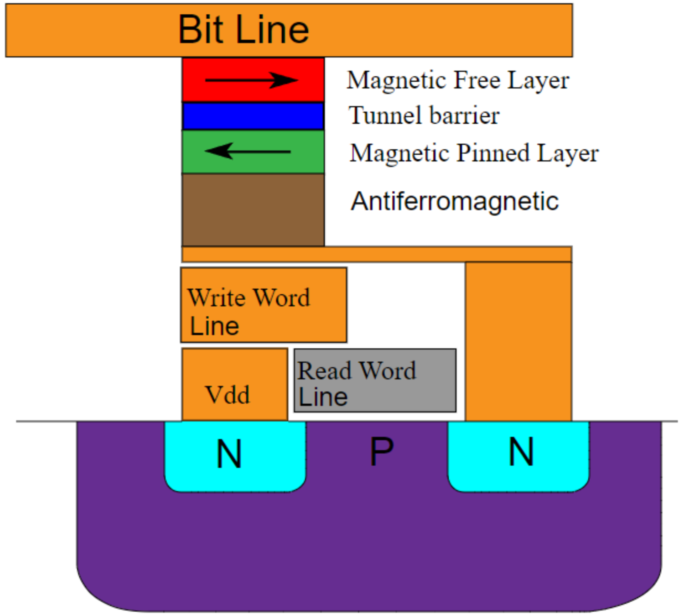
https://www.rit.edu/kgcoe/eta/docs/Student%20Presentation-5-Hard%20Disk%20Reading%20Process.pdf

Spintronics

- Spin transport electronics



- MRAM - based on GMR, magnetoresistive random access memory
  - Same magnetization "0"
  - Different magnetization "1"



https://www.sciencedirect.com/science/article/pii/S0304885320302353
https://en.wikipedia.org/wiki/Magnetoresistive_RAM

Where Are We Now

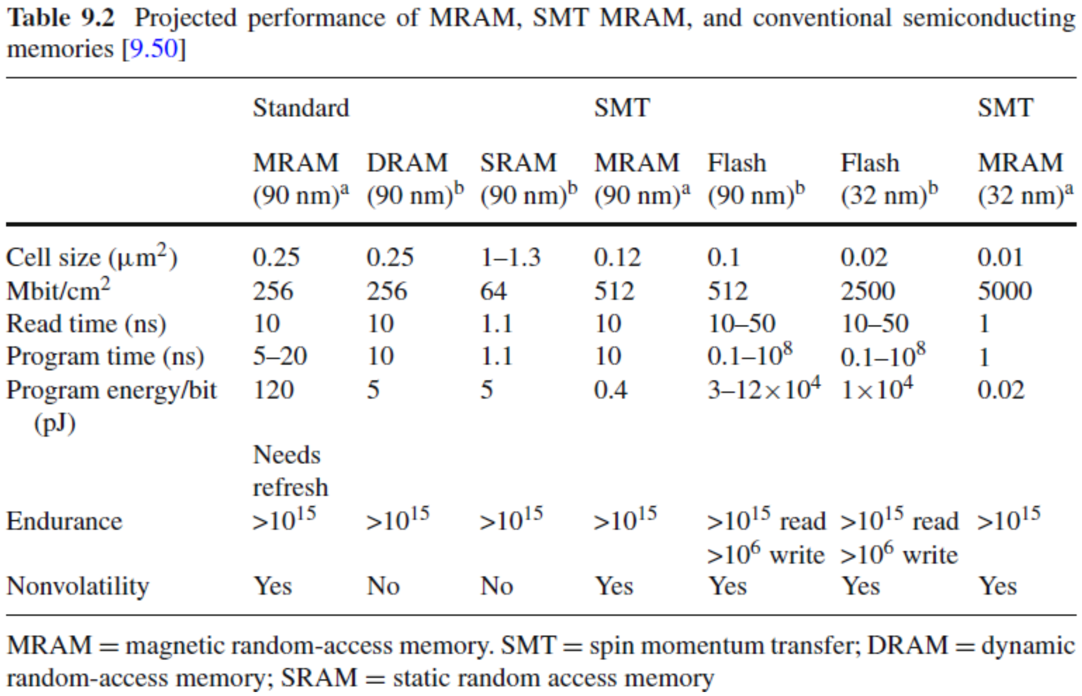
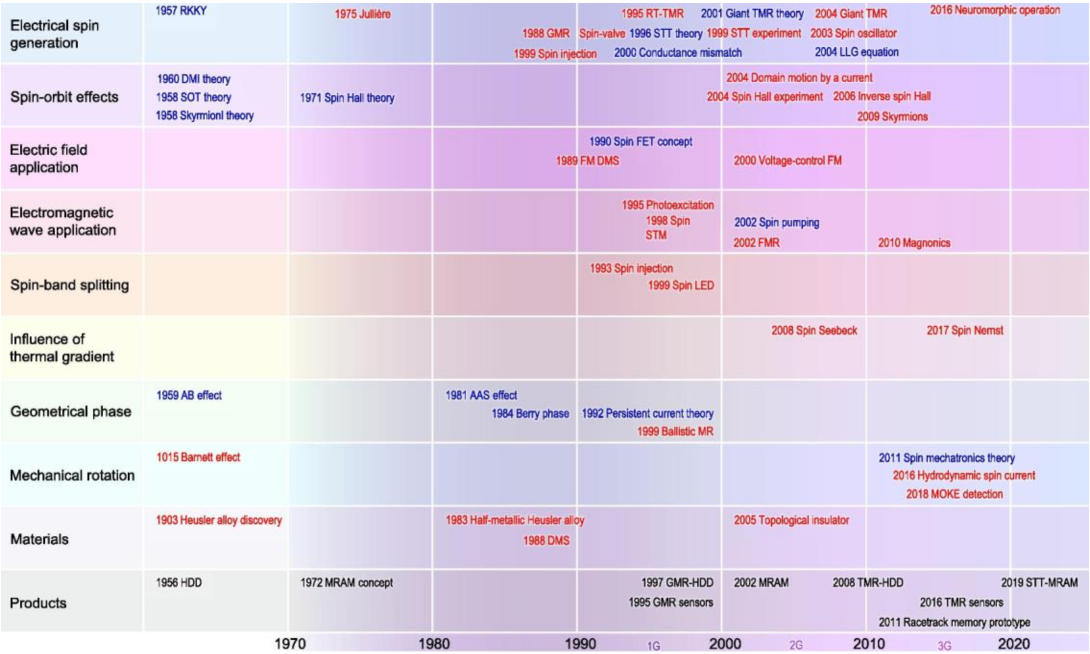


Table 9.2 Projected performance of MRAM, SMT MRAM, and conventional semiconducting memories [9.50]

	Standard			SMT			SMT
	MRAM (90 nm)[a]	DRAM (90 nm)[b]	SRAM (90 nm)[b]	MRAM (90 nm)[a]	Flash (90 nm)[b]	Flash (32 nm)[b]	MRAM (32 nm)[a]
Cell size (μm^2)	0.25	0.25	1–1.3	0.12	0.1	0.02	0.01
Mbit/cm^2	256	256	64	512	512	2500	5000
Read time (ns)	10	10	1.1	10	10–50	10–50	1
Program time (ns)	5–20	10	1.1	10	$0.1–10^8$	$0.1–10^8$	1
Program energy/bit (pJ)	120	5	5	0.4	$3–12\times10^4$	1×10^4	0.02
Endurance	Needs refresh $>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$ read $>10^6$ write	$>10^{15}$ read $>10^6$ write	$>10^{15}$
Nonvolatility	Yes	No	No	Yes	Yes	Yes	Yes

MRAM = magnetic random-access memory. SMT = spin momentum transfer; DRAM = dynamic random-access memory; SRAM = static random access memory



https://www.sciencedirect.com/science/article/pii/S0304885320302353

H.E. Schaefer, Nanoscience: The Science of the Small in Physics, Engineering, Chemistry, Biology and Medicine, Springer, 2010

Conclusion

- Spin magnetisation of matter
  - Magnetic properties are explained by unpaired spins
- Distribution of matter
  - Diaamagnetics
  - Paramagnetics
  - Ferromagnetics
  - Ferrimagnetics
- Magnetic domains
- Nanomagnetism and its applications
  - GMR