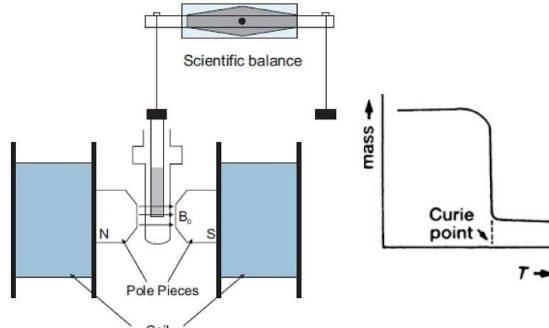
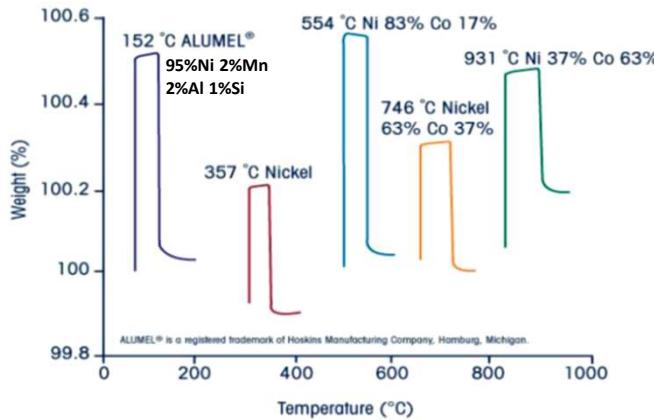




Ferromagnetic Curie (T_c) transition via Thermal Analyses techniques

Curie Point Standards for Temperature Calibration

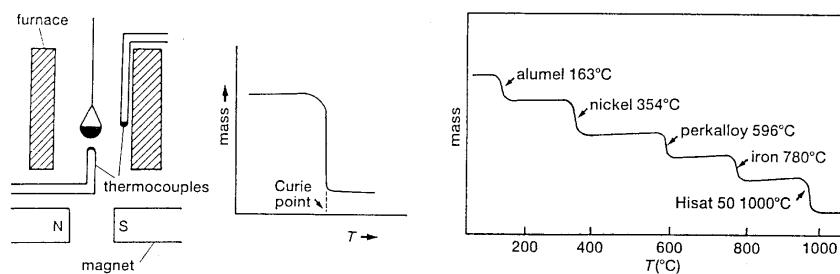


Gouy microbalance for magnetic susceptibility (1889)

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❖ Calibration can also be done by placing a series of ferromagnetic materials in the specimen basket and a magnet below or above it, external to the furnace. When each material goes through its Curie temperature (ferro- to paramagnetic transition), a sharp 'weight' change will be indicated.

Gouy derived a mathematical expression showing that force is proportional to volume susceptibility for the interaction of material in a uniform magnetic field in 1889.



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Electron Spin Magnetic Moment

Magnetic moment (μ): relates directly to the *number of unpaired electrons*

Magnetic properties of unpaired electrons arise from *electron spin* and *electron orbital motion*

Bohr magneton (BM): A natural constant which arises in the treatment of magnetic effects. The magnetic moment is usually expressed as a multiple of the Bohr magneton.

The gyromagnetic ratio (γ , gamma) of a particle or system is the ratio of its magnetic moment to its angular momentum. Its SI unit is the radian per second per tesla (rad·s⁻¹·T⁻¹) or, equivalently, the coulomb per kilogram (C·kg⁻¹).

$$\text{BM} = \frac{e\hbar}{4\pi mc}$$

e: electron charge
 \hbar : Planck's constant
 m : electron mass
 c : velocity of light

Magnetic moments of single electron

$$\mu_s = g\sqrt{s(s+1)}$$

$$\mu_s = 1.73 \text{ BM}$$

g: gyromagnetic ratio ~2 (for electron spin magnetic moment)

s: spin quantum number

S: sum of spin quantum number

> 1 unpaired electron

$$\mu_s = g\sqrt{S(S+1)}$$

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Electron-Orbit Magnetic Moment

The motion of an electron around the nucleus may in some materials, give rise to an *orbital moment*, which contributes to the overall magnetic moment

$$\mu_{S+L} = [4S(S+1) + L(L+1)]^{1/2} \quad \begin{matrix} \text{L: orbital angular momentum} \\ \text{quantum number} \end{matrix}$$

Ion	Number of unpaired electrons	$\mu_S(\text{calc})$	$\mu_{S+L}(\text{calc})$	μ_{observed}
V ⁴⁺	1	1.73	3.00	~ 1.8
V ³⁺	2	2.83	4.47	~ 2.8
Cr ³⁺	3	3.87	5.20	~ 3.8
Mn ²⁺	5 (high spin)	5.92	5.92	~ 5.9
Fe ³⁺	5 (high spin)	5.92	5.92	~ 5.9
Fe ²⁺	4 (high spin)	4.90	5.48	5.1–5.5
Co ³⁺	4 (high spin)	4.90	5.48	~ 5.4
Co ²⁺	3 (high spin)	3.87	5.20	4.1–5.2
Ni ²⁺	2	2.83	4.47	2.8–4.0
Cu ²⁺	1	1.73	3.00	1.7–2.2

Simplified approach: a single unpaired electron is set equal to 1 BM

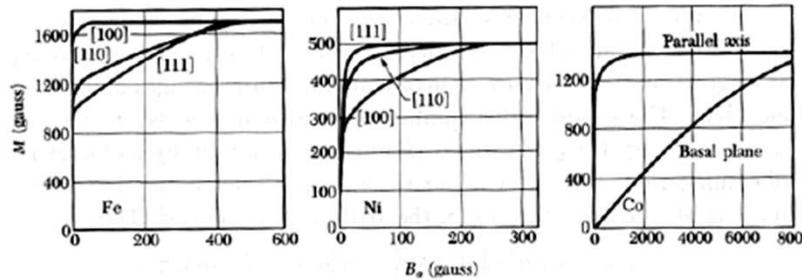
$$\mu = gS$$

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Domains

One thing is missing from our explanation:

Real magnetic materials need an external magnetic field to be applied in order to produce strong or permanent magnetisation - depends on crystal orientation

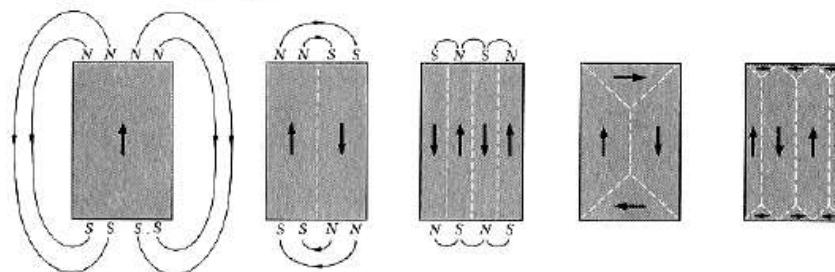


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Why do Domains form?

Magnetisation of a single crystal costs a large amount of energy of magnetisation = $\int B_0 \cdot dM$

Balanced by anisotropy energy - spins only like to align along particular crystal directions - energy cost is K per electron spin



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Domains in real crystals

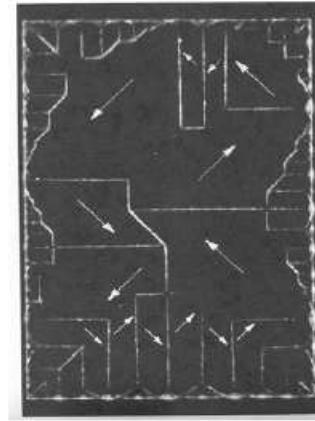
Single 'whisker'
of iron



Domains can be 'pinned' by the presence of impurities, which make it easy for the domain boundary to sit in one place

Causes the difference between 'soft' and 'hard' magnetic materials

Larger crystal of Nickel



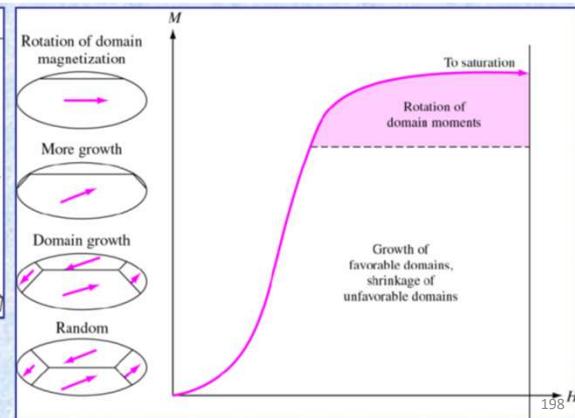
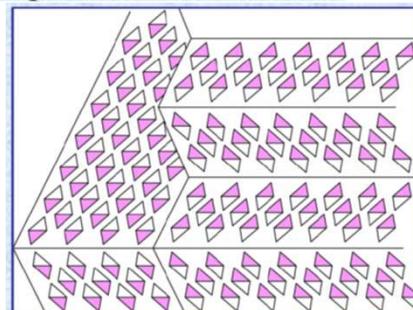
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ferromagnetic domains

magnetic dipole moments align themselves in parallel direction in small-volume regions called **magnetic domains**

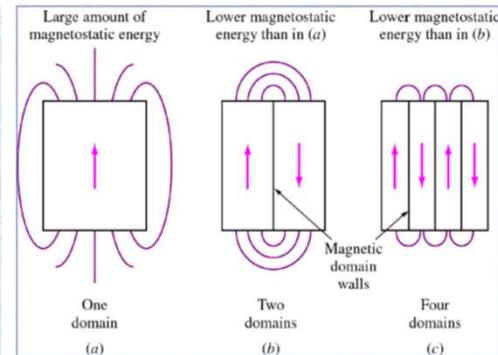
- when demagnetized by slowly cooling from above its Curie temperature, domains are rearranged in random order
➡ no net magnetic moment

- when external magnetic field is applied, the magnetic domains whose moments are initially parallel to the applied field grow
- when domain growth finishes, **domain rotation** occurs and domain rotation requires more energy than domain growth



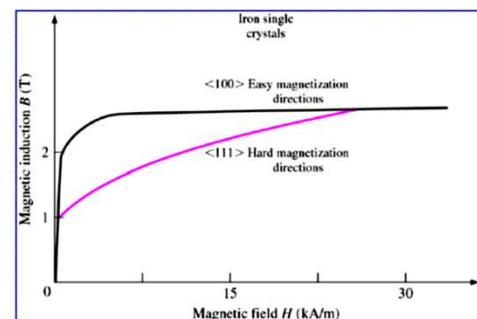
types of energies that determine the structure
most stable structure is attained when overall
potential energy is minimum
total magnetic energy of a ferromagnetic
material is the sum of the following energies:

- (a) **exchange energy** – potential energy within
a domain is minimized when all atomic
dipoles are aligned in single direction
the alignment is associated with a positive
exchange energy
- (b) **magnetostatic energy** – potential magnetic
energy produced by its external field
formation of multiple domain reduces
magnetostatic energy



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- (c) **magnetocrystalline anisotropy energy**
magnetization with applied field for a single
crystal varies with crystal orientation
ex. for BCC Fe
saturation magnetization occurs most
easily for the $<100>$ direction
saturation magnetization occurs with
highest applied field for $<111>$ direction



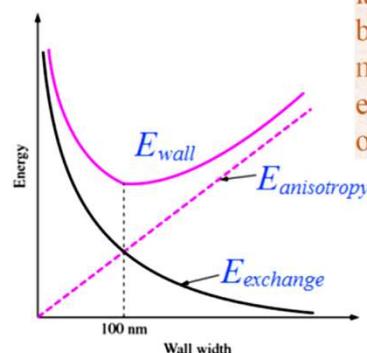
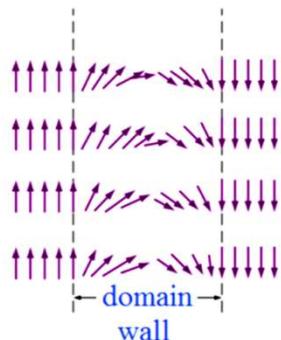
for FCC Ni
the easy directions of magnetization are
 $<111>$ and $<100>$ the hard direction
grains at different orientations will reach
saturation magnetization at different field
strength
magnetocrystalline anisotropy energy – the
work done to rotate all domains to reach
saturation

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(d) domain wall energy

domain wall – the boundary between two domains whose overall moments are at different directions

domain changes orientation gradually with a boundary about 300 atoms wide



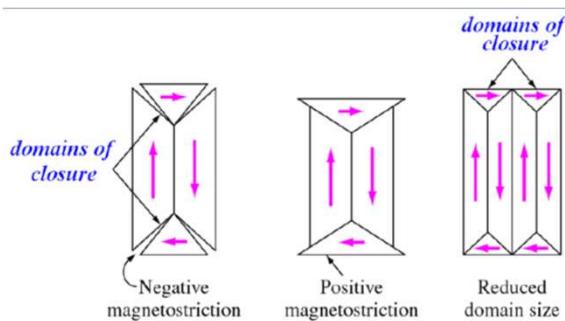
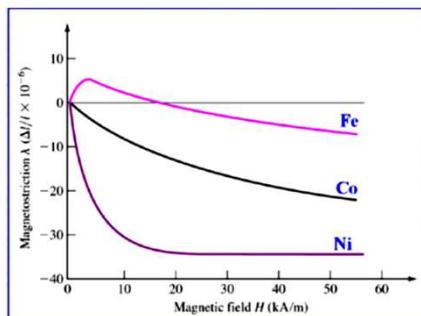
large width of domain wall is due to balance between two forces: exchange force and magnetocrystalline anisotropy
equilibrium wall width is width at which sum of two energies are minimum

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(e) magnetostrictive energy

magnetostriction – magnetically induced reversible elastic strain ($\Delta l/l$) the order of 10^{-6}

magnetostrictive energy – the energy due to mechanical stress created by magnetostriction it is due to change in bond length caused by rotation of electron-spin dipole moments equilibrium domain configuration is reached when sum of magnetostrictive and domain wall energies are minimum

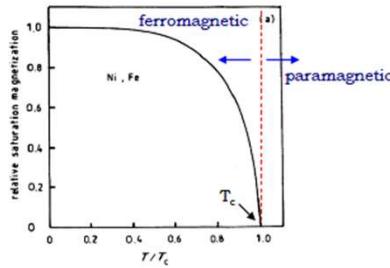


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Magnetic Materials-Metal and Alloys

Five transition metals: Cr, Mn, Fe, Co, Ni; and most lanthanides are either ferro- or antiferromagnetic

Fe, Co, Ni are ferromagnetic; Cr and Mn are antiferromagnetic



Perfect magnetic order is attainable only at absolute zero

How many unpaired electrons are available to contribute to ferromagnetism:

Table 8.4 Electronic constitution of iron, cobalt and nickel

Metal	Free ion configuration	Ferromagnetic state	
		Number of unpaired spins	Configuration
Fe	$d^6 s^2$	2.2	$d^{7.4} s^{0.6}$
Co	$d^7 s^2$	1.7	
Ni	$d^8 s^2$	0.6	

Fact: *2.4 unpaired electron per atom*

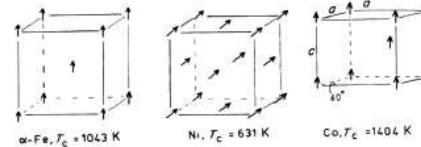
(in $Fe_{0.8}Co_{0.2}$ alloy)

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Some More Definitions

1. Magnetocrystalline anisotropy

The energy required to rotate the magnetization out of the preferred direction



2. Eddy current

The source of energy loss in an alternating magnetic field

Energy loss:

$$IV = V^2 / R$$

Eddy currents are minimized in highly resistive materials.

Metal oxides vs. metals

3. Magnetostriction

Magnetic materials change their shape on magnetization

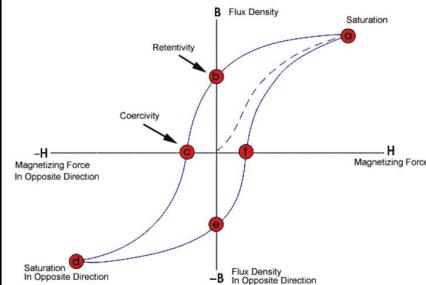
- The effect increase with H
- Dimensional changes involved are small, which is comparable to changing the temperature of the material by a few degree

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All electric motors experience [rotational losses](#) during the conversion of electrical power to mechanical power. These losses are generally categorized as magnetic losses, mechanical losses, stray losses, etc depending on the underlying cause and mechanism. Included in the category of magnetic losses are two types — **hysteresis loss** and **eddy current loss**.

Hysteresis loss

Hysteresis loss is caused by the **magnetization and demagnetization of the core as current flows in the forward and reverse directions**. As the magnetizing force (current) increases, the magnetic flux increases. But when the **magnetizing force (current) is decreased, the magnetic flux doesn't decrease at the same rate, but less gradually**. Therefore, when the magnetizing force reaches zero, the flux density still has a positive value. In order for the flux density to reach zero, the magnetizing force must be applied in the negative direction. **The area of the hysteresis loop shows the energy required to complete a full cycle of magnetizing and demagnetizing, and the area of the loop represents the energy lost during this process.**



$$P_b = \eta * B_{max}^n * f * V$$

P_b = hysteresis loss (W)

η = Steinmetz hysteresis coefficient, depending on material (J/m^3)

B_{max} = maximum flux density (Wb/m^2)

n = Steinmetz exponent, ranges from 1.5 to 2.5, depending on material

f = frequency of magnetic reversals per second (Hz)

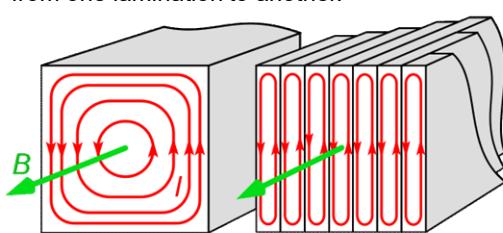
V = volume of magnetic material (m^3)

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Eddy current losses

Eddy current losses are the result of [Faraday's law](#), which states that, “**Any change in the environment of a coil of wire will cause a voltage to be induced in the coil, regardless of how the magnetic change is produced.**” Thus, when a motor core is rotated in a magnetic field, a voltage, or EMF, is induced in the coils. This induced EMF causes circulating currents to flow, referred to as eddy currents. The power loss caused by these currents is known as **eddy current loss**.

Motors armature cores use many, thin pieces of iron (referred to as “laminations”), rather than a single piece, because the resistance of individual pieces is higher than the resistance of one, solid piece. This higher resistance (due to smaller area per piece) reduces eddy currents, and in turn, eddy current losses. The laminations are insulated from each other with a lacquer coating (thermoplastic coating) to prevent the eddy currents from “jumping” from one lamination to another.



$$P_e = K_e * B_{max}^2 * f^2 * t^2 * V$$

P_e = eddy current loss (W)

K_e = eddy current constant

B = flux density (Wb/m^2)

f = frequency of magnetic reversals per second (Hz)

t = material thickness (m)

V = volume (m^3)

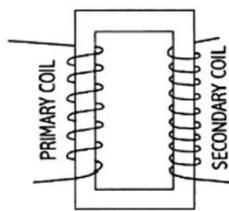
Eddy currents in laminated cores (right) are smaller than those in solid cores (left).

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Applications

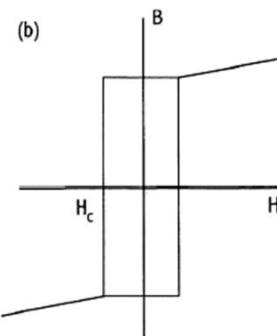
1. Transformers/motor core

- Soft magnetic materials
- Low hysteresis and eddy current loss



2. Information storage

- Soft magnetic materials
- unique hysteresis loop
- binary digital system



3. Permanent magnet

- Hard magnetic materials
- High curie temperature

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(a) iron-silicon alloys

- Fe–3 to 4% Si alloys are commonly used soft magnetic materials
- Si increases electrical resistivity
 ➡ reduces the eddy-current losses
- Si decreases magnetoanisotropy energy and increases magnetic permeability
 ➡ decreases hysteresis core losses
- Si decreases magnetostriction and lower hysteresis energy losses and transformer noise
- Si decreases saturation induction and Curie temperature (disadvantage)
- laminated structure further reduces eddy-current losses
- decrease in energy loss is also achieved by using grain oriented silicon sheet

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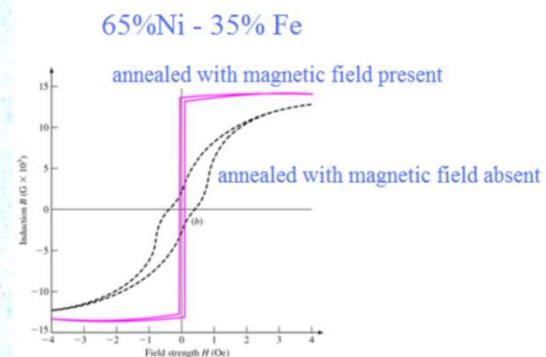
Table 16.3 Selected magnetic properties of soft magnetic materials

Material and composition	Saturation induction B_s (T)	Coercive force H_c (A/cm)	Initial relative permeability μ_i
Magnetic iron, 0.2-cm sheet	2.15	0.88	250
M36 cold-rolled Si-Fe (random)	2.04	0.36	500
M6 (110) [001], 3.2% Si-Fe (oriented)	2.03	0.06	1,500
45 Ni-55 Fe (45 Permalloy)	1.6	0.024	2,700
75 Ni-5 Cu-2 Cr-18 Fe (Mumetal)	0.8	0.012	30,000
79 Ni-5 Mo-15 Fe-0.5 Mn (Superalloy)	0.78	0.004	100,000
48% MnO-Fe ₂ O ₃ , 52% ZnO-Fe ₂ O ₃ (soft ferrite)	0.36		1,000
36% NiO-Fe ₂ O ₃ , 64% ZnO-Fe ₂ O ₃ (soft ferrite)	0.29		650

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(c) nickel-iron alloys

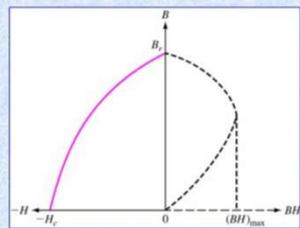
- higher permeability at lower field because of low magnetoanisotropy and magnetostrictive energy
- used in highly sensitive communication equipments
- **50% Ni alloy** – moderate permeability, high saturation induction
- **79% Ni alloy** – high permeability, low saturation induction
- initial permeability is increased by annealing in presence of magnetic field



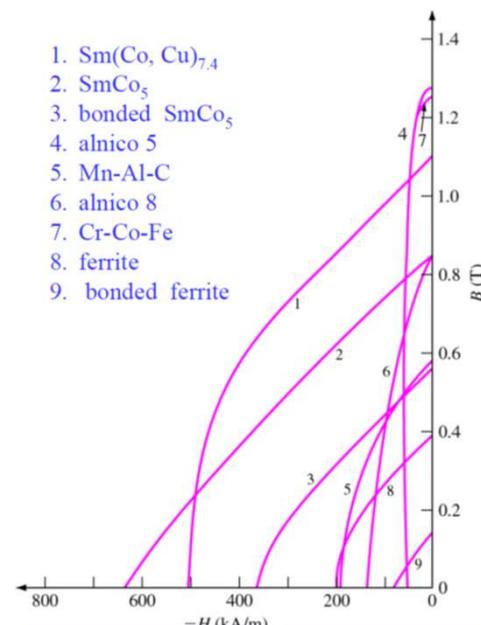
210

hard magnetic materials – properties

- high coercive force H_c and remanent magnetic induction B_r
 - wide and high hysteresis loops and difficult to demagnetize
 - demagnetizing curves can be used for comparing the strength of permanent magnets
 - magnetic potential energy is measured by maximum energy product $(BH)_{\max}$
- $(BH)_{\max}$ is the area of largest rectangle that can be inscribed in the second quadrant of the hysteresis loop



1. $\text{Sm}(\text{Co, Cu})_{7.4}$
2. SmCo_5
3. bonded SmCo_5
4. alnico 5
5. Mn-Al-C
6. alnico 8
7. Cr-Co-Fe
8. ferrite
9. bonded ferrite

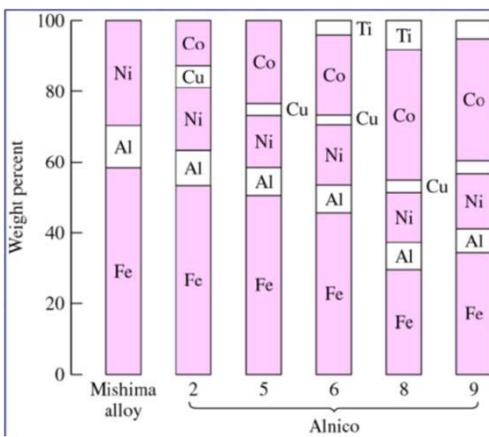


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(a) alnico alloys

alnico : aluminum + nickel + cobalt

- high energy product $(BH)_{\max} = 40\sim70 \text{ kJ/m}^3$
high remnant induction $B_r = 0.7\sim1.5 \text{ T}$
moderate coercivity $H_c = 40\sim160 \text{ kA/m}$
- compositions of the alnico alloys



- produced by casting or powder metallurgy
- structure
single phase BCC at 1250°C
cooling to $750\sim850^\circ\text{C}$, α and α' form
 α is rich in Ni and Al, is weakly magnetic
 α' is rich in Fe and Co, is highly magnetic
- if heat treated in magnetic field, α' becomes elongated and hence is difficult to rotate – high coercivity

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(b) rare earth alloys

- very high maximum energy product $(BH)_{\max}$ to 240 kJ/m³ and coercivity to 3200 kA/m due to unpaired 4f electrons
- SmCo₅ single phase magnets coercivity is based on nucleation and pinning down of domain walls at surfaces and grain boundaries high magnetic strengths with $(BH)_{\max}$ in the range of 130~160 kJ/m³

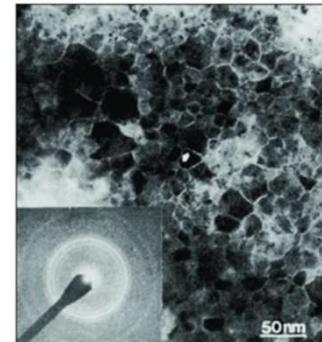
precipitation-hardened Sm(Co,Cu)_{2.5} alloy

part of Co substituted by Cu precipitate produced at low temperatures and domain walls are pinned at precipitates addition of small amount of Fe and Zr promote the development of high coercivity

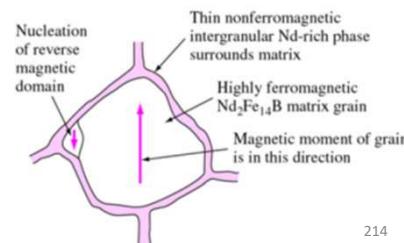
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(c) neodymium-iron-boron magnetic alloys

- produced by powder metallurgy and rapid solidification melt-spun ribbon process
- highly ferromagnetic Nd₂Fe₁₄B grains are surrounded by nonferromagnetic Nd rich intergranular phase
- high coercivity and energy product due to difficulty in reverse nucleating
- used in automotive starting motors

TEM for Nd₂Fe₁₄B

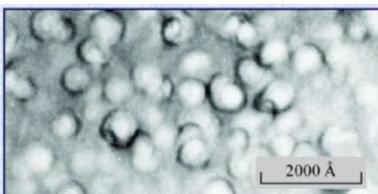
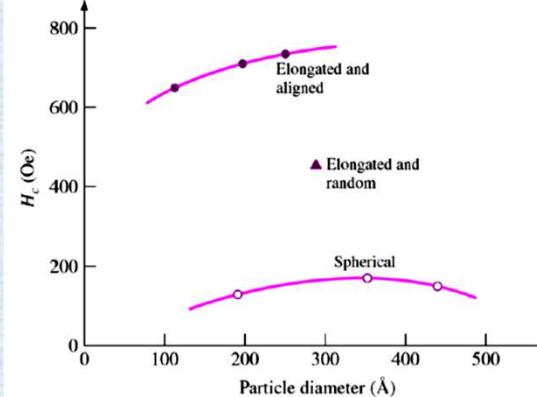
nucleation of reverse magnetic domain



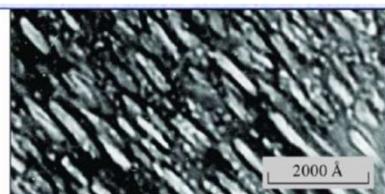
214

(d) iron-chromium-cobalt magnetic alloys

- structure and properties analogues to alnico
61% Fe, 28% Cr, 11% Co
- single phase **BCC** structure forms at elated temperature (1200°C)
- slow-cooling precipitates of Cr-rich α_2 phase forms in a matrix of Fe-rich α_1 phase below 650°C
- particles are elongated by forming to increase coercivity

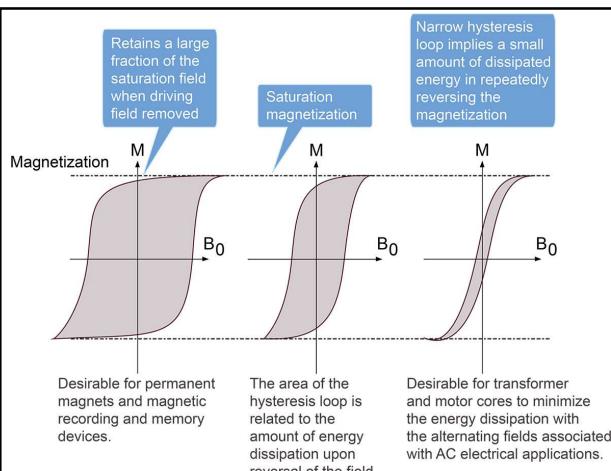


(a)



(b)

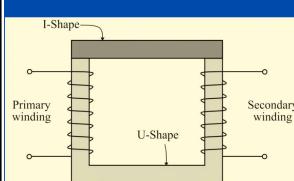
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❑ A transformer core is a static device that uses electromagnetic induction to transport electricity from one source to another. **Low stray magnetic fields** in Iron Core Coils are ideal because if stray magnetic fields are strong enough, they can disrupt adjacent power systems and **cause eddy currents in steel**.

❑ The higher the magnetism of the material, the more magnetic field can be “transported” by it. Since, higher permeability translates to more magnetism, so the cores are made with a substance of high permeability. Hence, the core is made of a high permeability material to allow efficient transfer of magnetic field. With small magnetizing current in primary, a large magnetic flux is generated. Alternately, **for same current, higher permeability will require less number of turns and save in winding cost**.

Transformer Core



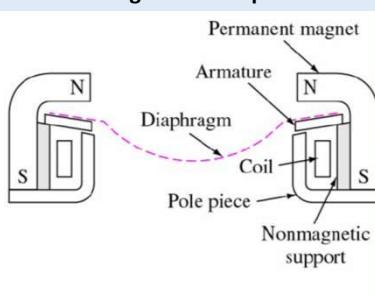
❑ The current flowing through the resistance of the metal heats it by Joule heating, causing significant power losses. Therefore, solid iron cores are not used in transformers or inductors, they are **replaced by laminated or powdered iron cores, or nonconductive cores like ferrite**.

❑ We can see that soft magnets, while they can achieve a high value of B_{sat} , dissipate relatively little energy in the loop. This makes soft magnets preferable for use in transformer cores, where the field is switched rapidly.

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(a)



(b)

Permanent magnets in telephone receivers

Material and composition	Remanent induction B_r (T)	Coercive force H_c (kA/m)	Maximum energy product $(BH)_{\max}$ (kJ/m ³)
Alnico 1, 12 Al, 21 Ni, 5 Co, 2 Cu, bal Fe	0.72	37	11.0
Alnico 5, 8 Al, 14 Ni, 25 Co, 3 Cu, bal Fe	1.28	51	44.0
Alnico 8, 7 Al, 15 Ni, 24 Co, 3 Cu, bal Fe	0.72	150	40.0
Rare earth-Co, 35 Sm, 65 Co	0.90	675–1200	160
Rare earth-Co, 25.5 Sm, 8 Cu, 15 Fe, 1.5 Zr, 50 Co	1.10	510–520	240
Fe-Cr-Co 30 Cr, 10 Co, 1 Si, 59 Fe	1.17	46	34.0
MO·Fe ₂ O ₃ (M = Ba, Sr) (hard ferrite)	0.38	235–240	28.0

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$H_c < 10 \text{ A/Cm}$: soft magnetic;
 $H_c > 300 \text{ A/Cm}$: hard magnetic (permanent magnets).

The comparative properties of soft and hard magnetic materials

Soft magnetic	Hard magnetic
High saturation magnetization (1–2T)	High saturation magnetization (0.3–1.6T)
Low coercivity (H_c)	High coercivity
High permeability	Not important, but low
Low anisotropy	High anisotropy
Low magnetostriction	Not important
High Curie temperature (T_c)	High T_c
Low losses	High-energy product
High electrical resistivity	Not important

Table 2.1 Various Ferrites with their structures and general formula

Sr. No.	Types	Crystal structure	General formula	Replacements
1	Spinel	Cubic	$\text{A}^{\text{II}}\text{Fe}_2\text{O}_4$	A^{II} - Mn, Zn, Ni, Mg, Co
2	Garnet	Cubic	$\text{Ln}^{\text{III}}\text{Fe}_5\text{O}_{12}$	Ln^{III} - Y, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Lu
3	Ortho ferrite	Perovskite	$\text{Ln}^{\text{III}}\text{FeO}_3$	Ln^{III} - Y, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Lu
4	Magnetoplumbite	Hexagonal	$\text{A}^{\text{II}}\text{Fe}_{12}\text{O}_{19}$	A^{II} - Ba, Sr, Pb

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Material	General properties and application
(a) Hard magnetic materials	
Aluminium–nickel–cobalt alloy (ALNICO), sometimes with copper and titanium	Magnets can be cast into complex shapes and perform well at high temperatures Used in applications such as instruments and meters that require very stable ten properties like electronic ignition systems, generators, vending machines, etc.
Rare-earth alloys (samarium)	High magnetic strength Used in wrist watches and medical implants
Neodymium–iron–boron alloys	Very low magnetic strength Used in low weight requirement applications
Hard ferrite–barium and strontium ferrite	Low cost Widespread use, including electronic applications
(b) Soft magnetic materials	
Iron with 3–4% silicon	AC motors, generators and transformers
Metallic glass-combinations of Fe, Co, Ni, B and Si	Low energy loss Use in power transformers, magnetic sensors and recording equipment
Nickel–iron alloys	Low permeability applications Used in telecommunications, aeronautical, aerospace engineering, cryogenic eng (liquefied natural gas tankers), etc.
Hard ferrite–iron, nickel and cobalt ferrite	Low electrical conductivity reduces eddy current losses Used in high-frequency applications

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Giant Magnetoresistance (GMR) effect

- In general, **magnetoresistance** refers to the change in resistance of any material when placed in a magnetic field.
- With a non-magnetic material the change in resistivity is very small.
- For a magnetic material, the change in resistivity depends on the direction of the current flow w.r.t the magnetic field.
- The resistivity $\rho(//)$ for current flow parallel to magnetic field decreases and $\rho(\perp)$, perpendicular to the field increases by the same amount.
- This change in resistivity is anisotropic and is hence called **anisotropic magnetoresistance**.

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- The differences in the resistivities is roughly 10% or less.
- But in multilayered structures , the change can be large exceeding 100% at low temperatures and 60-80% at room temperature.
- GMR effect measured by the change in resistance w.r.t R_p :

$$(\Delta R/R_p)_{\text{GMR}} = (R_{\text{AP}} - R_p)/R_p$$

- The GMR effect can be measured by passing a current in the plane of layers or perpendicular to the plane.

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9 October 2007

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2007 jointly to

Albert Fert

Unité Mixte de Physique CNRS/THALES, Université Paris-Sud, Orsay, France,

and

Peter Grünberg

Forschungszentrum Jülich, Germany,

“for the discovery of Giant Magnetoresistance”.

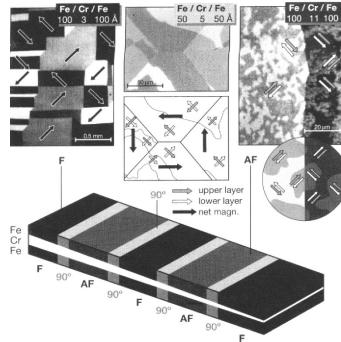


Nanotechnology gives sensitive read-out heads for compact hard disks

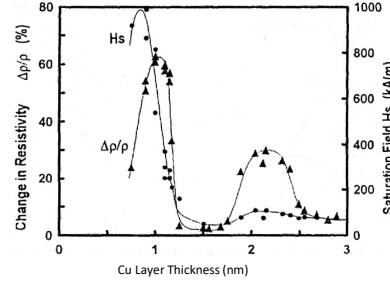
This year's physics prize is awarded for the technology that is used to read data on hard disks. It is thanks to this technology that it has been possible to miniaturize hard disks so radically in recent years. Sensitive read-out heads are needed to be able to read data from the compact hard disks used in laptops and some music players, for instance.

In 1988 the Frenchman **Albert Fert** and the German **Peter Grünberg** each independently discovered a totally new physical effect – Giant Magnetoresistance or GMR. Very weak

Interlayer Coupling



Different types of coupling in a layered magnetic structure



The saturation field H_s and $\Delta\rho/\rho$ as a function of the interlayer thickness x of glass/Fe(6nm)/[Co(1nm)/Cu \times A]50 superlattices

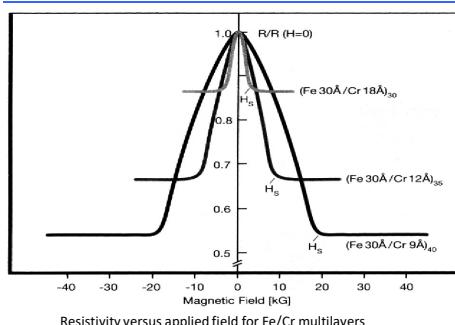
In 1986 was identified and characterized in Fe/Cr superlattice structures and rare earth yttrium multilayers

Transport of spin along the interfaces results in torque acting on the magnetization which is due to the fact that majority and minority electrons have different reflection coefficients at the interfaces. The torque aligns the magnetization according to the associated ratio of reflection coefficients

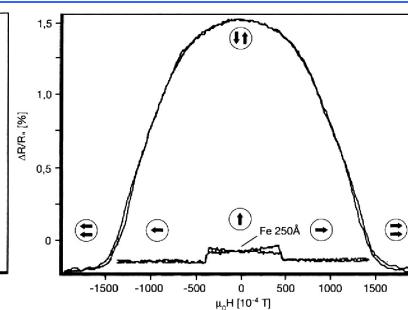
P.Günberg, R.Schreiber, Y.Pang, M.B.Brodsky and H.Sowers, Phys. Rev.Lett. 57, 2442 (1986)

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First Evidence of GMR



Resistivity versus applied field for Fe/Cr multilayers



Relative resistance change as a function of the external magnetic field for Fe/Cr/Fe and 250 Å thick Fe film

Discovered in 1988 in antiferromagnetically coupled magnetic multilayers by Baibich *et al* and on Fe/Cr superlattices

In Fe/Cr multilayers the low field antiparallel configuration was induced by antiferromagnetic coupling between Fe layers across Cr

Does not depend on the angle between the current and magnetization → spin-orbit coupling and resulting anisotropy

MR=79% at T=4.2K and 20% at room temperature

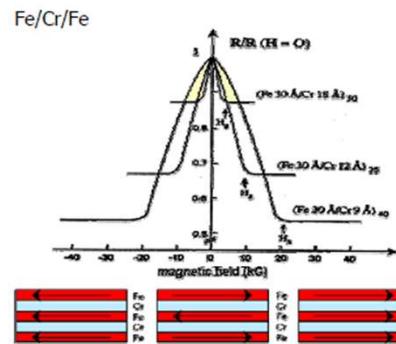
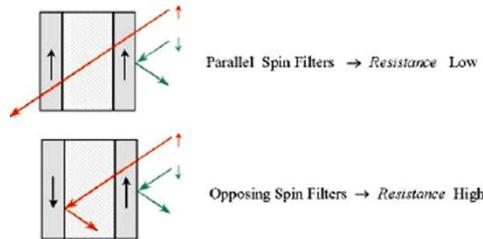
$$MR = \frac{R_{AP} - R_P}{R_P} = \frac{\sigma_P}{\sigma_{AP}} - 1$$

M.Baibich, J.Brote, A.Fert, F.Nguyen Van Dau, F.Petroff, P.Etienne, G.Greuzet, A.Friederich and J.Chazelas, Phys.Rev.Lett 61, 2472 (1988)

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The giant magnetoresistance effect (GMR)

When electrons are injected into two ferromagnetic layers separated by a normal material, the transmission (i.e. the resistance) depends on the relative orientation of the two magnetic layers.



The GMR effect is the large increase in resistance when the relative orientation of the magnetizations in neighboring ferromagnetic layers is switched from parallel to antiparallel by applying a magnetic field.

- 1988 P. Grünberg/A. Fert entdecken GMR
- Widerstandsänderung von bis zu 80% (300 K) bzw. 220% (4.2 K)

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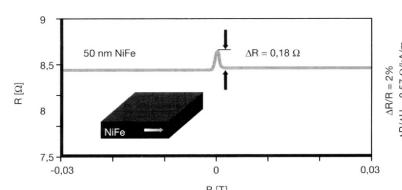
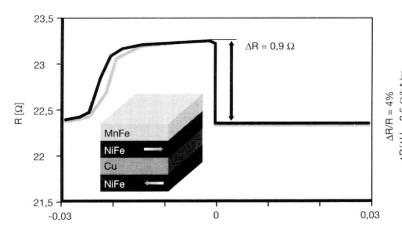
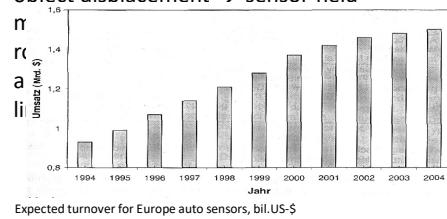
Applications of GMR

- Sensors on GMR are very sensitive and can be made very small.

- Use:

direct field measurements → in disk drives
in compute systems, tape heads in consumer products (audio, video), magnetometers, compass systems

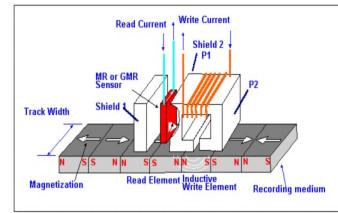
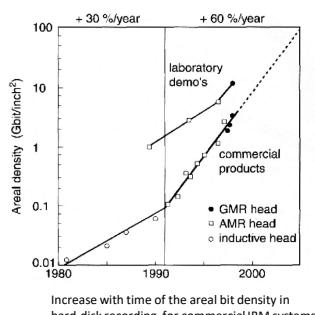
Position detection → permanent magnetization pattern is attached to the object that has to be detected. A sensor detects the change in the field as a result of object displacement → sensor field



Comparison of performance of magnetic-field sensors based on GMR and AMR effects

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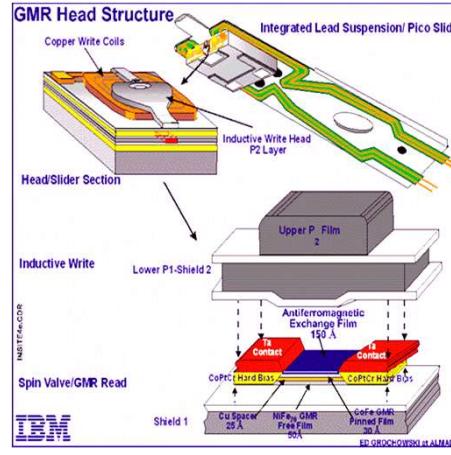
Read Heads



GMR – higher sensitivity and better signal-to-noise ratio

Contactless sensors do not exhibit mechanical wear

Thin film MR heads are produced by photolithographic processing



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SUPERCONDUCTIVITY

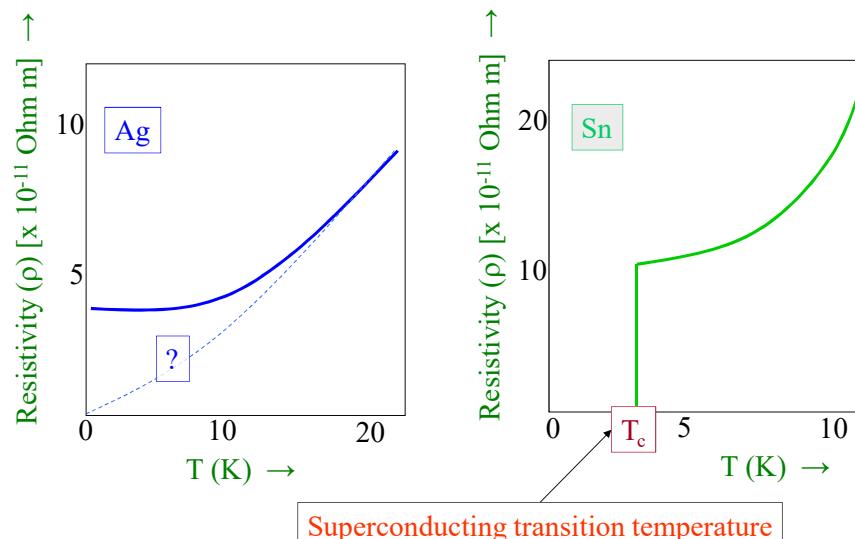
228

Superconductivity

1. *Zero Resistivity* (No electron-phonon collision occur, no heat loss)
2. *Perfect Diamagnetism* ($\chi = -1$)
3. Confined to low temperature (critical temperature T_c)
 - Conventional superconductor
 - High temperature superconductor

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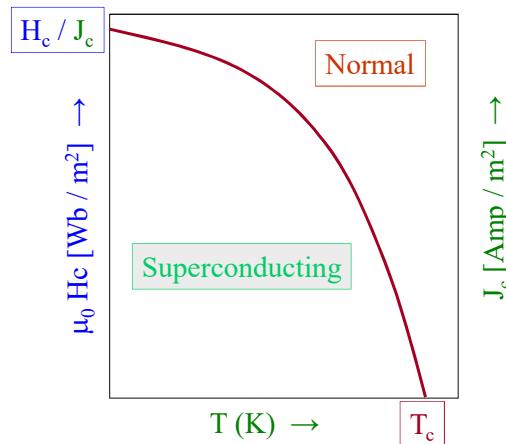
Superconducting transition



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Current carrying capacity

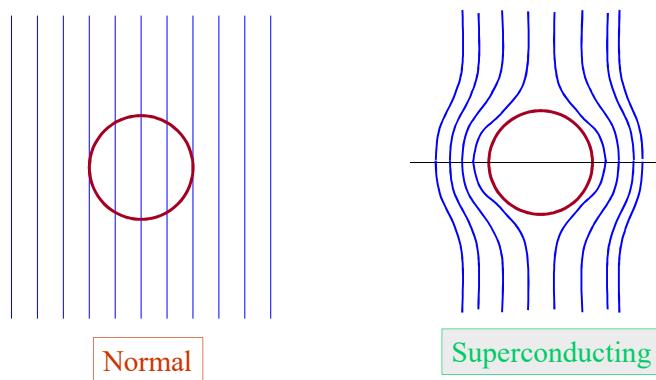
- The maximum current a superconductor can carry is limited by the magnetic field that it produces at the surface of the superconductor



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Meissner effect

- A superconductor is a perfect diamagnet (magnetic susceptibility $\chi = -1$)
- Flux lines of the magnetic field are excluded out of the superconductor
⇒ Meissner effect



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Theory of low temperature superconductivity- Bardeen-Cooper-Schreiffer (BCS) theory

- Three way interaction between an two electron and a phonon
- Phonon scattering due to lattice vibrations felt by one electron in the Cooper pair is nullified by the other electron in the pair
⇒ the electron pair moves through the lattice without getting scattered by the lattice vibrations
- The force of attraction between the electrons in the Cooper pair is stronger than the repulsive force between the electrons when $T < T_c$

Cooper pair: a loosely bound pair of electrons with opposite spins and moving with the same speed in opposite directions, i.e., a pair of electrons in a superconductor that are attractively bound and have equal and opposite momentum and spin.

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Type I and Type II superconductors

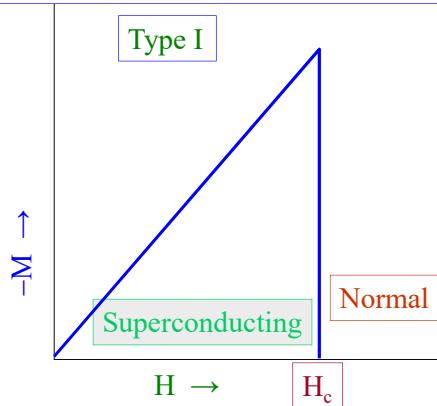
Trivia facts

- Superconductors used in magnet technology could carry extreme currents because of their ability to keep the magnetic flux motionless. The dynamics of the magnetic flux interaction with superconductors is controlled by this property.
- Superconducting wire can carry immense electrical currents with no heating, which allows it to generate large magnetic fields. An electromagnet with non-superconducting copper windings would melt with the same current.
- It can withstand the highest current densities (up to 200,000 Amperes per square centimeter) at the highest working magnetic field (15 T).
- Because they have no resistance, superconductors do not lose any current in the form of heat, and are therefore totally energy efficient (except for the energy required to cool them, at Earth temperatures). Zero resistance allows for many strange phenomena, including the ability to levitate a magnet in mid-air.

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Type I (*Ideal*) superconductors

- Type I SC placed in a magnetic field totally repels the flux lines till the magnetic field attains the critical value H_c



Entropy of all superconductors decreases considerably upon cooling below T_C i.e., decrease in a superconductor signifies that the superconducting state is more ordered than the normal state.

$$M = \begin{cases} -H & \rightarrow H < H_c \\ 0 & \rightarrow H > H_c \end{cases}$$

At any temperature T less than the critical temperature T_C for a superconducting material, the critical field $H_C(T)$ depends approximately on temperature according to

$$H_C(T) = H_C(0) [1 - (T/T_C)^2]$$

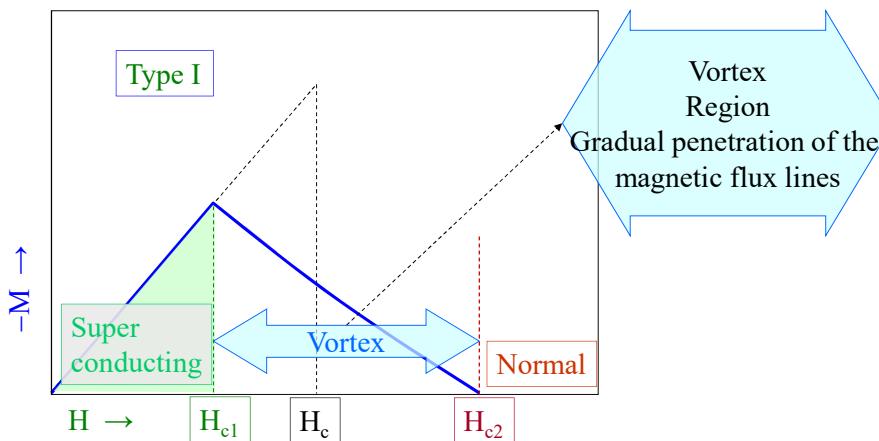
where $H_C(0)$ is the critical field at 0 K.

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Type II (*Hard*) superconductors

- Type II SC has three regions

$$M = \begin{cases} -H & \rightarrow H < H_{c1} \\ < -H & \rightarrow H \in (H_{c1}, H_{c2}) \\ 0 & \rightarrow H > H_{c2} \end{cases}$$



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- As type II SC can carry high current densities (J_c) they are of great practical importance
- The penetration characteristics of the magnetic flux lines (*between H_{c1} and H_{c2}*) is a function of the microstructure of the material \Rightarrow presence of pinning centres in the material
- Pinning centres:
 - \Rightarrow Cell walls of high dislocation density
(cold worked/recovery annealed)
 - \Rightarrow Grain boundaries
(Fine grained material)
 - \Rightarrow Precipitates
(Dispersion of very fine precipitates with interparticle spacing $\sim 300 \text{ \AA}$)
- $J_c \uparrow$ as $H_{c2} \uparrow$

The thermal conductivity of superconductors undergoes a continuous change between the two phases and usually lower in a superconducting phase and at very low temperatures approaches zero. This suggests that the electronic contribution drops, the superconducting electrons possibly plays no part in heat transfer. **but what about entropy?**

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Nb – 40%Ti alloy, T = 4.2 K, Magnetic field strength = 0.9 H_{c2}

Microstructure	$J_c (\text{A} / \text{m}^2)$
Recrystallized	10^5
Cold worked and recovery annealed	10^7
Cold worked and precipitation hardened	10^8

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Potential Applications

- ❑ Strong magnetic fields → 50 Tesla
(*without heating, without large power input*)
- ❑ Logic and storage functions in computers
Josephson junction → fast switching times ($\sim 10 \text{ ps}$)
- ❑ Magnetic levitation (*arising from Meissner effect*)
- ❑ Power transmission

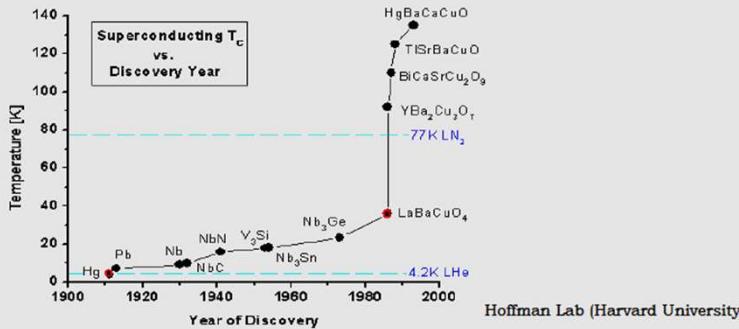
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High T_c superconductivity

Compound	T_c	Comments
Nb_3Ge	23 K	Till 1986
La-Ba-Cu-O	34 K	Bednorz and Mueller (1986)
$\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$	90 K	> Boiling point of Liquid N_2
Tl (Bi)-Ba(Sr)-Ca-Cu-O	125 K	

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Discovery of Superconductors



Dr. Kamerlingh-Onnes (*Nobel Prize of Physics 1913*)

- Superconductivity in mercury at liquid helium temperature (~4K)

Drs. Johannes G. Bednorz and Karl A. Müller (*Nobel Prize of Physics 1987*)

- Ceramic superconductors e.g. $\text{La}_{2-x}\text{Ba}_x\text{CuO}_{4-x}$; $\text{YBa}_2\text{Cu}_3\text{O}_7$
- Critical temperature 35K

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The Nobel Prize in Physics 1987



Photo from the Nobel Foundation archive.
J. Georg Bednorz
Prize share: 1/2

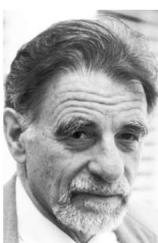


Photo from the Nobel Foundation archive.
K. Alexander Müller
Prize share: 1/2

Affiliation : IBM Zurich Research Laboratory, Rüschlikon, Switzerland Affiliation: IBM Zurich Research Laboratory, Rüschlikon, Switzerland

The Nobel Prize in Physics 1987 was awarded jointly to J. Georg Bednorz and K. Alexander Müller "for their important break-through in the discovery of superconductivity in ceramic materials."

In 1986, Bednorz and Müller synthesized a ceramic material consisting of **lanthanum-barium-copper-oxide** in carefully determined ratios which underwent an abrupt transition to "zero" resistance at a temperature near 35K, which was subsequently shown to exhibit all the properties of a superconductor - including the Meissner Effect. **This transition temperature was about 50% higher than the then highest known value of 23K found in a Nb_3Ge film that was first synthesized by John Gavaler in 1973.**

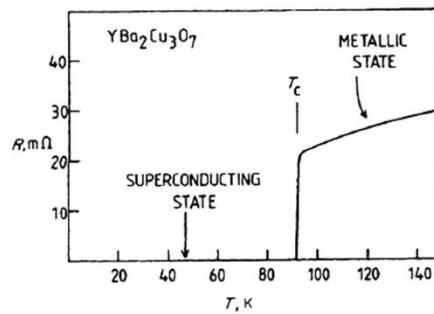
The Bednorz and Müller collaboration had started in 1983 when they initiated a program to search for superconductivity in oxides. They began by investigating oxide systems which exhibited a **large Jahn-Teller effect**, La-Ni-O , then replacing some Ni by aluminum and later by copper. Although these oxides showed promising behavior they did not exhibit superconductivity.

In late 1985 stimulated by the work of French scientists on the catalytic properties of Ba-La-Cu oxides with a Perovskite structure which exhibited metallic properties, they synthesized a series of solid state solutions - varying the Ba/La ratio and then measuring their temperature dependent resistance down to liquid helium temperatures.

By this careful work imbued with innate insight, they finally managed to prepare the superconducting ceramic mentioned above with a T_c of 35K. Stimulated by their published results of superconductivity at 35K, scientists world wide began investigating these and other oxide systems which soon achieved T_c 's exceeding 100K.

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Zero Resistivity

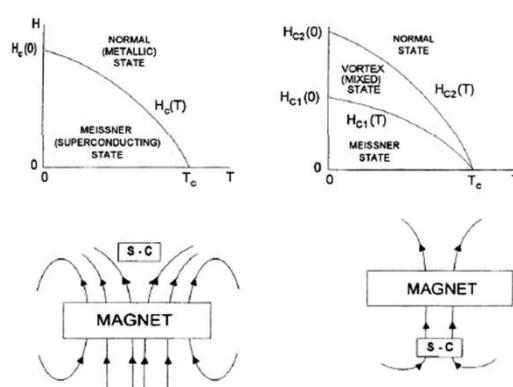


BCS theory (for conventional superconductor)

- Prof. Bardeen, Cooper and Schrieffer; Nobel prize of physics in 1972
- Cooper pairs (strong electron-phonon interaction)
- Weakly bound, with a typical separation of hundreds nanometers
- Pairing only occurs at low temperature

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Type I and Type II Superconductors



- Magnetic line of force are NOT completely expelled in the vortex state
- *Flux pinning* due to crystal defects or impurities
- Levitation and suspension

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Superconducting Materials

	Substance	T_c (K)	Substance	T_c (K)
Metals	Hg	4	Nb	9.5
	V	5.4	Tc	7.8
	Pb	7.2		
Alloys	Nb ₃ Ge	23	V ₃ Si	17
	Nb ₃ Sn	18	V ₃ Ga	16.5
Non-cuprate oxides	Nb ₃ Al	17.5	NbN	16
	LiTi ₂ O ₄	12	BaPb _{0.75} Bi _{0.25} O ₃	13
Cuprates	La _{1.85} Sr _{0.15} CuO ₄	40	Ba _{0.6} K _{0.4} Bi ₂ O ₃	30
	YBa ₂ Cu ₃ O ₇	93	Tl ₂ Ba ₂ CuO ₆	80
	Bi ₂ Sr ₂ Ca ₂ Cu ₃ O ₁₀ (BiSCCO)	110	Tl ₂ Ba ₂ Ca ₂ Cu ₃ O ₁₀	125
Organics	HgBa ₂ Ca ₂ Cu ₃ O ₁₀	134*	Tl ₂ Ba ₂ Ca ₃ Cu ₄ O ₁₂	115
	(ET) ₂ Cu(NCS) ₂	11.4		
Others	YNi ₂ B ₂ C	15.5		
	Fullerenes, e.g. Cs ₂ RbC ₆₀ ,	33		
	Chevrel phases, Mo ₆ S ₈			
	Sulphur: at 93 GPa at 160 GPa	10 17†		

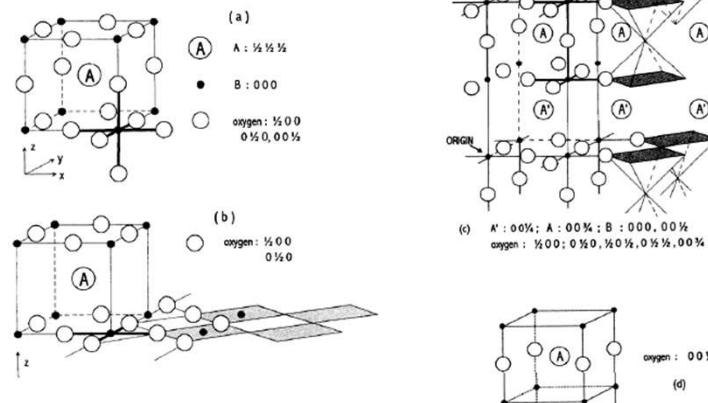
Family of *cuprates* are known to be high temperature superconductor!

e.g. YBa ₂ Cu ₃ O ₇ , NdBa ₂ Cu ₃ O ₇	High H_{c2}
Bi ₂ Sr ₂ CaCu ₂ O _{8+d}	High J_c
HgBaCaCuO	highest T_c

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Crystal Structure of Cuprate Perovskites

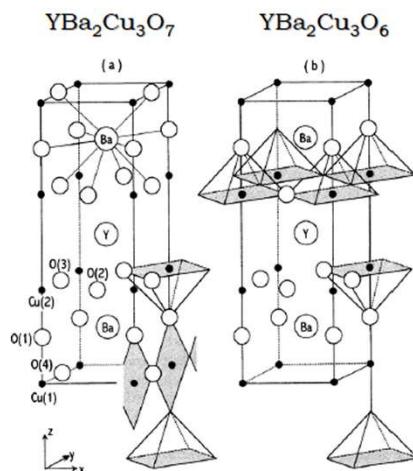
Ideal Perovskites



- Perovskites: ABO_3 compound
- Oxygen-deficient structure
- Cu can have various coordination and valence states (+1, +2 and +3)

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Crystal Structure of $\text{YBa}_2\text{Cu}_3\text{O}_7$



$\text{YBa}_2\text{Cu}_3\text{O}_7$

- $\text{BaCuO}_{2.5}$: Cu^{2+} (square pyramid)
- YCuO_2 : Cu^{3+} (square planar)

$\text{YBa}_2\text{Cu}_3\text{O}_4$

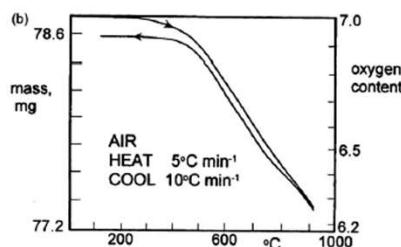
δ decrease, T_c decrease
 $\delta < 6.4$, no superconductivity

$\text{YBa}_2\text{Cu}_3\text{O}_6$

$\text{Cu}^{3+} \rightarrow \text{Cu}^+$ (linear)

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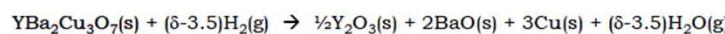
Oxygen Content in $\text{YBa}_2\text{Cu}_3\text{O}_7$



Vary easily over the range $6 < d < 7$ simply by heating the material at different temperature and different oxygen partial pressure

Determination of oxygen content in $\text{YBa}_2\text{Cu}_3\text{O}_7$

- hydrogen reduction TG



- Iodometry

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Importance of Superconductors

- Zero resistance
 - Efficient power transmission
 - Miniaturization of circuit boards and electronic components (heating dissipation will be solved)

- Perfect diamagnetism
 - Detect minute magnetic field (application in medicine)
 - Levitation, such as Maglev trains



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Magnetic Properties at Different Length-scale

3.9 Ferromagnetic properties

* Ferromagnetic materials

- Unpaired electrons in d -orbit : directed spin

e.g., Fe, Co, Ni

- Exchange energy: alignment of atomic spins

- Domain theory

- Lowering magnetostatic energy by forming multiple domains

- Hysteresis loop

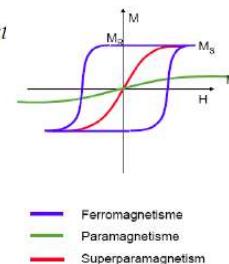
H : magnetic field; M : magnetization (magnetic moment / volume)

Coercivity, saturation magnetization, BH product

- Magnetic alignment

- Rotation of magnetic dipoles

- Movement of domain boundary



* Single-domain particles

- Energy lowering by domain formation is balanced ($E_{ms} \propto d^3$ d : domain size)

by energy increase for boundary formation ($E_{bf} \propto d^2$) as d decreases...

- For small particles, single domain is in the lowest energy state...

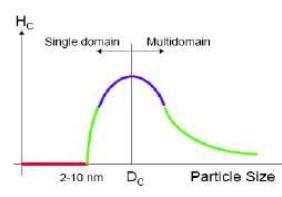
d_p : 10 ~ 100 nm

- Used for magnetic recording media

* Superparamagnetism:

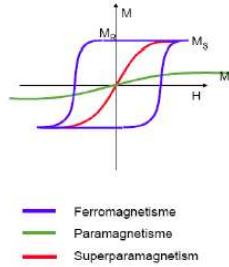
- Thermal fluctuation > magnetic alignment as the size decreases

Usually, $d_p < \sim 15$ nm



- No hysteresis loop

- Used in biomedical application, ferrofluids, sensors



- ❑ Nanoscale amorphous alloy powders of $\text{Fe}_{69}\text{Ni}_9\text{CO}_2$ having grain sizes of 10-15 nm prepared by decomposition of solutions of $\text{Fe}(\text{CO})_5$, $\text{Ni}(\text{CO})_5$, and $\text{Co}(\text{NO})(\text{CoO})_3$, under an inert-gas atmosphere showed almost no hysteresis in the magnetization curve.
- ❑ A magnetic material with grain-sized single domain magnetic moments, which has no hysteresis at any temperature, is said to be super-paramagnetic.

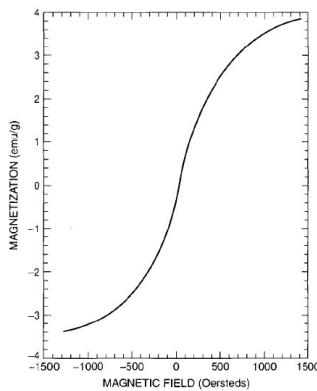
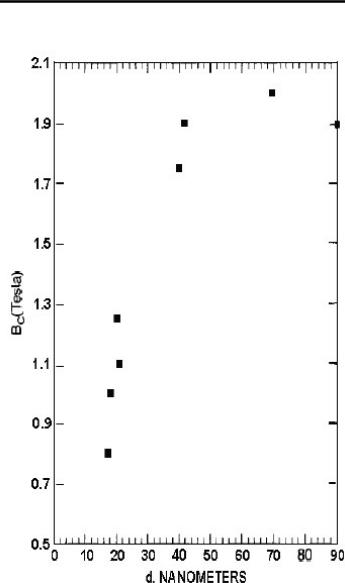


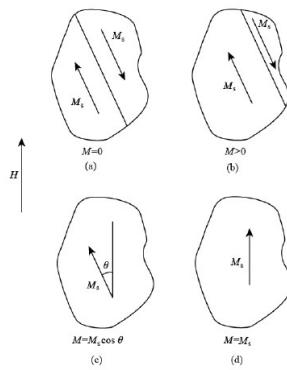
Figure 7.4. Reversible magnetization curve for nanosized powders of a Ni-Fe-Co alloy that exhibits no hysteresis. An oersted corresponds to 10^{-4} T (tesla). [Adapted from K. Shafi et al., *J. Mater. Res.* **15**, 332 (2000).]



- ❑ The effect of the size of the nanoparticle grain structure on $\text{Nd}_2\text{Fe}_{14}\text{B}$ has been investigated. The results, shown in Figs. 7.6, indicate that in this material the coercive field decreases significantly below 40 nm and the remnant magnetization increases.
- ❑ This is believed to be due to the exchange coupling between the hard and soft nanoparticles, which forces the magnetization vector of the soft phase to be rotated to the direction of the magnetization of the hard phase.
- ❑ The size of magnetic nanoparticles has also been shown to influence the value M , at which the magnetization saturates.
- ❑ Example: The effect of particle size on the saturation magnetization of zinc ferrite, illustrated how the magnetization increases significantly below a grain size of 20 nm. *J Phys Condens Matter* **12**, 7795 (2000)

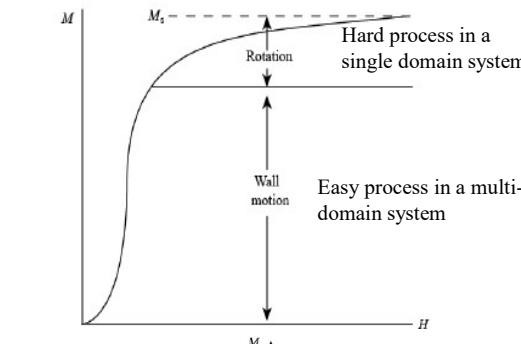
Figure 7.6. Dependence of the coercive field B_c (i.e., H_c) on the granular particle size d of a Nd-Fe permanent magnet. [Adapted from A. Manaf et al., *J. Magn. Magn. Mater.* **101**, 360 (1991).]

Process of Magnetic Saturation of a Multi-domain Particle

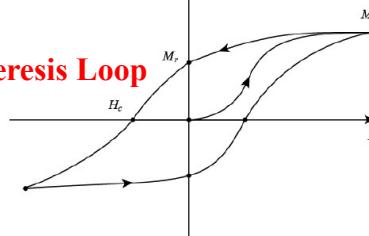


The hysteresis loop defines the technological properties of the magnetic material

M_s = Saturation Magnetization
 M_r = Remnant Magnetization
 H_c = Coercivity

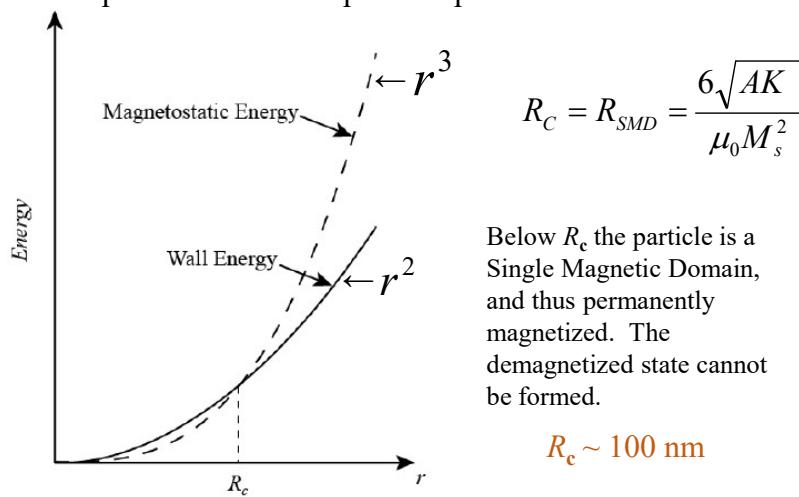


Hysteresis Loop

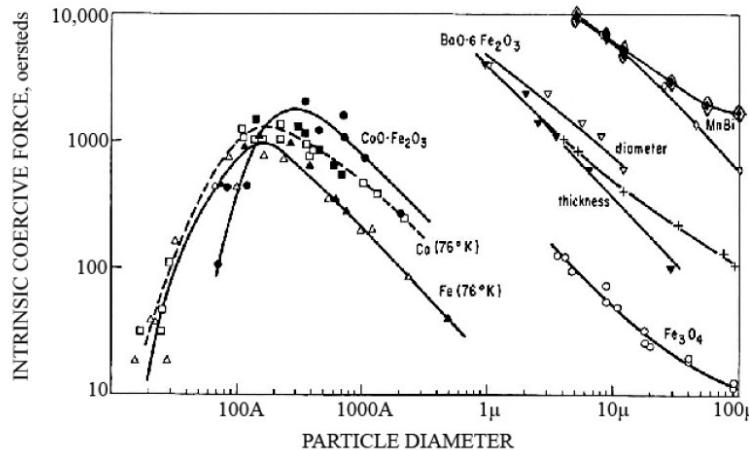


Critical Size for SMD Particles

Magnetostatic vs. wall energy as a function of particle size for a spherical particle of radius r

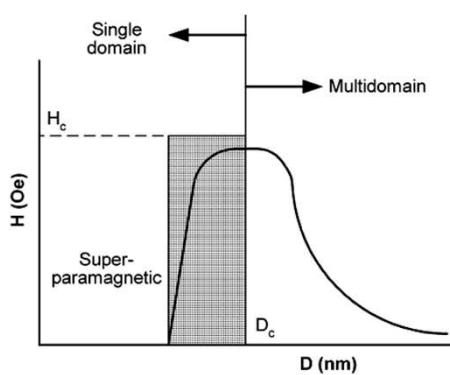


Coercivity as a function of particle size



F. E. Luborsky J. Appl. Phys. 32 (1961) S171

It was found that the coercivity H_c increases with decreasing grain size D down to values of about 40 nm, independent of the kind of material. The increase of H_c is proportional to $1/D$. The reason for this is that in small particles the formation of a closed magnetic flux becomes energetically less favorable so that the magnetic domain size with a uniform magnetization becomes more and more identical with the grain size. This grain size is defined as the first critical size (D_c , which is characteristic of each material) where the multidomain materials change to a monodomain material. This leads to a strong increase of the coercivity (or high remanence) because a change of magnetization in this case cannot happen only by shifting the domain walls which normally requires only a weak magnetic field.



As the size of magnetic element scales below 20 nm, the transformation from ferromagnetic to superparamagnetic behavior occurs. In the superparamagnetic state of the material, the room temperature thermal energy overcomes the magnetostatic energy well of the domain or the particle, resulting in zero hysteresis. In other words, although the particle itself is a single-domain ferromagnet, the ability of an individual magnetic "dot" to store magnetization orientation information is lost when its dimension is below a threshold. Consequently, the magnetic moments within a particle rotate rapidly in unison, exhibiting the superparamagnetic relation phenomenon.

Fig. 2. Qualitative illustration of the behavior of the coercivity in ultrafine systems as the particle size changes, where H is the magnetic field amplitude (Oe) and D is the particle diameter (nm).