Magnetic Materials and (some) Applications

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Acknowledgement

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- Anja Waske (IfW Dresden)
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Thanks to all colleagues!

For reading…

M. Coey: Magnetism and Magnetic Materials.
Cambridge University Press (2010)

B.D. Cullity and C.D. Graham: Introduction to Magnetic Materials.
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R. Hilzinger and W. Rodewald: Magnetic Materials.
Edited by Vacuumschmelze GmbH, Publicis Publishing, Erlangen (2013)

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D.C. Jiles: Introduction to Magnetism and Magnetic Materials.
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J.P Liu, E. Fullerton, O. Gutfleisch, D. Sellmyer (ed.): Nanoscale Magnetic Materials an Applications. Springer Verlag (2009)

R. O`Handley: Modern Magnetic Materials, Wiley (2000)

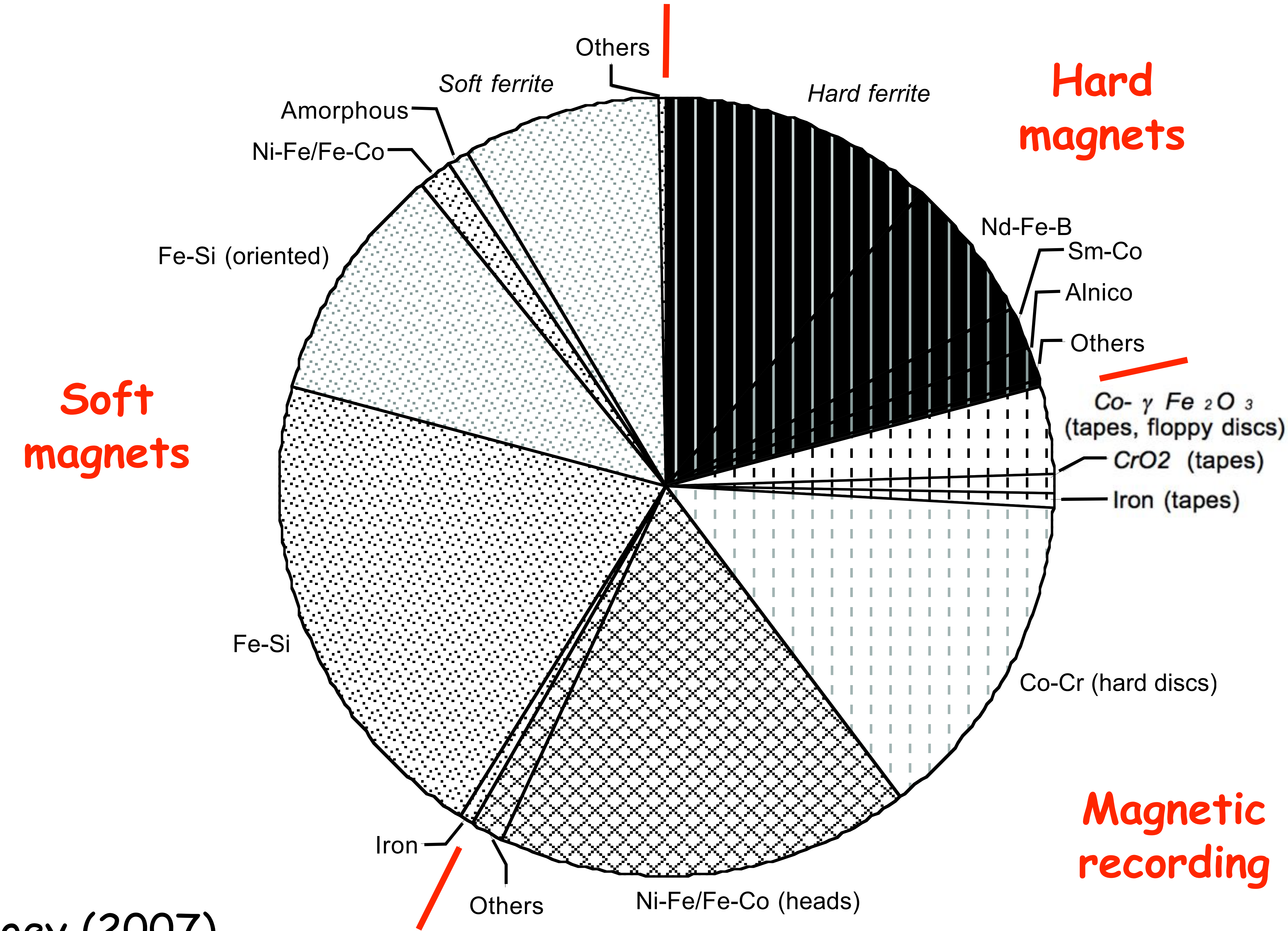
Many figures in this presentation are taken from these references – special thanks to the authors

Magnetic Materials...

Fe/Cr/Fe
Cobalt (Co)
Nickel (Ni)
FeSi 3wt%
Non-oriented
Grain-oriented
Ni_2MnIn
Co_2FeSi
Co_2MnSi
Cu_2MnAl
$La(Fe_xSi_{1-x})_{13}H_x$
NiFe 56wt%
Iron (Fe)
Ni_2MnCo
Co_2MnGa
$Gd_5(Si_xGe_{1-x})_4$
Ni_2MnGa
Sendust FeSi9.5Al5.5wt%
$MnFeP_{1-x}As_x$
SiFe 6.5wt%
$Co_{73}Fe_5Si_5B_{17}$
NiFe 50wt%
CoCrPt
MnZn-Ferrite
CoFe 35wt%
Fe_3O_4
CoFe 50wt%
NiZn-Ferrite
Ni_2MnGa
NiO
$Fe_{86}Cu_1Zr_7B_6$
Co_2FeAl
Co/Cu/Co
Amorphous Fe-Si-B
$Fe_{74}Cu_1Nb_3Si_{15}B_7$
Permalloy
$SmCo_5$
$Nd_2Fe_{14}B$
Sm_2Co_{17}
Co49Fe49V2wt%
$(Tb_{0.3}Dy_{0.7})Fe_2$
Ni80Fe15(Cu,Mo)5wt%
$Tb_2Fe_{14}B$
$TbFe_2$
CoPt
$Pr_2Fe_{14}B$
FePt
$Co_{68}Fe_4Mo_2Si_{16}B_{10}$
$BaFe_{12}O_{19}$
NiFe 48wt%
FeCrCo
MnIr/NiFe
etc....

Magnetic Materials…

Magnetic applications: a 30 Billion EUR/Dollar market



M. Coey (2007)

Magnetic Materials…

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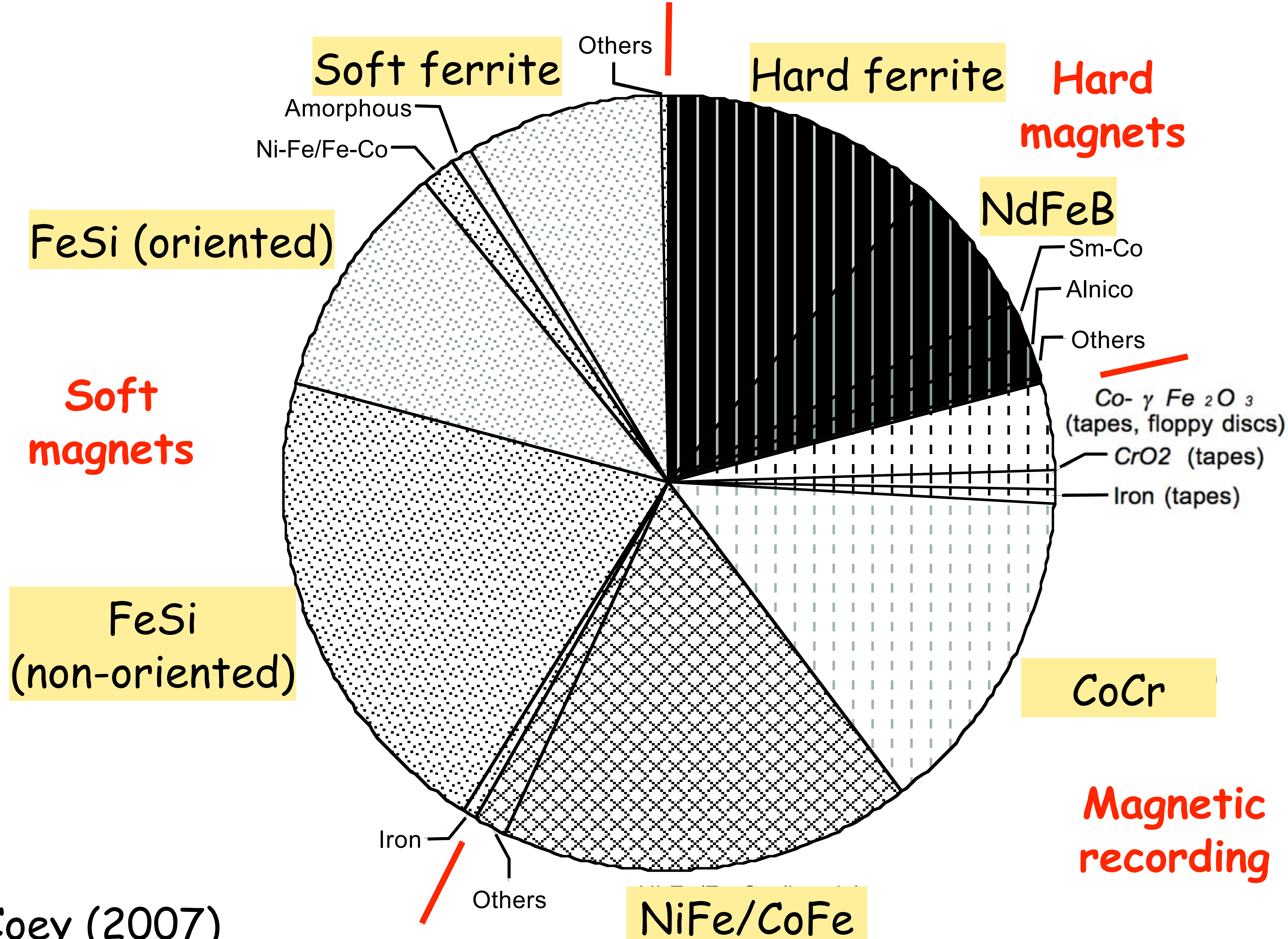
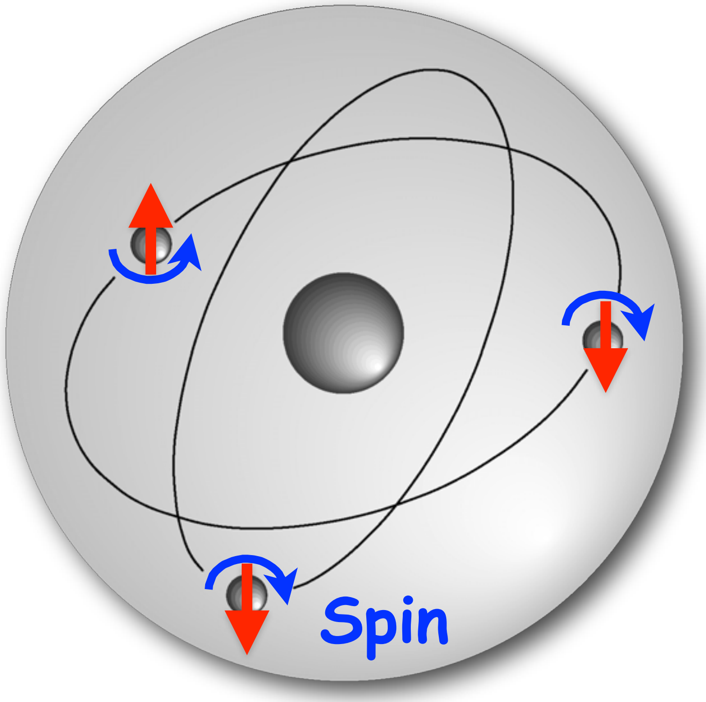


M. Coey (2007)

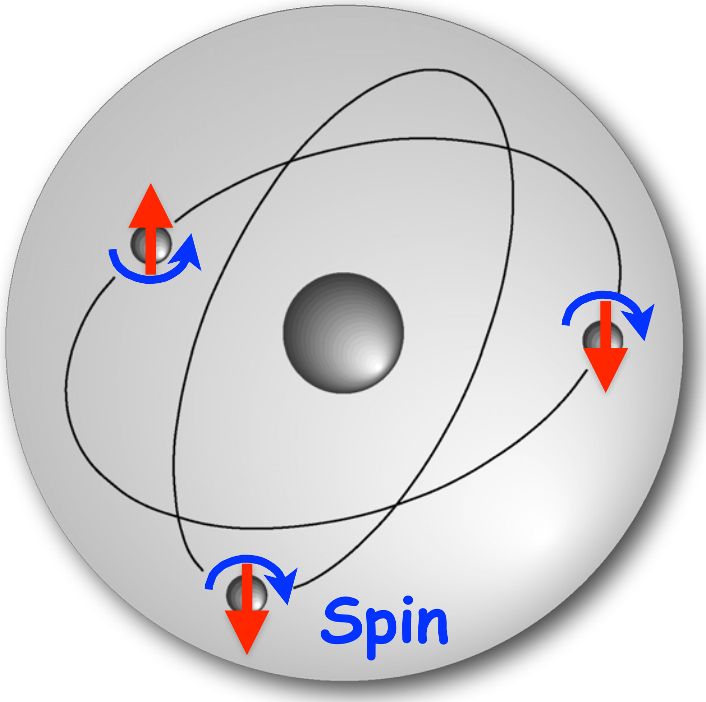
3 descriptive levels of magnetic materials

3 descriptive levels of magnetic materials



1. Microscopic level
(atomic level theory)

3 descriptive levels of magnetic materials

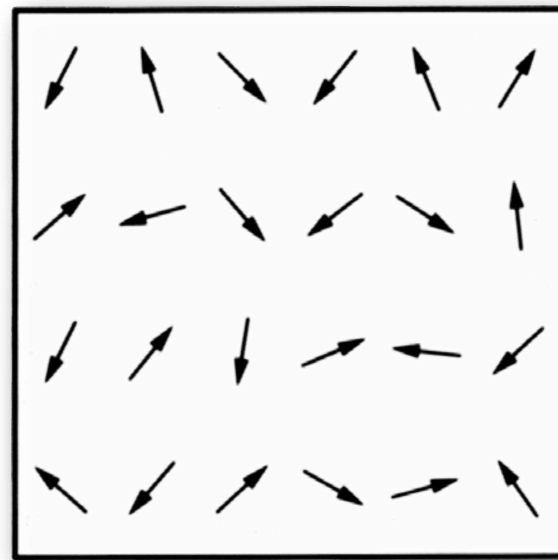


1. Microscopic level
(atomic level theory)

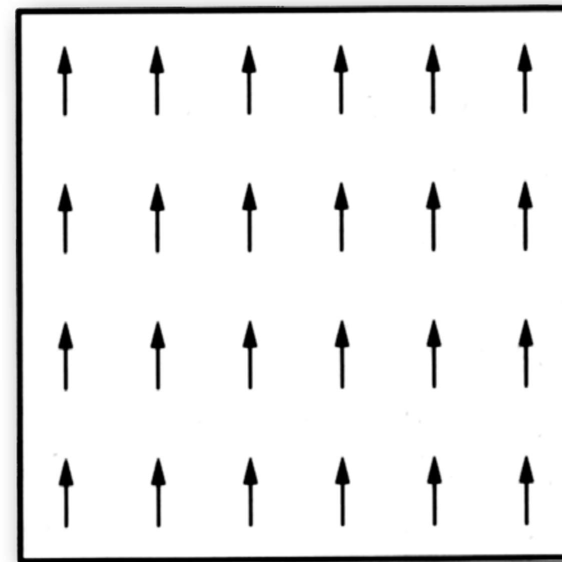
Describing the origin, interaction and arrangement of magnetic moments. Explanation of saturation magnetization, anisotropy, magnetoelastic interaction etc.

„Microscopic“ classification of materials

Diamagnet

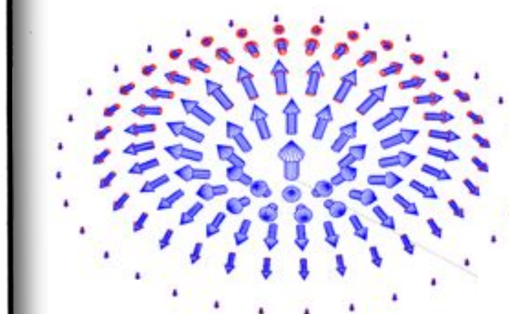


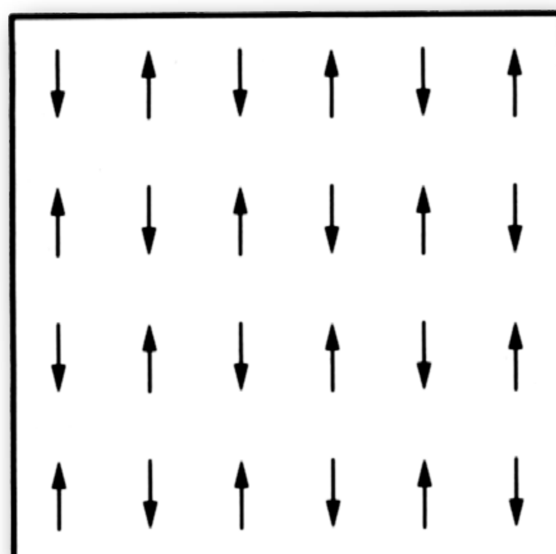
Paramagnet



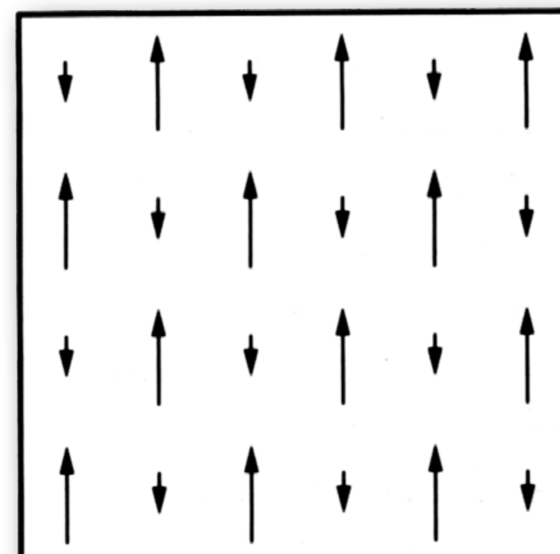
Ferromagnet

Skyrmions

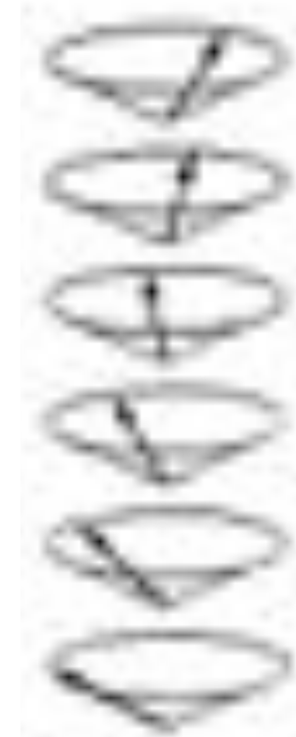




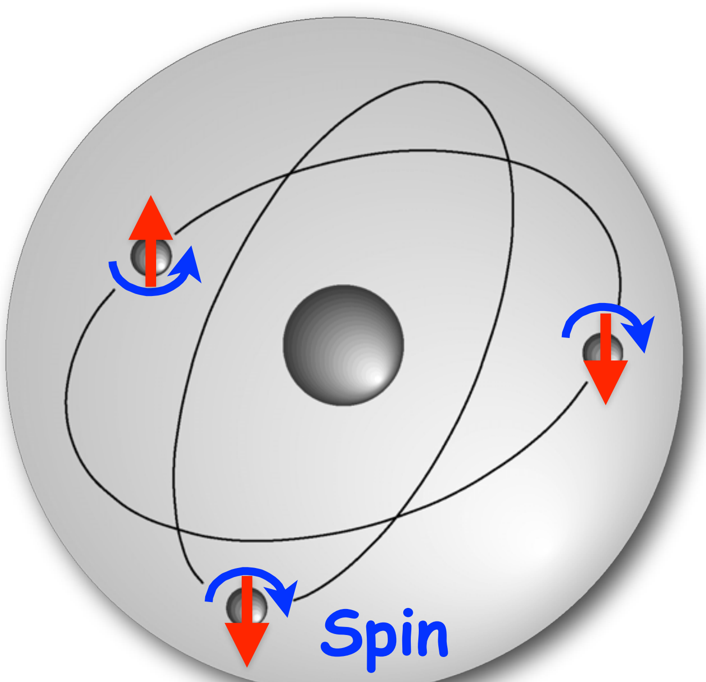
Antiferromagnet



Ferrimagnet



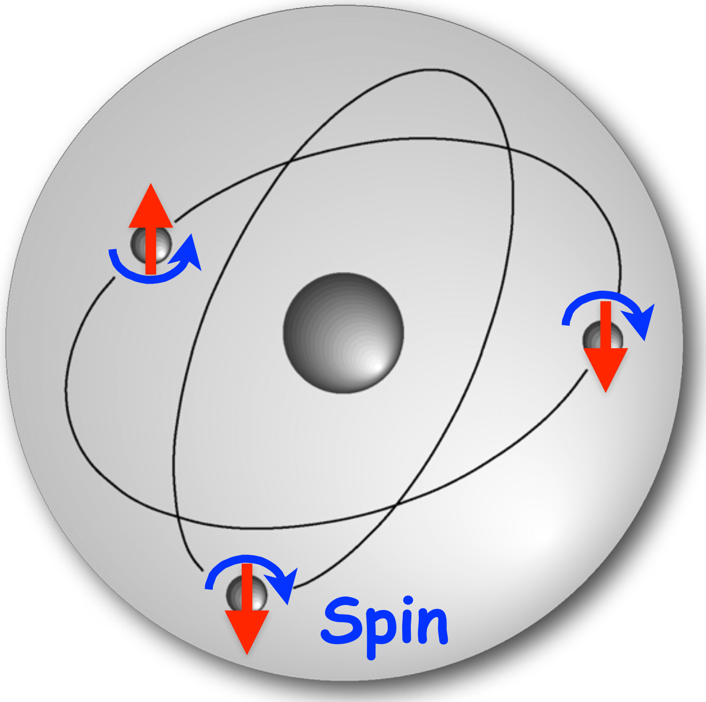
Helimagnet



1. Microscopic level (atomic level theory)

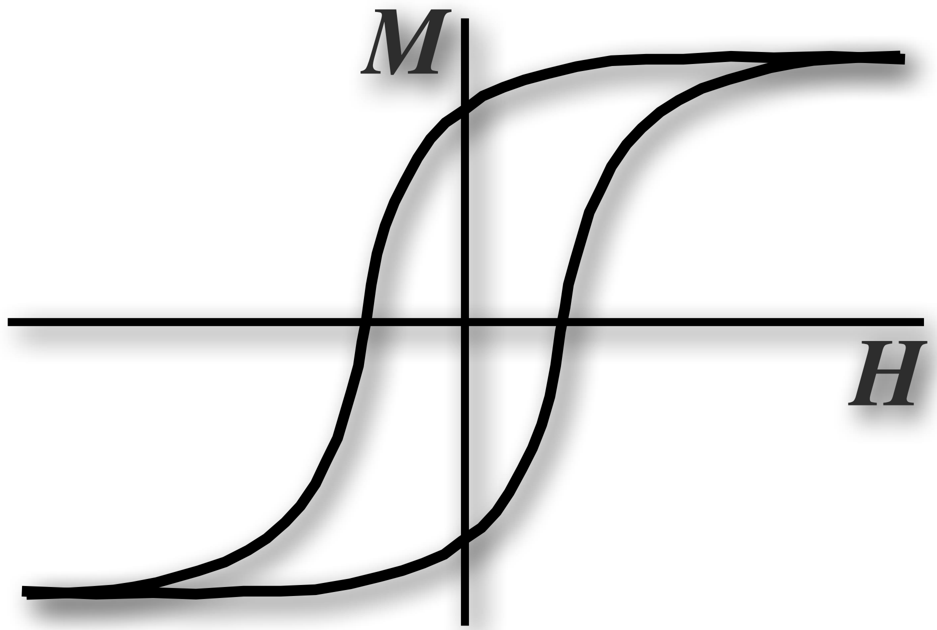
Describing the origin, interaction and arrangement of magnetic moments. Explanation of saturation magnetization, anisotropy, magnetoelastic interaction etc.

3 descriptive levels of magnetic materials

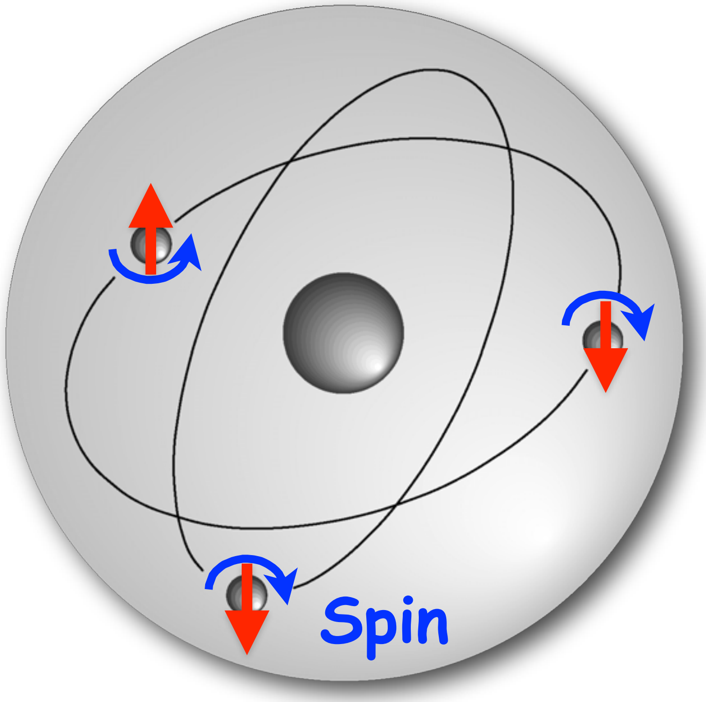


1. Microscopic level:
Atomic level theory

3 descriptive levels of magnetic materials



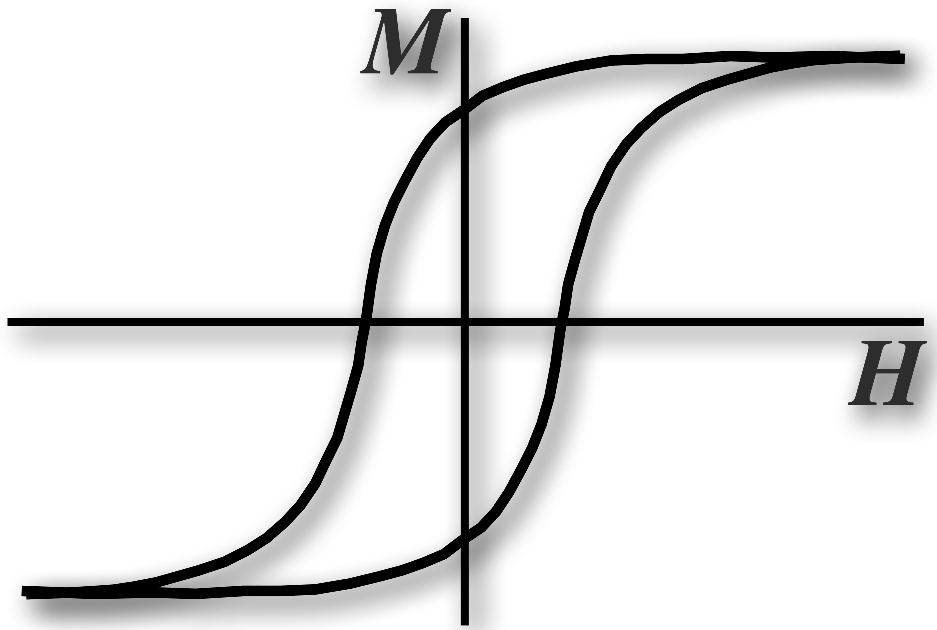
3. Macroscopic level:
Magnetization curve



1. Microscopic level:
Atomic level theory

3 descriptive levels of magnetic materials

Describing the average magnetization vector of a sample as a function of the external magnetic field



3. Macroscopic level: Magnetization curve

3 descriptive levels of magnetic materials

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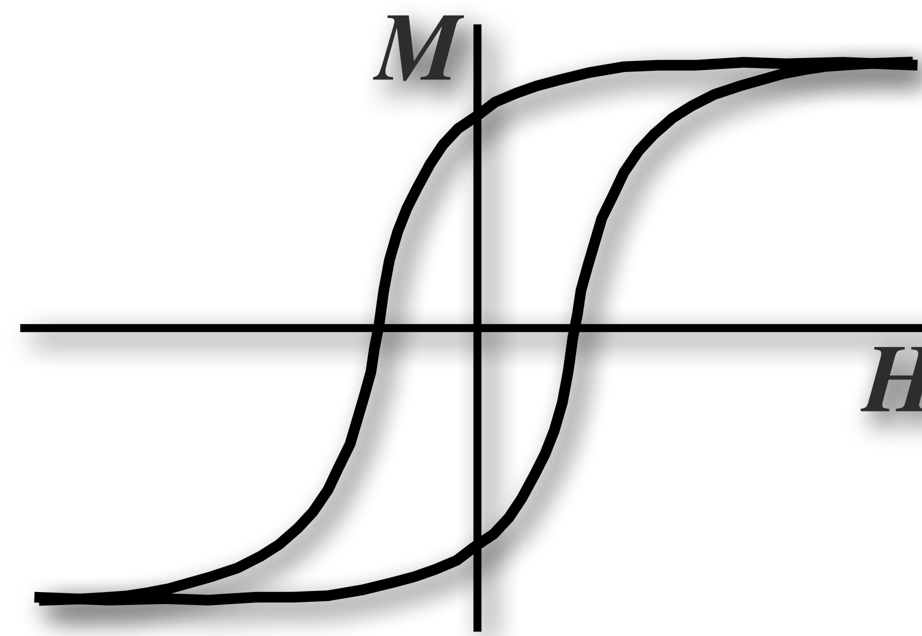
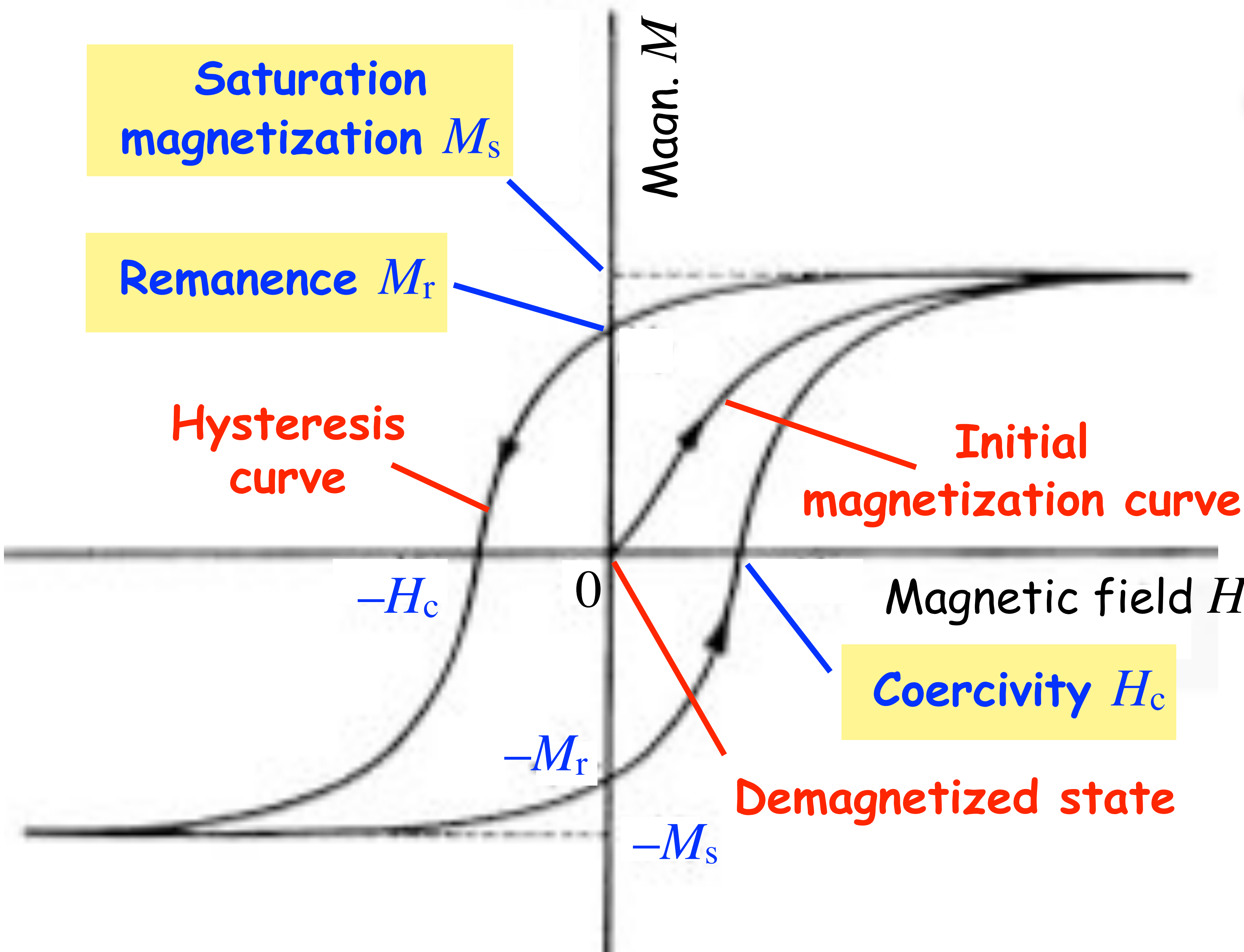
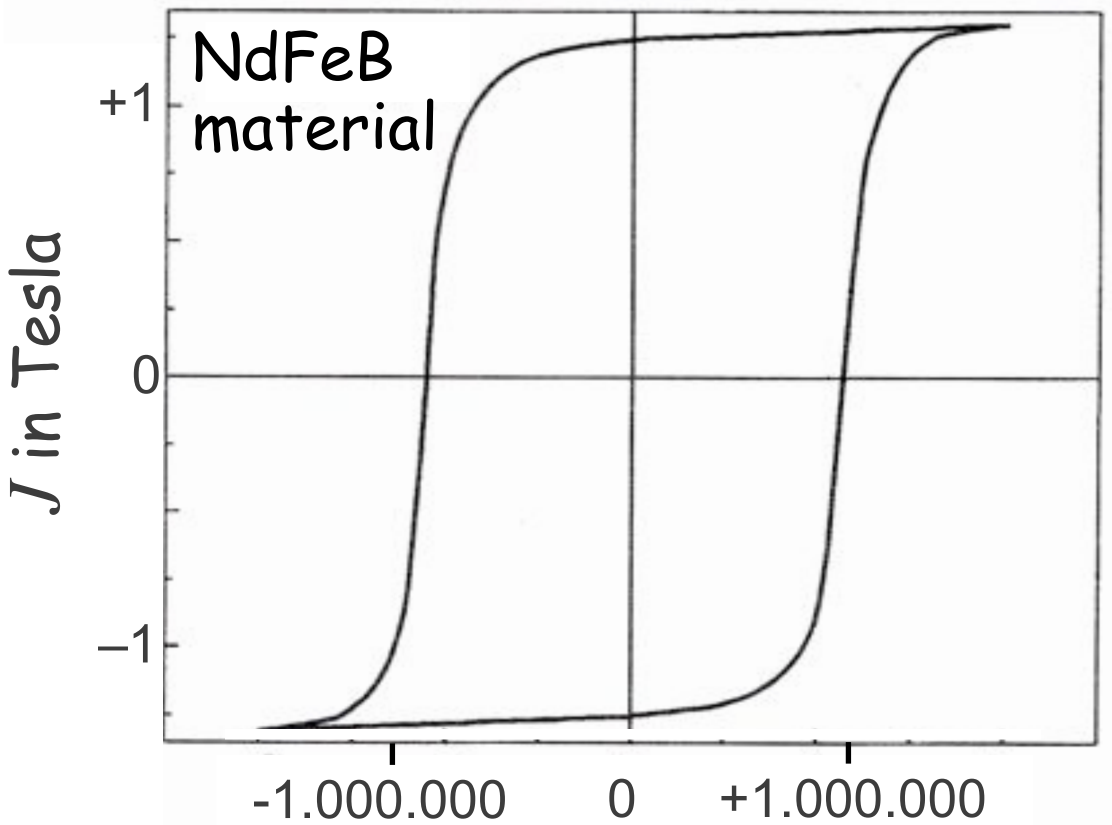


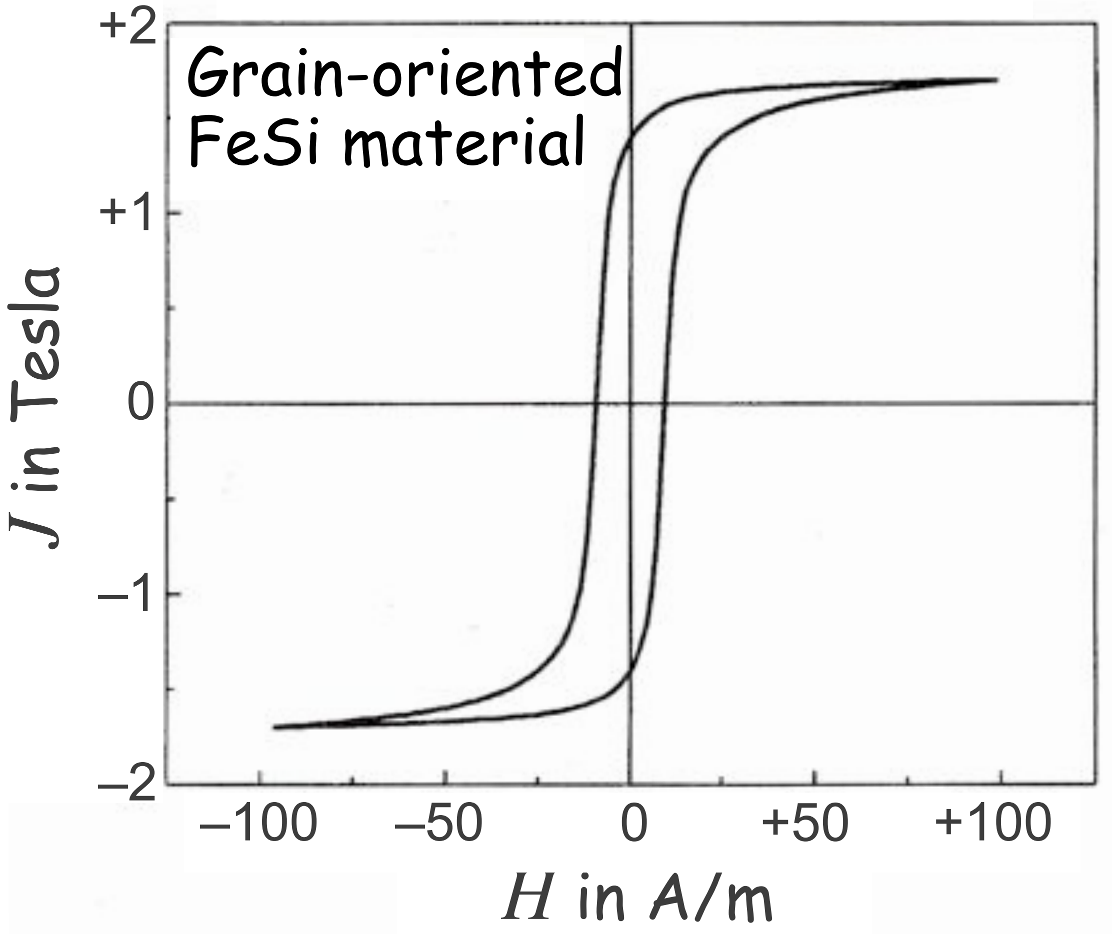
3. Macroscopic level: Magnetization curve



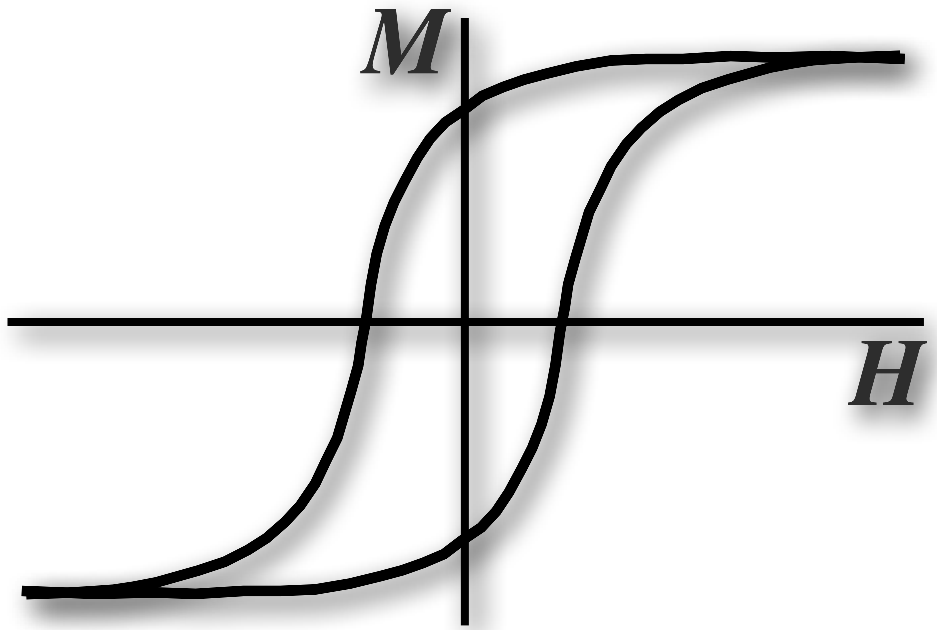
3 descriptive levels of magnetic materials



Hard magnet



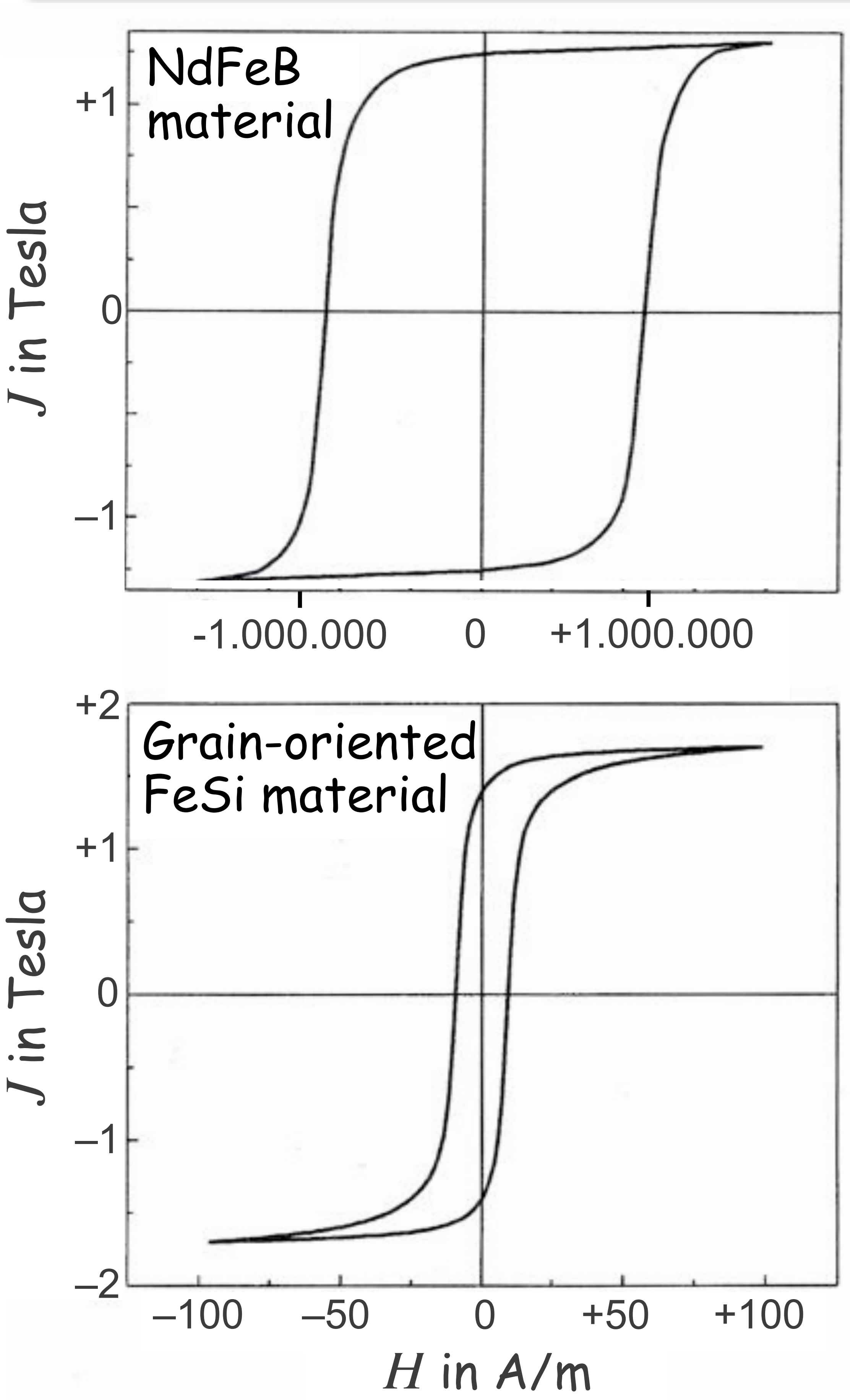
Soft magnet



3. Macroscopic level: Magnetization curve

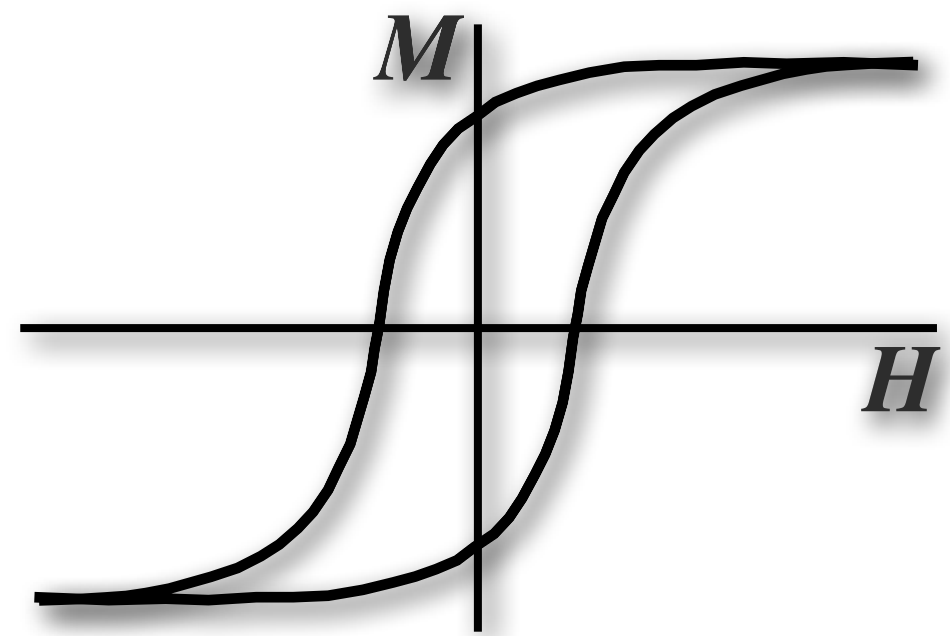
Loop widths differ by factor of 10^5

„Macroscopic" classification of materials



Hard magnet

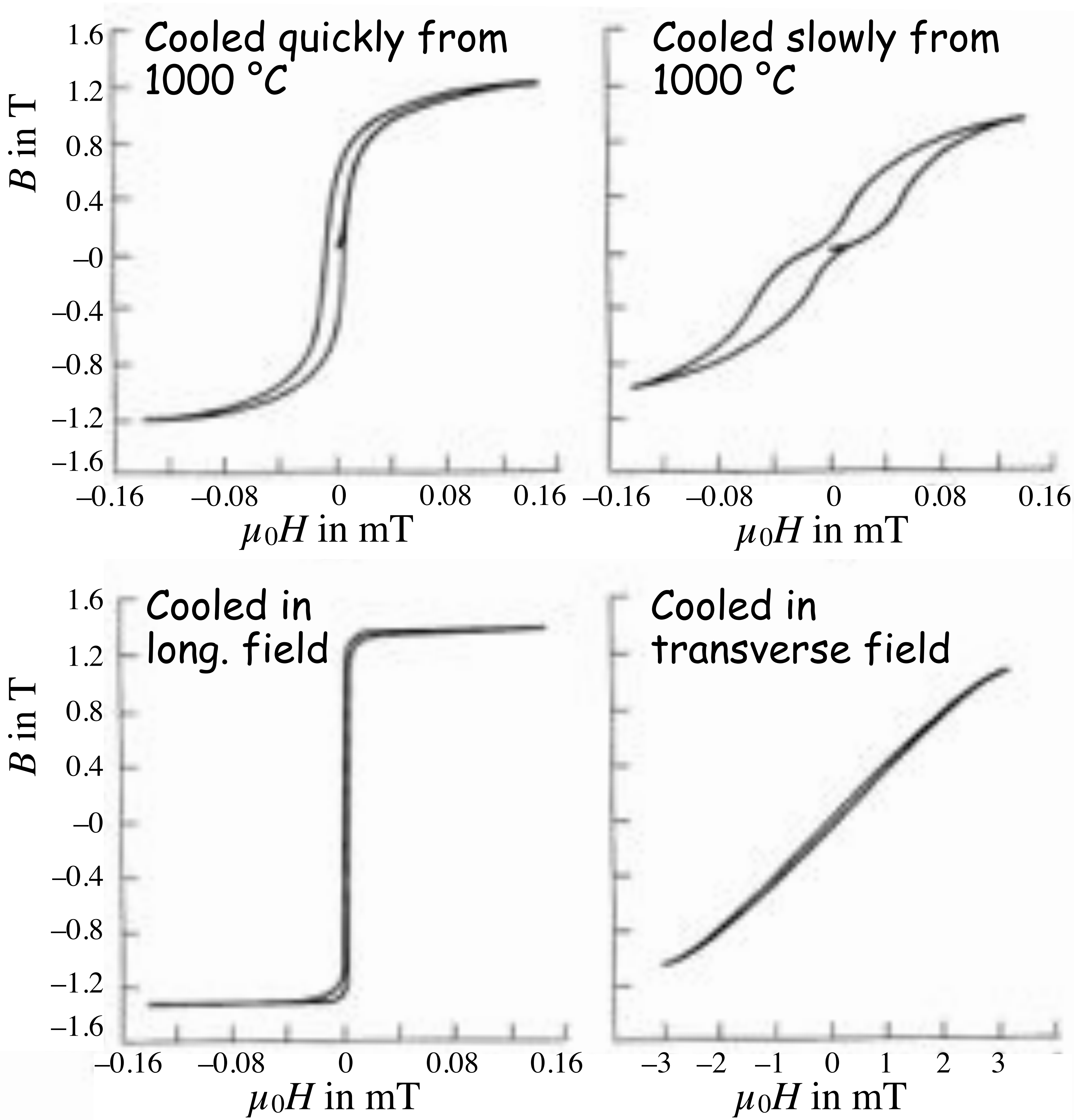
Soft magnet

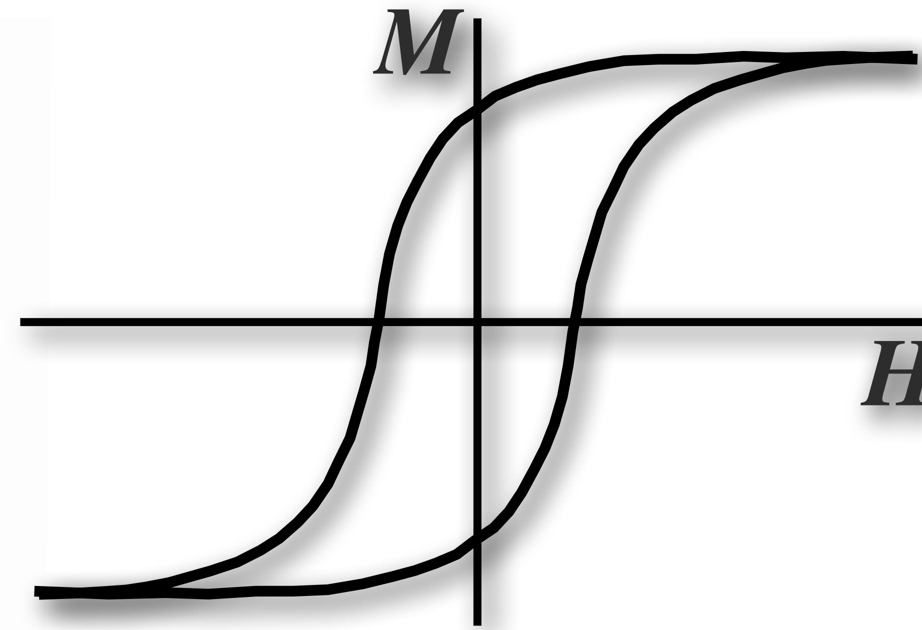


3. Macroscopic level: Magnetization curve

Loop widths differ by factor of 10^5

Hysteresis loops and coercivity…



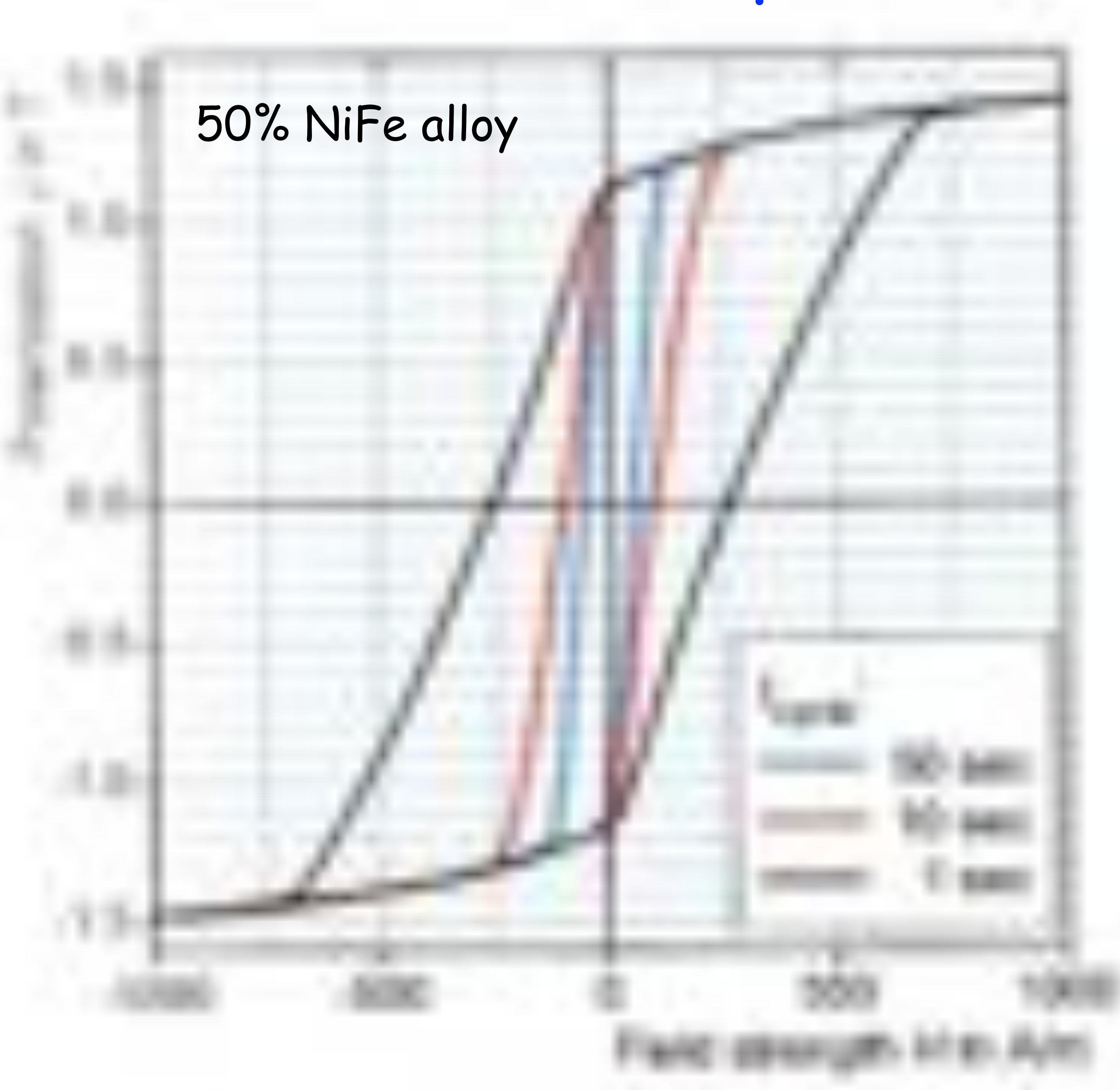


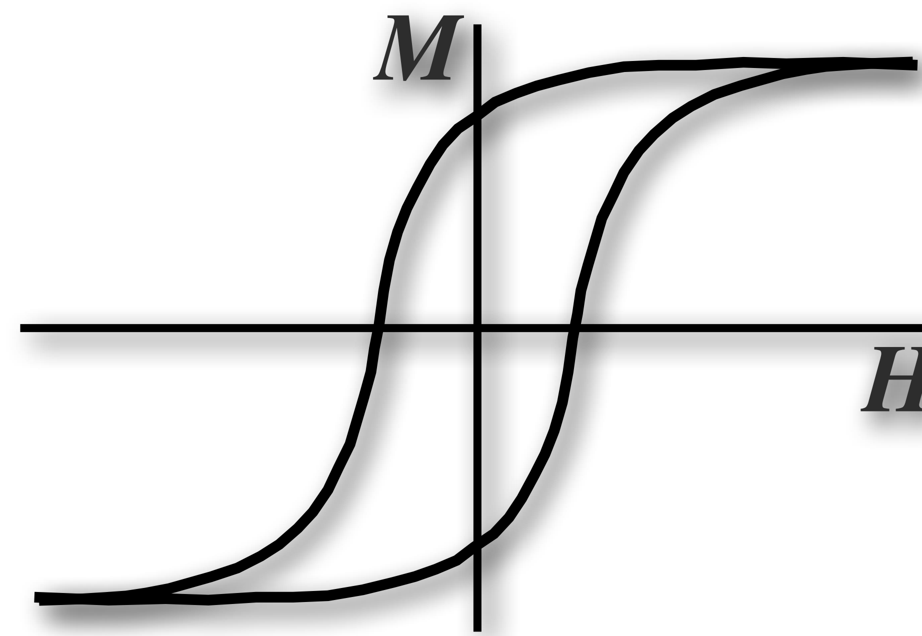
3. Macroscopic level: Magnetization curve

65 Ni – 35 Fe alloy after various heat treatments

Hysteresis loops and coercivity…

Quasi-static M(H)-loop depends on magnetization rate. Reason: eddy currents, relaxation processes

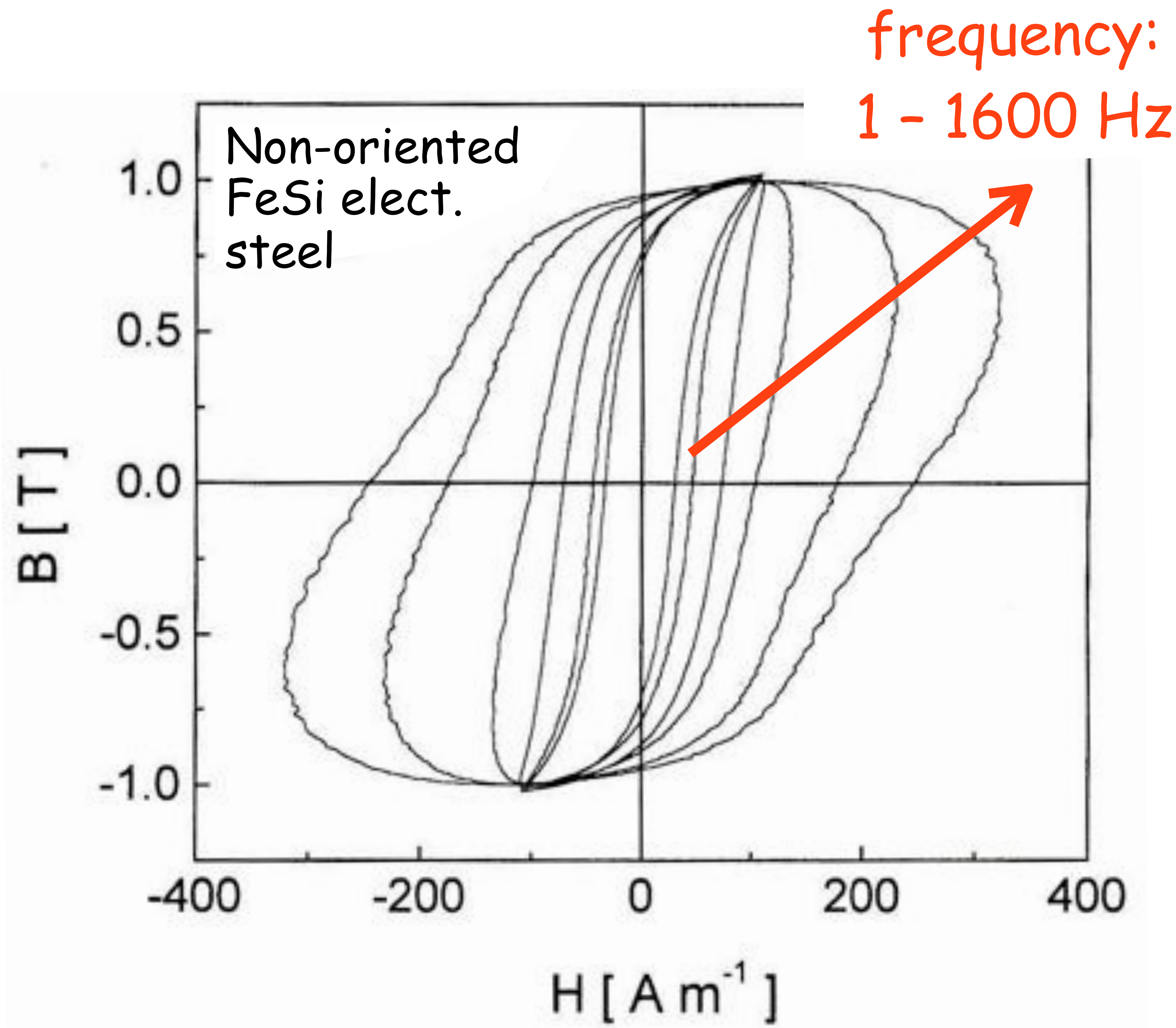


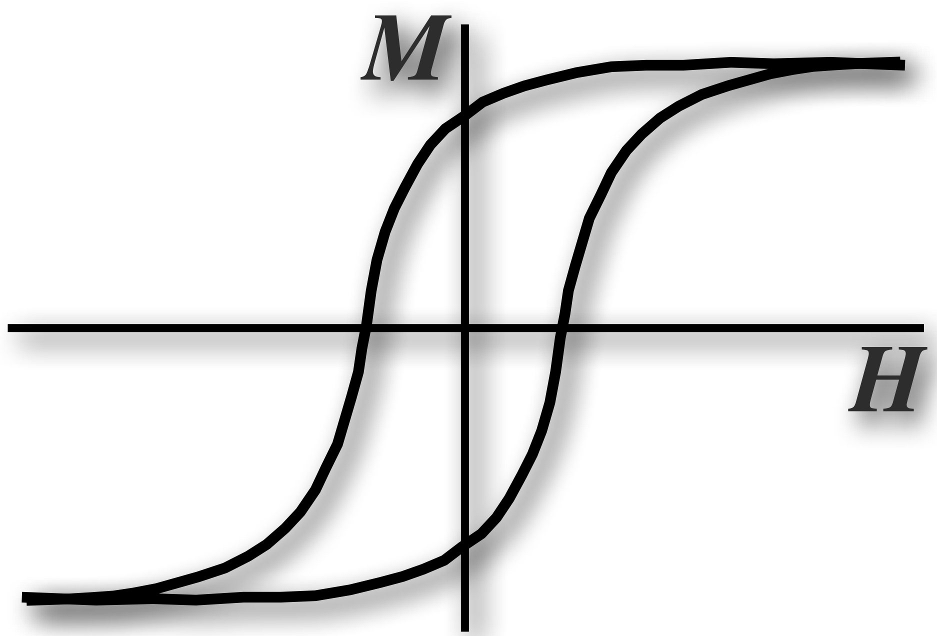


3. Macroscopic level: Magnetization curve

Hysteresis loops and coercivity…

M(H)-loop depends on measuring frequency. Reason: eddy current- and other losses

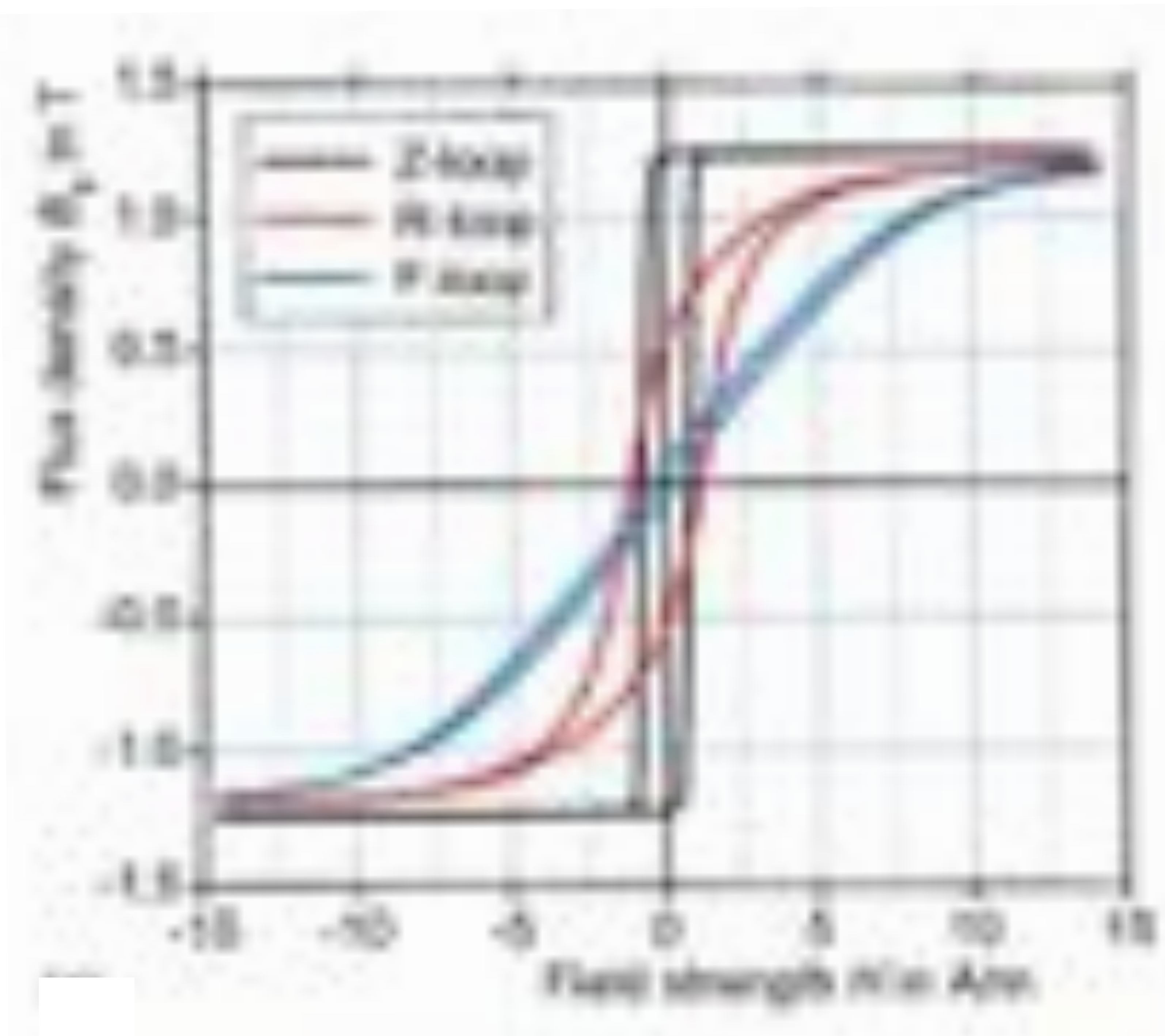


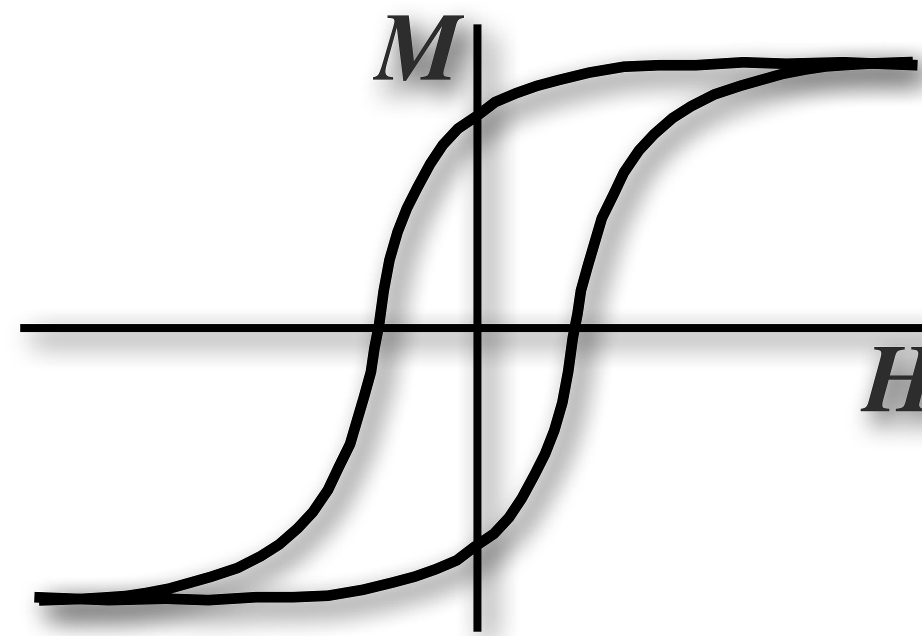


3. Macroscopic level: Magnetization curve

Hysteresis loops and coercivity…

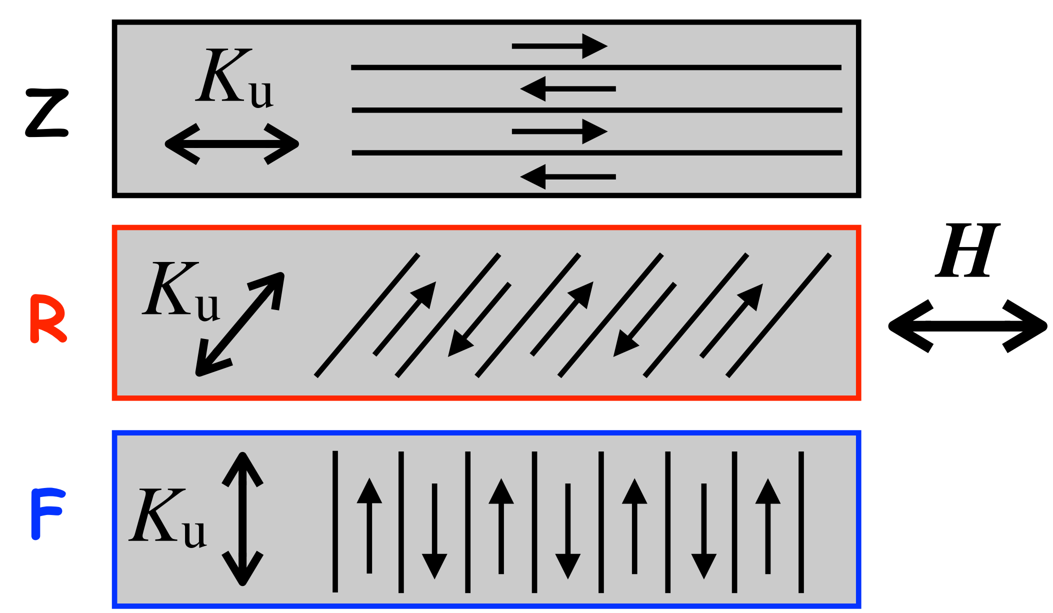
M(H)-loop depends on
field direction





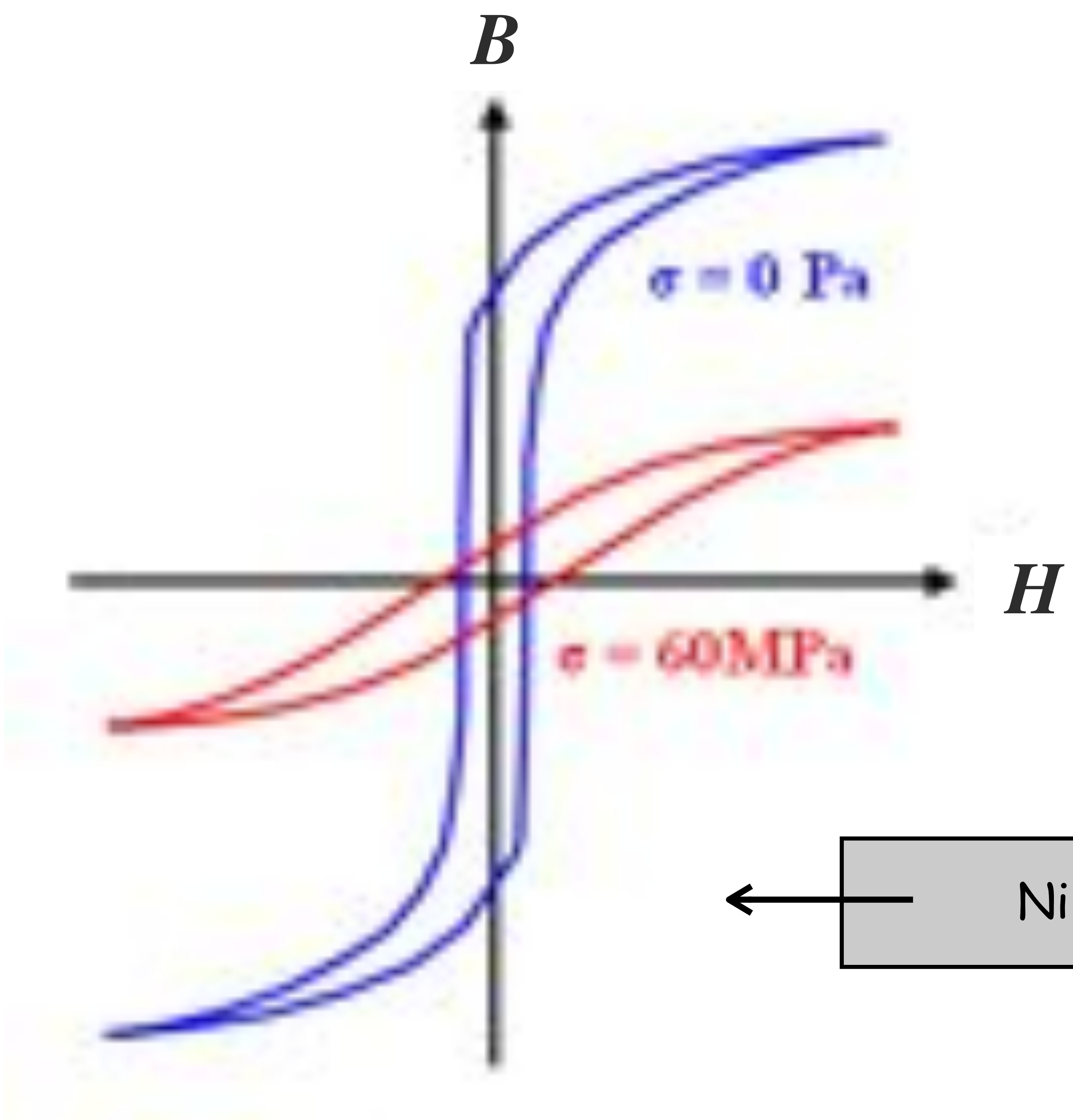
3. Macroscopic level:
Magnetization curve

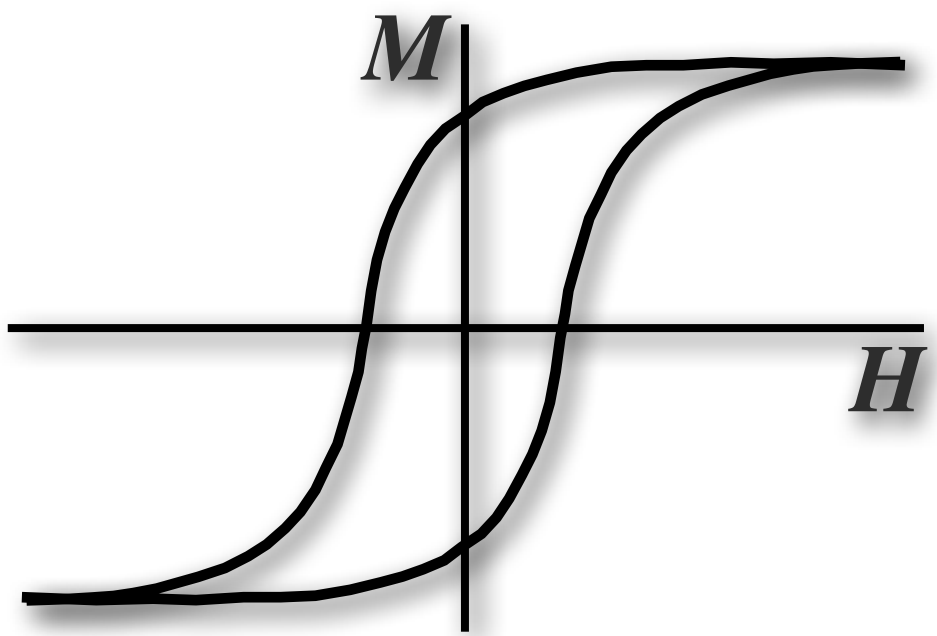
Amorphous ribbon



Hysteresis loops and coercivity…

M(H)-loop depends on mechanical stress

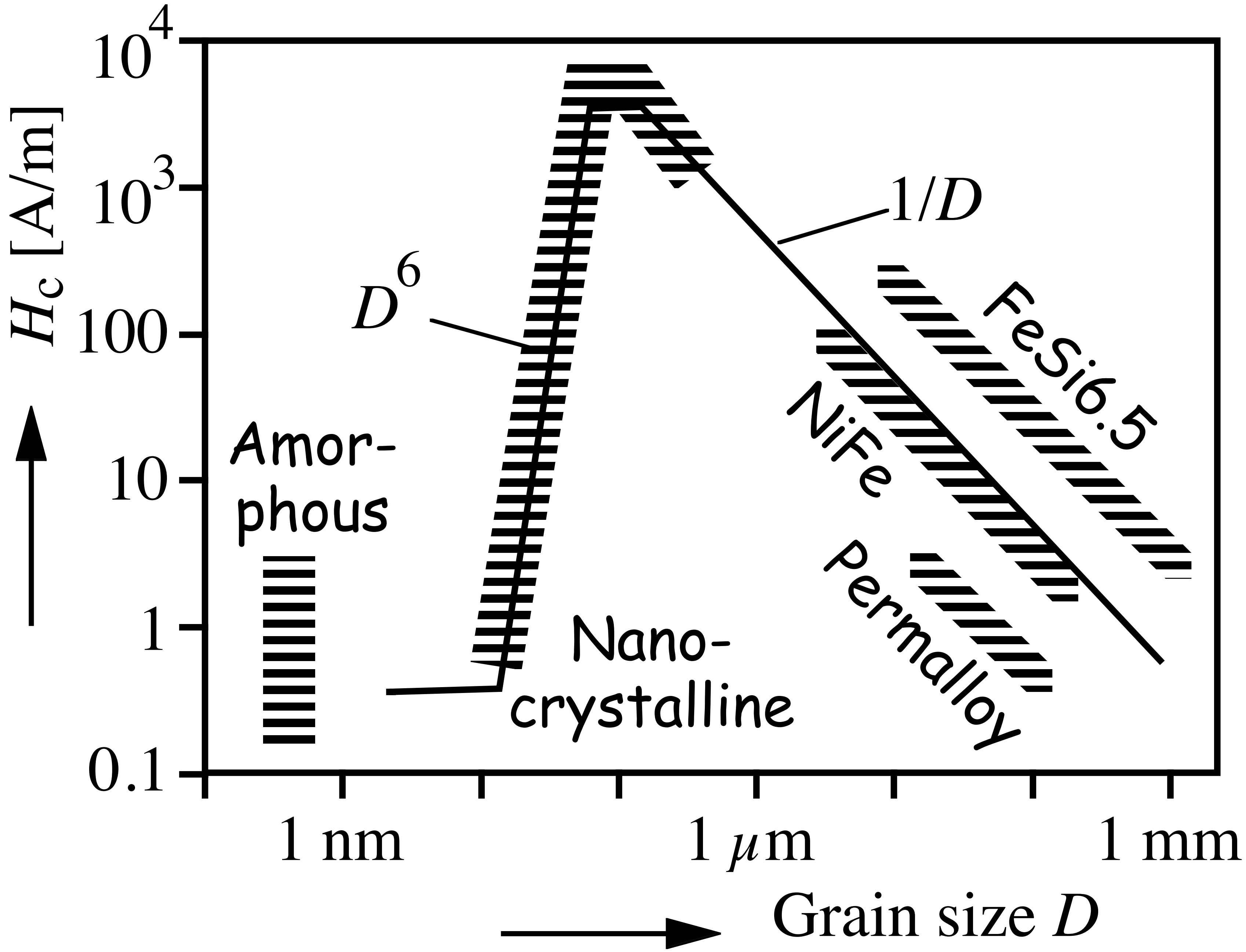


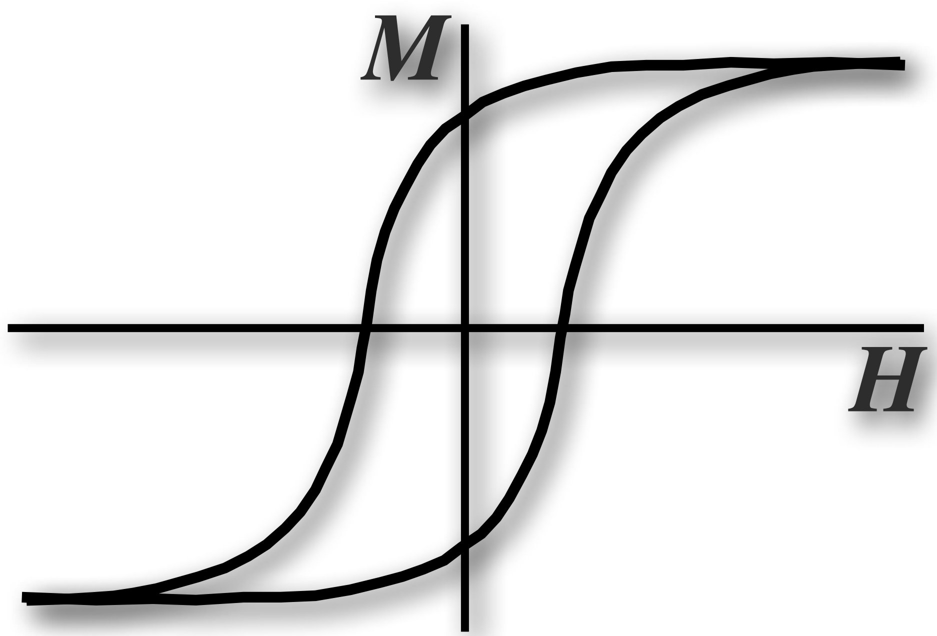


3. Macroscopic level: Magnetization curve

Hysteresis loops and coercivity…

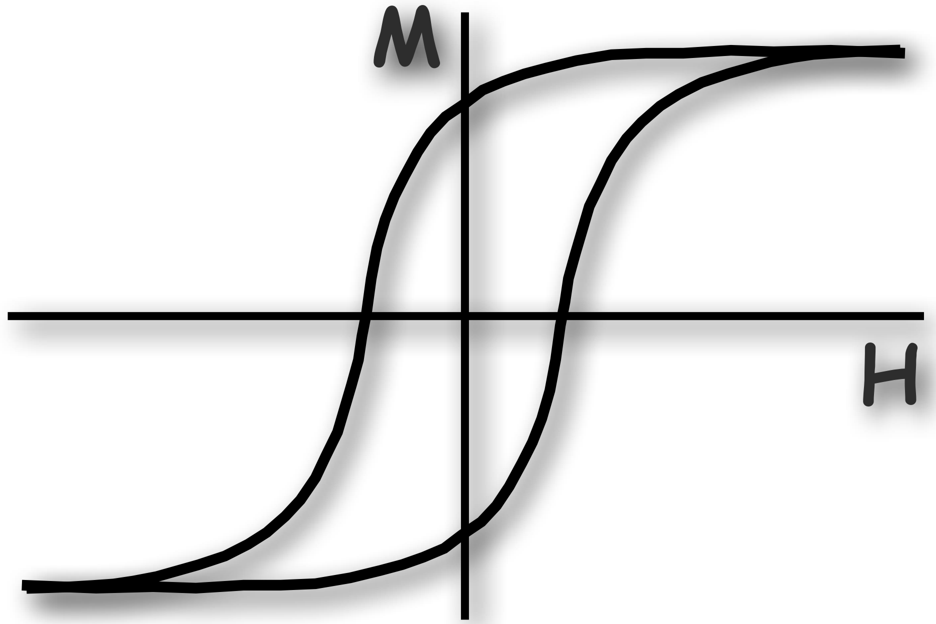
Coercivity depends on microstructure (grain size)





3. Macroscopic level: Magnetization curve

3 descriptive levels of magnetic materials



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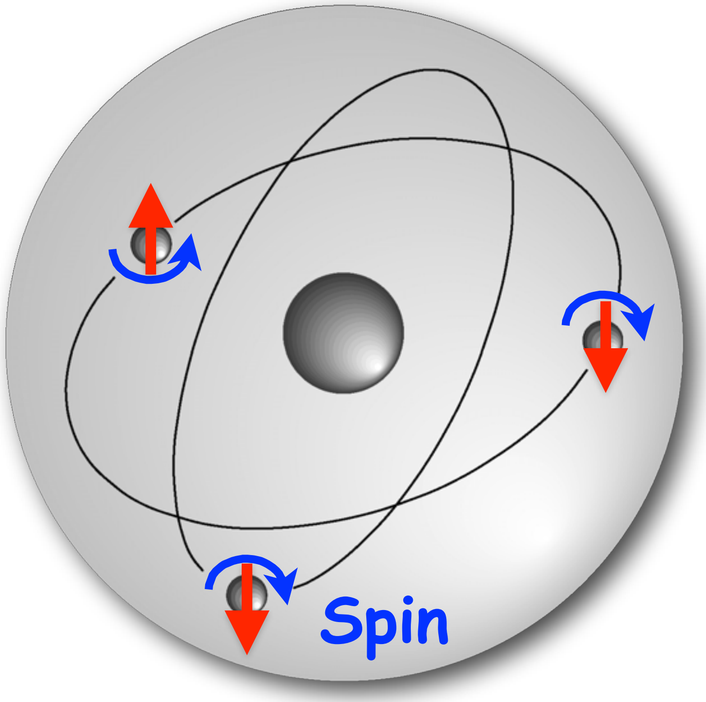
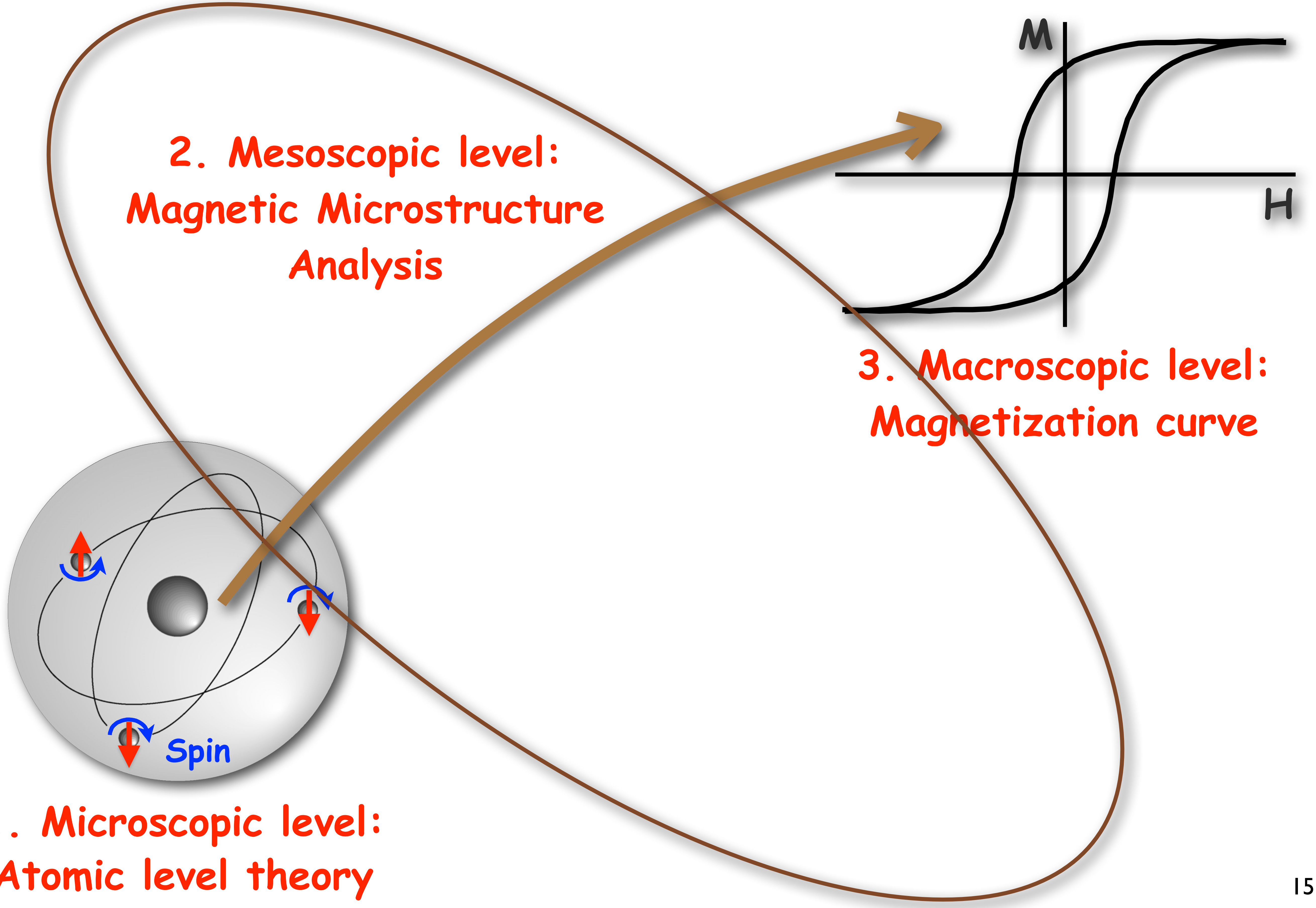
Magnetization curve



1. Microscopic level:
Atomic level theory

3 descriptive levels of magnetic materials



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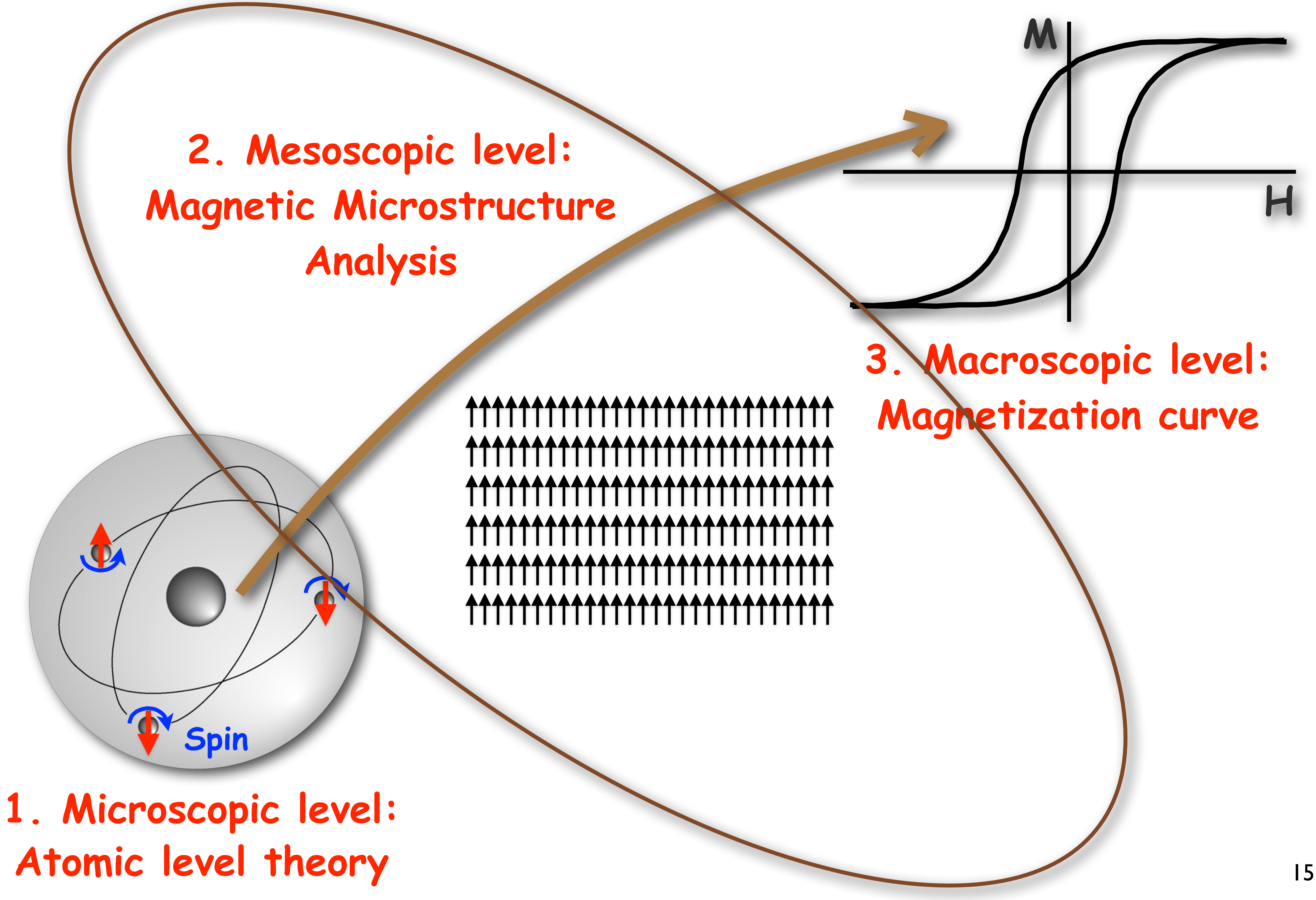

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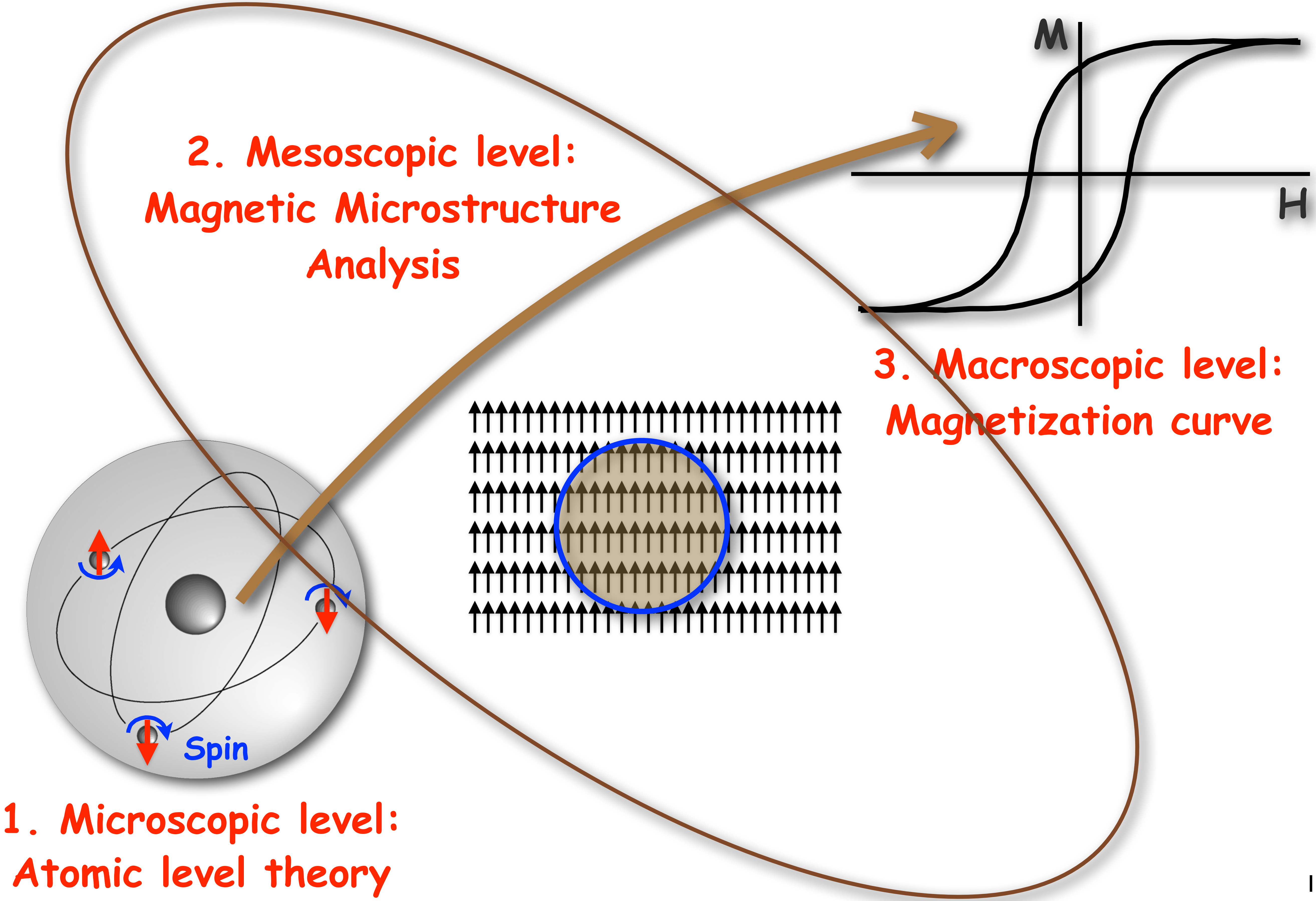

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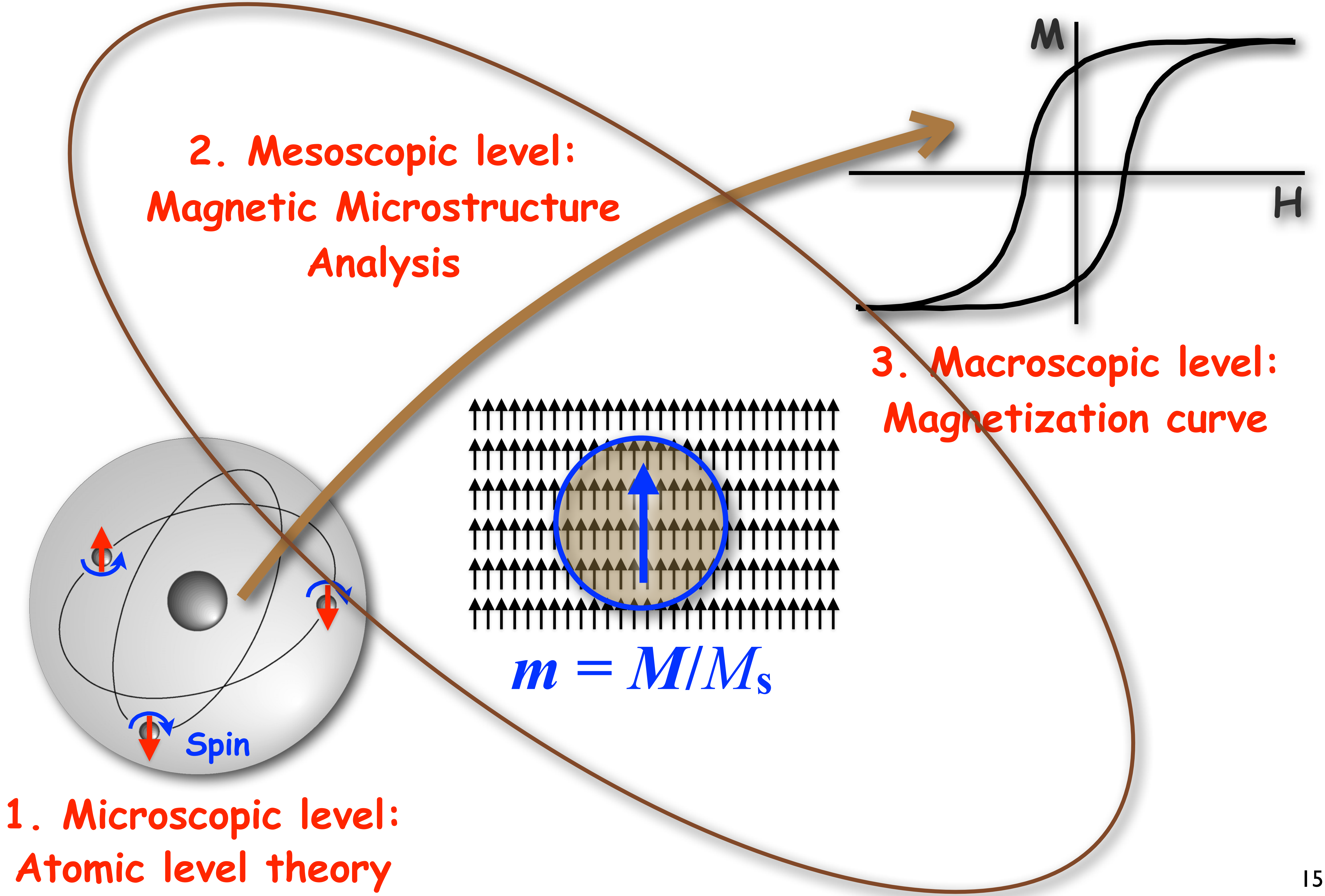
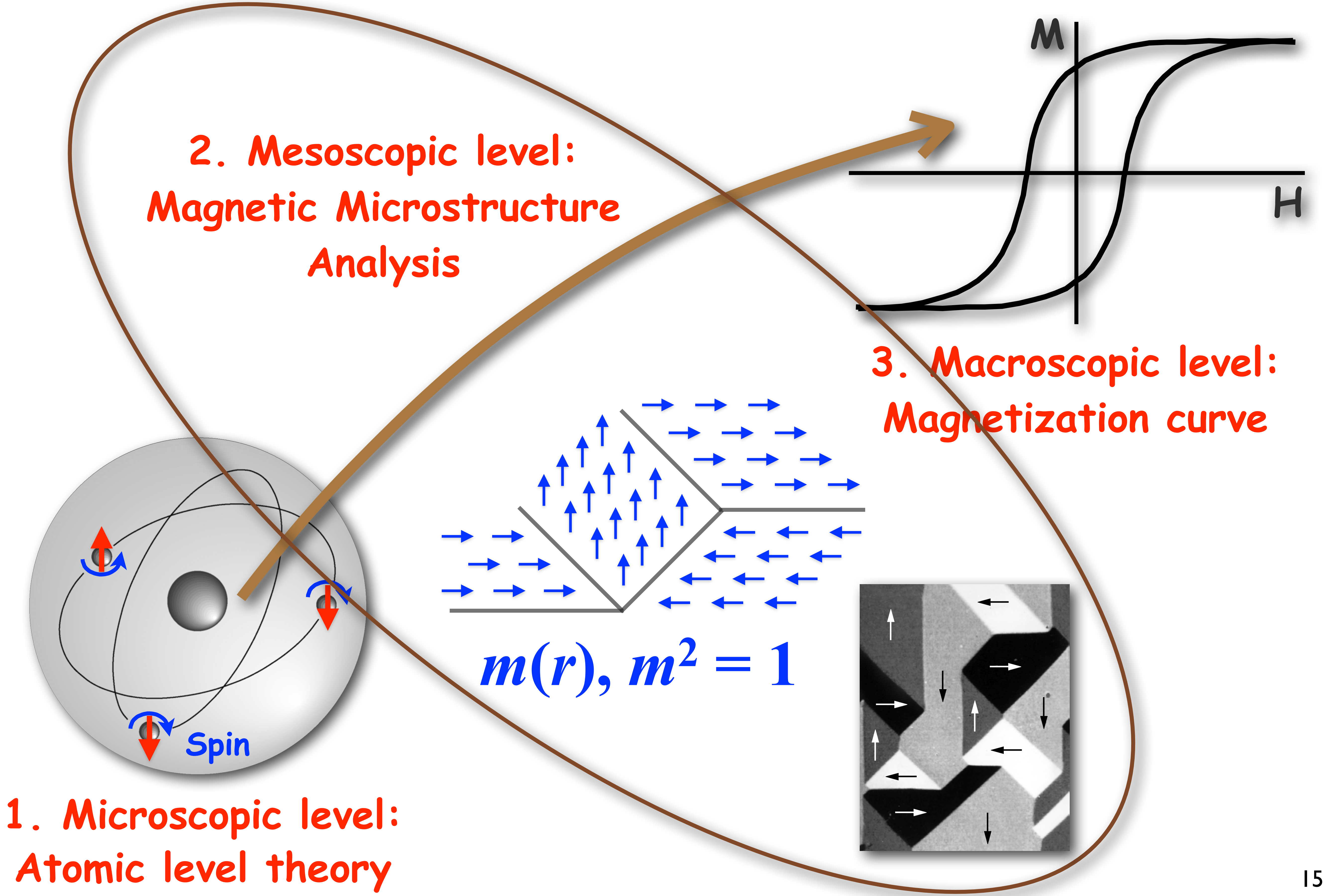
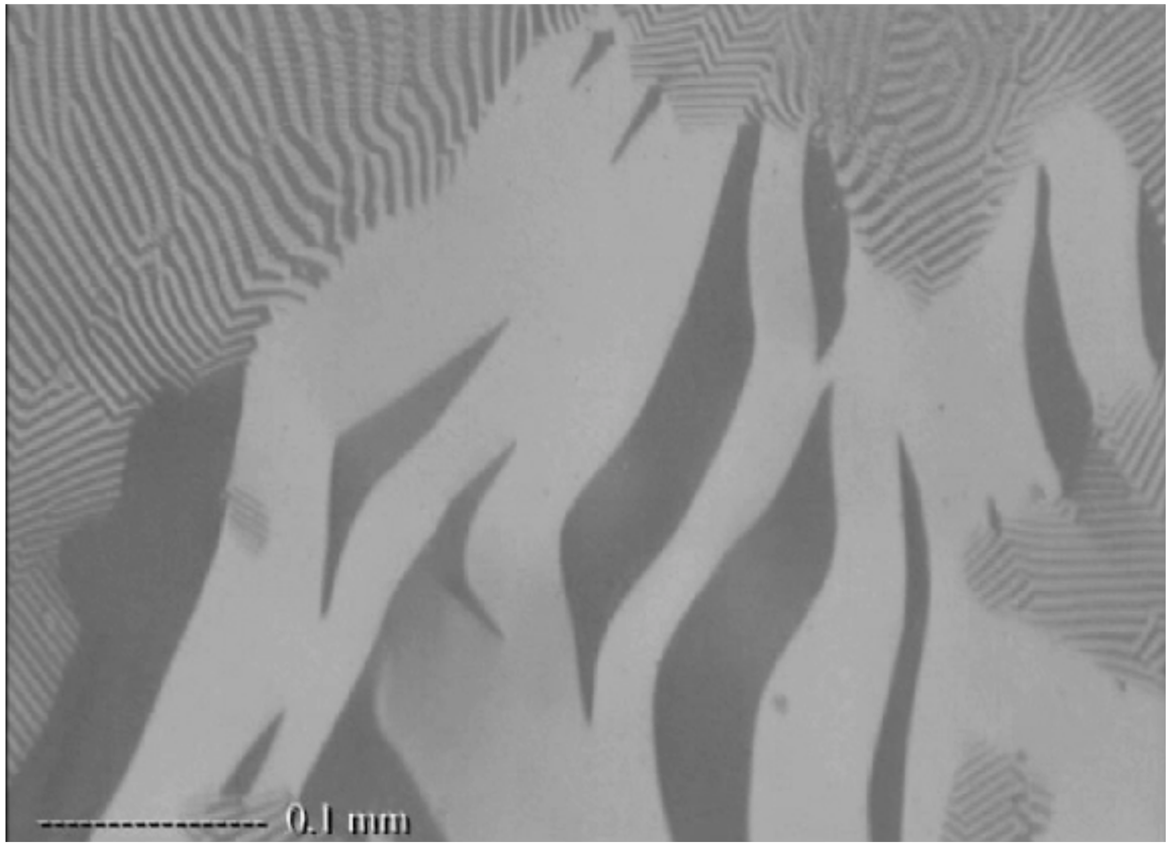
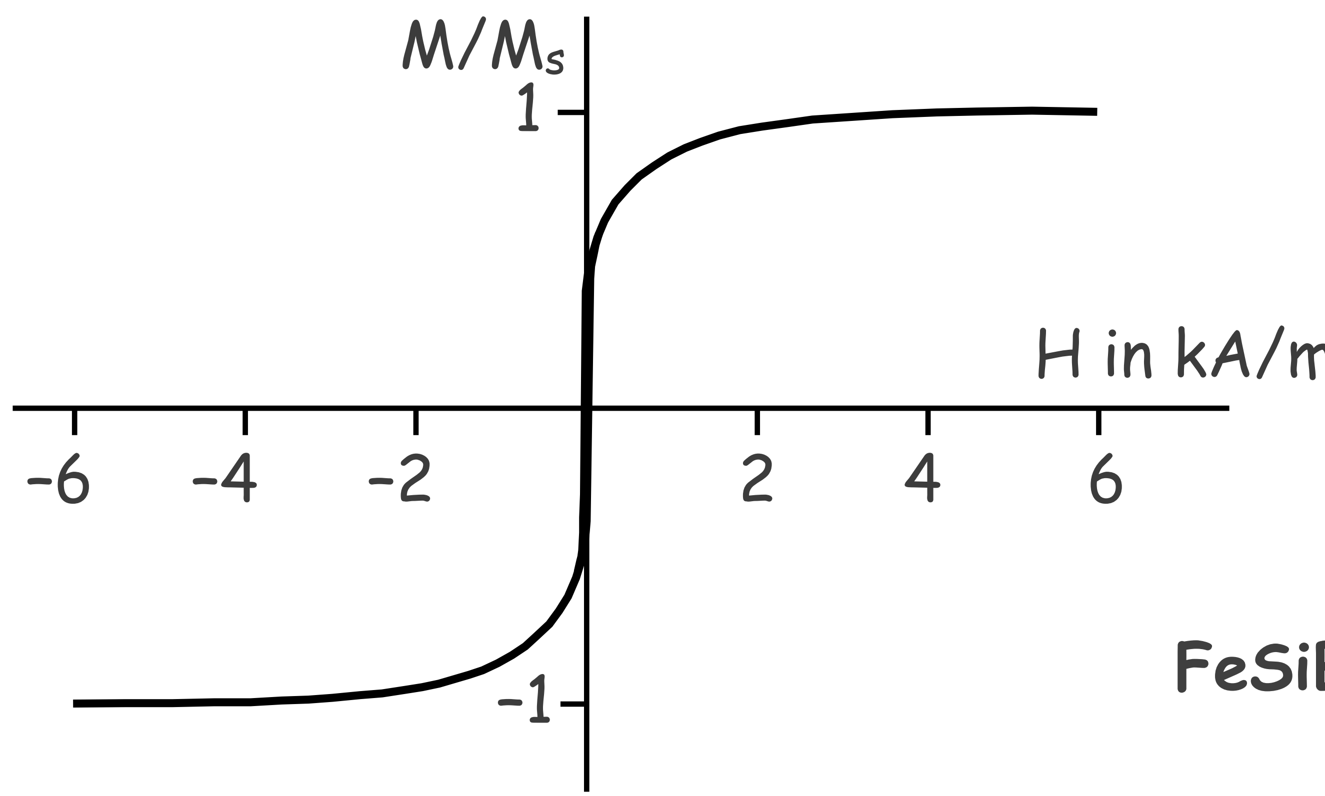



2. Mesoscopic level:
Magnetic Microstructure
Analysis
M
H
3. Macroscopic level:
Magnetization curve
$m(r), m^2 = 1$
Spin
1. Microscopic level:
Atomic level theory

M(H) loops and magnetic microstructure…

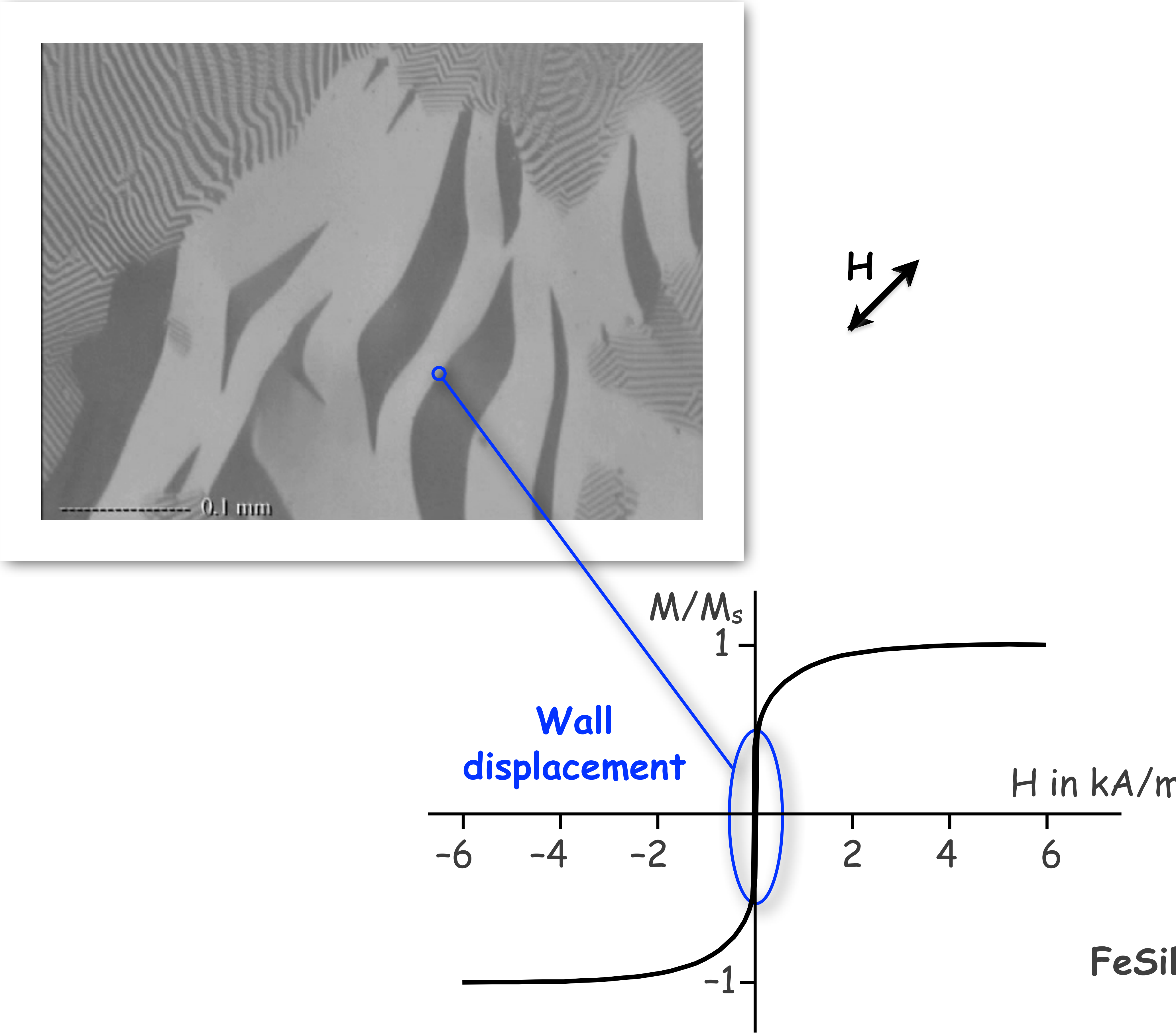


H



FeSiB amorphous ribbon
(rapidly quenched)

M(H) loops and magnetic microstructure…



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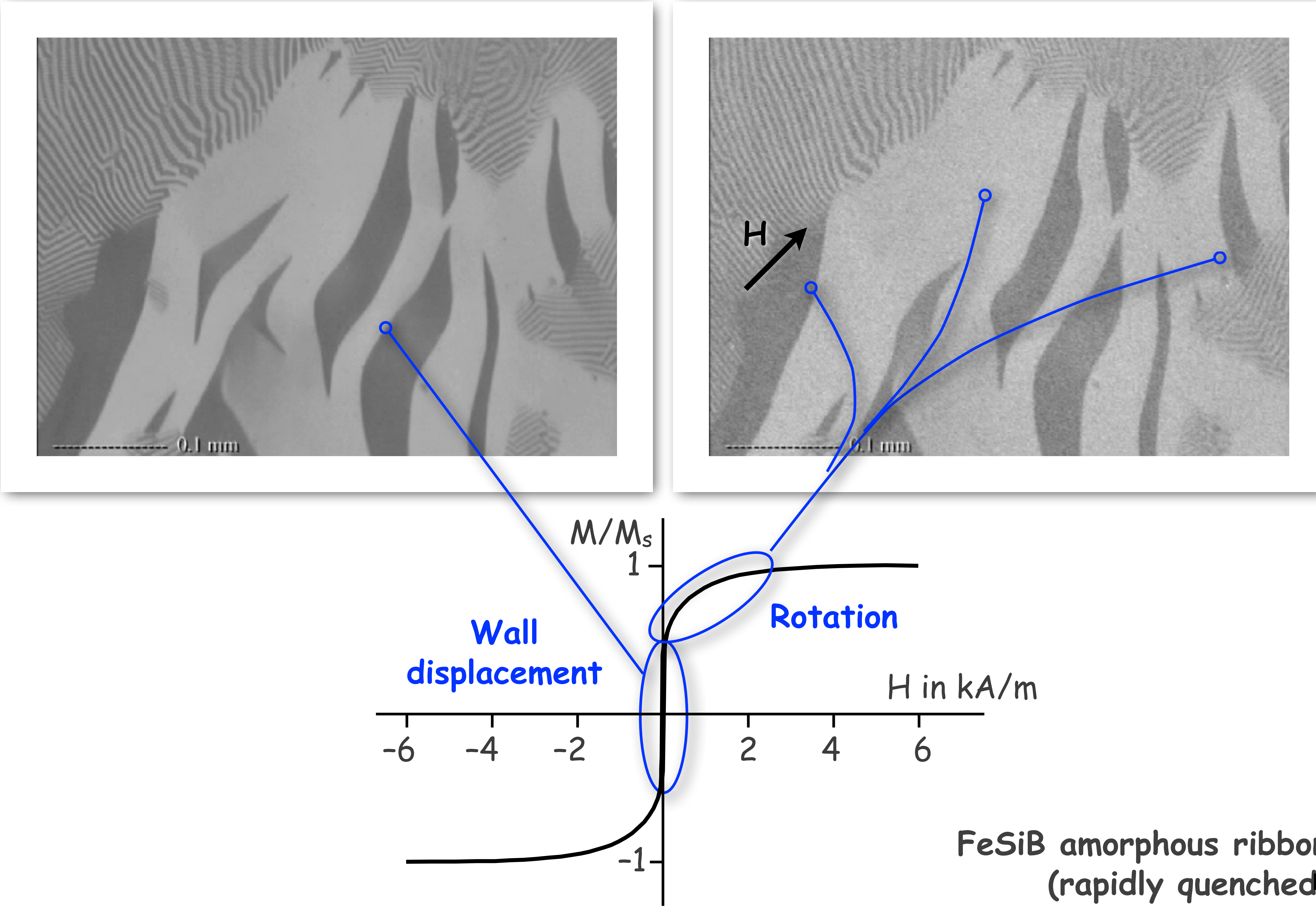


FeSiB amorphous ribbon (rapidly quenched)

Classification of magnetic materials with respect to magnetic microstructure

1. Manifold of easy directions

2. Quality factor

Classification of magnetic materials

with respect to magnetic microstructure

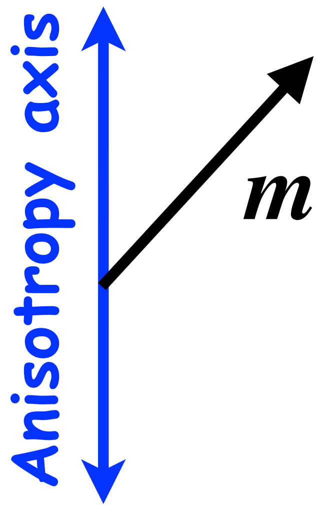
1. Manifold of easy directions

2. Quality factor

Excursus to magnetic anisotropy

Excursus: Magnetic Anisotropy

Magnetic anisotropy: dependence of internal energy from magnetization direction



Deviation of magnetization from anisotropy axes costs anisotropy energy

a) Magnetocrystalline anisotropy

depends on crystal symmetry, intrinsic

b) Induced anisotropy

e.g. adjustable by heat treatment, extrinsic

c) Stress-induced anisotropy

depends on magnetostriction, extrinsic (scales with size of mech. stress)

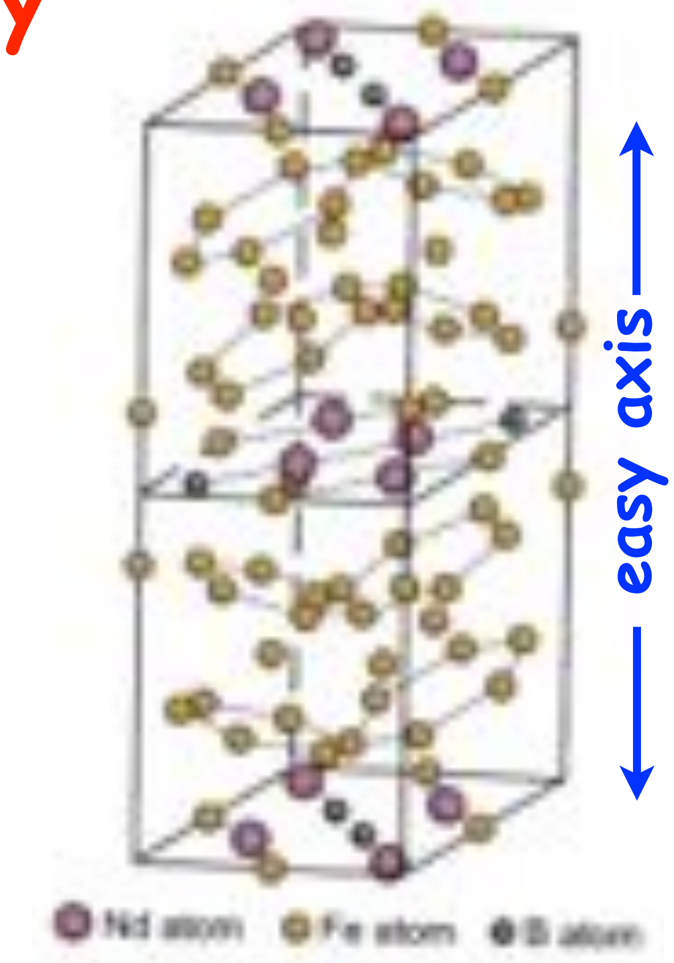
d) Shape anisotropy

depends on sample shape, extrinsic

Excursus: Magnetic Anisotropy

a) Magnetocrystalline anisotropy

$Nd_2Fe_{14}B$:

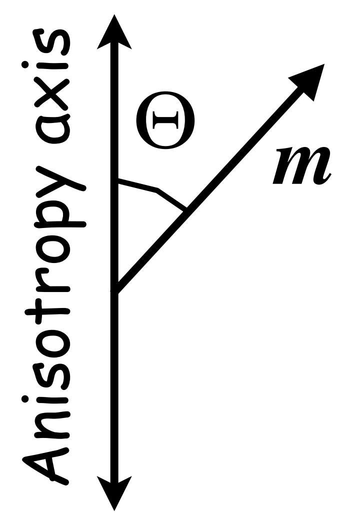


1. Uniaxial anisotropy:

e.g. hexagonal cobalt, tetragonal NdFeB: c-axis = easy axis

$$e_{Ku} = K_{u1} \cdot \sin^2\Theta + K_{u2} \cdot \sin^4\Theta + \ldots \text{ (potential series)}$$

Anisotropy energy density (e_{Ku}) — Anisotropy constant (K_{u1})



Example NdFeB: $K_{c1} = 5 \cdot 10^6$ J/m^3

2. Cubic anisotropy:

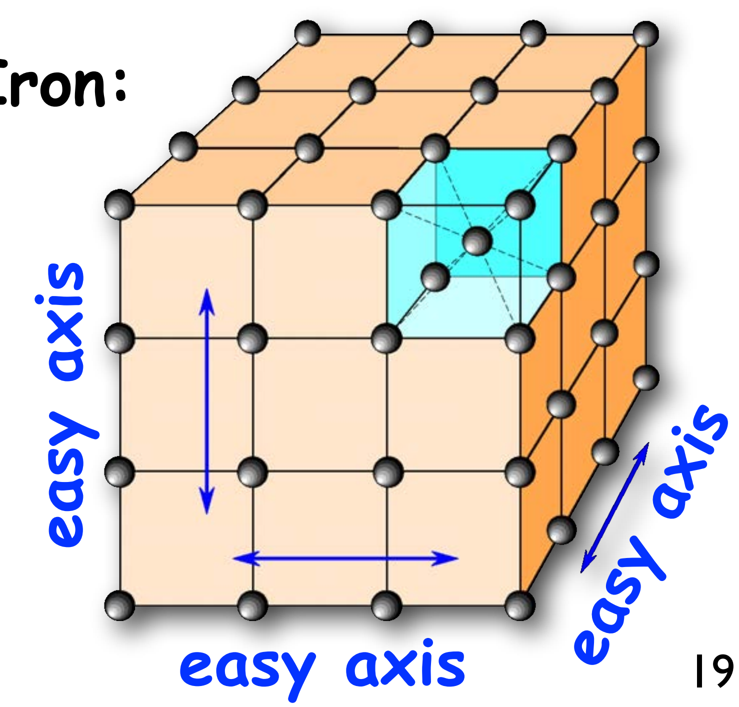
e.g. iron or nickel

$$e_{Kc} = K_{c1} \cdot (m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2) + K_{c2}\, m_1^2 m_2^2 m_3^2$$

m_i = Magnetization components along cubic axes (direction cosine)

Example iron: $K_{c1} = 4.7 \cdot 10^4$ J/m^3

Iron:



Excursus: Magnetic Anisotropy

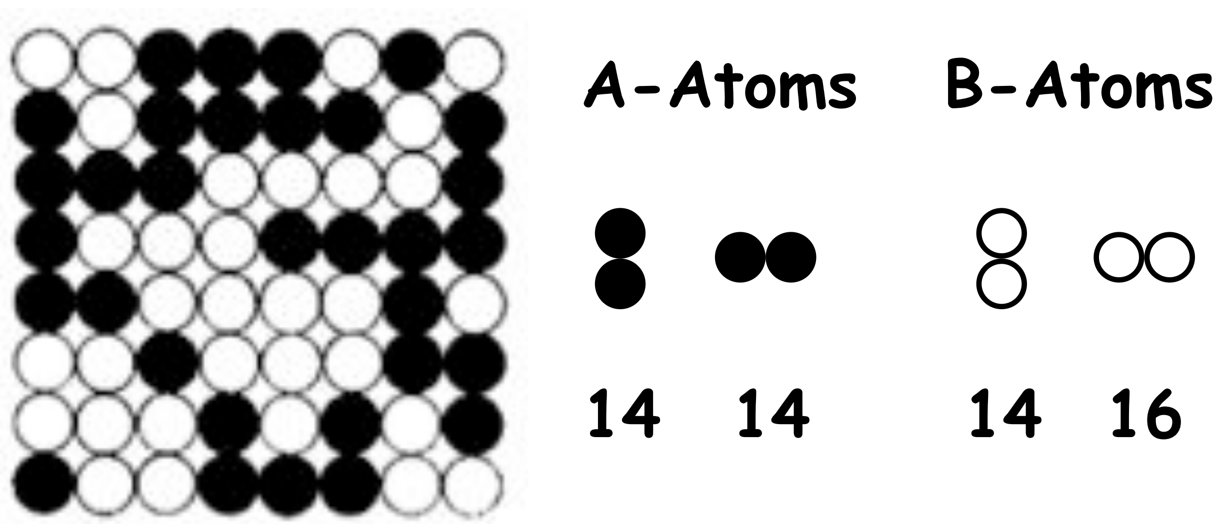
b) Induced anisotropy

Annealing of magnetic alloy in magnetic field below T_c

⟶ causes easy axis parallel to magnetization vector

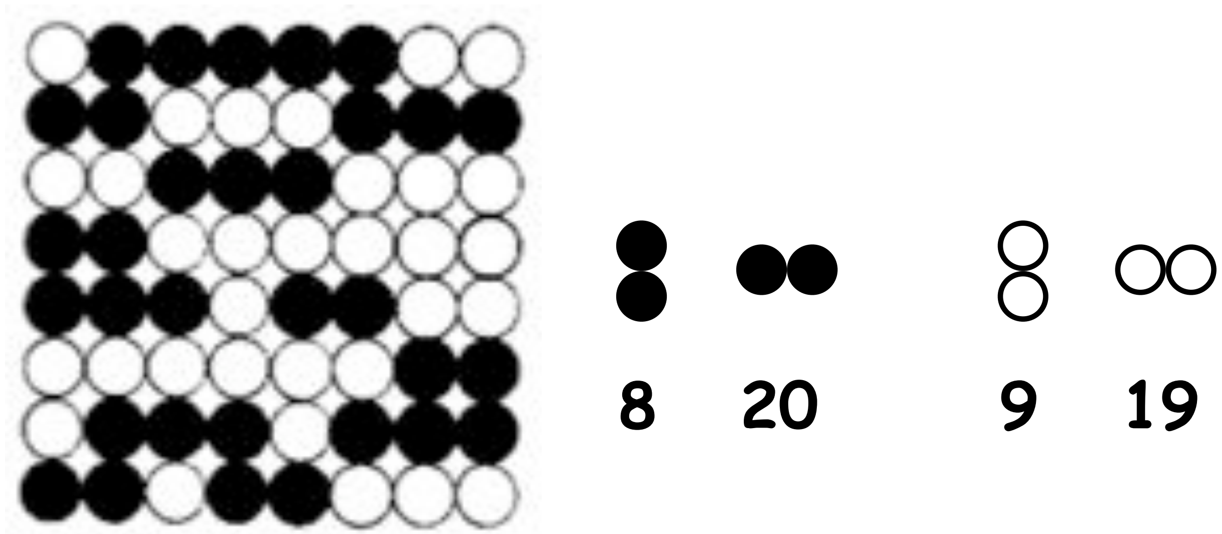
⟶ uniaxial anisotropy ⟶ **Magnetization-induced anisotropy**

Reason: anisotropic pair ordering of equal atoms



$T > T_{\mathrm{Curie}}$: $M=0$

Statistical distribution of A- and B-atoms (non-ordered solid solution)



$T < T_{\mathrm{Curie}}$ ⟶ M

Pair ordering along M-direction

Precondition:

$T < T_c$ (presence of M_s), but T large enough to allow diffusion (sufficient kinetics)

Excursus: Magnetic Anisotropy

c) Stress-induced anisotropy

$$e_{\mathrm{me}} = \frac{3}{2}\lambda_{\mathrm{s}} \cdot \sigma \cdot \sin^2\theta$$

Magnetoelastic energy (isotropic material)

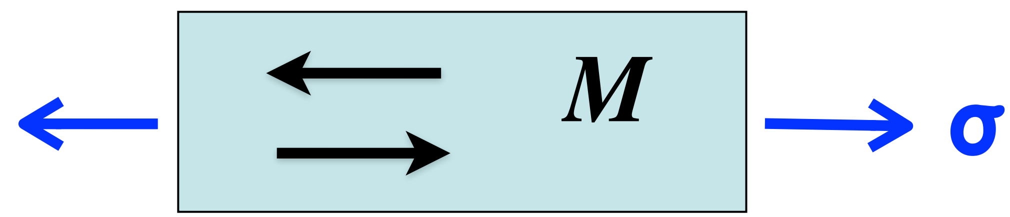
Magnetostriction-constant → λ_s

Mechanical stress → σ

Angle between M and stress σ → θ

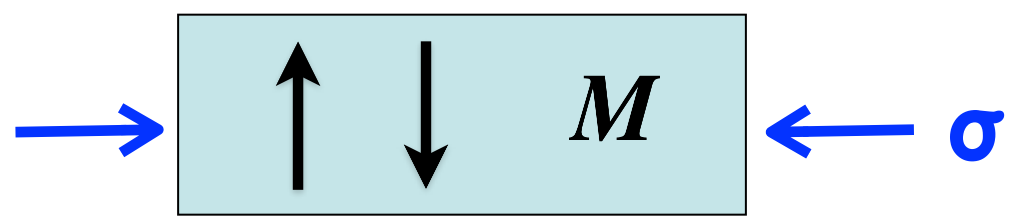
$\lambda_s > 0, \sigma > 0:$

(tensile stress)



$\sigma < 0:$

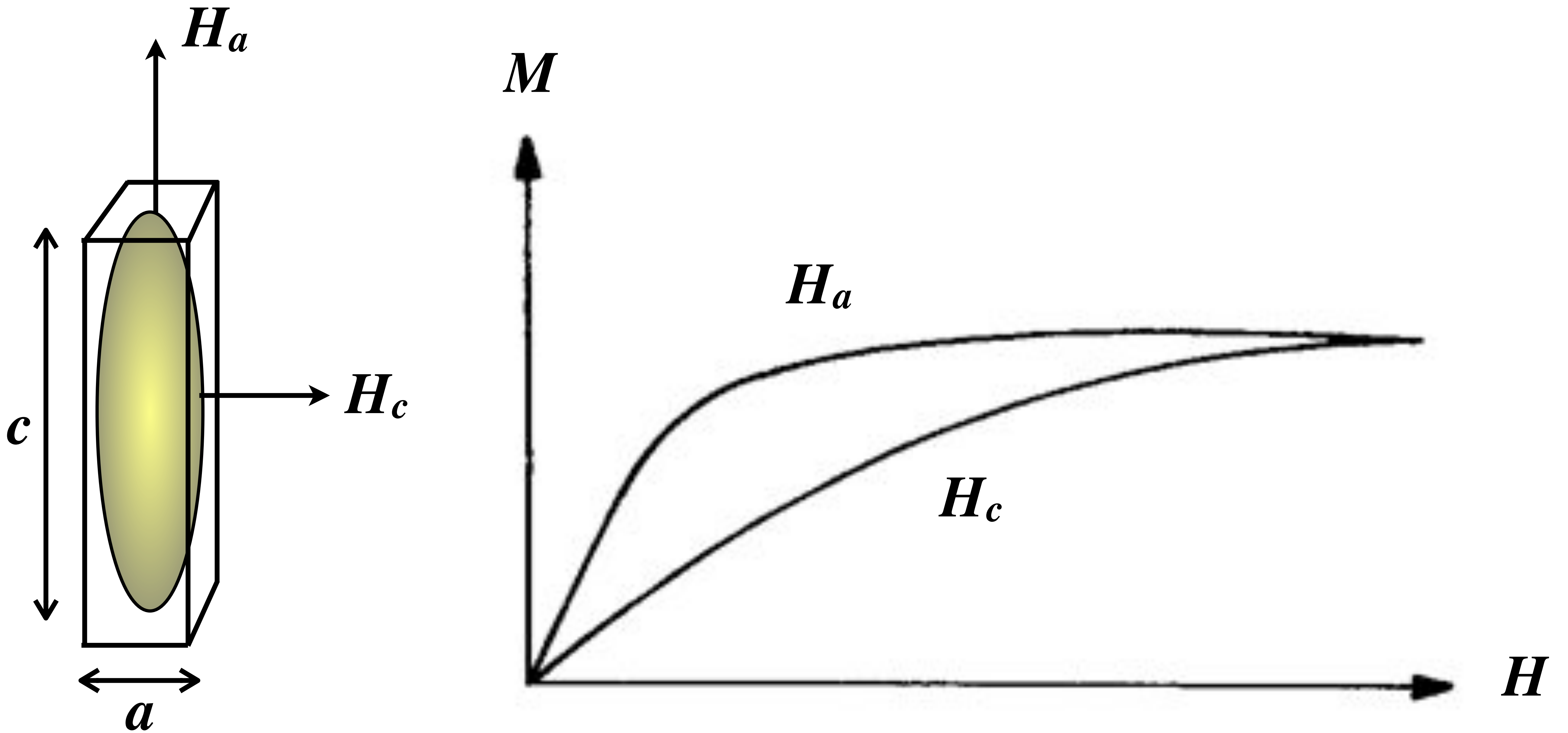
(uniaxial compressive stress)



Uniaxial anisotropy with $K_{u,\sigma} = 3/2\ \lambda_s\ \sigma$

Excursus: Magnetic Anisotropy

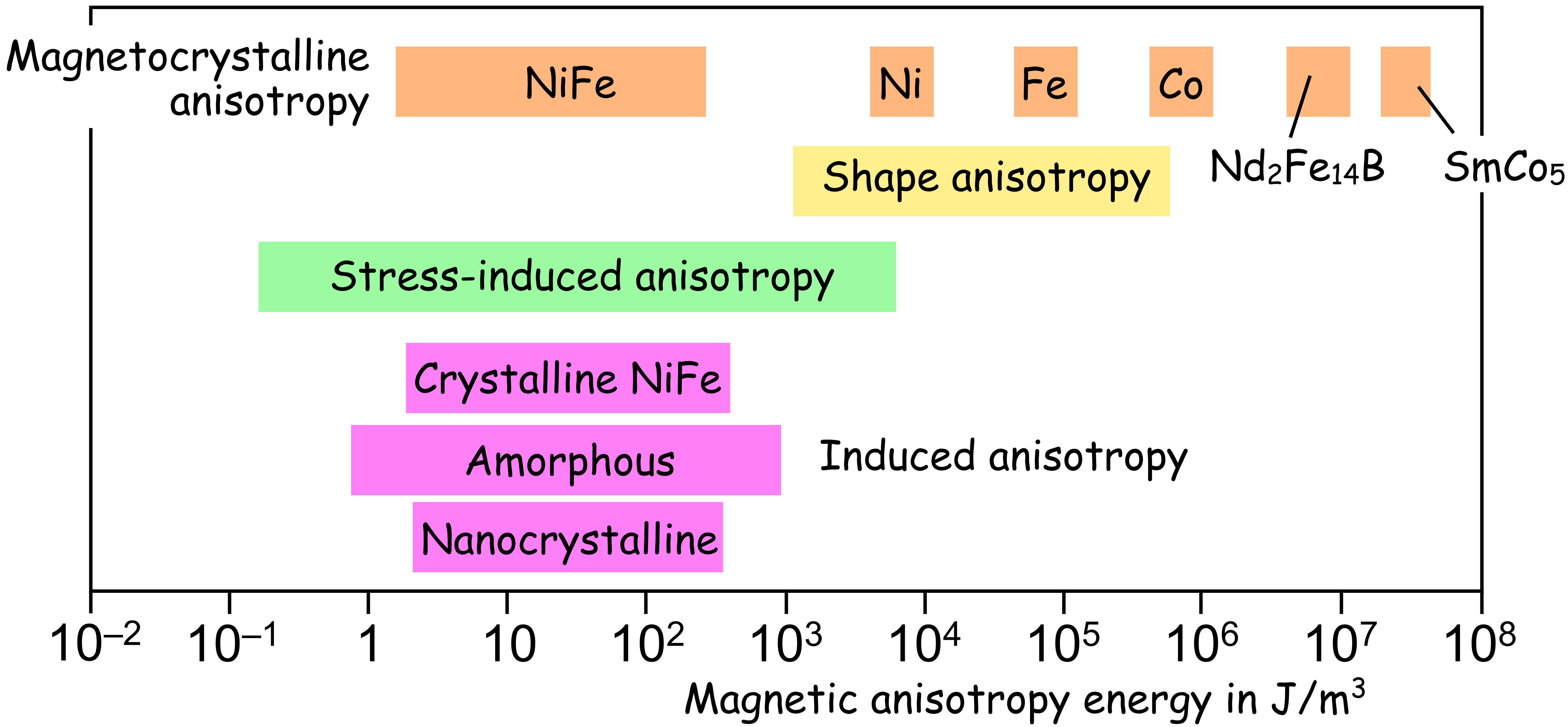
d) Shape anisotropy



Uniaxial anisotropy with $K_{u,s} = 1/2\mu_0(N_c - N_a)M^2$

Demagnetizing factors

Excursus: Magnetic Anisotropy



Classification of magnetic materials with respect to magnetic microstructure

1. Manifold of easy directions

Classification of magnetic materials

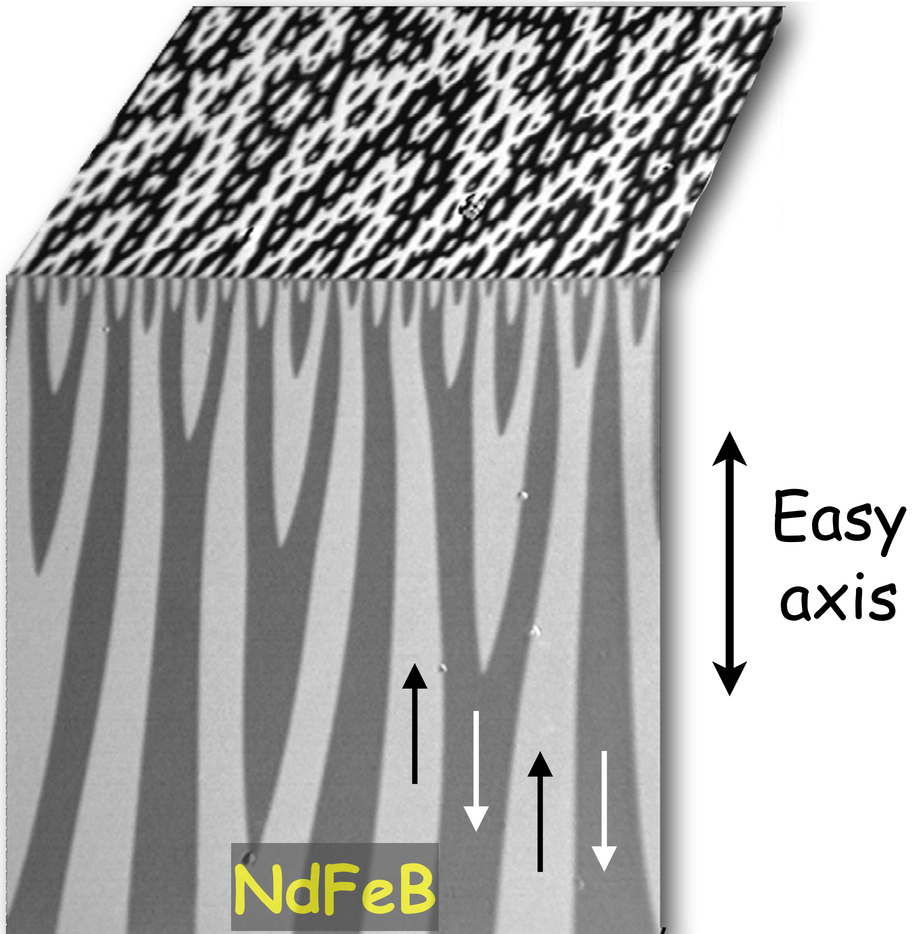
with respect to magnetic microstructure

1. Manifold of easy directions

Uniaxial materials

One (strong) easy axis

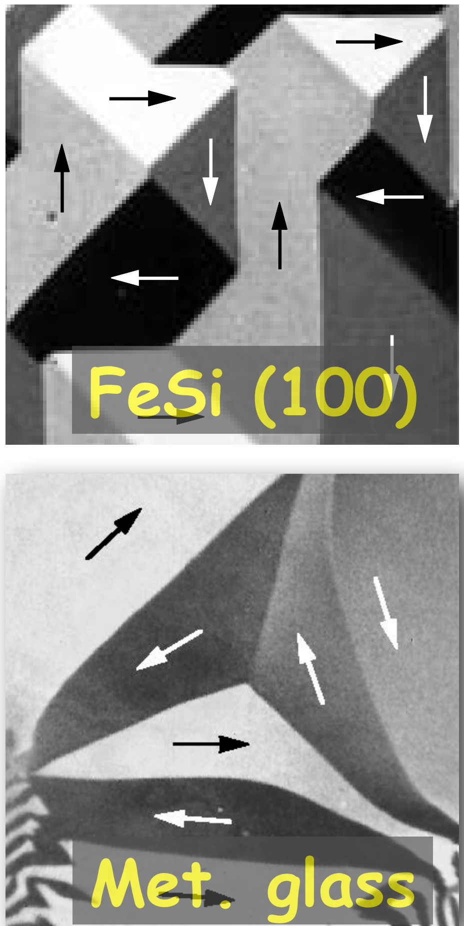
Examples:
hexagonal, orthorhombic, tertragonal crystals with positive anisotropy



Mulitaxial materials

3 or more non-planar easy axes in space

Examples:
cubic crystals, metallic glasses, polycrystalline materials



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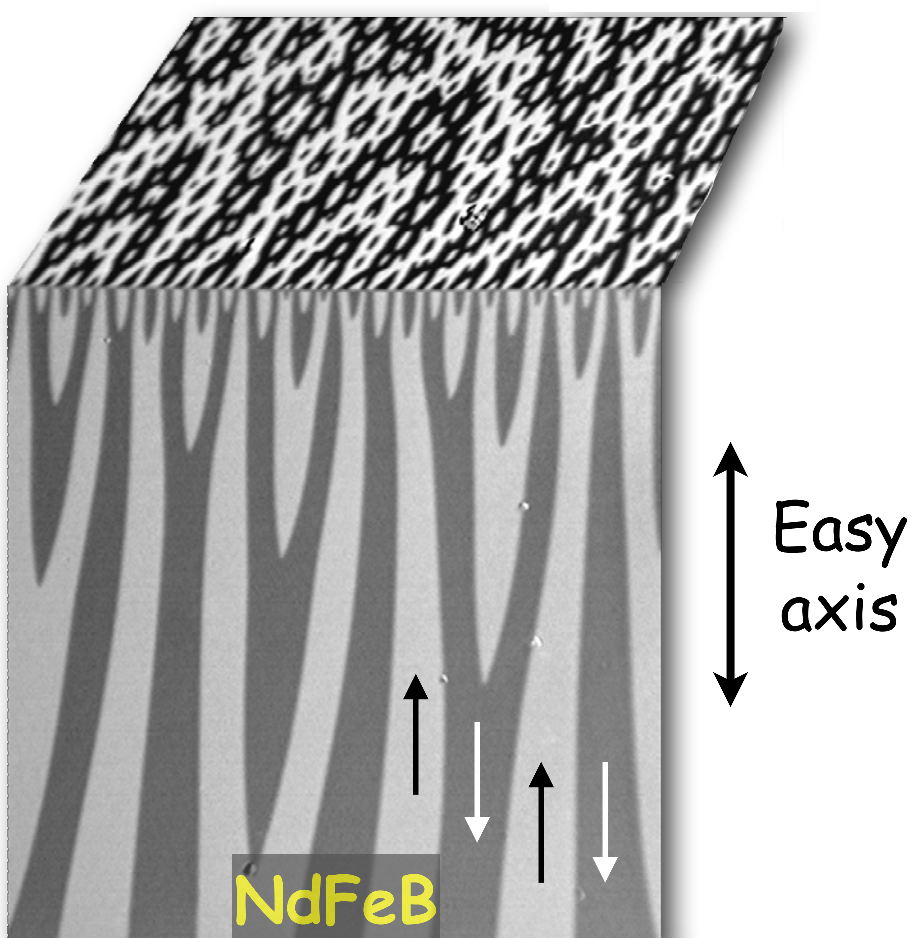

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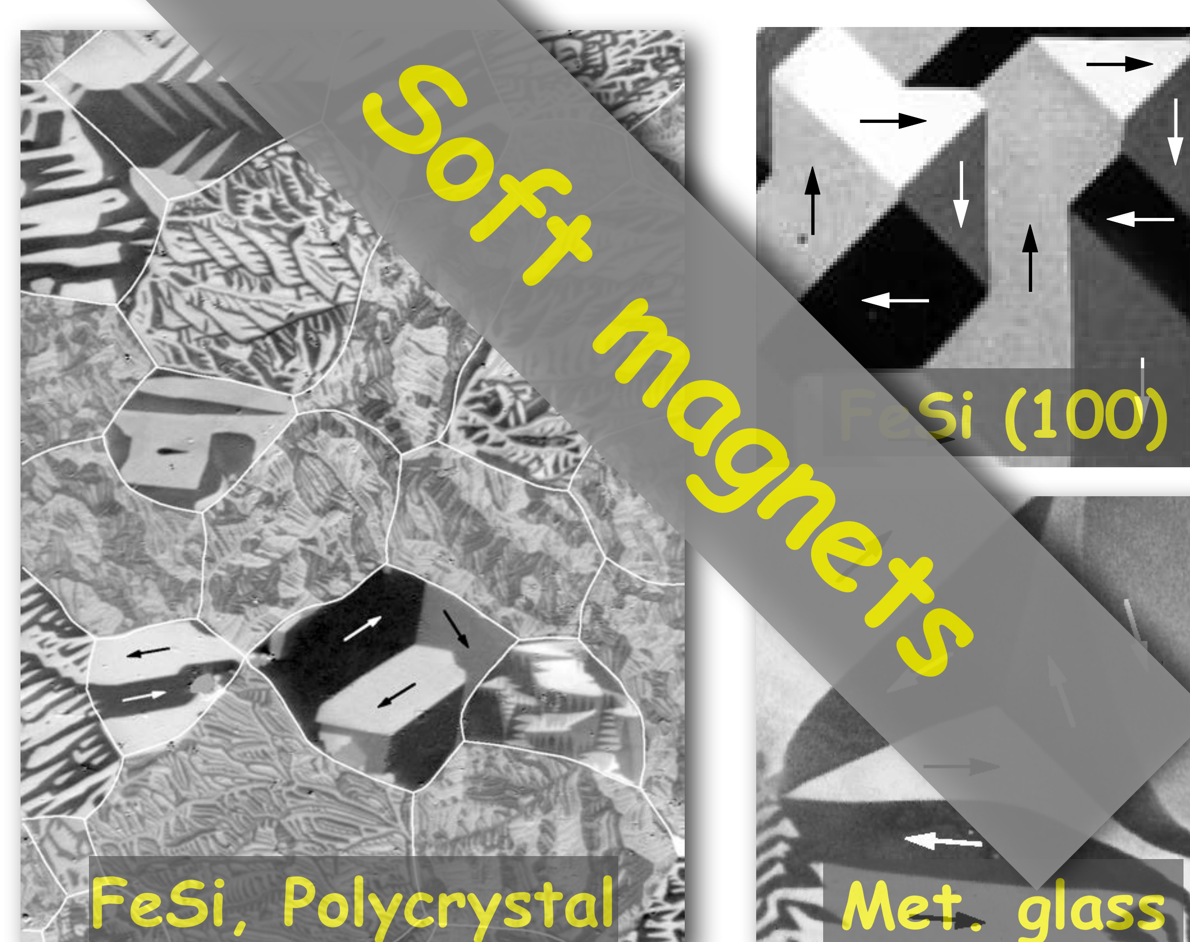

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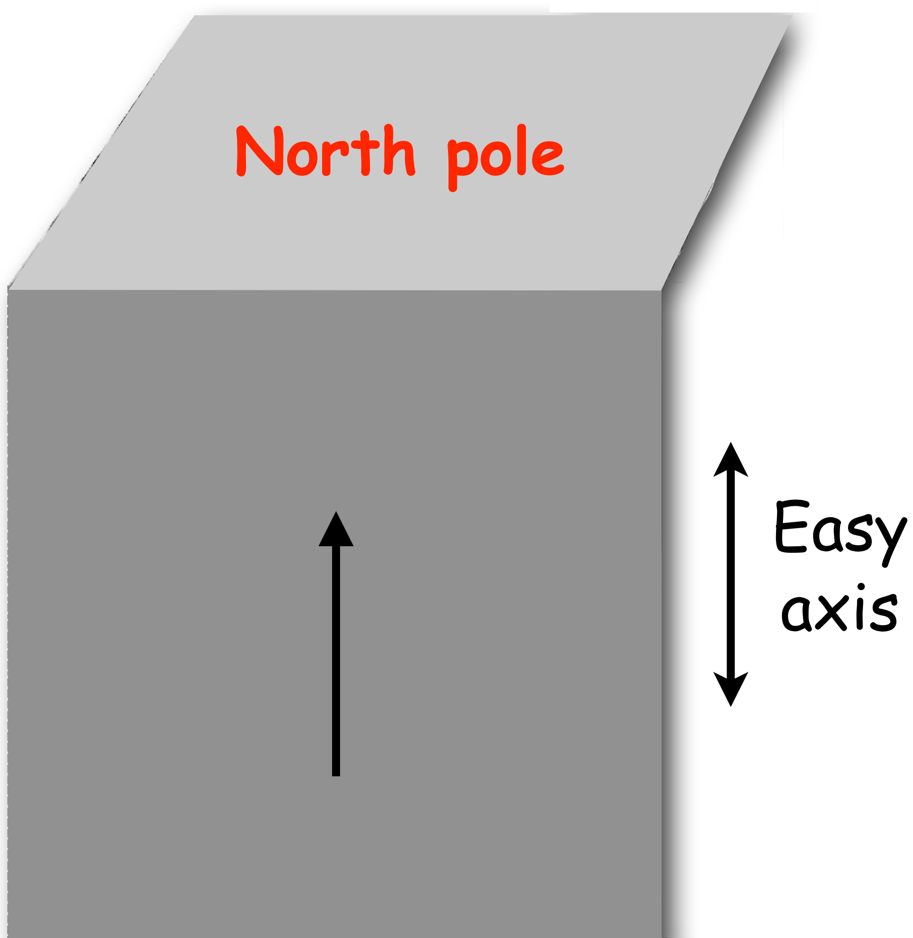

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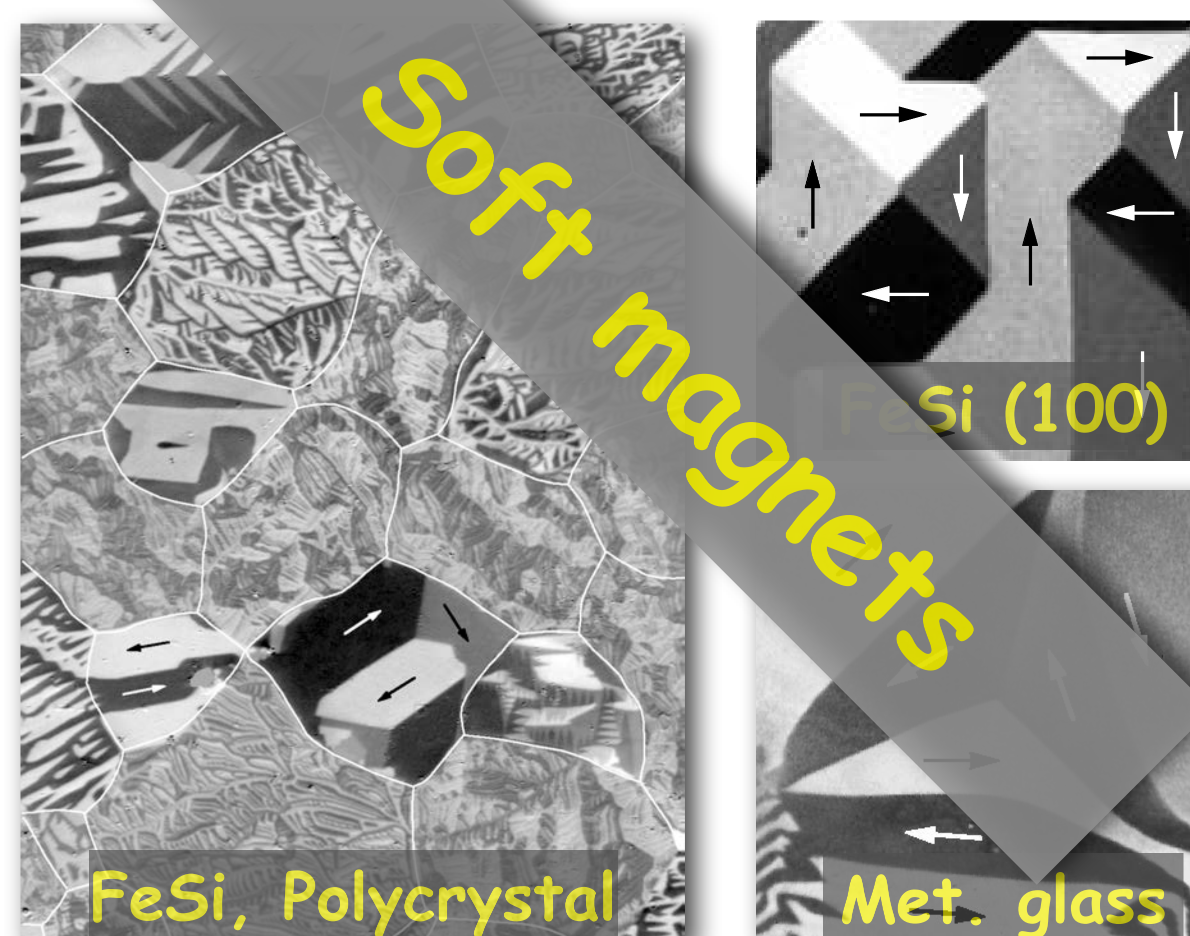

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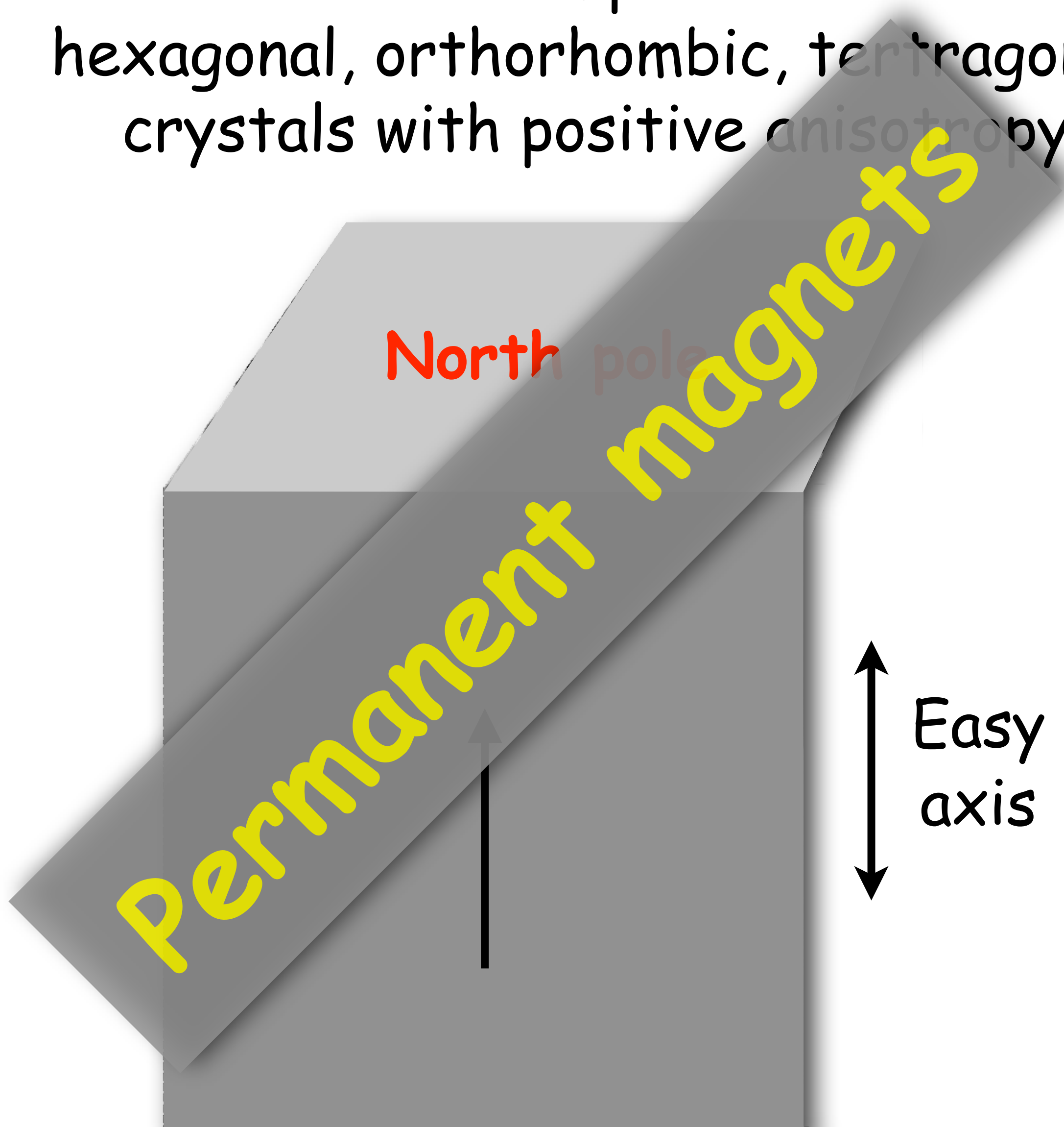

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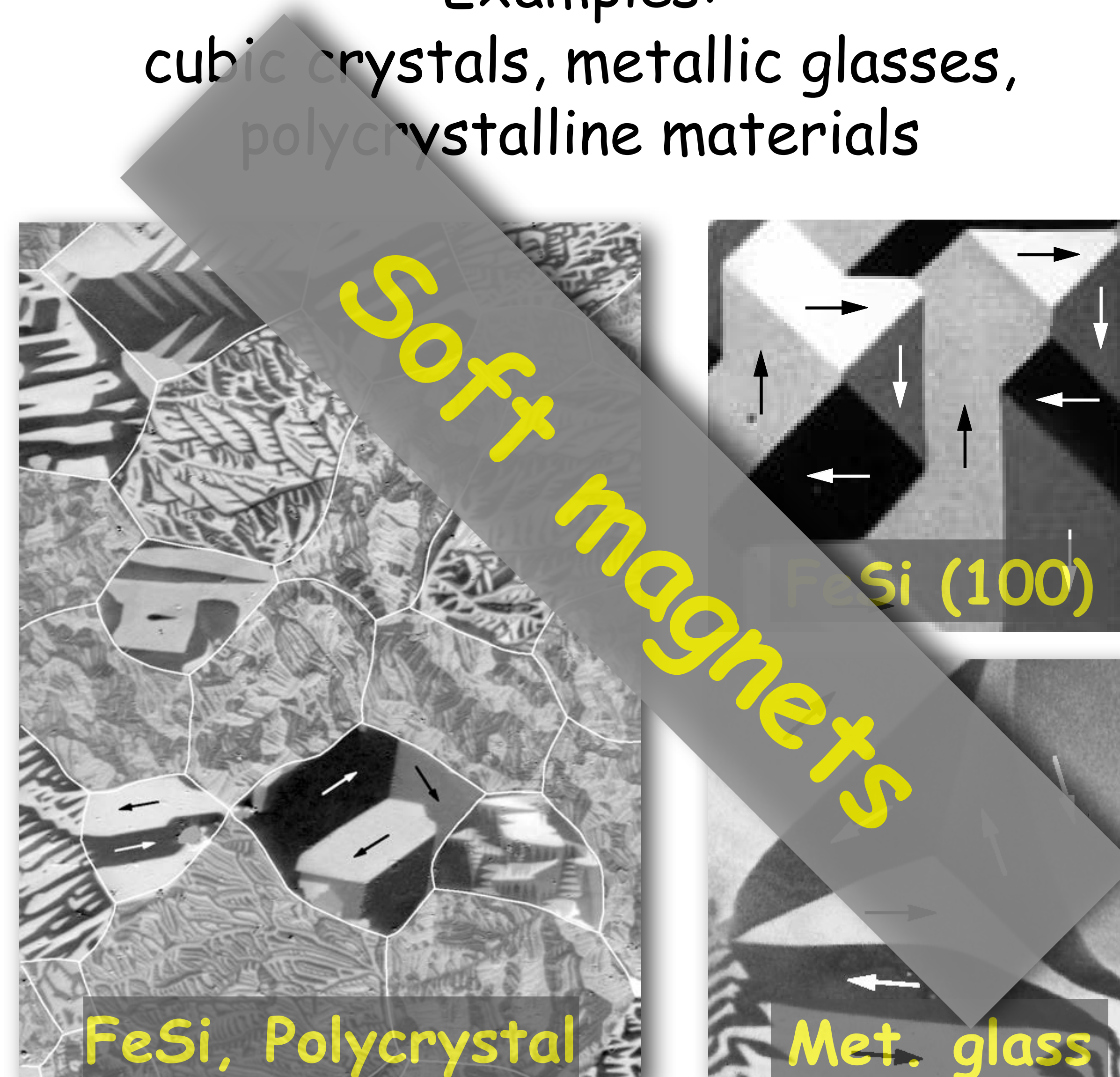

Classification of magnetic materials

with respect to magnetic microstructure

Classification of magnetic materials with respect to magnetic microstructure

2. Quality factor

$$Q = \frac{\text{Anisotropy constant } K}{\text{Stray-field energy coefficient } (K_\mathrm{d} = \mu_0 M_\mathrm{S}^2/2)}$$

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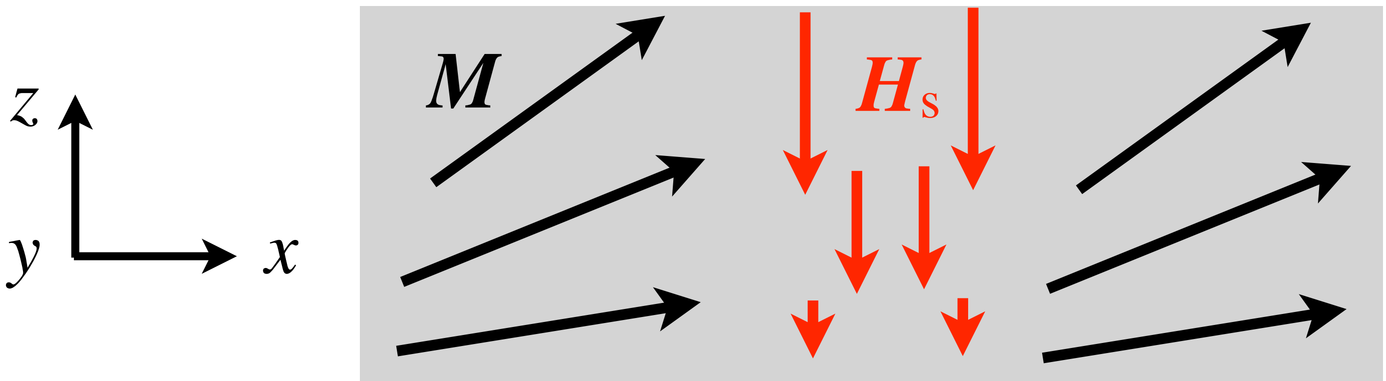
Excursus to Stray-field energy

Excursus: Stray field energy

Example: thin plate
(stray-field exists only in interior - compare charged capacitor)



$$\text{div}\,\boldsymbol{H}_\text{s} = -\,\text{div}\,\boldsymbol{M}$$

1-dimensional change in z-direction ($\partial M_\text{x}/\partial x = \partial M_\text{y}/\partial y = 0$):

$$\partial H_\text{s}/\partial z = -\,\partial M_\text{z}/\partial z \quad |\int$$

$$\boldsymbol{H}_\text{s} = -\,\boldsymbol{M}_\text{z} + \text{const} \qquad (\text{const} = 0,\ \text{since no field outside})$$

$$E_s = \tfrac{1}{2}\,\mu_0 \int \boldsymbol{H}_\text{s}^2\, dV = \tfrac{1}{2}\,\mu_0 \int M_z^2\, dV$$

Special case (strongest stray-field): perpendicular magnetization $\longrightarrow M_\text{z} = M_\text{s}$

$$E_s = \tfrac{1}{2}\,\mu_0\, M_\text{s}^2\, V$$

Definition: $K_d = \tfrac{1}{2}\,\mu_0\, M_\text{s}^2$ = **Stray-field-energy coefficient**

Measure for maximum stray-field energy density, material constant

Excursus: Stray field energy

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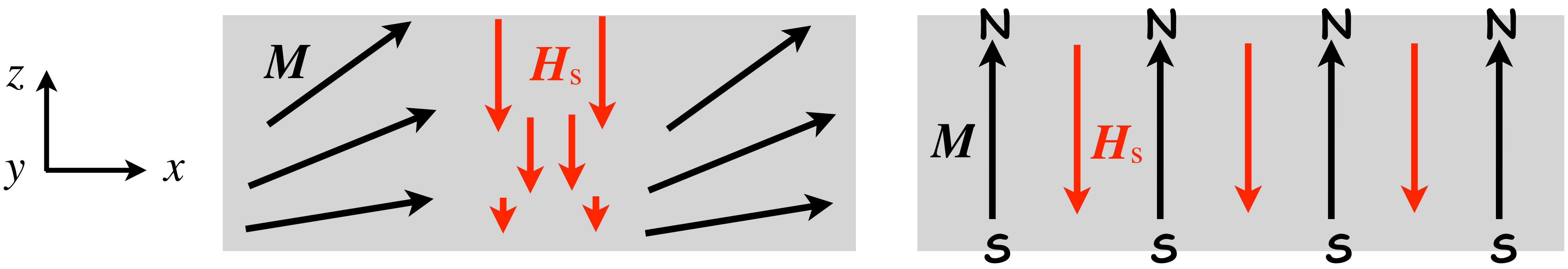
(stray-field exists only in interior - compare charged capacitor)



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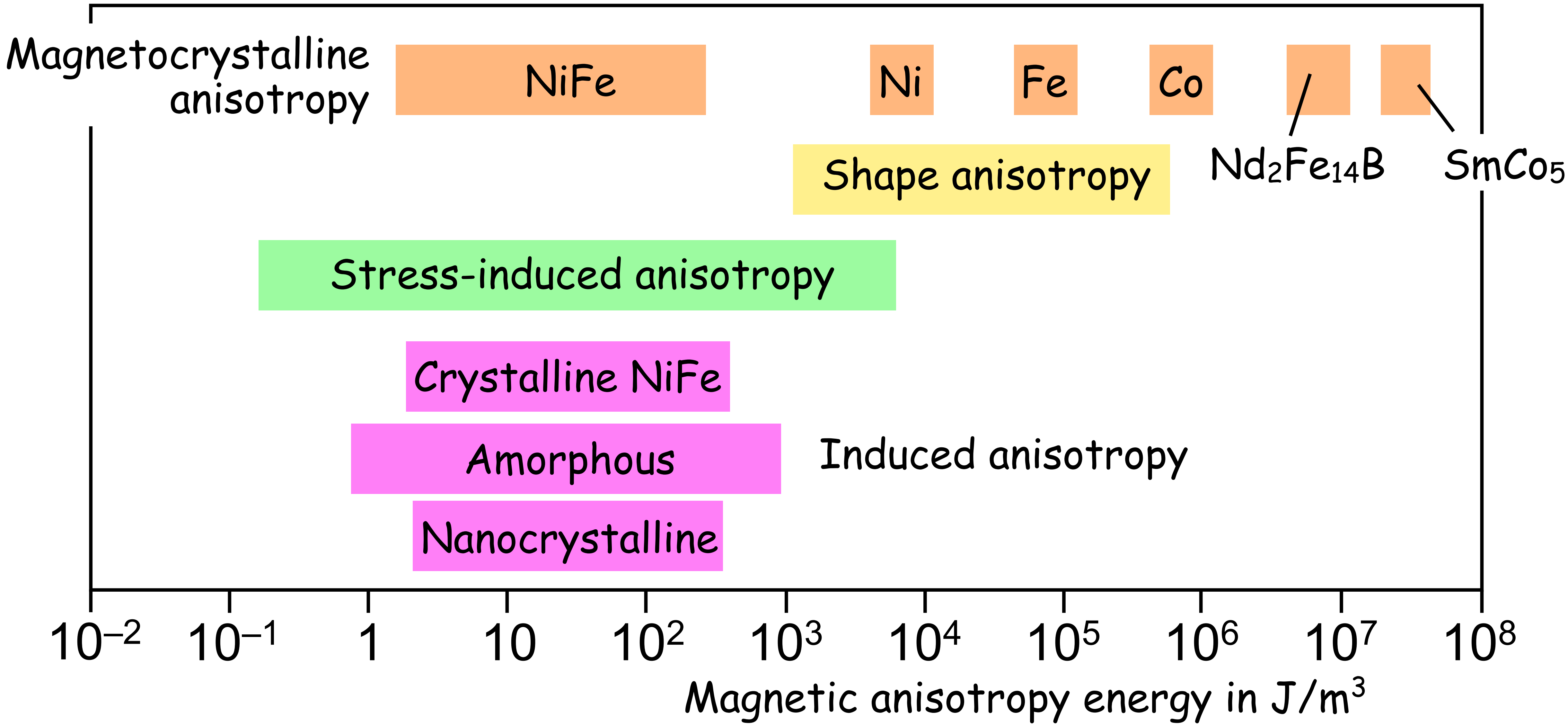

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$Q >> 1$

Anisotropy energy dominates

↓

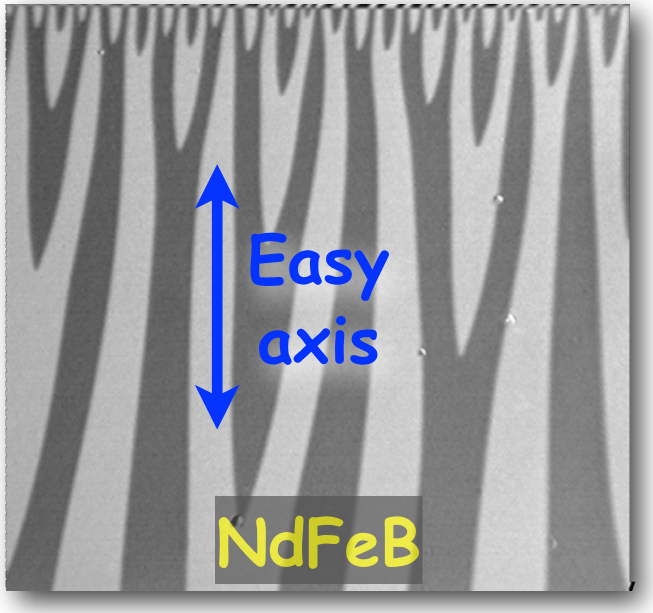
Anisotropy energy avoided

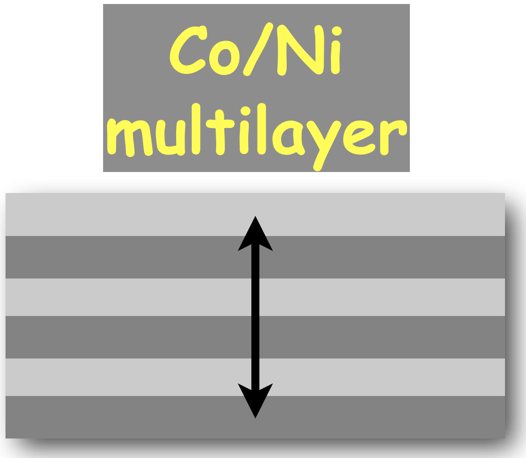
$Q << 1$

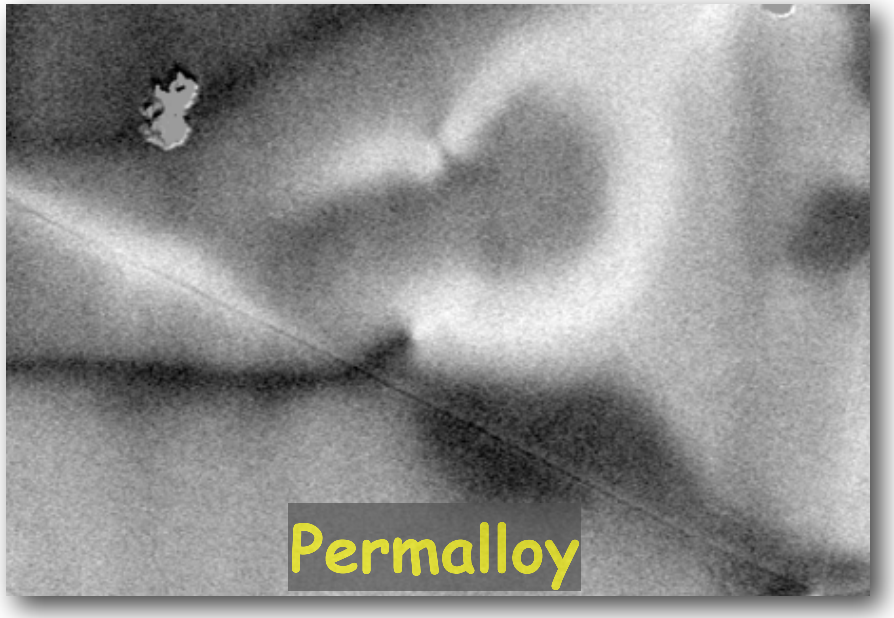
Stray-field energy dominates

↓

Stray-field energy avoided







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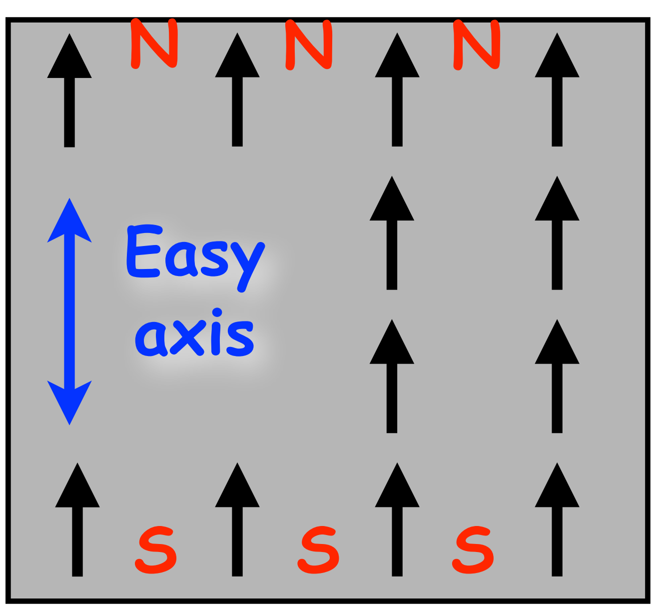


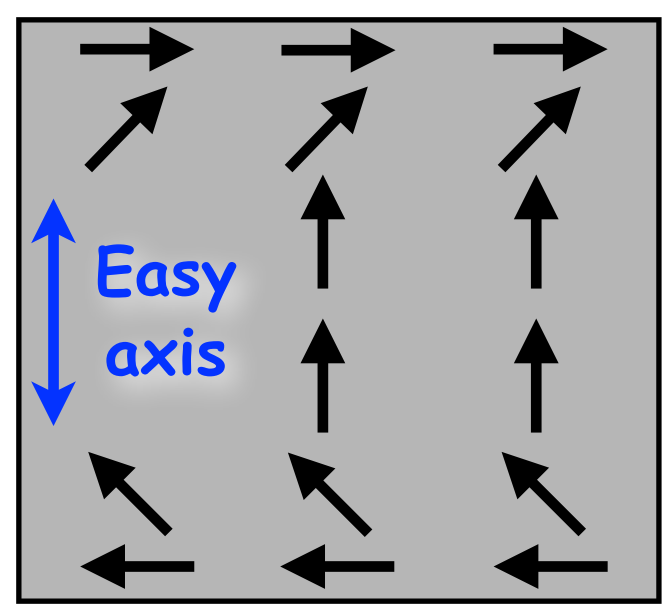
After being magnetized, M stays along easy axis all through to surface → poles at surface

$Q << 1$

Stray-field energy dominates

↓

Stray-field energy avoided



At remanence, M bends over at surface to avoid poles

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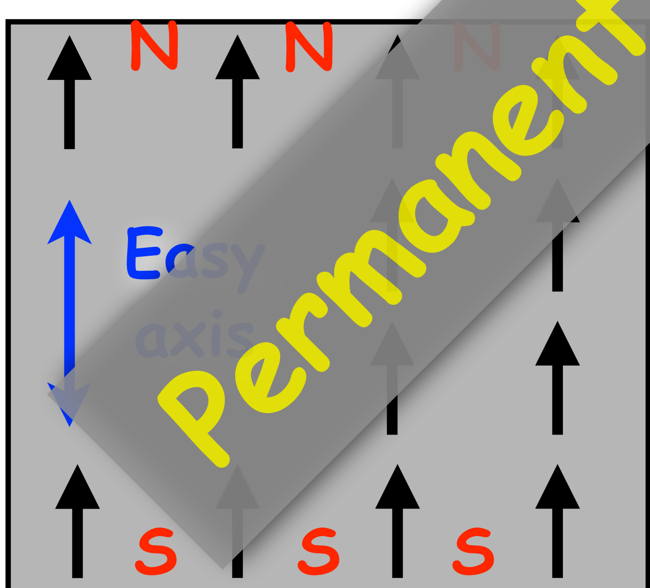

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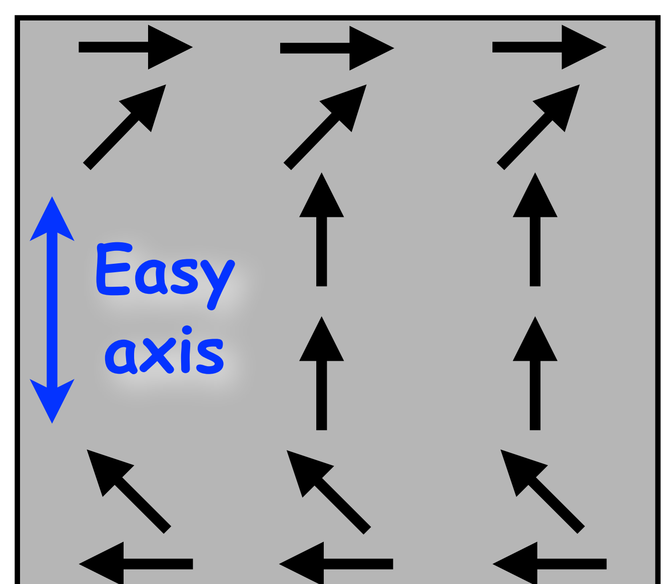

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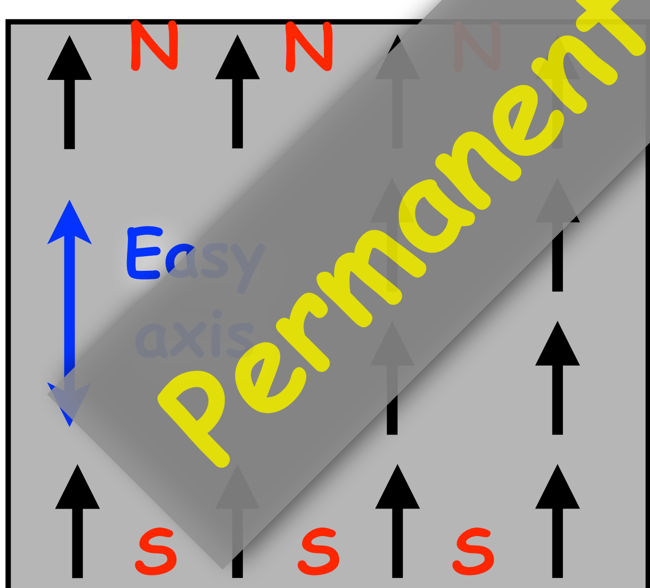
Permanent magnets

$Q >> 1$

Anisotropy energy dominates

↓

Anisotropy energy avoided



After being magnetized, M stays along easy axis all through to surface → poles at surface

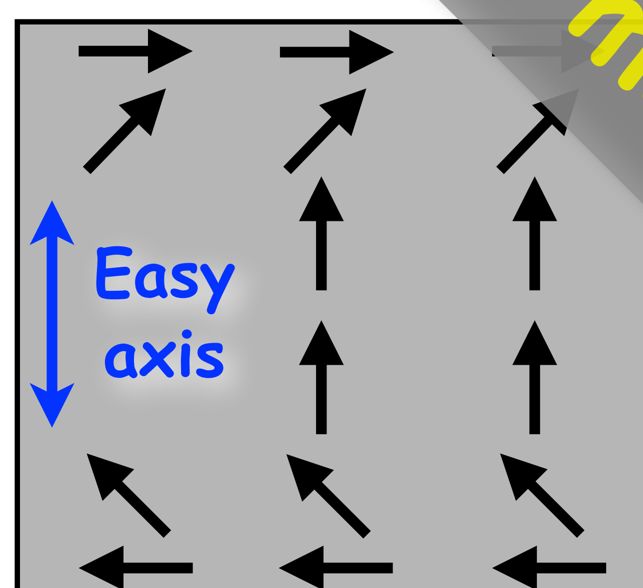
Soft magnets

$Q << 1$

Stray-field energy dominates

↓

Stray-field energy avoided



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Classification of magnetic materials with respect to magnetic microstructure

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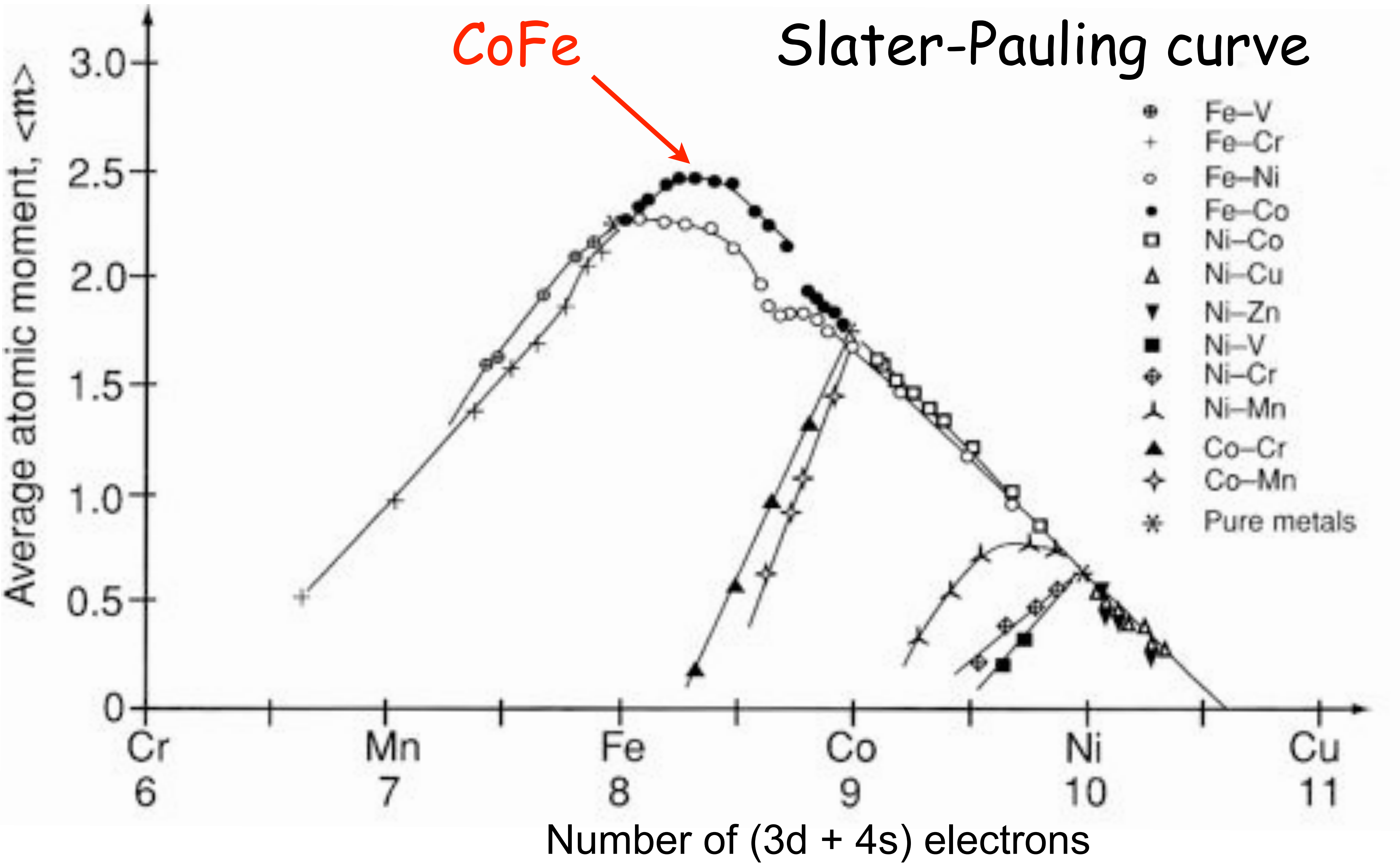
However:

Coercivity is **extrinsic** parameter, determined by structural features (lattice defects, grain boundaries, partile size etc.)

Intrinsic Quality factor determines the ease with which a desired magnetic hardness (or softness) can be achieved

Magnetic softness and hardness

Example 1: CoFe



Magnetic softness and hardness

Example 1: CoFe

$Co_{65}Fe_{35}$ is low-anisotropy material: $Q = 0.008 << 1$

Application as soft magnet

for maximum flux concentration in pole pieces of electromagnets

Magnetic softness and hardness

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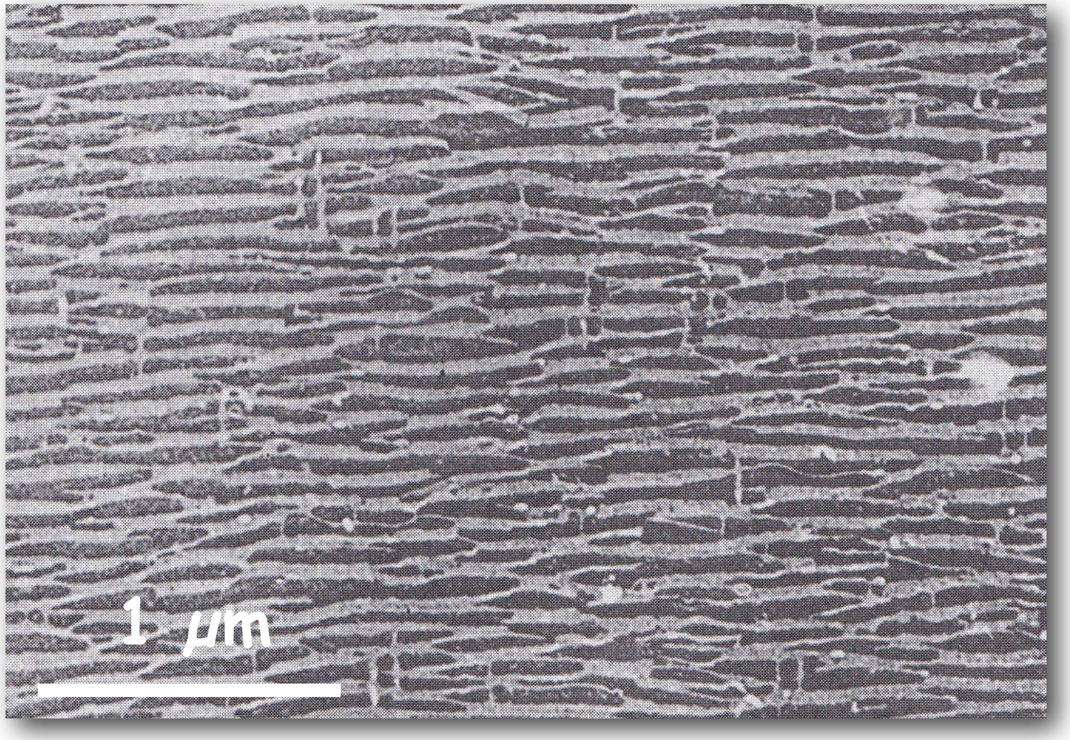
$Co_{65}Fe_{35}$ is low-anisotropy material: $Q = 0.008 << 1$

Application as soft magnet

for maximum flux concentration in pole pieces of electromagnets

Application in hard magnet

CoFe is ferromagnetic phase in Alnico permanent magnets



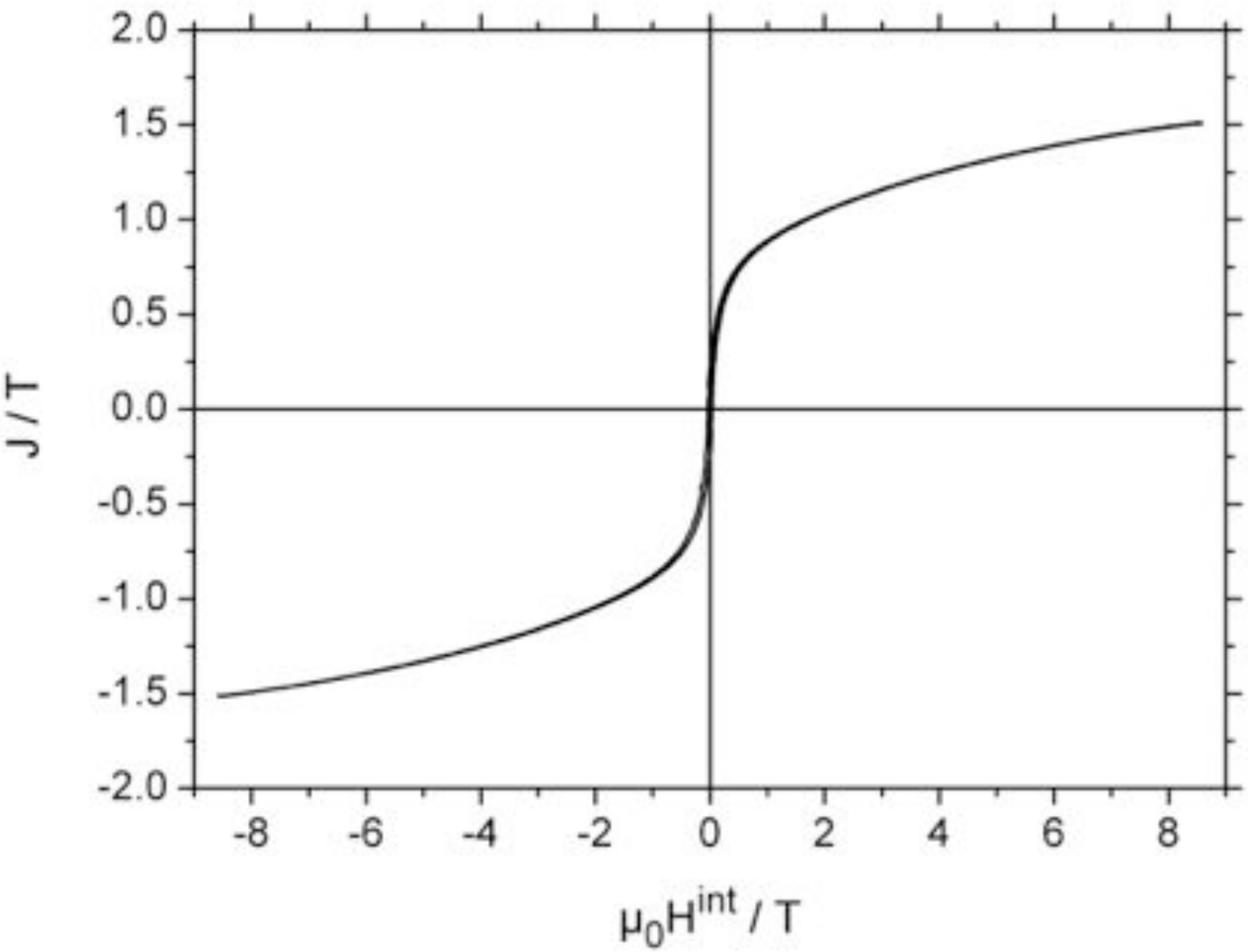
FeCo-needles in non-magnetic AlNi-matrix

↓

Large shape anisotropy

Magnetic softness and hardness

$Nd_2Fe_{14}B$-phase has very high anisotropy: $Q = 4.7 >> 1$



Stoichometric $Nd_2Fe_{14}B$ single-phase material, microcrystalline, no texture

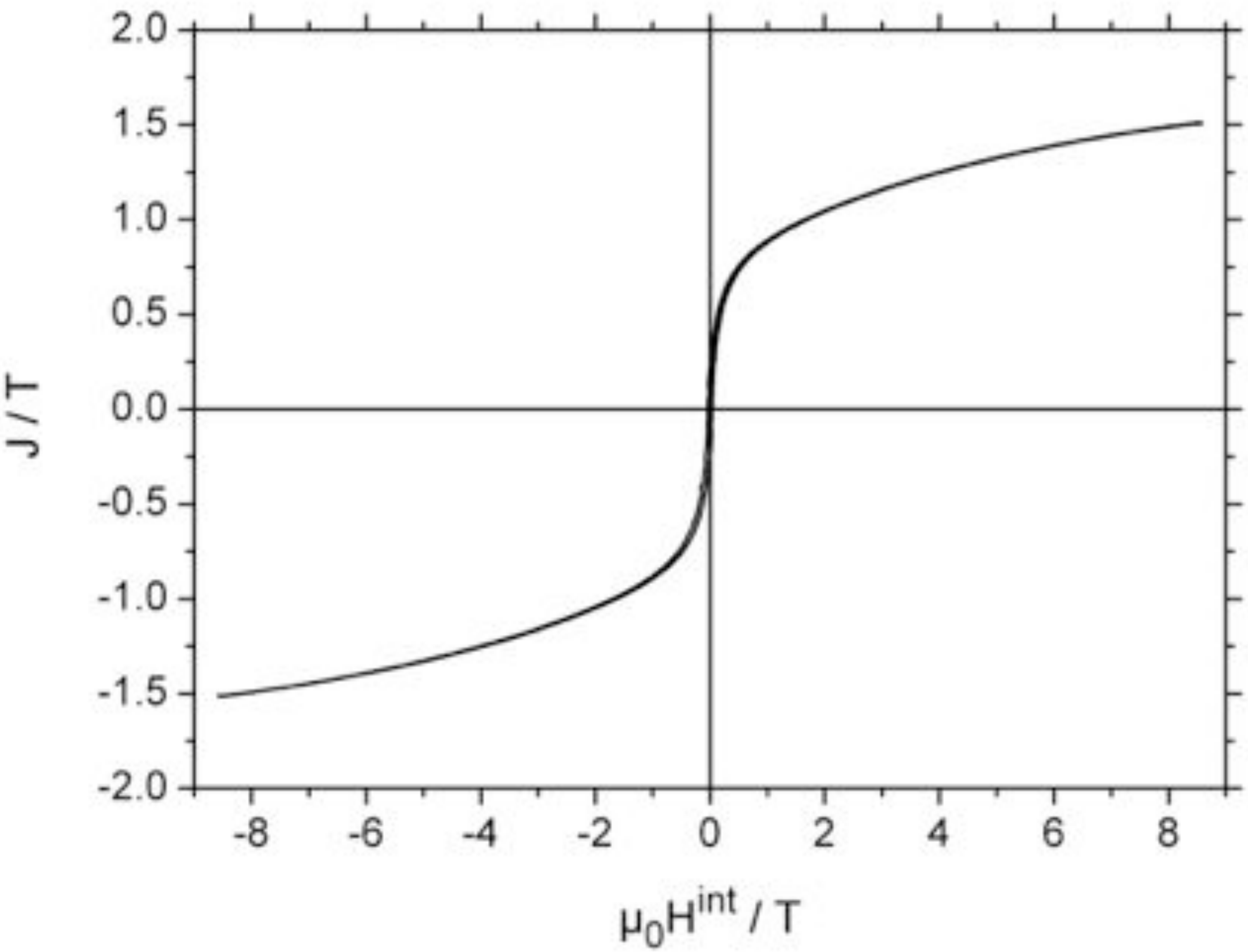
↓

Soft magnetic hysteresis curve

Magnetic softness and hardness

Example 2: NdFeB

$Nd_2Fe_{14}B$-phase has very high anisotropy: $Q = 4.7 >> 1$



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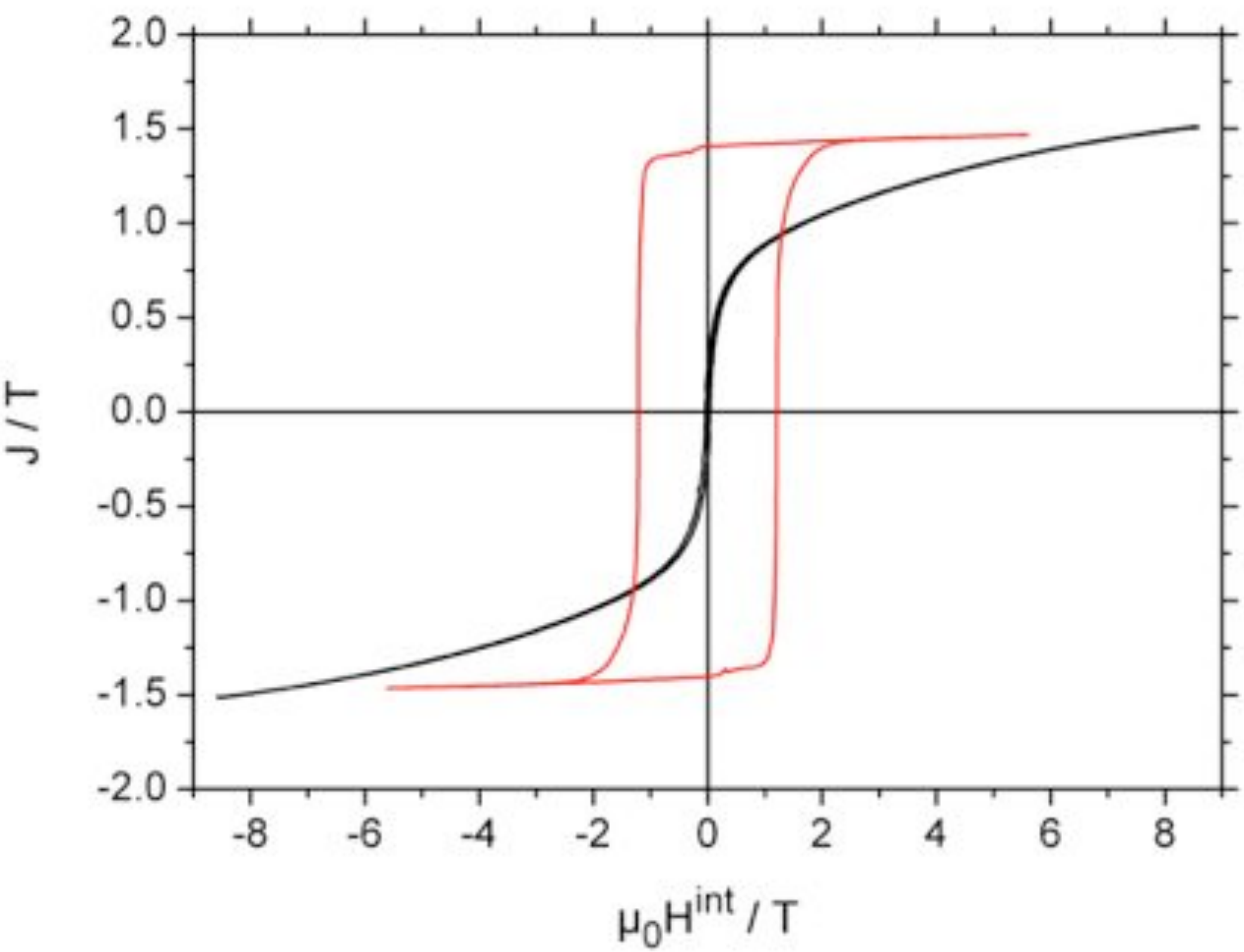


Stoichometric $Nd_2Fe_{14}B$ single-phase material, microcrystalline, no texture

↓

Soft magnetic hysteresis curve

Two-phase microstructure ($Nd_2Fe_{14}B$ + Nd-rich phase), texture

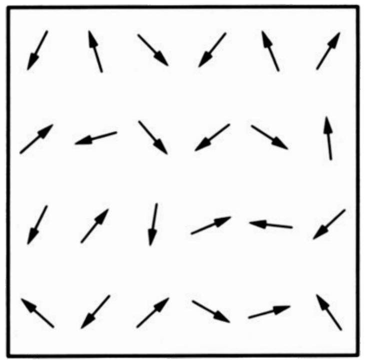
↓

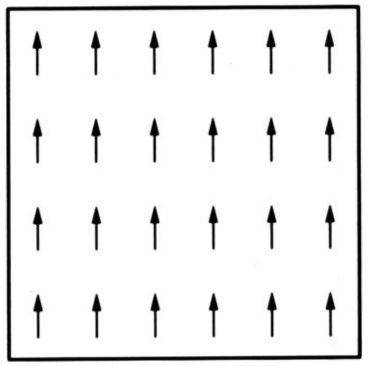
Hard magnetic hysteresis curve

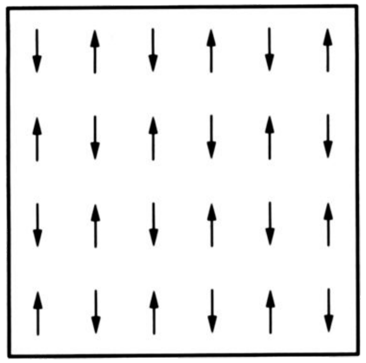
Summary: Classification of magnetic materials

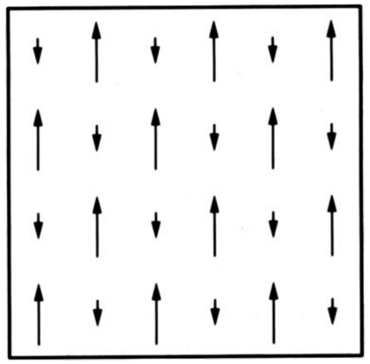
1. Microscopic level (atomic level theory)

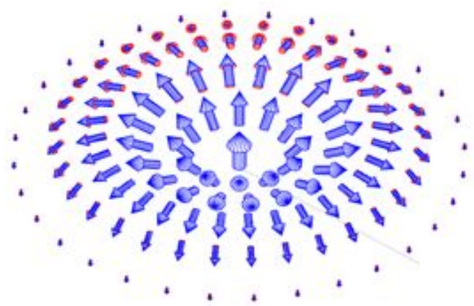
Paramagnets, Ferromagnets, Antiferromagnets, Ferrimagnets, Helimagnets





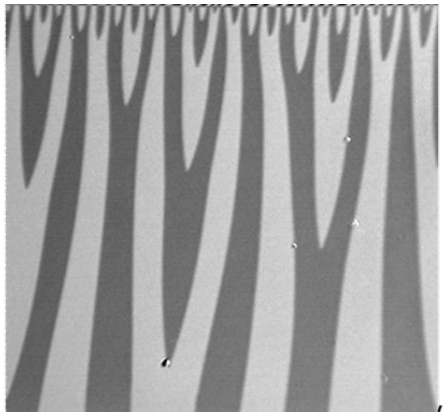






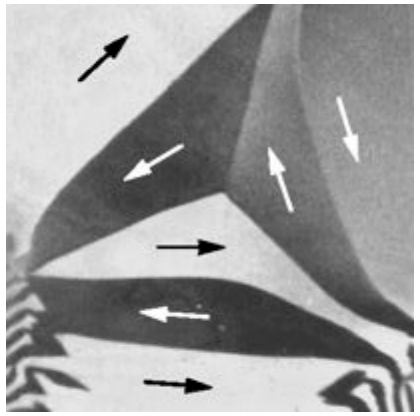
2. Mesoscopic level (Magnetic microstructure)

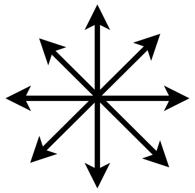
Uniaxial, high-anisotropy materials



Easy axis

Multiiaxial, low-anisotropy materials

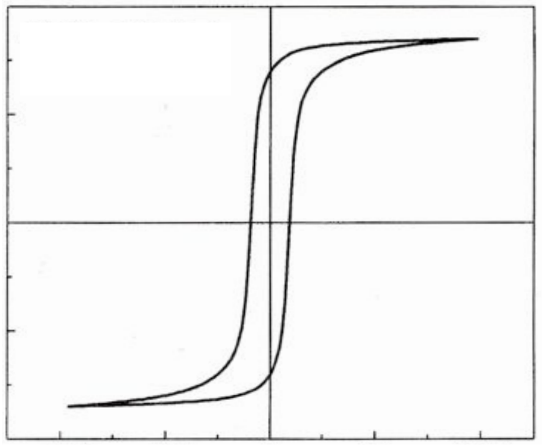




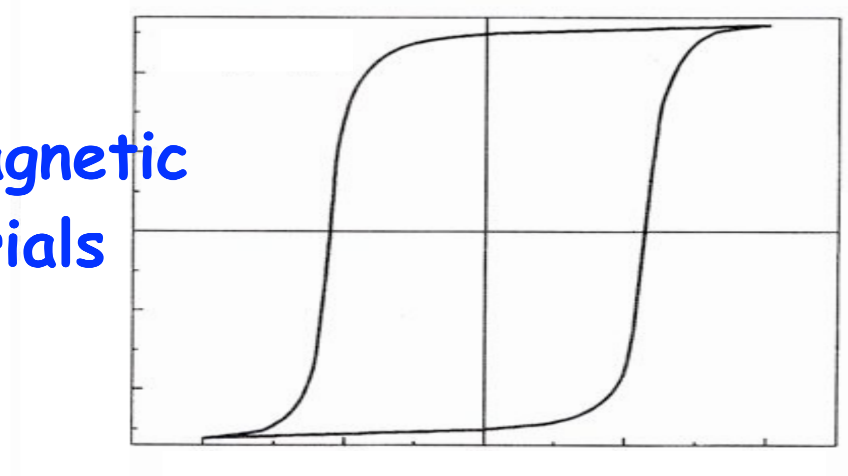
Easy axis

3. Macroscopic level (Magnetization curve)

Soft magnetic materials



Hard magnetic materials



Contents of lecture

1) Soft magnetic materials
- Basics
- FeNi alloys
- Cubic ferrites
- FeSi electric steel
- Amorphous ribbons
- Nanocrystalline ribbons

2) Hard magnetic materials
- Basics
- NdFeB sintered
- NdFeB nanostructured
- Hexa-Ferriete
- SmCo
- AlNiCo

3) Special materials
- Heusler alloys
- Magnetic shape memory materials
- Magnetocaloric materials
- Multiferroics
- Helimagnets

1.
Soft Magnetic Materials

1.

Soft Magnetic Materials

General considerations

Soft magnets: General Considerations

a) Purpose of soft magnetic material

Enhancement of flux density B, produced by current-carrying coil

- Inductor without and with soft magnetic core

Without core: $\boldsymbol{B} = \mu_0 \boldsymbol{H}$, with $\mu_0 = 4\,\pi\,10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}$

With core: $\boldsymbol{B} = \mu_0 \boldsymbol{H} + \boldsymbol{J} = \mu_0\,(\boldsymbol{H} + \boldsymbol{M}) = \mu_0\,\mu_r\,\boldsymbol{H} = \mu\,\boldsymbol{H}$

- $\boldsymbol{B}$: Flux density [Tesla]
- $\boldsymbol{H}$: Magn. field [A/m]
- $\boldsymbol{J}$: Polarization [Tesla]
- $\boldsymbol{M}$: Magnetization [A/m]
- μ_r: Rel. Permeability [ ]

- Soft magnets: applied H is small $\longrightarrow B(H) \sim J(H)$

- Rel. Permeability μ_r : inital permeabilty $\mu_{r,\,in}$ and maximum permeability $\mu_{r,\,max}$

  $\mu_r = 1 + \chi$ up to 100.000 up to 1.000.000

- Example: $\boldsymbol{B} = \mu_0 \boldsymbol{H} = 0.001$ T in air coil (for $\boldsymbol{H} \approx 800$ A/m)

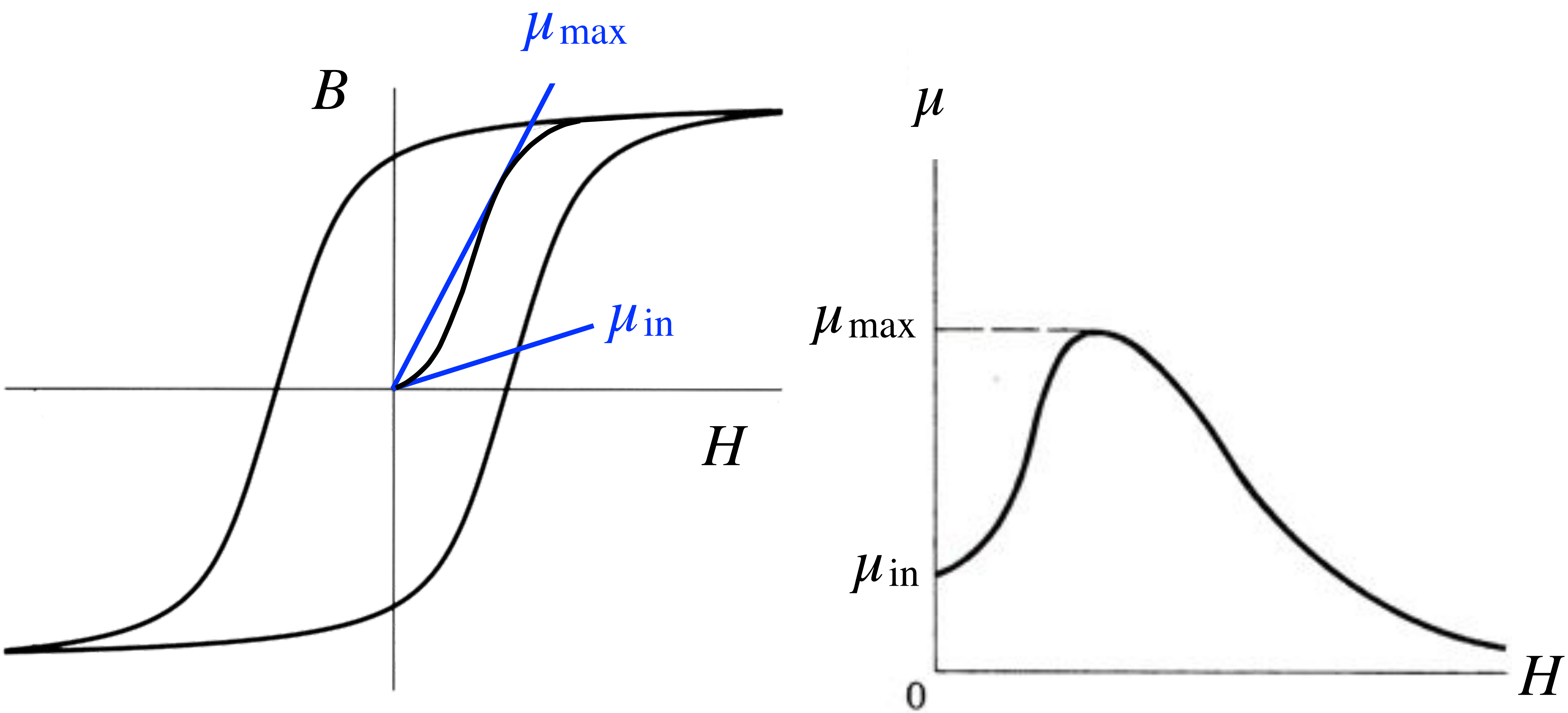
  Soft magnetic core with μ_r = 1000 : $\boldsymbol{B} = \mu_0\,\mu_r\,\boldsymbol{H} = 1$ T (multiplication by factor μ_r)

  Limit: set by saturation induction: $B_s \approx J_s = \mu_0\,M_s$

Soft magnets: General Considerations

a) Purpose of soft magnetic material

Permeability



$$\mu_{in,\,max} = \frac{B}{H}$$: slope of line from origin to point on $B(H)$ curve

Soft magnets: General Considerations

a) Purpose of soft magnetic material

Enhancement of flux density B, produced by current-carrying coil

Without core: $\boldsymbol{B} = \mu_0 \boldsymbol{H}$, with $\mu_0 = 4\,\pi\,10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}$

With core: $\boldsymbol{B} = \mu_0 \boldsymbol{H} + \boldsymbol{J} = \mu_0\,(\boldsymbol{H} + \boldsymbol{M}) = \mu_0\,\mu_r \boldsymbol{H} = \mu\,\boldsymbol{H}$

- $\boldsymbol{B}$: Flux density [Tesla]
- $\boldsymbol{H}$: Magn. field [A/m]
- $\boldsymbol{J}$: Polarization [Tesla]
- $\boldsymbol{M}$: Magnetization [A/m]
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- Rel. Permeability μ_r : inital permeabilty $\mu_{r,\,in}$ and maximum permeability $\mu_{r,\,max}$

  $\mu_r = 1 + \chi$; $\mu_{r,\,in}$: up to 100.000 ; $\mu_{r,\,max}$: up to 1.000.000

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  Limit: set by saturation induction: $B_s \approx J_s = \mu_0\,M_s$

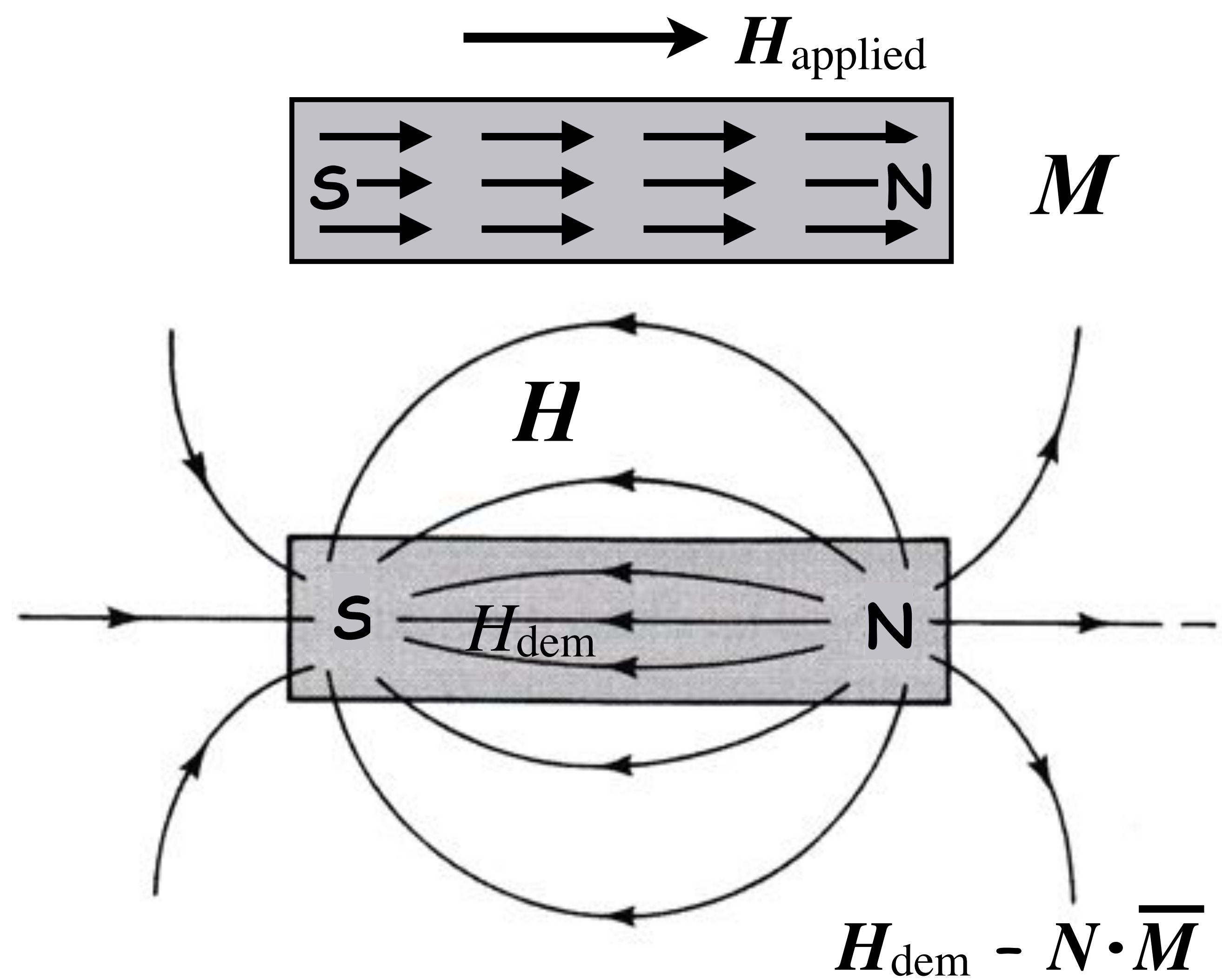
Soft magnets: General Considerations

Remark on Permeability: depends on sample shape

- Open sample

Demagnetizing field $\boldsymbol{H}_{\text{dem}} = -N\overline{\boldsymbol{M}}$:
acts opposite to magnetization $\boldsymbol{M}$ that creates it

Internal field: $H_{\text{in}} = H_{\text{applied}} - N \cdot \overline{M}$



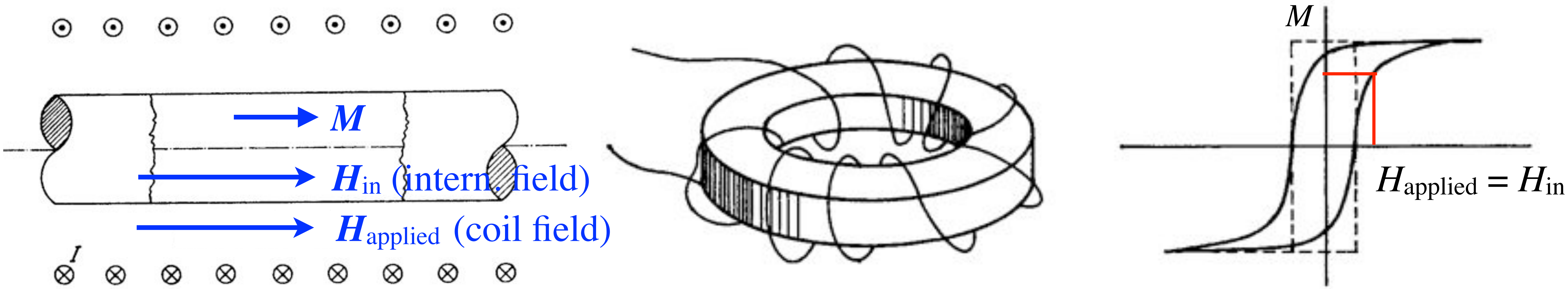
- Closed sample

Internal field: $H_{\text{in}} = H_{\text{applied}}$, $N = 0$

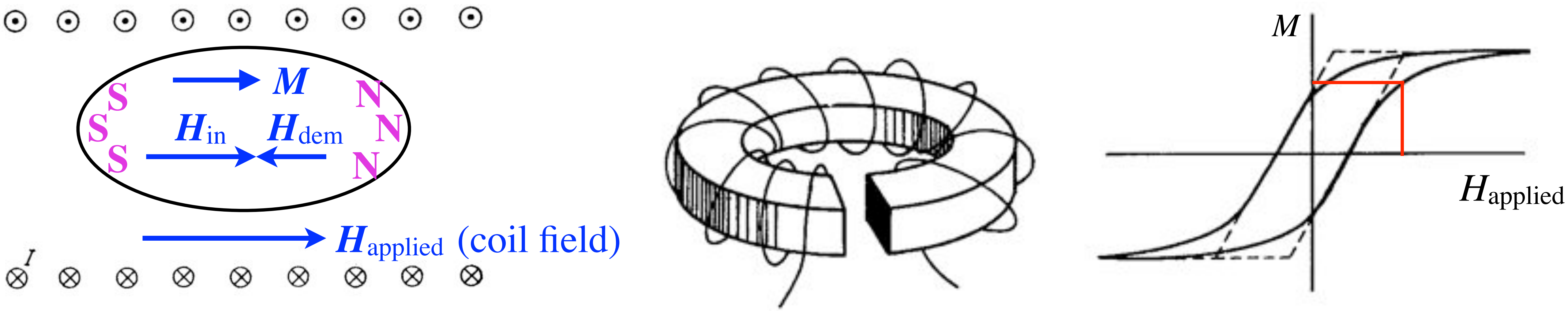
Soft magnets: General Considerations

Remark on Permeability: depends on sample shape

Demagnetization effect → Shearing of magnetizaton curve



Infinite sample or closed ring: unsheared hysteresis curve: $N = 0$, i.e. $H_{in} = H_{ext}$

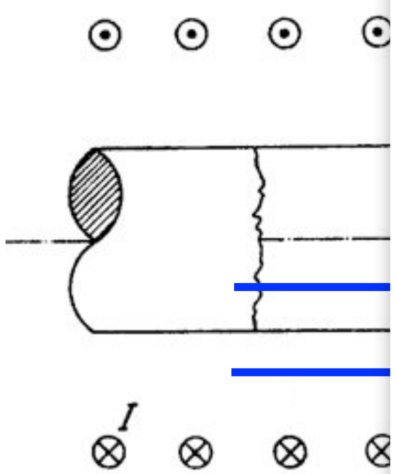


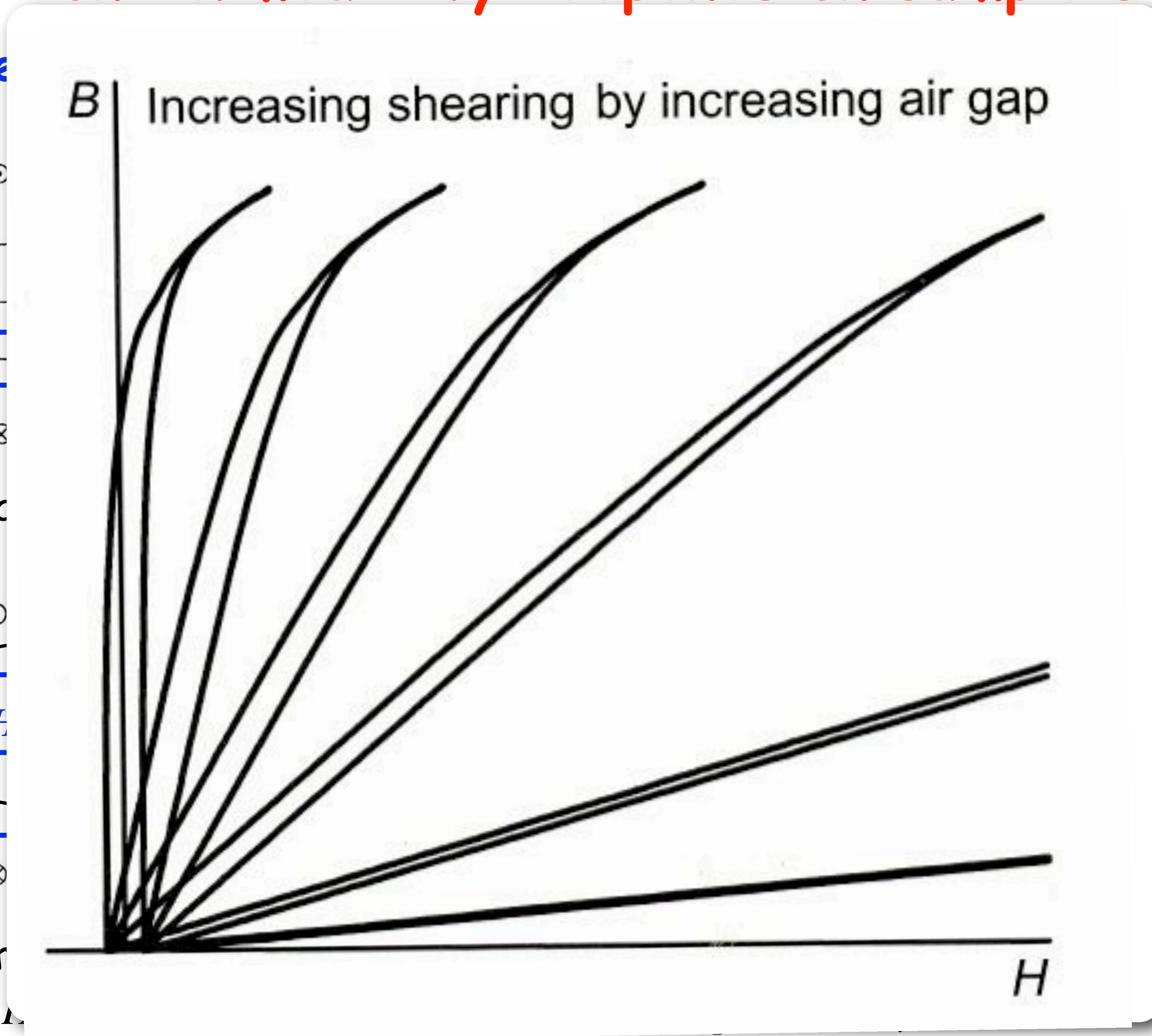
Finite sample or open core: sheared hysteresis curve due to demagnetization effect (a higher $H_{applied}$ is needed to achieve a given degree of M)

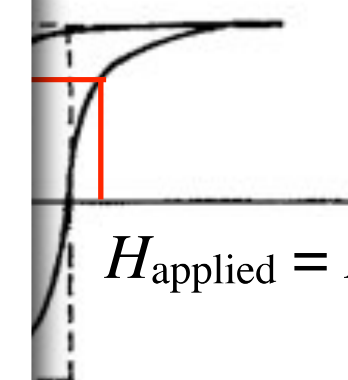
Soft magnets: General Considerations

Remark on Permeability: depends on sample shape

Demagne







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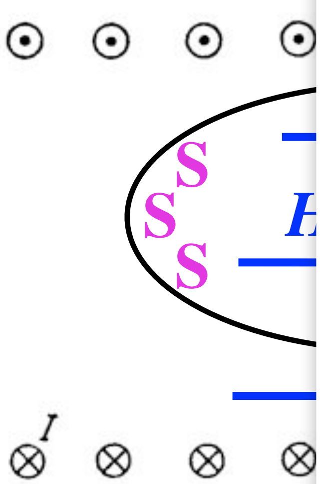

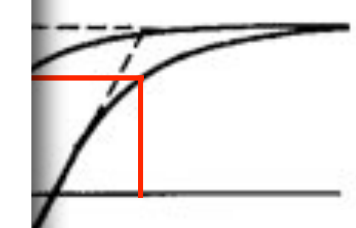

Finite sam

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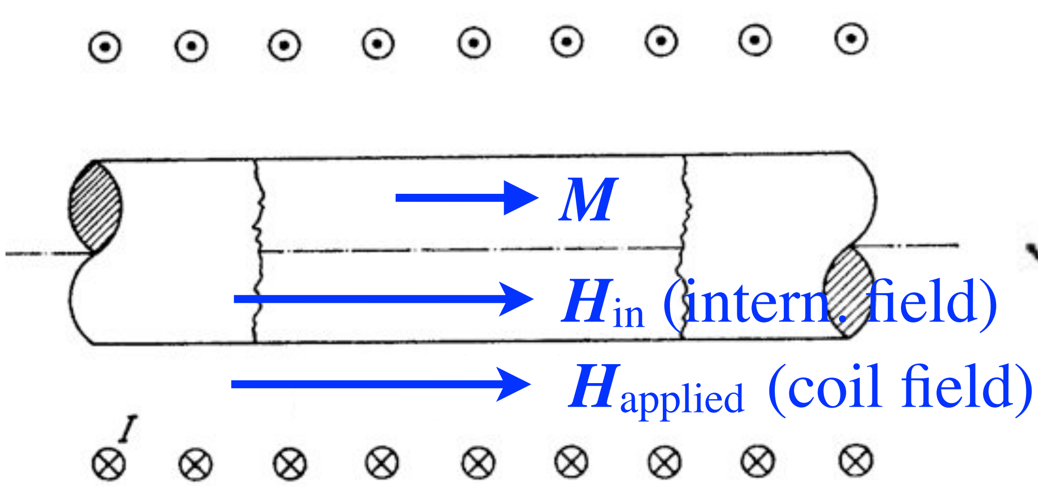

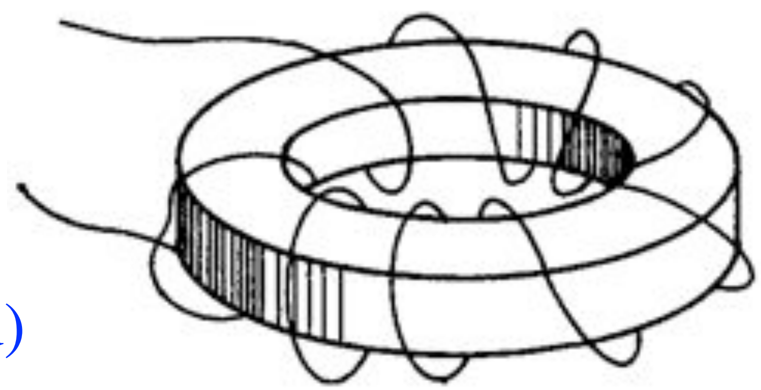

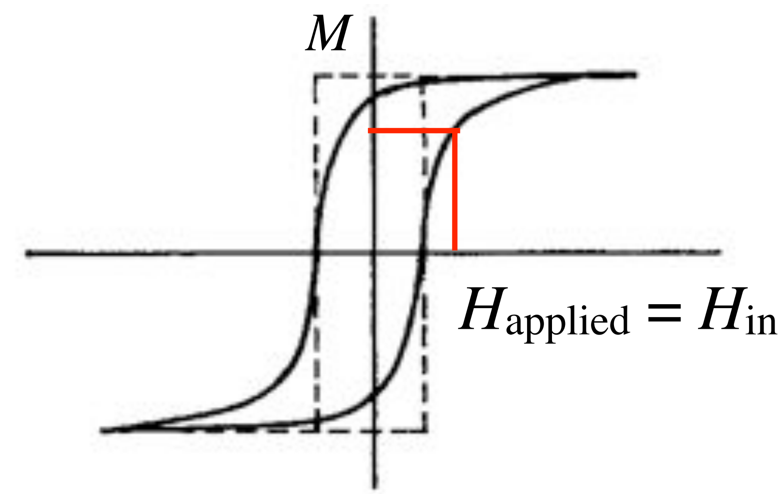

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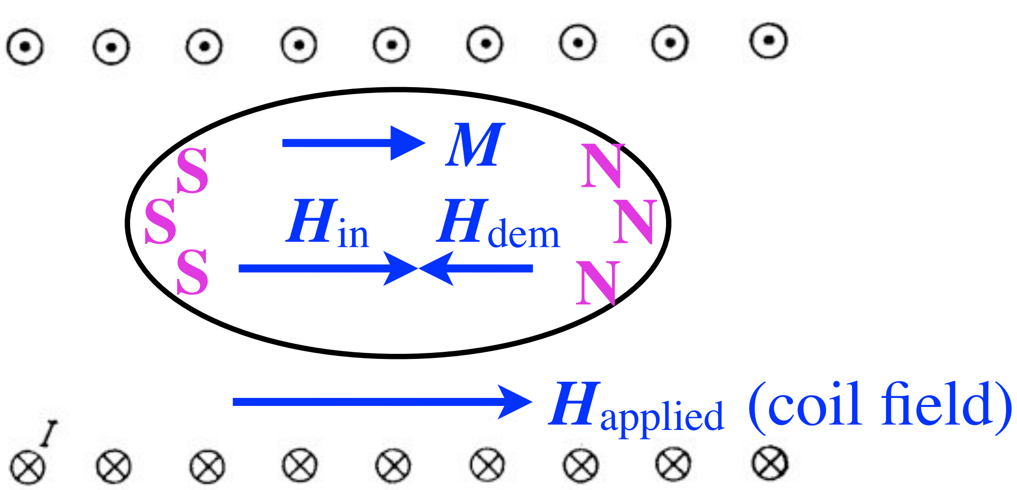

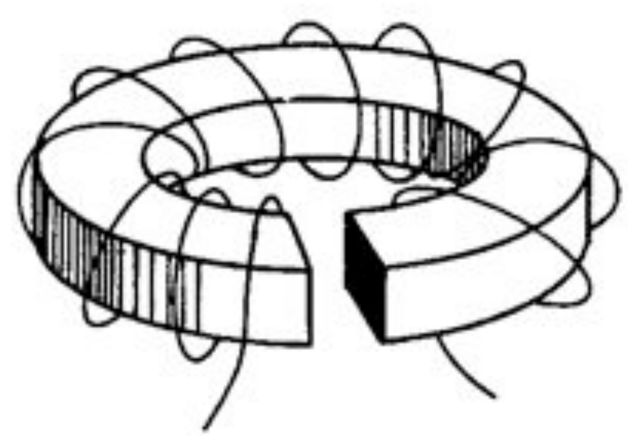

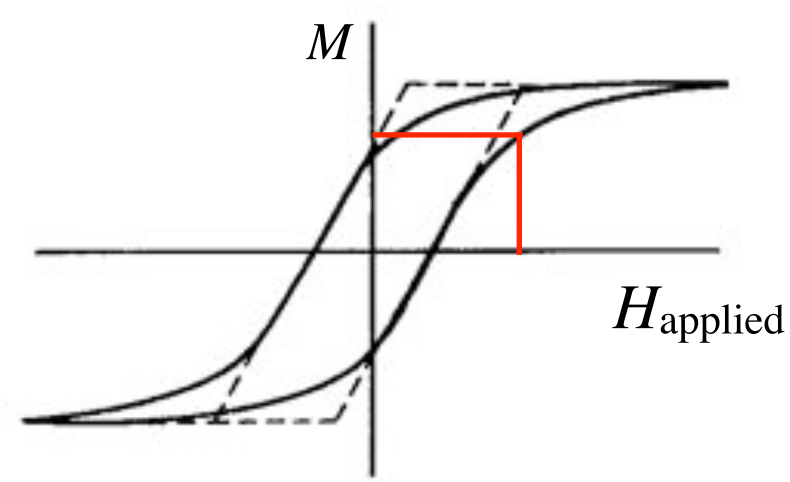

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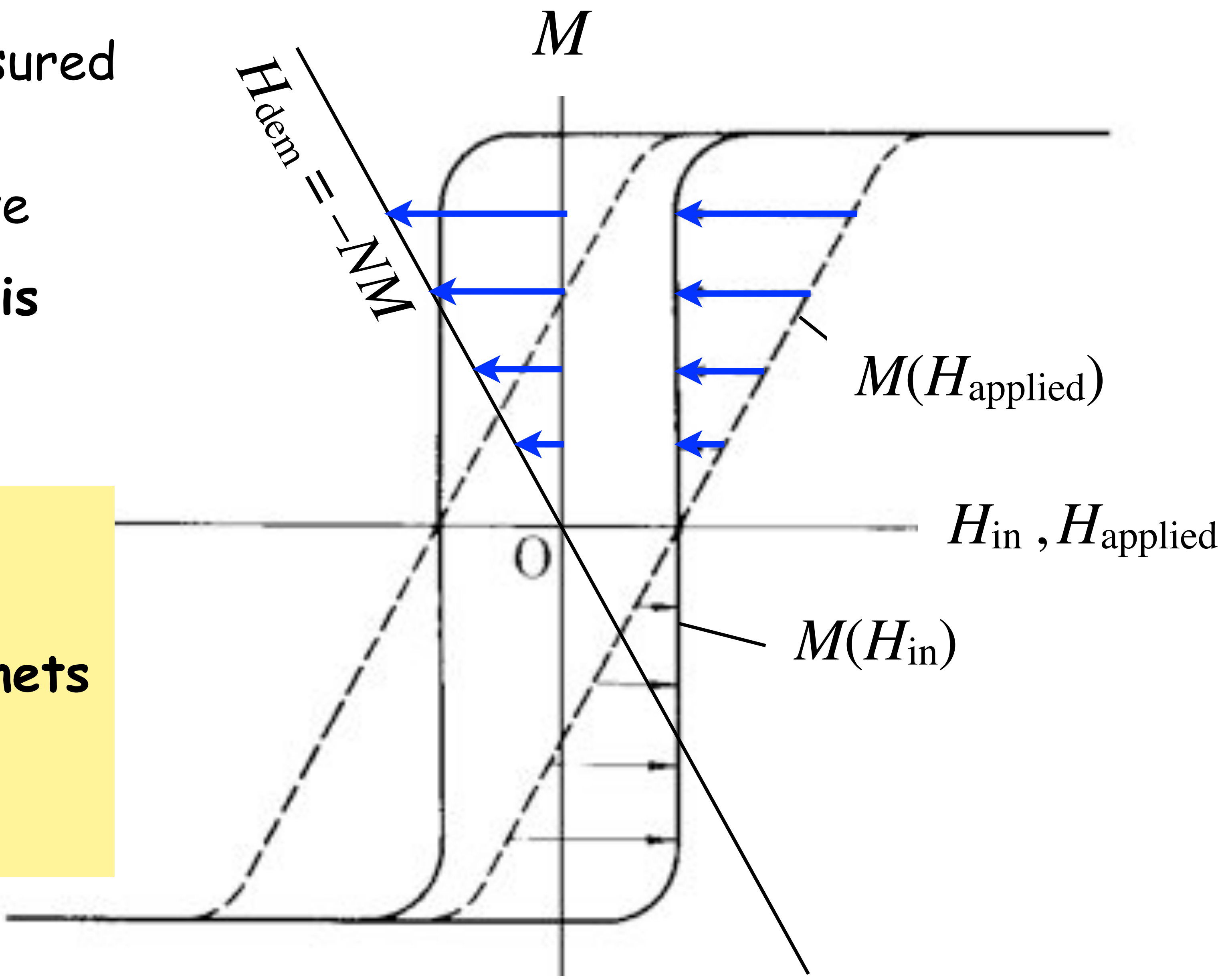
Soft magnets: General Considerations

Remark on Permeability: depends on sample shape

Demagnetization effect → Shearing of magnetizaton curve

- Internal field: $H_{in} = H_{applied} - N \cdot M$
- If a magnetization curve was measured on a finite sample, it has to be re-sheared to obtain the $M(H_{in})$-curve
- **Relevant for magnetic materials is the $M(H_{in})$-curve, as it is independent of the sample shape**
- **Permeability for soft magnetic materials is usually referred to internal field, because soft magnets tend to be used in torroidal geometry**



Soft magnets: General Considerations

a) Purpose of soft magnetic material

Enhancement of flux density B, produced by current-carrying coil

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Large magnetization changes in small applied magnetic fields

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⟶ Large saturation magnetization M_s

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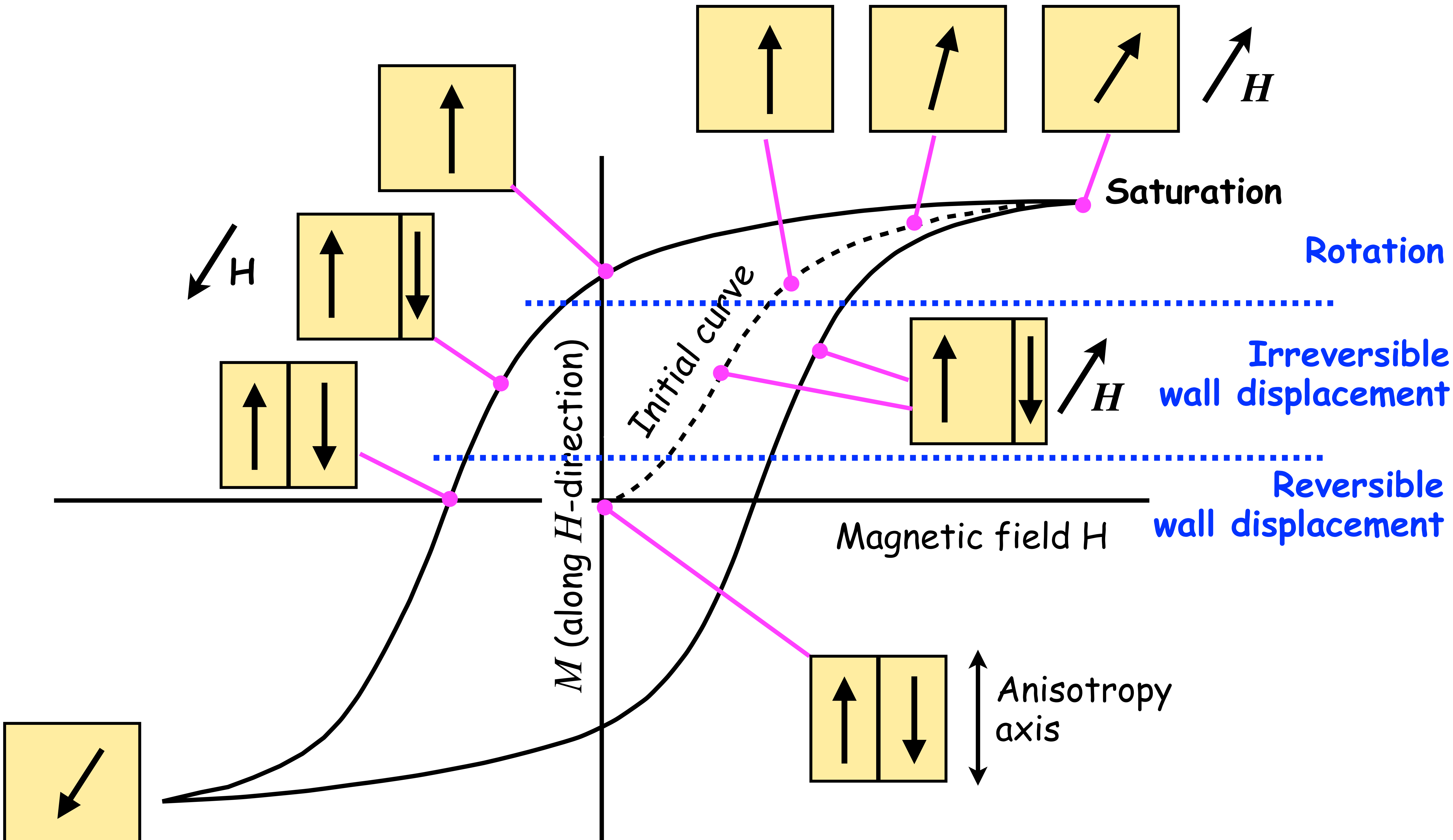
Why?

↳ Excursus to magnetization processes and magnetostriction

Hysteresis curve and magnetization processes



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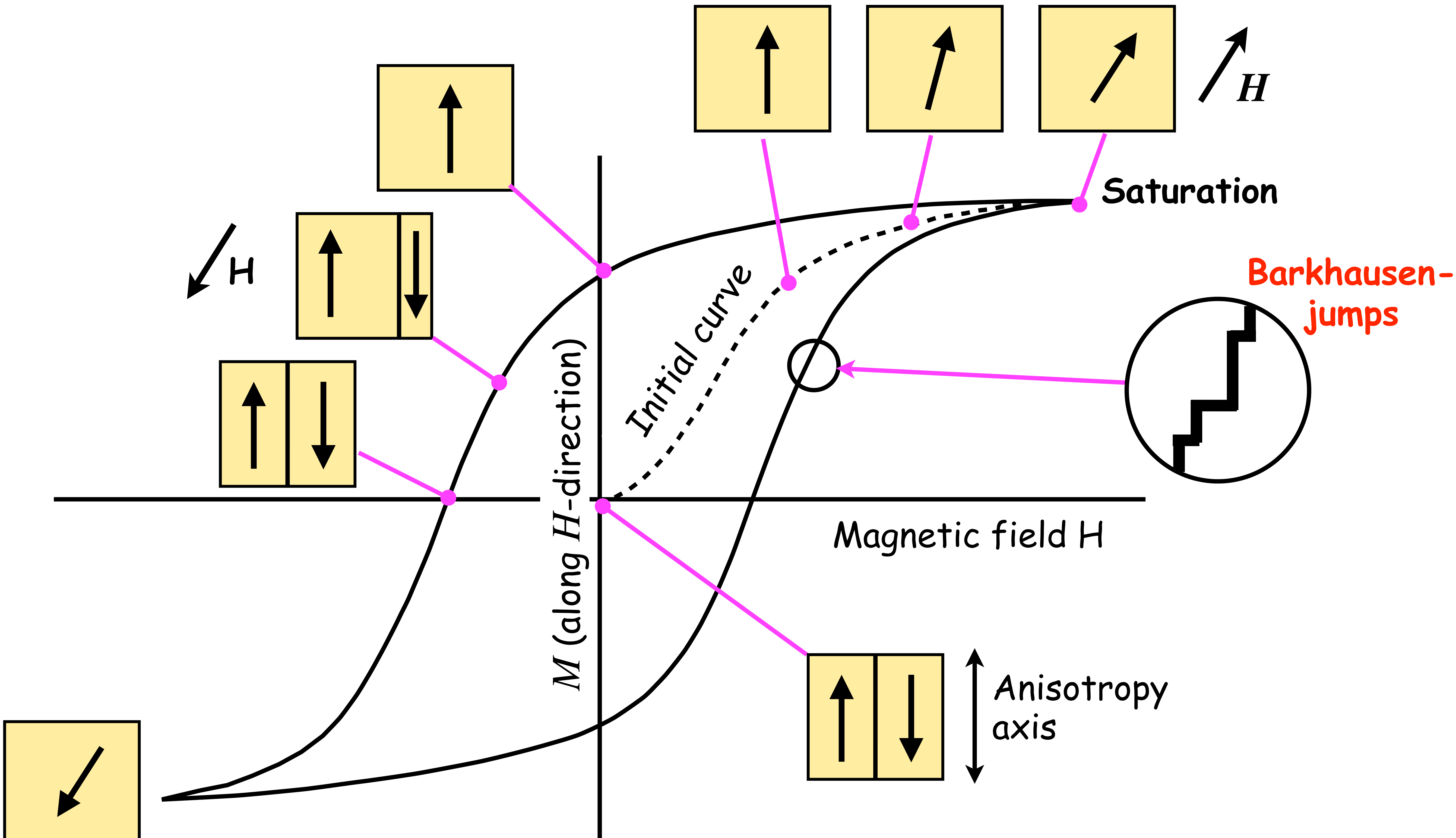

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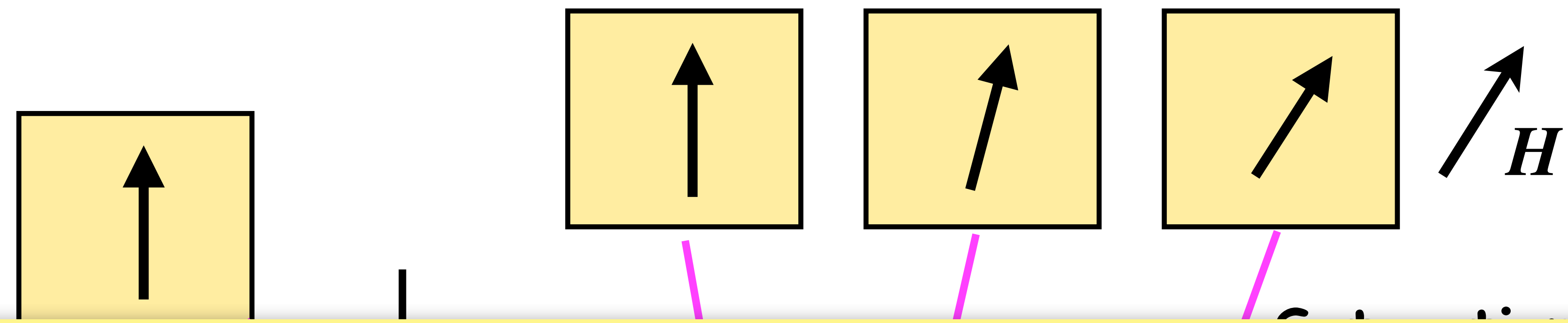
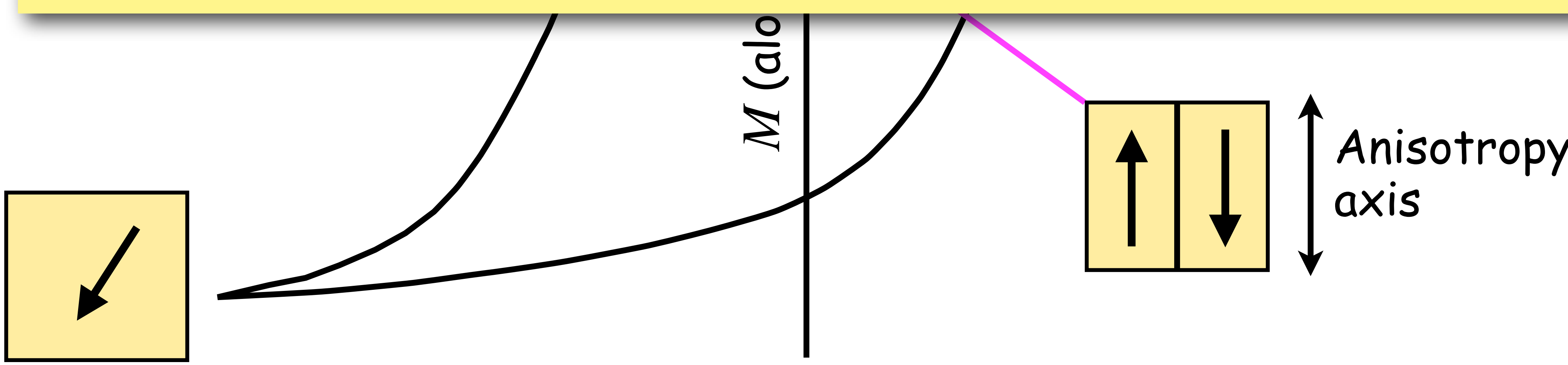


Magnetization proceeds via rotation and wall motion

→ soft magnetic properties require easy rotation of M and easy motion of domain walls



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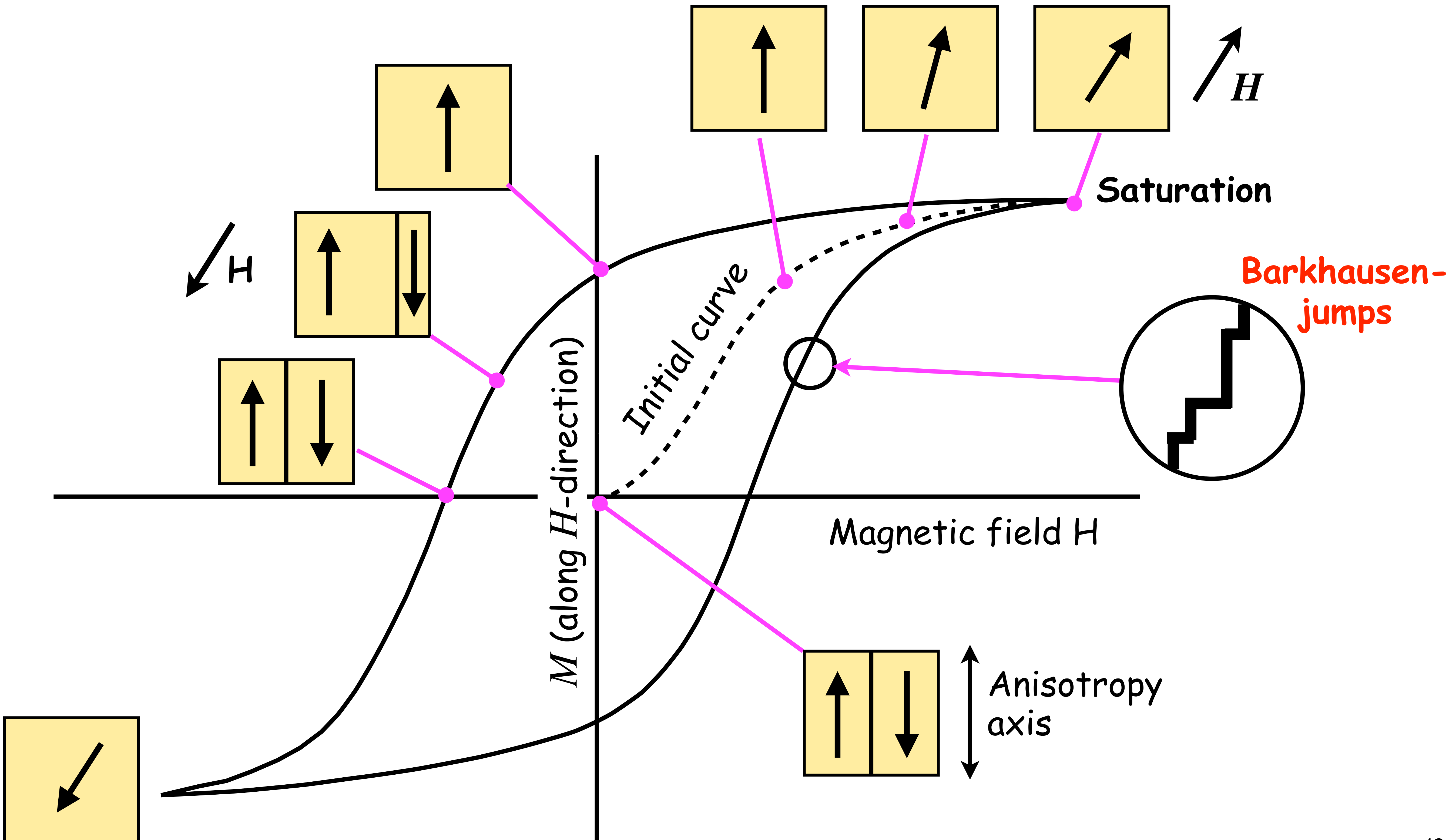
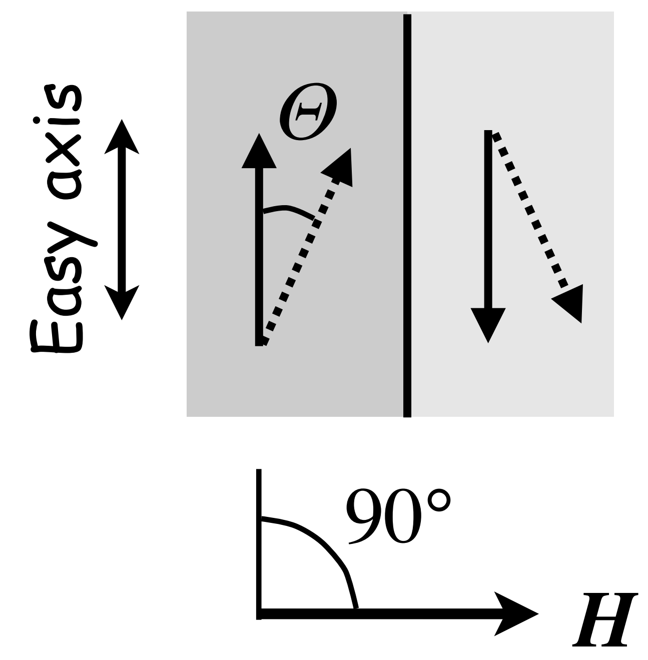


a) Rotation of magnetization

Given: uniaxial anisotropy, 180° wall, $H \perp$ easy axis



Excursus: Magnetization processes

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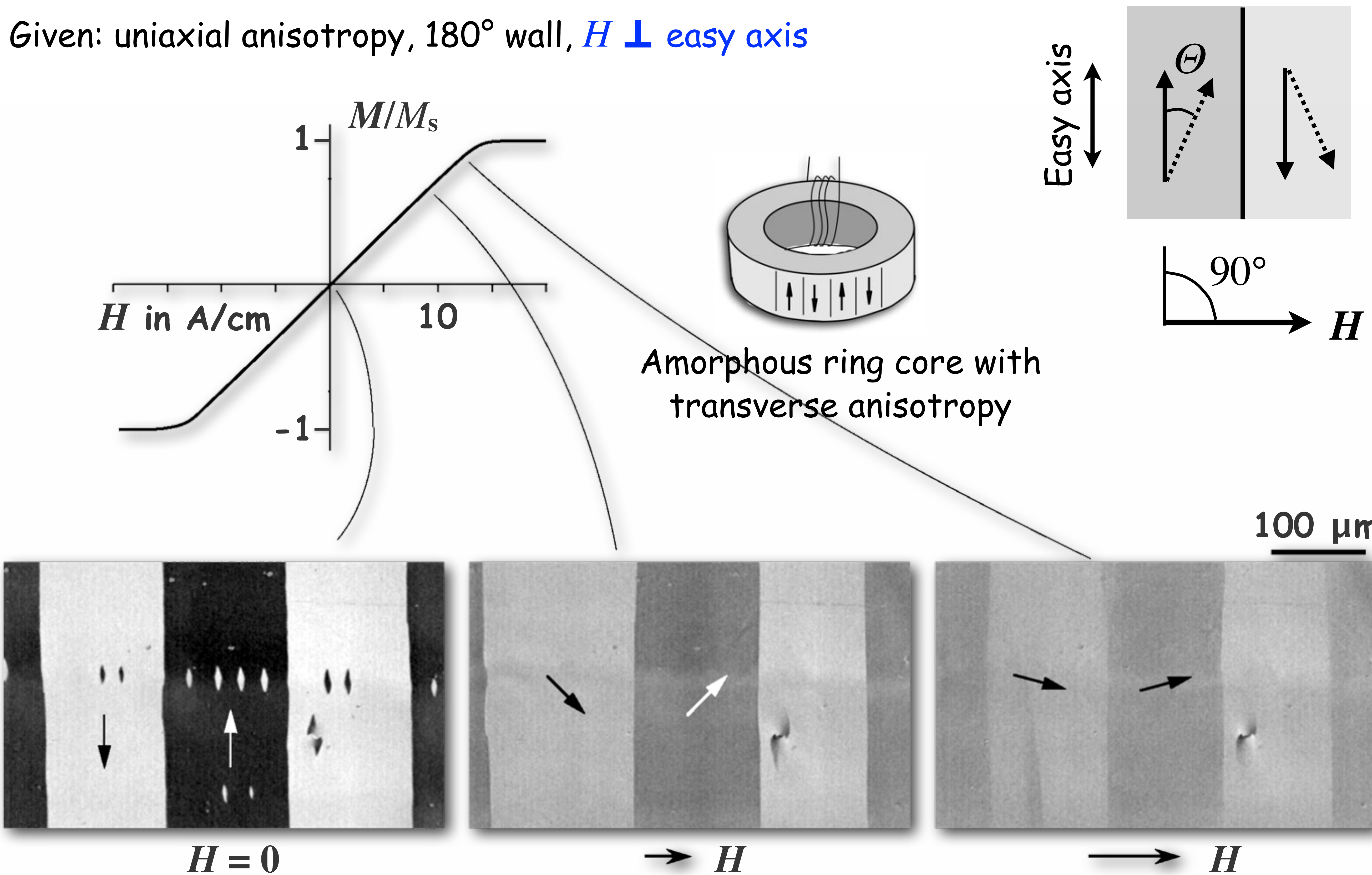

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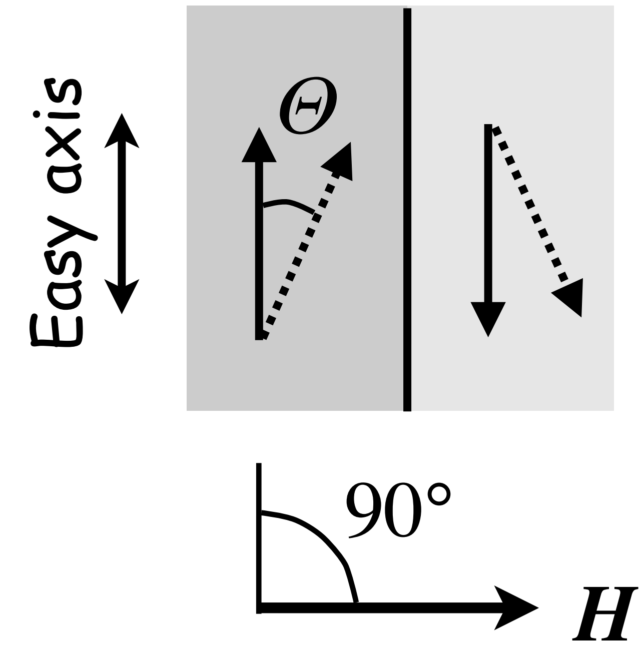
a) Rotation of magnetization

Given: uniaxial anisotropy, 180° wall, $H \perp$ easy axis

- Anisotropy energy: $e_K = K_u \sin^2\Theta$
- External field energy: $e_H = -\mu_0 H M_s \sin\Theta$



Total energy: $e_{tot} = e_K + e_H$

Minimization: $\partial e_{tot}/\partial\Theta = 2K_u \sin\Theta \cos\Theta - \mu_0 H M_s \cos\Theta = 0$

$2K_u \sin\Theta = \mu_0 H M_s$

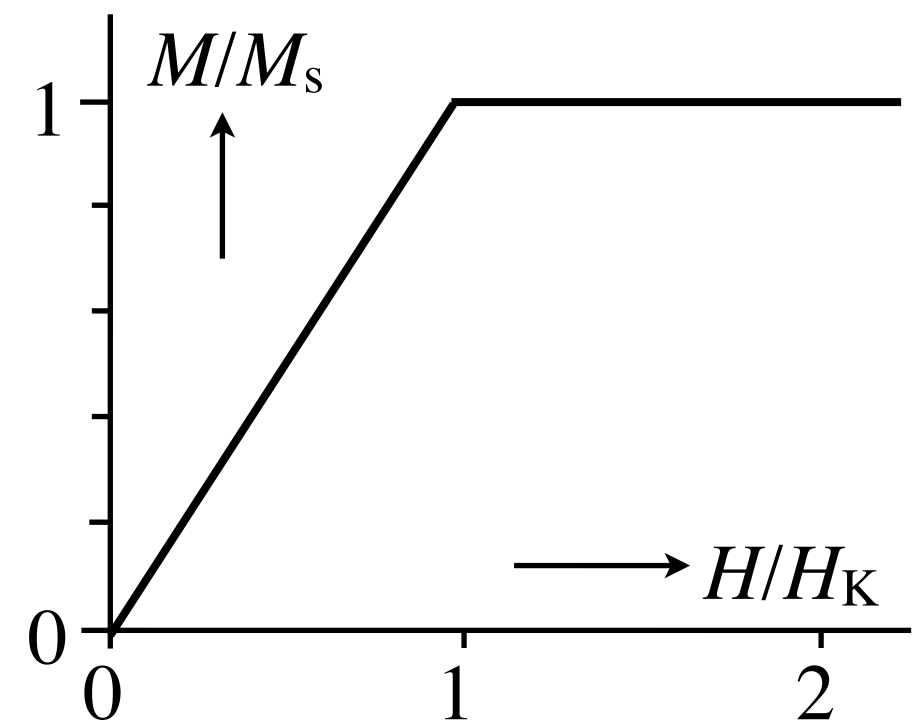
Magnetization in field direction: $M = M_s \sin\Theta$

$2K_u\,(M/M_s) = \mu_0 H M_s$

$M/M_s = H(\mu_0 M_s / 2K_u)$ → linear M(H) curve,

Saturation $(M/M_s = 1)$ at $H = 2K_u/\mu_0 M_s = H_K$

Anisotropy field



$B = \mu_0 \mu_r H$

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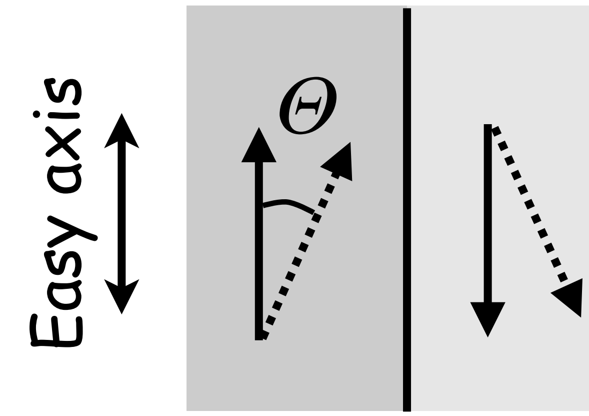

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→ High permeability requires small anisotropy to allow for easy rotation of magnetization

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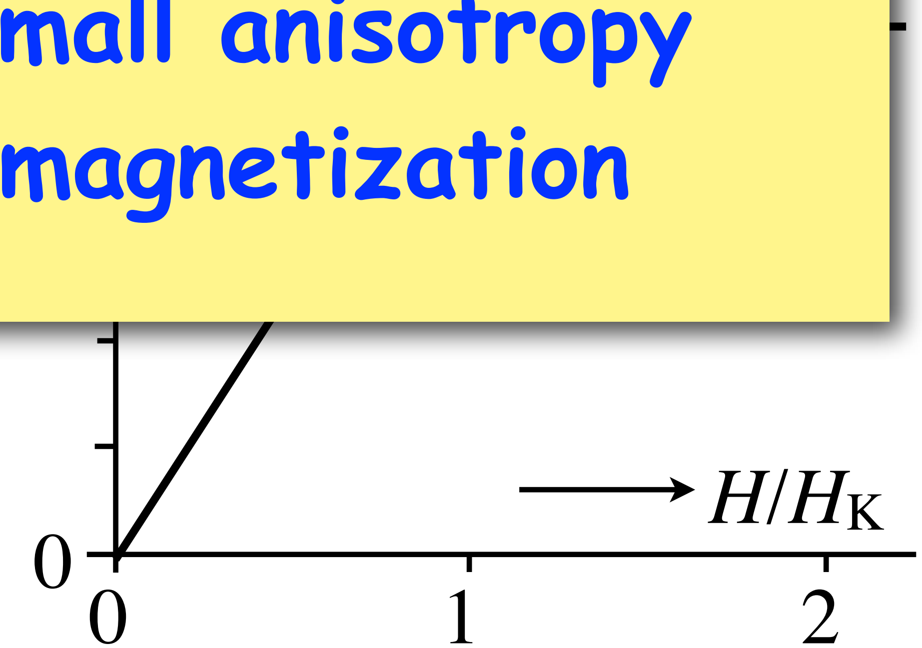

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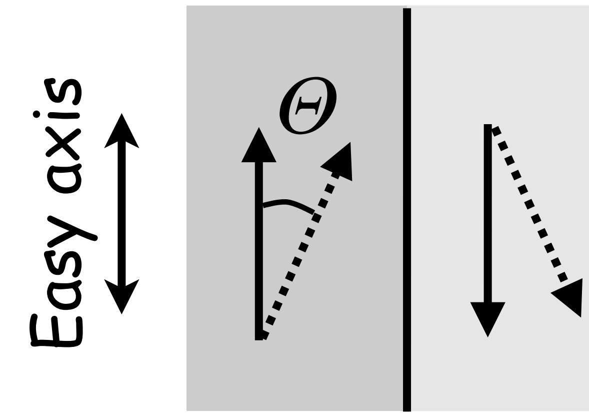

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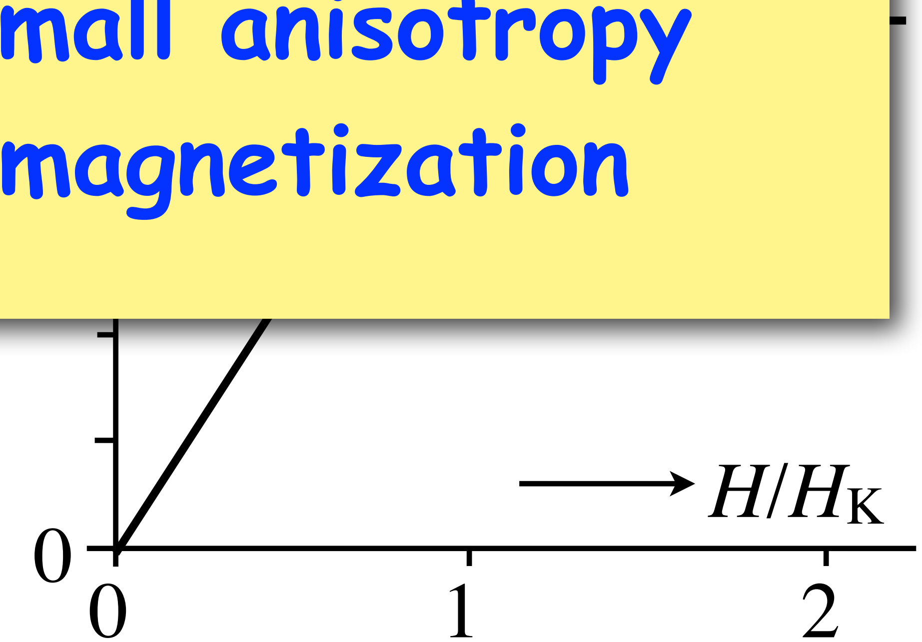

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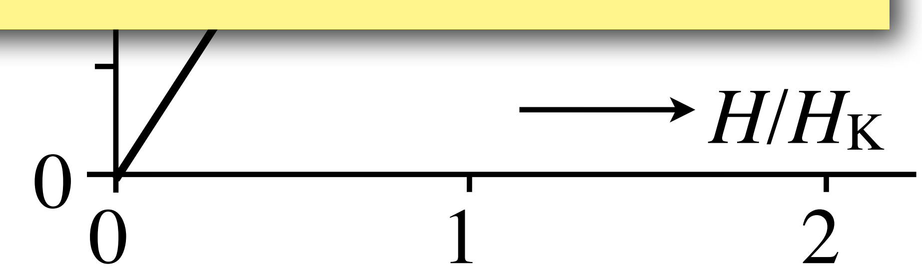

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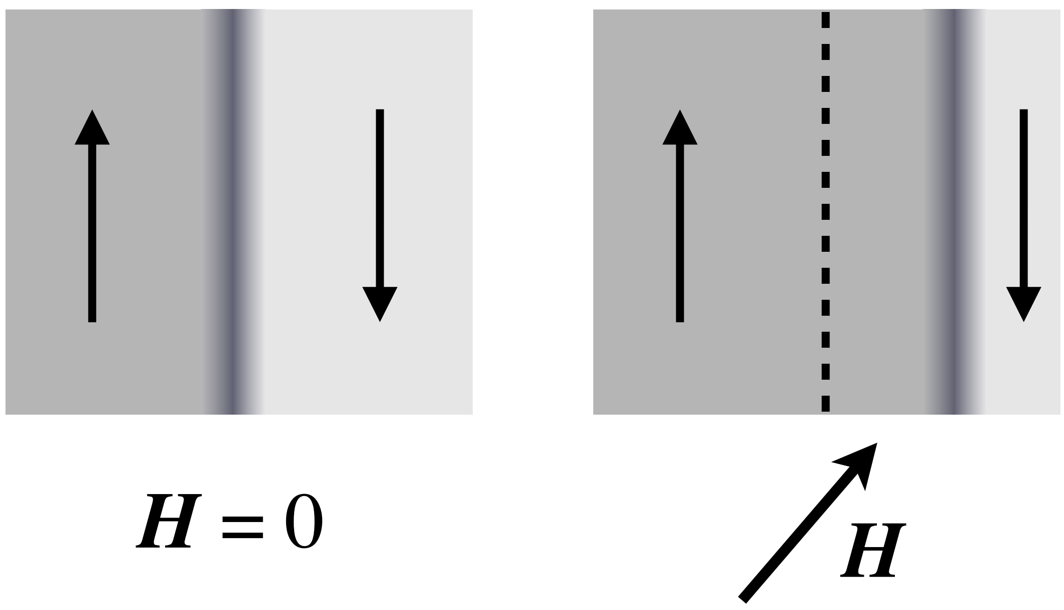
Excursus: Magnetization processes

b) Wall motion

- Domain wall displacement increases volume of domains with magnetization component along field direction

- Specific wall energy: $\gamma_{180} = 4\sqrt{A \cdot K}$

  Domain wall width: $W_{\mathrm{wall}} = \pi\sqrt{A/K}$



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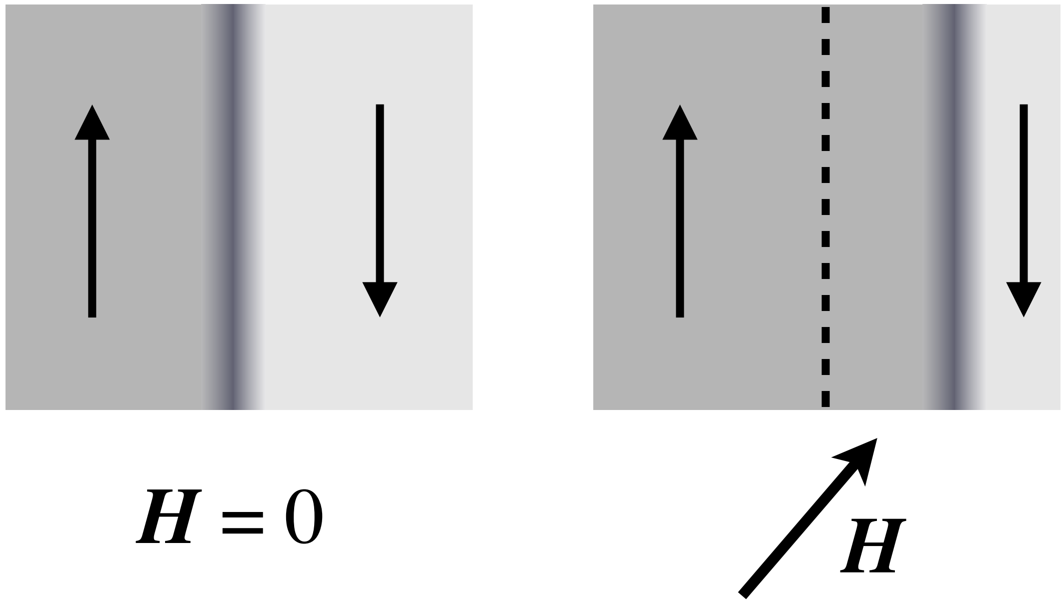

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- Pinning of domain walls by:

  1) Inhomogeneities in microstructure: Non-magnetic inclusions

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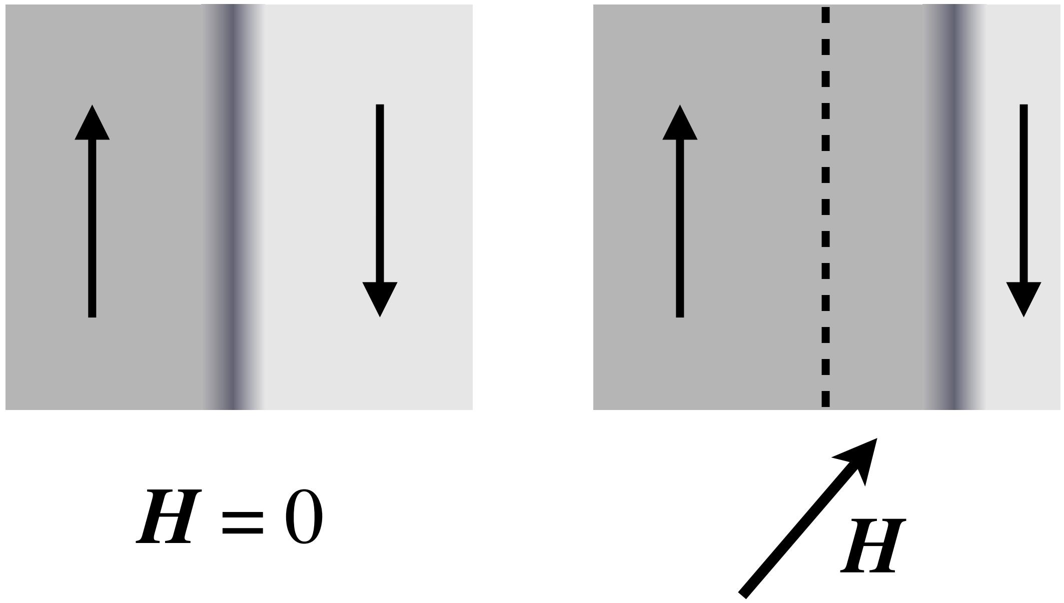

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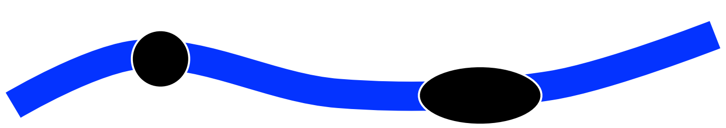
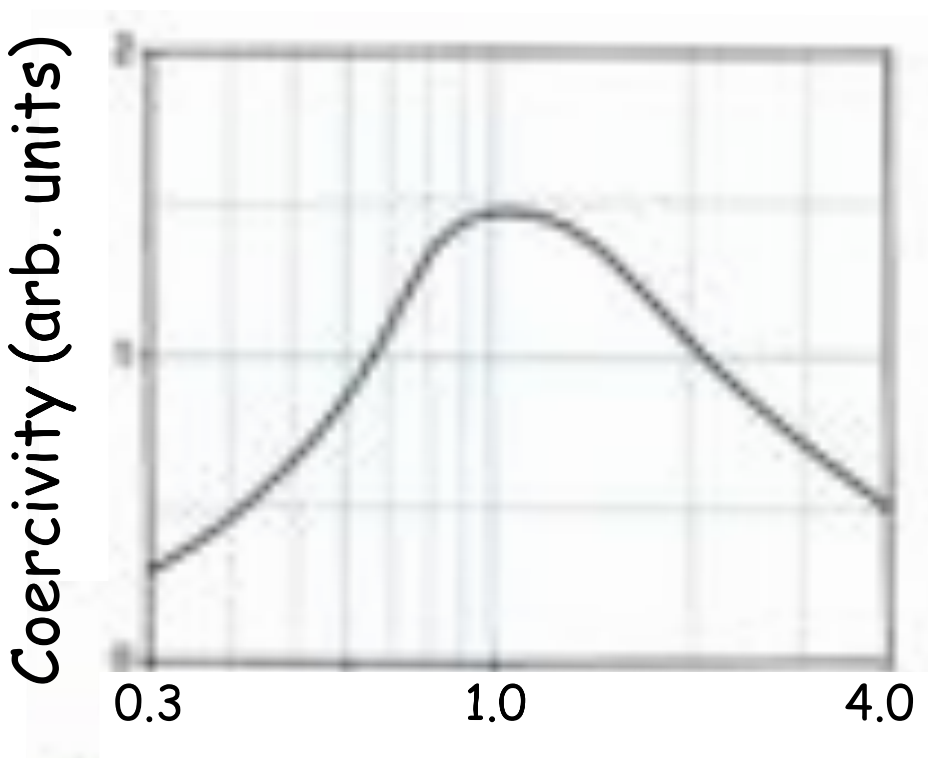
  Mechanism 1: If inclusion size ≈ wall width
  → wall is pinned, because it saves wall area
  → wall energy ↓
  → the greater specific wall energy ($\sim\sqrt{K}$), the more effective pinning force





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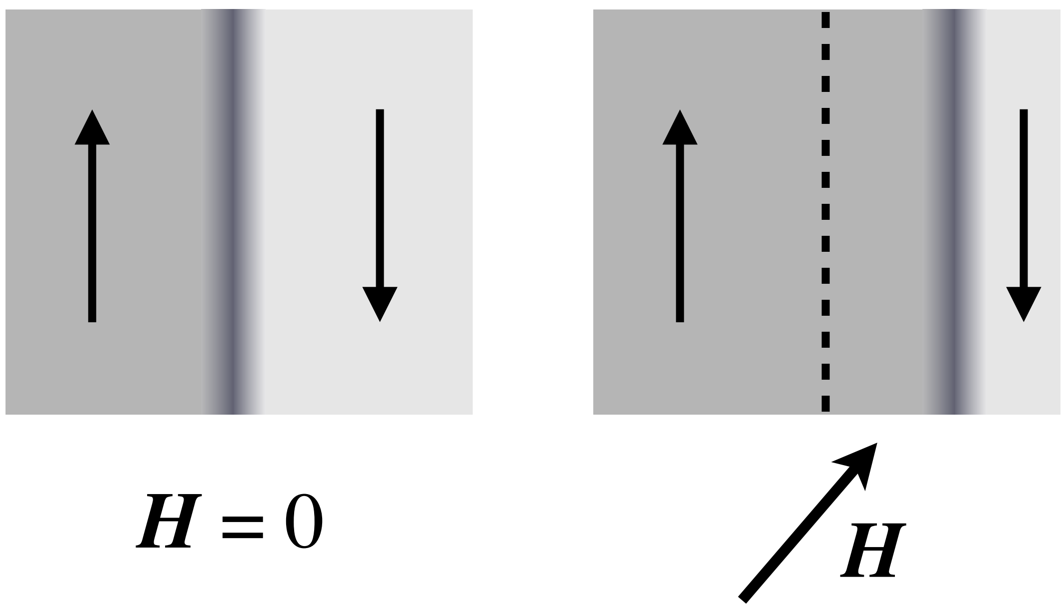

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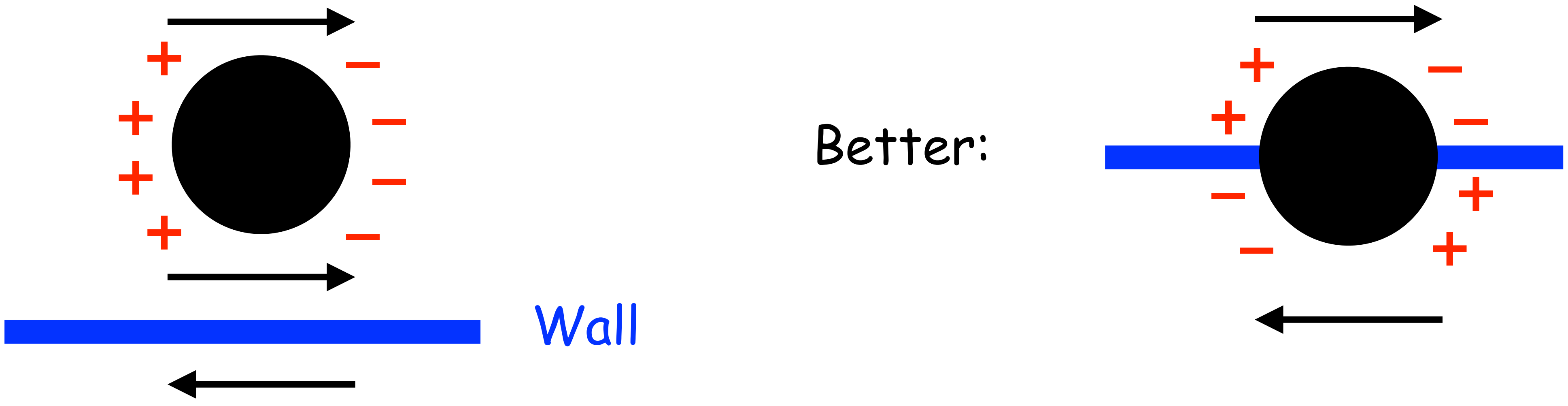
  Mechanism 2: Large inclusions: Reduction of pole density by wall → wall pinning



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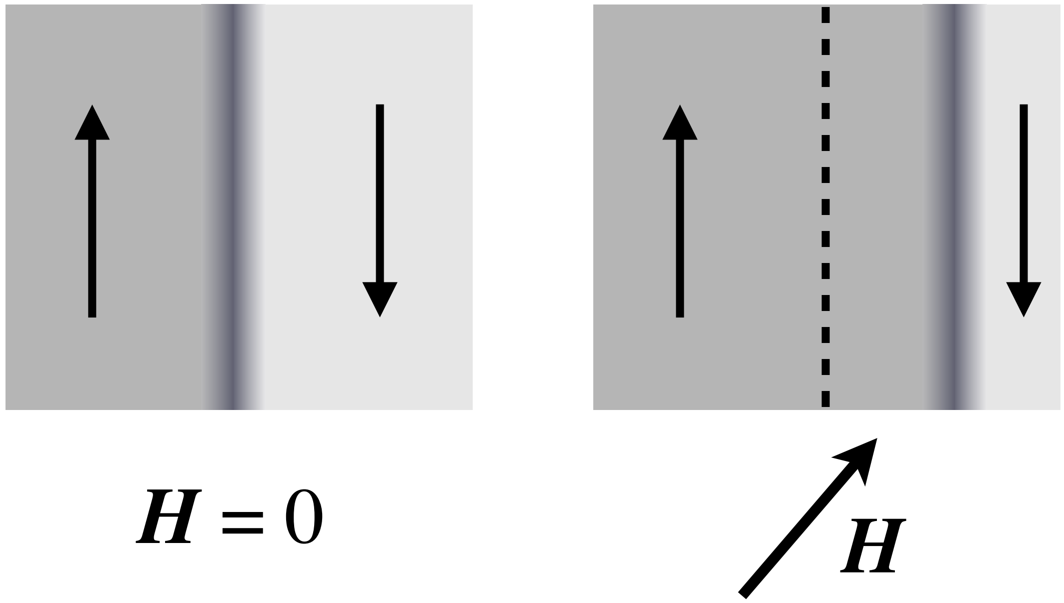

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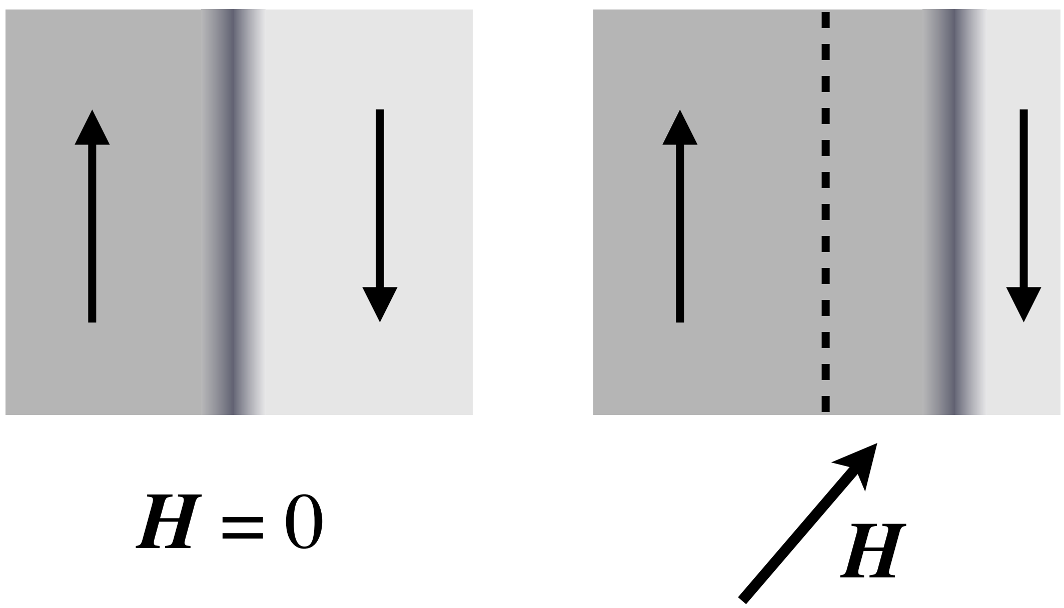

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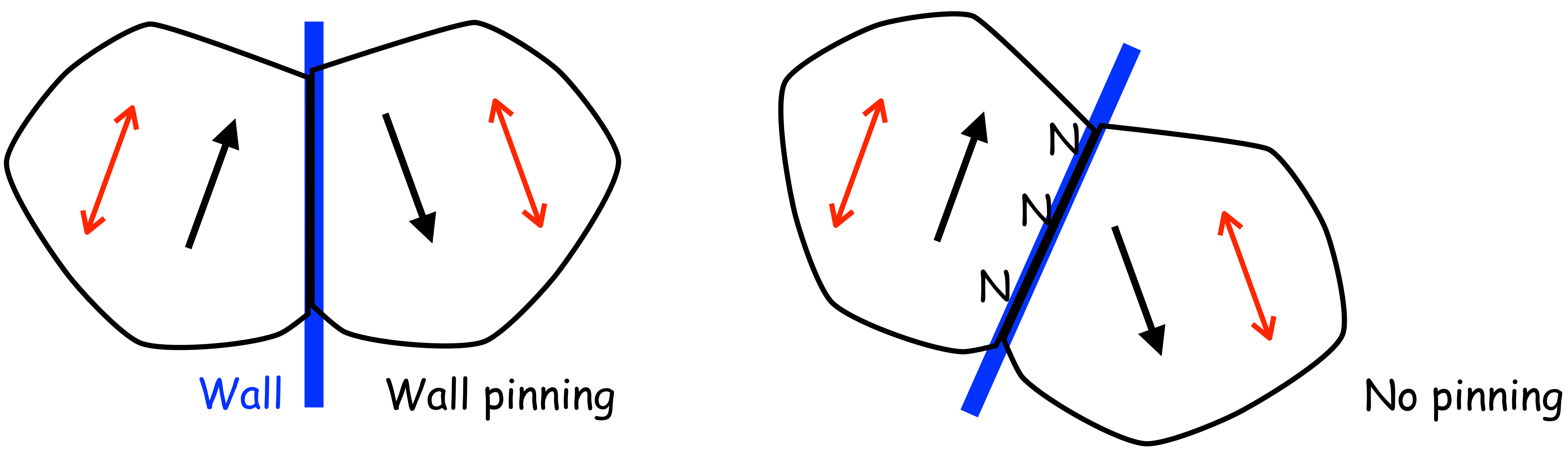
- Pinning of domain walls by:

2) Inhomogeneities in microstructure: Phase- and grain boundaries



Wall pinning at boundary as long as stray field does not consume more energy than is saved by pinning wall at boundary

Excursus: Magnetization processes

b) Wall motion

- Domain wall disp
  domains with m
  field direction

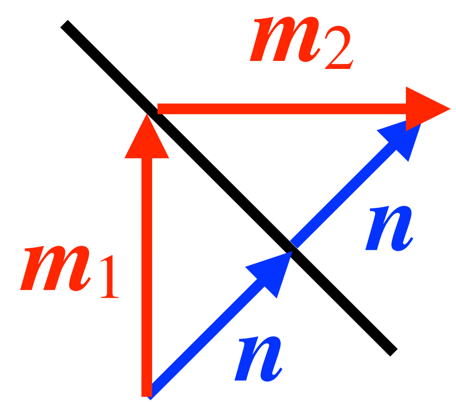
- Specific wall en

  Domain wall wid

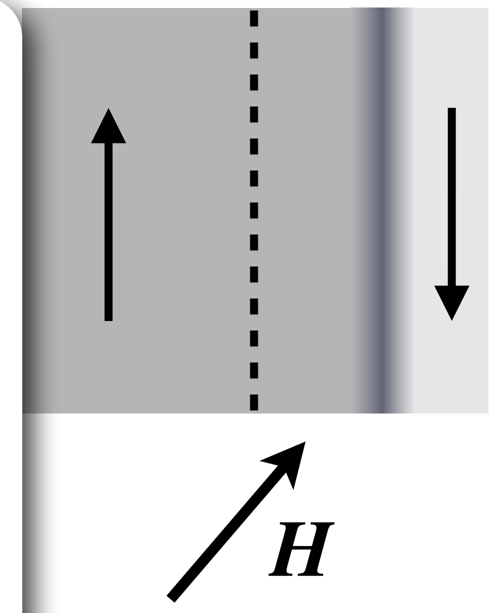
- Pinning of doma

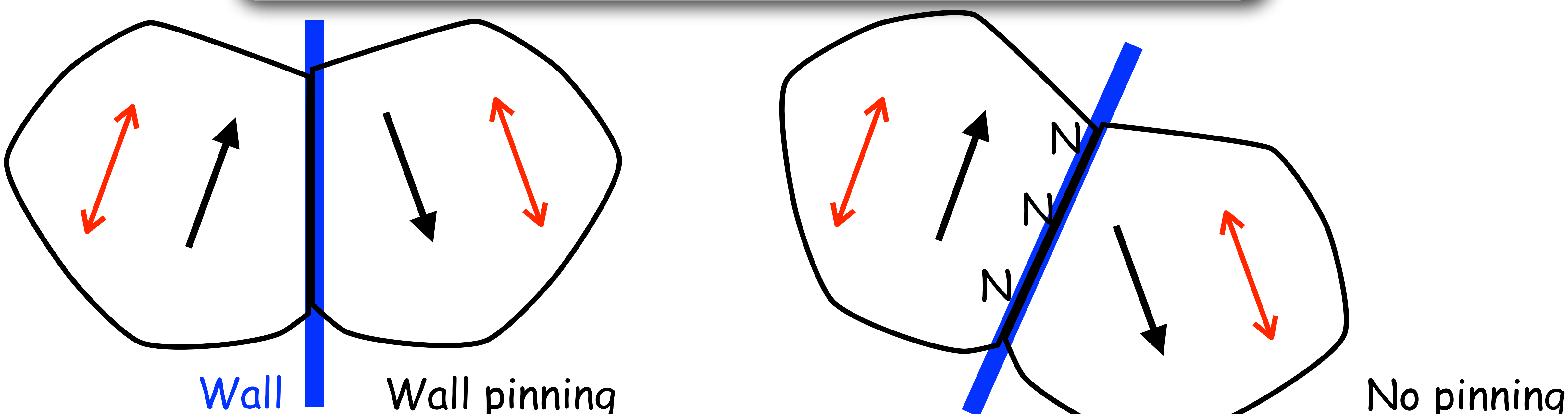
  2) Inhomogenei s

Charge-free wall orientation:



$$(m_1 - m_2) \cdot n = 0$$





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Excursus: Magnetization processes

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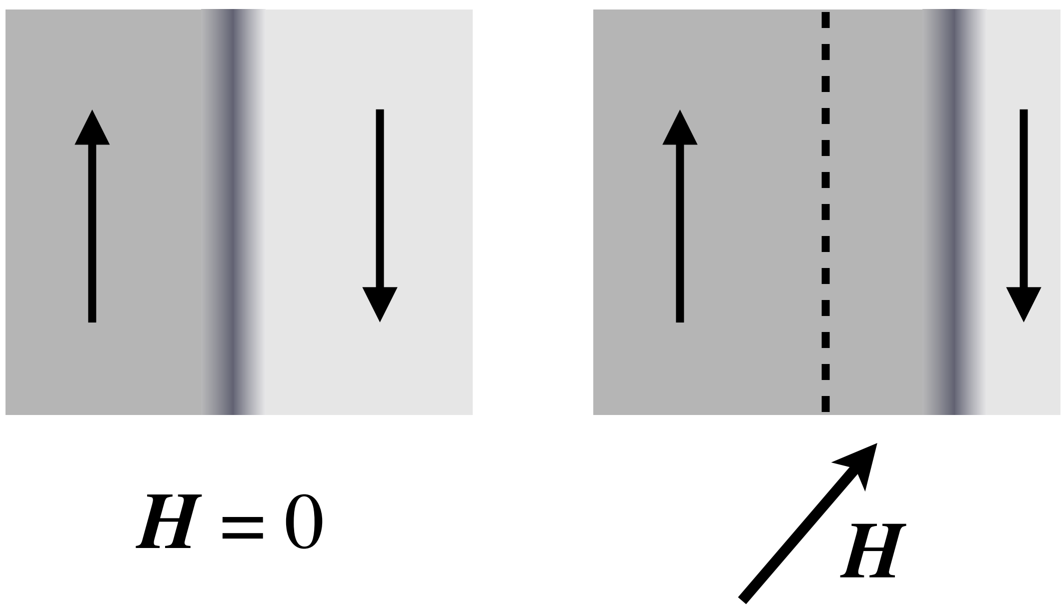

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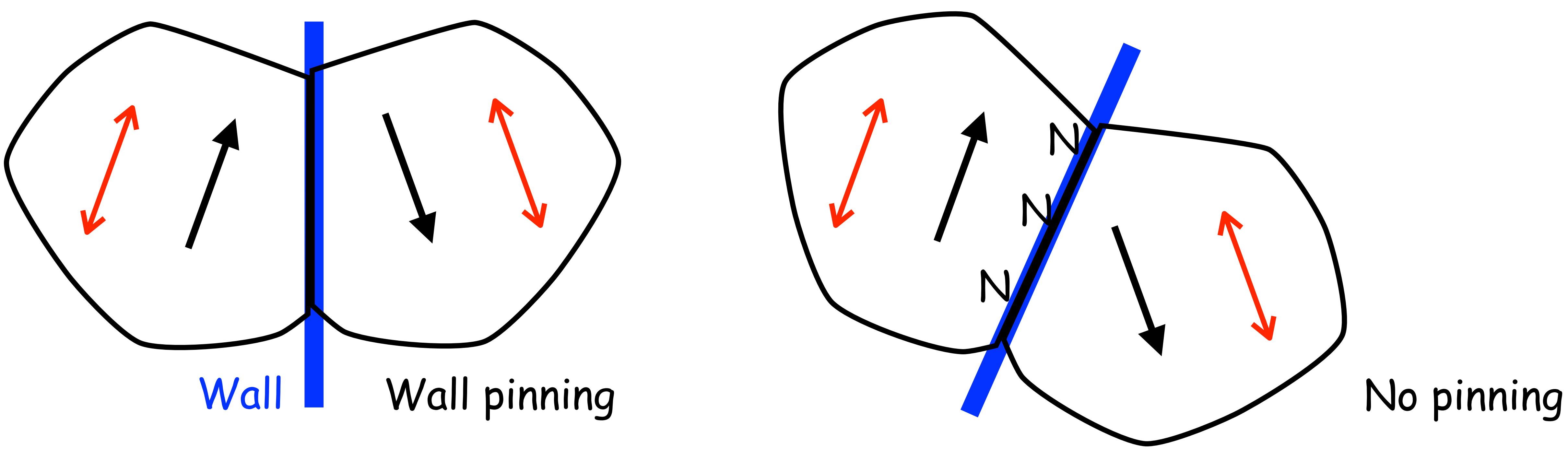

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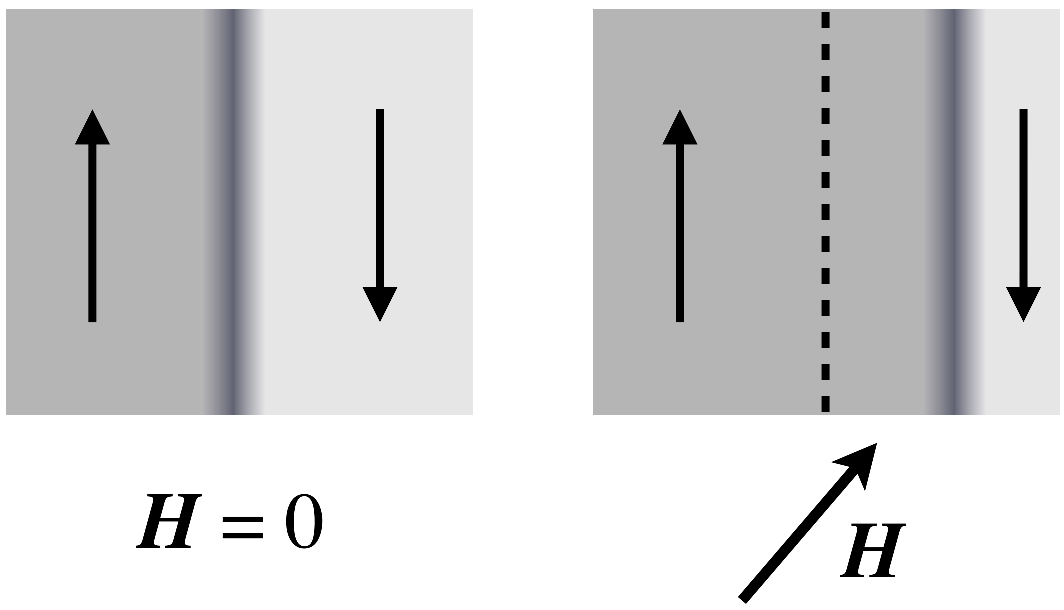

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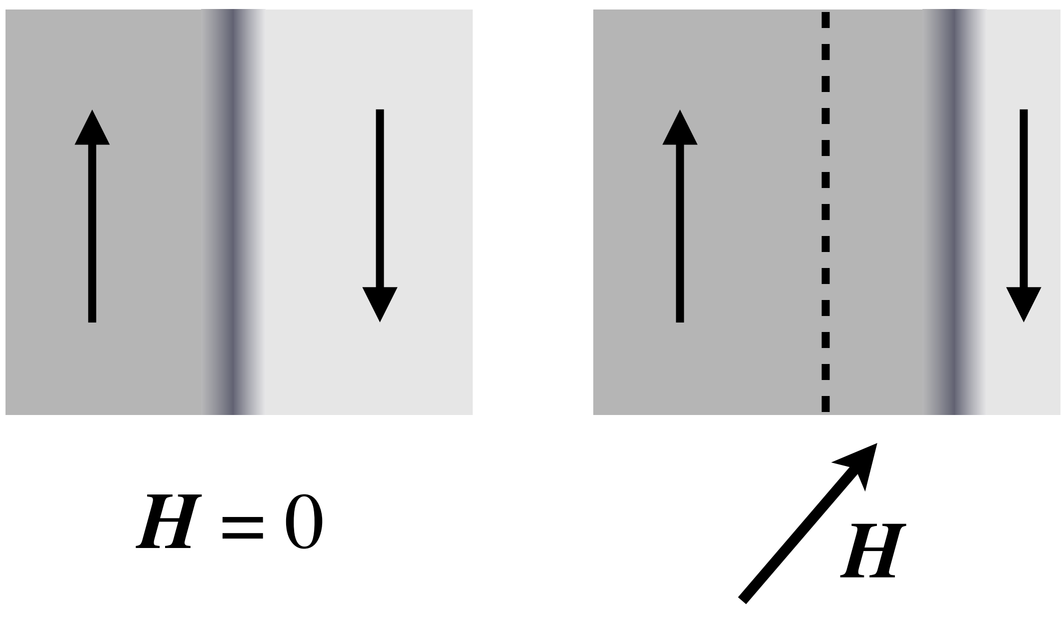

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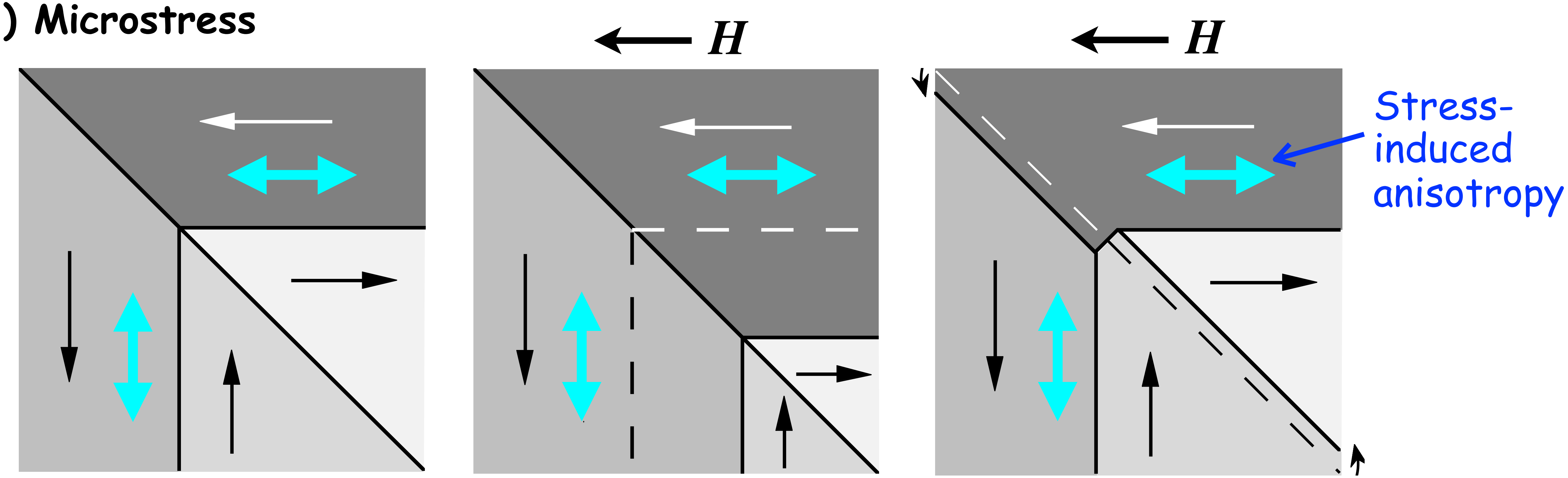
  Domain wall width: $W_{\mathrm{wall}} = \pi\sqrt{A/K}$

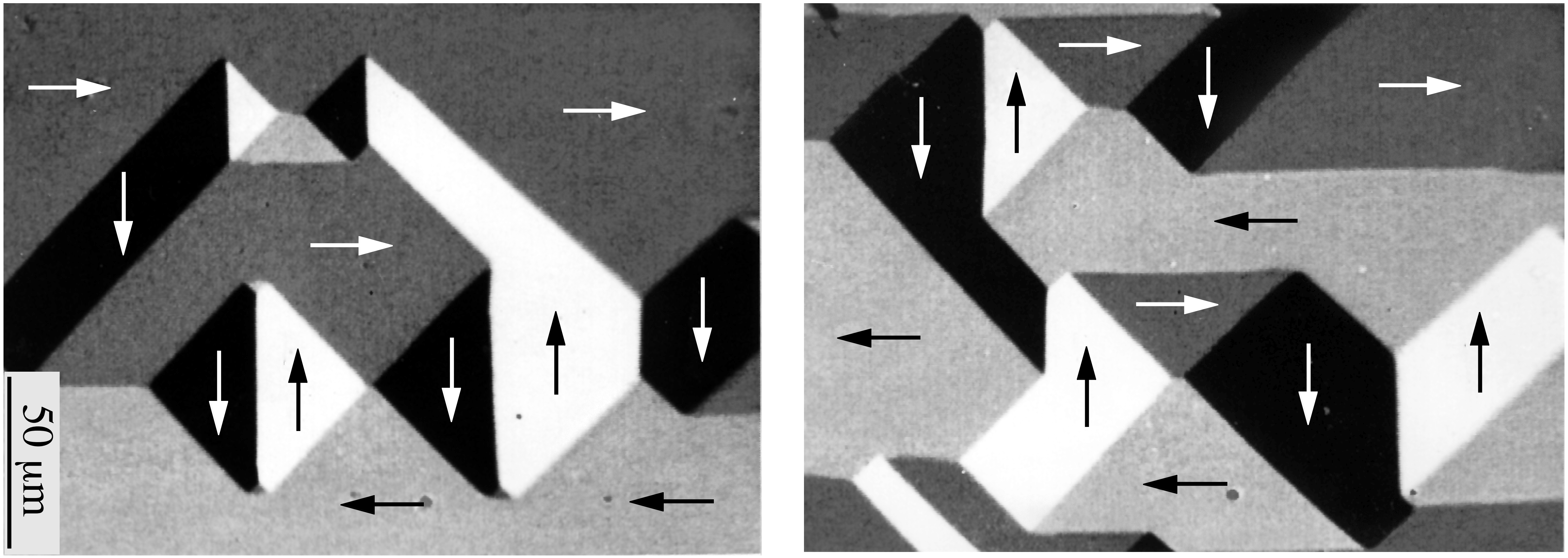
- Pinning of domain walls by:

3) Microstress



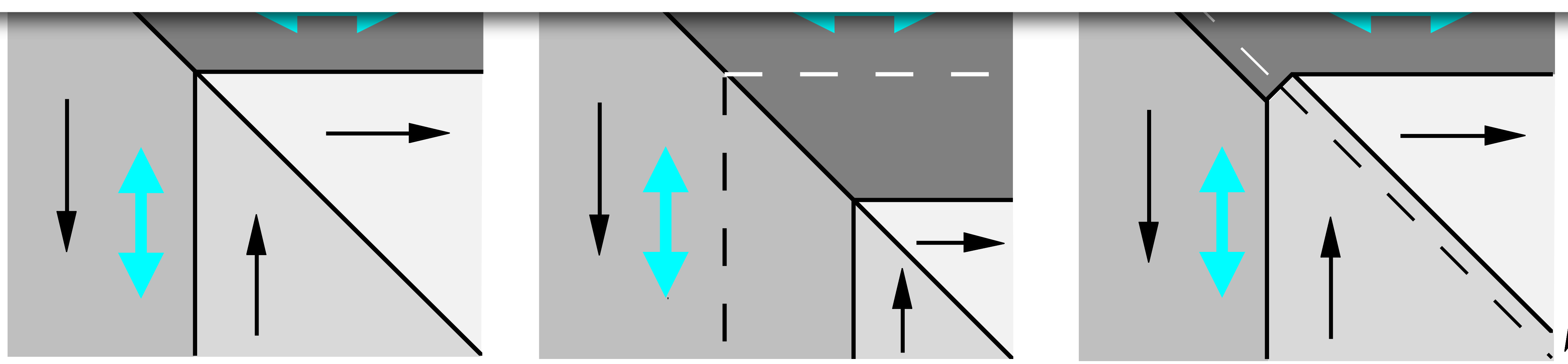
180° wall motion compatible with stress pattern, but 90° wall motion would generate conflict with stress pattern (note: more 90° walls in bulk materials)

Excursus: Magnetization processes



Fe-3 wt%-Si sheet (0.4 mm thick)
same location after different demagnetization

anisotropy



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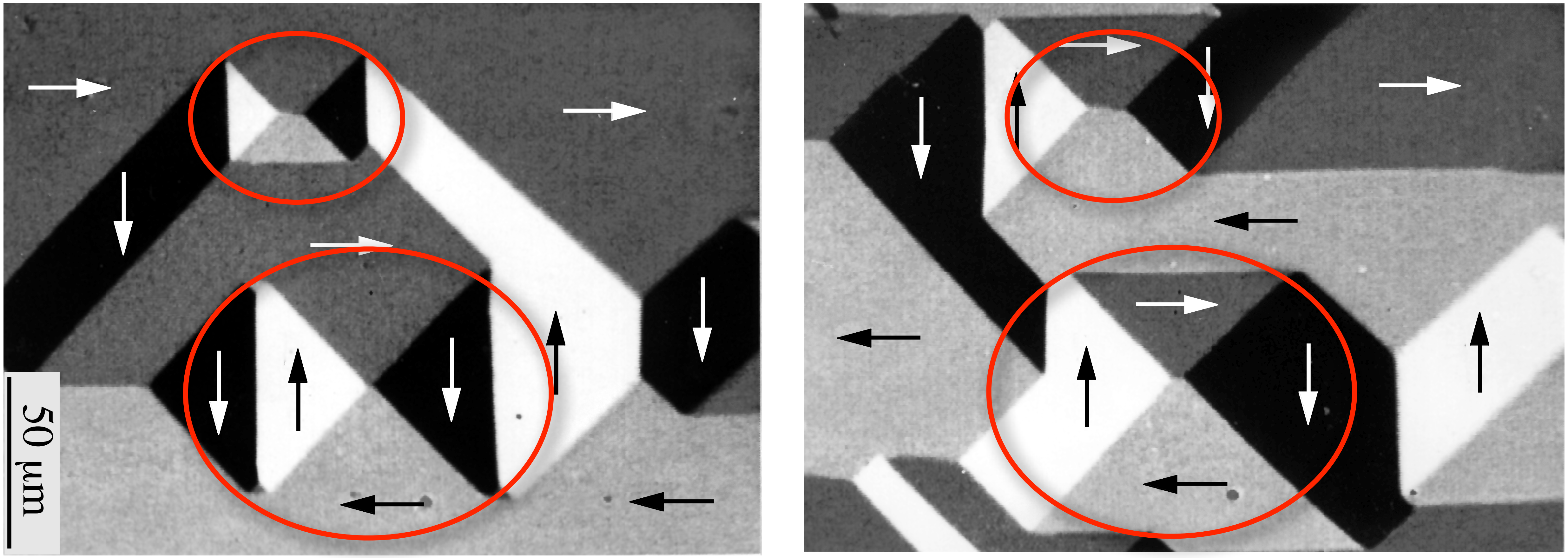

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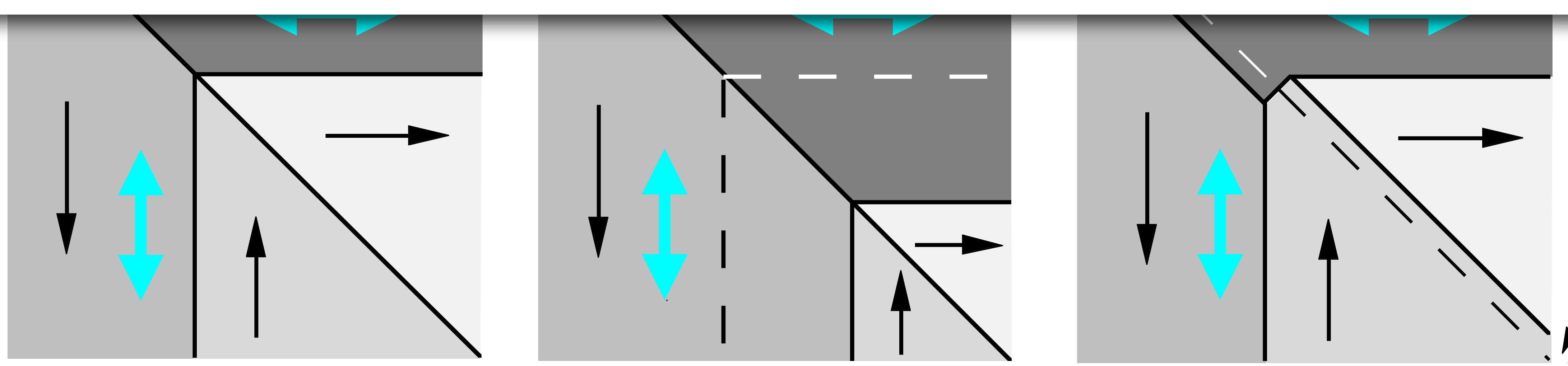


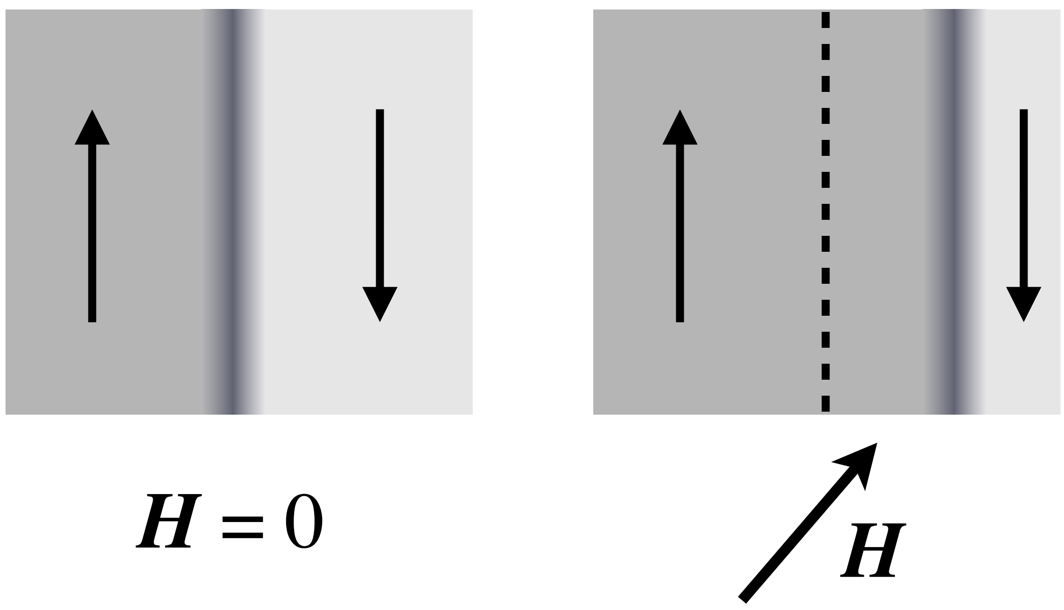
anisotropy

180° wall motion compatible with stress pattern, but 90° wall motion would generate conflict with stress pattern (note: more 90° walls in bulk materials)

Excursus: Magnetization processes

b) Wall motion

- Domain wall displacement increases volume of domains with magnetization component along field direction



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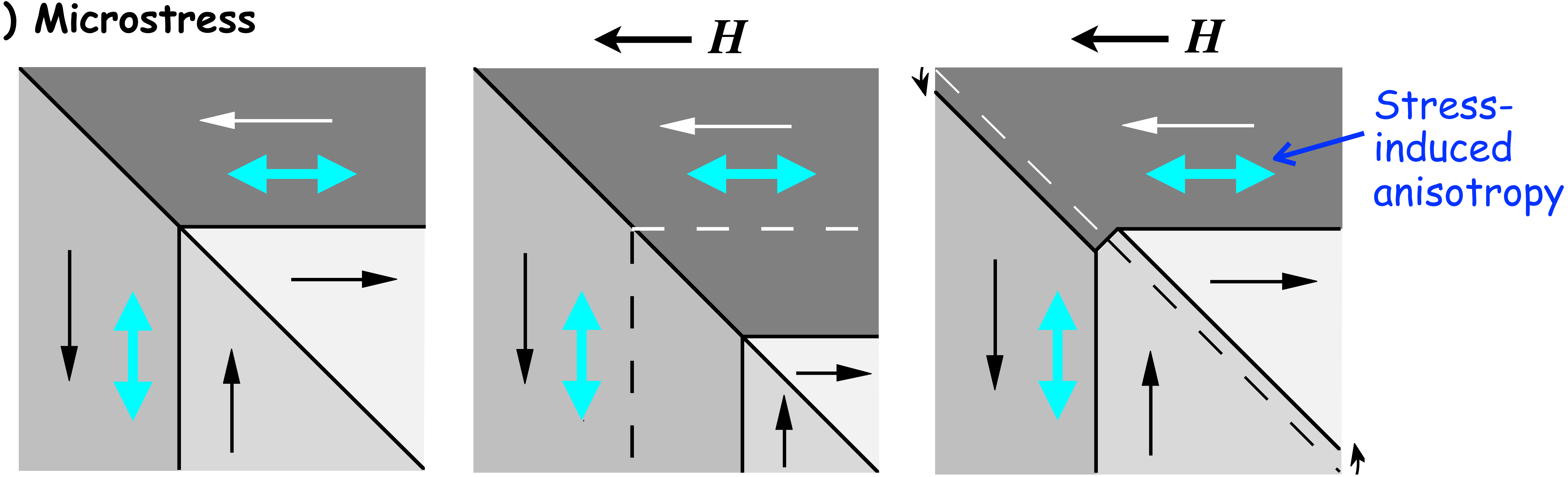
- Pinning of domain walls by:

3) Microstress



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Excursus: Magnetization processes

b) Wall motion

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Pinning of domain walls by:

Inhomogeneities in microstructure (non-magnetic inclusions, phase boundaries, grain boundaries), microstress, etc.

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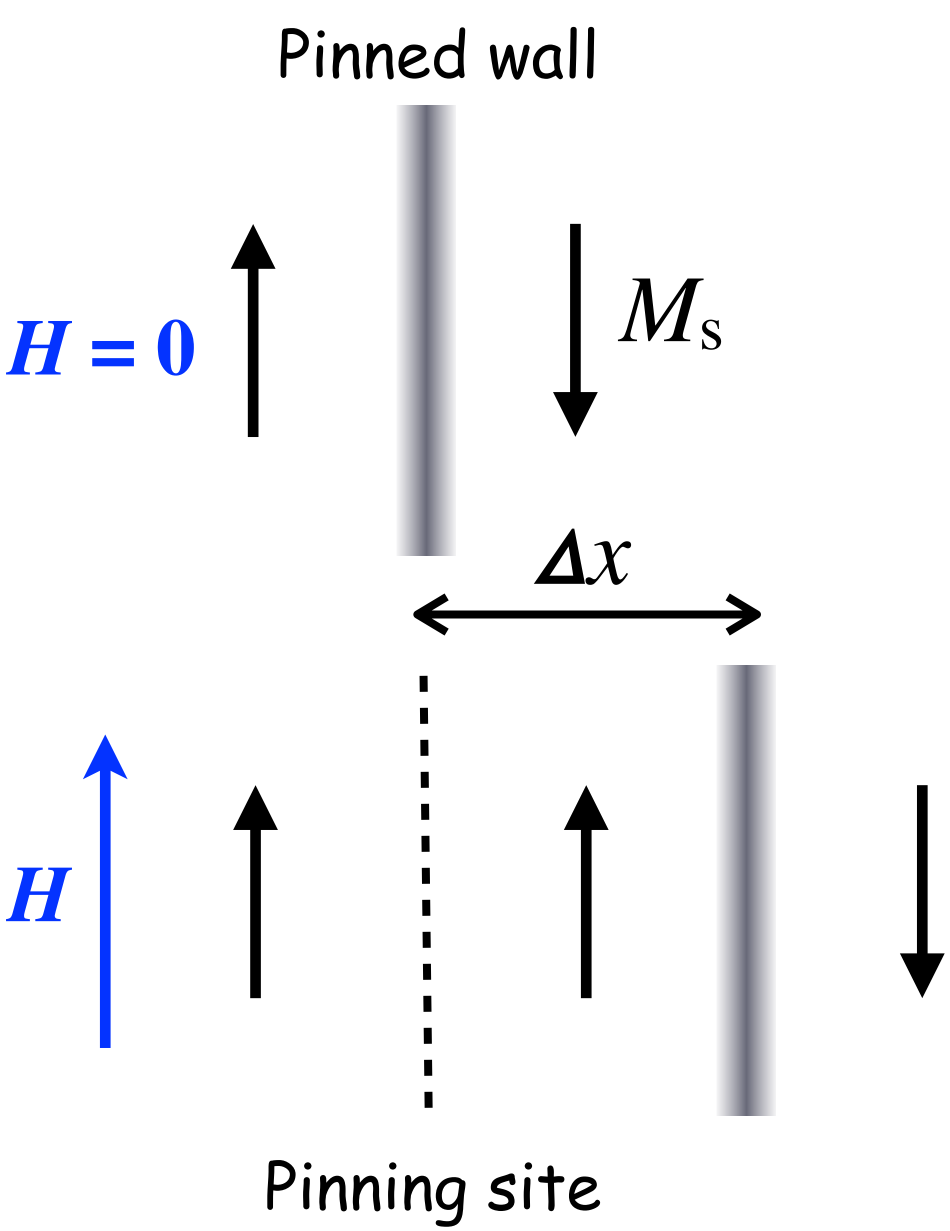
Pinning causes Barkhausen jumps and coercivity

Excursus: Magnetization processes

b) Wall motion

Pinning causes Barkhausen jumps and coercivity



Pinning force:

Ballance between **gain** in Zeeman energy (when moving wall by distance Δx) and **increase** in wall energy $\Delta\gamma_{180}$:

$$2\,\mu_0 M_s H \Delta x = \Delta\gamma_{180}(x)$$

$$2\,\mu_0 M_s H = \frac{\Delta\gamma_{180}(x)}{\Delta x} = \frac{d\gamma_{180}(x)}{dx}$$

Force of applied field on wall

Gradient of spec. wall energy corresponds to force exerted by pinning sites on wall

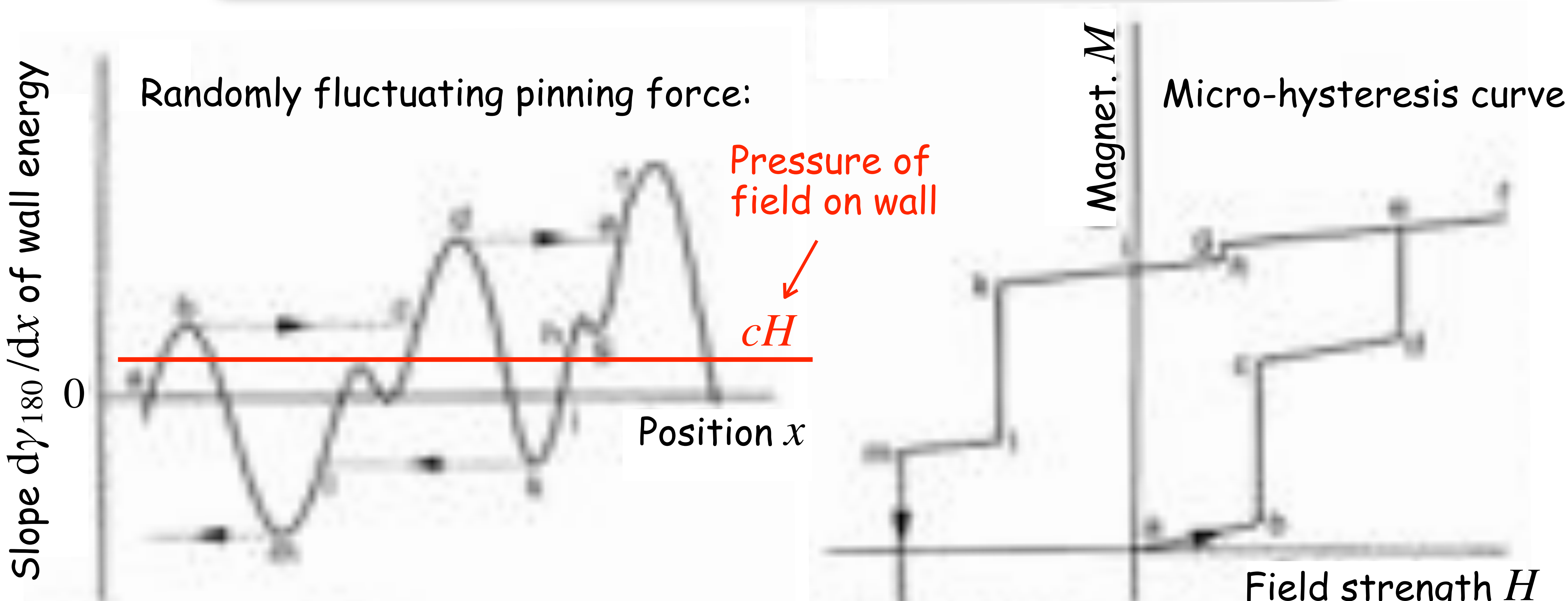
Overcoming pinning requires critical field:

$$H_{crit} = \frac{d\gamma_{180}/dx}{2\,\mu_0 M_s} \quad ; \quad H > H_{crit} : \text{jump}$$

Excursus: Magnetization processes

b) Wall motion

Pinning causes Barkhausen jumps and coercivity



$H = 0$: wall is at position (a) in energy minimum (no gradient, i.e. no force)

$H > 0$: reversible wall motion to right: finite slope $d\gamma_{180}/dx$ ballances force of applied field. At point (b): maximum energy gradient = maximum restoring force

$H >> 0$: irreversible jump to position (c) : equal gradient as (b), i.e. equal restoring force.

At (c): wall is again pinned by stronger pinning force $d\gamma_{180}/dx$

b) Wall motion

Pinning of domain walls by:

- Inhomogeneities in microstructure (non-magnetic inclusions, phase boundaries, grain boundaries), because wall saves energy when sitting at pinning sites.

  As specific wall energy γ_{180} scales wth $\sqrt{A \cdot K}$:

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  → Low coercivity requires small anisotropy to prevent wall pinning

- Microstress

  → Low coercivity requires small magnetostriction to prevent wall pinning

Soft magnets: General Considerations

a) Purpose of soft magnetic material

Enhancement of flux density B, produced by current-carrying coil

b) Characteristics of soft magnetic material

Large magnetization changes in small applied magnetic fields

$\longrightarrow$ High permeability μ
$\longrightarrow$ Large saturation magnetization M_s
$\longrightarrow$ Low coercivity H_c

c) (Basic-) Requirements to material:

Low anisotropy & low magnetostriction

Why?

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⟶ Large saturation magnetization M_s
⟶ Low coercivity H_c

c) (Basic-) Requirements to material:

Low anisotropy & low magnetostriction

Why?

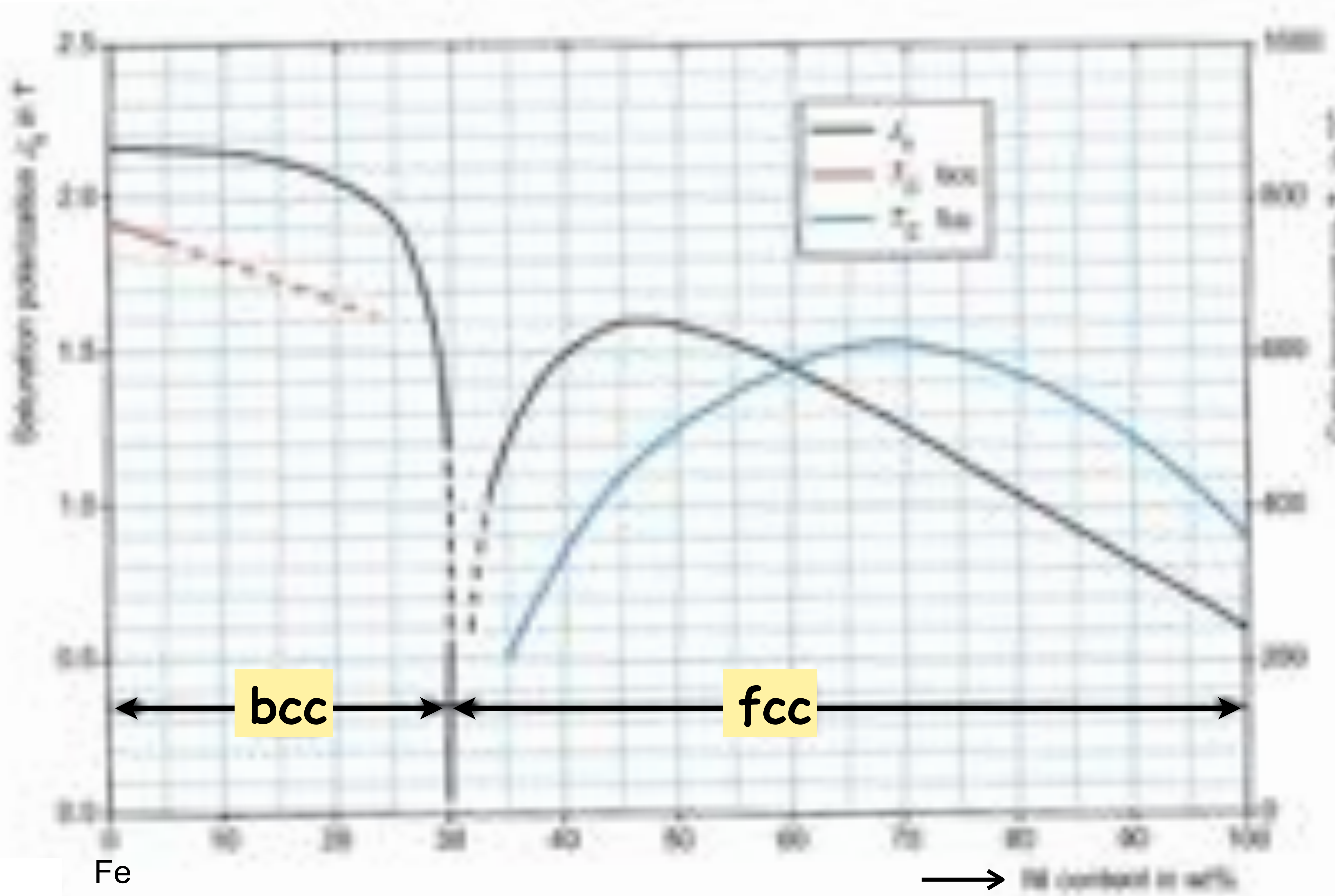
↳ To prevent wall pinning (low coercivity) and allow for high permeability

Soft magnets,

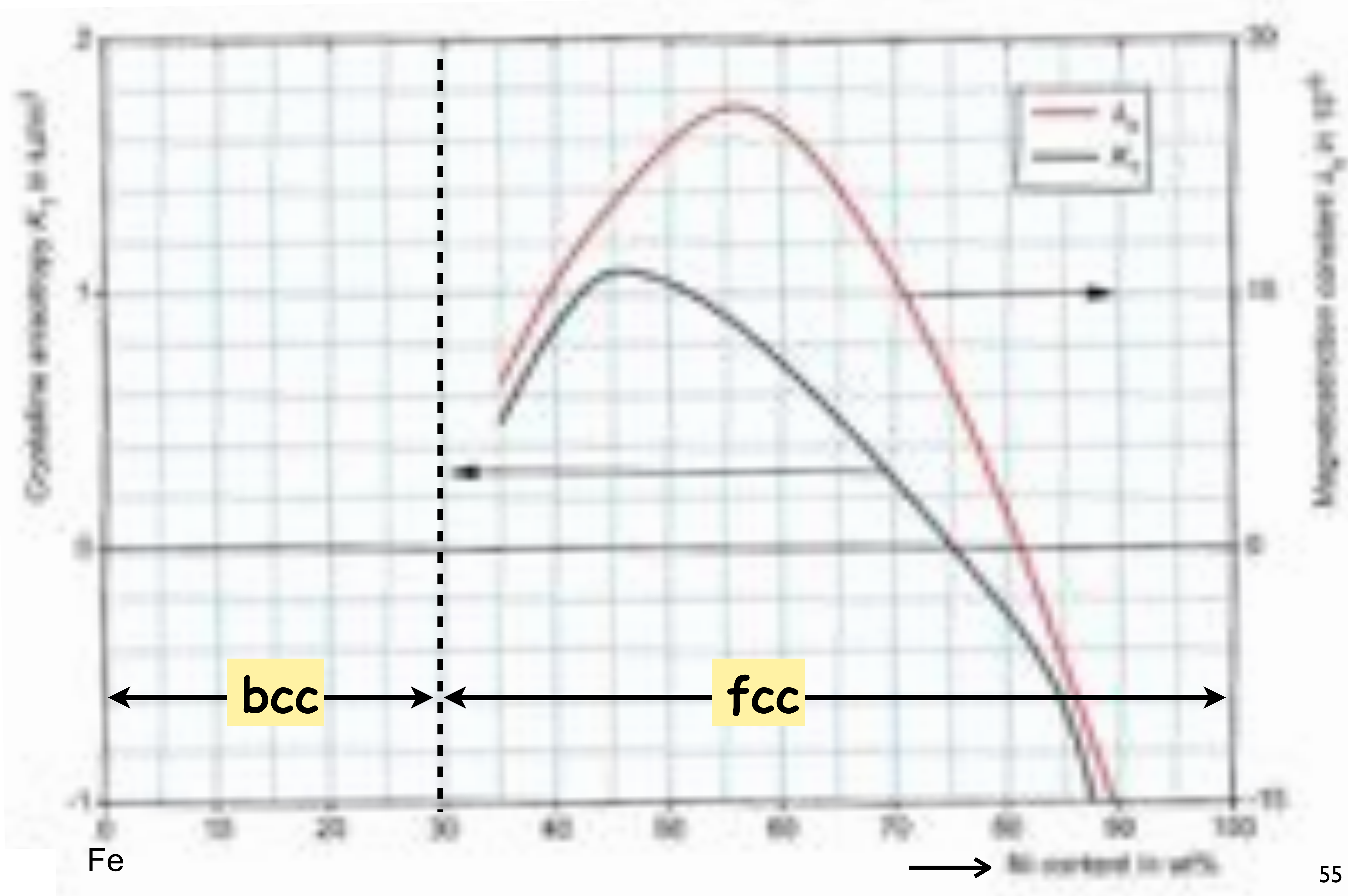
Example 1:

NiFe alloys

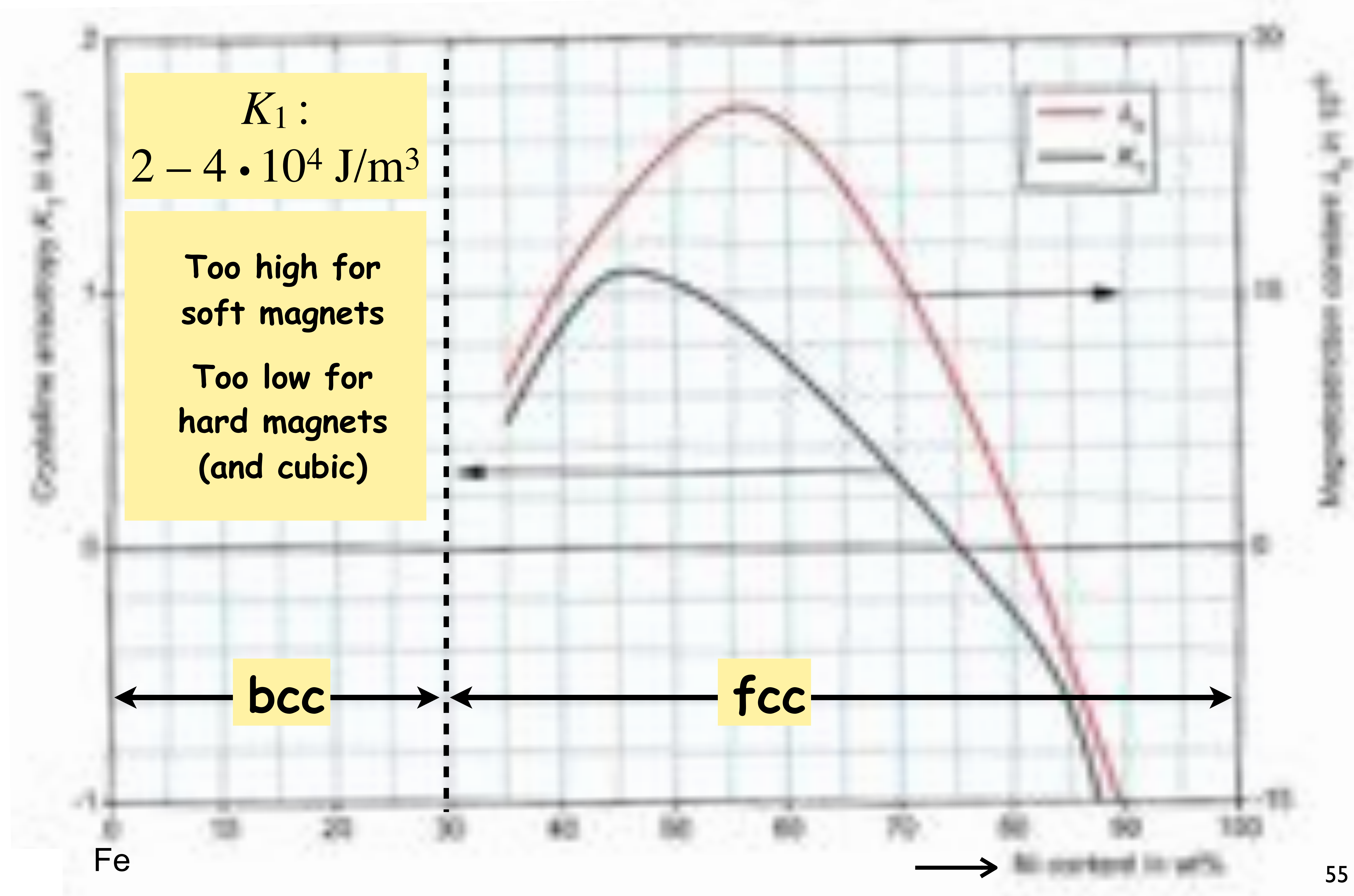
NiFe alloys



NiFe alloys

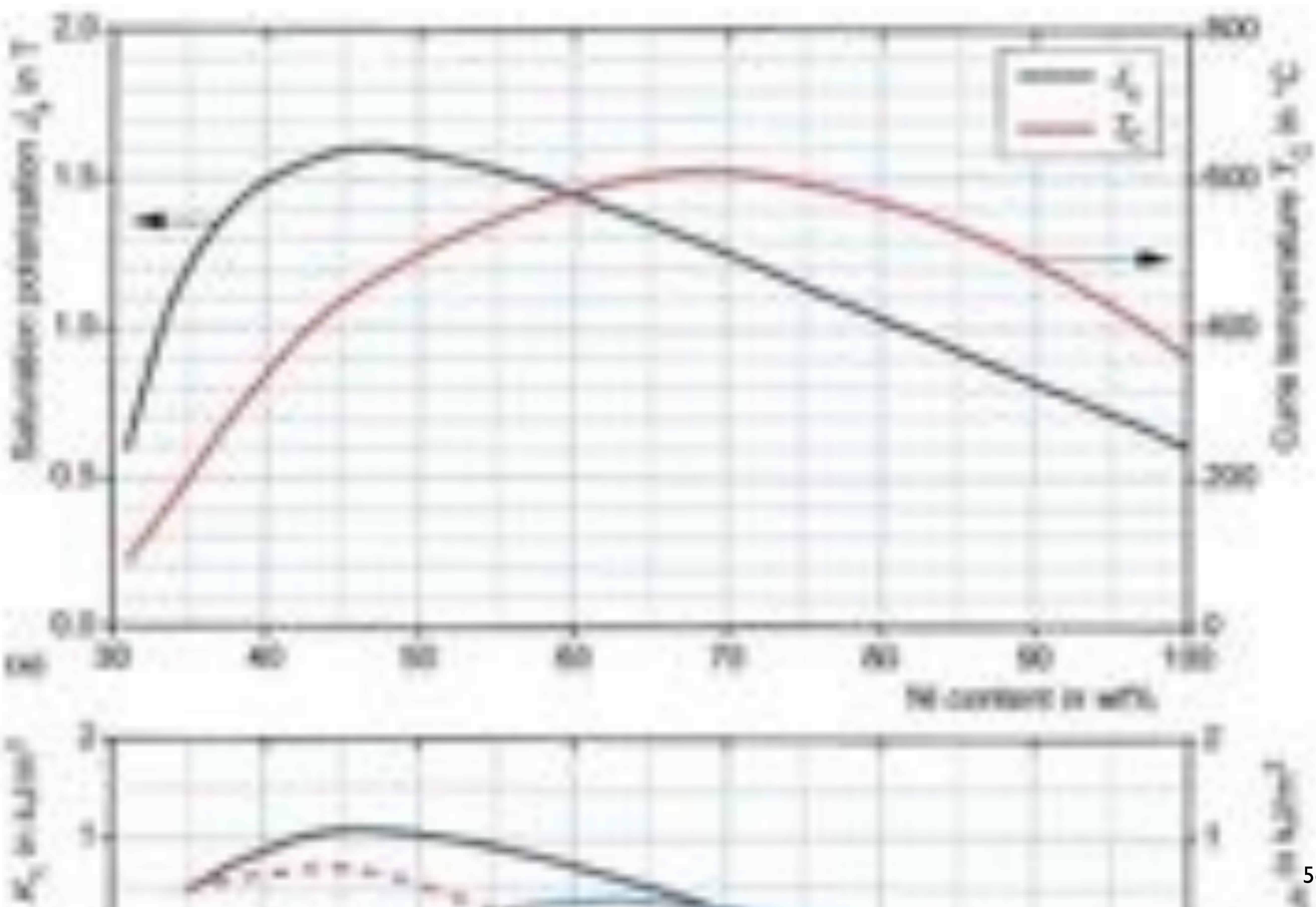


NiFe alloys

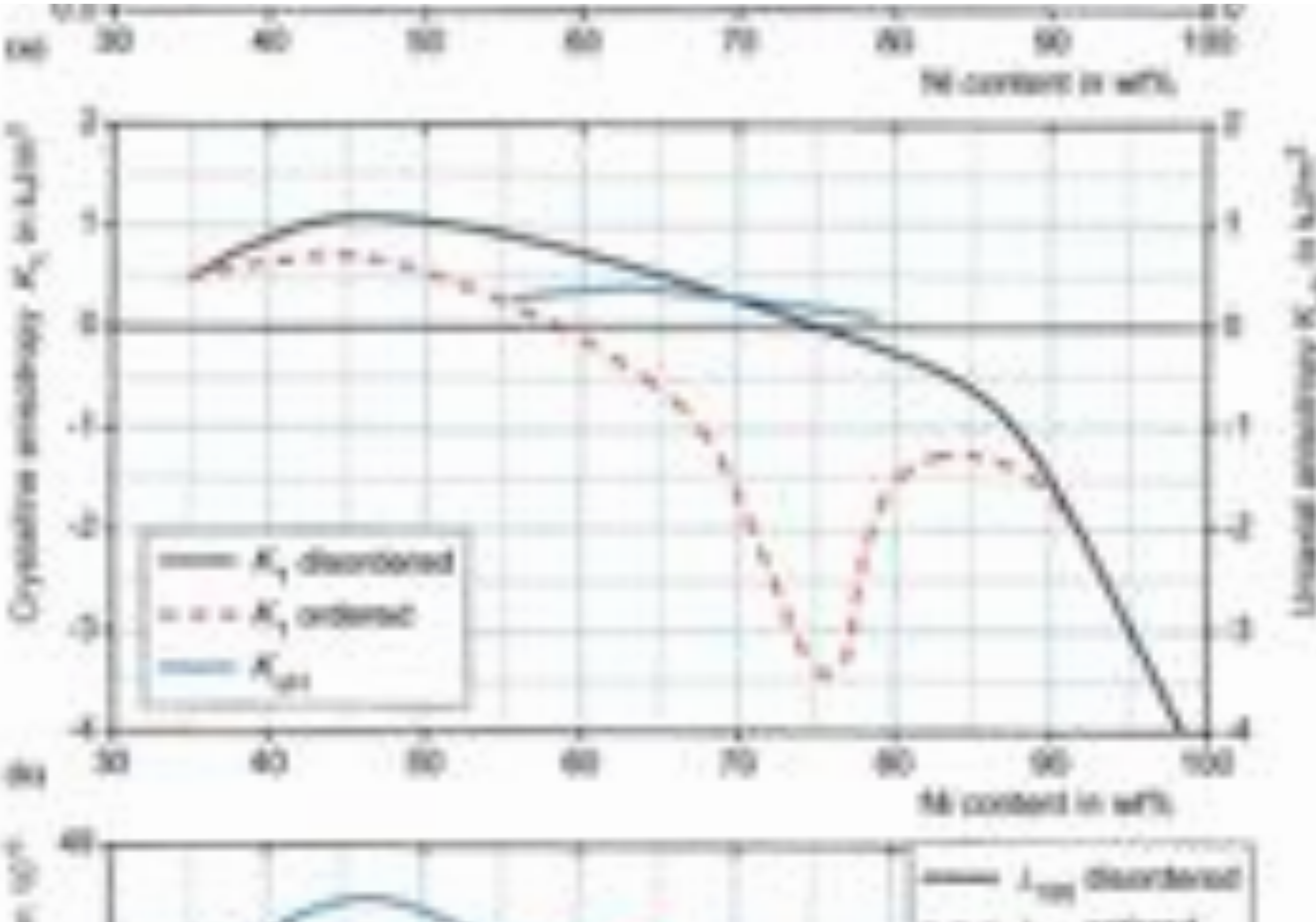


K_1 :
$2 - 4 \cdot 10^4$ J/m^3
Too high for soft magnets
Too low for hard magnets (and cubic)
bcc
fcc
Fe
0
10
20
30
40
50
60
70
80
90
100

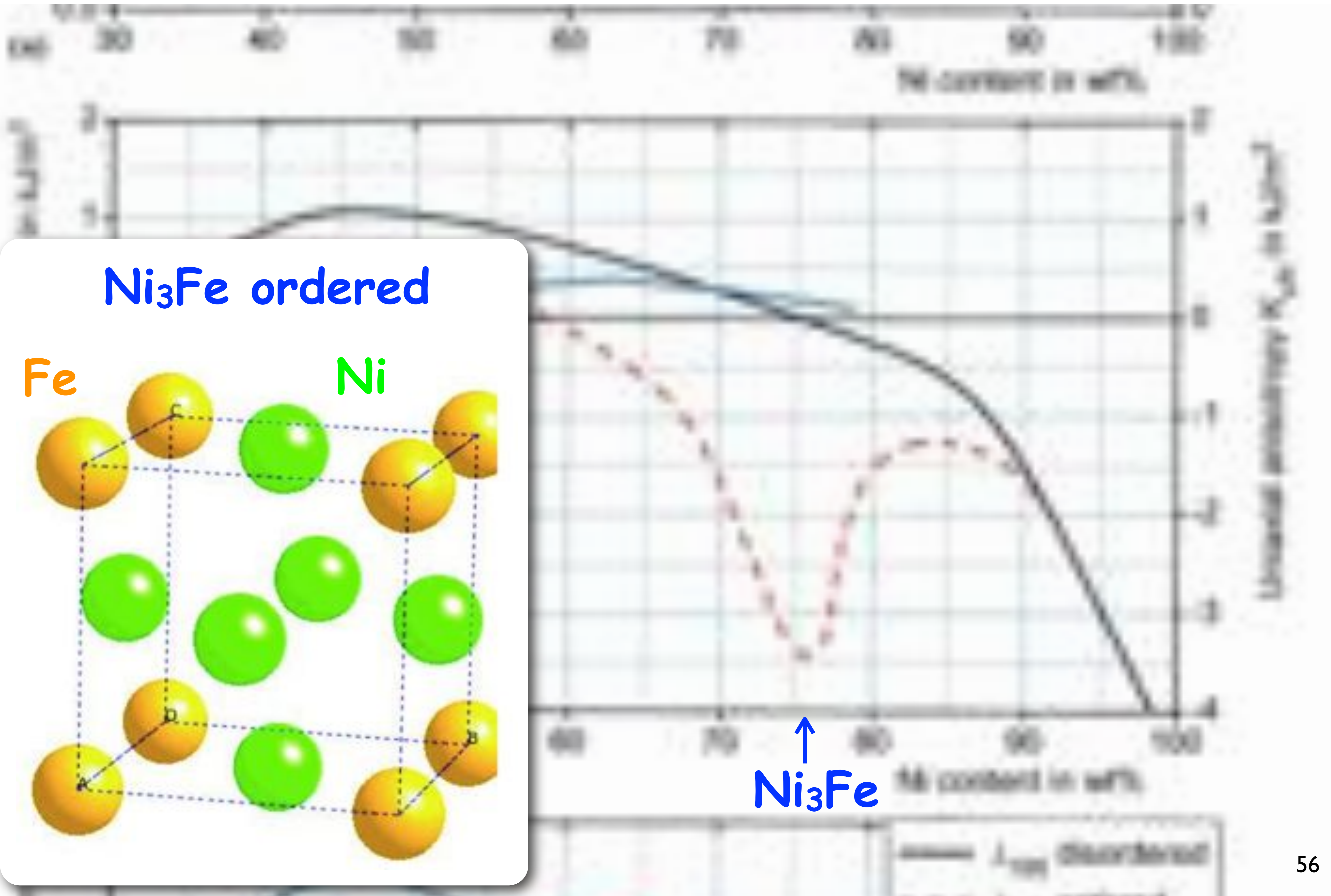
NiFe alloys



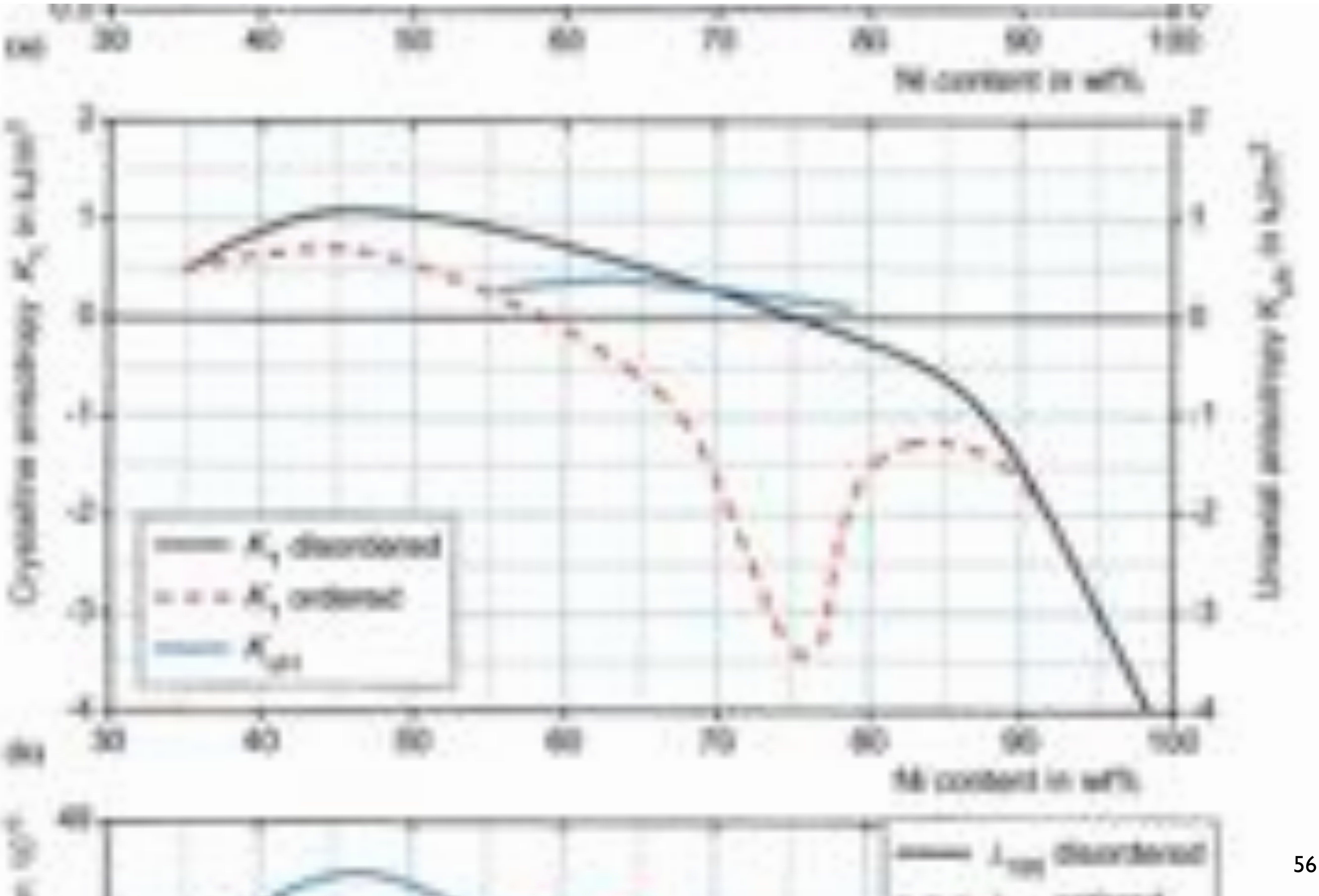
NiFe alloys


30
40
50
60
70
80
90
100
Ni content in wt%
K1 disordered
K1 ordered

NiFe alloys

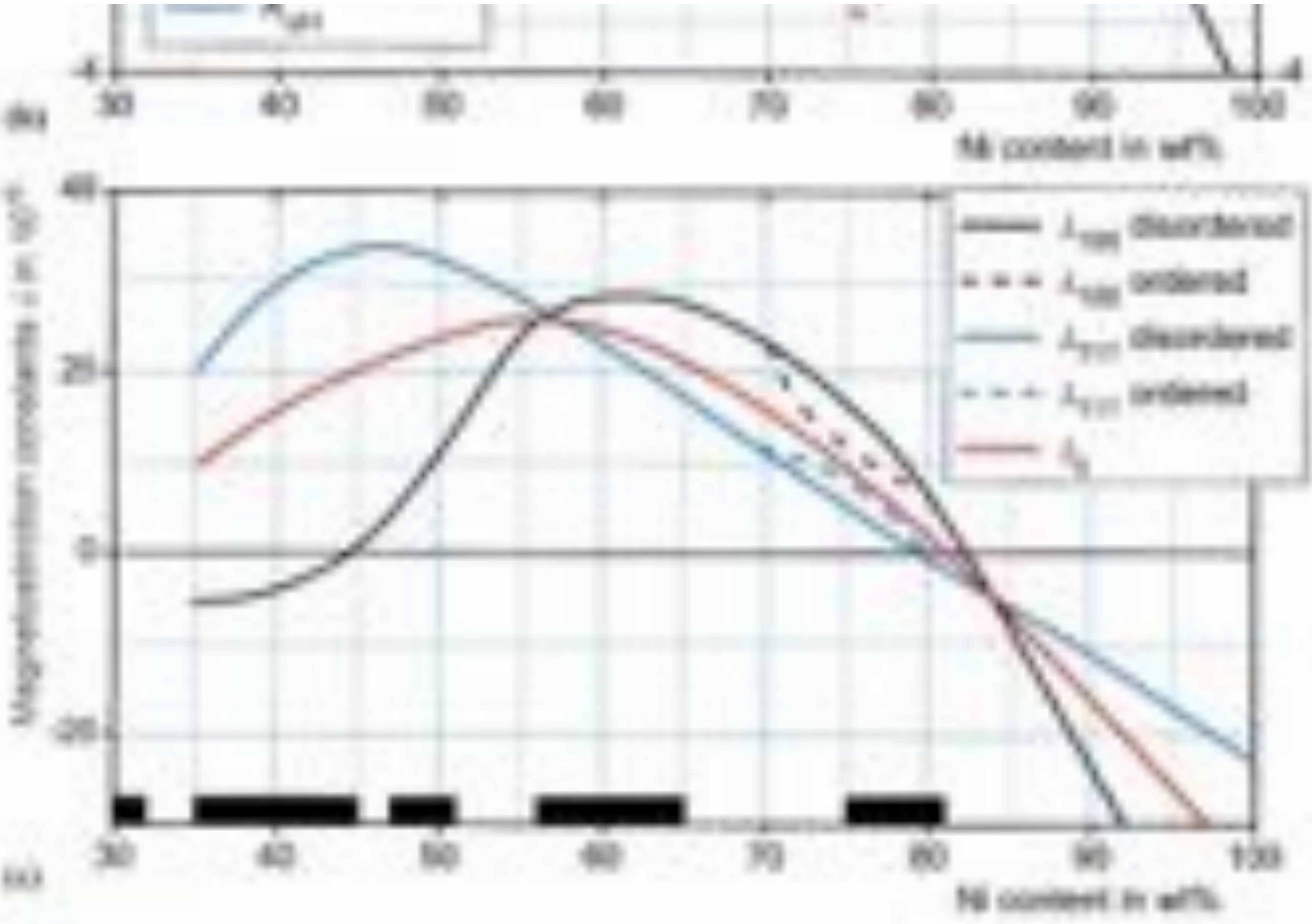


NiFe alloys

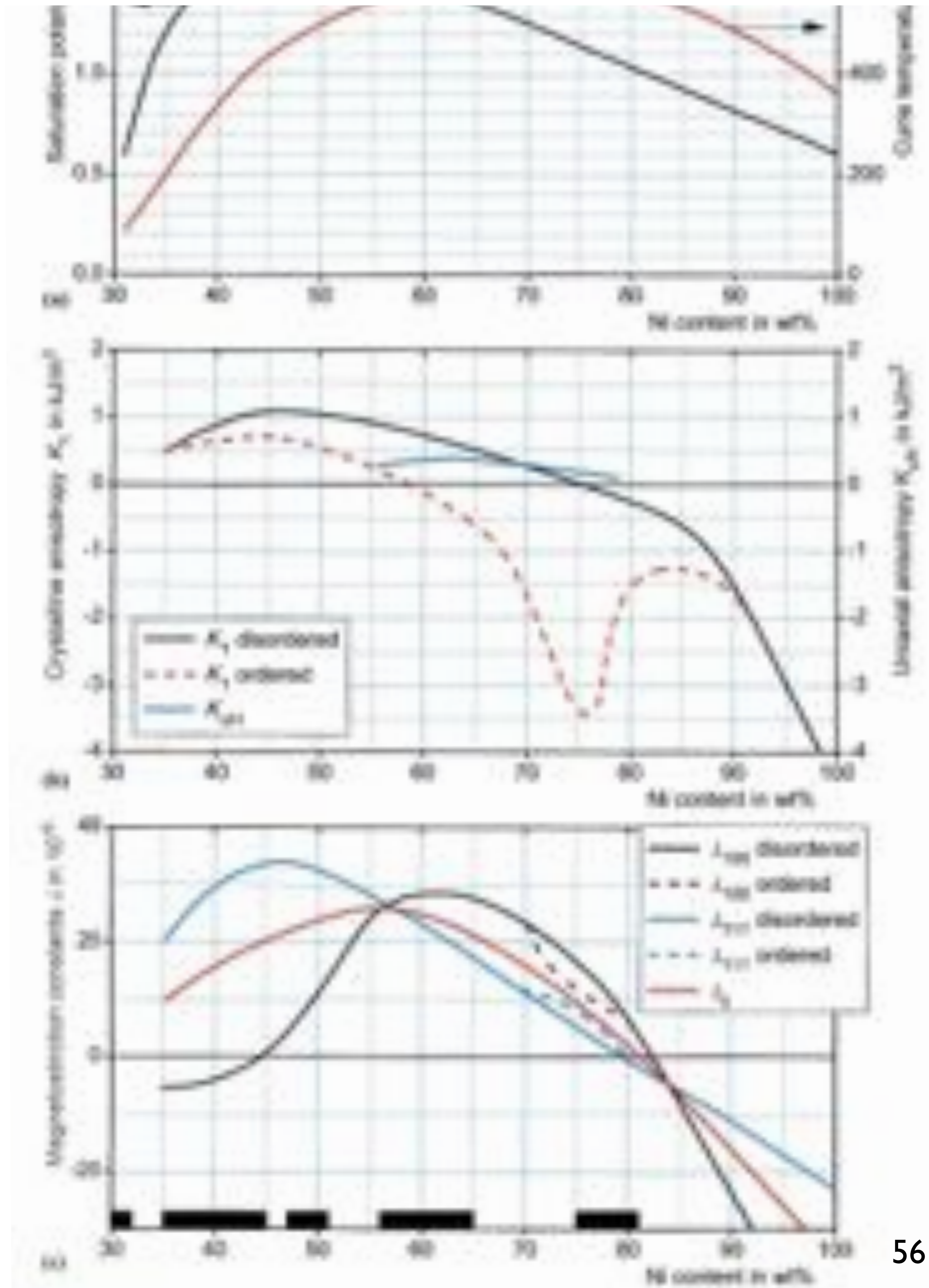


30 40 50 60 70 80 90 100
Ni content in wt%
K1 disordered
K1 ordered

NiFe alloys

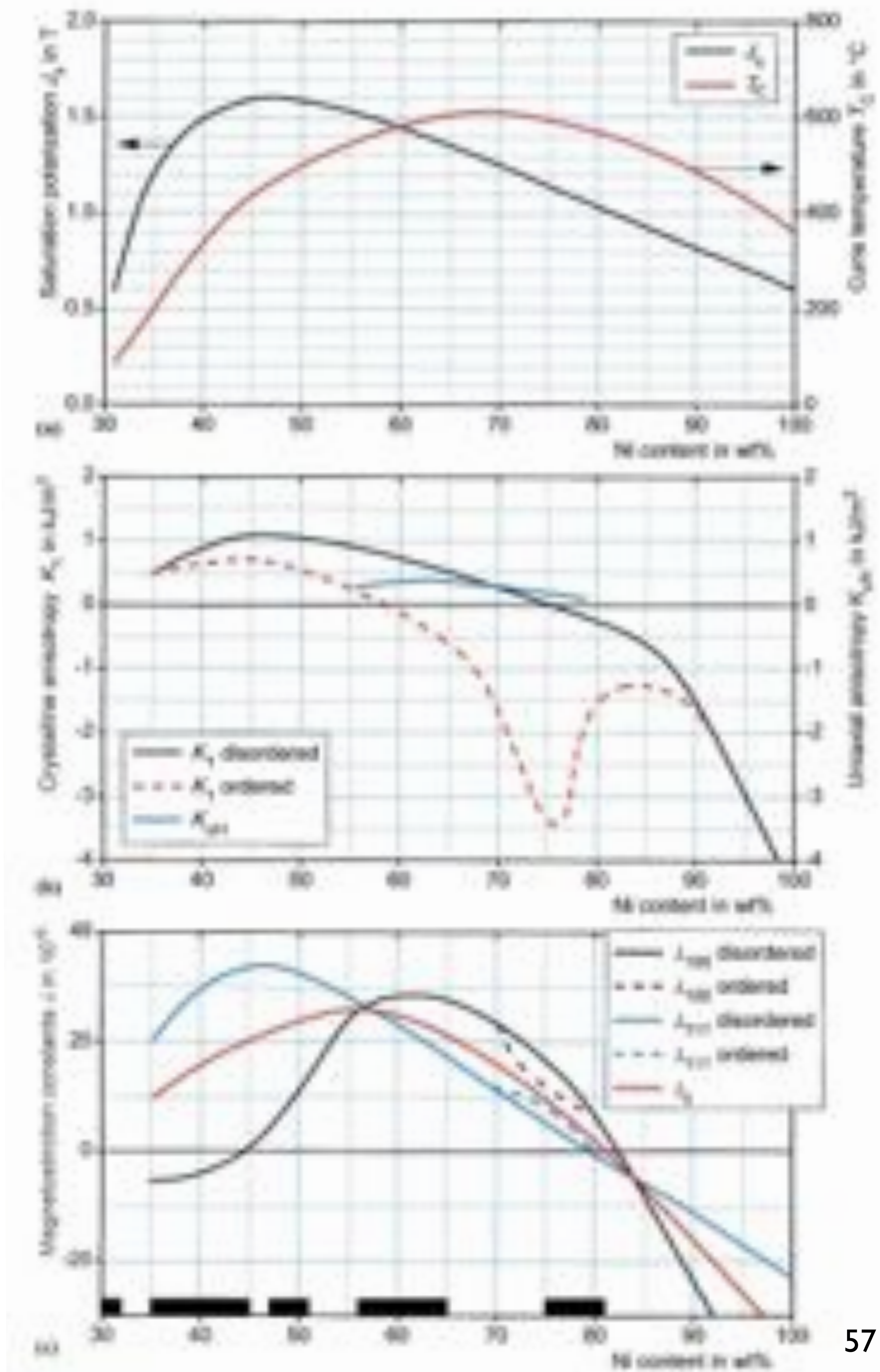

30
40
50
60
70
80
90
100
Ni content in at%
40
20
0
-20
disordered
ordered
disordered
ordered
30
40
50
60
70
80
90
100
Ni content in at%

NiFe alloys



NiFe alloys

a) Ni content around 80 wt%:



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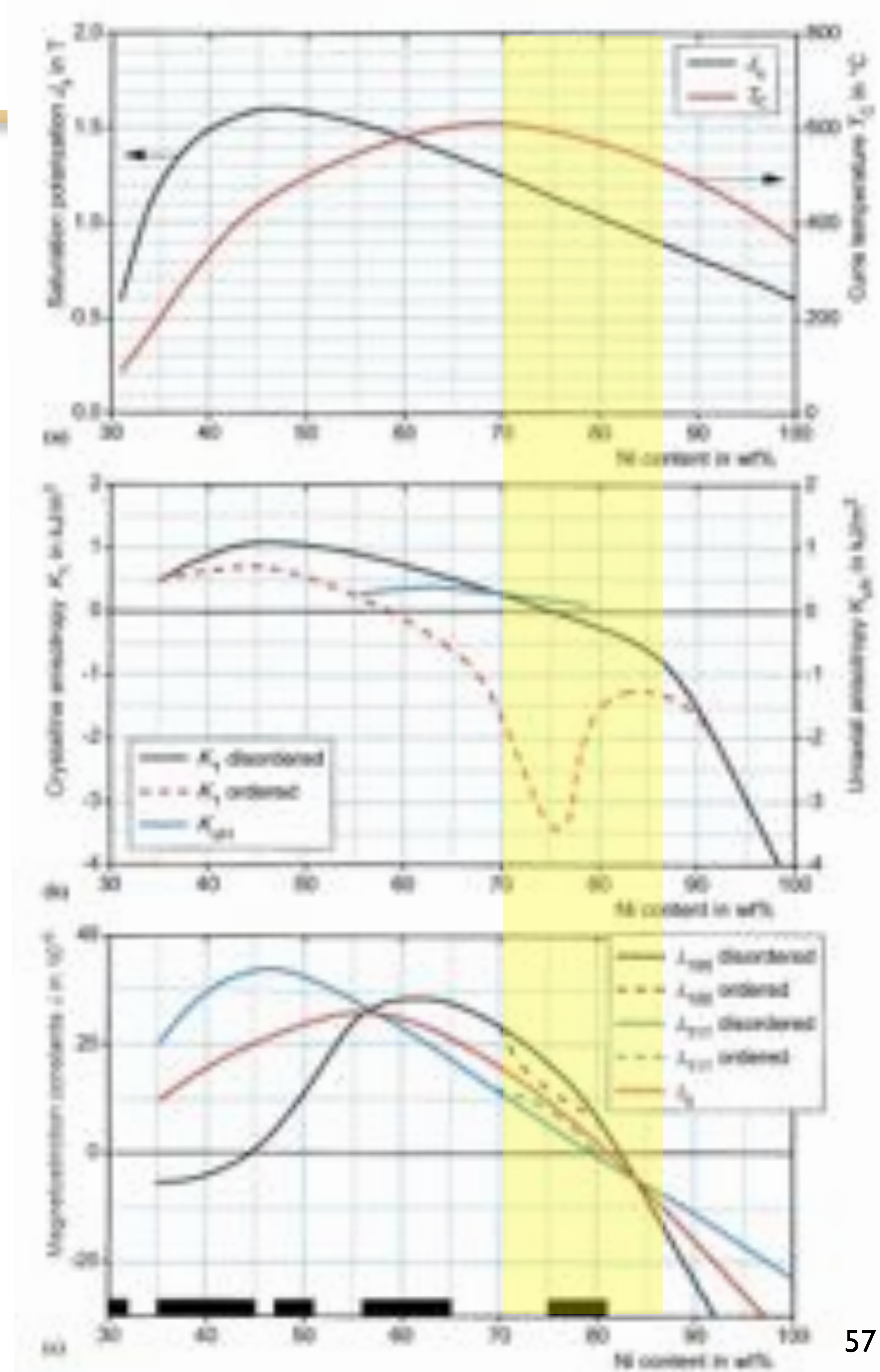

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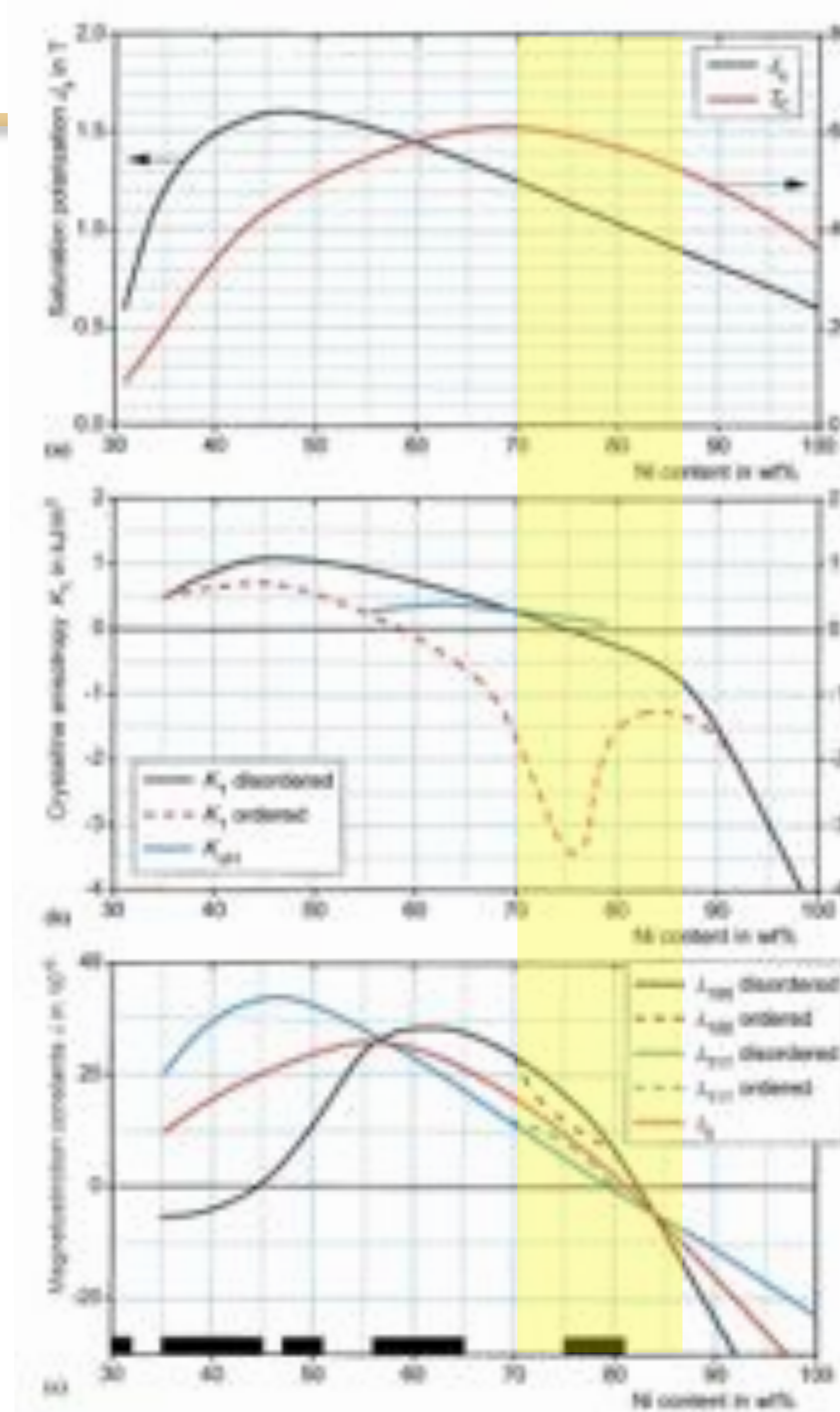

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- K_1 and λ small
  → high permeability expected in disordered state

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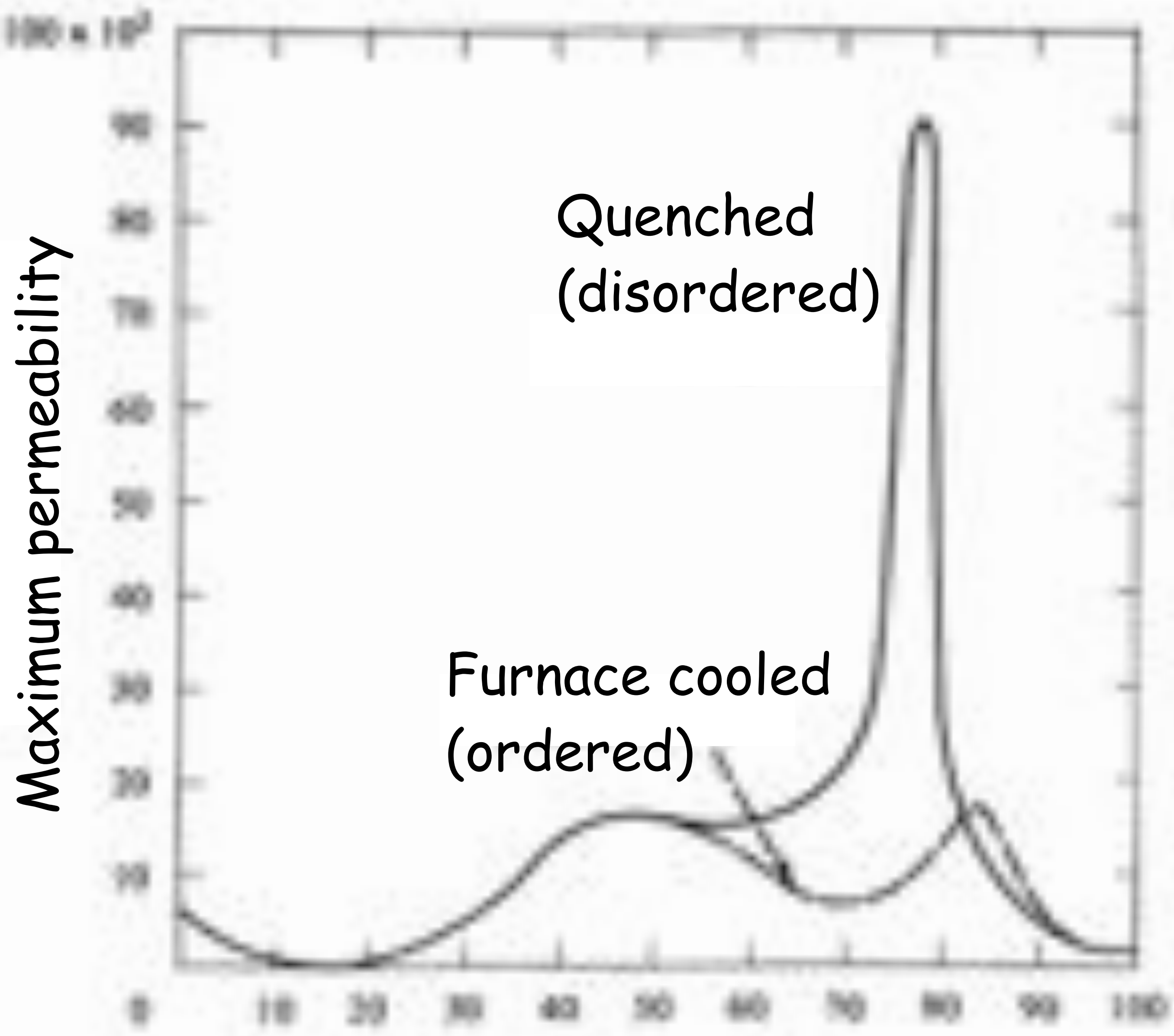

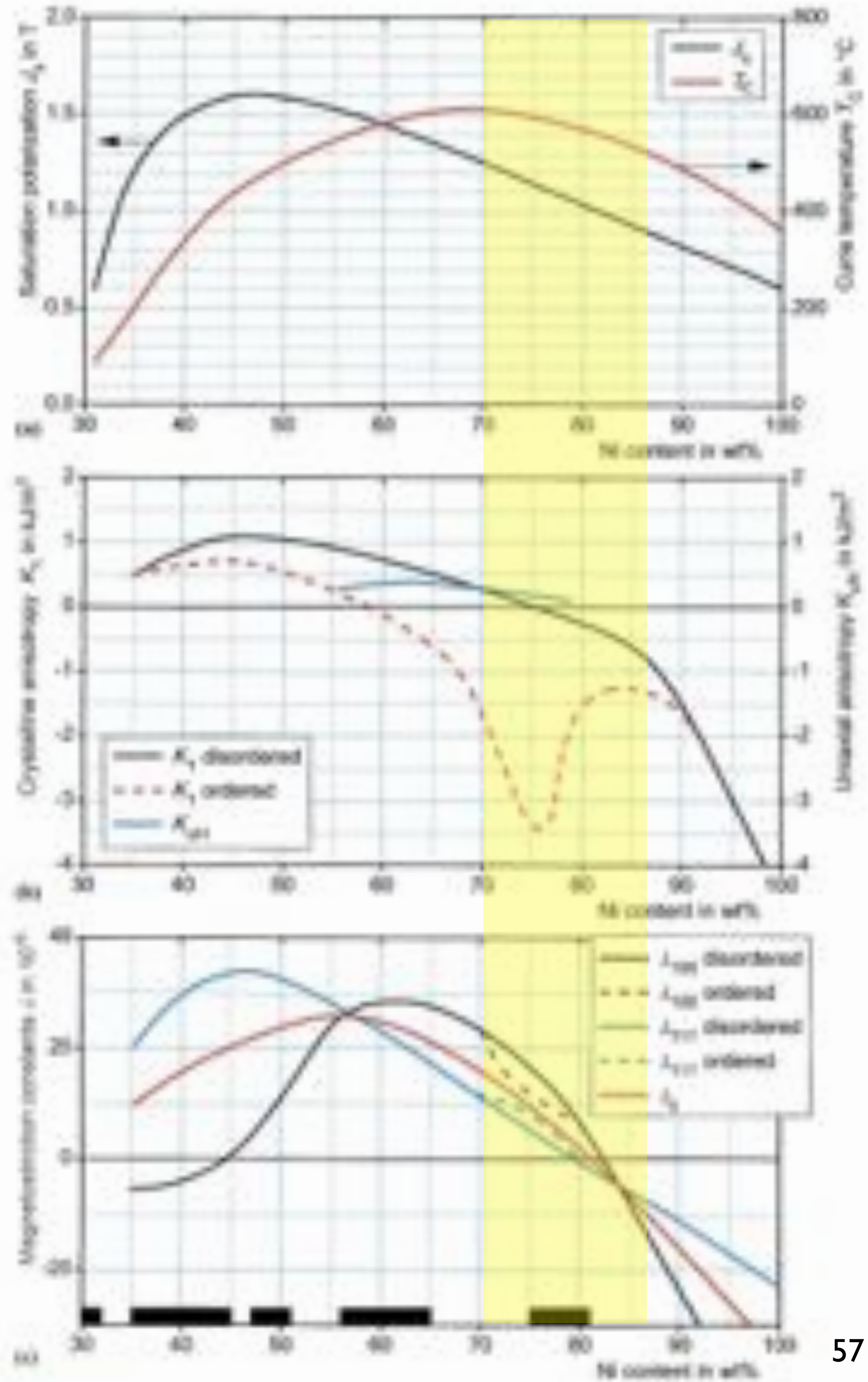

NiFe alloys

a) Ni content around 80 wt%:

- K_1 and λ small
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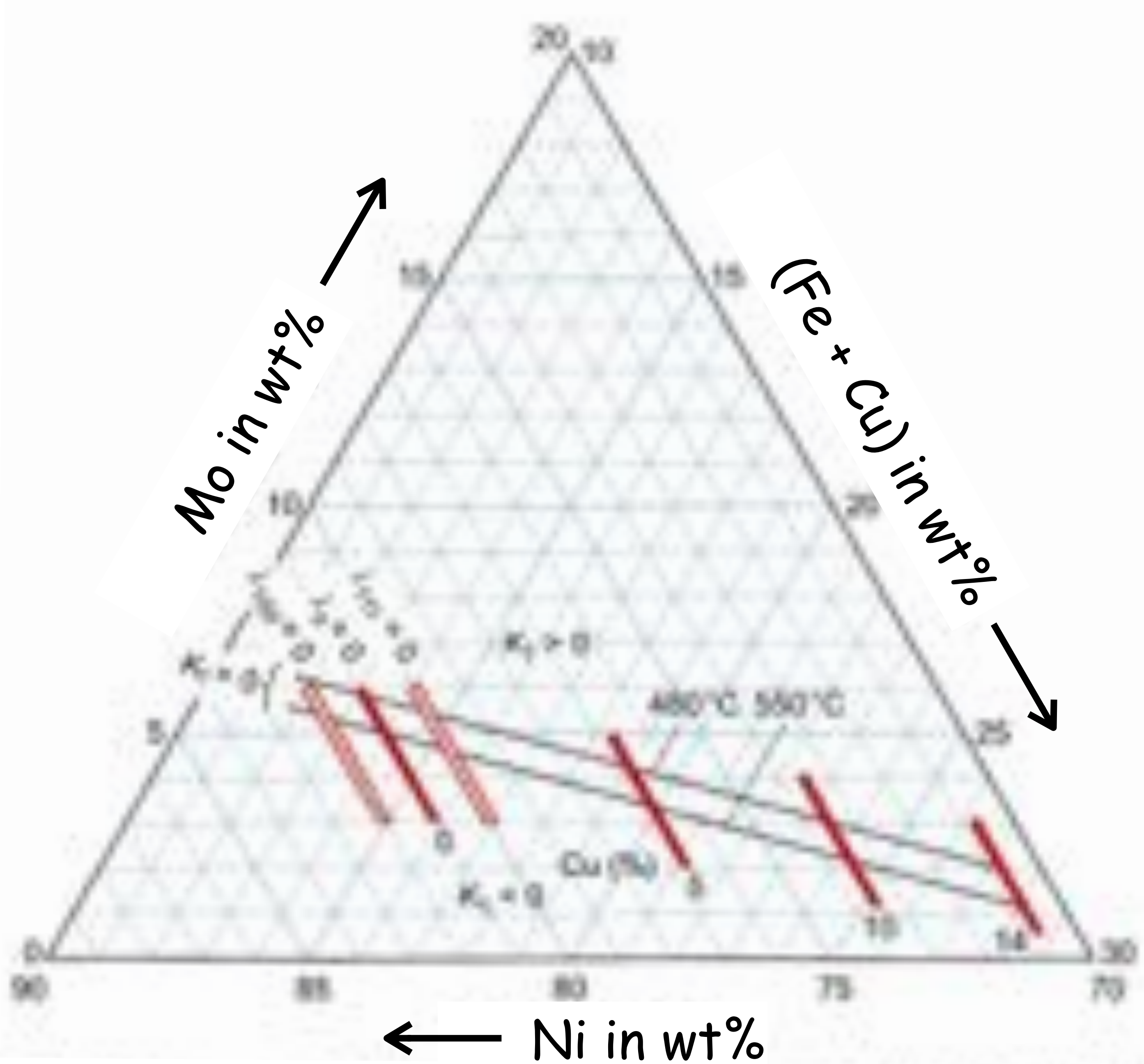
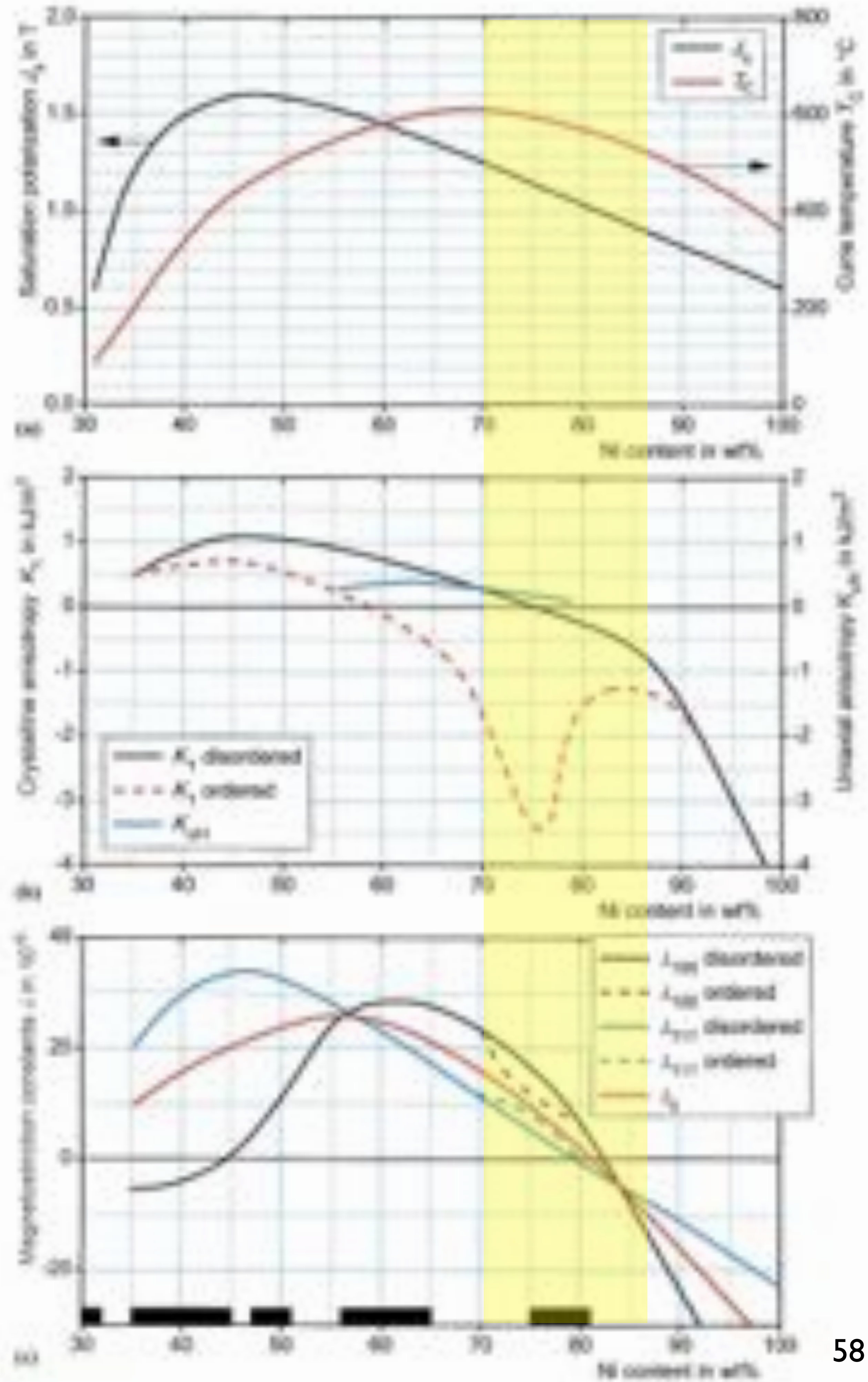
- $K_1 = 0$ and $\lambda = 0$ requires additions:





NiFe alloys

a) Ni content around 80 wt%:

- K_1 and λ small
  → high permeability expected in disordered state
- $K_1 = 0$ and $\lambda = 0$ requires additions:
- **Rule of Rassmann and Hofmann**:

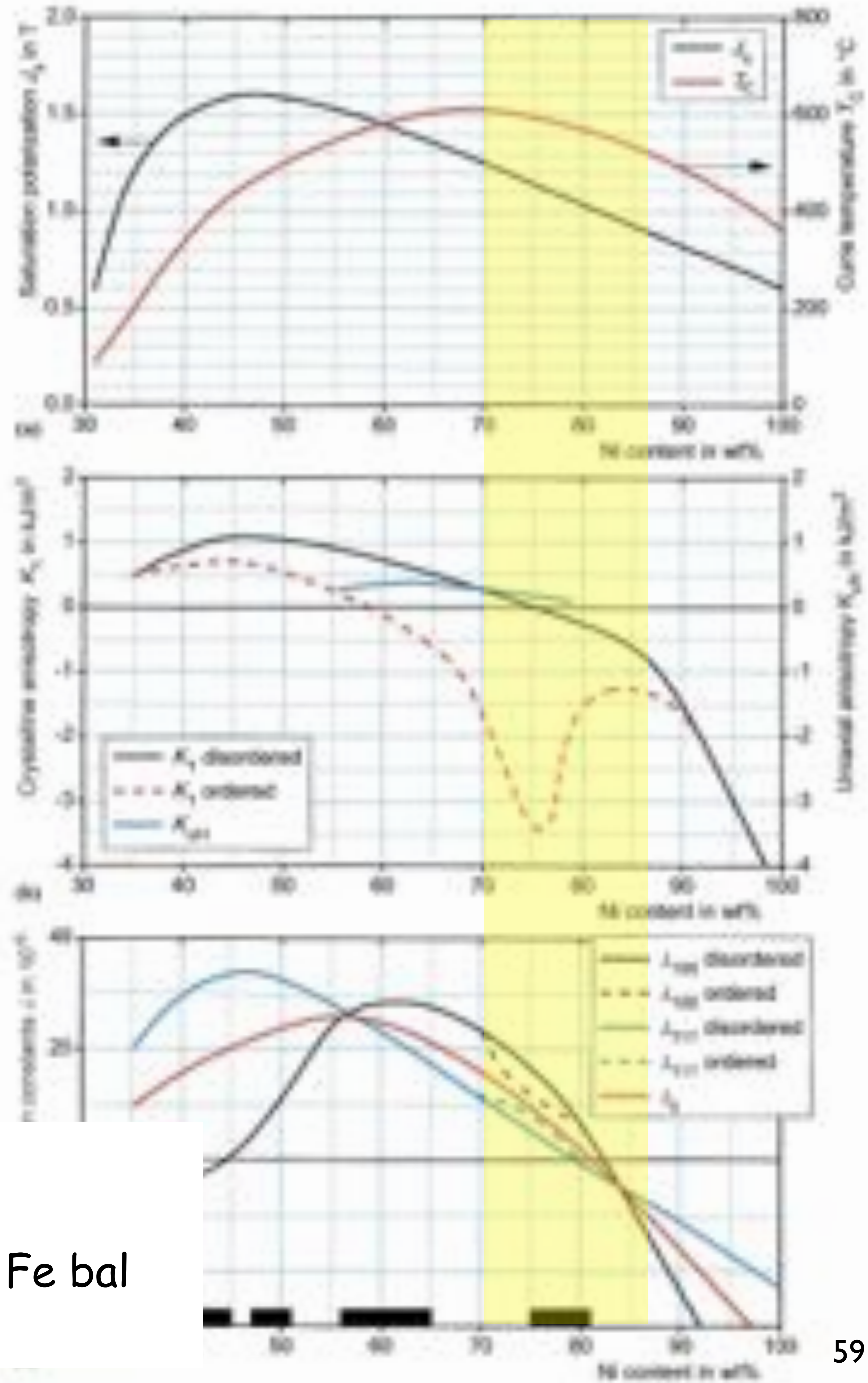
  A NiFe alloy shows maximum permeability if cubic anisotropy and average magneto-striction vanish simultaneously. This is obtained by the following recipe:

  - Take 14.5 at% Fe
  - Take other metals, their atomic percentage multiplied with their valence summing up to 19.5 at%
  - Fill up with Ni

Alloys with $K_1 = 0$ and $\lambda_s = 0$:

- Ni 81 wt%   Mo 5 wt%
- Ni 77 wt%   Mo 4 wt%   Cu 5 wt%
- Ni 74 wt%   Mo 3 wt%   Cu 10 wt%

} Fe bal



NiFe alloys

a) Ni content around 80 wt%:

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  → high permeability expected
  in disordered state
- $K_1 = 0$ and $\lambda = 0$ requires additions:
- **Rule of Rassmann and Hofmann:**

→ Permeability > 300.000

→ Permalloy

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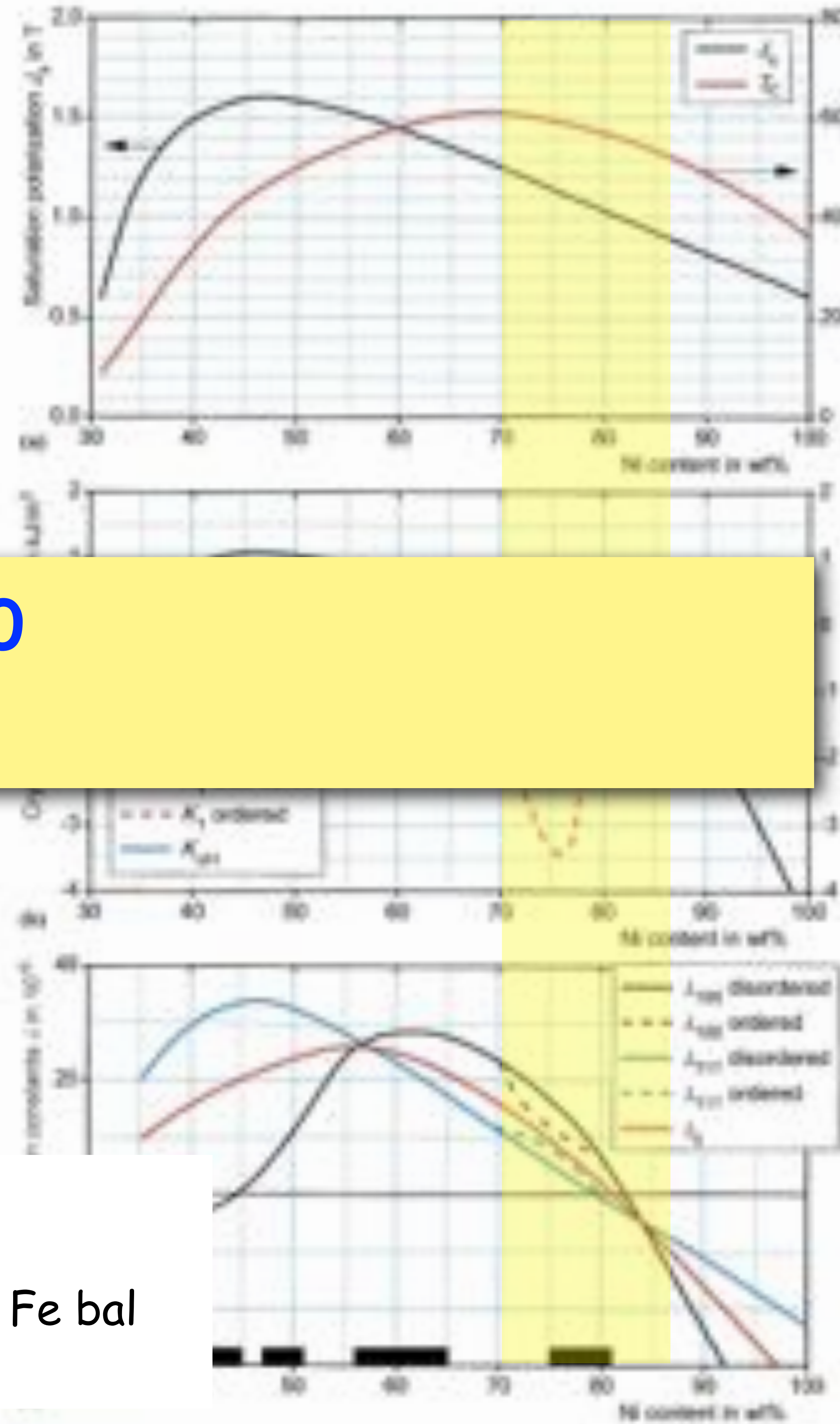

NiFe alloys

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- K_1 and $\lambda = 0$ small
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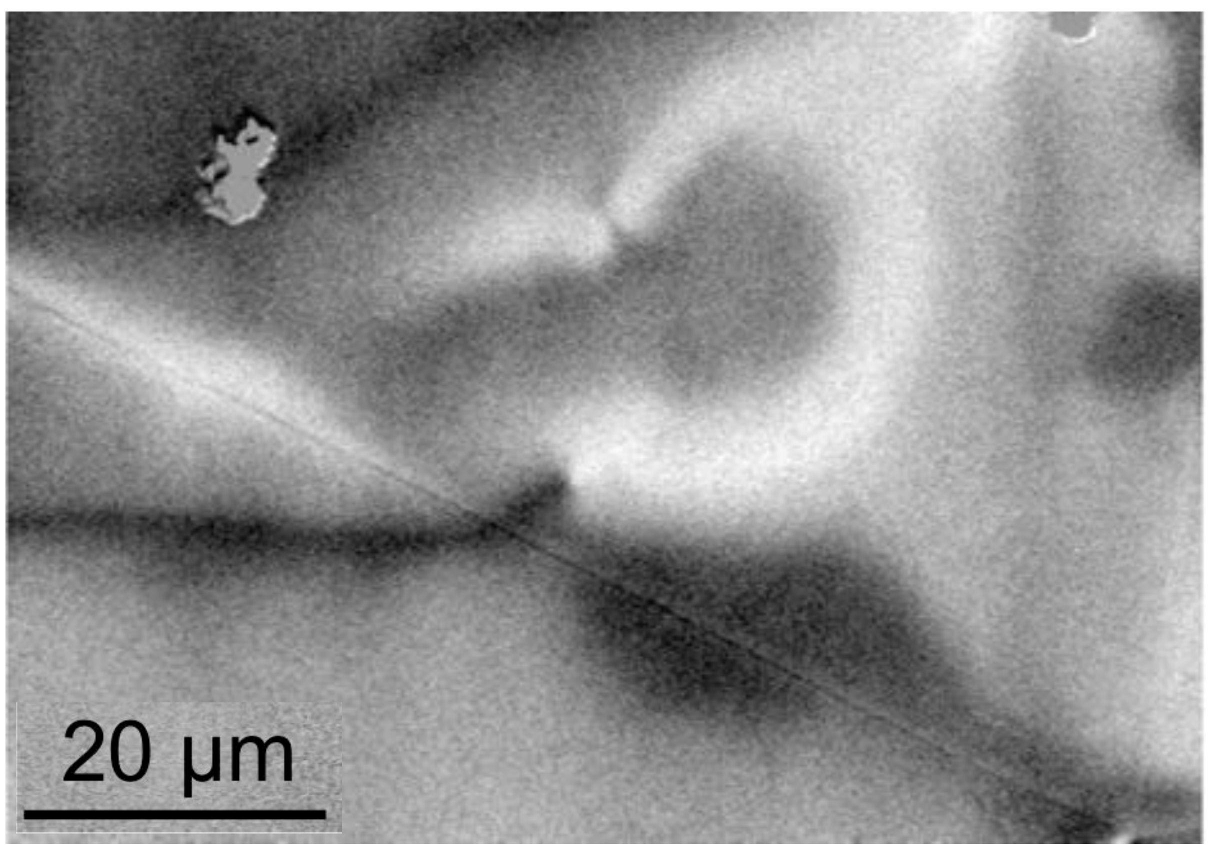
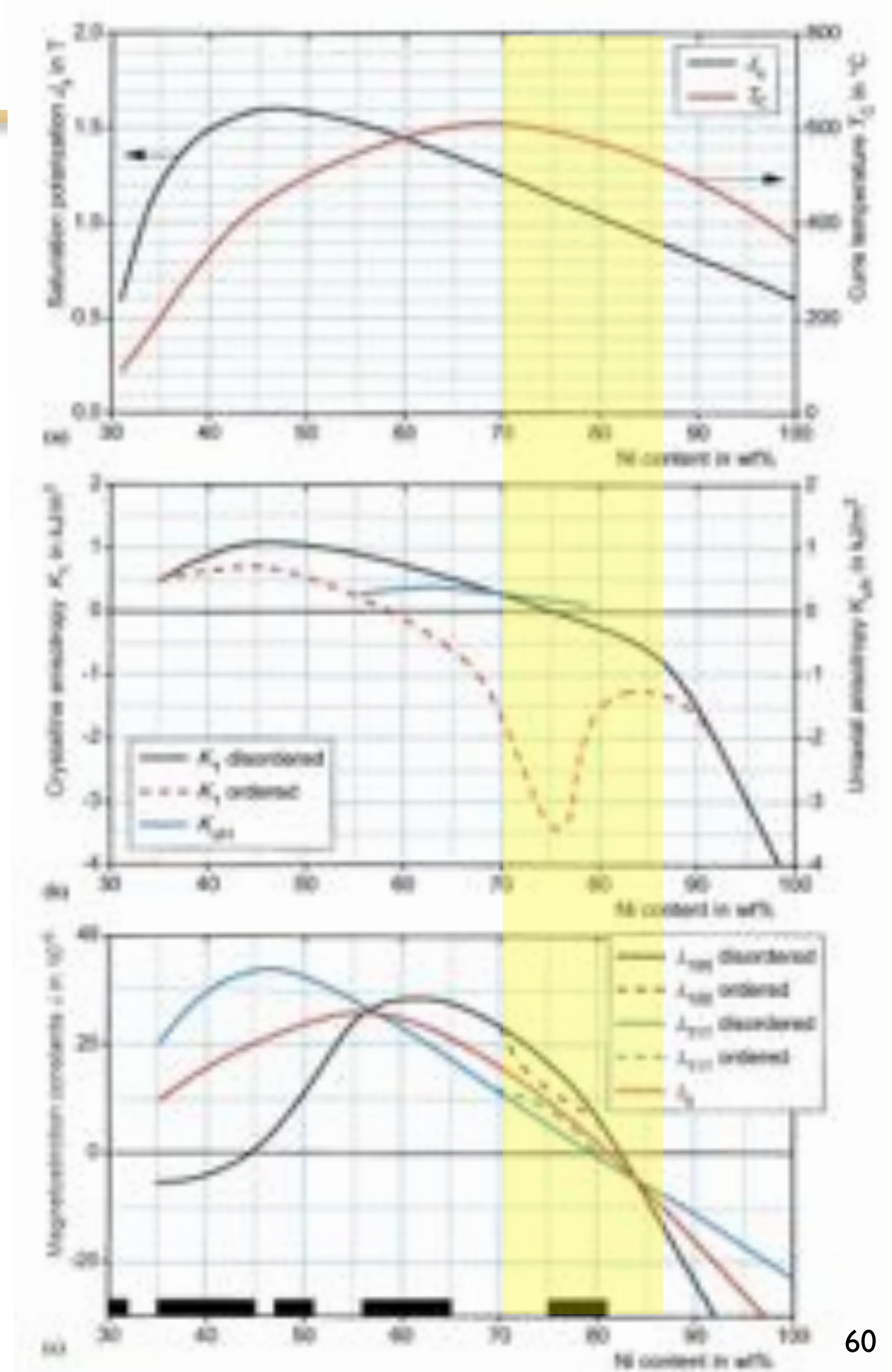
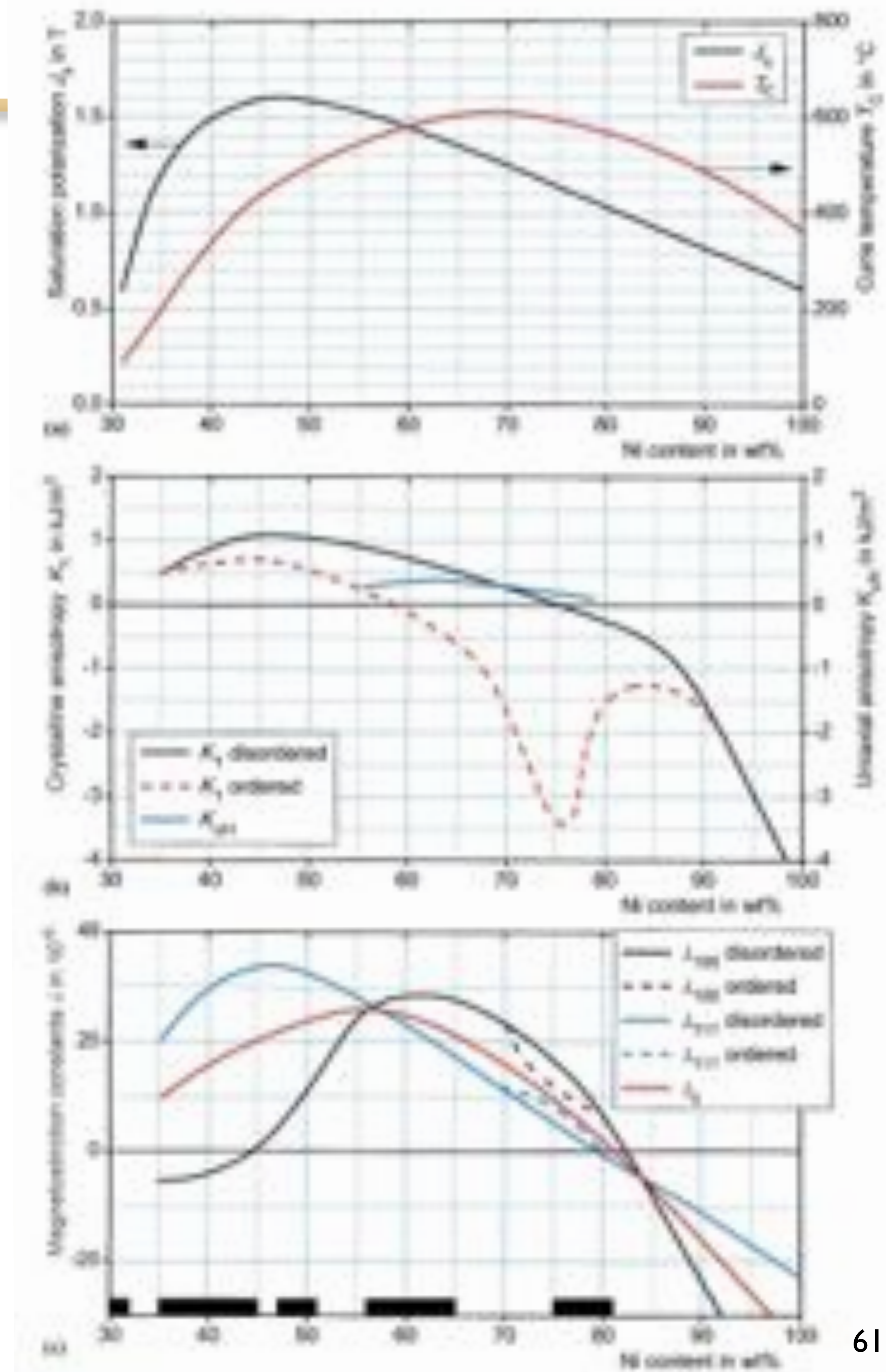
  in disordered state
- $K_1 = 0$ and $\lambda = 0$ requires additions:
- Rule of Rassmann and Hofmann
- Wide domain walls ($W_{\text{wall}} \sim \sqrt{A/K}$),
  continuous magnetization configurations





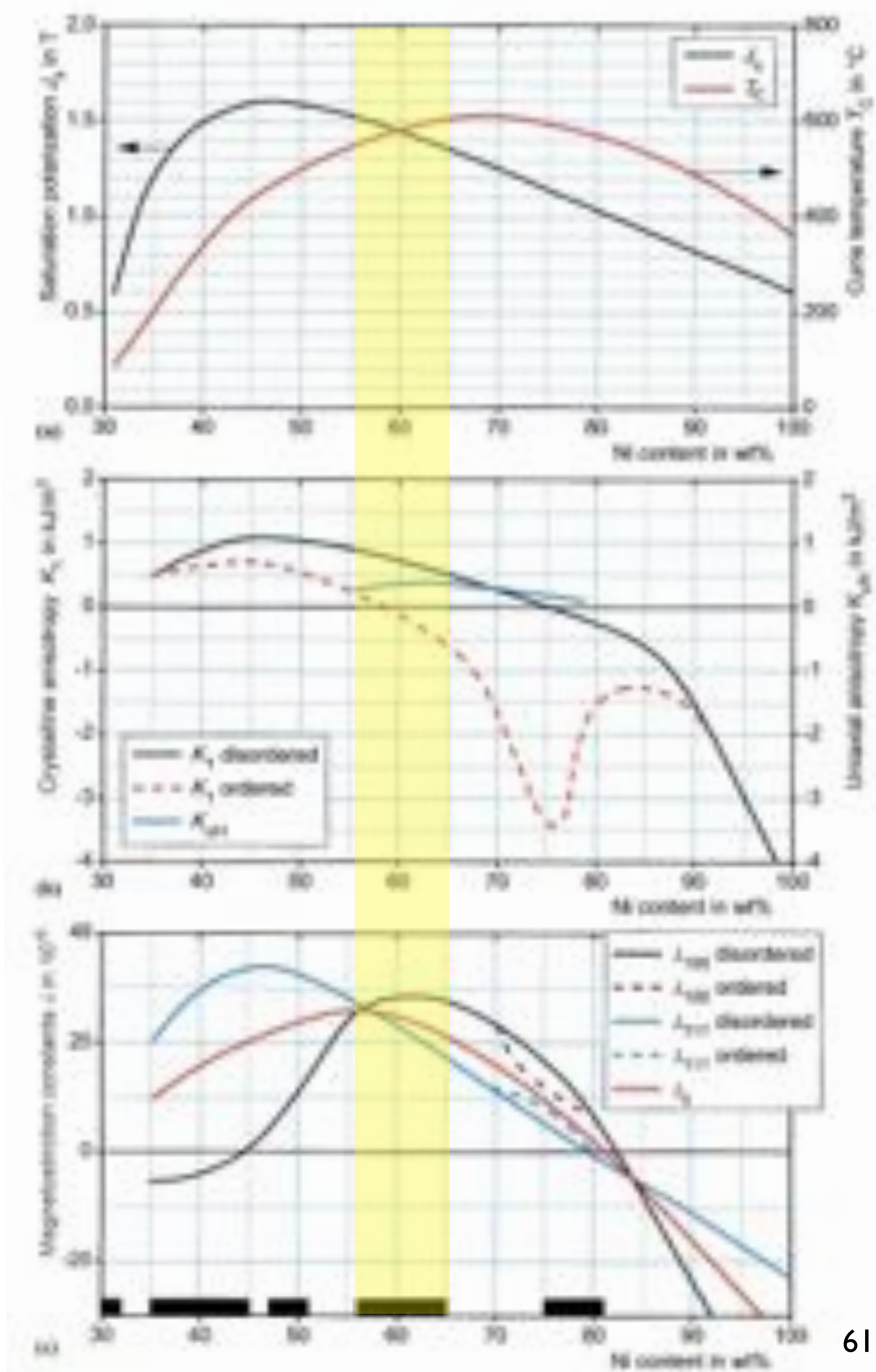
NiFe alloys



30
40
50
60
70
80
90
100
Ni content in wt%
K1 disordered
K1 ordered
λ100 disordered
λ100 ordered
λ111 disordered
λ111 ordered

NiFe alloys

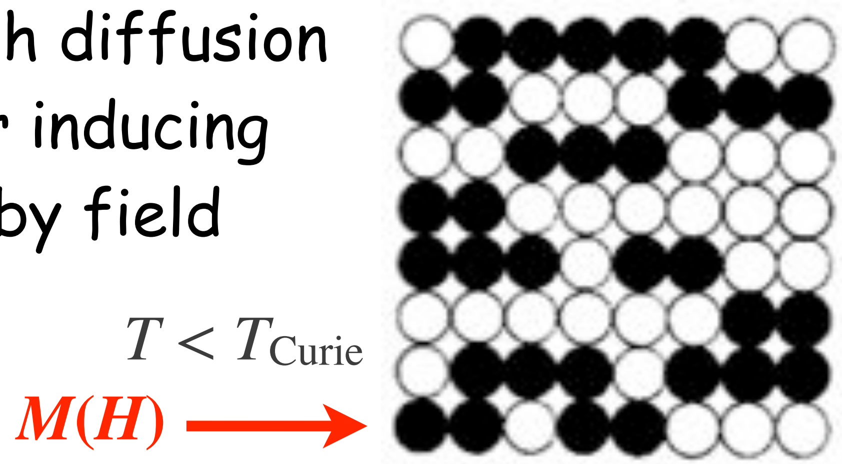
b) Ni content around 60 wt%:



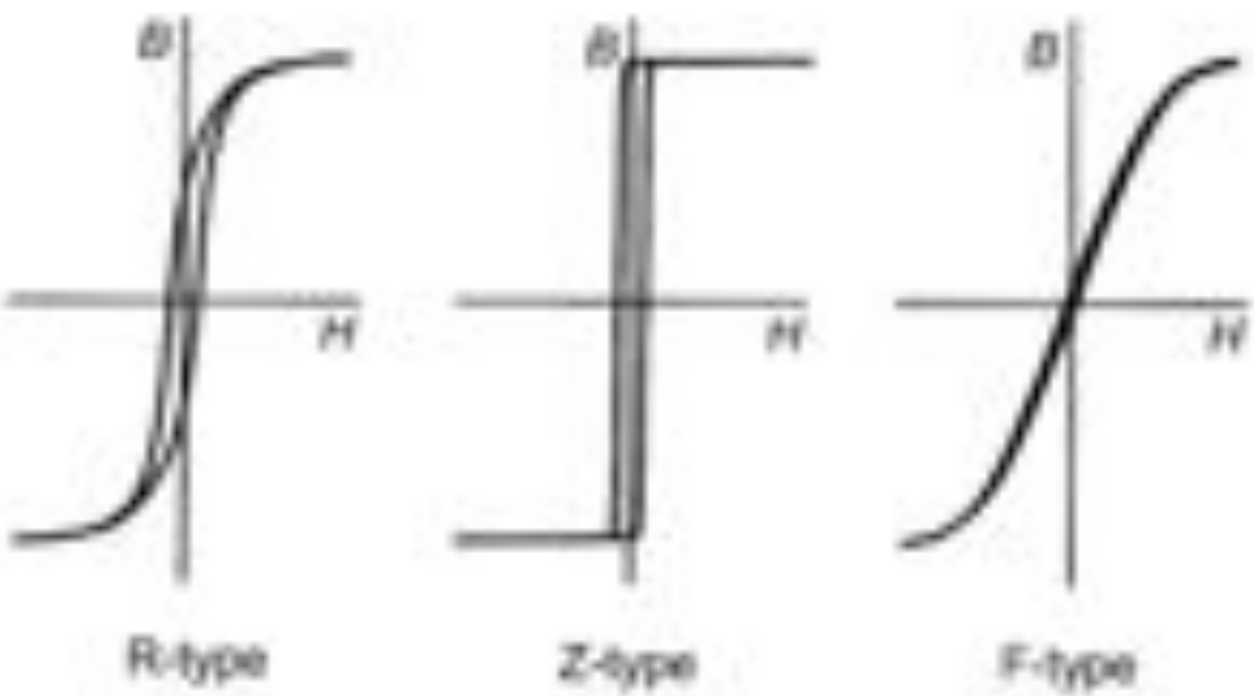
NiFe alloys

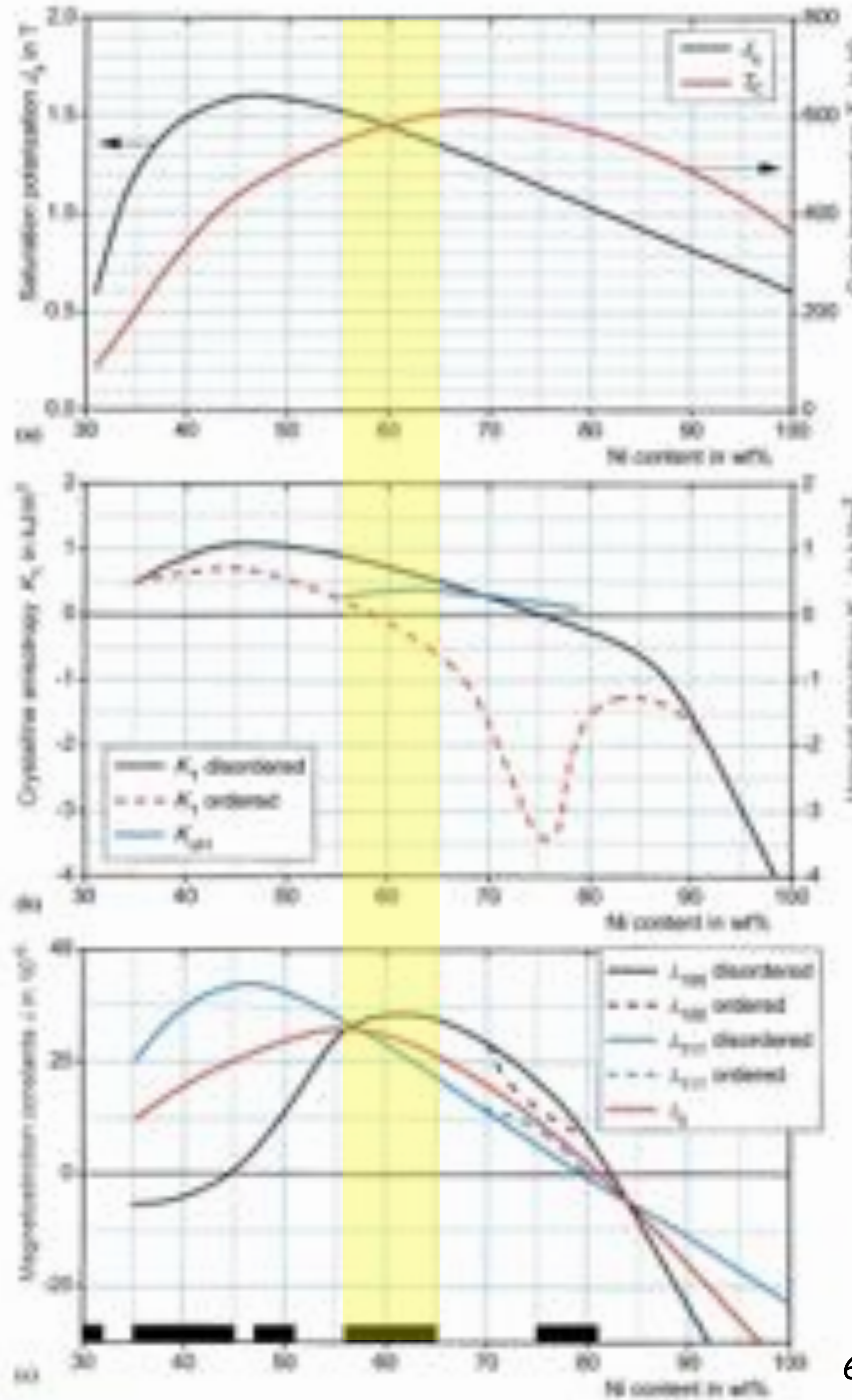
b) Ni content around 60 wt%:

- K_1 still small, can be tuned by degree of ordering
- T_c high: high diffusion kinetics for inducing anisotropy by field annealing



- → pronounced Z and F loops can be achieved





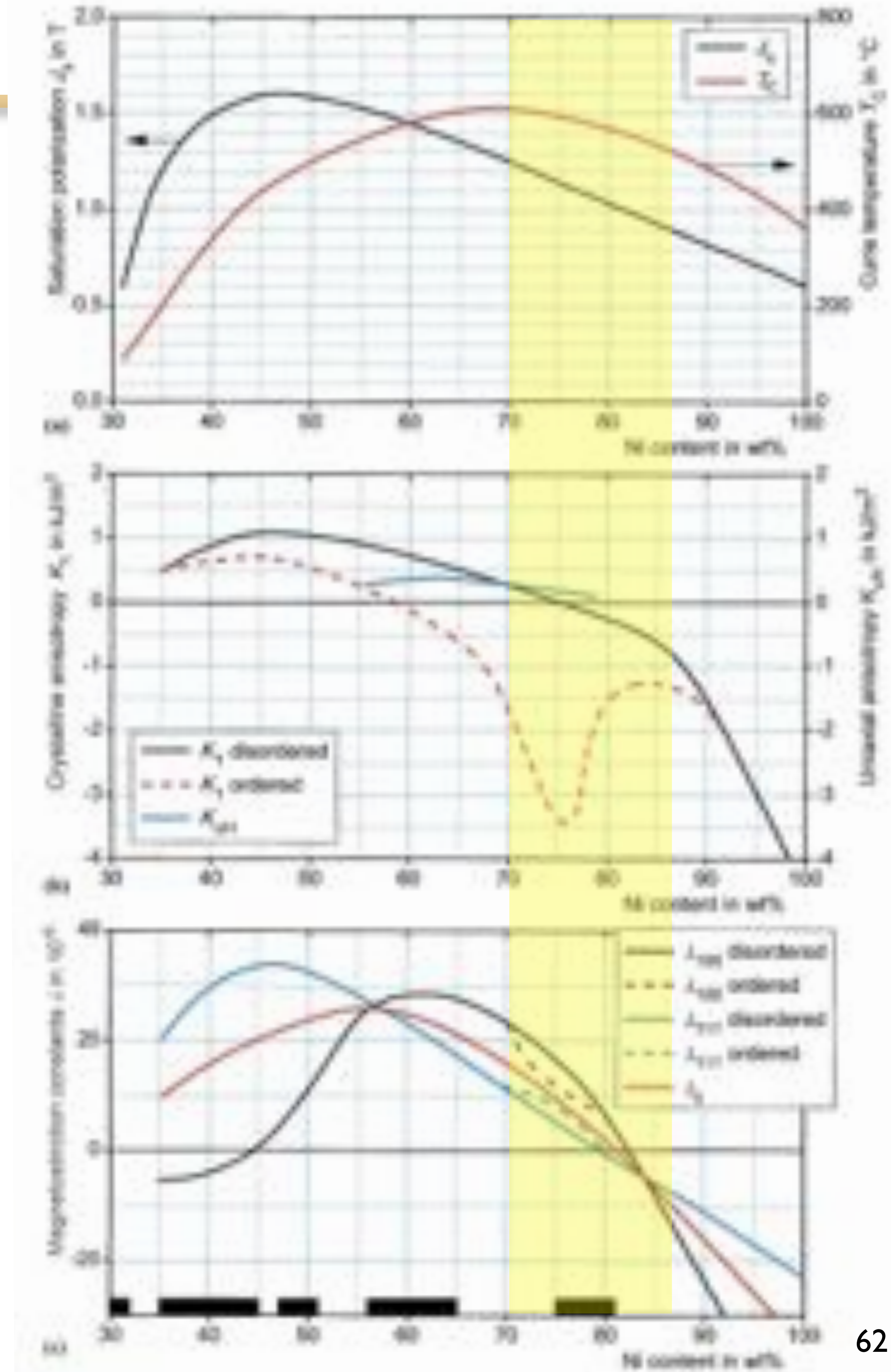
NiFe alloys

Microstructure of NiFe alloys:

- Large grain size prefered, as $H_c \sim 1/D$ → careful cold-working processing and heat treatment required to obtain proper recrystallization

T_{ann} = 950°C

T_{ann} = 1150°C



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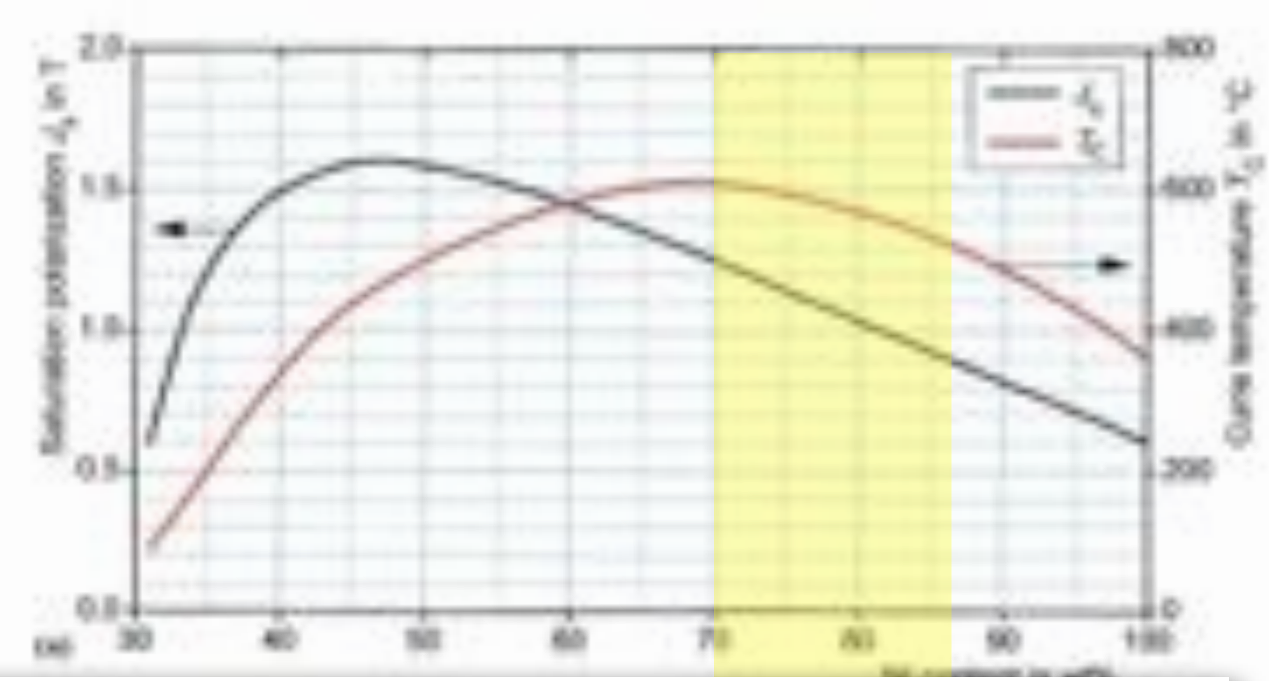
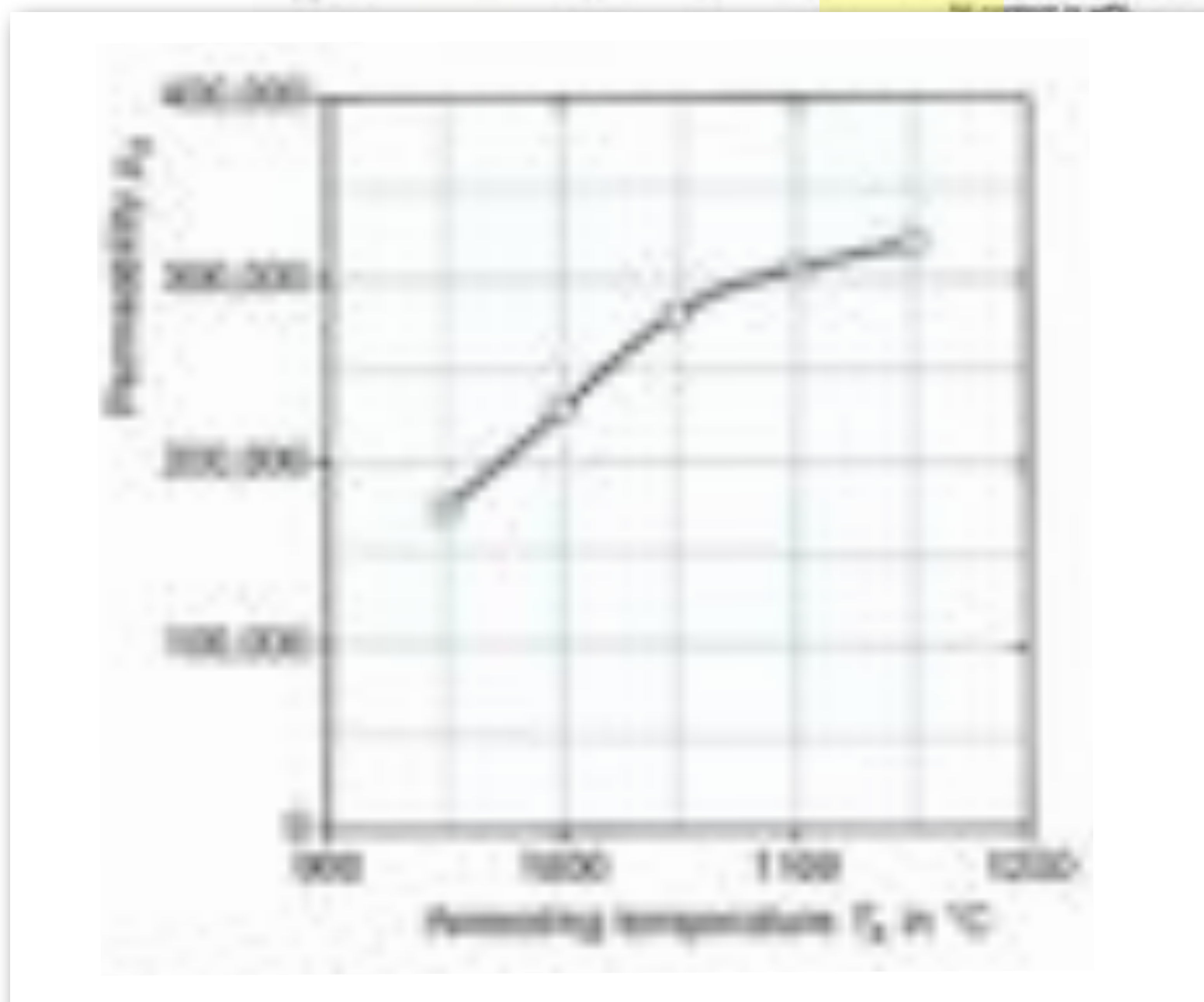
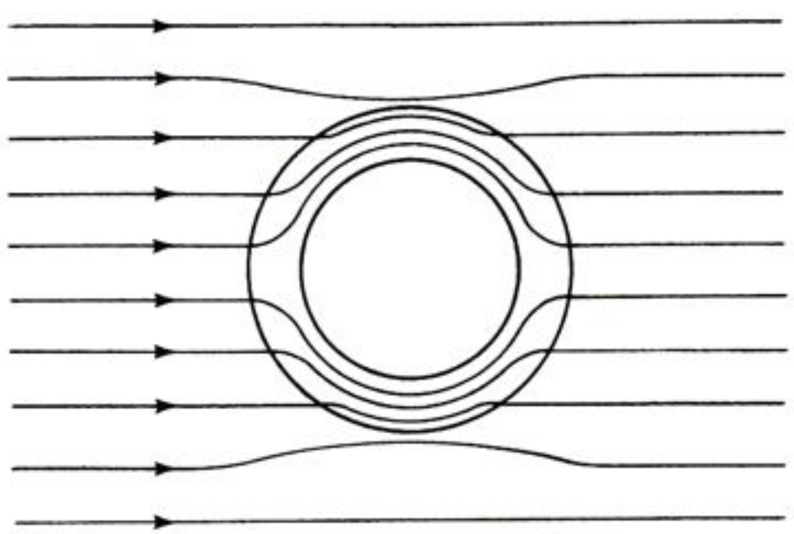


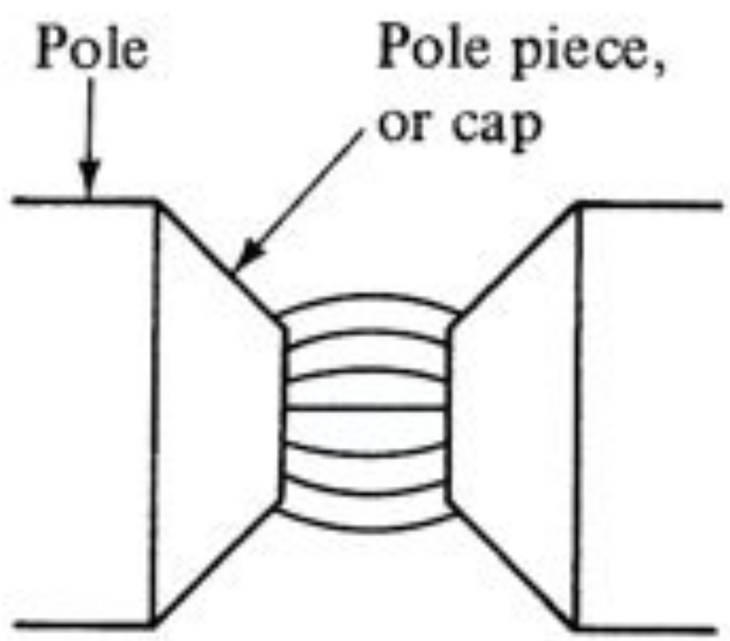


Soft magnets: General Considerations

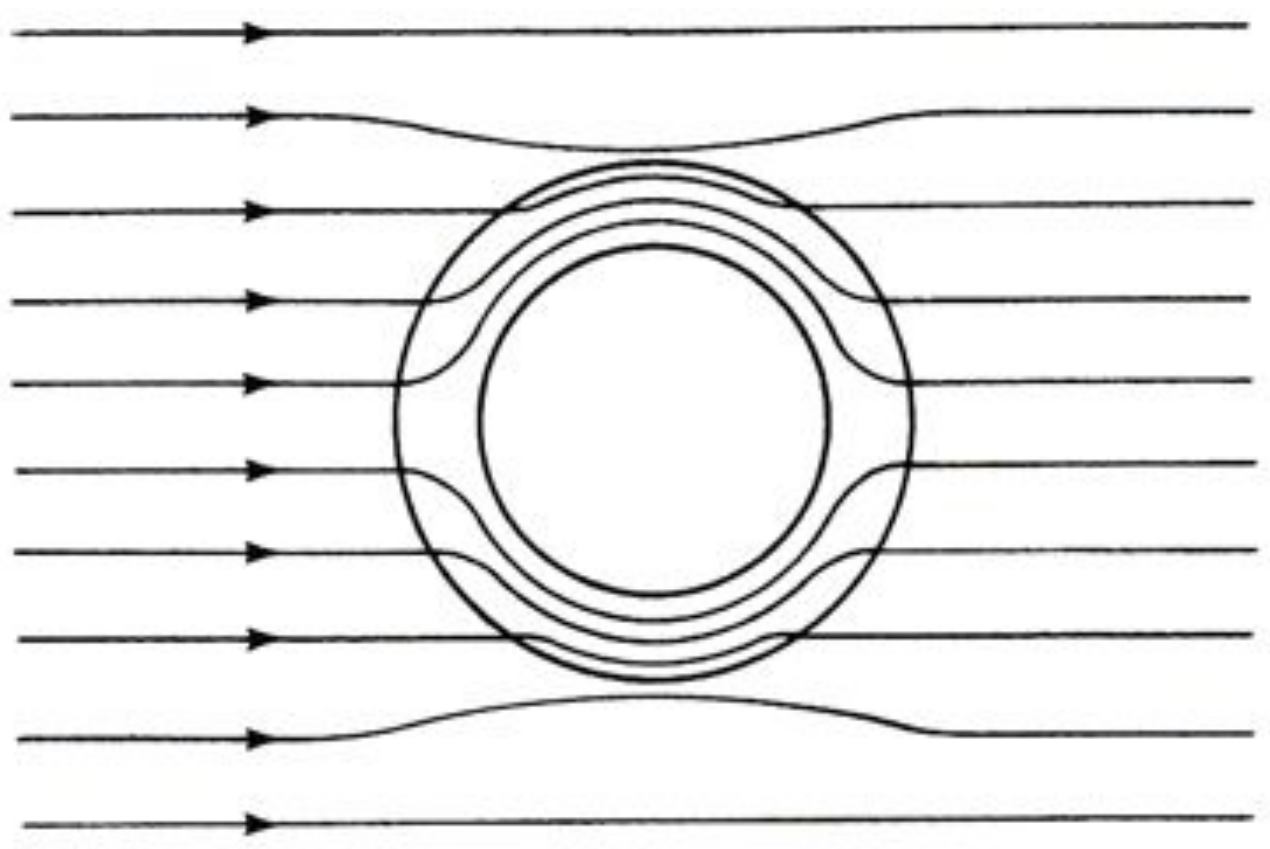
So far:
Only static properties have been considered,
i.e. material is magnetized in dc magnetic field or at very low magnetization rate (quasistatic conditions)

Applications:
- Shielding of dc magnetic field
- Pole pieces in electromagnets





Magnetic shielding



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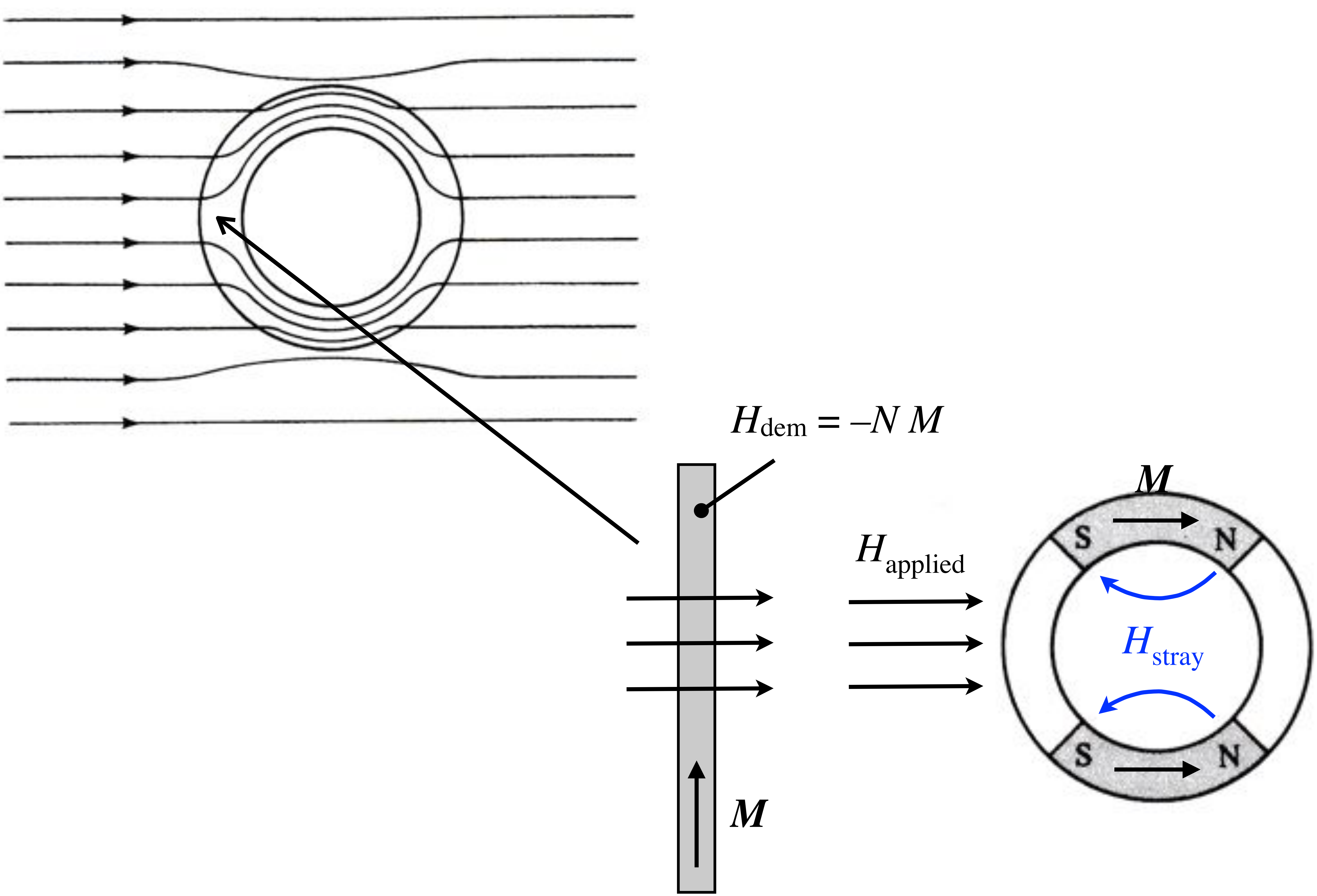
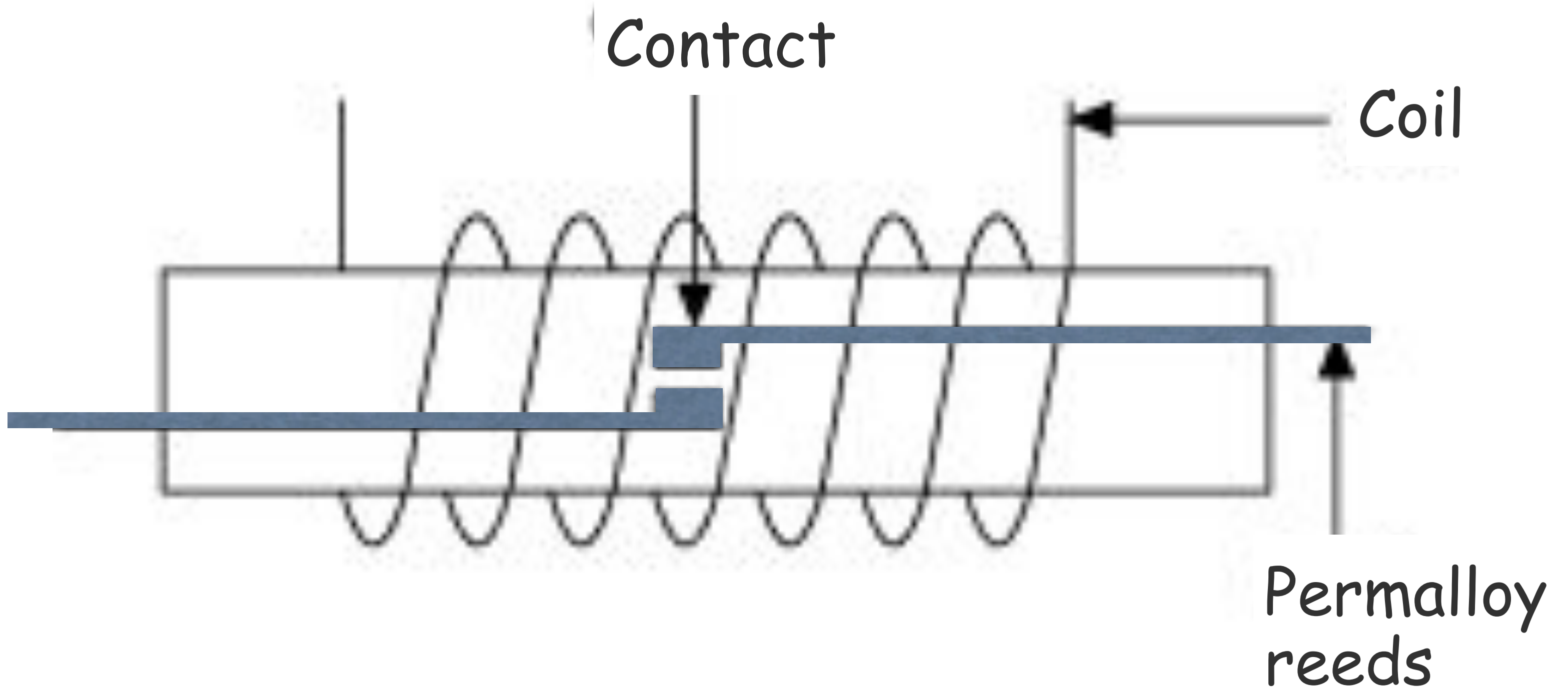
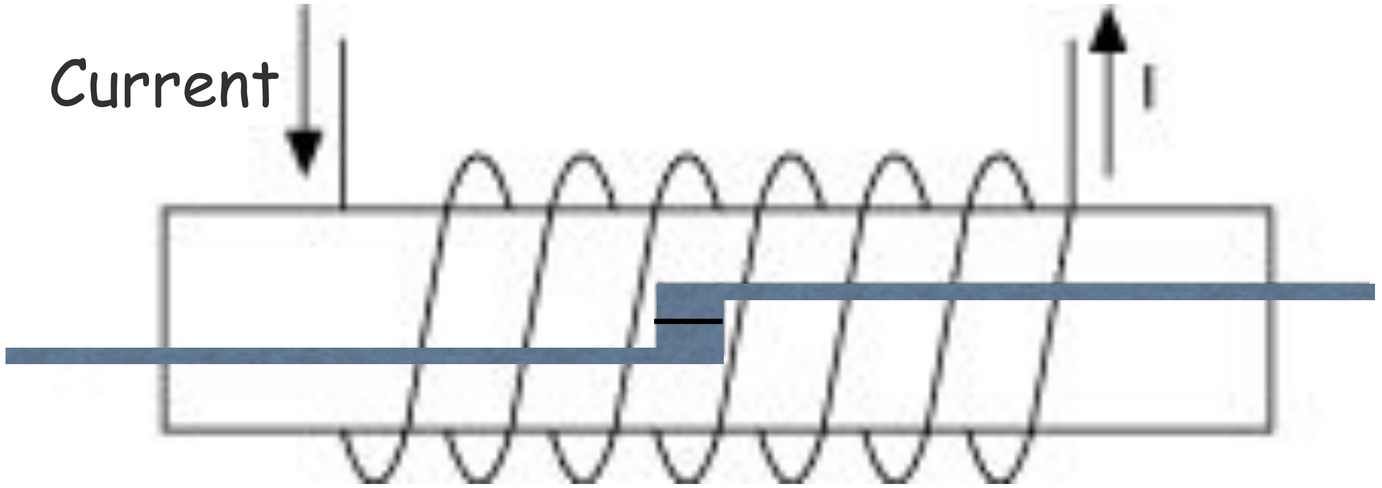


Reed relay



No current in coil:

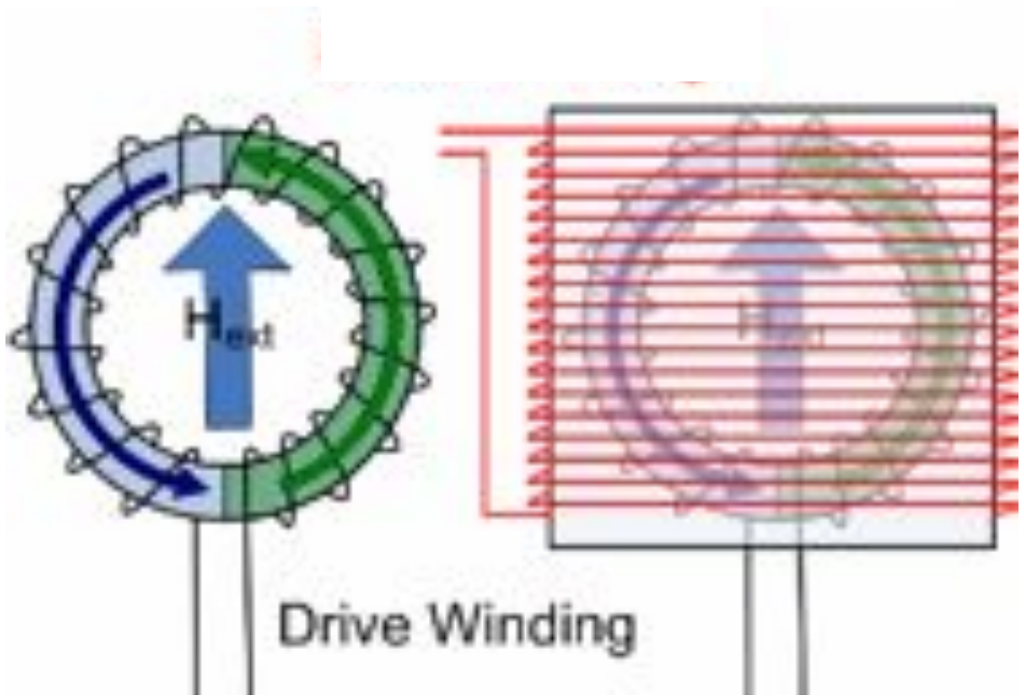
strips separated



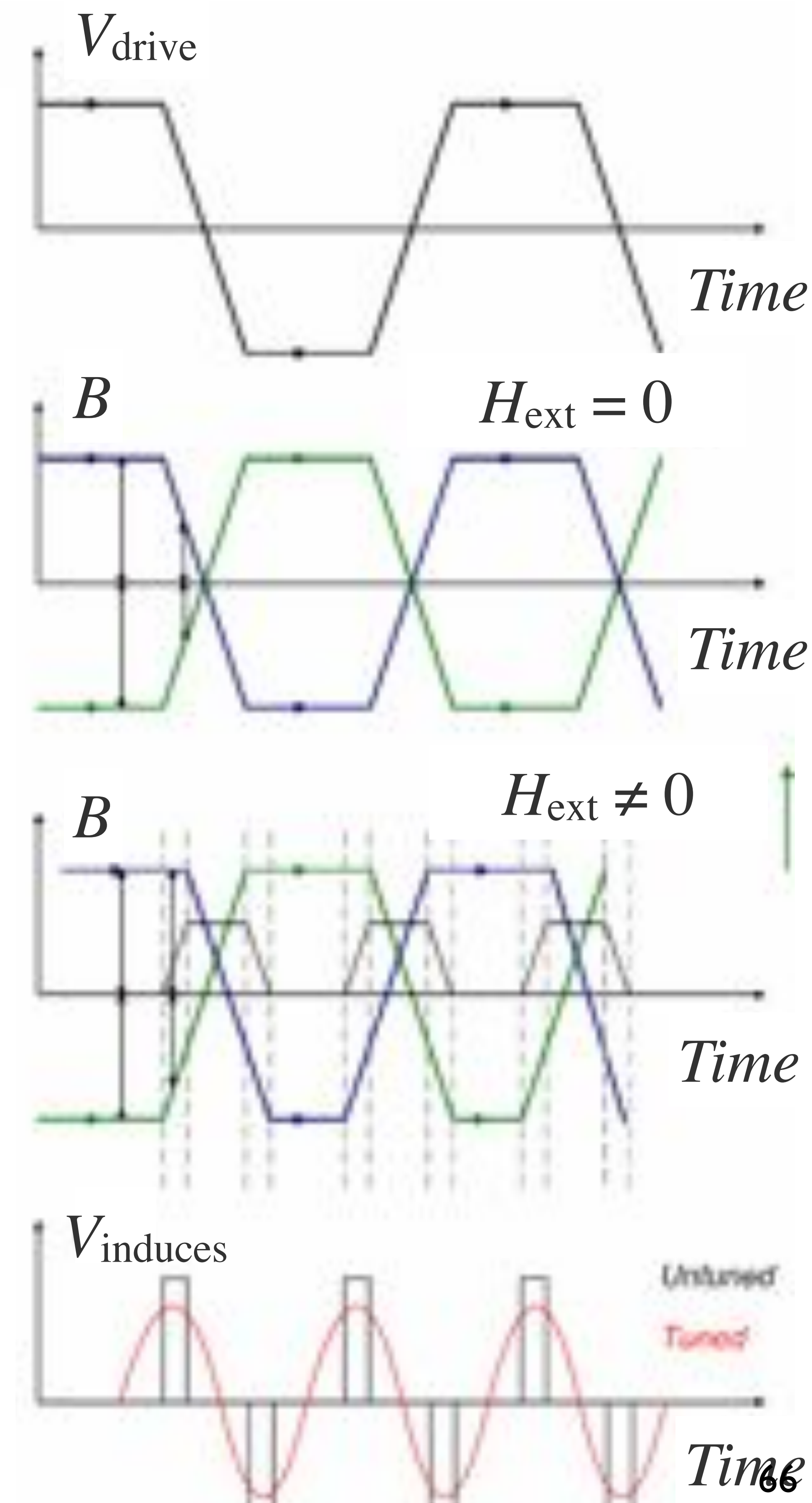
Current in coil:

strips are magnetized and attract each other
→ contact closed

Fluxgate Magnetometer

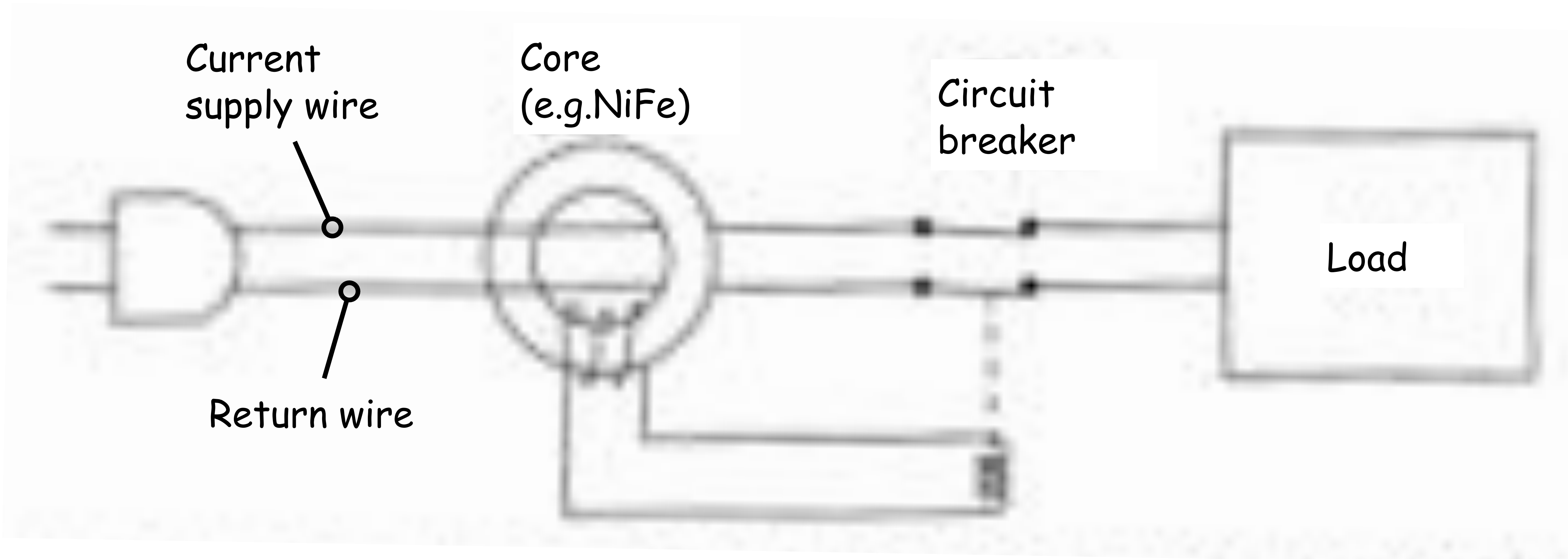


http://
www3.imperial.ac.uk



- Current through the drive: one half core generates B along H_{ext}, other half core in opposite direction
- $H_{\text{ext}} = 0$: two half cores go into and come out of saturation at same time → B-fields cancel → no net change of flux in sense winding → no voltage induced
- $H_{\text{ext}} \neq 0$: one half core comes out of saturation sooner, other half core later → net flux change → voltage → two spikes in voltage for each transition in drive
- Size and phase of induced spikes → magnitude and direction of H_{ext}
- Typical field range: 0.1 nT – 1 mT (used in e.g. geomagnetic and archeological surveys)

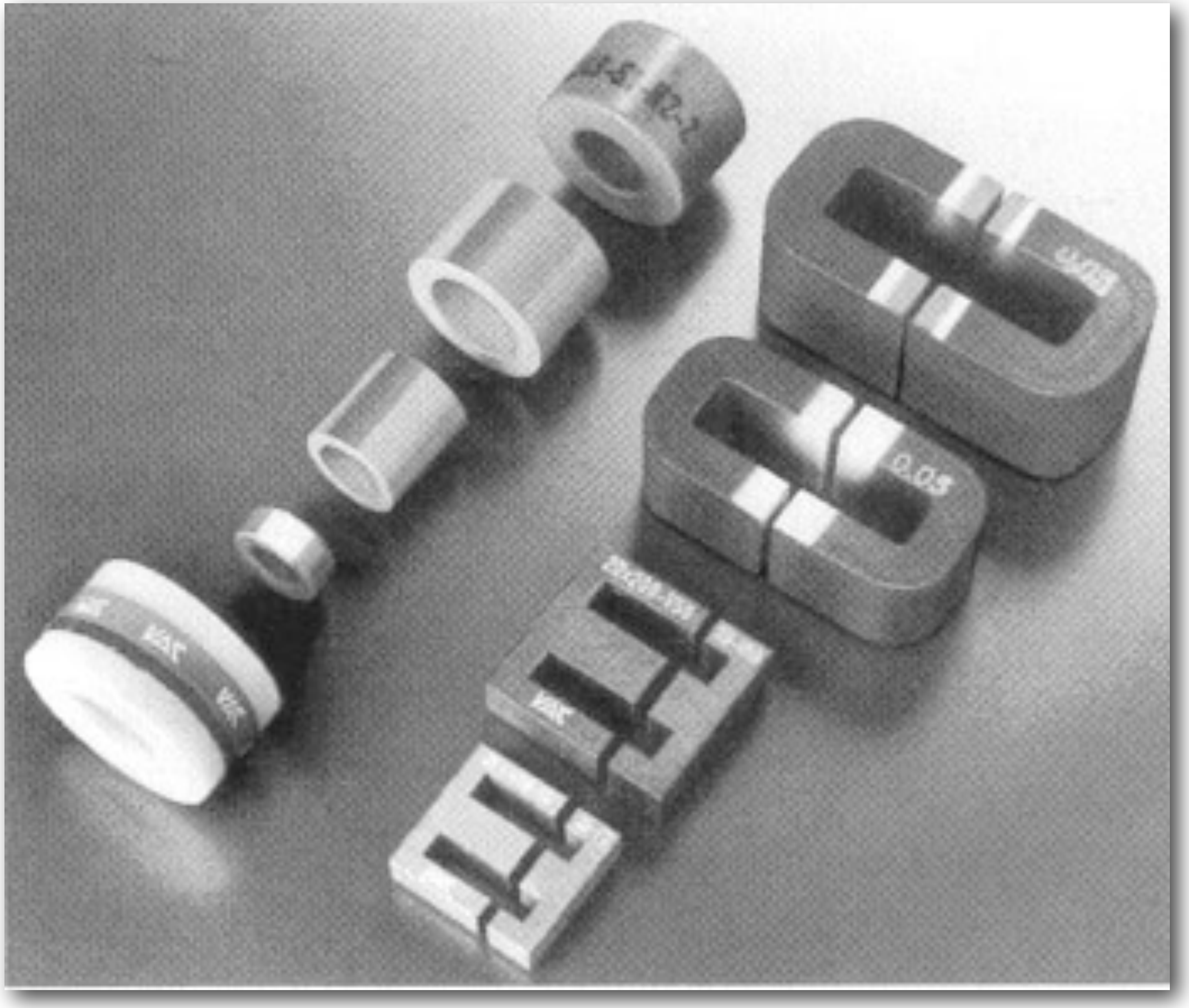
Ground-fault interrupter



- Current supply wire and return wire pass through magnetic core, they create magnetic field/flux
- No leackage current in device → 2 current are equal and opposite → no flux change in core
- Leackage current → supply current > return current → non-zero ac field in core → generates voltage in secondary winding that opens circuit

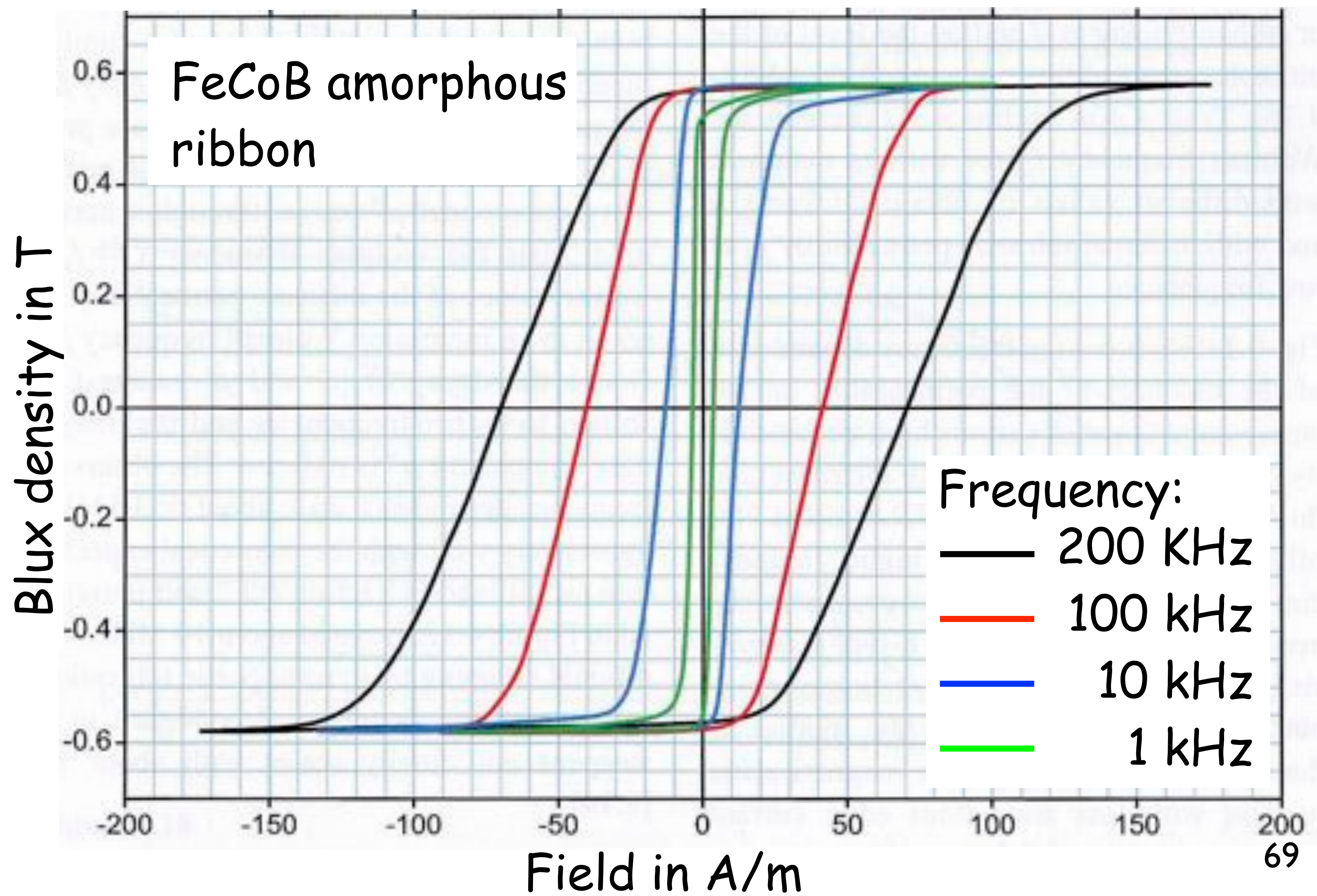
Soft magnets: General Considerations

In most applications, soft magnetic materials are magnetized in ac magnetic fields!



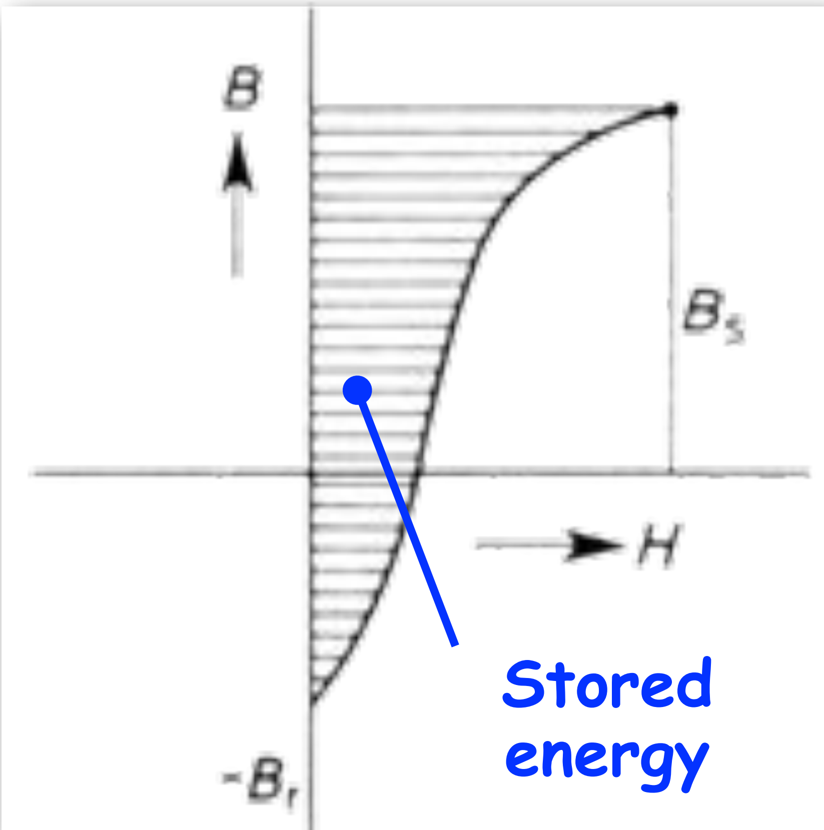
Soft magnets: General Considerations

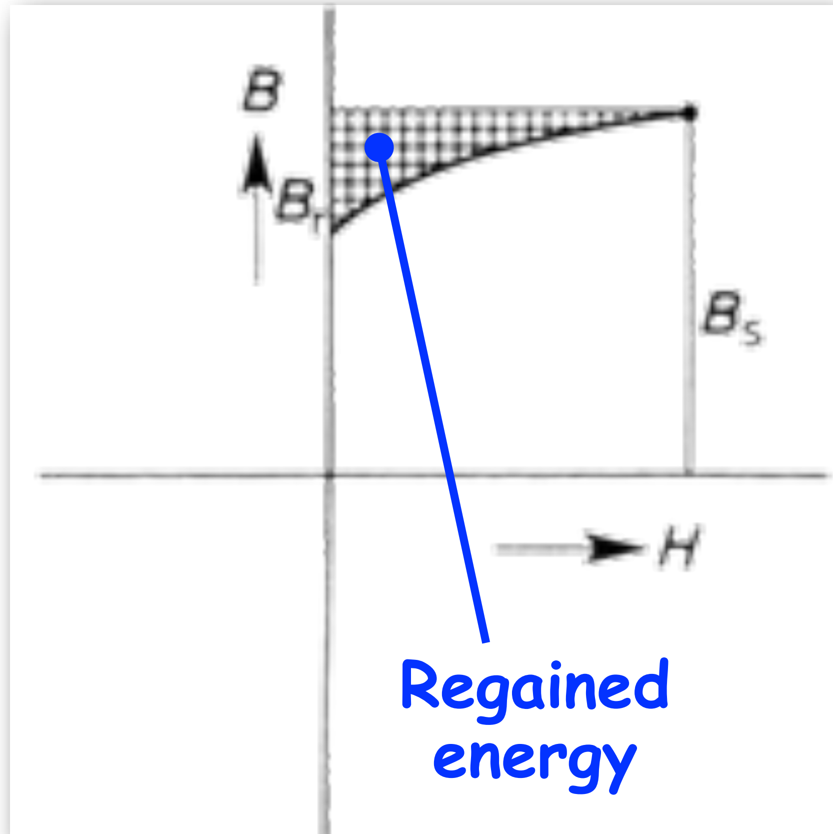
Area of hysteresis curve (≙ power loss) increases with frequency

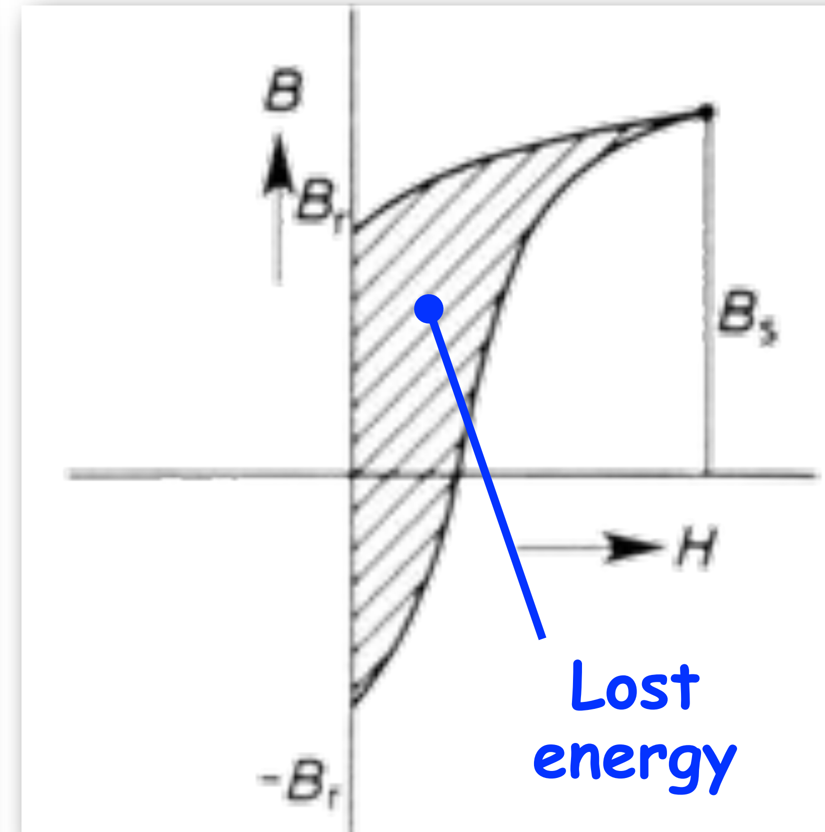


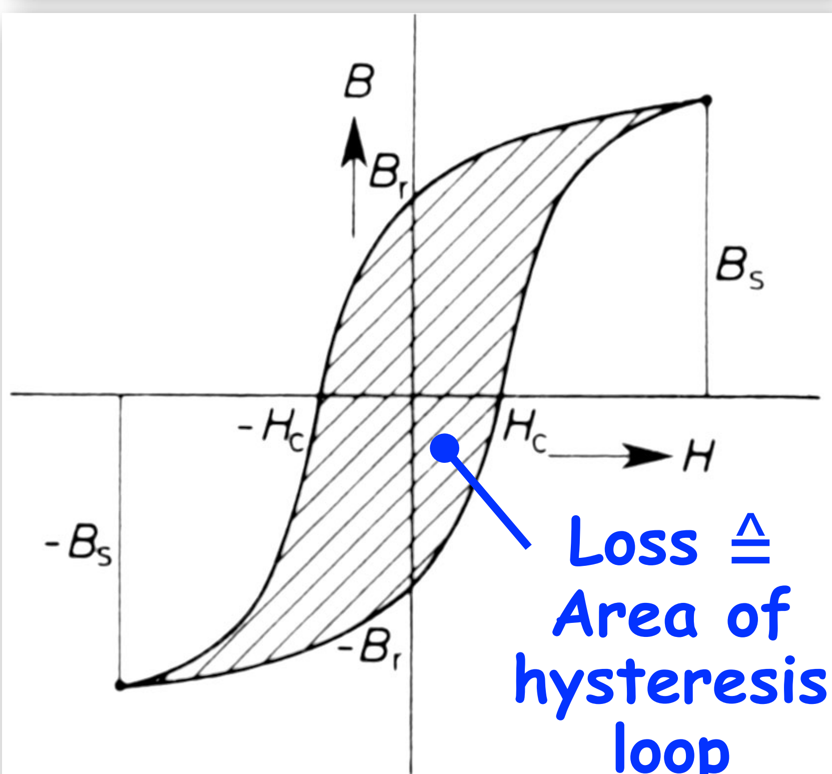
Losses

General: Loss of energy ≙ Area of hysteresis loop









During each cycle of frequency f an amount of energy $P/f = \oint H \, \mathrm{d}B$ is irreversibly transformed into heat

($\oint$ = area of loop) ≙ work required to unpin walls from pinning sites or to reorder domains

$P/f =$ specific loss per cycle in [Ws/m^3]
(„specific" means: related to volume)

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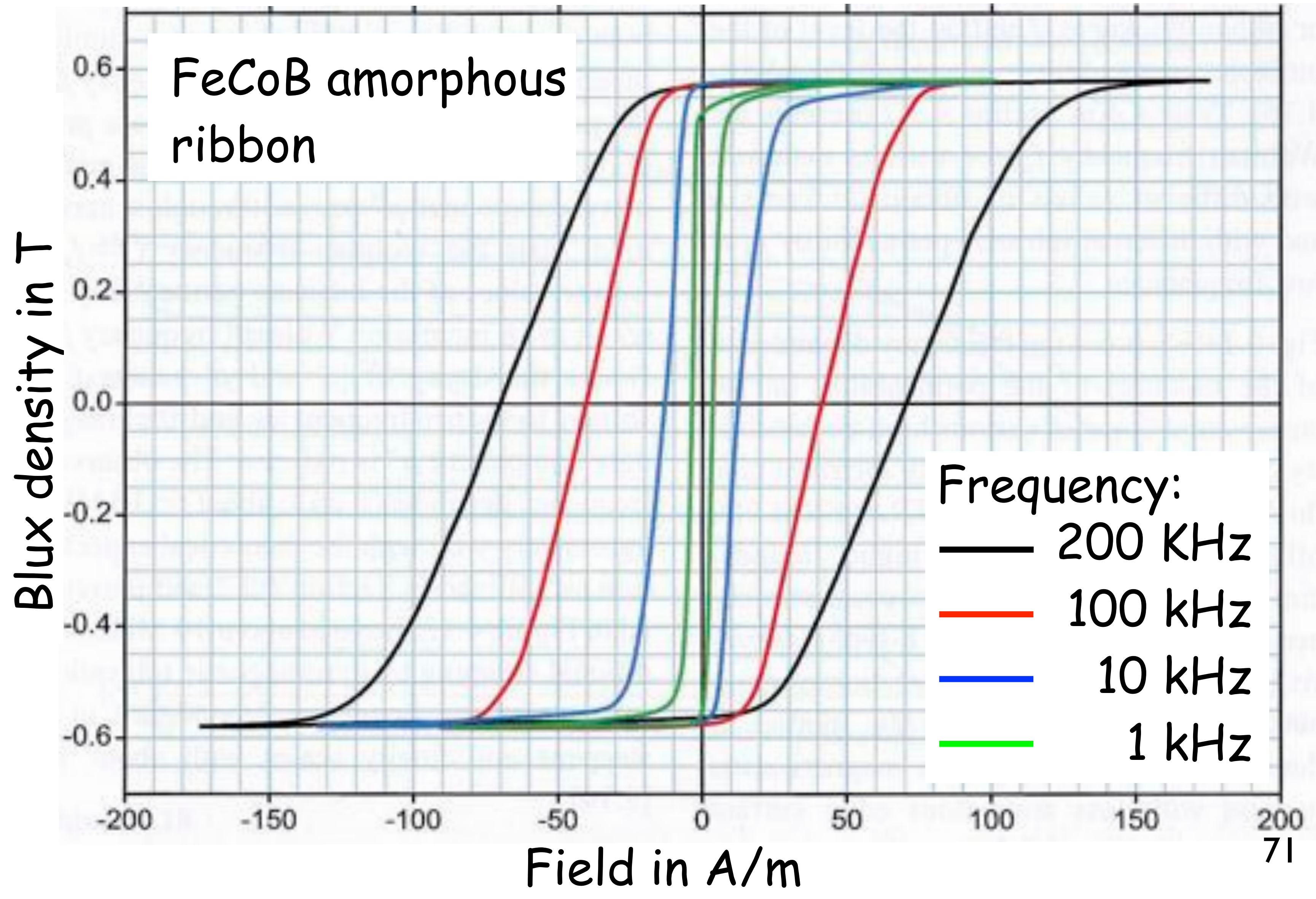
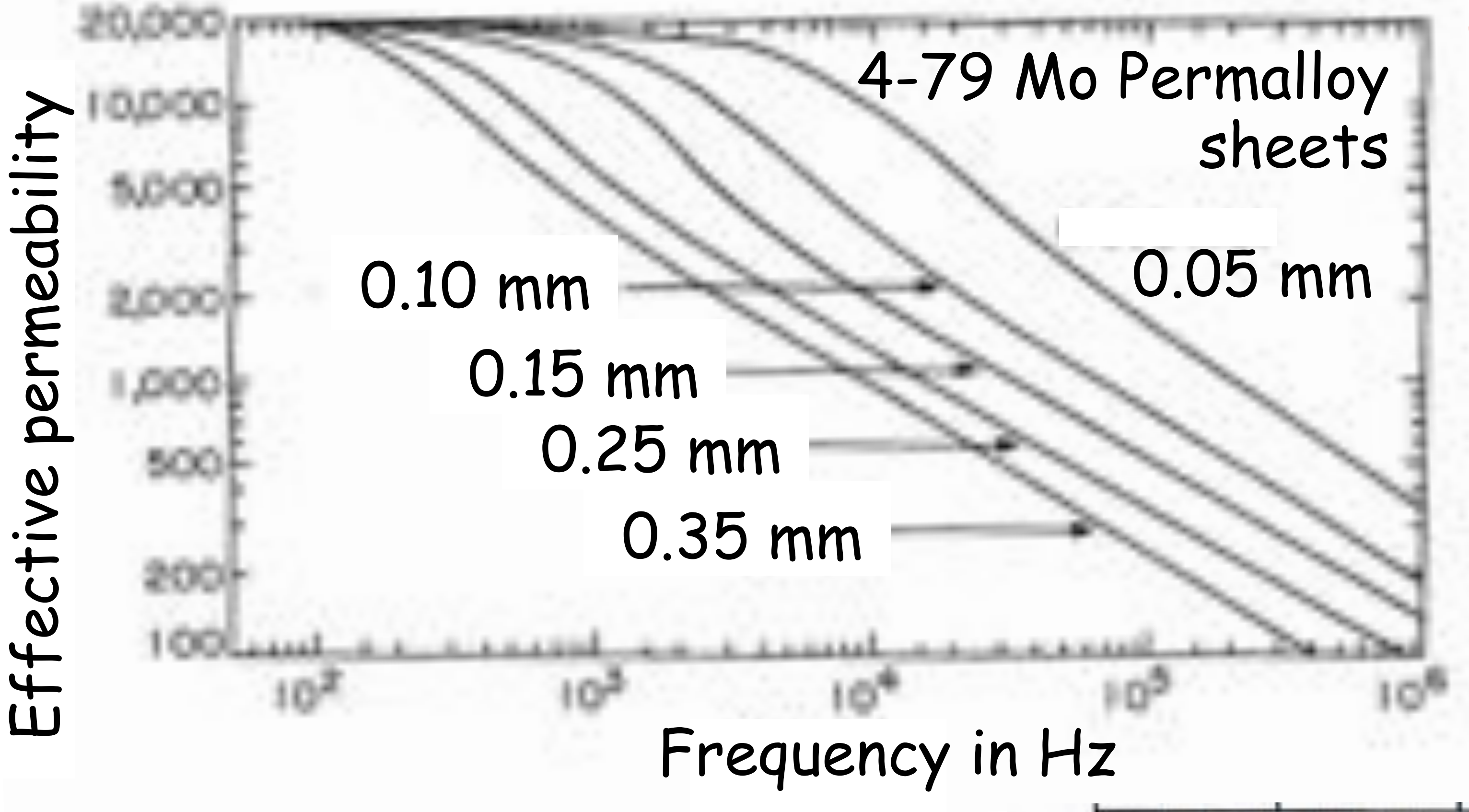
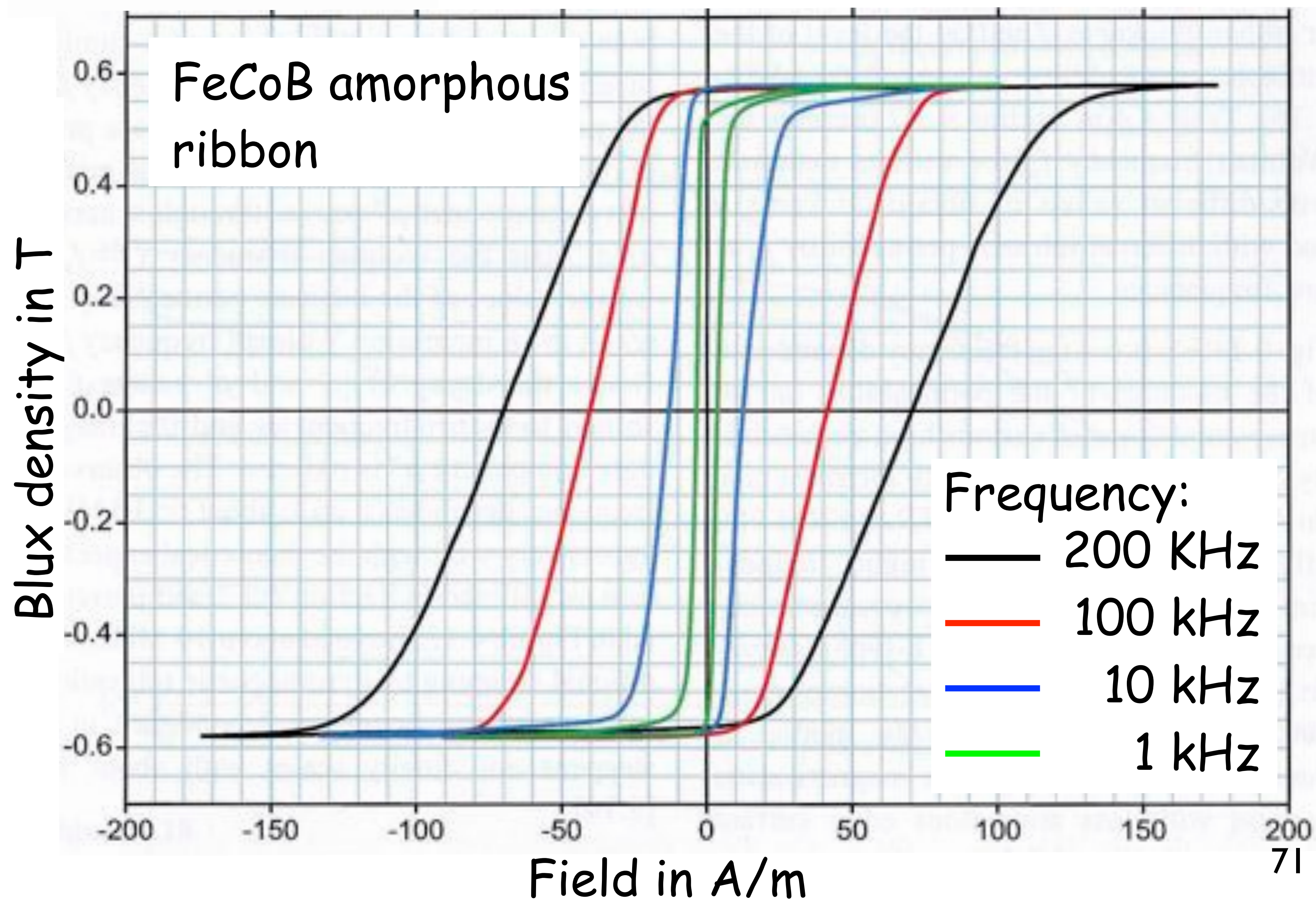


l Considerations



Area of hysteresis curve (≙ power loss) increases with frequency

Permeability decreases with frequency (depends on sheet thickness)



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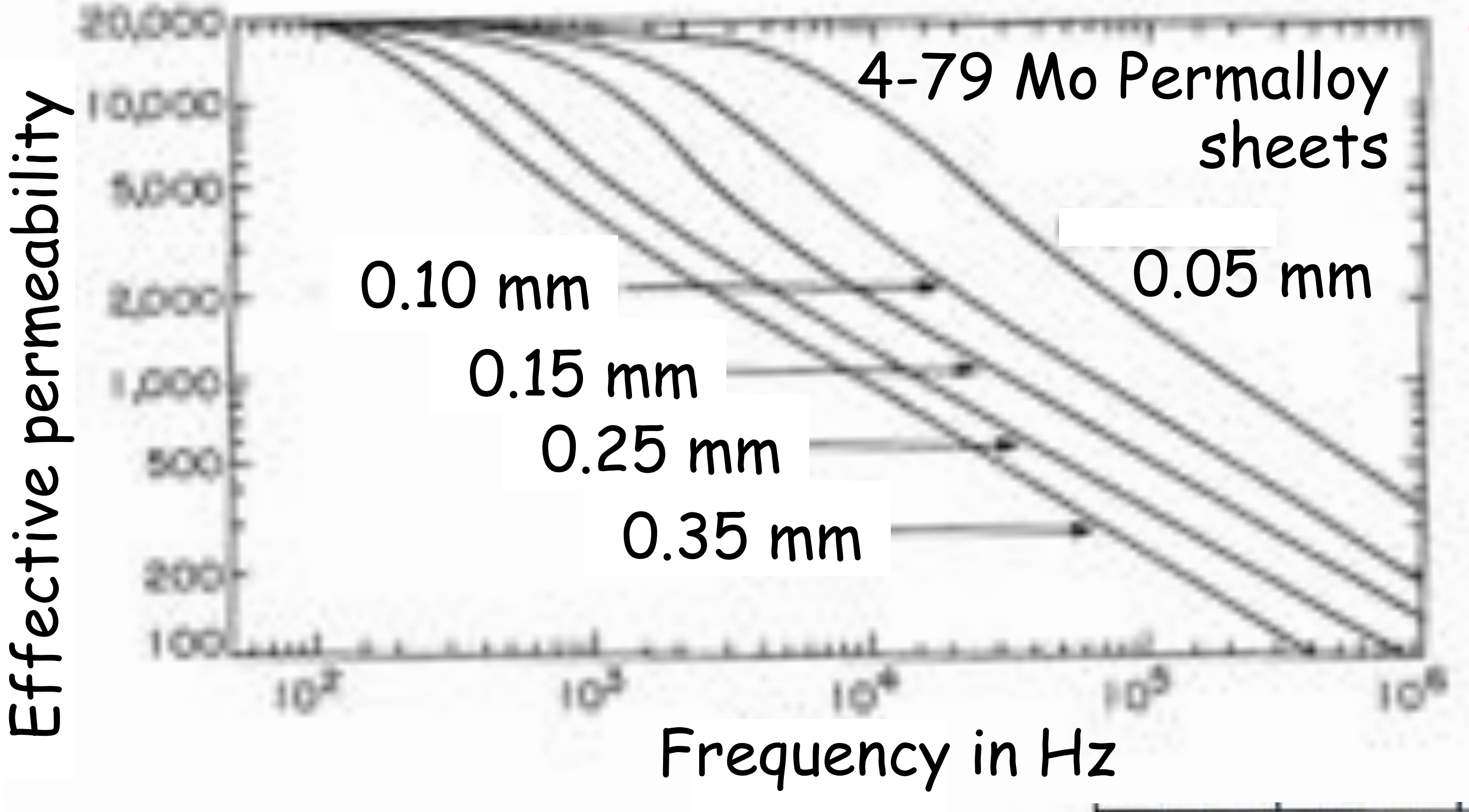

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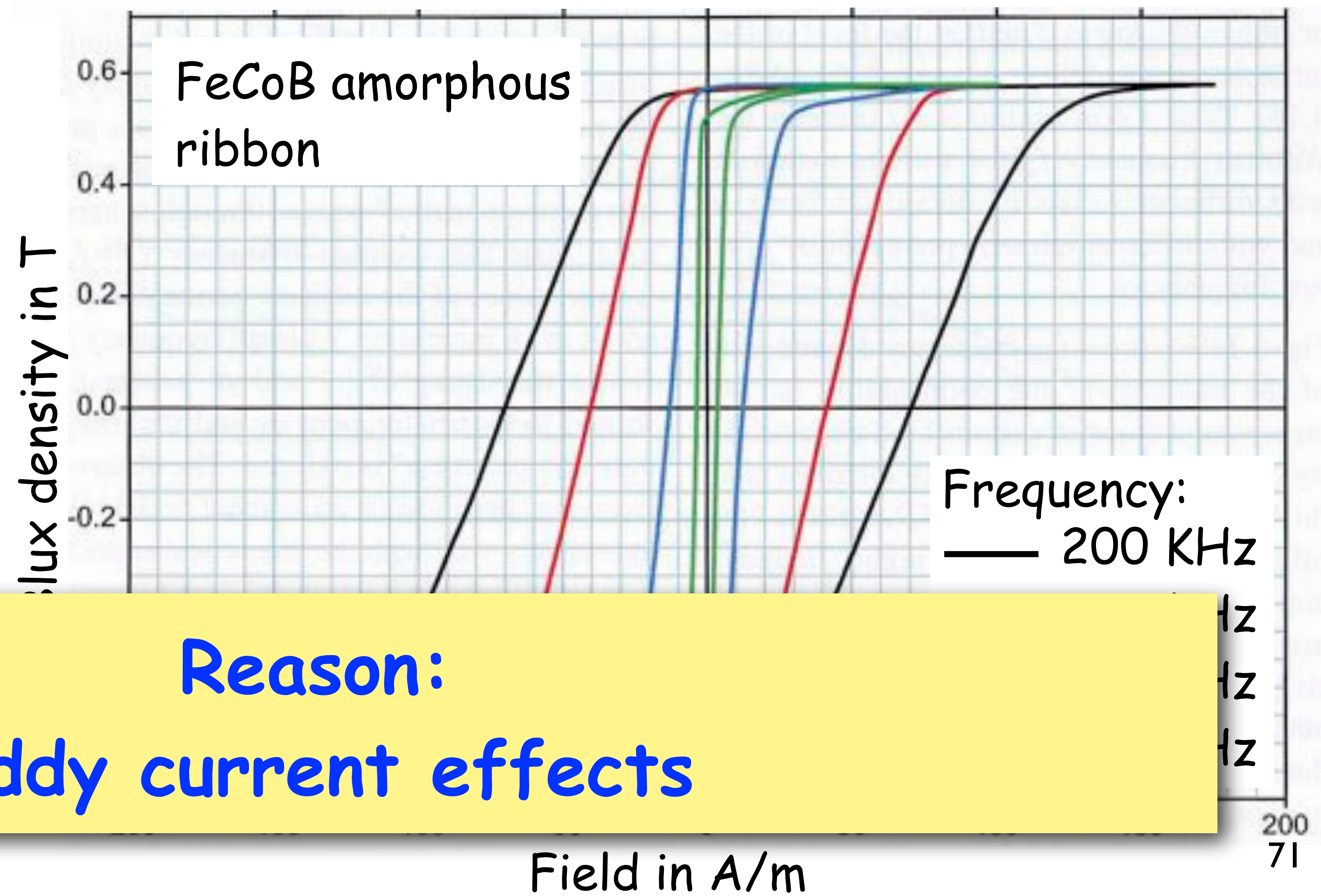
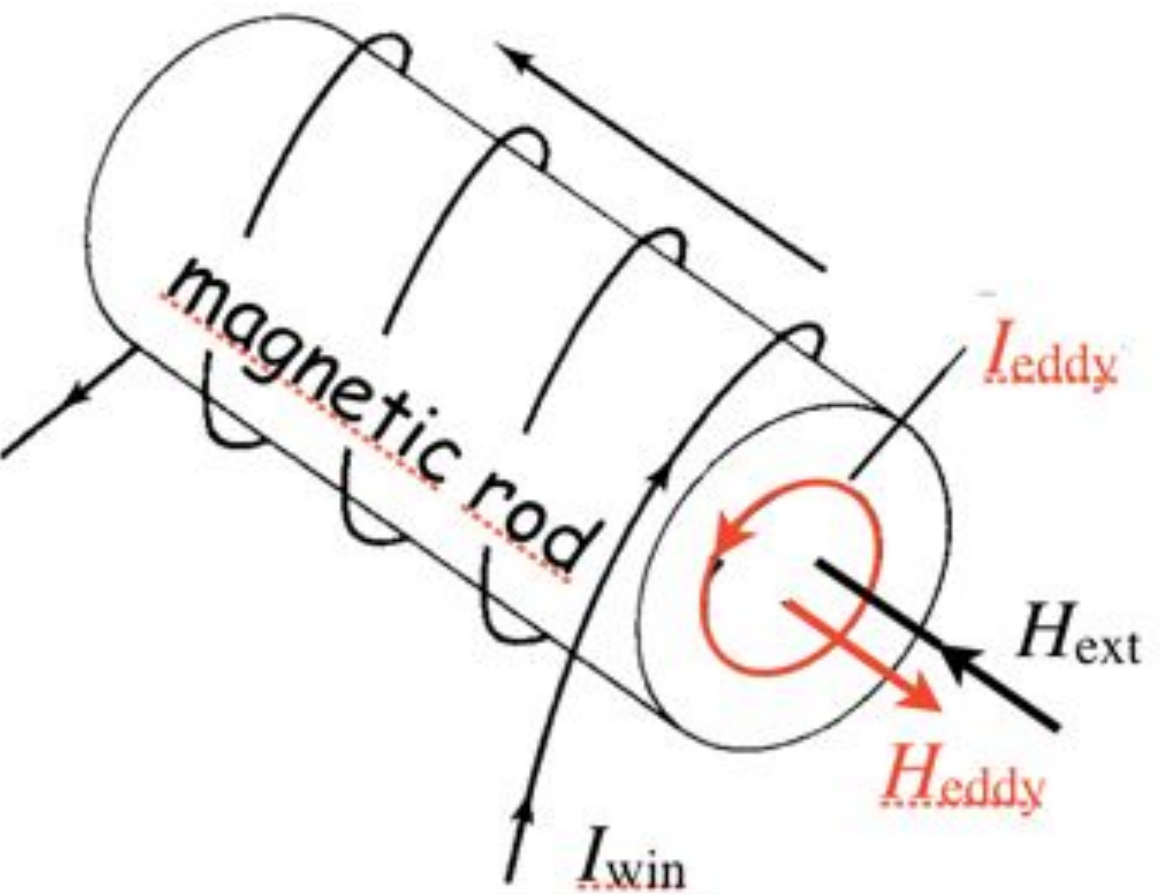
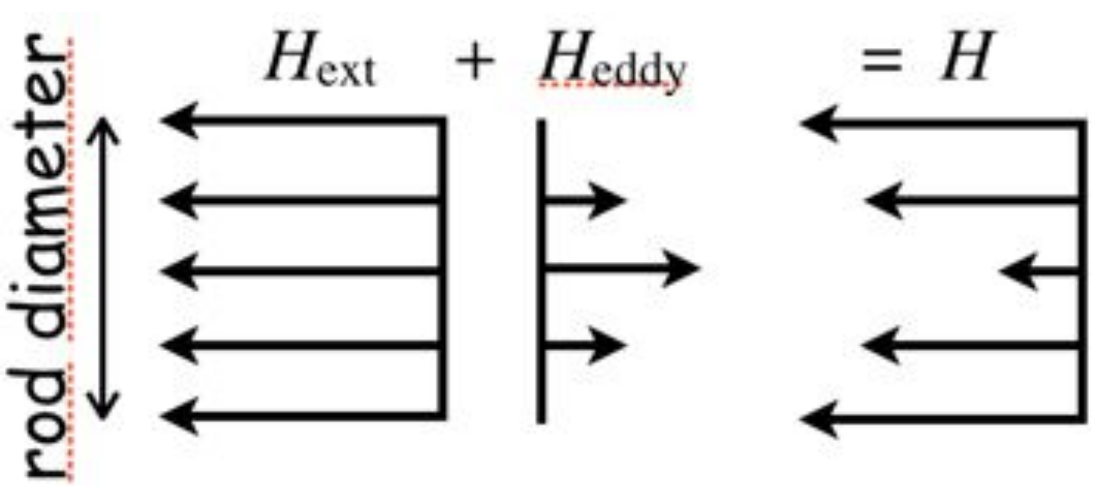


Reason:
Eddy current effects

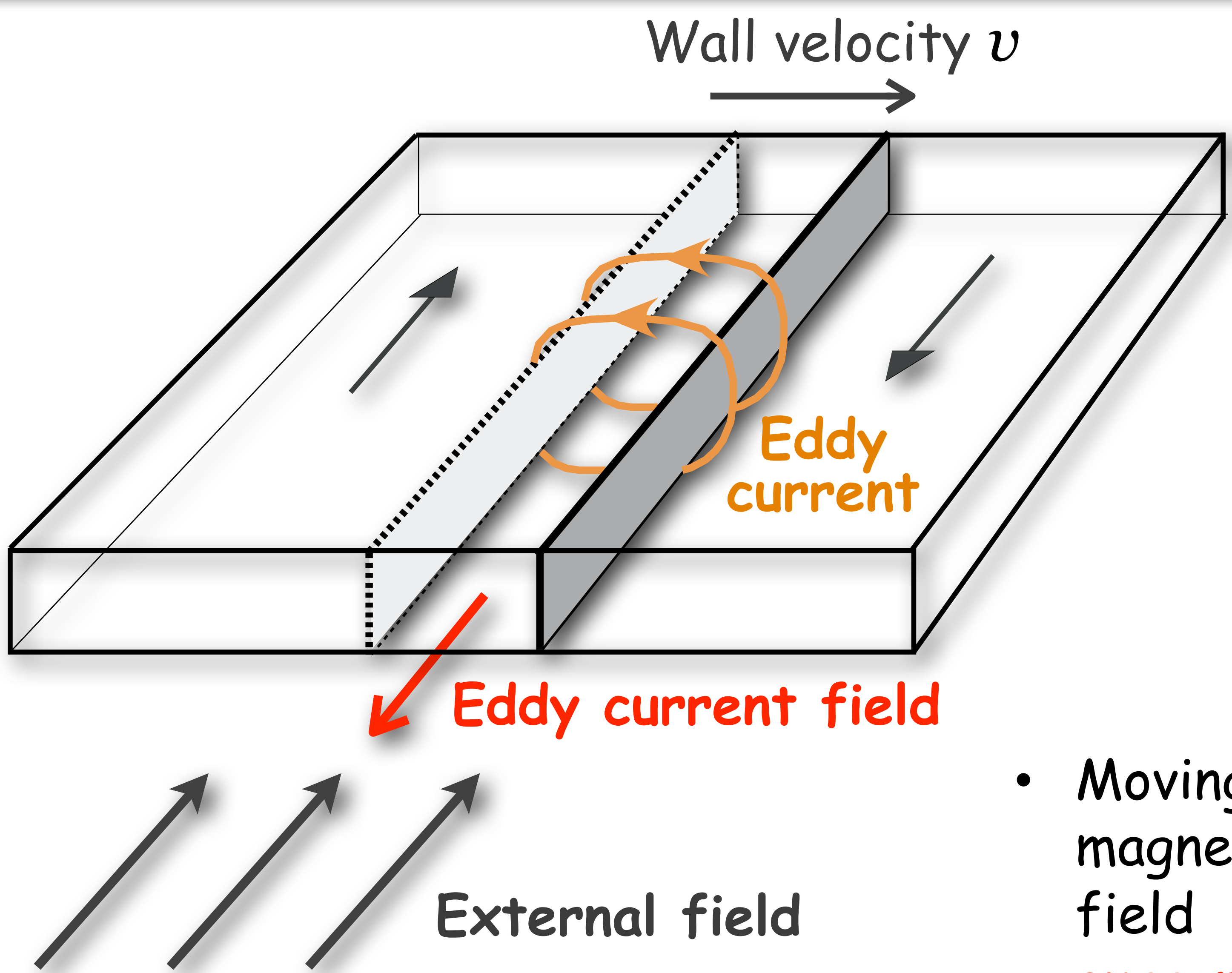
Eddy currents





- Current pulse in coil
  → changing magnetic flux $\partial \boldsymbol{B}/\partial t$
- Faraday law $\mathrm{rot}\boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$
  → circular electric field → **eddy currents**
- Lenz's rule: eddy current field opposes $\boldsymbol{H}_{\mathrm{ext}}$ (in magnetic material: eddy currents are high as permeability μ is very large and $\boldsymbol{B} = \mu \boldsymbol{H}$)
- Interior of rod: eddy current field strong because contributions from current rings add up
- Applied ac field: Eddy currents change direction permanently → middle of rod: maximum induction $\boldsymbol{B}$ of outer parts is never reached because $\boldsymbol{H}_{\mathrm{ext}}$ already decreases before $\boldsymbol{B}$ gets maximum in middle → Interior of rod is shielded from external field by eddy currents → magnetic flux restricted to surface region („**skin effect**“). Effect increases with rising frequency

Eddy currents and permeability: wall damping



- When wall is set in motion → change of magnetization is restricted to moving wall (permeability of domains can be neglected)
- Moving wall generates eddy currents, the magnetic field of which weakens the driving field → wall velocity decreases = **eddy current damping**
- With increasing frequency (i.e. wall velocity) this effect increases, so that wall contribution to magnetization process decreases with frequency → permeability ↓
- Eddy currents generate heat and loss. The lost energy has to be delivered by the power source to keep the wall in motion

Specific eddy current loss due to wall motion ~ v^2 (v = const)

Eddy currents and permeability: wall damping

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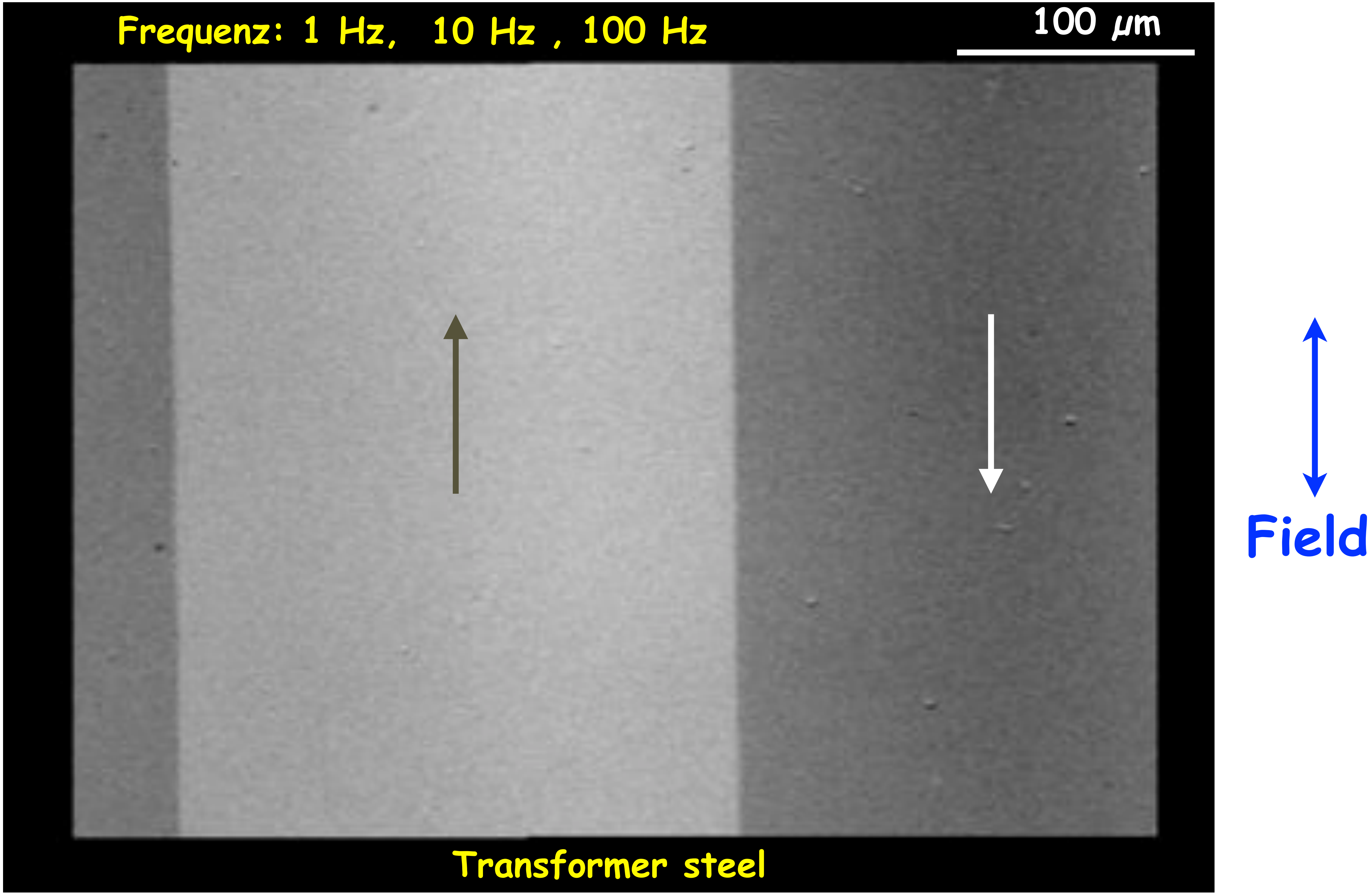

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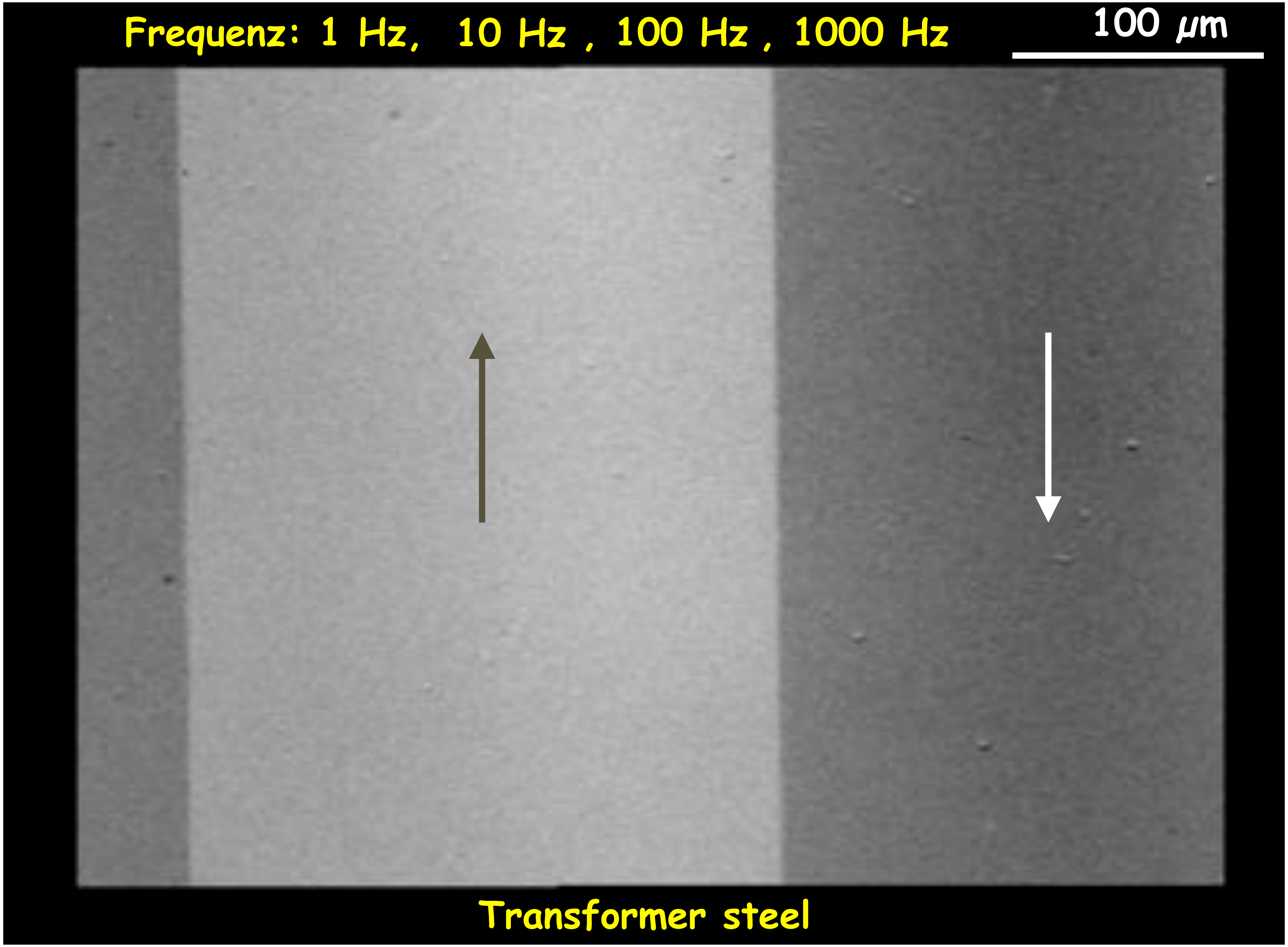
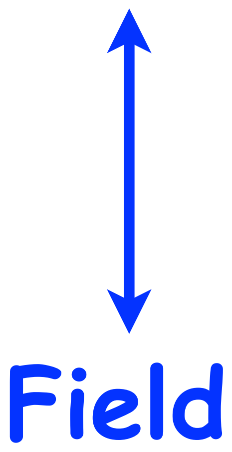
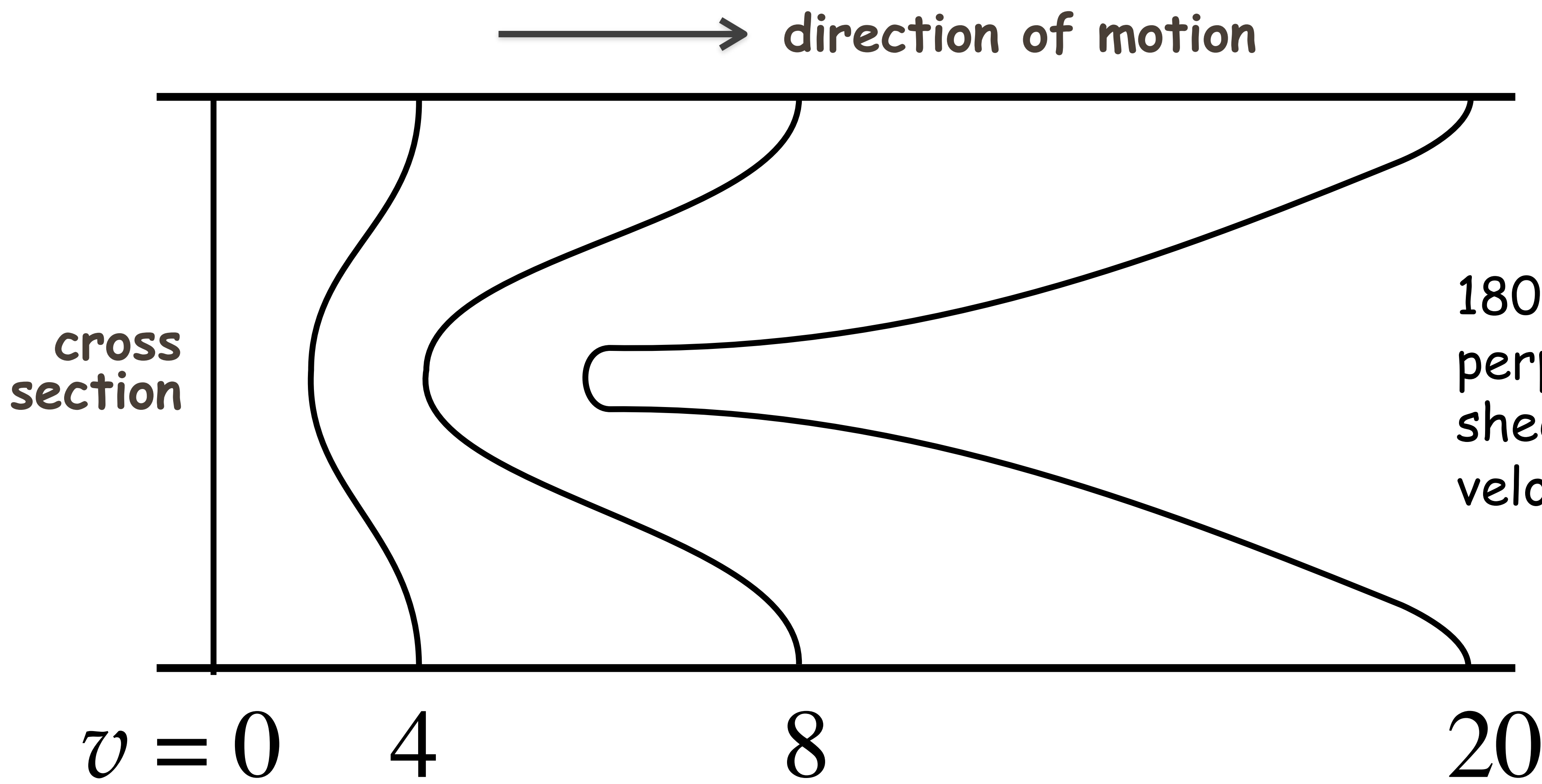




Eddy currents and permeability: wall bowing



180° wall that runs perpendicular across the sheet, with increasing velocity (in reduced units)

Eddy current-induced magnetic field is weaker at surface than in the bulk

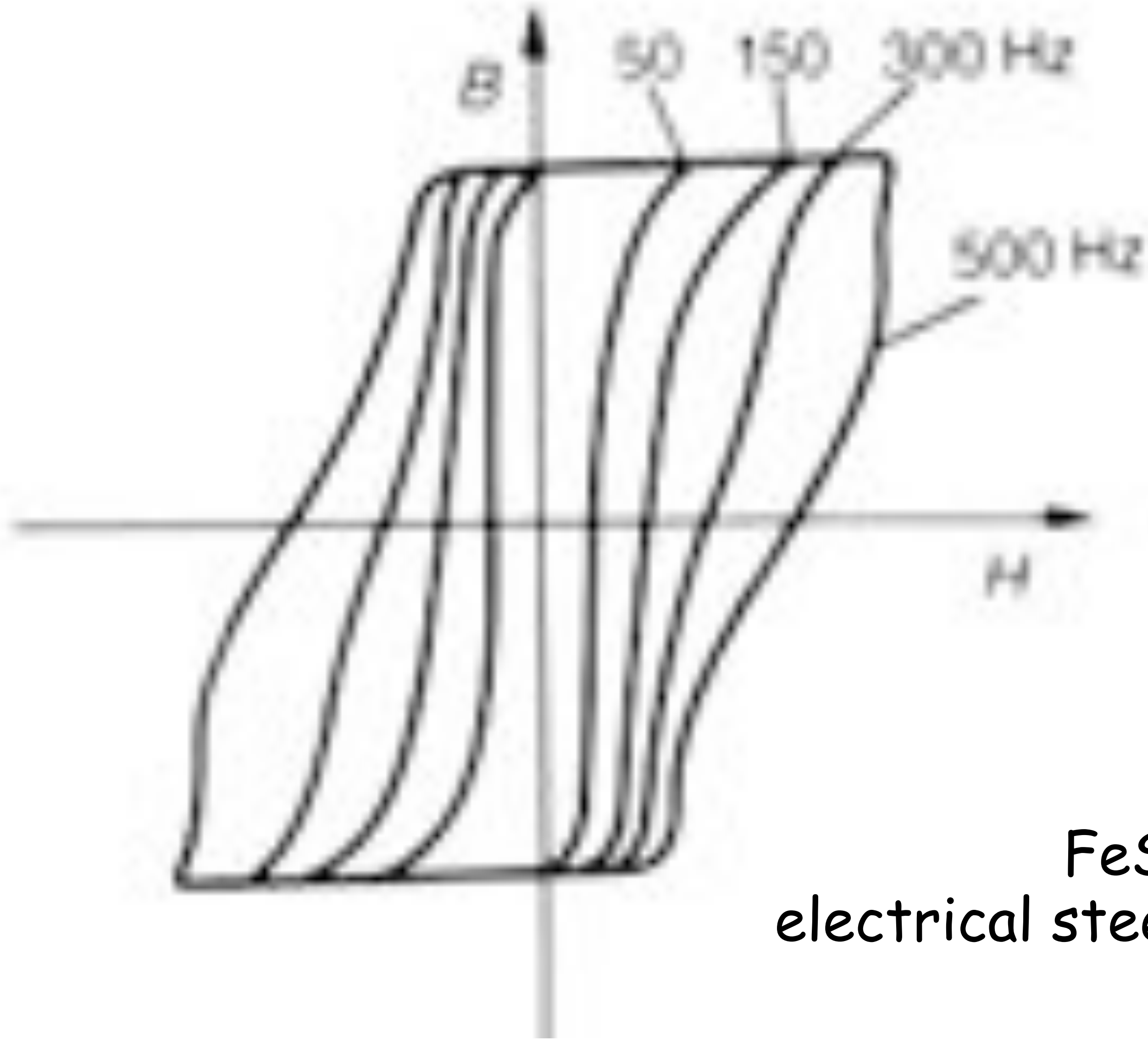
→ Wall moves faster at the surface

High velocities: walls run mostly parallel to the surface (**skin effect**)

Power losses

- General: loss of energy ≙ area of hysteresis loop
- Rising frequency
  → Hysteresis area increases
  → Loss increases
- **5 loss mechanisms:**

(A) Hysteresis loss
(B) Eddy current loss
(C) Anomalous loss
(D) After-effect loss
(E) Intrinsic loss



FeSi
electrical steel

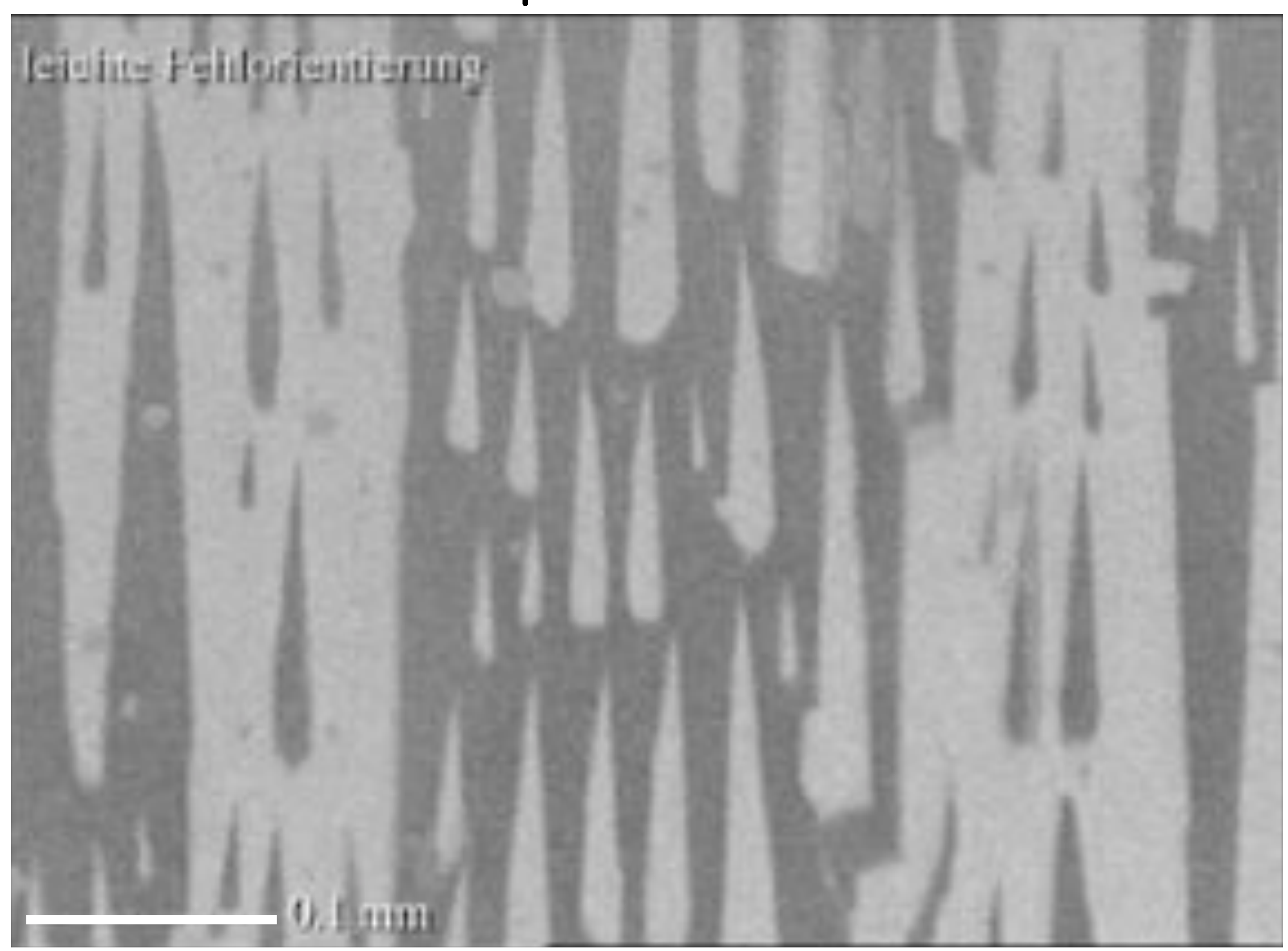
(A) Hysteresis loss

- Occurs at slow remagnetizaton ($f < 0.1$ Hz → quasistatic magnetization)
- Reasons:
  - (i) Localized eddy currents at Barkhausen jumps.
  - (ii) Rearrangement of domain patterns (e.g. transformer steel: system of lancet domains is cyclically destroyed and rebuilt again → energy, that is connected with lancet pattern, gets lost in each cycle)
  - Hysteresis loss per cycle:

$$\frac{P_{hys}}{f} = \frac{4 H_c B_m}{d}$$

B_m: induction amplitude
f: frequency
d: density

Lancet pattern in transformer steel



alternating field

(B) Eddy current loss

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- Eddy currents: Cause heat ~ $I_{\mathrm{eddy}}^{2} \bullet R$ (R = elect. resistance along current path)

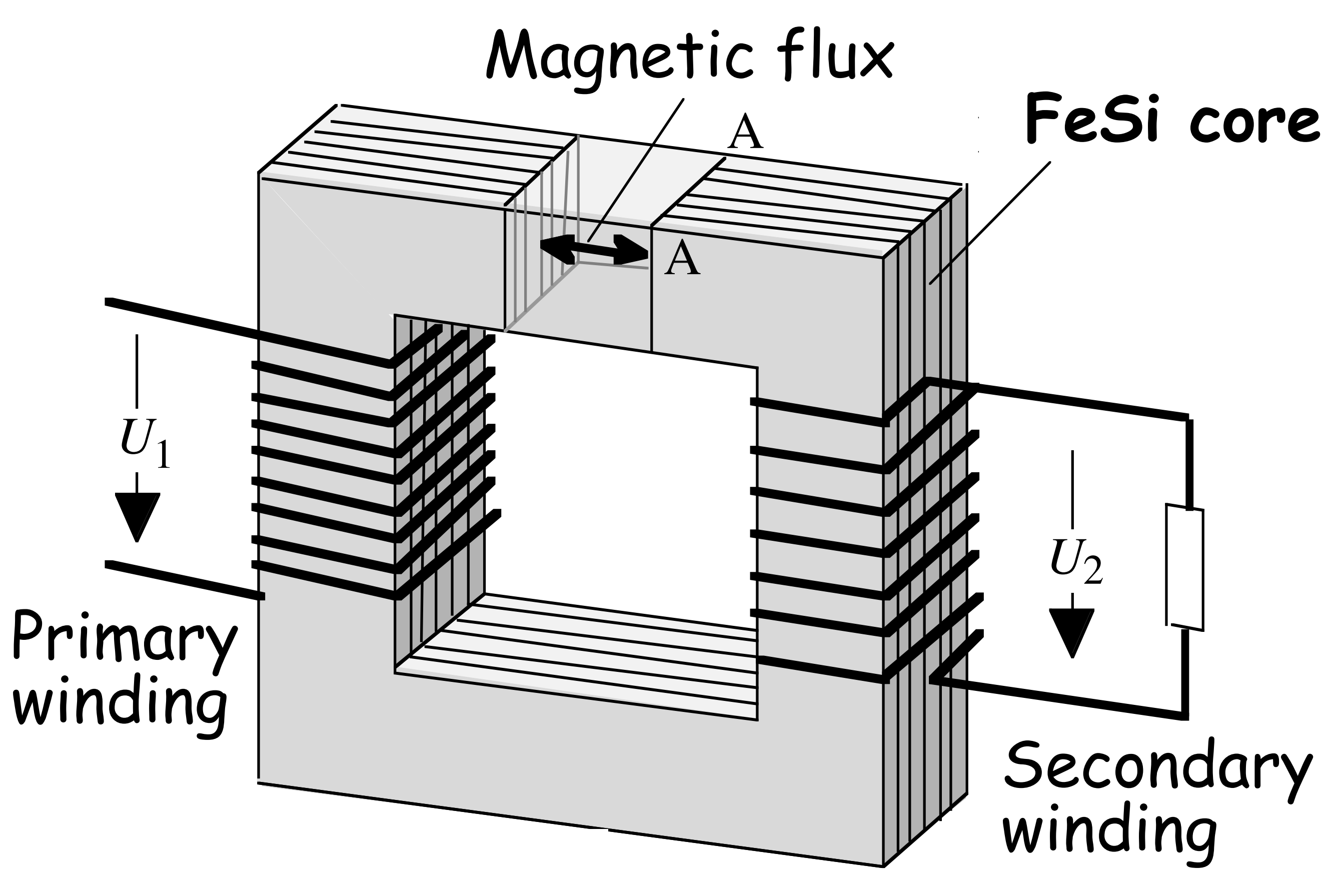
  → **Eddy current loss**

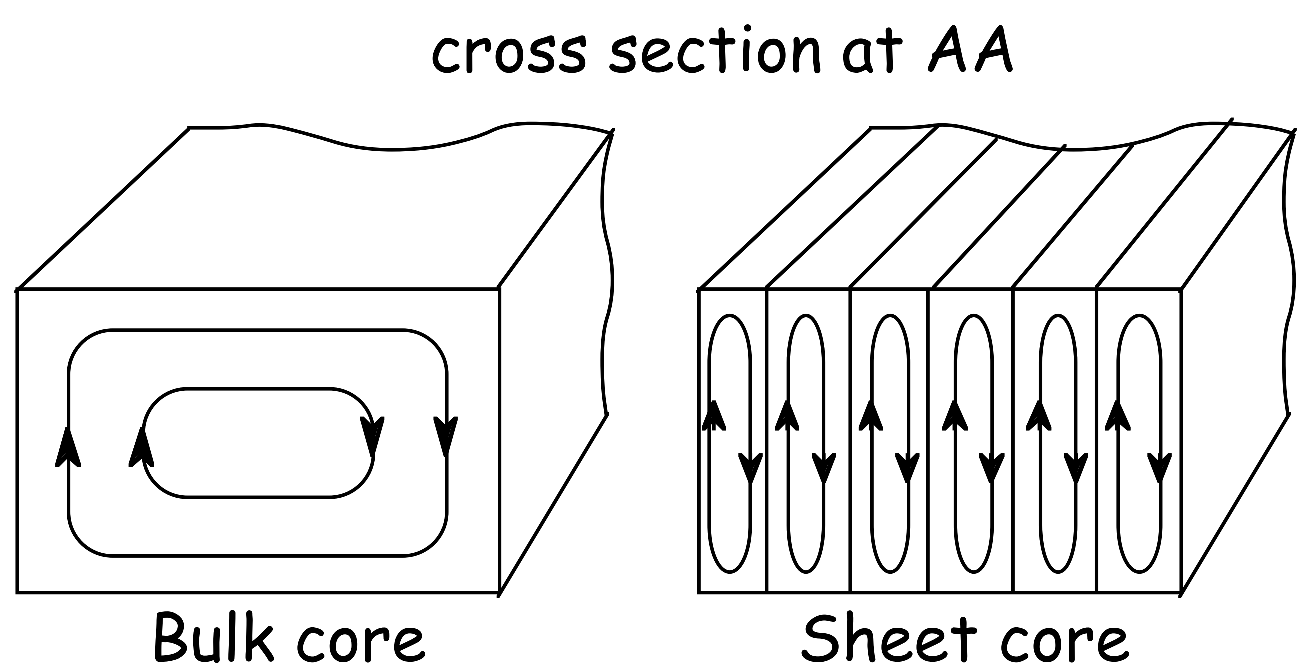
(B) Eddy current loss

- Eddy currents: Cause heat ~ $I_{\text{eddy}}^2 \cdot R$ (R = elect. resistance along current path)

  → **Eddy current loss**

- Reduction of loss: Core made of isolated sheets →
  - Shorter current path → $R\downarrow$
  - Smaller cross sectional area → $\partial \boldsymbol{B}/\partial t\downarrow$ → $U_{\text{ind}}\downarrow$ (Faraday's law) → $I_{\text{eddy}}\downarrow$





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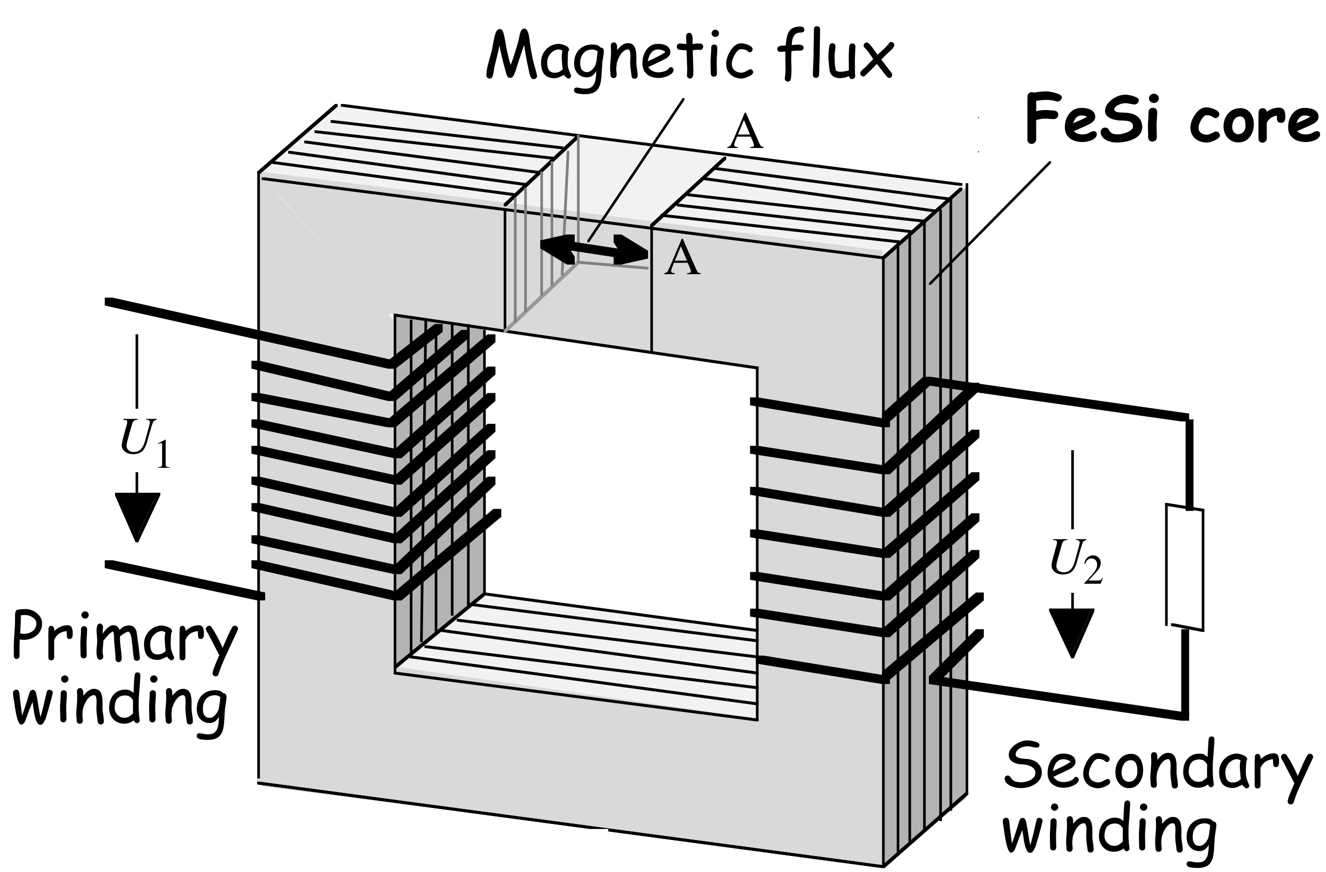
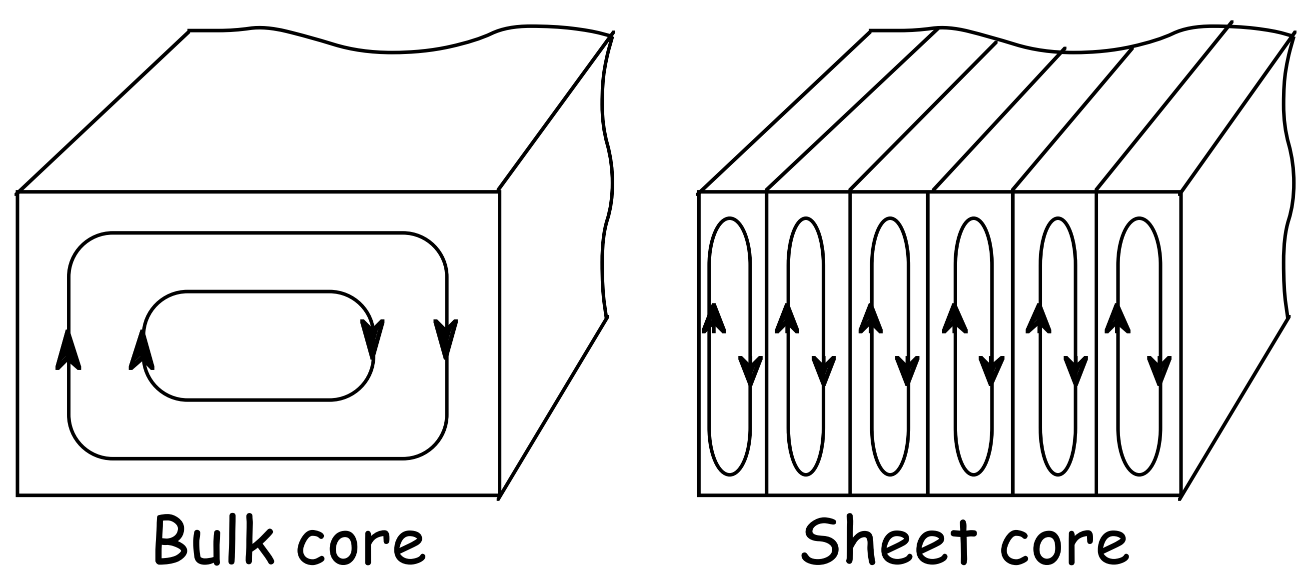
- For sheets: $$\frac{P_{\text{class}}}{f} = \frac{\pi^2 D^2 f B_{\text{m}}^2}{6\,\varrho\, d}$$

P_{class} : classical eddy current loss per cycle
D : sheet thickness
B_{m} : induction amplitude
f : frequency, ϱ : resistivity, d: density



cross section at AA



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Assumption: uniform sinusoidal induction, complete flux penetration

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Assumption: uniform sinusoidal induction, complete flux penetration

- Example: FeSi sheet,

  D = 0.5 mm, B_{m} = 1.5 Tesla, f = 50 Hz, ϱ = 55 µΩcm, d = 7.6 g/cm^3

  → P_{class}/f = $11\cdot10^{-3}$ J/kg

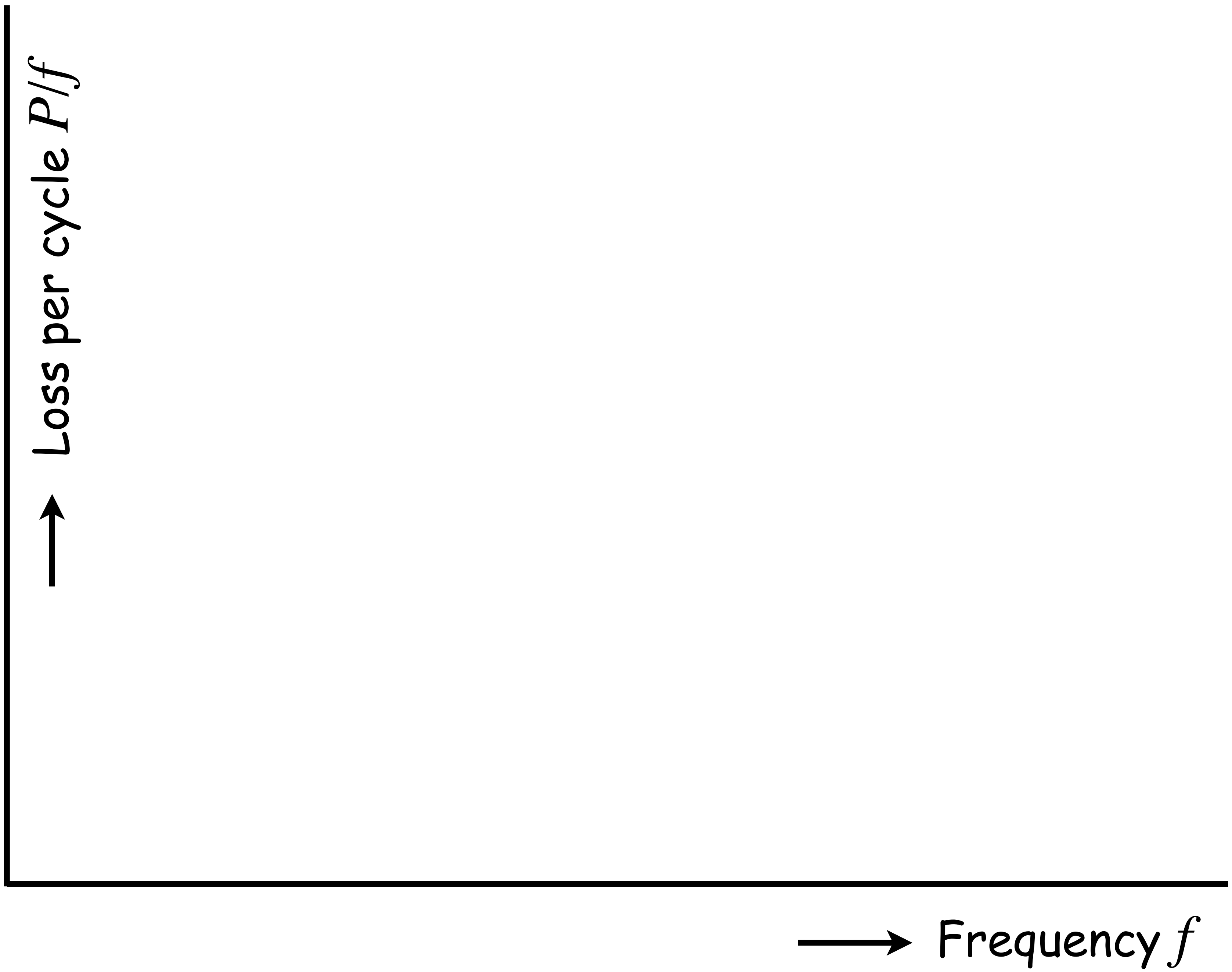
(B) Eddy current loss

Hysteresis loss per cycle:

$$\frac{P_{\text{hys}}}{f} = \frac{4H_c B_m}{d}$$

Classical eddy current loss per cycle:

$$\frac{P_{\text{class}}}{f} = \frac{\pi^2 D^2 f B_m^2}{6\,\varrho\,d}$$



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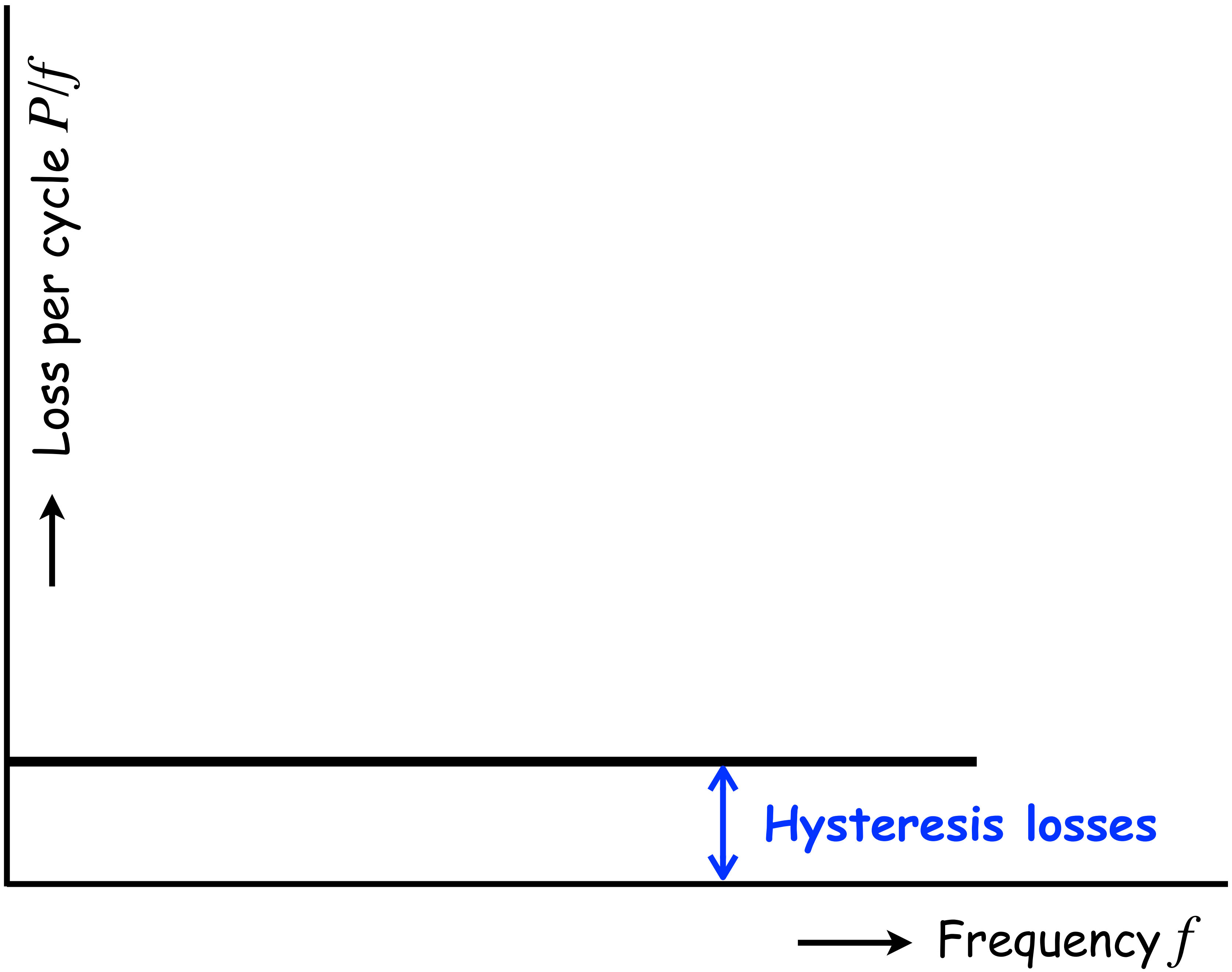

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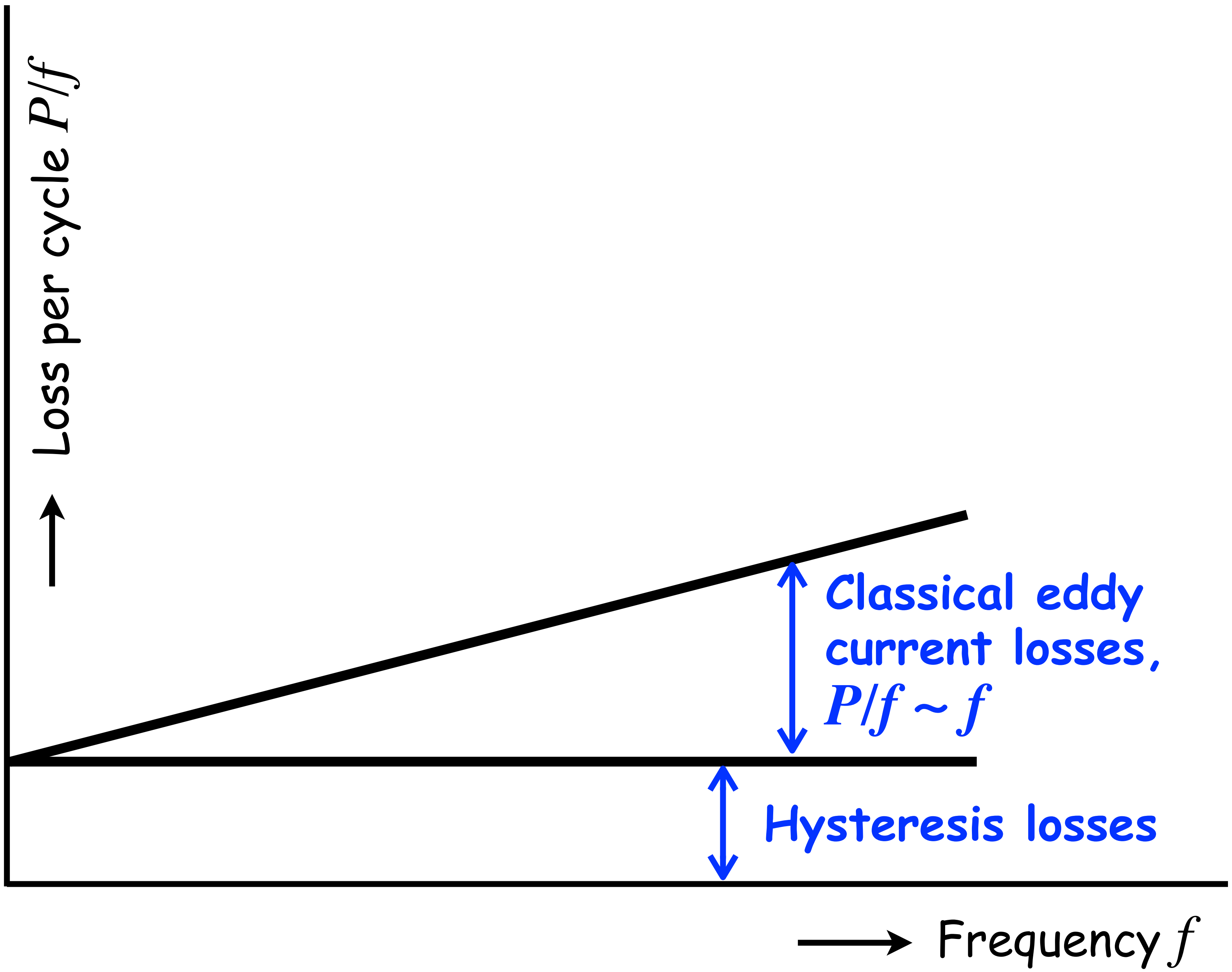

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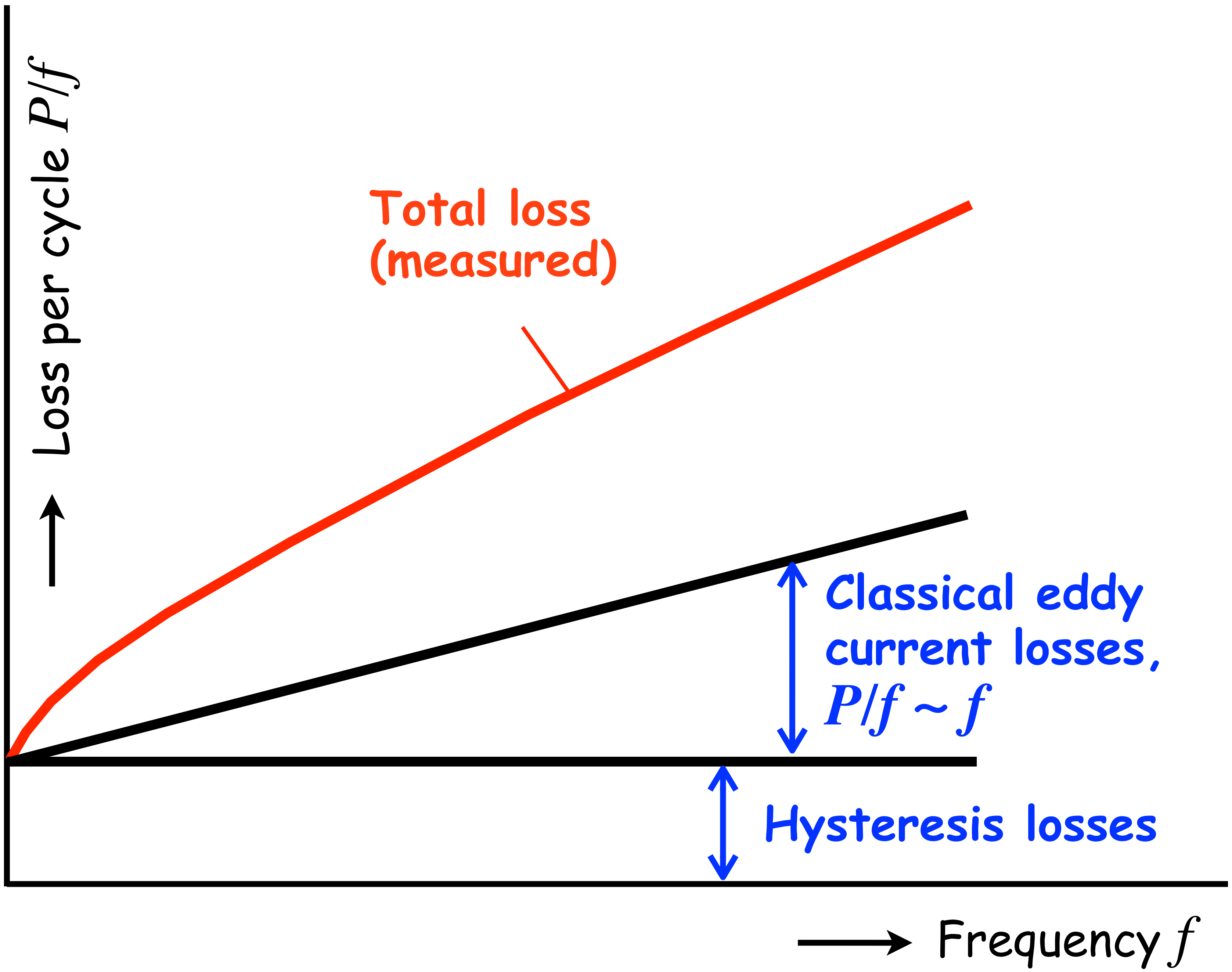

- Measured losses higher than classical eddy current losses

(C) Anomalous eddy current (excess) loss

Hysteresis loss per cycle:

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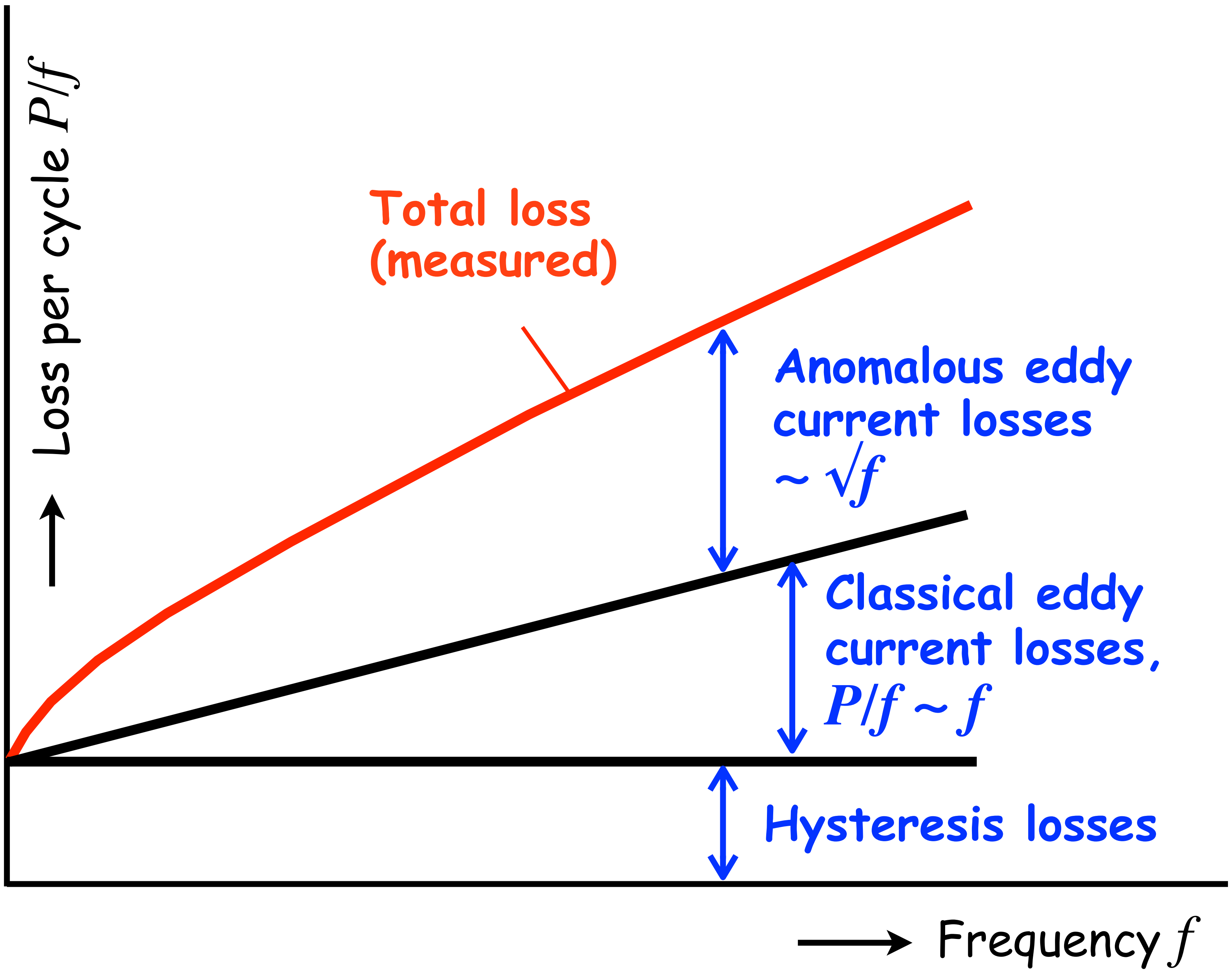

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- → **Excess (anomalous) eddy current losses**

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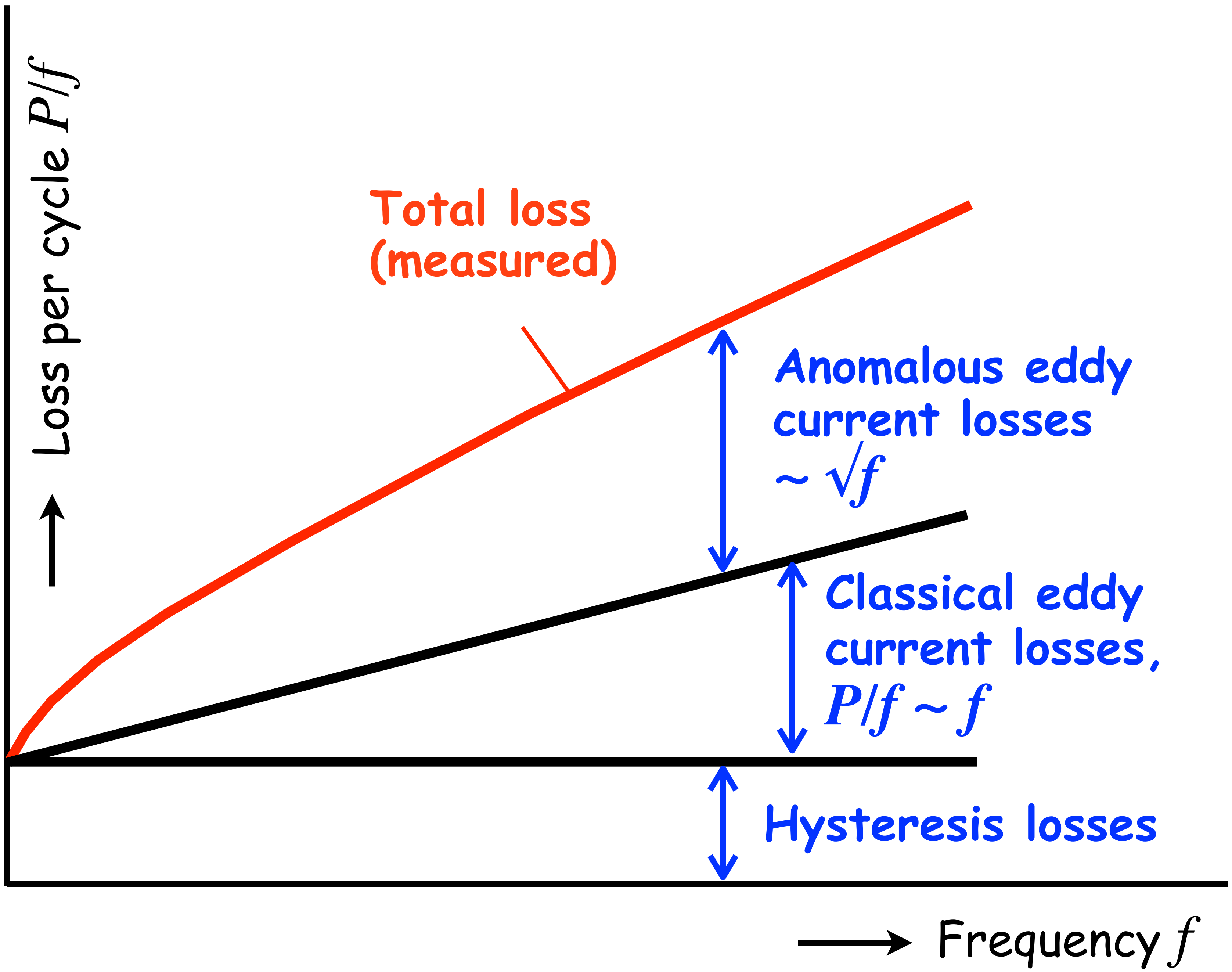

- Measured losses higher than classical eddy current losses
- → **Excess (anomalous) eddy current losses**
- Reason: Domain wall motion is inhomogeneous magnetization process: change of magnetization and consequently eddy currents are concentrated around moving domain walls (see above). This effect is not considered in formula of classical eddy current loss

(C) Anomalous eddy current (excess) loss

Hysteresis loss per cycle:

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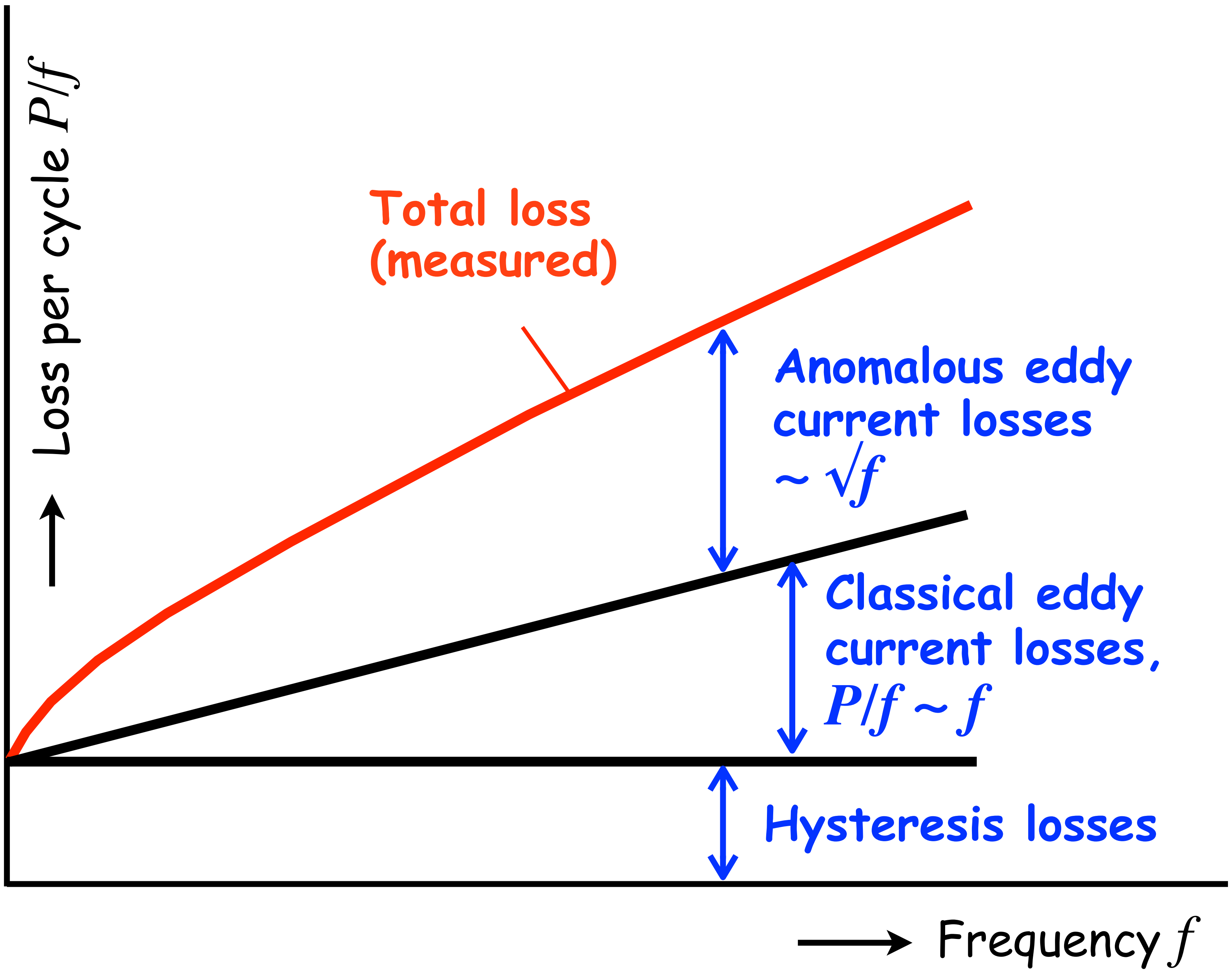
Eddy currents at moving walls:



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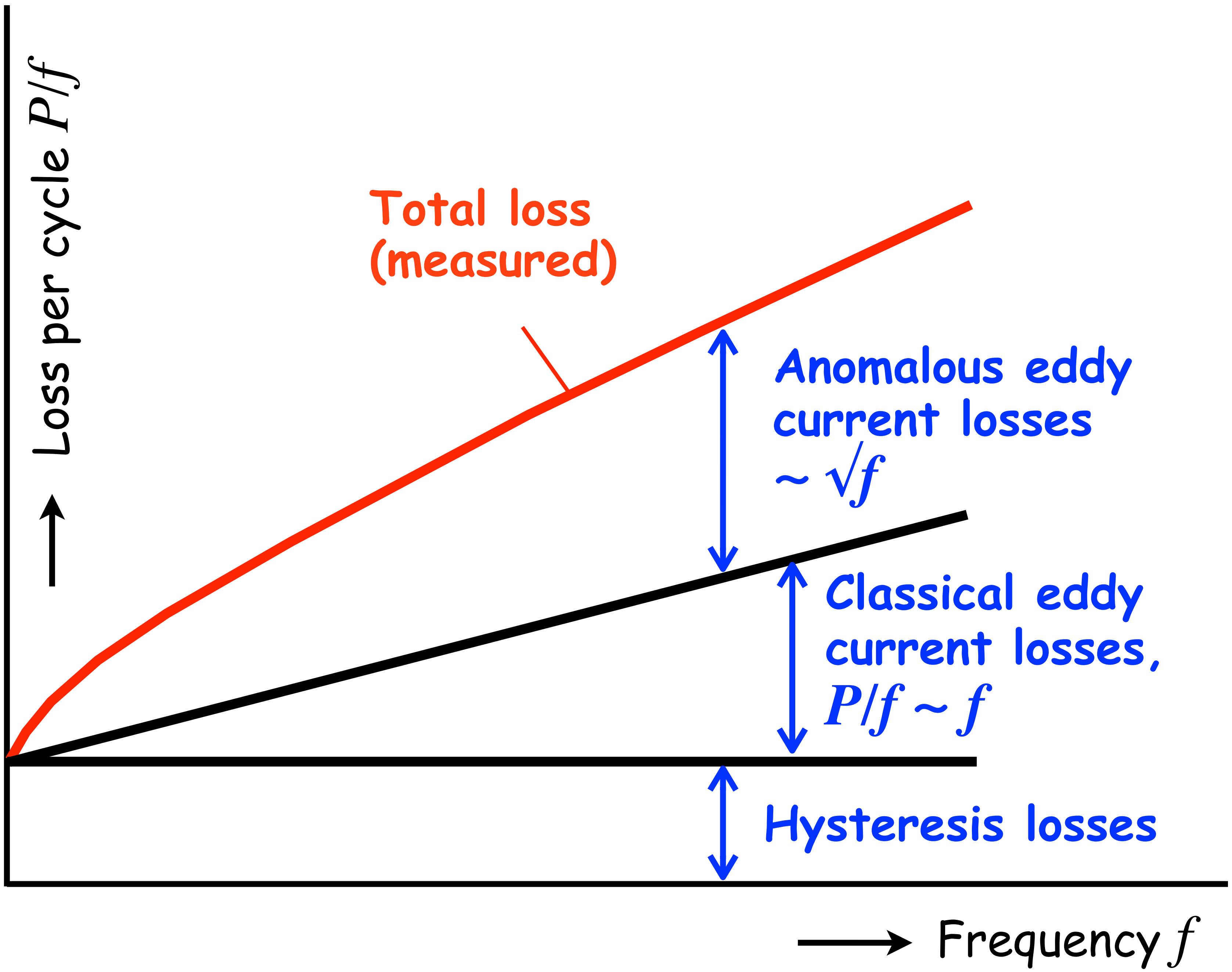

Eddy currents at moving walls:

- $\upsilon \sim f$
  - → $P_{eddy} \sim \upsilon^2 \sim f^2$
  - → $P/f \sim f$ expected

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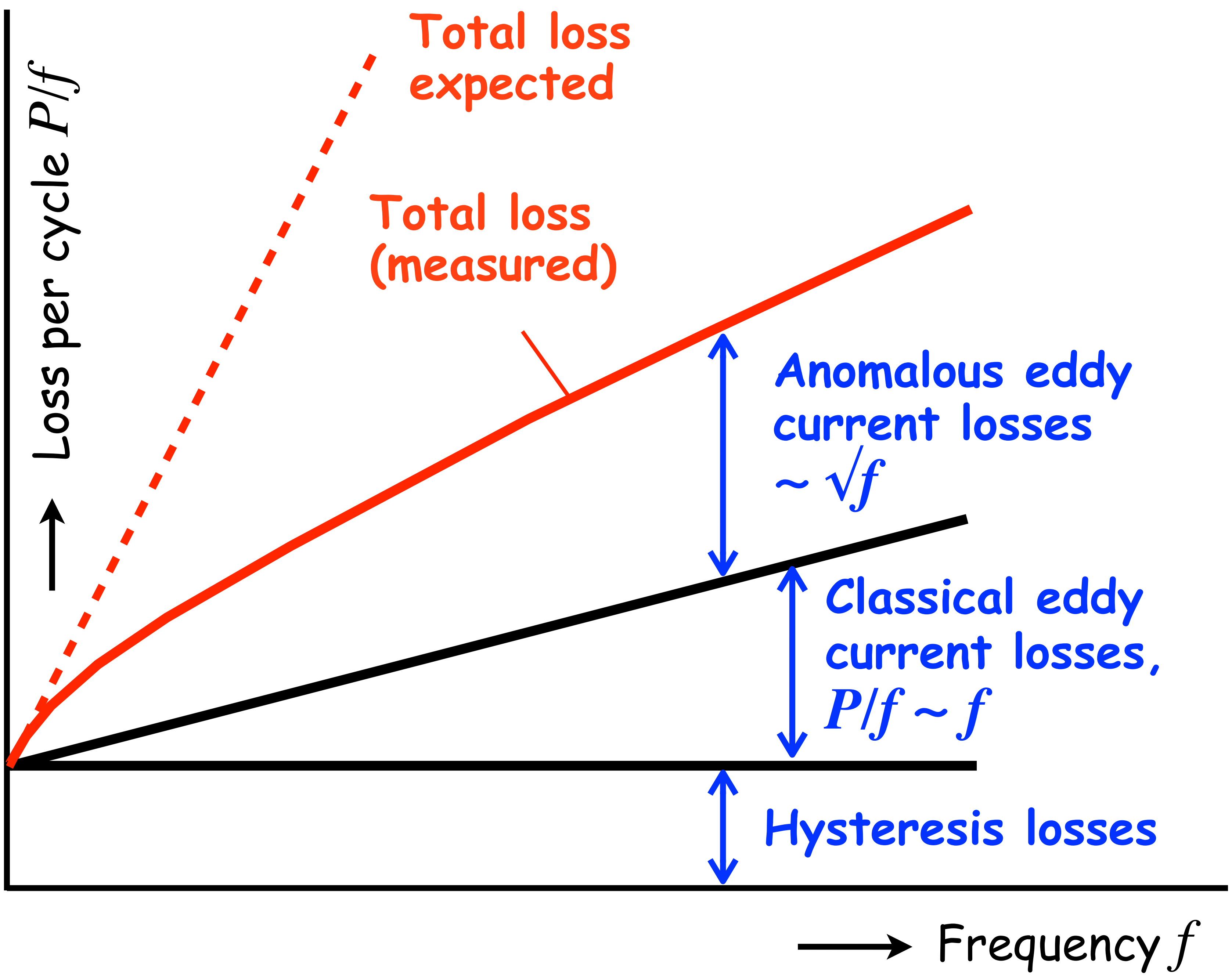

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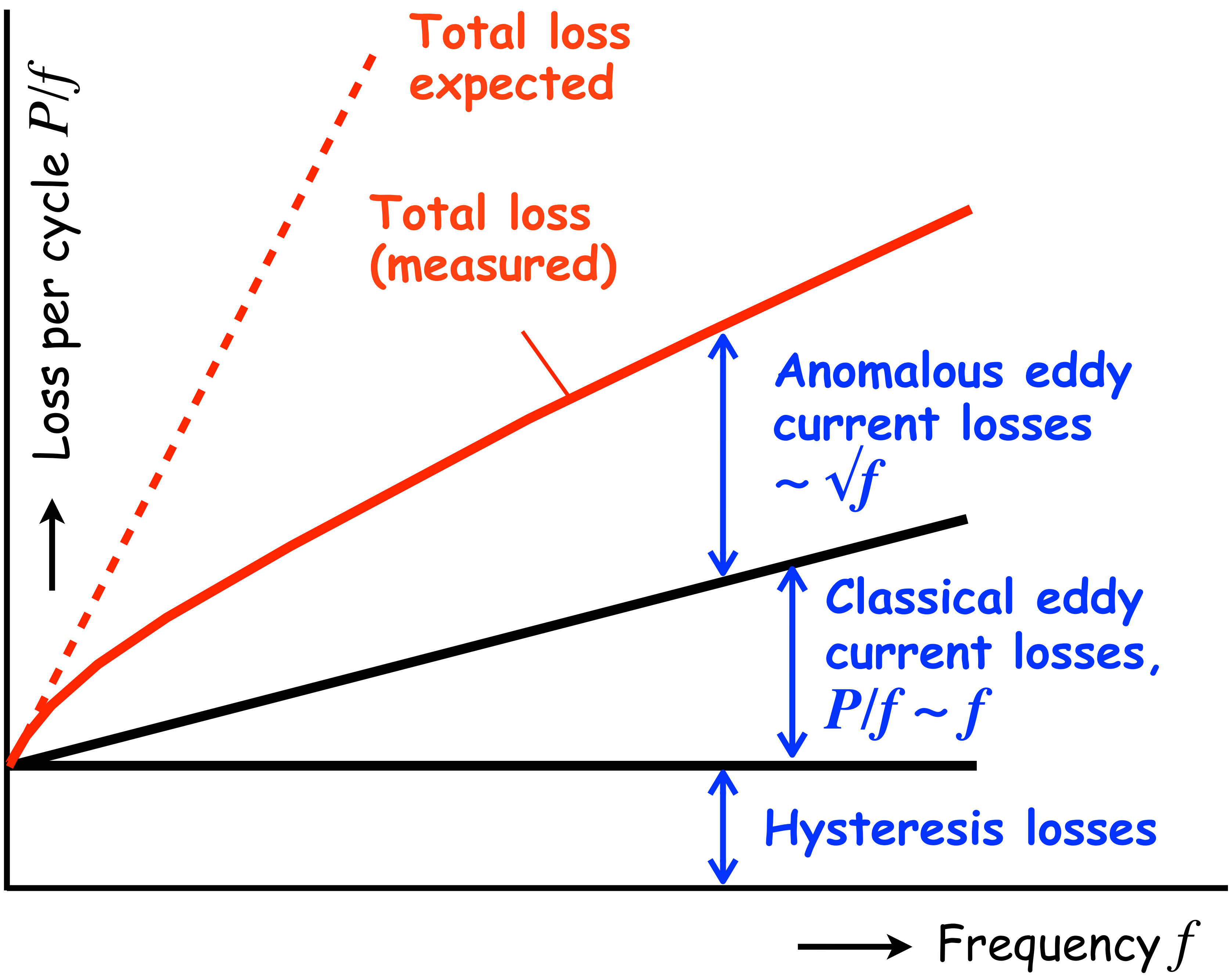

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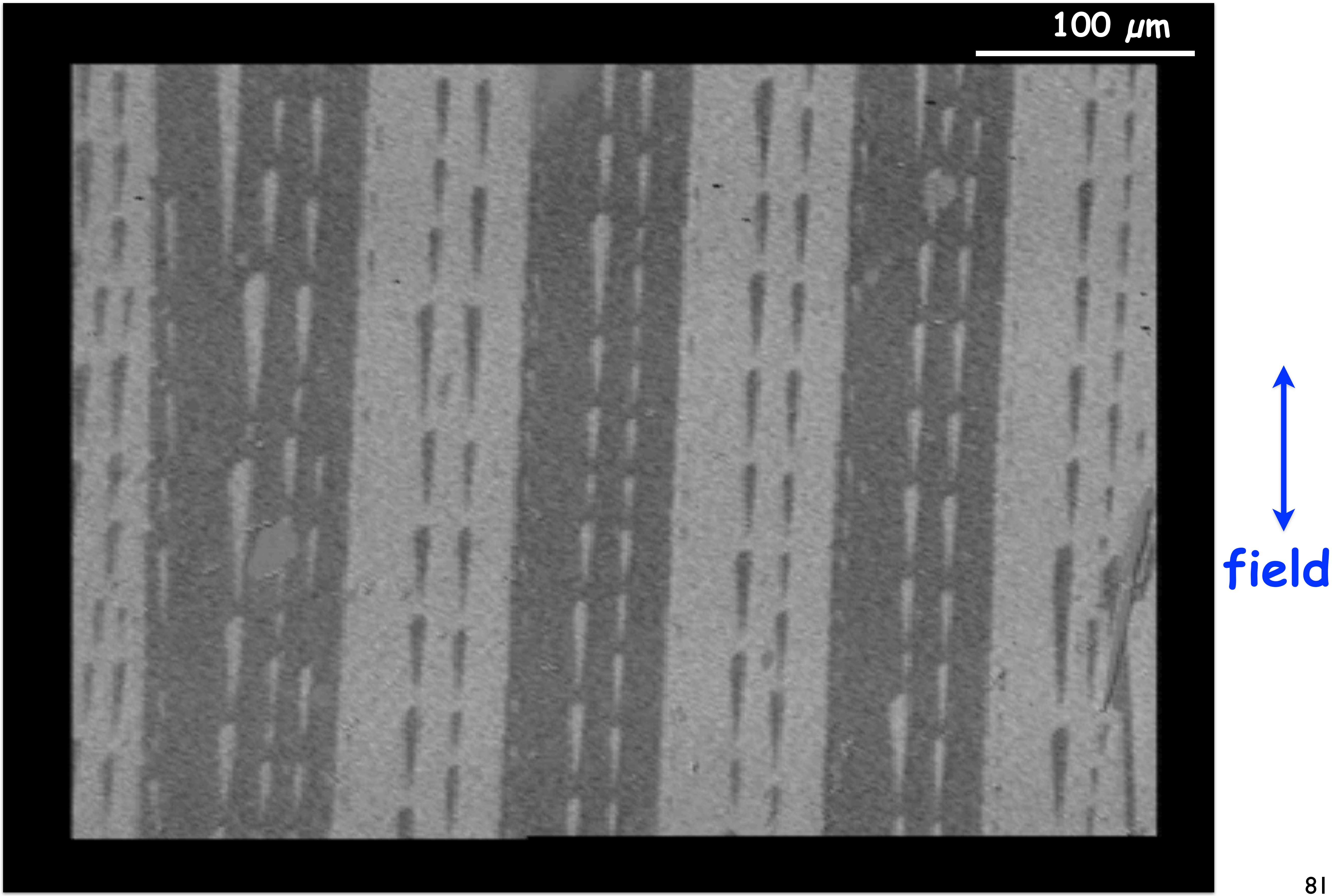
- However: P/f-curve non-linear

Domain multiplication in transformer steel



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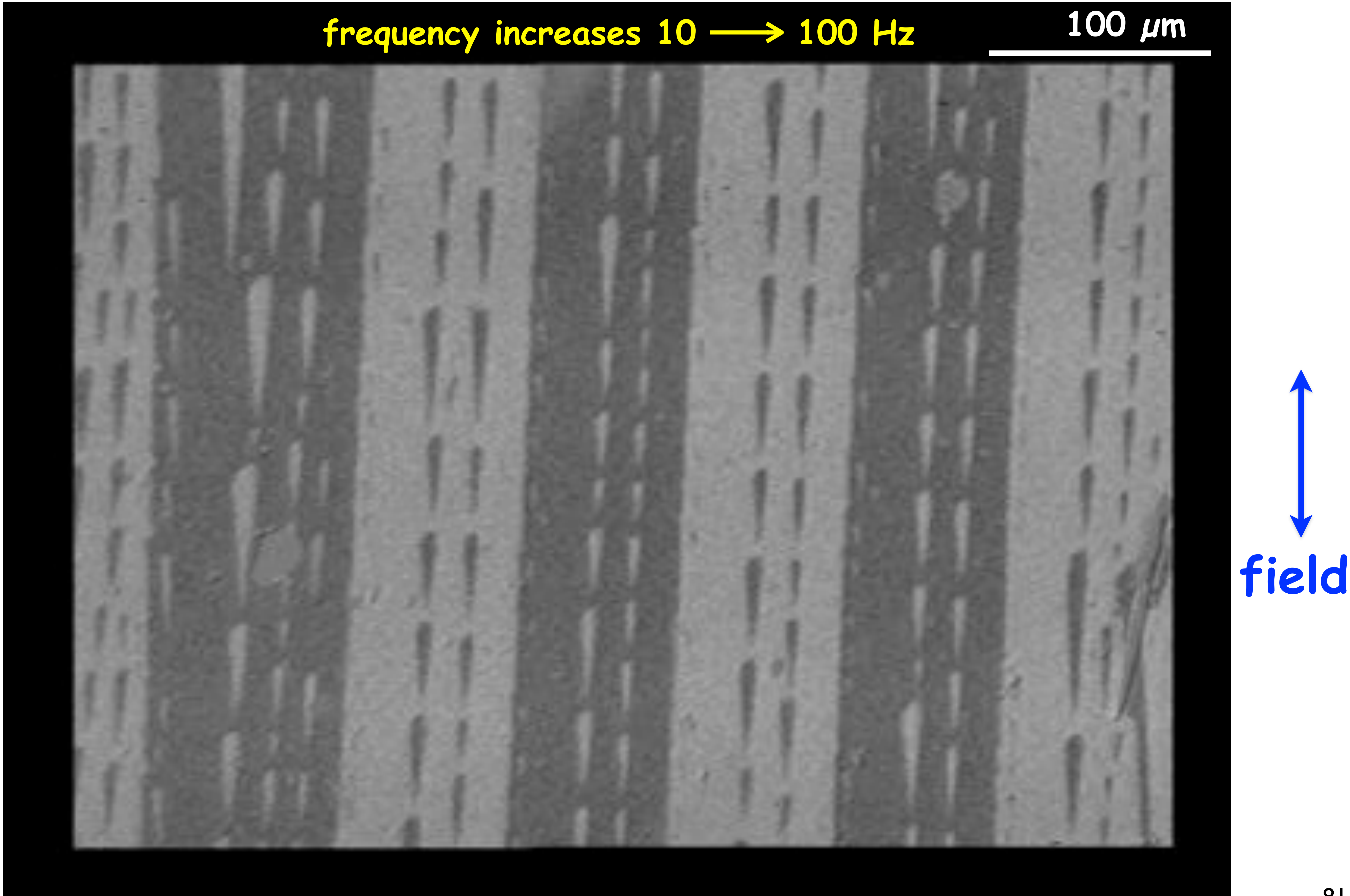

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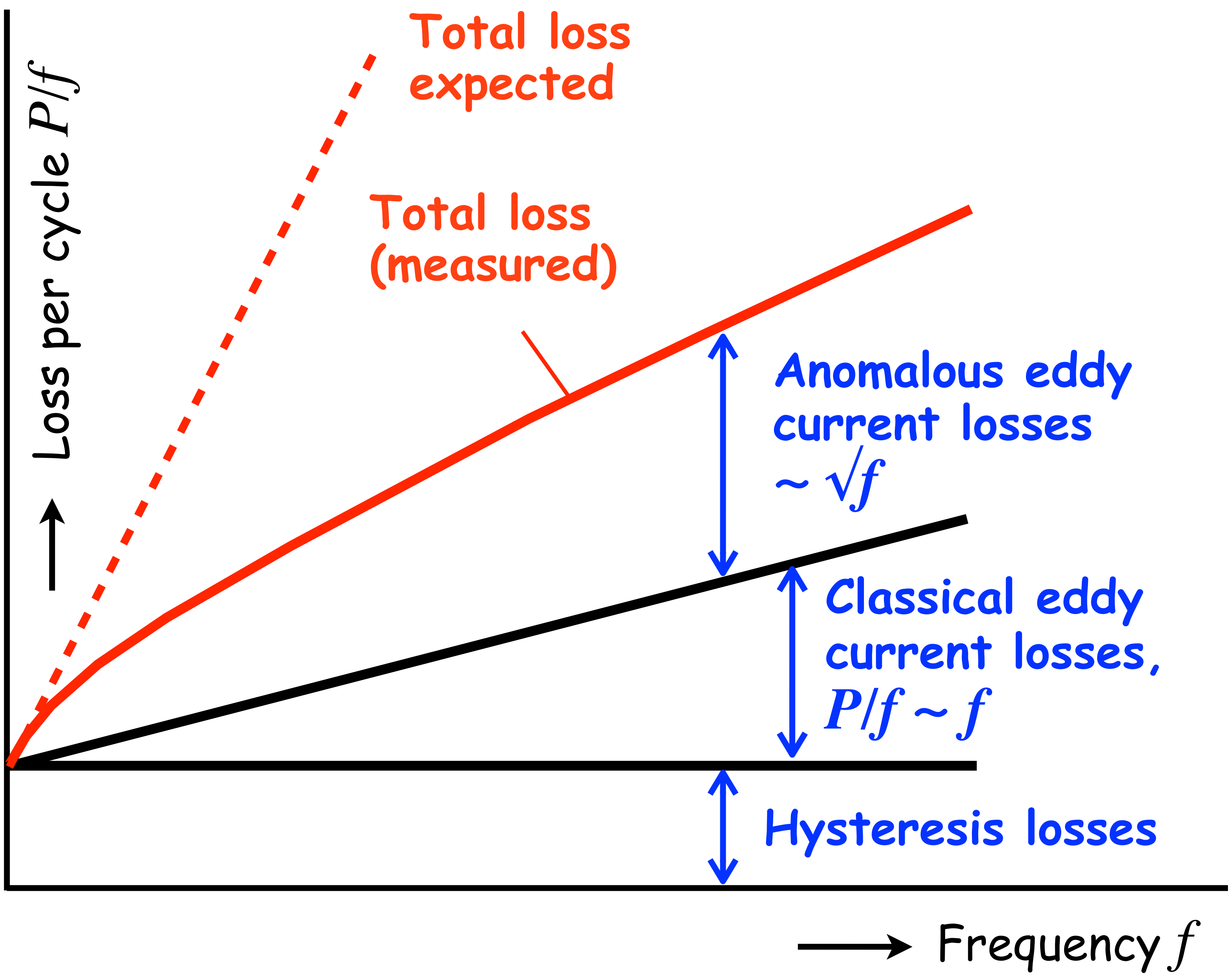

Eddy currents at moving walls:

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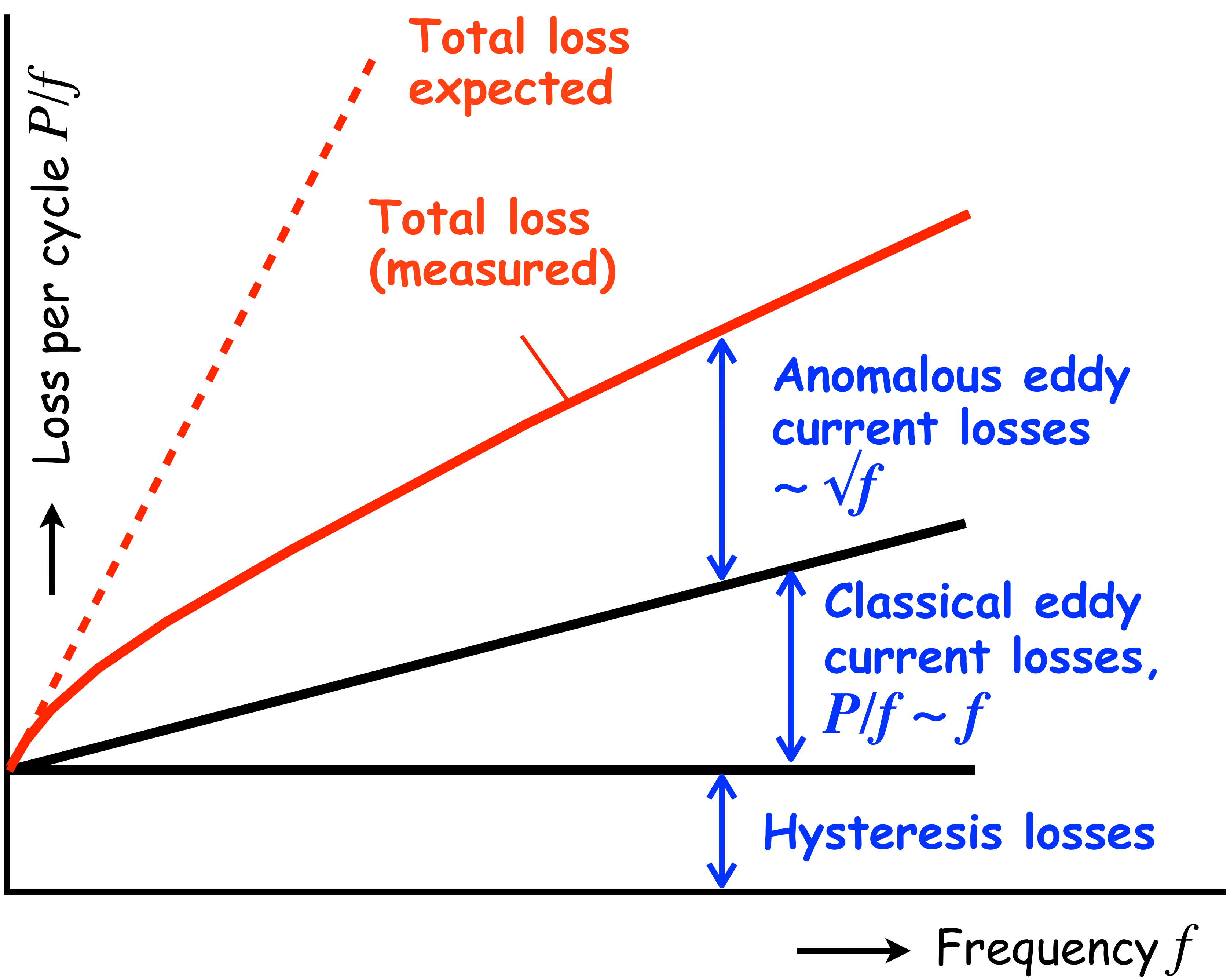


Eddy currents at moving walls:

- $v \sim f$
  → $P_{eddy} \sim v^2 \sim f^2$
  → $P/f \sim f$ expected
- However: P/f-curve non-linear
- Reason: Increasing frequency
  → number of mobile domain walls increases (wall multiplication)

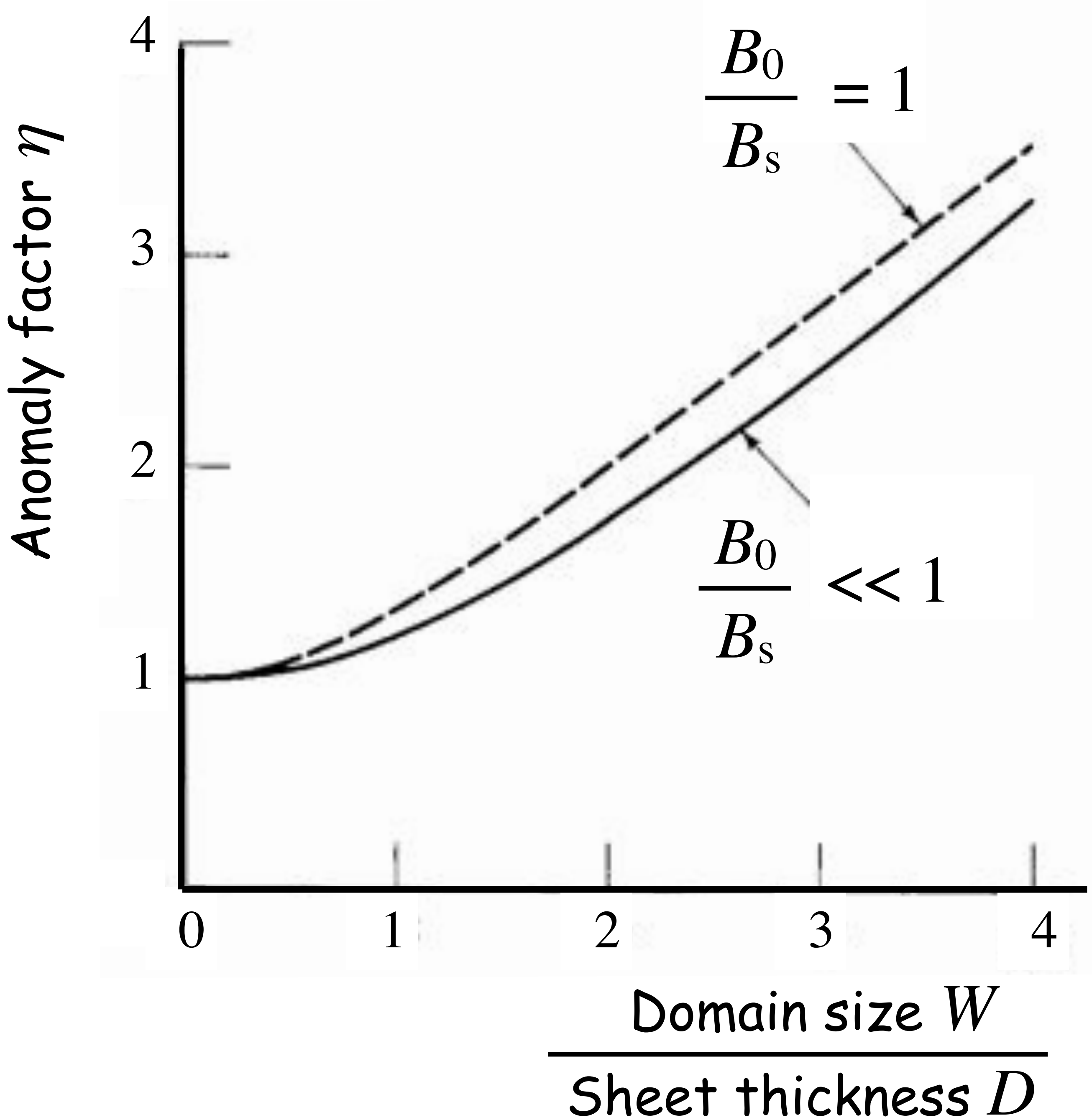
  → velocity of each wall can stay smaller to achieve a given induction change

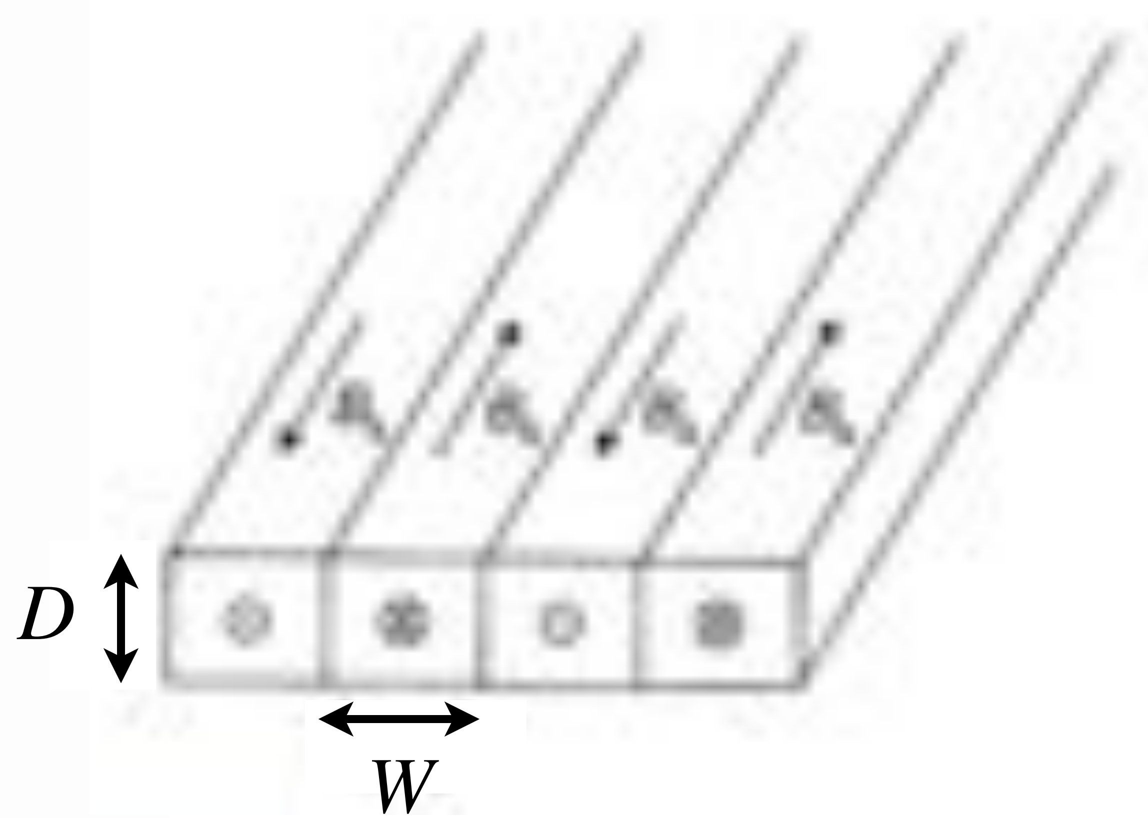
  → reduction of eddy current losses ($P \sim v^2$) compared to case of fewer mobile walls

(C) Anomalous eddy current (excess) loss

$$P_{total} = P_{hys} + P_{class} + P_{excess}$$
$$= P_{hys} + P_{class} \bullet \eta$$

Anomaly factor $\eta = \dfrac{P_{excess}}{P_{class}} + 1$





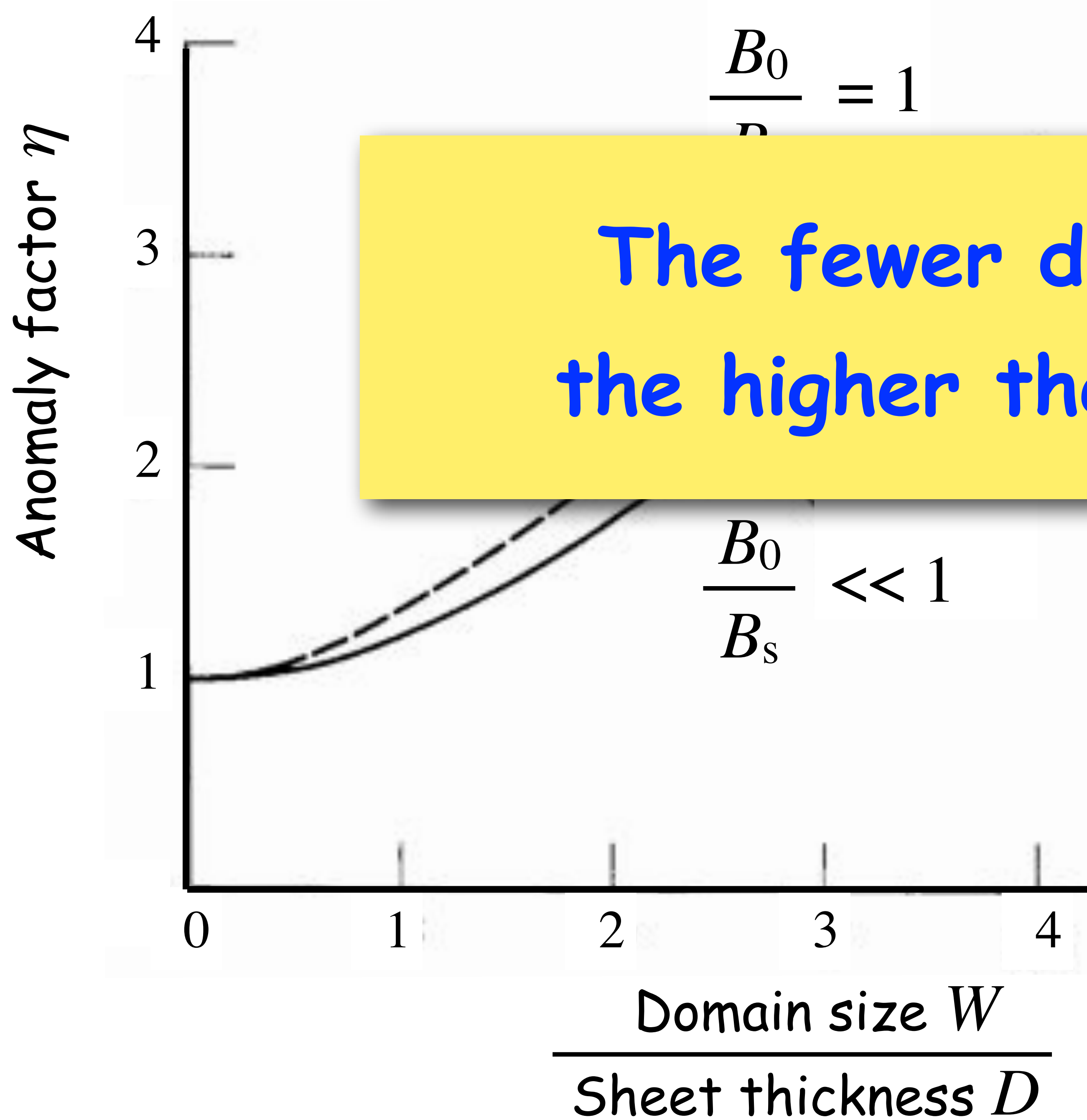
Pry and Bean model:

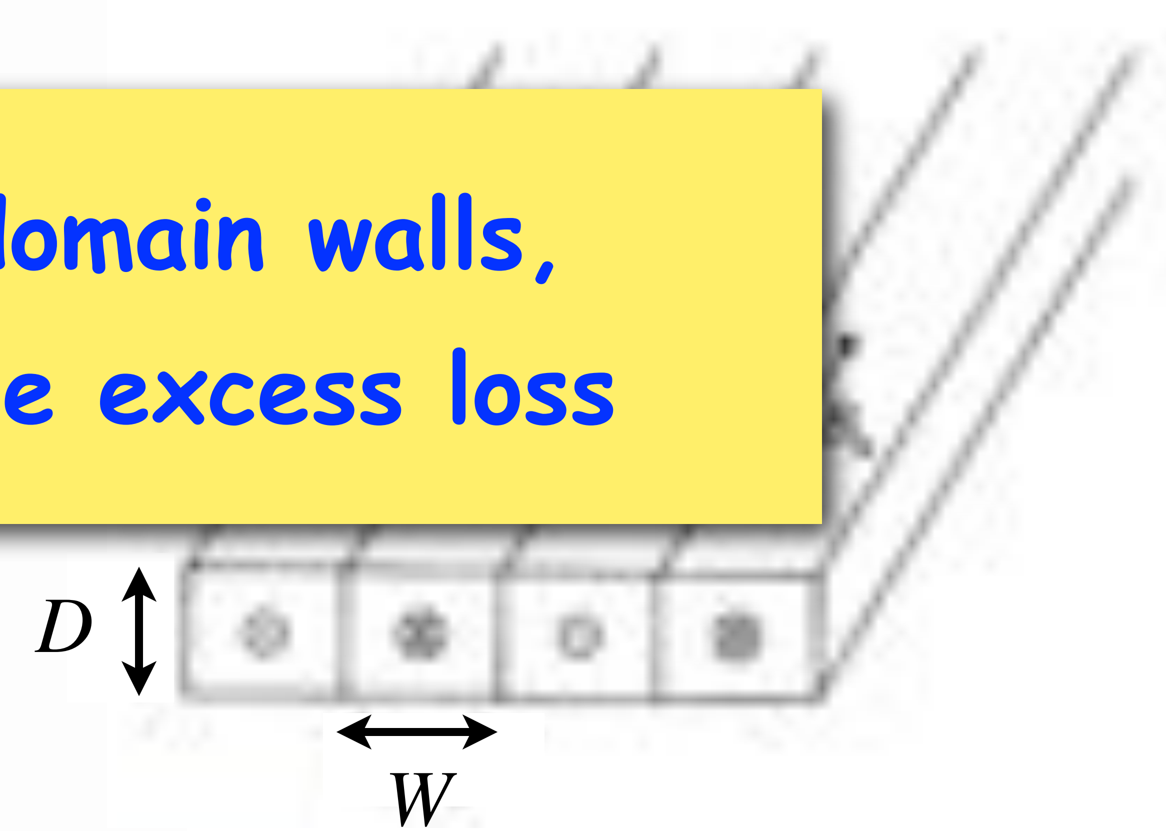
$$\eta_{PB} = 3.256 \frac{W}{D} \quad (\text{for } W/D >> 1)$$

(C) Anomalous eddy current (excess) loss

$$P_{\text{total}} = P_{\text{hys}} + P_{\text{class}} + P_{\text{excess}}$$
$$= P_{\text{hys}} + P_{\text{class}} \cdot \eta$$

Anomaly factor $\eta = \dfrac{P_{\text{excess}}}{P_{\text{class}}} + 1$



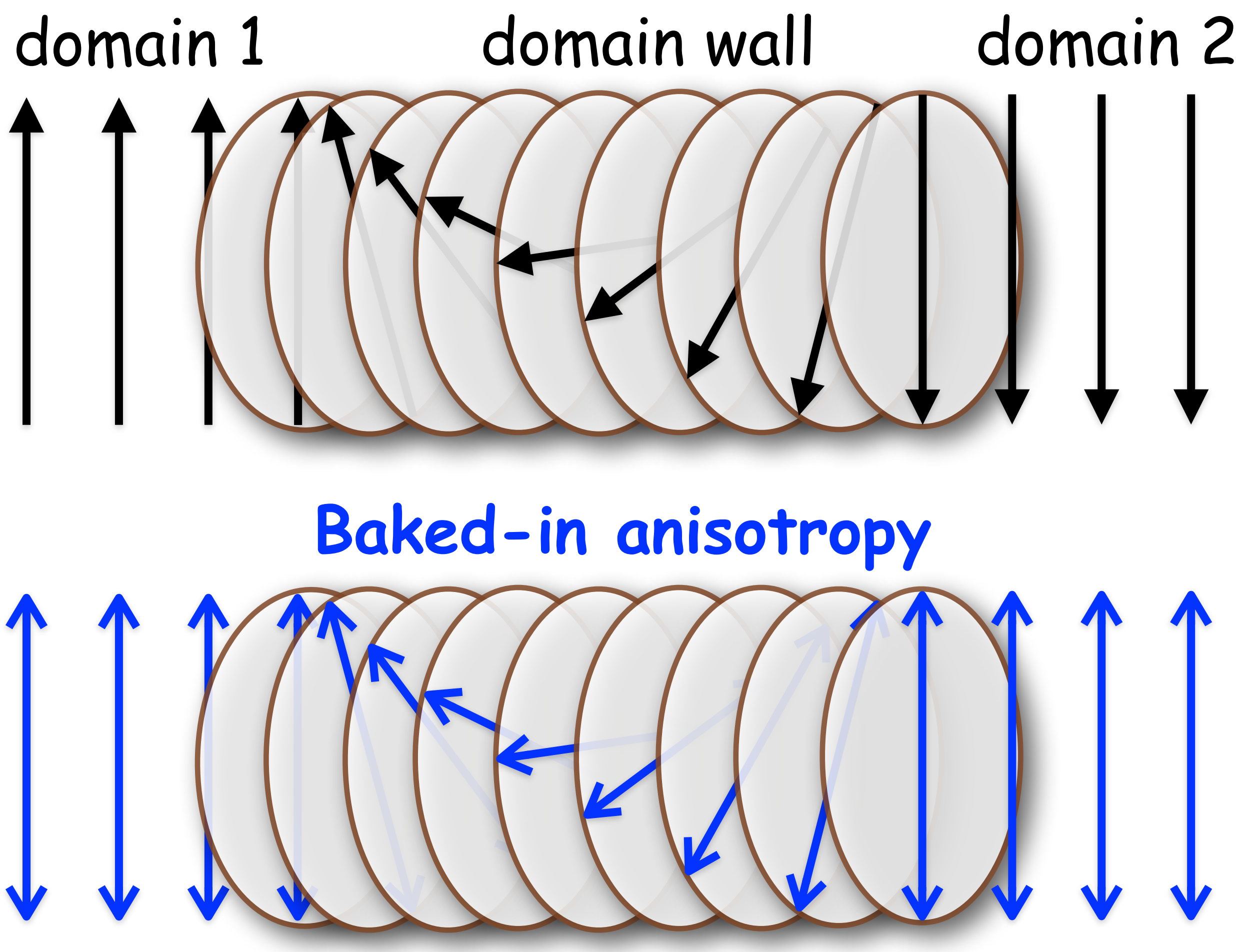


The fewer domain walls, the higher the excess loss

Pry and Bean model:

$$\eta_{\text{PB}} = 3.256\,\frac{W}{D} \quad (\text{for } W/D >> 1)$$

- Occurs if lattice defects (like vacancies, foreign atoms, dislocations, etc.) are moved under the action of magnetization or temperature
- Thermal diffusion → induced anisotropy: rotation sense of wall is „baked-in" as anisotropy = pinning site for wall



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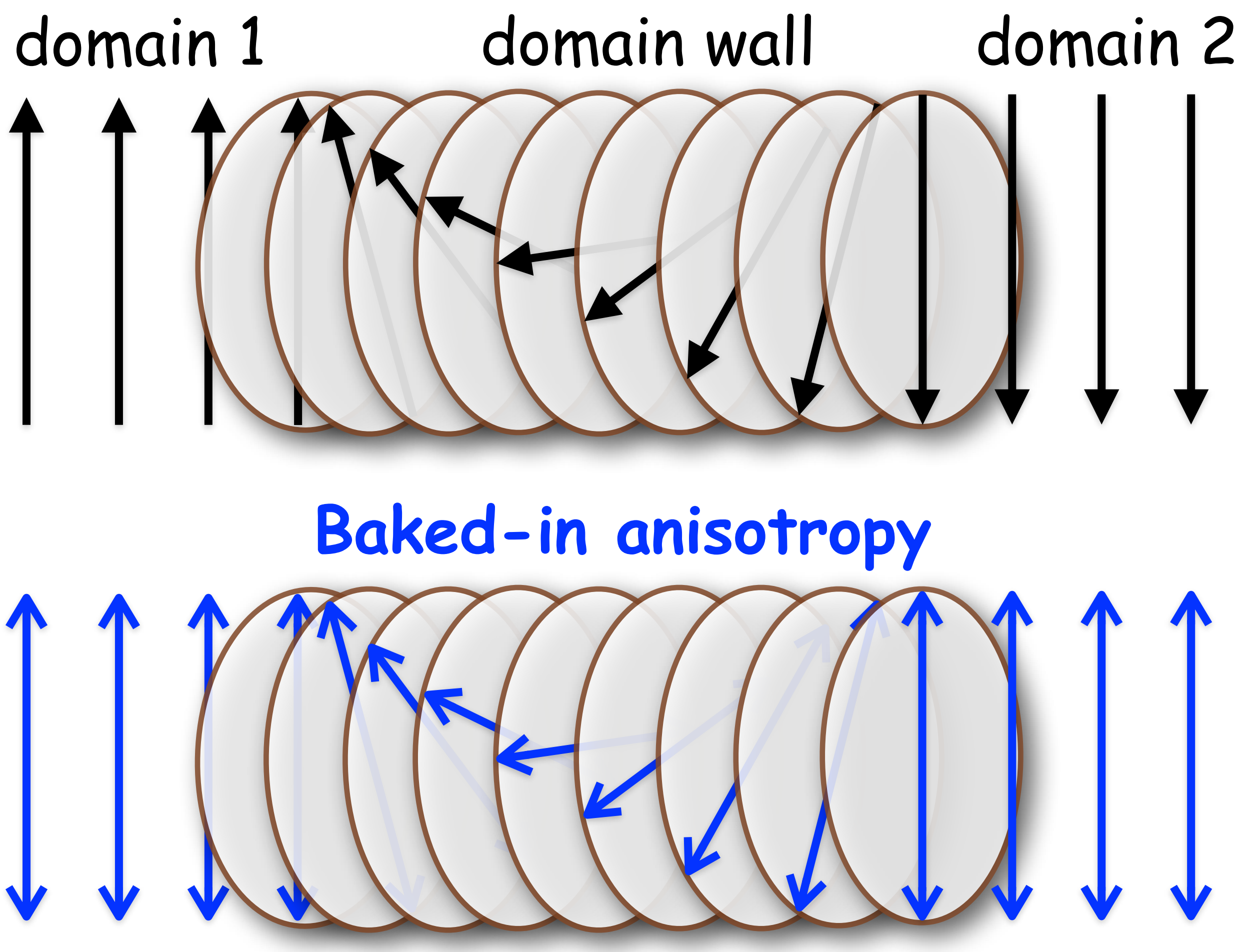

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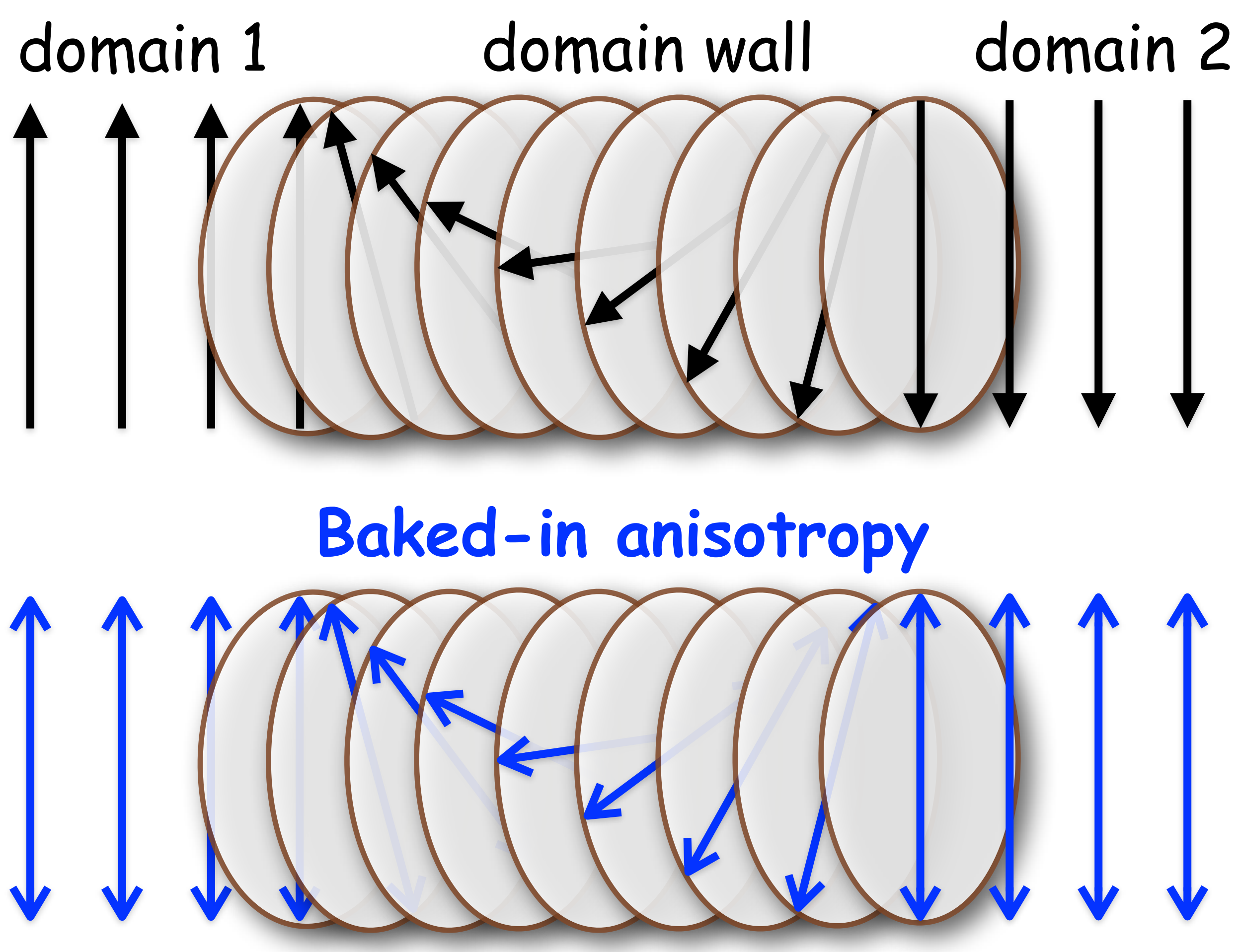
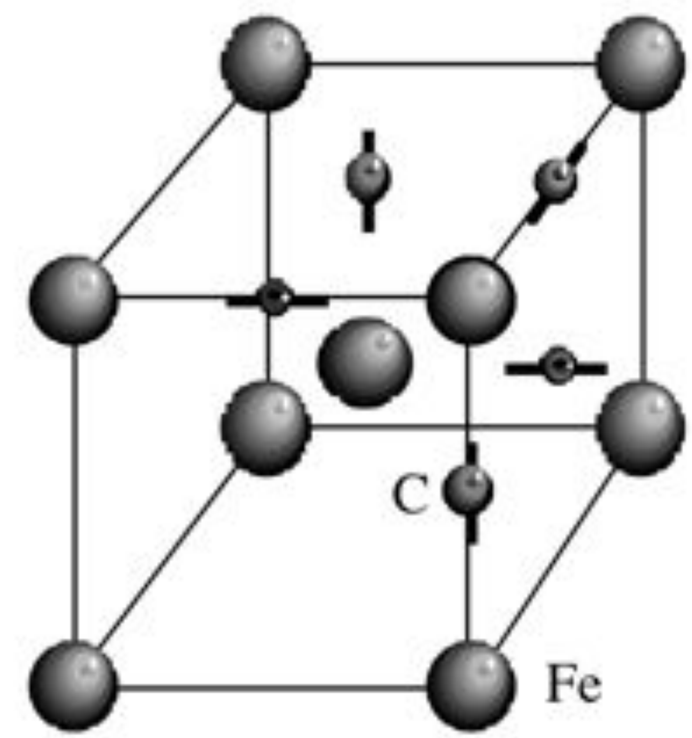


Example:
Carbon in iron



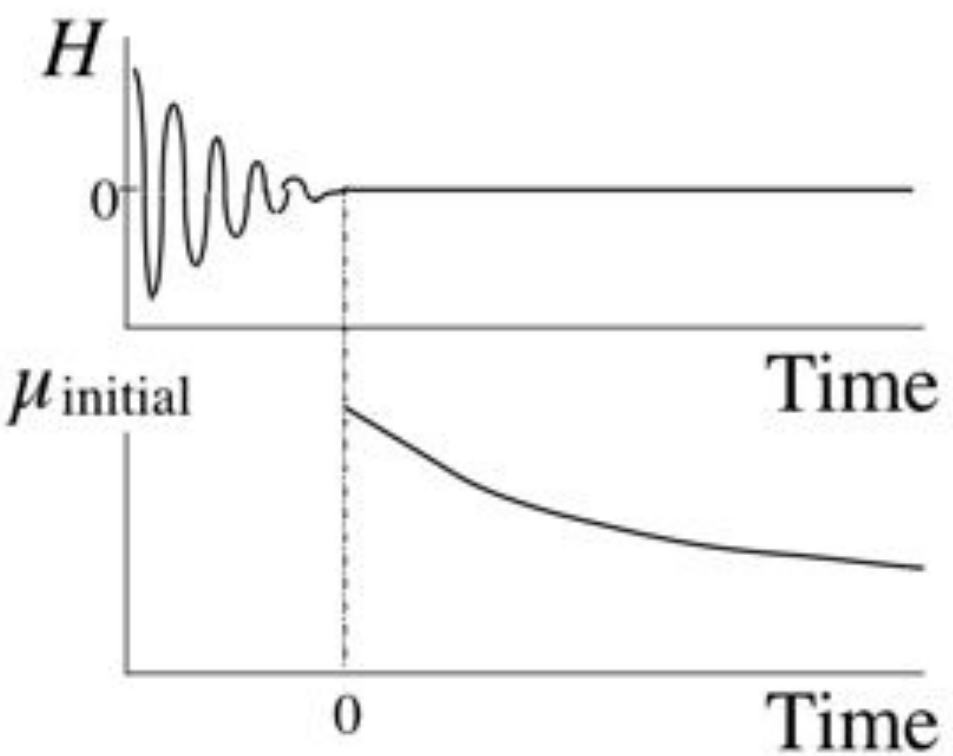
C-atoms occupy octahedral interstitial positions in bcc iron

For given M-direction: 3 possible interstitial sites have three different energies, because presence of interstitial influences exchange interaction between iron atoms

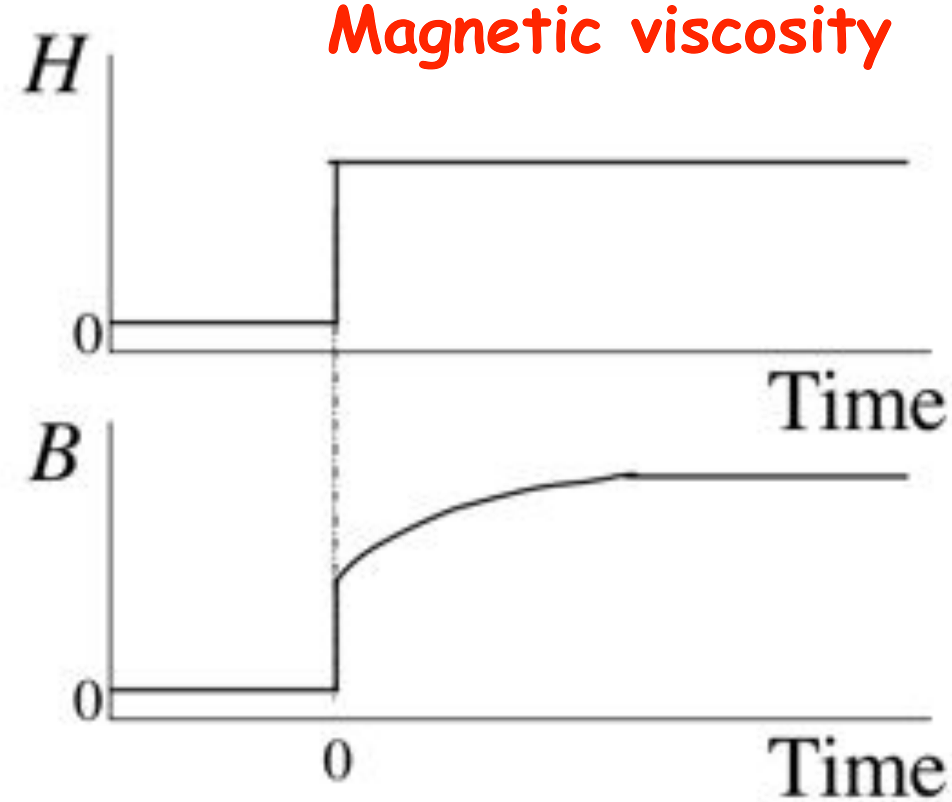
(D) After effect Loss

- Occurs if lattice defects (like vacancies, foreign atoms, dislocations, etc.) are moved under the action of magnetization or temperature
- Thermal diffusion → induced anisotropy: rotation sense of wall is „baked-in“ as anisotropy = pinning site for wall
  - If wall moves fast enough: induced anisotropy changes little during motion → friction-like loss
  - If wall rests: becomes hard to move after some time → static coercivity
  - In between: time dependence of permeability and wall mobility

⟶ **After effect or disaccommodation**



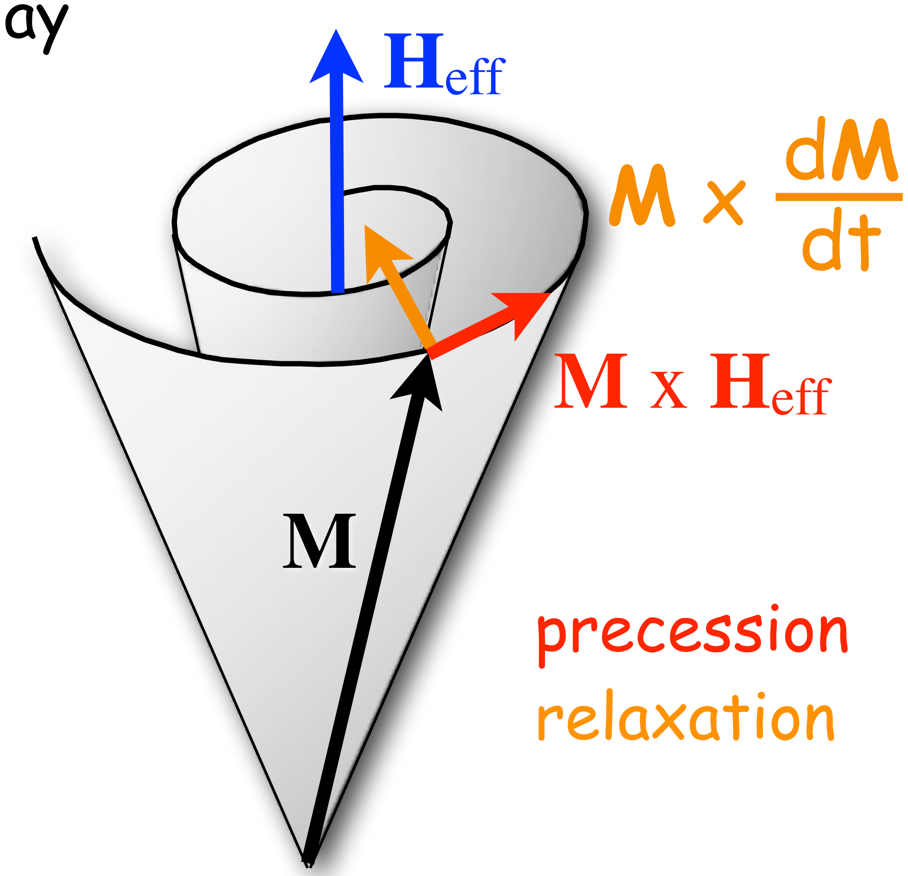
Magnetic viscosity



(E) Intrinsic Loss

- Eddy currents and after effect: cause phase shift between M and H (= loss)
- Non-conducting and after effect-free samples:
  M follows H up to frequencies > 100 MHz without delay

  Very high frequencies (> 1 GHz, **microwave** regime):
  it shows that magnetization is caused by
  angular momentum → gyrotropic motion



precession

relaxation

- Consequences:
  - Ferromagnetic resonance
  - Effective wall mass
  - Limiting frequencies for domain walls

- Phenomenological description by Landau-Lifshitz-Gilbert equation

$$\frac{d\boldsymbol{M}}{dt} = -\gamma_0 \, [\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}] + \frac{\alpha}{M_s} \, [\boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}]$$

$\boldsymbol{H}_{\mathrm{eff}}$: acting magnetic field
α : damping parameter
γ_0 : gyromagnetic ratio

- All these phenomena cause intrinsic loss. Important in insulators and thin films

Soft magnets: General Considerations

Summary:
In **bulk metallic** soft magnetic materials:
Permeability decreases and coercivity increases with frequency due to increasing eddy current effects

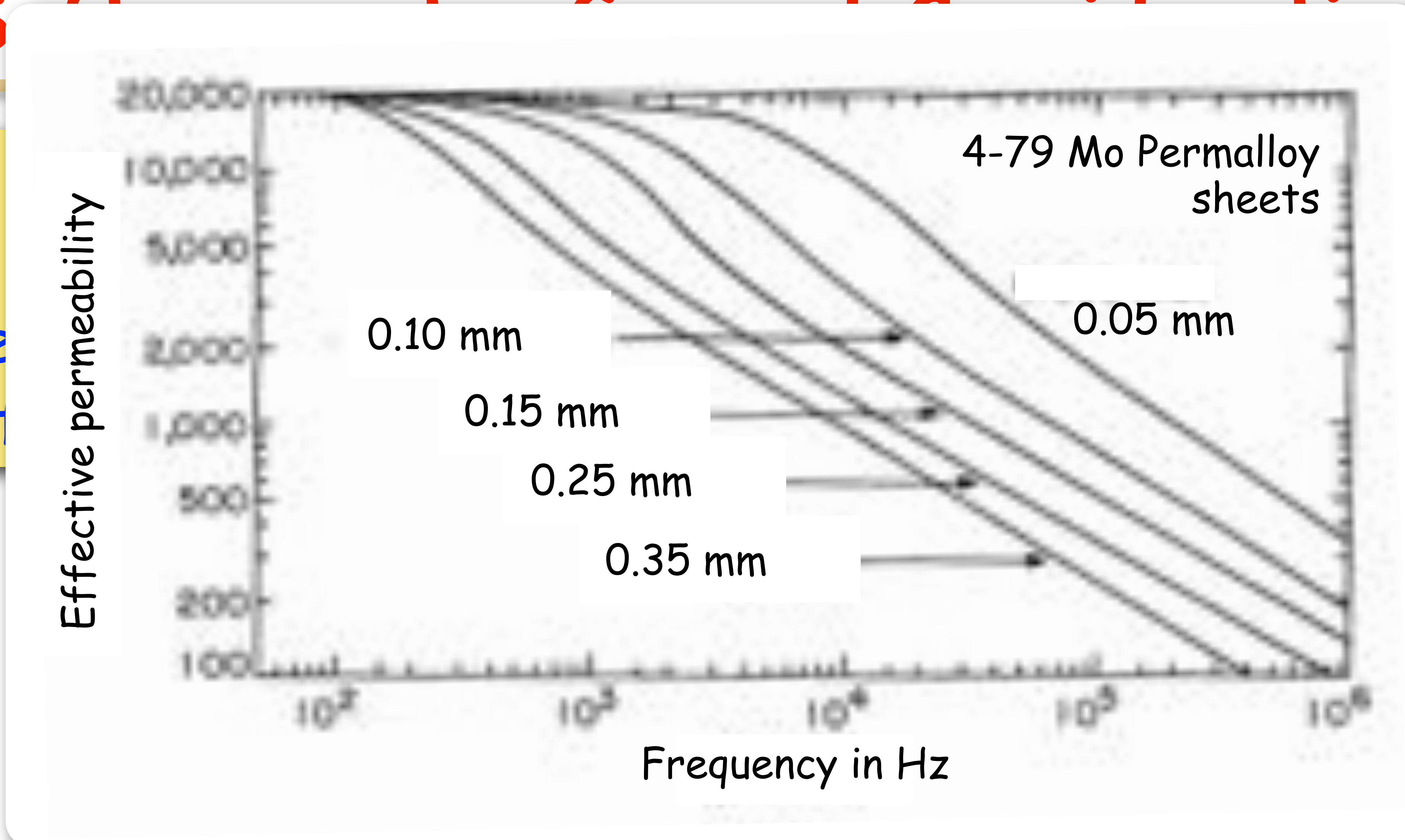
To reduce losses:

Tape-wound cores

- Sheet thickness: 0.36 – 0.032 mm
- Permeability drops at 1.000 –10.000 Hz
- Metallic films thinner 100 nm: drop in GHz regime

Powder core

- Fe- or NiFe powder, 50 – 100 μm diameter, electr. isolated by coating
- Up to 100.000 Hz, but permeability only 10 – 100 (demag. fields of particles)



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Applications up to MHz regime: Cubic Ferrites (insulators)

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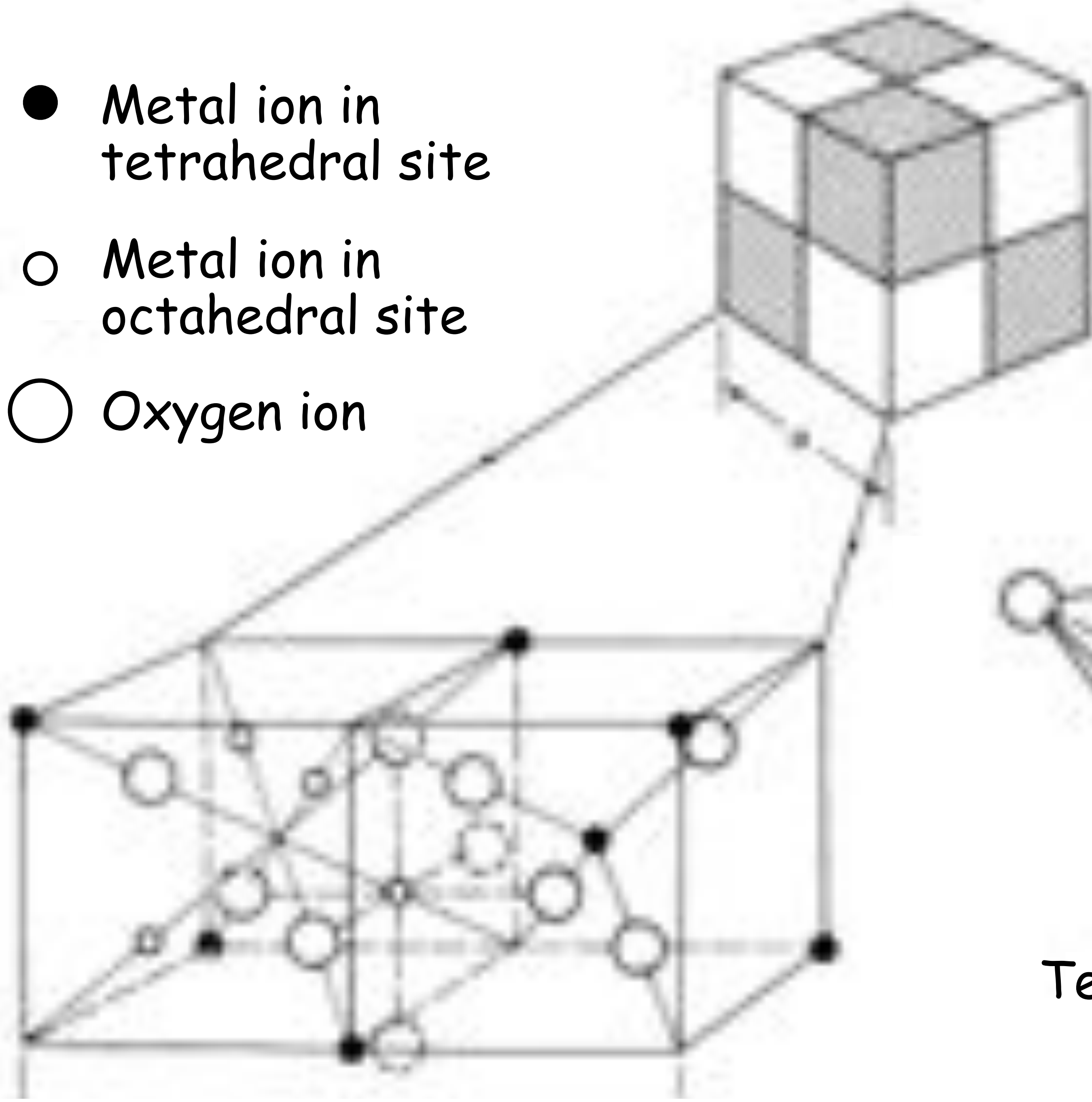
Soft magnets,
Example 2:
Cubic Ferrites

Cubic Ferrites



Spinel structure

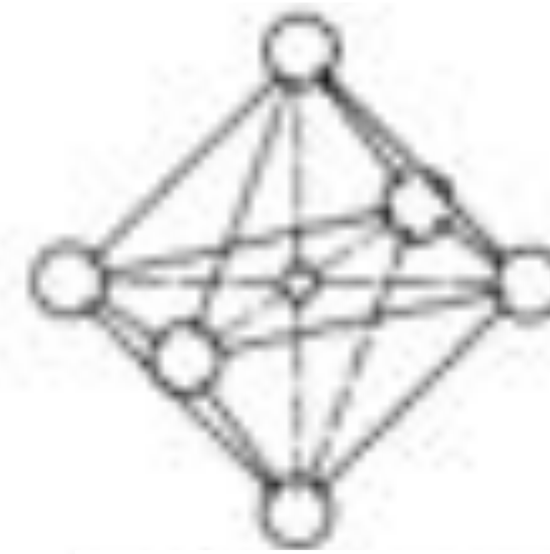
$MO \cdot Fe_2O_3$

Mn^{2+}, Ni^{2+}, Fe^{2+}, Zn^{2+} etc. → M

Fe^{3+} → Fe

O^{2-} → O

Tetrahedral (A) site

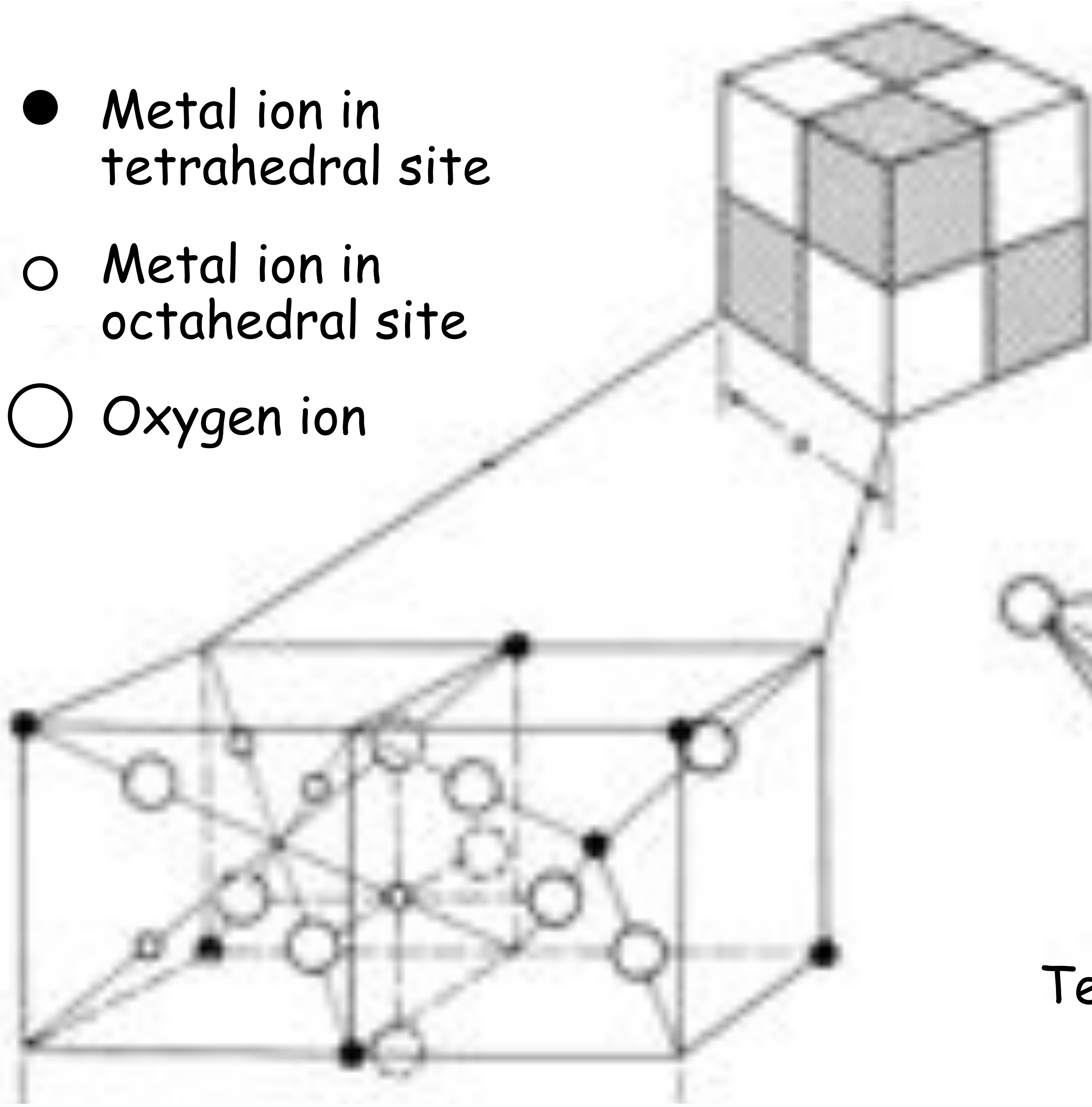


Octahedral (B) site

			Occupants	
Kind of Site	Number Available	Number Occupied	Normal Spinel	Inverse Spinel
Tetrahedral (A)	64	8	$8M^{2+}$	$8Fe^{3+}$
Octahedral (B)	32	16	$16Fe^{3+}$	$8Fe^{3+}$ $8M^{2+}$

Cubic Ferrites

- ● Metal ion in tetrahedral site
- ○ Metal ion in octahedral site
- ◯ Oxygen ion



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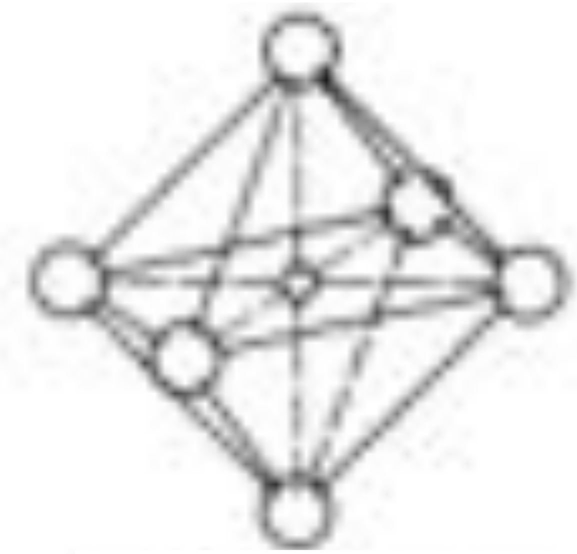
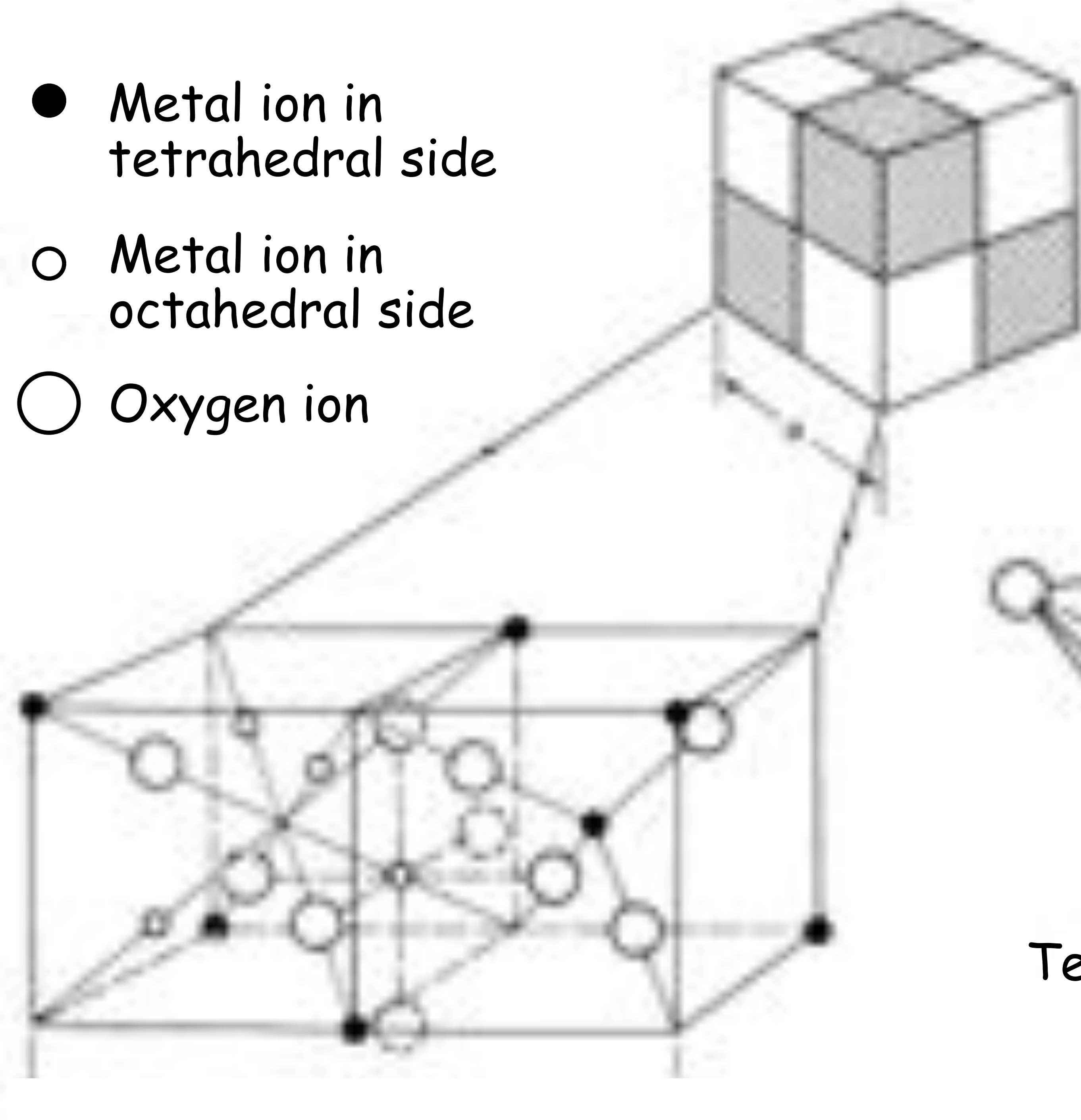


Octahedral (B) site

Antiparallel spin alignment (superexchange across O-ions)

Cubic Ferrites

- ● Metal ion in tetrahedral side
- ○ Metal ion in octahedral side
- ◯ Oxygen ion



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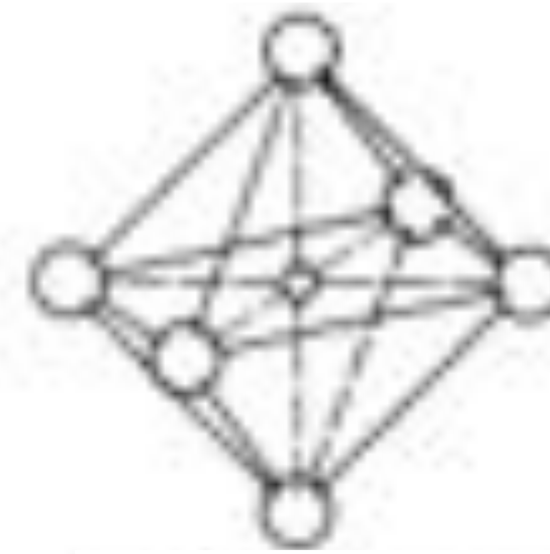

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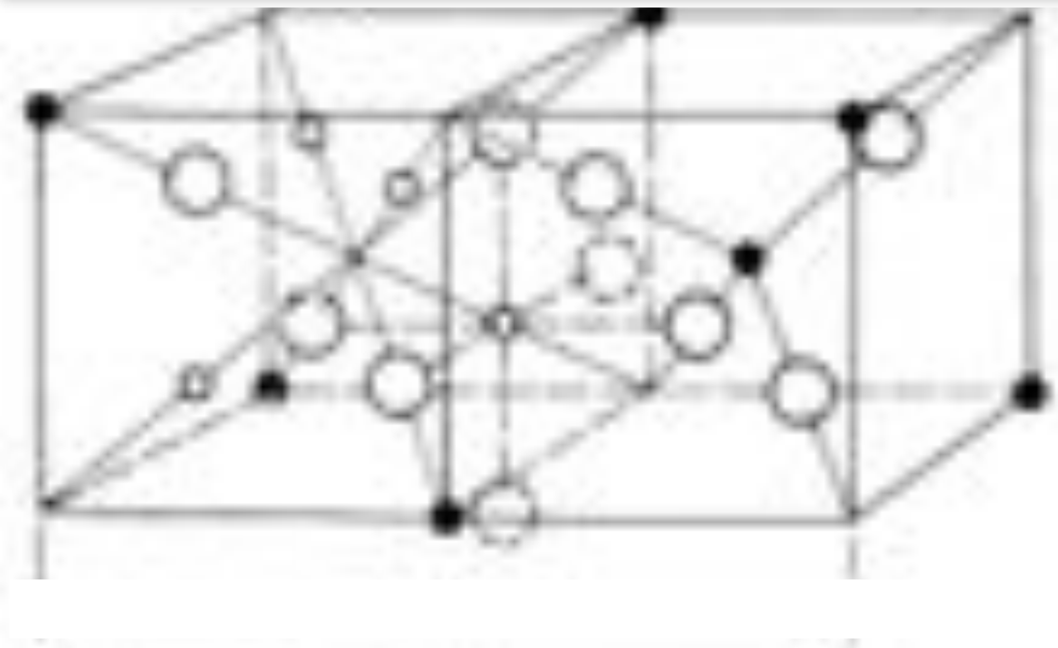
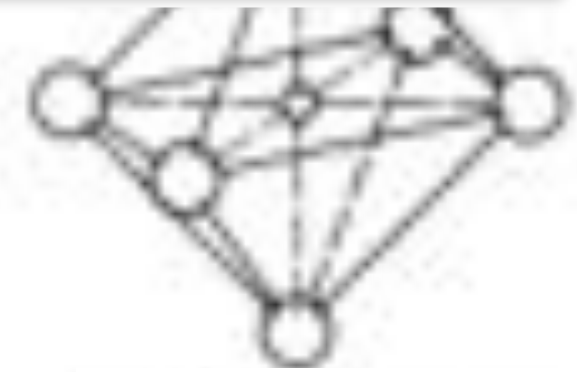
Antiparallel spin alignment (superexchange across O-ions)

Cubic Ferrites



Tetrahedral (A) side



Octahedral (B) side

Antiparallel spin alignment (superexchange across O-ions)

Example: Ni-Ferrit $Fe^{3+}_{8}\,[Fe^{3+}_{8}\,Ni^{2+}_{8}]\,O^{2-}_{32}$ (ions per unit cell)

$\underbrace{Fe^{3+}_{8}}_{\text{Tetrahedral sites}}$ $\underbrace{Fe^{3+}_{8}\,Ni^{2+}_{8}}_{\text{Octahedral sites}}$

3d-electrons		
Ni^{2+}	↑↑↑↑↑↓↓↓	$2\mu_B$
Fe^{3+}	↑↑↑↑↑	$5\mu_B$

Calculation of saturation magnetization:

$[8\cdot5\mu_B + 8\cdot2\mu_B] - 8\cdot5\mu_B = 16\mu_B$ per unit cell

$$J_s = \mu_0\cdot M_s = \mu_0\cdot\frac{z\cdot\mu_B}{a^3} = 4\pi\cdot10^{-7}\frac{Vs}{Am}\cdot\frac{16\cdot9.3\cdot10^{-24}\ Am^2}{8.5^3\cdot10^{-30}\ m^3} = 0.3\ Vs/m^2$$

Experimental: $J_s = 0.38\ Vs/m^2$

(a = lattice constant)

Cubic Ferrites

Table 11.23. Room-temperature magnetic properties of oxide spinel ferrites

	a	a_0 (pm)	T_C (K)	M_s (MA/m)	K_1 (kJ/m^3)	λ_s (10^{-6})	ϱ (Ω m)
$MgFe_2O_4$	I	836	713	0.14	−3	−6	10^5
$Li_{0.5}Fe_{2.5}O_4$		829	943	0.33	−8	−8	1
$MnFe_2O_4$	I	852	575	0.50	−3	−5	10^5
Fe_3O_4	I	840	860	0.48	−13	40	10^{-4}
$CoFe_2O_4$	I	839	790	0.45	290	−110	10^5
$NiFe_2O_4$	I	834	865	0.33	−7	−25	10^5
$ZnFe_2O_4$	N	844	$T_N = 9$				1
γFe_2O_3		834	985[a]	0.43	−5	−5	~1

Cubic Ferrites

Table 11.2[illegible]. Room-temperature magnetic properties of oxide spinel ferrites

	[illegible]	a_0 (pm)	T_C (K)	M_s (MA/m)	K_1 (kJ m^{-3})	λ_s (10^{-6})	ρ (Ω m)
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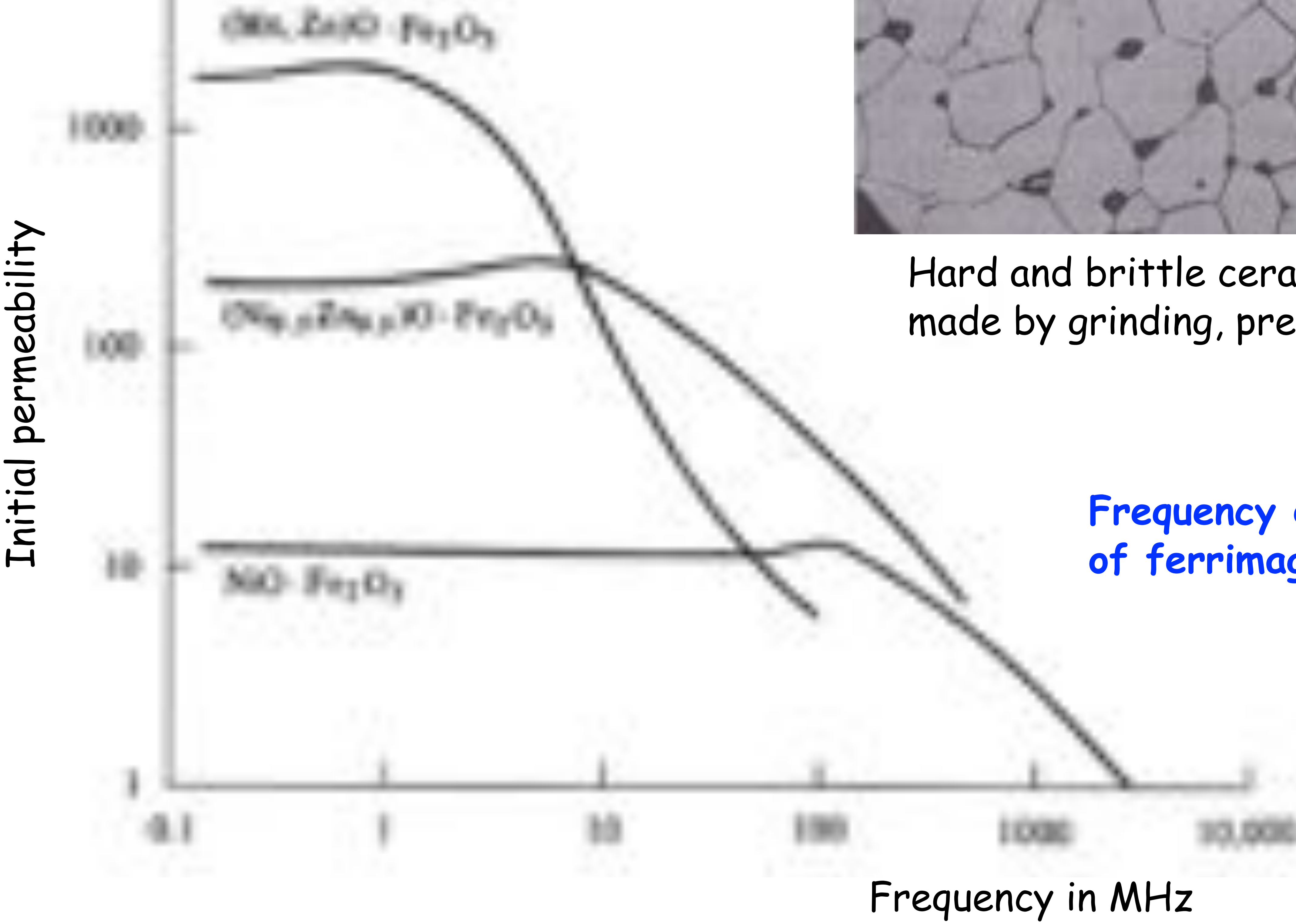
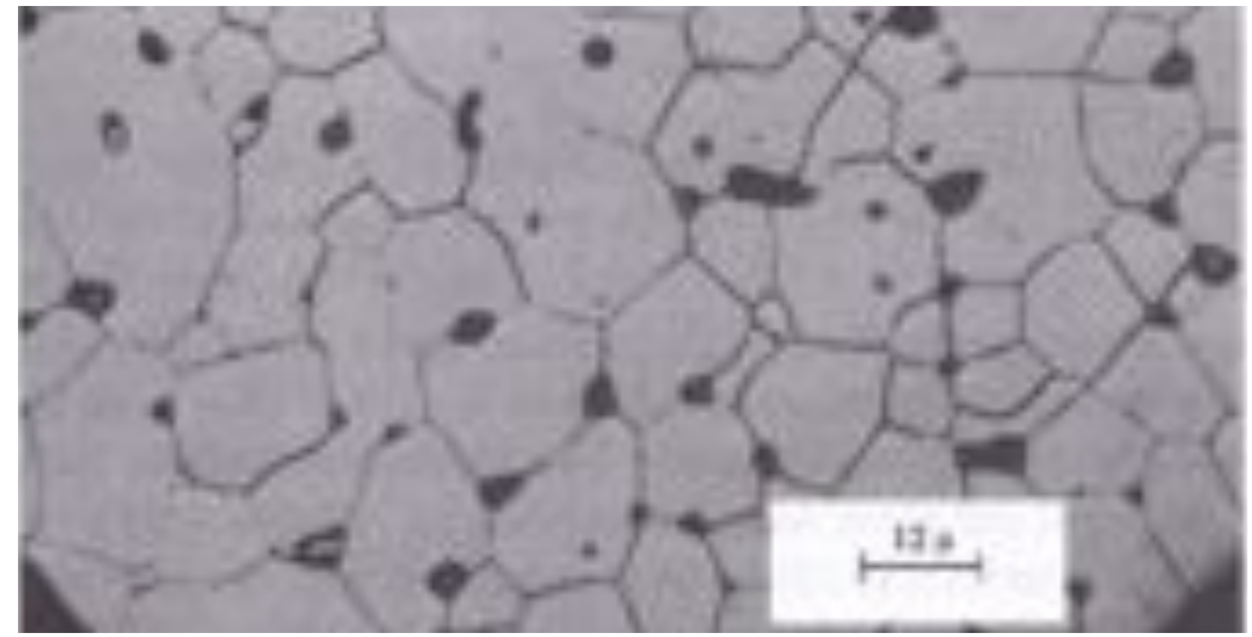
Anisotropy: 10^3 J/m^3 regime

↓

Permeability moderate…

Cubic Ferrites

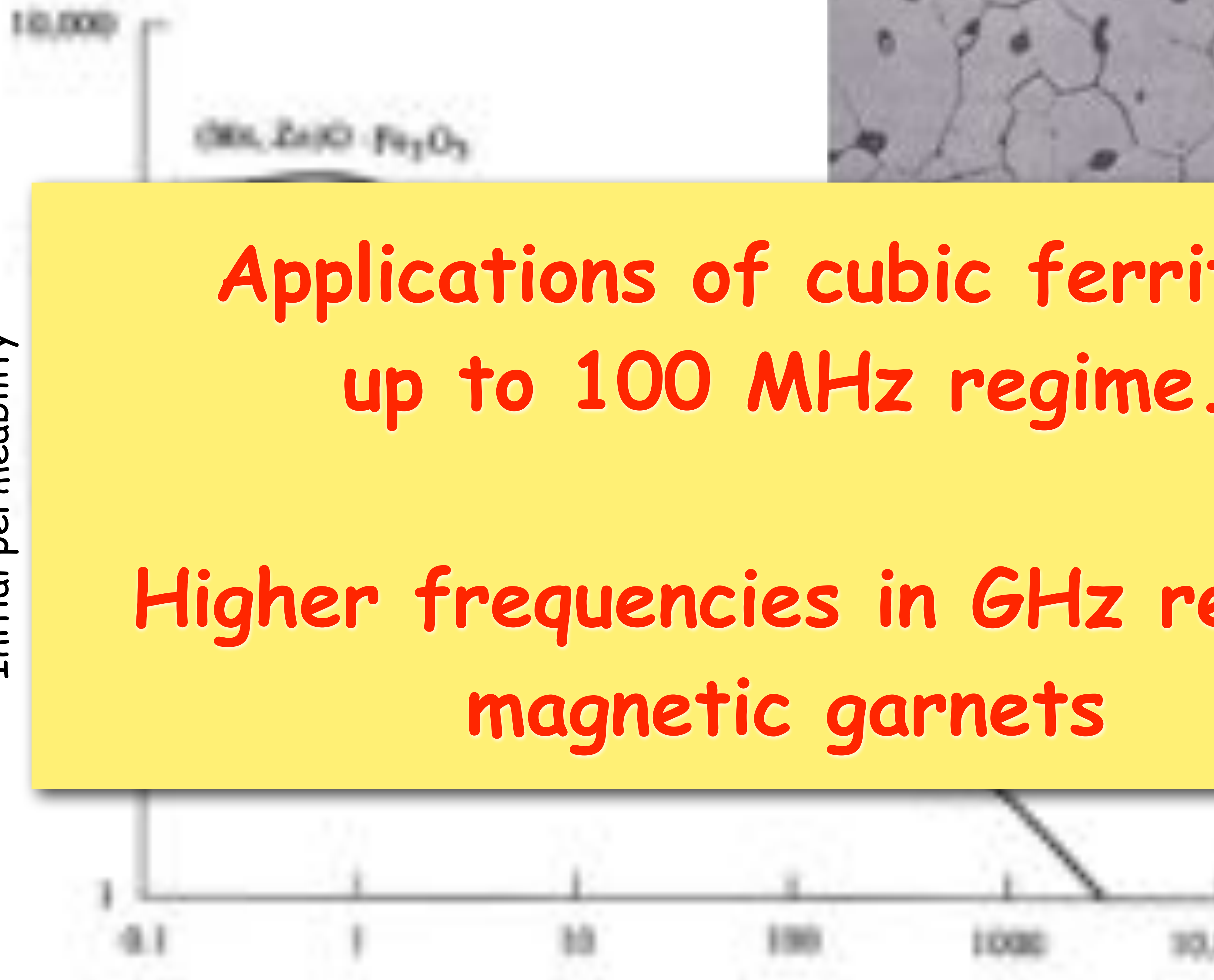




Hard and brittle ceramic material, made by grinding, pressing, sintering

Frequency drop at onset of ferrimagnetic resonance

Cubic Ferrites

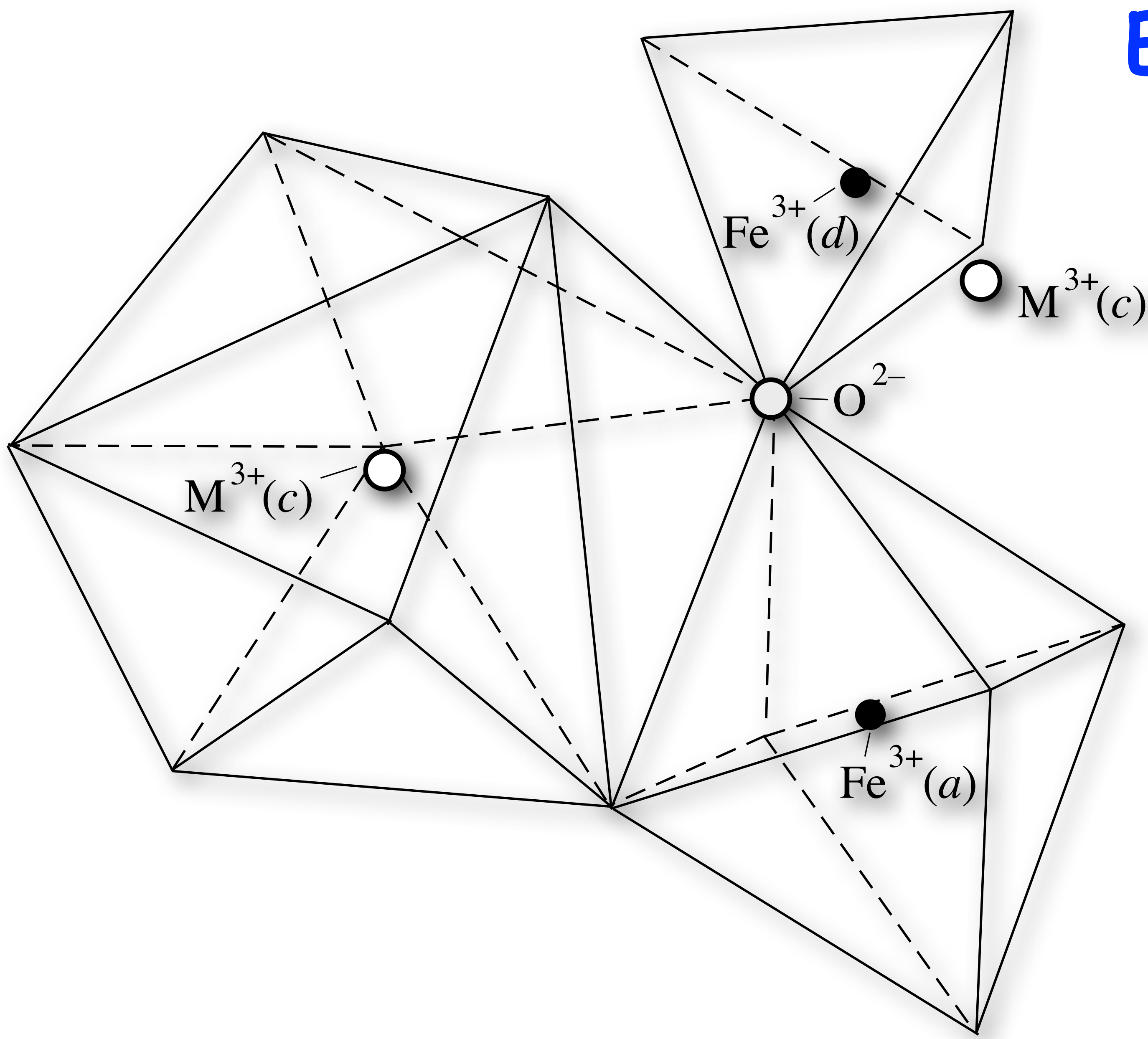


Applications of cubic ferrites: up to 100 MHz regime.

Higher frequencies in GHz regime: magnetic garnets

Magnetic garnets

Example YIG: $Y_3Fe_5O_{12}$



- Complex crystal structure:
  160 atoms per elemetary cell
  - 16 Fe^{3+}-ions in octahedral sides
  - 24 Fe^{3+}-ions in tetrahedral sides
  - 24 Y^{3+}-ions in dodecaedral sides
- Antiparallel superexchange between octahedral and tetrahedral sides
- Net 40 μ_B per elementary cell. However: $J_s = 0.175$ T only (large elementary cell)

- All lattice sides occupied (↔ cubic ferrites)
  → high degree of ordering
  → low loss at high frequencies
- Application: microwave materials

Soft magnets: General Considerations

Previous conclusion:

Good soft magnetic material is characterized by low anisotropy and low magnetostriction to obtain low coercivity and high permeability

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(Moderate) anisotropy and magnetostriction can also be favorably applied

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However:

(Moderate) anisotropy and magnetostriction can also be favorably applied

Example:

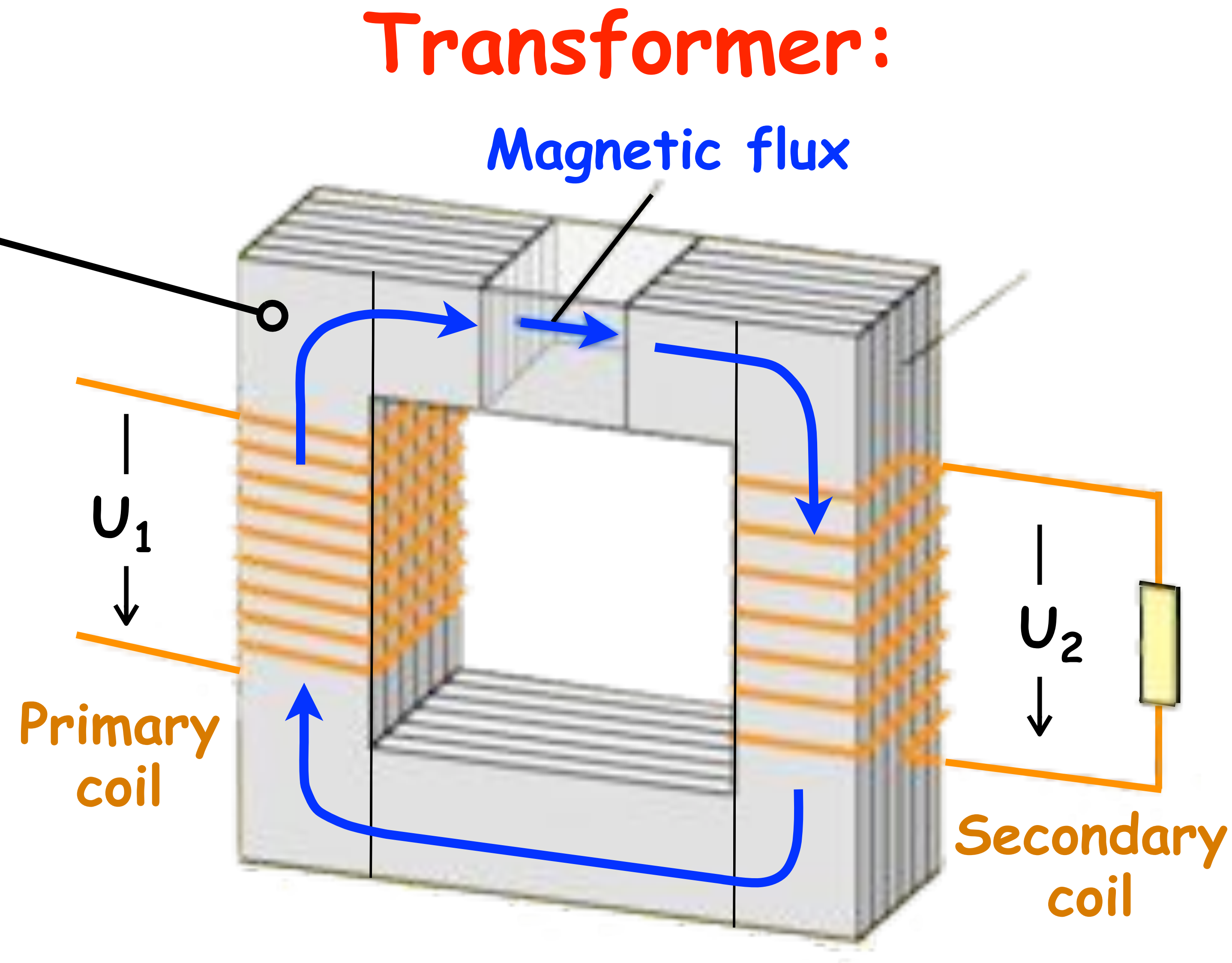
Grain-oriented electrical steel

Soft magnets,
Example 3:
Electrical steel

Grain-oriented FeSi transformer material

FeSi sheets

- Function: flux propagation from primary to secondary winding



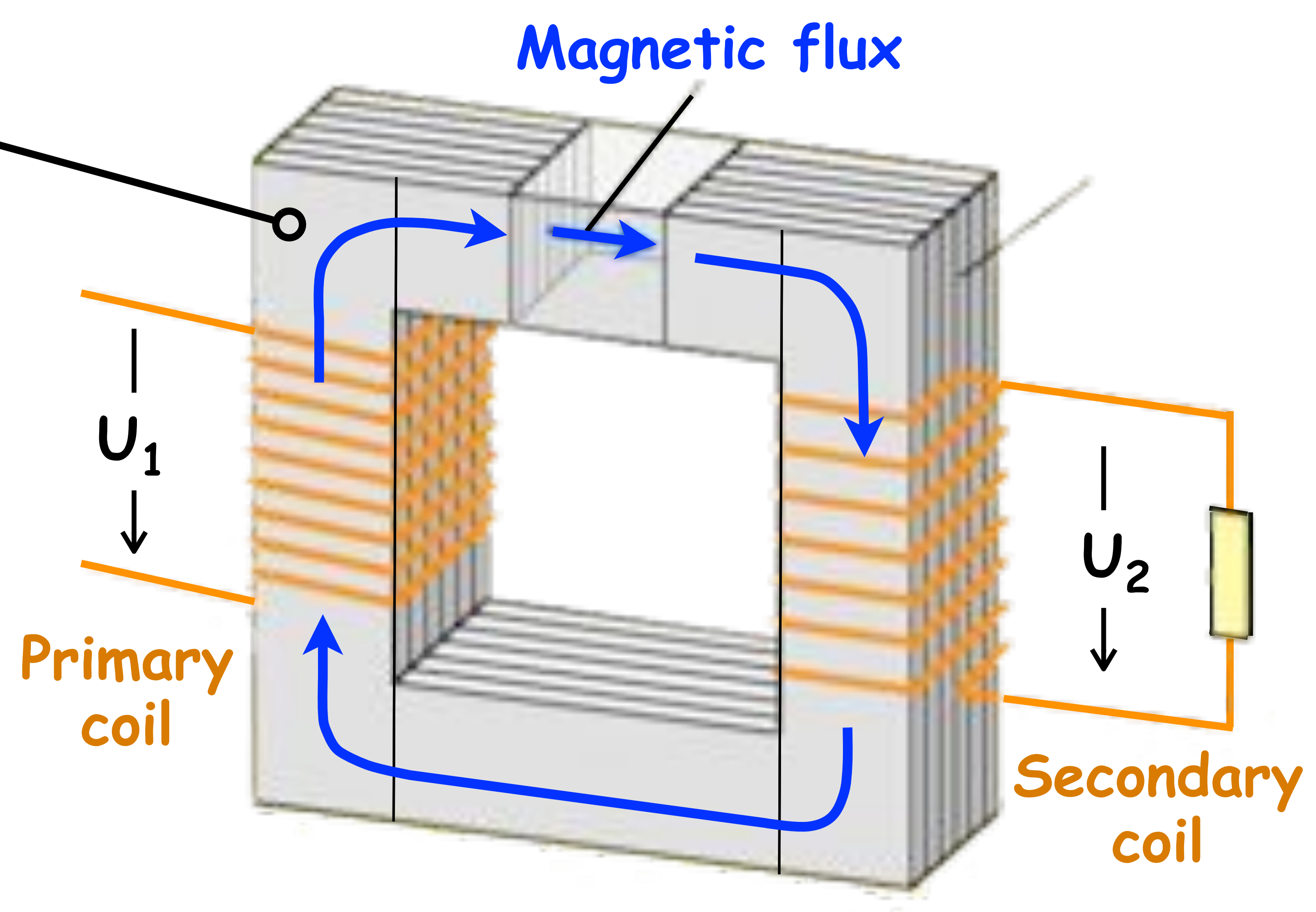
Grain-oriented FeSi transformer material

FeSi sheets

- Function: flux propagation
  from primary to secondary winding

- Most important quality number:
  Loss per cycle!
  Permeability is secondary quantity

Transformer:



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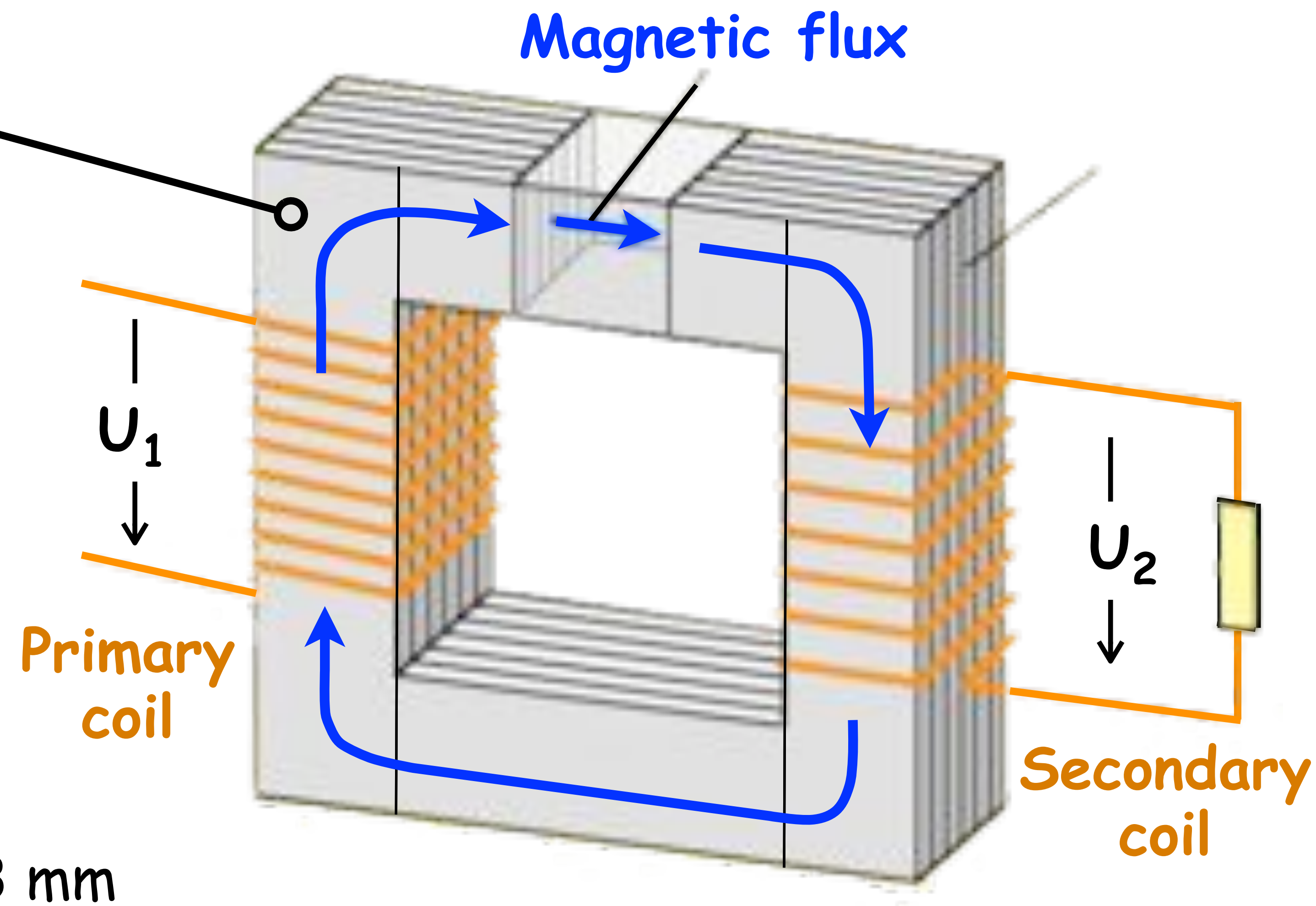

- Function: flux propagation from primary to secondary winding
- Most important quality number: **Loss per cycle**! Permeability is secondary quantity
- Reduction of eddy current loss:
  - Electrically insulated sheets, Thickness: 0.1 – 0.5 mm, typical: 0.3 mm
  - Fe 3.2wt% Si: silicon increases electrical resistance of iron (ϱ : 10 → 50 $\mu\Omega$cm)

Grain-oriented FeSi transformer material

Transformer:

FeSi sheets

- Fu
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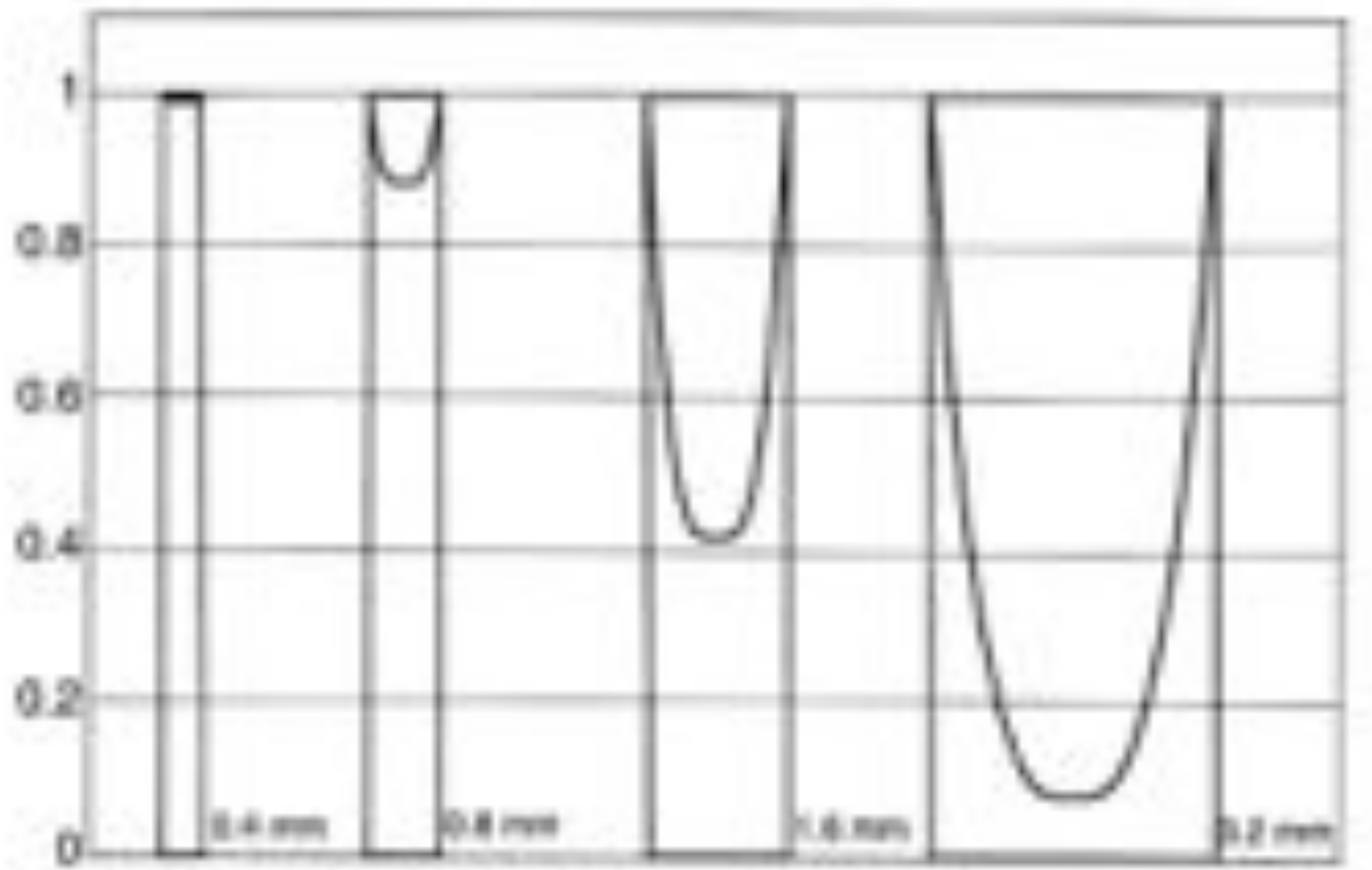
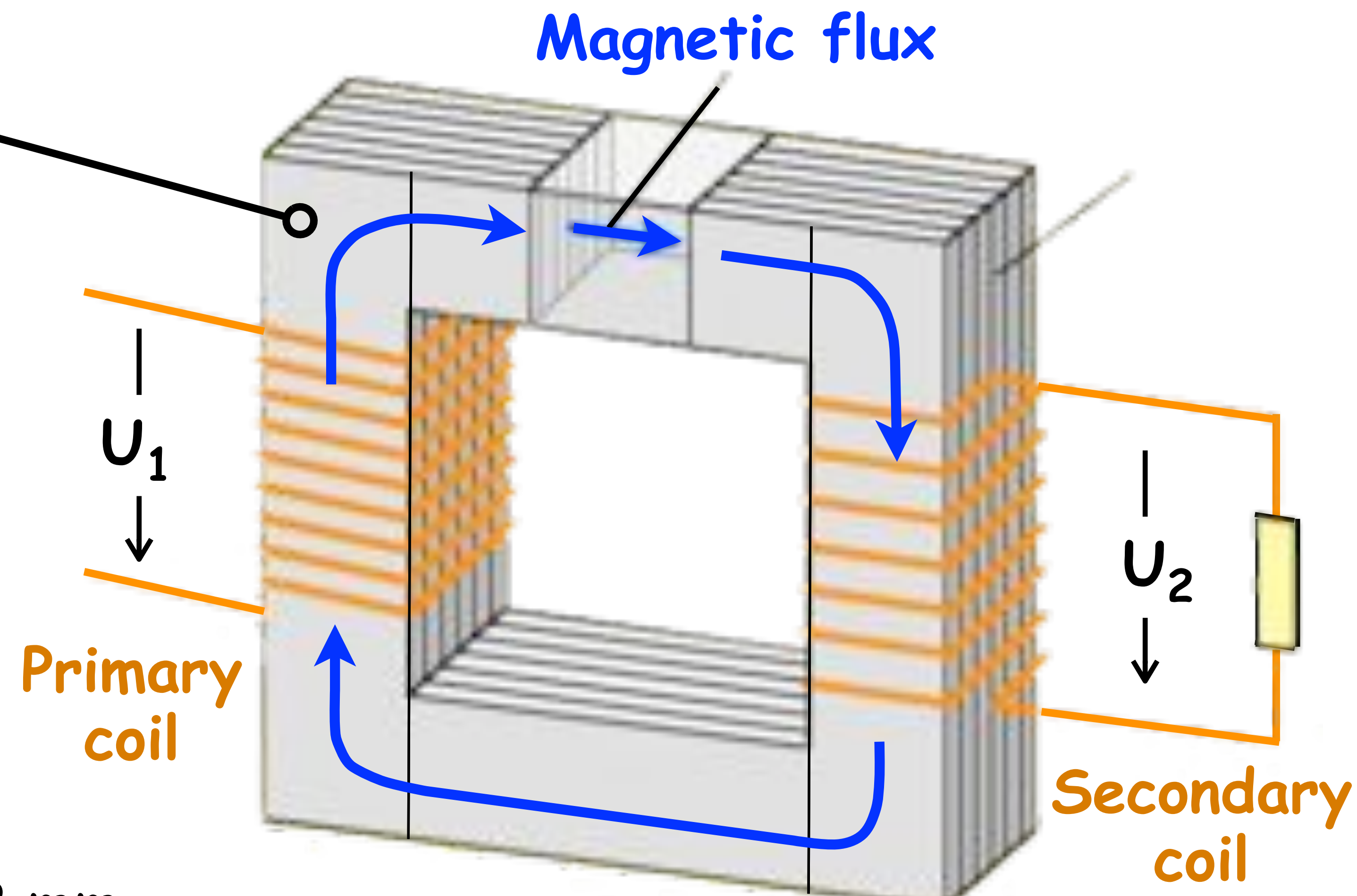


Flux amplitudes in FeSi steel sheets of various thickness (at 60 Hz).
Skin depth: 0.5 mm

Grain-oriented FeSi transformer material

FeSi sheets

Transformer:



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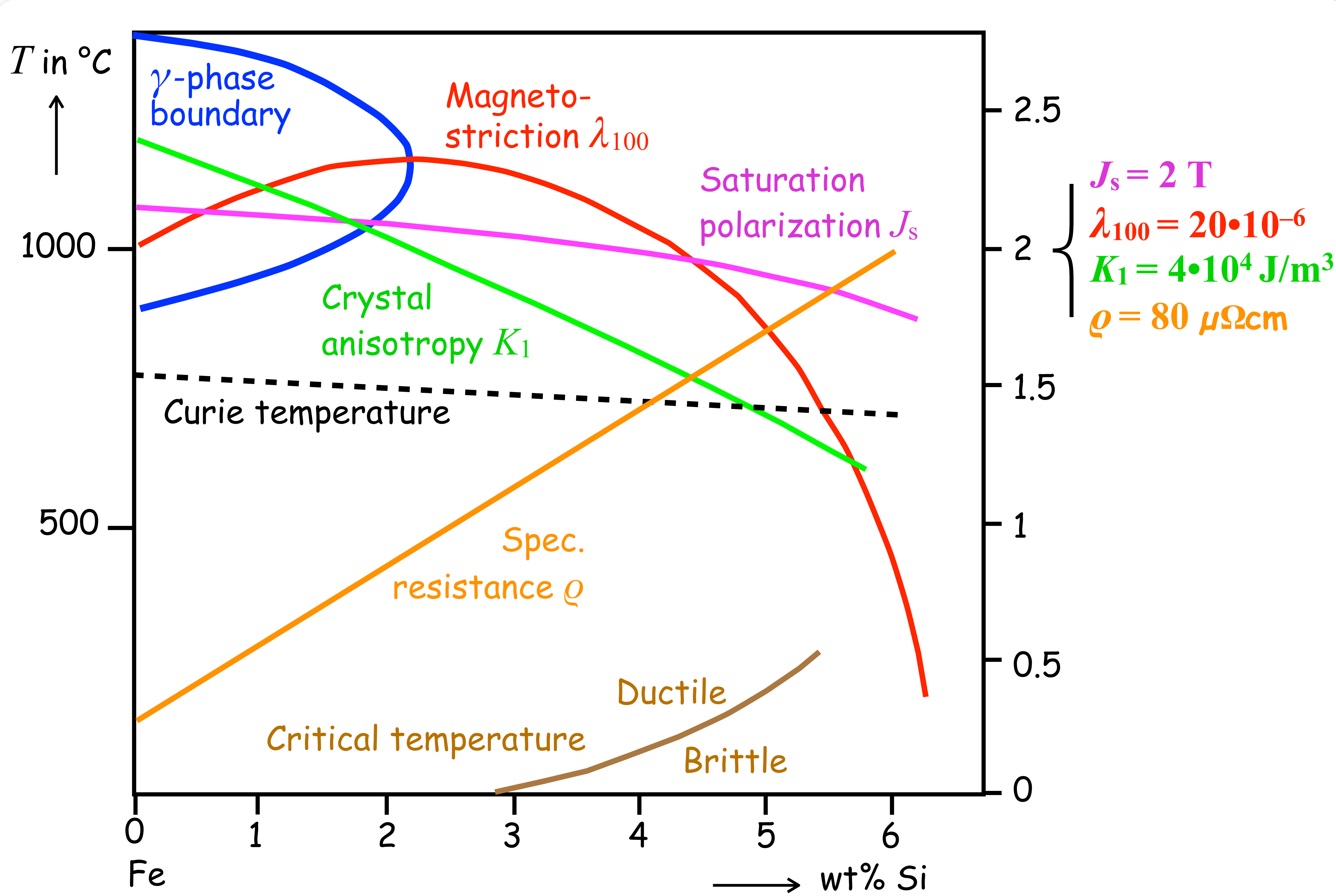

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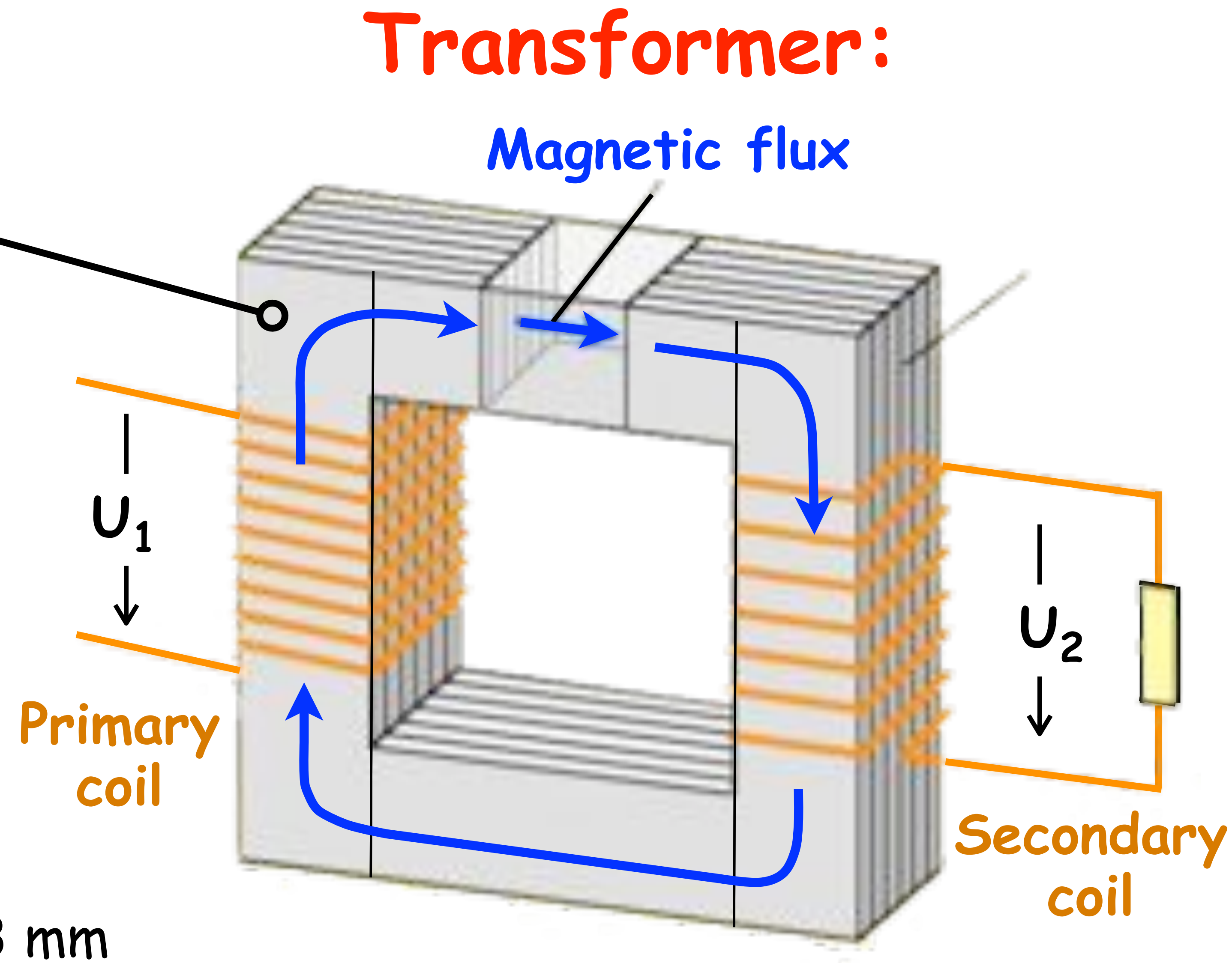

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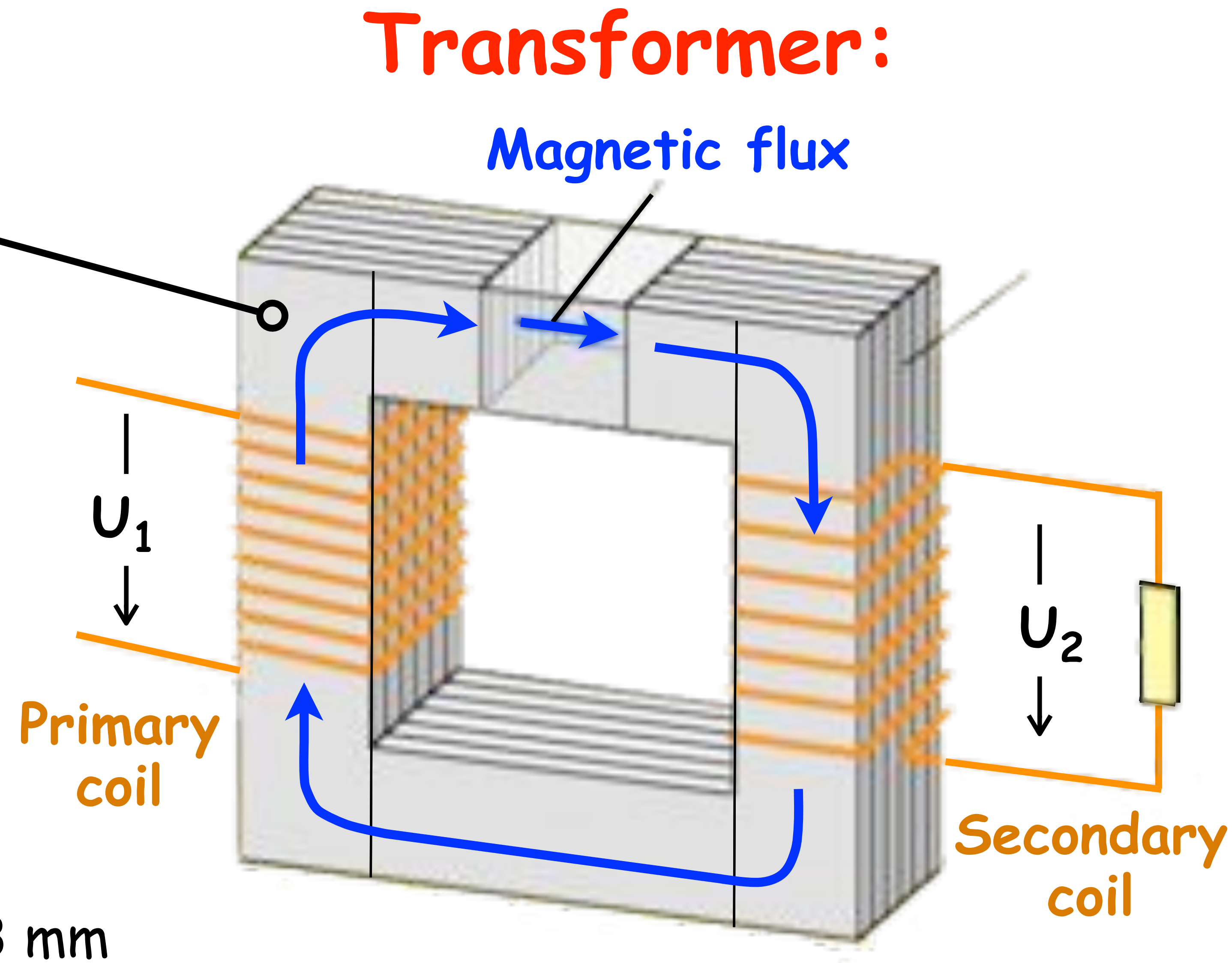

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  - Still sufficiently ductile for cold-rolling
  - No α–γ transition for > 2.2 wt% Si → stays bcc on heat treatment
  - Crystal anisotropy somewhat lower (K_1 : $4.8 \cdot 10^4$ → $3.6 \cdot 10^4$ J/m^3)
  - Magnetostriction higher (λ_{100} : $20 \cdot 10^{-6}$ → $23 \cdot 10^{-6}$)

Grain-oriented FeSi transformer material

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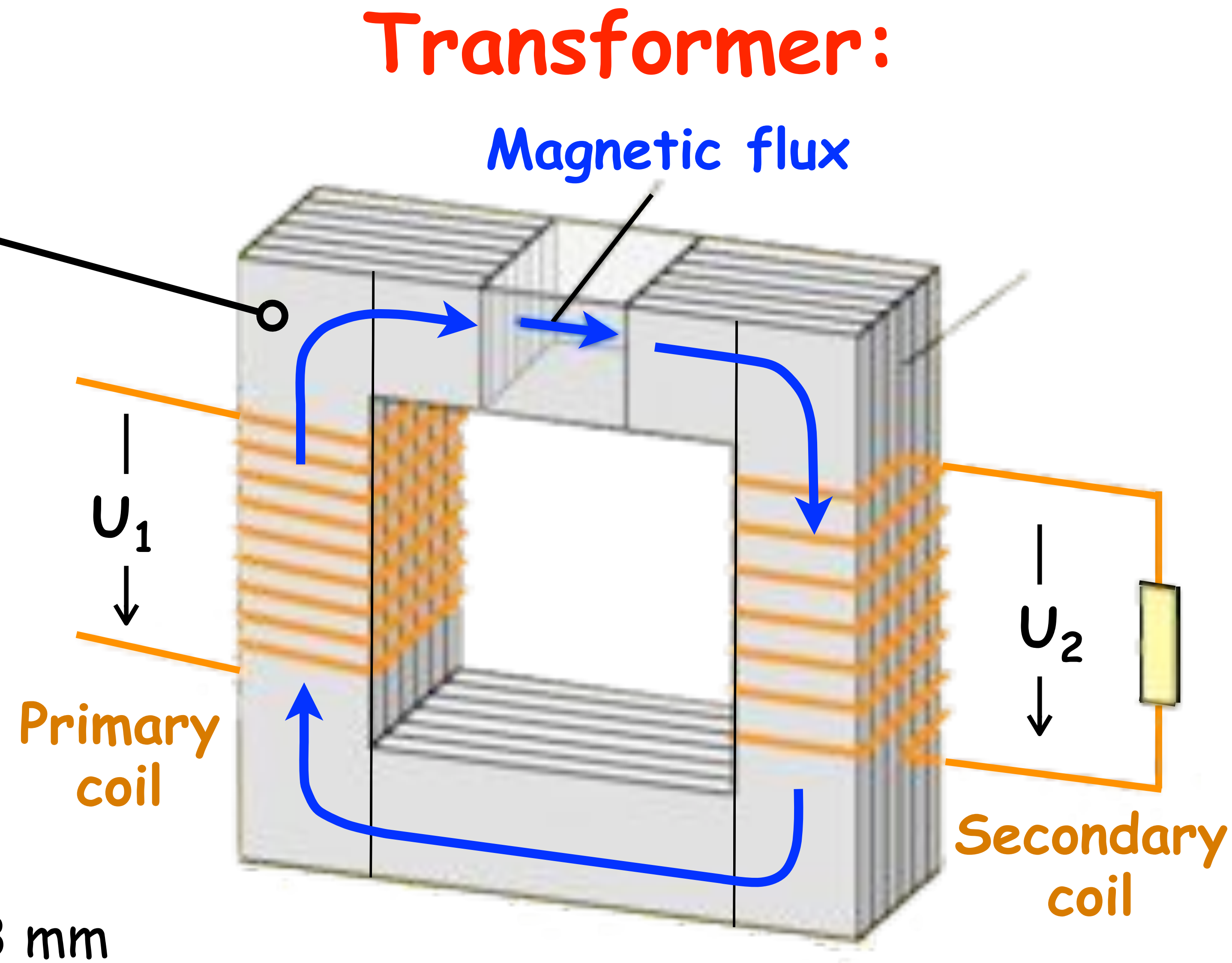

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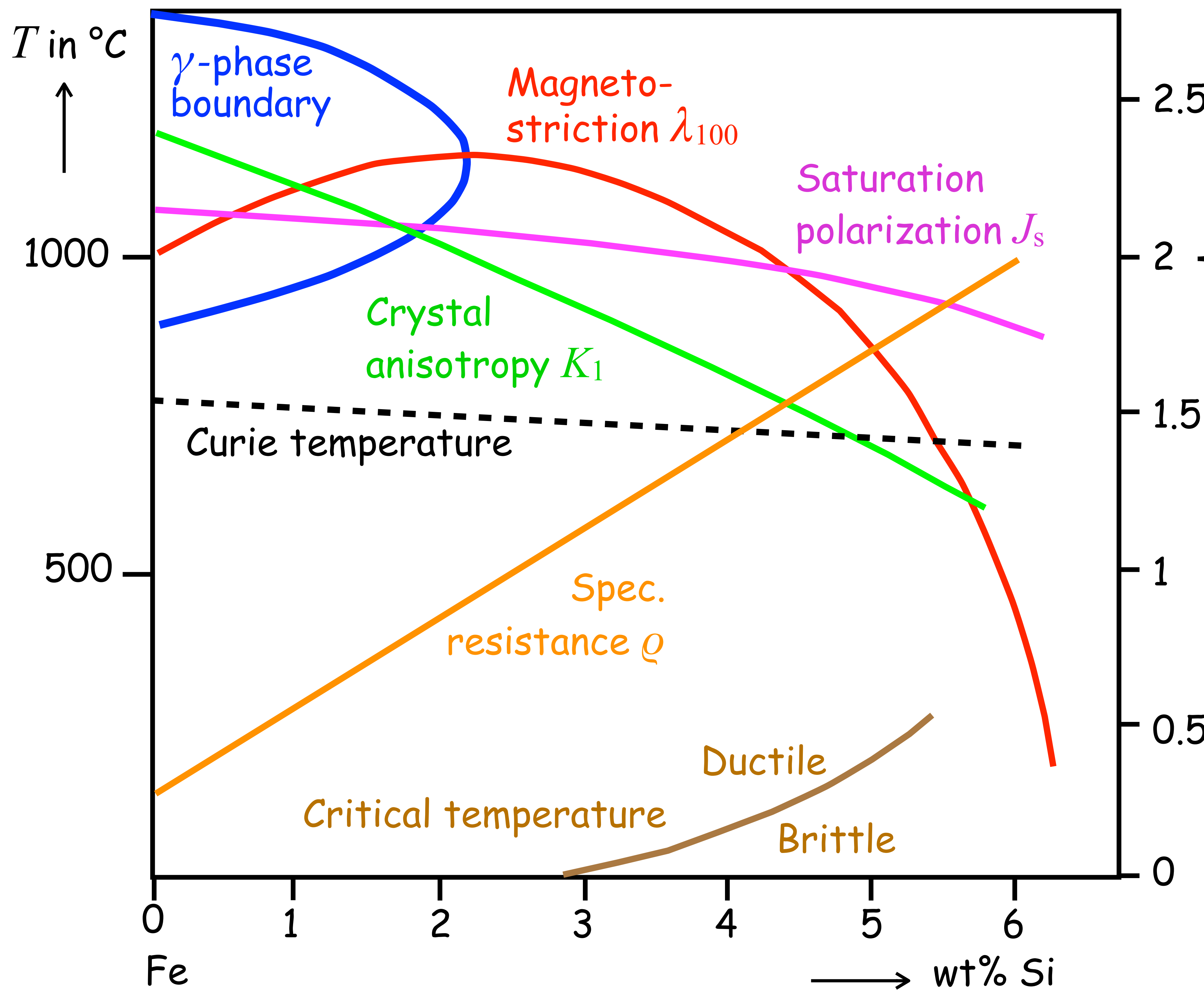
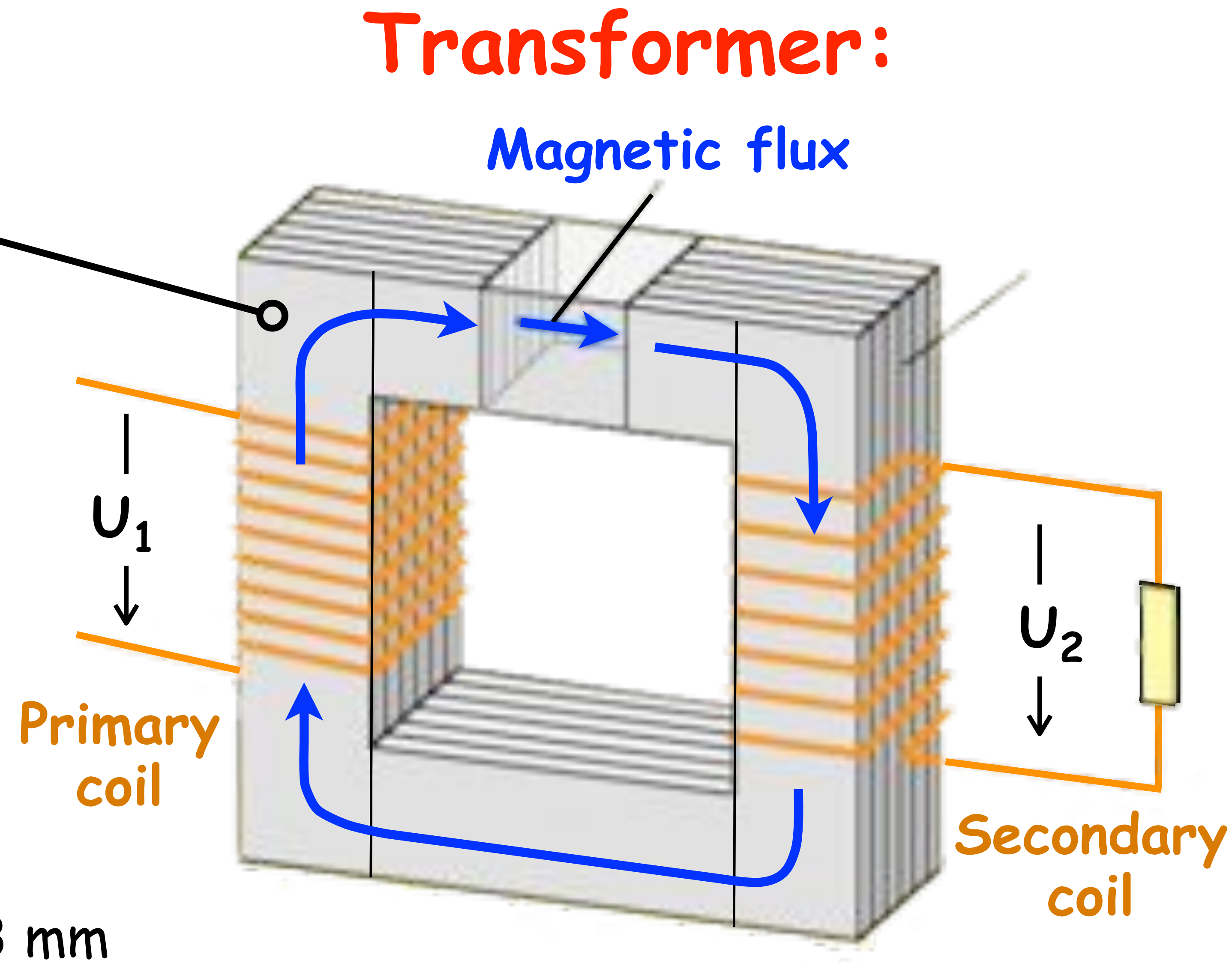


$J_s = 2$ T
$\lambda_{100} = 20 \cdot 10^{-6}$
$K_1 = 4 \cdot 10^4$ J/m^3
$\varrho = 80$ µΩcm

Grain-oriented FeSi transformer material



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Anisotropy and magnetostriction not negligible:
→ make use of them

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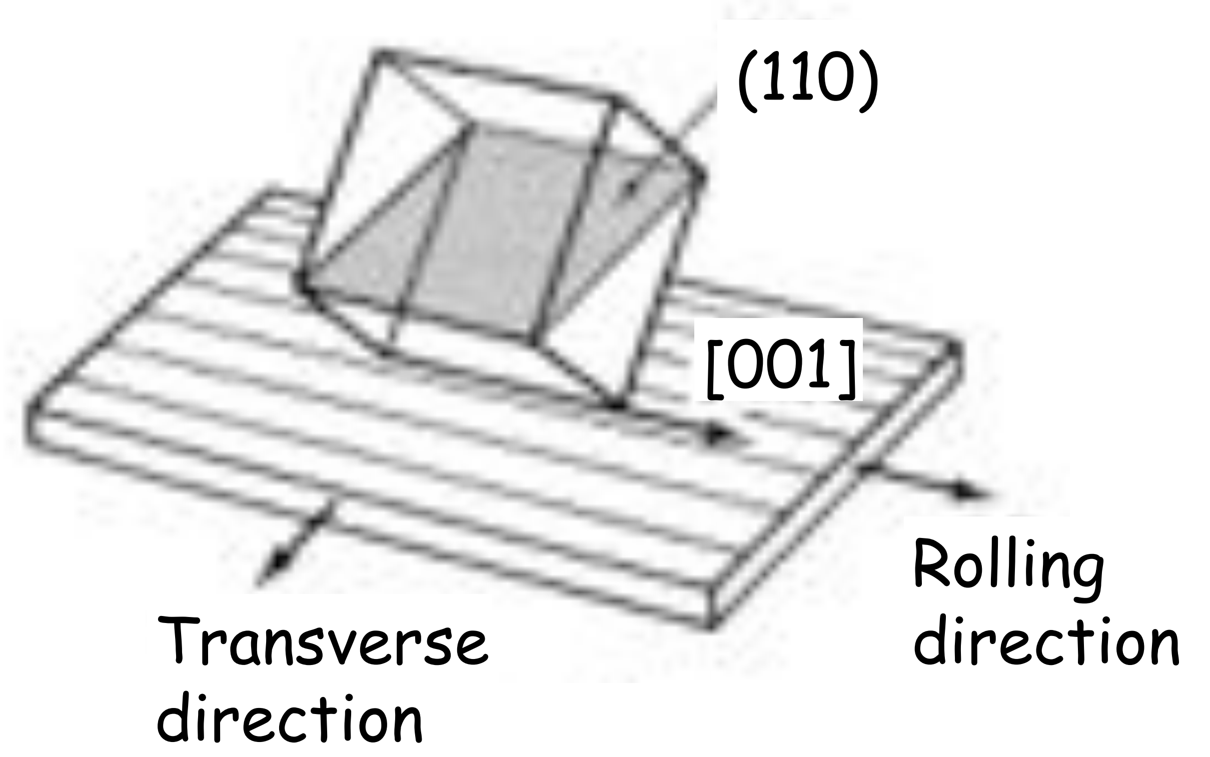
- Proper rolling and annealing
  (Mn- and S-additions: prevent primary recrystallization, grain growth by secondary recrystallization)
  → **Goss texture (cube-on-edge)**

  Grain size: millimeters up to centimeters

  Coating (~3 μm) for electrical insulation



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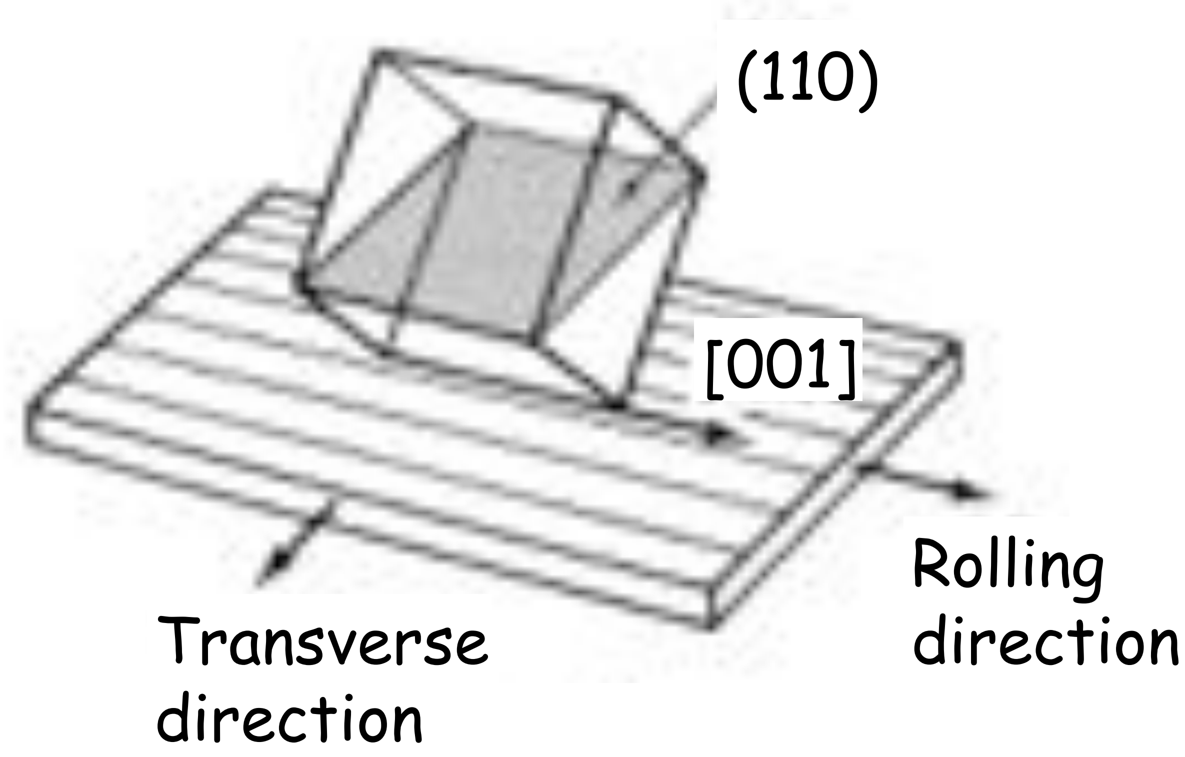
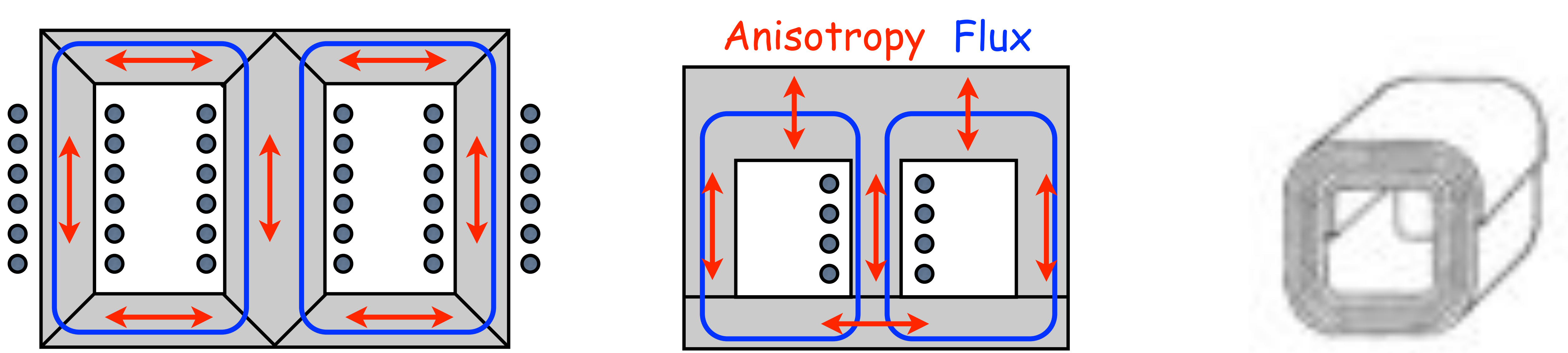
Grain size: millimeters up to centimeters
Coating (~3 μm) for electrical insulation



- Because of anisotropy → rolling direction parallel to direction of flux travel



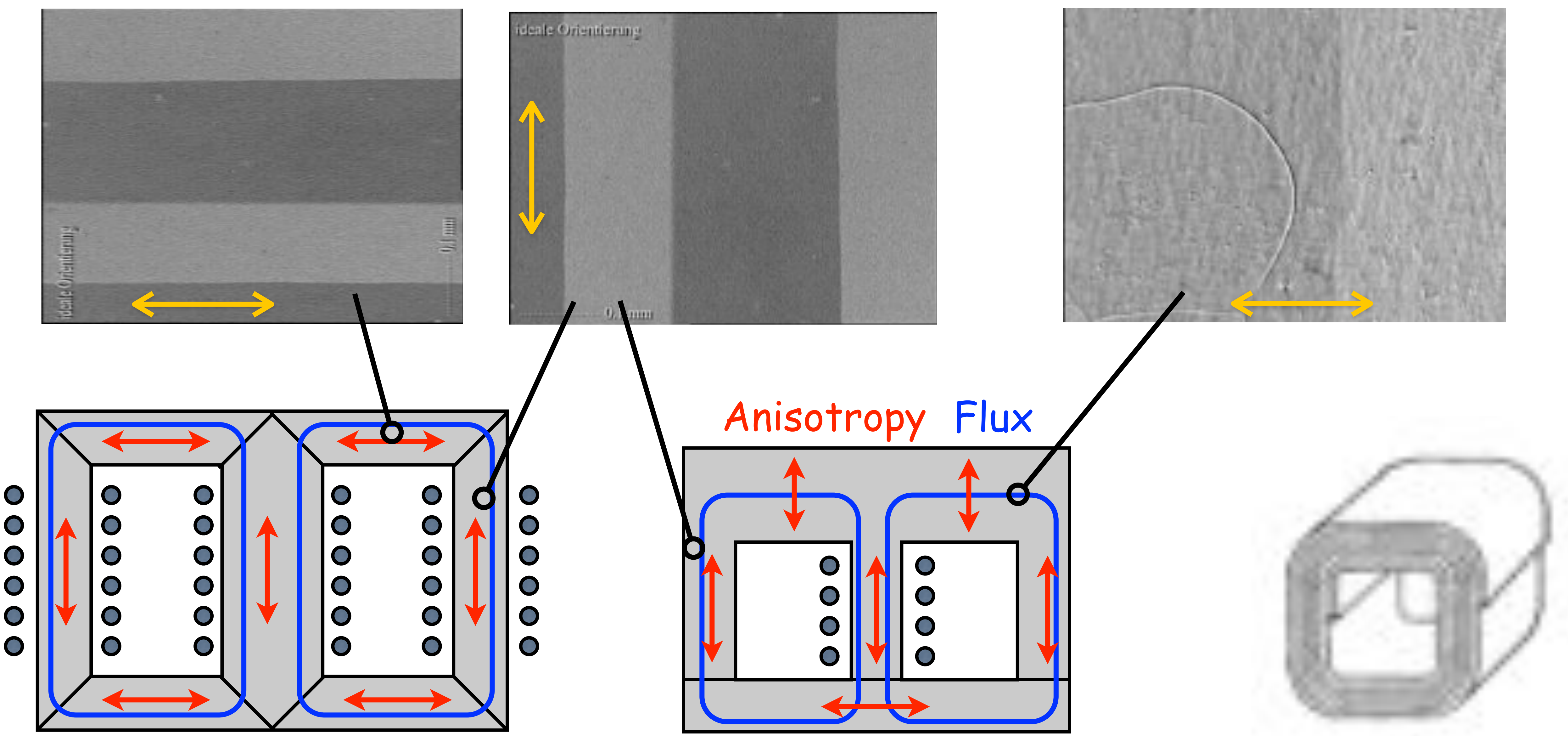
Power transformer (large) Distribution transformer (small) Stripe-wound core

Grain-oriented FeSi transformer material

Anisotropy and magnetostriction not negligible:
→ make use of them

Permeability by wall displacement, magnetostriction irreleveant

Complex Domain reordering in transverse direction → loss ; higher crossection to keep μ

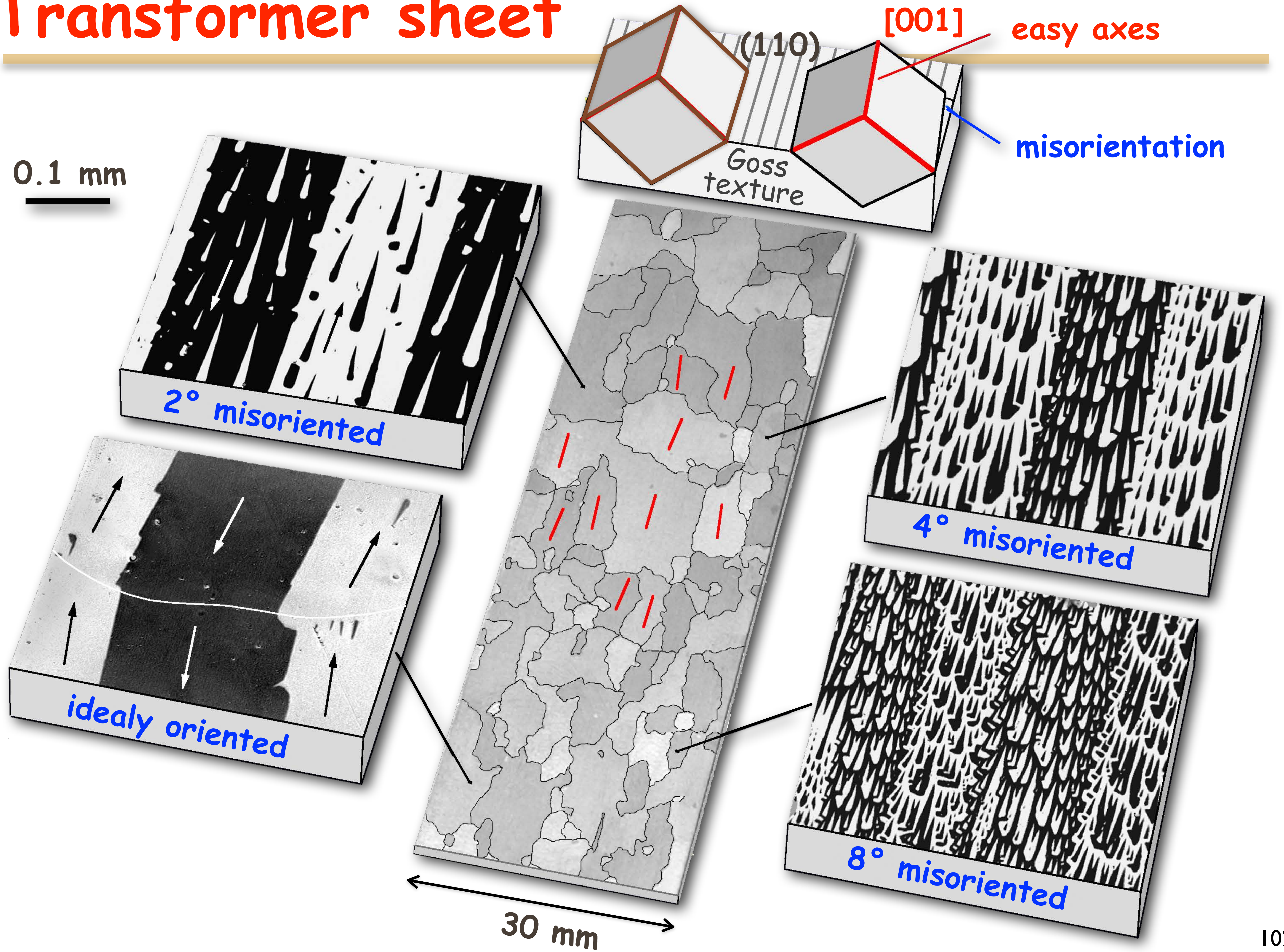


Power transformer (large)

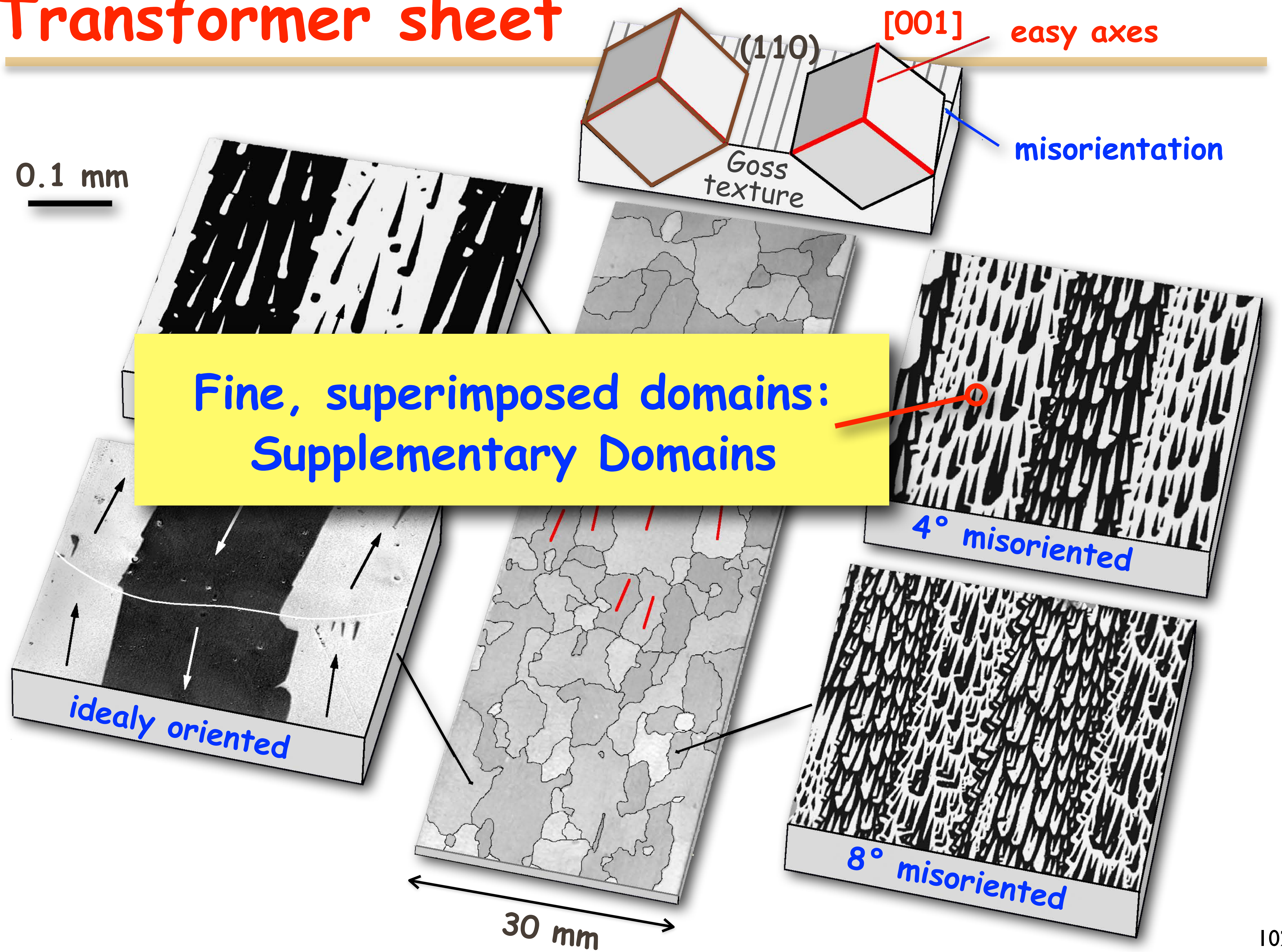
Distribution transformer (small)

Stripe-wound core

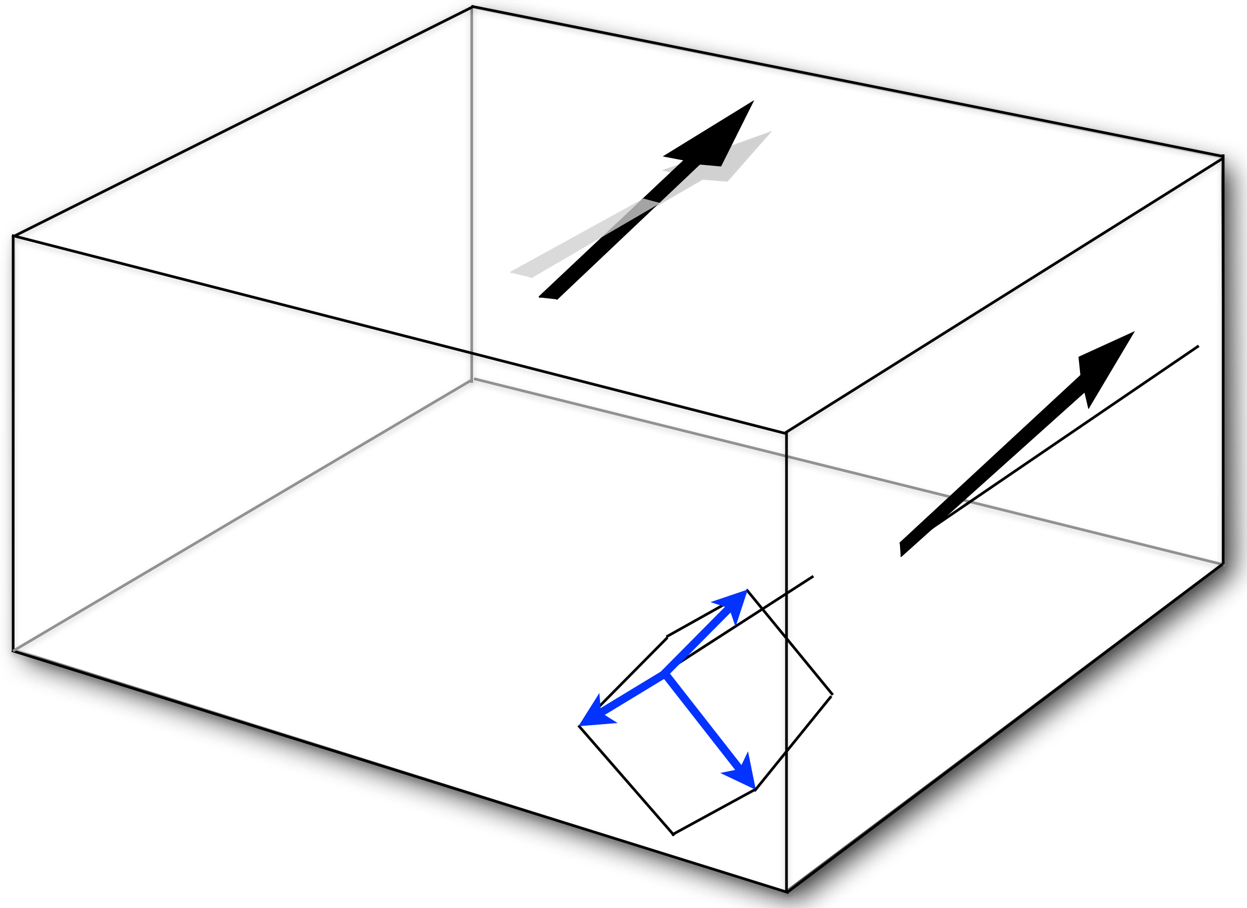
Transformer sheet



Transformer sheet



Grain-oriented FeSi transformer material



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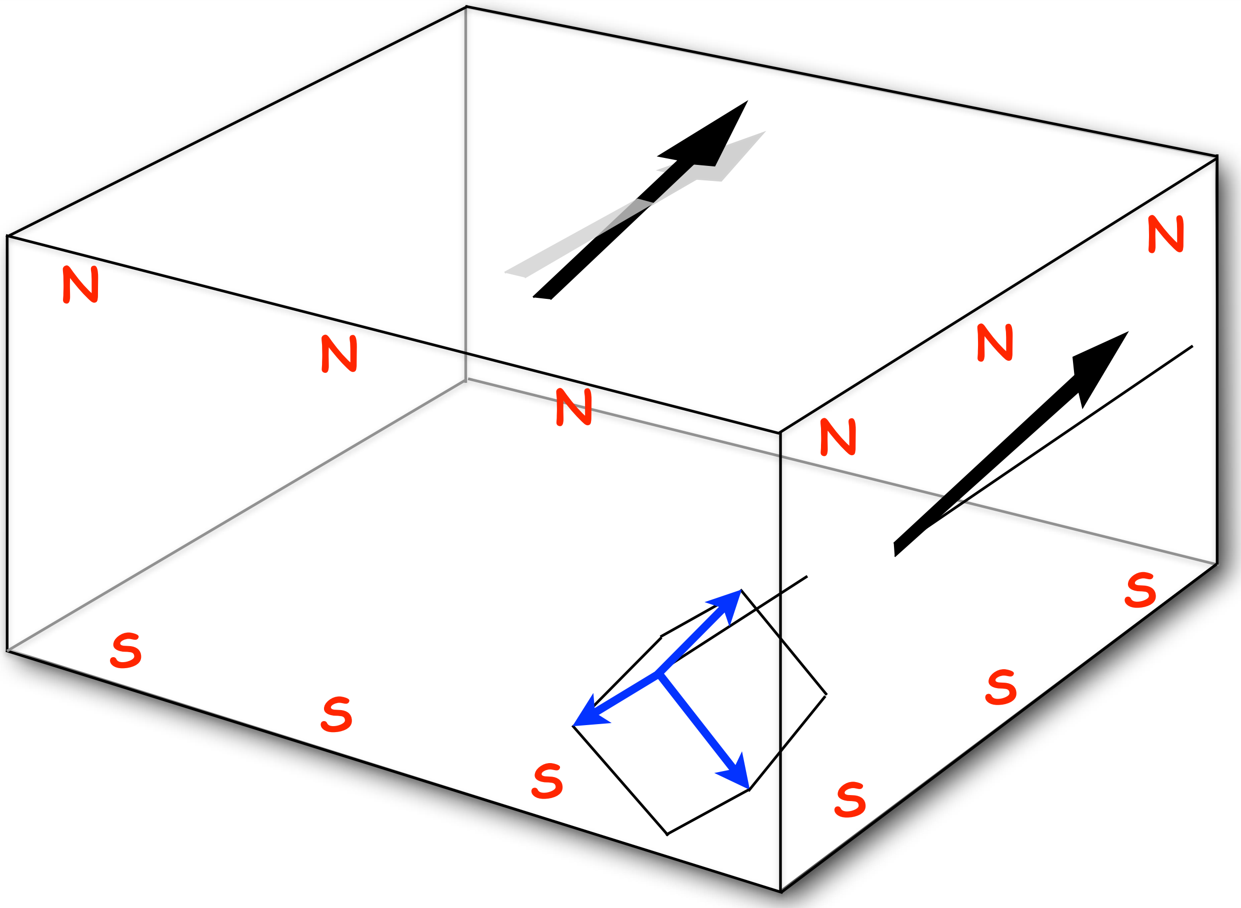

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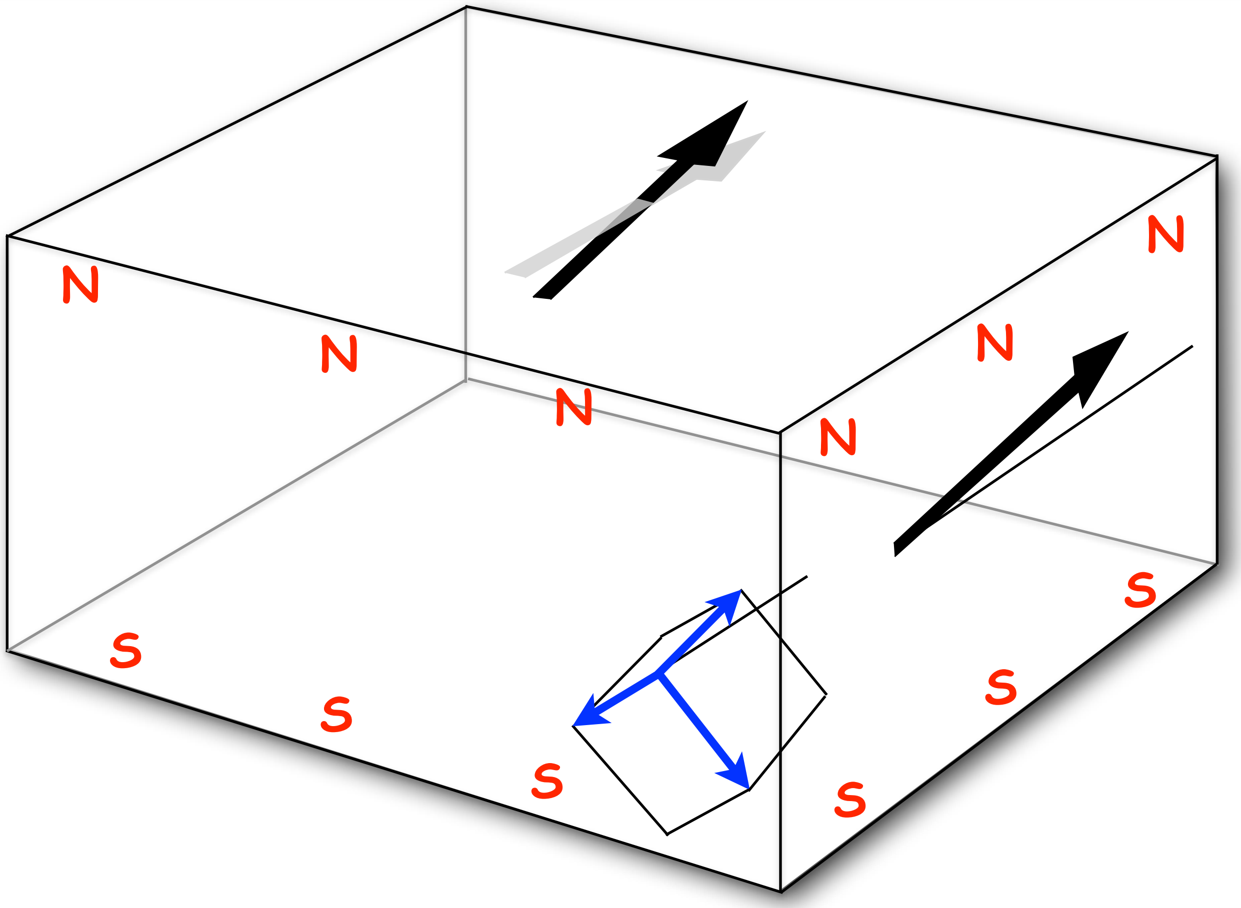

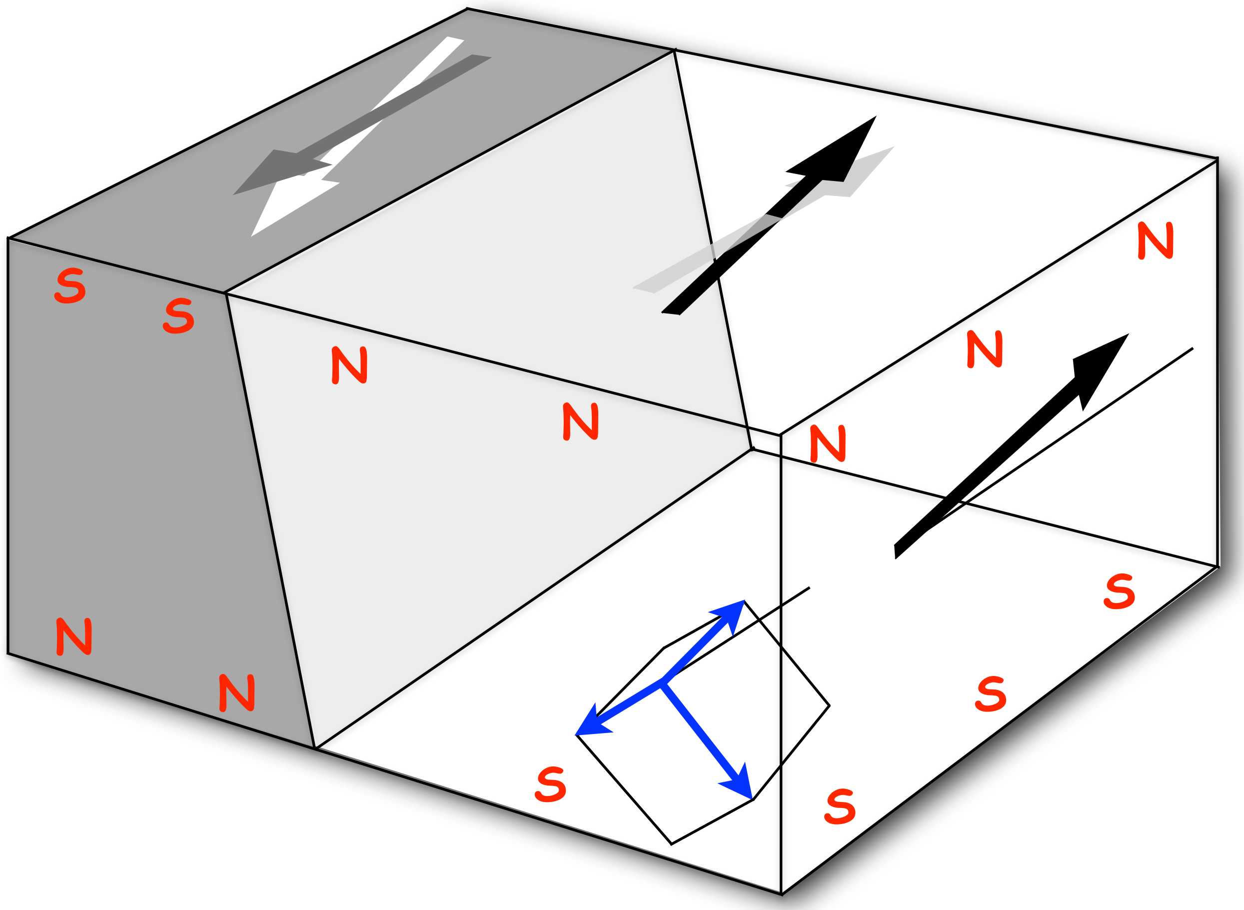

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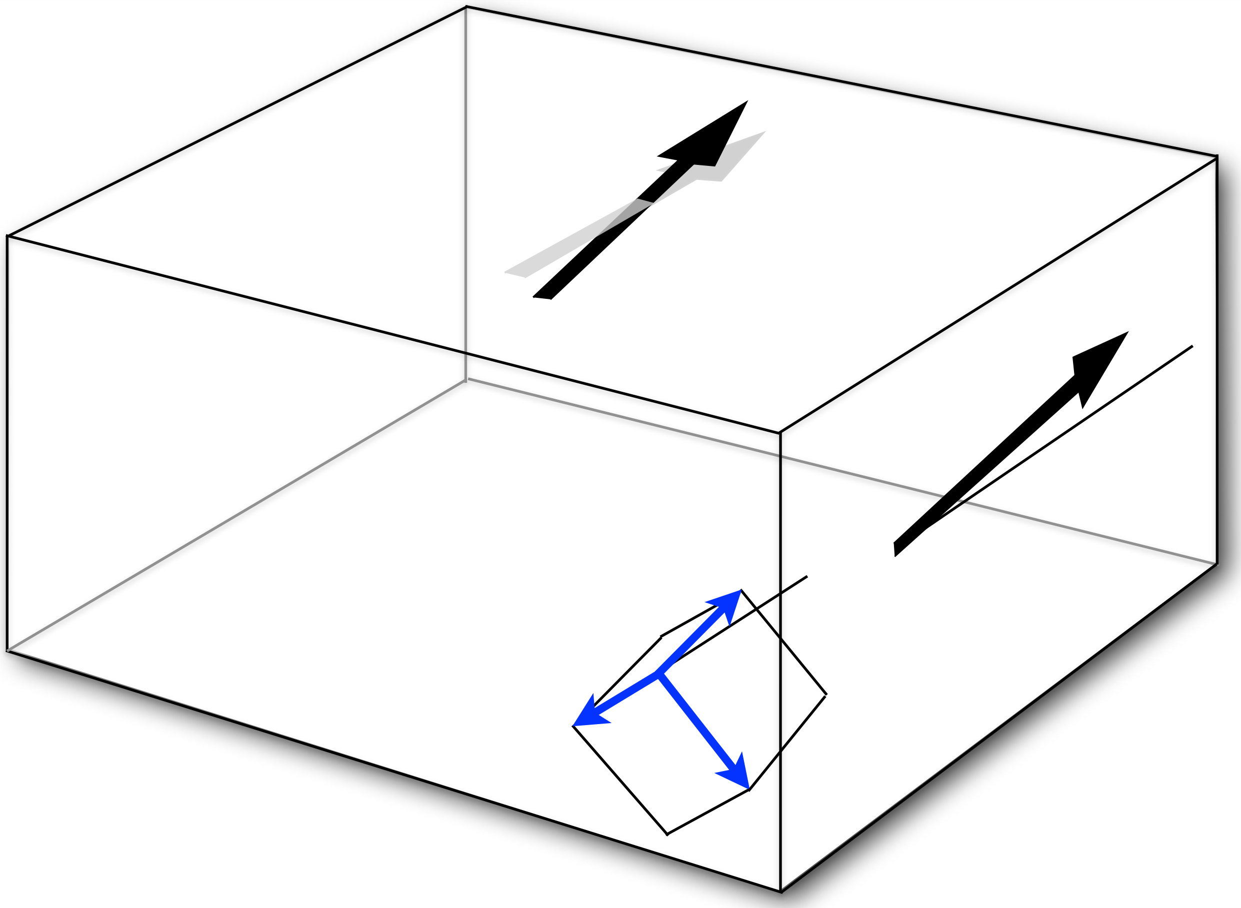
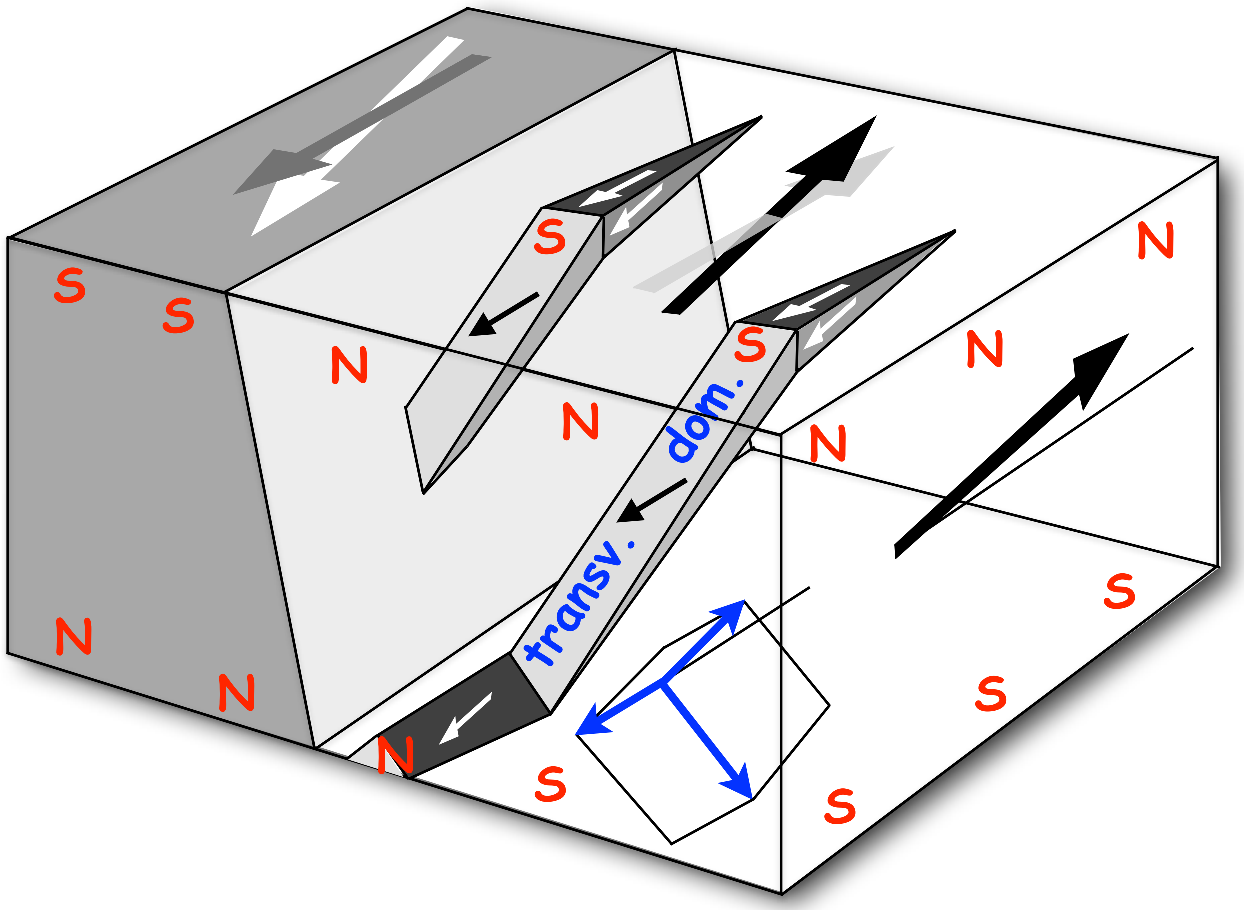
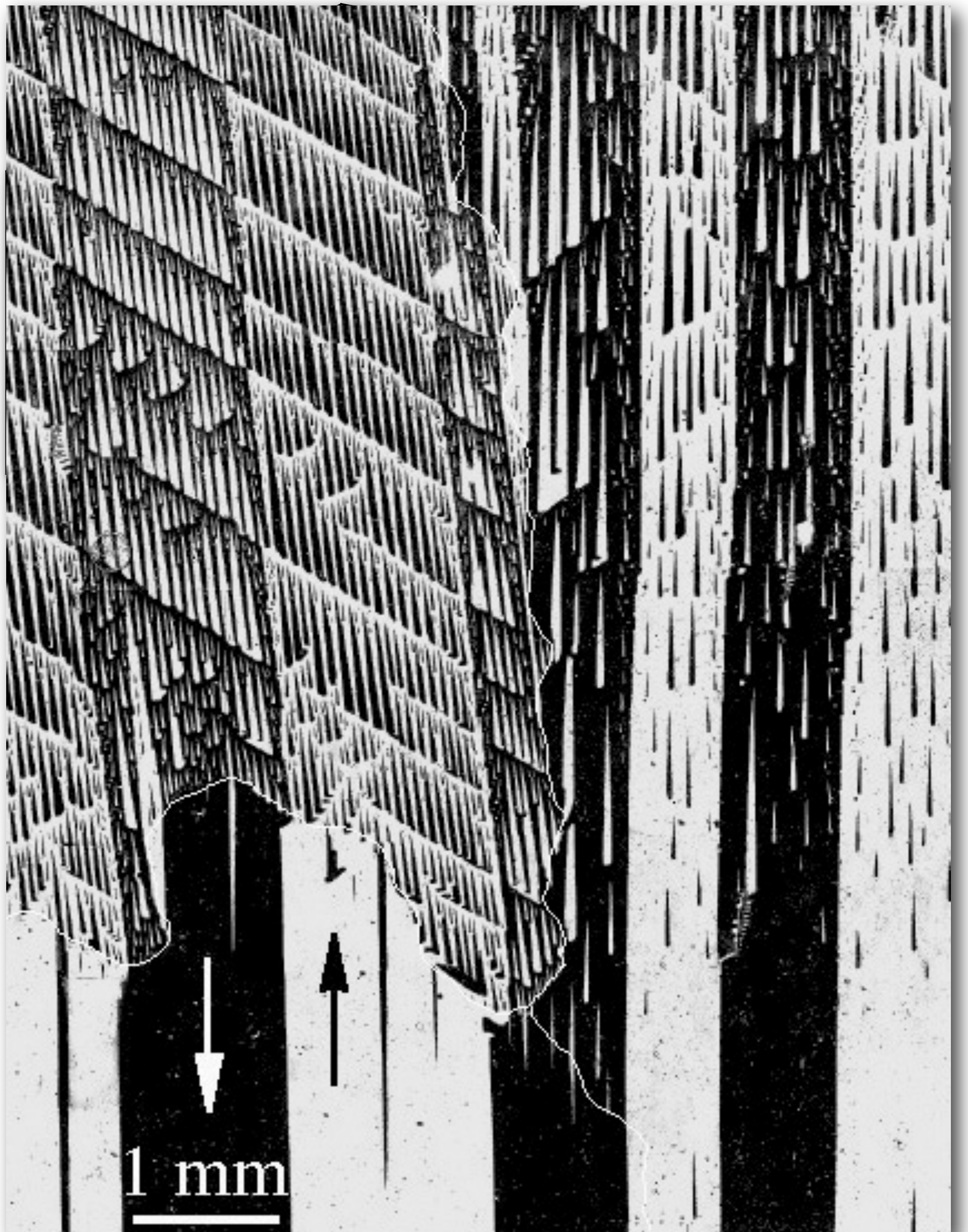
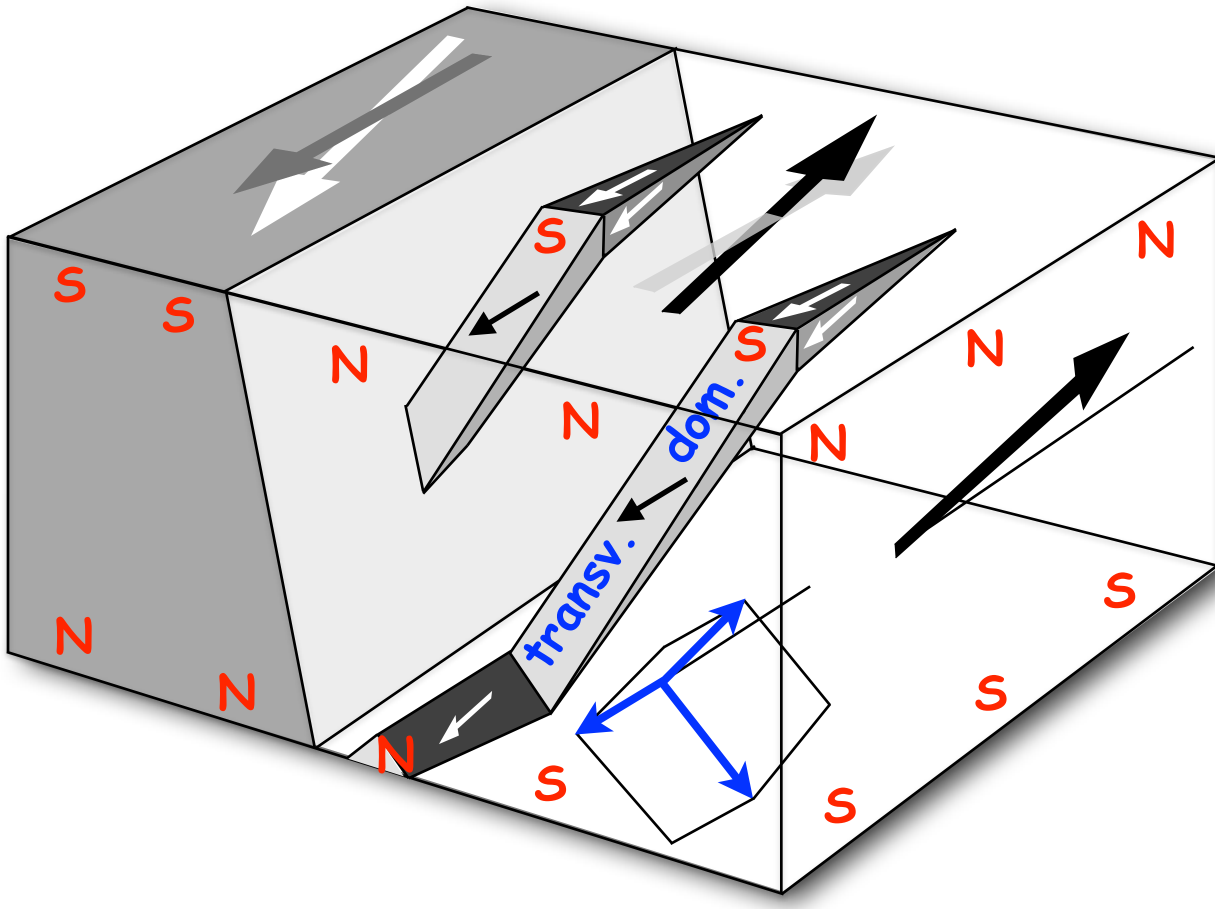


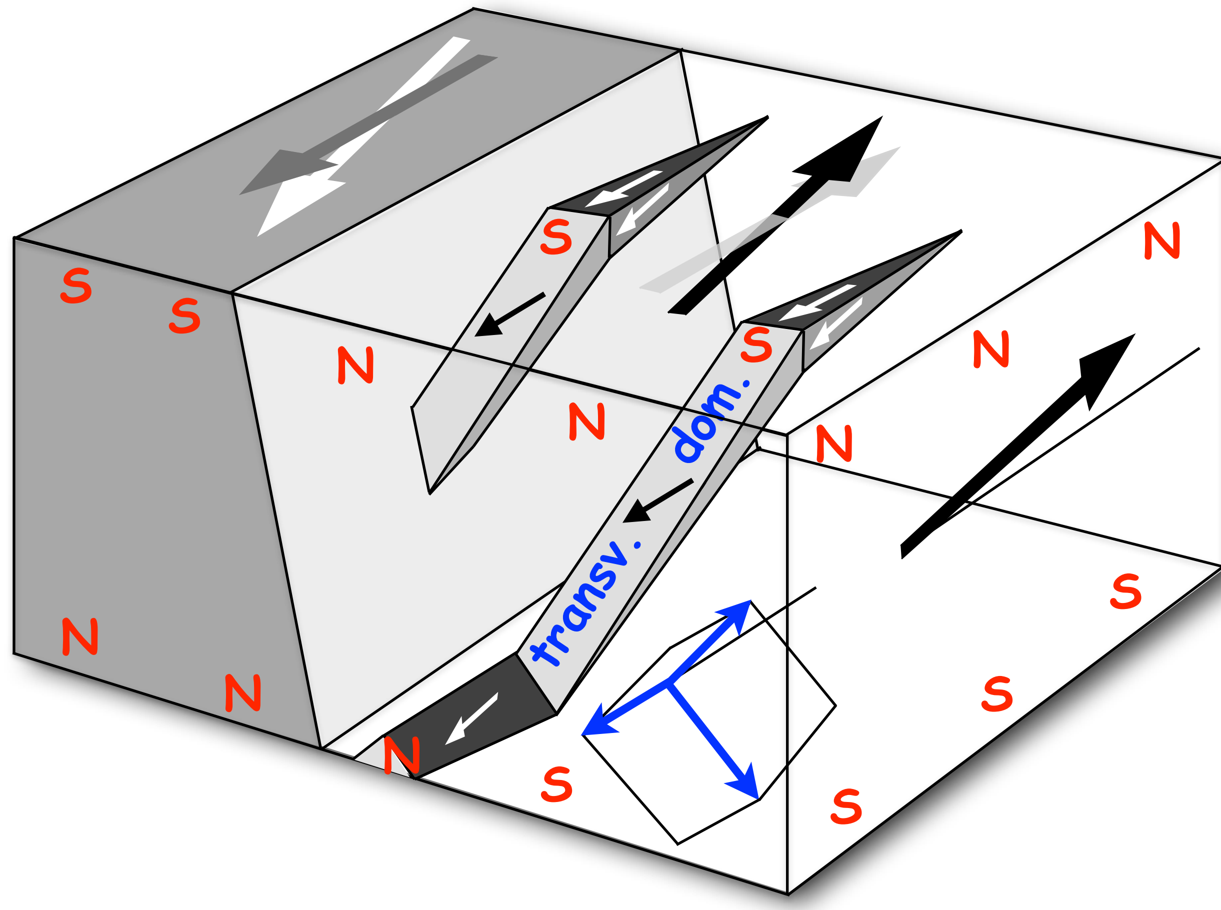


Grain-oriented FeSi transformer material

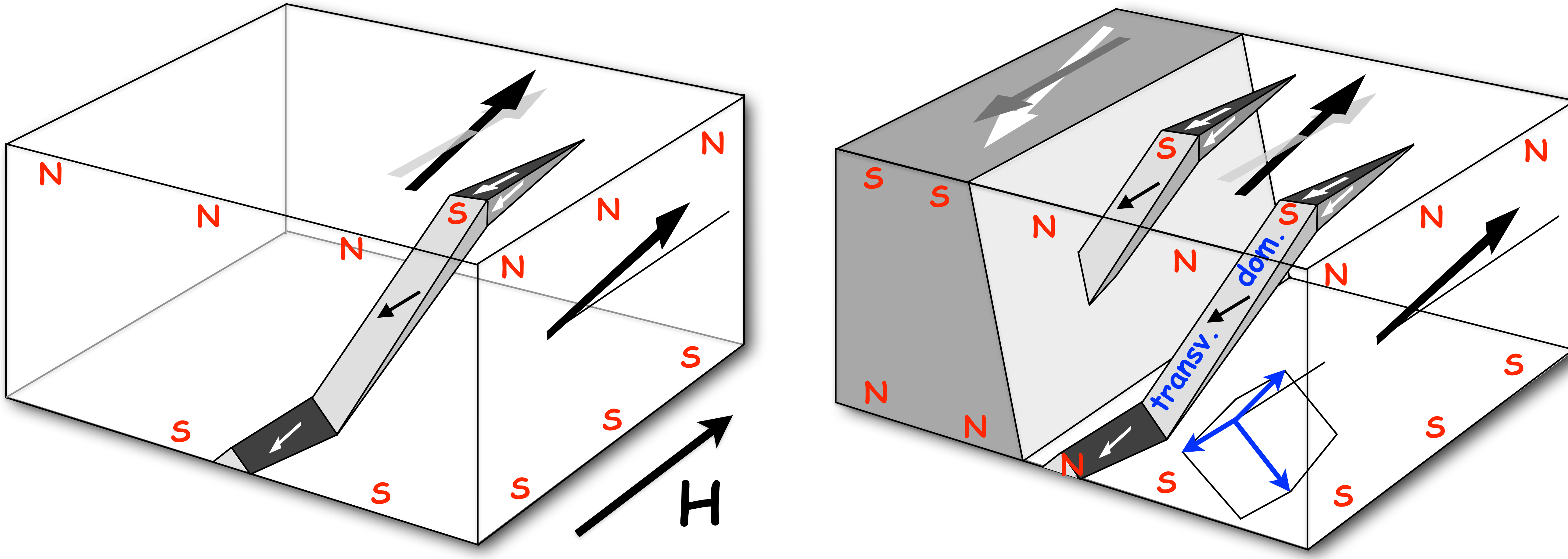




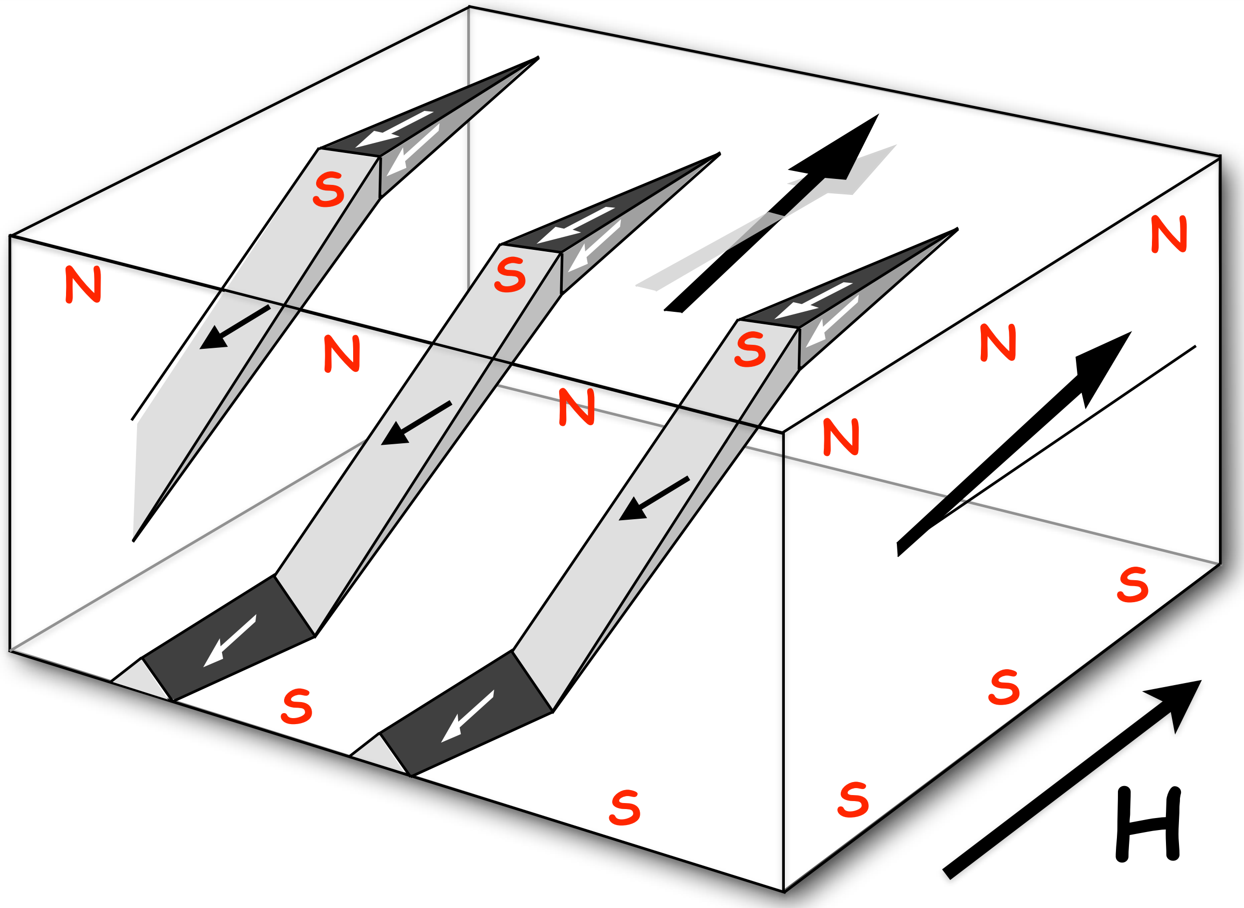
Grain-oriented FeSi transformer material

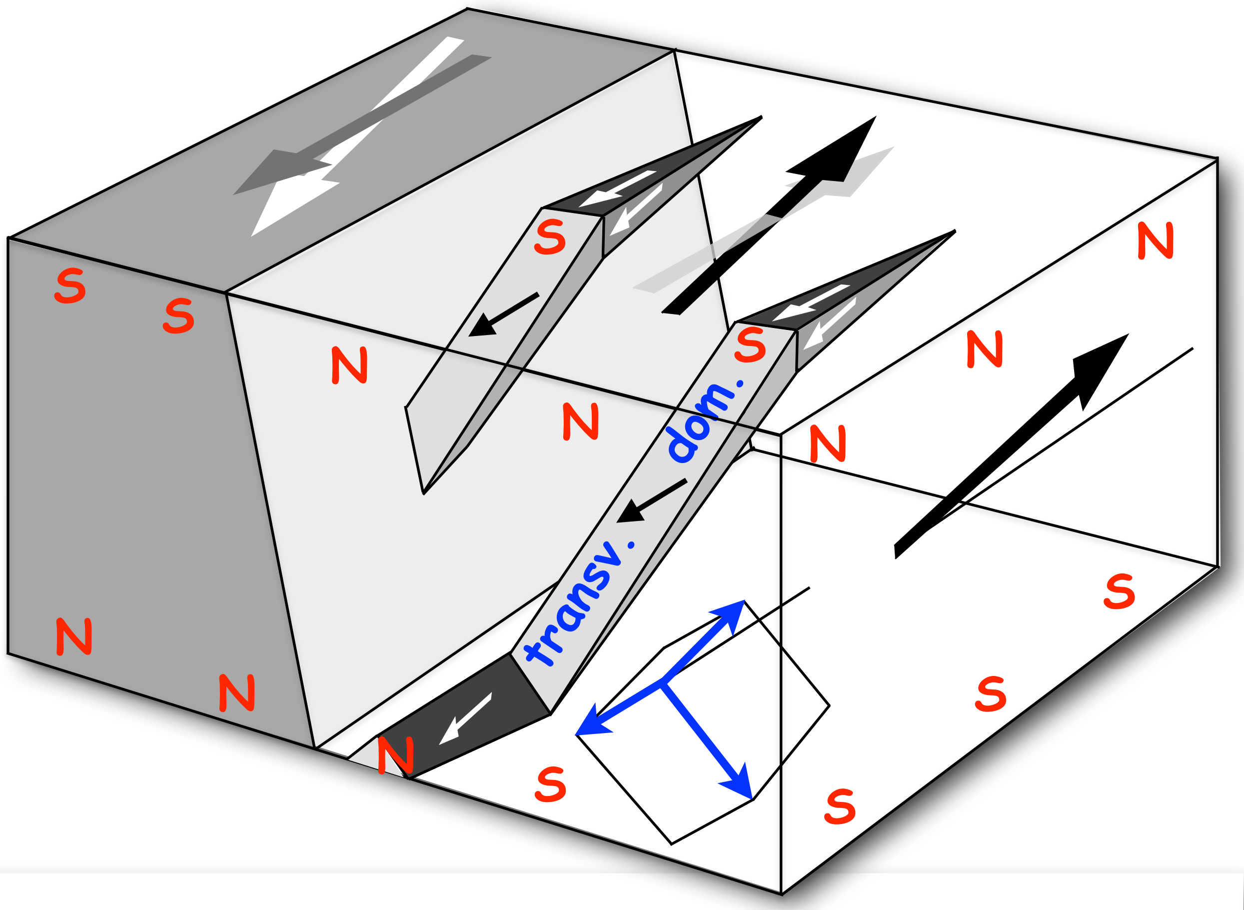


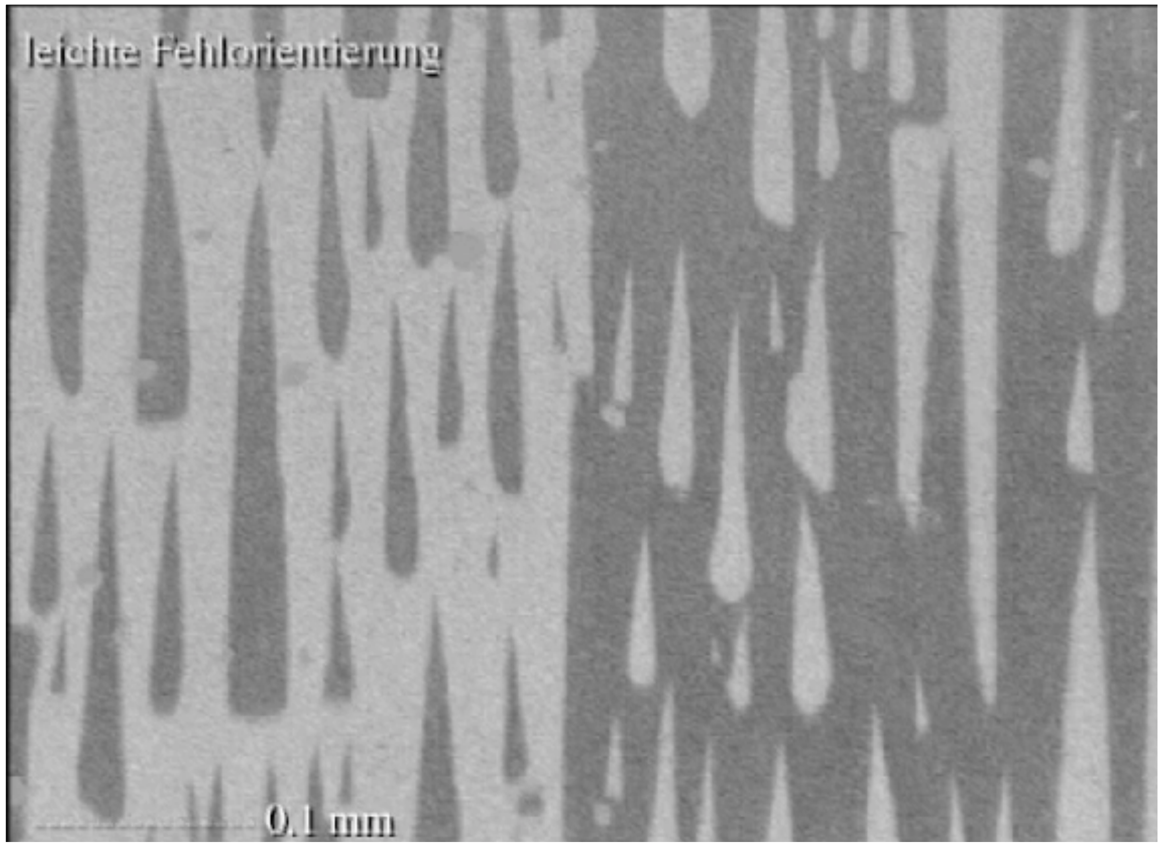
Grain-oriented FeSi transformer material



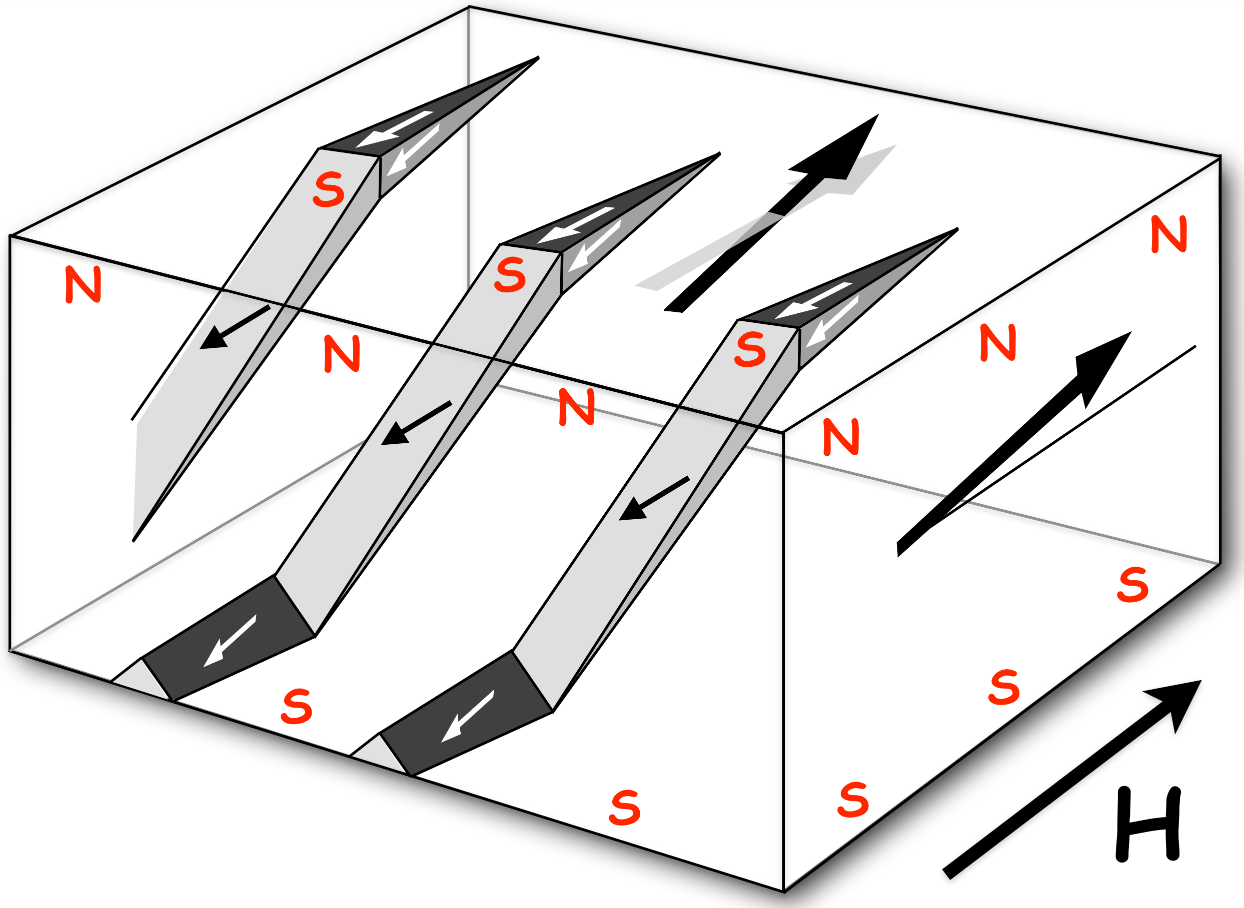
Grain-oriented FeSi transformer material

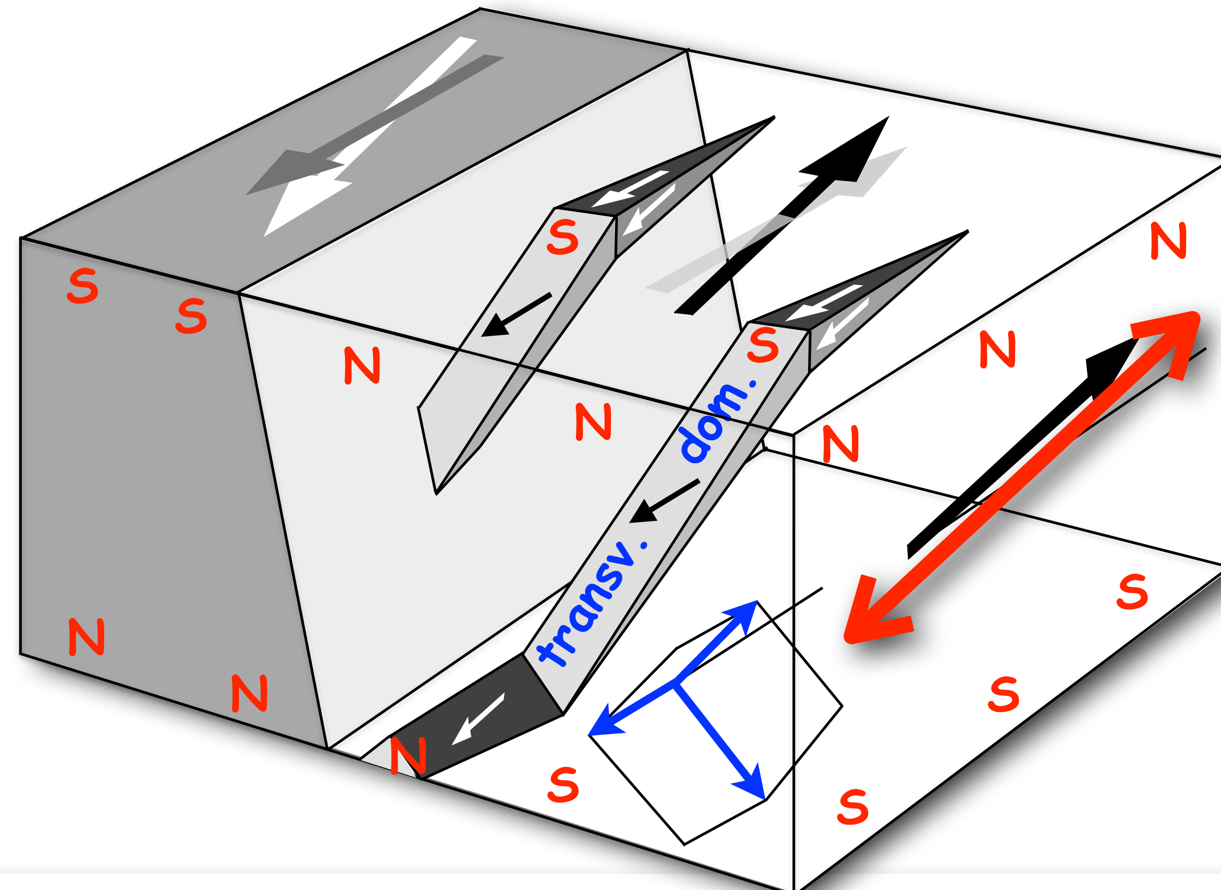


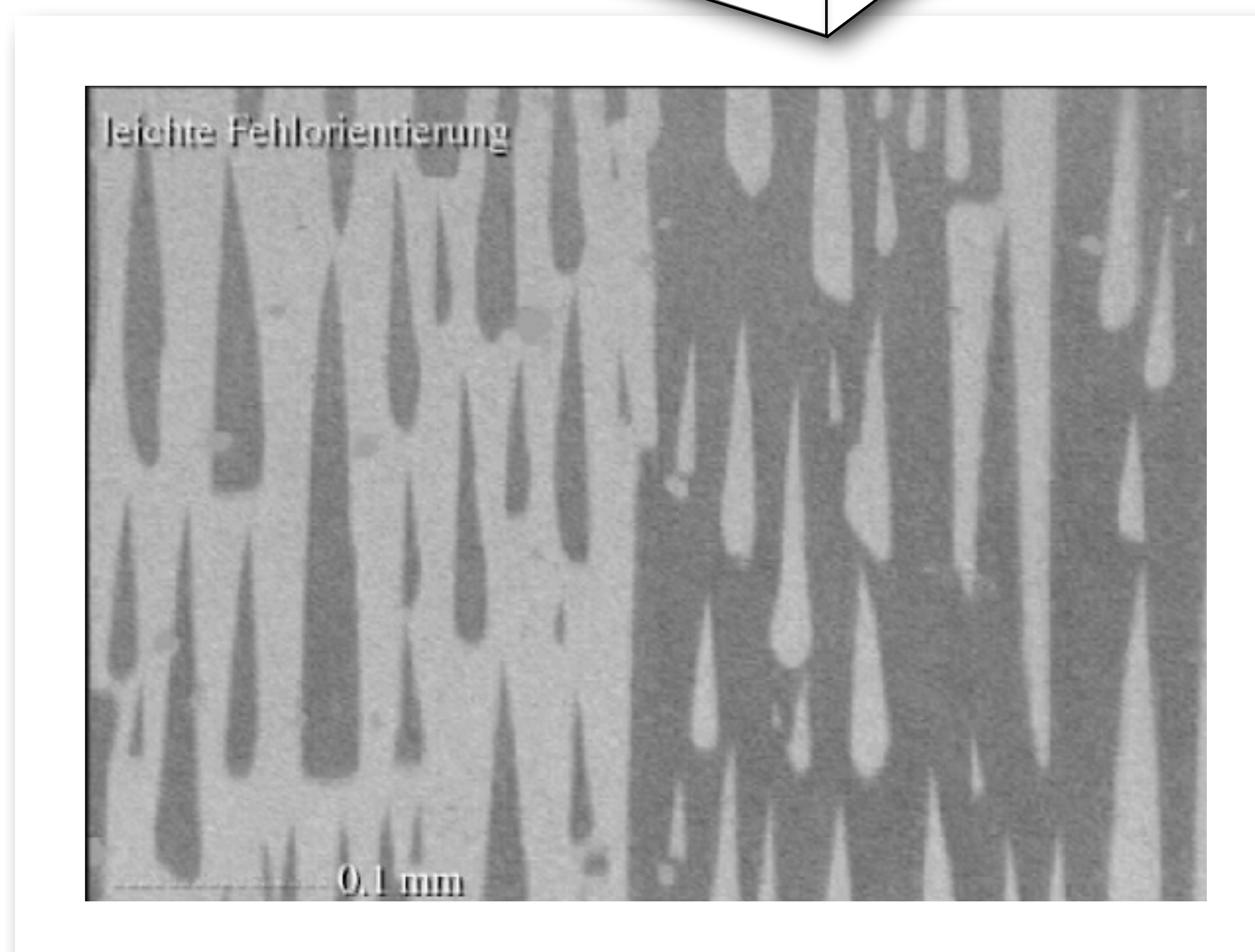




Grain-oriented FeSi transformer material







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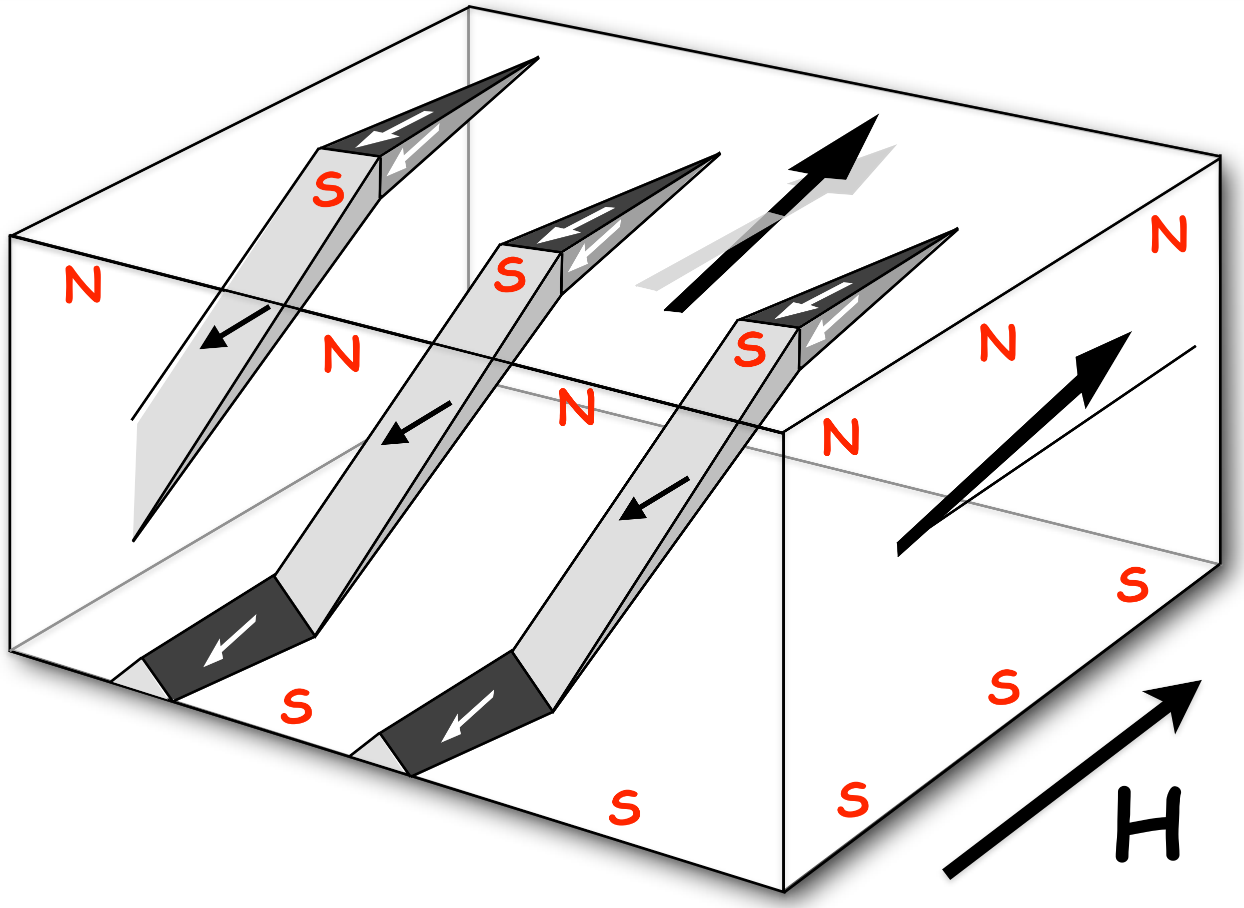

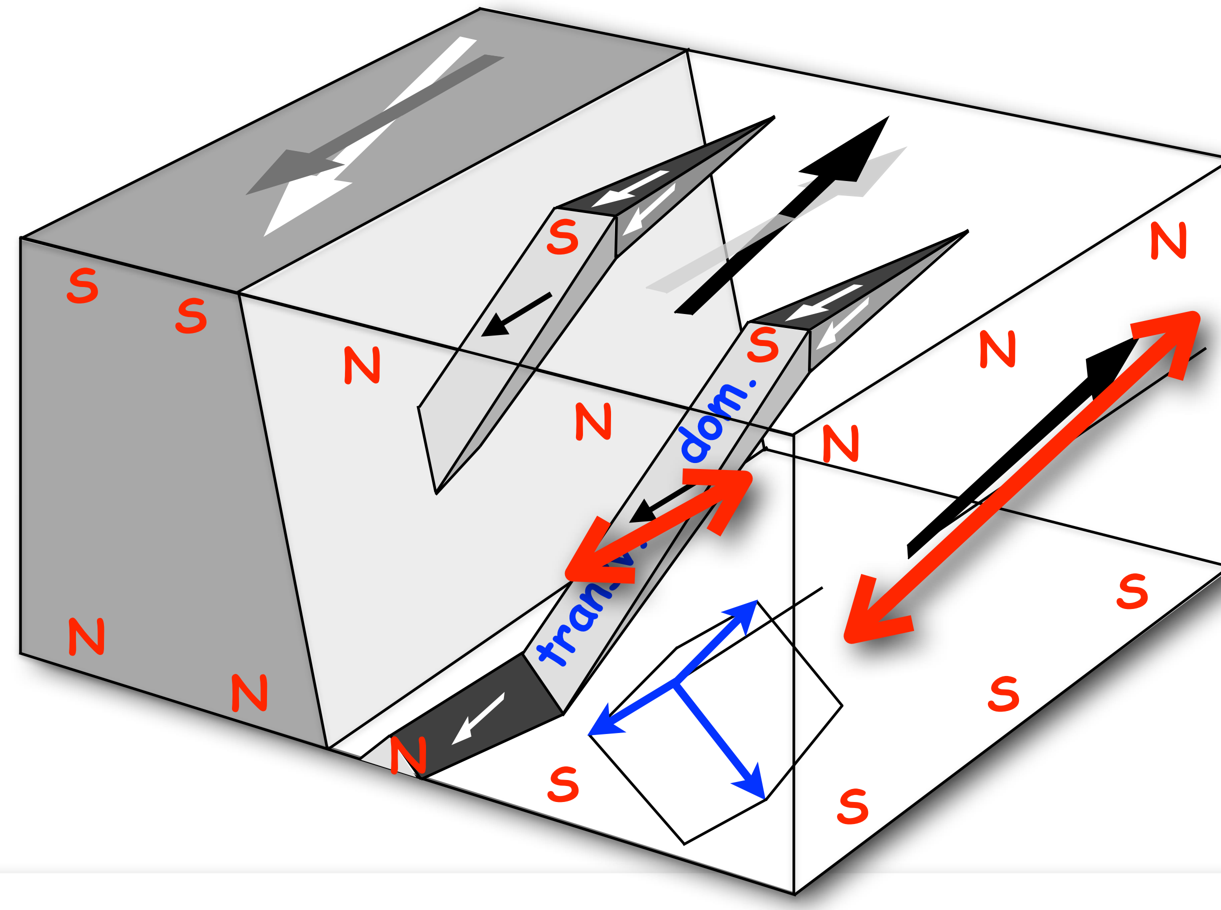

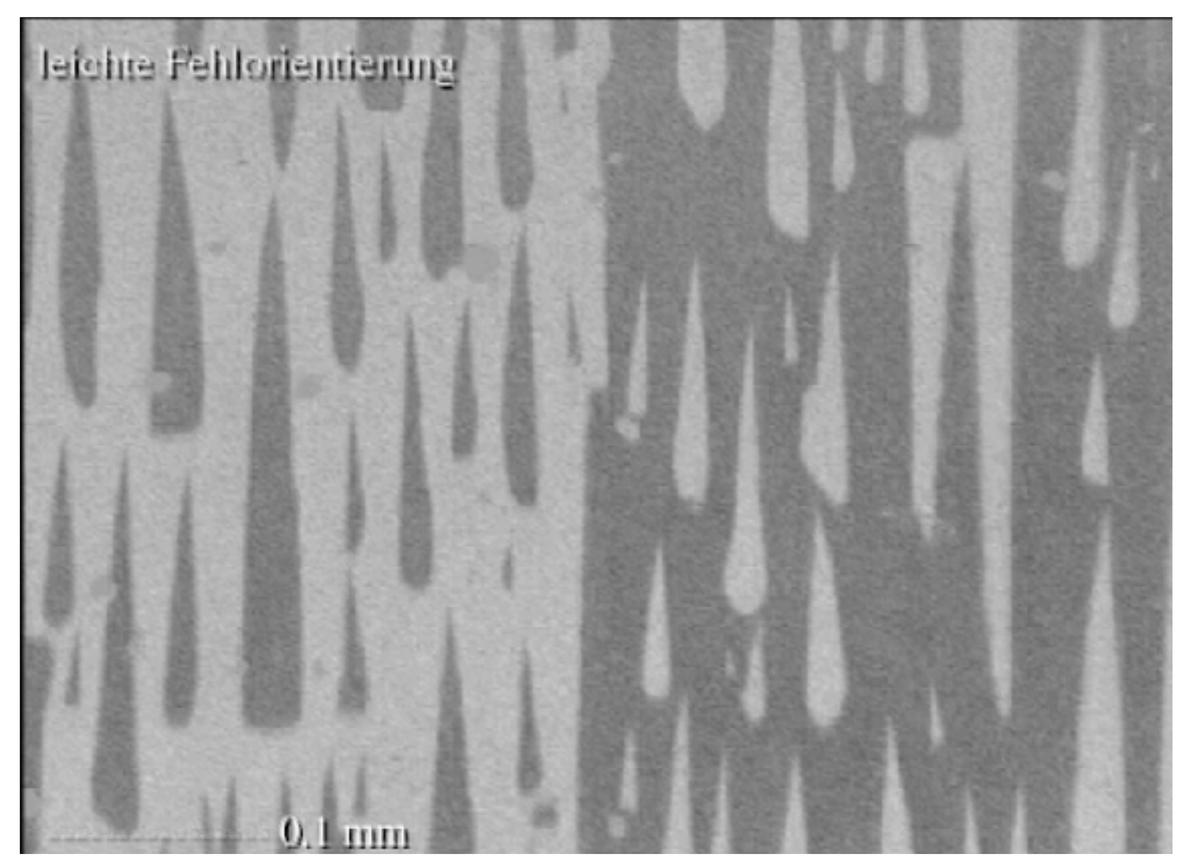

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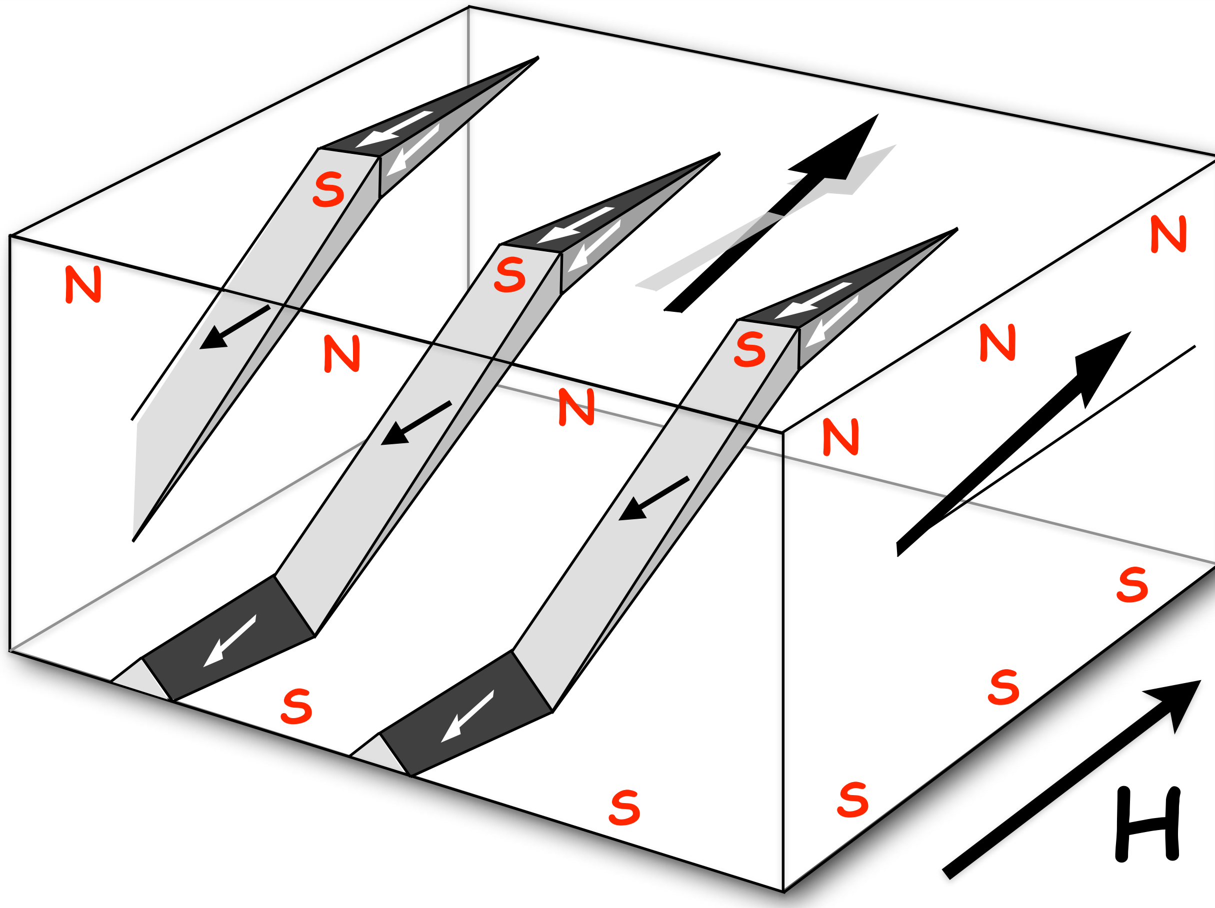
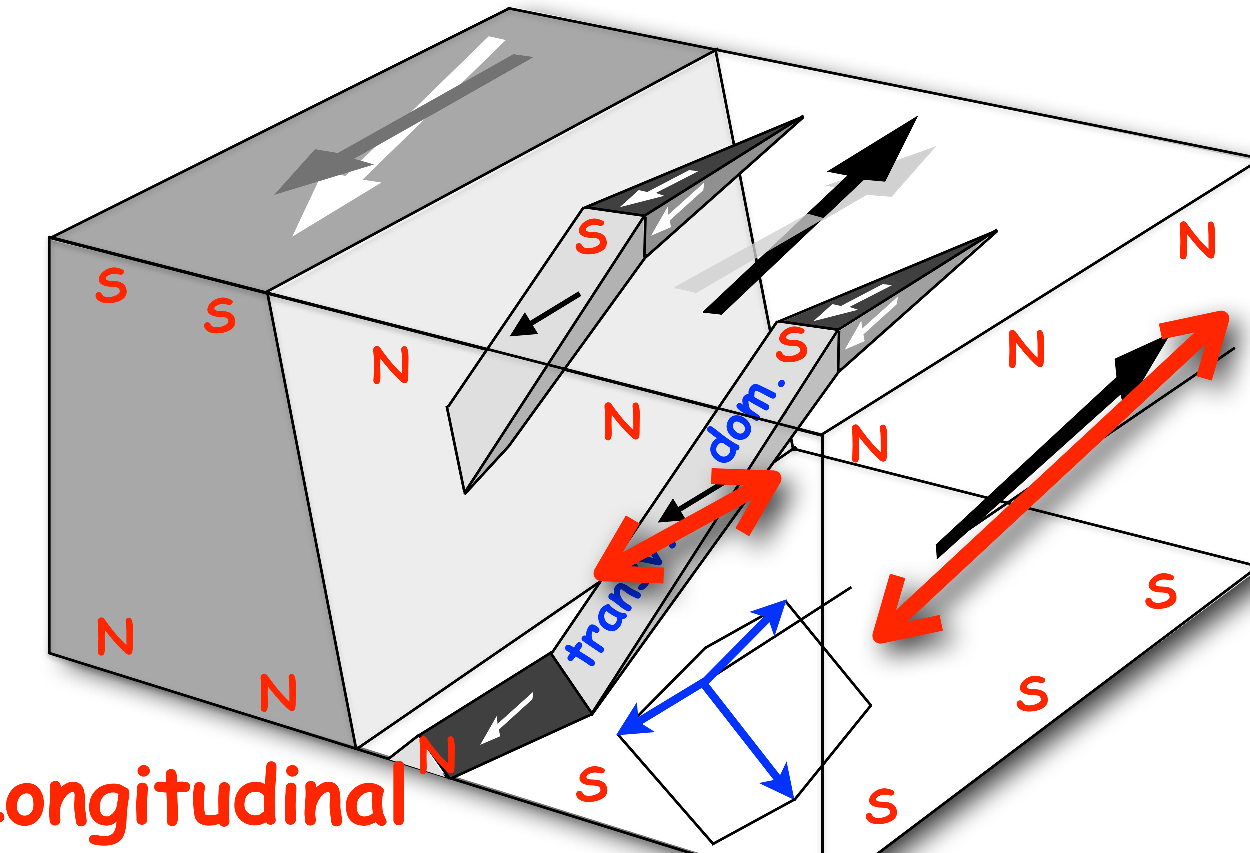
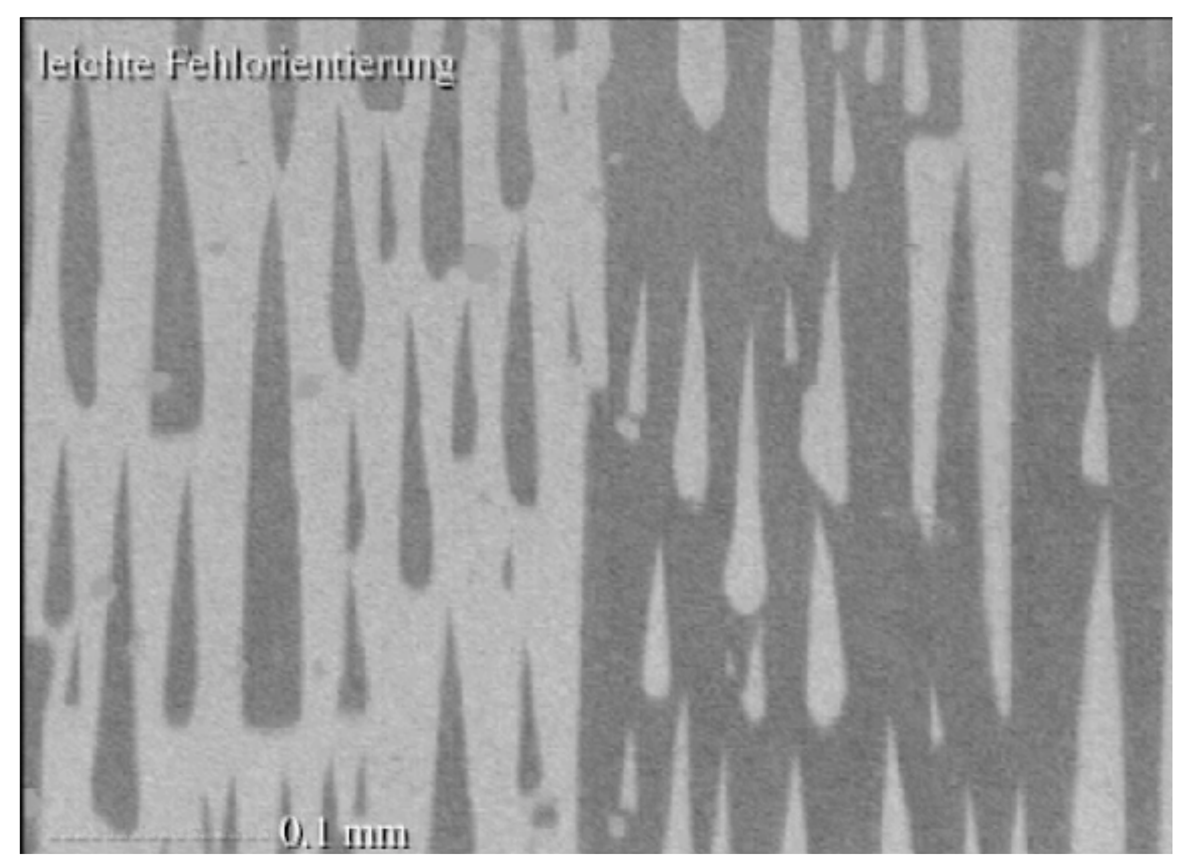
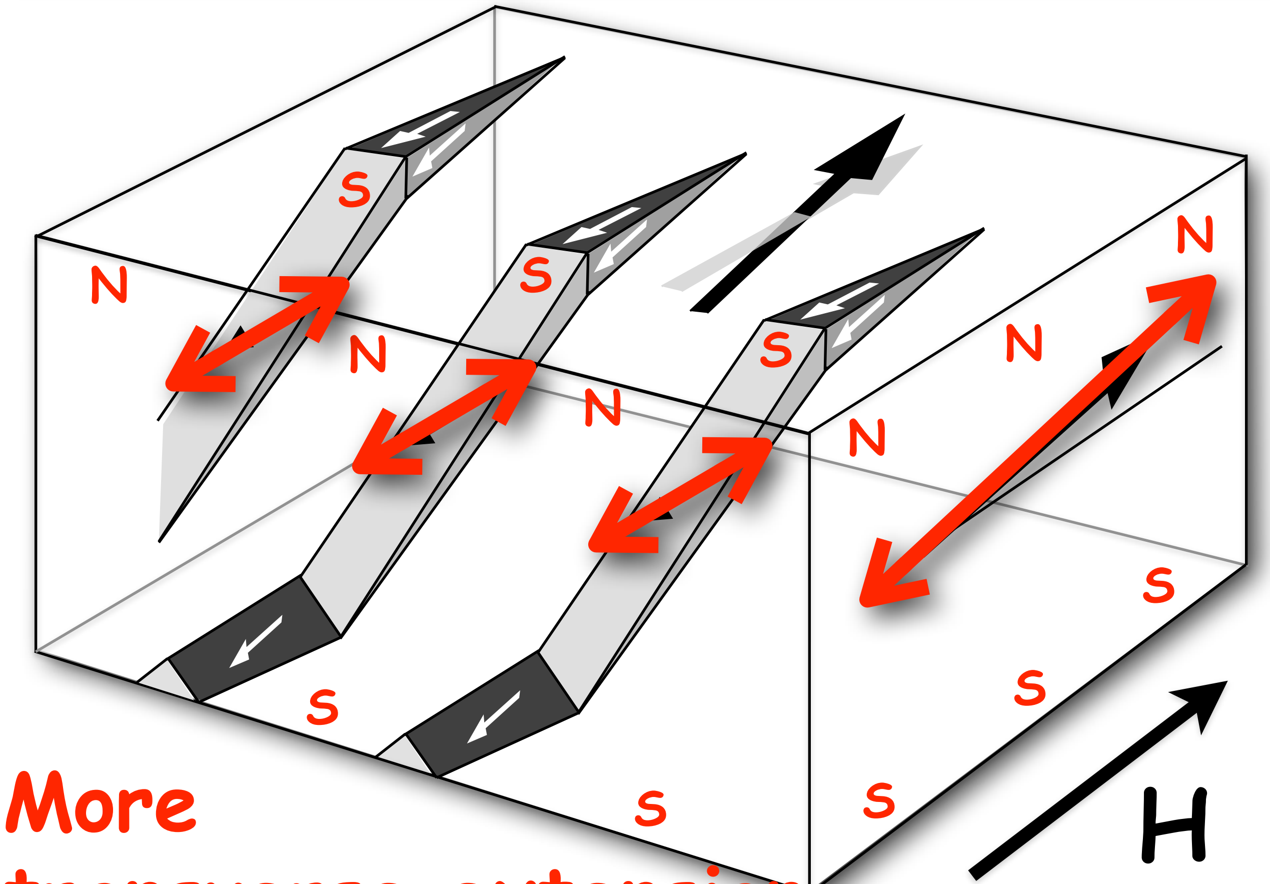




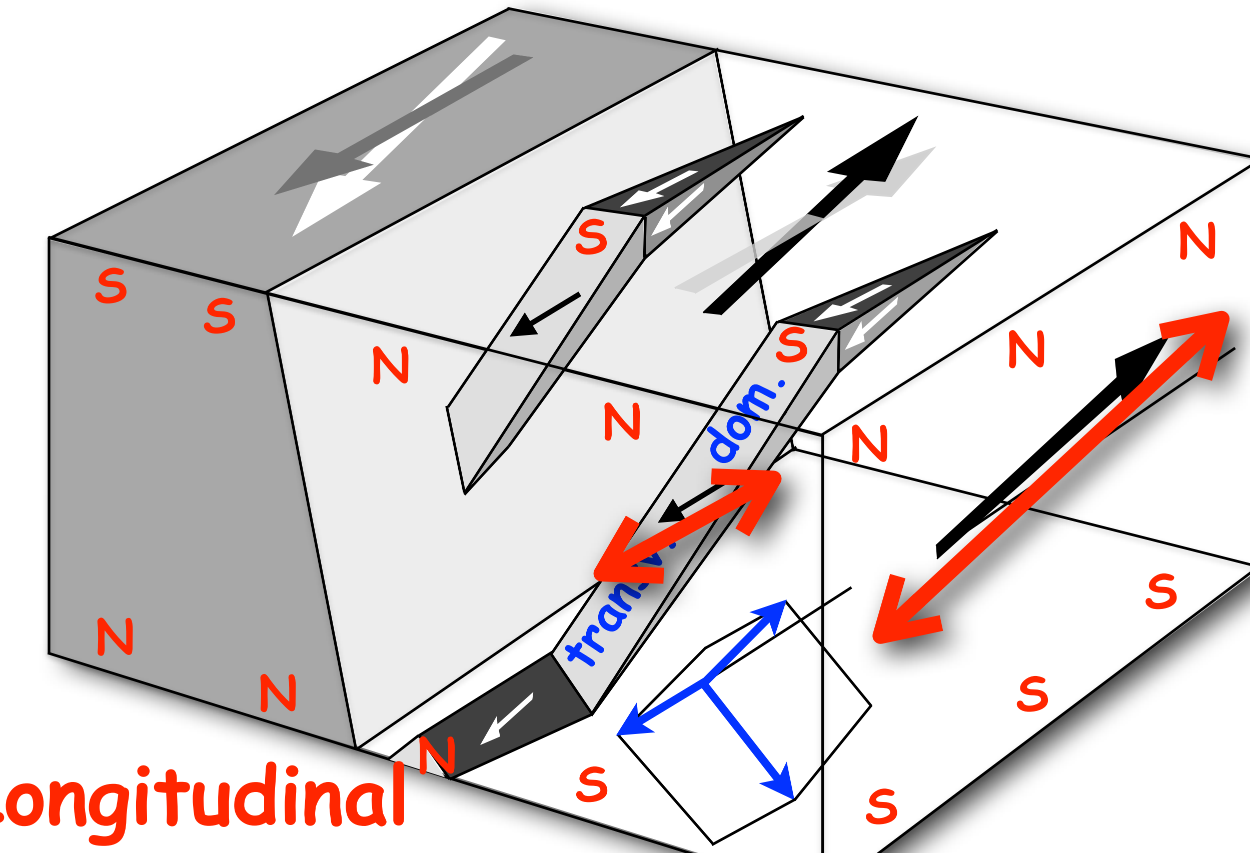
Longitudinal
and transverse extension



Grain-oriented FeSi transformer material



More
transverse extension



Longitudinal
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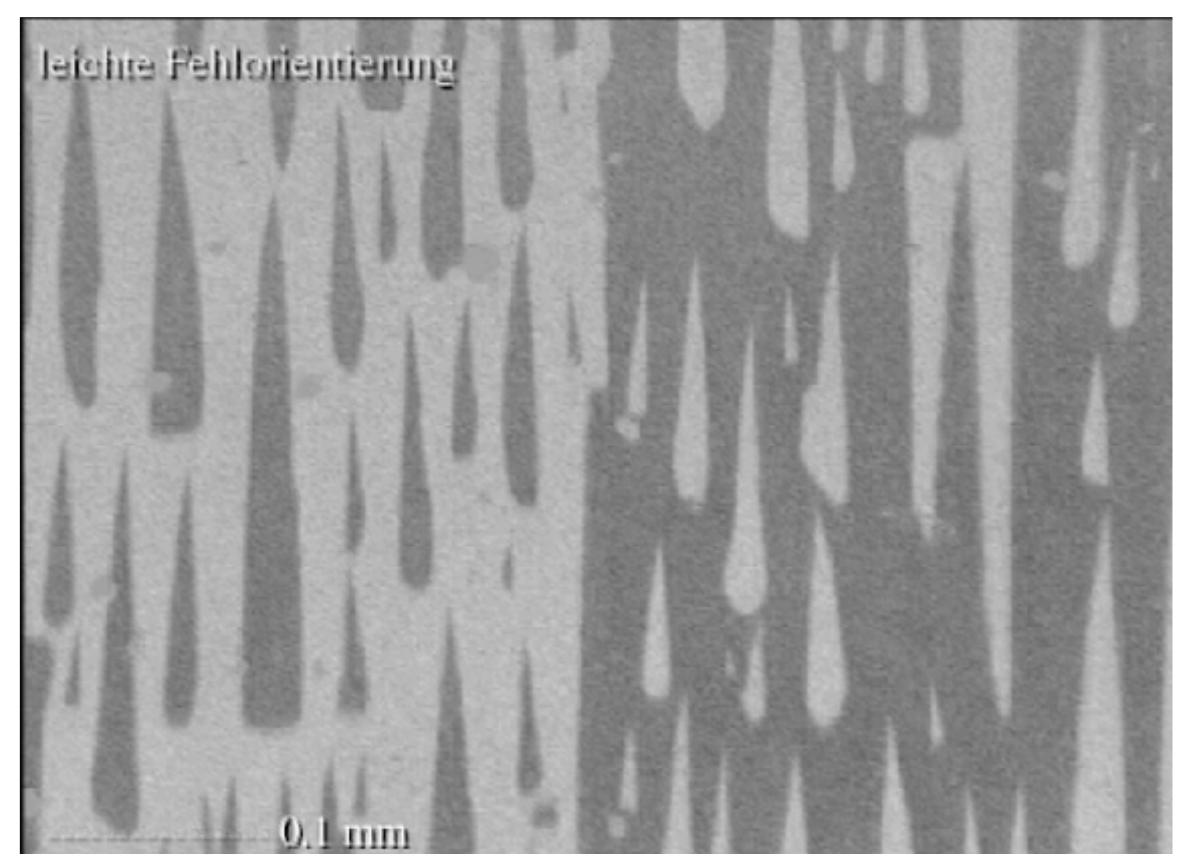
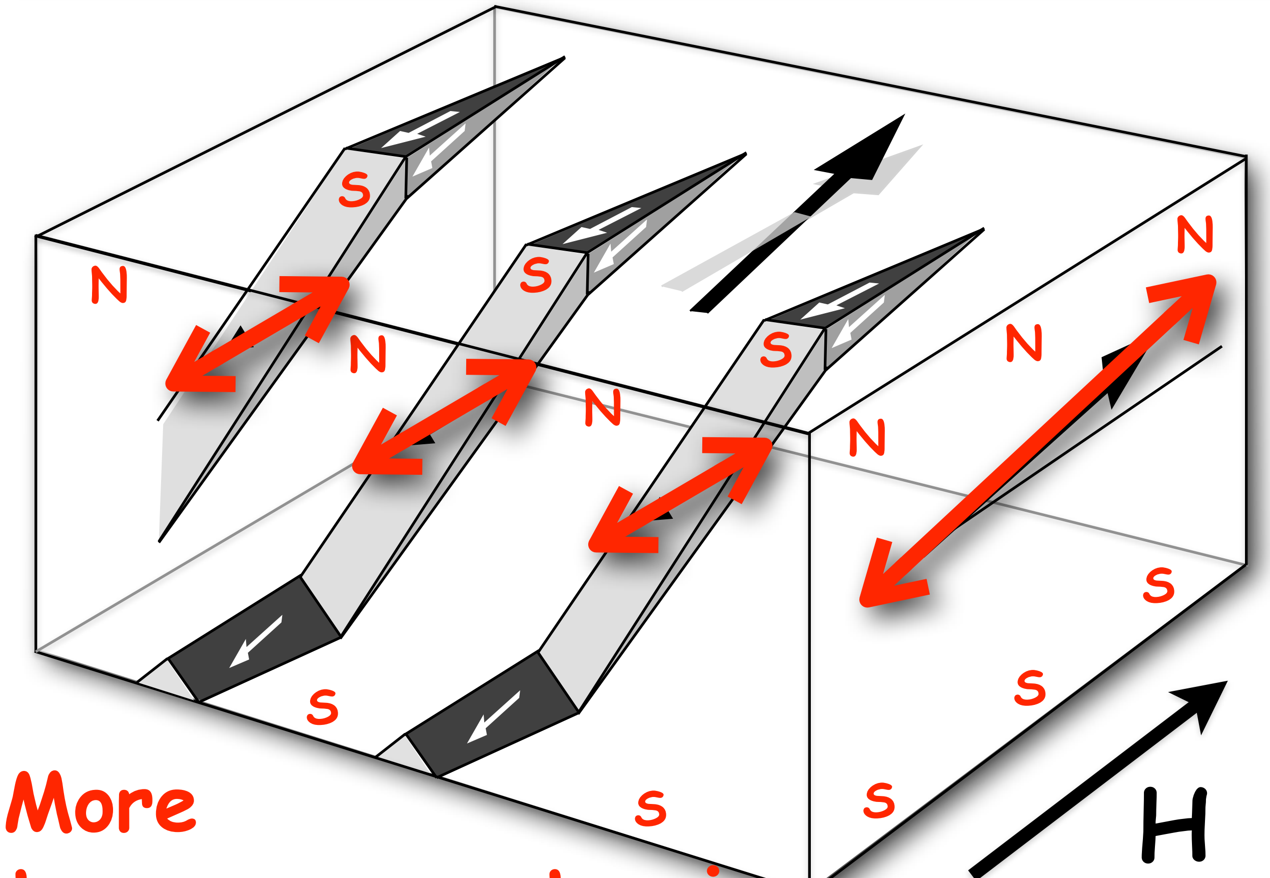
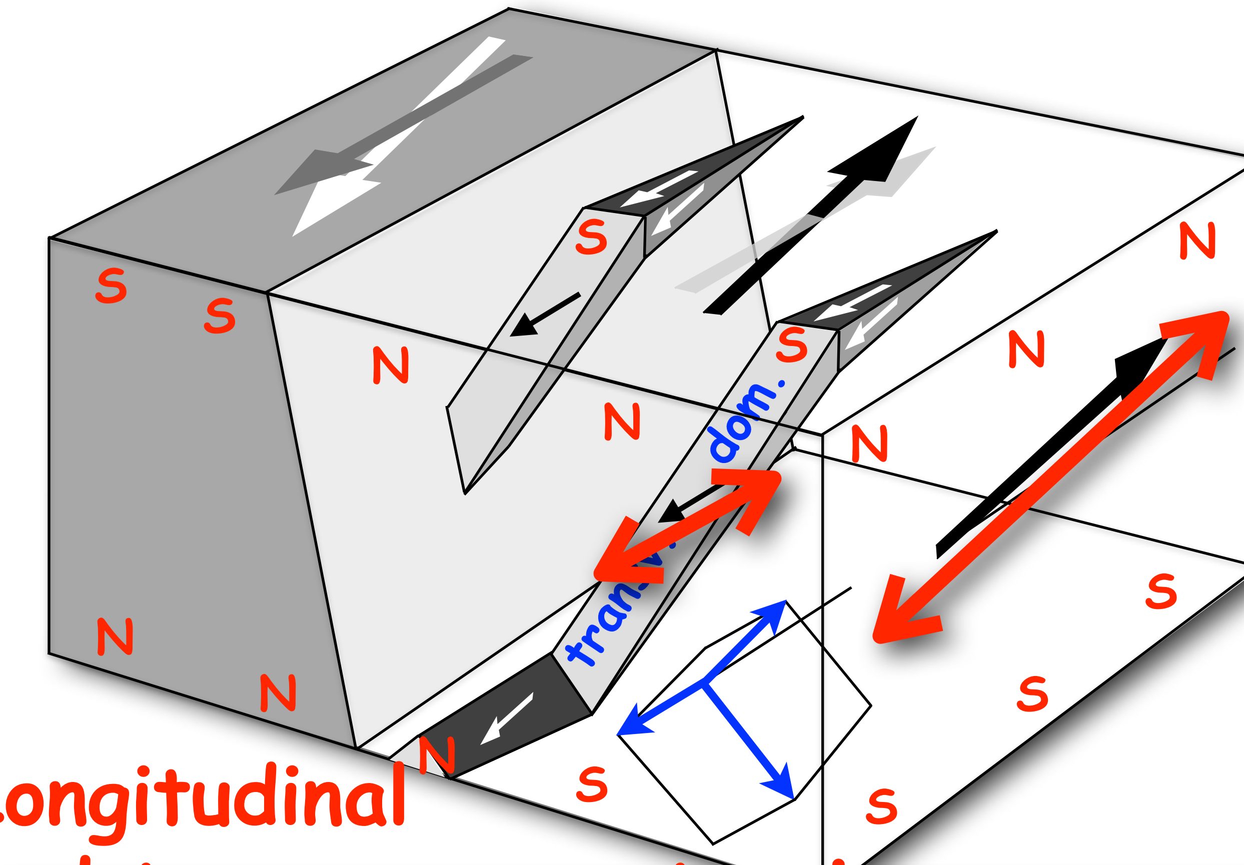


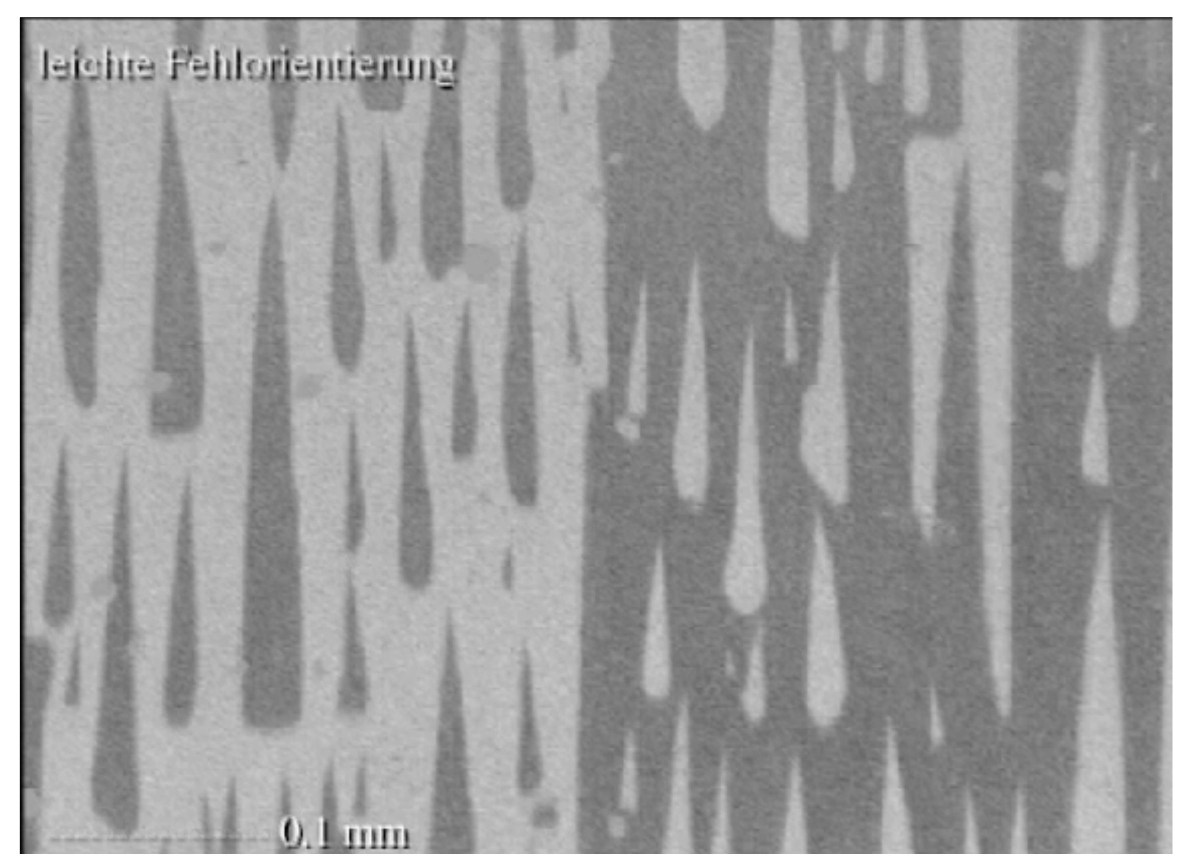
Grain-oriented FeSi transformer material



More transverse extension

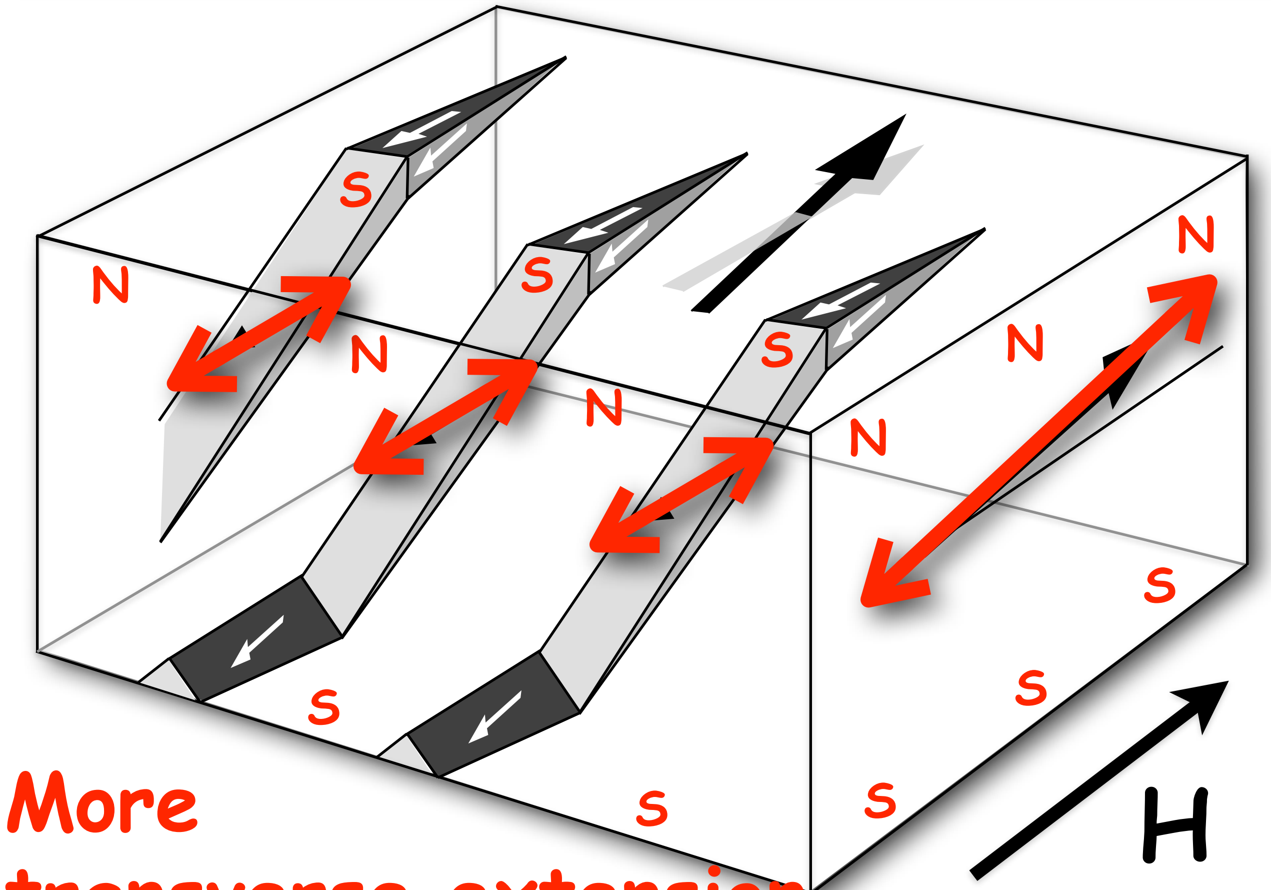


Longitudinal and transverse extension

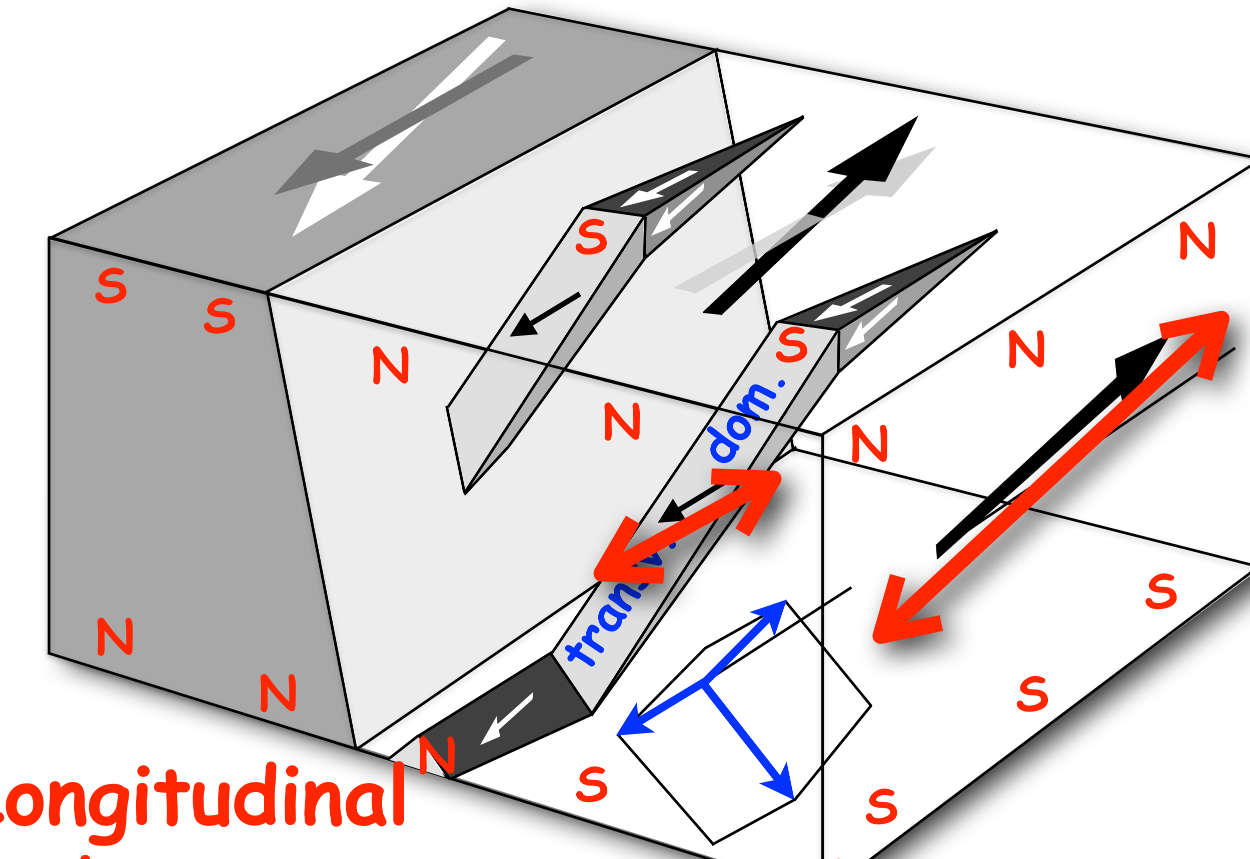


Tension and compression in rhythm of magnetic field

Grain-oriented FeSi transformer material



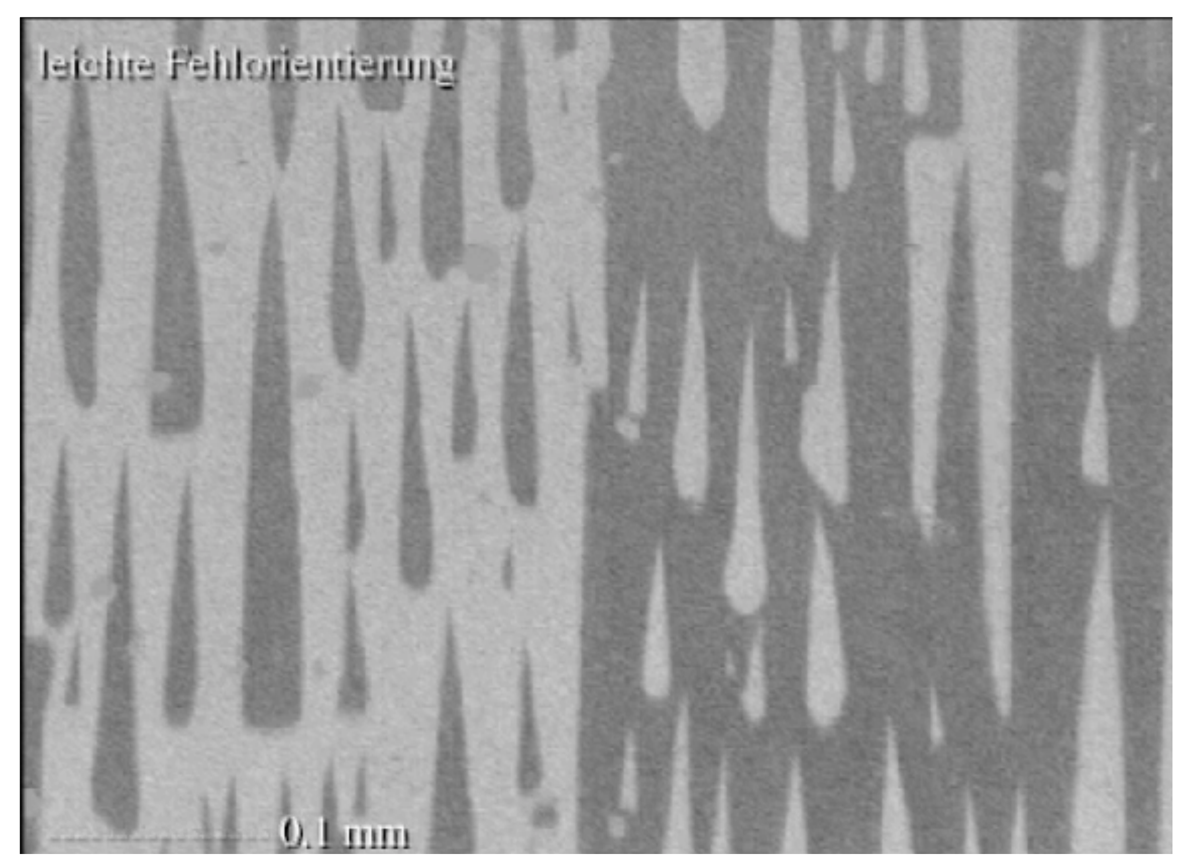
More
transverse extension



Longitudinal
and transverse extension

Tension and compression in rhythm of magnetic field

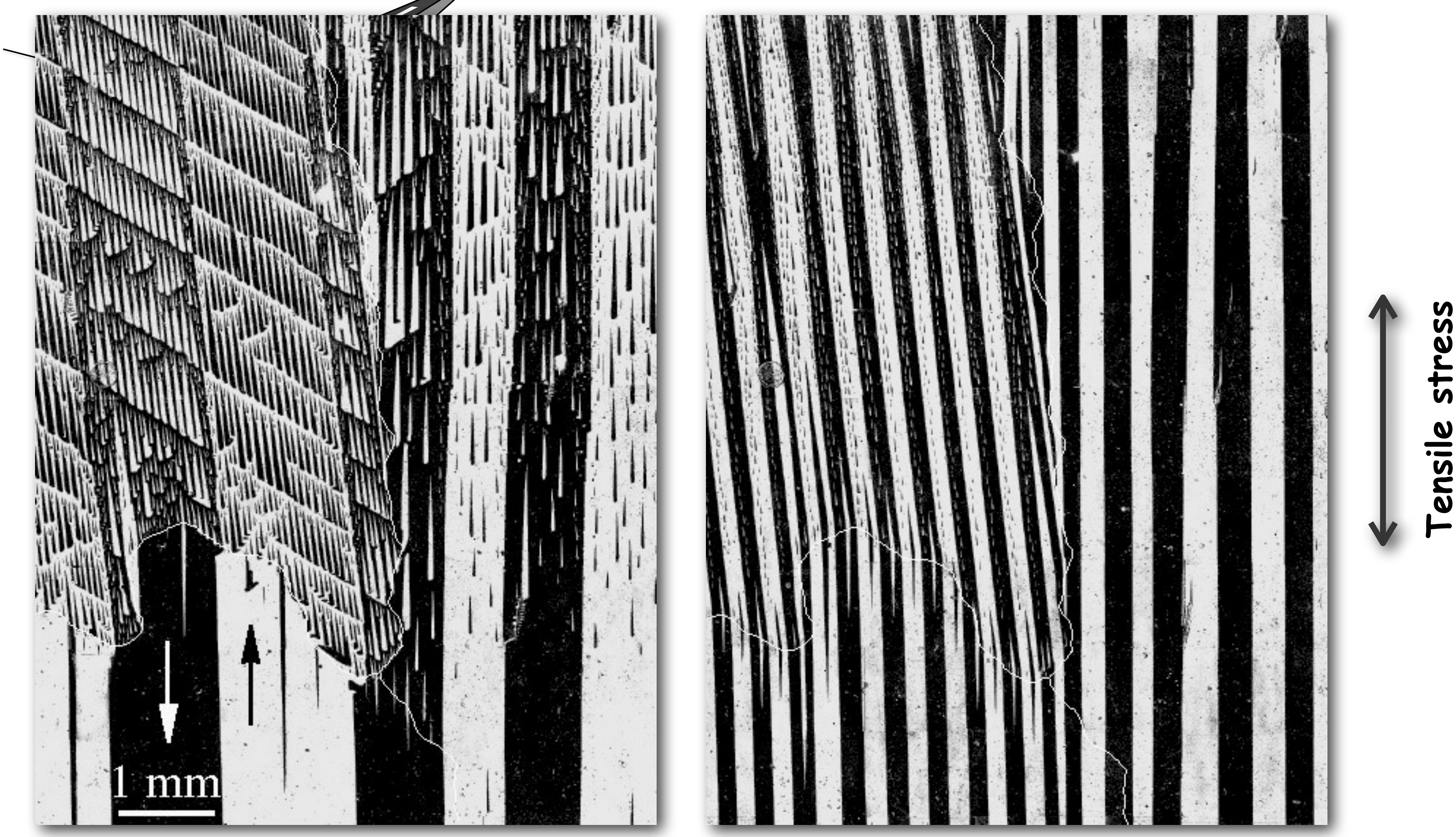
The sheet vibrates
= transformer noise



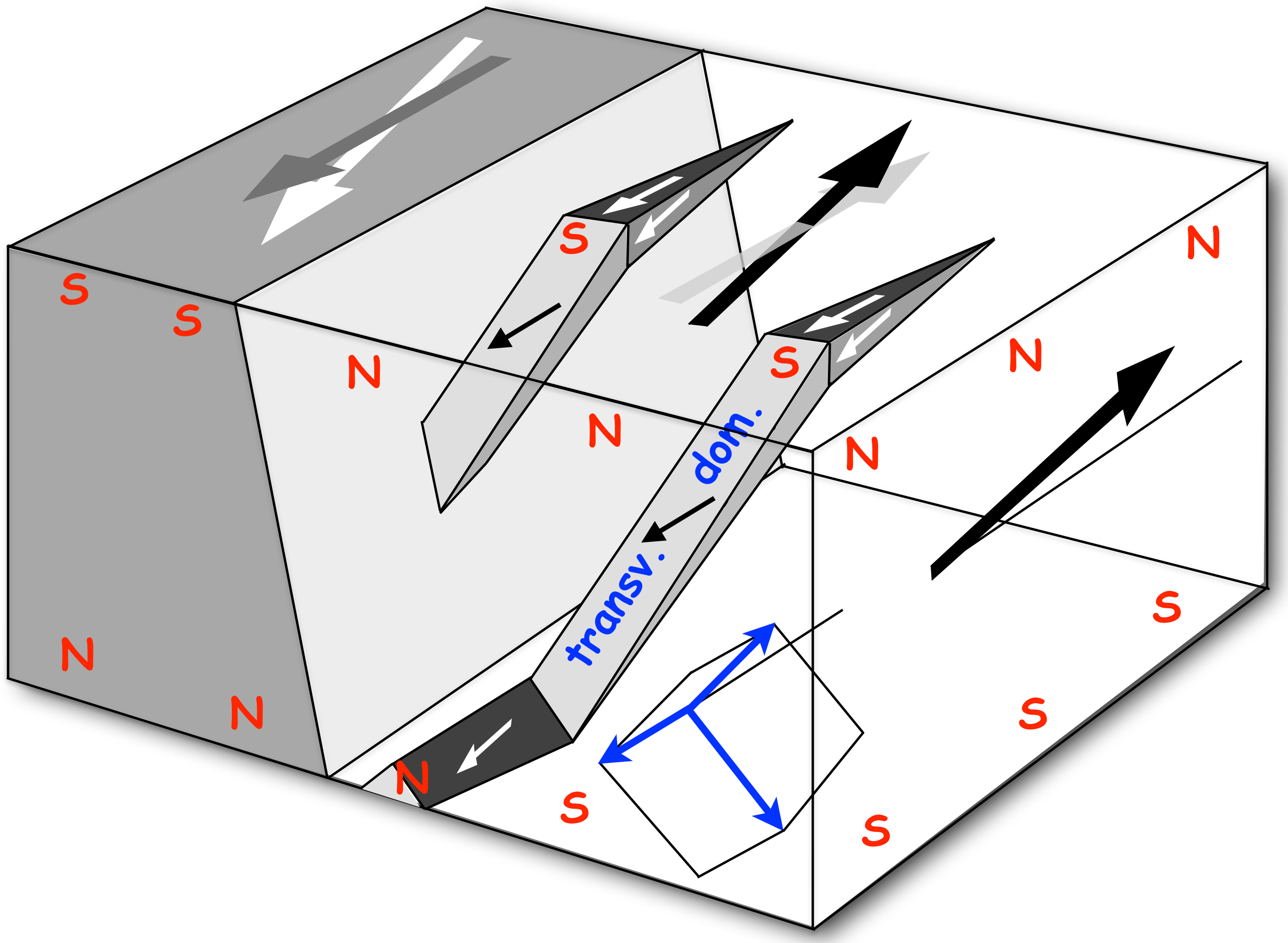
Grain-oriented FeSi transformer material

Without tensile stress

With tensile stress



Grain-oriented FeSi transformer material



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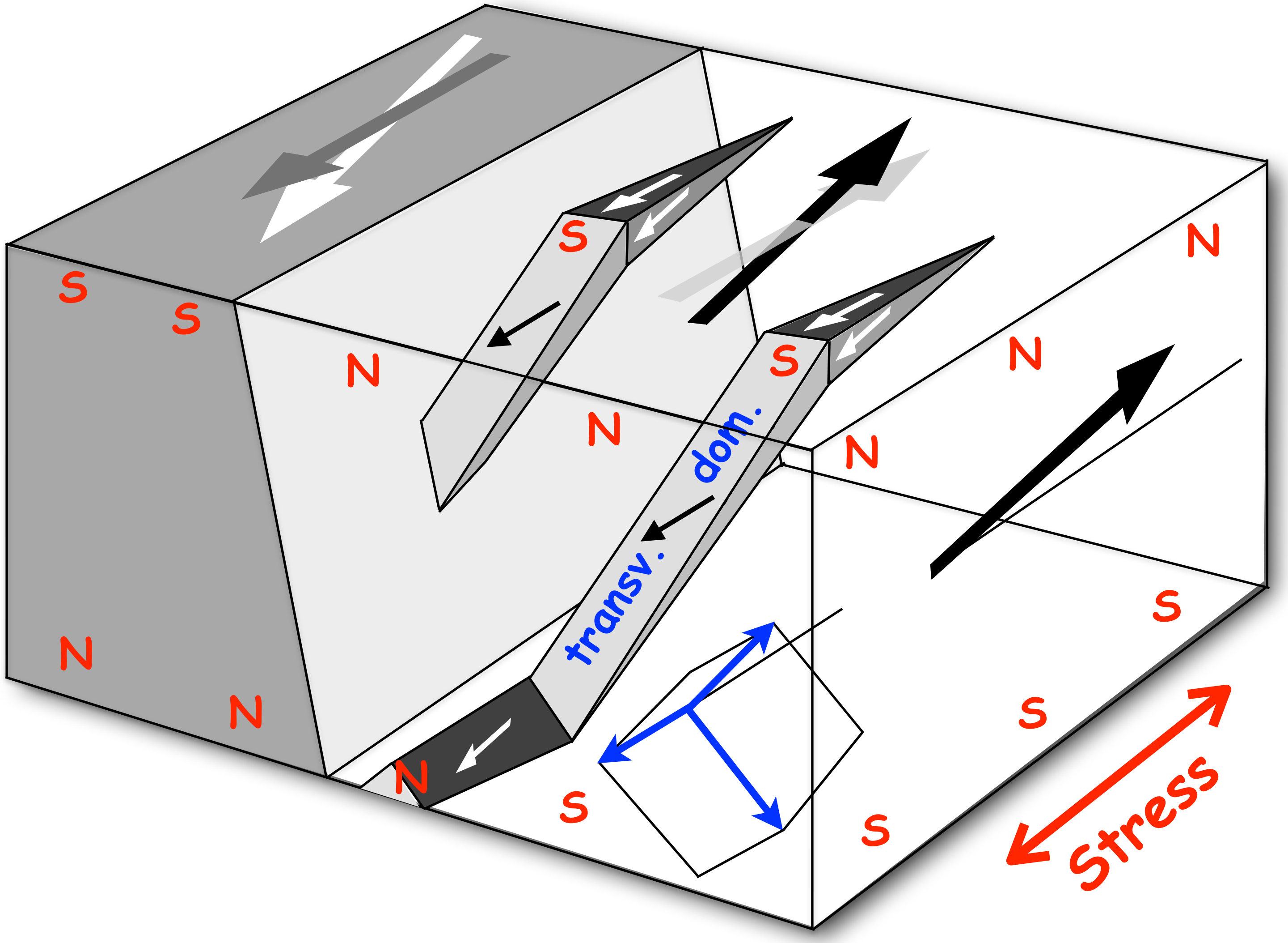

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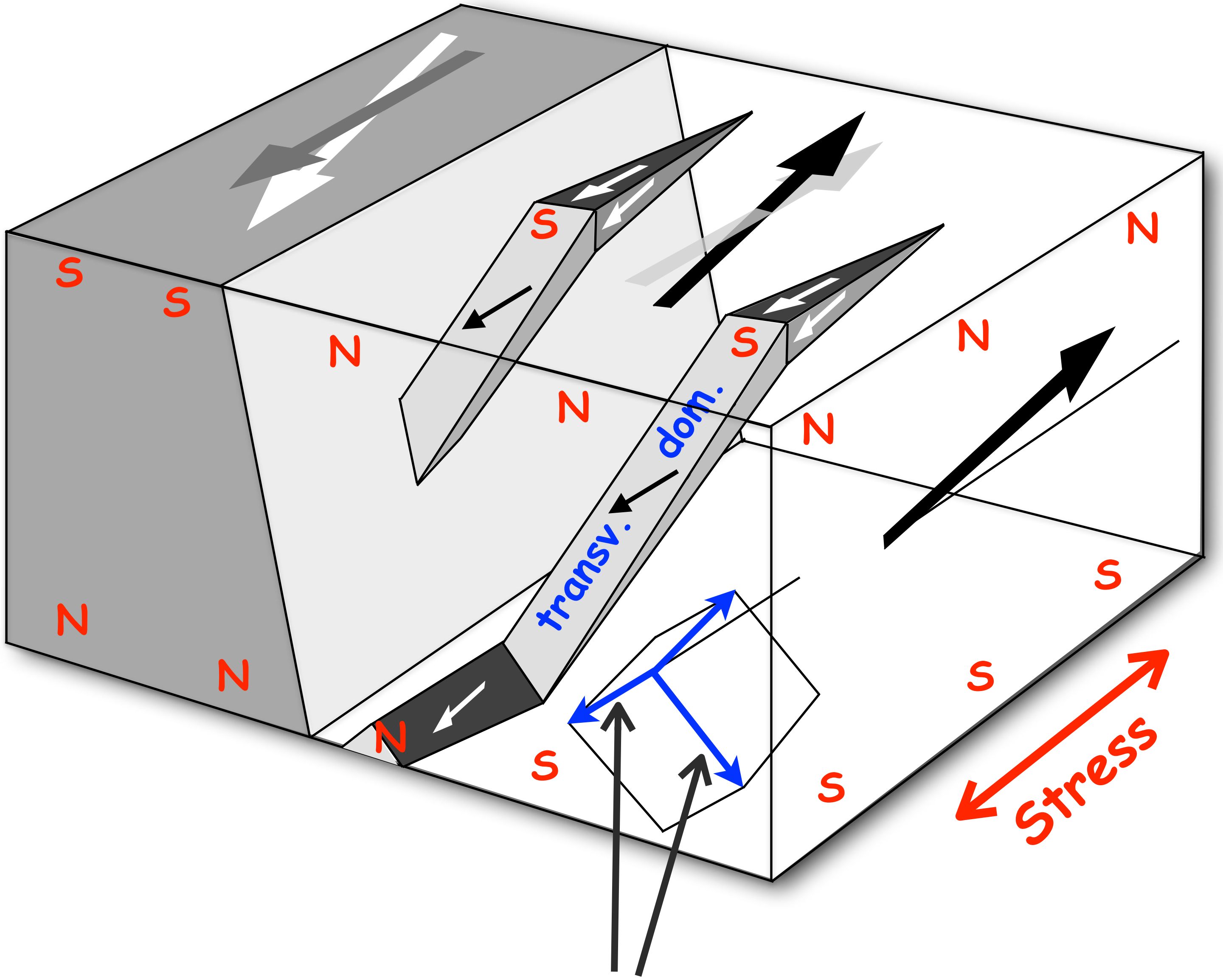
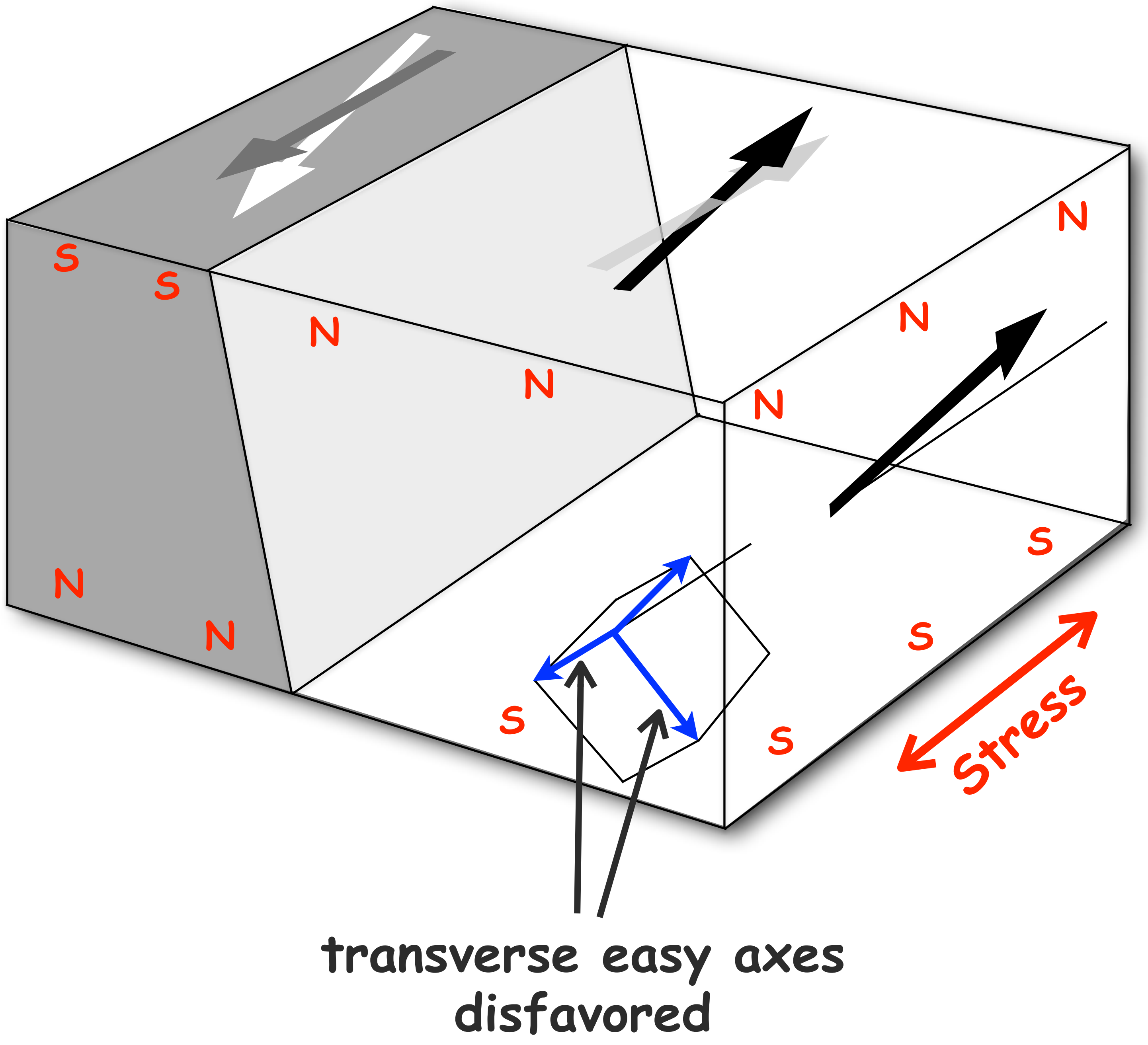
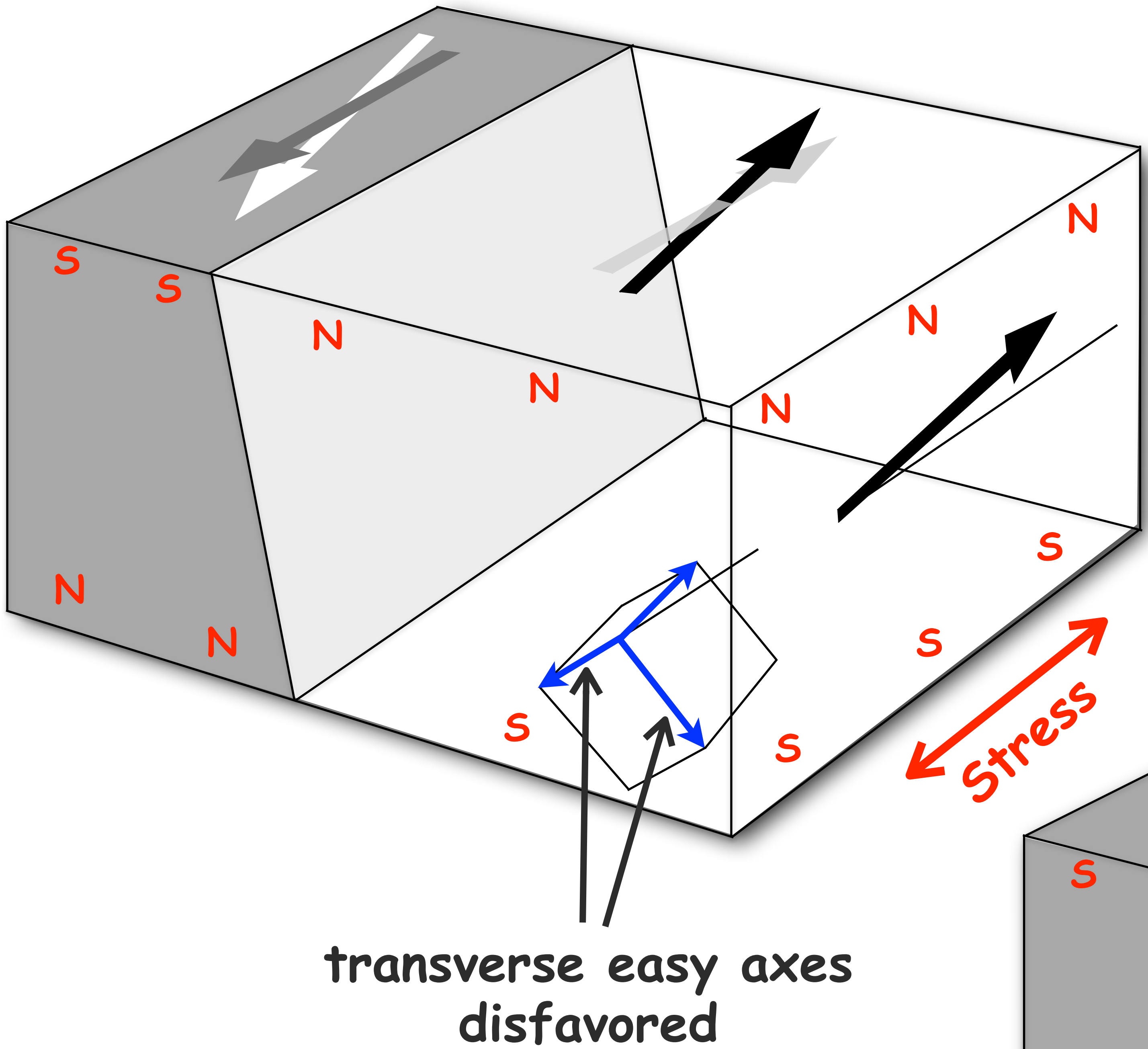


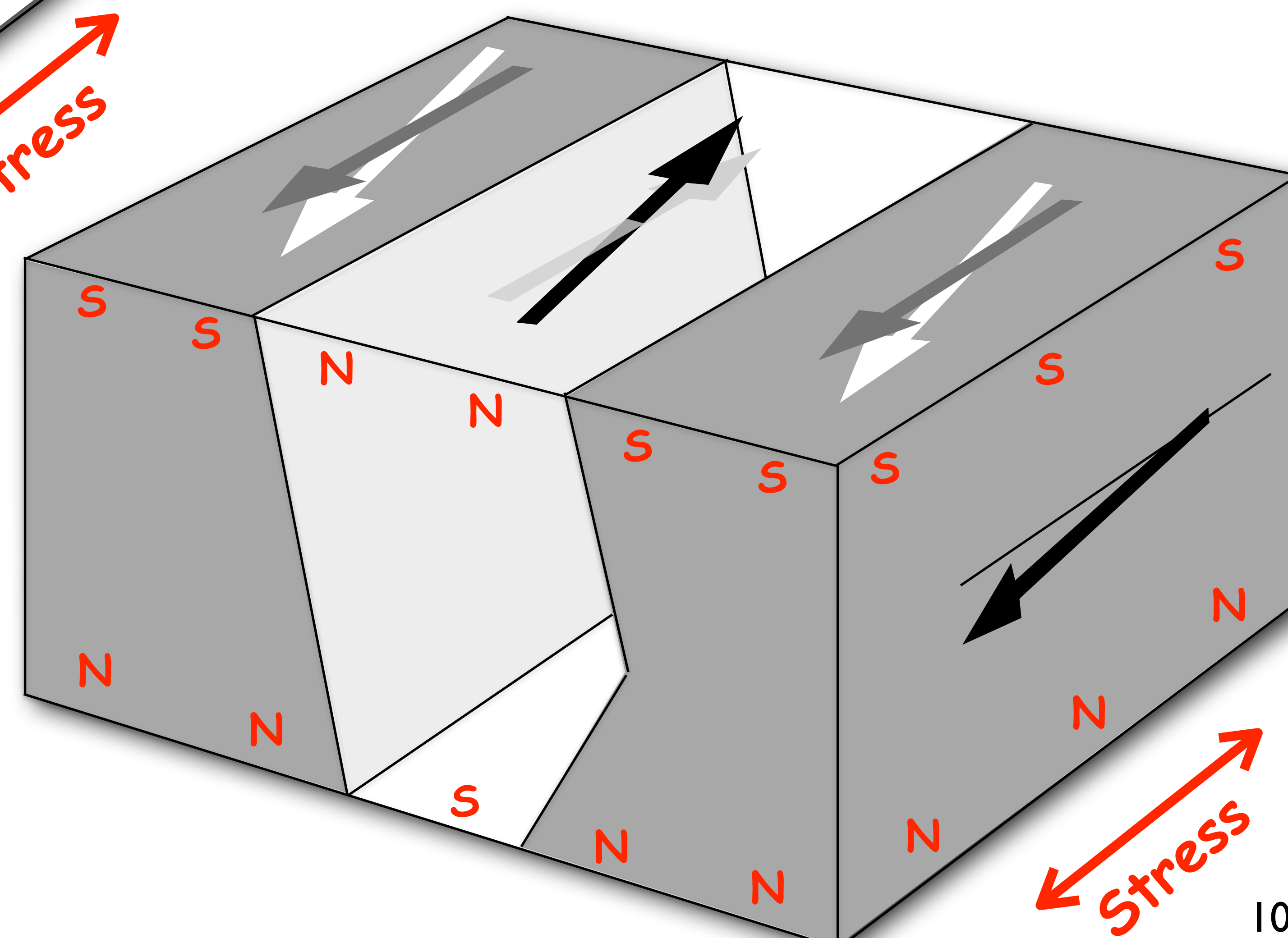
transverse easy axes
disfavored

Grain-oriented FeSi transformer material



Grain-oriented FeSi transformer material





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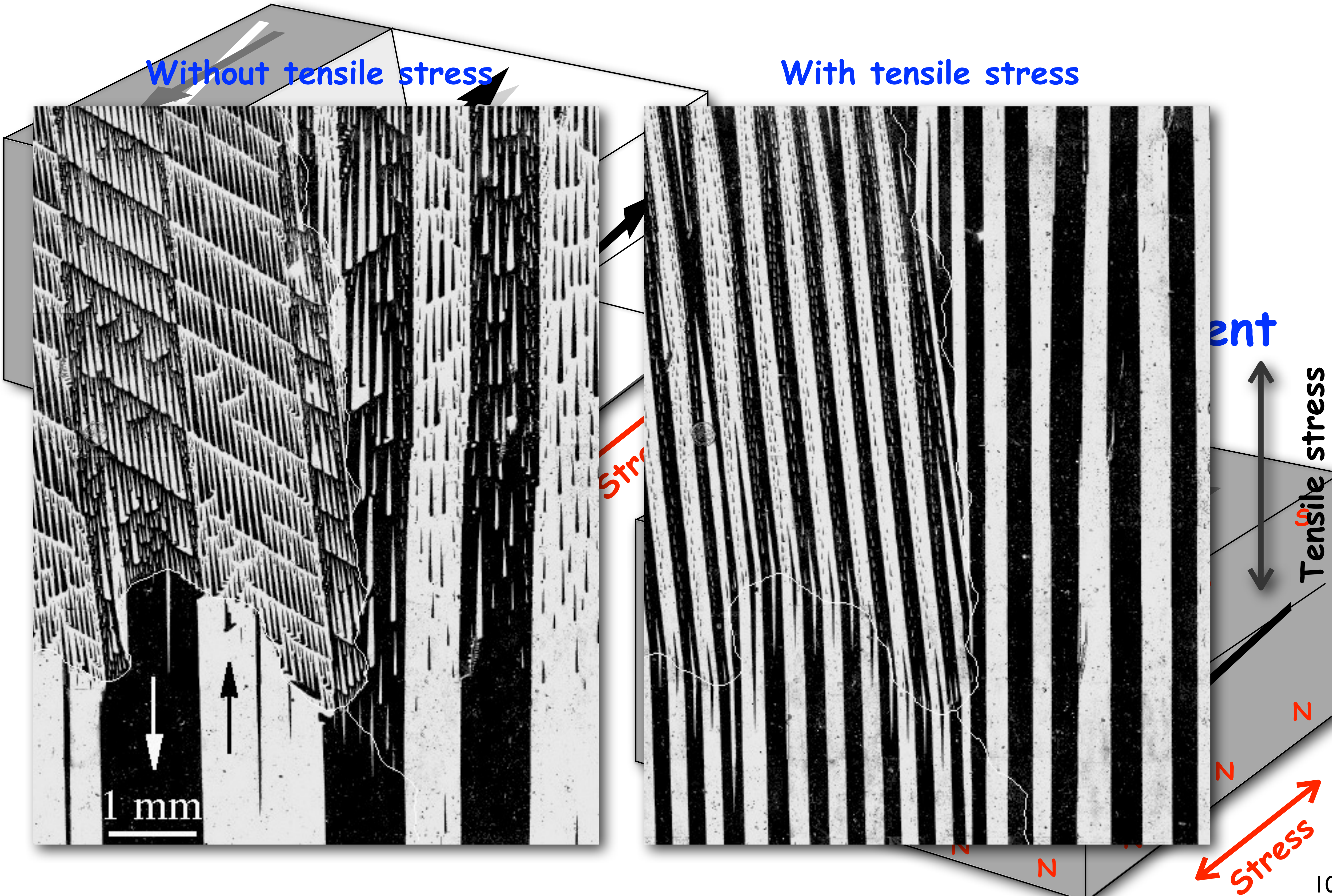
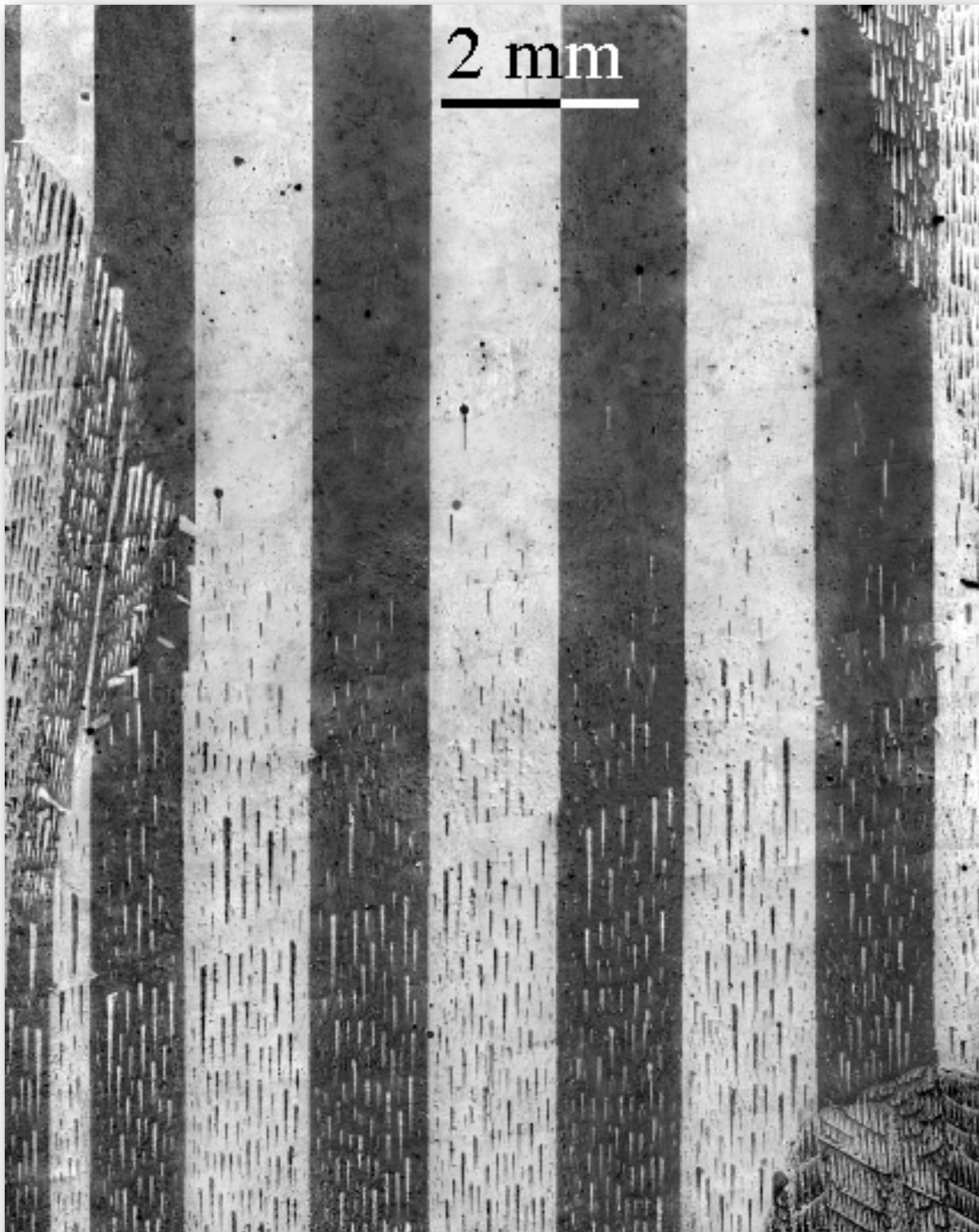


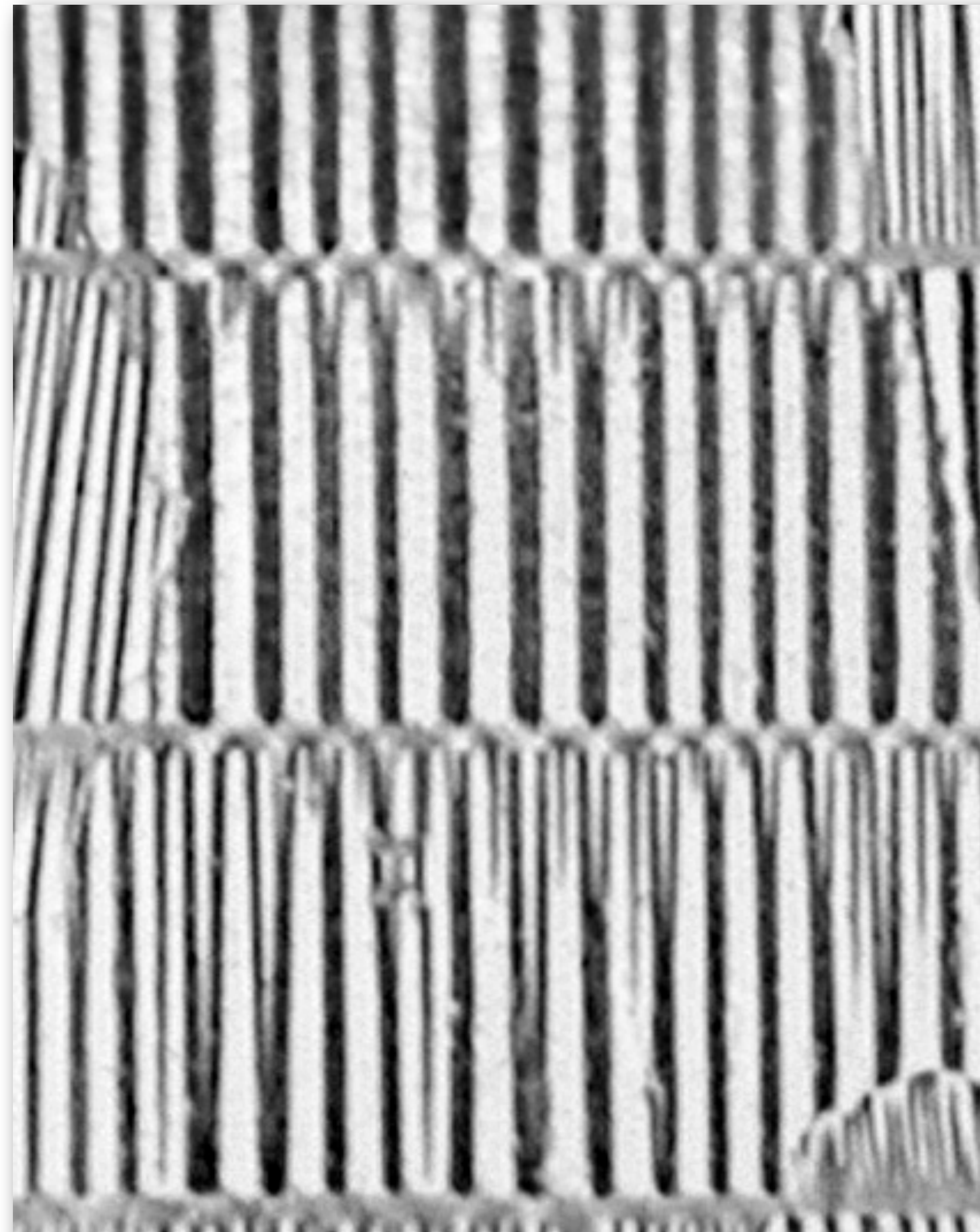
Grain-oriented FeSi transformer material

Loss control by domain control

Without artificial domain refinement

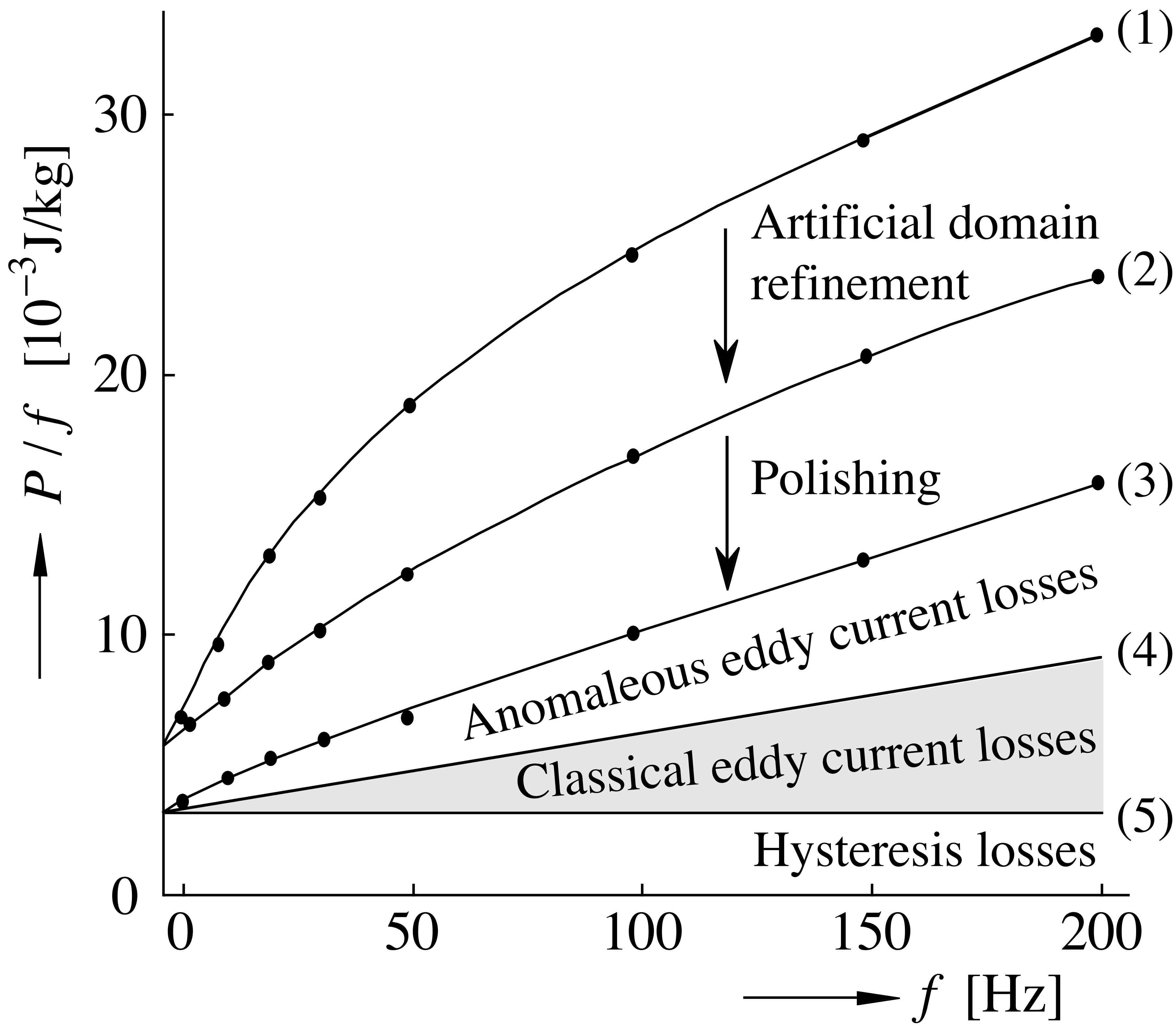


After laser scribing



Grain-oriented FeSi transformer material

Loss control



Unmodified material, thickness 0.18 mm

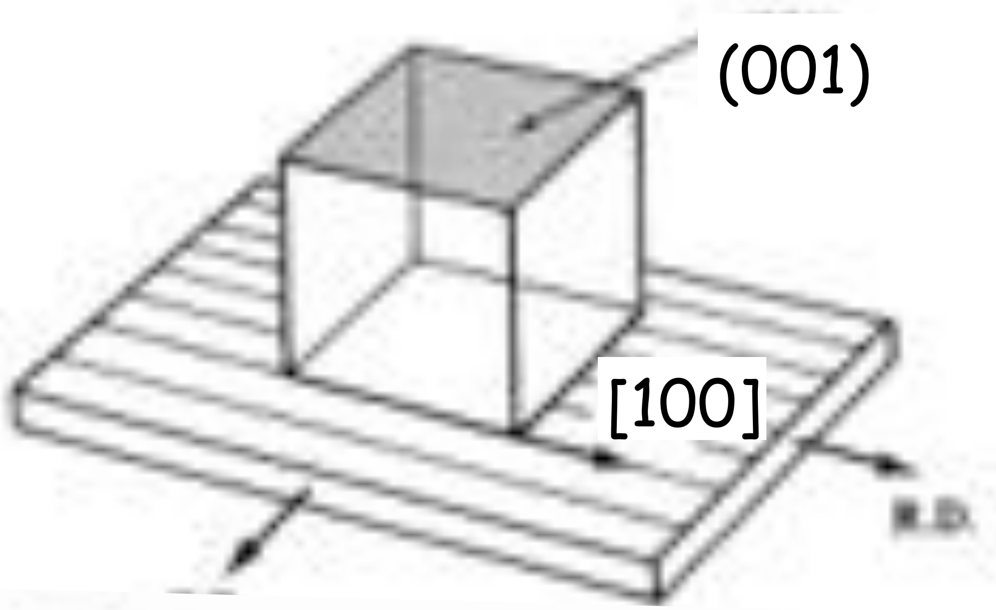
Domain refinement by laser scribing

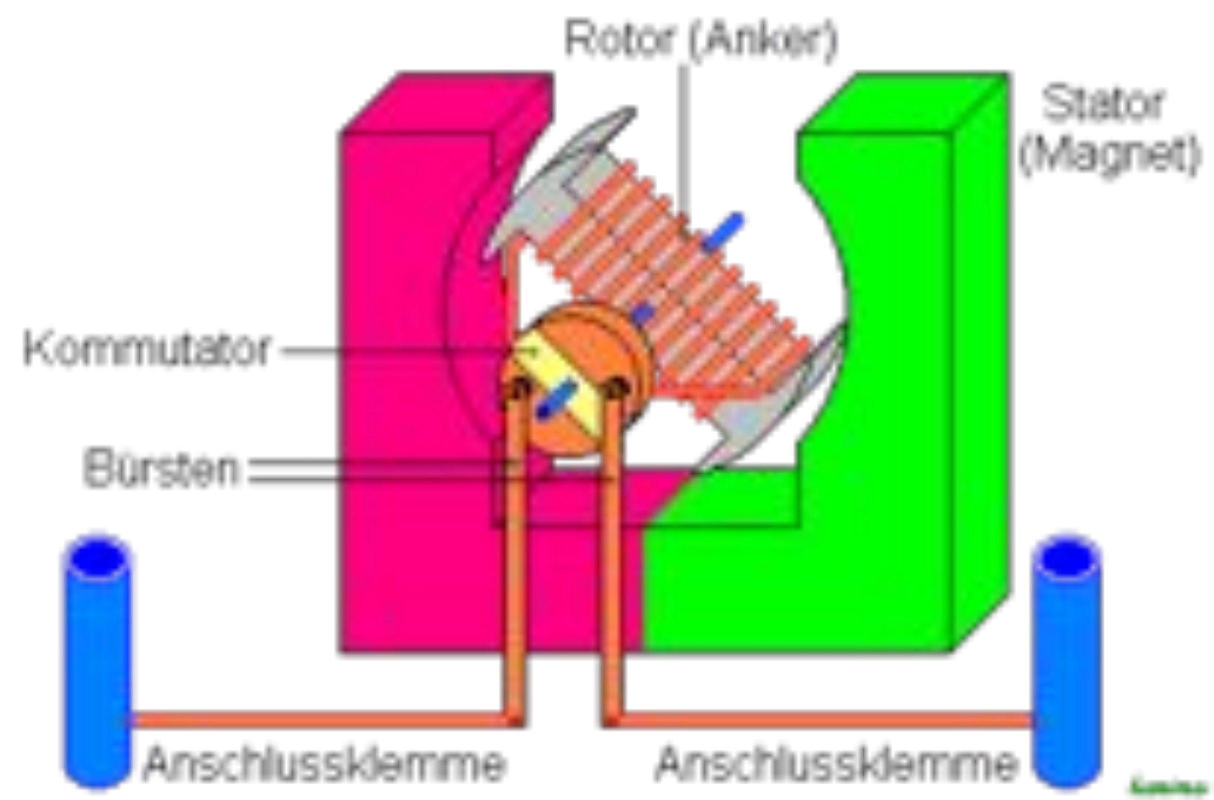
Reducing thickness to 0.15 mm (P_{class} ↓)

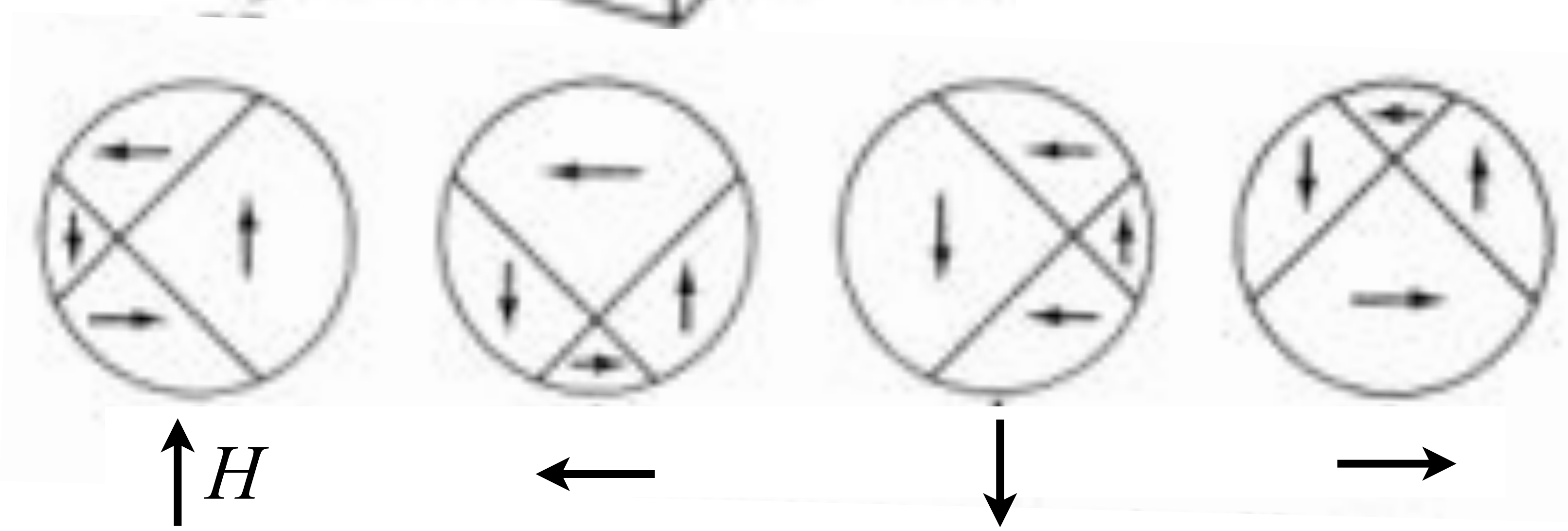
Non-oriented FeSi material

For motors and generators

- Rotating machines: core is subjected to fields that change direction → „uniaxial" material (like Goss steel) not useful
- Ideal: cube-textured FeSi material

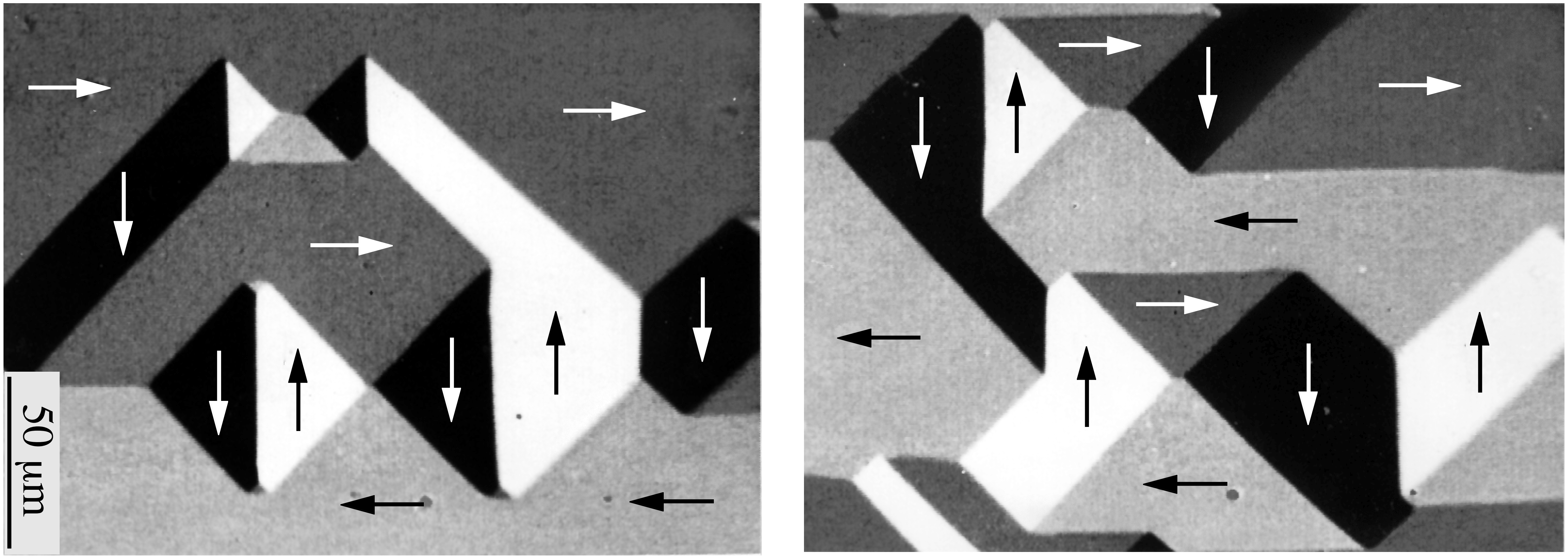




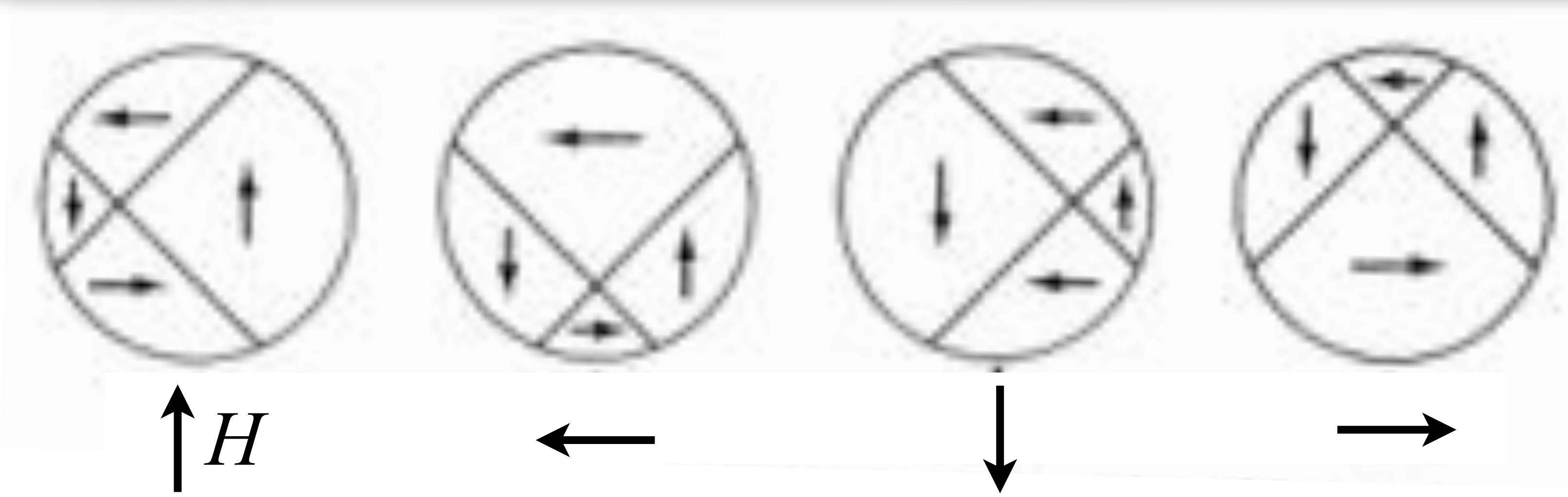


- Barkhausen jumps → micro eddy currents → heat = **rotational hysteresis loss**

Non-oriented FeSi material



Fe-3 wt%-Si sheet (0.4 mm thick)
same location after different demagnetization



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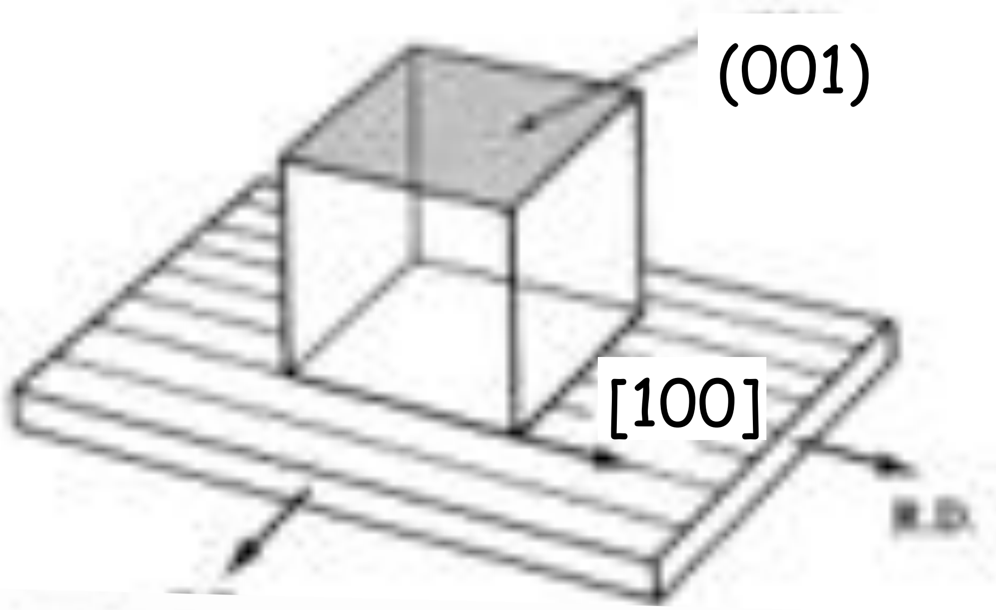

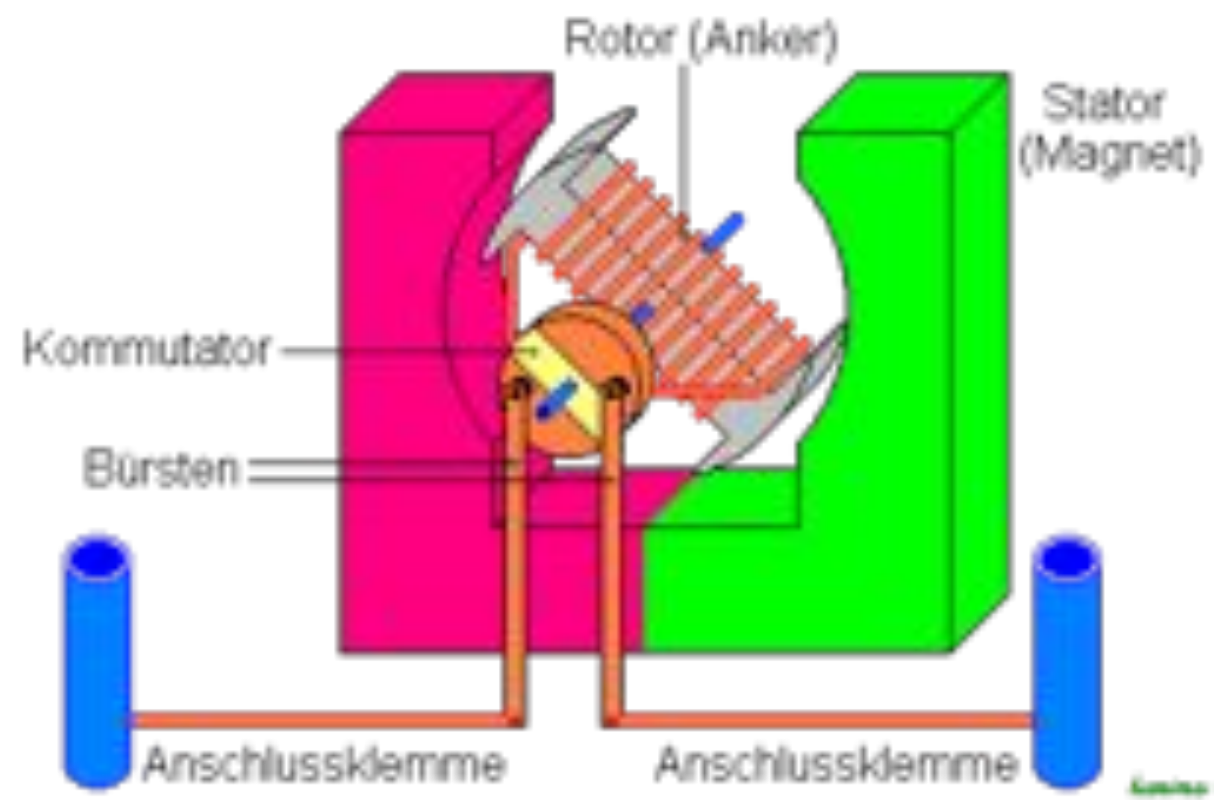

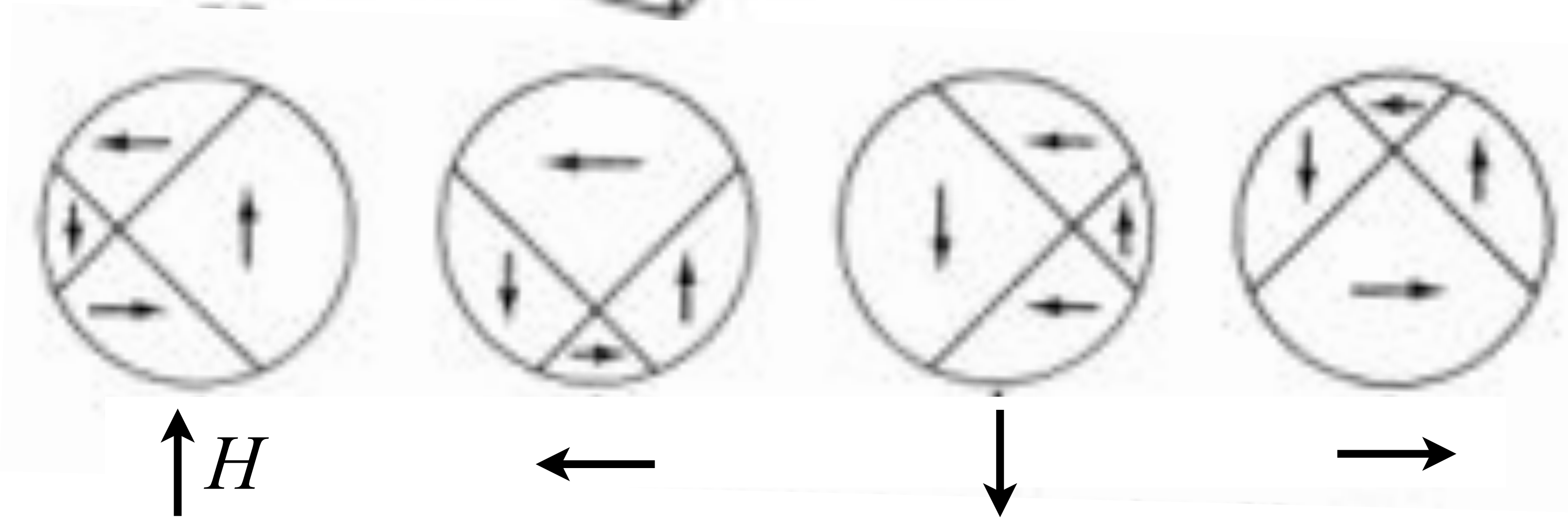

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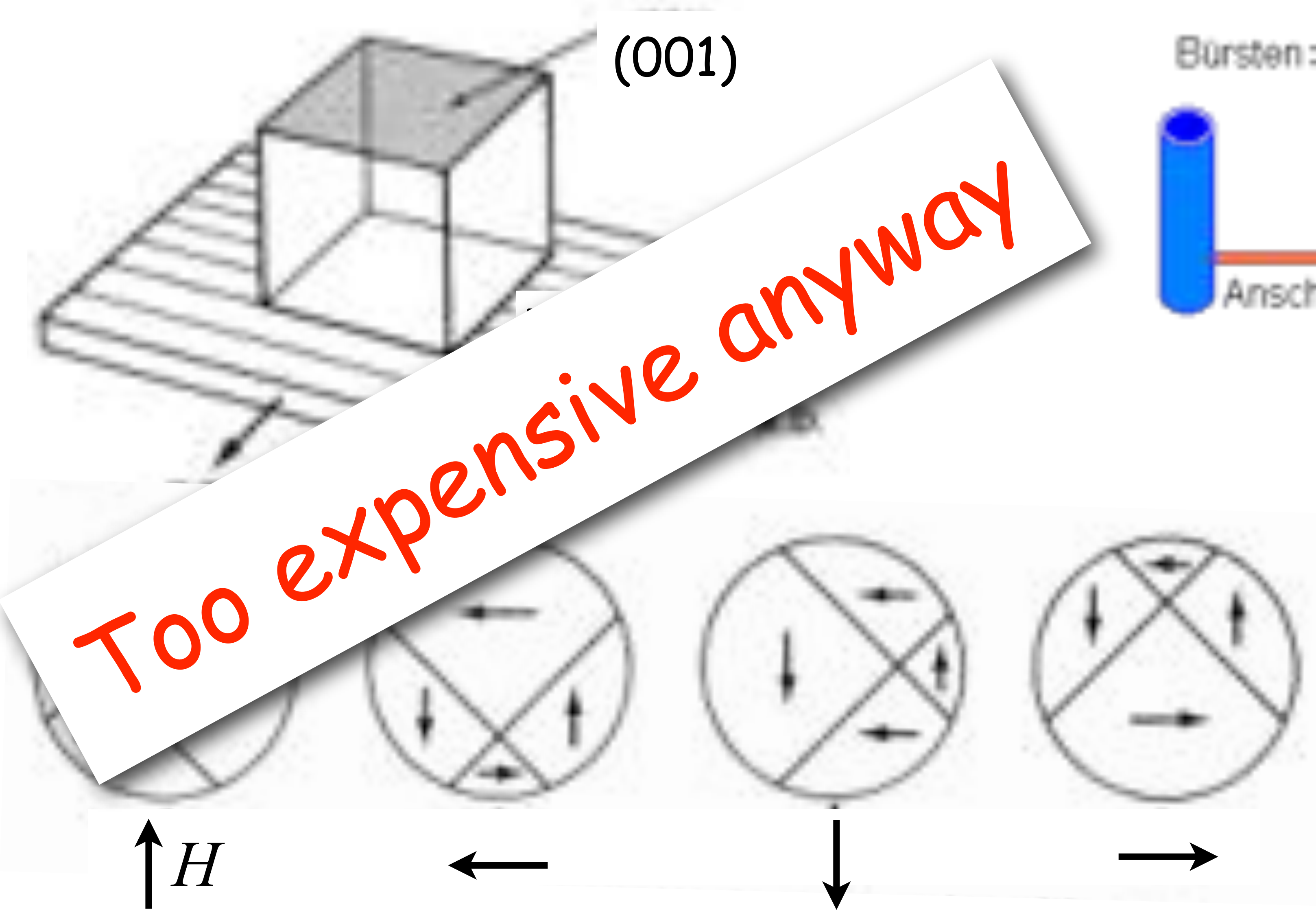
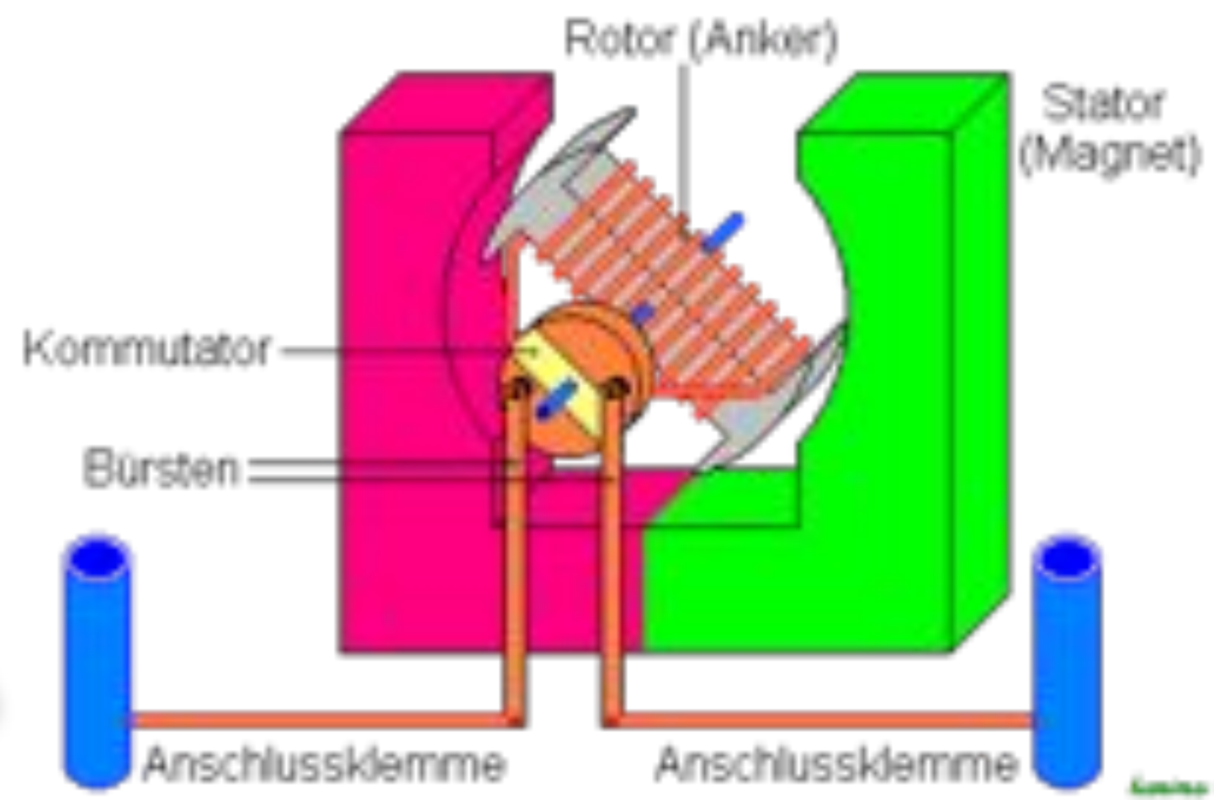


Too expensive anyway



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Non-oriented FeSi material

For motors and generators

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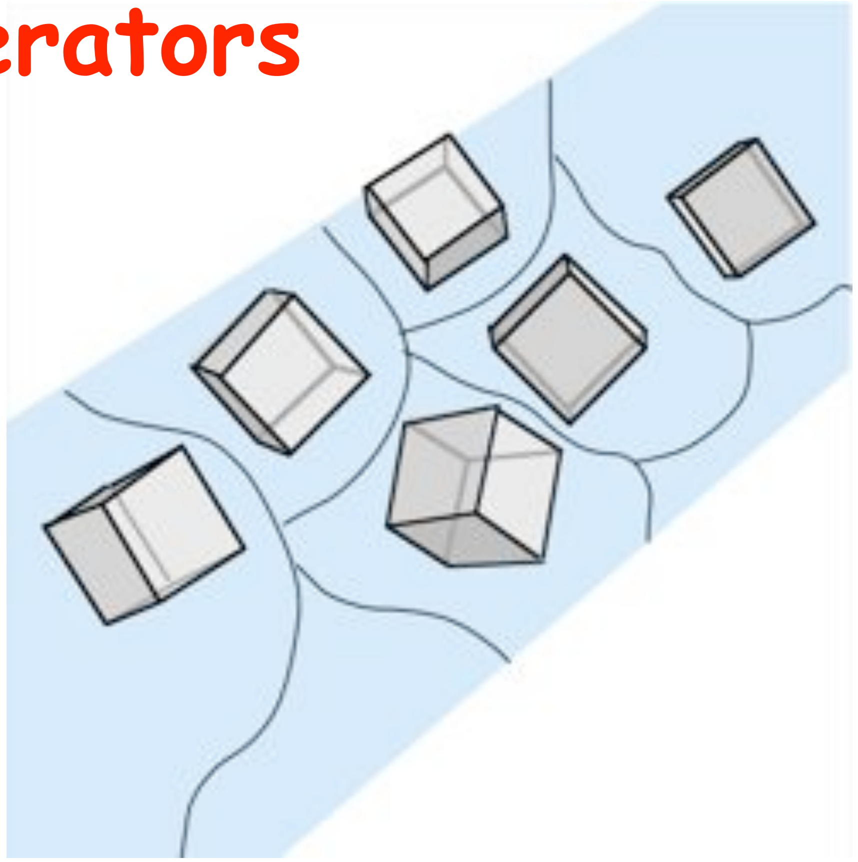
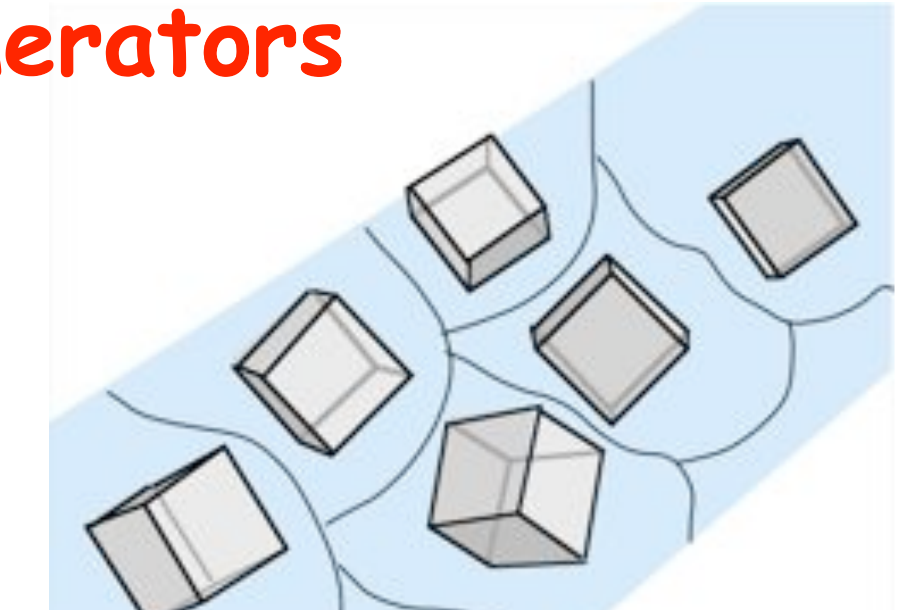


Non-oriented FeSi material

For motors and generators



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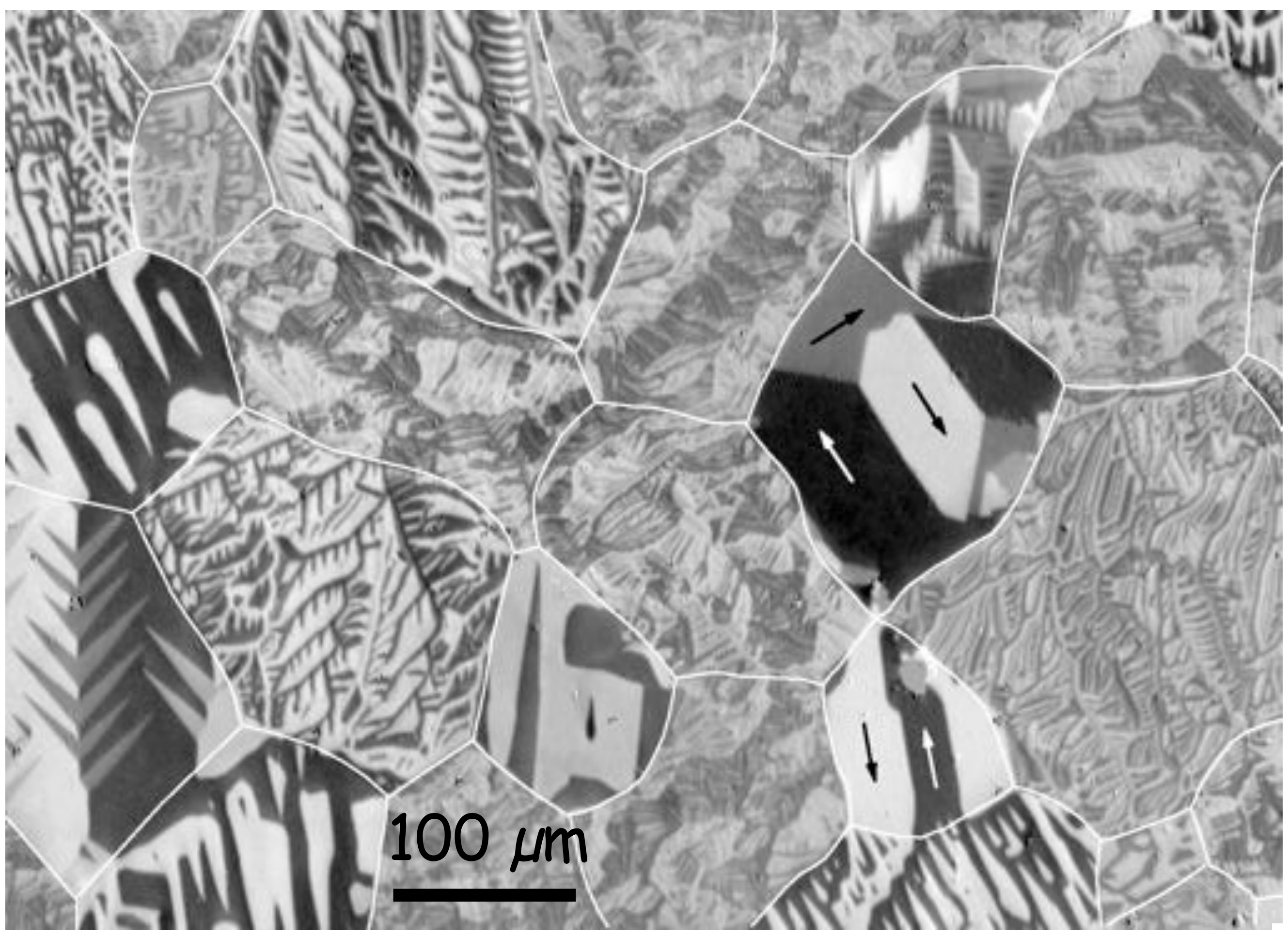
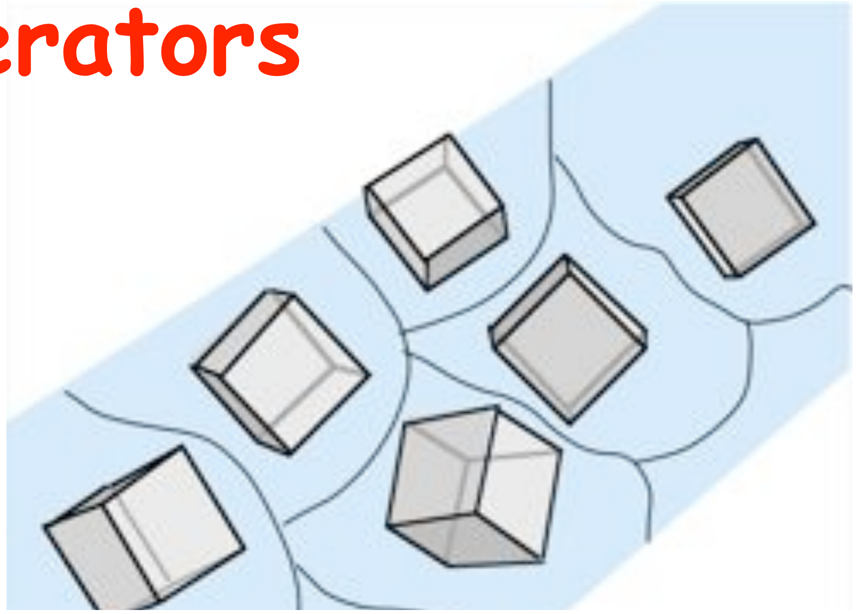


Non-oriented FeSi material

For motors and generators



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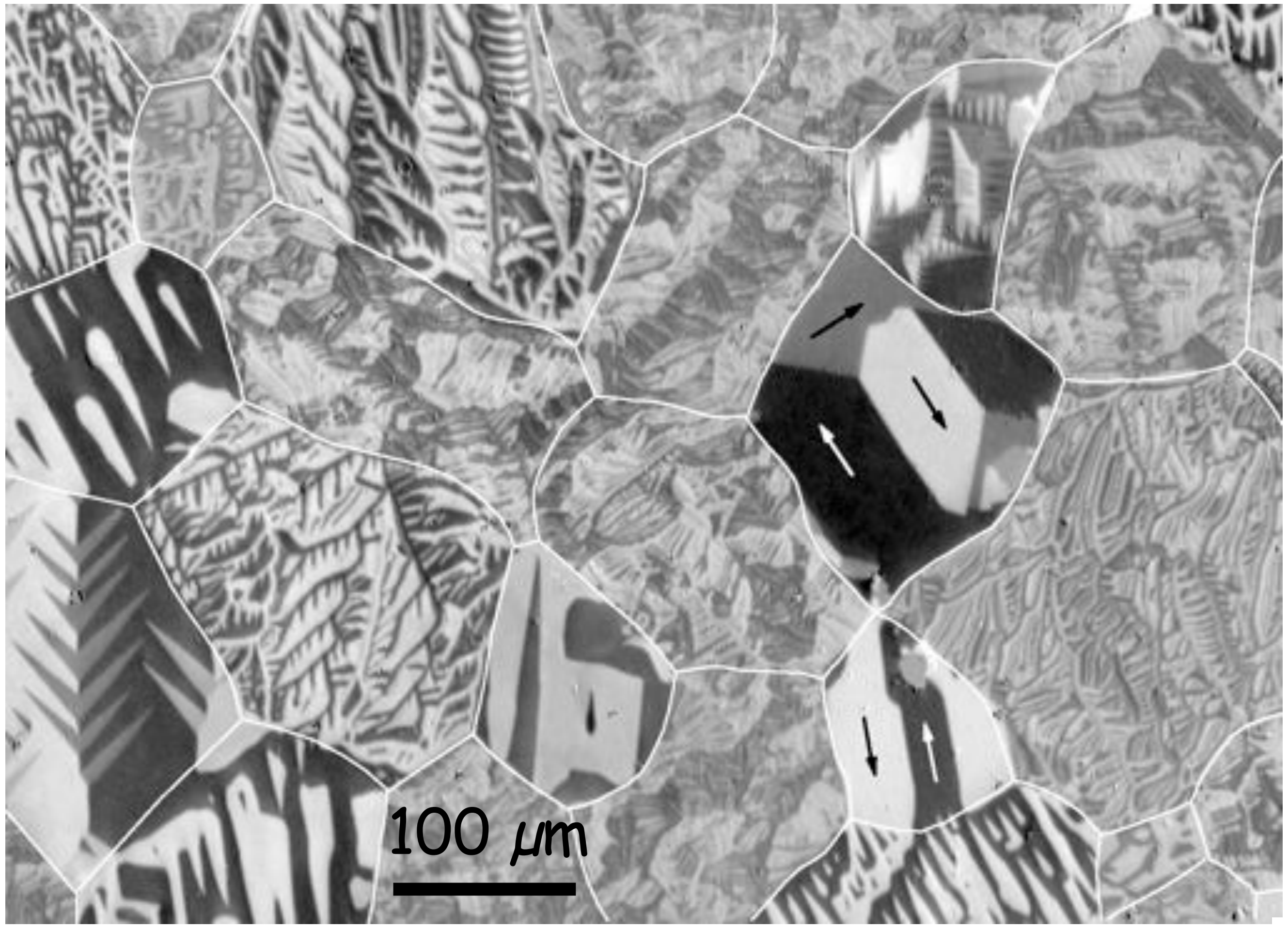
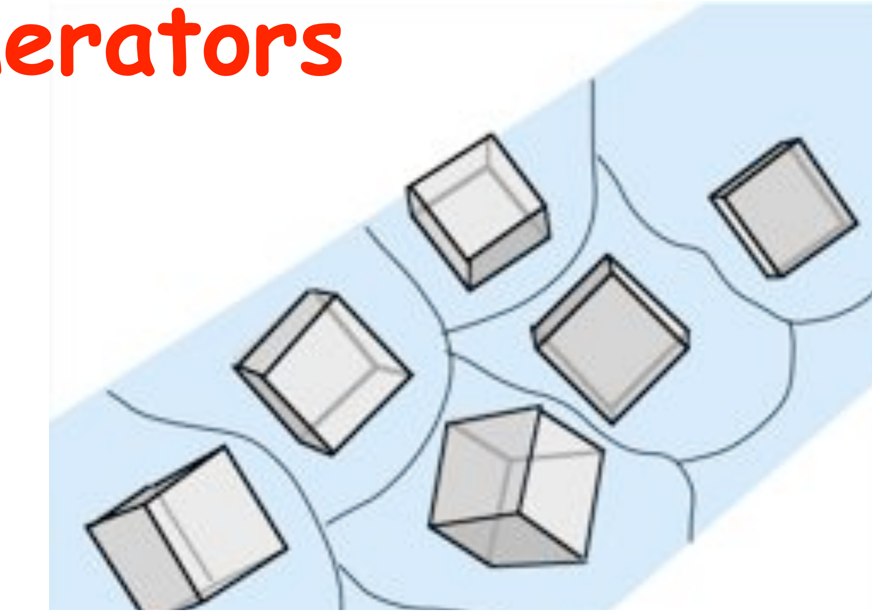


- Complex domain reorganization → unavoidable loss

Non-oriented FeSi material

For motors and generators



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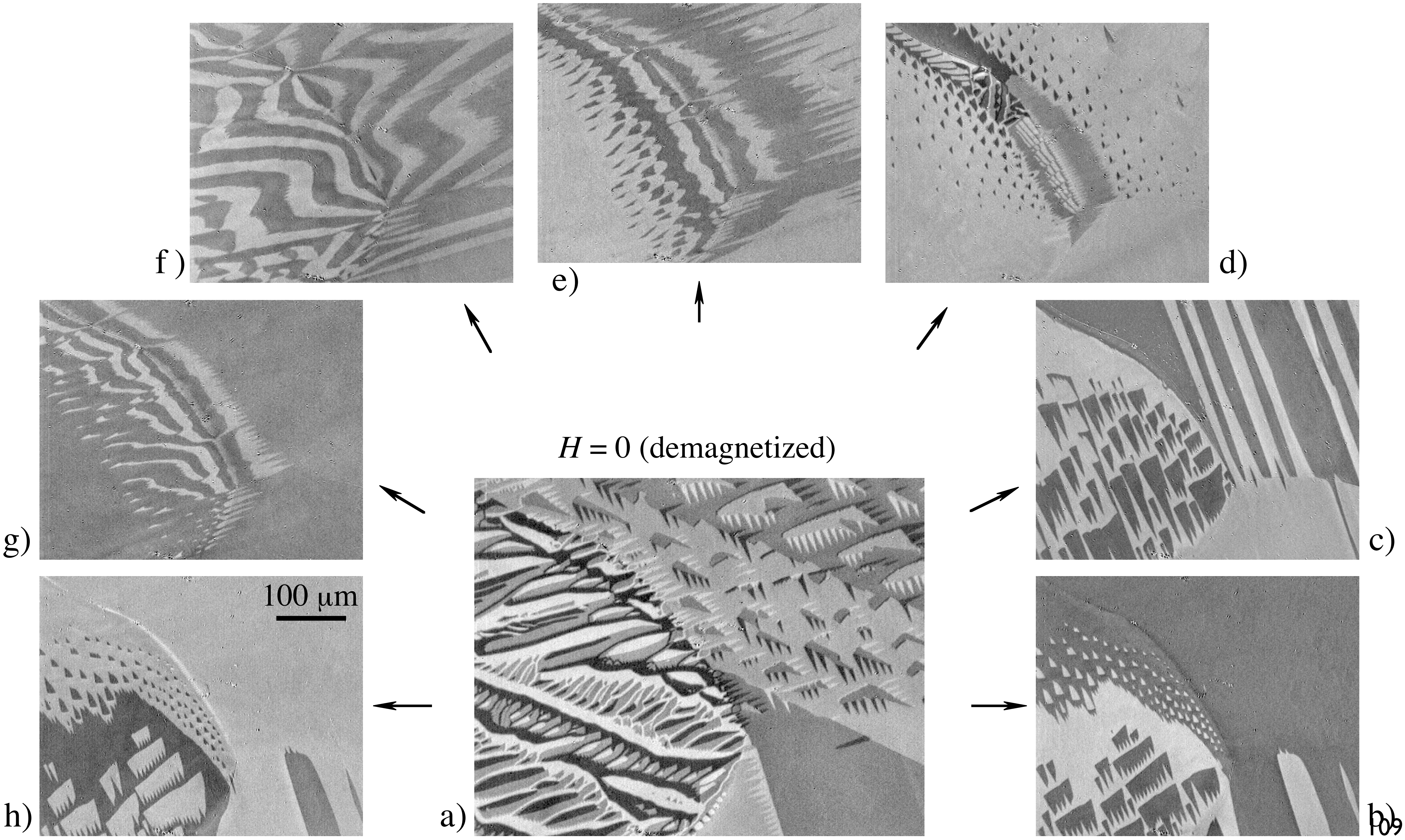
The more irregular domains and processes, the worse performance of inductive device

- Complex domain reorganization → unavoidable loss

Non-oriented FeSi material

For motors and generators



Soft magnets: General Considerations

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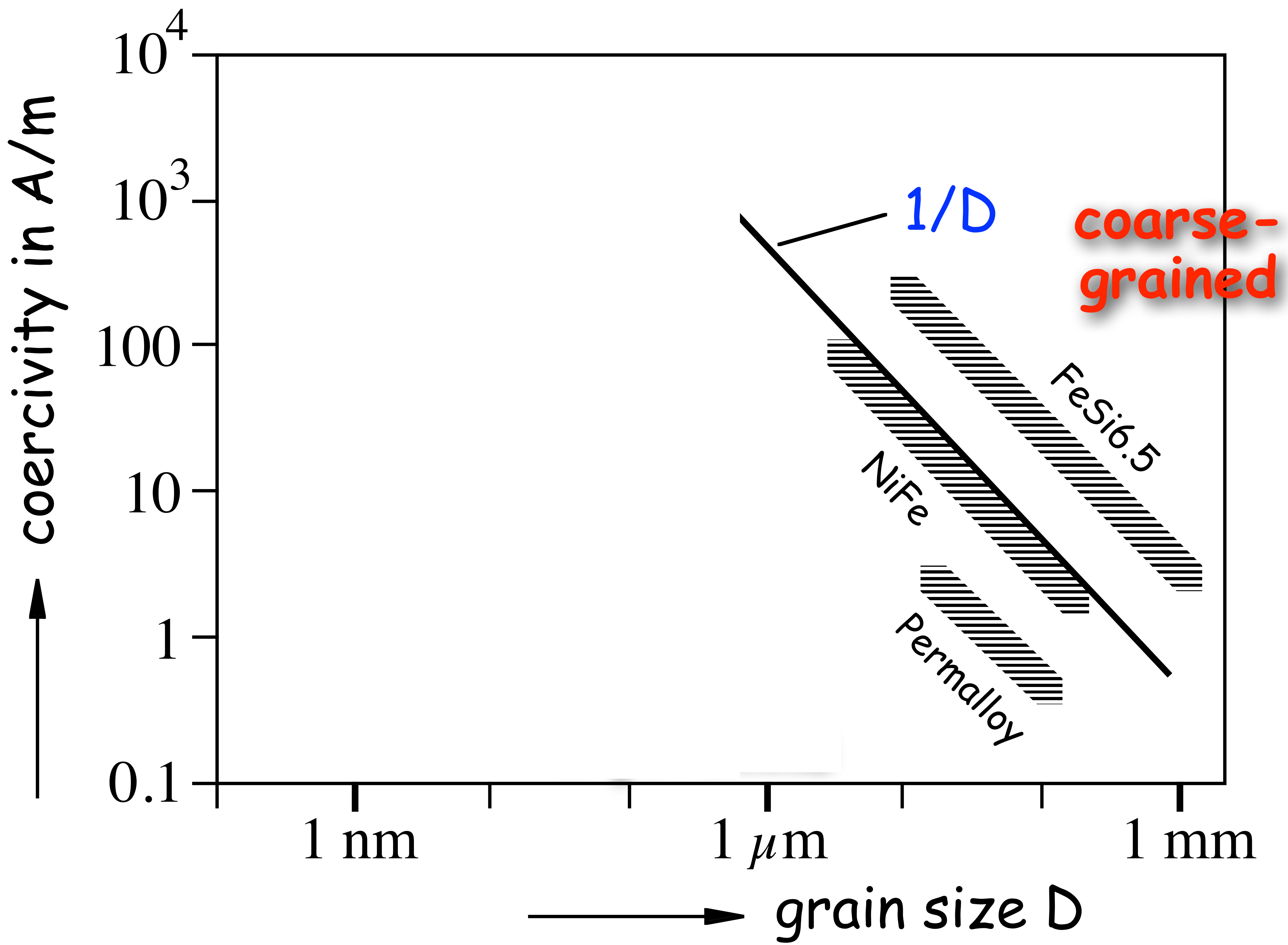
Conclusion from previous examples (NiFe, ferrites, electrical steel):

Good soft magnetic material needs large grains to obtain low coercivity and high permeability

Soft magnets: General Considerations



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Soft magnets: General Considerations

Conclusion from previous examples
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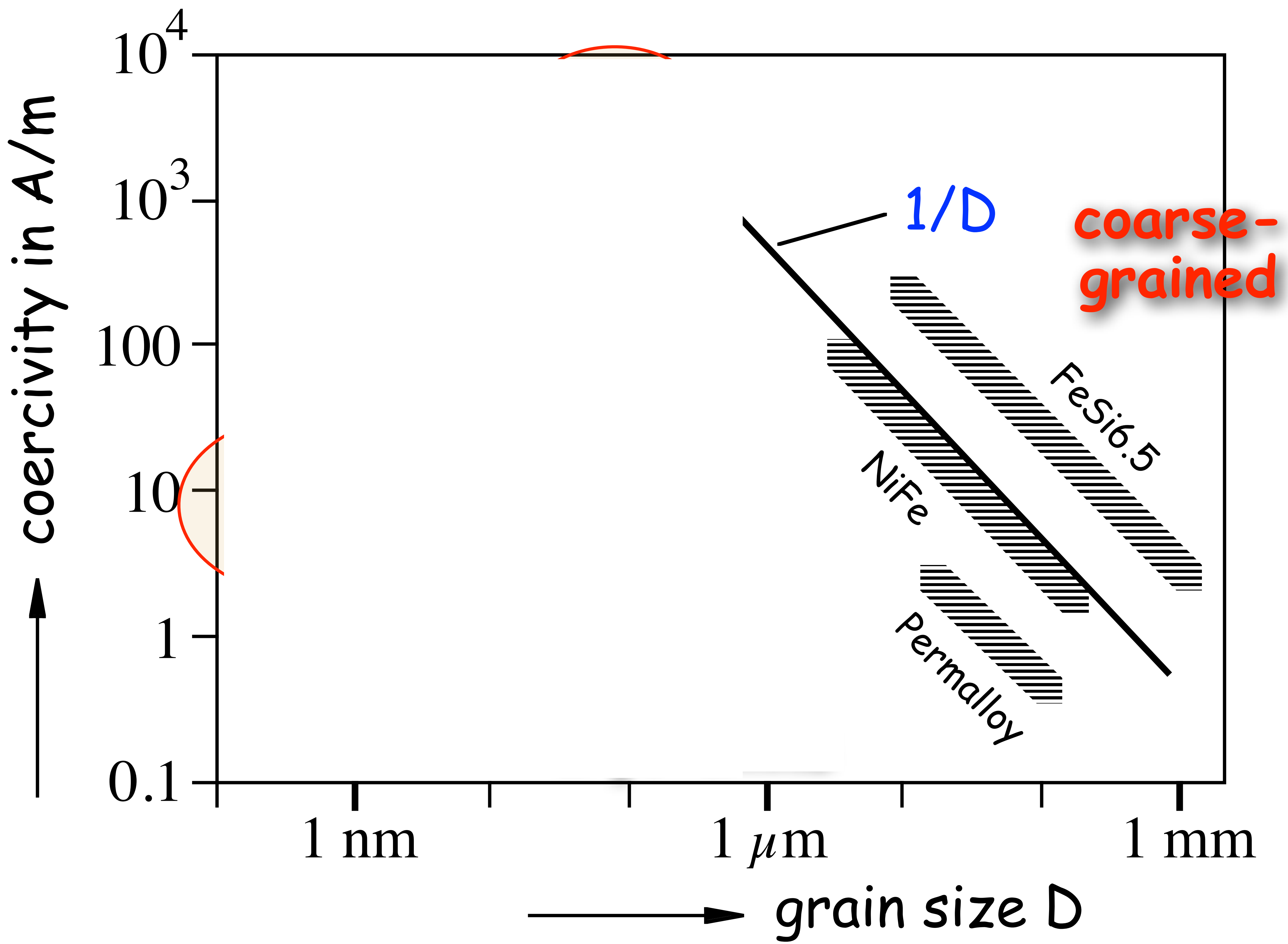
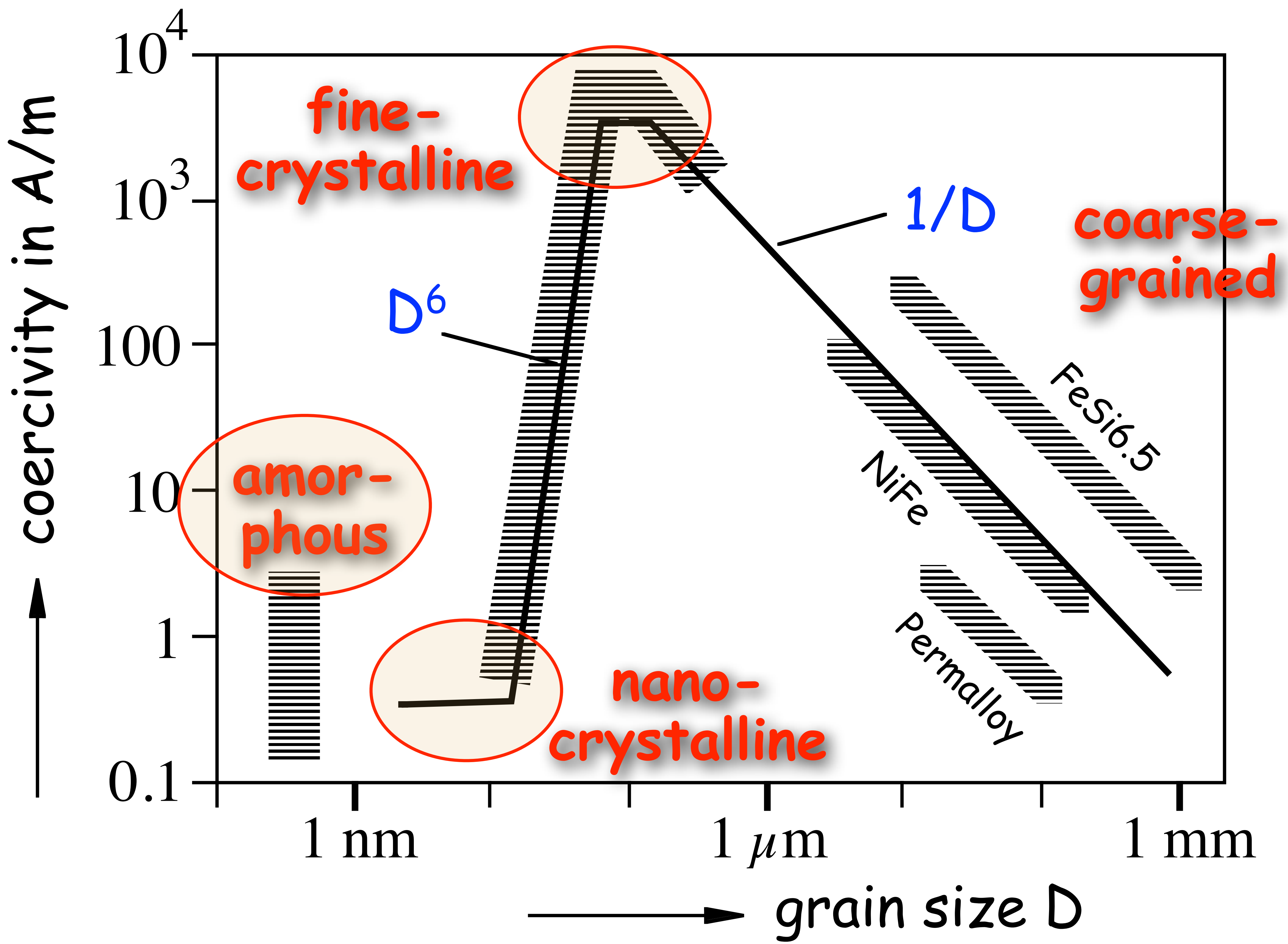
However:

This is not necessarily true !

Soft magnets: General Considerations



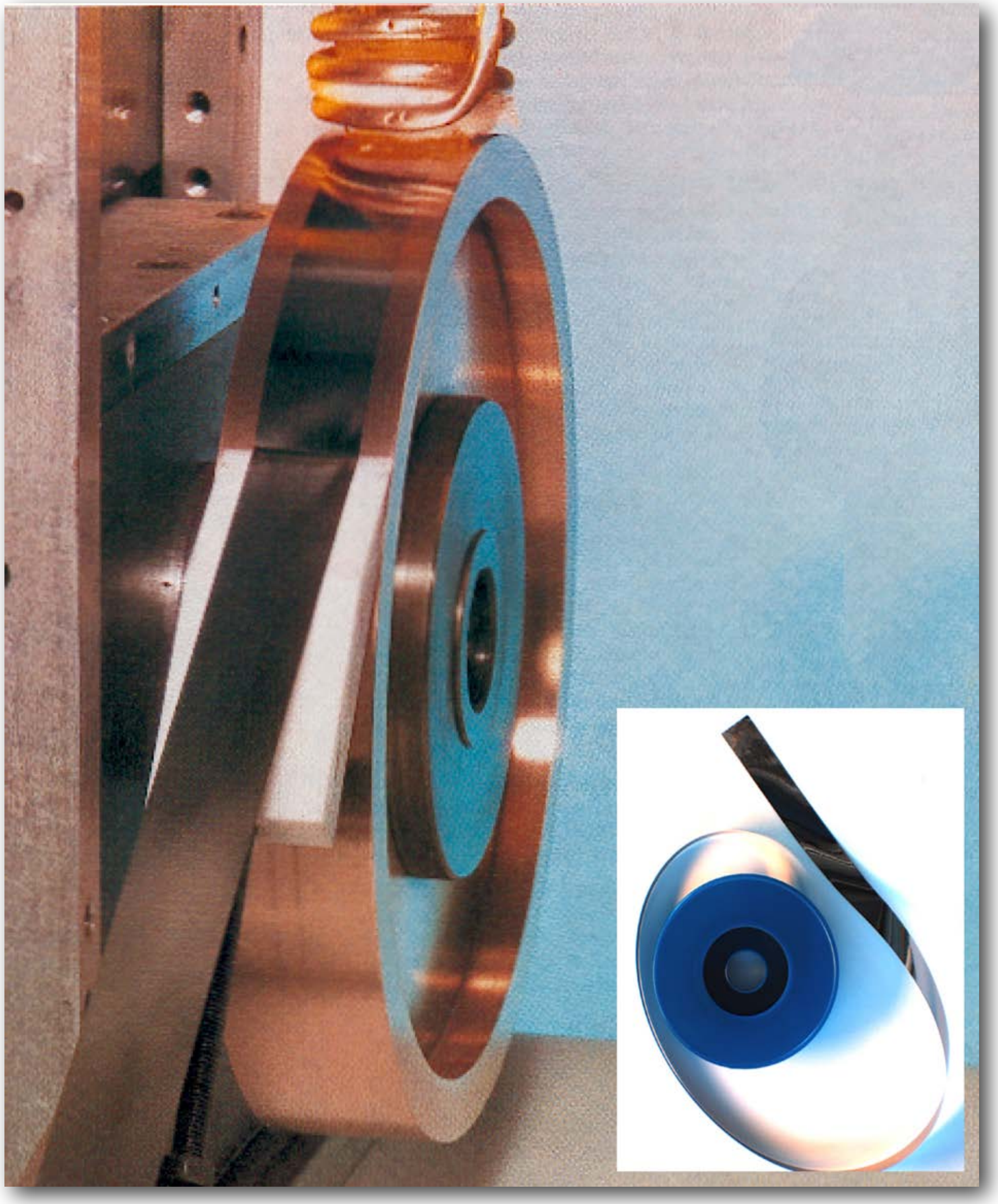
Soft magnets: General Considerations



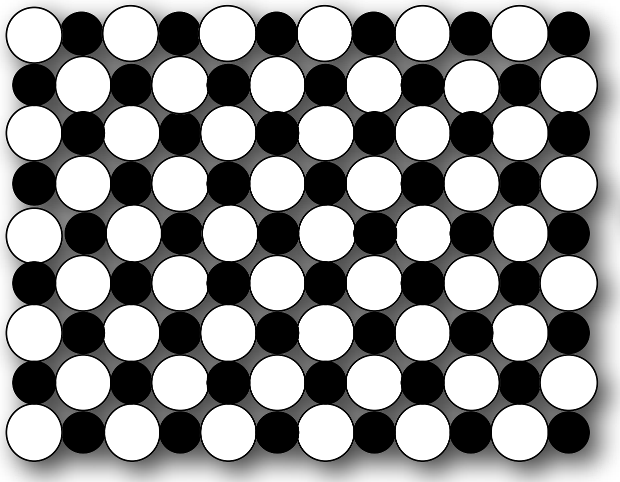
Soft magnets,
Example 4:
Amorphous ribbons

Amorphous ribbons

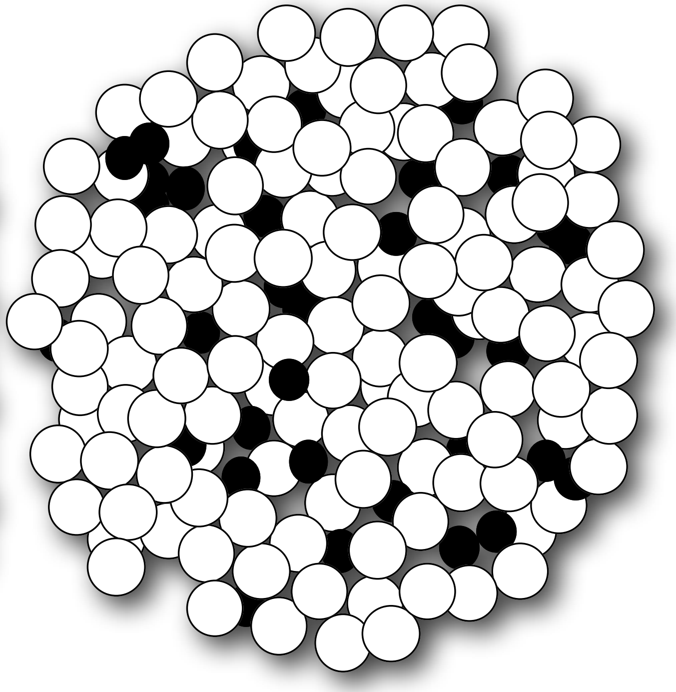
Fabrication: rapid quenching



- Ribbons, thickness **20 μm**
- **Ferromagnetic**, if they contain Fe, Ni, Co (short-range order determines exchange coupling, not long-range crystalline order)
- $T_{75\text{-}83} M_{25\text{-}17}$ T = Fe, Co, Ni
  M = P, C, B, Si, Al....
- Amorphous
  → **no magnetocrystalline anisotropy**



Crystalline



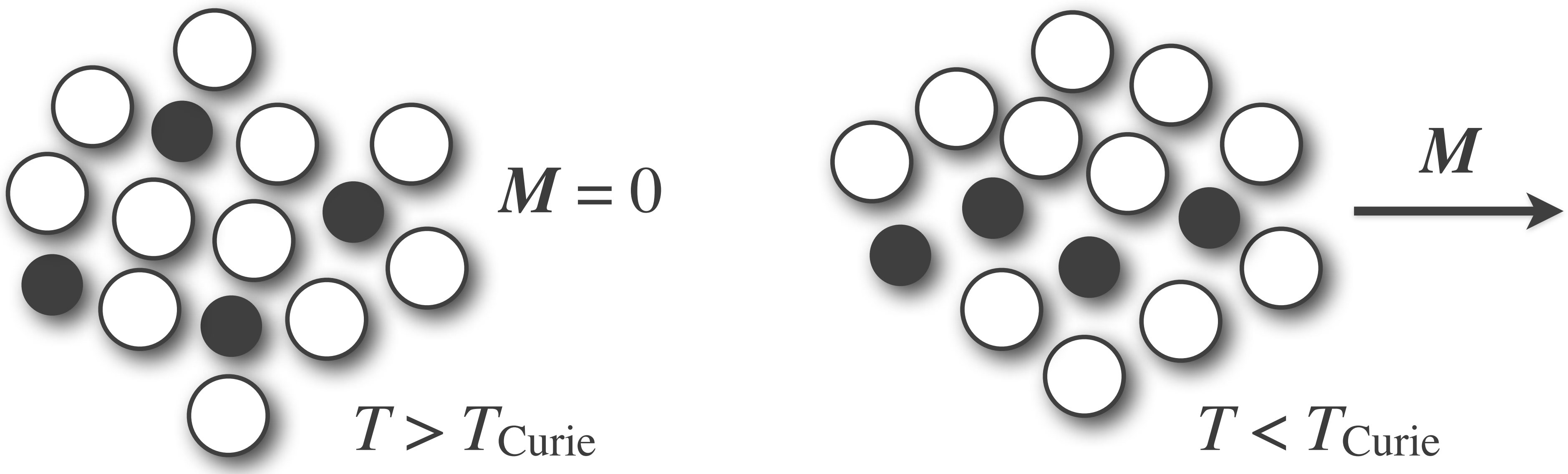
Amorphous

Amorphous ribbons

Residual anisotropies in amorphous ribbons

- **Magnetization-induced**

  minute deviations from random pair ordering

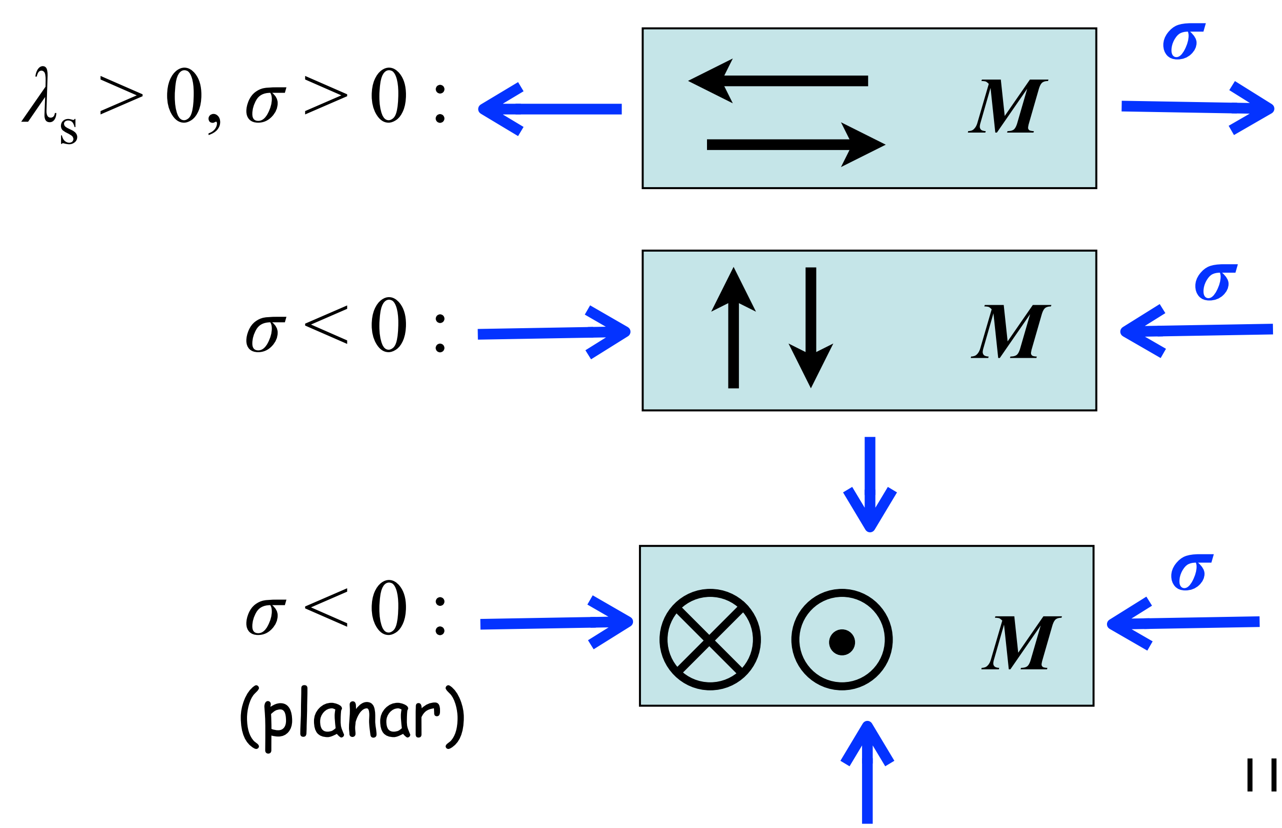


- **Stress-induced**

  Internal mechanical stress, e.g. due to differences in quenching speed

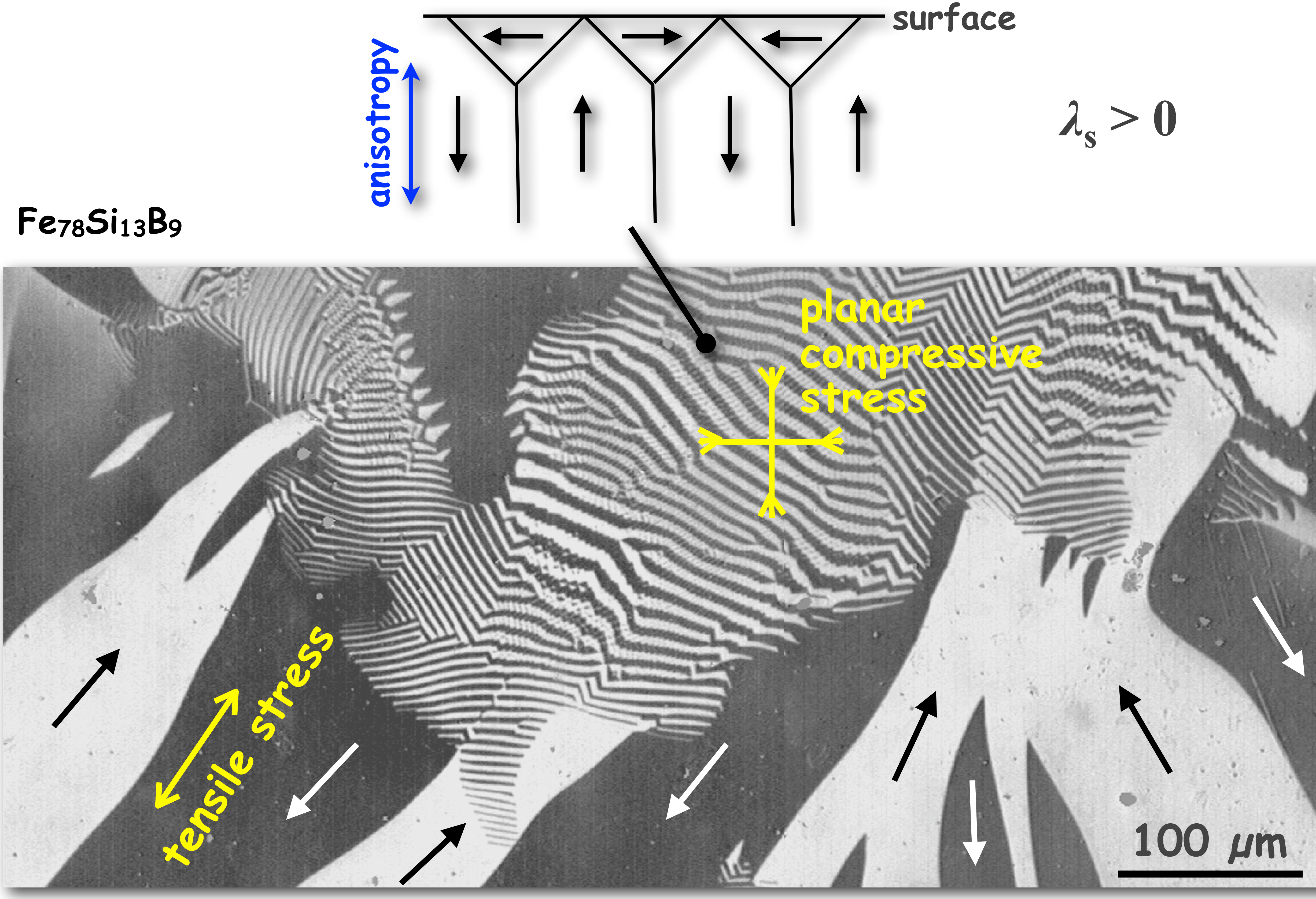
$$e_{\mathrm{me}} = \frac{3}{2}\lambda_s \sigma \sin^2\theta$$

Magnetostriction constant (λ_s); Mechanical stress (σ); Angle between M and stress σ (θ)



Amorphous ribbons

Stress-induced anisotropy in amorphous ribbon

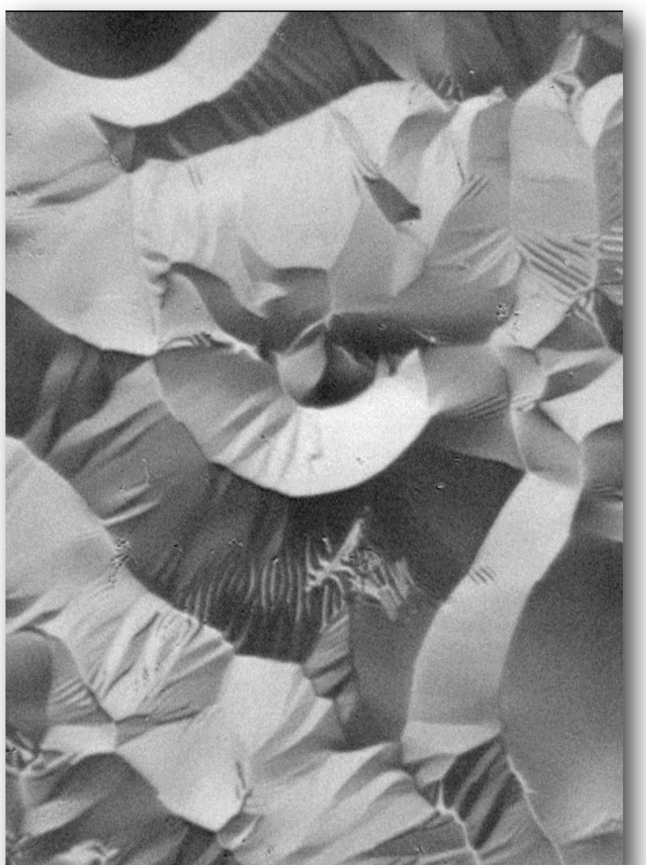


Amorphous ribbons

Stress-induced anisotropy in amorphous ribbon

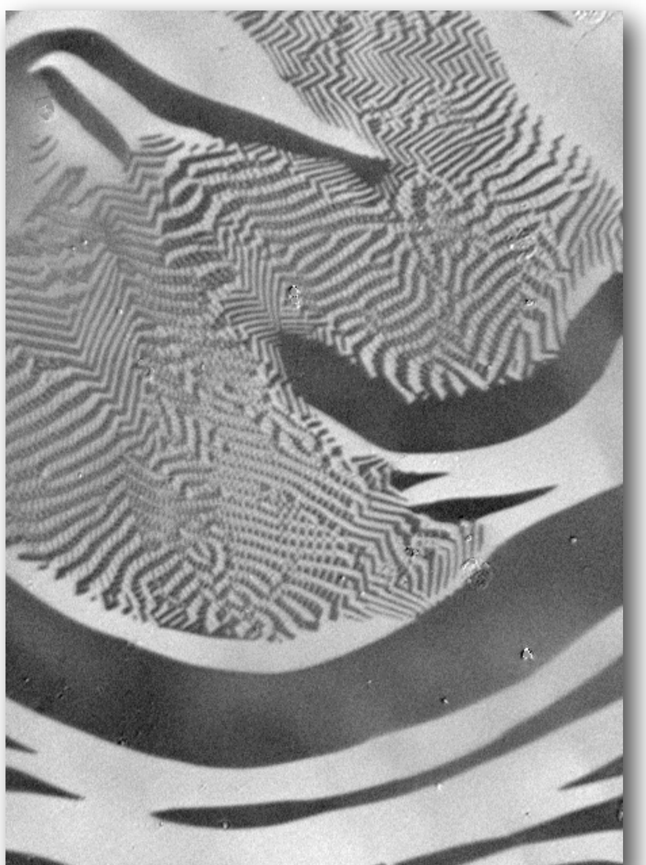
$$e_{\text{me}} = \frac{3}{2}\lambda_s \sigma \sin^2\theta$$

Magnetostriction constant — Mechanical stress — Angle between M and stress σ



$\lambda_s = +35 \cdot 10^{-6}$

$(FeCo)_{83}(Si,B)_{17}$

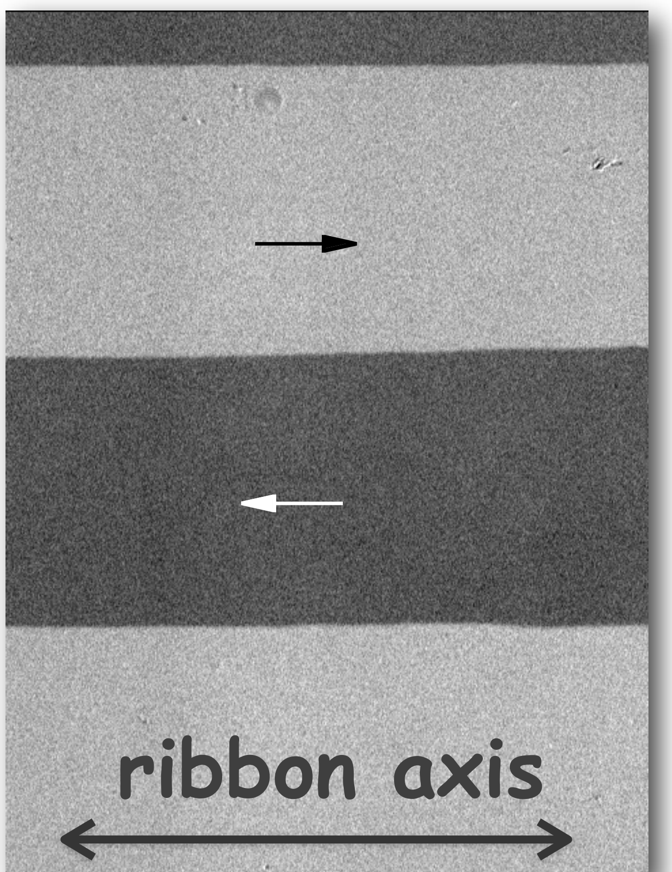


$\lambda_s = +24 \cdot 10^{-6}$

$Fe_{76}(Si,B)_{24}$

$\lambda_s = +8 \cdot 10^{-6}$

$Ni_{39}Fe_{39}(Si,B,C)_{22}$



$\lambda_s < 0.2 \cdot 10^{-6}$

$(Co,Fe,Mn,Mo)_{77}(Si,B)_{23}$

Amorphous ribbons

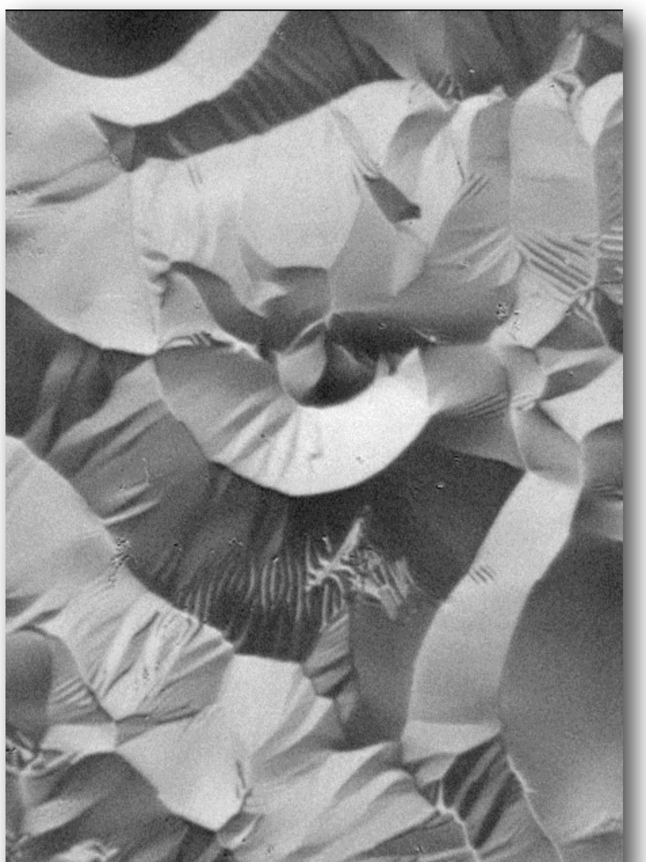
Stress-induced anisotropy in amorphous ribbon

Magnetostriction-free material: Co-rich alloys

Magnetostriction constant

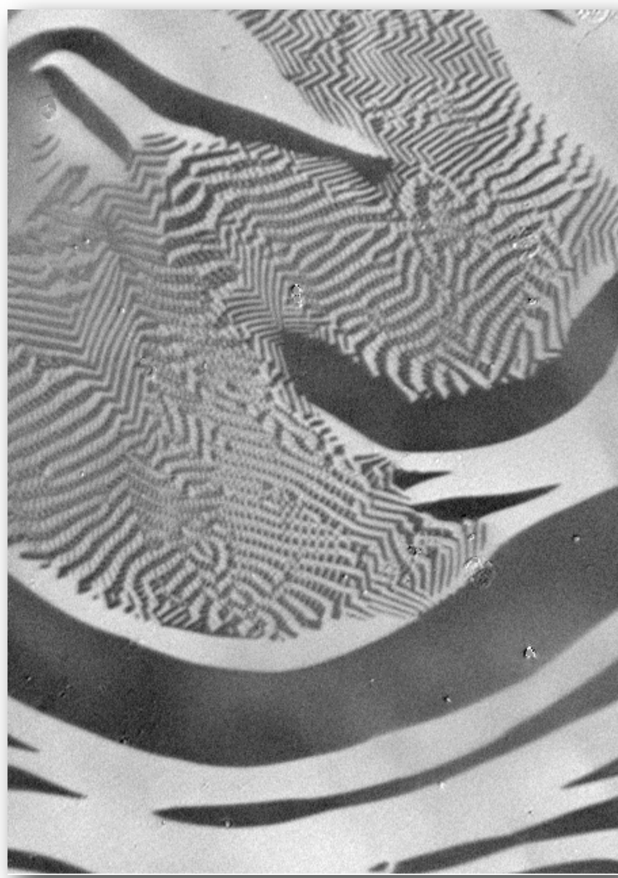
Mechanical stress

Angle between M and stress σ



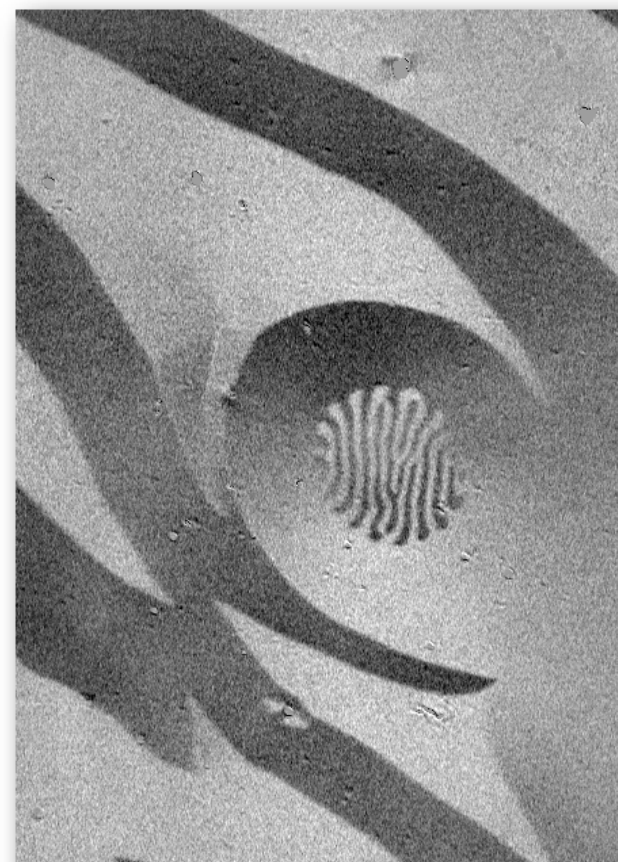
$\lambda_s = +35 \cdot 10^{-6}$

$(FeCo)_{83}(Si,B)_{17}$



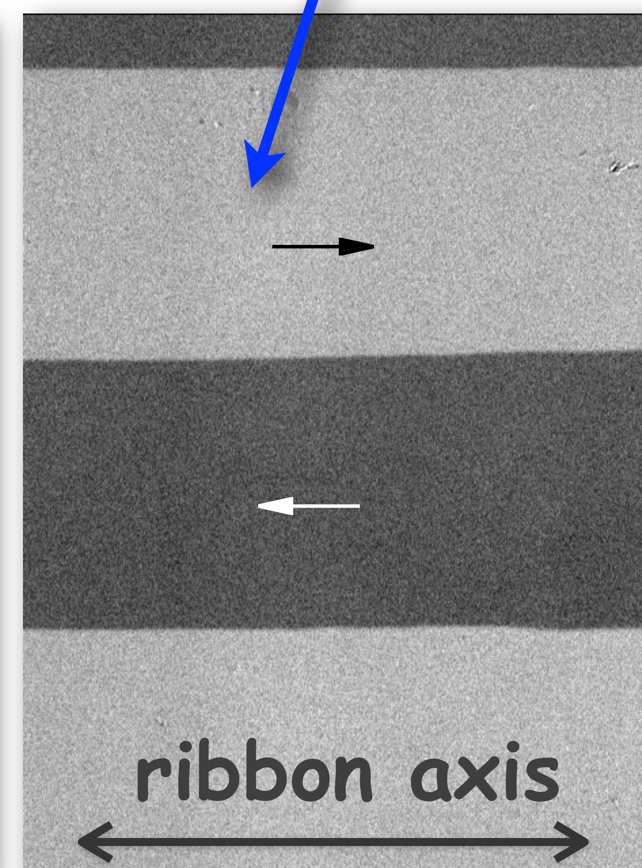
$\lambda_s = +24 \cdot 10^{-6}$

$Fe_{76}(Si,B)_{24}$



$\lambda_s = +8 \cdot 10^{-6}$

$Ni_{39}Fe_{39}(Si,B,C)_{22}$



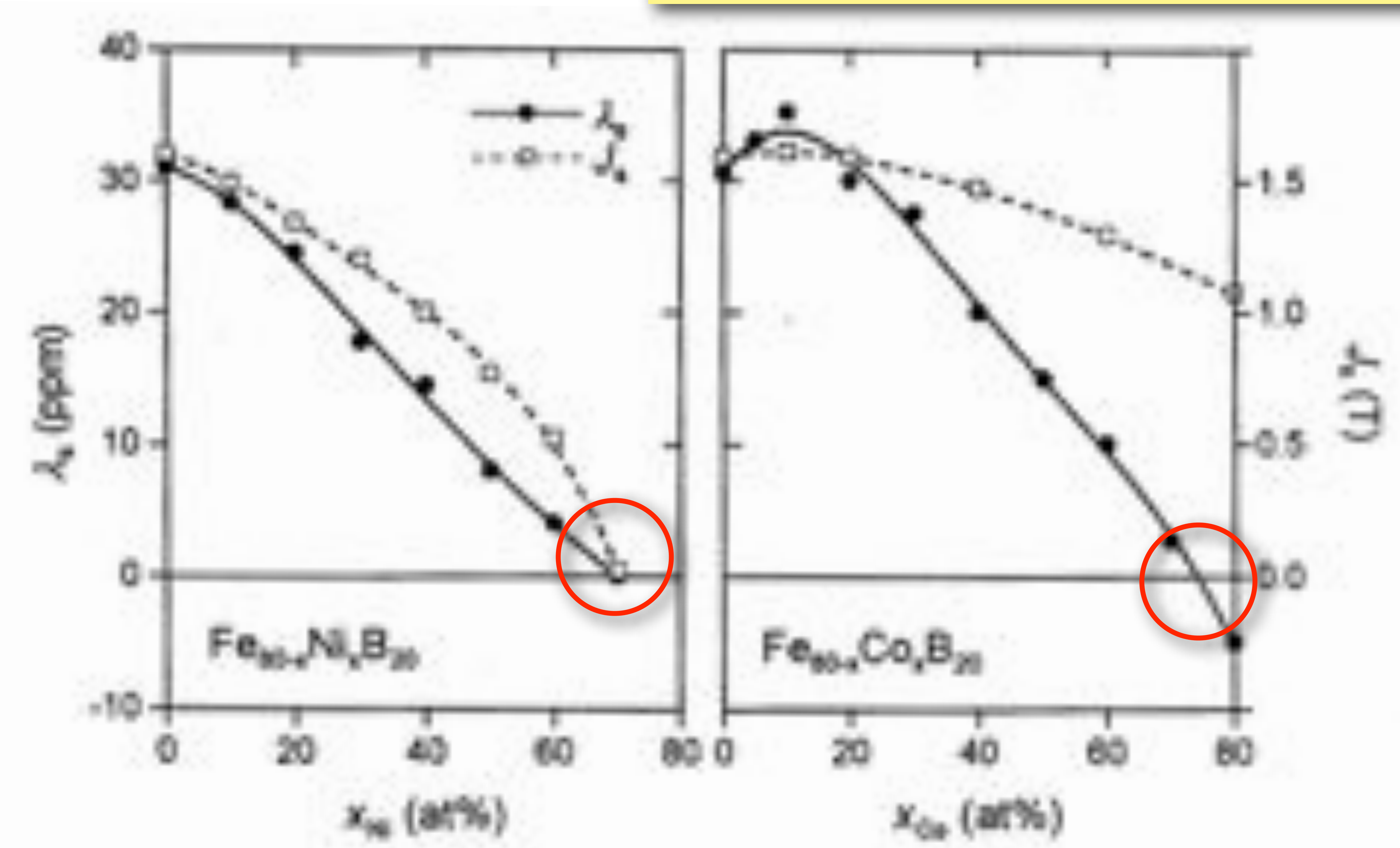
$\lambda_s < 0.2 \cdot 10^{-6}$

$(Co,Fe,Mn,Mo)_{77}(Si,B)_{23}$

Amorphous ribbons

Stress-induced anisotropy in amorphous ribbon

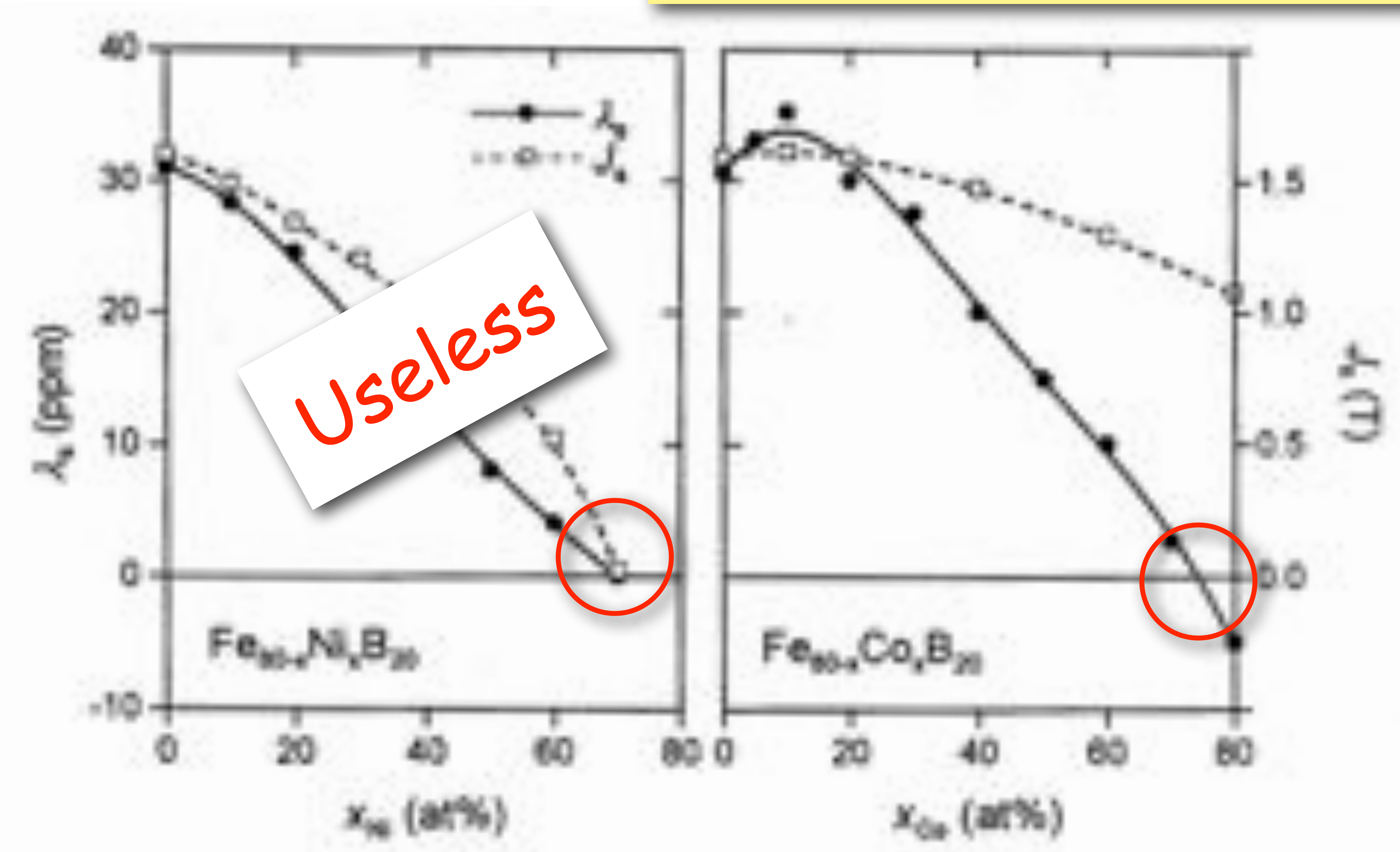
Magnetostriction-free material: Co-rich alloys



Amorphous ribbons

Stress-induced anisotropy in amorphous ribbon

Magnetostriction-free material:
Co-rich alloys



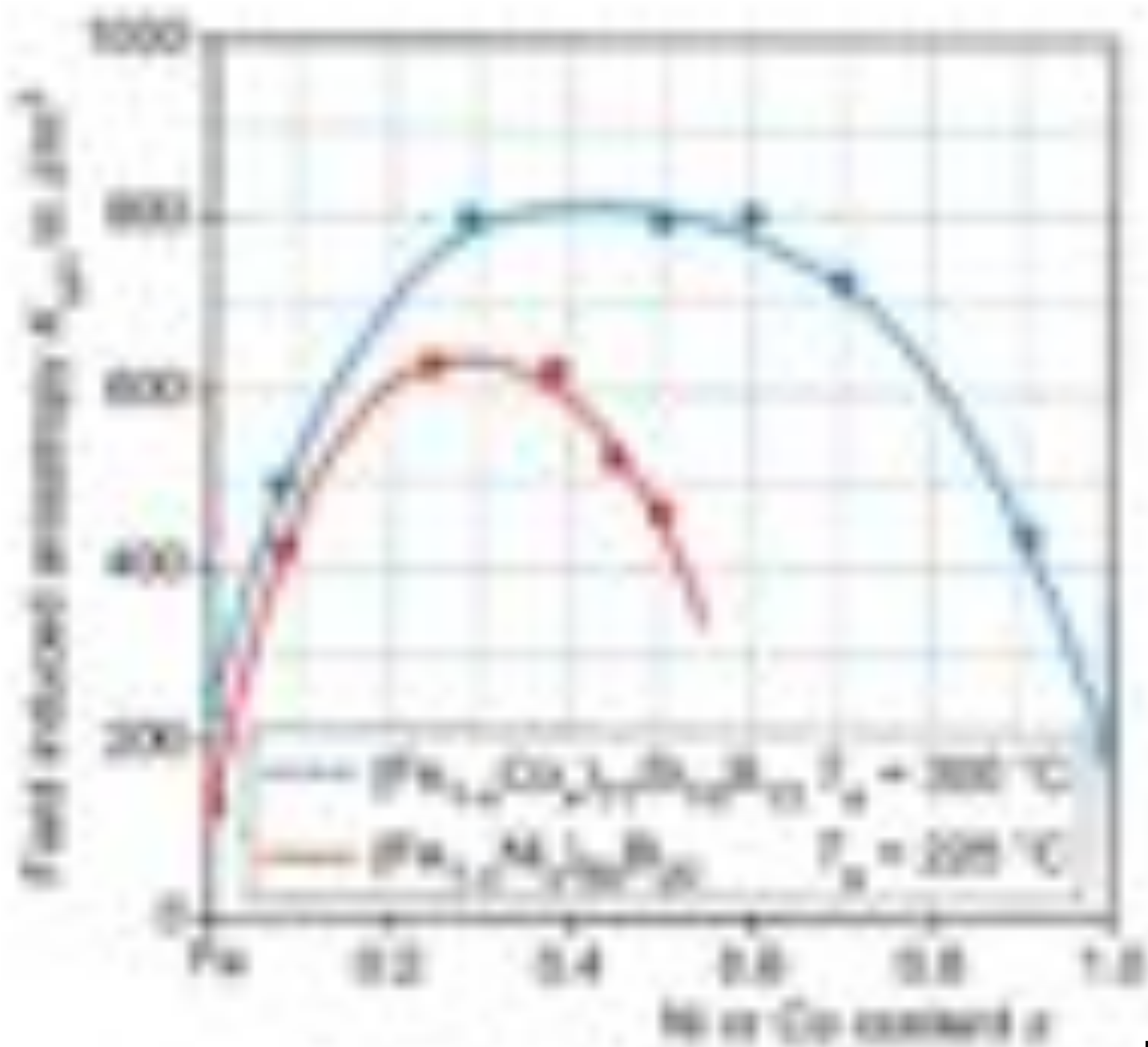
Amorphous ribbons

Induced anisotropy in amorphous ribbon

CoFeSiB-alloy with $\lambda_s \sim 0$

→ no stress effects

→ controlled anisotropy by field-annealing

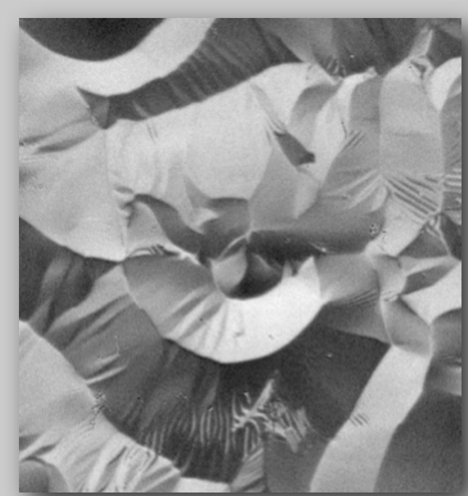


Amorphous ribbons

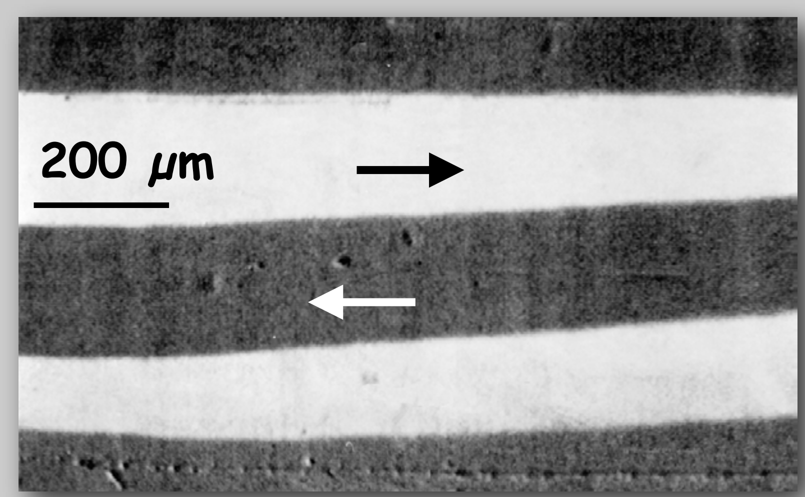
Induced anisotropy in amorphous ribbon

← Ribbon axis →

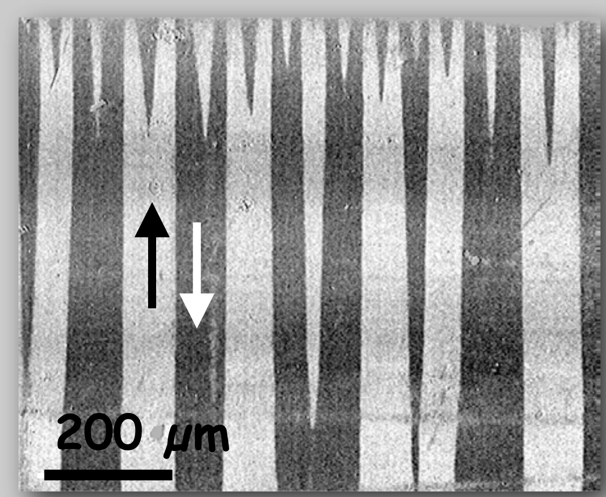
Magnetostrictive material



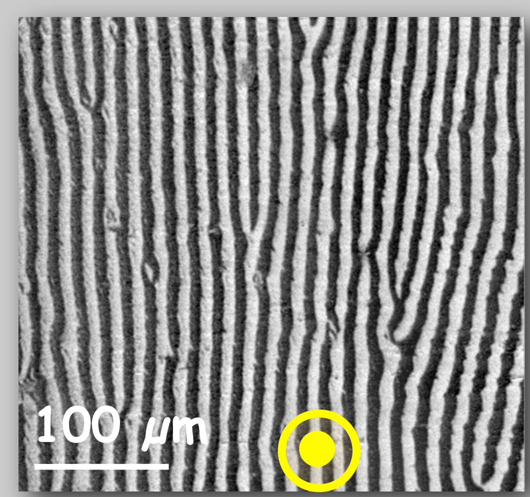
Magnetostriction-free material



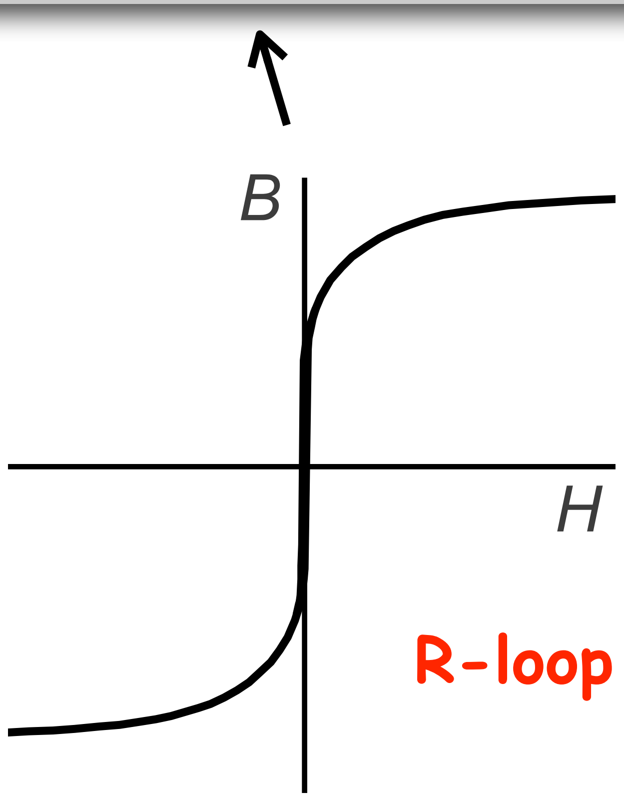
annealed in longit. field

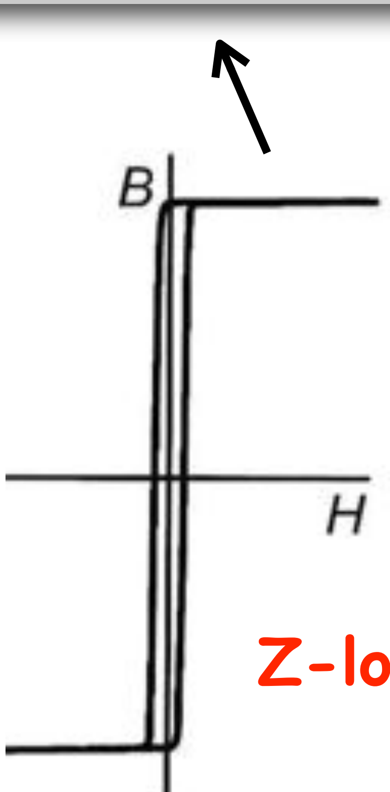


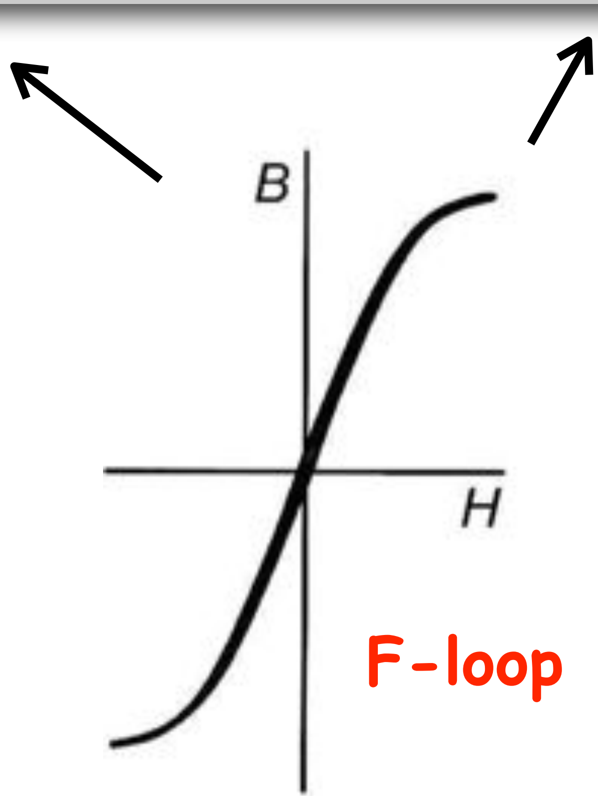
… transv. field



… perpend. field







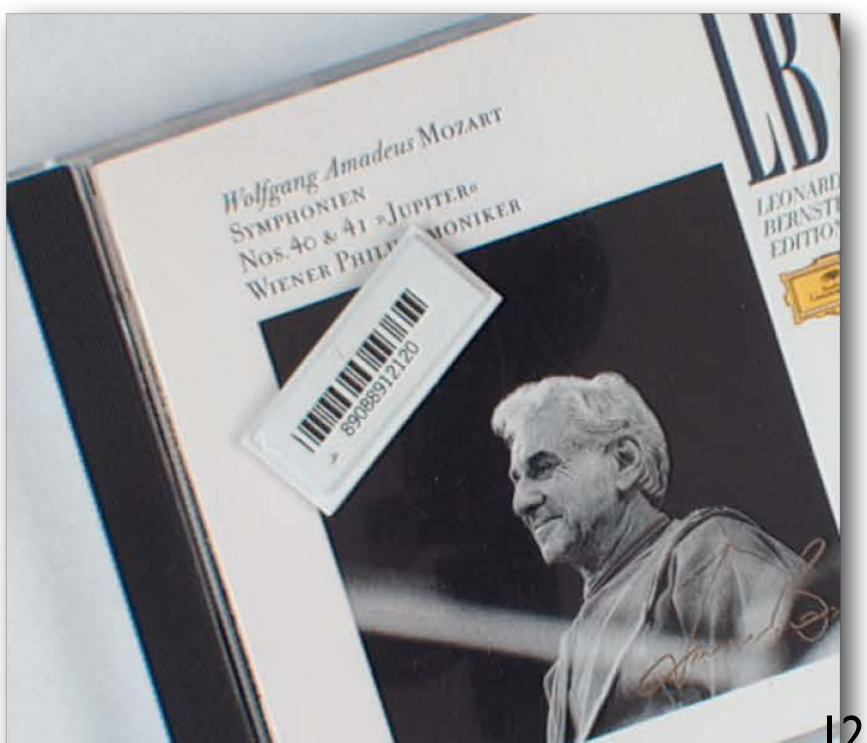
Amorphous ribbons

Typical application:
tape-wound cores for inductive devices

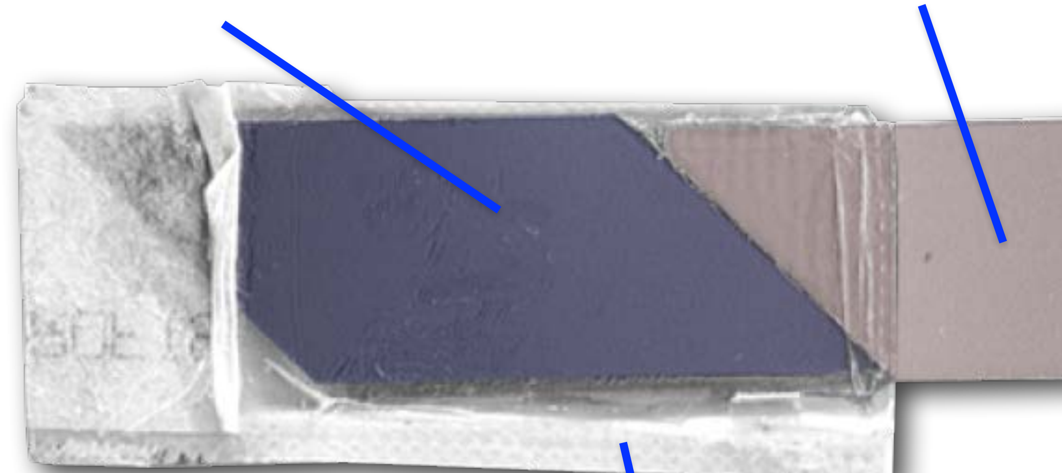
Further example for application:

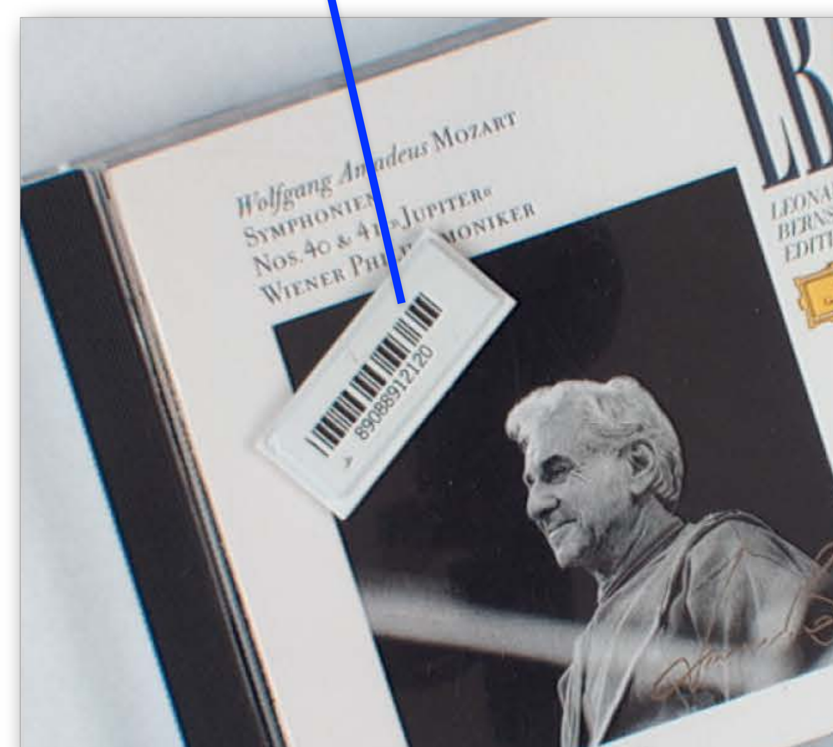
Article surveillance

Magneto-acustic article surveillance



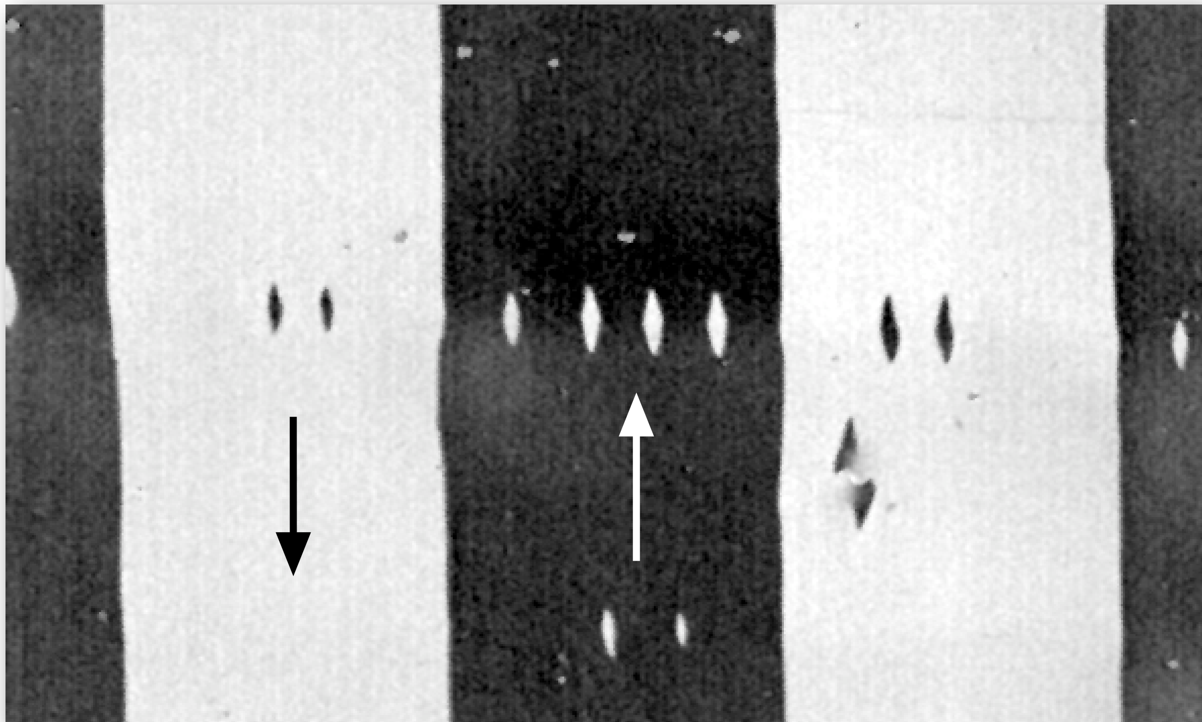
Magneto-acustic article surveillance





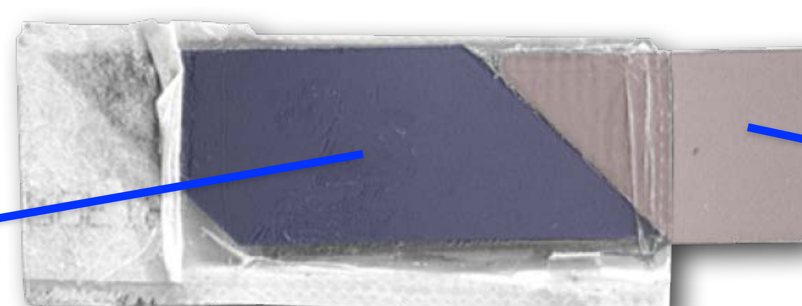
Magneto-acustic article surveillance

deactivated



metallic glass without magnetic field

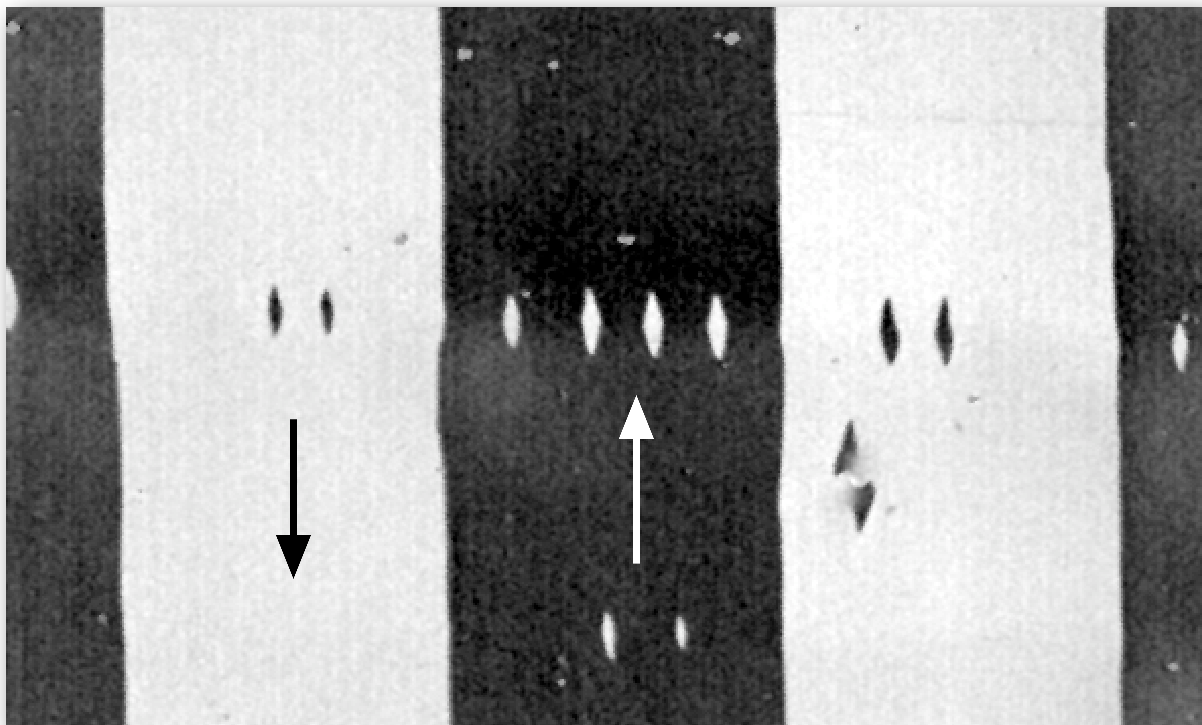
semi-hard metal
(on-/off-switch)



metallic glass
(sensor)

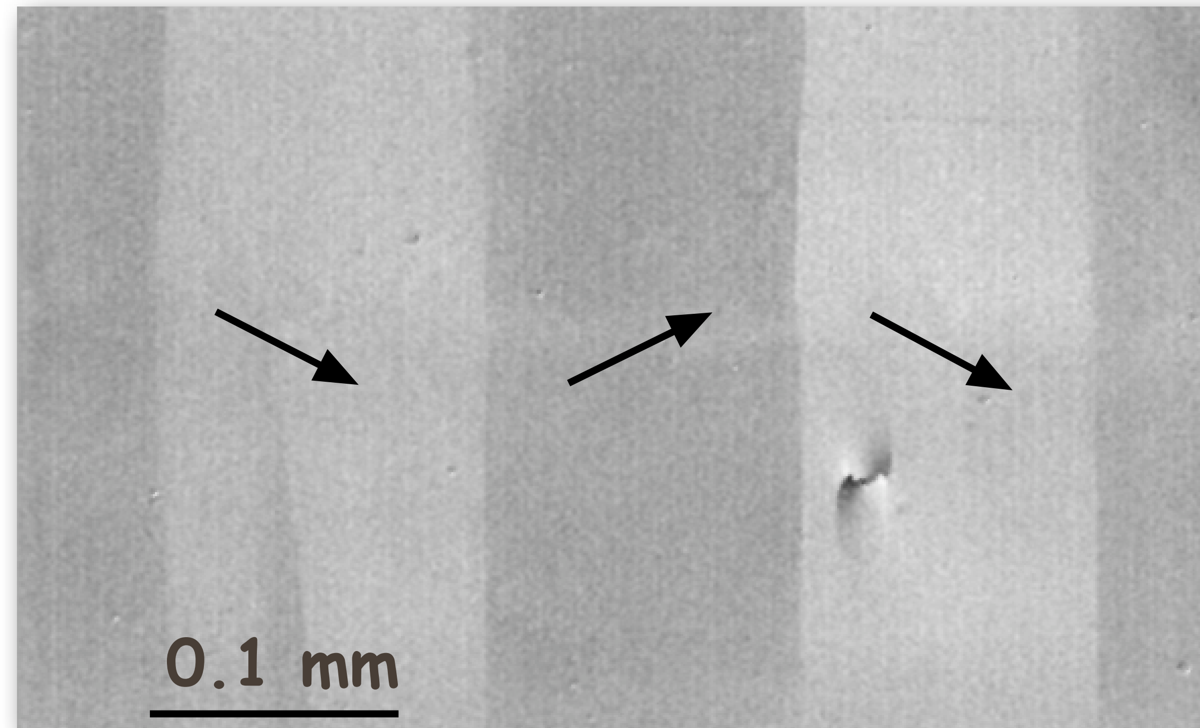
Magneto-acustic article surveillance

deactivated

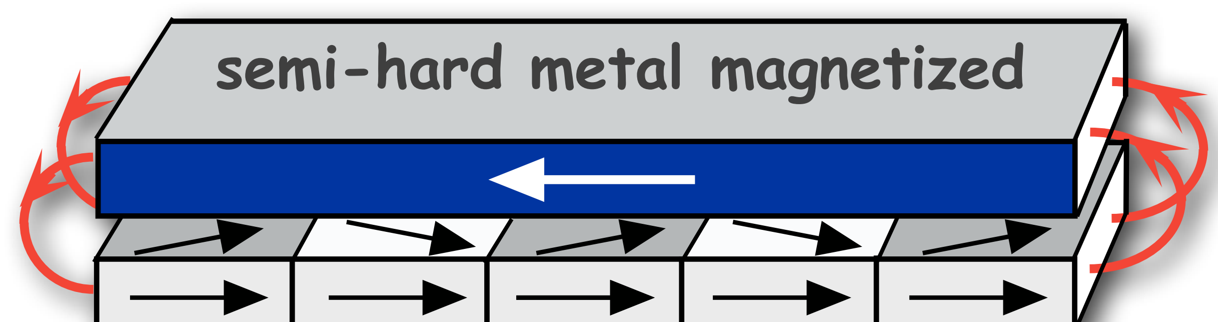


metallic glass without magnetic field

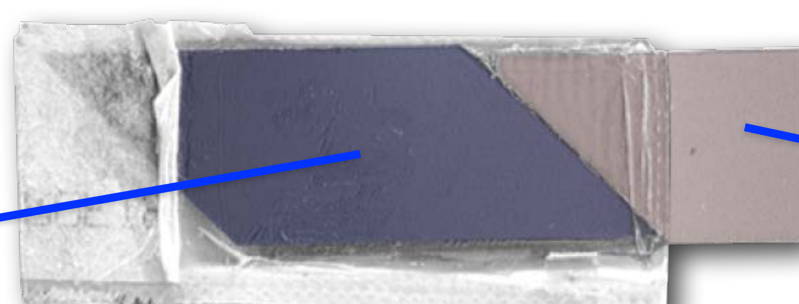
active



metallic glass in magnetic field

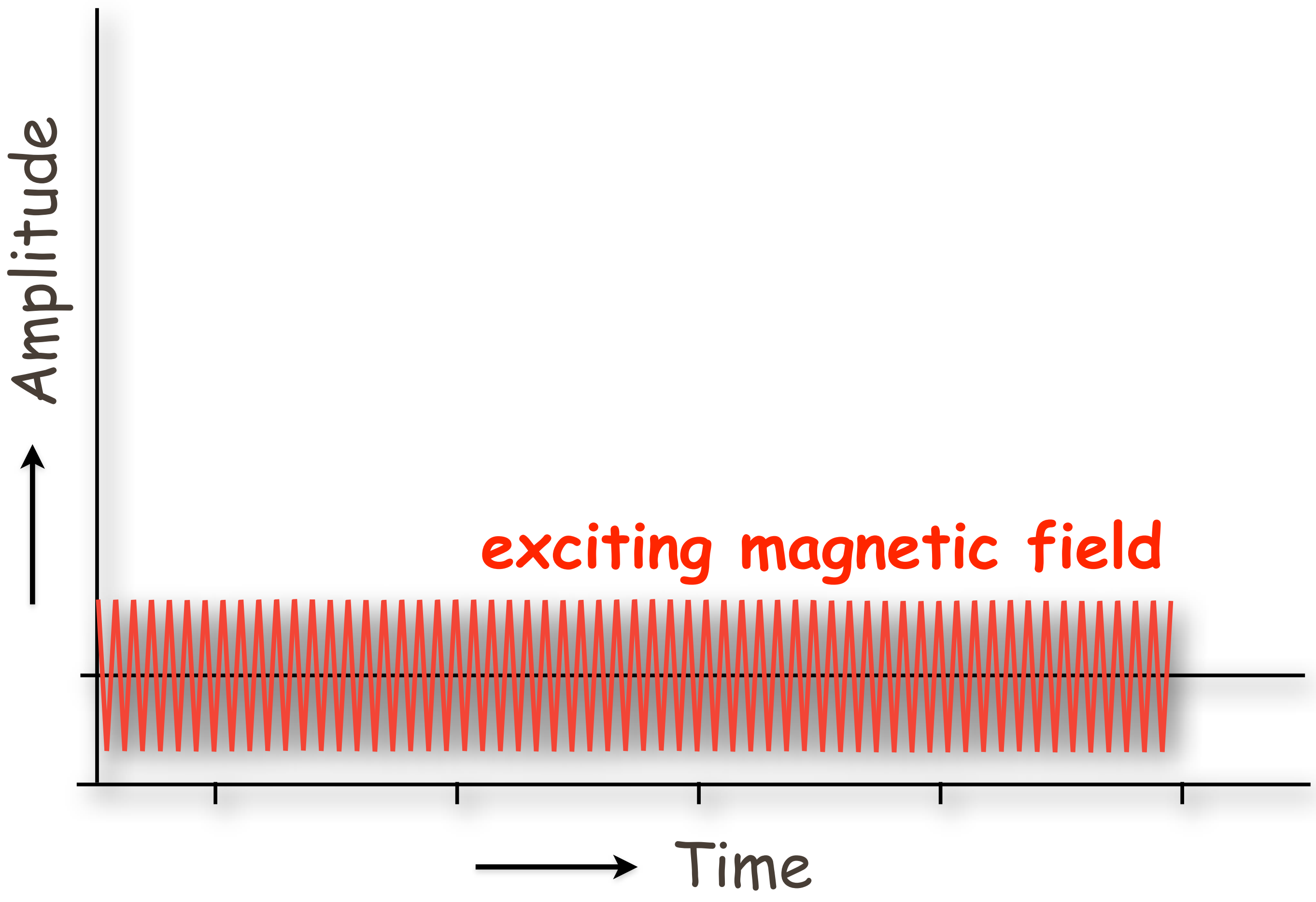


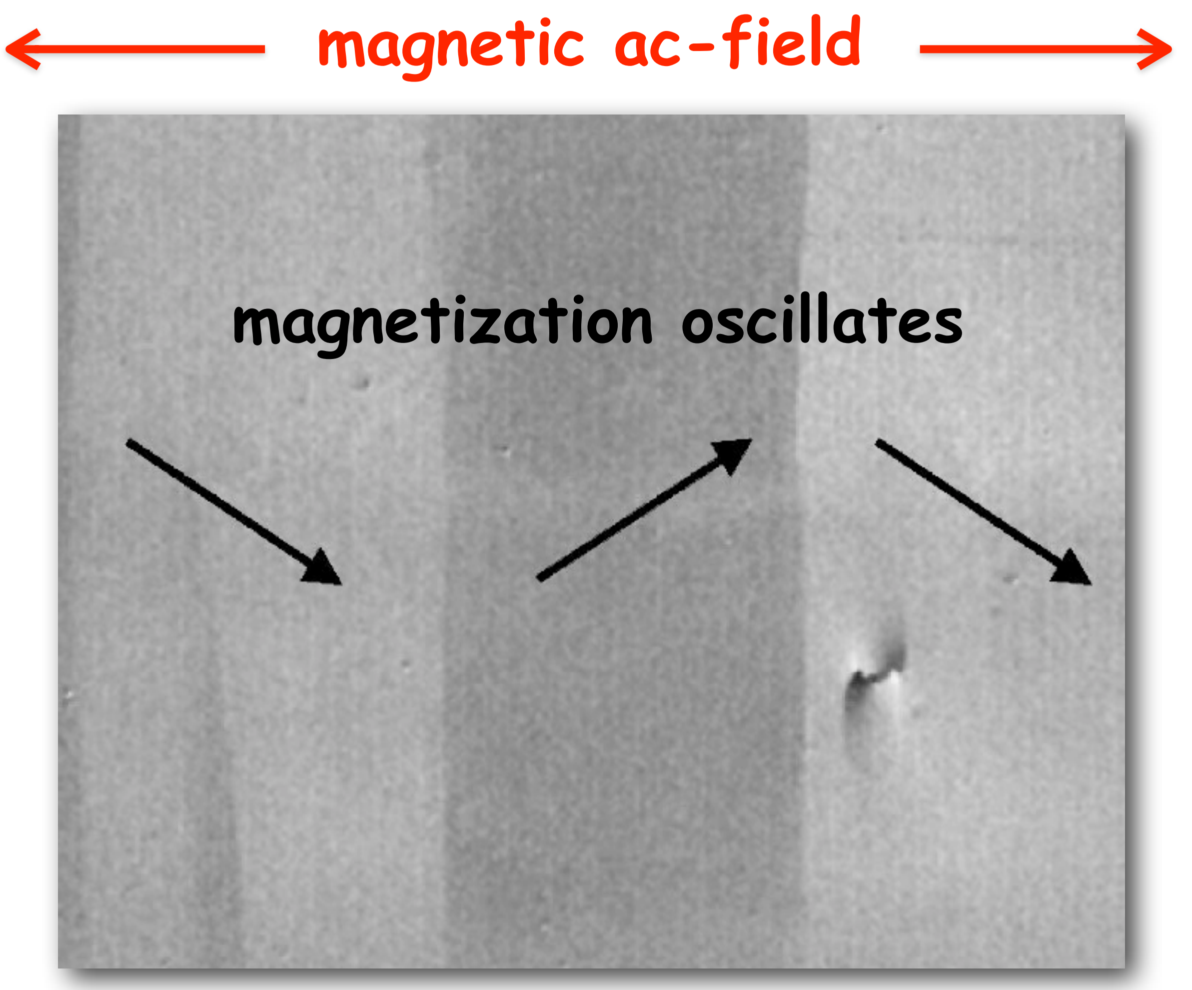
semi-hard metal
(on-/off-switch)



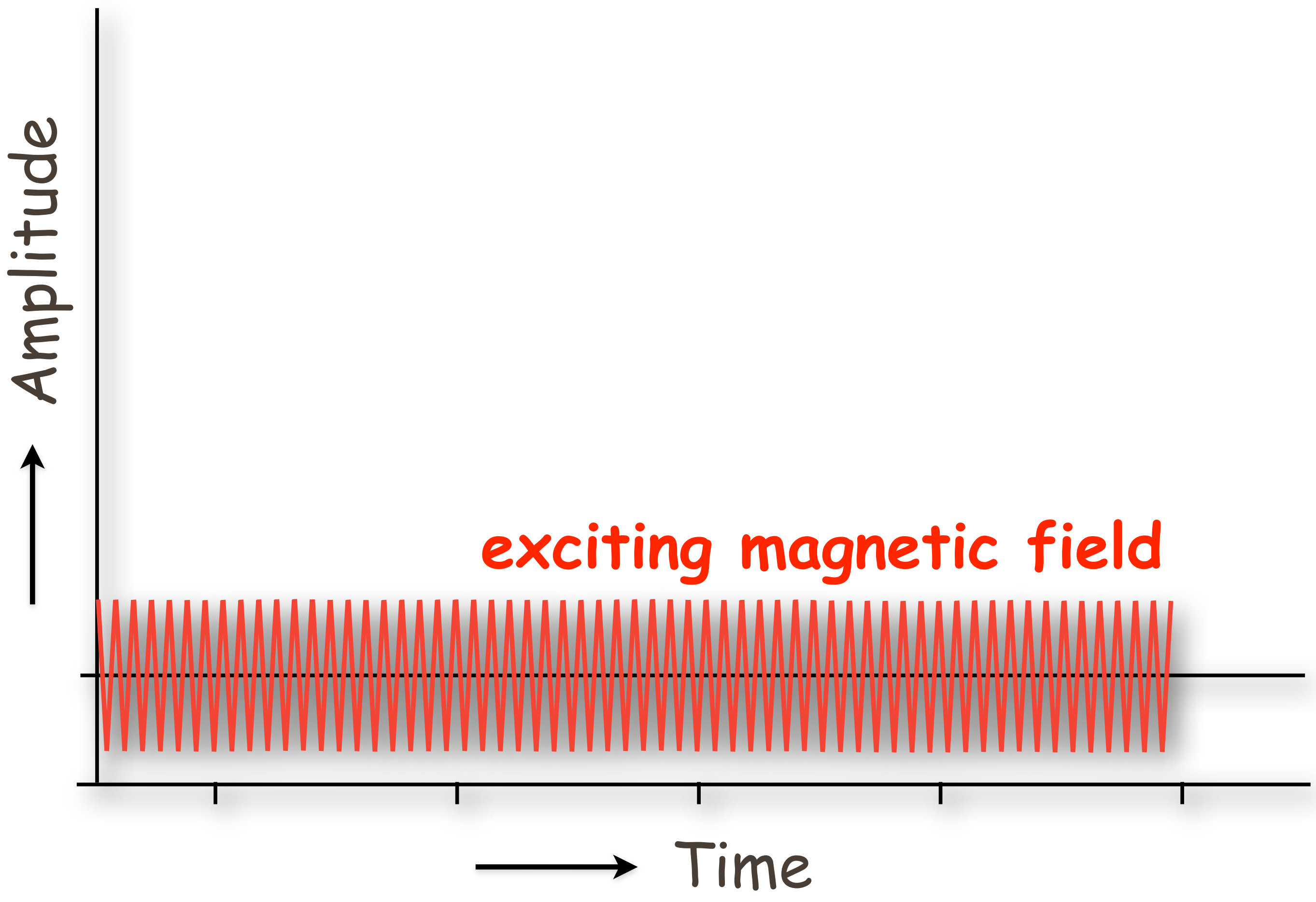
metallic glass
(sensor)

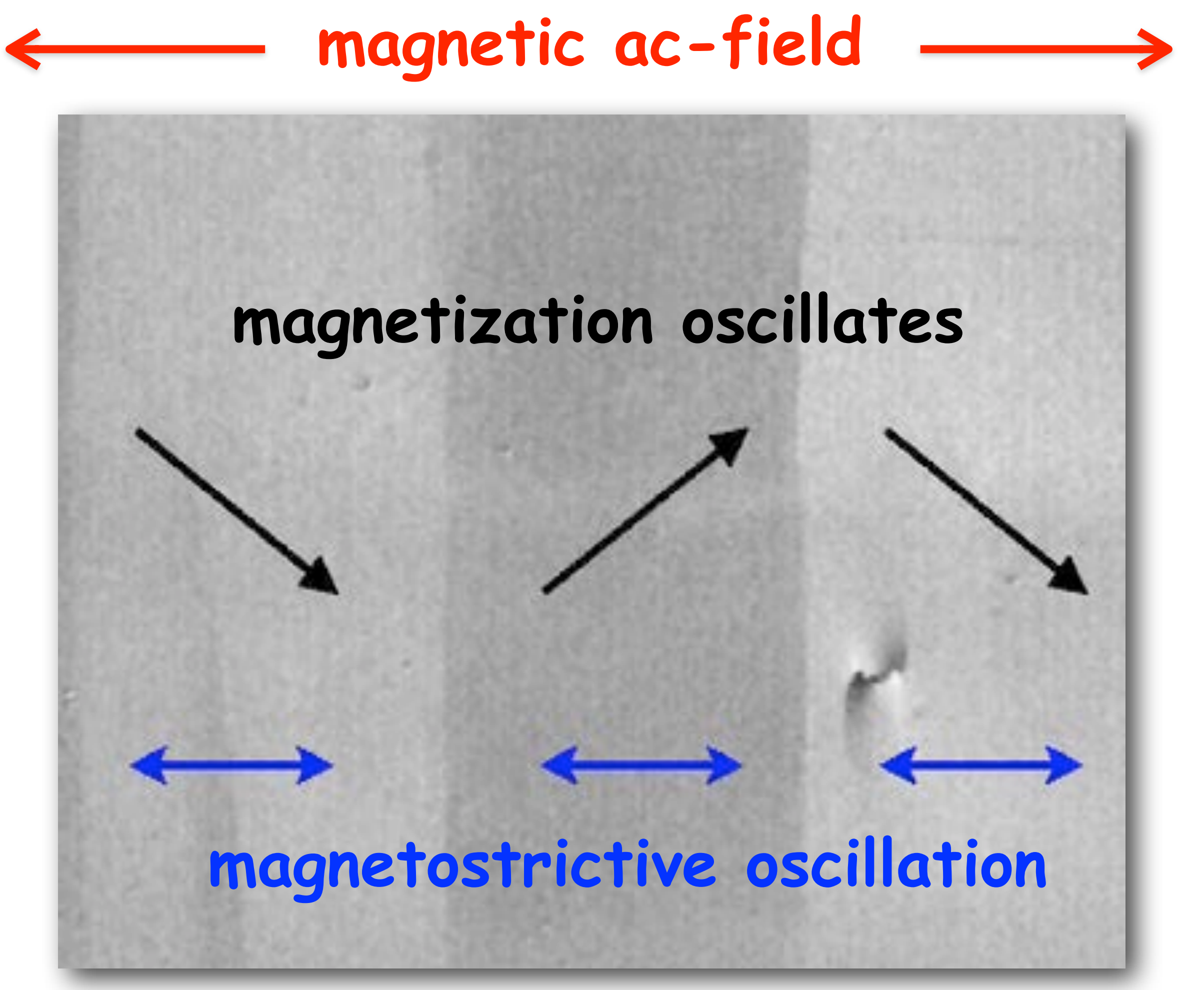
Magneto-acustic article surveillance



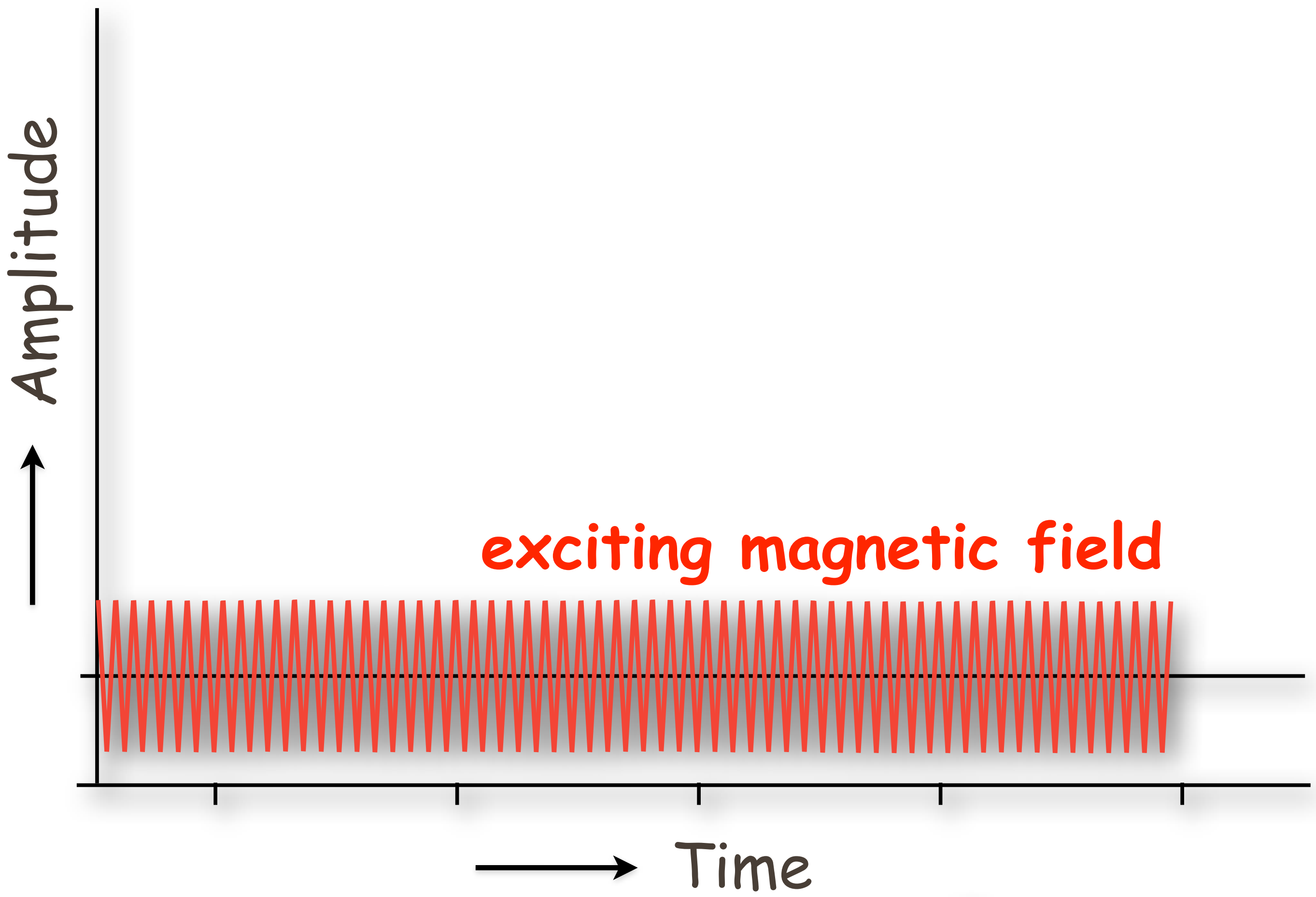


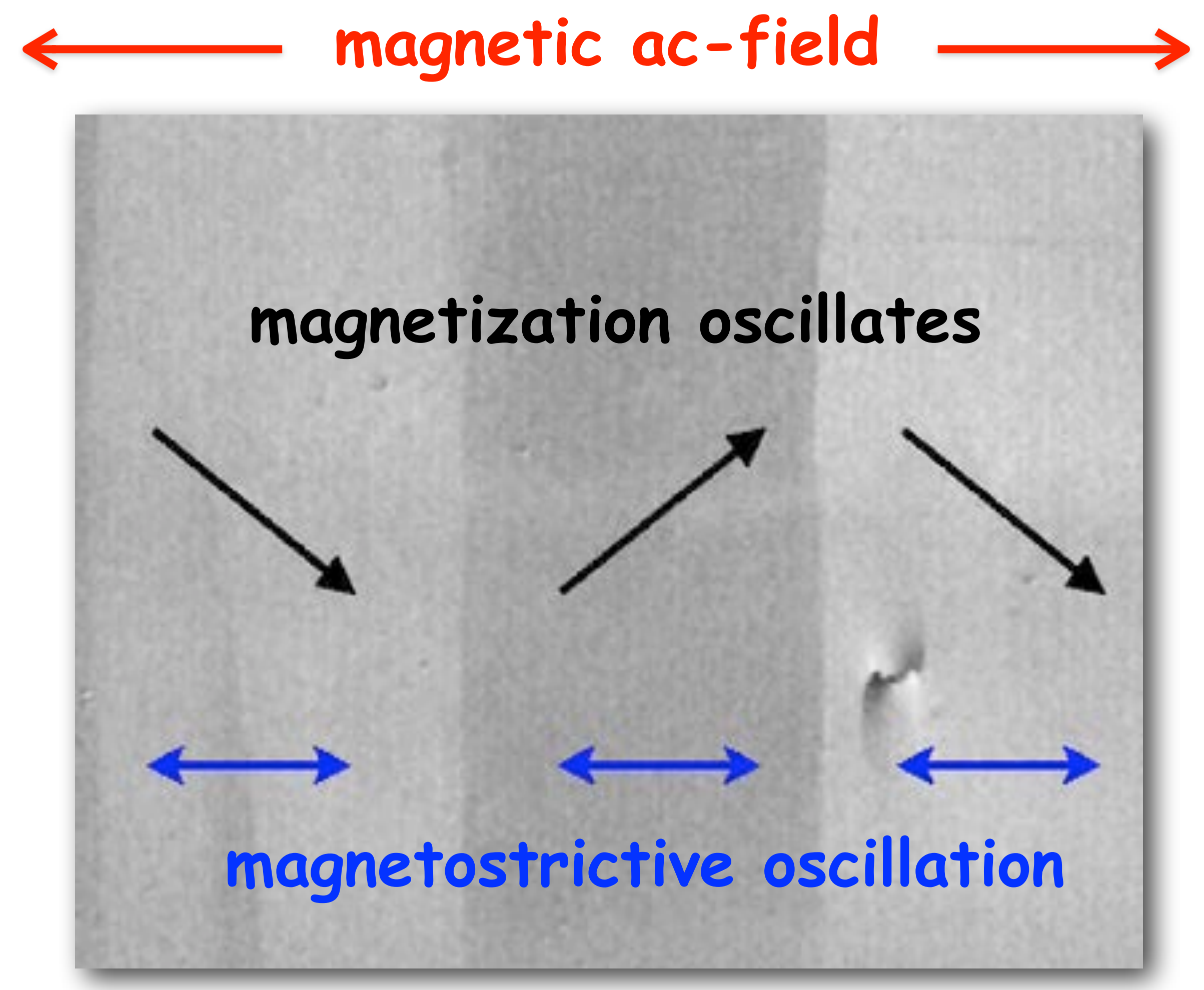
Magneto-acustic article surveillance

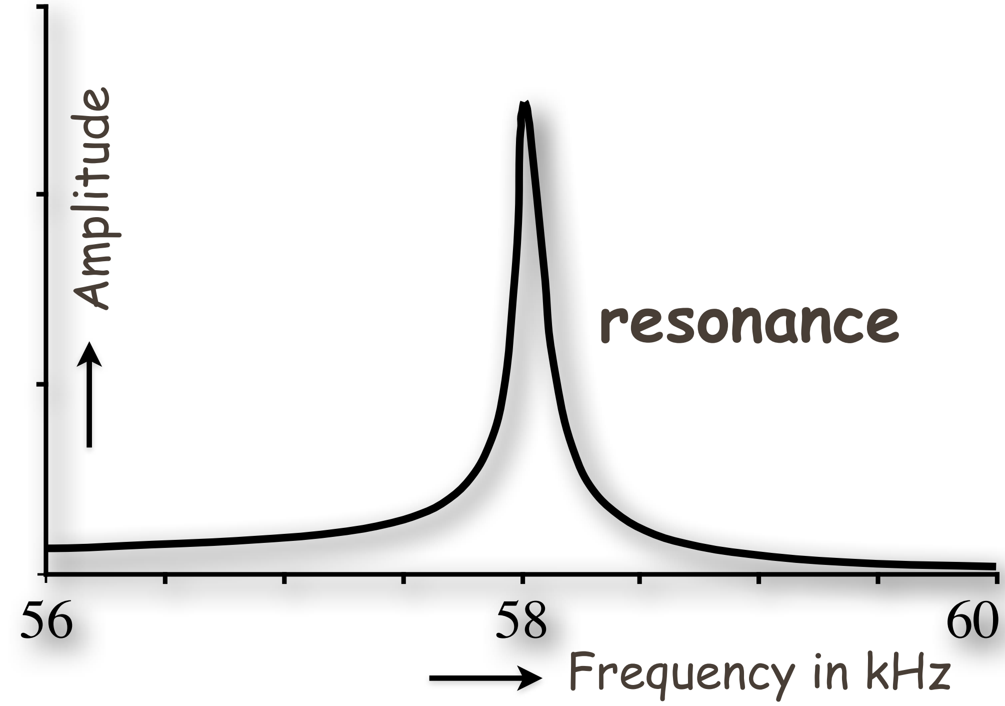




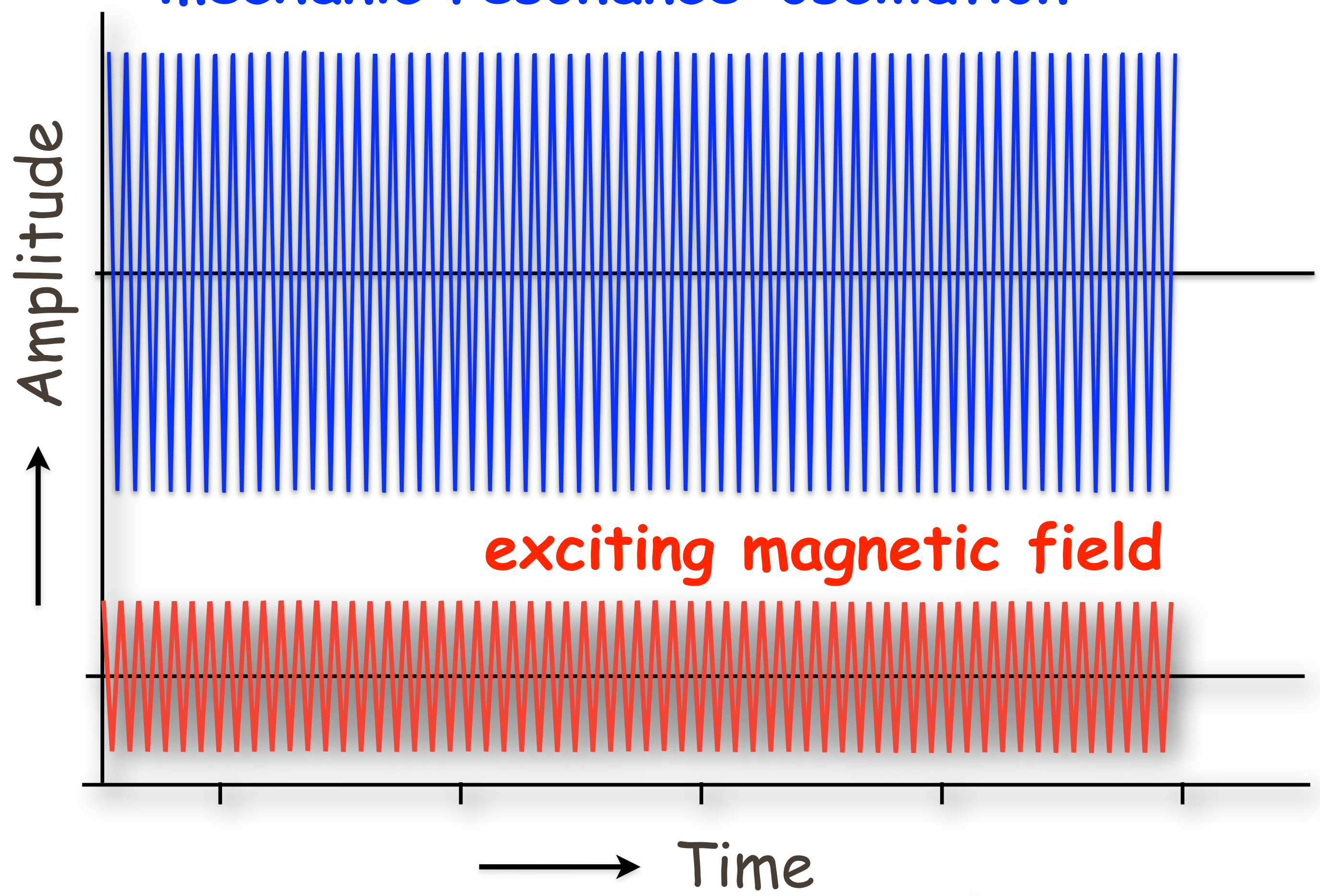
Magneto-acustic article surveillance

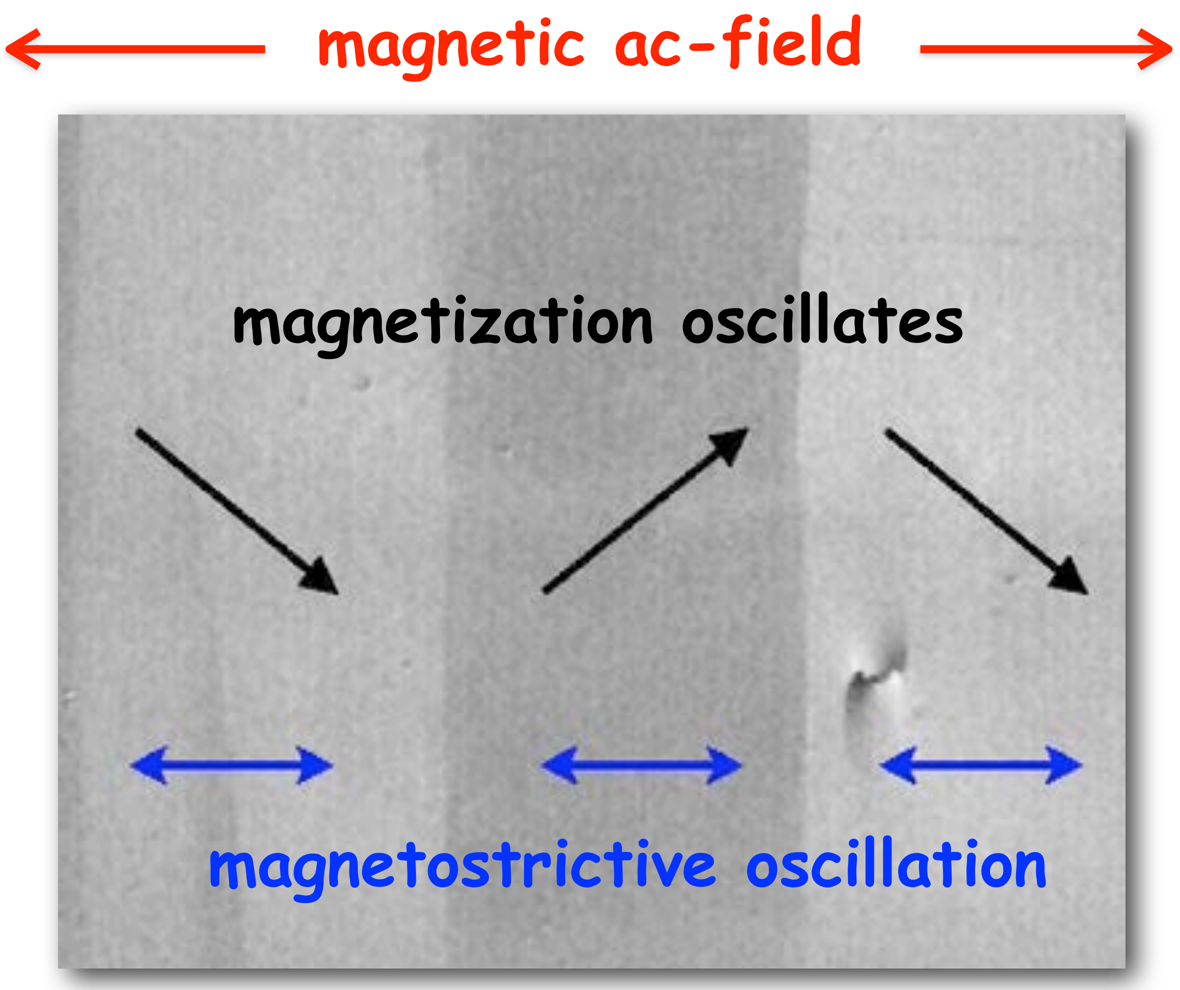


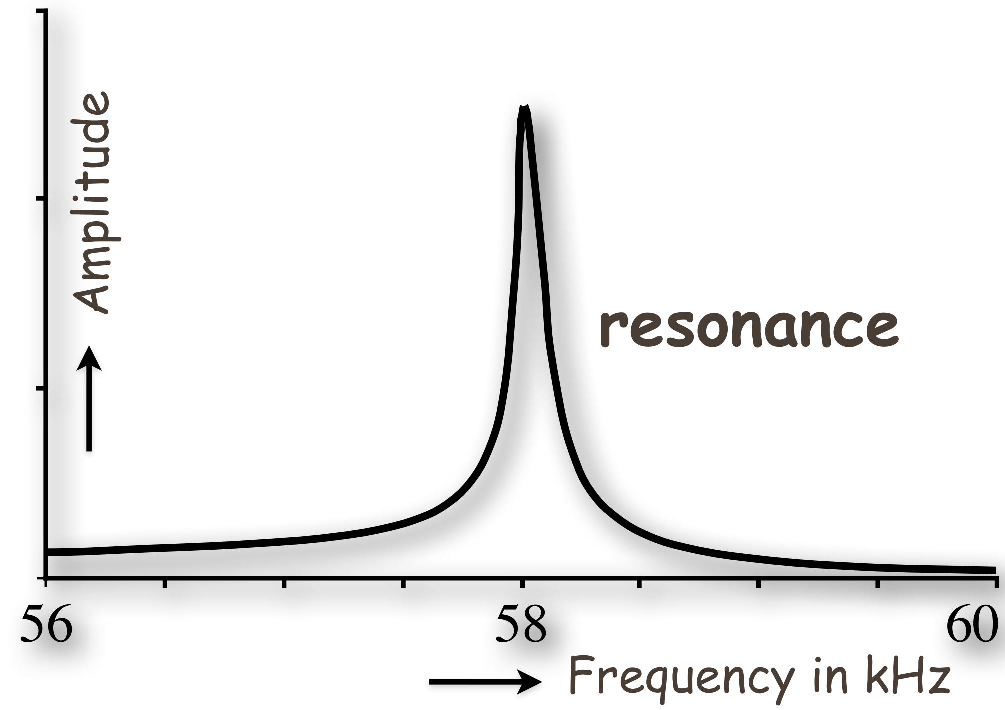




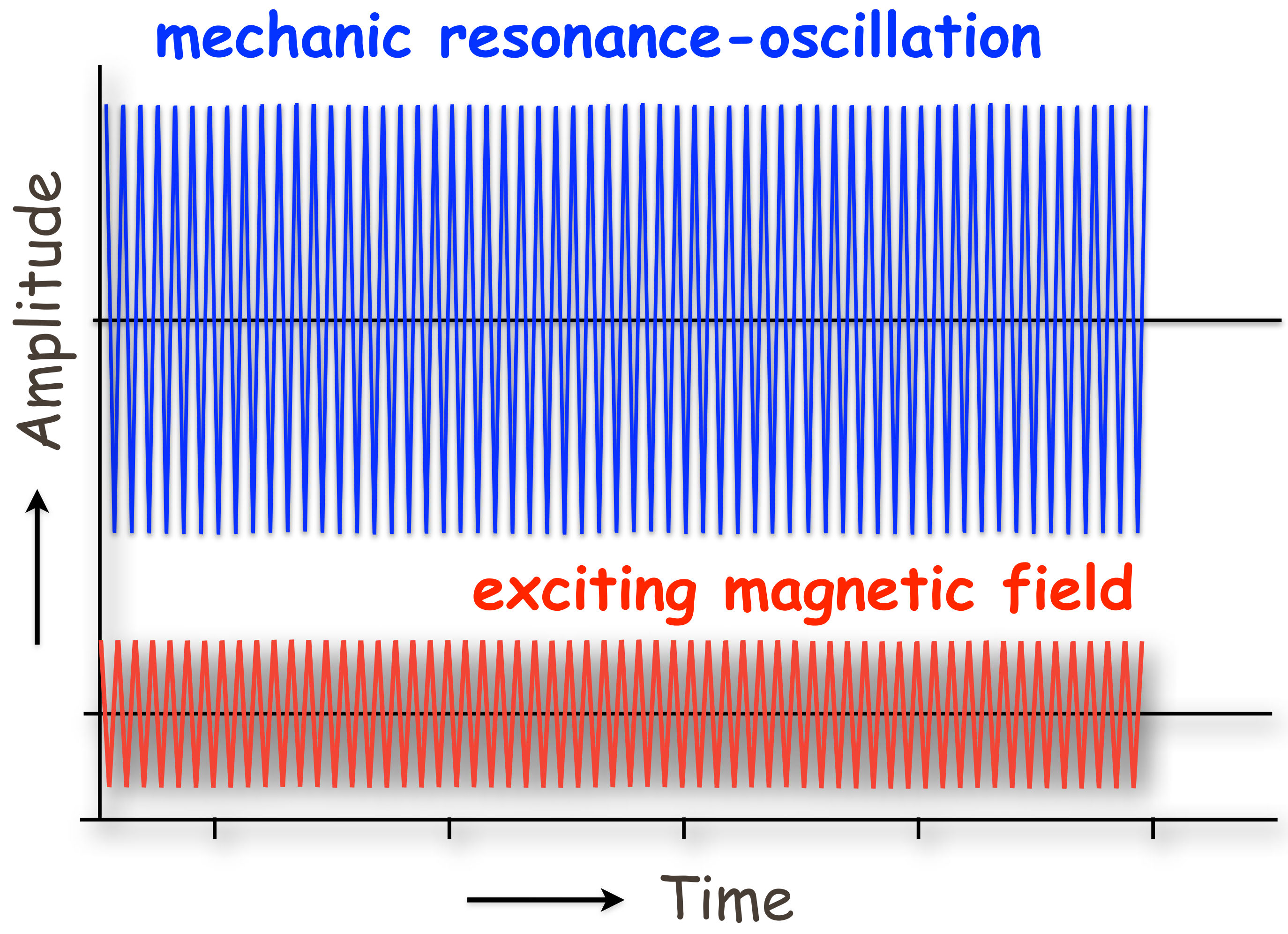
Magneto-acustic article surveillance

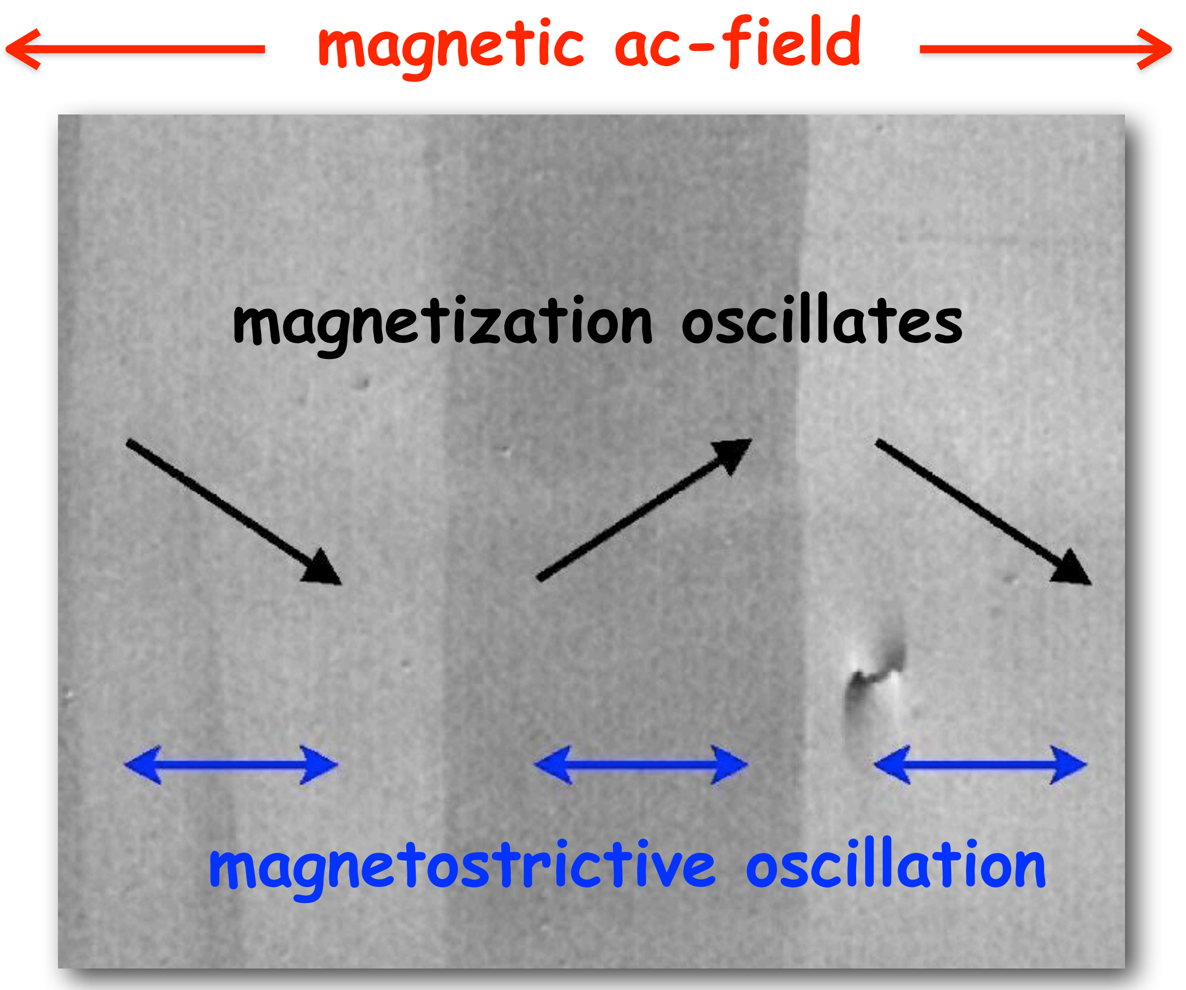




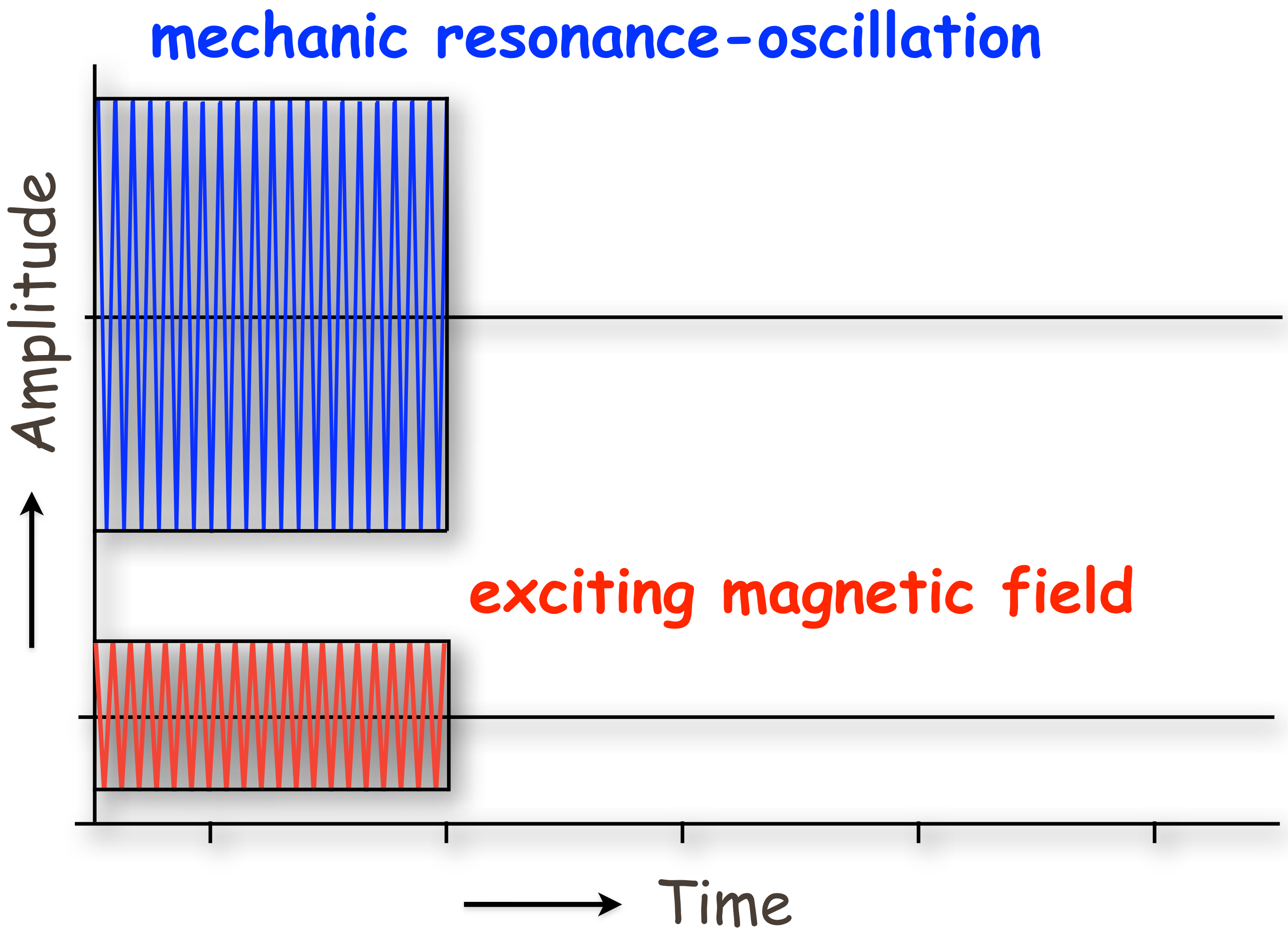


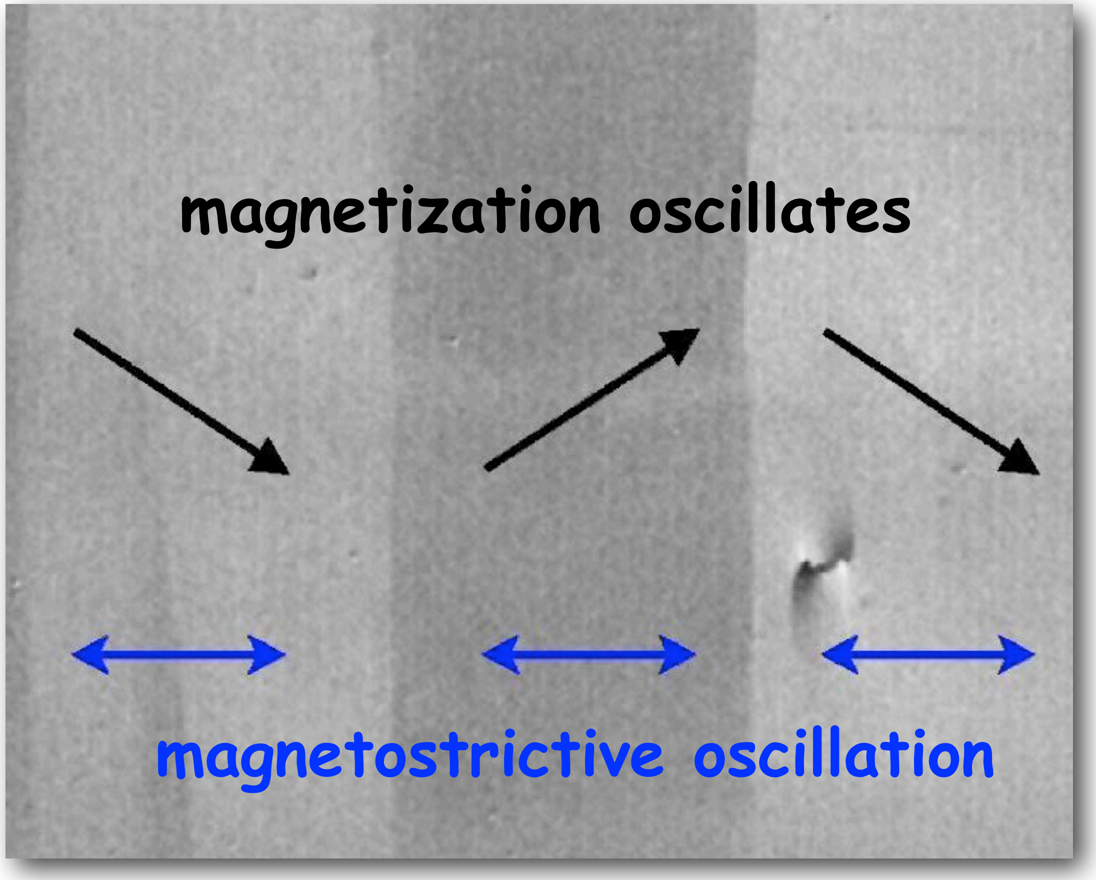
Magneto-acustic article surveillance



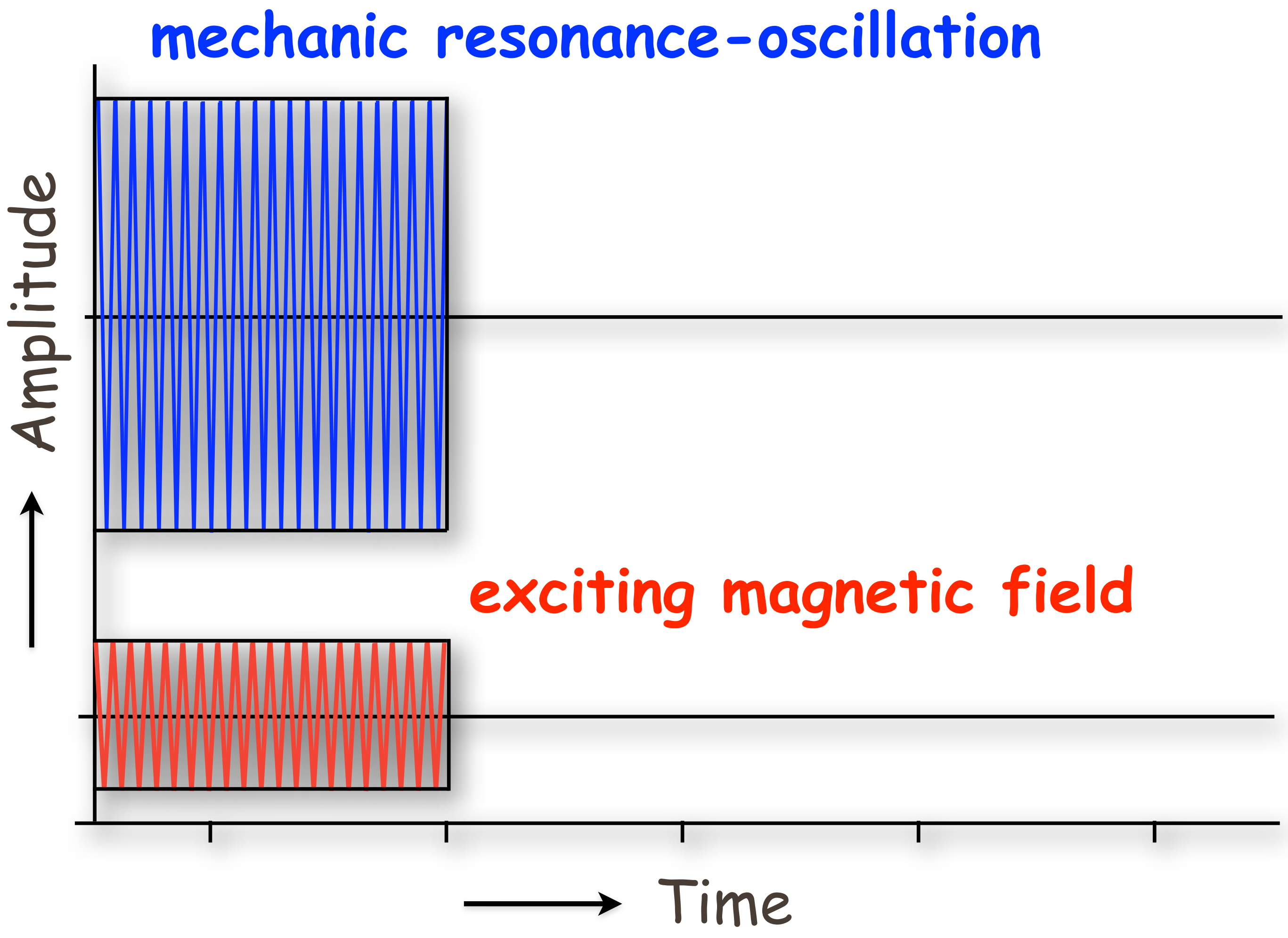


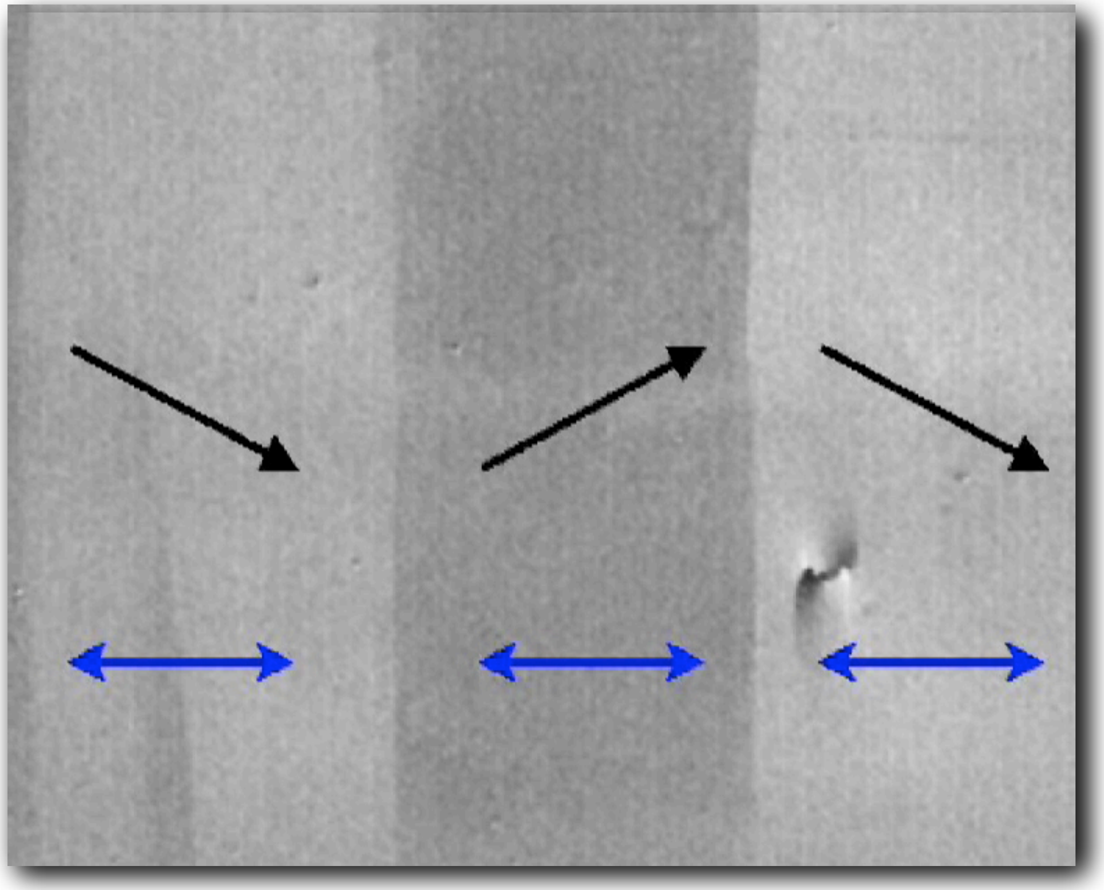
Magneto-acustic article surveillance



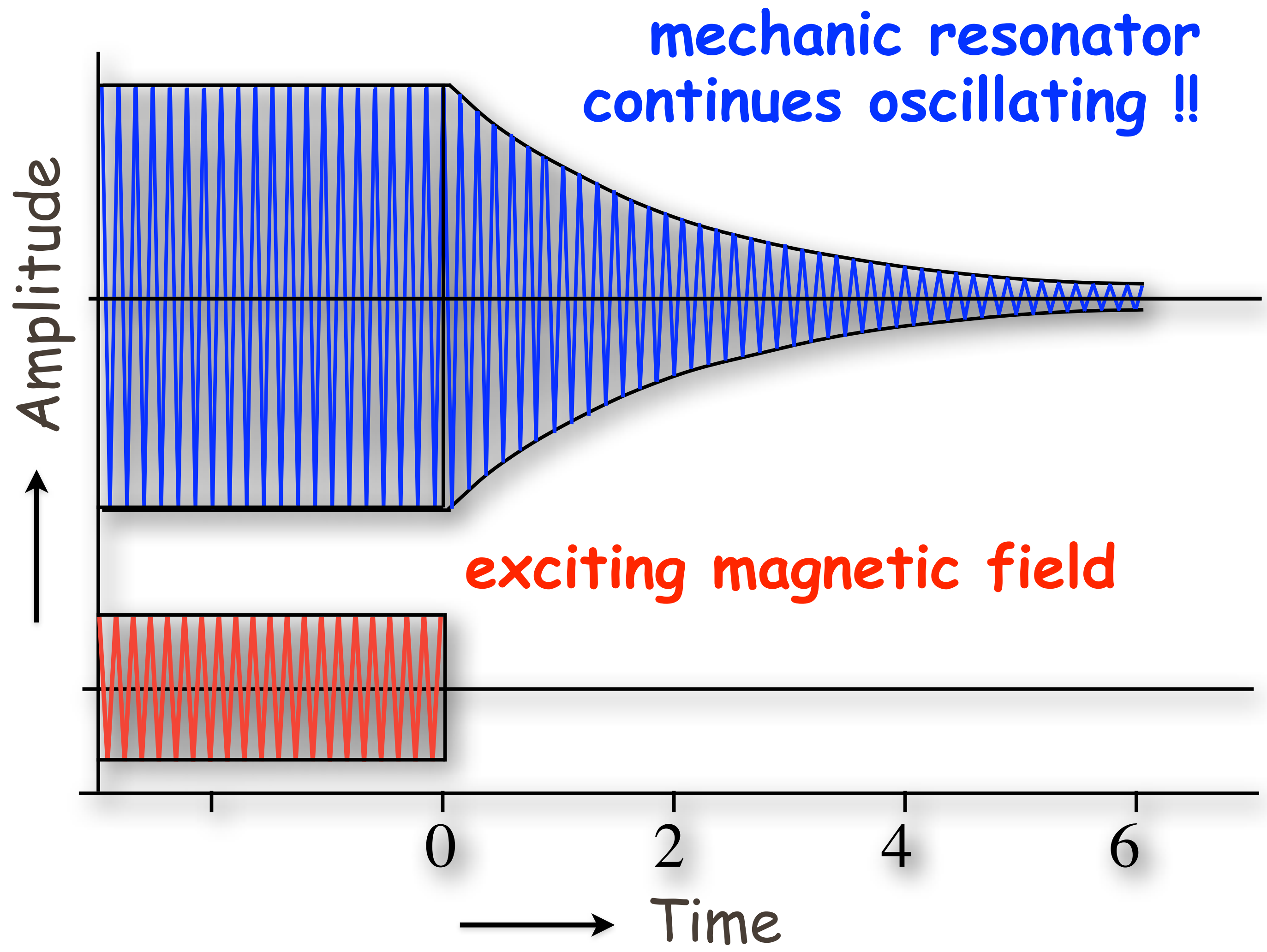


Magneto-acustic article surveillance

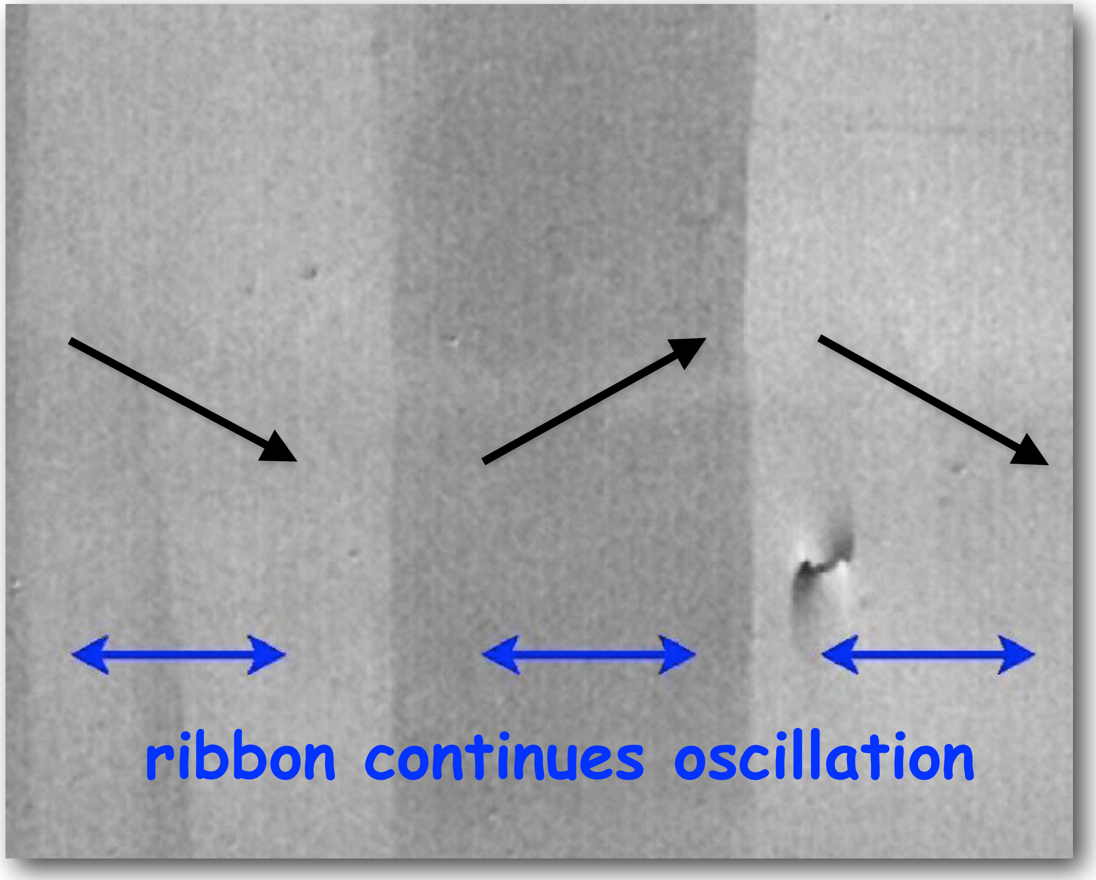




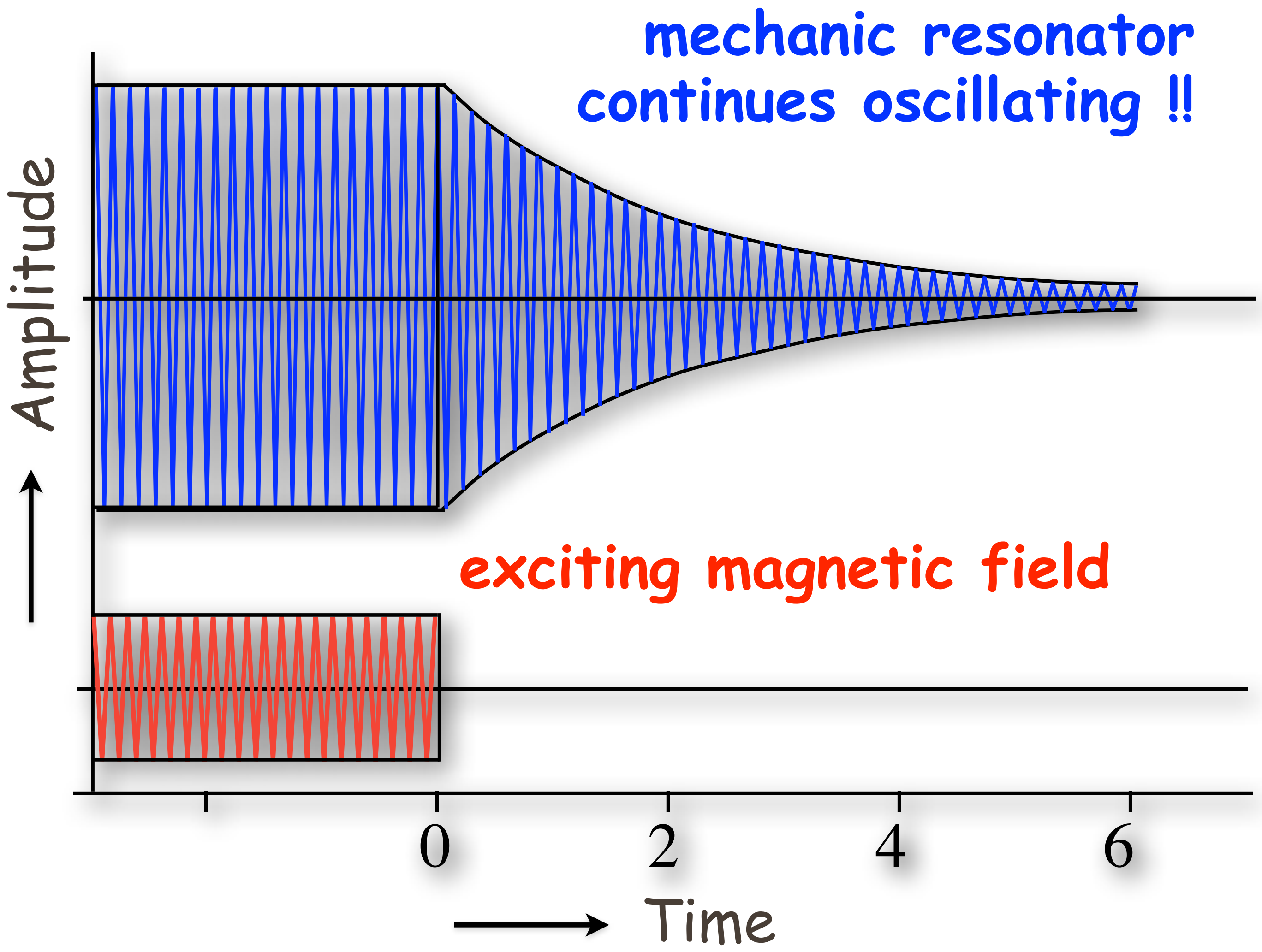
Magneto-acustic article surveillance



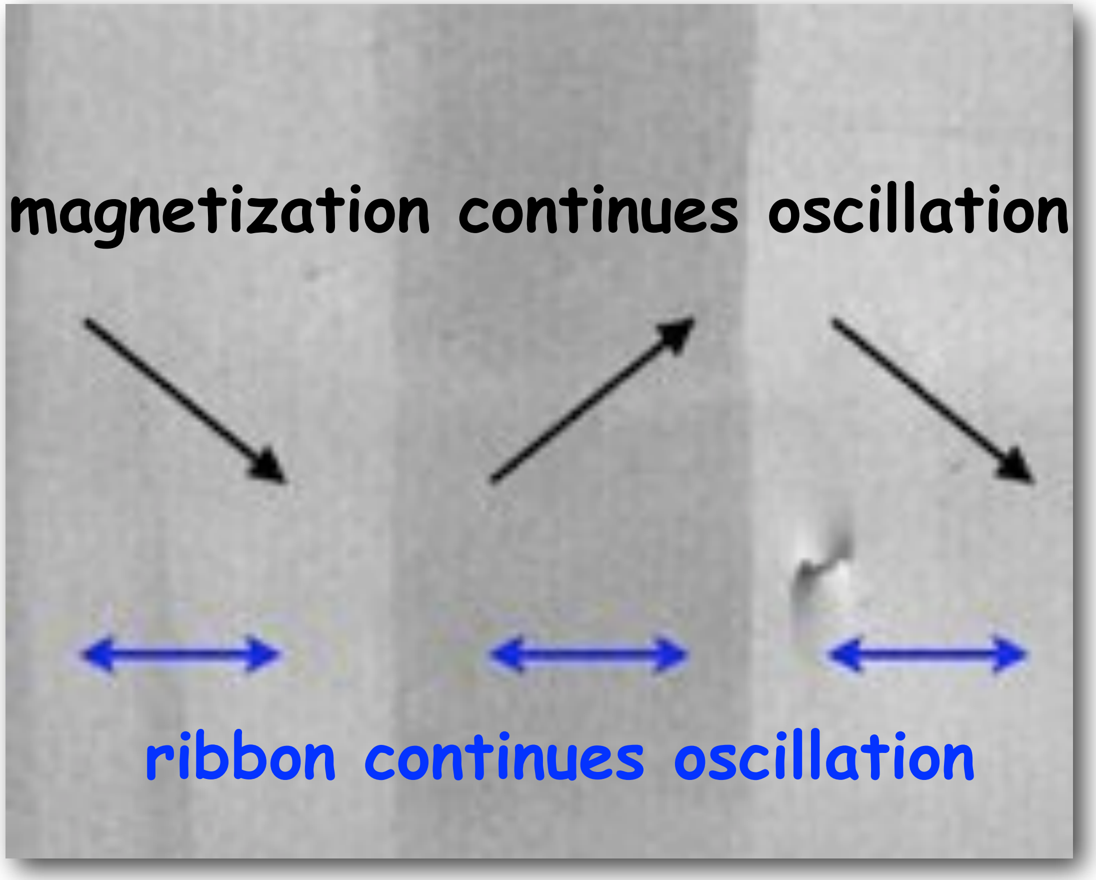
after switching-off pulse



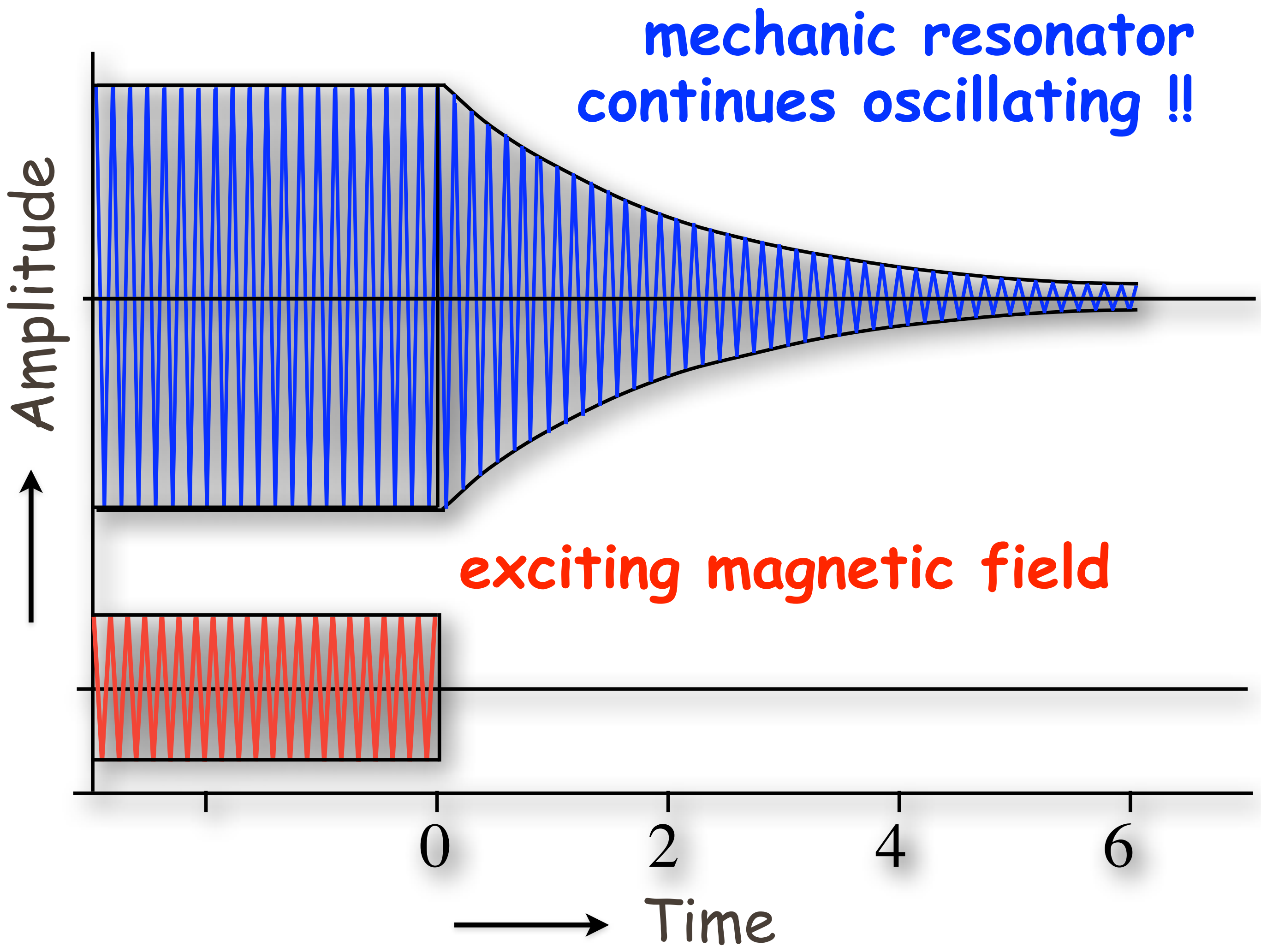
Magneto-acustic article surveillance



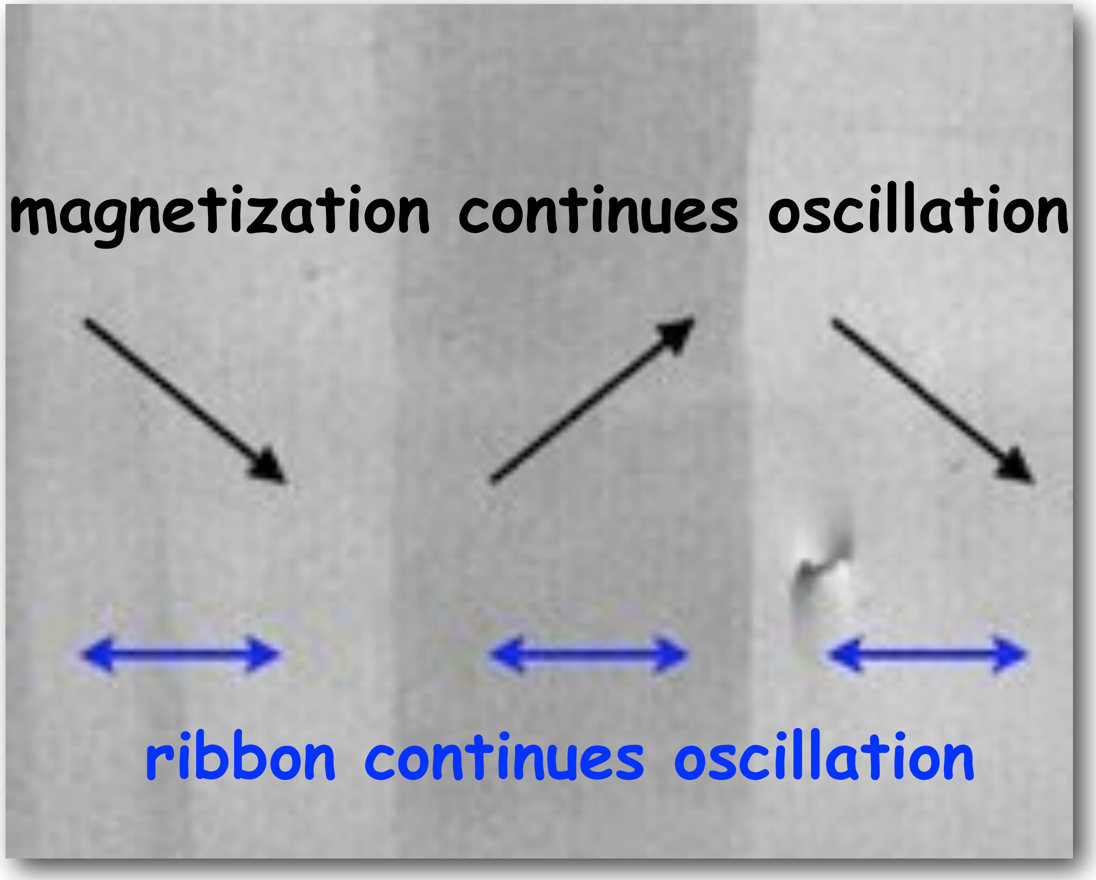
after switching-off pulse



Magneto-acustic article surveillance



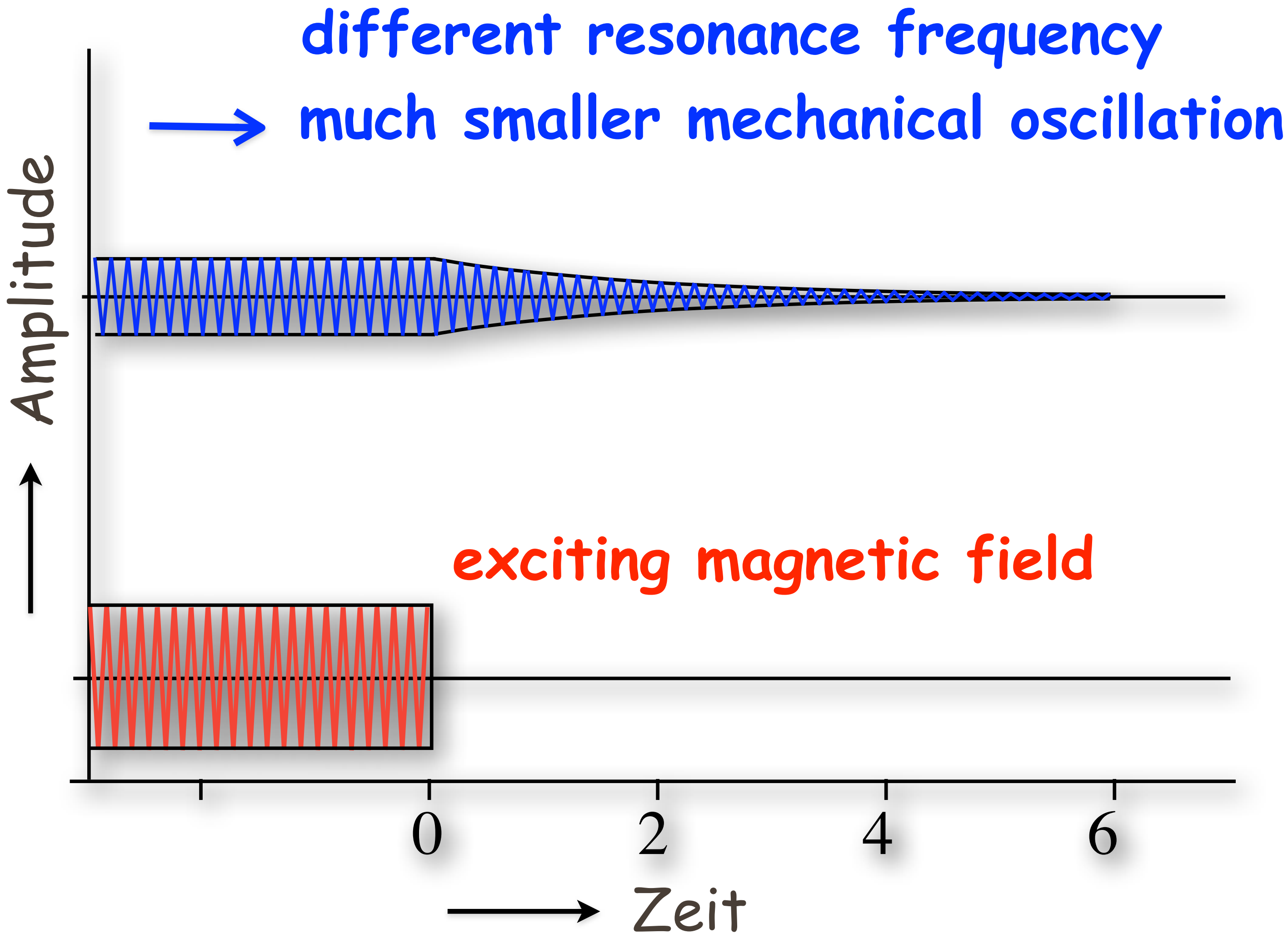
after switching-off pulse

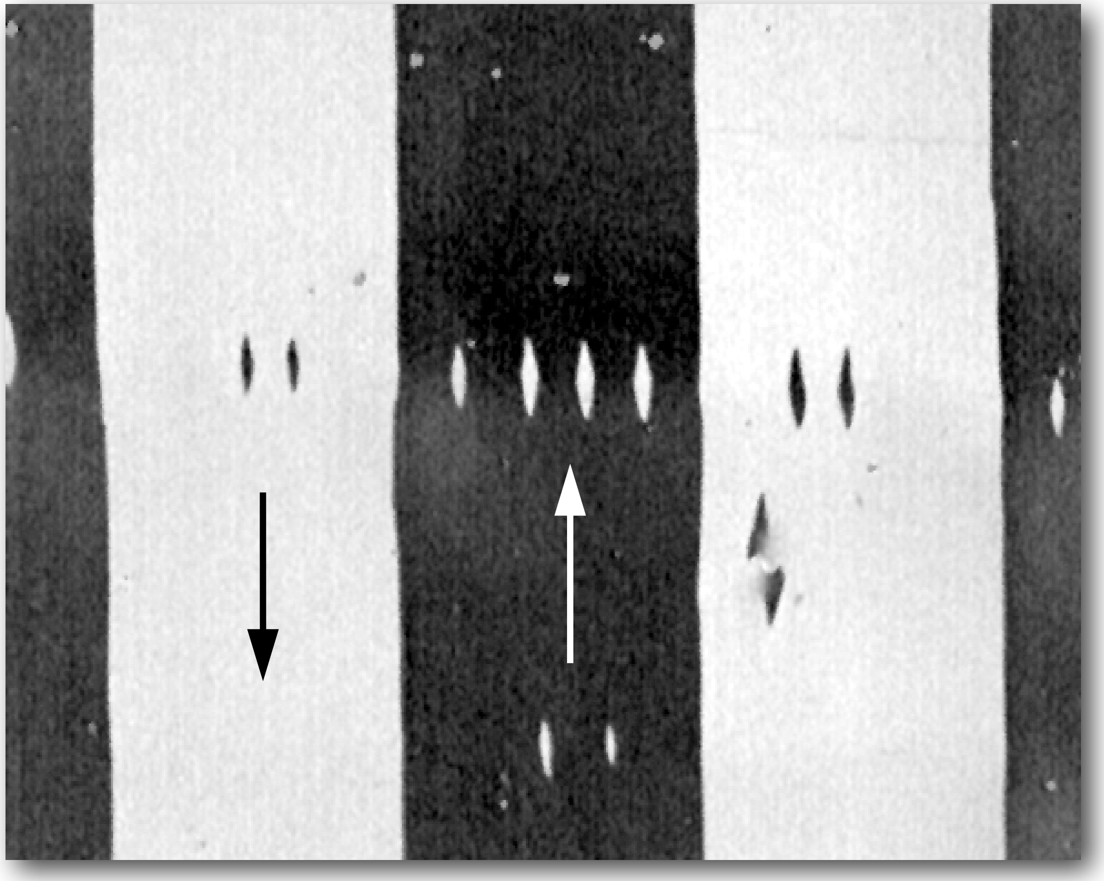


Induction-signal after switching-off field pulse

Alarm

Magneto-acustic article surveillance

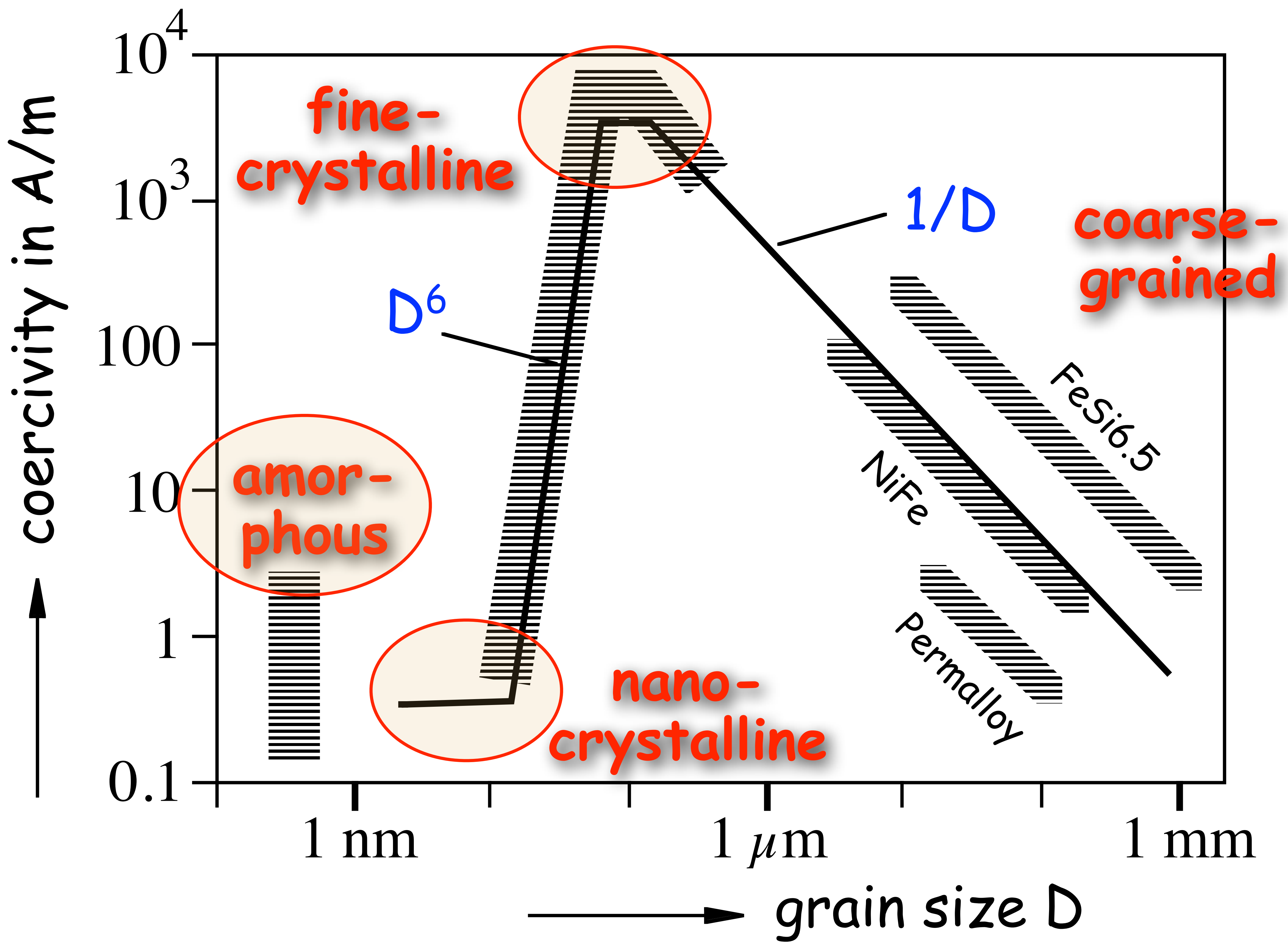




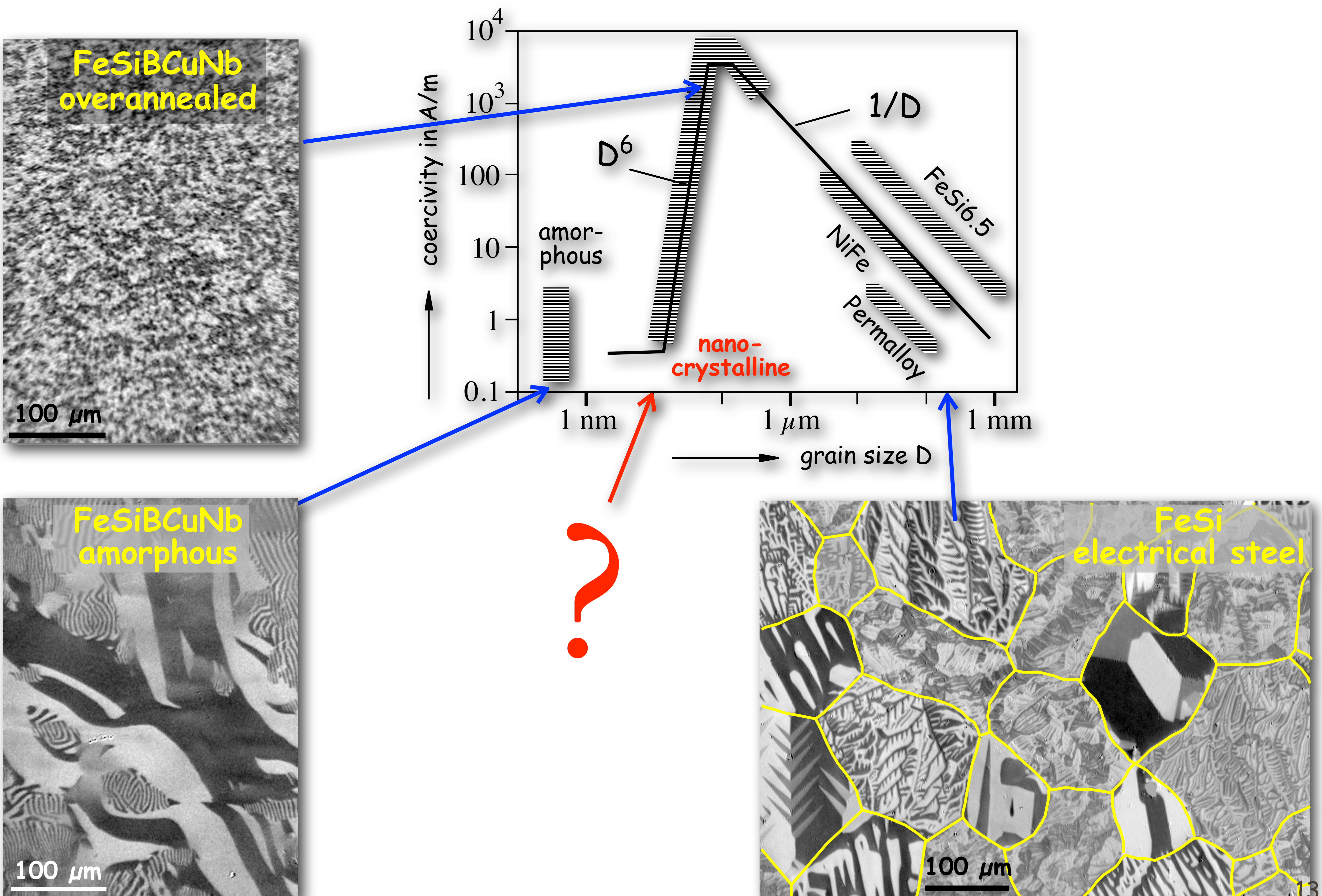
after deactivation

Soft magnets,
Example 5:
Nanocrystalline ribbons

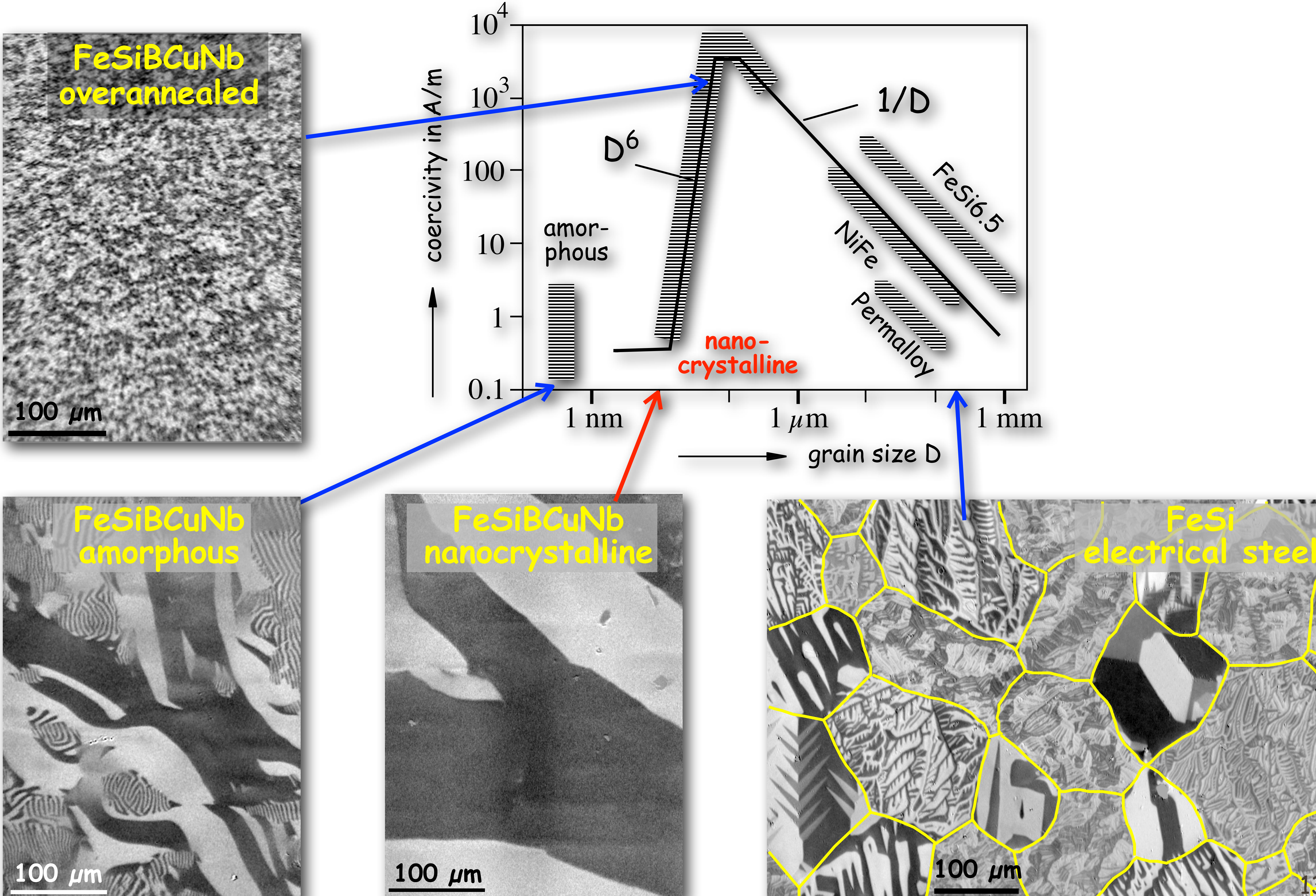
Grain size dependence of coercivity



Grain size dependence of coercivity



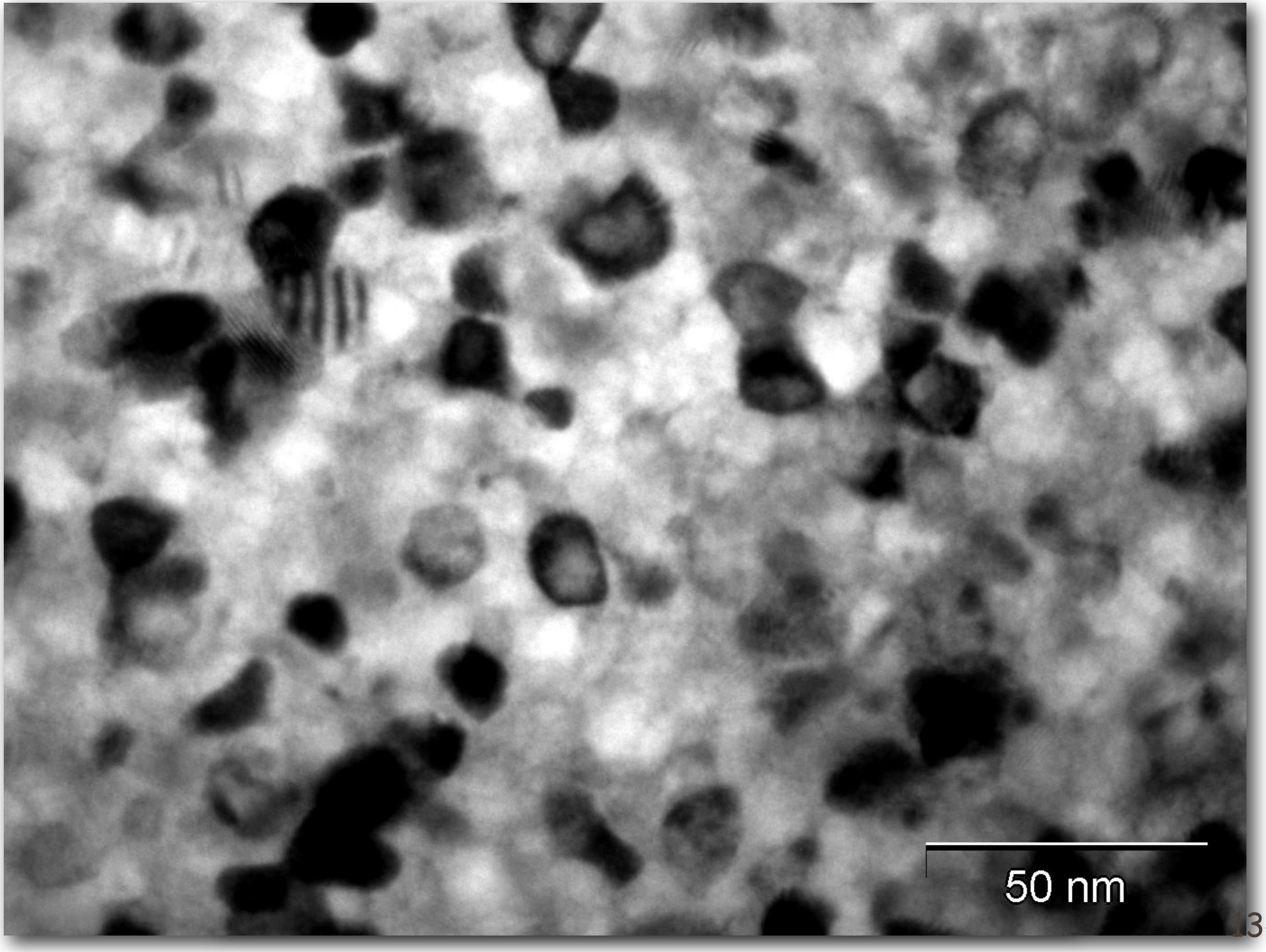
Grain size dependence of coercivity



Nanocrystalline ribbons

Nanocrystalline ribbon $Fe_{73}Si_{16}B_7Cu_1Nb_3$
(Finemet, Vitroperm)

rapid quenching
↓
amorphous ribbon
↓ 550°C
nanocrystalline ribbon



Nanocrystalline ribbons

Nanocrystalline ribbon $Fe_{73}Si_{16}B_7Cu_1Nb_3$
(Finemet, Vitroperm)

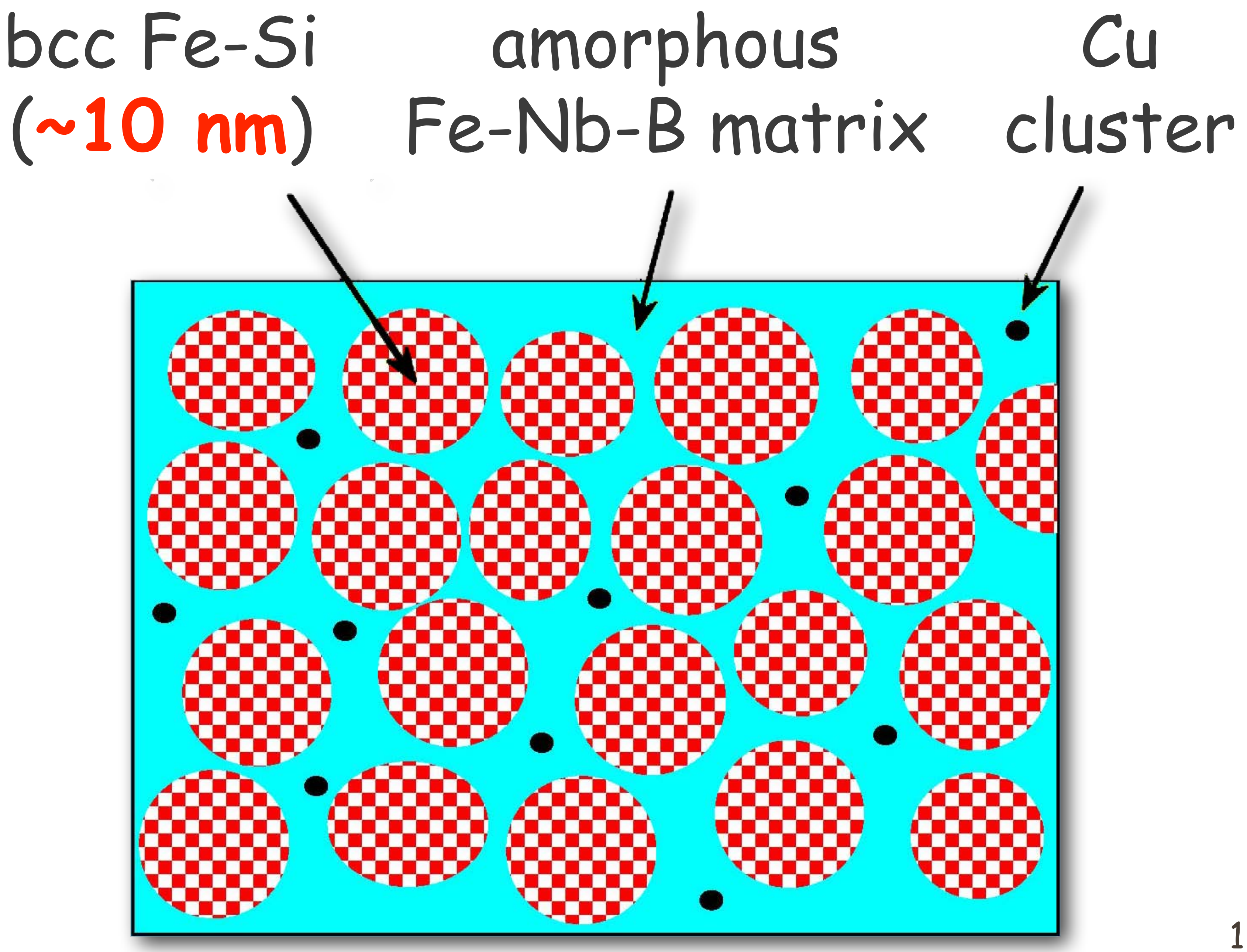
rapid
quenching

↓

amorphous
ribbon

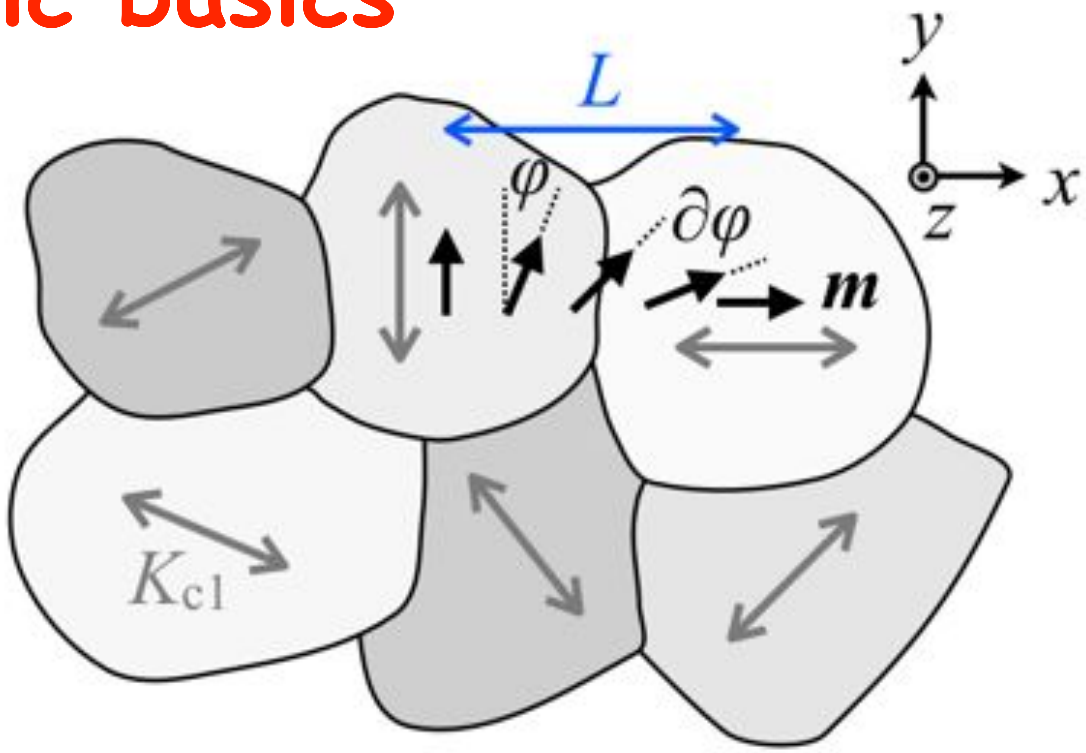
↓ 550°C

nanocrystalline
ribbon



Nanocrystalline ribbons

Micromagnetic basics



Exchange stiffness energy:

$$E_{ex} = A \int (\mathbf{grad}\,\boldsymbol{m})^2 \, dV$$

One-dimensional case:

$$\varphi = kx$$

$$m_1 = \sin\varphi,\; m_2 = \cos\varphi,\; m_3 = 0$$

$$(\mathbf{grad}\,\mathbf{m})^2 = (\partial m_1/\partial x)^2 + (\partial m_1/\partial y)^2 + (\partial m_1/\partial z)^2 + \ldots\ldots + (\partial m_3/\partial z)^2 = k^2$$

With $\partial\varphi/\partial x = k$:

$$e_{ex} = A\,(\mathbf{grad}\,\boldsymbol{m})^2 = A\,(\partial\varphi/\partial x)^2$$

For $L = 1$ mm:

$$e_{ex} = A(\partial\varphi/\partial x)^2 = A[(\pi/2)/0.001\,\text{m}]^2 \approx 2.5 \cdot 10^{-5}\ \text{J/m}^3$$ → negligible

For $L = 10$ nm:

$$e_{ex} = 2.5 \cdot 10^{+5}\ \text{J/m}^3$$ → exchange energy exceeds maximum anisotropy energy

$$e_{Ku} \approx K_{c1} \sin^2 90^\circ = 4.7 \cdot 10^4\ \text{J/m}^3$$

Nanocrystalline ribbons

Micromagnetic basics

On scale of some 10 nm:
Nature tends to diminish exchange energy by aligning magnetization vectors along a common direction even though this will locally cause anisotropy energy

Critical scale for this effect to occur:

$e_{ex} = A(\partial\varphi/\partial x)^2 \longrightarrow$ e_{ex} scales as A/L^2 if magnetization changes its orientation on the length scale L

For $A/L^2 > K_1$, the exchange energy would exceed the local anisotropy energy, which is the case on a scale smaller than :

$$L_{ex} = \sqrt{A/K_1}$$

Nanocrystalline ribbons

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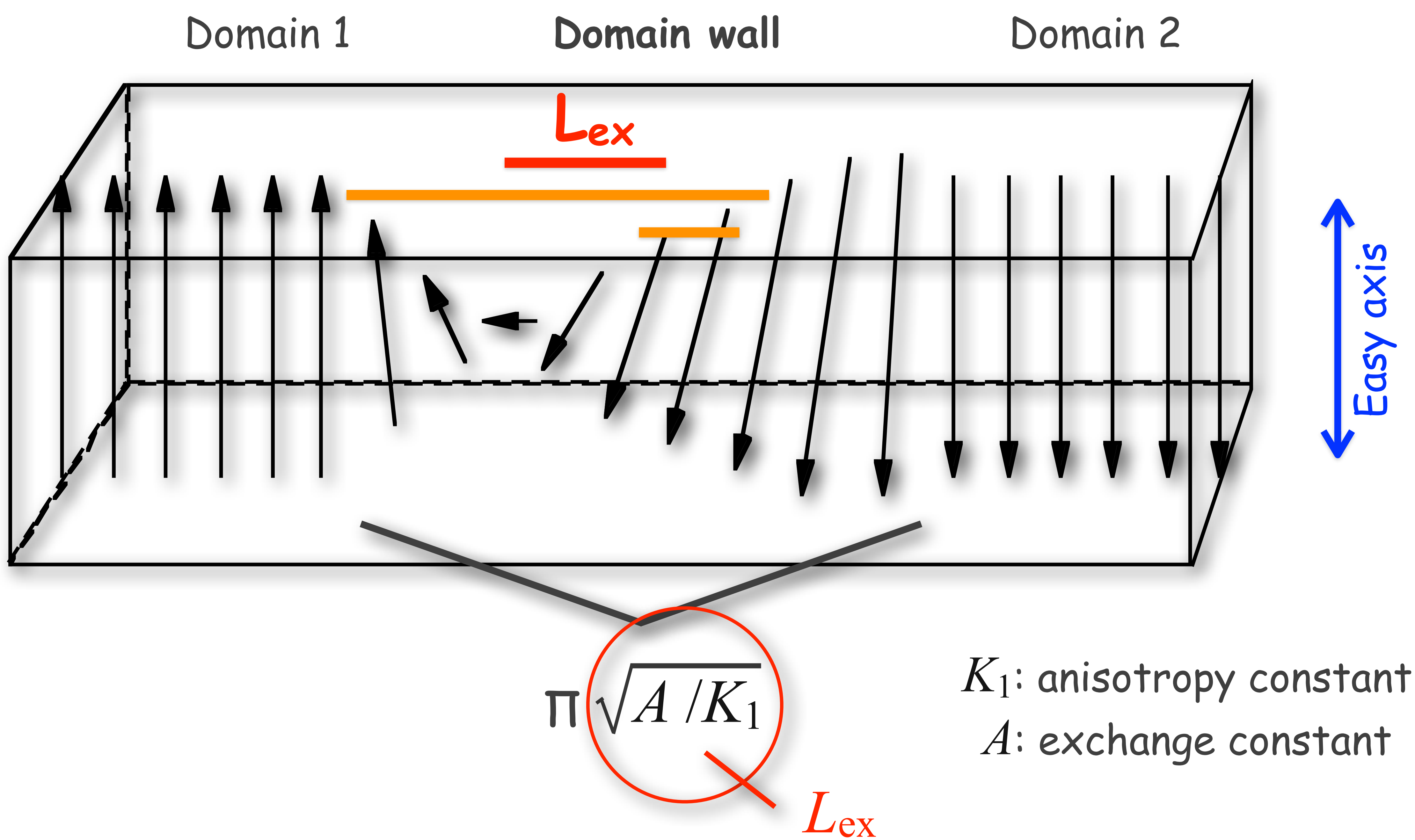
Ferromagnetic correlation length (exchange length)

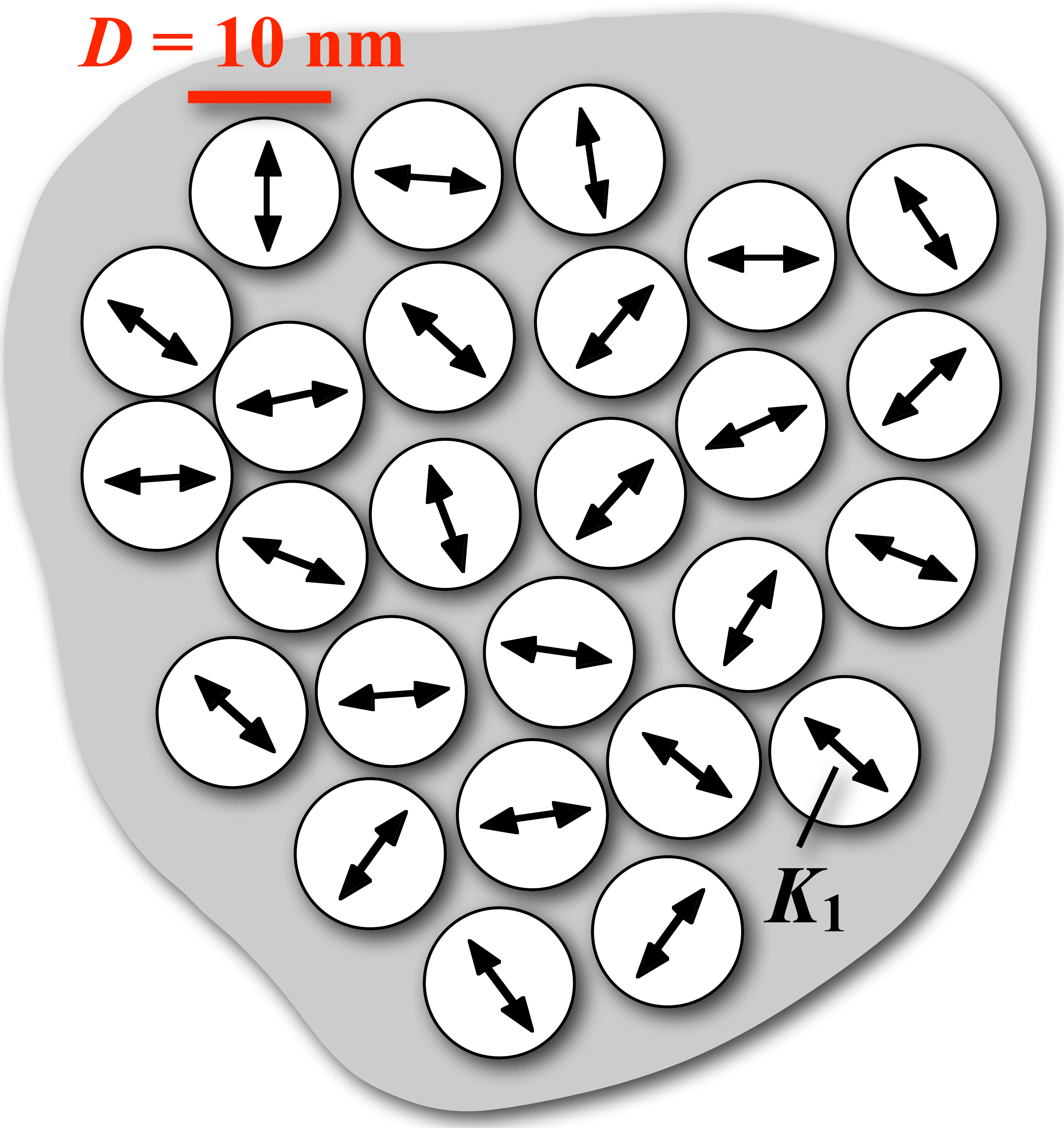
Nanocrystalline ribbons

Micromagnetic basics



L_{ex} : minimum scale for appreciable variation of magnetization (parallel moments for $L < L_{ex}$)

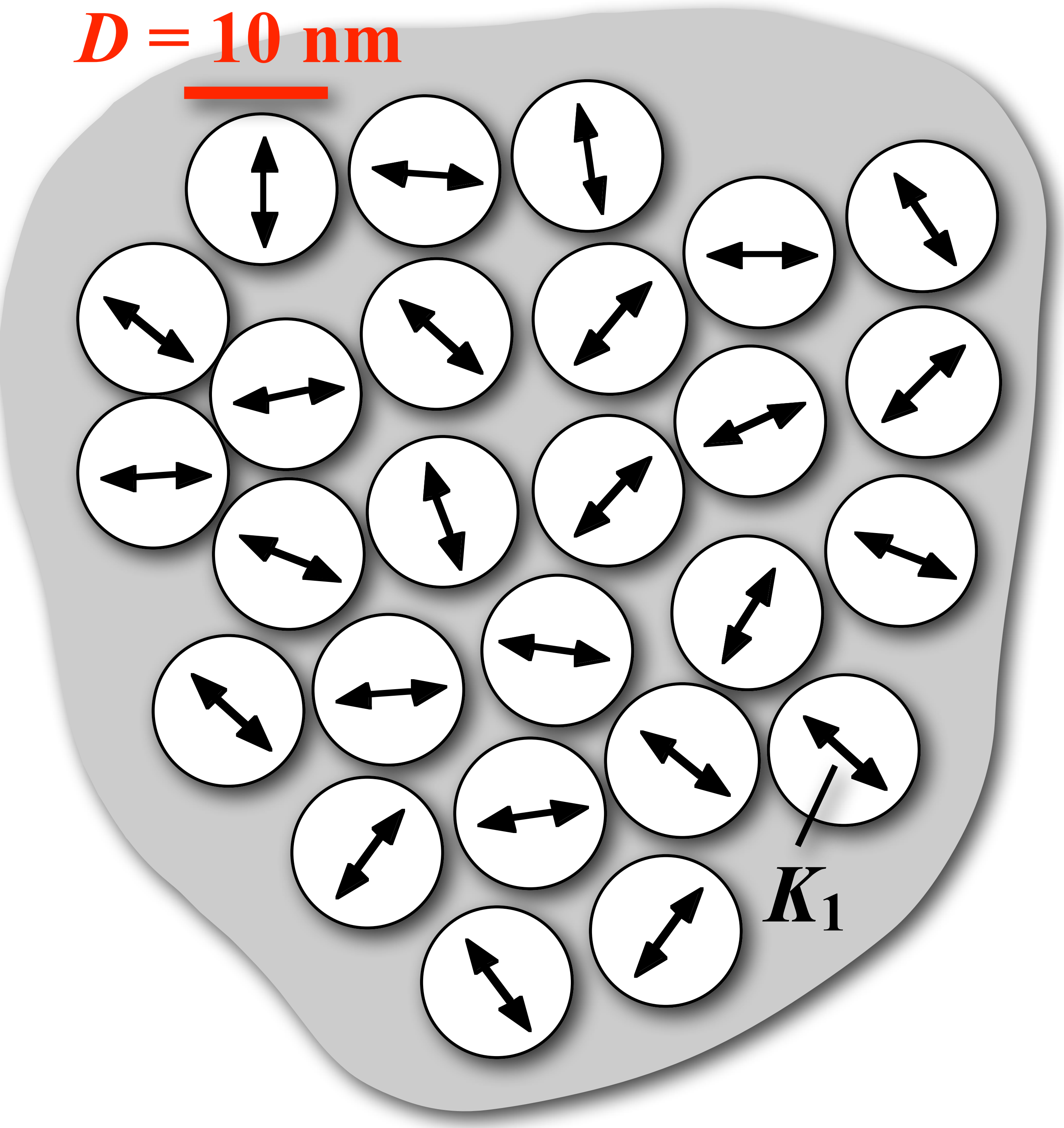
Nanocrystalline ribbons



Nanocrystalline ribbons

$Fe_{80}Si_{20}$:

$$K_1 = 8 \text{ kJ/m}^3$$
$$A = 10^{-11} \text{ J/m}$$



Nanocrystalline ribbons

$Fe_{80}Si_{20}$:

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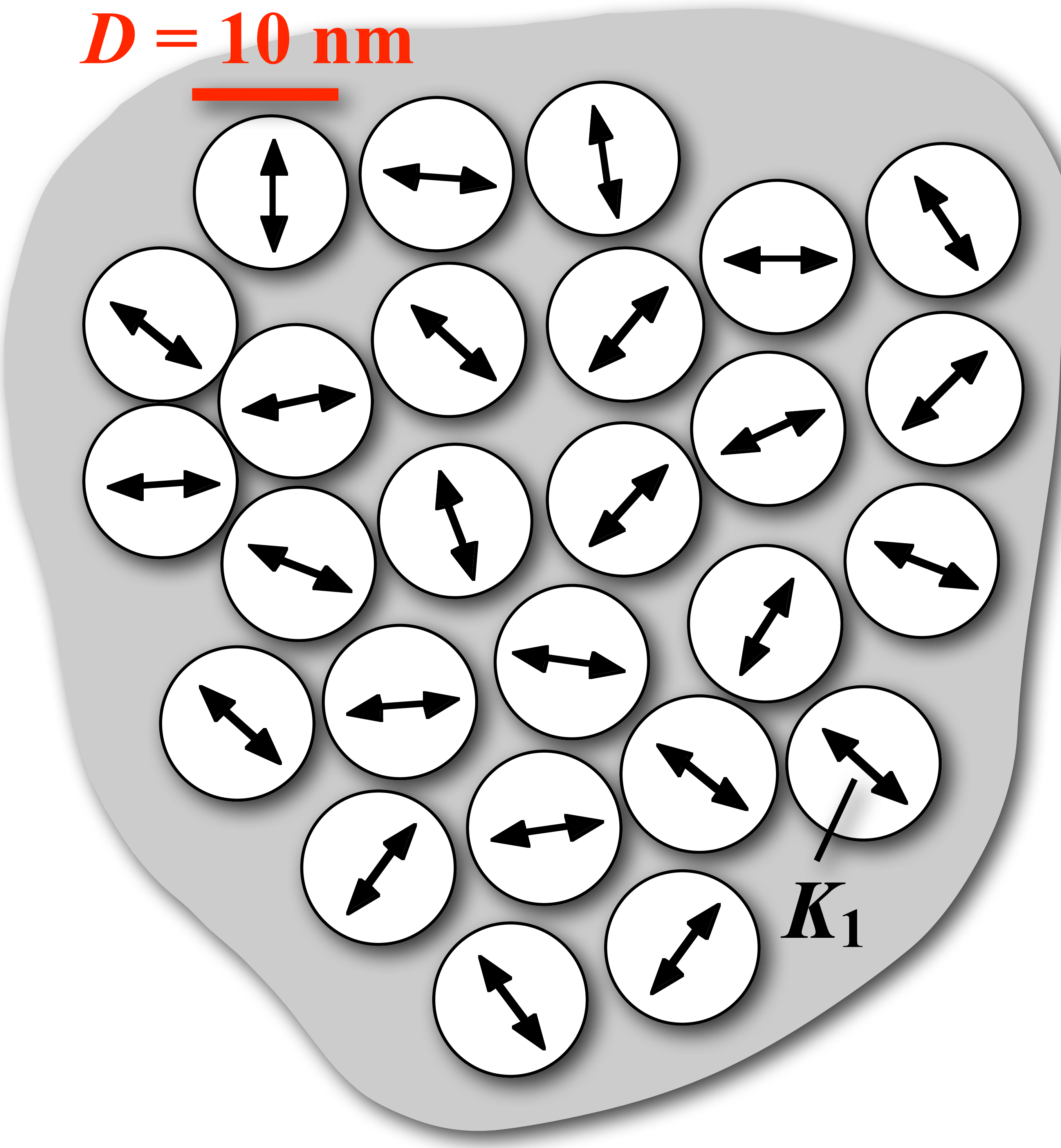
$\longrightarrow L_{ex} = \sqrt{A/K_1} =$ 35 nm

$\longrightarrow D < L_{ex}$



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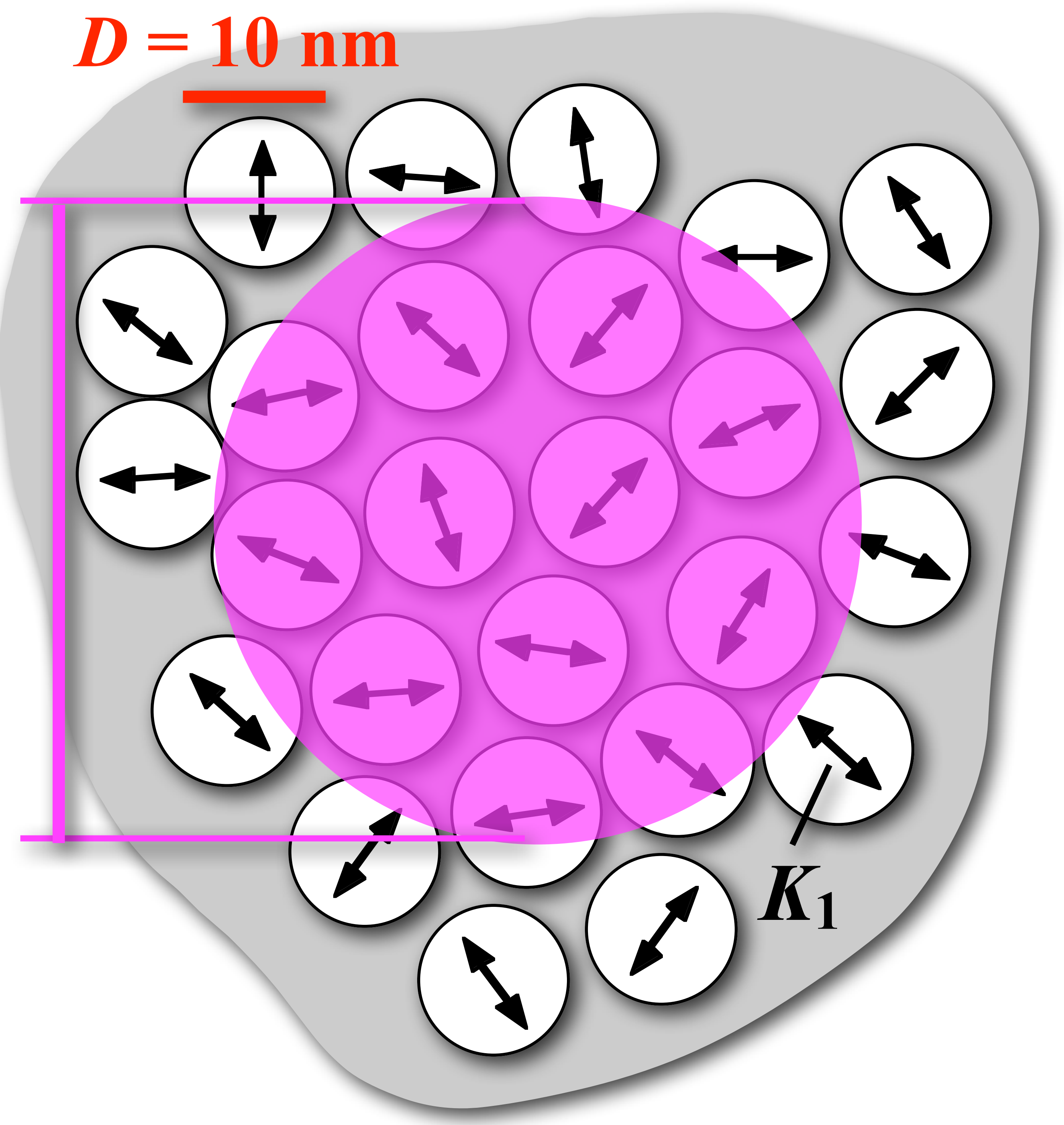

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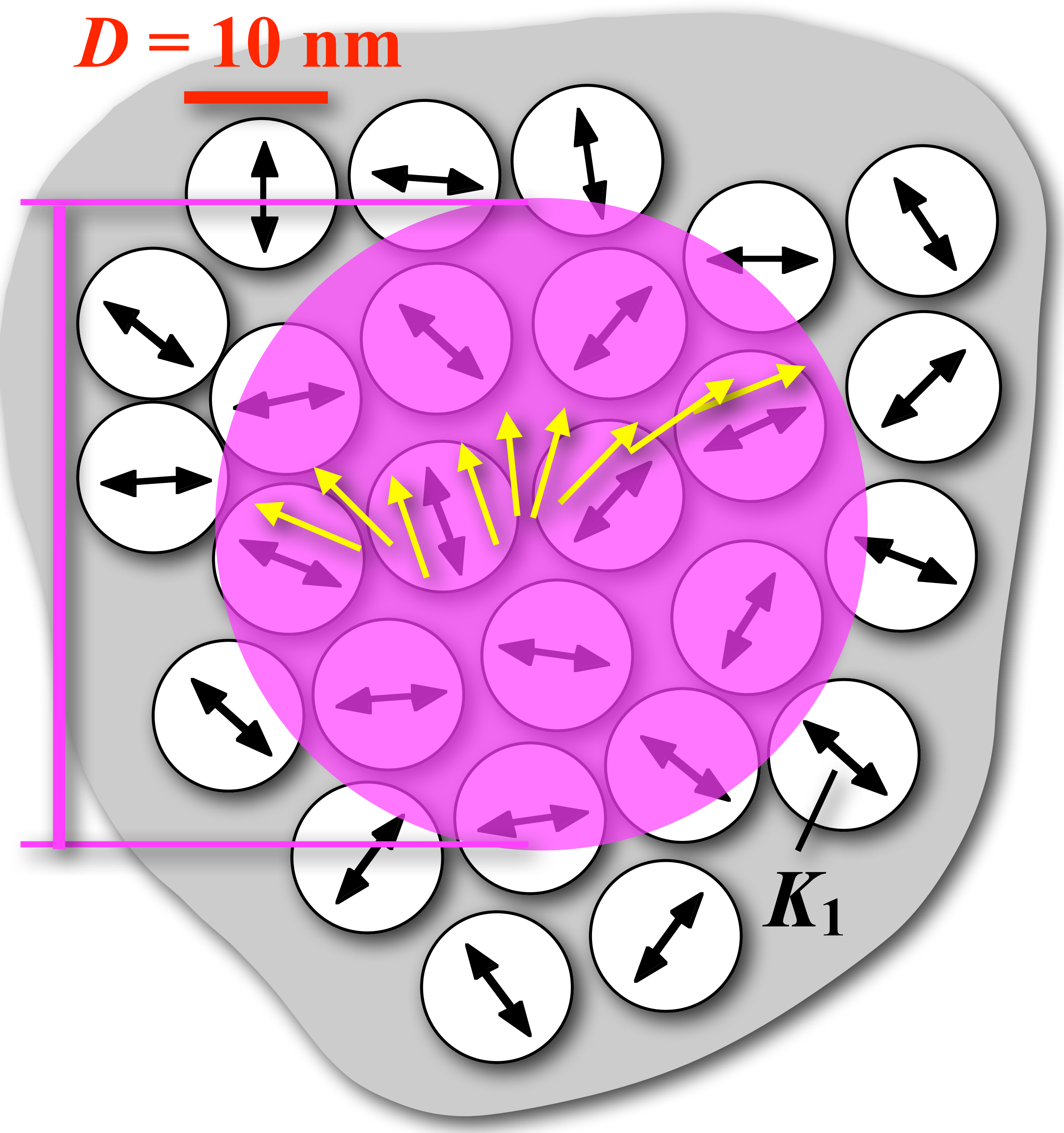

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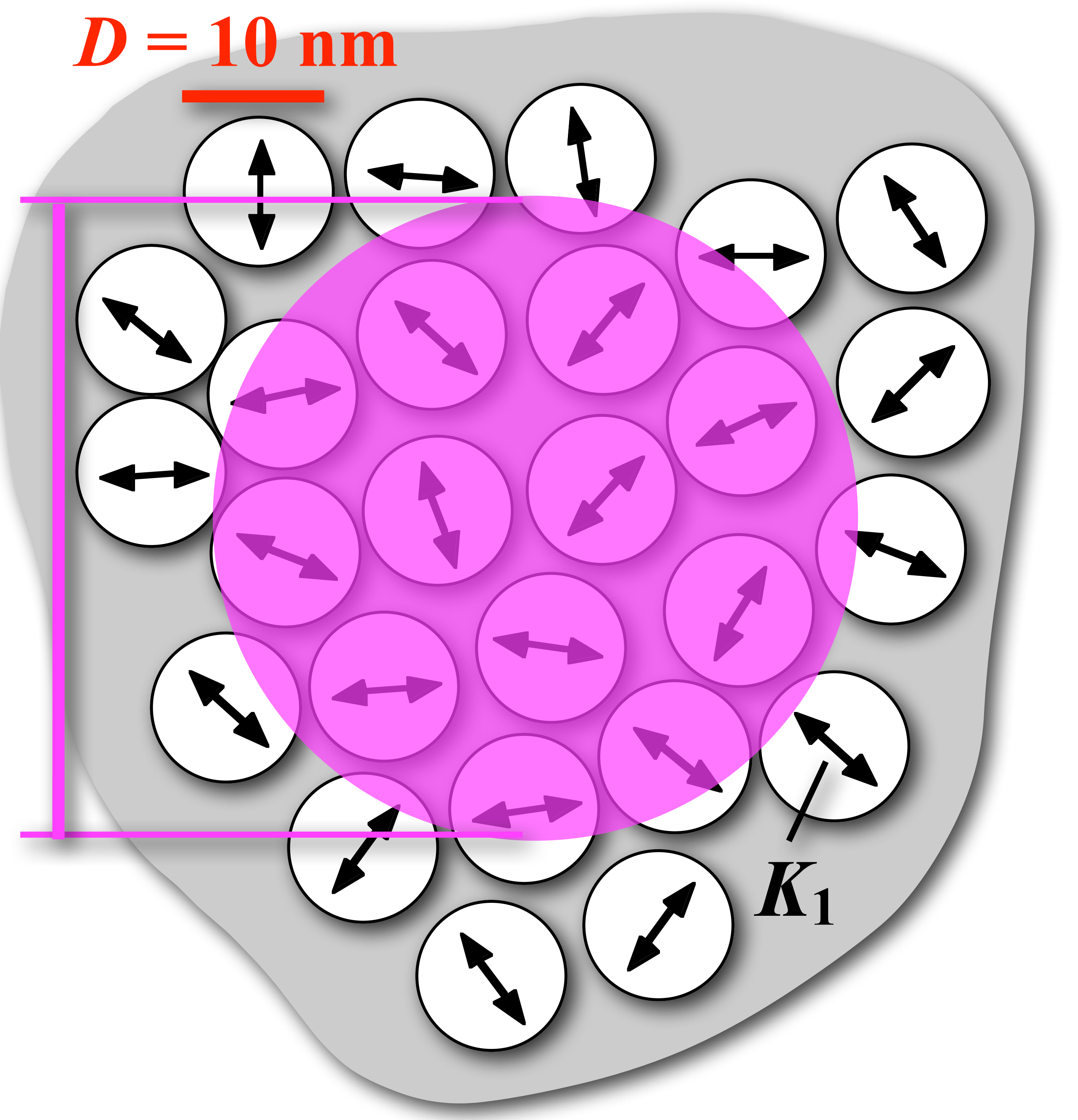

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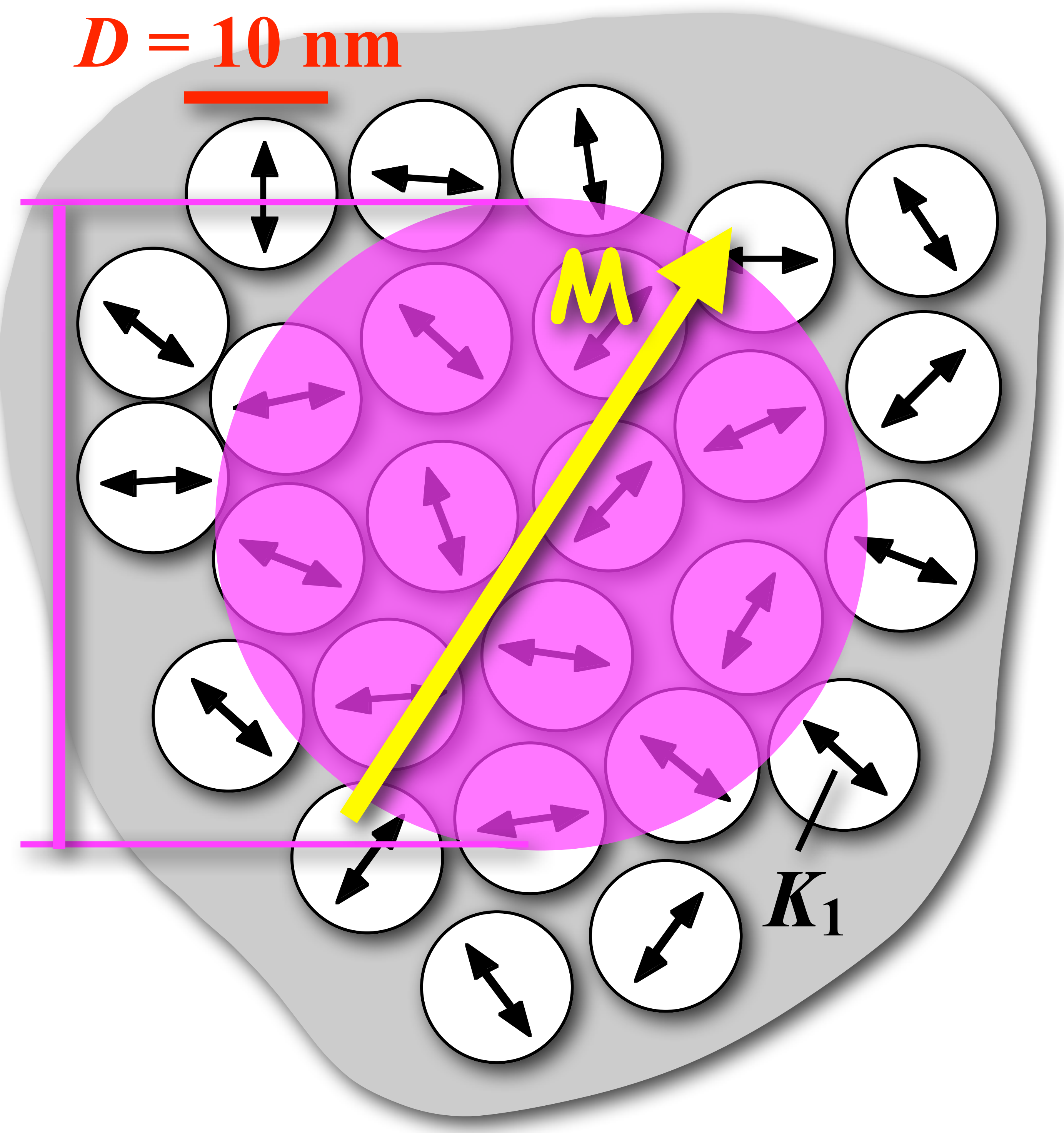

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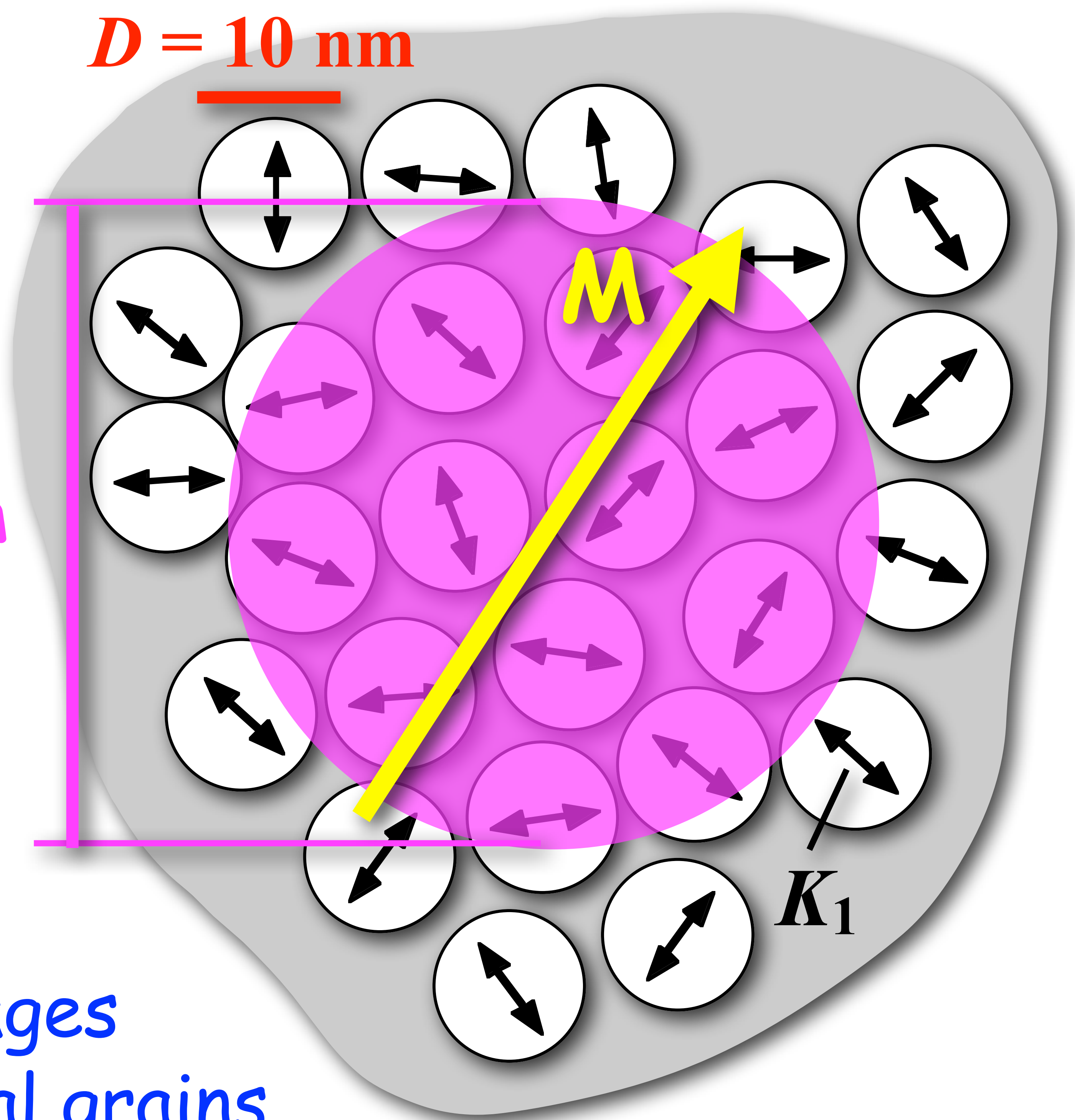

Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of individual grains

Nanocrystalline ribbons

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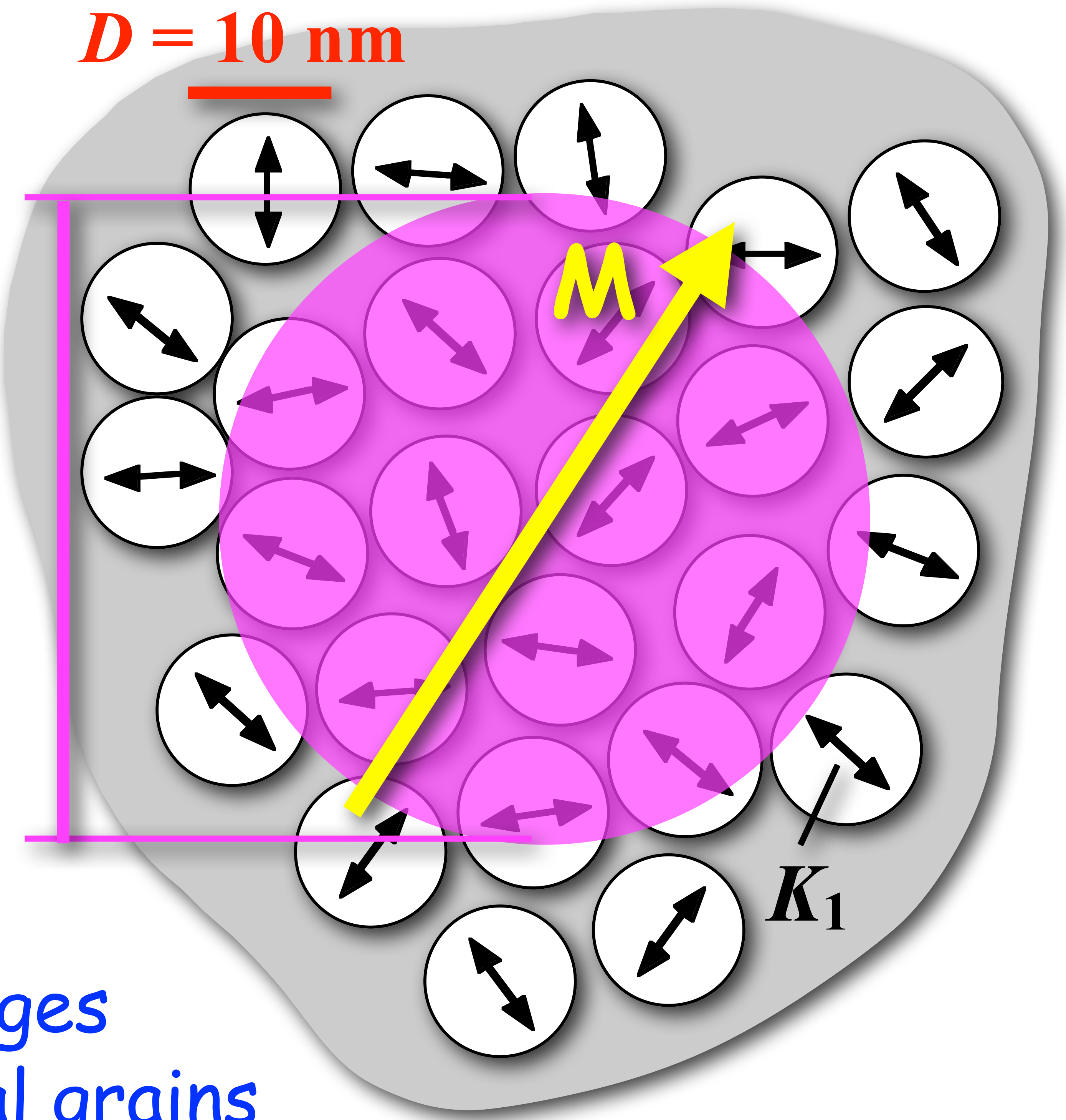
$$\longrightarrow D < L_{ex}$$



Random anisotropy model [Herzer 1989]:
Exchange interaction averages over anisotropy of individual grains

$$\longrightarrow \langle K_1 \rangle \approx |K_1| \, (D/L_{ex})^6 = 3 \text{ J/m}^3$$

Nanocrystalline ribbons

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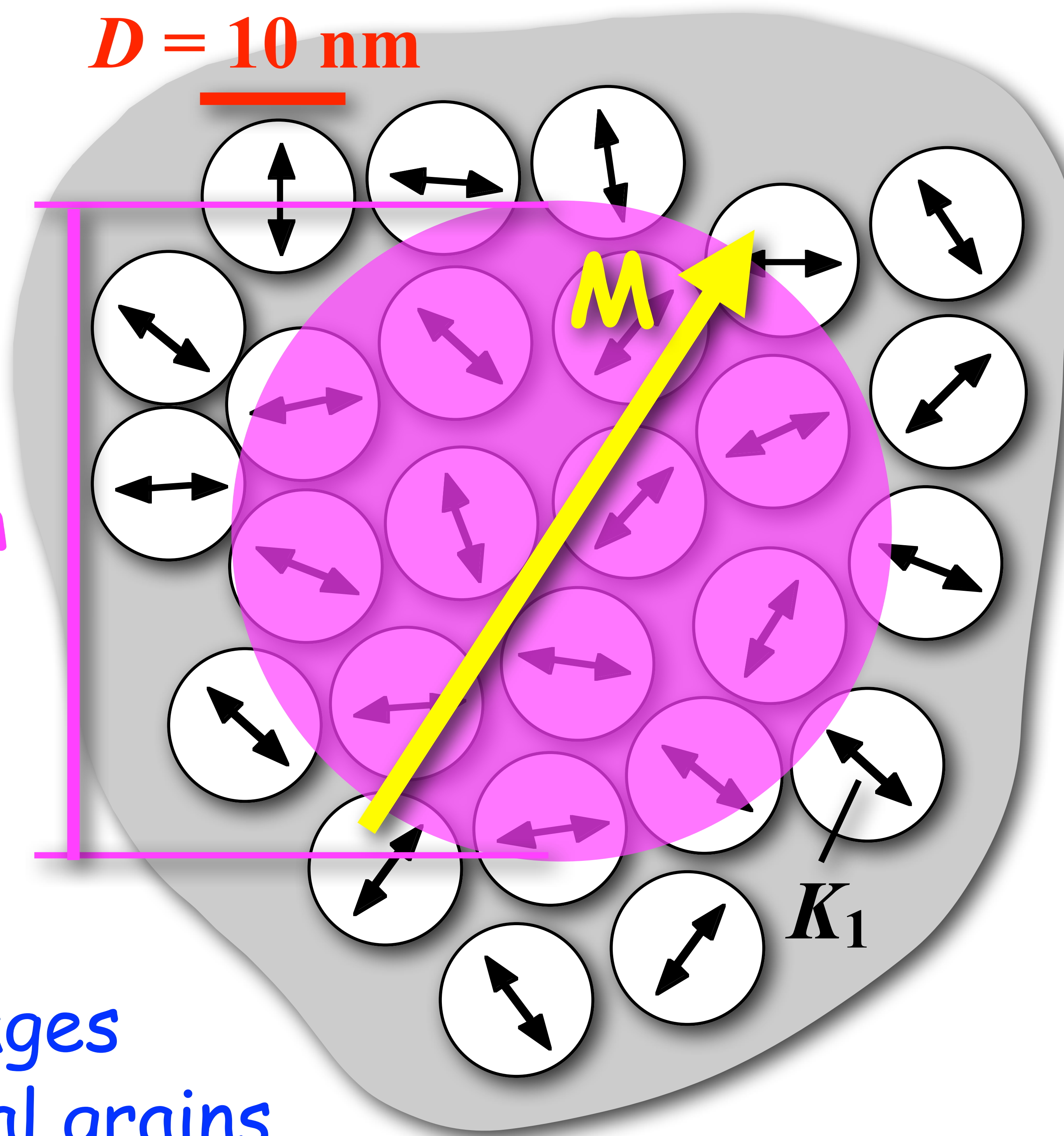


Random anisotropy model [Herzer 1989]:

Exchange interaction averages over anisotropy of individual grains

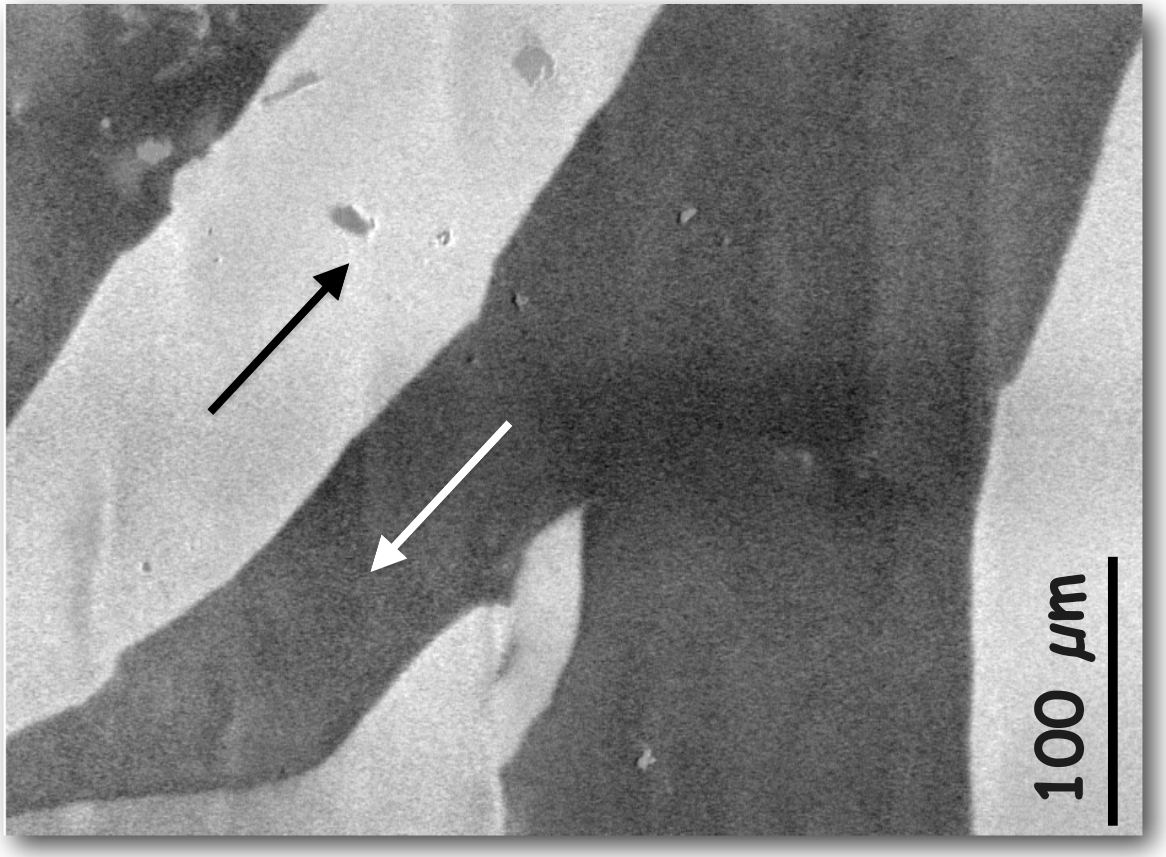
$\longrightarrow \langle K_1 \rangle \approx |K_1| \, (D/L_{ex})^6 = 3 \text{ J/m}^3 \longrightarrow$ very weak eff. anisotropy

Nanocrystalline ribbons

Amorphous (as-quenched)

„Stress patterns"

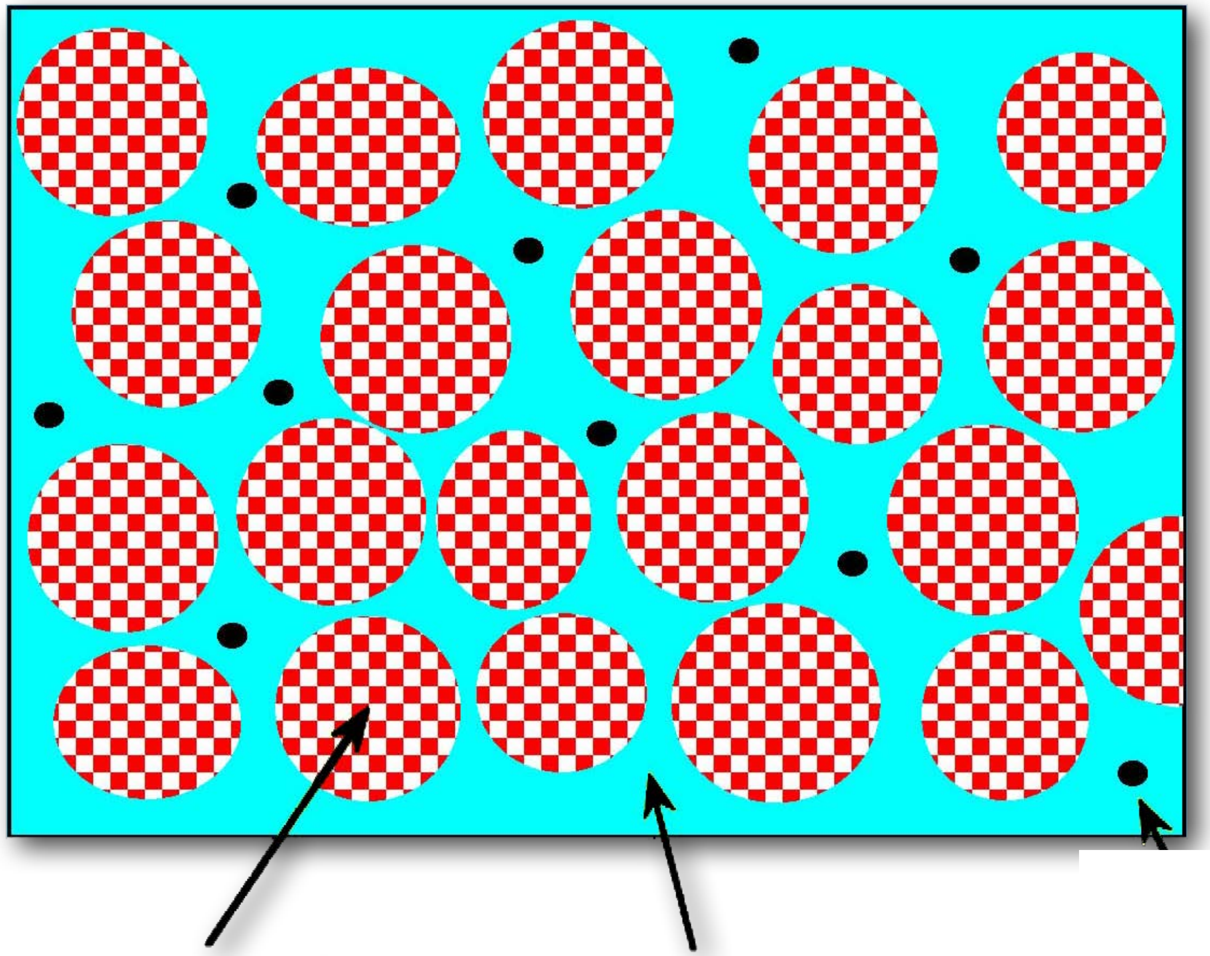
Nanocrystalline



- Homogeneous domains on macroscopic scale
- No stress patterns

  ⟶ $\lambda_s \approx 0$
- Magnetization direction determined by induced anisotropy

Nanocrystalline ribbons



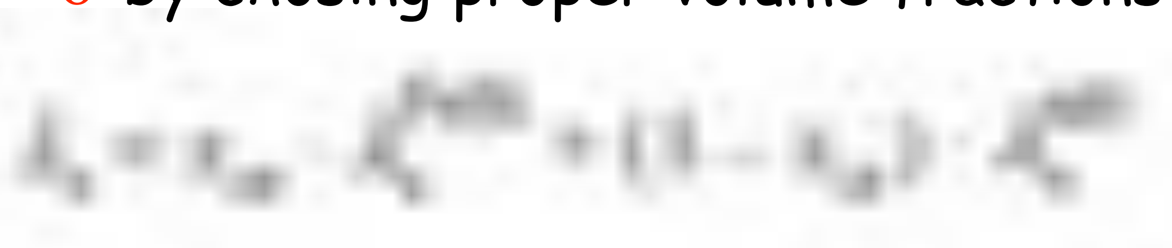
bcc Fe-Si
(~10 nm)

$\lambda_s > 0$

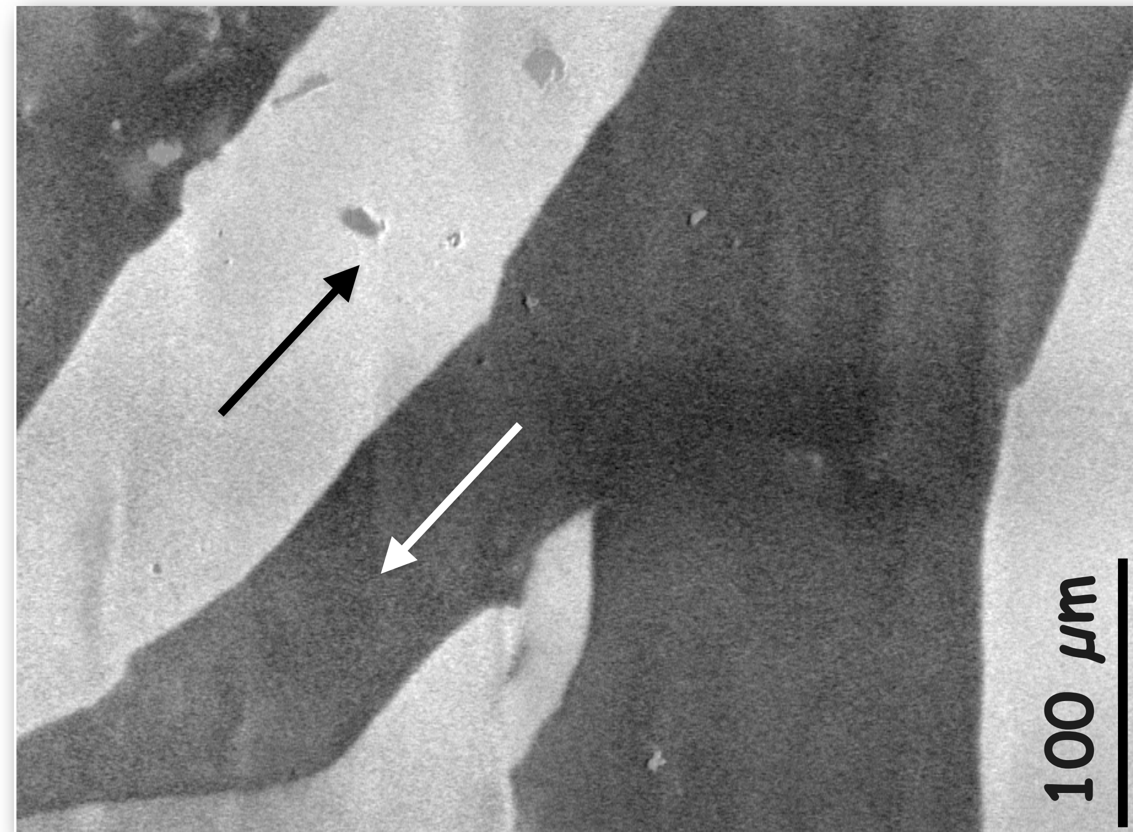
amorphous
Fe-Nb-B matrix

$\lambda_s < 0$

$\lambda_s \approx 0$ by chosing proper volume fractions x_{cr}



Nanocrystalline



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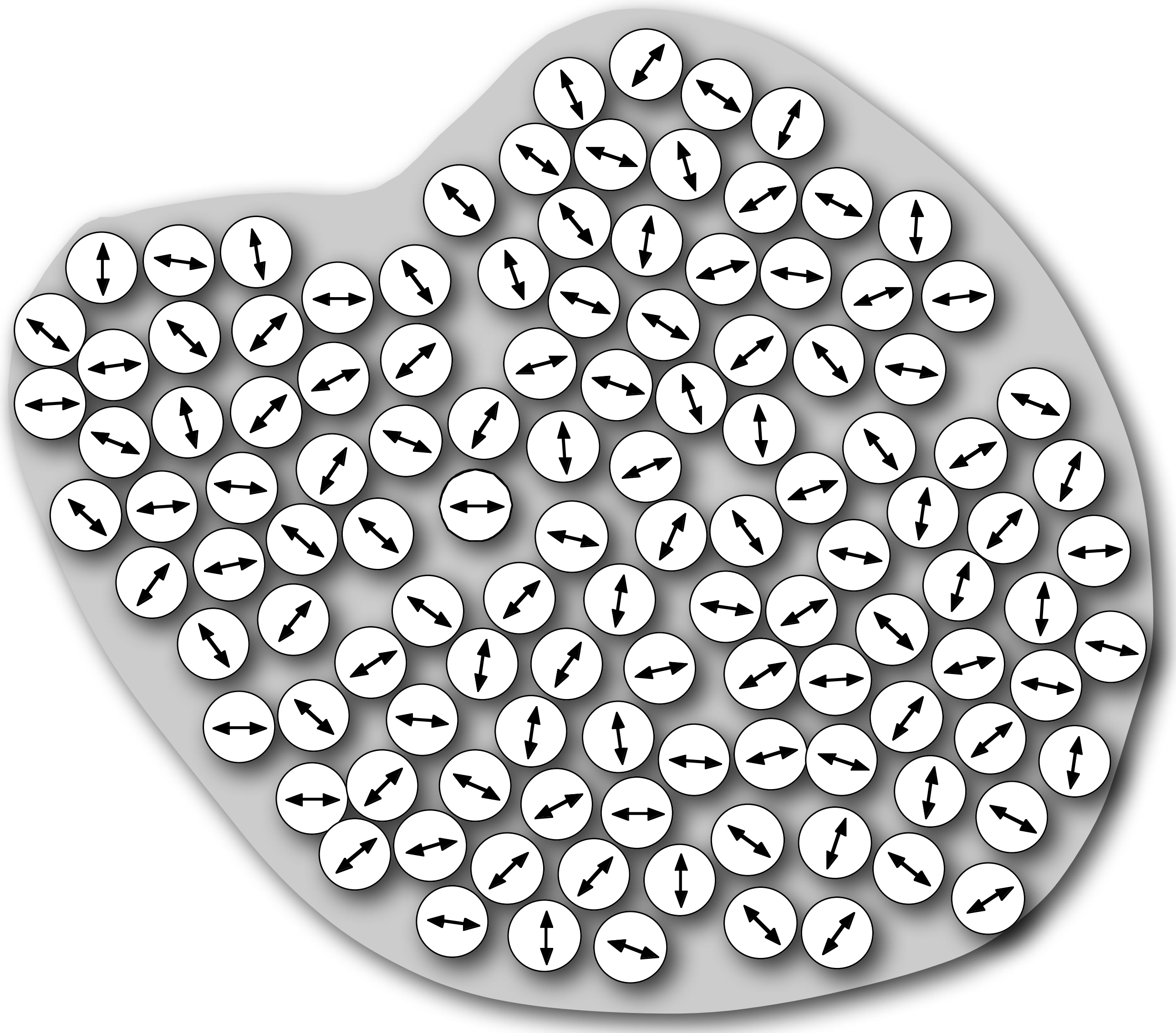
exchange length



Random anisotropy model:

$$\longrightarrow \langle K_1 \rangle \approx 3 \text{ J/m}^3$$

average anisotropy

$$\longrightarrow L_{ex} = \sqrt{A/\langle K_1 \rangle} = \textbf{2 } \mu\textbf{m}$$

renormalized exchange length

Nanocrystalline ribbons

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$K_1 = 8 \text{ kJ/m}^3$

$A = 10^{-11} \text{ J/m}$

$\longrightarrow L_{ex} = \sqrt{A/K_1} =$ **35 nm**

exchange length

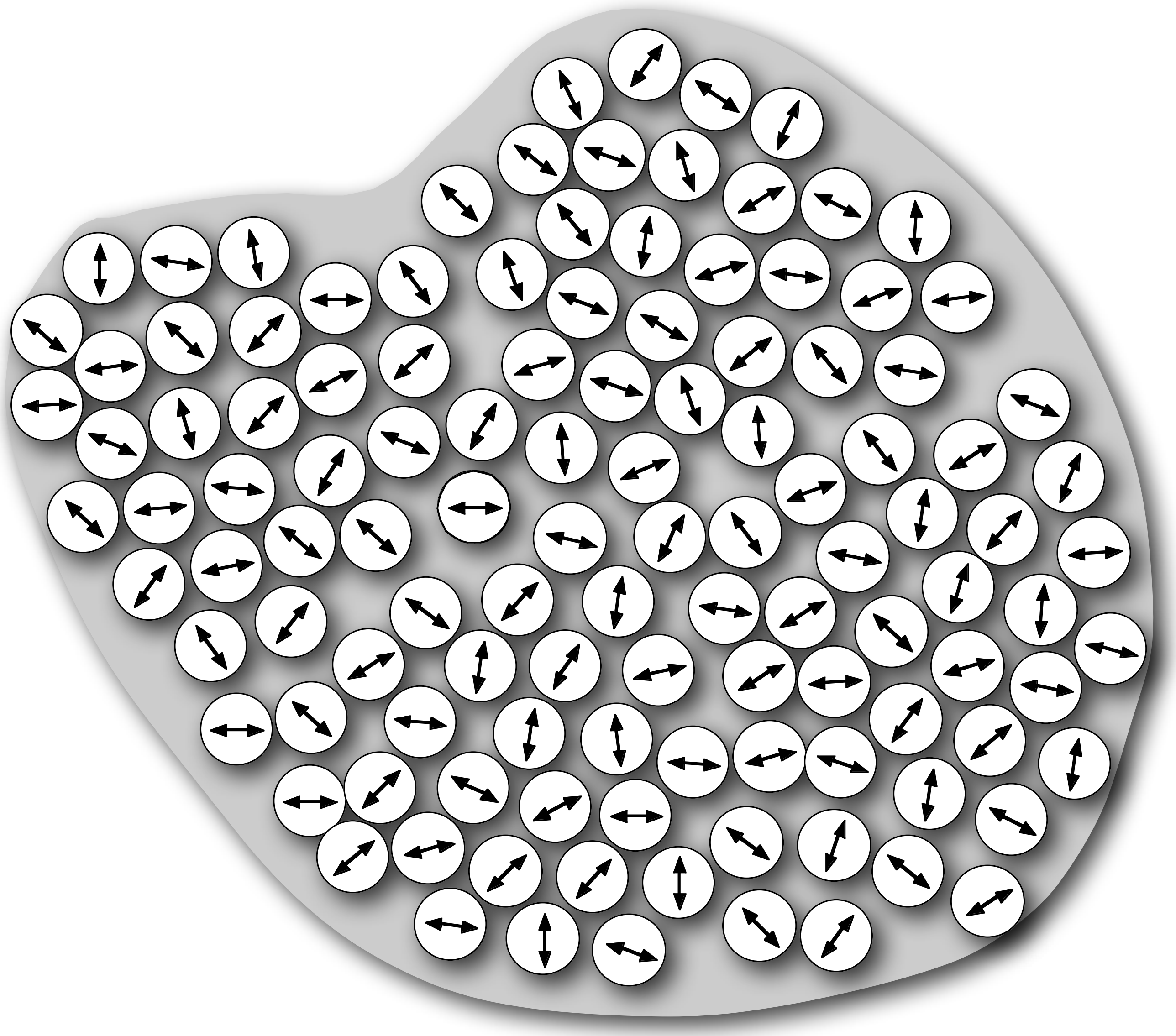
Random anisotropy model:

$\longrightarrow \langle K_1 \rangle \approx 3 \text{ J/m}^3$

average anisotropy

$\longrightarrow L_{ex} = \sqrt{A/\langle K_1 \rangle} =$ **2 μm**

renormalized exchange length



Nanocrystalline ribbons

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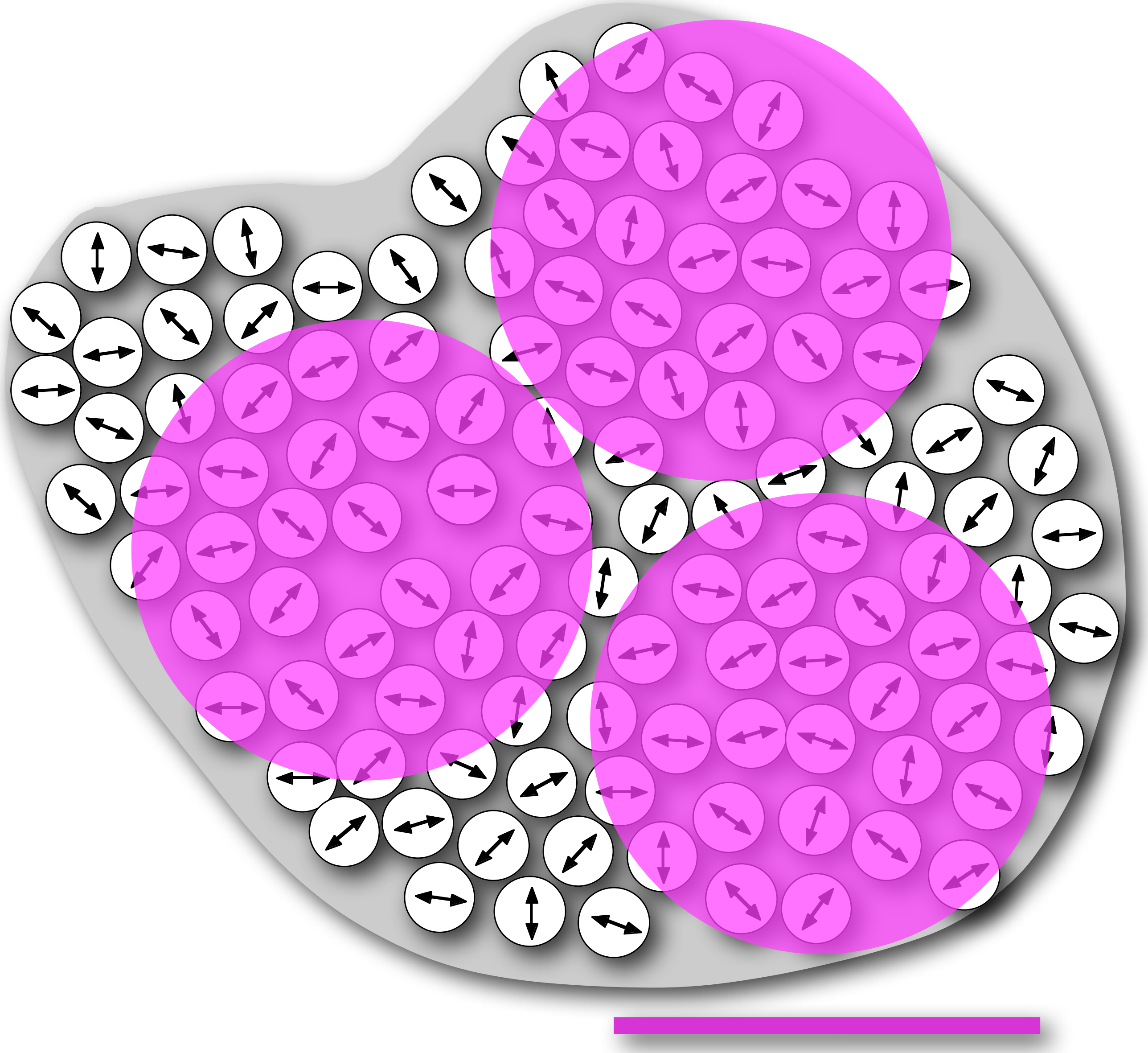

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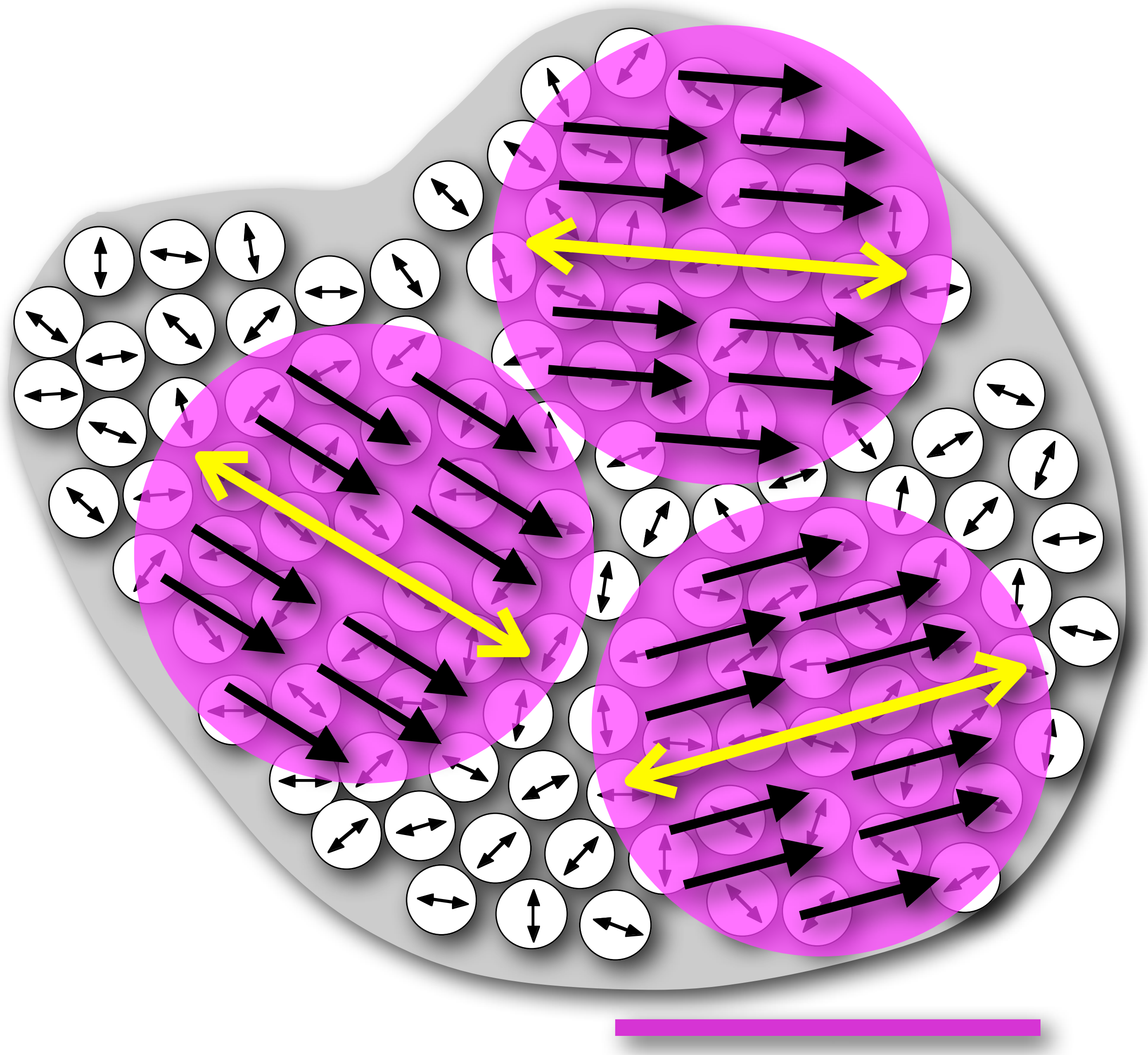

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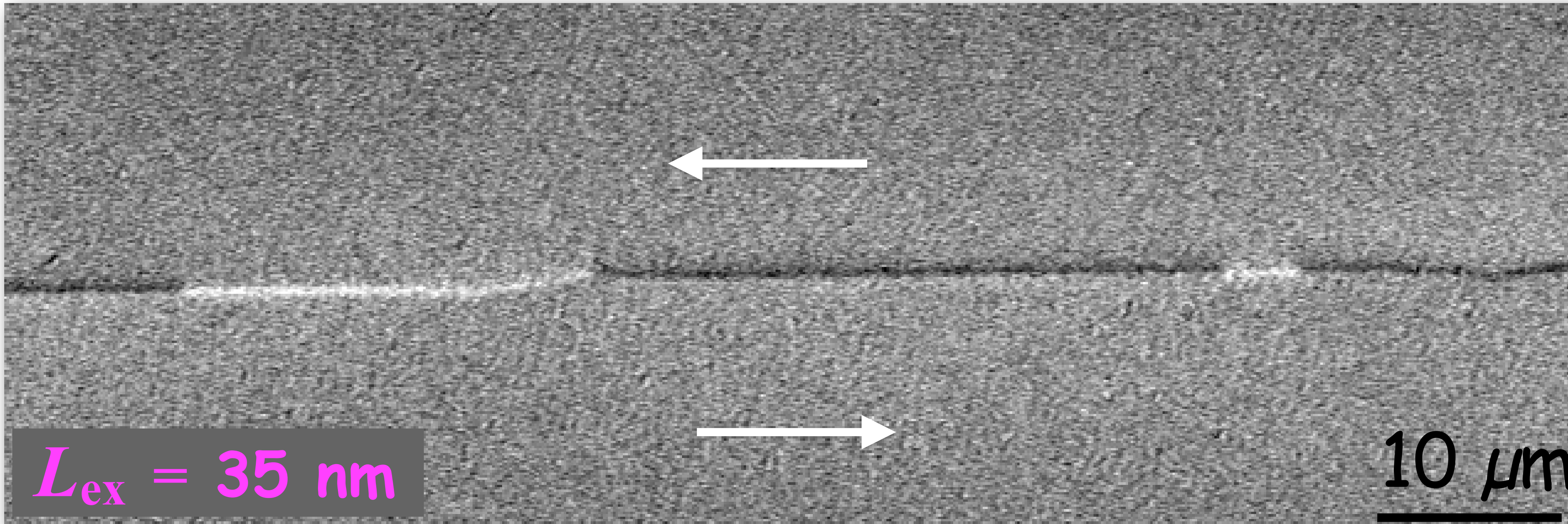
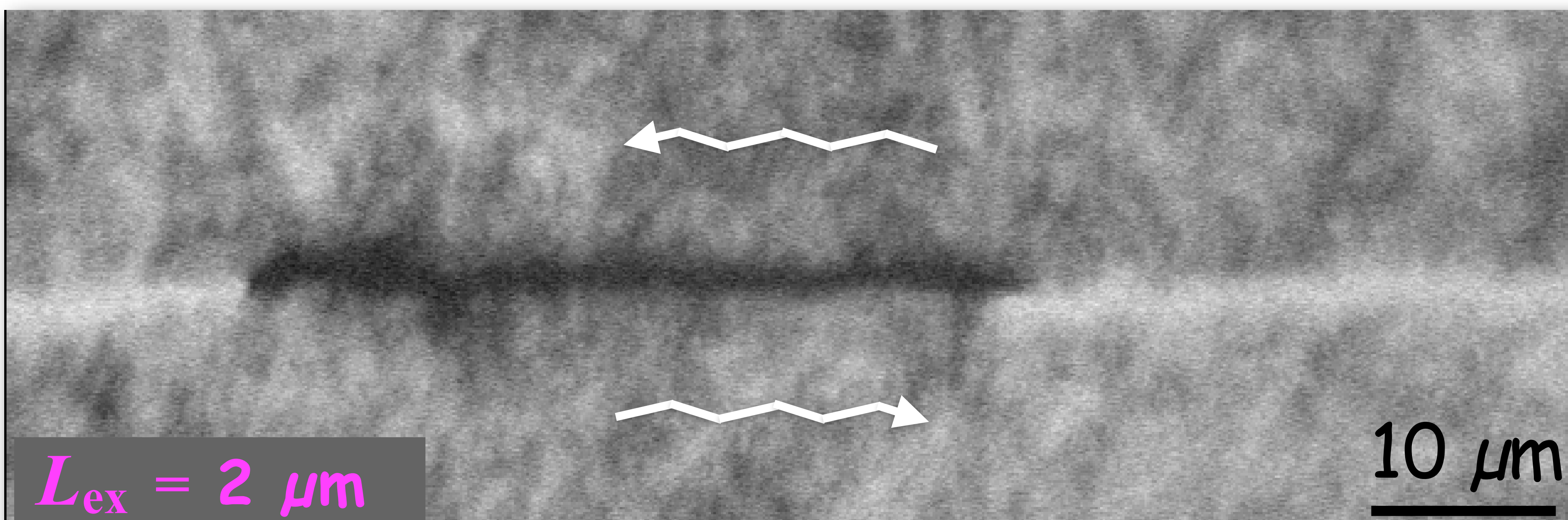
Nanocrystalline ribbons



Fe-Si Goss sheet, surface wall width: 150 nm



Nanocrystalline ribbon, surface wall width: several μm

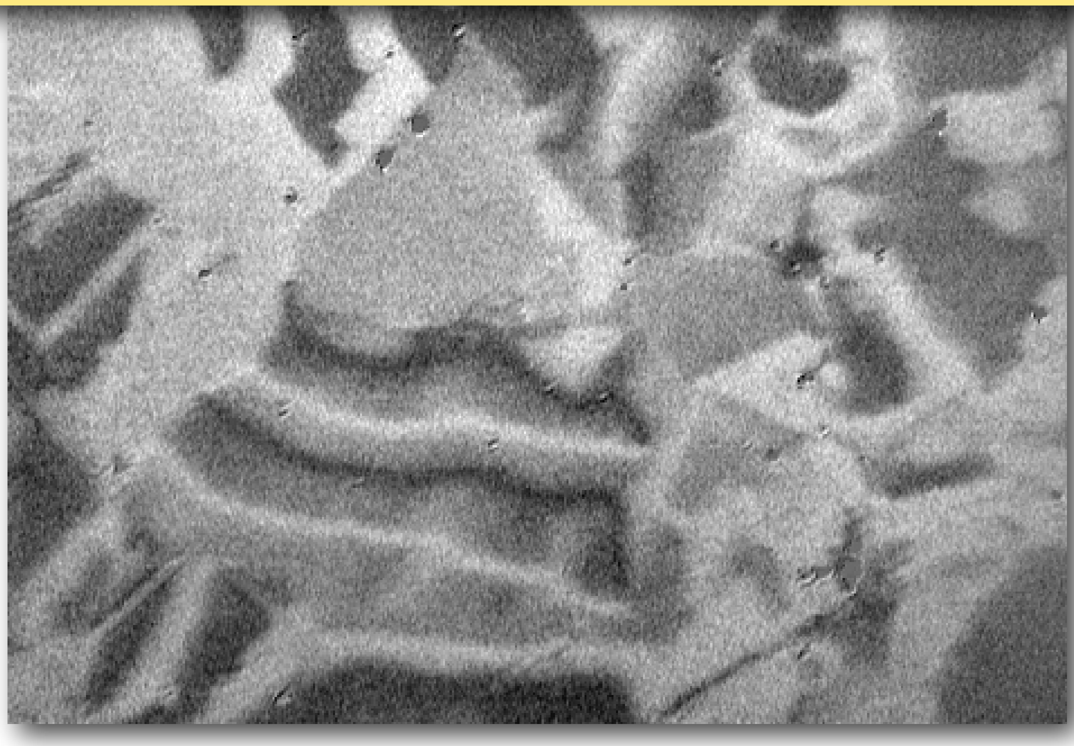
Random anisotropy effect in Permalloy

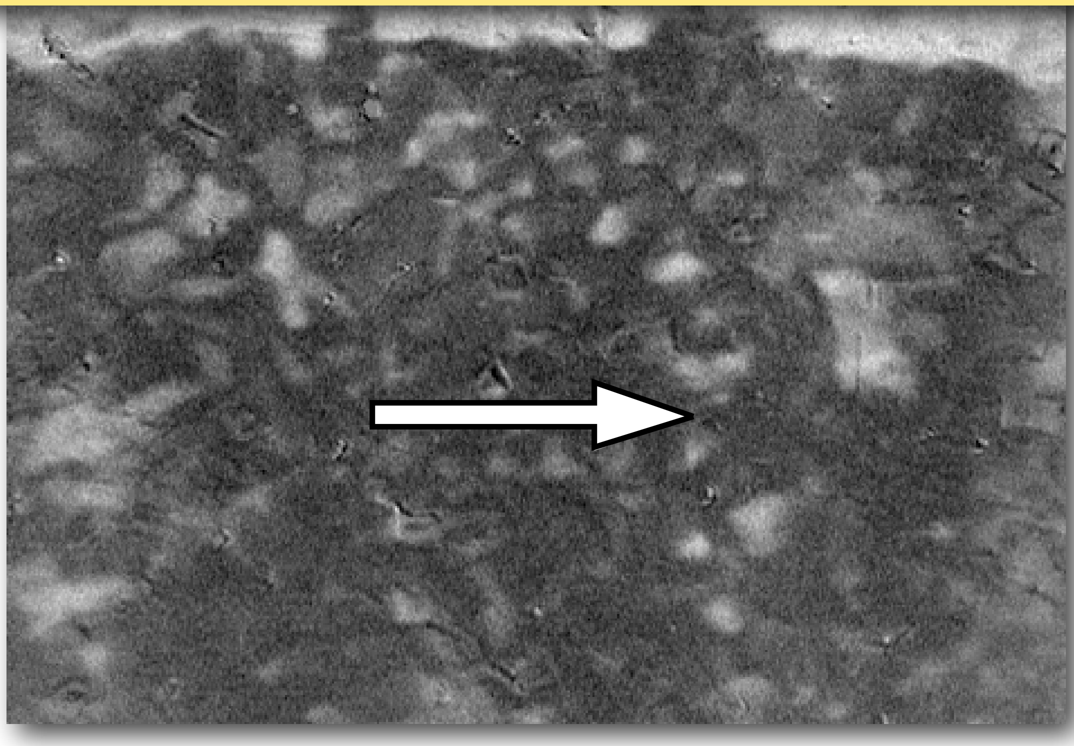
Permalloy ($Fe_{81}Ni_{19}$):

K_{cryst} much smaller than in FeSi

↓

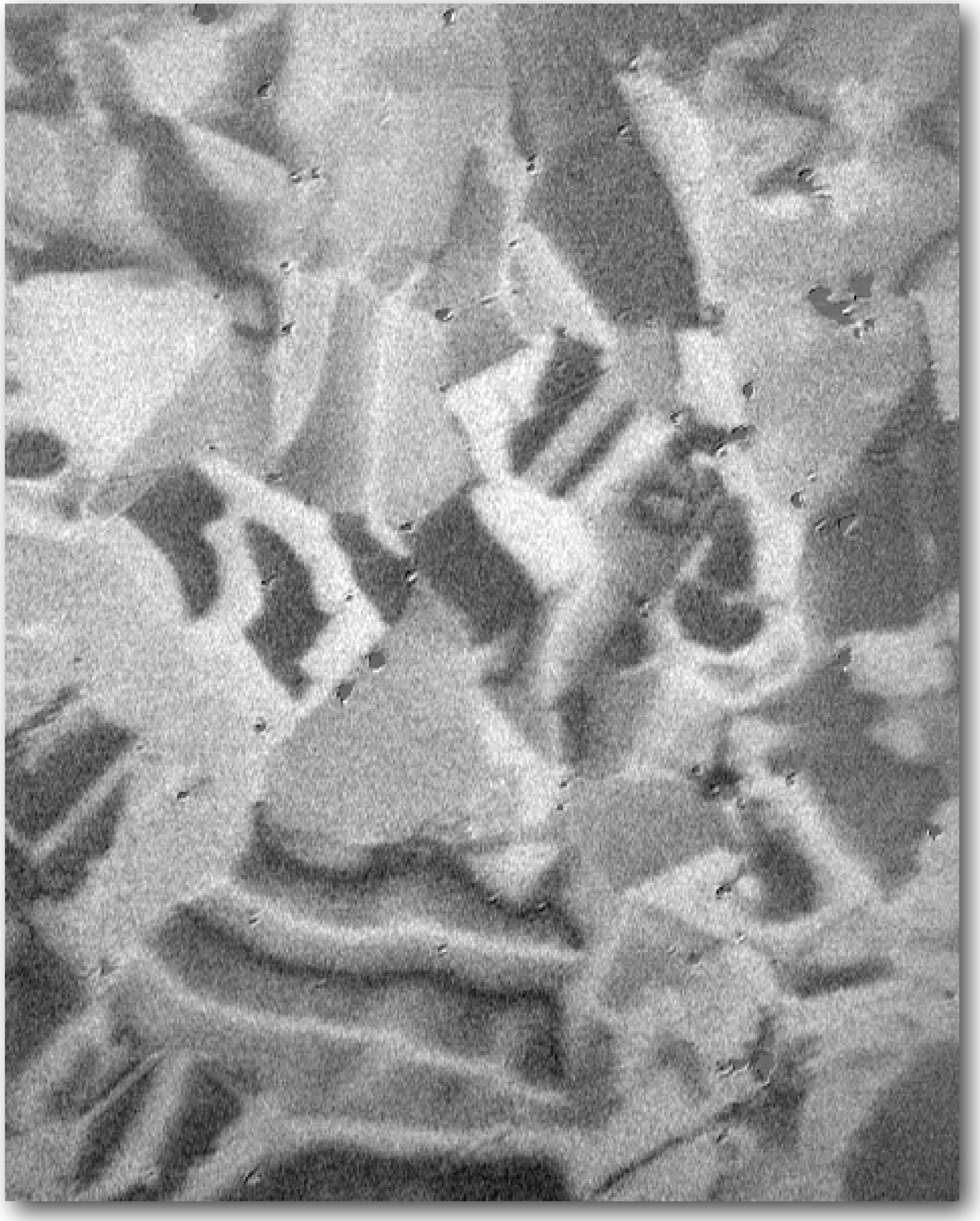
threshold for nanocrystalline behaviour is shifted from the 10-nanometer into the micrometer range



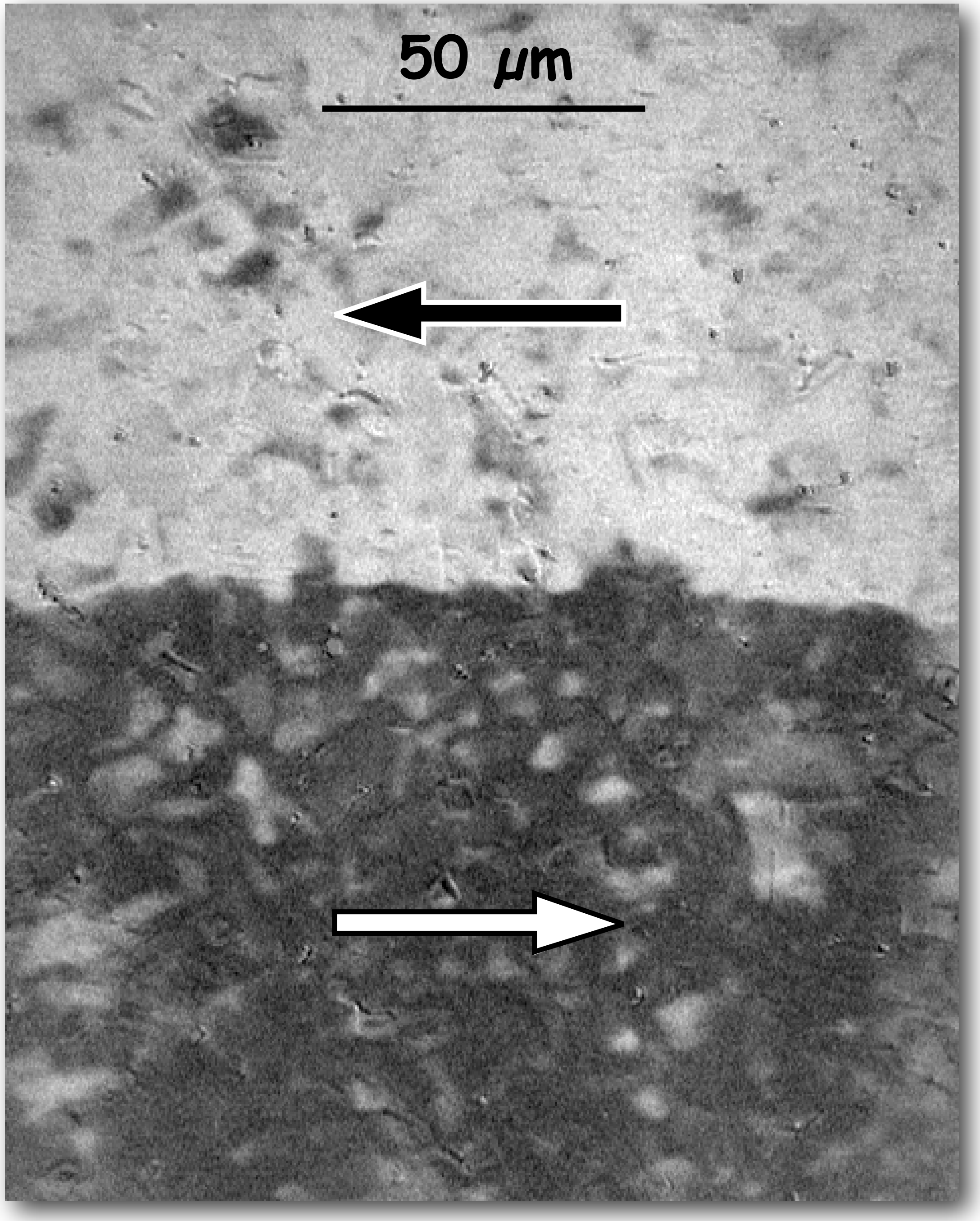


Random anisotropy effect in Permalloy

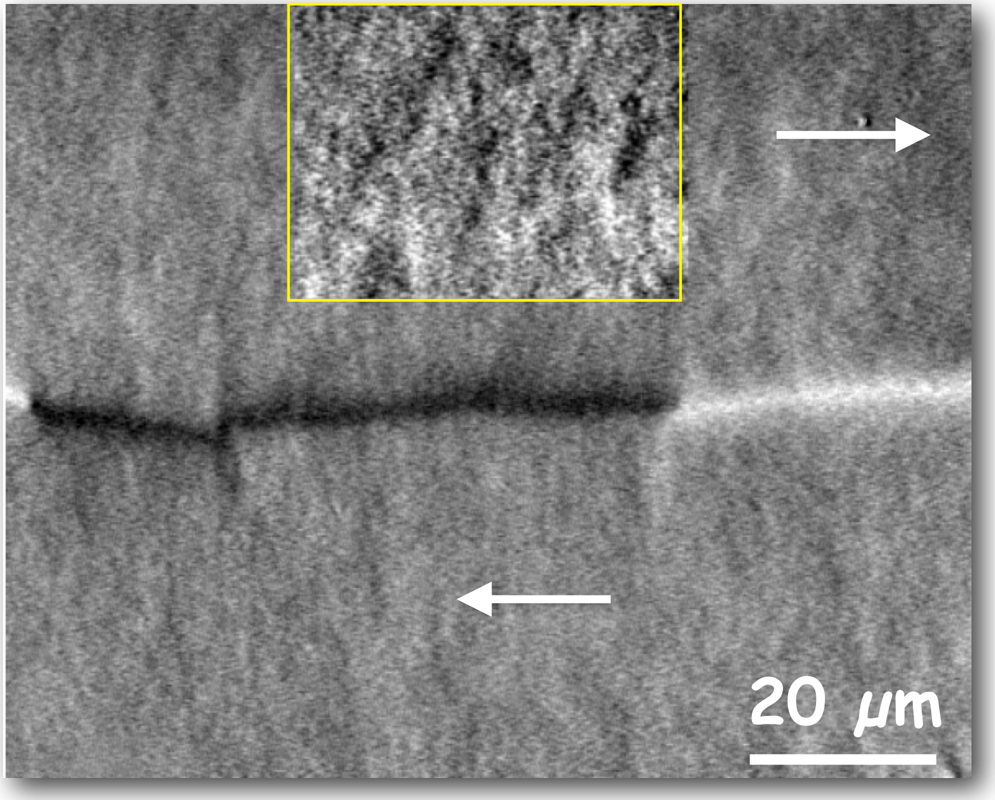
coarse-grained material
(grain size: 30 μm)

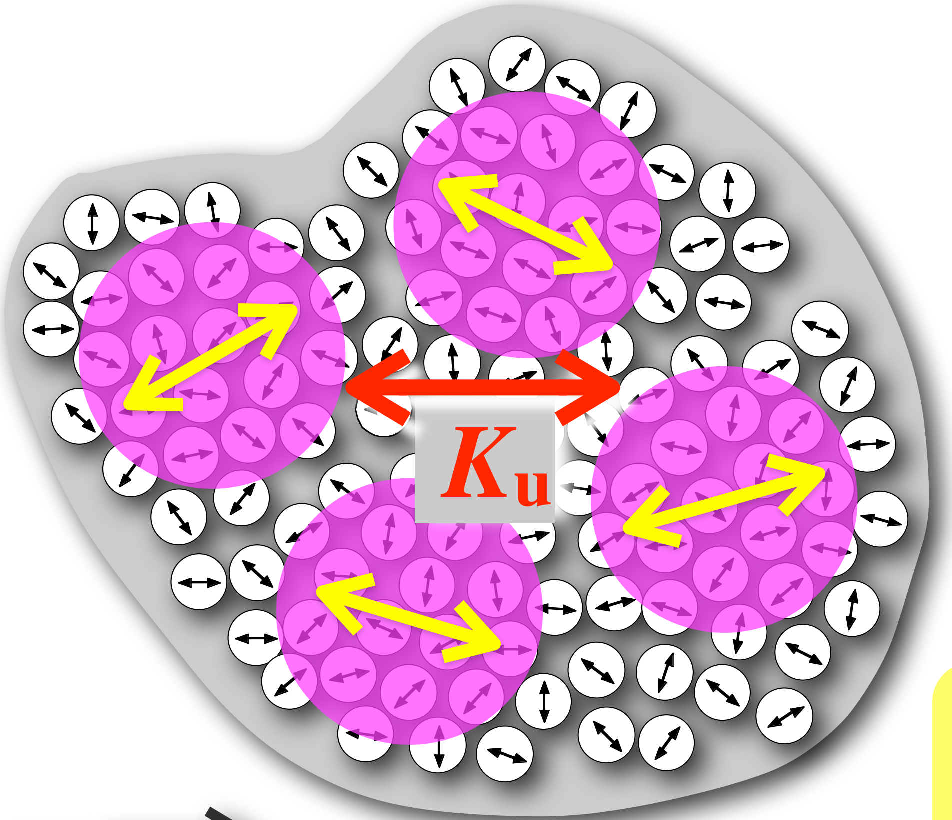


fine-grained material
(grain size: 13 μm)



Nanocrystalline ribbons: interplay of anisotropies





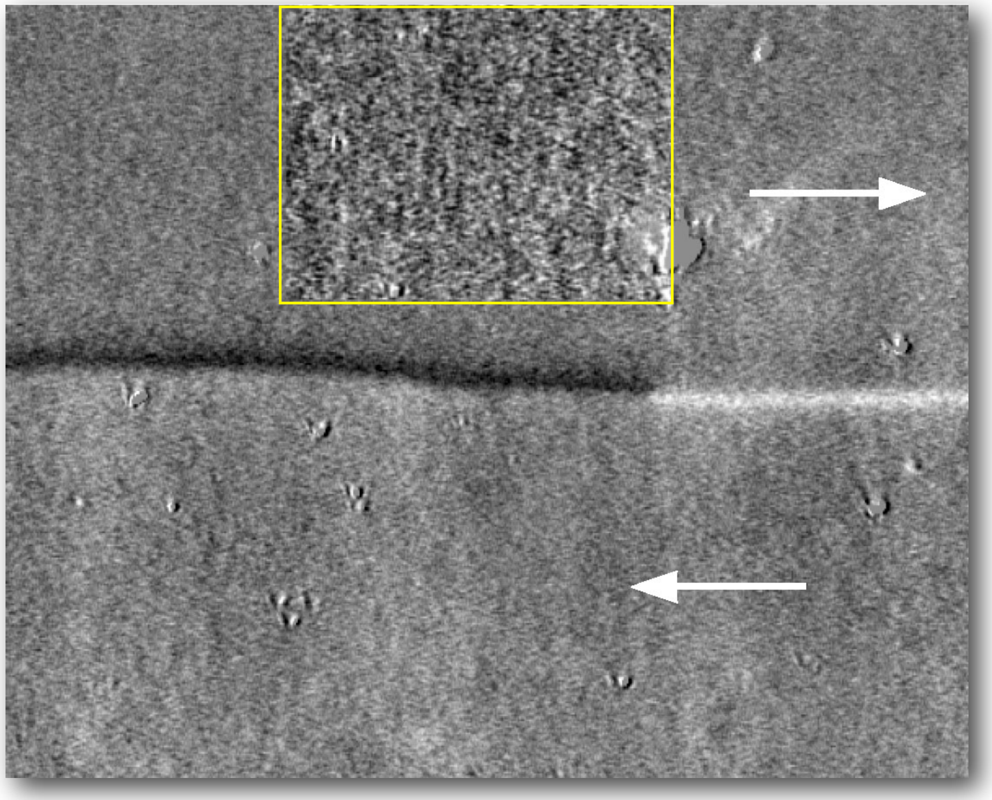
low induced anisotropy (K_u = 3 J/m³)

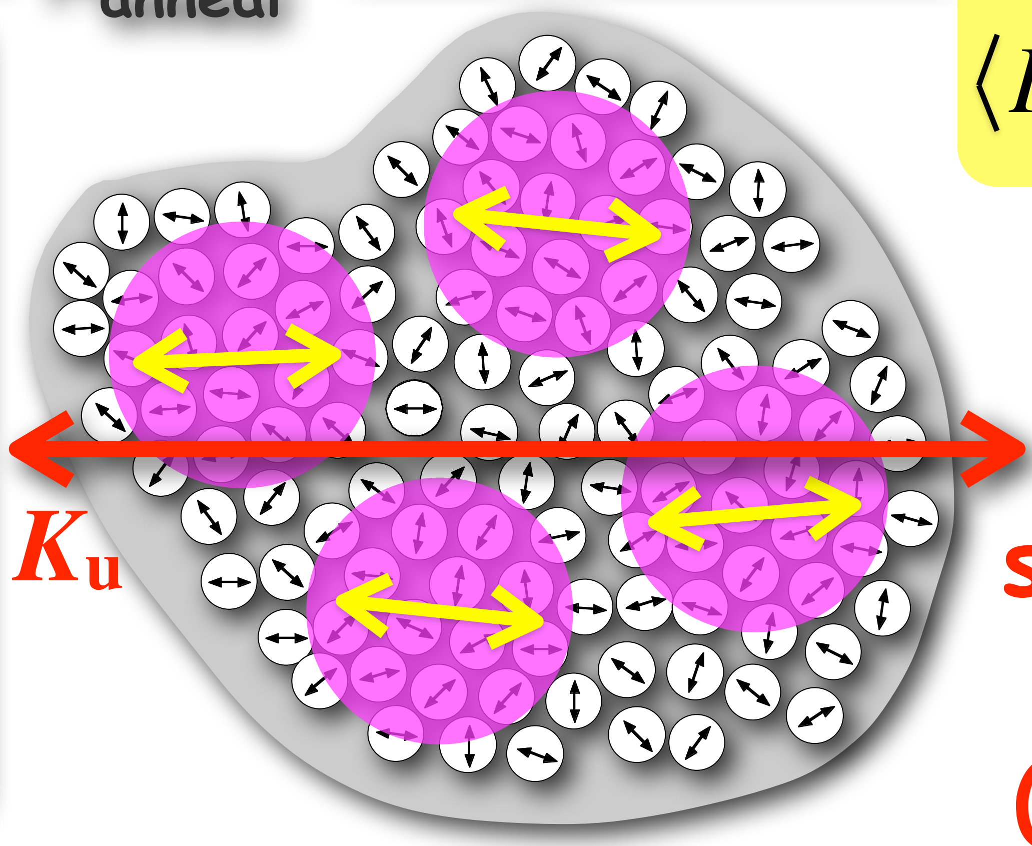
H_{anneal}

$$L_{ex} = \sqrt{A/\langle K \rangle}$$

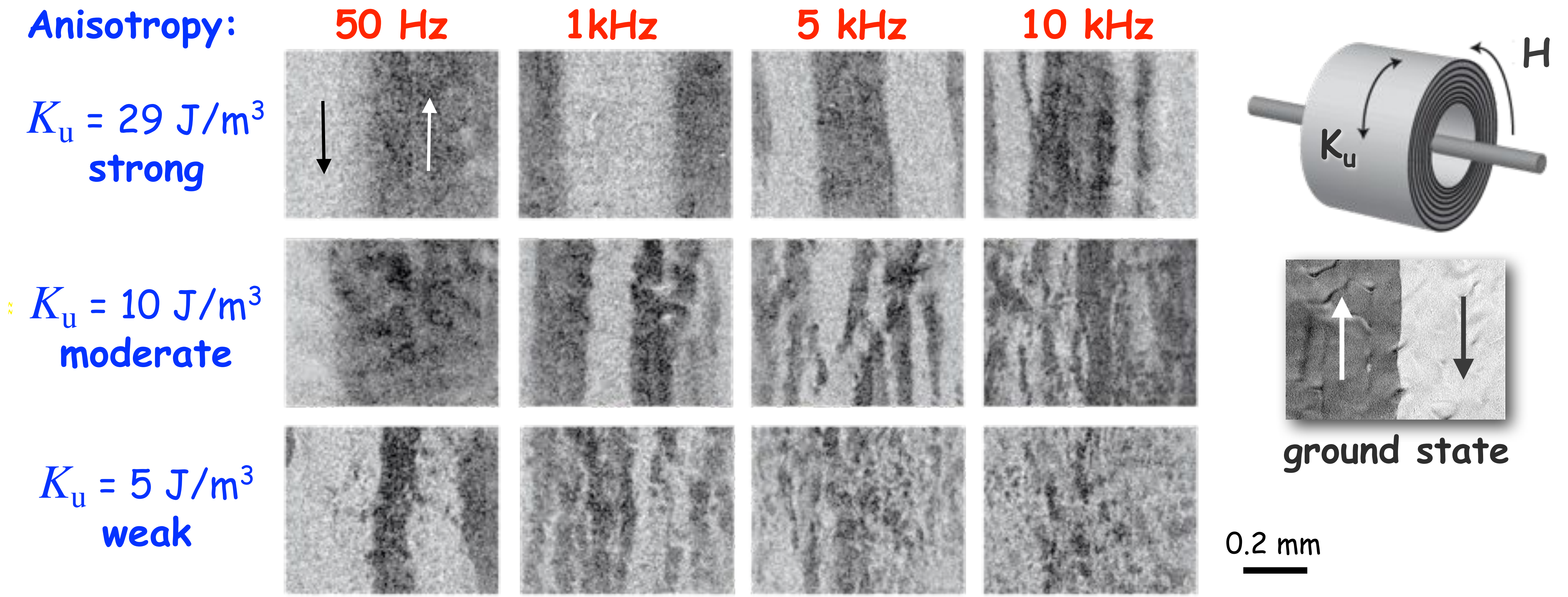
$$\langle K \rangle = \sqrt{\langle K_1^2 \rangle + K_u^2}$$

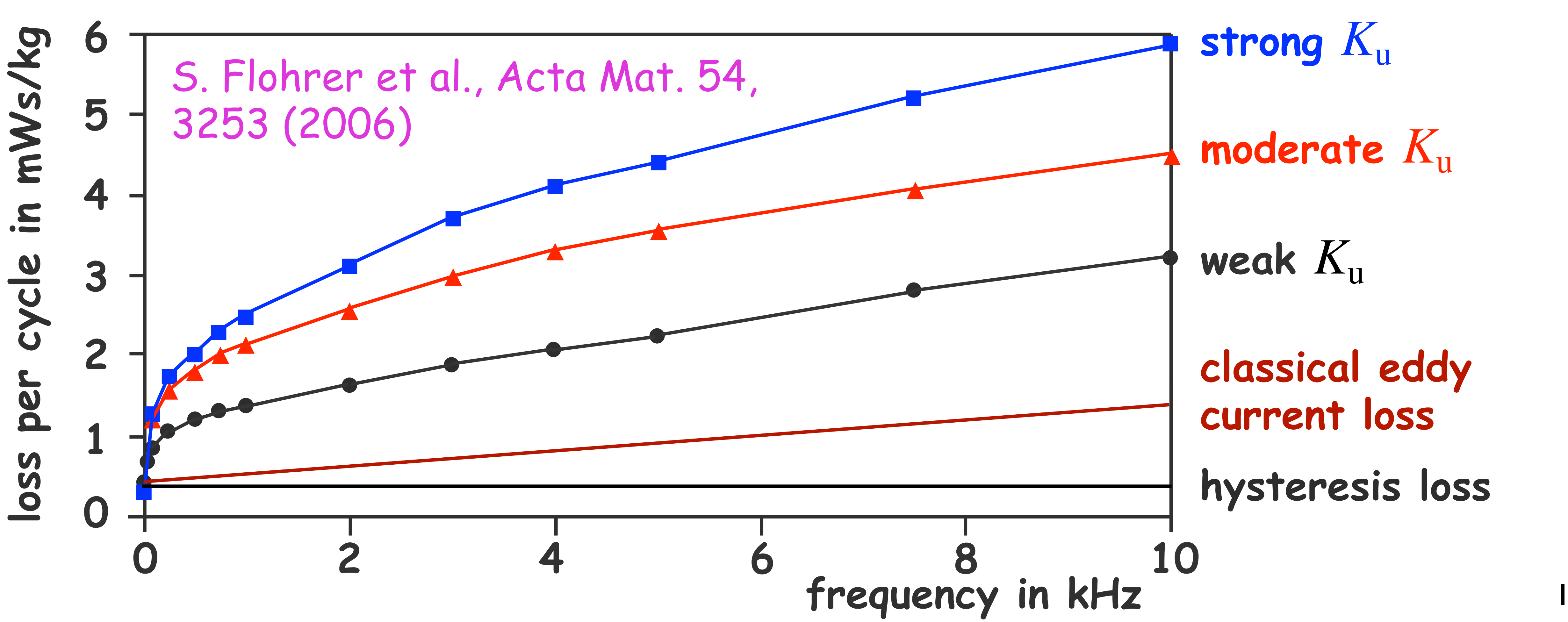
3 J/m³





strong induced anisotropy (K_u = 30 J/m³)


Anisotropy:
50 Hz
1kHz
5 kHz
10 kHz
K_u = 29 J/m^3
strong
K_u = 10 J/m^3
moderate
K_u = 5 J/m^3
weak
H
K_u
ground state
0.2 mm


S. Flohrer et al., Acta Mat. 54, 3253 (2006)
loss per cycle in mWs/kg
frequency in kHz
0
1
2
3
4
5
6
0
2
4
6
8
10
strong K_u
moderate K_u
weak K_u
classical eddy current loss
hysteresis loss

Soft magnets,
Summary

Soft magnets: Summary

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Purpose of soft magnetic material

Enhancement of flux density B, produced by current-carrying coil

$\longrightarrow$ material should be easily magnetized

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$\longrightarrow$ High permeability μ (magnetization large even in small fields)

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Requirements to material:

- Low anisotropy: prerequistite for high rotational permeability, reduction of domain wall pinning effects
- Low magnetostriction: prevent stress-sensitivity (exceptions: transformer steel, magnetoacoustic article surveilance...)
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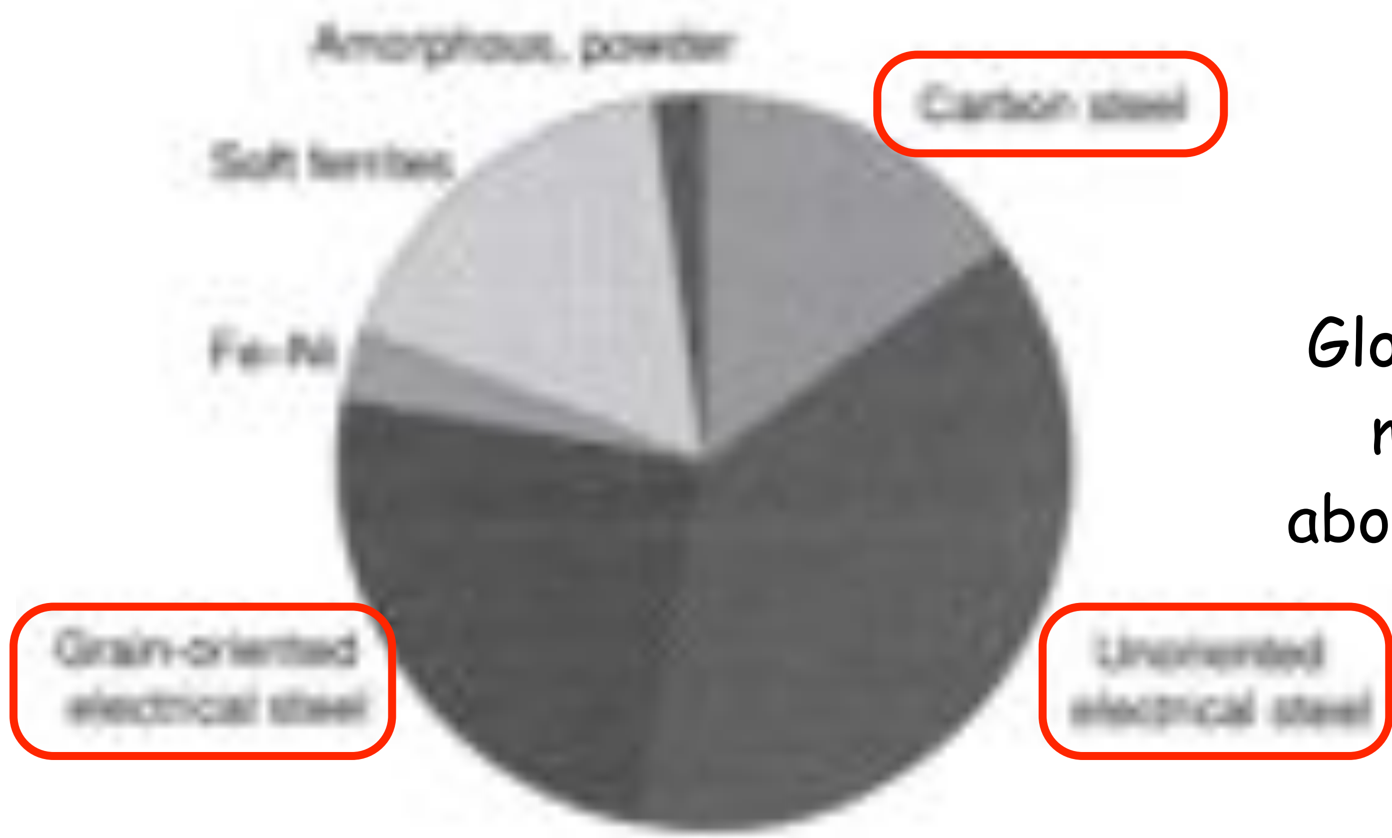
Relative importance of requirements is determined by frequency of magnetizing field:

- Zero frequency: best material is that with highest saturation magnetization
- Low frequency: high μ, large M_s , low H_c
- Increasing frequency: importance of high μ and low H_c rises relative to large M_s, because eddy current loss is proportional to frequency

Soft magnets: Summary

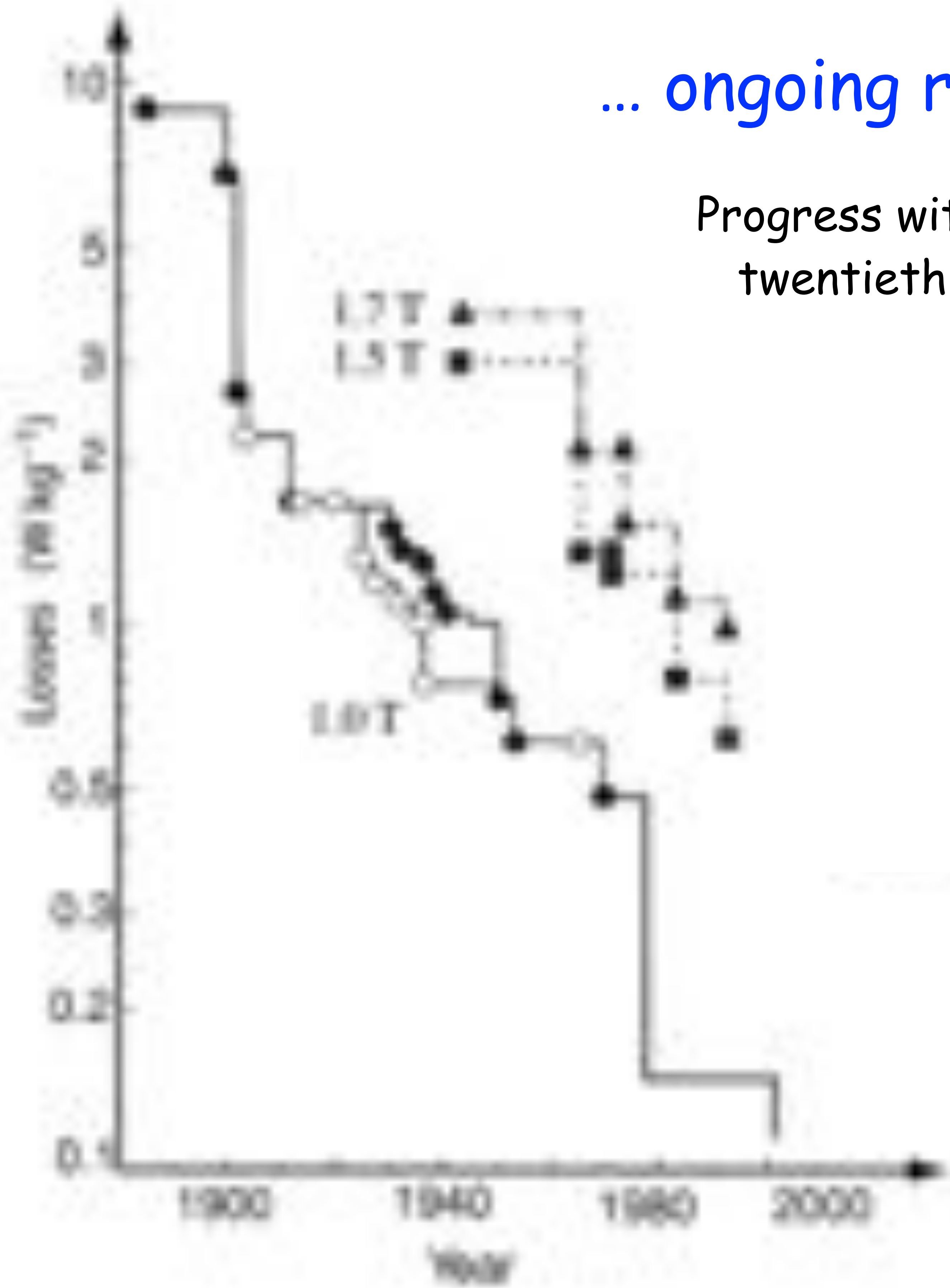
Soft magnetic materials and applications

Frequency	Materials	Applications
Static <1 Hz	Soft iron, Fe–Co (permendur) Ni–Fe (permalloy)	Electromagnets, relays
Low frequency 1 Hz–1 kHz	Si steel, permalloy, finemet, magnetic glasses	Transformers, motors, generators
Audio-frequency 100 Hz–100 kHz	Permalloy foils, finemet, magnetic glasses, Fe–Si–Al powder (sendust) Mn–Zn ferrite	Inductors, transformers for switched mode power supplies, TV flyback transformers
Radio-frequency 0.1–1000 MHz	Mn–Zn ferrite, Ni–Zn ferrite	Inductors, antenna rods
Microwave >1 GHz	YIG, Li ferrite	Microwave isolators, circulators, phase shifters, filters



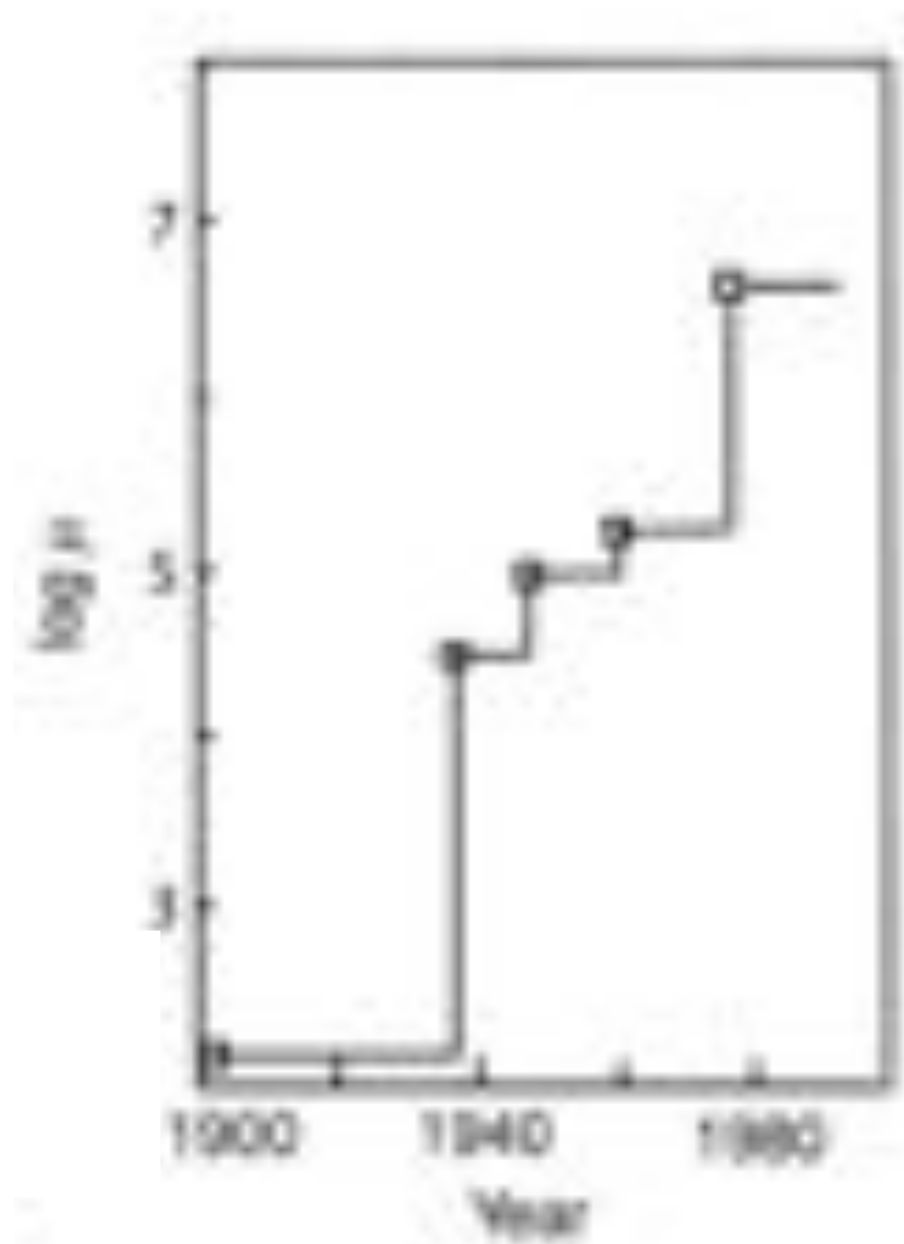
Global market for soft magnetic materials . The Pie represents about 10 Billions Dollars per year

Soft magnets: Summary



... ongoing research and development...

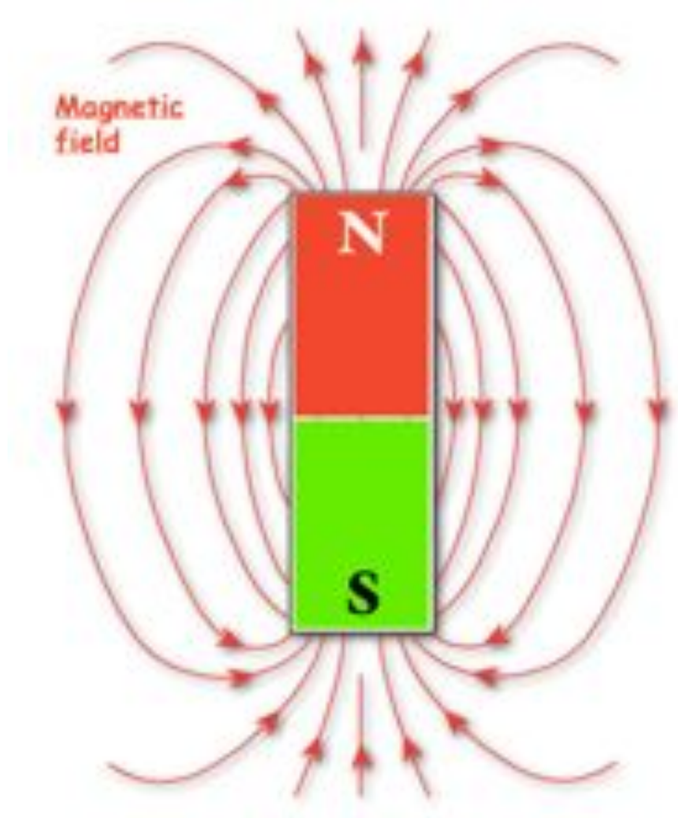
Progress with soft magnetic materials during the twentieth century: total loss and initial (static) permeability of transformer cores



2.
Hardmagnetic Materials

Hardmagnetic materials, basics

Purpose of permanent magnet:
provide magnetic field in particular volume of space by presence of free poles



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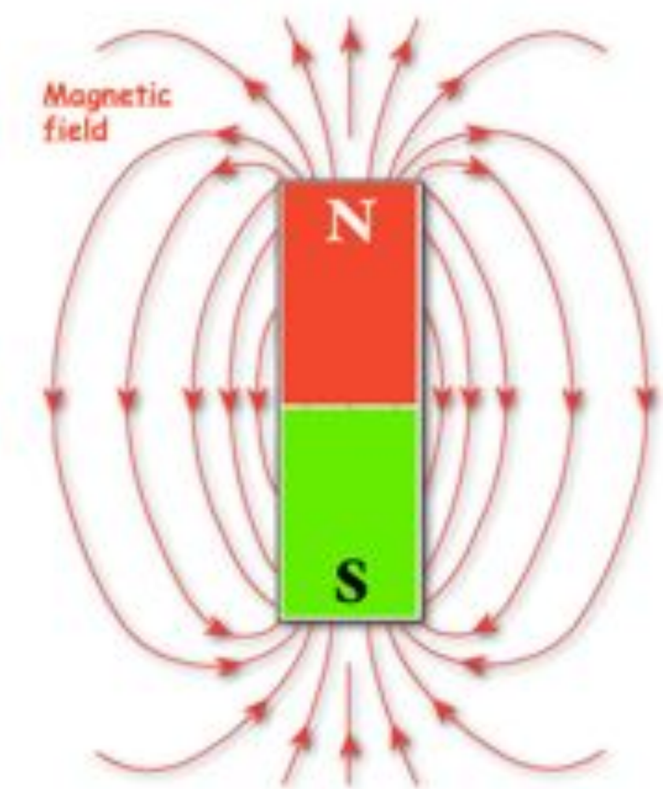
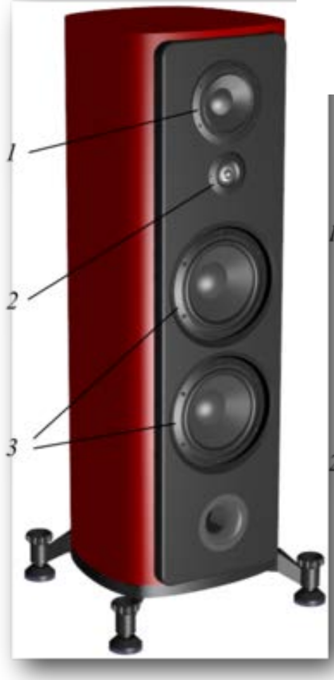
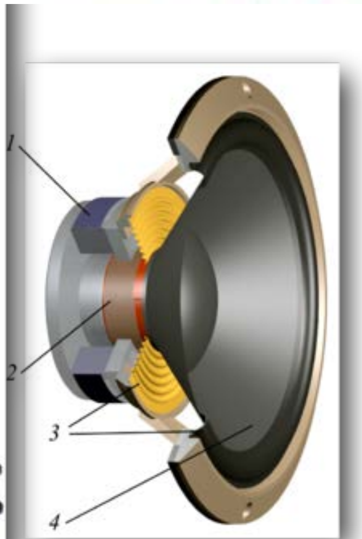
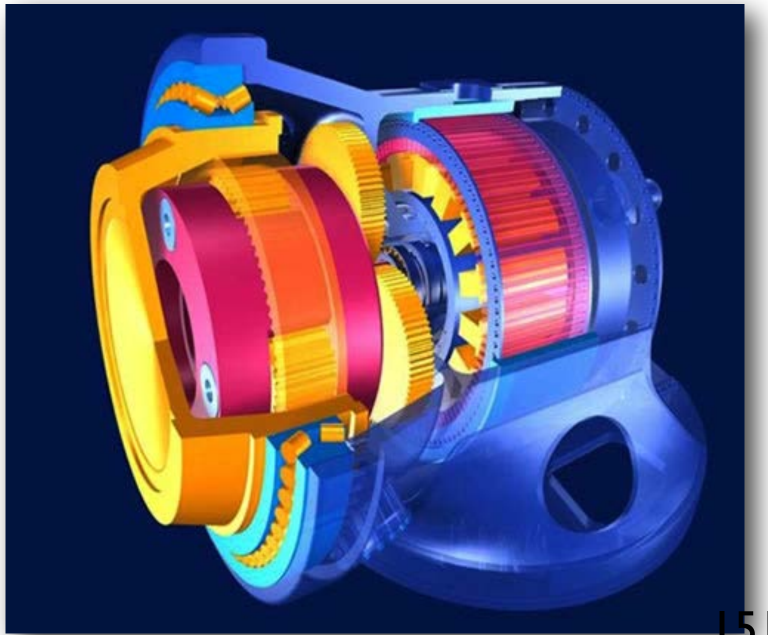






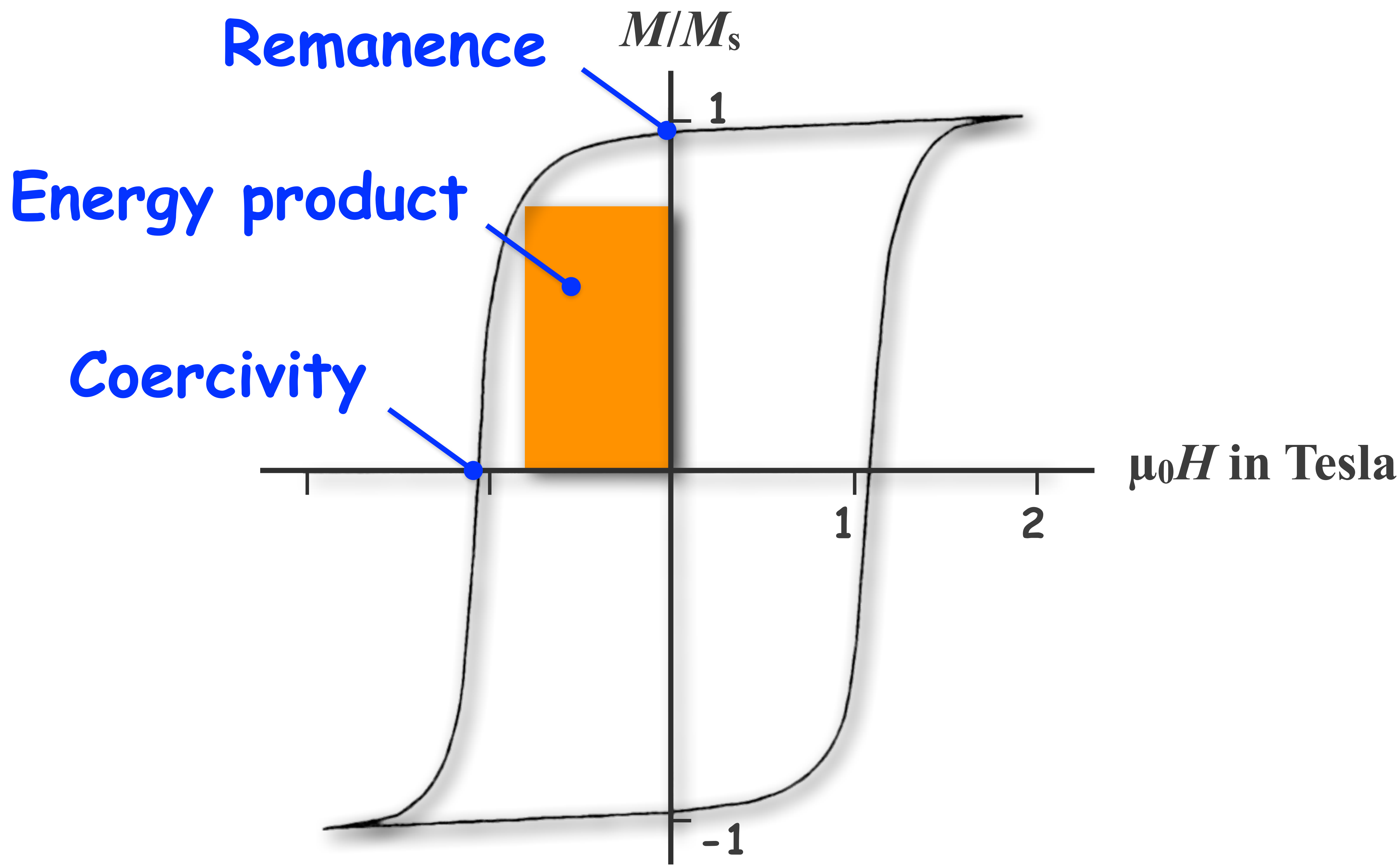


Hardmagnetic materials, basics

Requirements for permanent magnet:

high coercivity, high remanence, high energy product

⟶ Magnet can store high energy



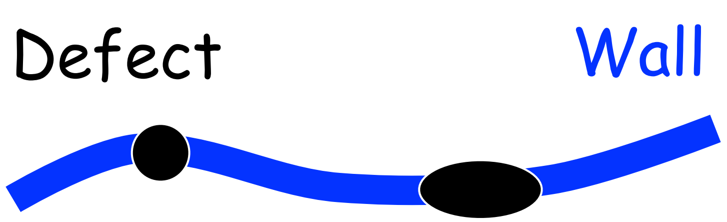
Hardmagnetic materials, basics

Hardmagnetic materials, basics

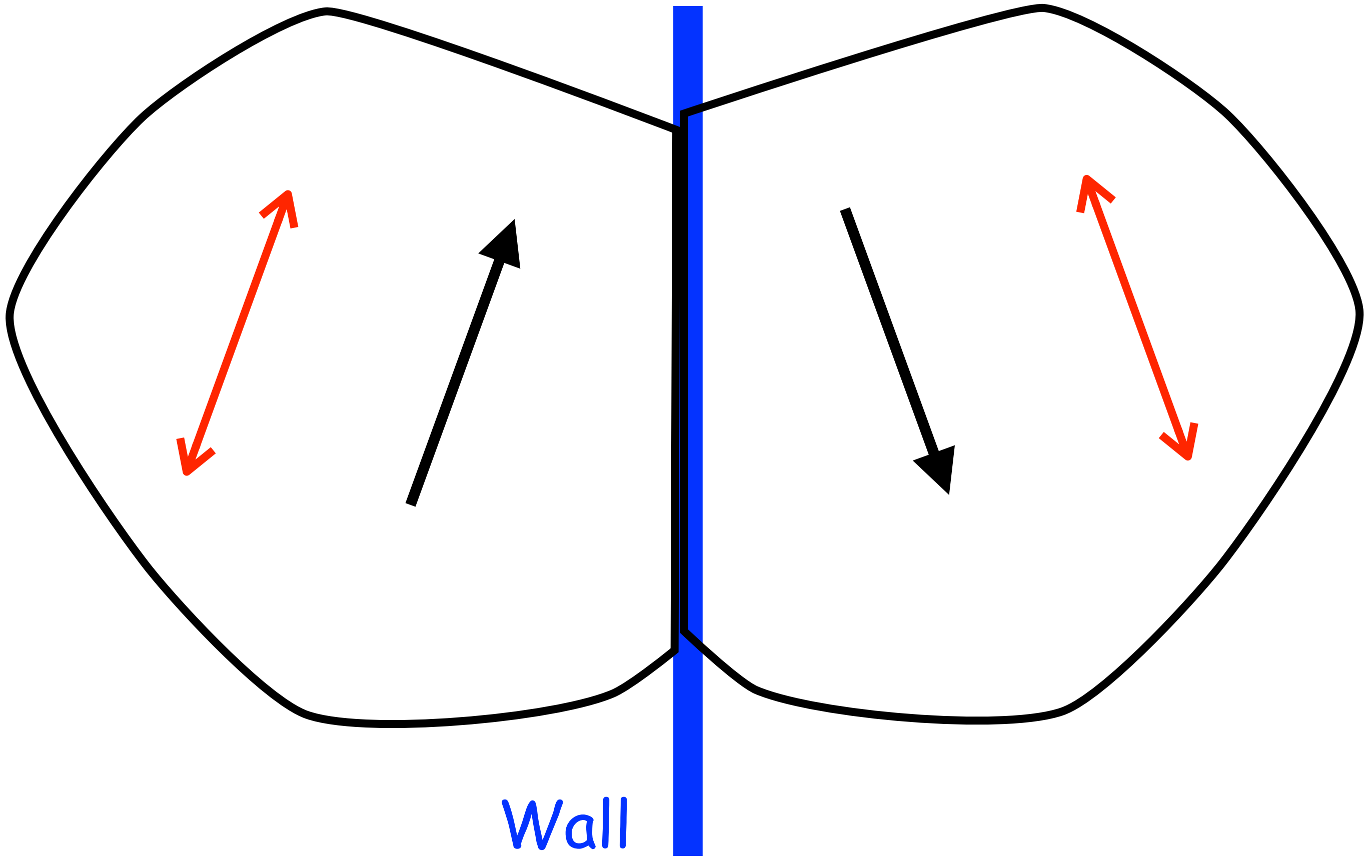
Coercivity

1) By domain wall pinning

At defects



At grain-, phase boundaries



Hardmagnetic materials, basics

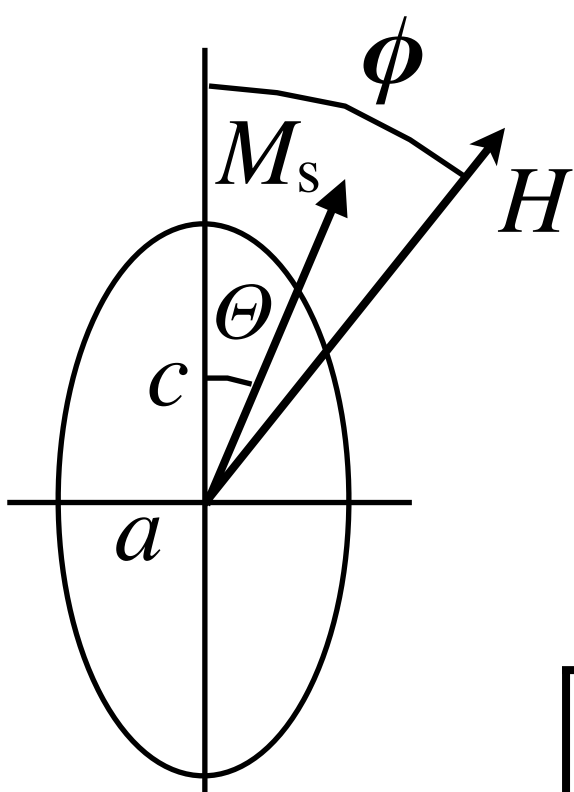
Coercivity

Hardmagnetic materials, basics

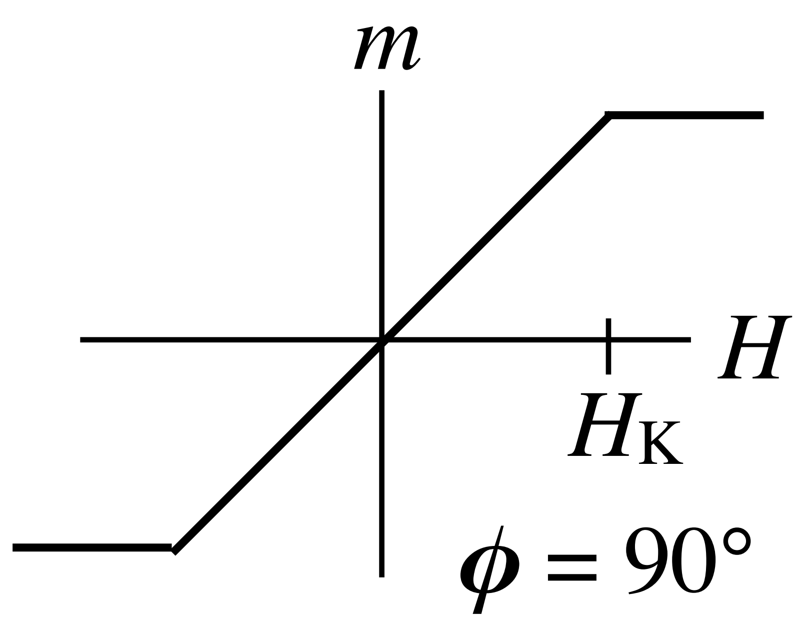
Coercivity

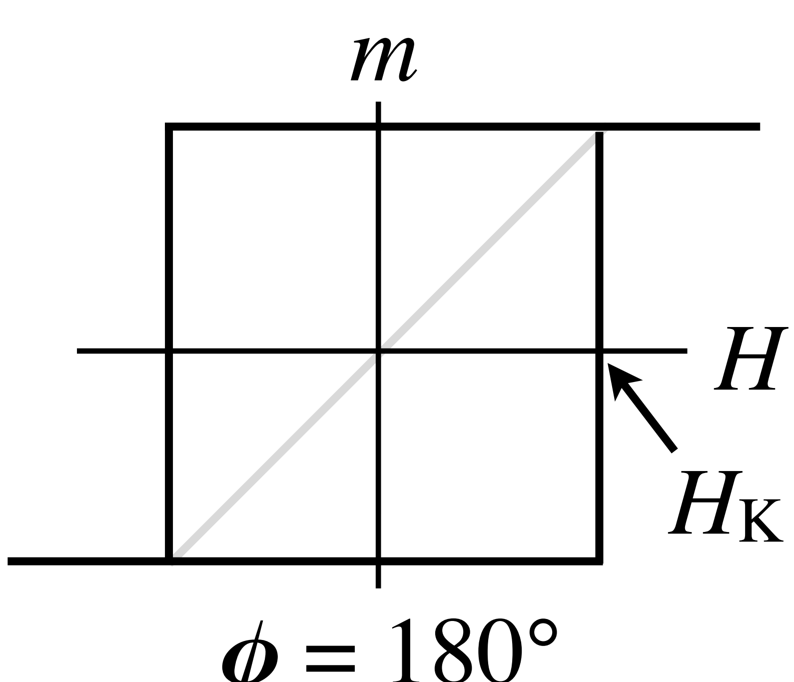
2) Single domain particles (Stoner/Wohlfarth)

Given: small ellipsoid (single domain)



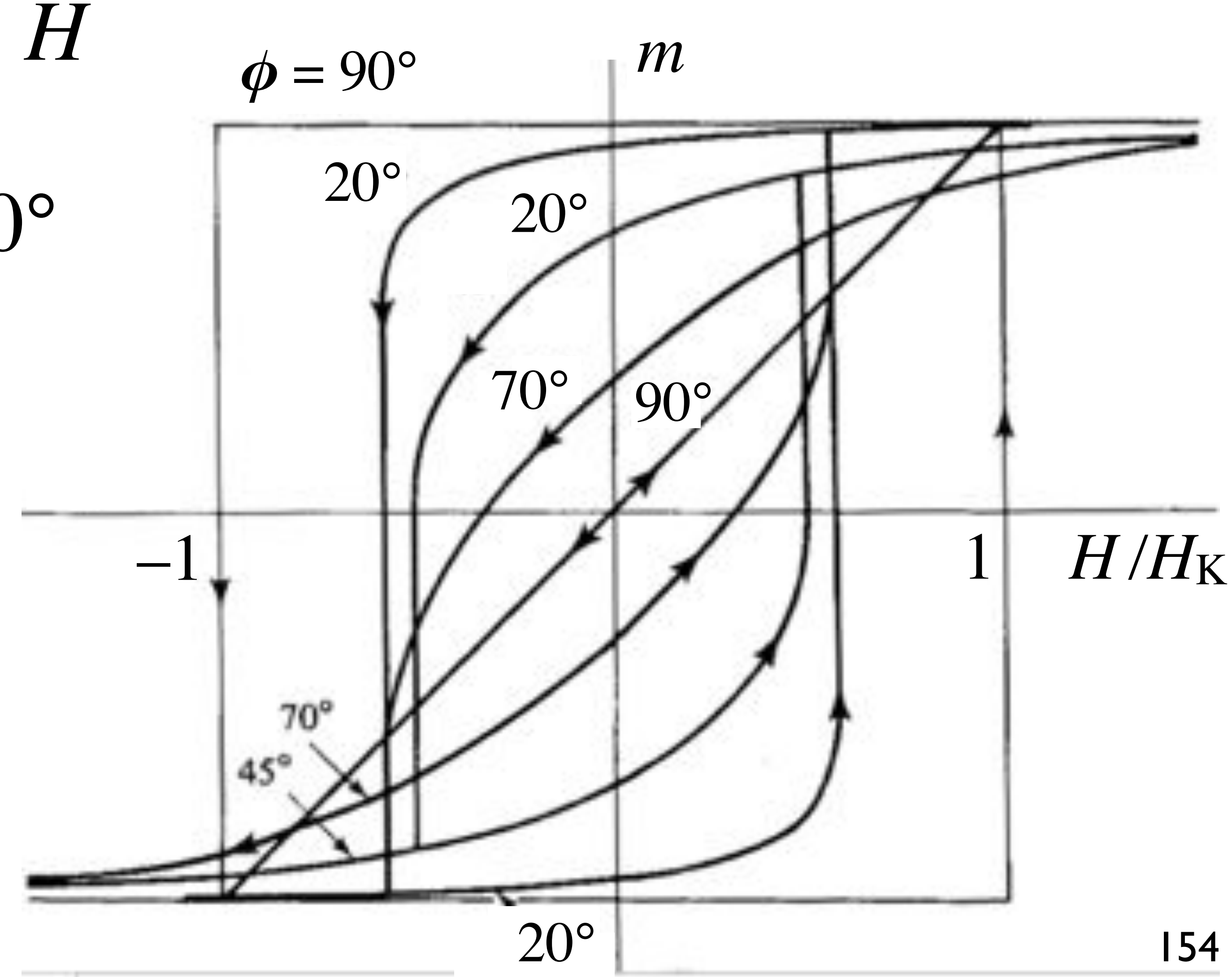
$K_u \parallel c$





Anisotropy field

$$H_K = 2K_u/\mu_0 M_s$$



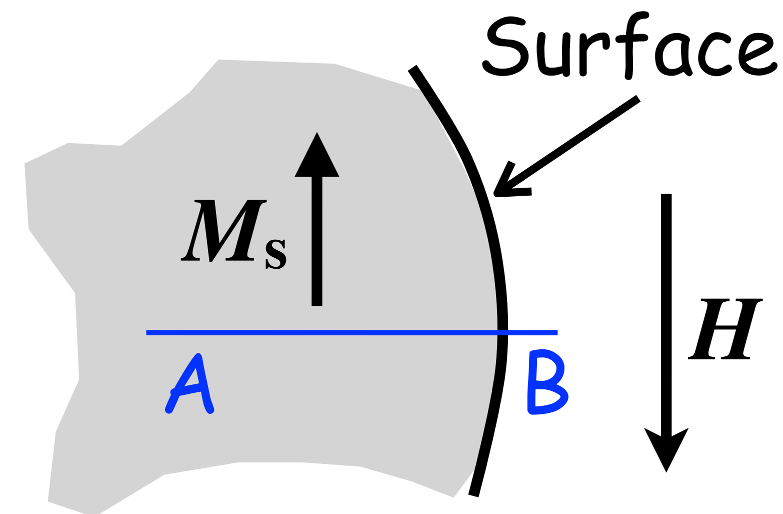
Coercivity

Hardmagnetic materials, basics

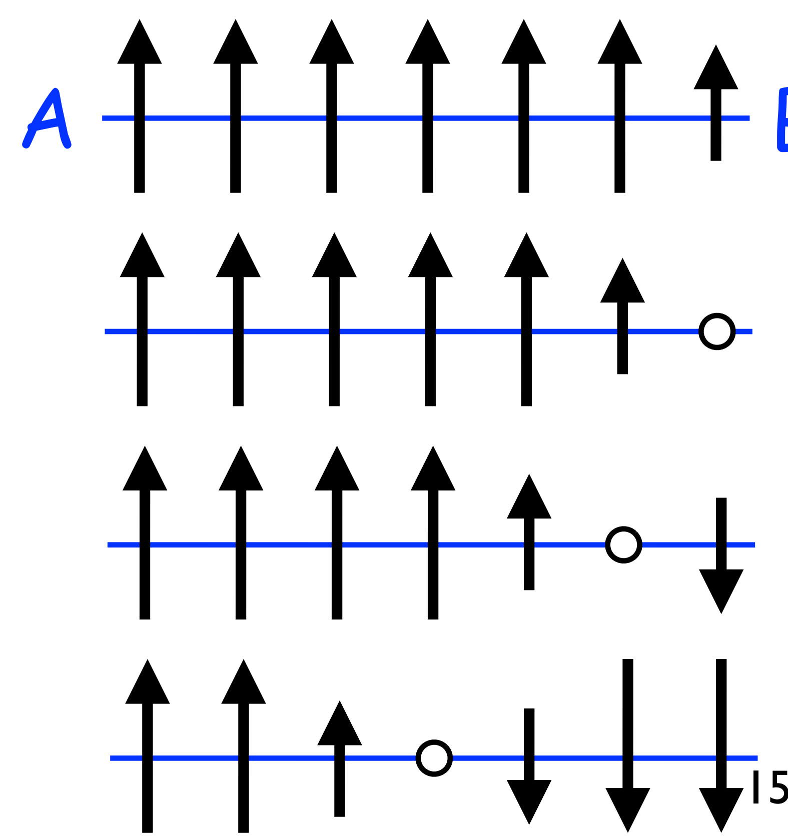
Coercivity

3) Large high-anisotropy particles ($Q > 1$)

- Elliptical particle, K_u, $d > d_{1\text{-dom}}$
- Expectation: walls do exist $\longrightarrow$ H_c small
- However, theory predicts: $H_c = H_K$ for $Q > 1$
- Explanation (W.F. Brown): after saturation along e.a.: domain nucleation hindered (although domain state energetically favorable)
- Reason: Nucleation = rotation against anisotropy $\longrightarrow$ requires $H_K \longrightarrow$ wall nucleation only for $H_{in} = H_{ext} + H_{dem} > 2K/\mu_0 M_s$ (independent of particle size)
- However: experimental H_c much smaller = **Brown's paradox**



Wall nucleation



Hardmagnetic materials, basics

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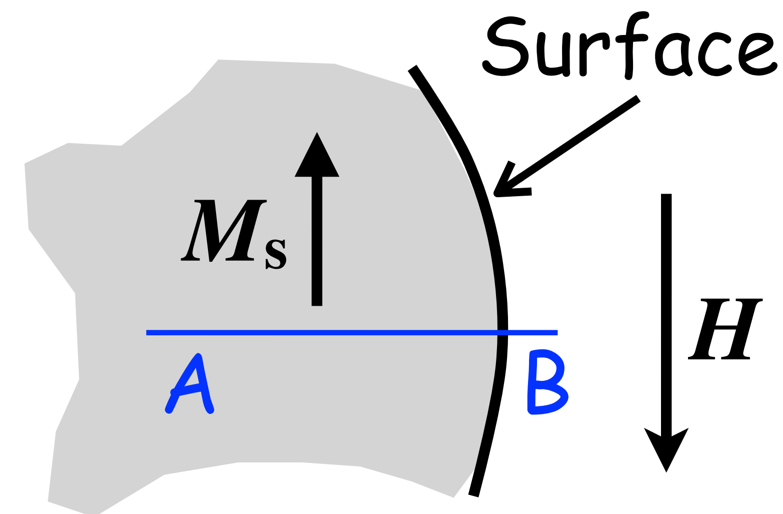
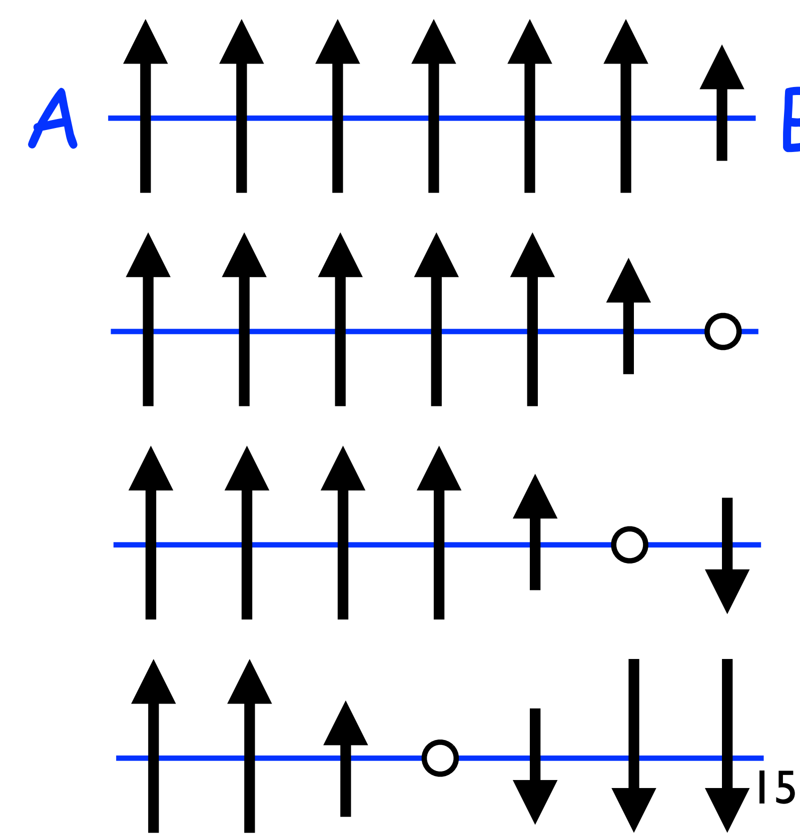


Wall nucleation



Hardmagnetic materials, basics

Coercivity

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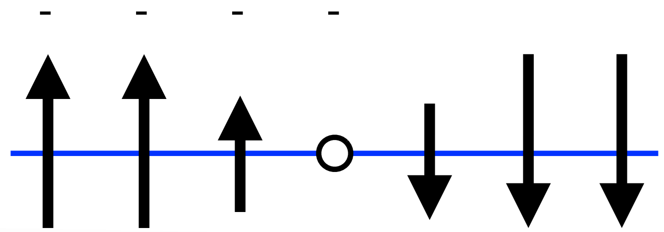
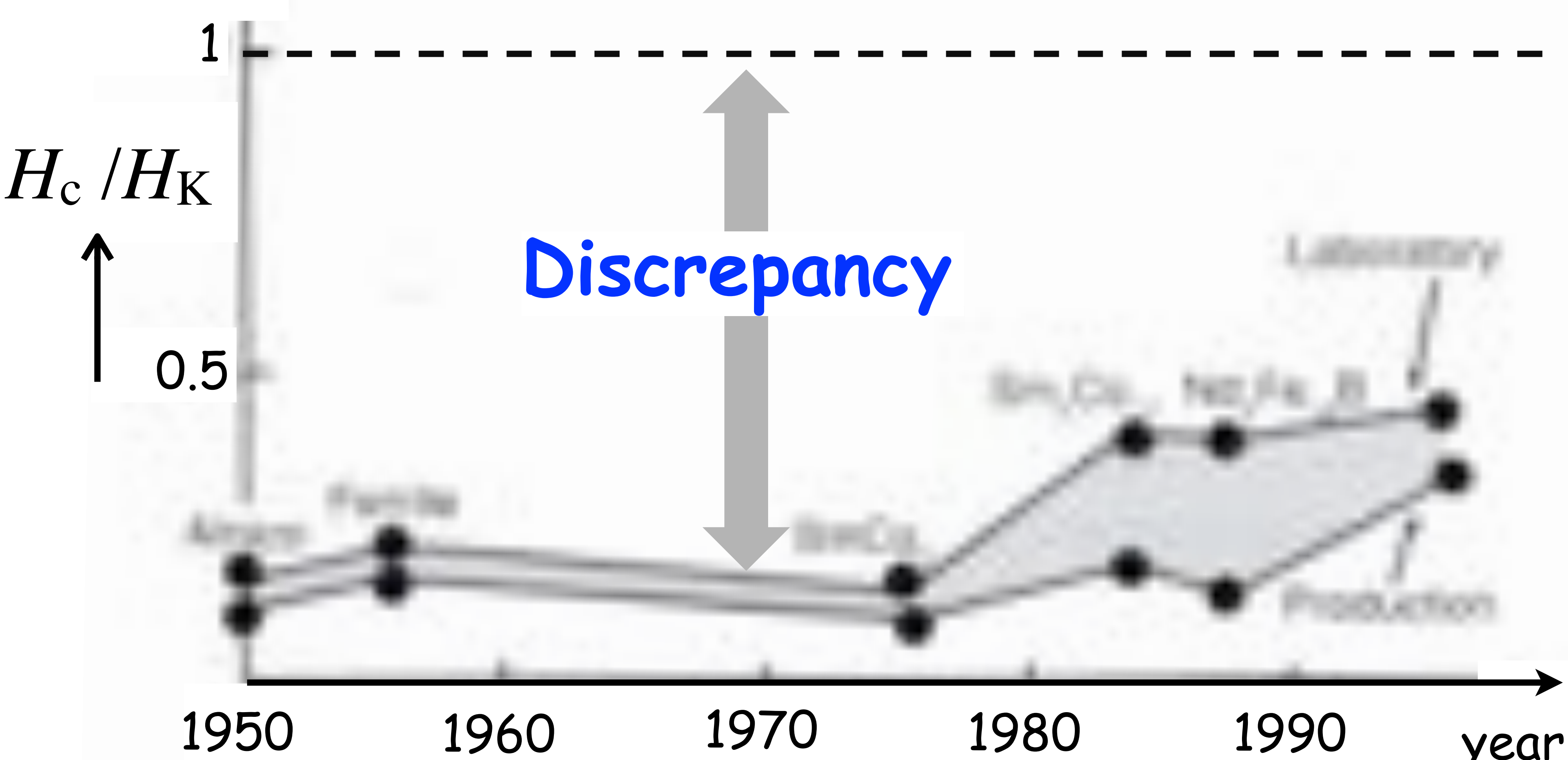
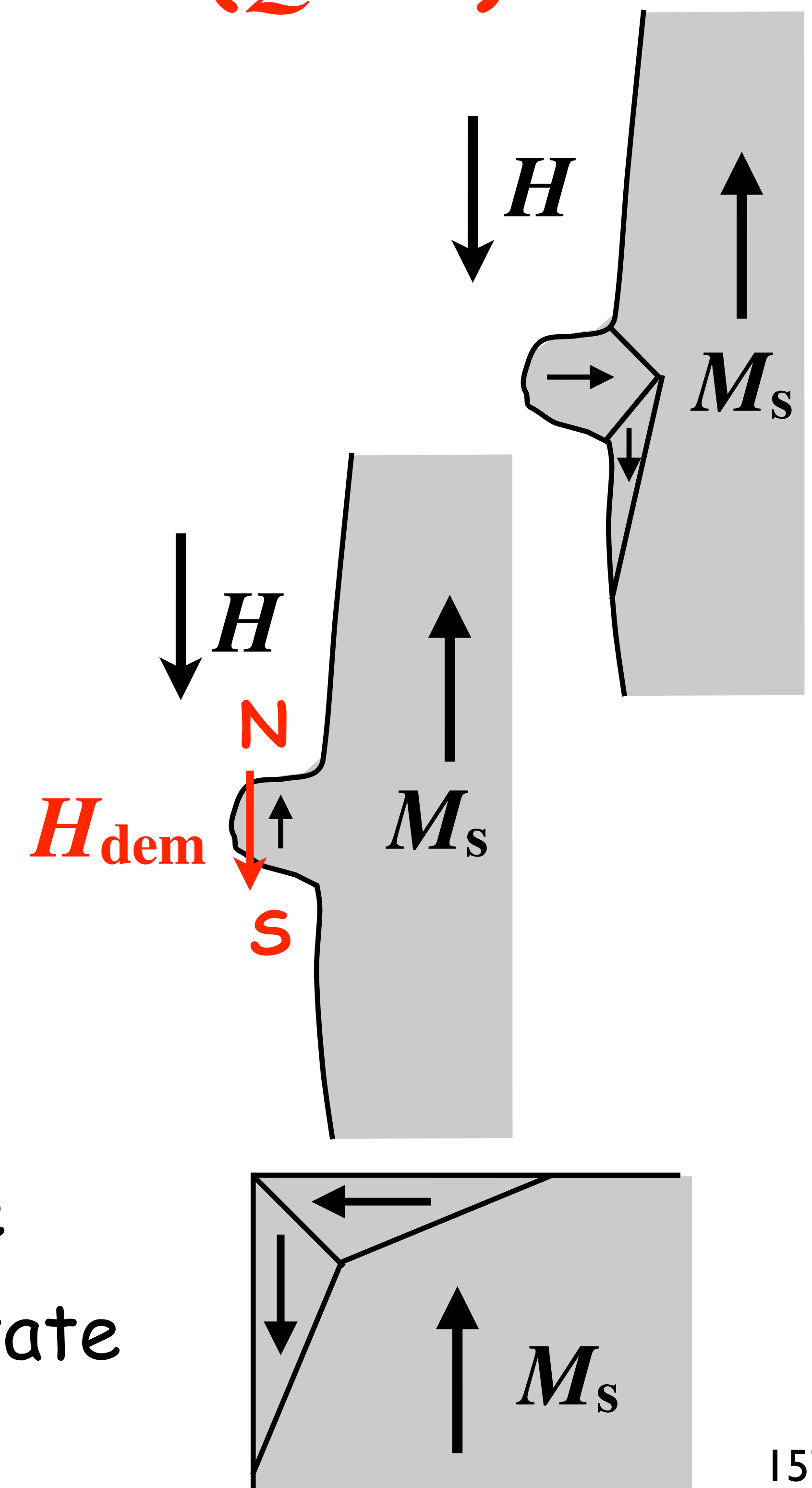




Coercivity

3) Large high-anisotropy particles ($Q > 1$)

- However: experimental H_c much smaller = **Brown's paradox**
- Reasons:
  - Real samples are not elliptical
  - Areas of reduced anisotropy (defects, etc.)
  - Sharp edges: $H_{dem} \longrightarrow \infty$
  - Defects, bulges: $H_{dem}\uparrow$ (reduction of nucleation field), or residual domain walls which can be easily mobilized
- The larger the particles, the larger is number of defects $\longrightarrow H_c$ decreases with particle size
- If premature nucleation: low-energy domain state is formed, magnetization by wall displacement



Hardmagnetic materials, basics

2 types of (large-grained) magnets

Reversal mechanisms:

(A) Nucleation in bulk

(B) Nucleation at defect

(C) Pinning at extended defects

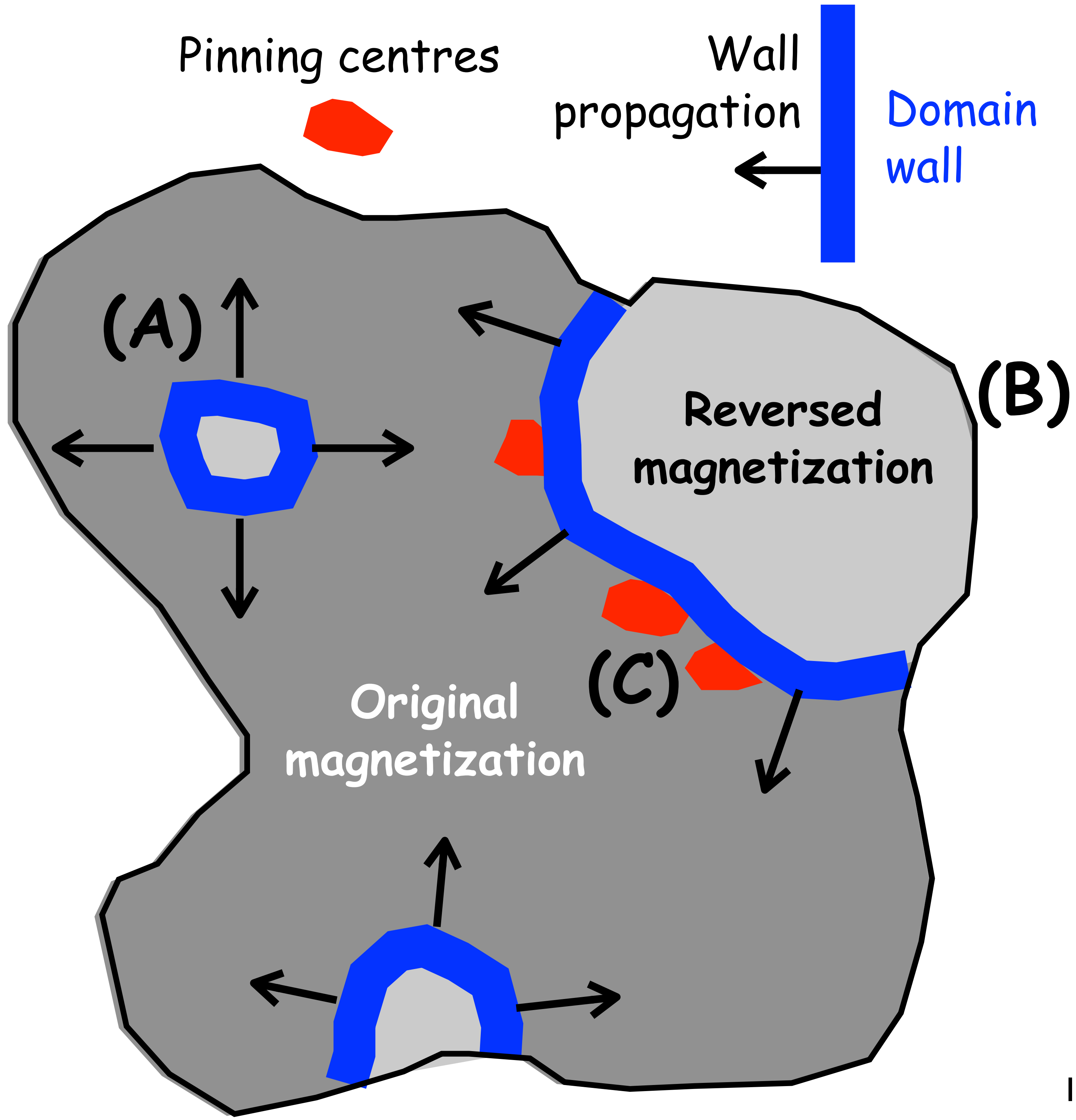
↓

Nucleation-type magnets

Magnetization reversal determined by nucleation of domains

Pinning-type magnets

Magnetization reversal (coercivity) determined by pinning of domain walls



Hardmagnetic materials, basics

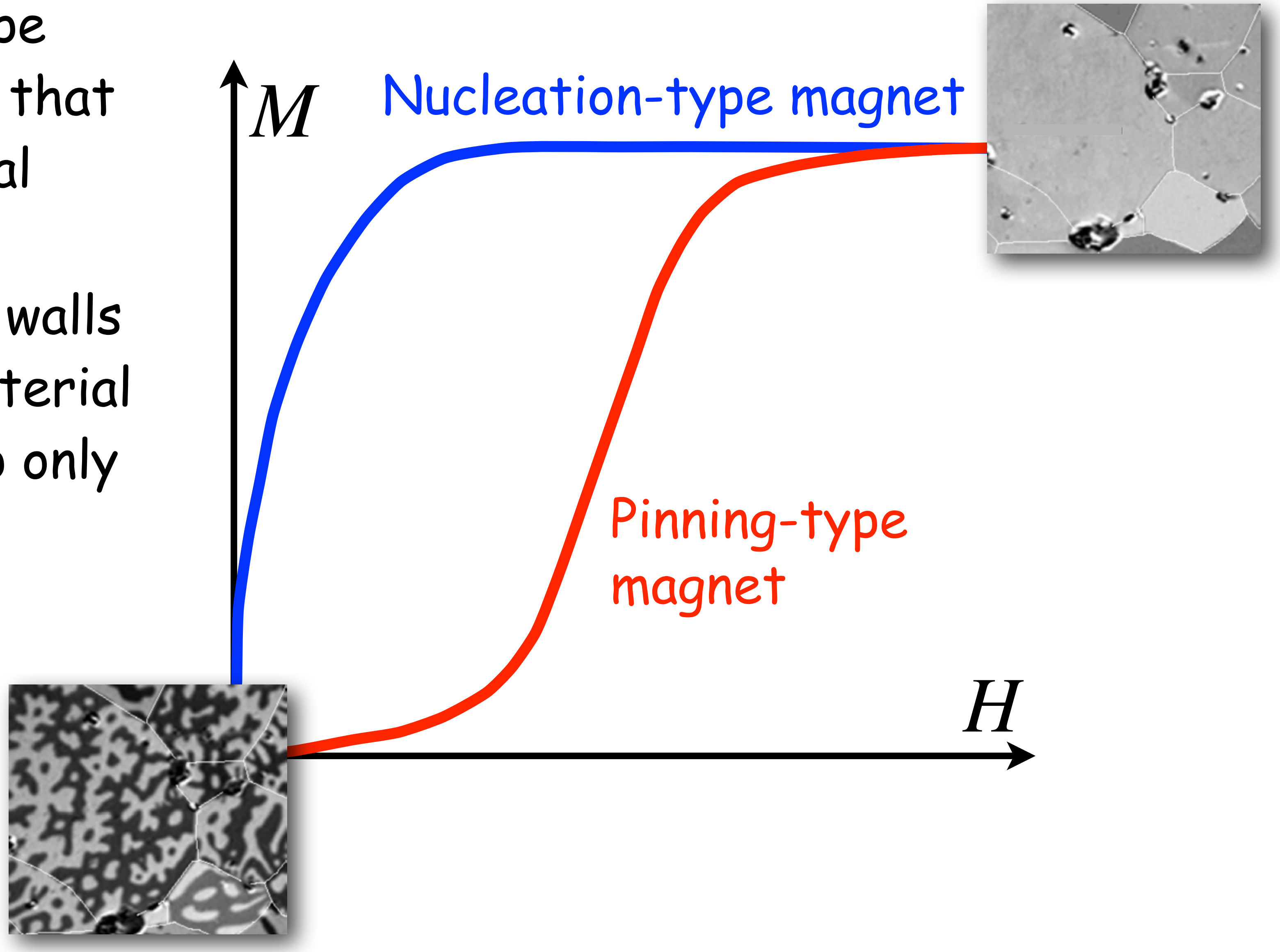
2 types of (large-grained) magnets

Difference between two types of large-grained magnets can best be seen in the initial magnetization curves:

Starting from thermally demagnetized state, every grain in a nucleation-type material contains many domain walls that can be displaced easily → large initial permeability. Permanent magnet properties appear only when domain walls are driven out in large field. The material can be remagnetized after this step only if new domain walls are nucleated.

In contrast, in a material with many defects (like precipitations) domain walls are effectively pinned, leading to low initial permeability.

Initial magnetization curves:

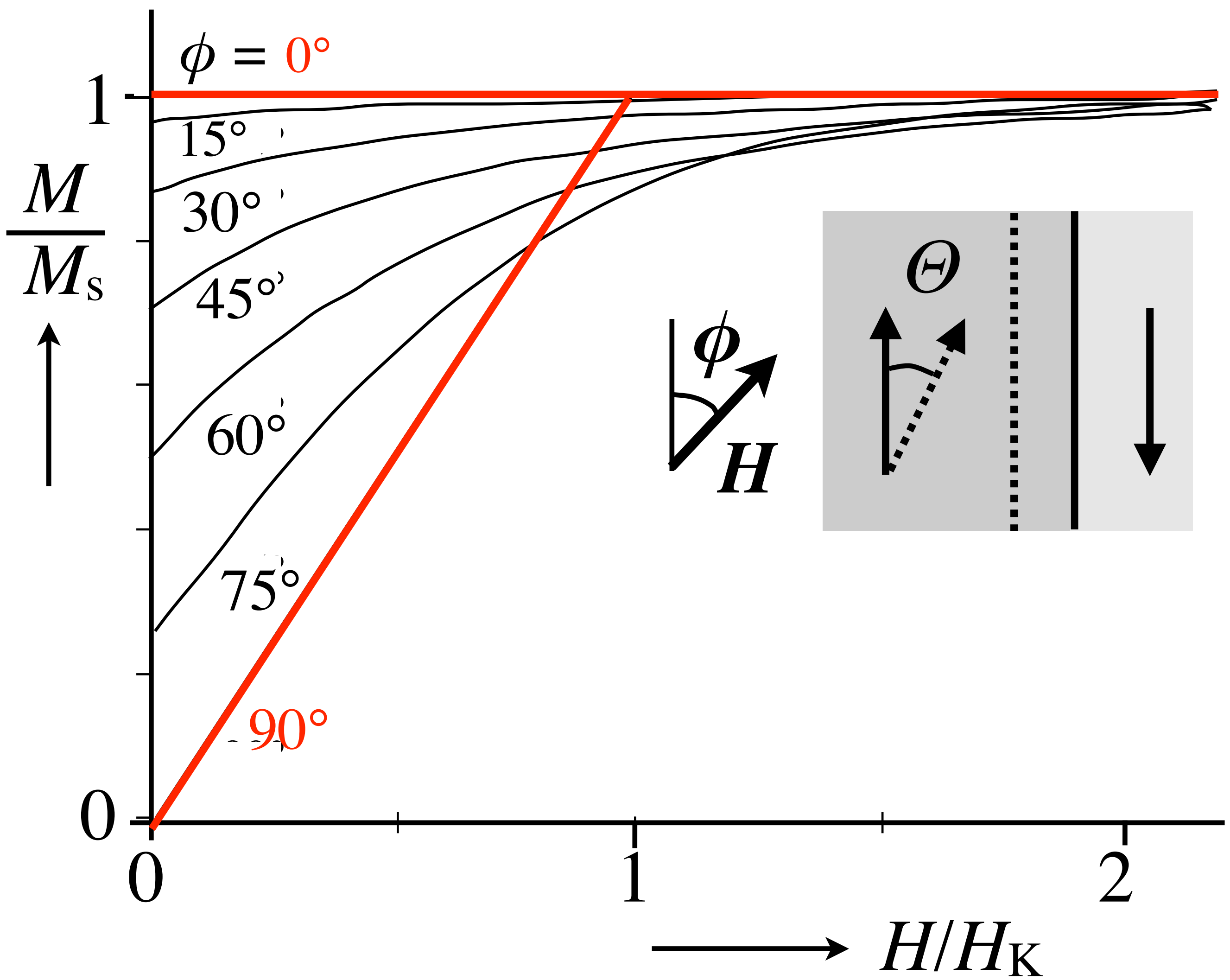


Hardmagnetic materials, basics

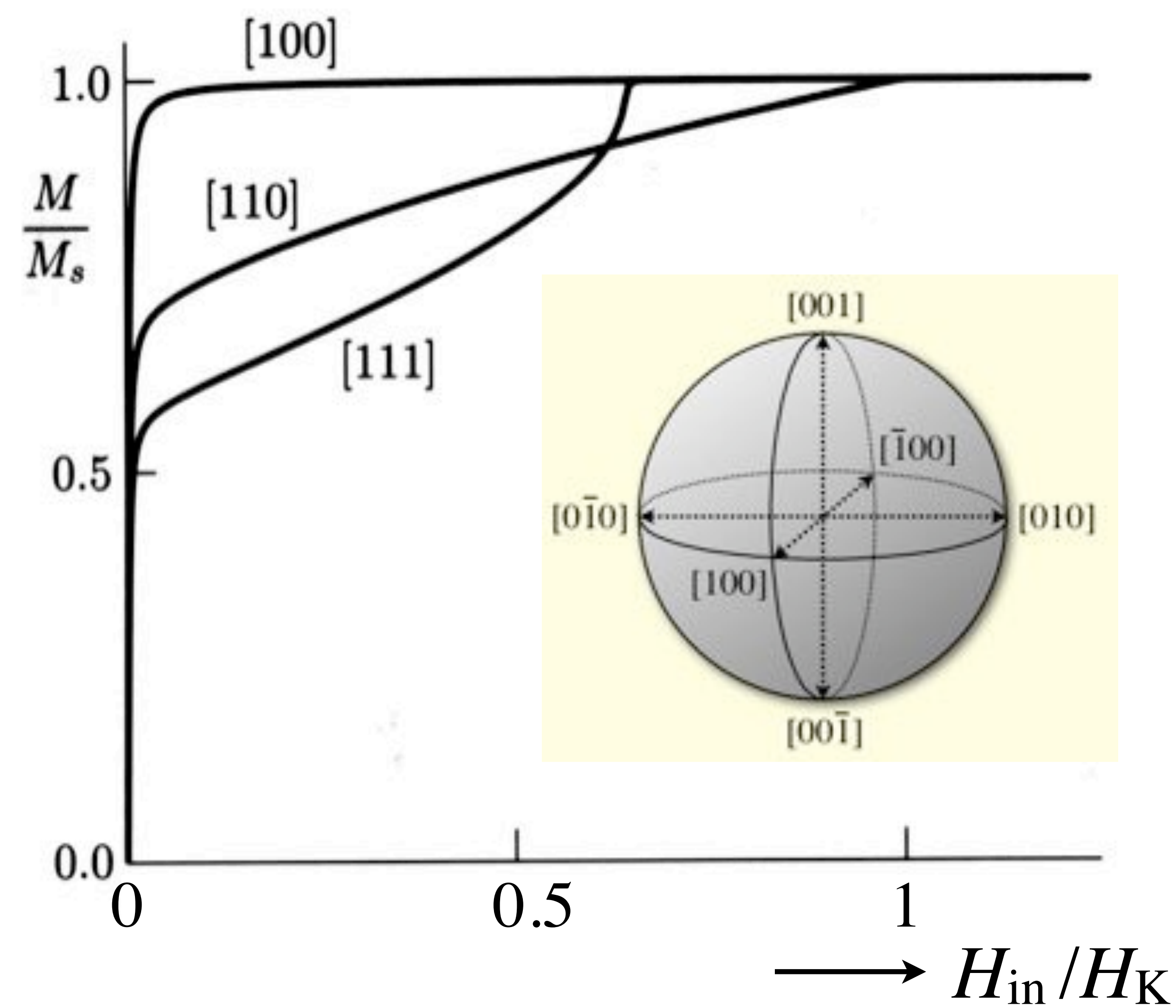
(A) Single crystals

Remanence depends on field direction relative to easy axes

Single crystal with uniaxial anisotropy



Iron single crystal with cubic anisotropy



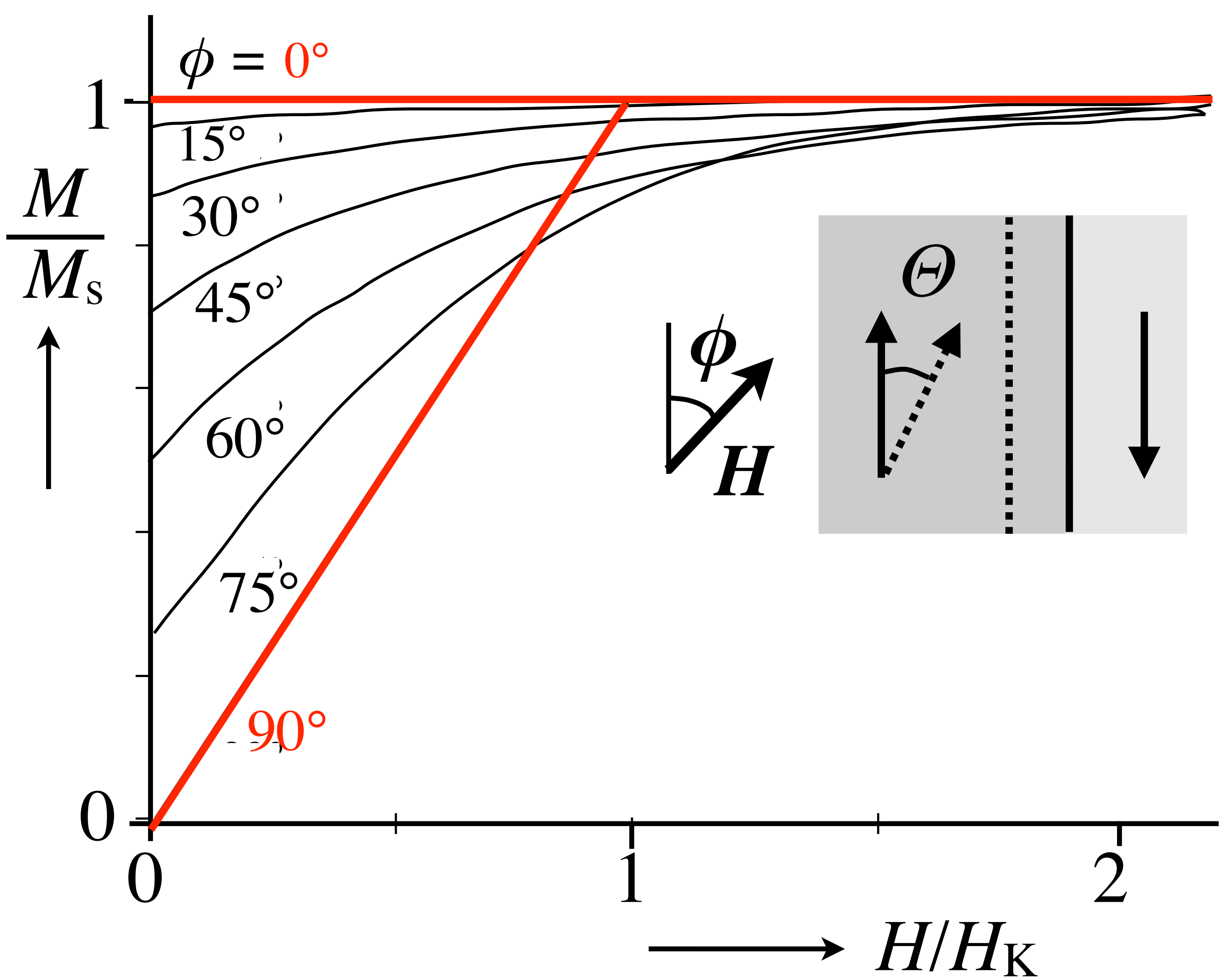
Hardmagnetic materials, basics

Remanence

(A) Single crystals

Remanence depends on field direction relative to easy axes

Single crystal with uniaxial anisotropy



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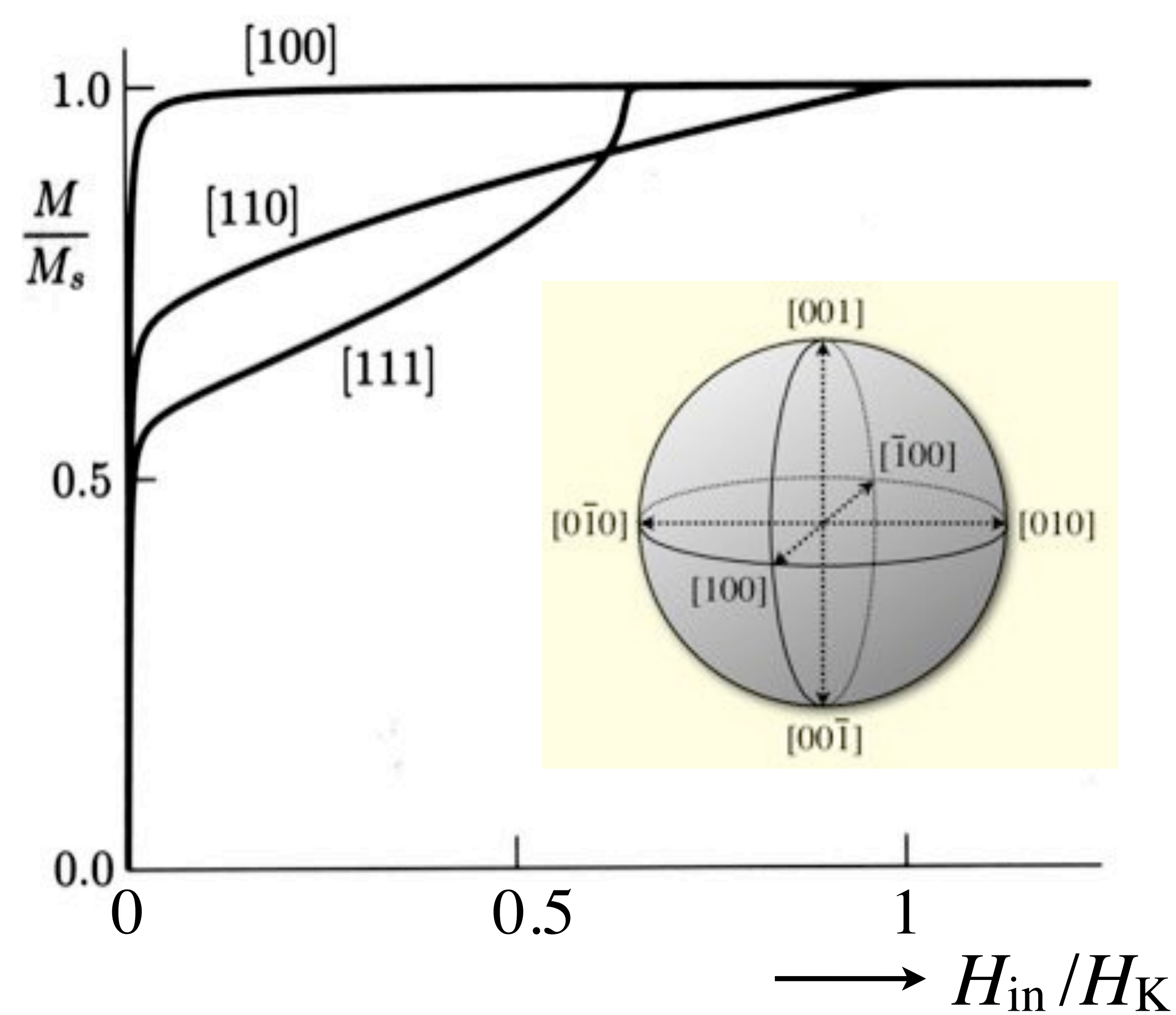

Hardmagnetic materials, basics

Remanence

(A) Single crystals

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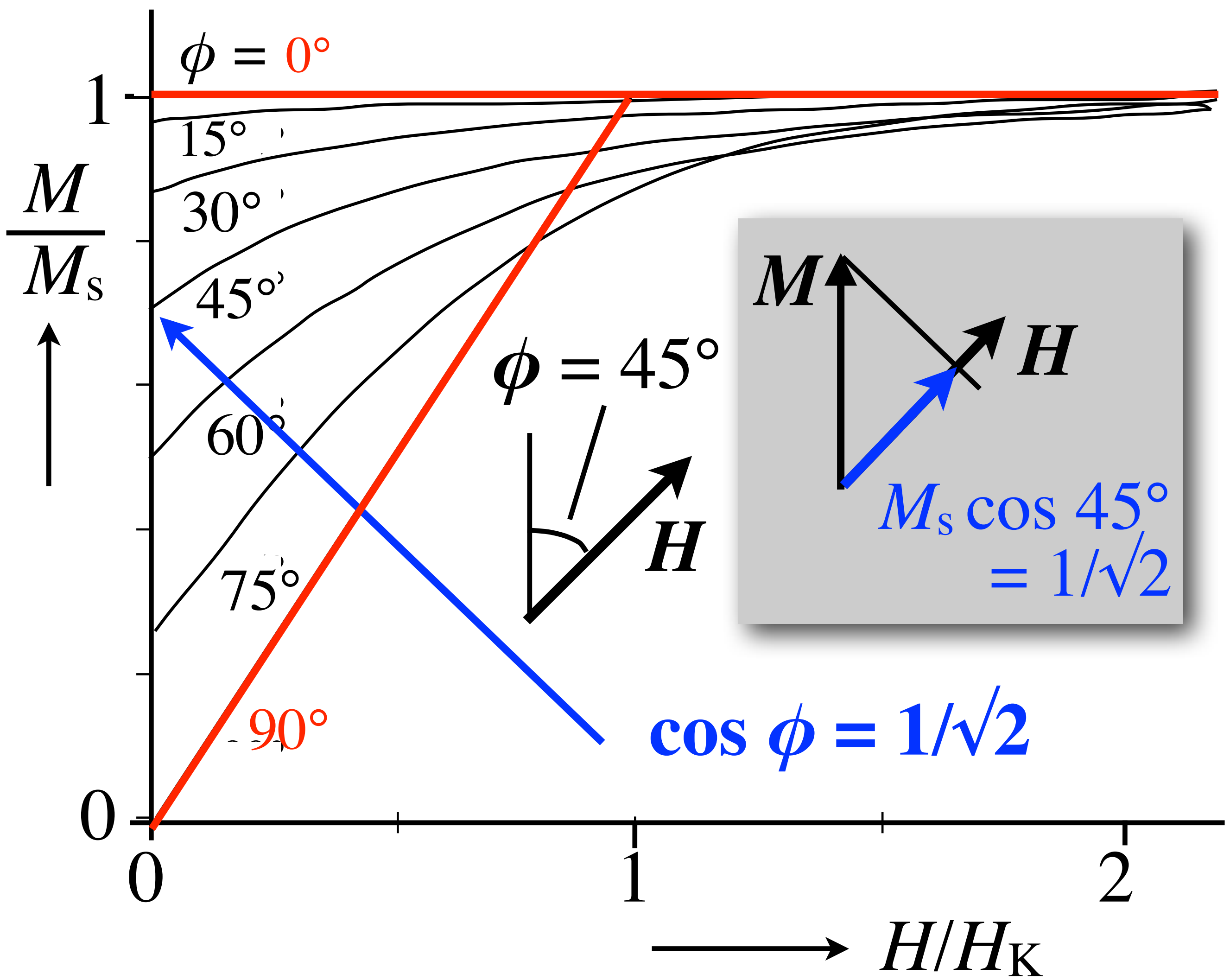
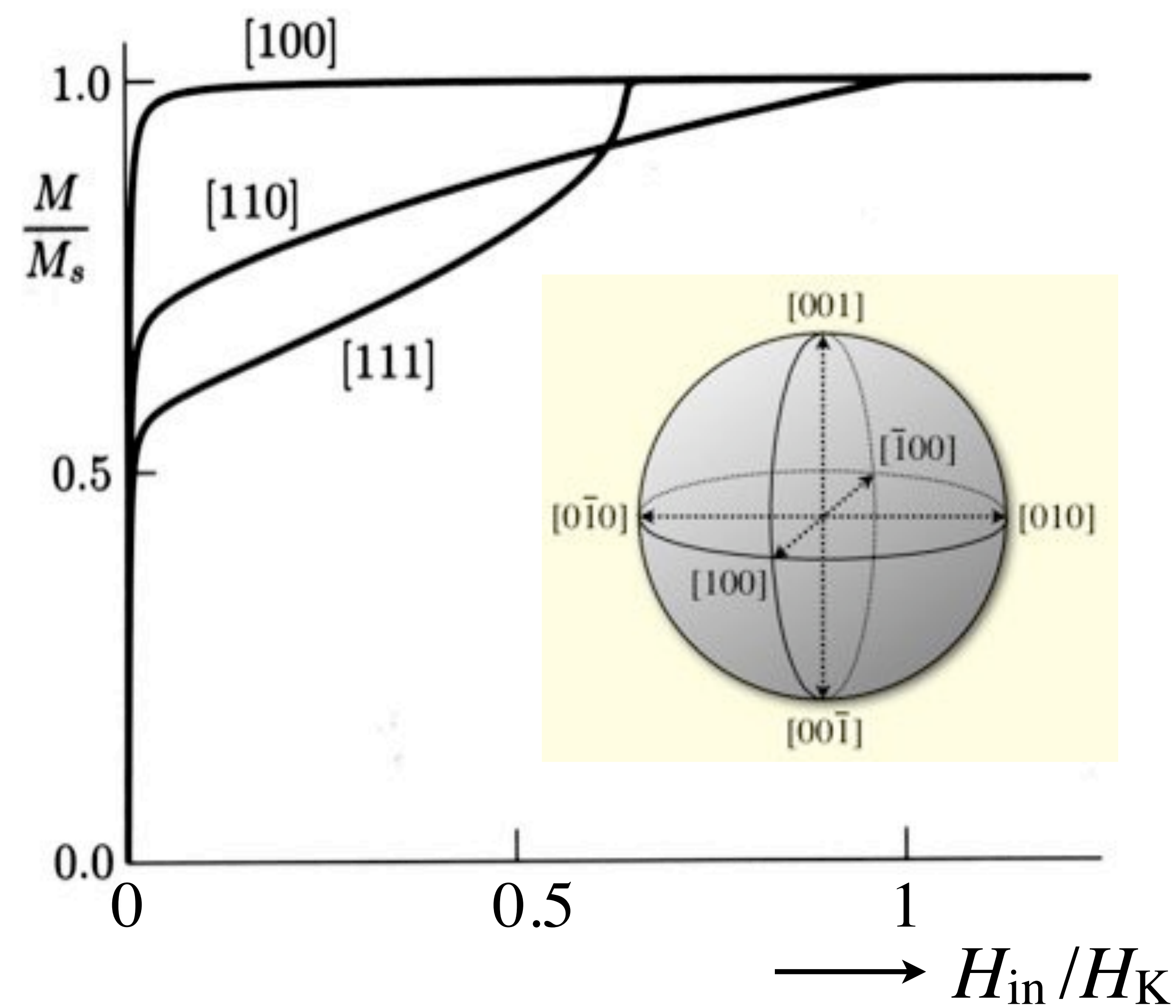
Single crystal with uniaxial anisotropy



Iron single crystal with cubic anisotropy

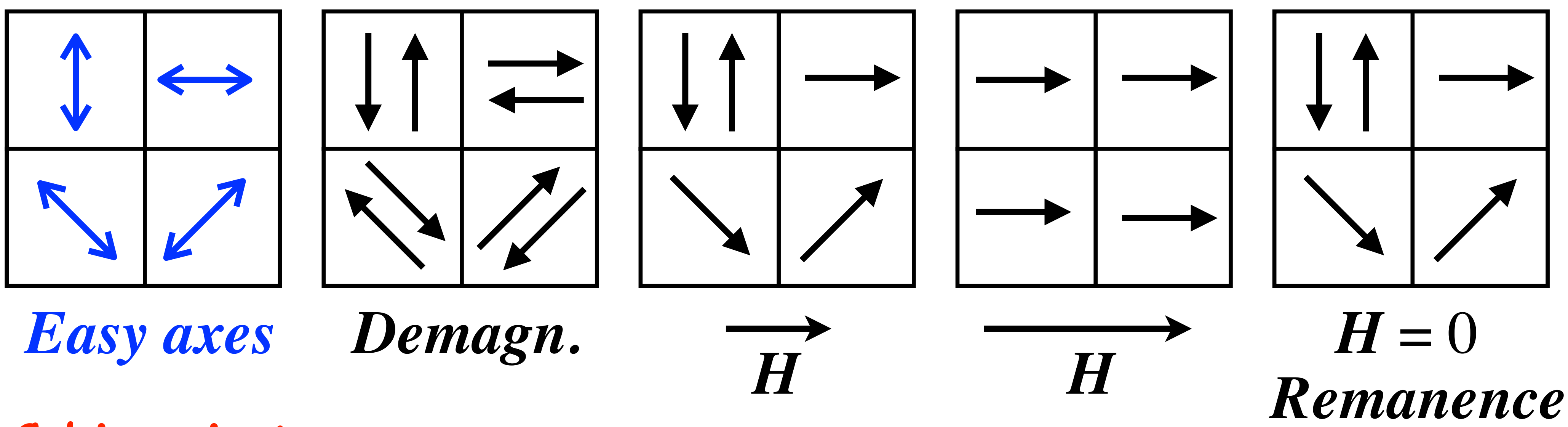


Hardmagnetic materials, basics

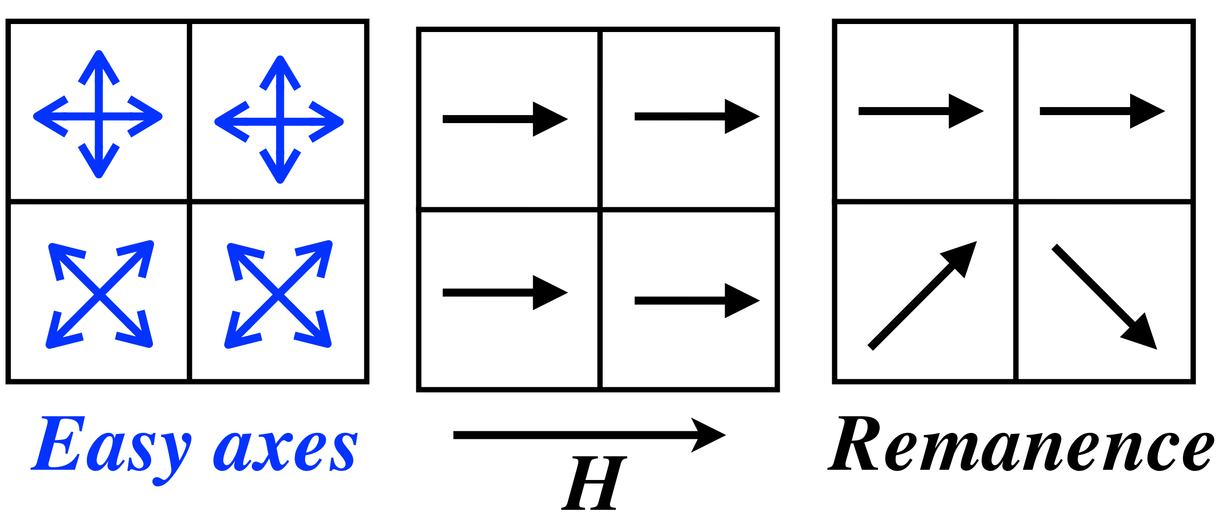
Remanence

(B) Polycrystals

Uniaxial anisotropy



Cubic anisotropy



After removing the field, the magnetization of each grain falls back to those easy axes that are closest to the field direction $\longrightarrow$ remanence

Uniaxial Polycrystal: $M_r = 0.5\ M_s$

Cubic Polycrystal ($K_{c1} > 0$): 3 easy $\langle 100 \rangle$ axes, $M_r = 0.83\ M_s$

Cubic Polycrystal ($K_{c1} < 0$): 3 easy $\langle 111 \rangle$ axes, $M_r = 0.87\ M_s$

} **No coercivity**

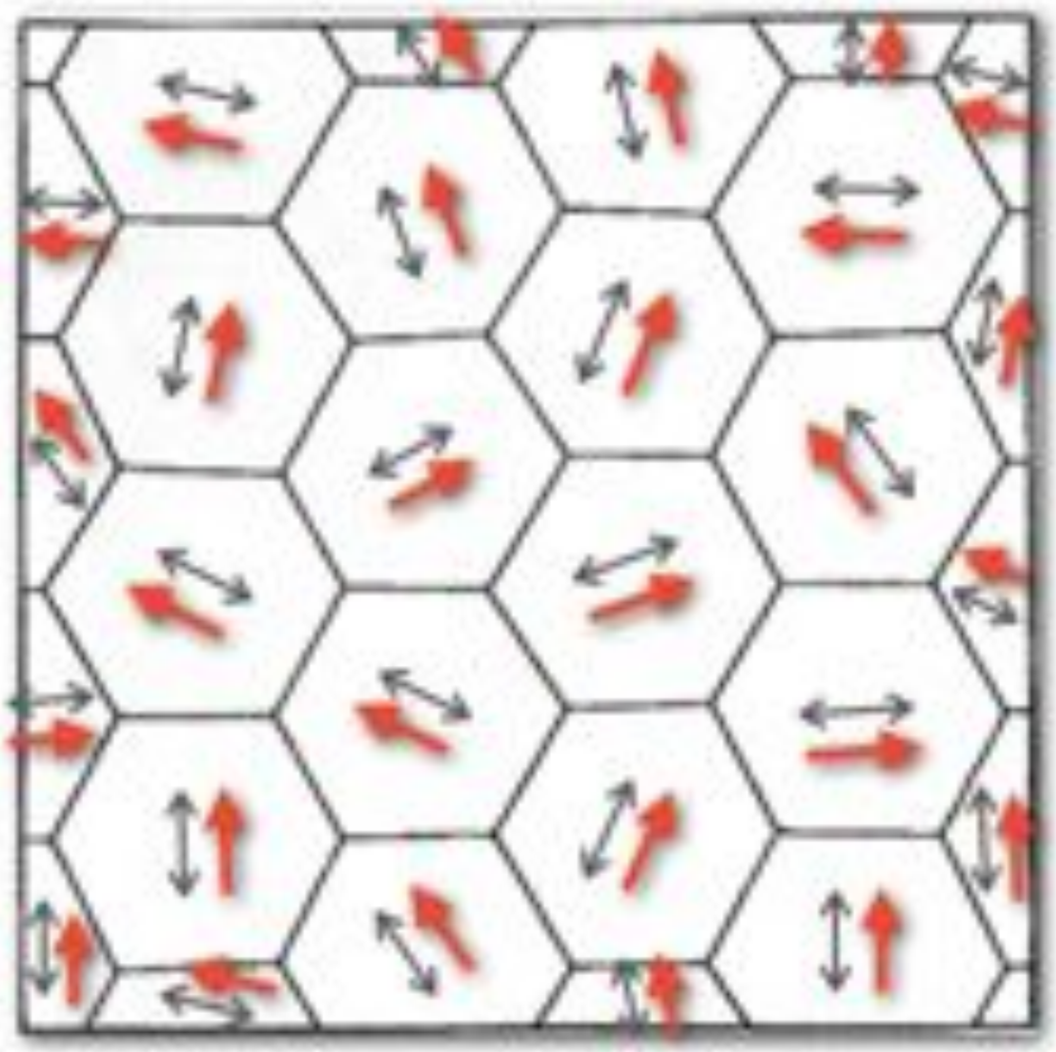
Hardmagnetic materials, basics

Remanence

(B) Polycrystals

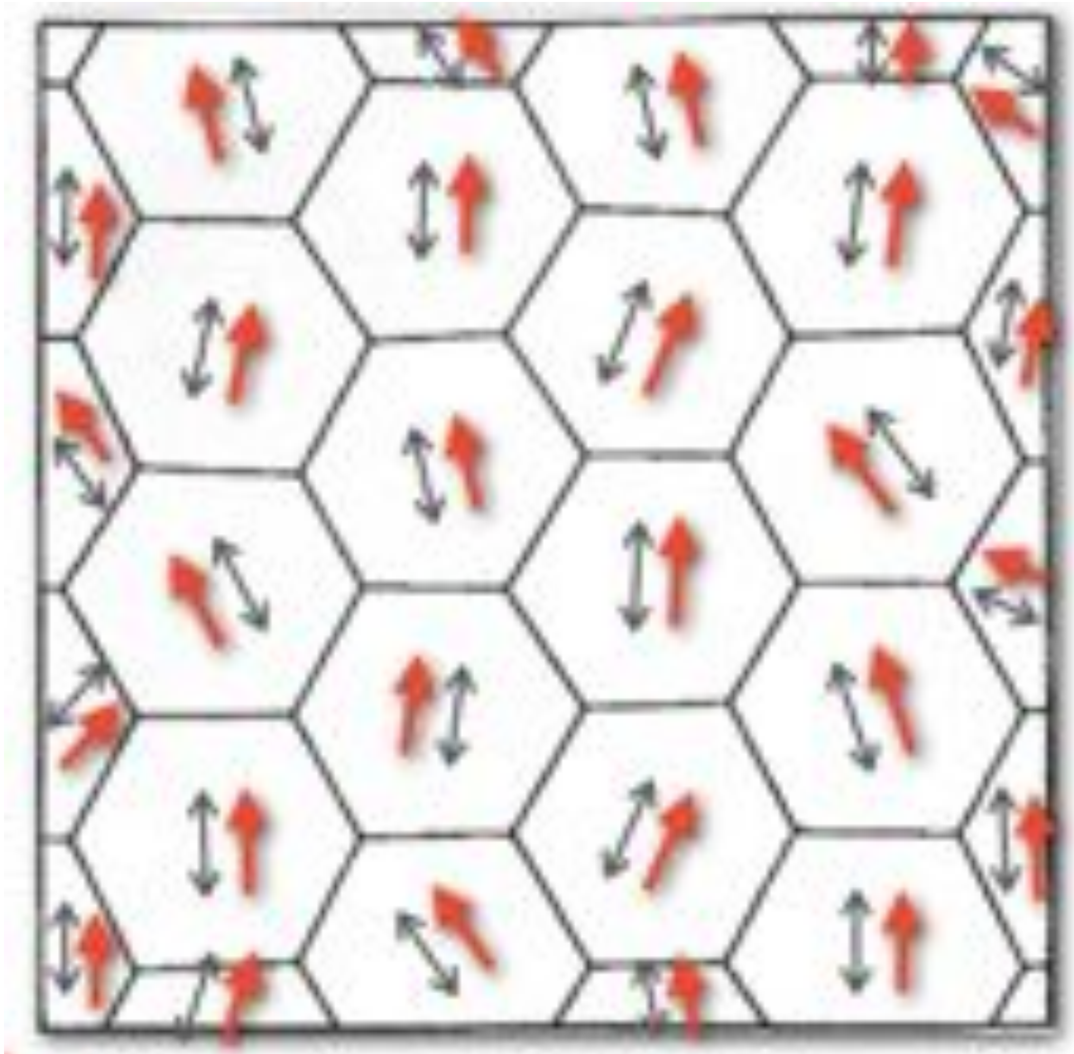
High remanence in uniaxial material: requires textured microstructure

Isotropic material



Remanence = 0.5 M_s

Anisotropic material (textured)



Remanence > 0.5 M_s

Magnetic field

Hardmagnetic Materials: Examples

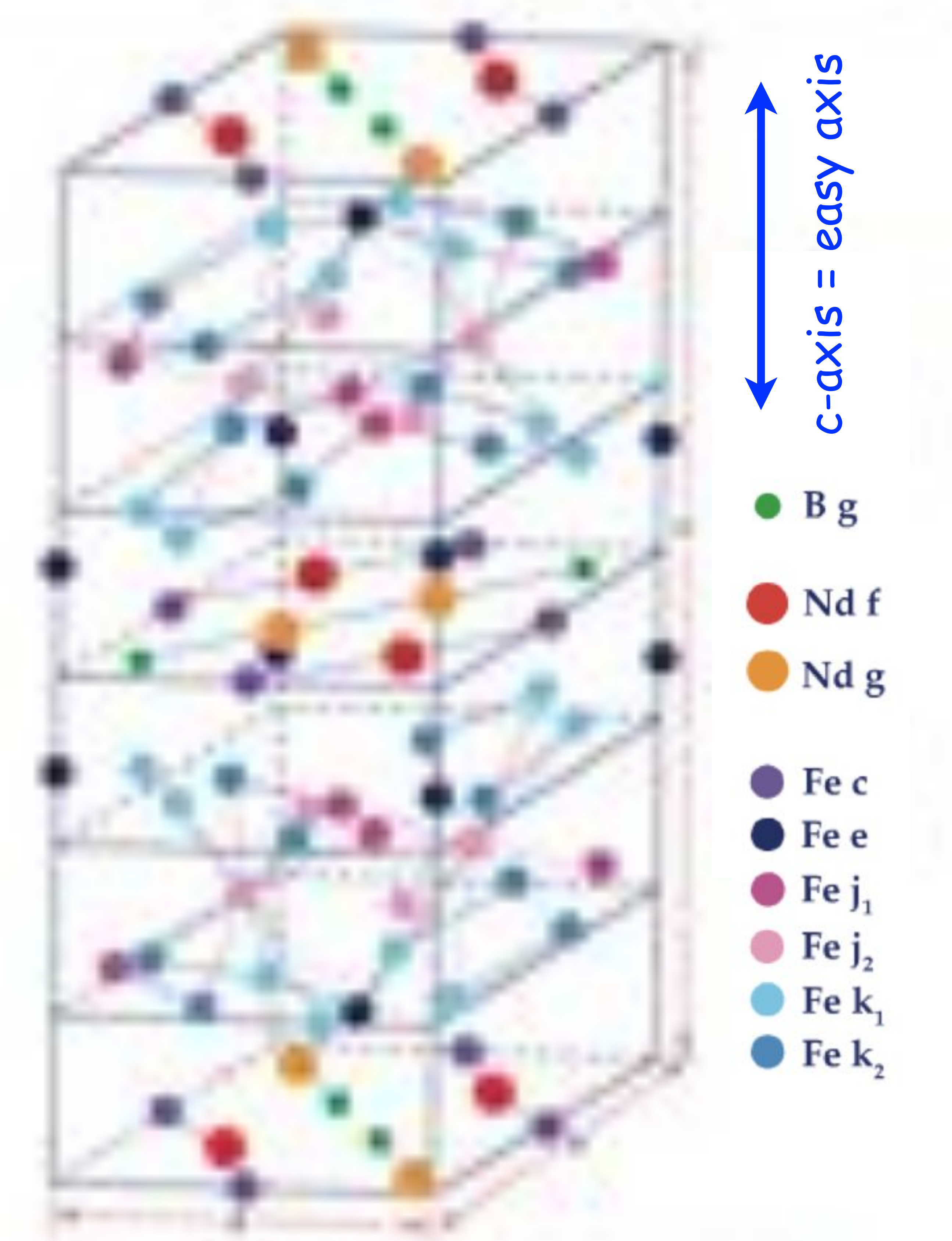
Hardmagnetic materials, examples

Hardmagnetic materials, examples

NdFeB, sintered

Hardmagnetic materials, examples

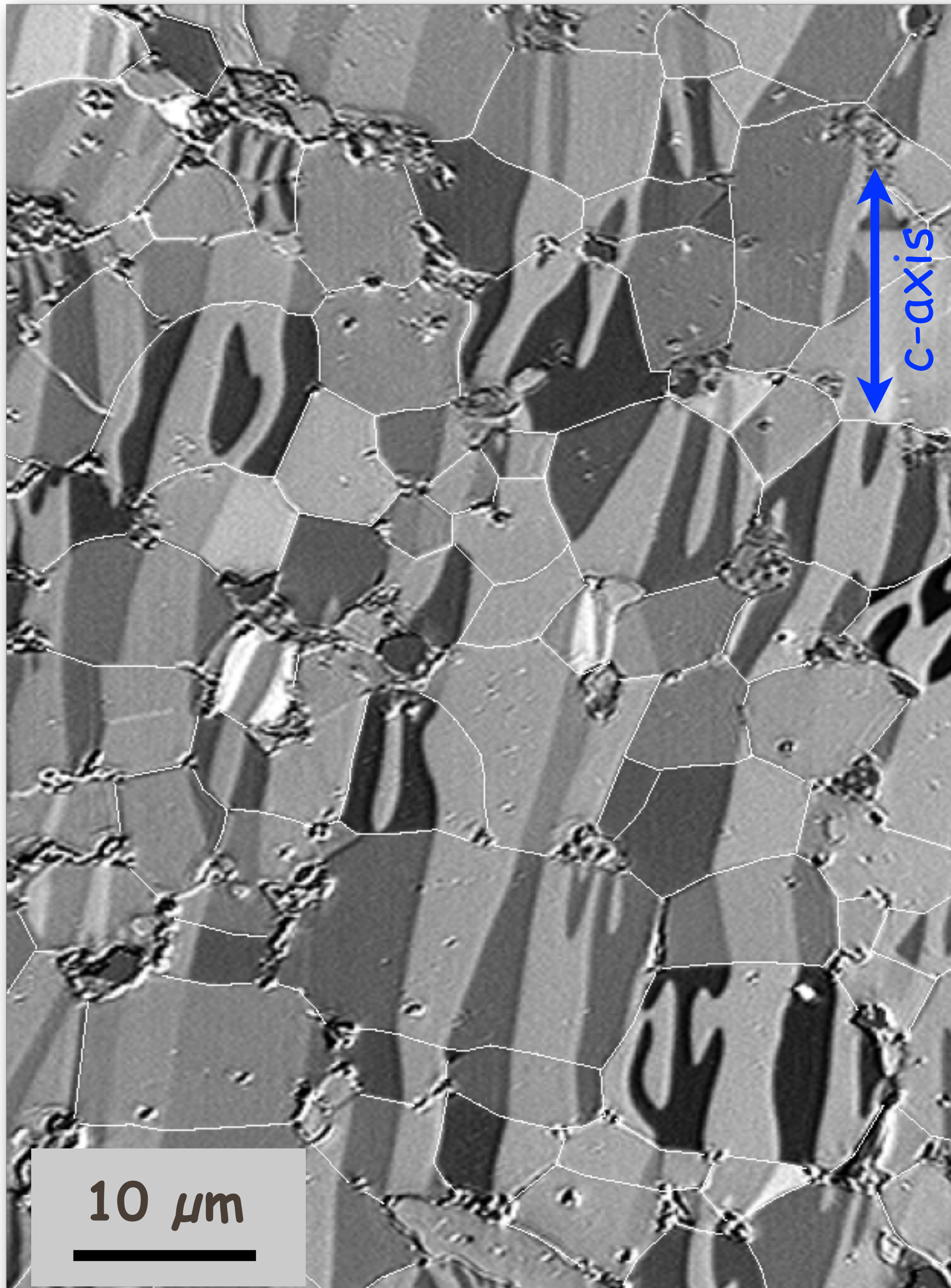
NdFeB, sintered



- Highest performance permanent magnets
- Based on $Nd_2Fe_{14}B$ phase: tetragonal, $K_c = 4900$ kJ/m^3, $T_c = 315$°C, $J_s \approx 1{,}61$ T
- Replace some Fe by Co: $T_c \uparrow$
  Replace some Nd by Dy: $H_c \uparrow$

Hardmagnetic materials, examples

Domains in sintered NdFeB magnet, thermally demagnetized



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Hardmagnetic materials, examples

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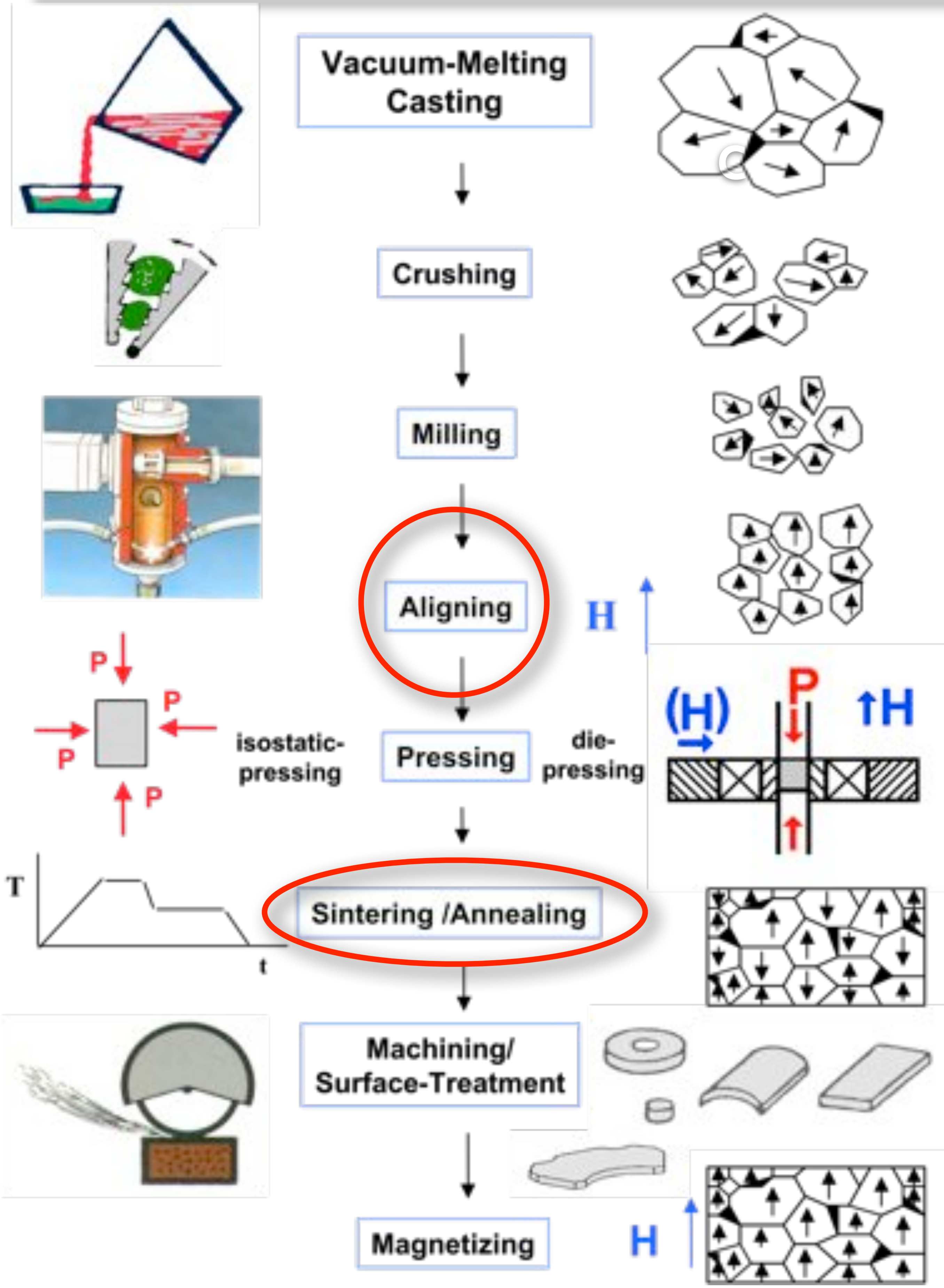
Hardmagnetic materials, examples



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- Preparation: aligning of single-grain particles, sintering

Hardmagnetic materials, examples

NdFeB, sintered

$Nd_2Fe_{14}B$ grains

Inpurities, e.g. oxides

Intergranular Nd-rich phase, **non-magnetic**

↓

Grains are „exchange-decoupled"
(domain walls do not pass grain boundaries)

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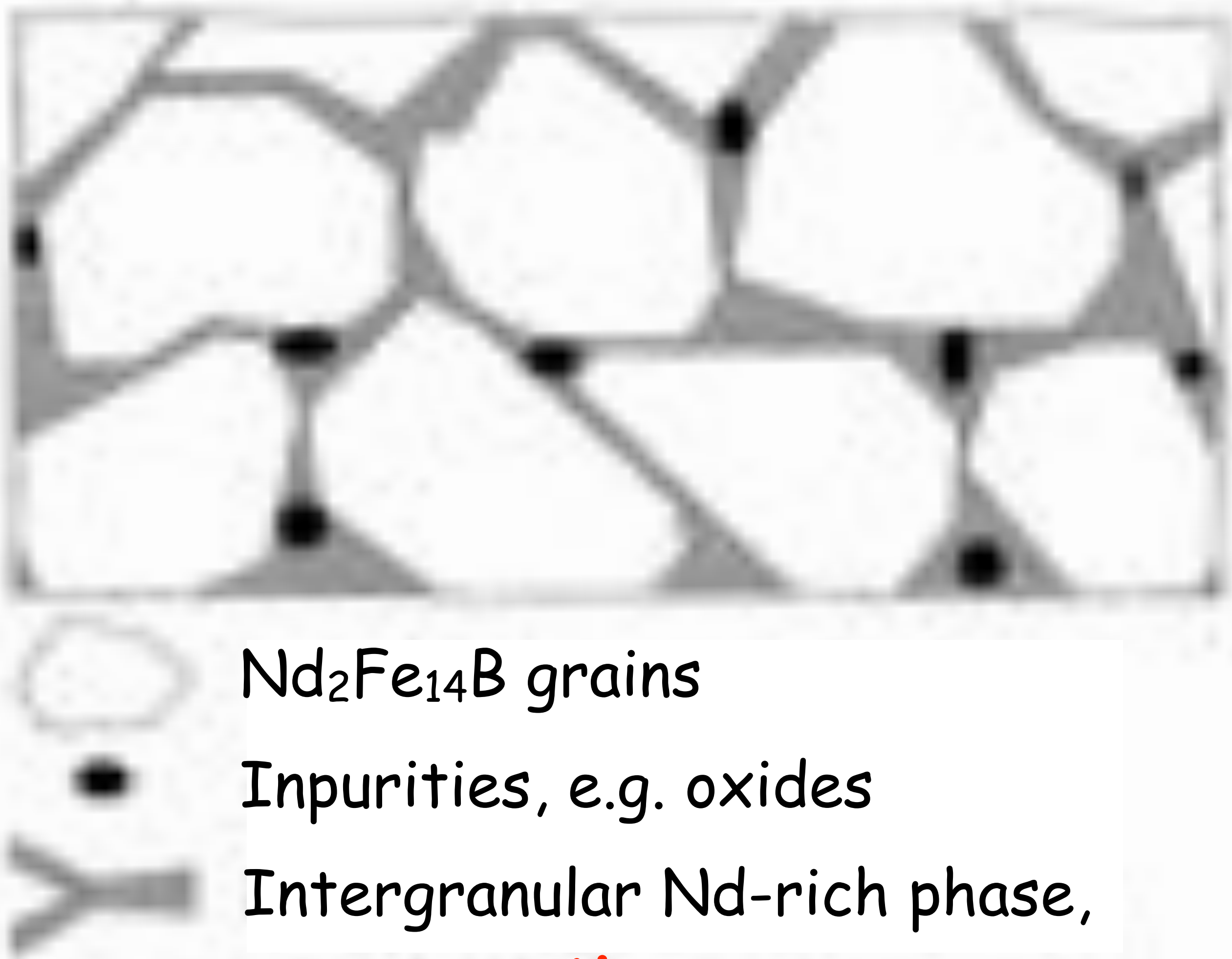
Hardmagnetic materials, examples

NdFeB, sintered



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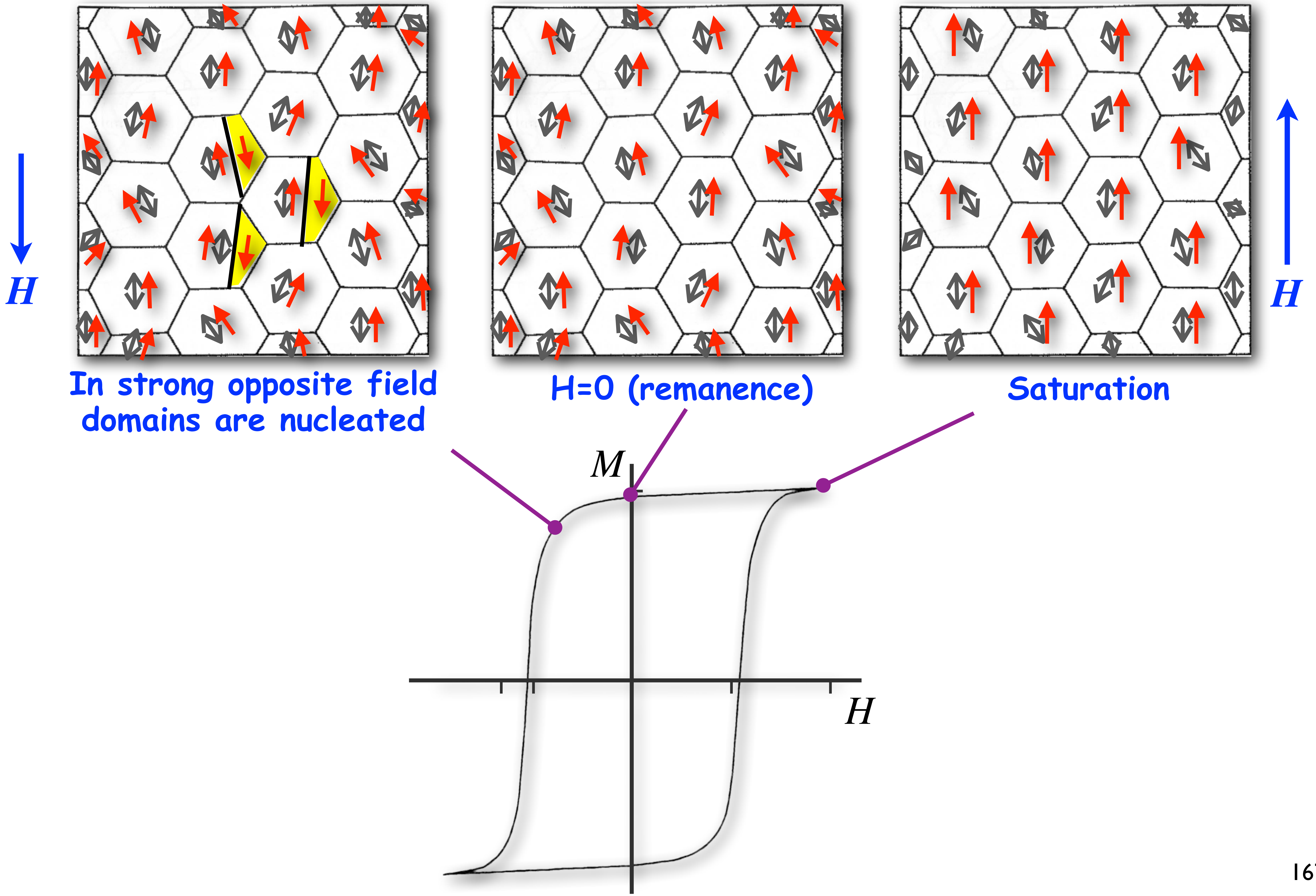
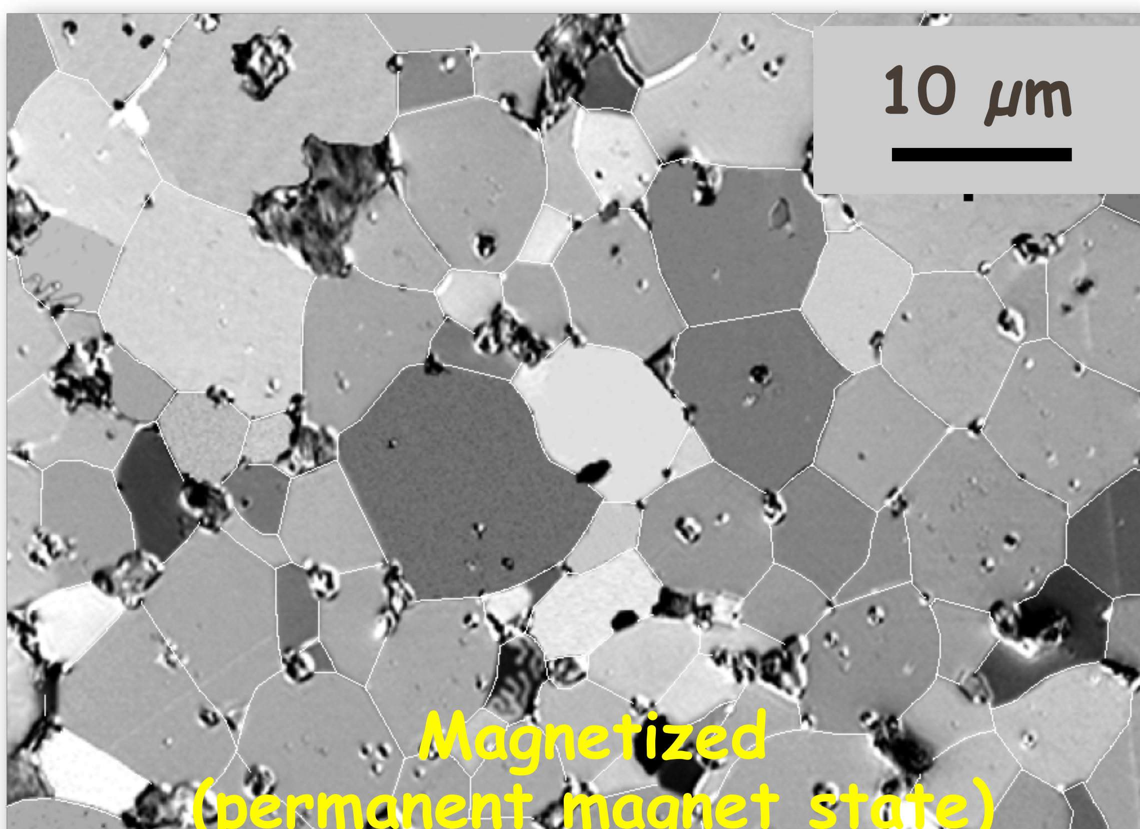
- Sintered magnet: „Isolated grains"
  → **Nucleation-type** magnet

Nucleation-type magnetization



Hardmagnetic materials, examples



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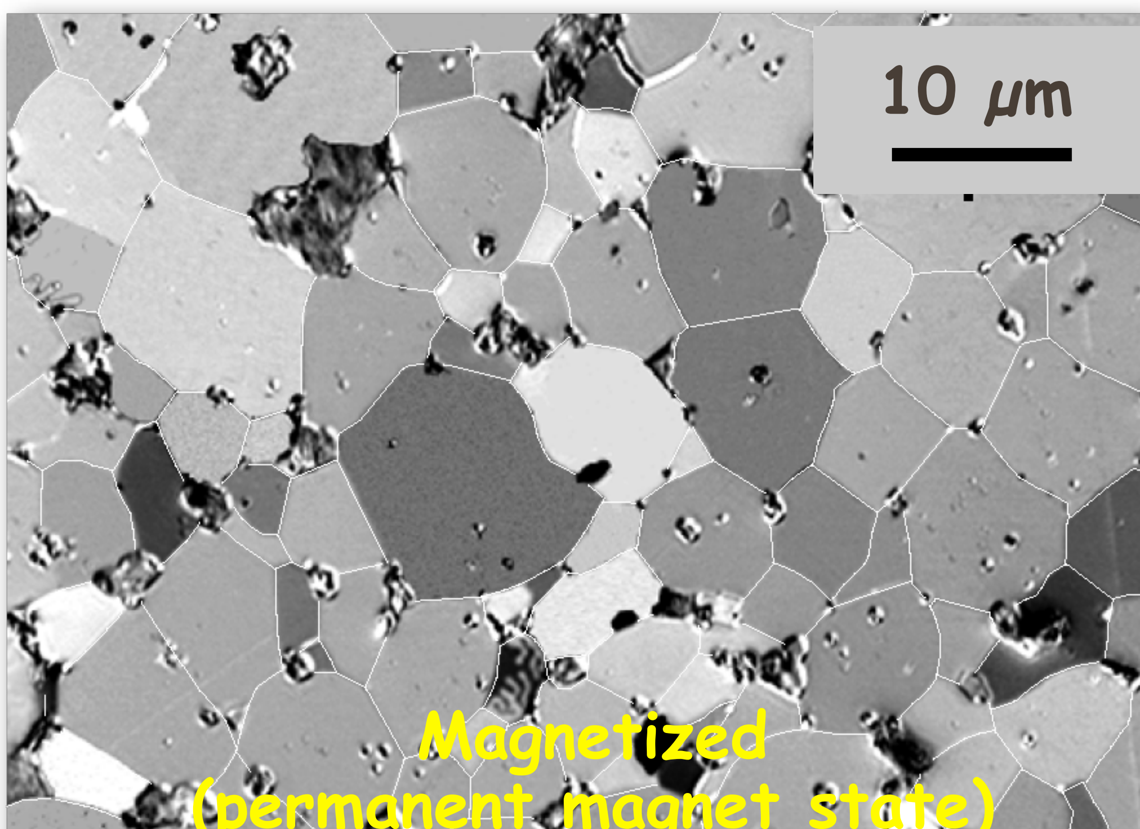
Hardmagnetic materials, examples

sintered



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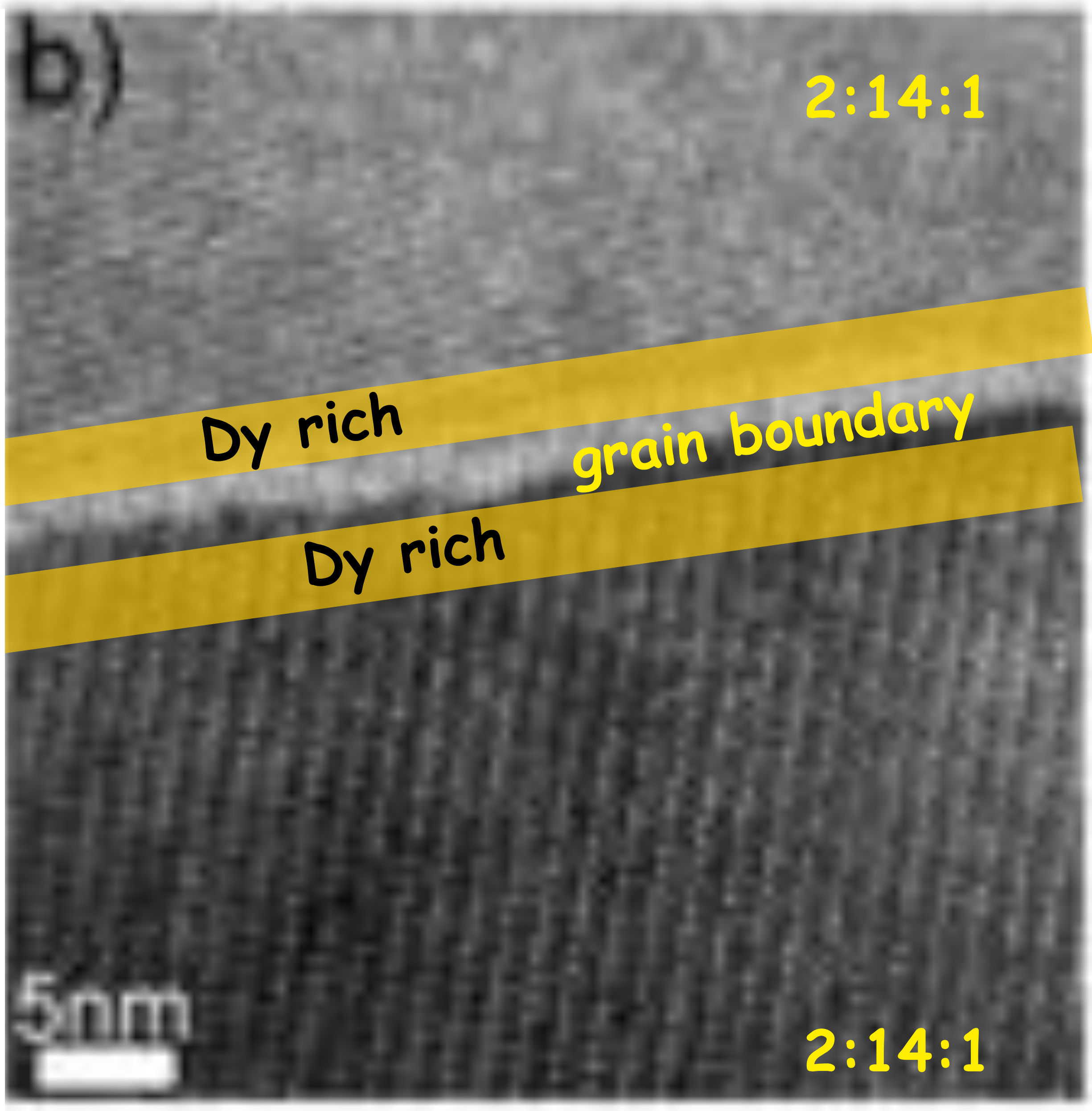
- Preparation: aligning of particles, sintering
- Sintered magnet: „Isolated grains"
  → **Nucleation-type** magnet
  → remove all domains by applying strong magnetic field → domain wall nucleation impeded due to high wall energy, caused by high crystal anisotropy ($\gamma_{180} \approx \sqrt{(A/K)}$

Hardmagnetic materials, examples

NdFeB, sintered



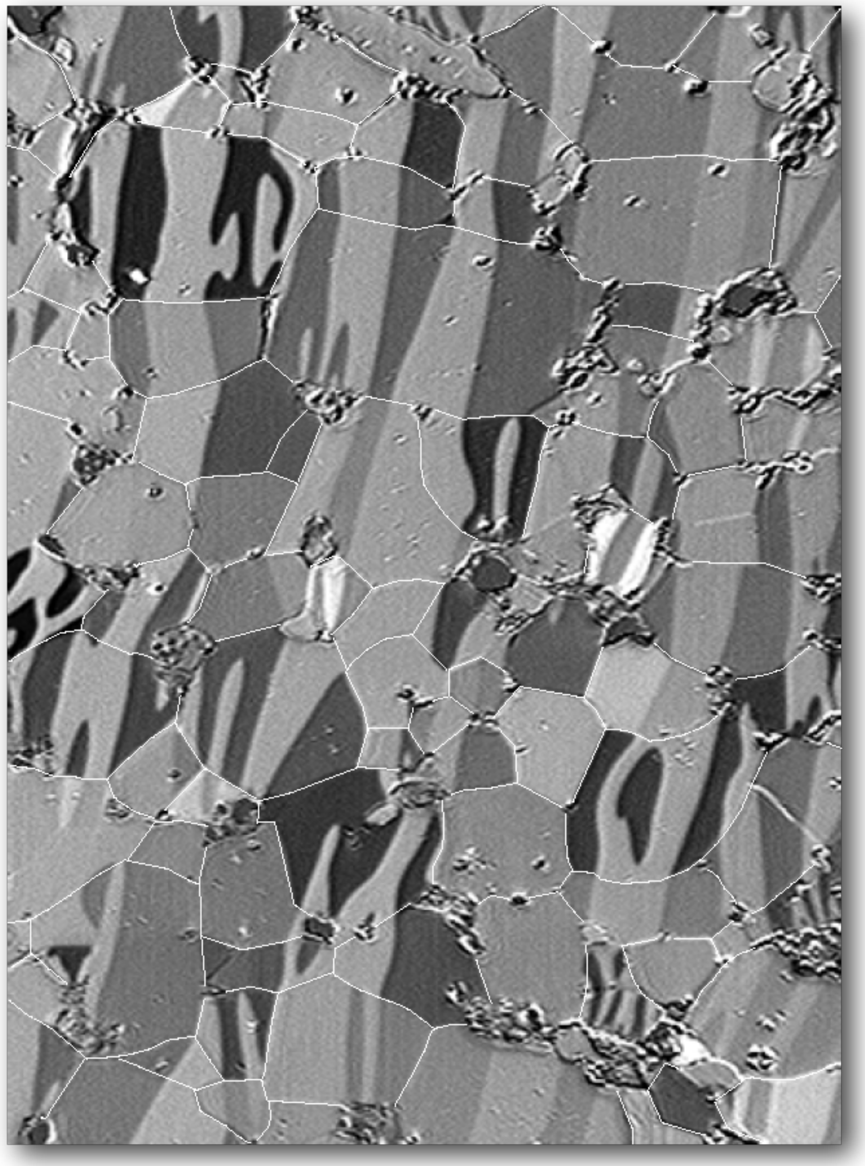
Sepehri-Amin et al. (2013)

- Additions of Dy are known to enhance anisotropy and consequently coercivity
- However: Dy also reduces remanence and is expensive (rare-earth crisis)
- Research: concentrate Dy close to grain boundaries by grain boundary diffusion during post-sintering annealing (in bulk of grain: Dy does not have any positive effect)

Research

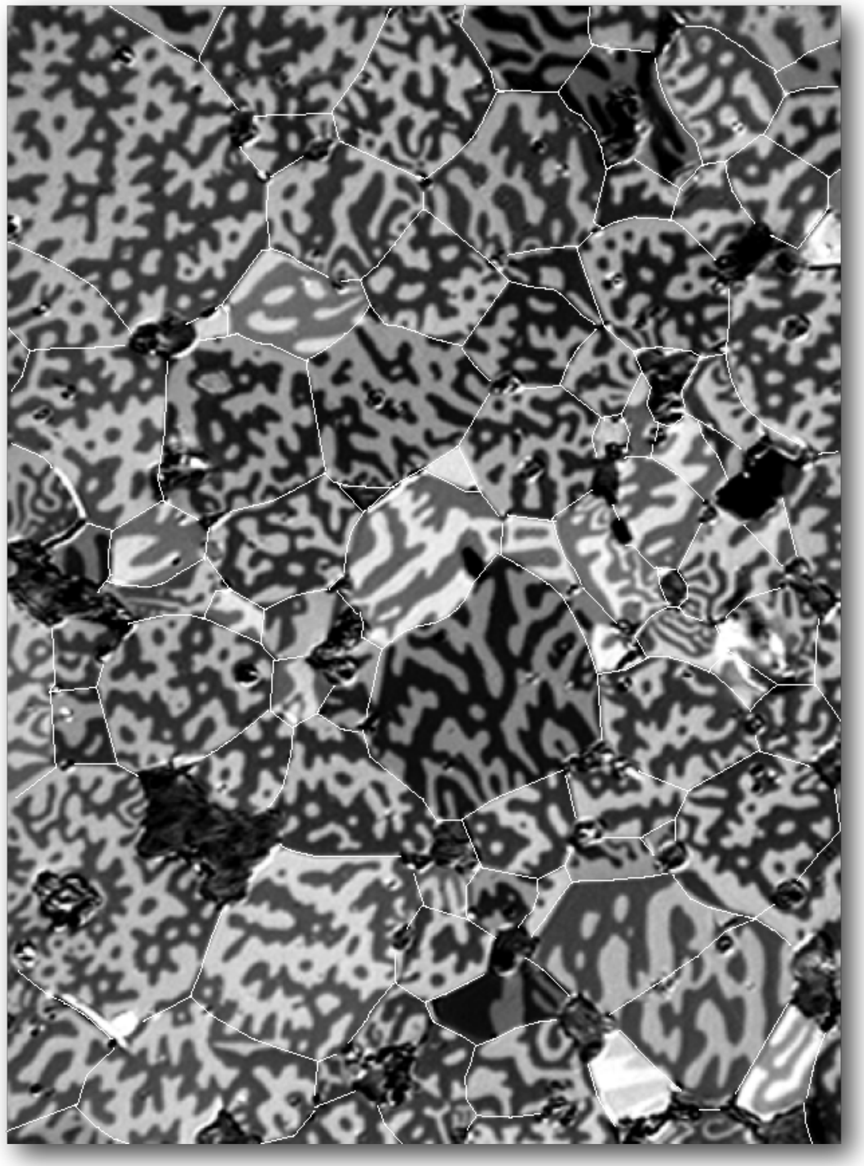
Hardmagnetic materials, examples

Thermally demagnetized



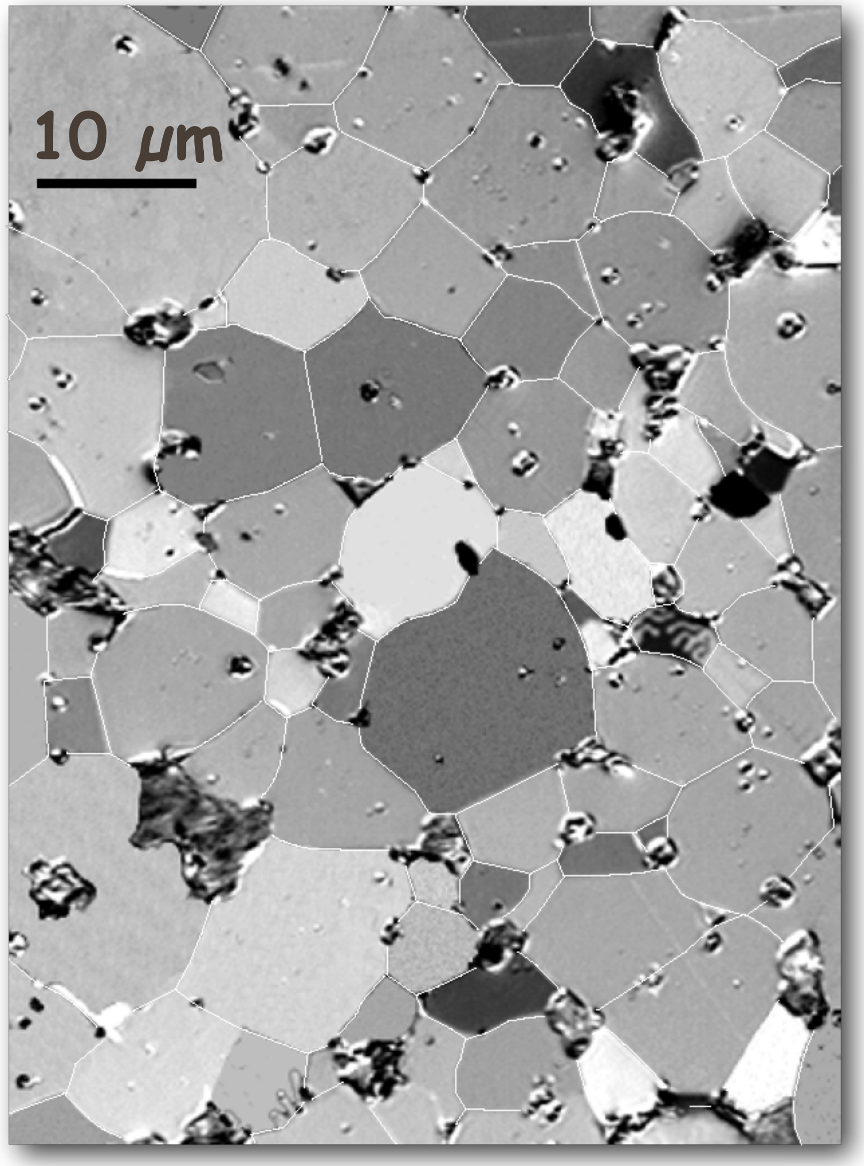
along texture axis

Thermally demagnetized



perpendicular texture axis

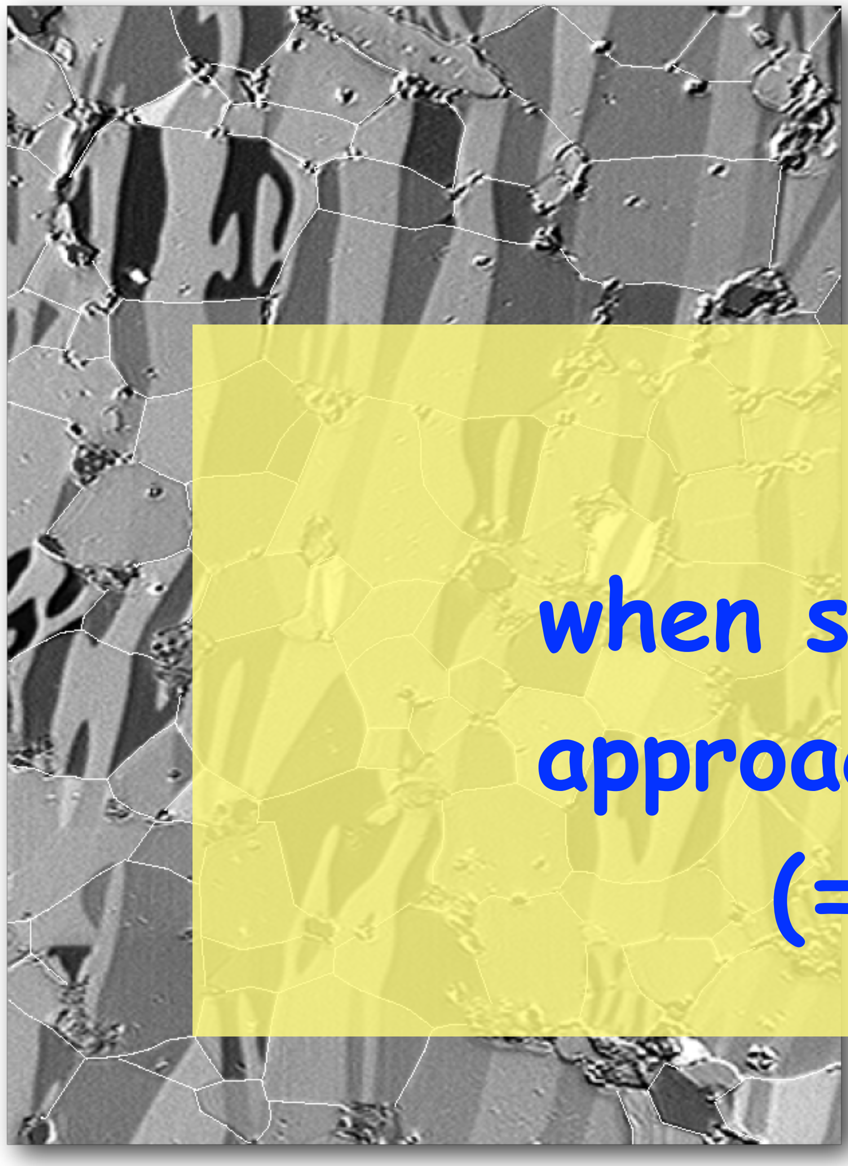
Magnetized



perpendicular texture axis

Hardmagnetic materials, examples

Thermally demagnetized



along texture axis

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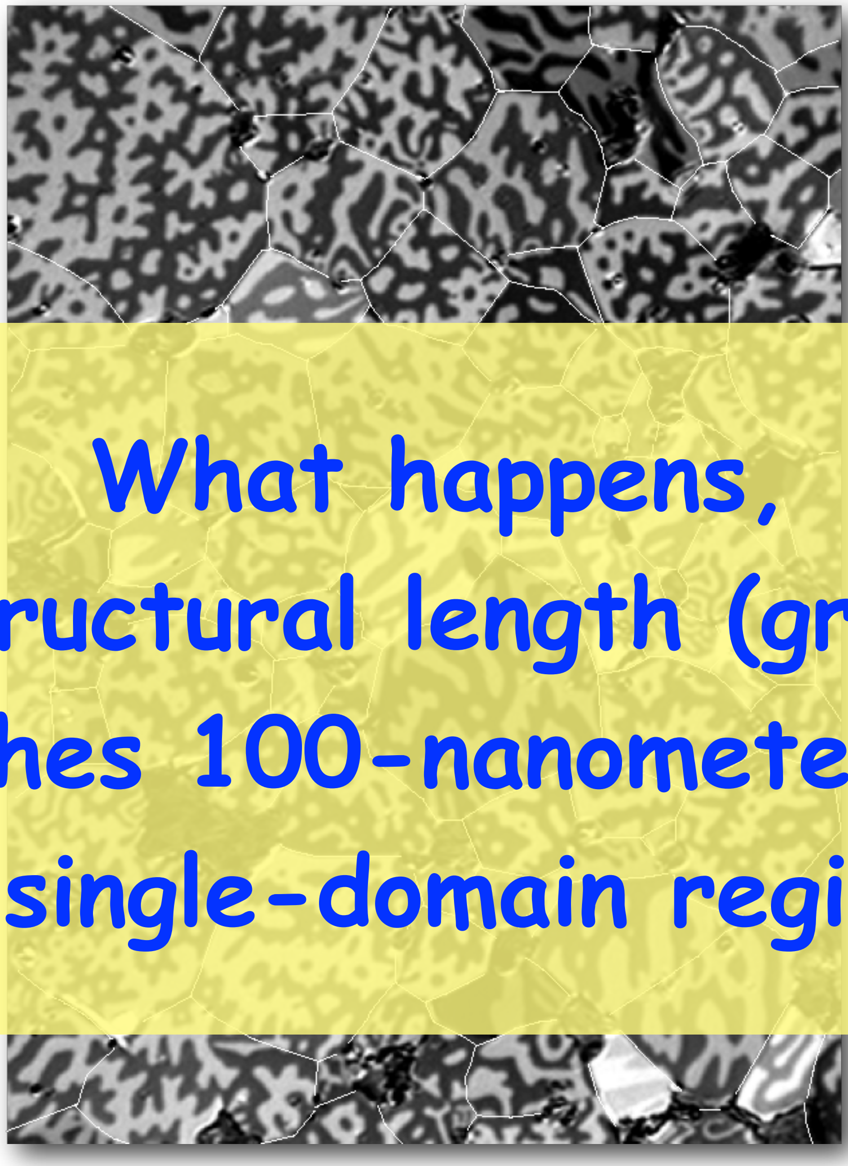
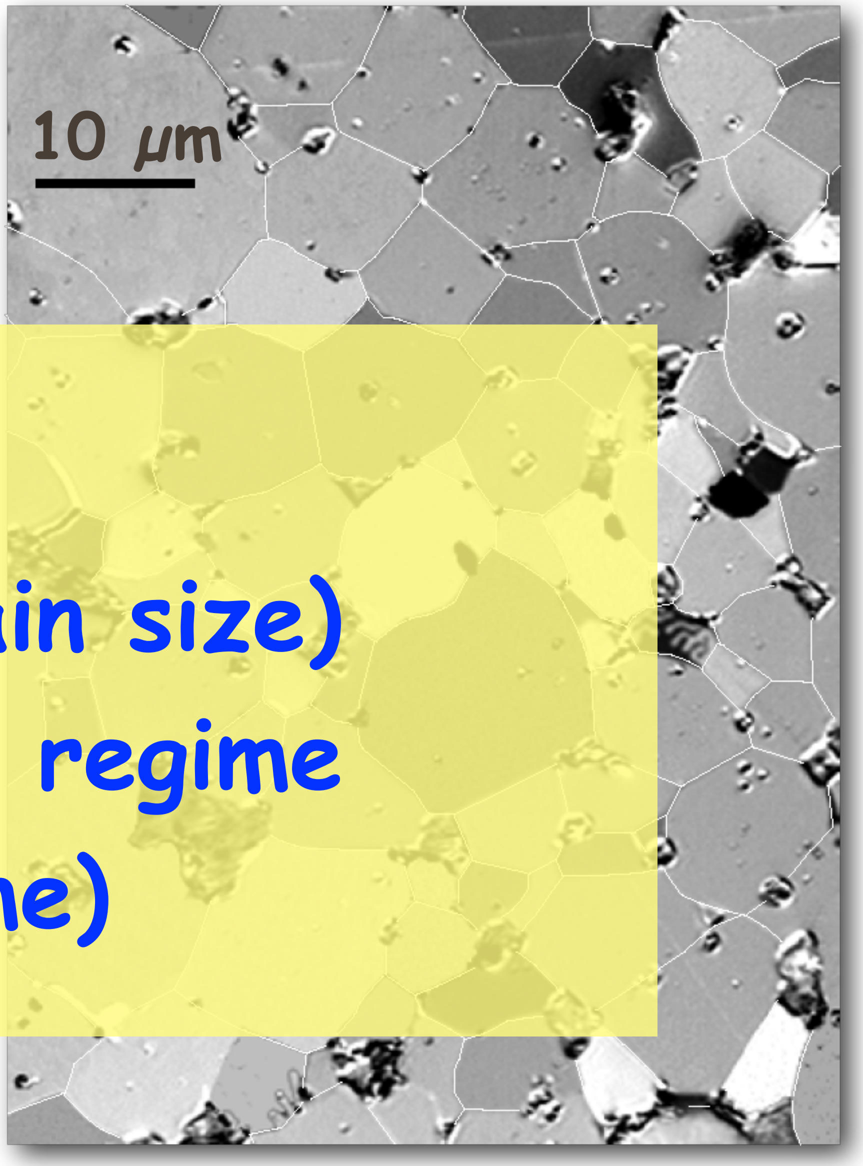


perpendicular texture axis

Magnetized



perpendicular texture axis

What happens,
when structural length (grain size)
approaches 100-nanometer regime
(= single-domain regime)

Har ... les

Therm
demagn

etized

Typical grain sizes: 20 - 300 nm

$Nd_2Fe_{14}B$:

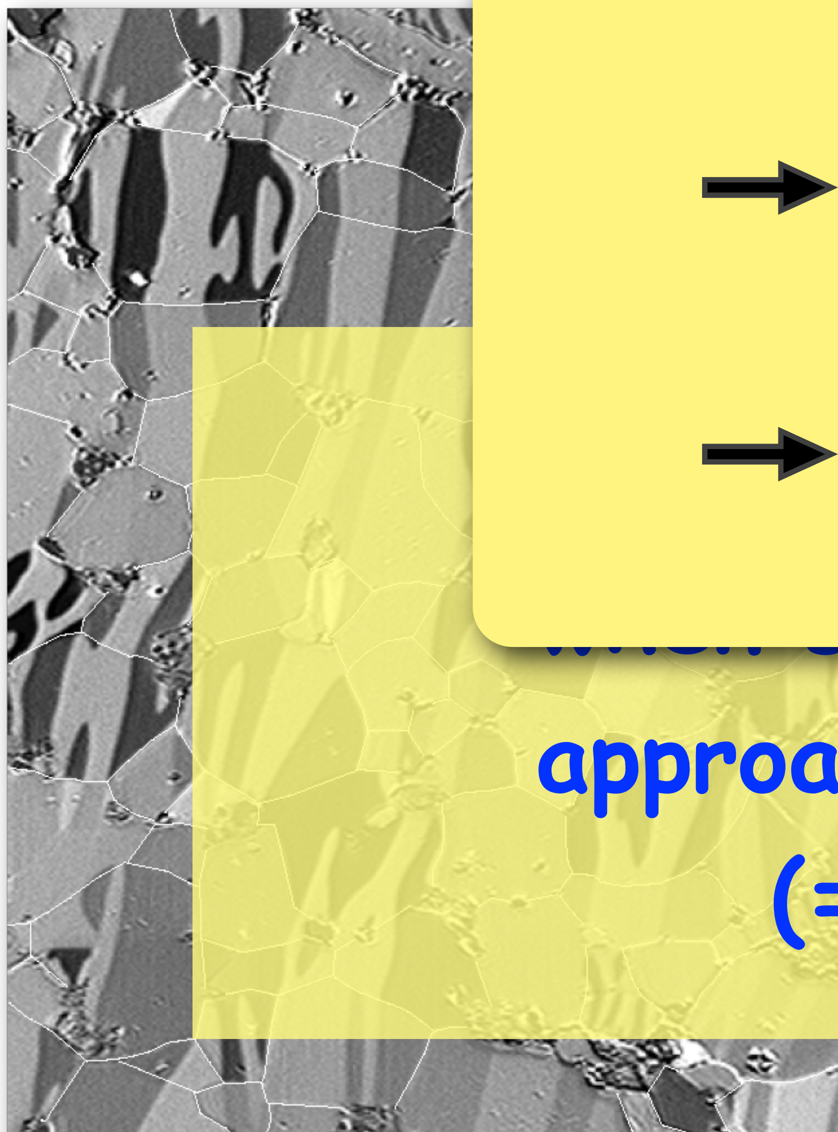
$$K_c = 4.3 \cdot 10^6 \text{ kJ/m}^3$$

$$A = 8 \cdot 10^{-12} \text{ J/m}$$

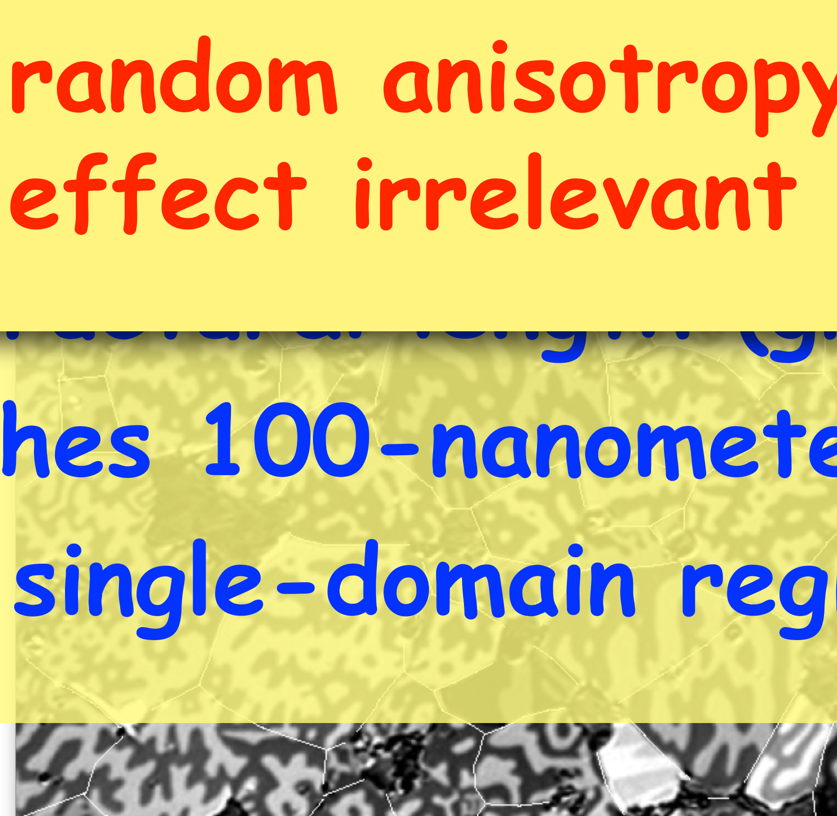
→ $L_{ex} = \sqrt{A/K_c} = 1.3 \text{ nm}$

→ random anisotropy effect irrelevant

approaches 100-nanometer regime
(= single-domain regime)



along texture axis

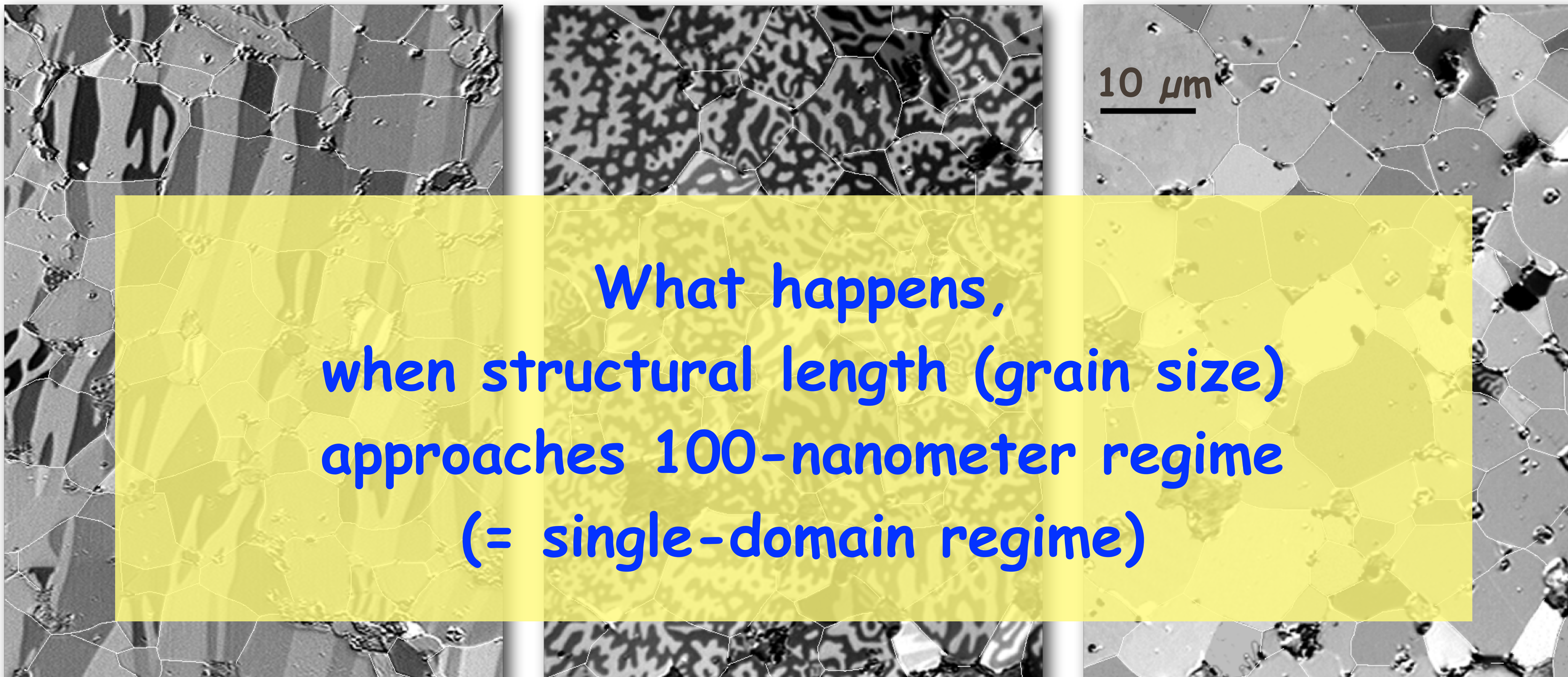


perpendicular texture axis

perpendicular texture axis

Hardmagnetic materials, examples

Thermally demagnetized | Thermally demagnetized | Magnetized



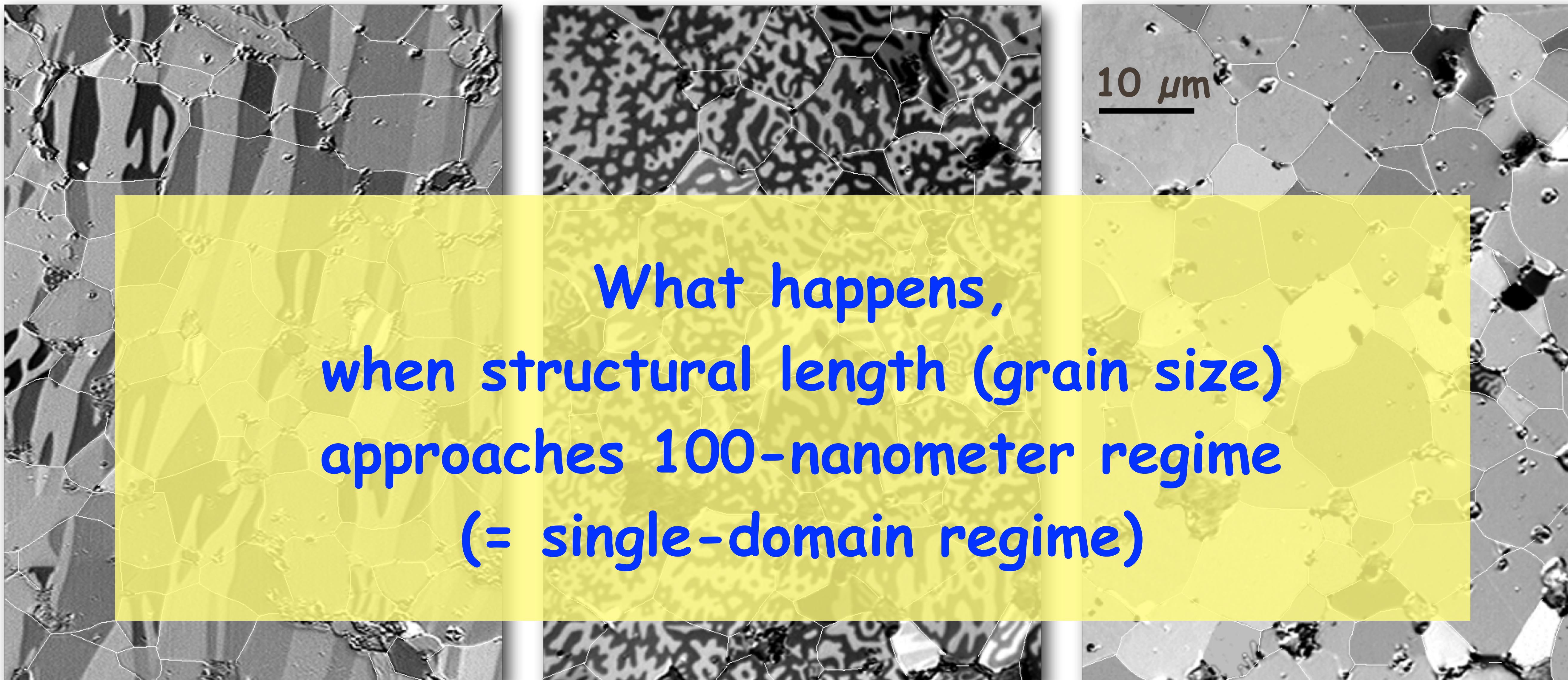
along texture axis | perpendicular texture axis | perpendicular texture axis

**What happens,
when structural length (grain size)
approaches 100-nanometer regime
(= single-domain regime)**

Hardmagnetic materials, examples

NdFeB, nano-structured

Thermally demagnetized | Thermally demagnetized | Magnetized

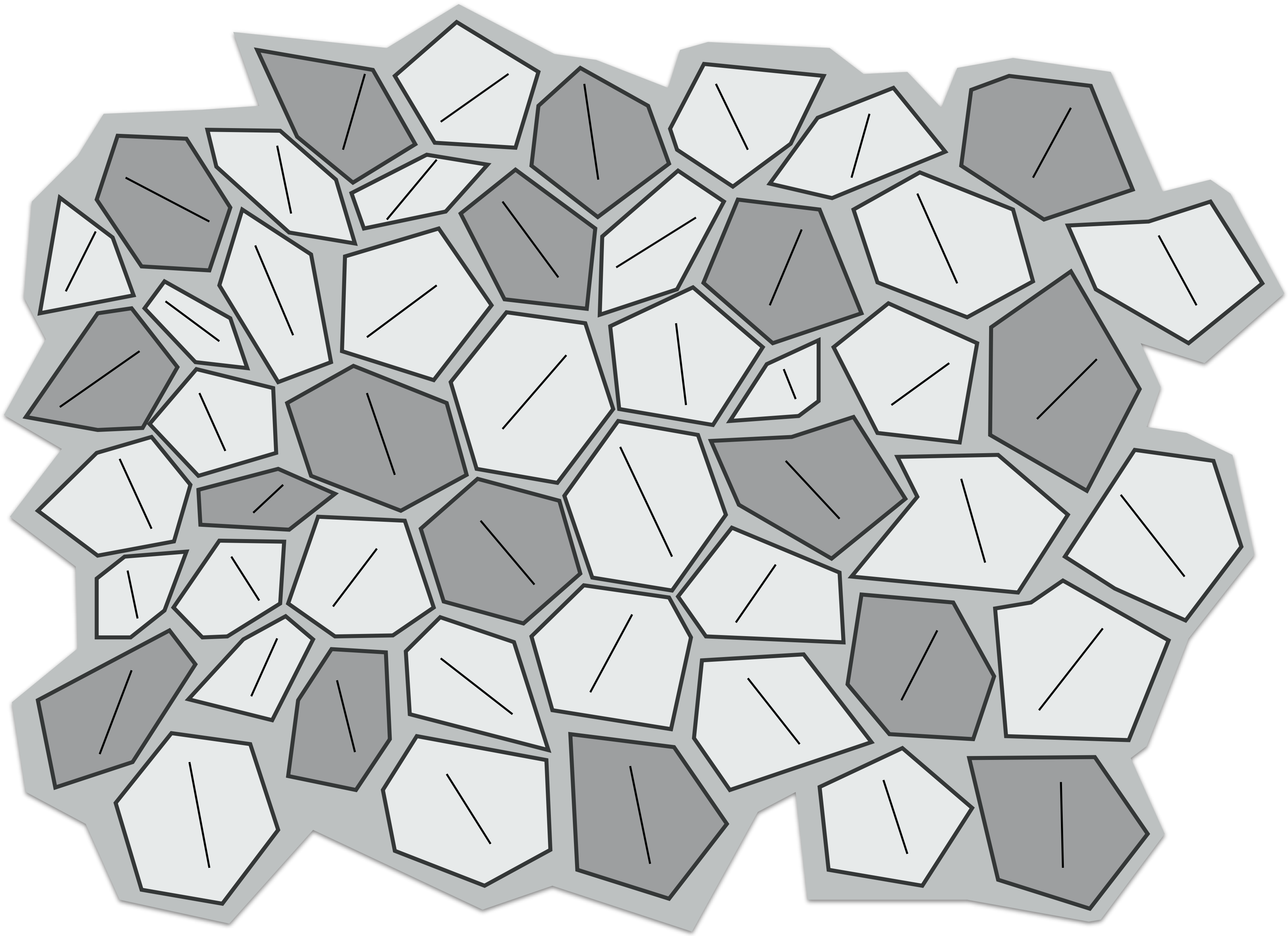


along texture axis | perpendicular texture axis | perpendicular texture axis

What happens,
when structural length (grain size)
approaches 100-nanometer regime
(= single-domain regime)

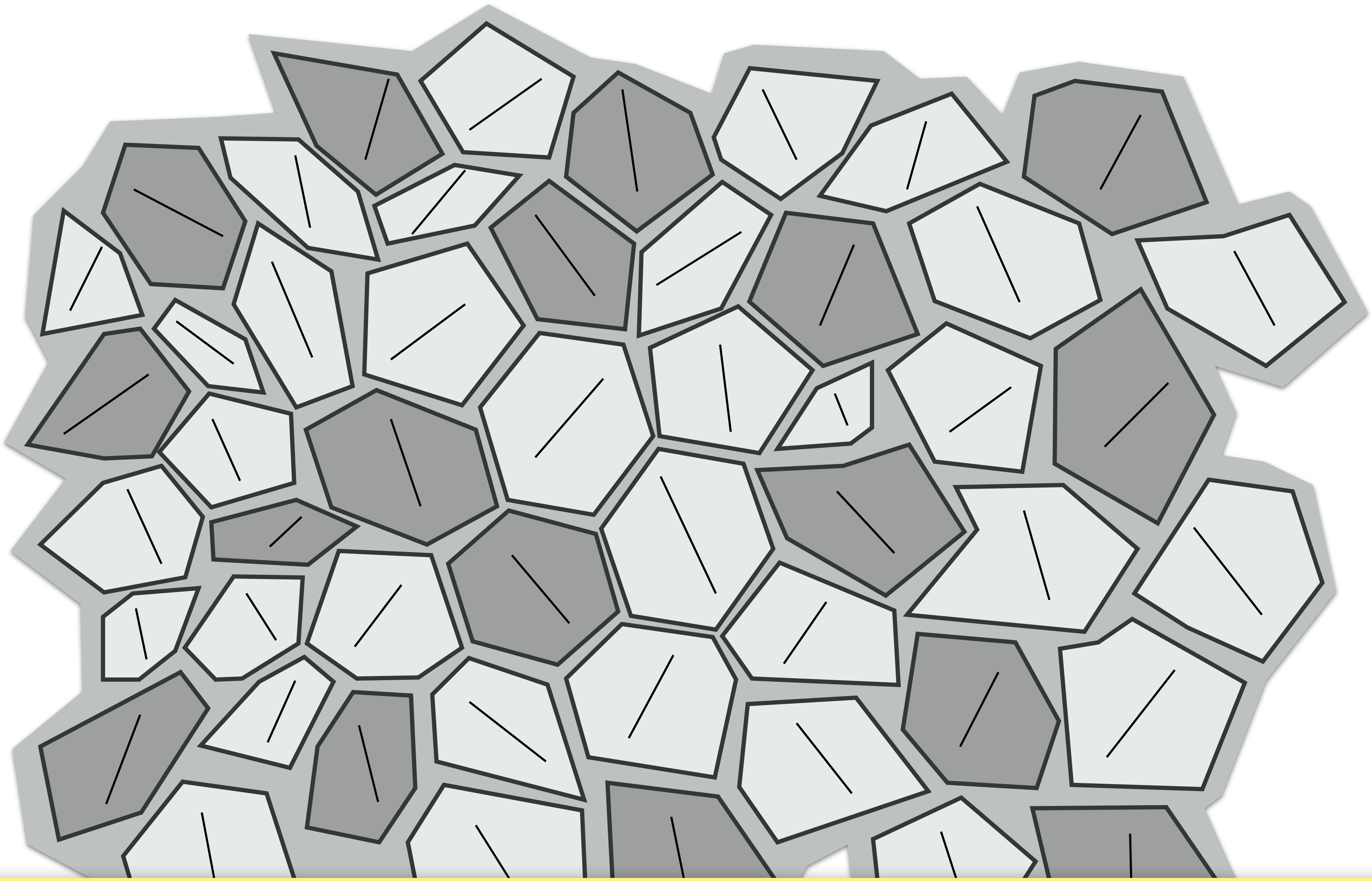
Nano-structured NdFeB

Ensemble of single-domain grains



Nano-structured NdFeB

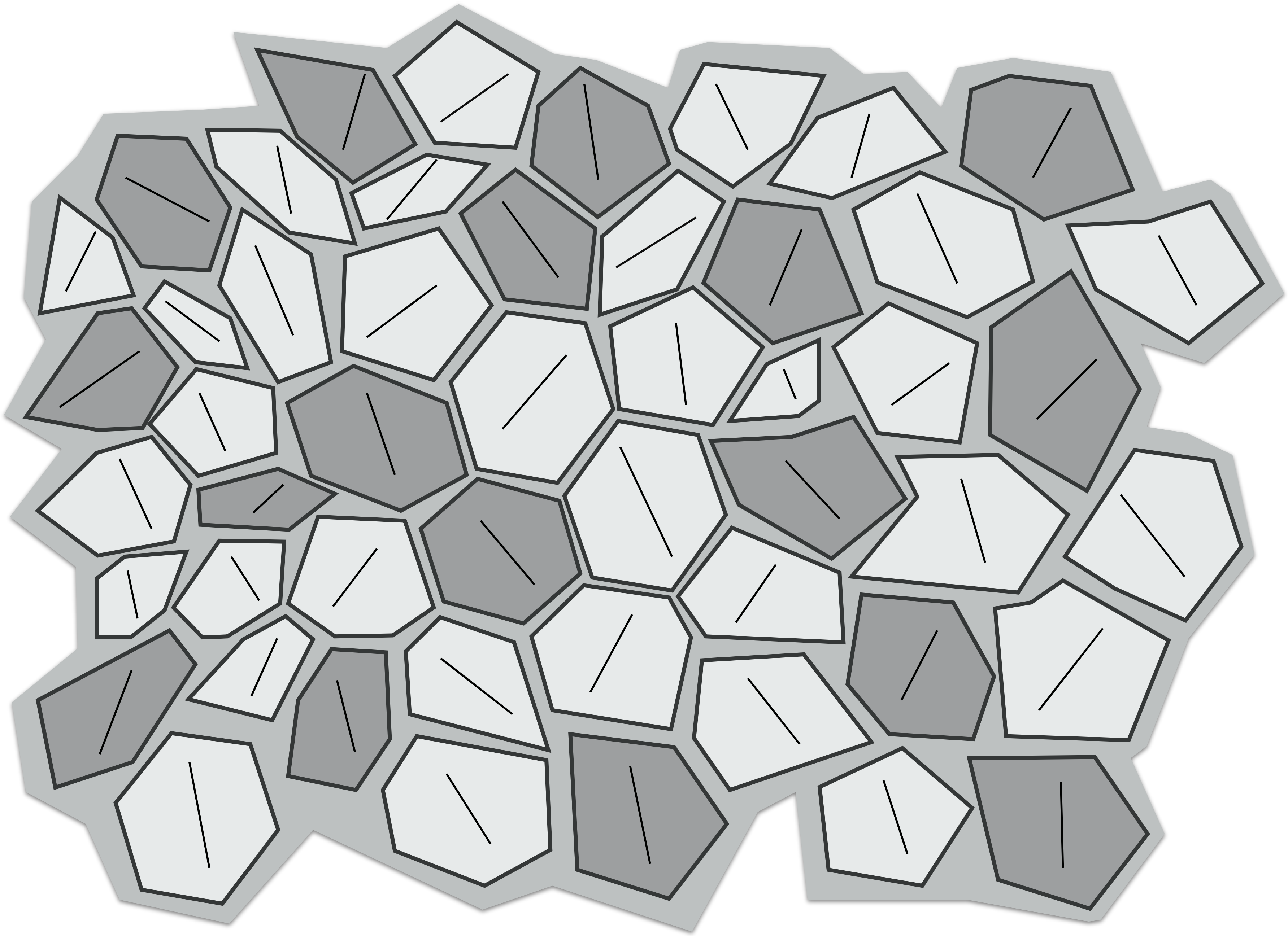
Ensemble of single-domain grains



Expectation:
each grain (particle) magnetized along its easy axis

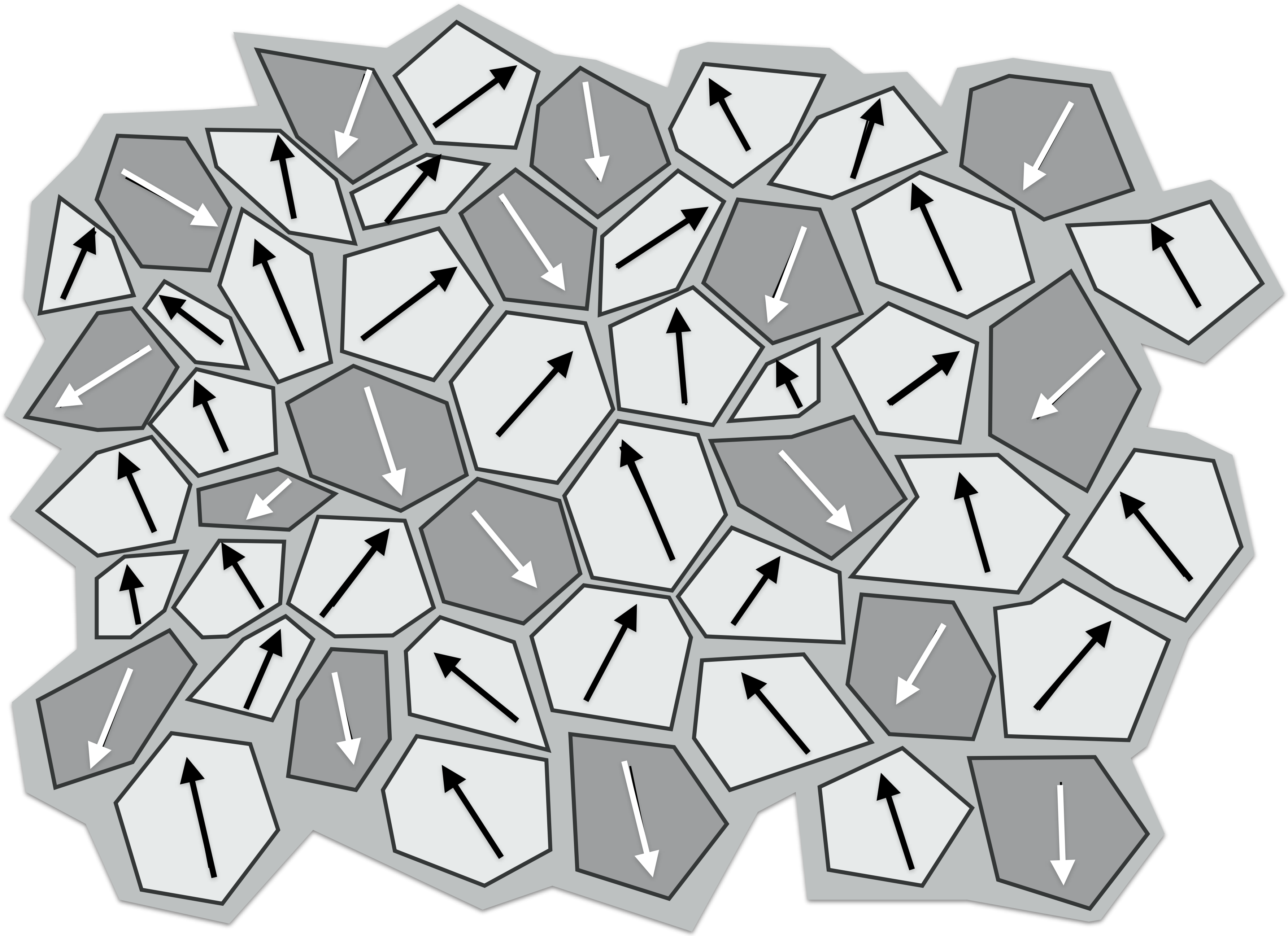
Nano-structured NdFeB

Ensemble of single-domain grains

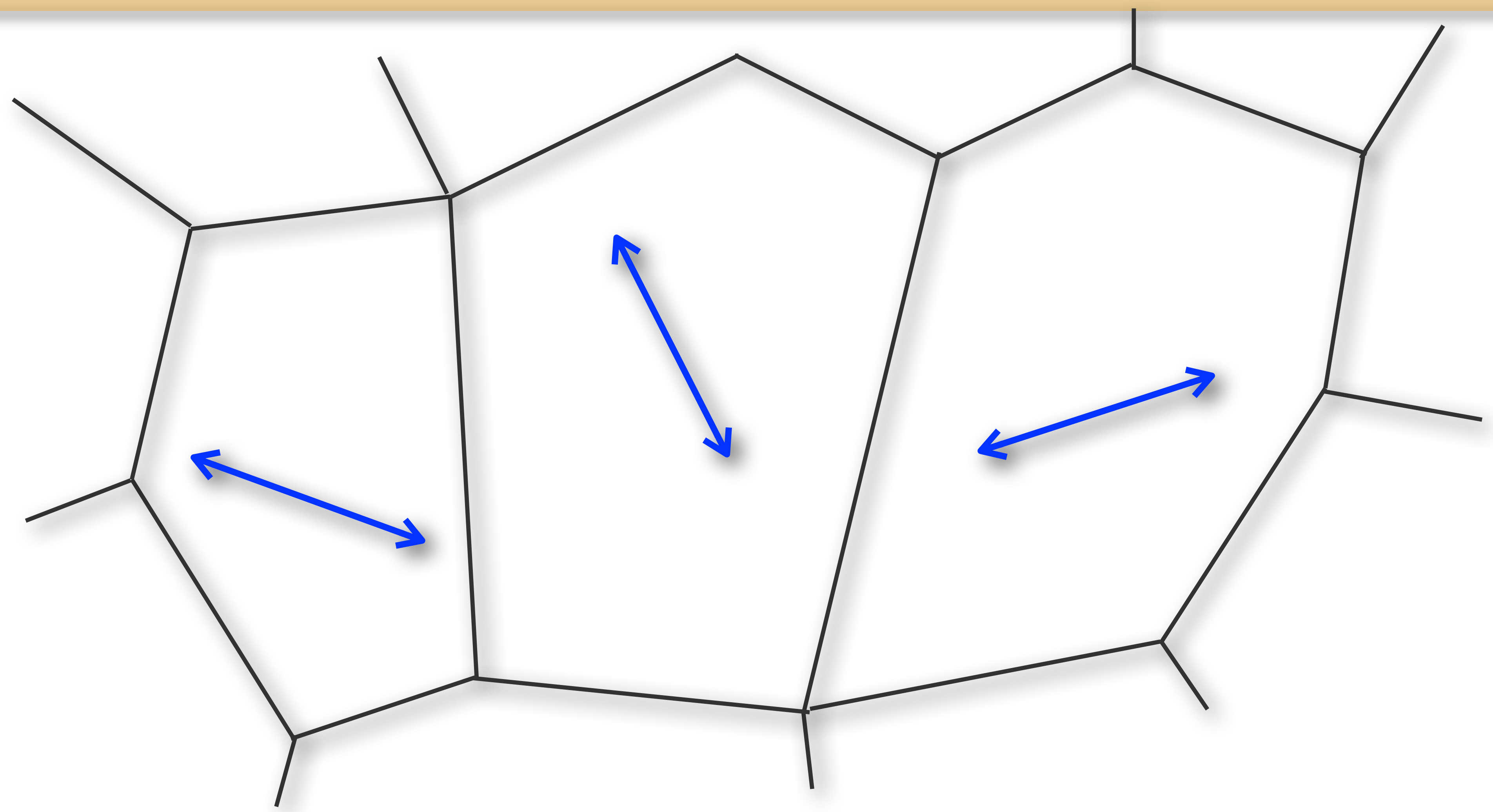


Nano-structured NdFeB

Ensemble of single-domain grains

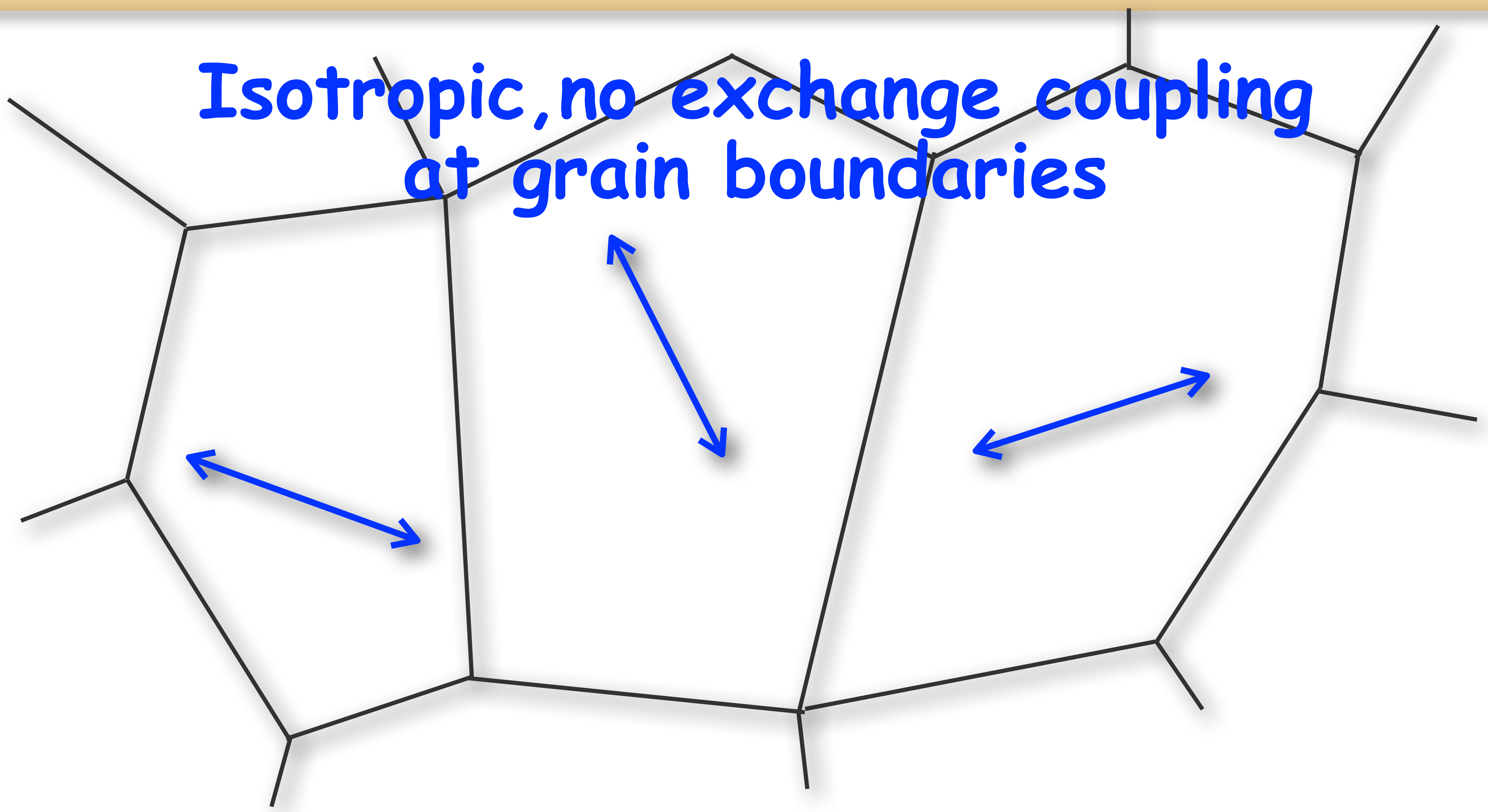


Nano-structured NdFeB: remanence enhancement

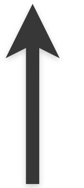


Remanent state after field

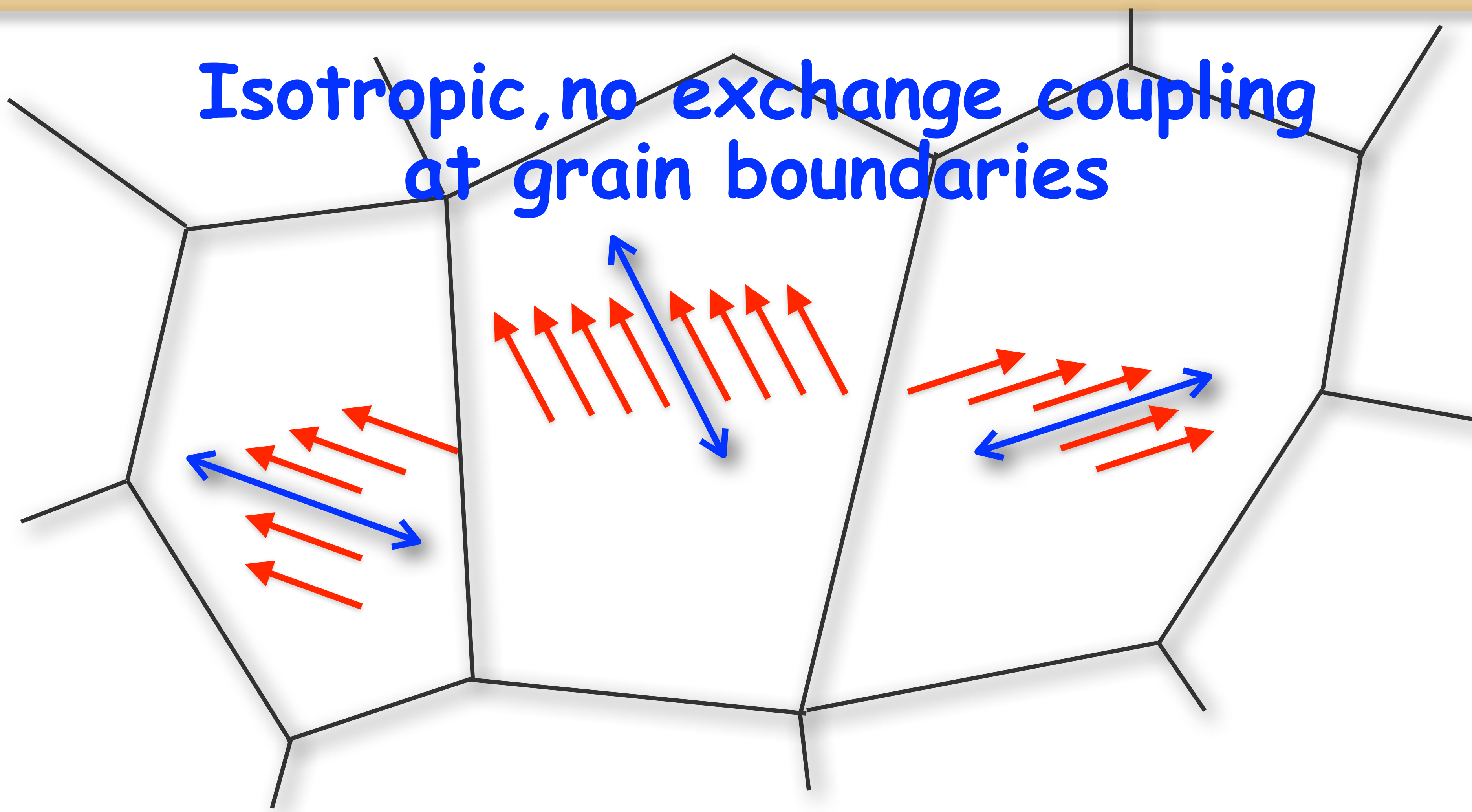
Nano-structured NdFeB: remanence enhancement

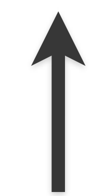


Remanent state after field

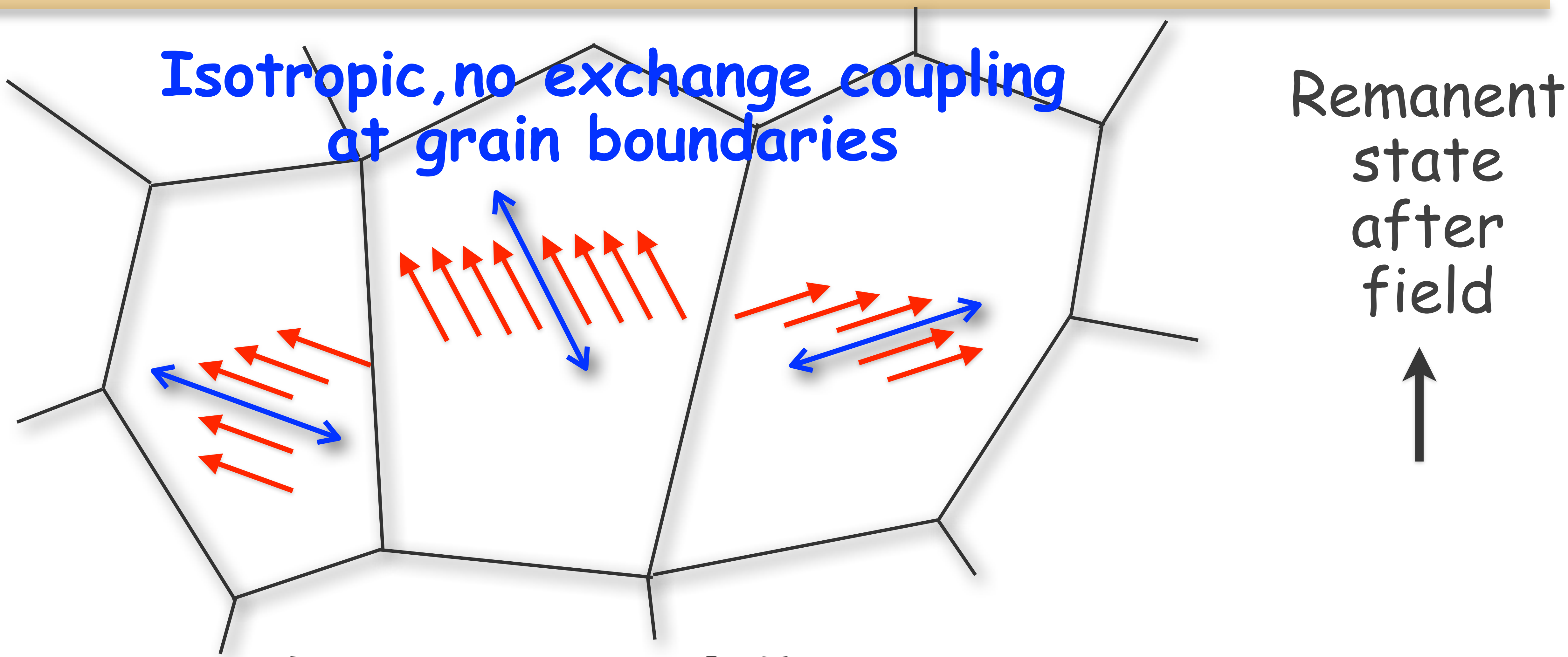


Nano-structured NdFeB: remanence enhancement



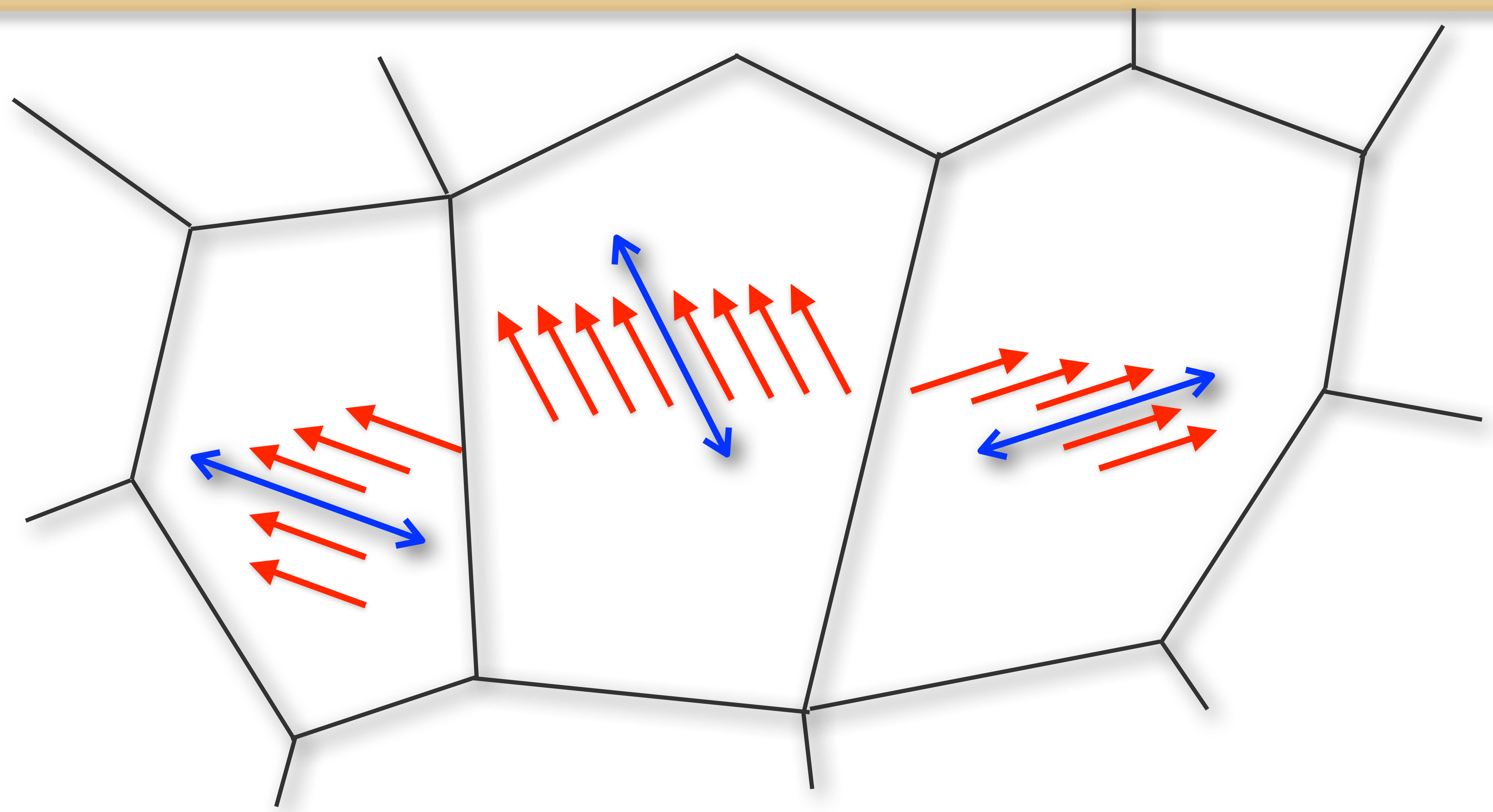


Nano-structured NdFeB: remanence enhancement

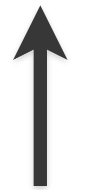


Remanence = 0.5 M_s

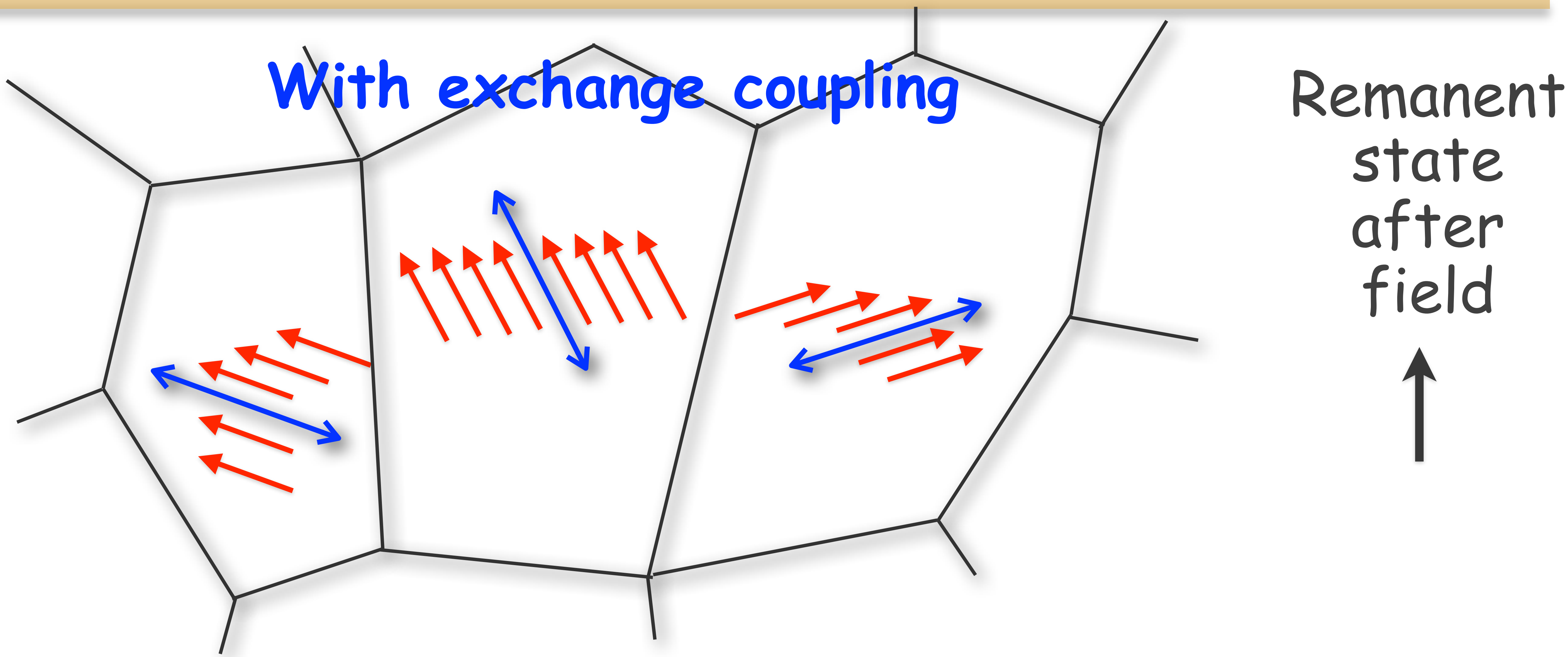
Nano-structured NdFeB: remanence enhancement



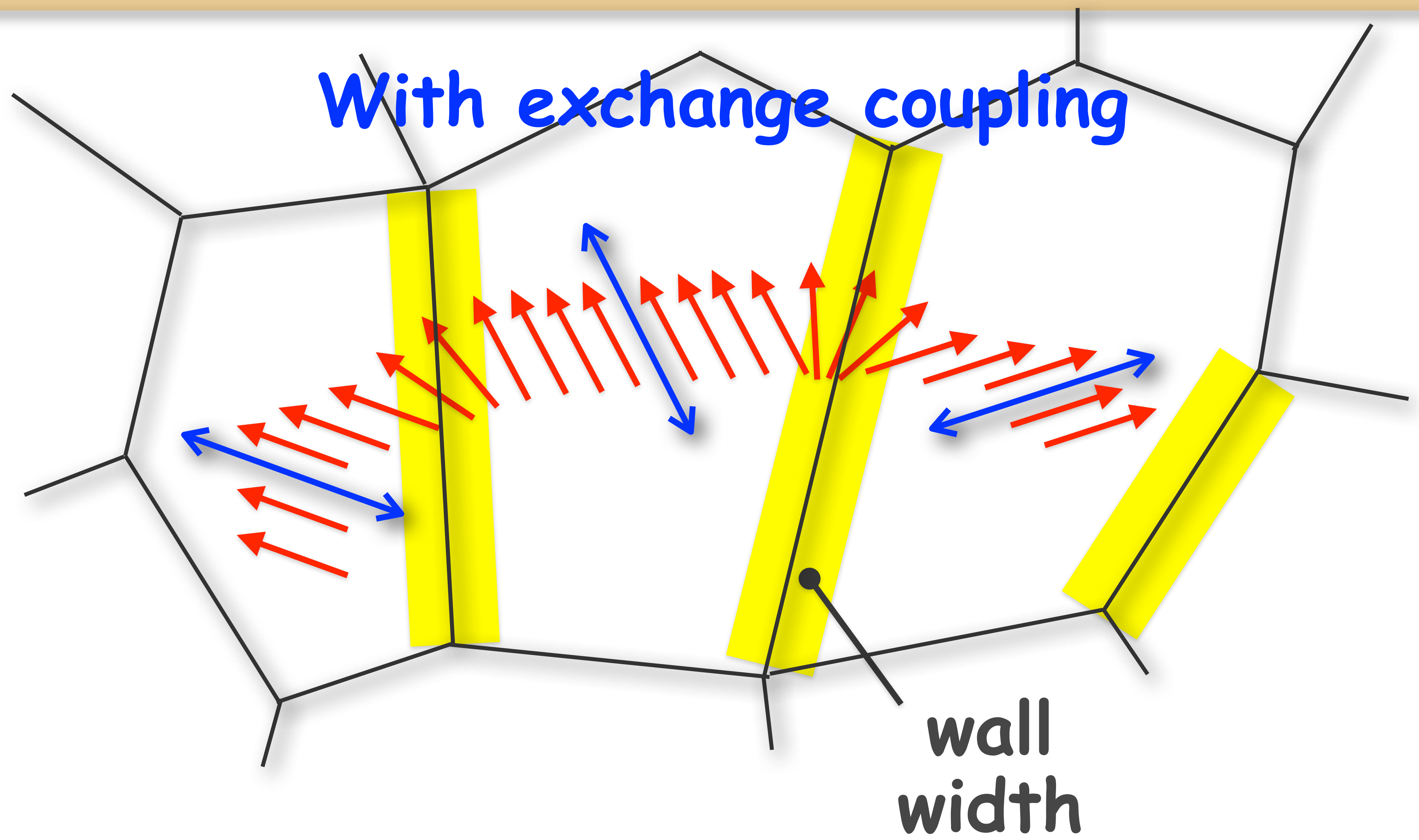
Remanent state after field



Nano-structured NdFeB: remanence enhancement

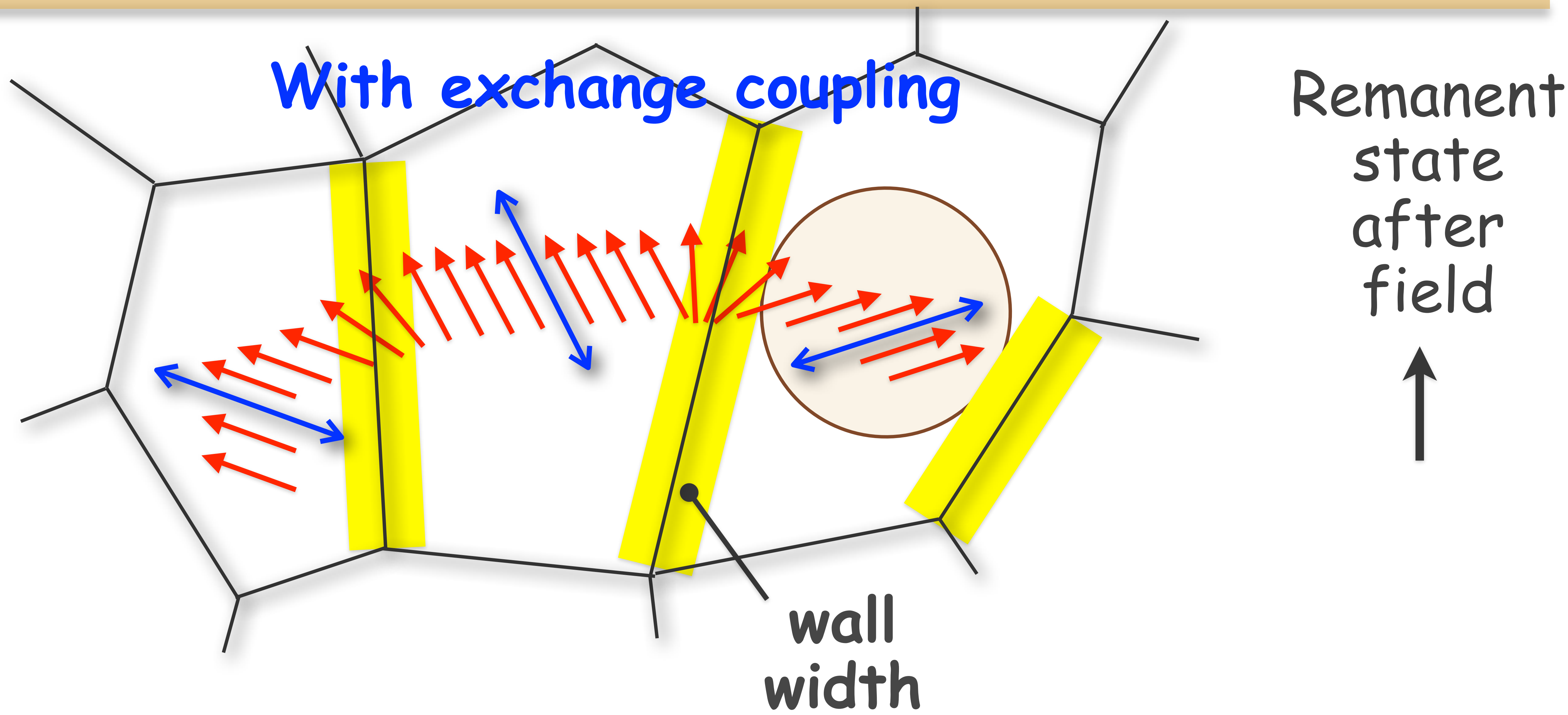


Nano-structured NdFeB: remanence enhancement

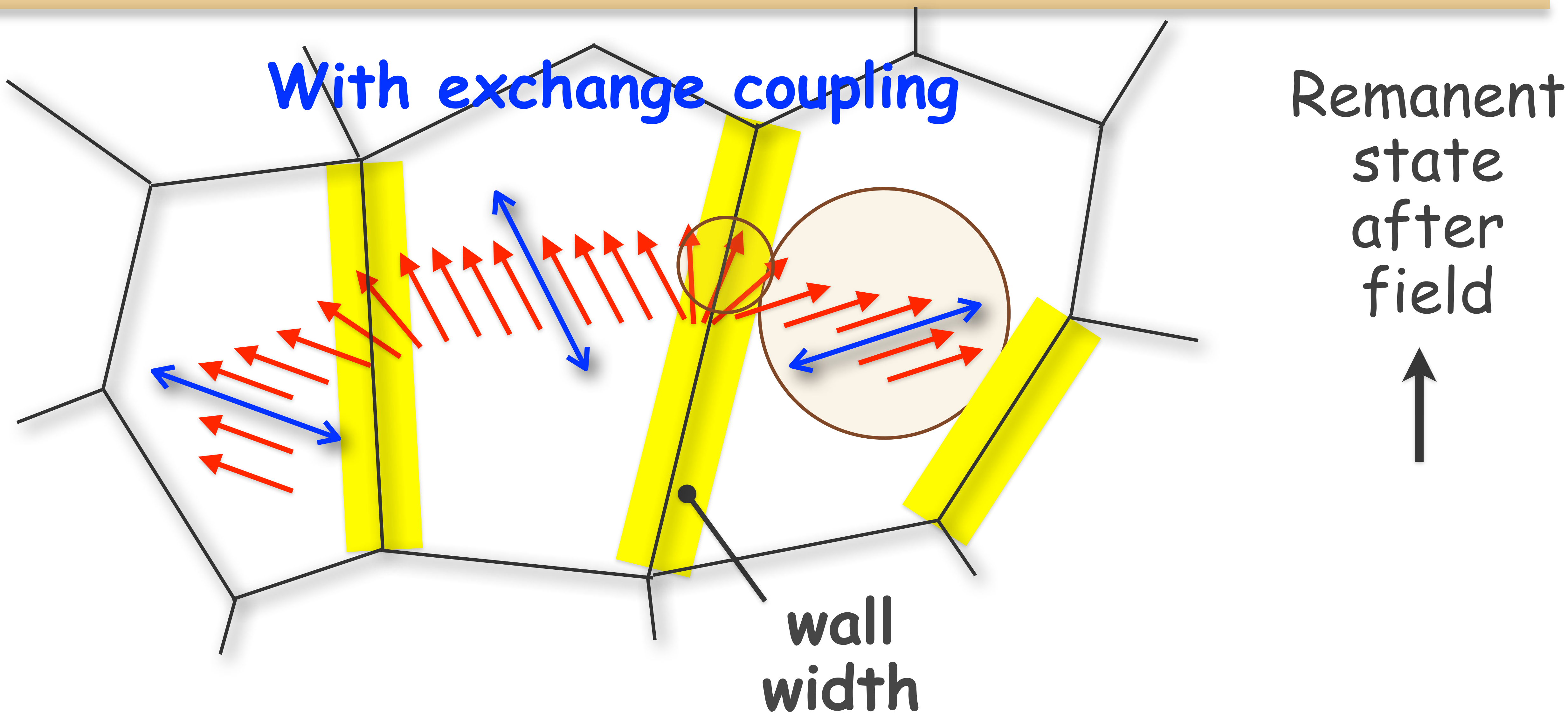


Remanent state after field

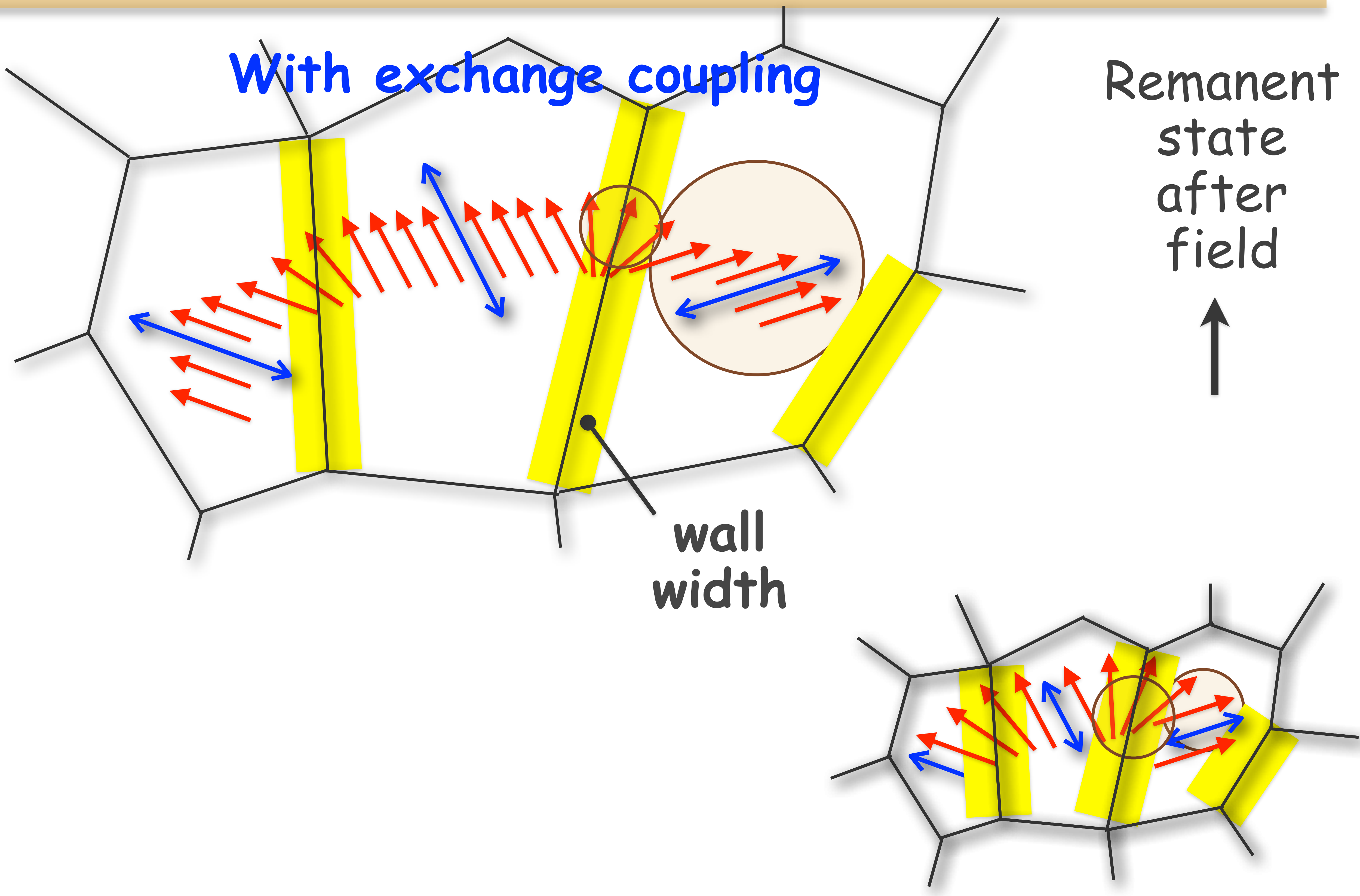
Nano-structured NdFeB: remanence enhancement



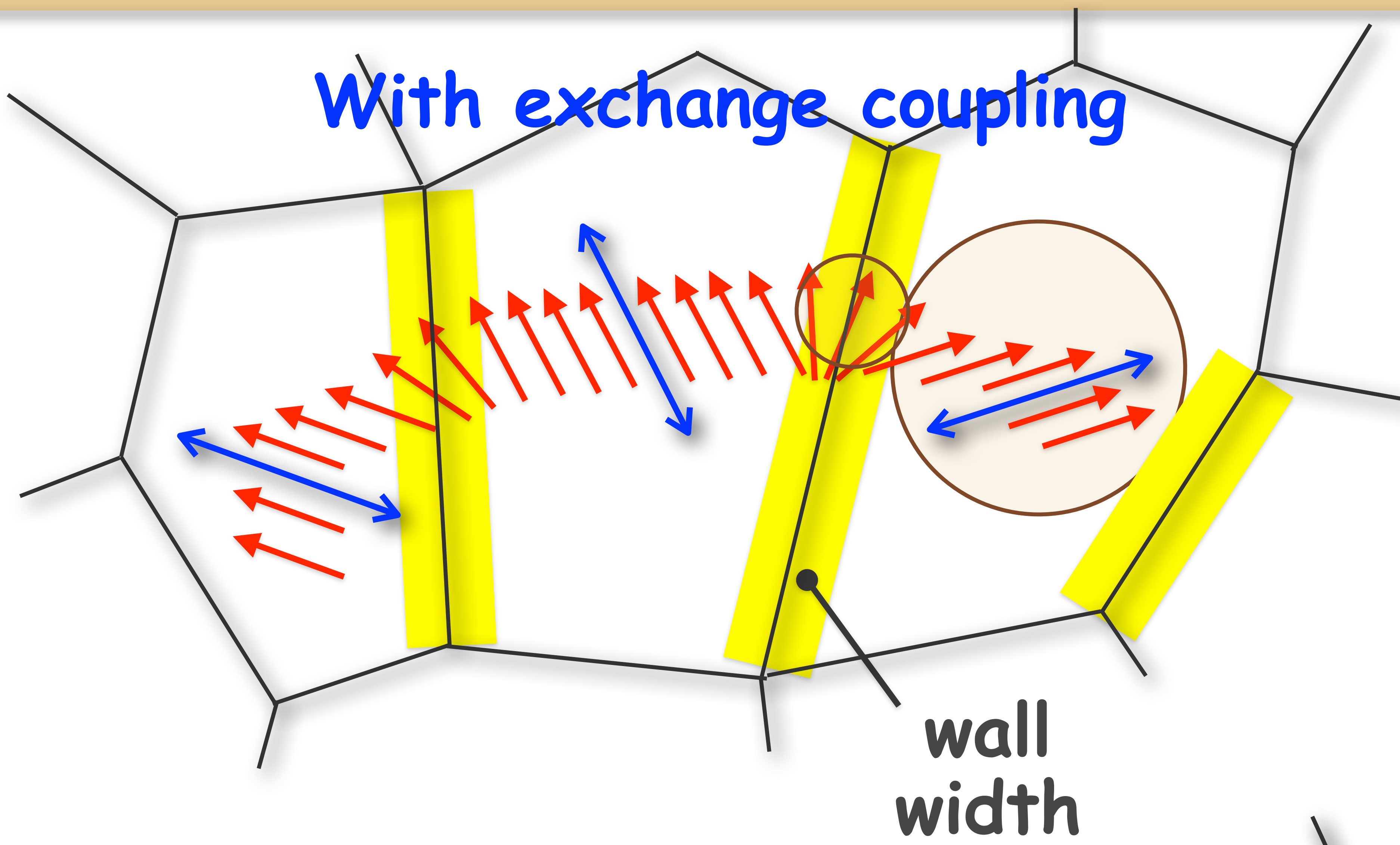
Nano-structured NdFeB: remanence enhancement



Nano-structured NdFeB: remanence enhancement

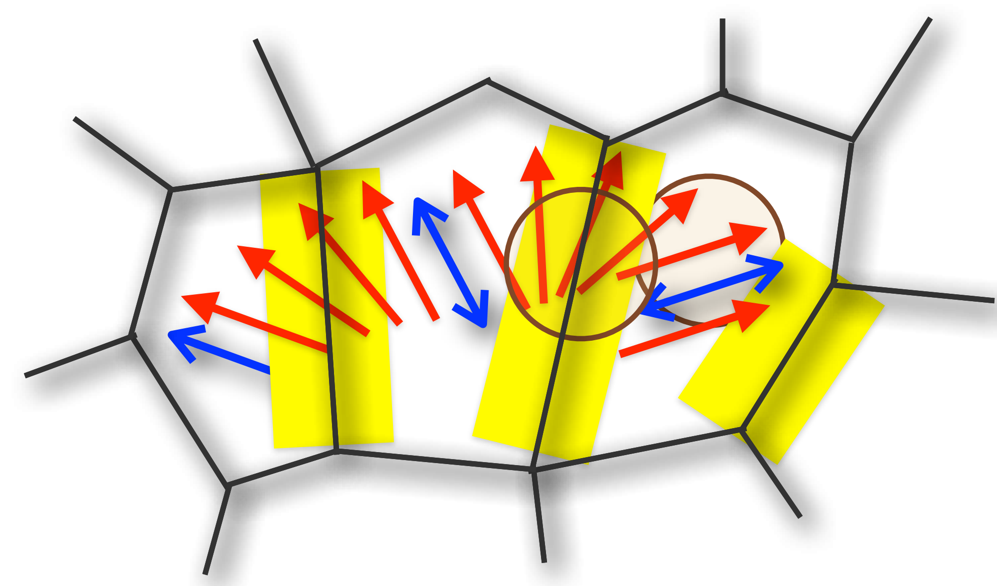


Nano-structured NdFeB: remanence enhancement

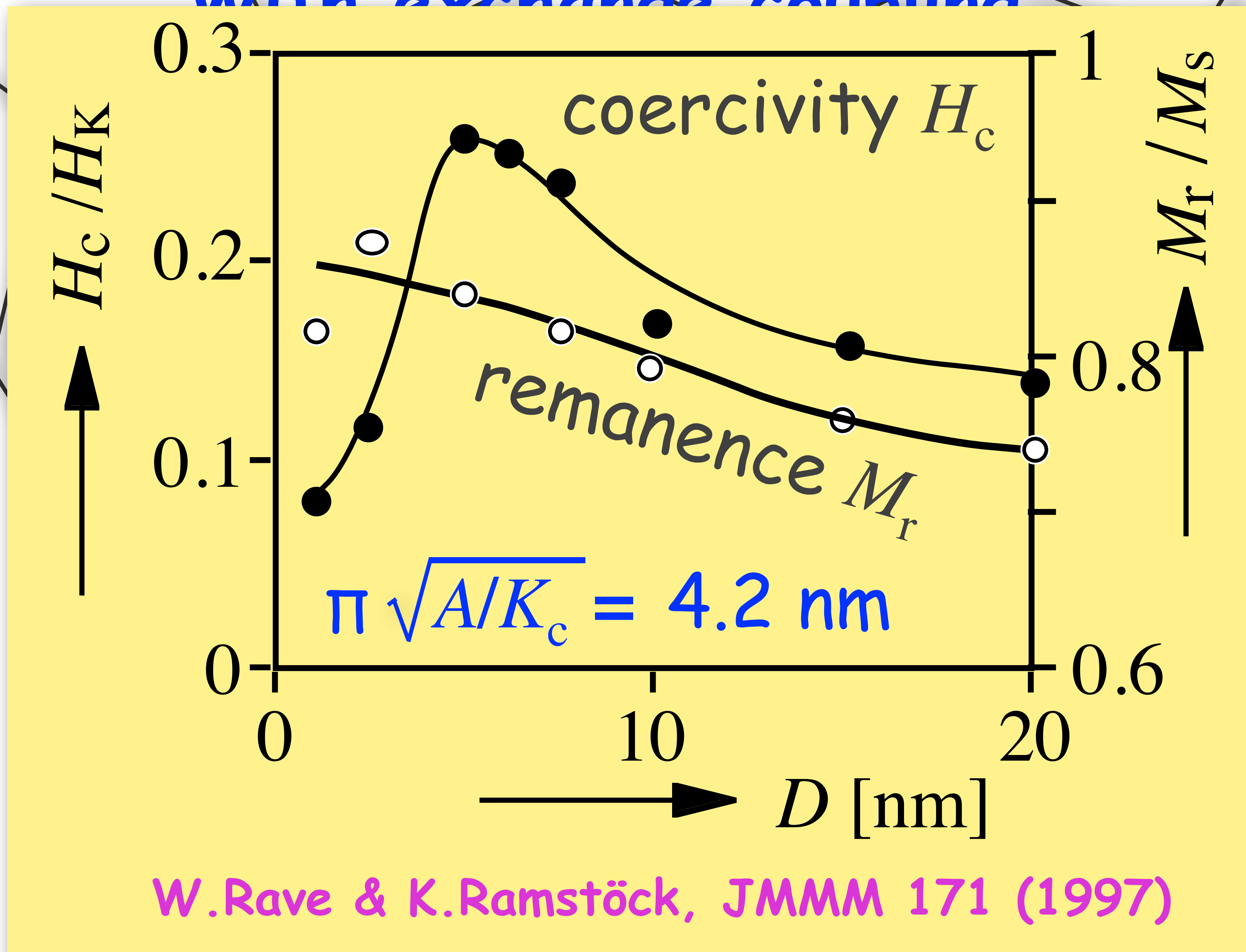


Remanent state after field ↑

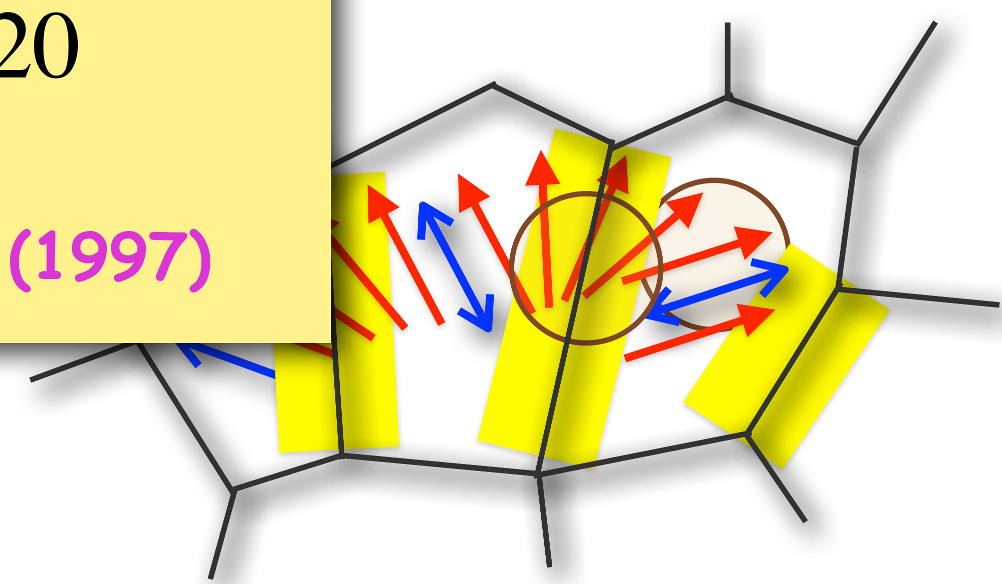
Remanence > 0.5 M_s



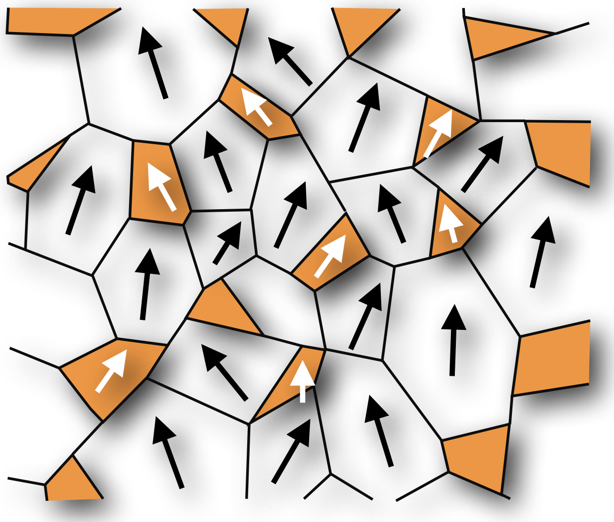
Nano-structured NdFeB: remanence enhancement



Remanent state after field

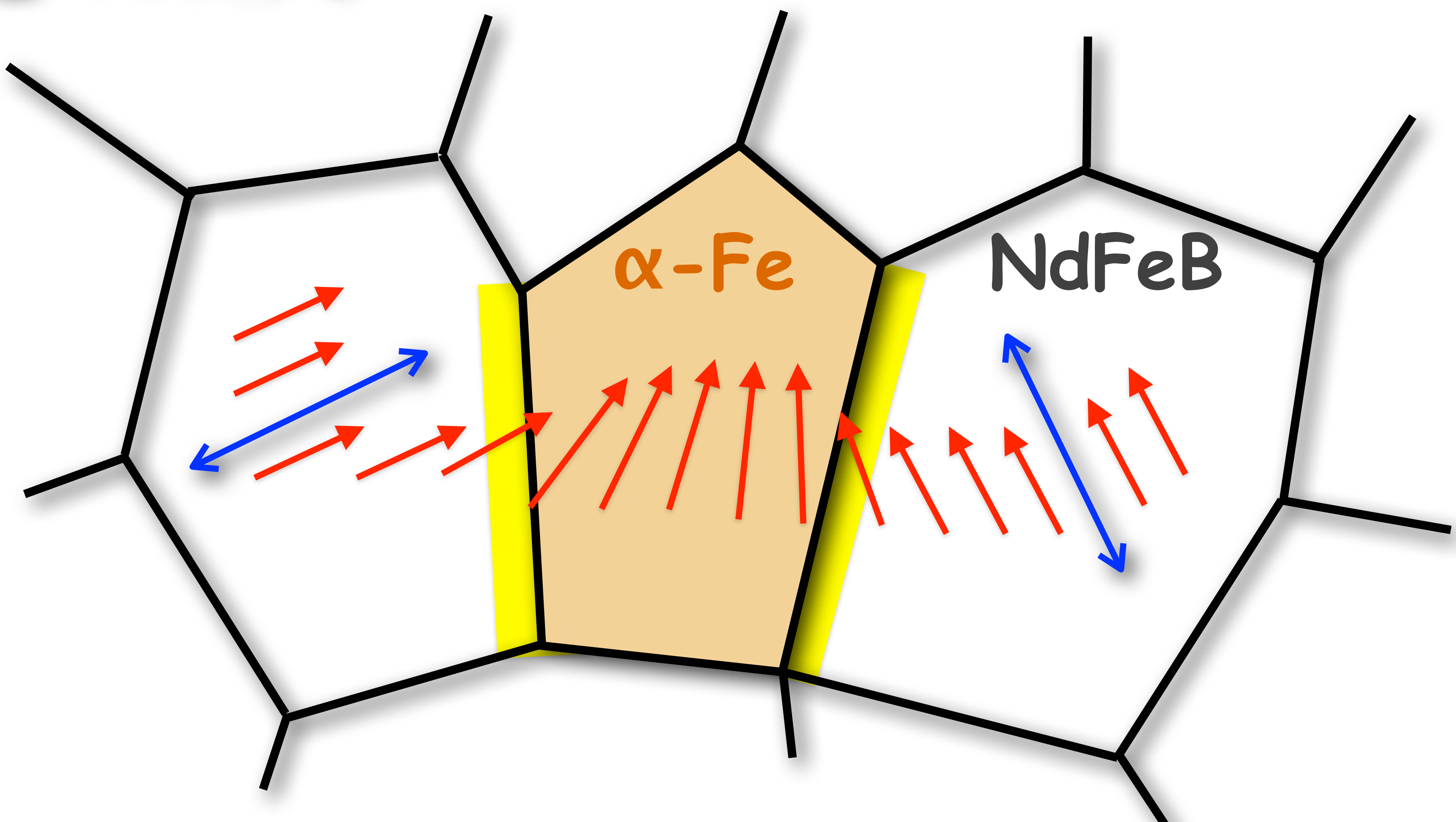


Nano-structured NdFeB: remanence enhancement



$Nd_2Fe_{14}B$ (J_s = 1.6 T)

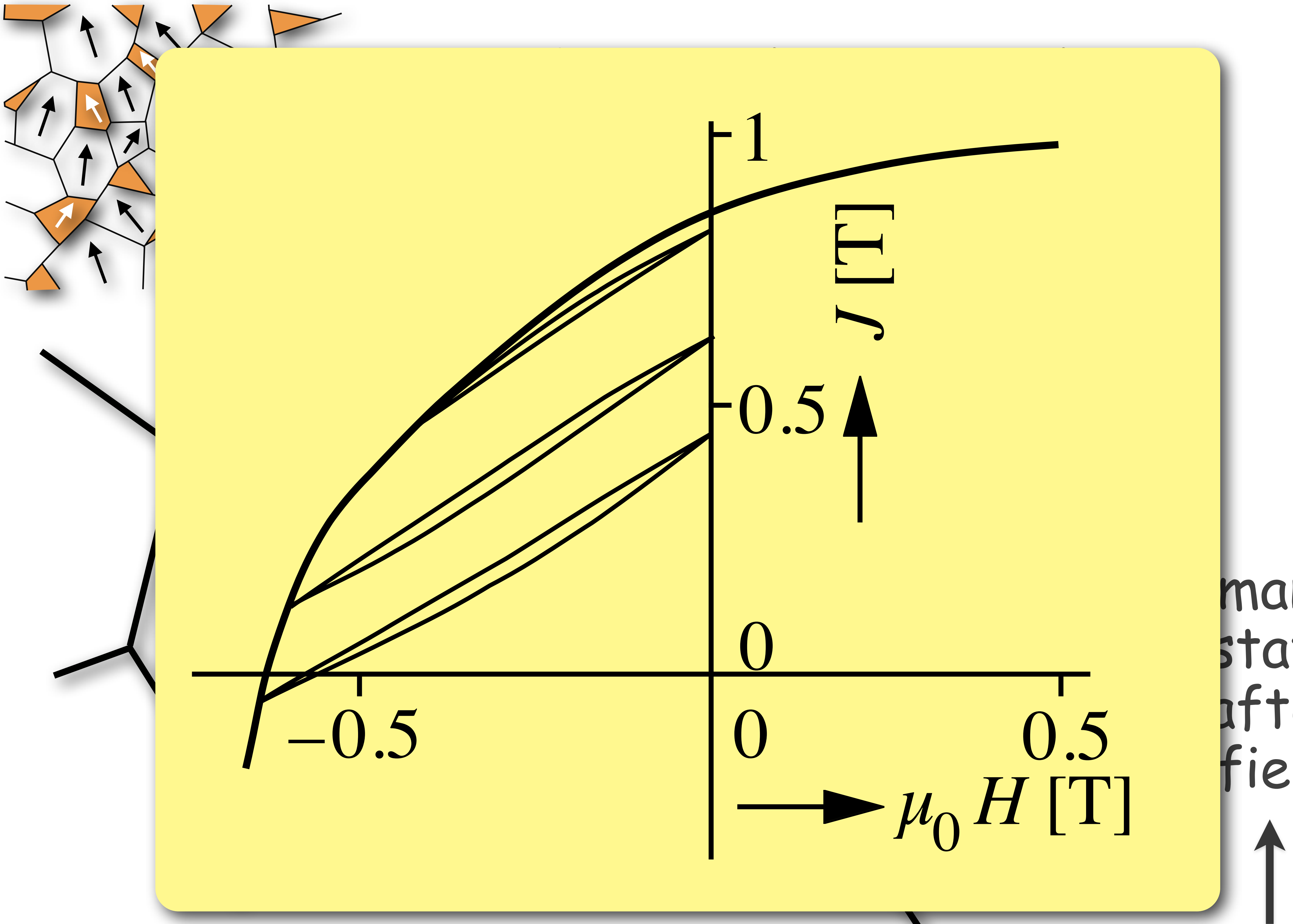
α-Fe (J_s = 2.1 T)



Remanent state after field

Exchange-spring magnet

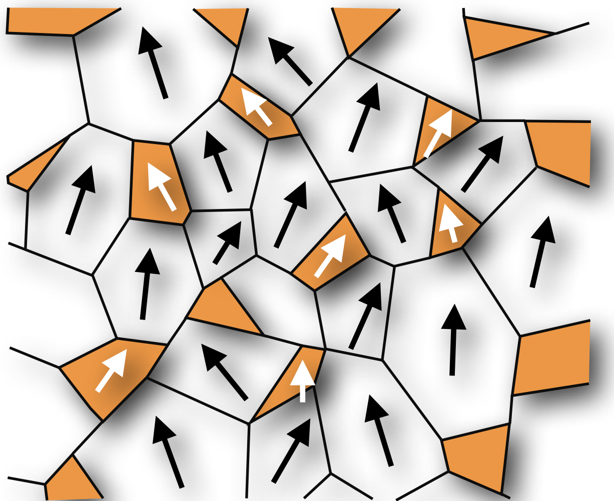
Nano-structured NdFeB: remanence enhancement



manent
state
after
field

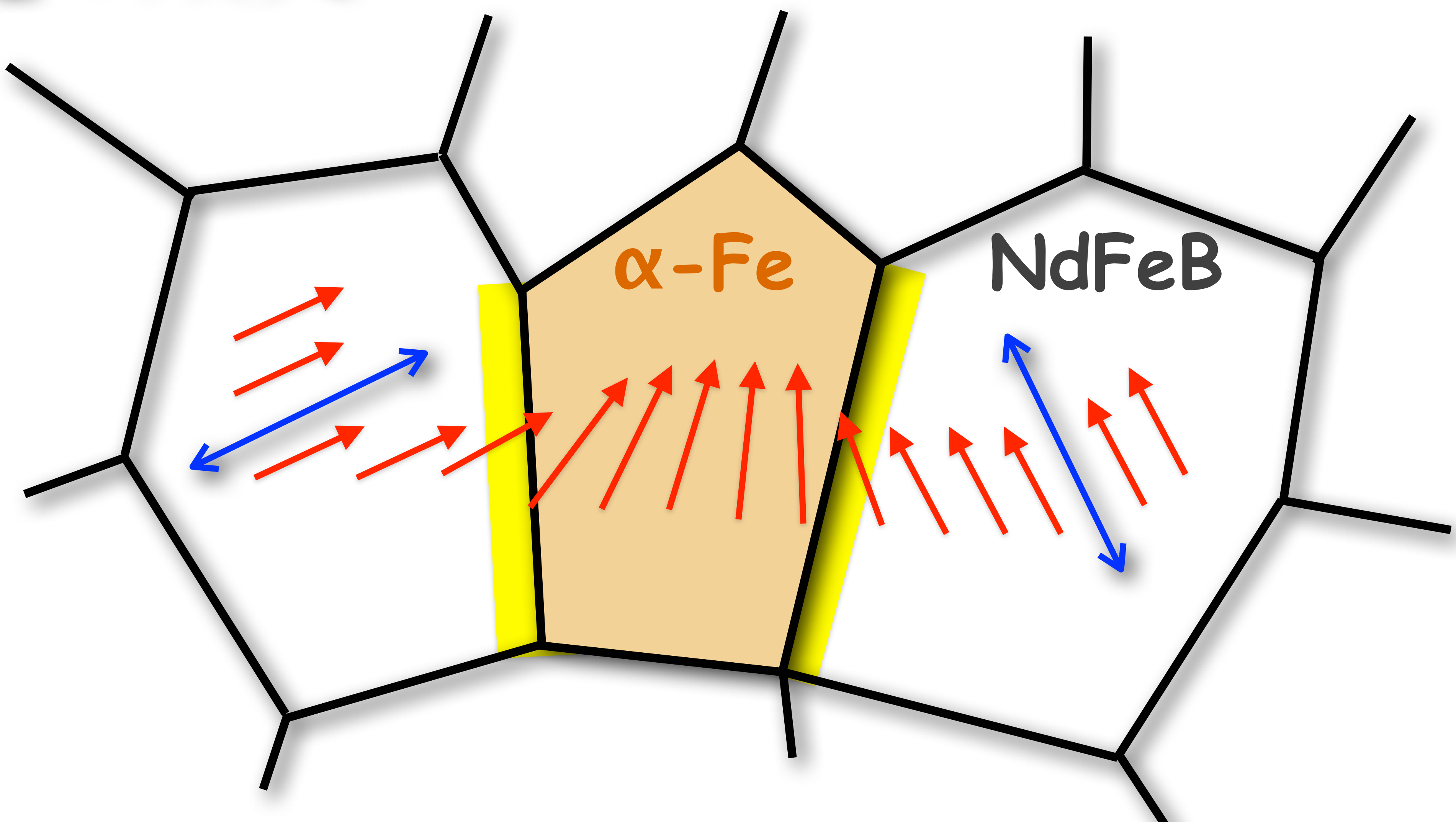
Exchange-spring magnet

Nano-structured NdFeB: remanence enhancement



$Nd_2Fe_{14}B$ (J_s = 1.6 T)

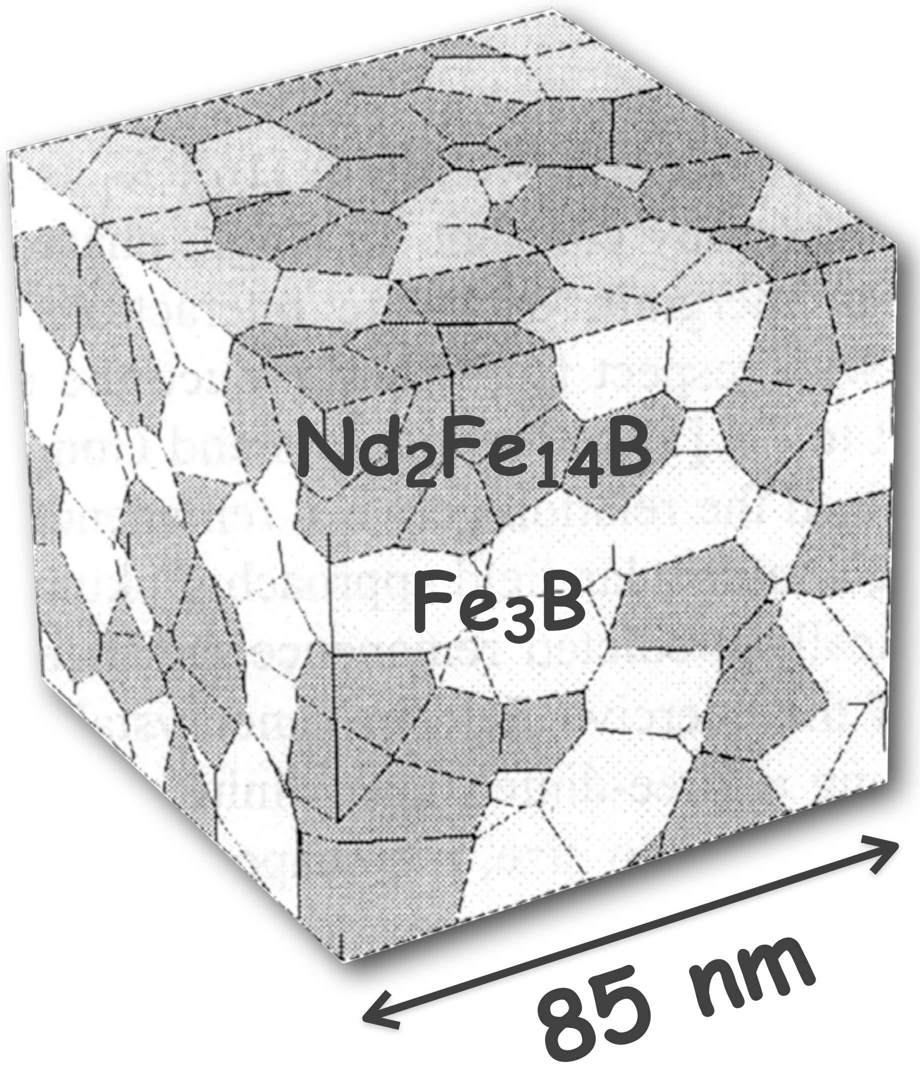
α-Fe (J_s = 2.1 T)



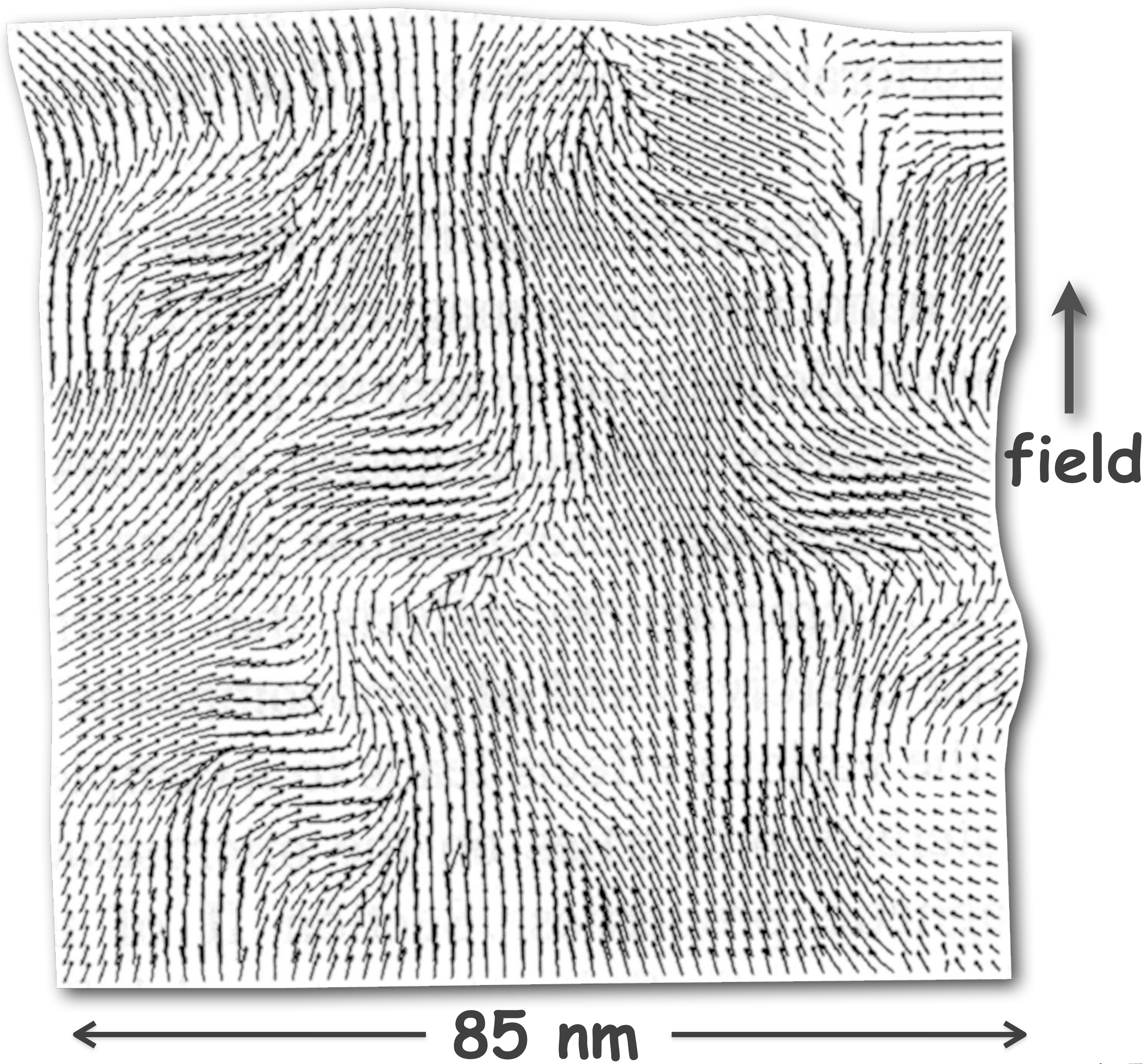
Remanent state after field ↑

Exchange-spring magnet

Nano-structured NdFeB: remanence enhancement



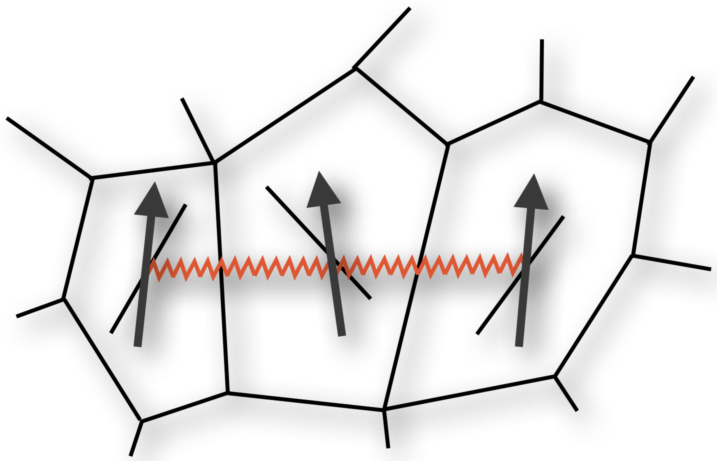
remanent state



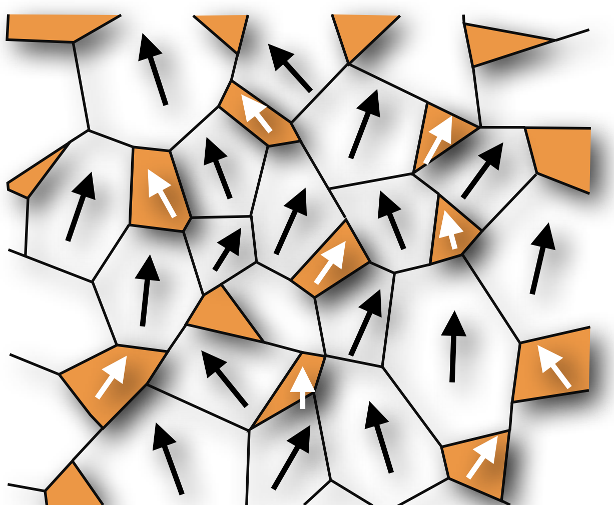
T. Schrefl and J. Fidler, IEEE Trans. Magn. 35, 3223 (1999)

3 types of nano-structured NdFeB magnets

Remanence enhancement ($M_r > M_s/2$)



Exchanged coupled grains based on stoichiometric $Nd_2Fe_{14}B$, grain size ~10 nm range

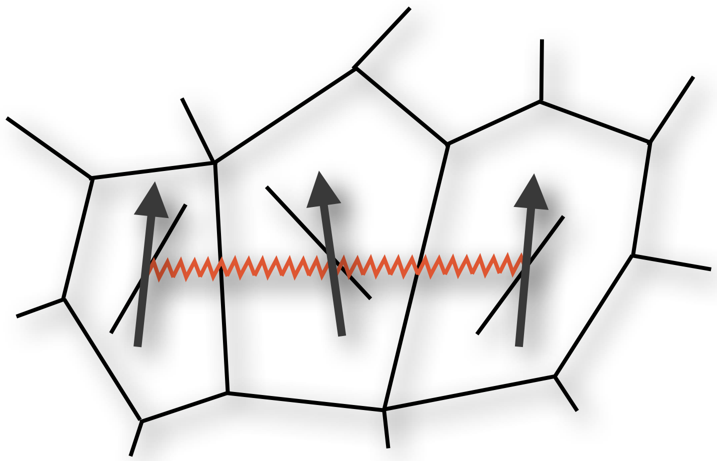


Exchanged coupled grains based on nanocomposite $Nd_2Fe_{14}B$ / α-Fe

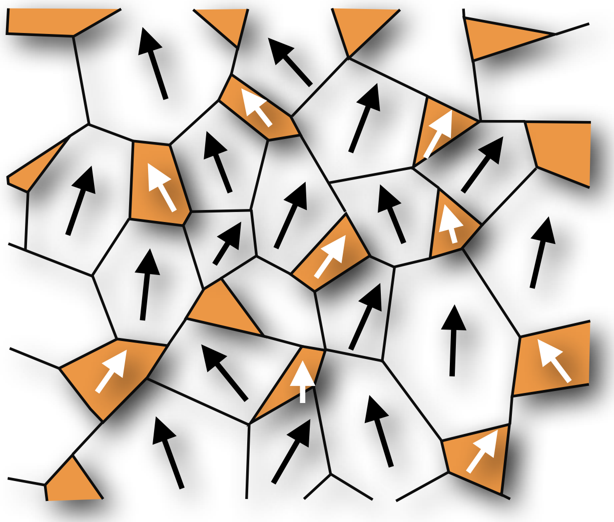
Remanence enhancement for isotropic magnets

3 types of nano-structured NdFeB magnets

Remanence enhancement ($M_r > M_s/2$)

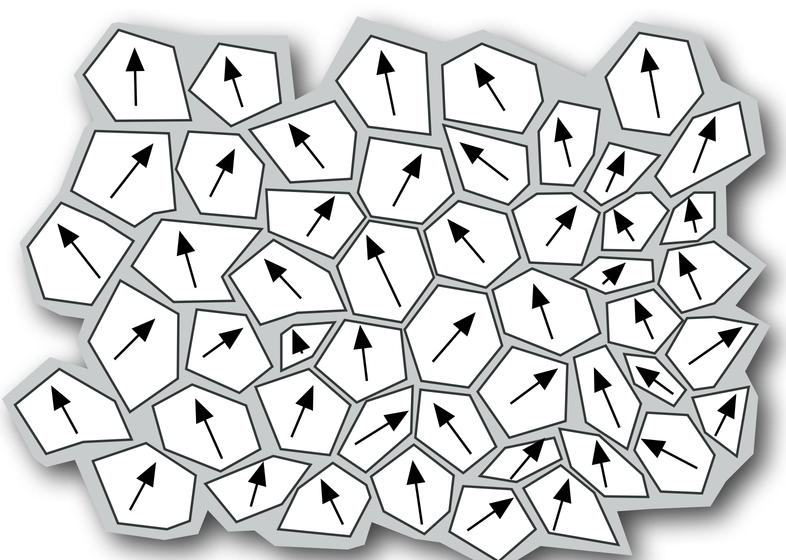


Exchanged coupled grains based on stoichiometric $Nd_2Fe_{14}B$, grain size ~10 nm range



Exchanged coupled grains based on nanocomposite $Nd_2Fe_{14}B$ / α-Fe

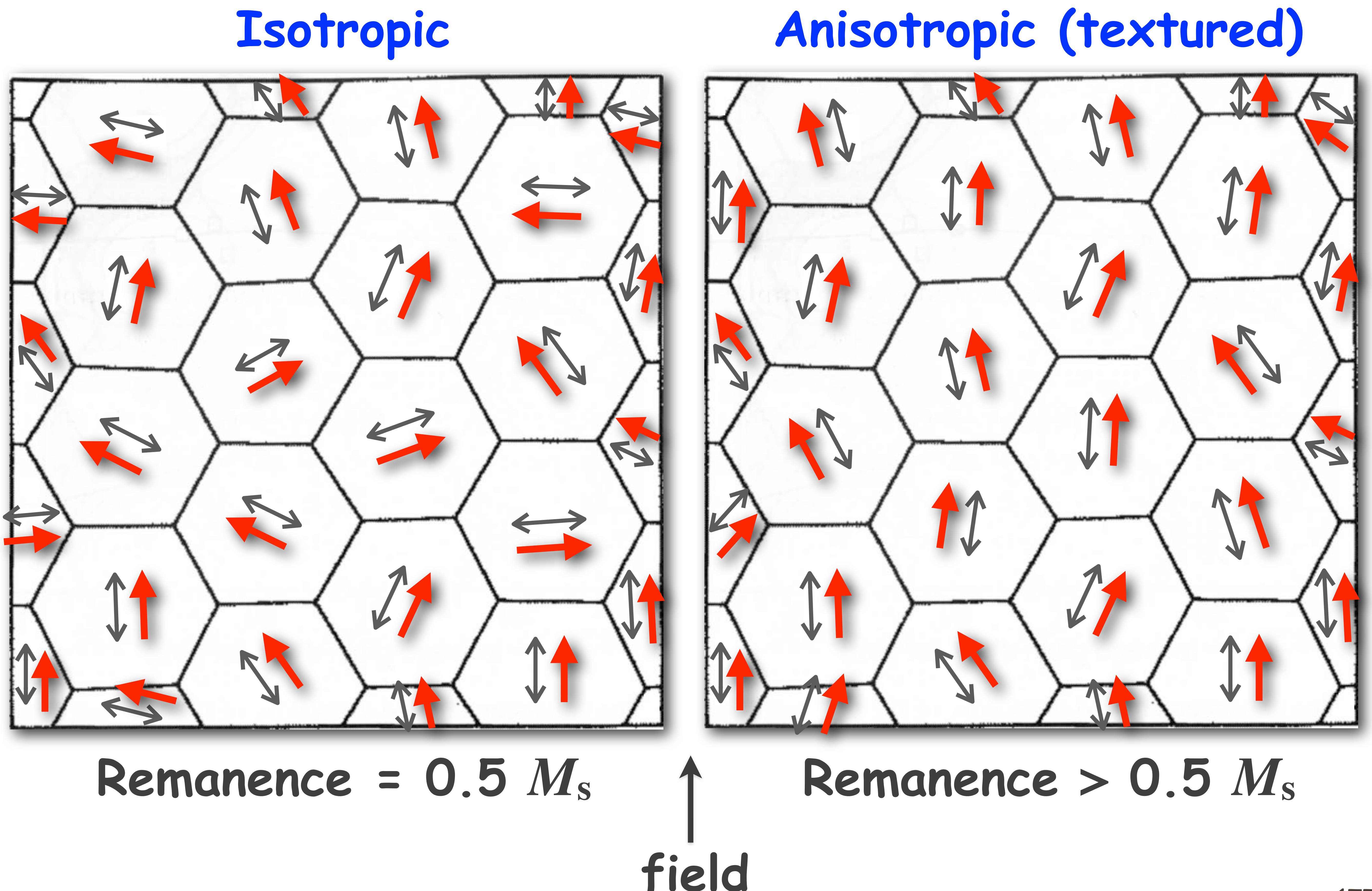
Remanence enhancement for isotropic magnets



Decoupled $Nd_2Fe_{14}B$ grains separated by thin paramagnetic layer

Remanence enhancement by texturing

Permanent magnets, basics



Processing routes for nano-structured NdFeB

- Melt spinning
- Mechanical alloying
- Intensive milling
- HDDR

↓

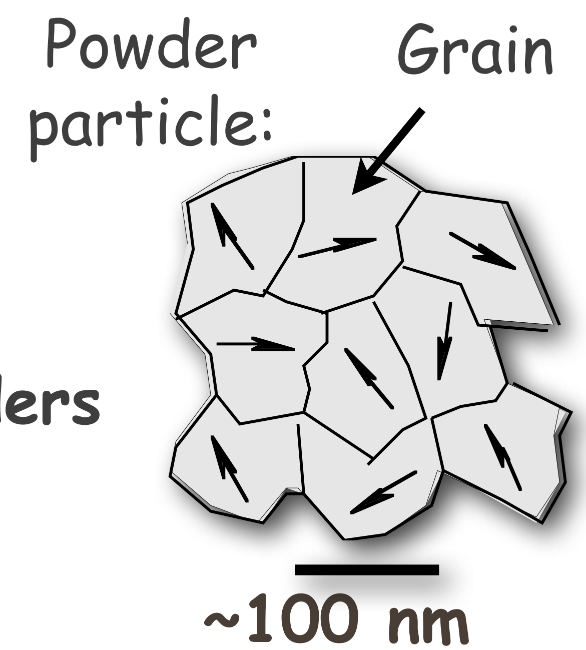
Isotropic nanocrystalline powders ($M_r = M_s/2$)

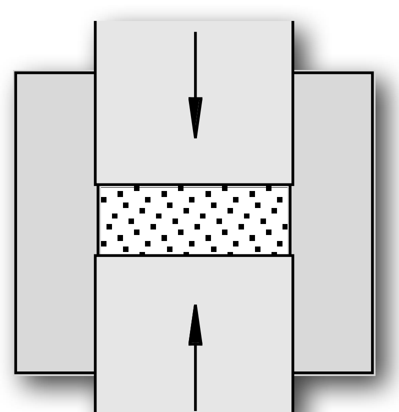
↓

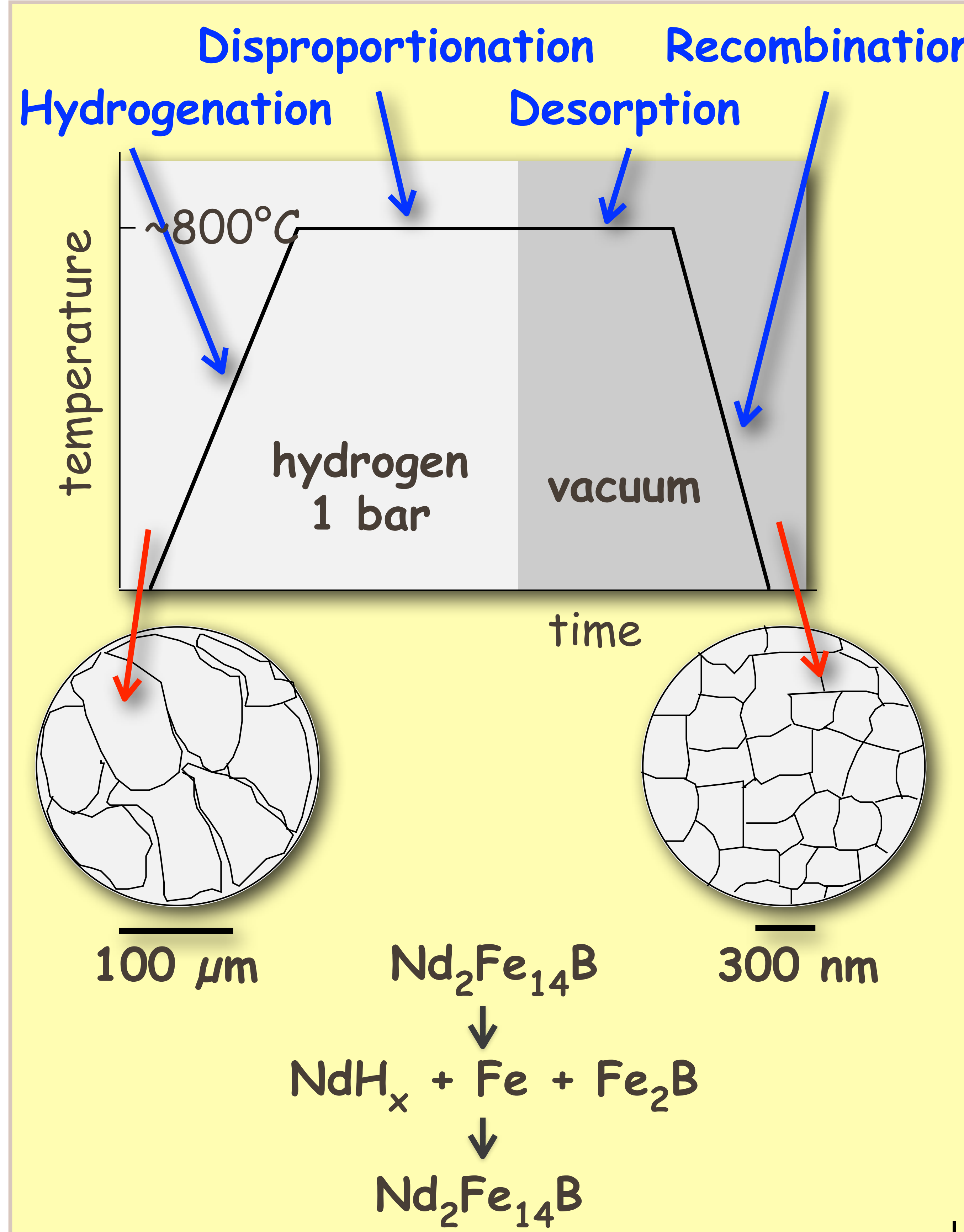
Hot pressing

↓

Isotropic, fully dense magnet (not very useful...)

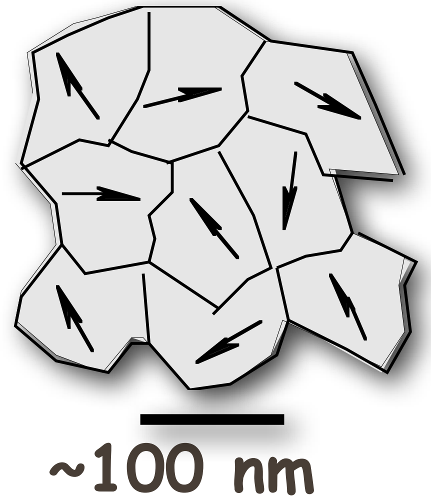






Processing routes for nano-structured NdFeB

Isotropic
nanocrystalline powder
($M_r = M_s/2$)

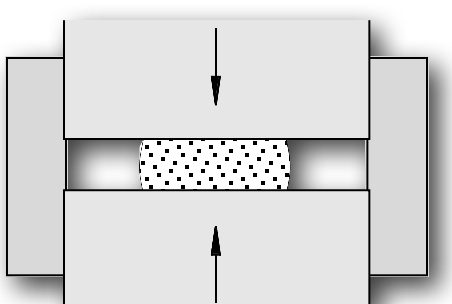


↓

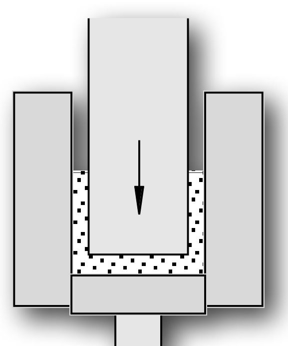
Hot deformation:

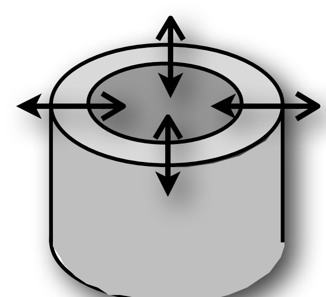
↙ ↘

Die upsetting



Backward extrusion



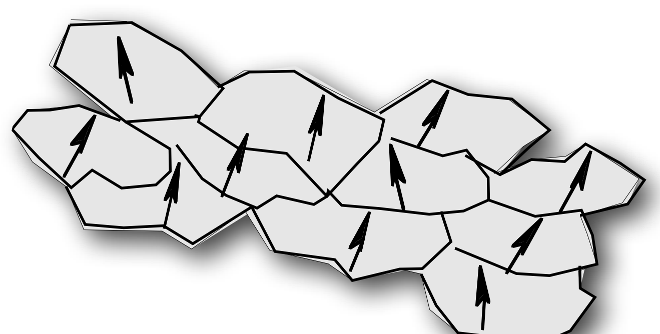


Axial texture

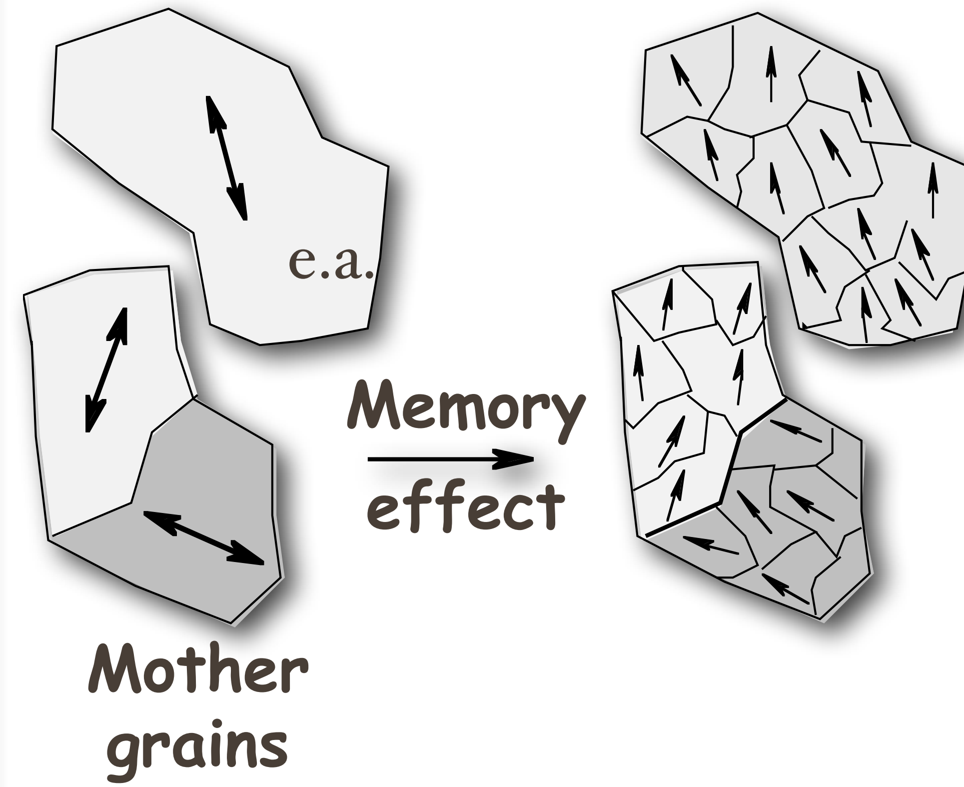
Radial texture

↓

Anisotropic
textured magnet
($M_r >> M_s/2$)

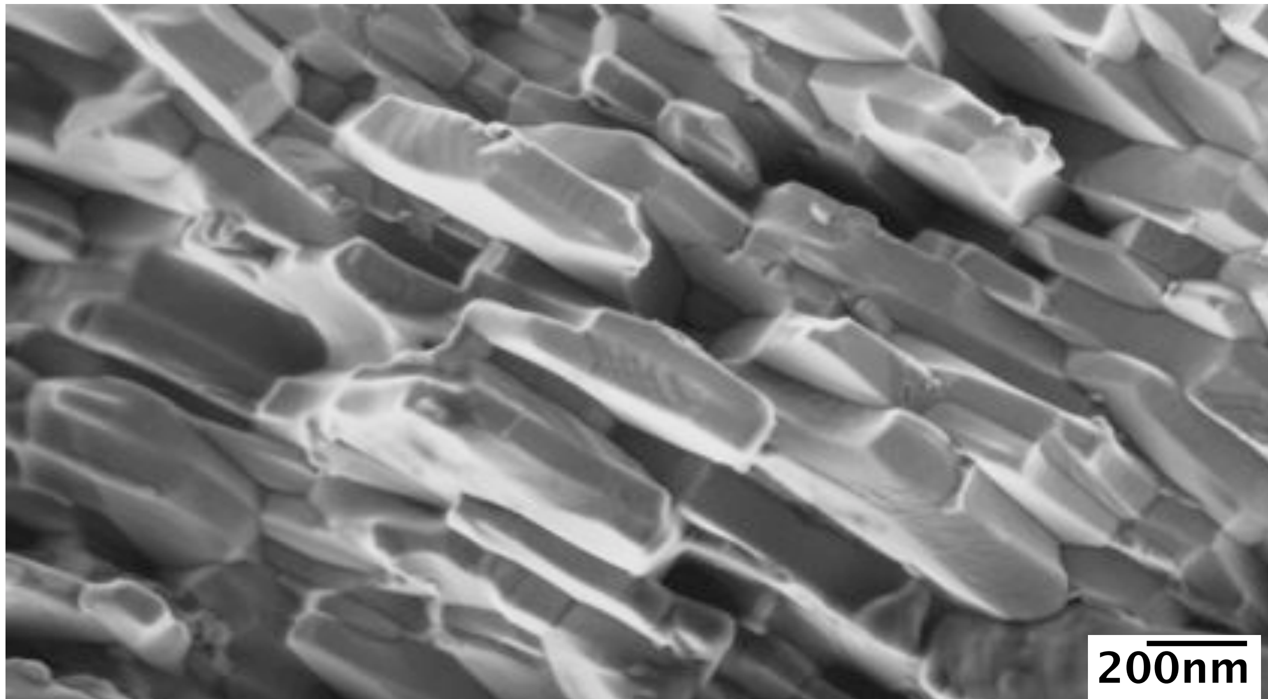


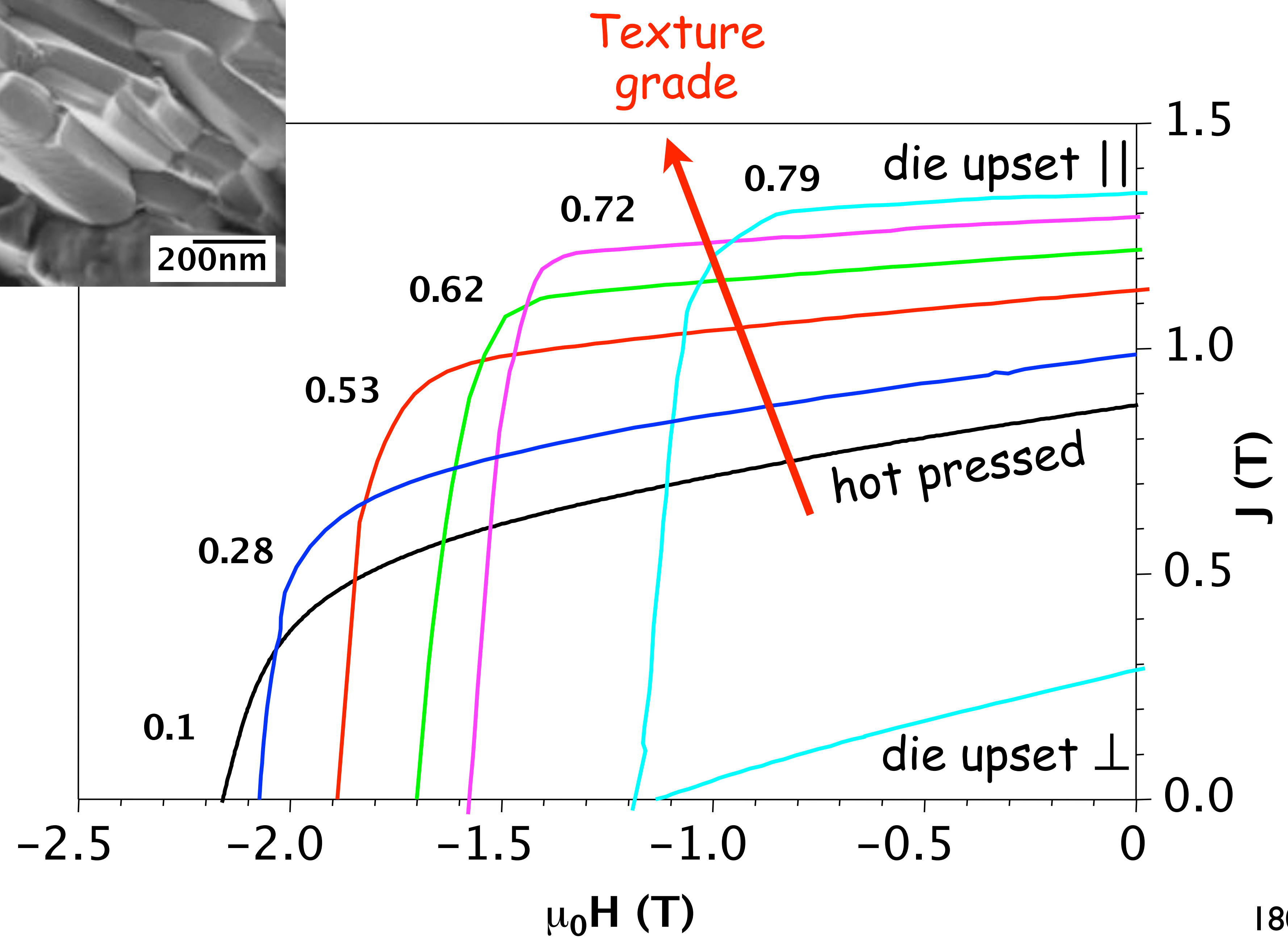
Anisotropic
HDDR
process



Nano-structured NdFeB

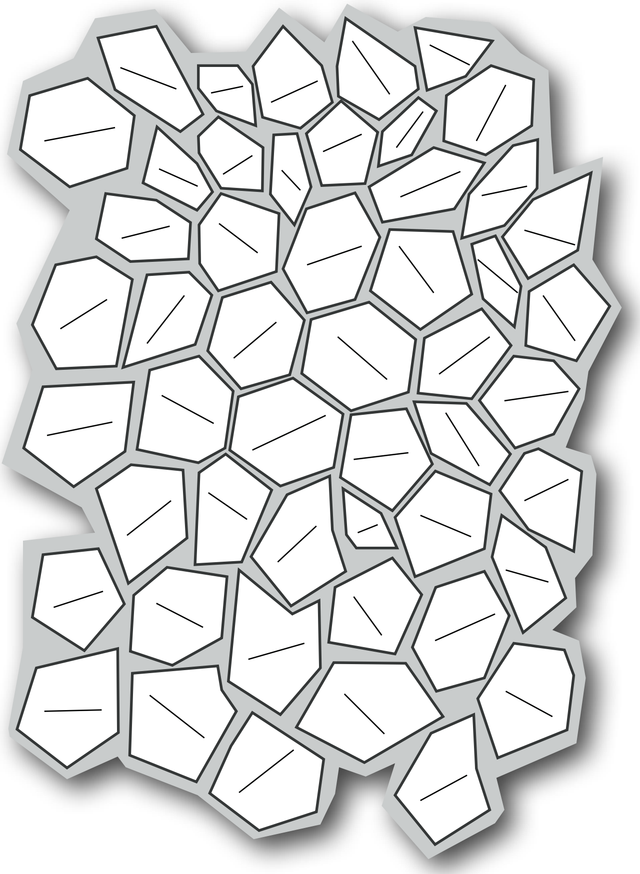
Die-upset melt-spun
$Nd_{13.6}Fe_{73.6}Ga_{0.6}Co_{6.6}B_{5.6}$





Magn. microstructure of nanostructured NdFeB

Decoupled grains,
size: ~300 nm



Magn. microstructure of nanostructured NdFeB

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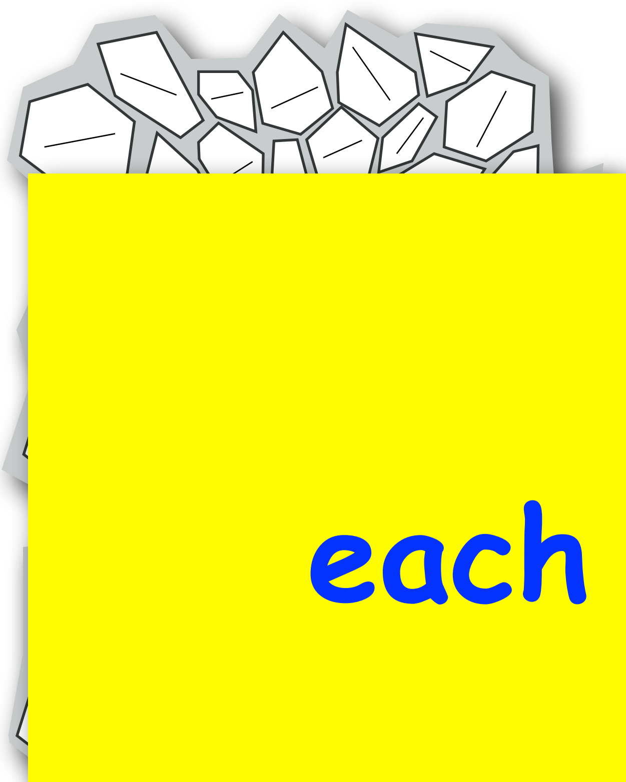

Expectation:
each grain (particle) magnetized along its easy axis.

Magn. microstructure of nanostructured NdFeB

Decoupled grains,
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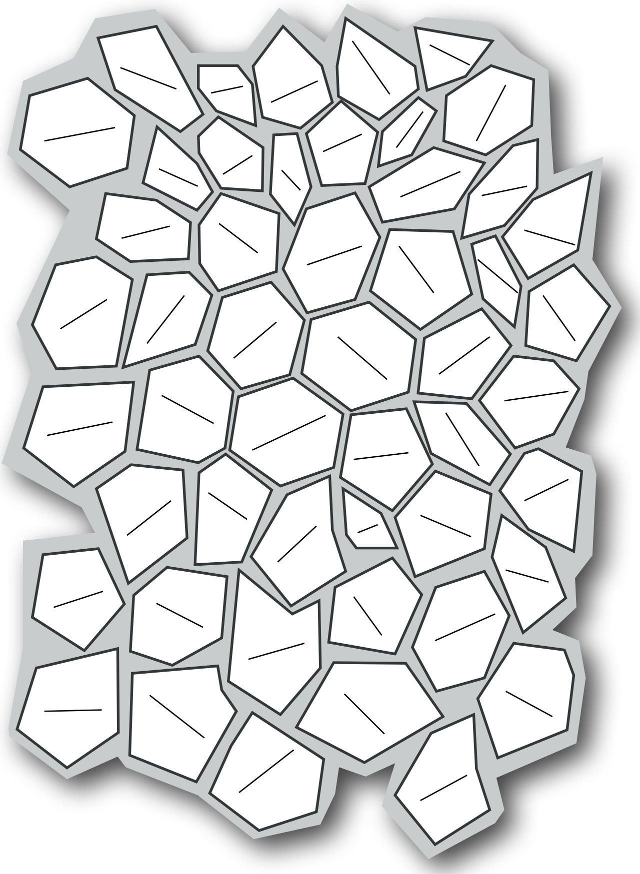
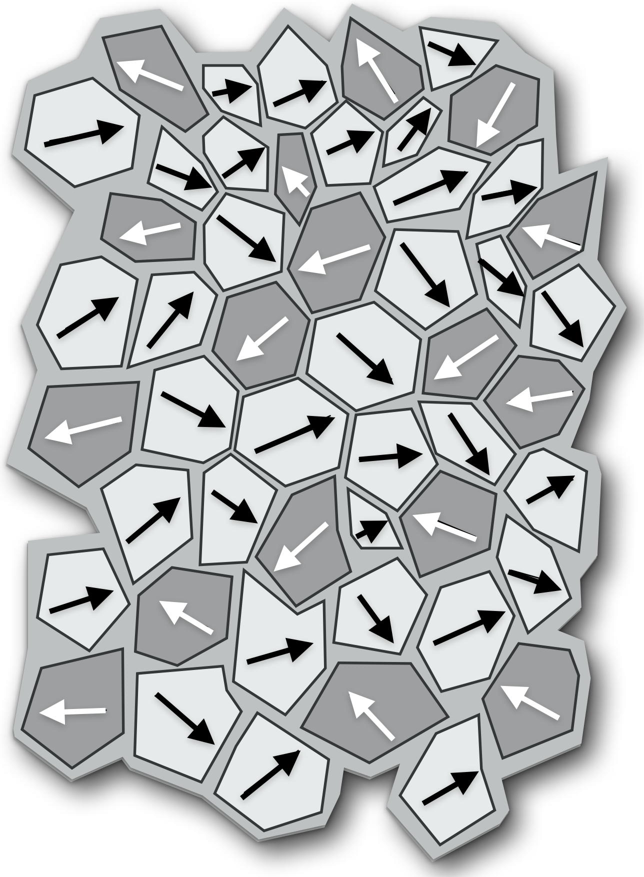


Magn. microstructure of nanostructured NdFeB

Decoupled grains,
size: ~300 nm



Magn. microstructure of nanostructured NdFeB

Decoupled grains,
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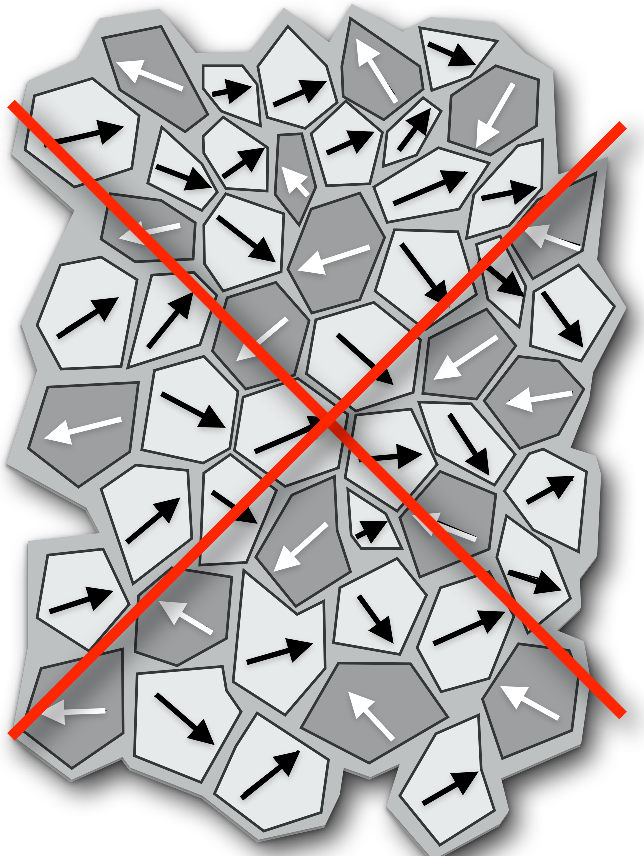
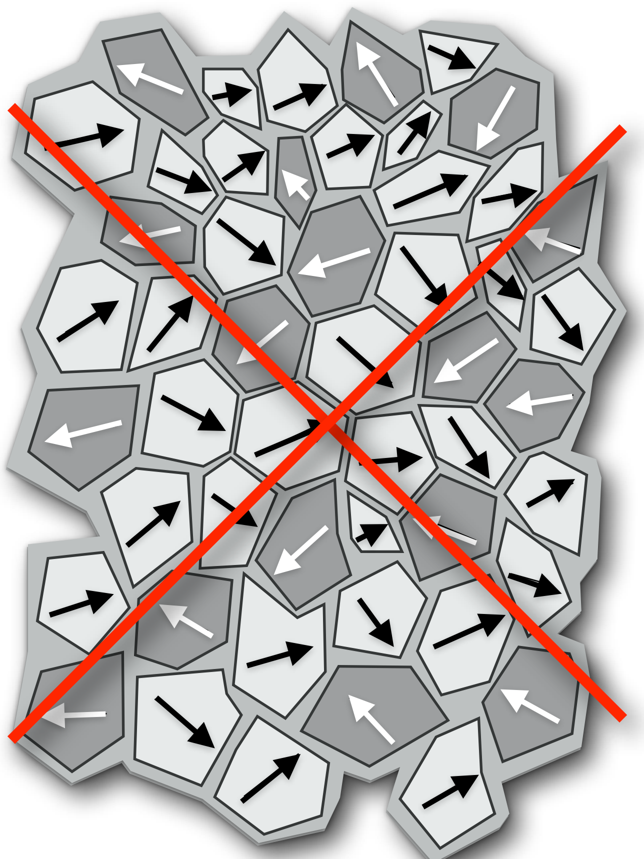
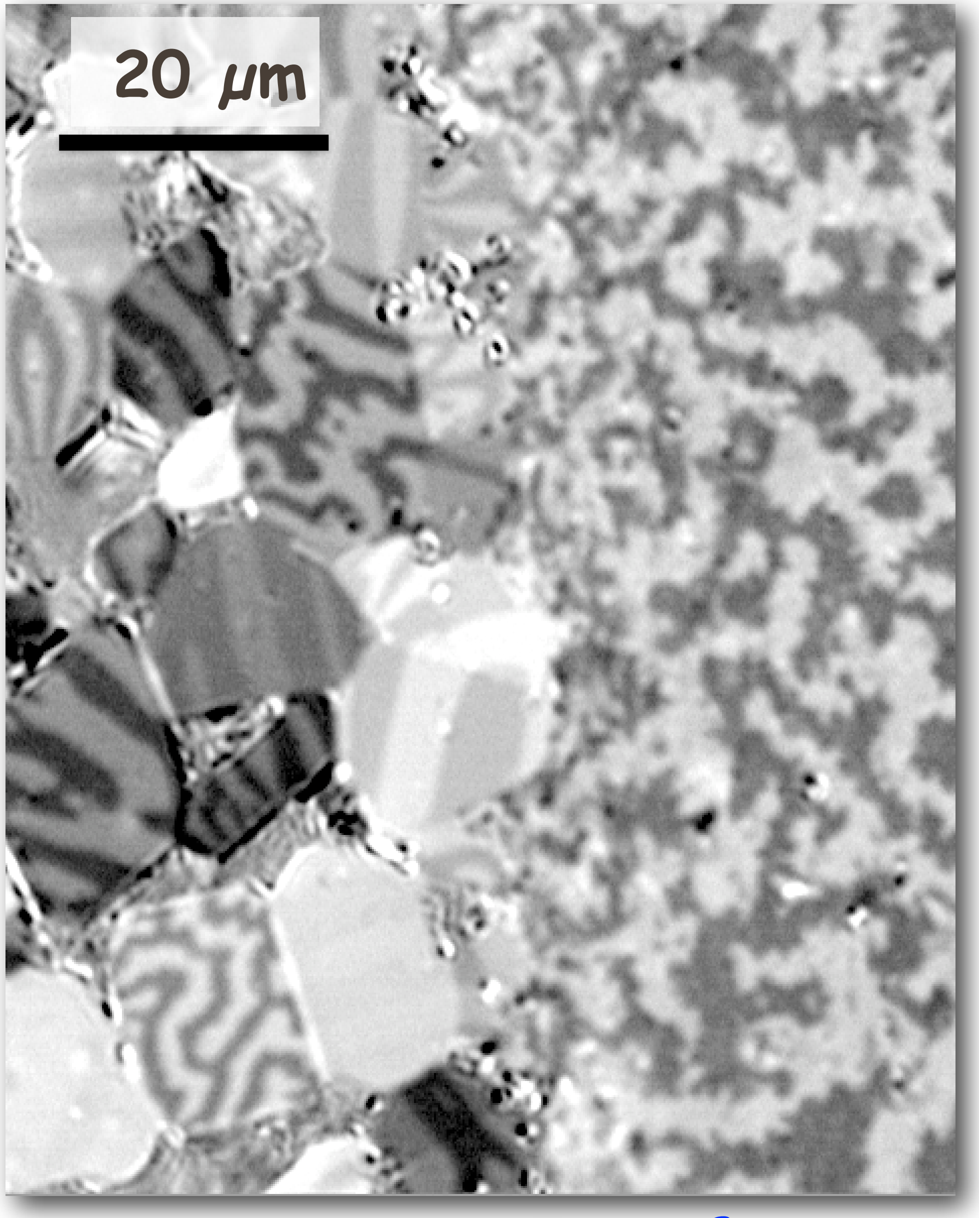


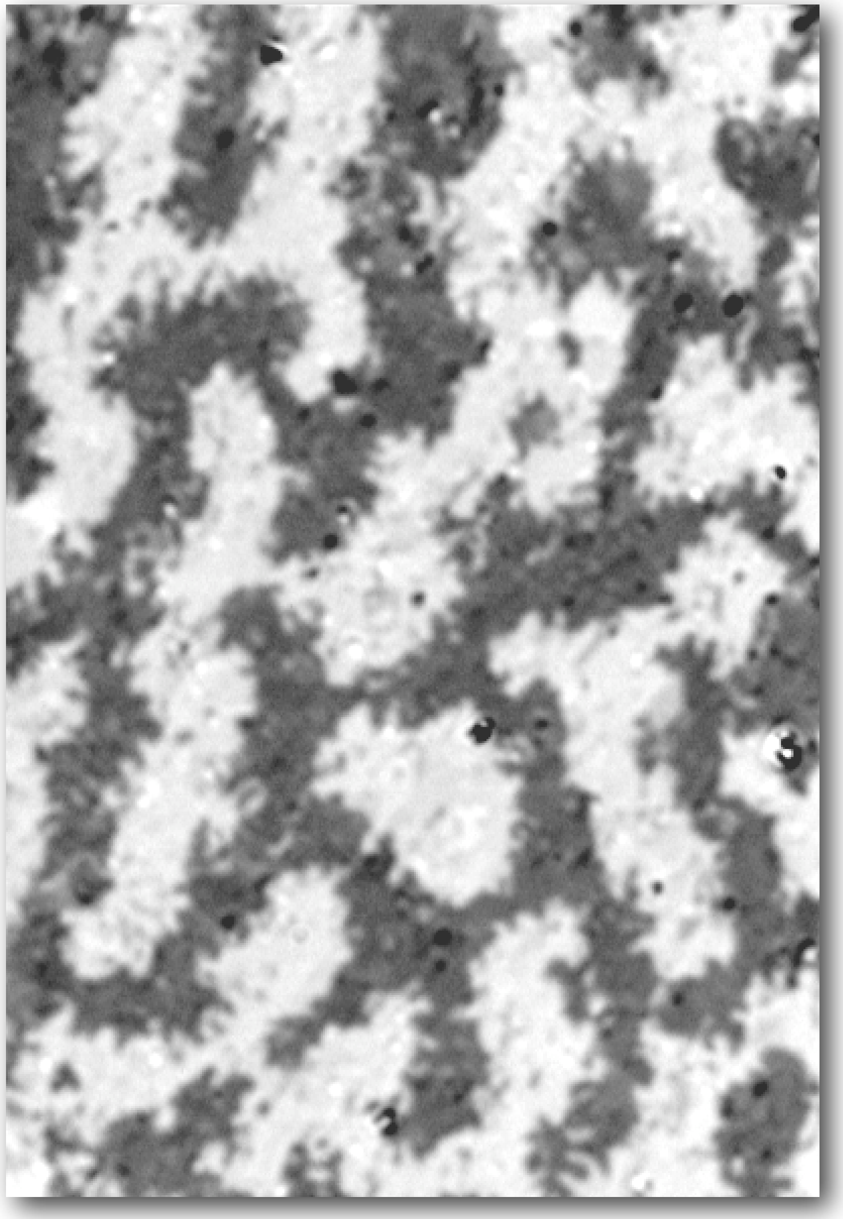
Magn. microstructure of nanostructured NdFeB

Observation perpendicular to texture axis

Decoupled grains,
size: ~300 nm







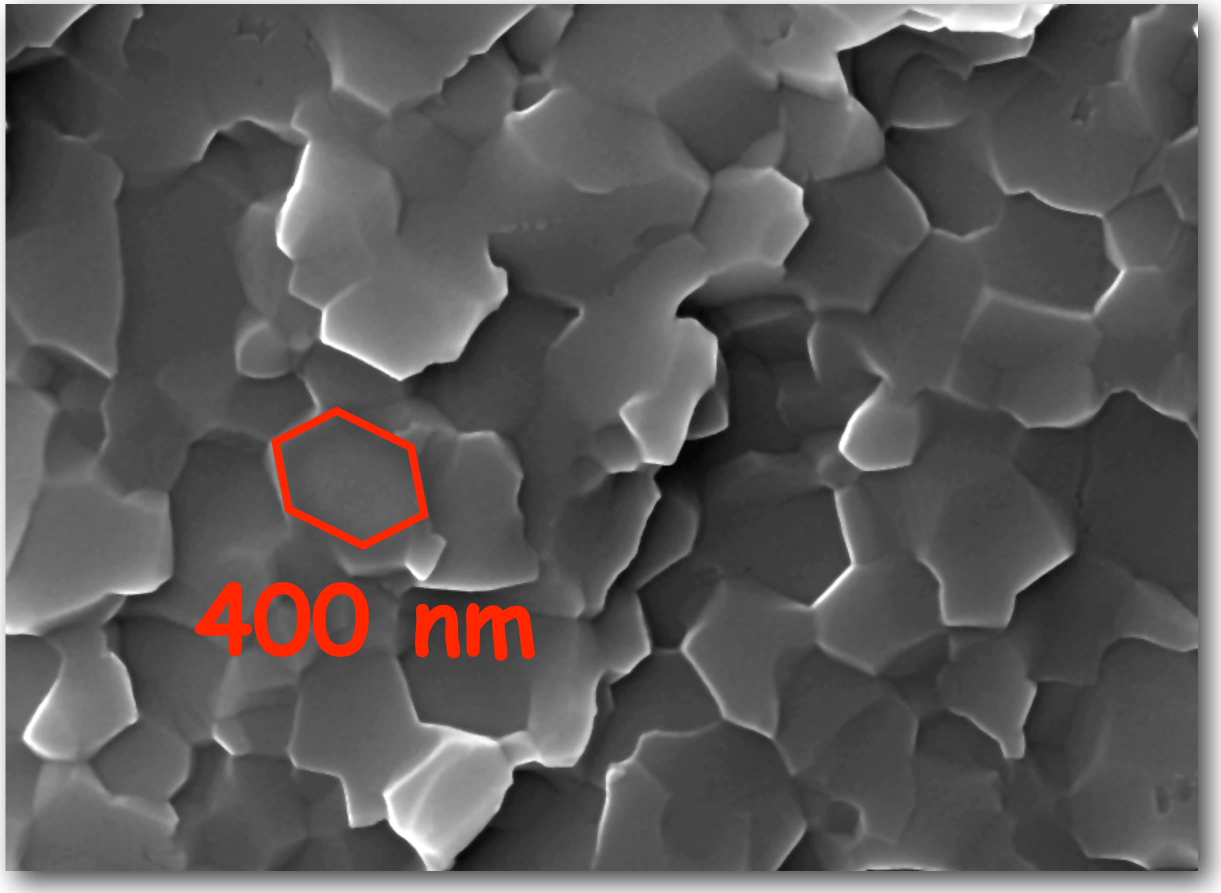
coarse grains | fine grains

Magn. microstructure of nanostructured NdFeB

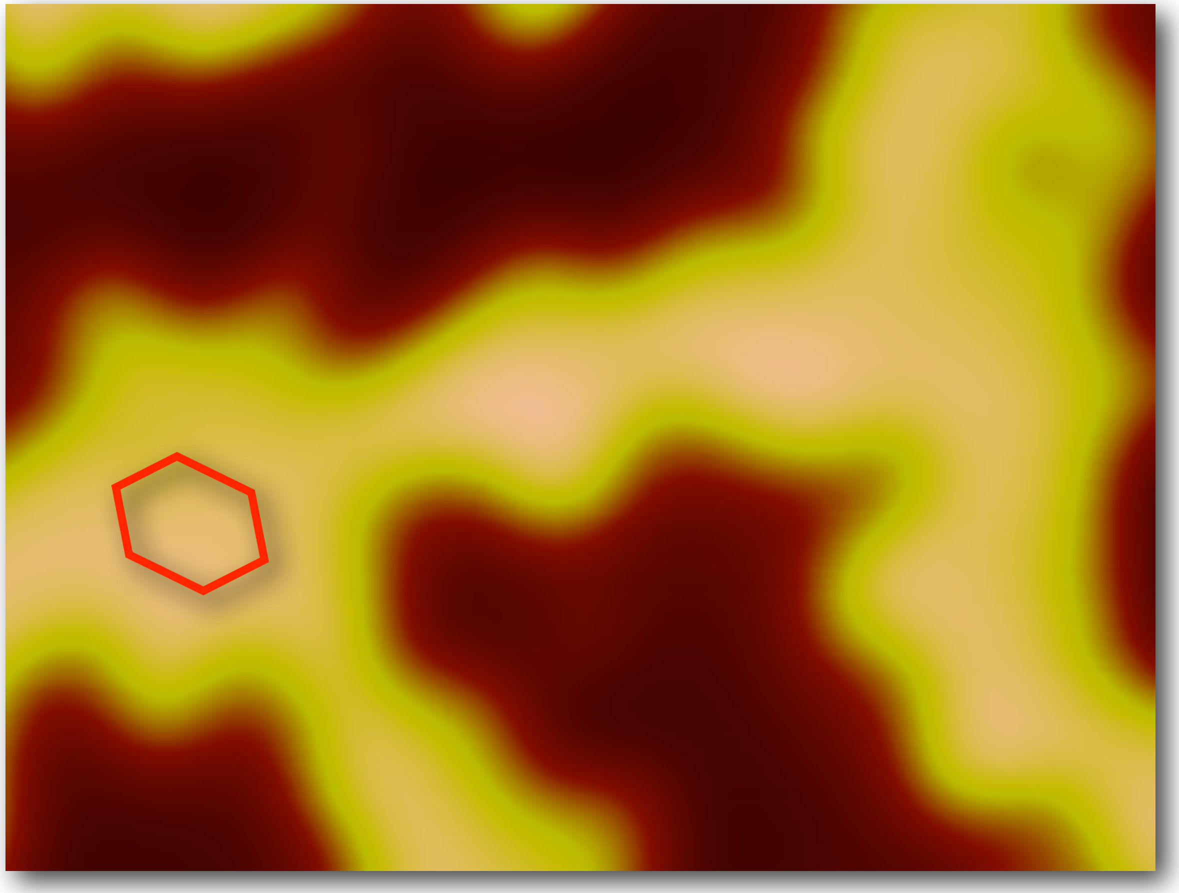
Hot deformed NdFeB magnet (thermally demagnetized)
(deformation degree ~ 76%, texture parameter $(B_r^{||}-B_r^{\perp})/B_r^{||} = 0.79$)

observed perpendicular to texture axis

grain structure

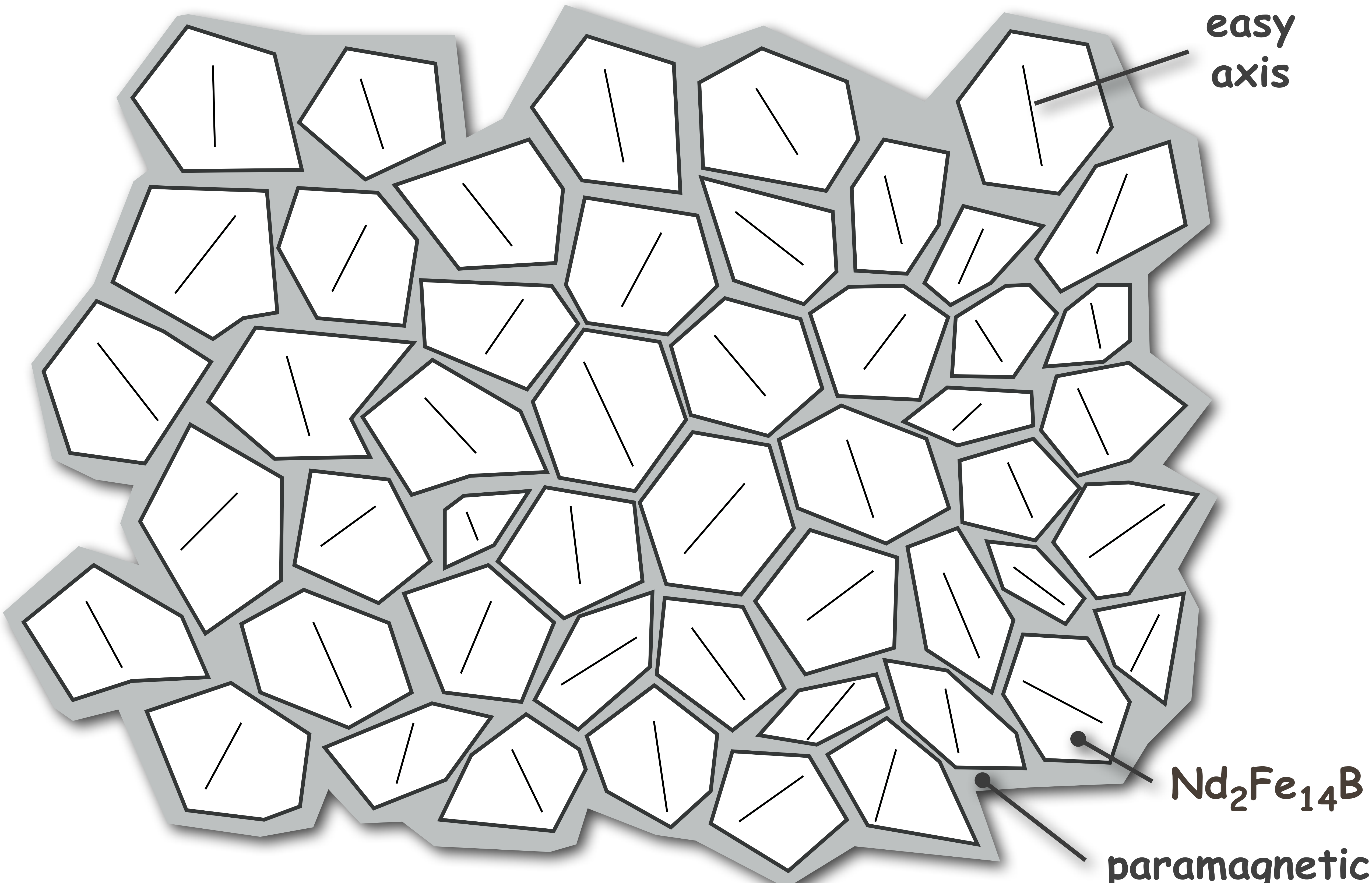


domains

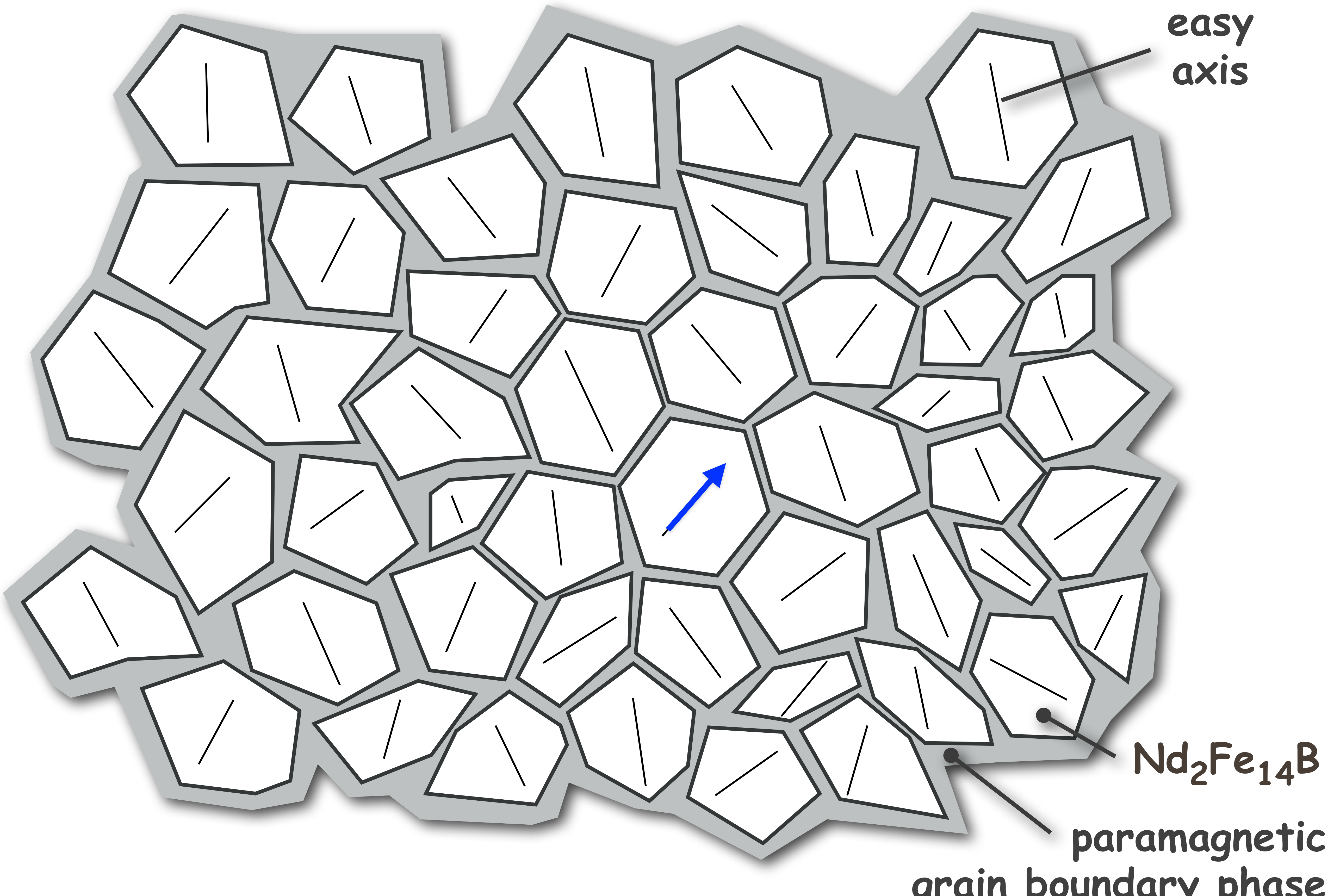


Courtesy K. Khlopkov and O. Gutfleisch (IFW Dresden)

Magn. microstructure of nanostructured NdFeB



Magn. microstructure of nanostructured NdFeB



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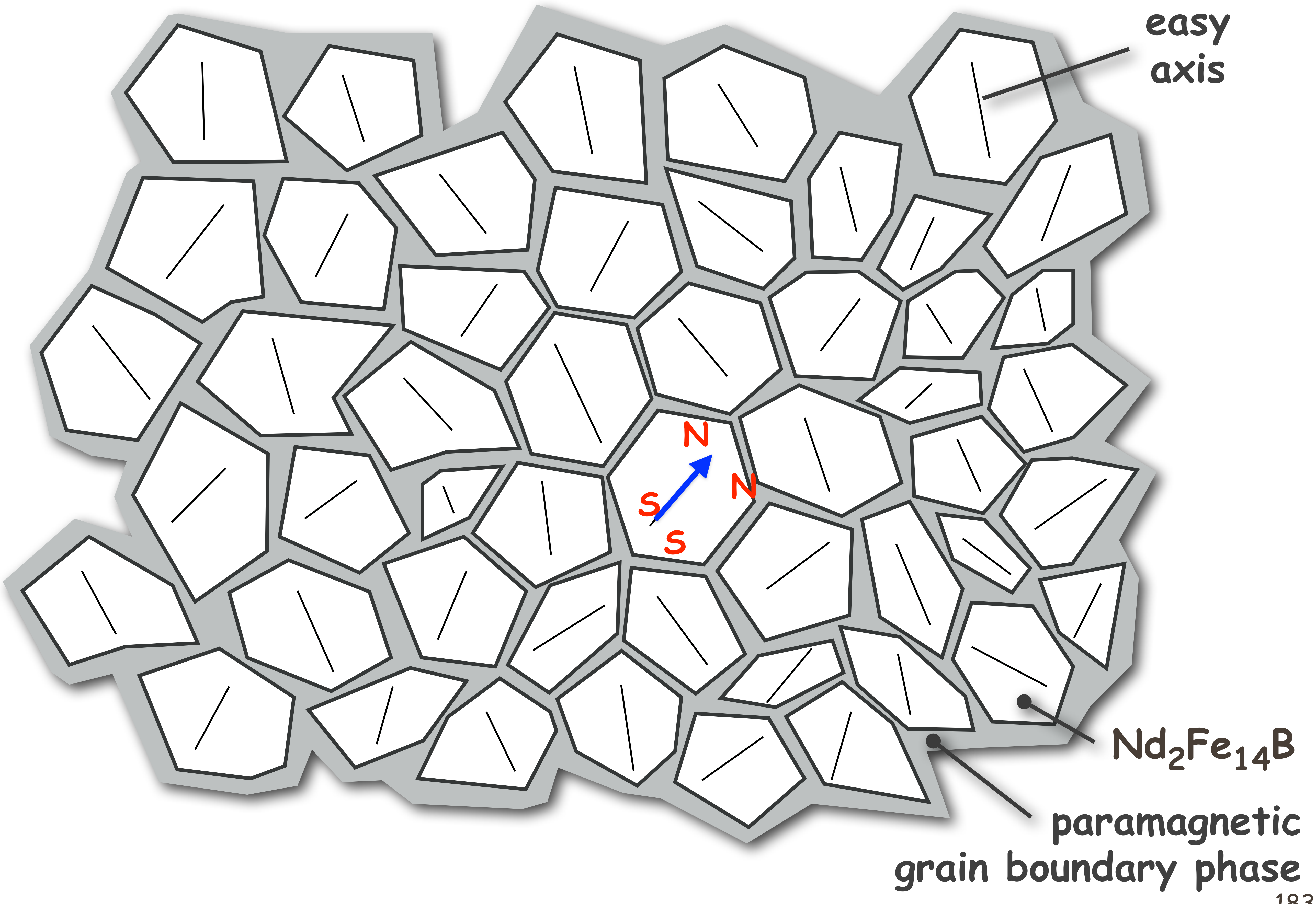

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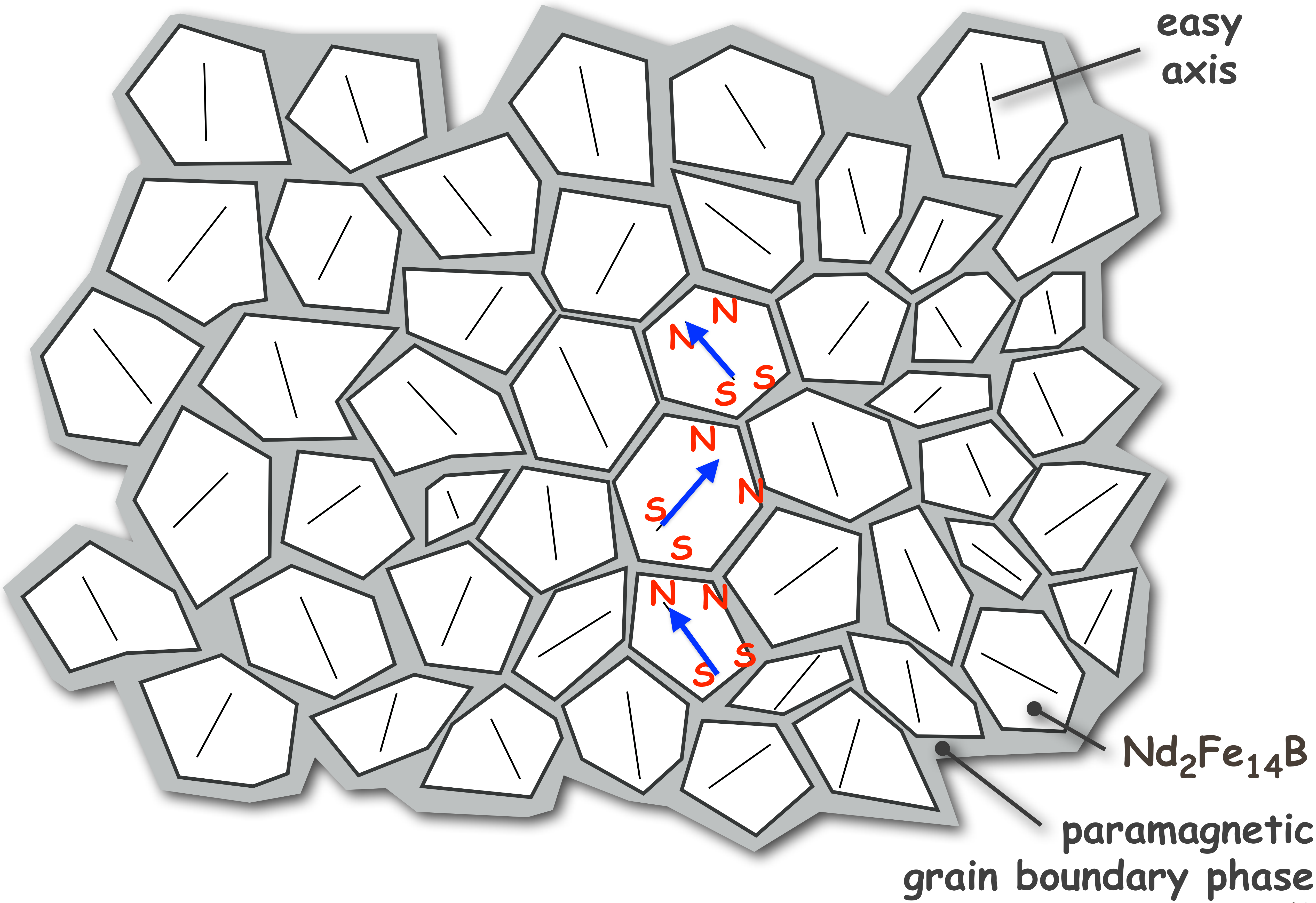

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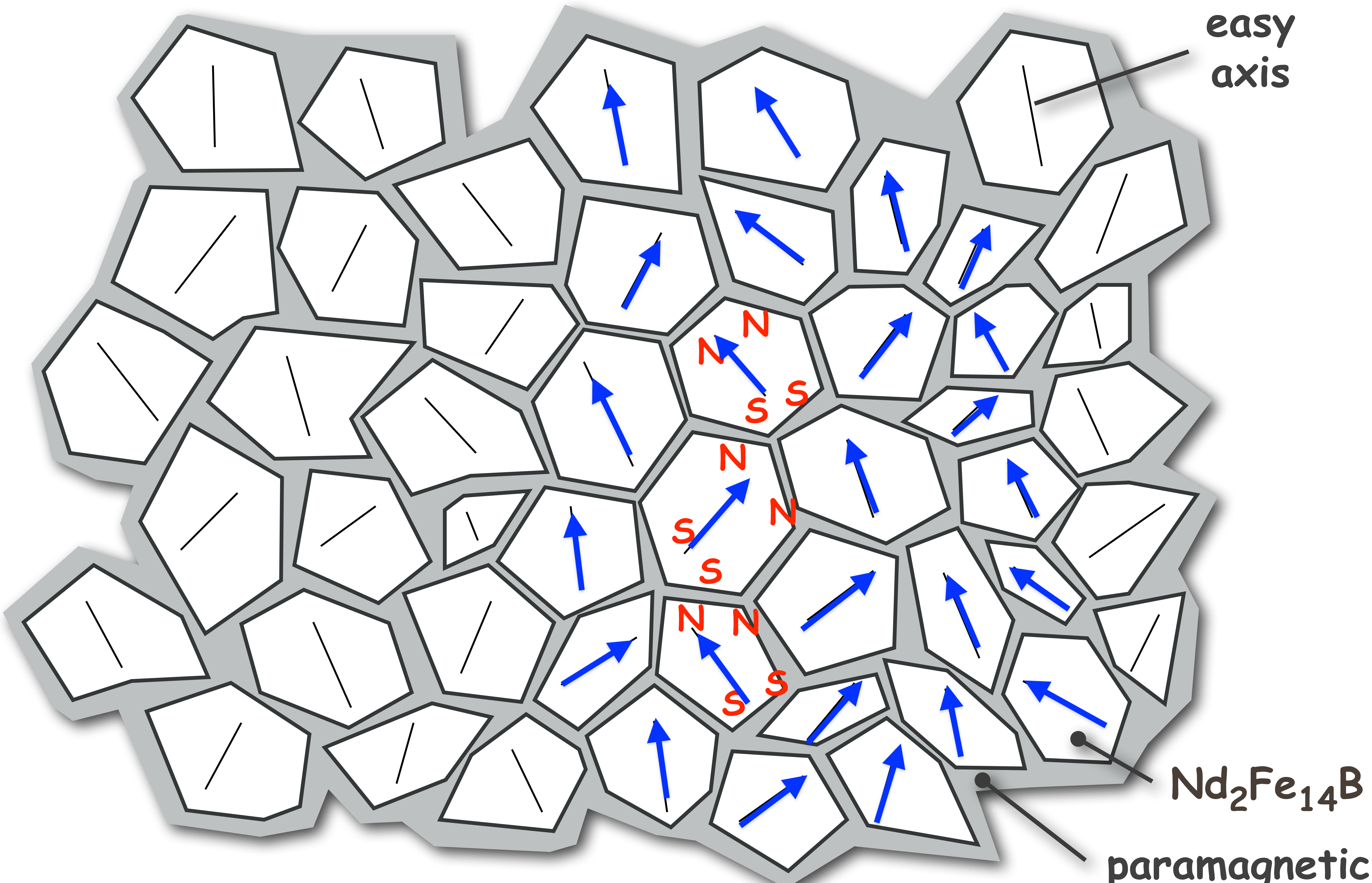

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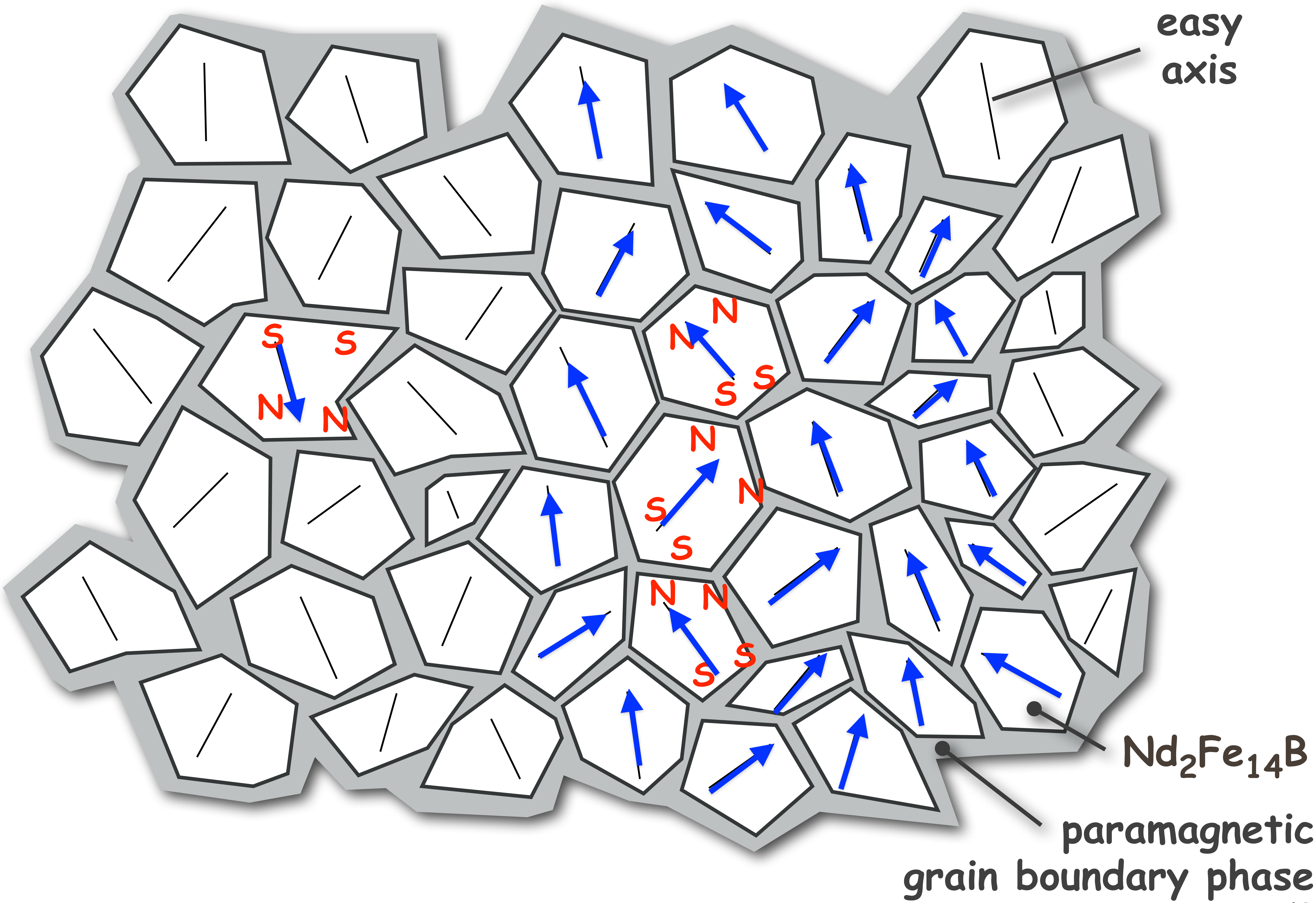
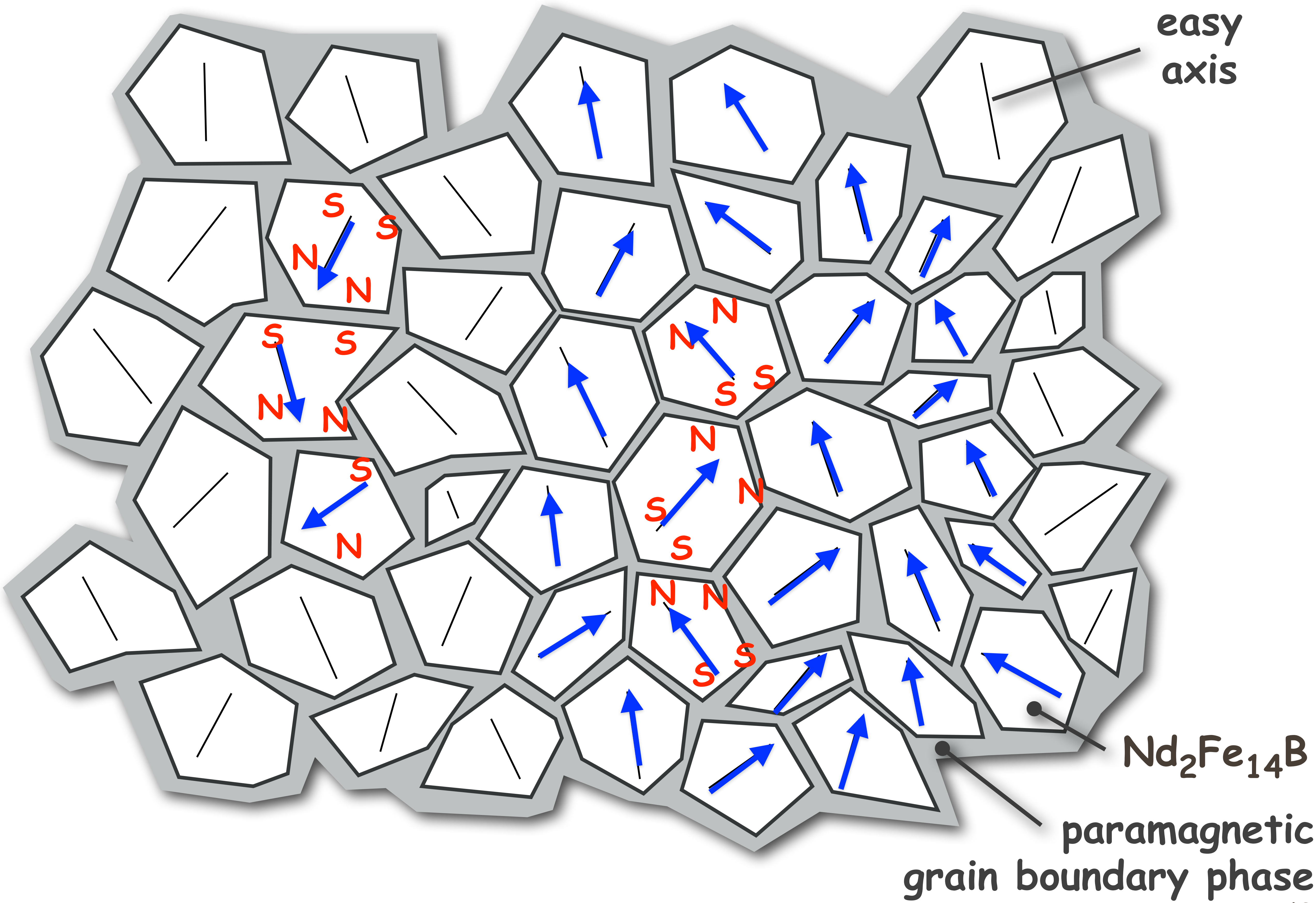
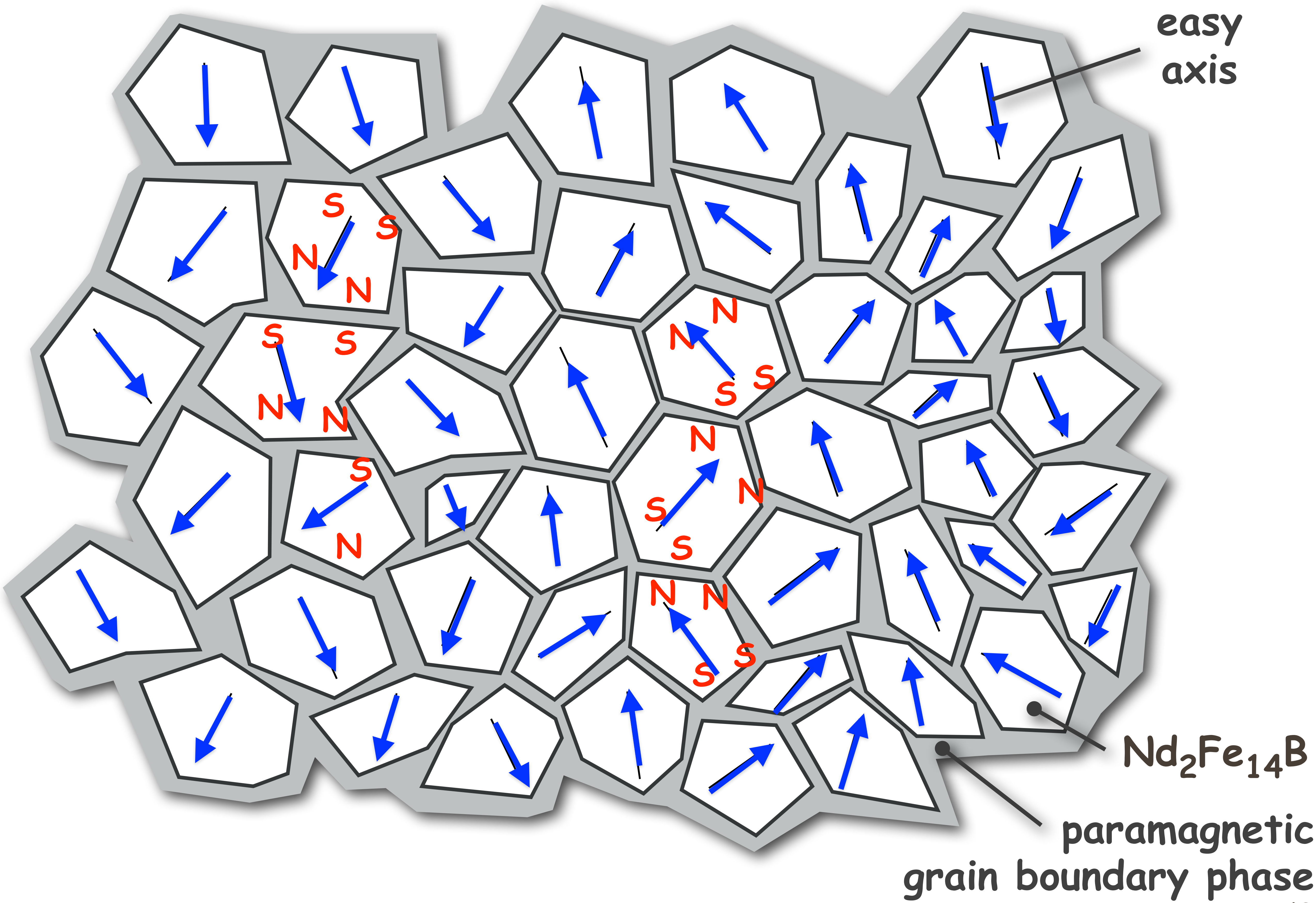


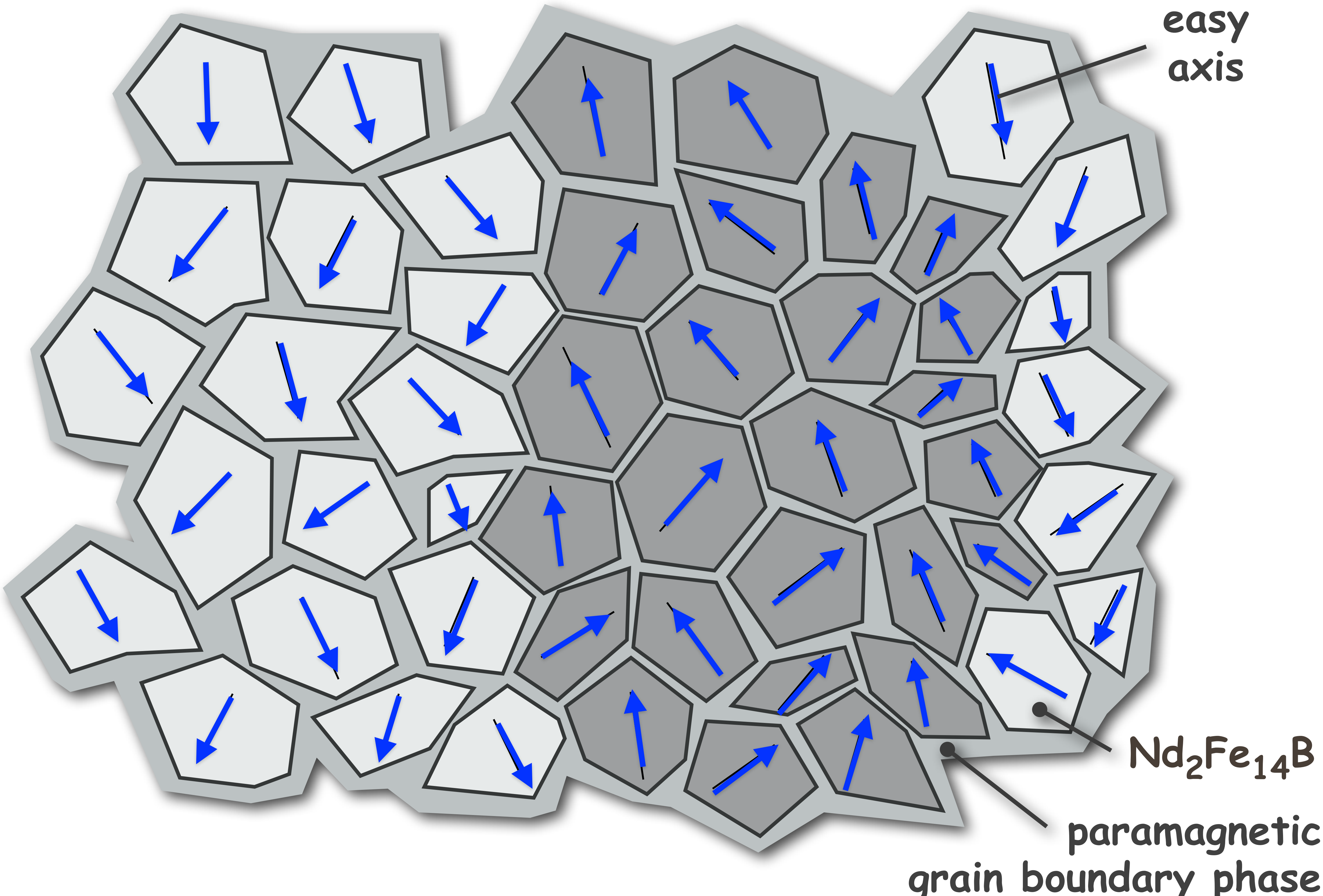
Magn. microstructure of nanostructured NdFeB



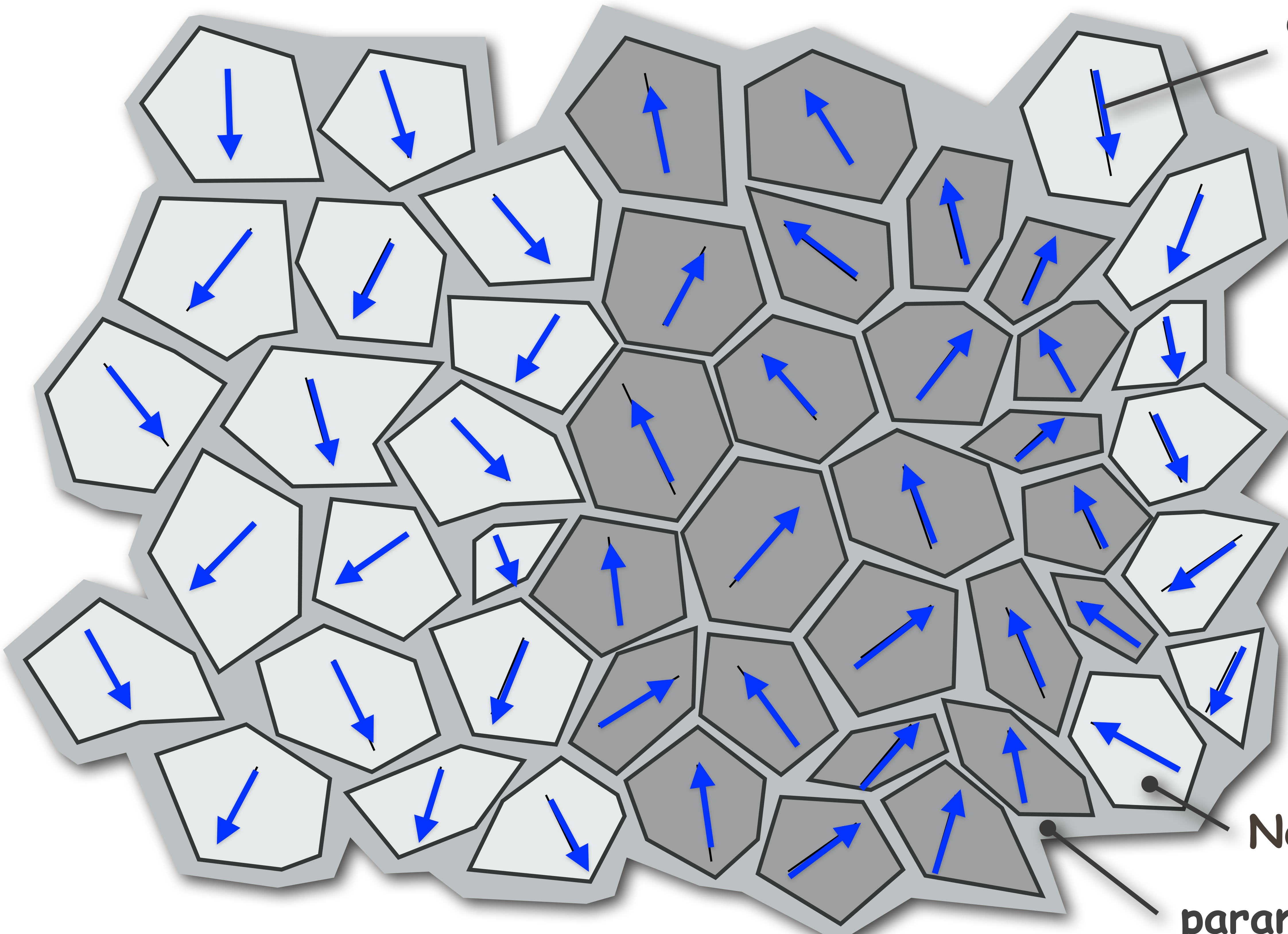
Magn. microstructure of nanostructured NdFeB



Magn. microstructure of nanostructured NdFeB

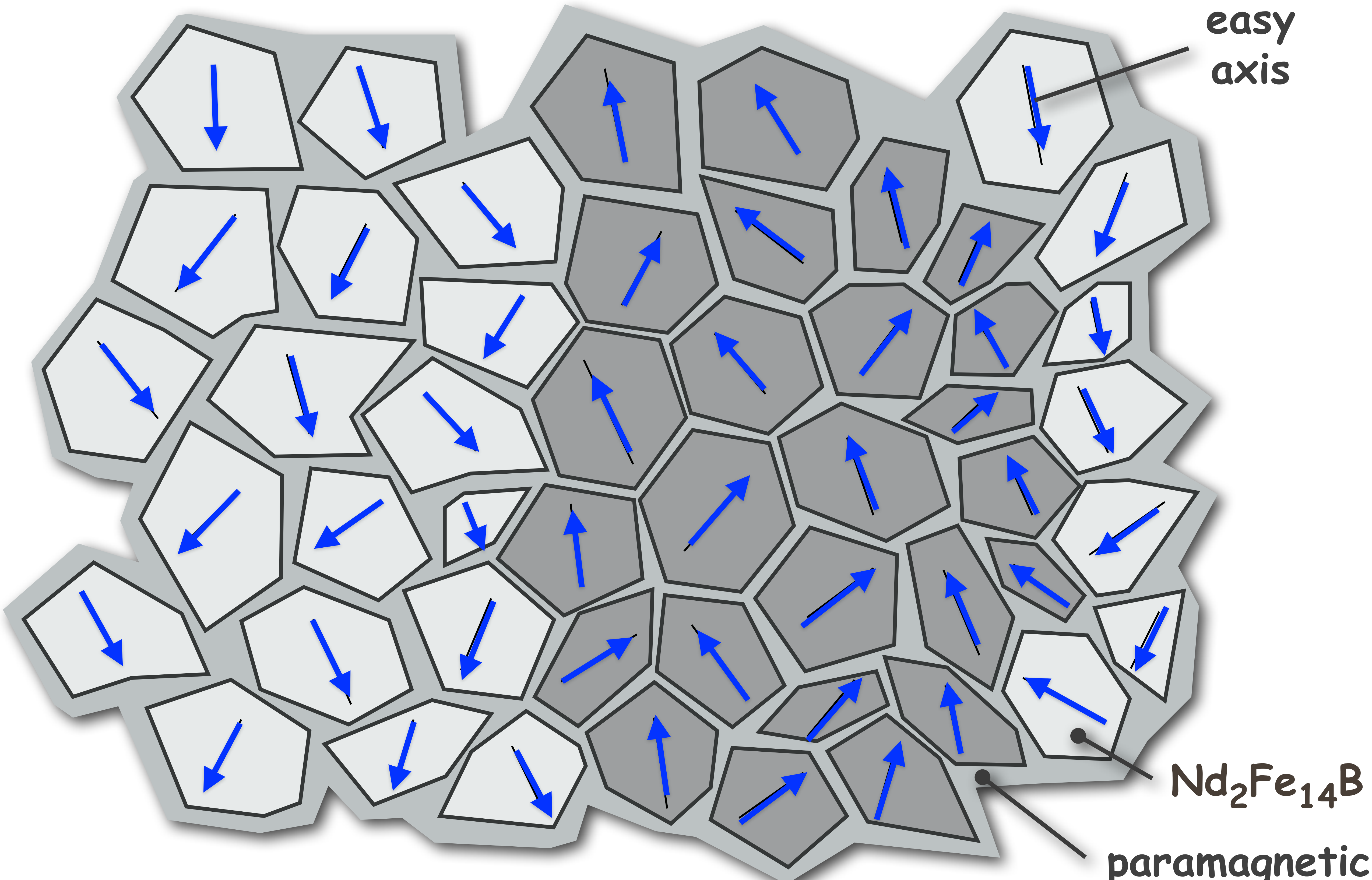


Magn. microstructure of nanostructured NdFeB



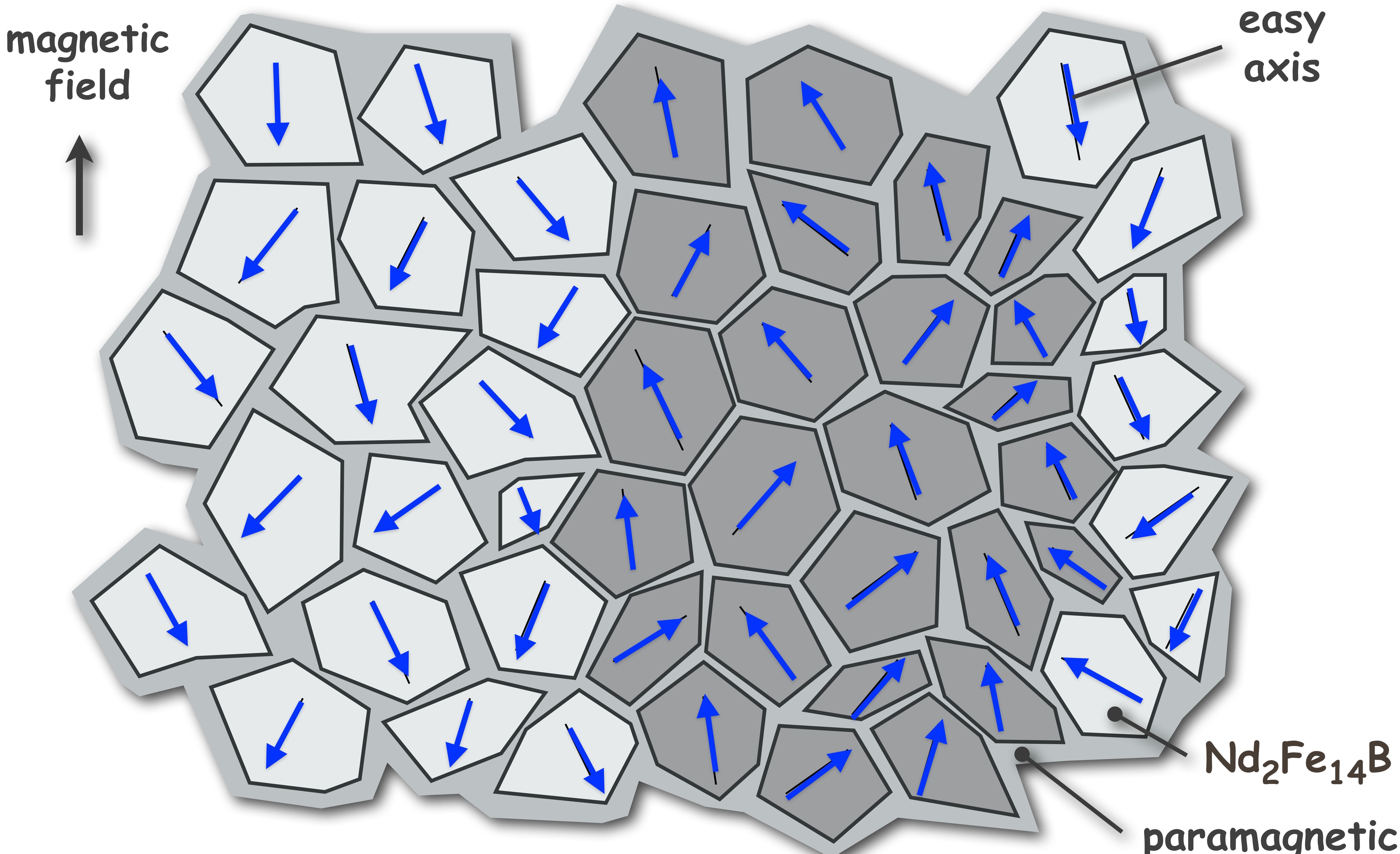
Magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB



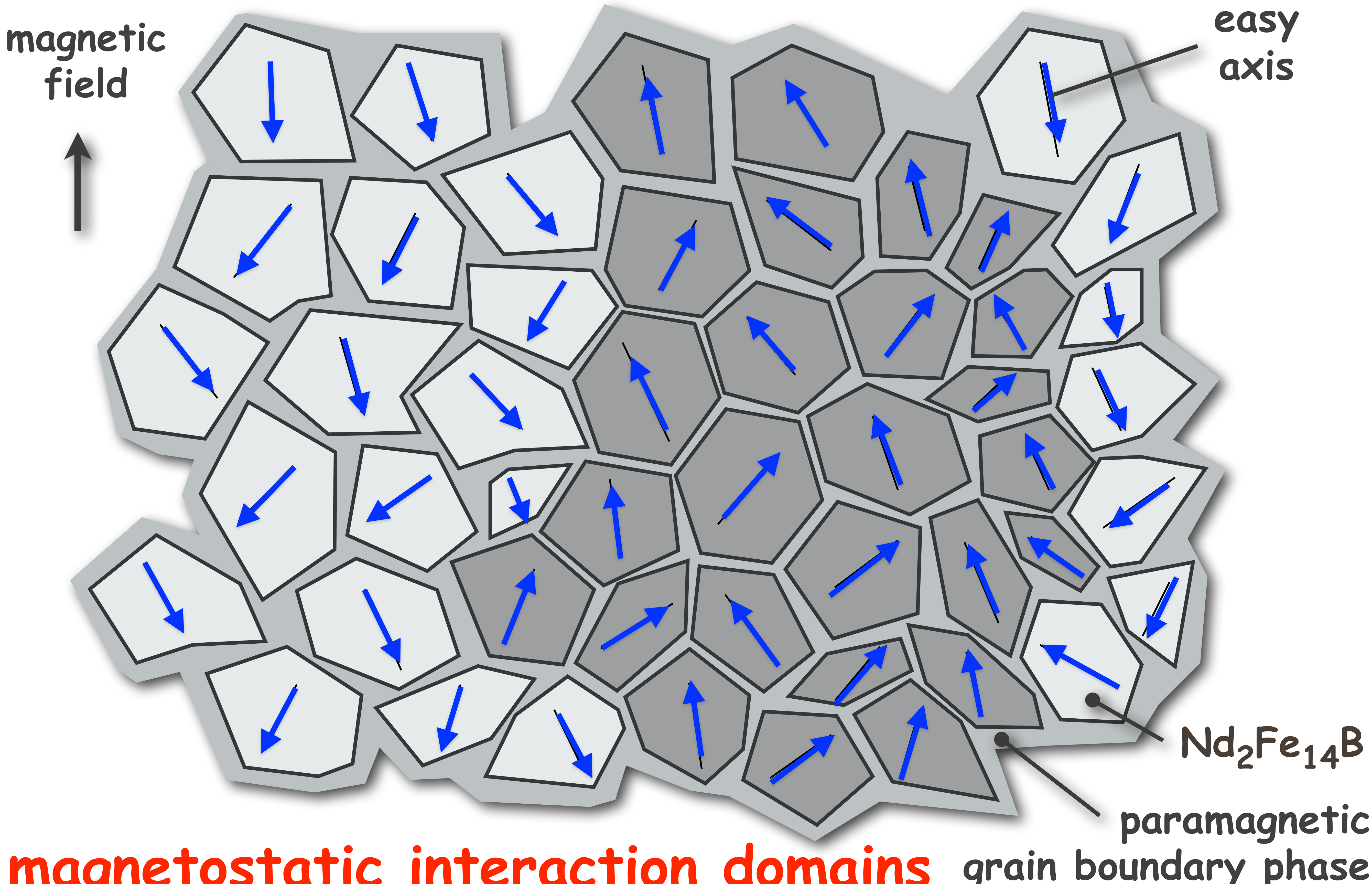
magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB



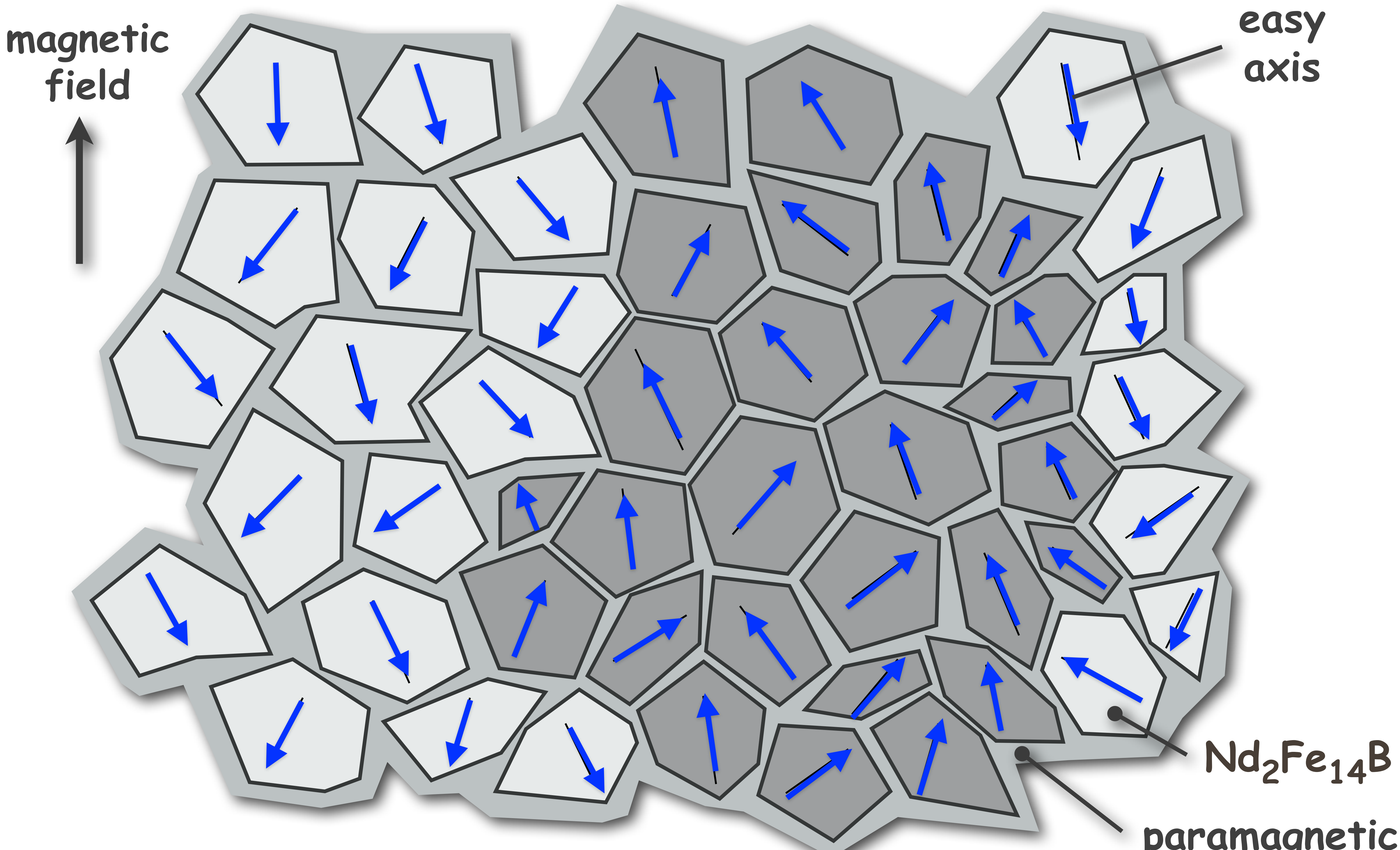
magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB



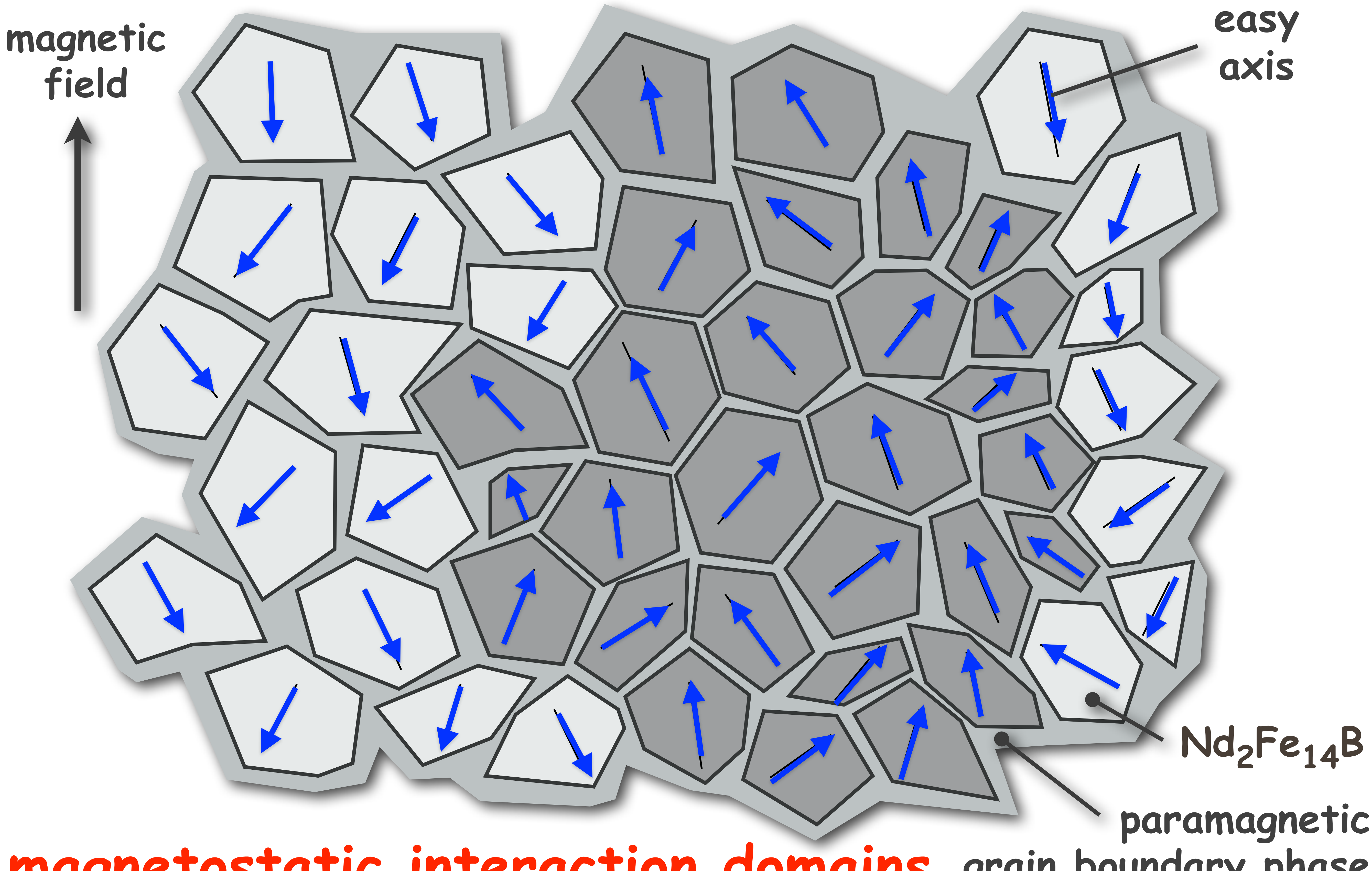
magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB



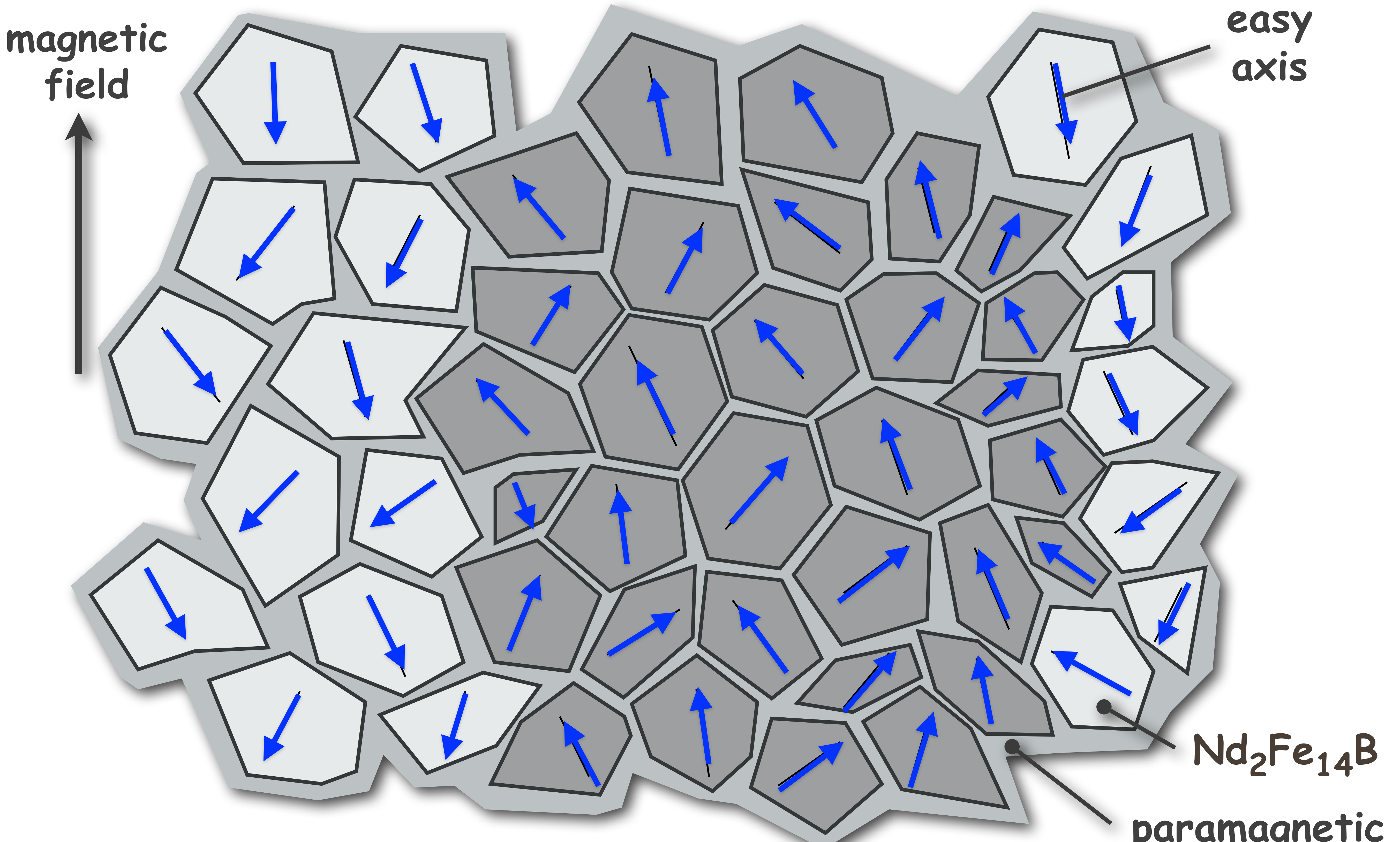
magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB



magnetostatic interaction domains

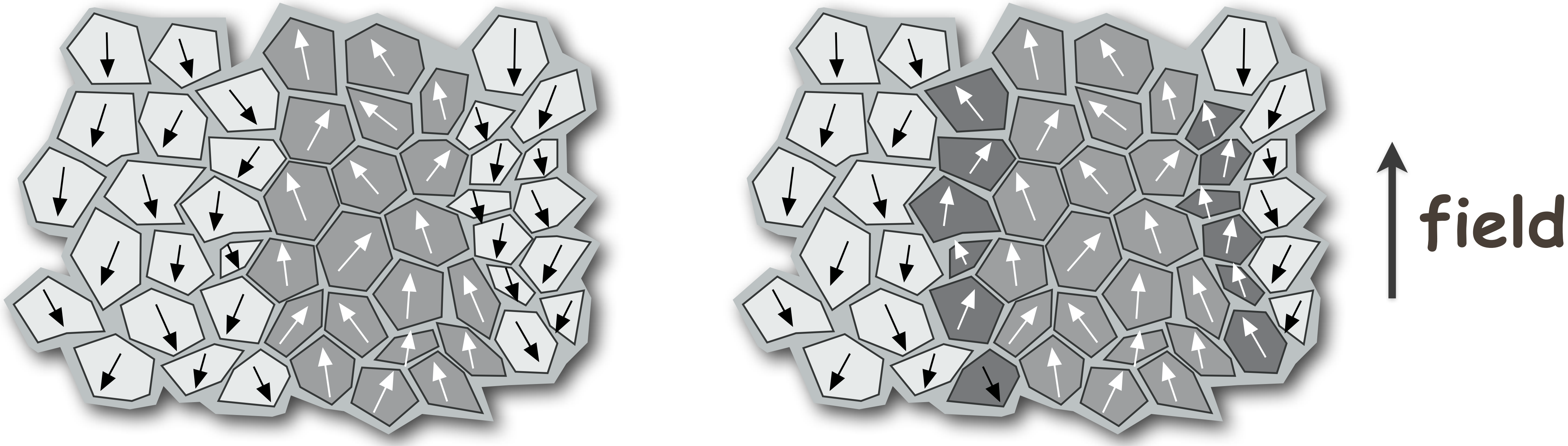
Magn. microstructure of nanostructured NdFeB

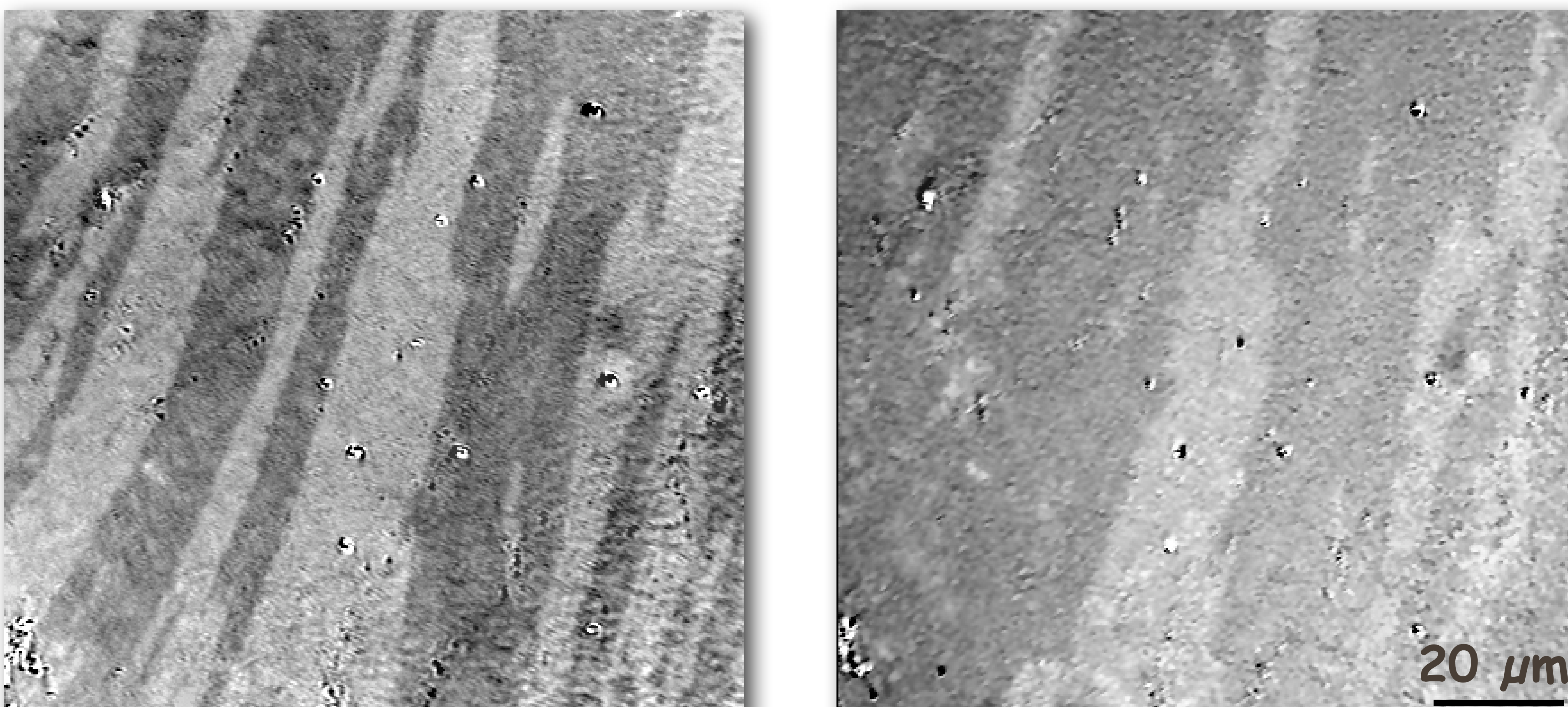


magnetostatic interaction domains

Magn. microstructure of nanostructured NdFeB

Magnetization process along preferred axis





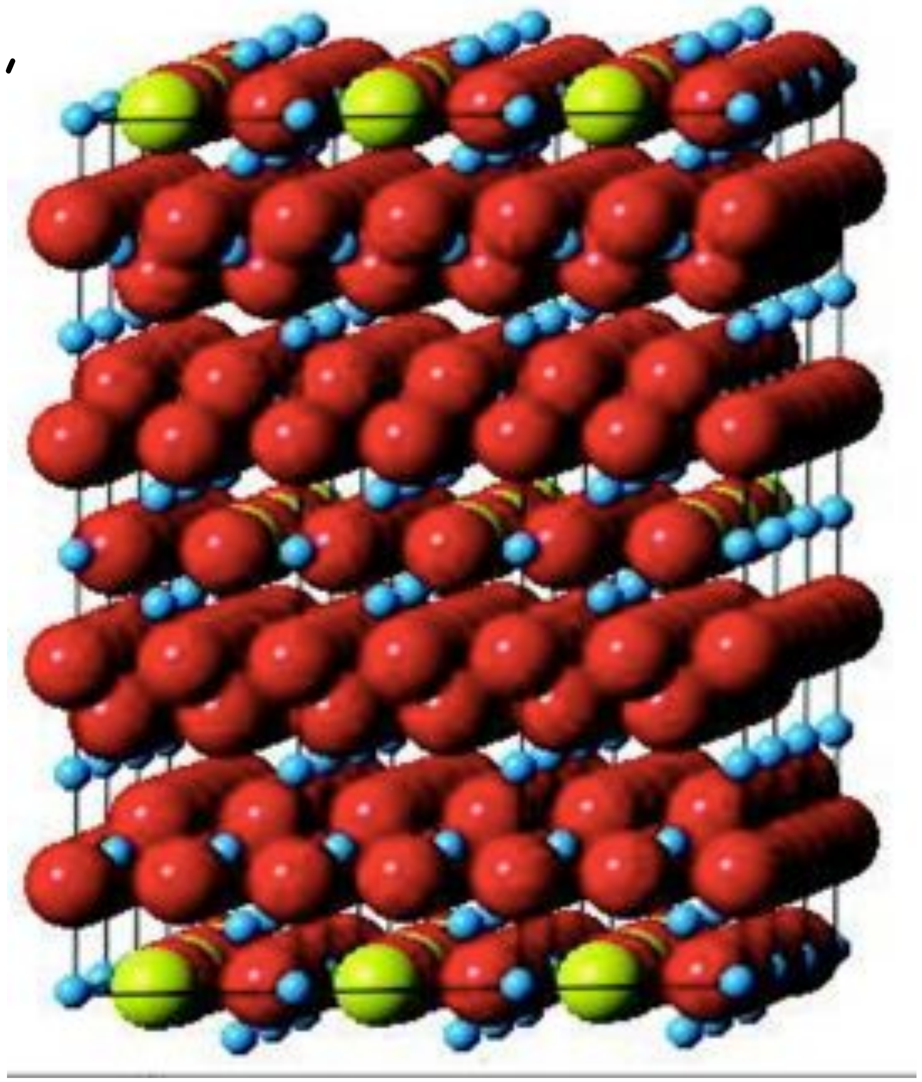
NdFeB
grain size
about 100 nm

Hardmagnetic materials, examples

Hardmagnetic materials, examples

Hexa-Ferrites

$BaO{\cdot}6\ Fe_2O_3$



Structure Barium-Hexaferrite: hcp lattice of O and Ba, with iron in octahedral, tetrahedral, and trigonal bipyramidal sites.

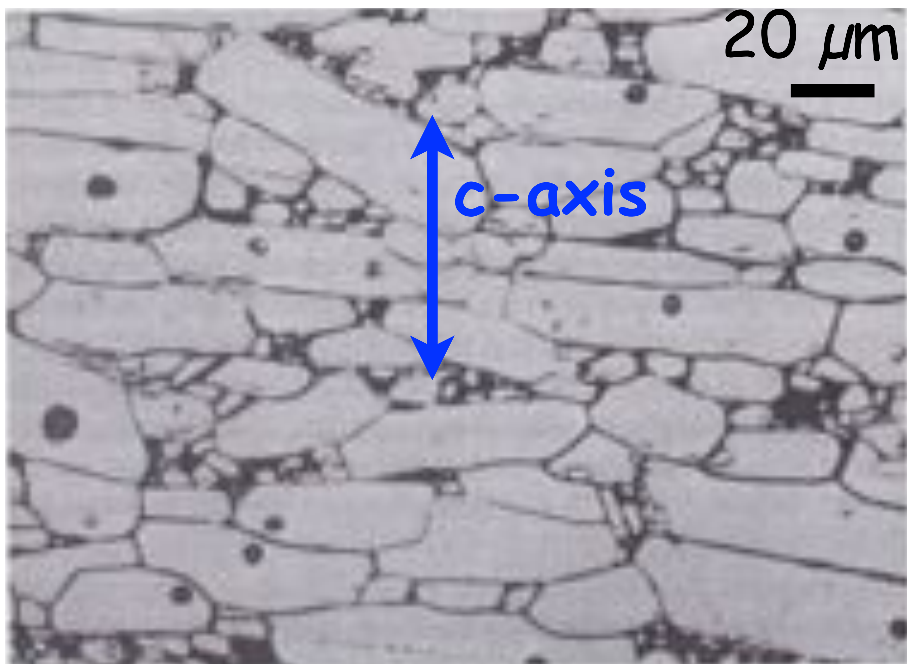
c-axis = easy axis

K_c = 450 kJ/m^3

J_s = 0.48 T

Nucleation-type magnet

Preparation: Presintering of $BaCO_3$ and Fe_2O_3 at 1200°C, milling, wet-pressing, final sintering at 1200°C → oriented grains

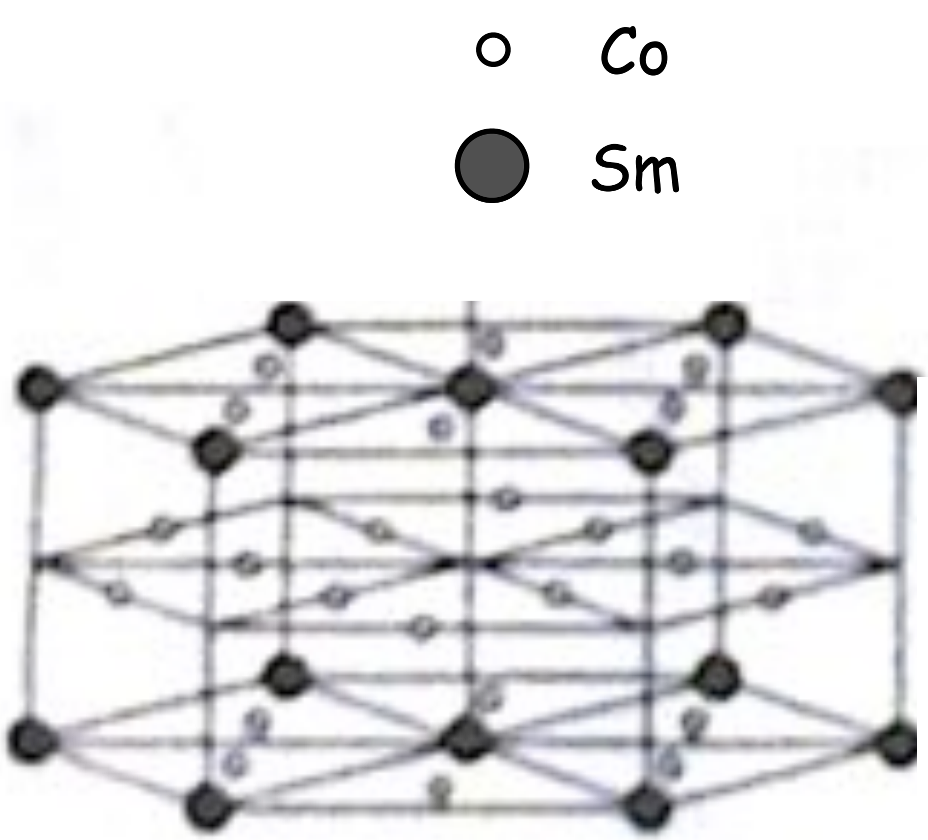


Application: Low-cost permanent magnet (98% of all permanent magnets by mass are Ba or Sr ferrite). Found on every fridge door and in innumerable catches, dc motors, microwave magnetrons, etc.

Hardmagnetic materials, examples

SmCo-magnets

$SmCo_5$



Nucleation-type magnet

K_c = 17200 kJ/m^3

J_s = 1,07 T

High fields required to fully magnetize (remove all nuclei)

c-axis = easy axis

Sm_2Co_{17}

Pinning-type magnet

K_c = 4200 kJ/m^3

J_s = 1,25 T

High temperature stability: H_c = 800 kA/m at 500°C

Hardmagnetic materials, examples

Hardmagnetic materials, examples

SmCo17

Hardmagnetic materials, examples

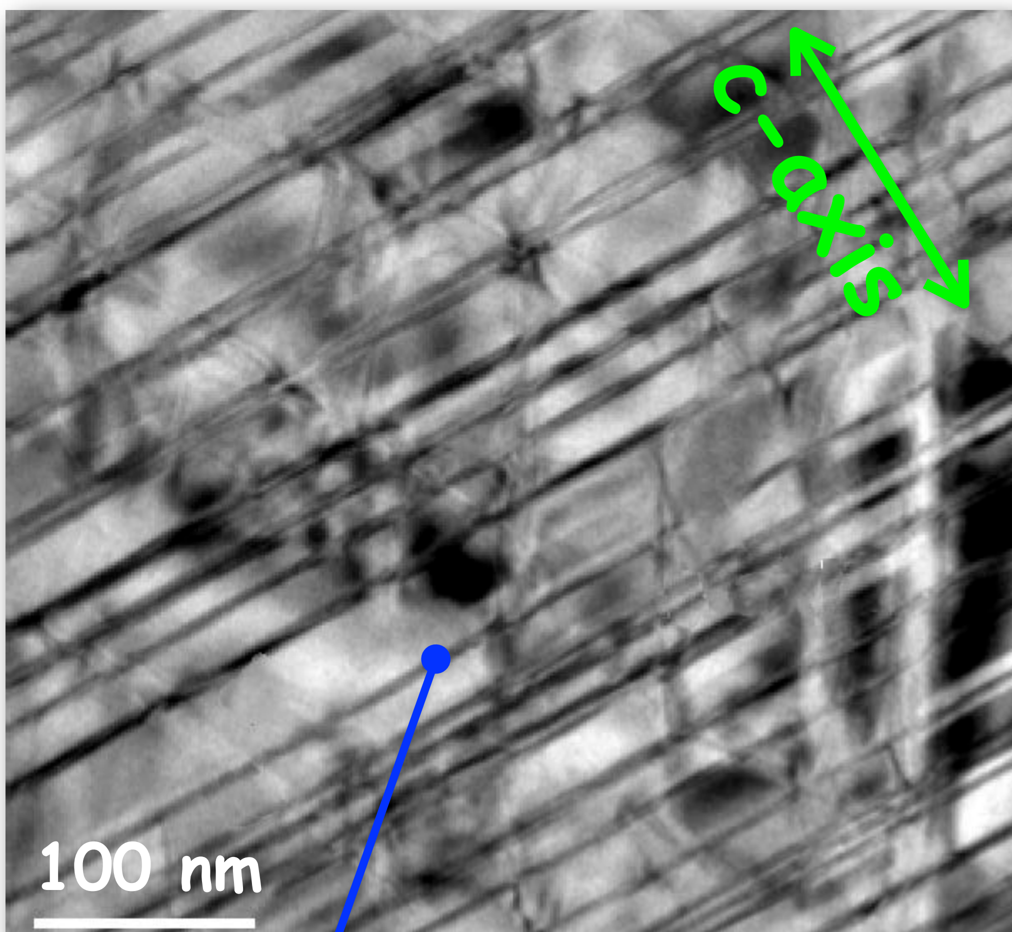
$Sm(Co_{0.784}Fe_{0.1}Cu_{0.088}Zr_{0.028})_{7.19}$

Hardmagnetic materials, examples

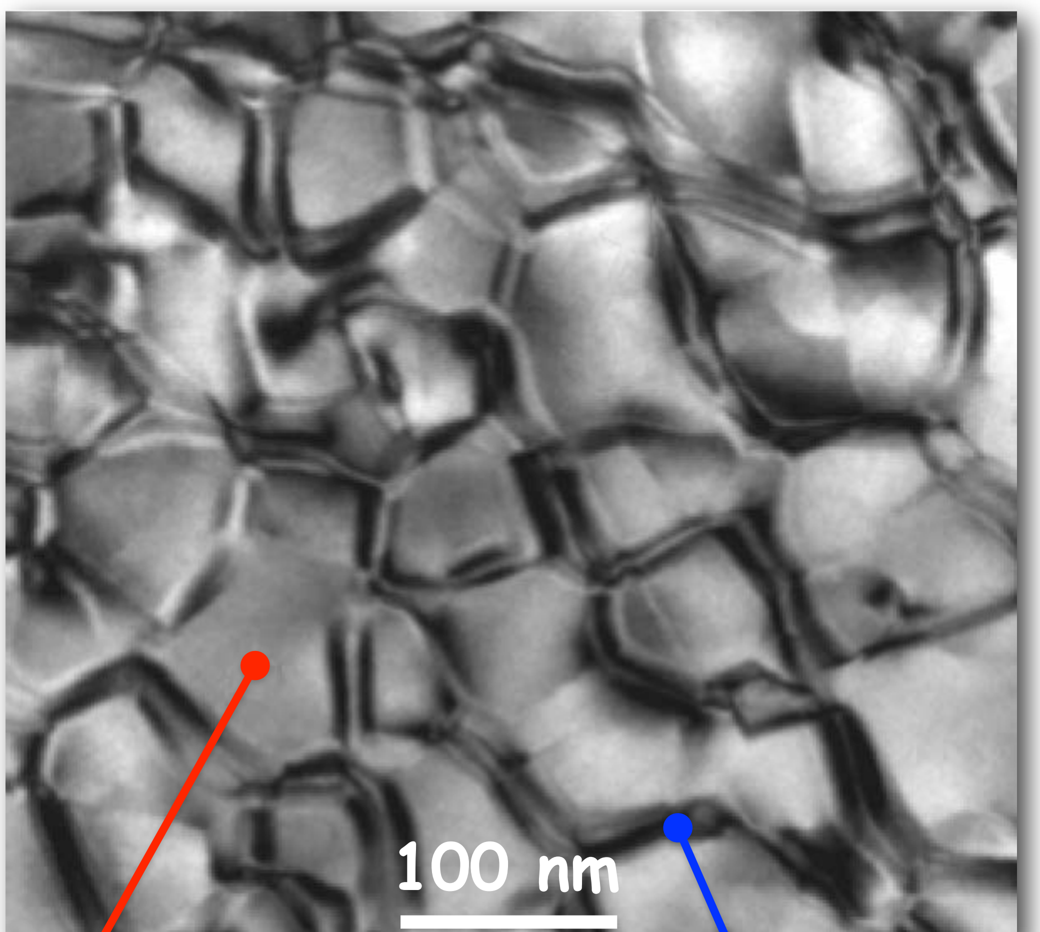
$Sm(Co_{0.784}Fe_{0.1}Cu_{0.088}Zr_{0.028})_{7.19}$

Pinning magnet:
coercivity determined by interaction of domain walls and precipitates

c-axis parallel



c-axis perpendicular



Zr-rich precipitation phase

$Sm_2(CoFe)_{17}$ cells (100 nm)

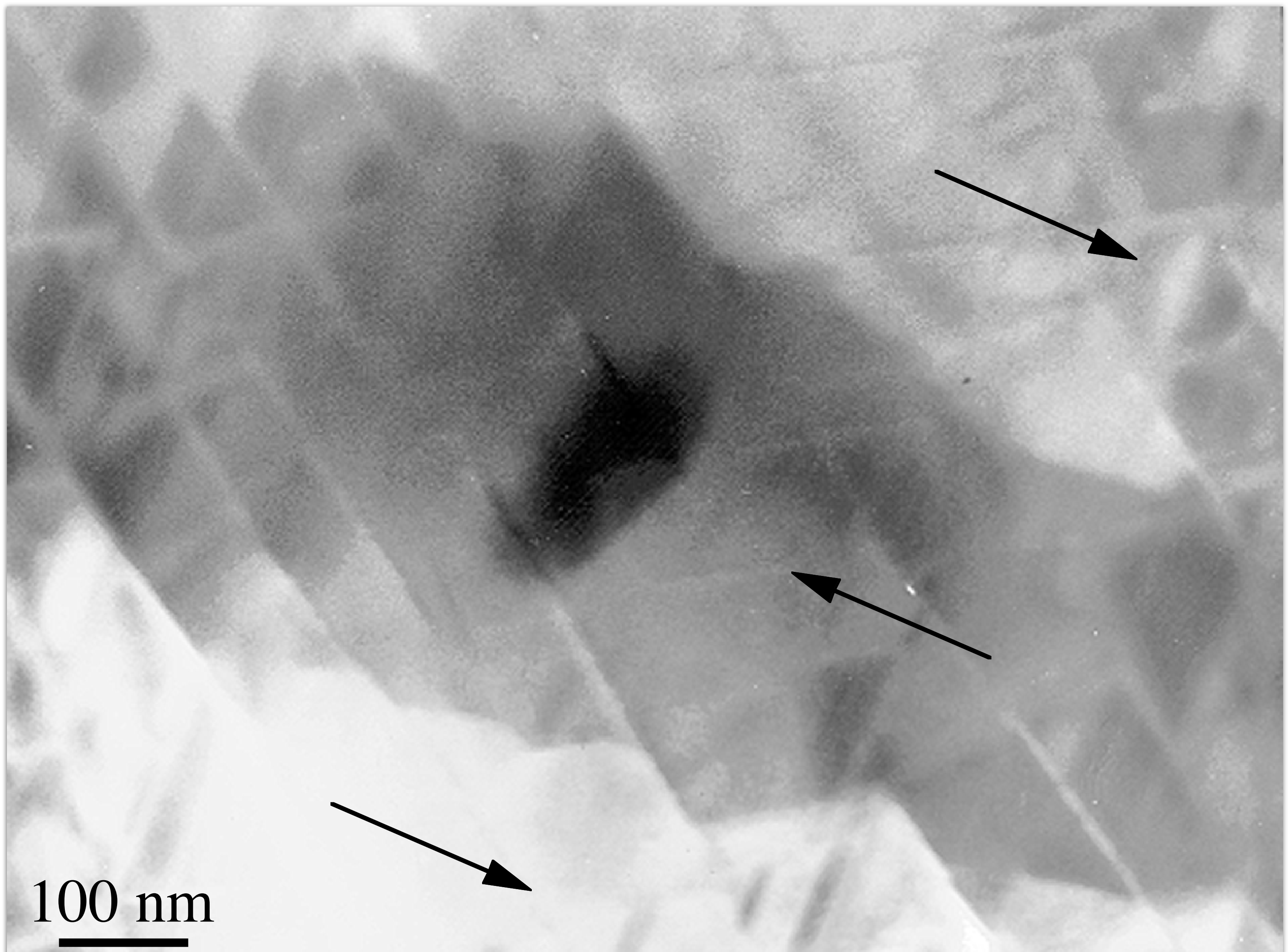
Cu-rich precip. phase

Hardmagnetic materials, examples

$Sm(Co_{0.784}Fe_{0.1}Cu_{0.088}Zr_{0.028})_{7.19}$

coerciv ... pitates

Domain wall pinning (Lorentz-TEM):



courtesy J. Fidler, Vienna

prec ... ase

Hardmagnetic materials, examples

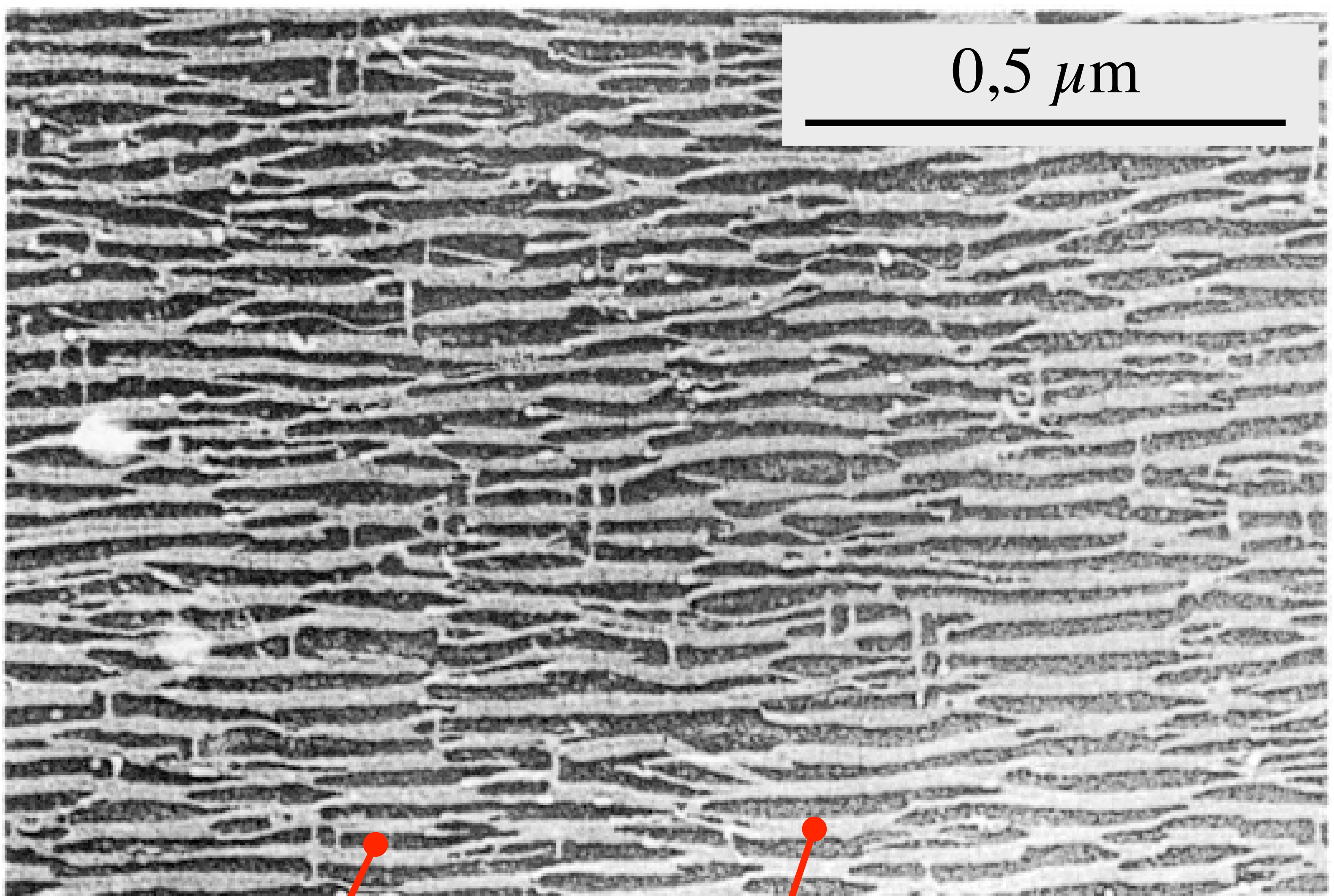
Hardmagnetic materials, examples

AlNiCo

Hardmagnetic materials, examples

AlNiCo

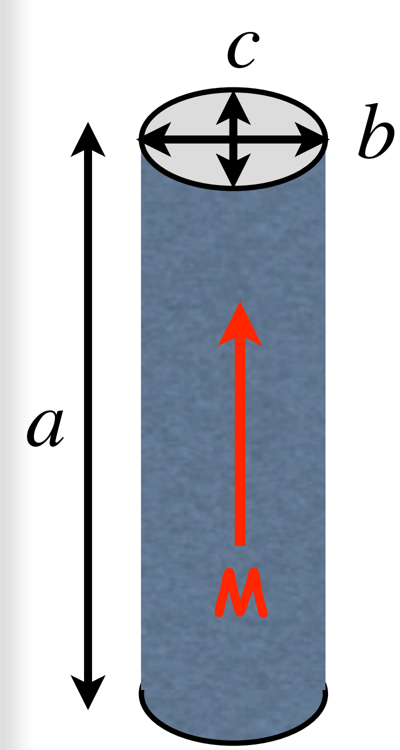
Preparation: spinoidal decomposition



ferromagnetic FeCo-needles (high M_s)

non-magnetic NiAl-matrix

Shape anisotropy

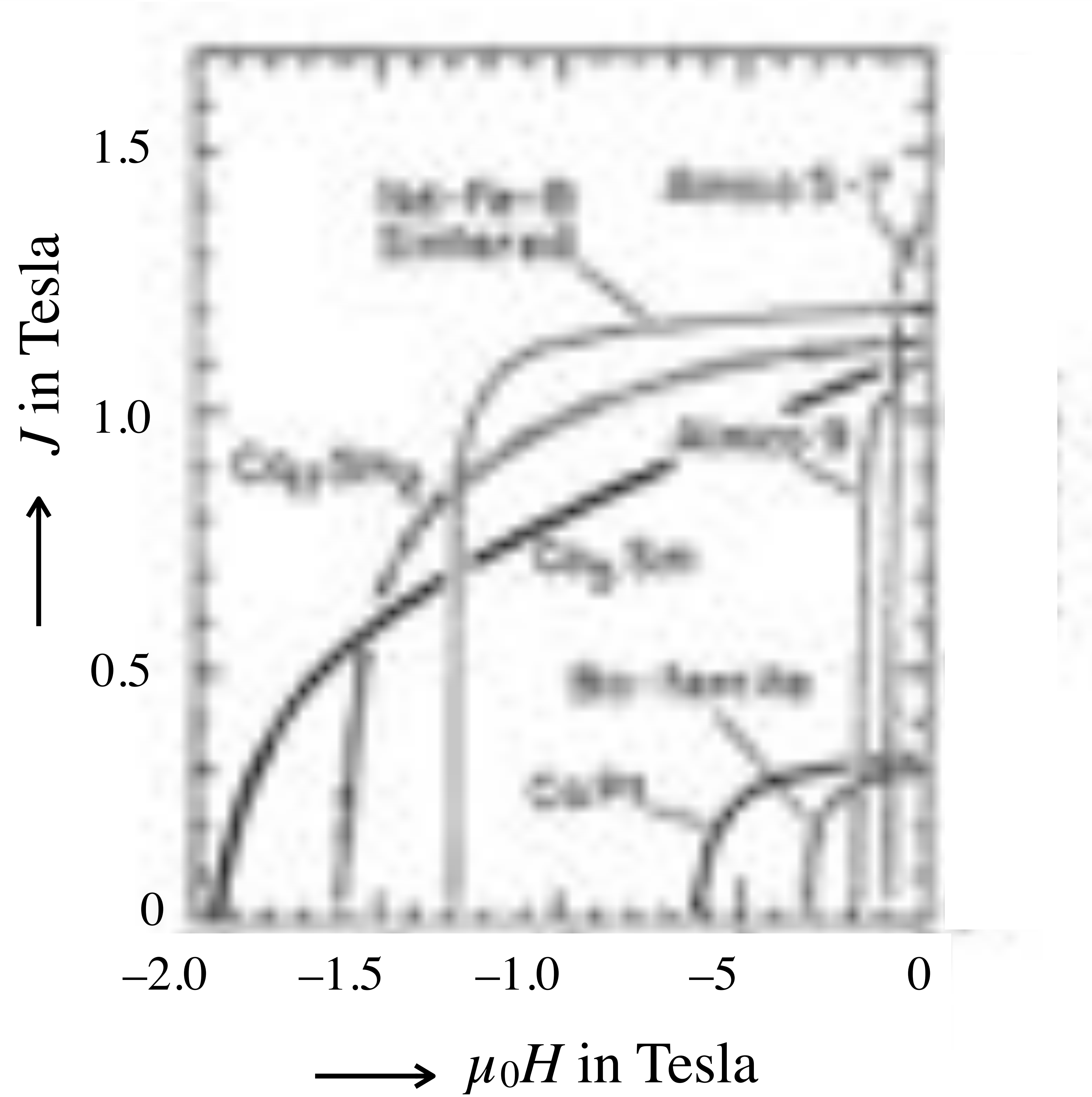


Long cylinder
(b = c; a → ∞):
$N_a \approx 0$;
$N_b = N_c \approx 1/2$
↓
cylinder preferably magnetized along axis

Application of shape anisotropy

↳ relatively small crystal anisotropy (⟷ to NdFeB)

Hardmagnetic materials, comparison



Coercivity and texture is not all:

Energy product

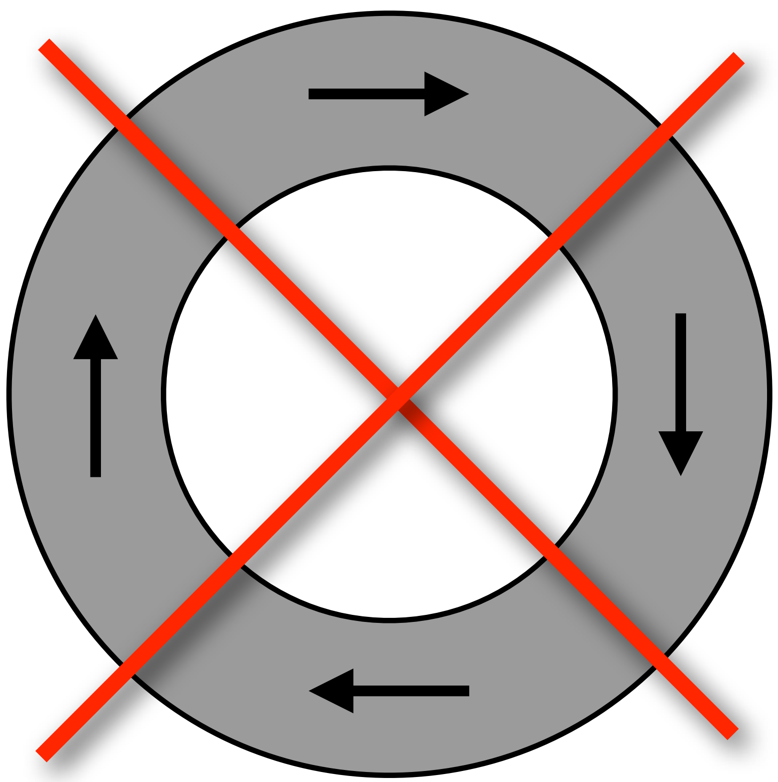
Hardmagnetic materials, basics

Energy product (BH)

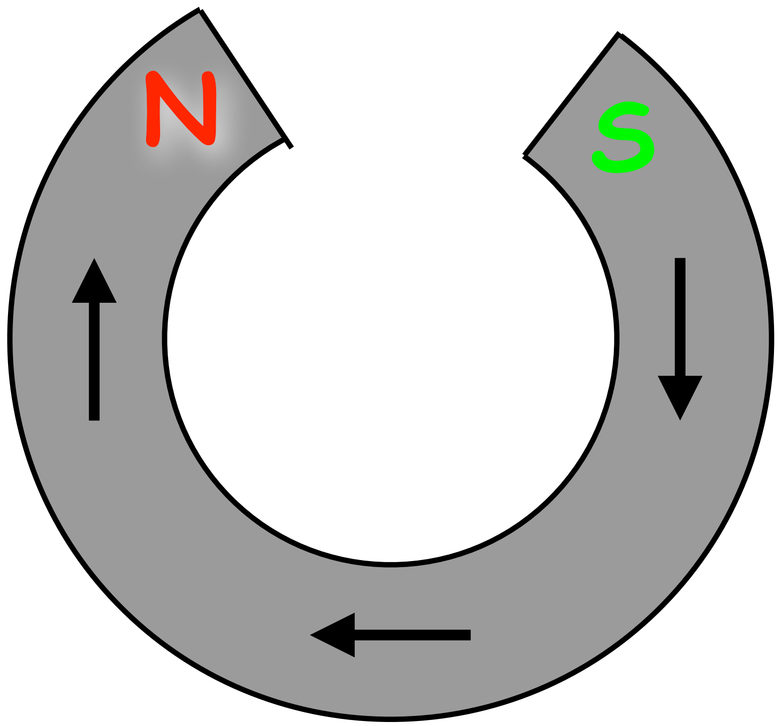
Hardmagnetic materials, basics

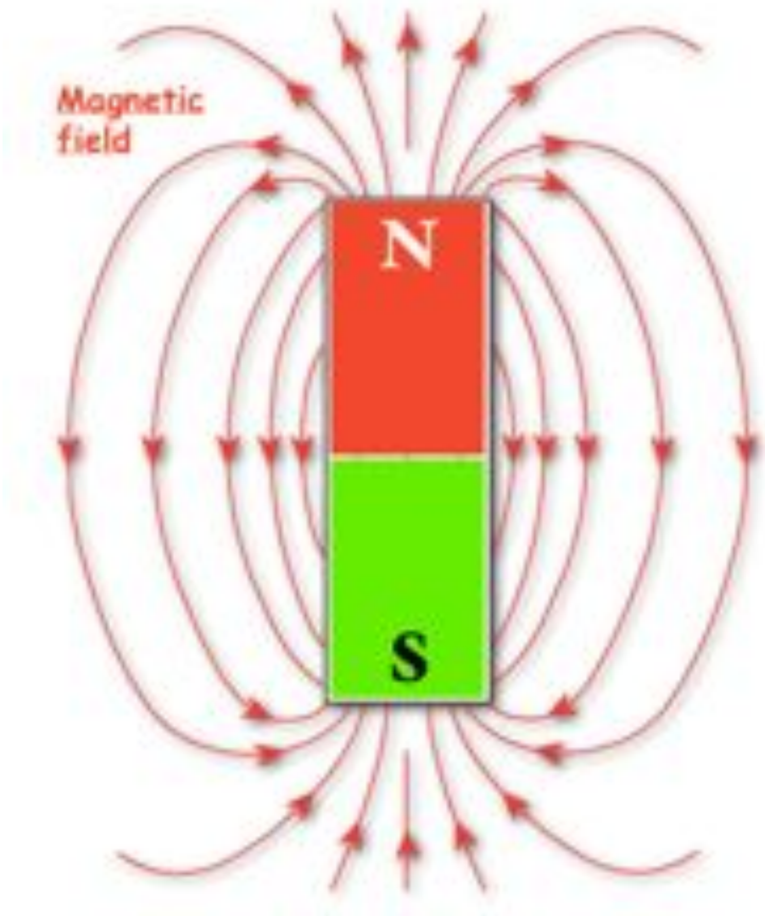
Energy product (BH)

To create poles and stray field ...



Closed magnet





... open magnets are needed

Hardmagnetic materials, basics

Energy product (*BH*)

- $\mathrm{rot}\,\boldsymbol{H} = j \;\rightarrow\; \oint H \mathrm{d}l = j$

  with $j = 0 \;\rightarrow\; H_\mathrm{m}\, l_\mathrm{m} + H_\mathrm{g}\, l_\mathrm{g} = 0$

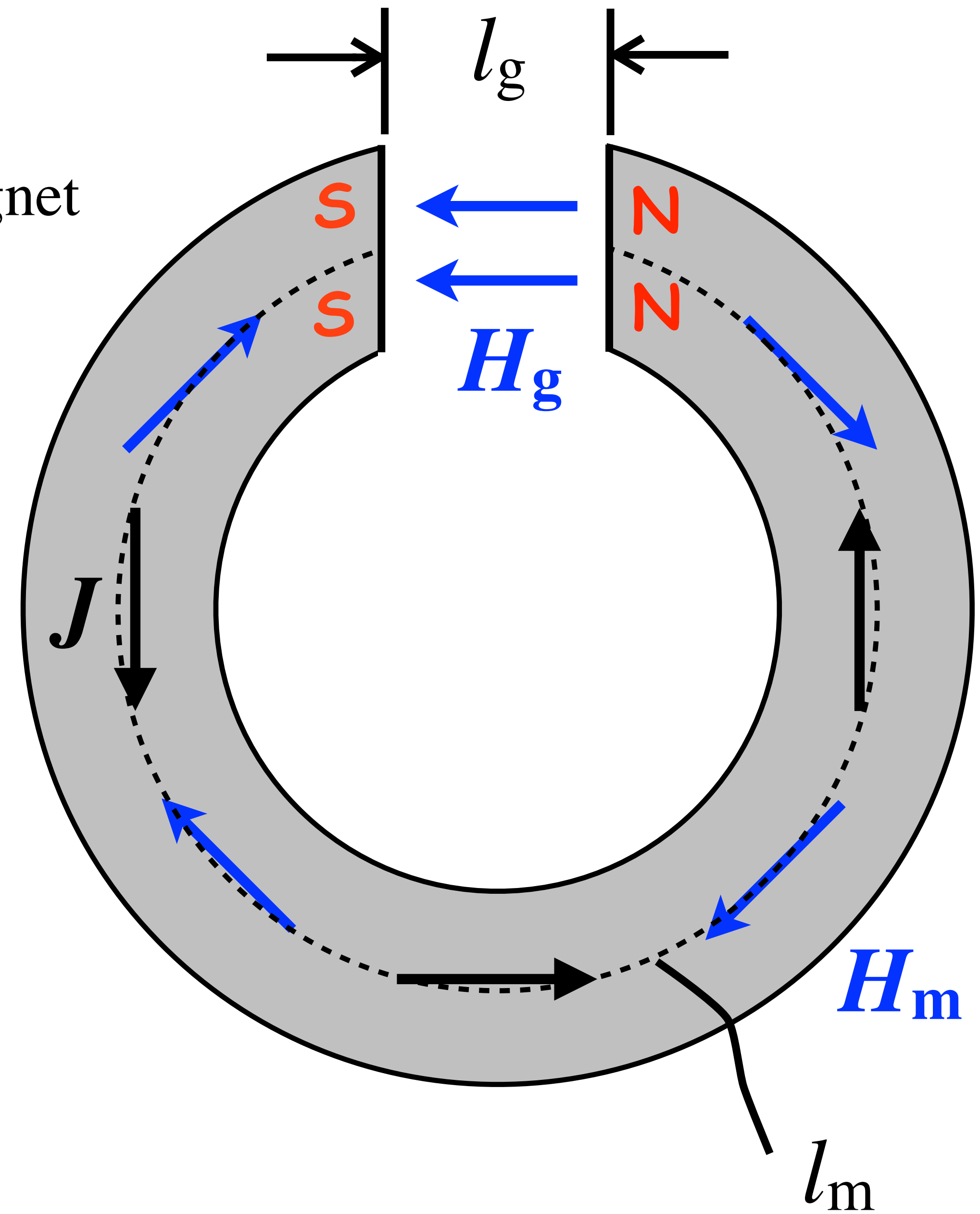
  g : gap
  m : magnet

- $\mathrm{div}\,\boldsymbol{B} = 0 \;\rightarrow\; B_\mathrm{m}\, A_\mathrm{m} = B_\mathrm{g}\, A_\mathrm{g}$

  A : cross section

- $B_\mathrm{g} = \mu_0\, H_\mathrm{g}$

  $B_\mathrm{m} = \mu_0\, H_\mathrm{m} + J_\mathrm{m}$



$$\longrightarrow \mu_0\, H_\mathrm{m} = -\frac{1}{1 + \dfrac{l_\mathrm{m}\, A_\mathrm{g}}{l_\mathrm{g}\, A_\mathrm{m}}} \cdot J_\mathrm{m}$$

$$\mu_0\, H_\mathrm{m} = -N\, J_\mathrm{m} = -N\,(B_\mathrm{m} - \mu_0\, H_\mathrm{m})$$

$$\longrightarrow B_\mathrm{m} = -\frac{1-N}{N}\, \mu_0\, H_\mathrm{m}$$ Load line

Hardmagnetic materials, basics

Energy product (BH)

- $\mathrm{rot}\,\boldsymbol{H} = j \;\rightarrow\; \oint H\mathrm{d}l = j$

  with $j = 0 \;\rightarrow\; H_m\, l_m + H_g\, l_g = 0$

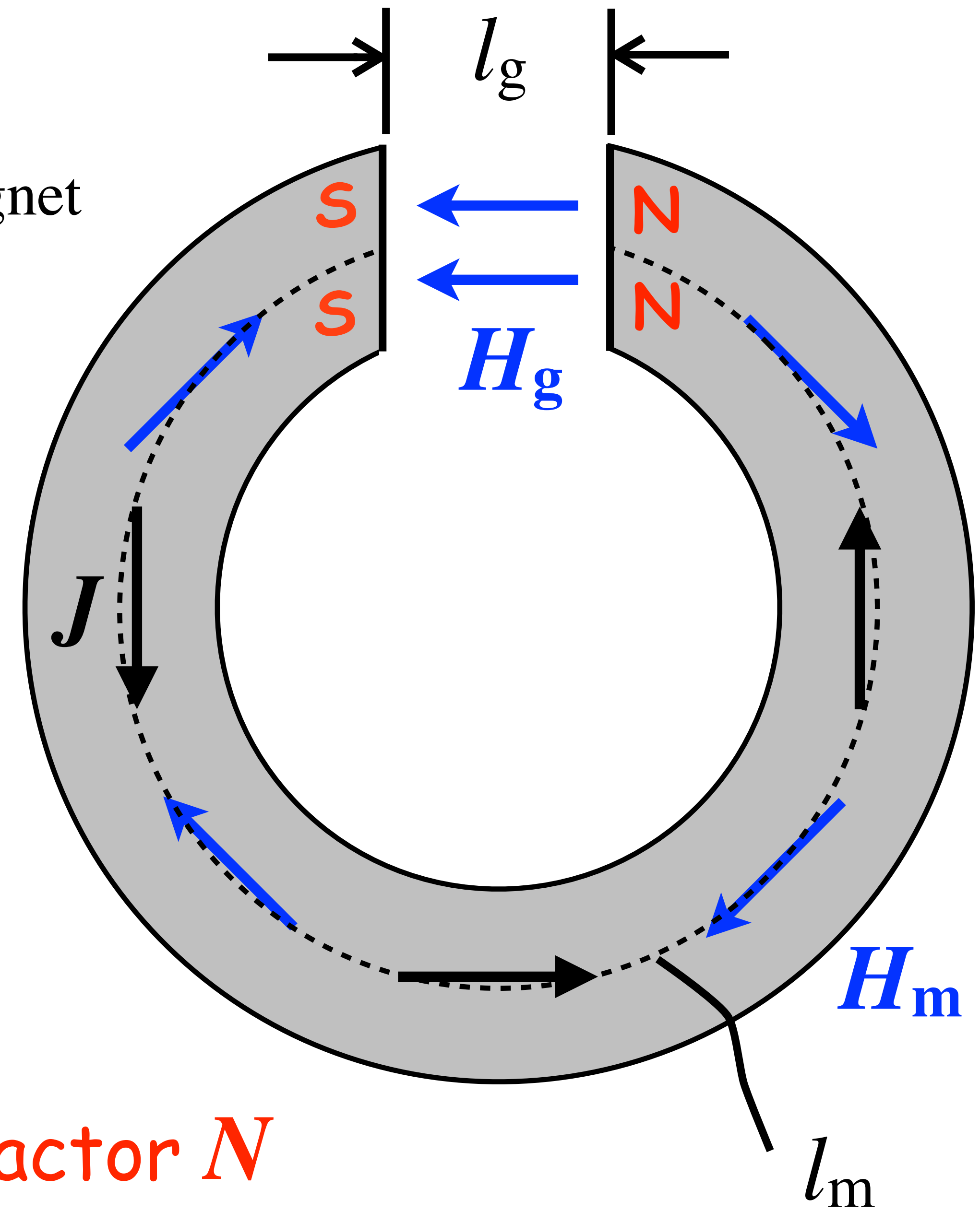
  g : gap
  m : magnet

- $\mathrm{div}\,\boldsymbol{B} = 0 \;\rightarrow\; B_m\, A_m = B_g\, A_g$

  A : cross section

- $B_g = \mu_0\, H_g$

  $B_m = \mu_0\, H_m + J_m$



$$\longrightarrow \mu_0\, H_m = -\frac{1}{1 + \dfrac{l_m\, A_g}{l_g\, A_m}} \cdot J_m$$

Demag factor N

$$\mu_0\, H_m = -N\, J_m = -N\,(B_m - \mu_0\, H_m)$$

$$\longrightarrow B_m = -\frac{1-N}{N}\,\mu_0\, H_m \qquad \text{Load line}$$

Hardmagnetic materials, basics

Energy product (BH)

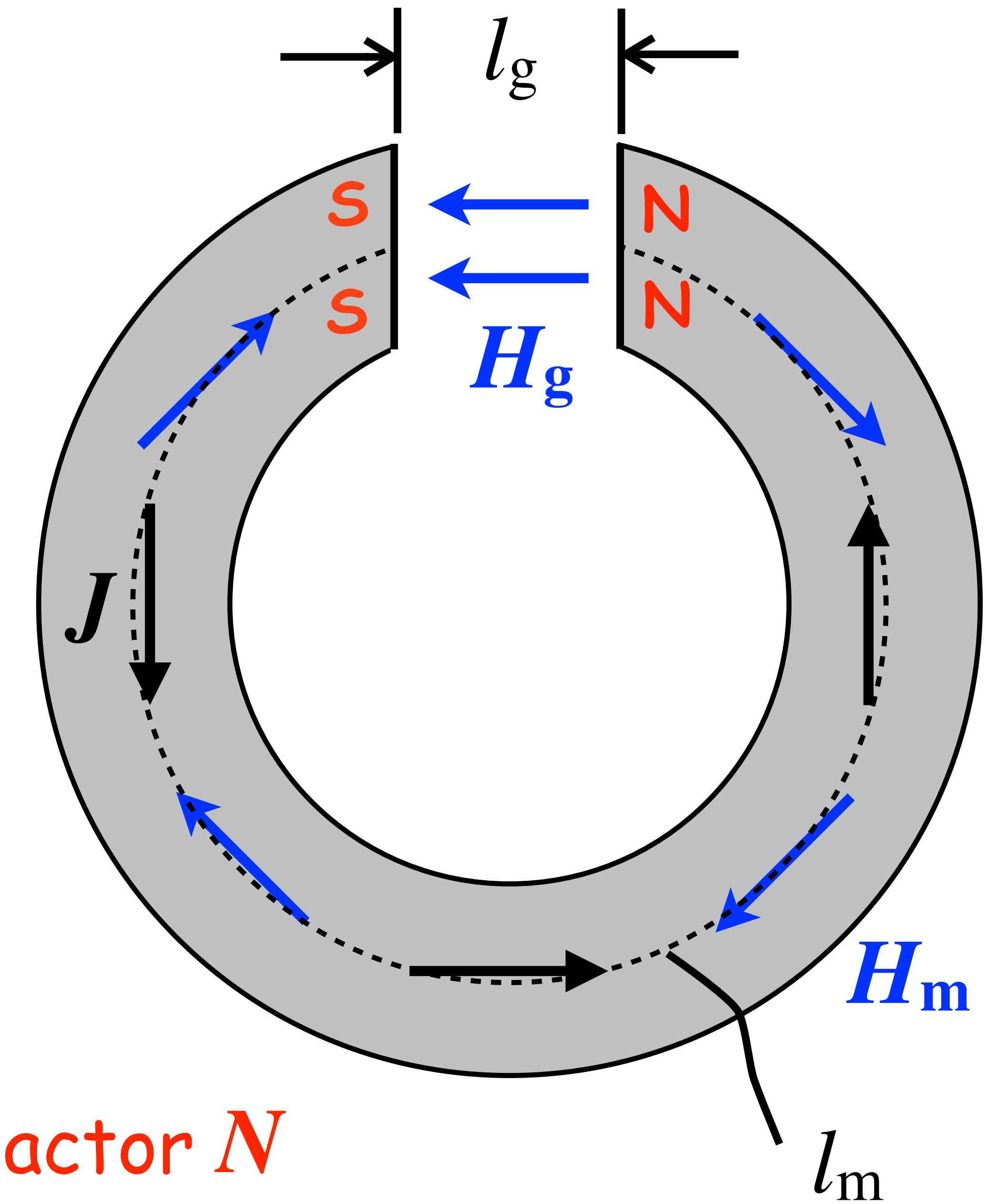
- $\mathrm{rot}\,\boldsymbol{H} = j \;\rightarrow\; \oint H\mathrm{d}l = j$

  with $j = 0 \;\rightarrow\; H_m\, l_m + H_g\, l_g = 0$

- $\mathrm{div}\,\boldsymbol{B} = 0 \;\rightarrow\; B_m\, A_m = B_g\, A_g$

- $B_g = \mu_0\, H_g$

  $B_m = \mu_0\, H_m + J_m$



$$\longrightarrow \mu_0\, H_m = -\boxed{\frac{1}{1 + \dfrac{l_m\, A_g}{l_g\, A_m}}} \cdot J_m$$

Demag factor N

$$\mu_0\, H_m = -N\, J_m = -N\,(B_m - \mu_0\, H_m)$$

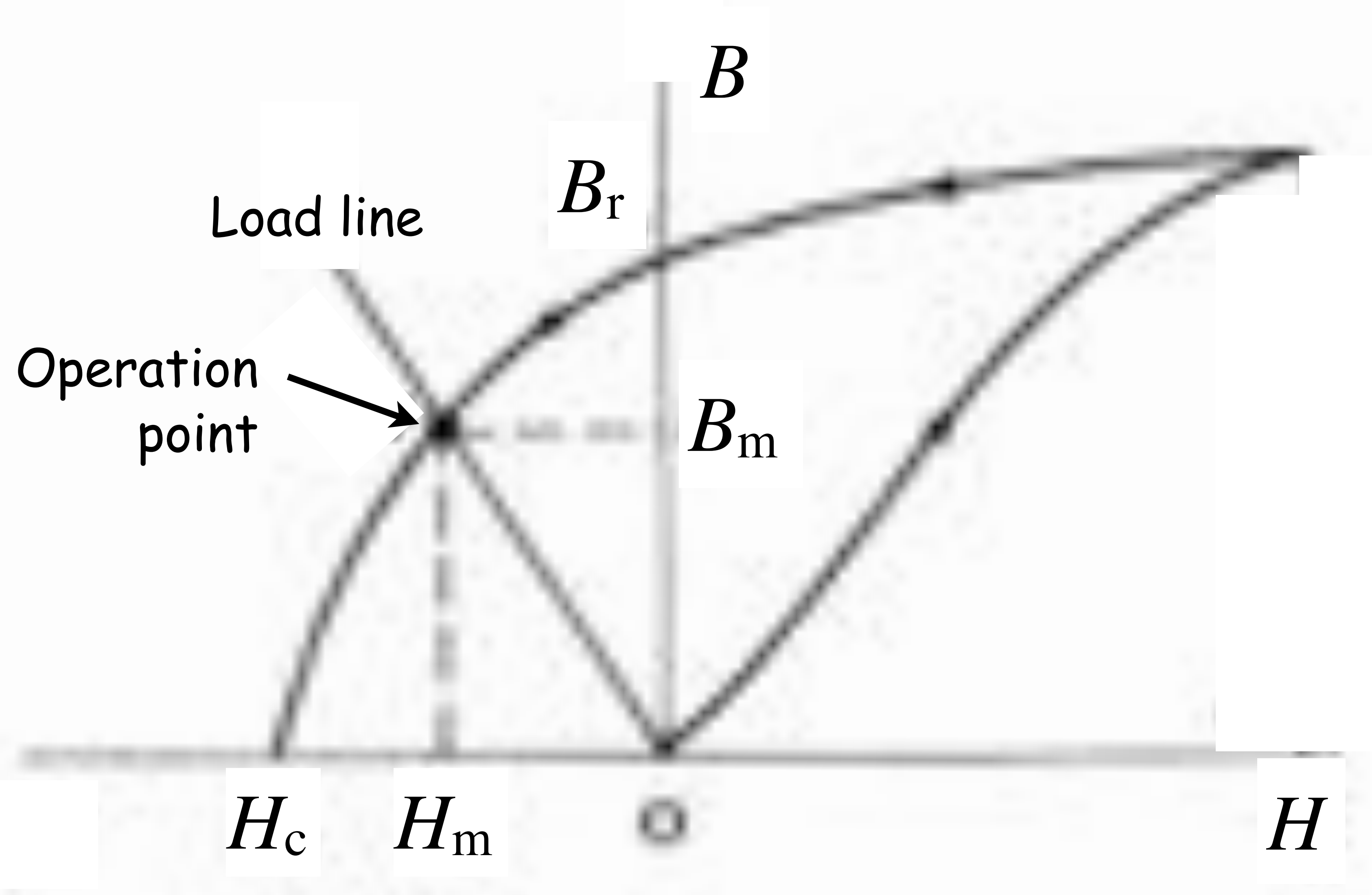
$$\longrightarrow B_m = -\frac{1-N}{N}\,\mu_0\, H_m$$

Load line

Hardmagnetic materials, basics

Energy product (BH)

$$\longrightarrow B_m = -\frac{1-N}{N}\mu_0 H_m$$ Load line



- Switching off field afer positive saturation:

  → demagnetizing field

  → reduces B in magnet to B_m at operating point
- N depends on geometry of magnet → slope of load line can be chosen → operation point can be put anywhere on demagnetization curve
- **What is best operating point?**

Hardmagnetic materials, basics

Energy product (BH)

- $H_m\, l_m + H_g\, l_g = 0 \qquad H_g = -\dfrac{H_m\, l_m}{l_g}$
- $B_m\, A_m = B_g\, A_g \qquad B_g = \mu_0\, H_g = \dfrac{B_m\, A_m}{A_g} \;\; / \bullet H_g$
- $\mu_0\, H_g^2 = -\dfrac{B_m\, A_m}{A_g}\,\dfrac{H_m\, l_m}{l_g} = -\dfrac{B_m\, H_m\, V_m}{V_g}$

$$\mu_0\, H_g^2\; V_g = -\, B_m\, H_m\, V_m$$

- Stray-field energy:

$$E_s = \frac{1}{2}\,\mu_0 \int H_s^2 \mathrm{d}V = \frac{1}{2}\mu_0\, H_g^2\, V_g = \frac{1}{2}\, B_m\, H_m\, V_m \qquad (H_s = H_g)$$

- Energy, stored in field of air gap $\sim (B_m \bullet H_m)$

Hardmagnetic materials, basics

Energy product (BH)

- $H_\mathrm{m}\, l_\mathrm{m} + H_\mathrm{g}\, l_\mathrm{g} = 0 \qquad H_\mathrm{g} = -\dfrac{H_\mathrm{m}\, l_\mathrm{m}}{l_\mathrm{g}}$

- $B_\mathrm{m}\, A_\mathrm{m} = B_\mathrm{g}\, A_\mathrm{g} \qquad B_\mathrm{g} = \mu_0\, H_\mathrm{g} = \dfrac{B_\mathrm{m}\, A_\mathrm{m}}{A_\mathrm{g}} \quad / \bullet H_\mathrm{g}$

- $\mu_0\, H_\mathrm{g}^2 = -\dfrac{B_\mathrm{m}\, A_\mathrm{m}}{A_\mathrm{g}} \dfrac{H_\mathrm{m}\, l_\mathrm{m}}{l_\mathrm{g}} = -\dfrac{B_\mathrm{m}\, H_\mathrm{m}\, V_\mathrm{m}}{V_\mathrm{g}}$

  $\mu_0\, H_\mathrm{g}^2\, V_\mathrm{g} = -B_\mathrm{m}\, H_\mathrm{m}\, V_\mathrm{m}$

- Stray-field energy:

  $E_\mathrm{s} = \frac{1}{2}\mu_0 \int H_\mathrm{s}^2 \mathrm{d}V = \frac{1}{2}\mu_0\, H_\mathrm{g}^2\, V_\mathrm{g} = \frac{1}{2} B_\mathrm{m}\, H_\mathrm{m}\, V_\mathrm{m} \qquad (H_\mathrm{s} = H_\mathrm{g})$

- Energy, stored in field of air gap $\sim (B_\mathrm{m} \bullet H_\mathrm{m})$ Energy product

Hardmagnetic materials, basics

Energy product (BH)

- $H_m\, l_m + H_g\, l_g = 0 \qquad H_g = -\dfrac{H_m\, l_m}{l_g}$

- $B_m\, A_m = B_g\, A_g \qquad \mu_0\, H_g = \dfrac{B_m\, A_m}{A_g} \quad / \bullet H_g$

- $\mu_0\, H_g^2 = -\dfrac{B_m\, A_m}{A_g}\;\dfrac{H_m\, l_m}{l_g} = -\dfrac{B_m\, H_m\, V_m}{V_g}$

  $\mu_0\, H_g^2\; V_g = -\, B_m\, H_m\, V_m$

- Stray-field energy:

  $E_s = \frac{1}{2}\,\mu_0 \int H_s^2 \mathrm{d}V = \frac{1}{2}\mu_0\, H_g^2\, V_g = \frac{1}{2}\, B_m\, H_m\, V_m \qquad (H_s = H_g)$

- Energy, stored in field of air gap $\sim (B \bullet H)$ Energy product

Hardmagnetic materials, basics

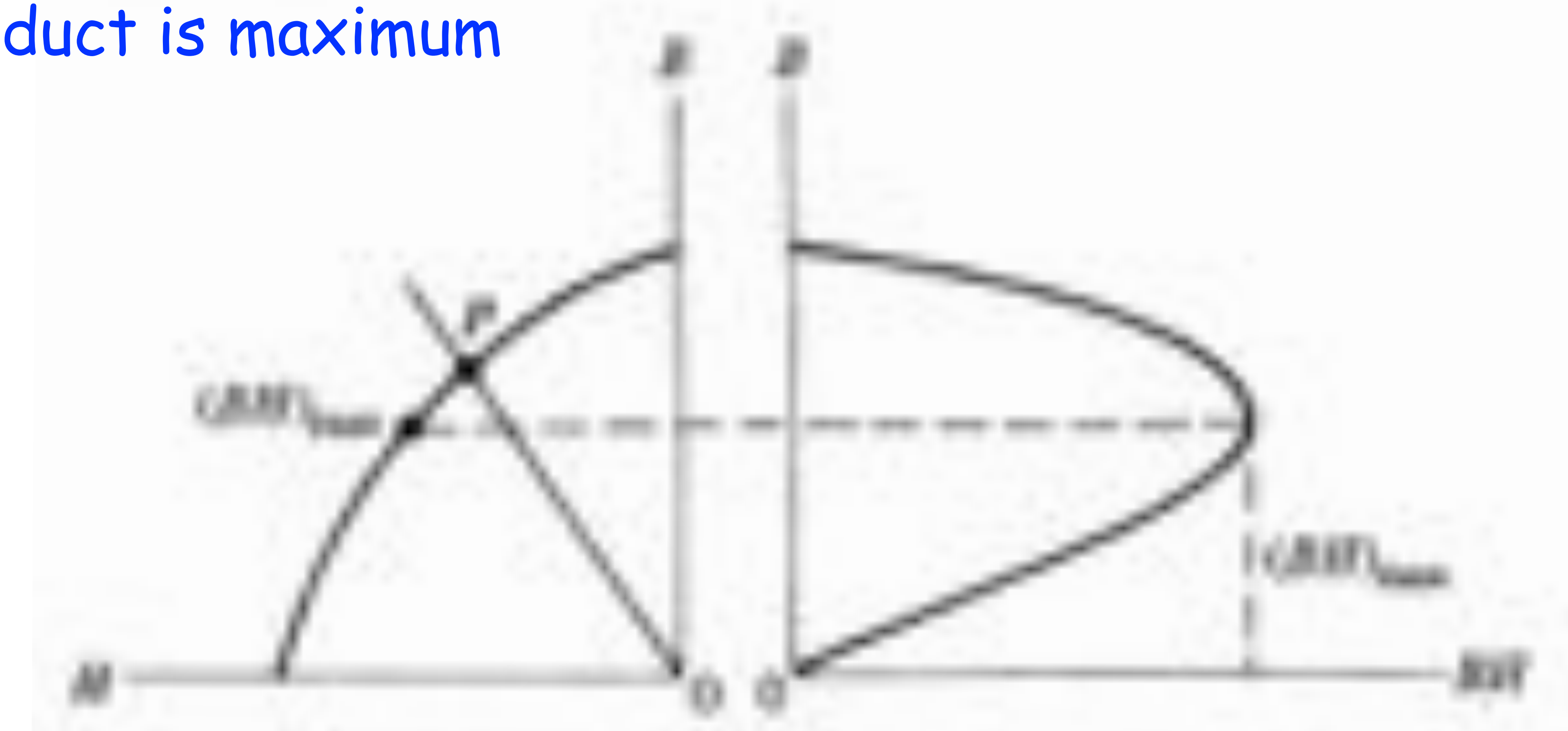
Energy product (BH)

- Stray-field energy:

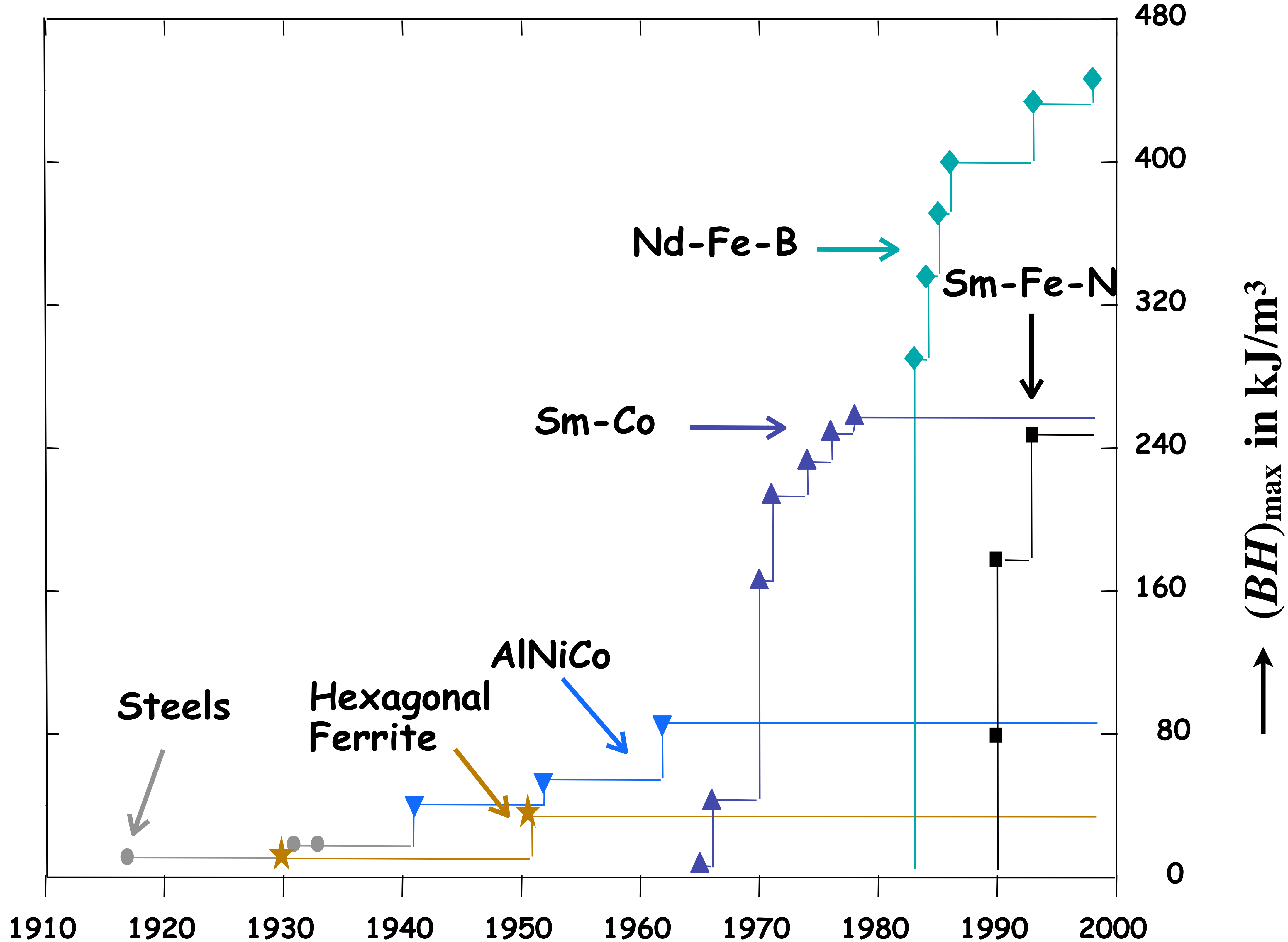
$$E_s = \frac{1}{2}\mu_0 \int H_s^2 \mathrm{d}V = \frac{1}{2}\mu_0 H_g^2 V_g = \frac{1}{2} B_m H_m V_m \qquad (H_s = H_g)$$

- Energy, stored in field of air gap $\sim (B \bullet H)$ Energy product
- Maximum energy product $(B\,H)_{max}$

$\longrightarrow$ Shape magnet so that load line passes through point at which energy product is maximum



Hardmagnetic materials, basics

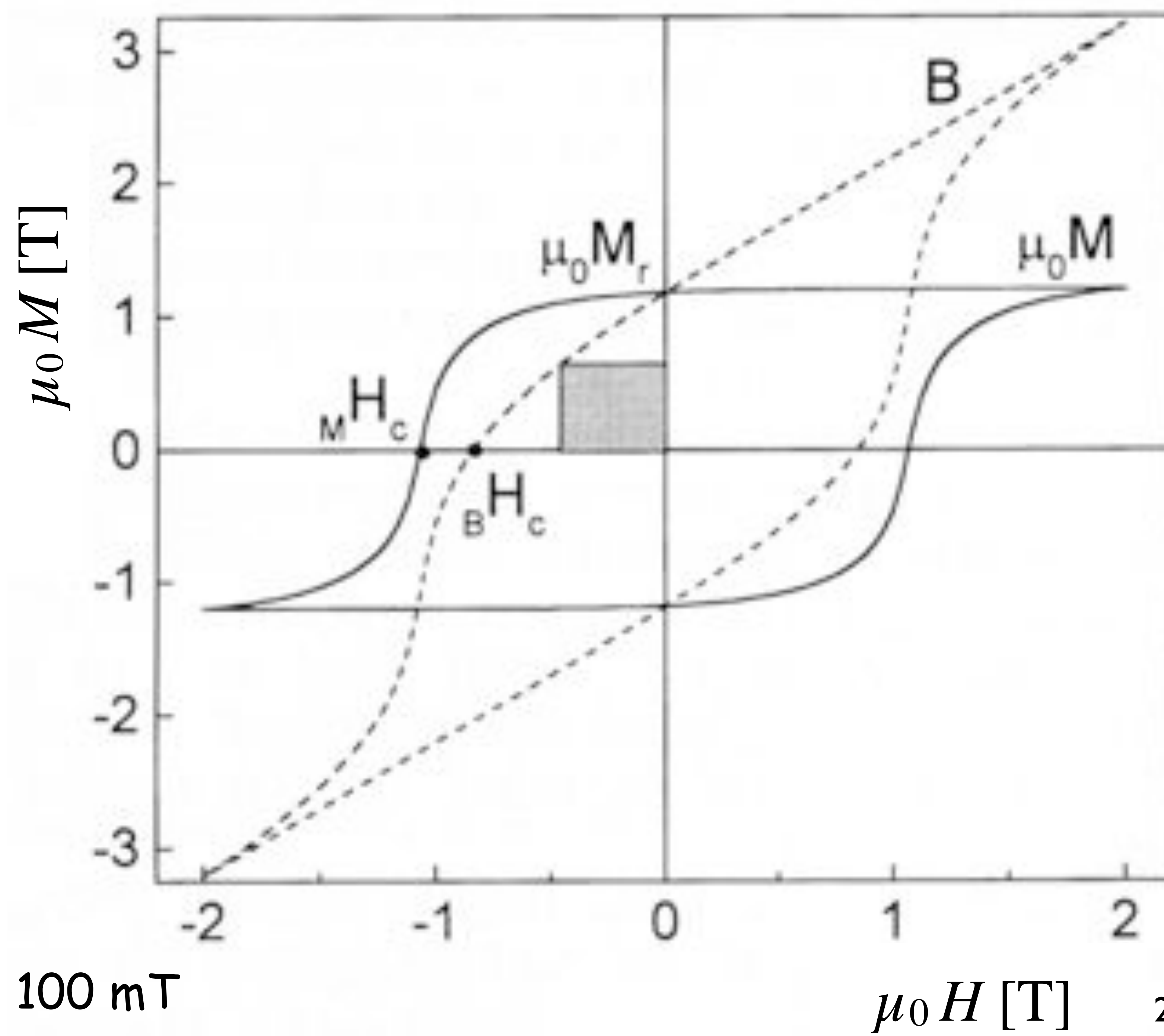


Hardmagnetic materials, basics

- Difference between $M(H)$ and $B(H)$

$$B(H) = \mu_0 (H + M)$$

- Soft magnets:
  Fields involved in hysteresis loop are much smaller than corresponding magnetization values
  $\rightarrow B \cong \mu_0 M$
  $\rightarrow$ difference between $B(H)$ and $M(H)$ negligible *
- Hard magnets:
  H and M have comparable orders $\rightarrow B(H)$ significantly different from $M(H)$



* Example Permalloy:
Saturation flux density = 1 T
Field to saturate ring sample = 100 mT

Hardmagnetic materials, basics

Difference $B(H)$ and $M(H)$

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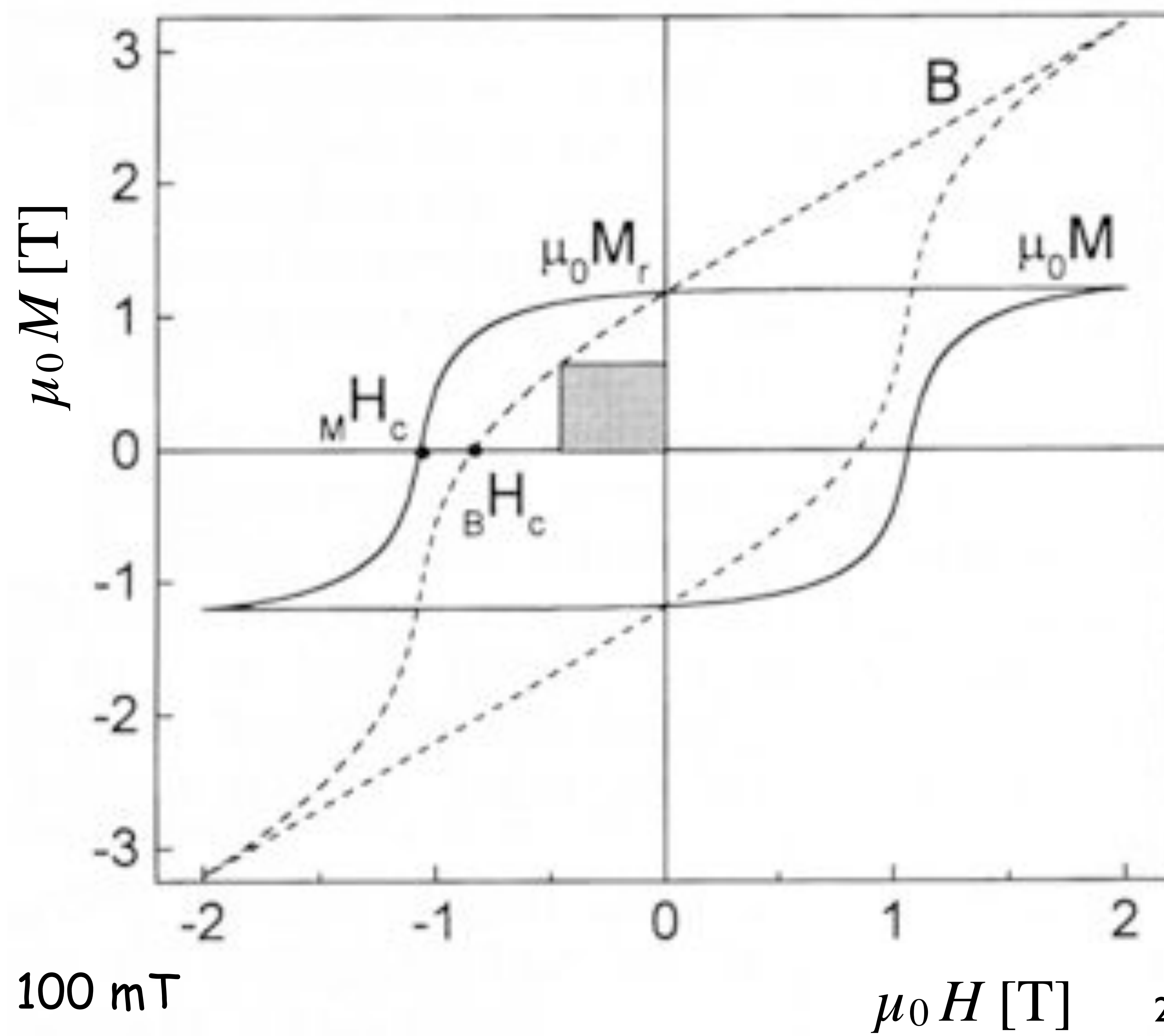


* Example Permalloy:
  Saturation flux density = 1 T
  Field to saturate ring sample = 100 mT

Hardmagnetic materials, basics

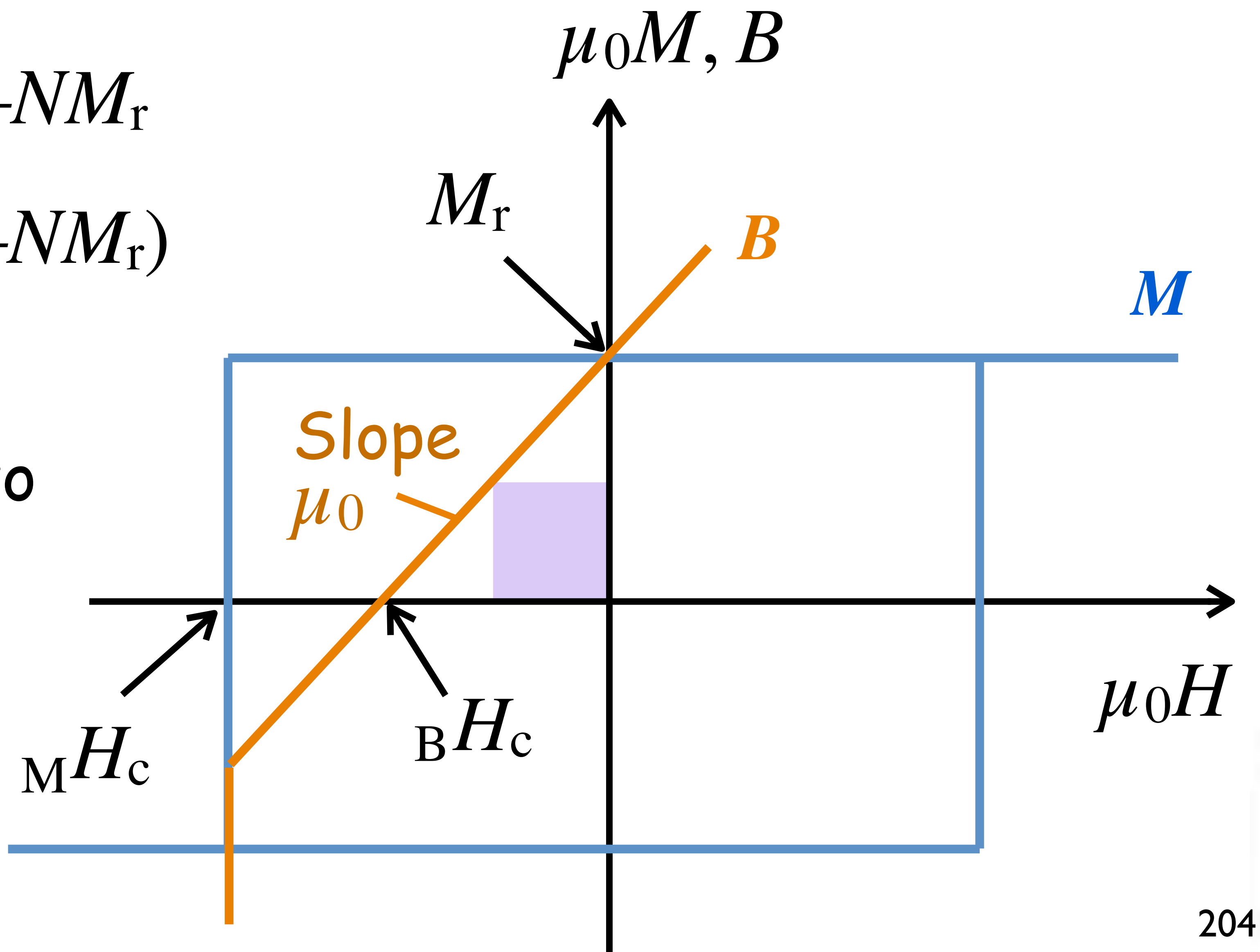
- Assumption: ideal magnet with square $M(H)$ loop and very high coercivity: ${}_{\mathrm{M}}H_{\mathrm{c}} > M_{\mathrm{r}}/2$
- $B = \mu_0(H + M)$
- $(B_{\mathrm{m}}H_{\mathrm{m}}) = \mu_0(H_{\mathrm{m}} + M_{\mathrm{r}})\cdot H_{\mathrm{m}}$
- Demag field: $H_{\mathrm{dem}} = H_{\mathrm{m}} = -NM_{\mathrm{r}}$

$$(B_{\mathrm{m}}H_{\mathrm{m}}) = \mu_0(-NM_{\mathrm{r}} + M_{\mathrm{r}})\cdot(-NM_{\mathrm{r}})$$
$$= -\mu_0 M_{\mathrm{r}}^2 (N - N^2)$$

- Maximization with respect to shape (i.e. demag factor N):

$\partial(B_{\mathrm{m}}H_{\mathrm{m}})/\partial N = 1 - 2N = 0$

$\rightarrow N_{\mathrm{opt}} = 1/2$



Hardmagnetic materials, basics

The ideal magnet…

- Assumption: ideal magnet with square $M(H)$ loop and very high coercivity: ${}_{M}H_c > M_r/2$
- $B = \mu_0(H + M)$
- $(B_m H_m) = \mu_0(H_m + M_r) \cdot H_m$
- Demag field: $H_{dem} = H_m = -NM_r$

$$(B_m H_m) = \mu_0(-NM_r + M_r) \cdot (-NM_r)$$
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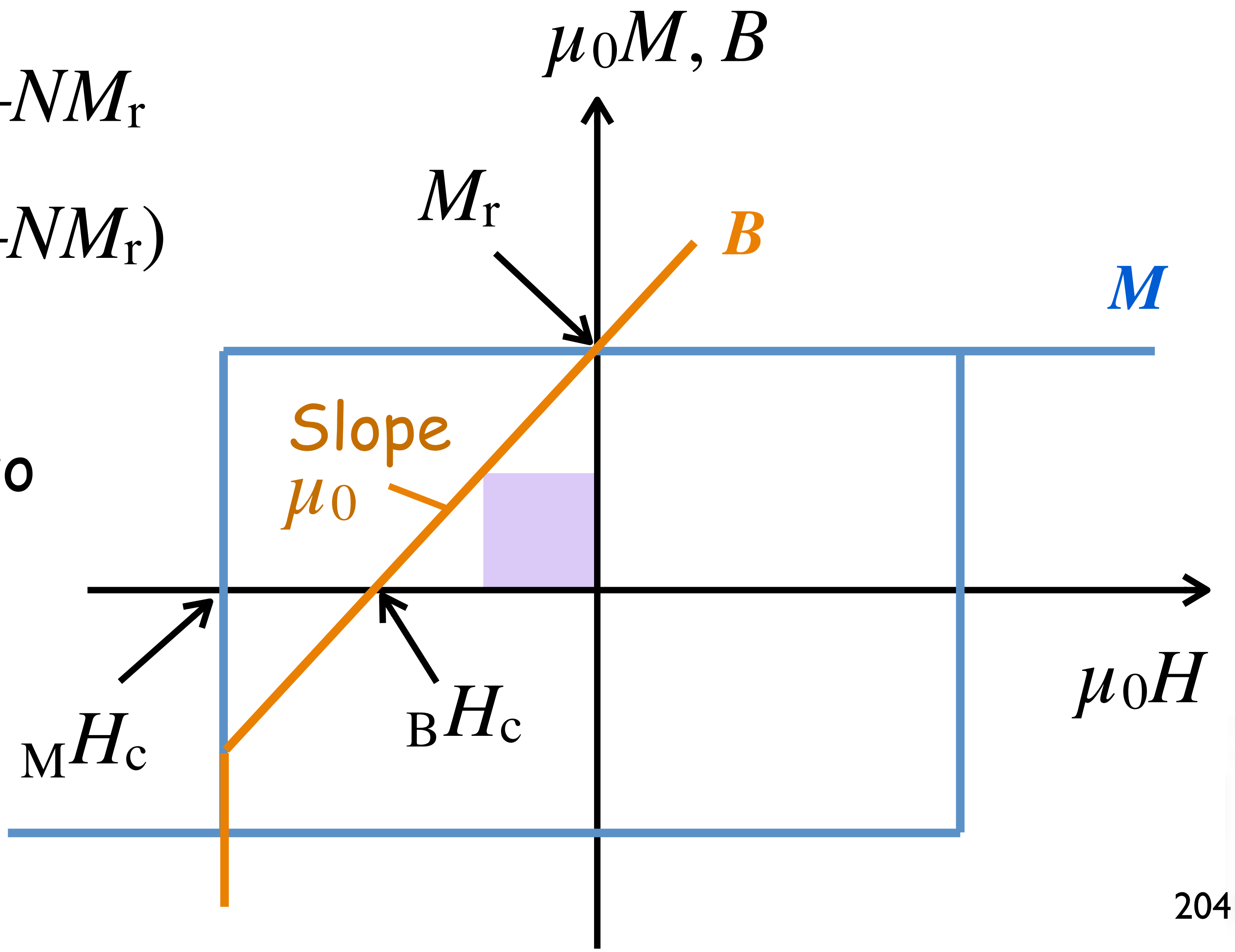

Hardmagnetic materials, basics

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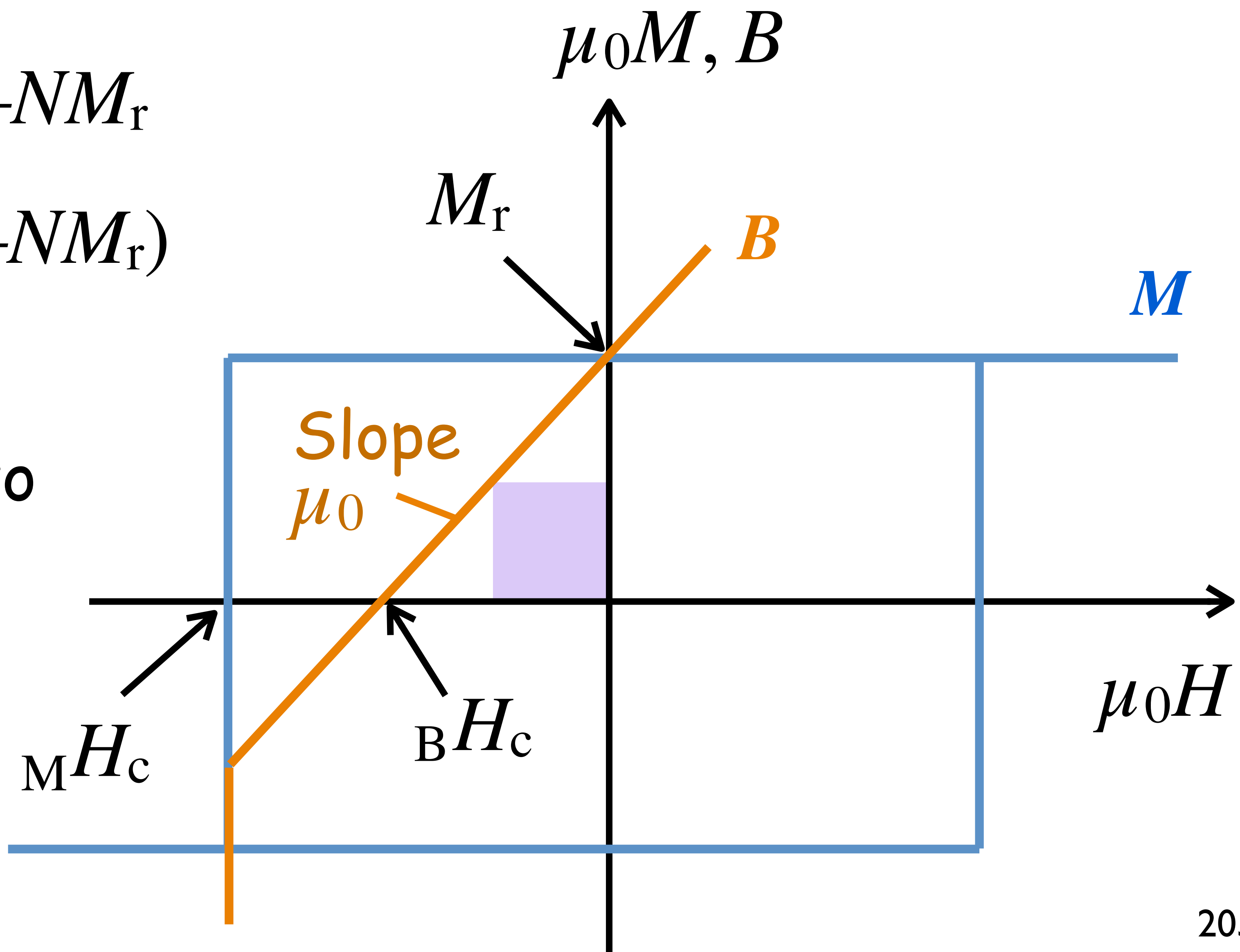

Hardmagnetic materials, basics

The ideal magnet…

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$$(B_m H_m) = \mu_0(-NM_r + M_r) \cdot (-NM_r)$$
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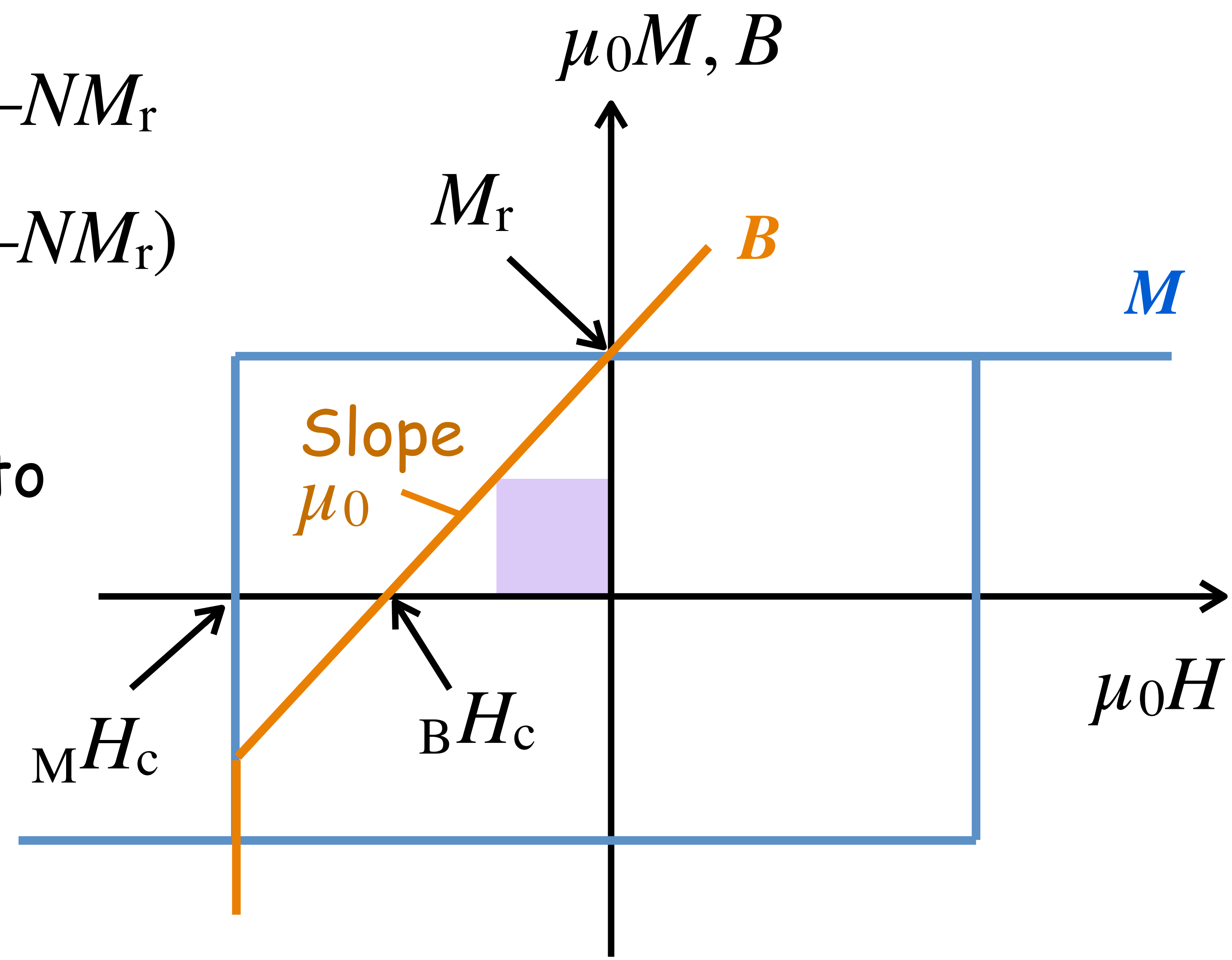


Shape of optimized high ${}_M H_c$ magnet with demag. factor 1/2

Example: textured rare-eart magnets (NdFeB, SmCo)

Hardmagnetic materials, basics

The ideal magnet…

- Demag field: $H_{dem} = H_m = -NM_r$

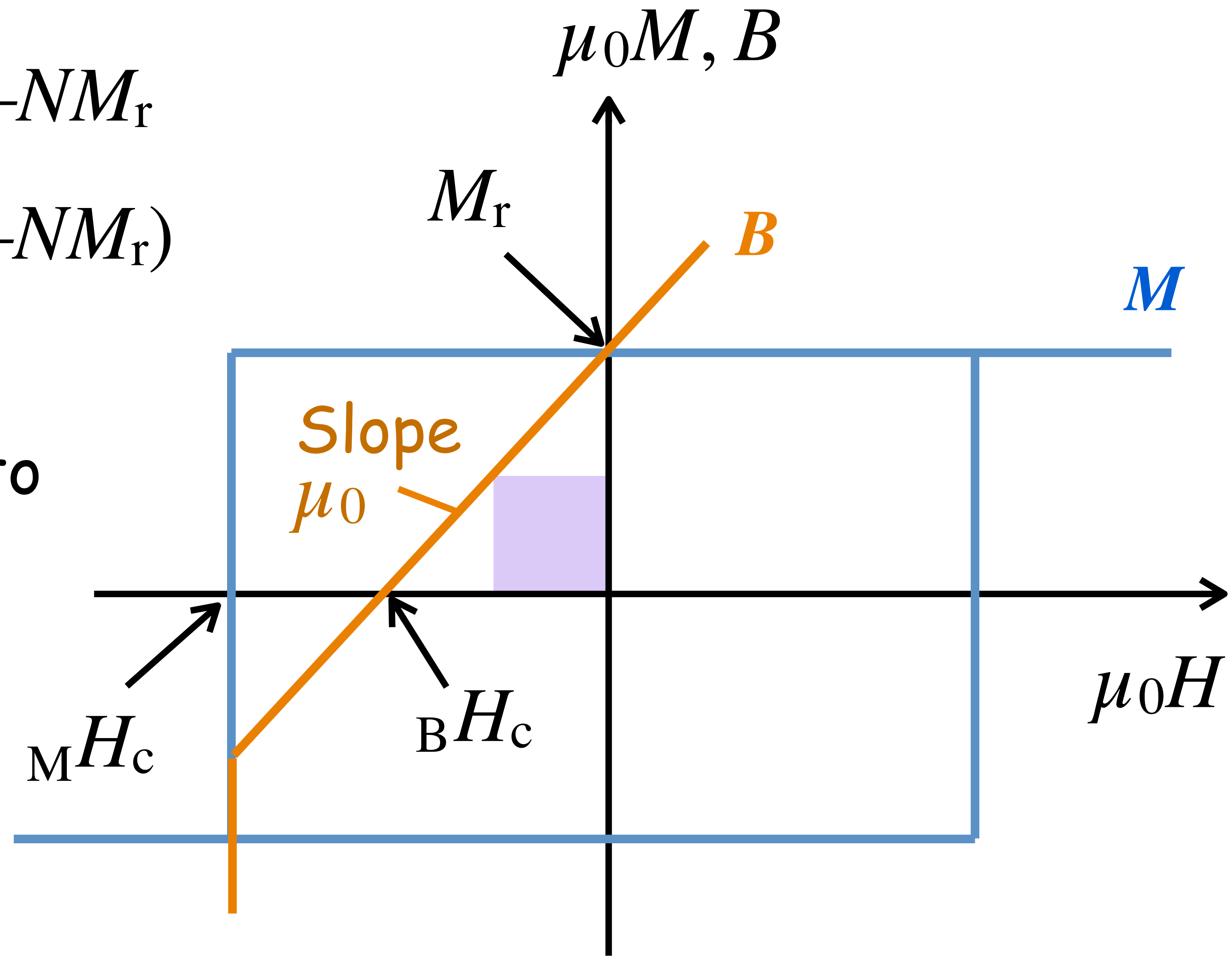
$$(B_m H_m) = \mu_0(-NM_r + M_r)\cdot(-NM_r)$$
$$= -\mu_0 M_r^2 (N - N^2)$$

- Maximization with respect to shape (i.e. demag factor N):

$$\partial(B_m H_m)/\partial N = 1 - 2N = 0$$
$$\rightarrow N_{opt} = 1/2$$

- Operating point at:

$$B = B_r/2 \text{ and } H = -M_r/2$$



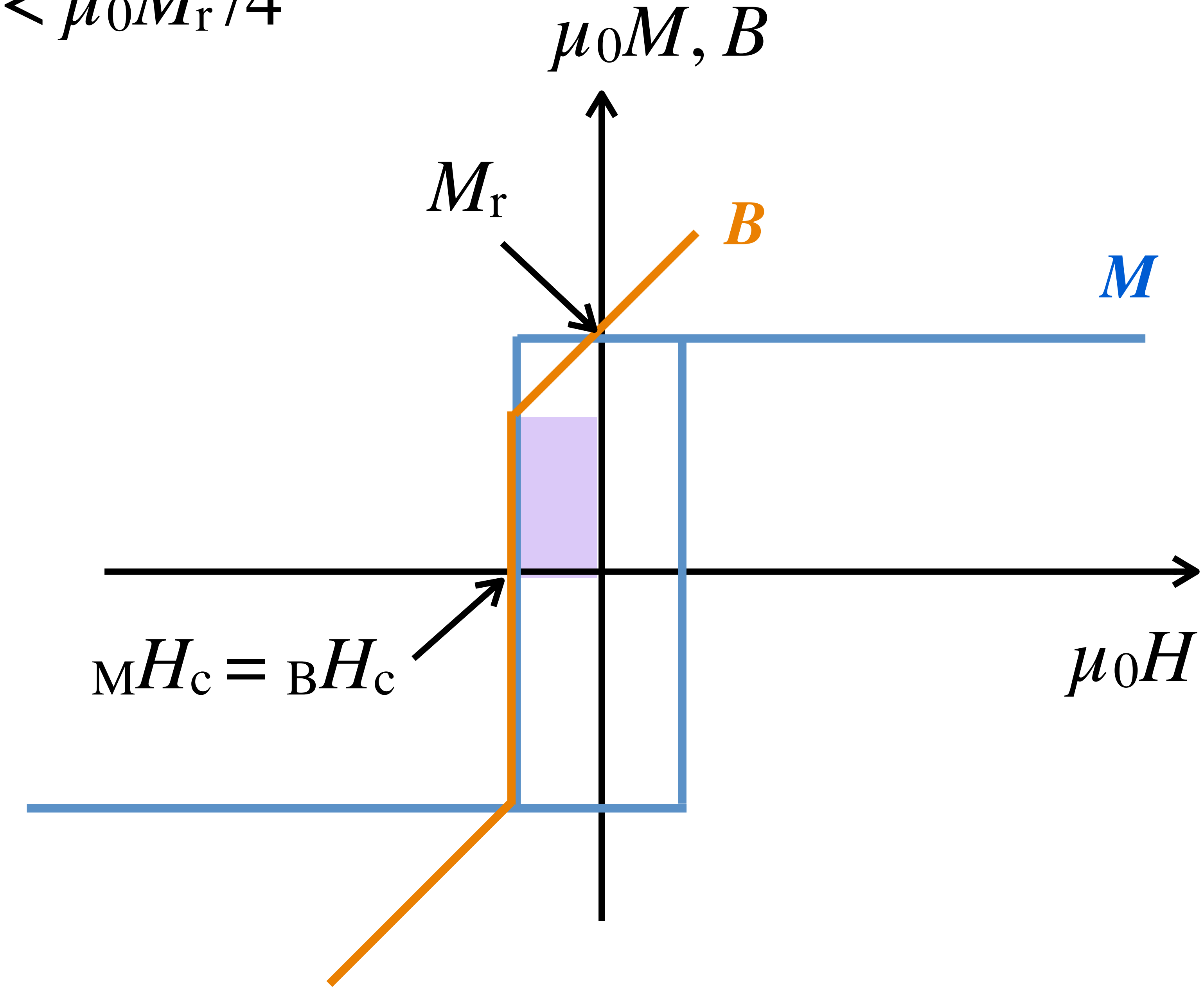
- Energy product:

$(BH) = \mu_0 M_r^2/4 \rightarrow$ does not depend on ${}_M H_c$

$\rightarrow$ better increase M_r rather than ${}_M H_c$

Hardmagnetic materials, basics

- Assumption: square $M(H)$ loop, but coercivity: ${}_{\mathrm{M}}H_{\mathrm{c}} < M_{\mathrm{r}}/2$
- $(BH)_{\max} = (M_{\mathrm{r}} - {}_{\mathrm{M}}H_{\mathrm{c}}) \cdot {}_{\mathrm{M}}H_{\mathrm{c}} < \mu_0 M_{\mathrm{r}}^2/4$
- $N_{\mathrm{opt}} = H_{\mathrm{c}}/M_{\mathrm{r}} < 1/2$
- Examples: steel, Alnico



Hardmagnetic materials, basics

The non-ideal magnet…

- Assumption: square $M(H)$ loop, but coercivity: ${}_{M}H_c < M_r/2$
- $(BH)_{max} = (M_r - {}_{M}H_c) \cdot {}_{M}H_c < \mu_0 M_r^2/4$
- $N_{opt} = H_c/M_r < 1/2$
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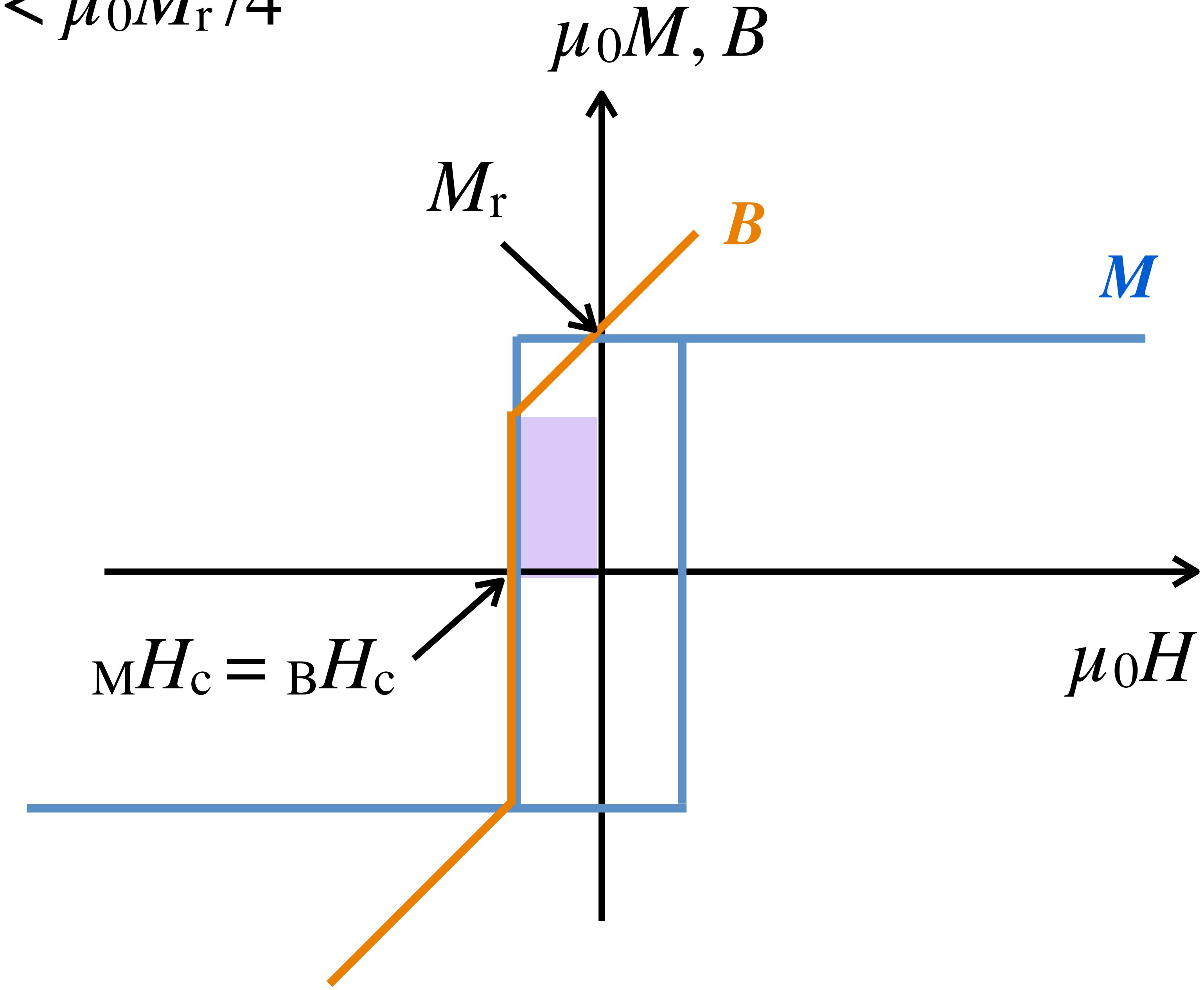
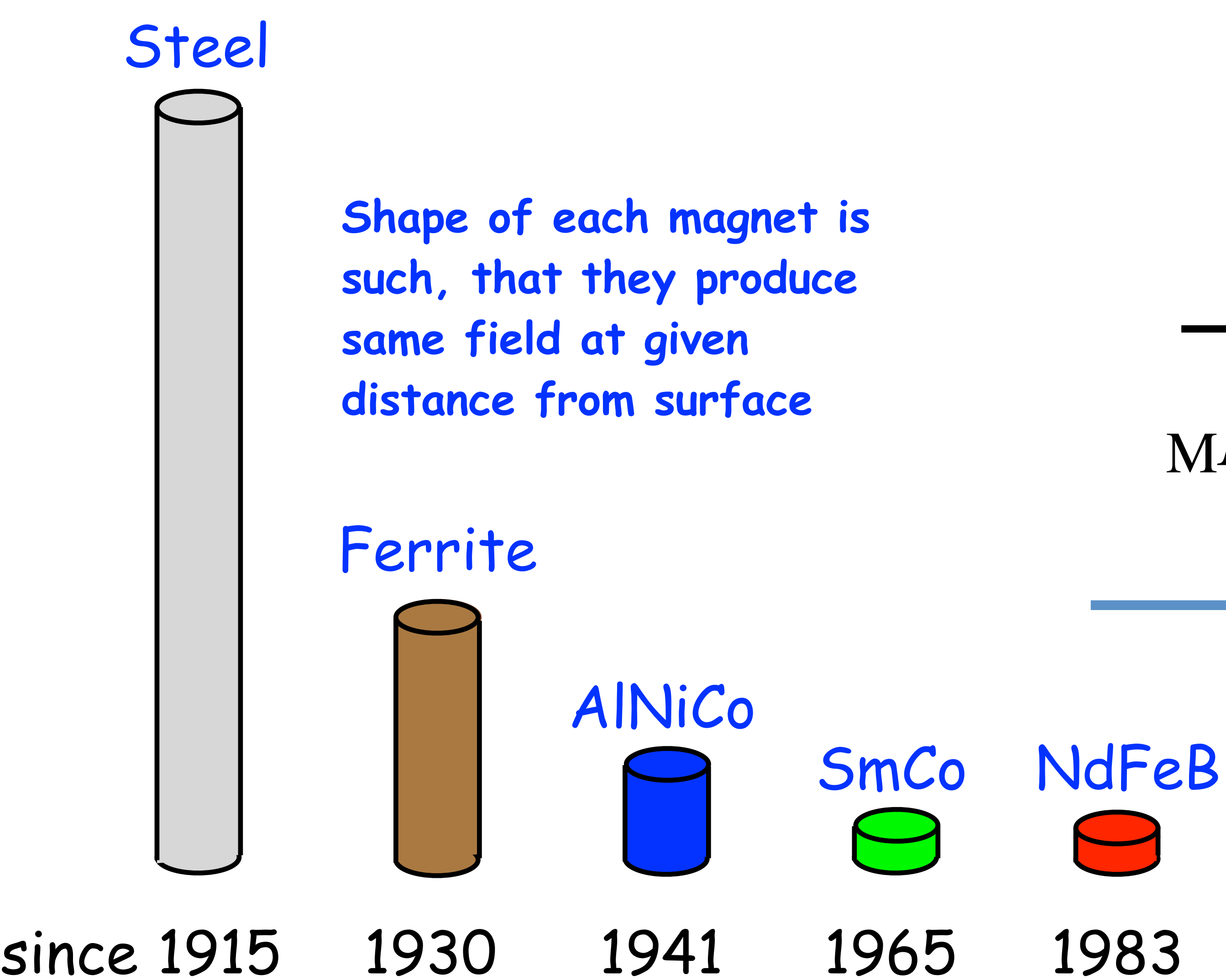
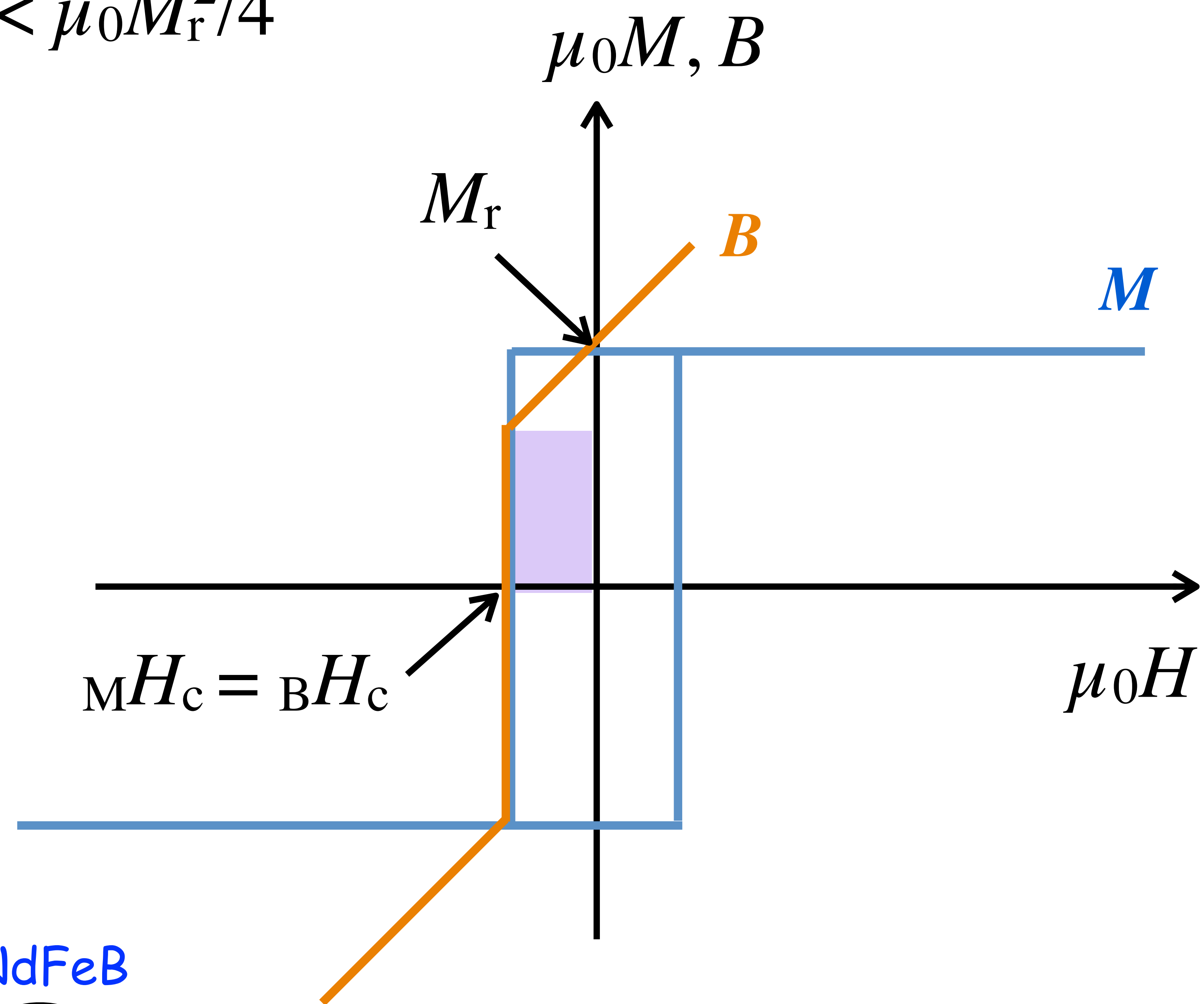


Hardmagnetic materials, basics

The non-ideal magnet…

- Assumption: square $M(H)$ loop, but coercivity: ${}_{M}H_c < M_r/2$
- $(BH)_{max} = (M_r - {}_{M}H_c)\cdot {}_{M}H_c < \mu_0 M_r^2/4$
- $N_{opt} = H_c/M_r < 1/2$
- Examples: steel, Alnico

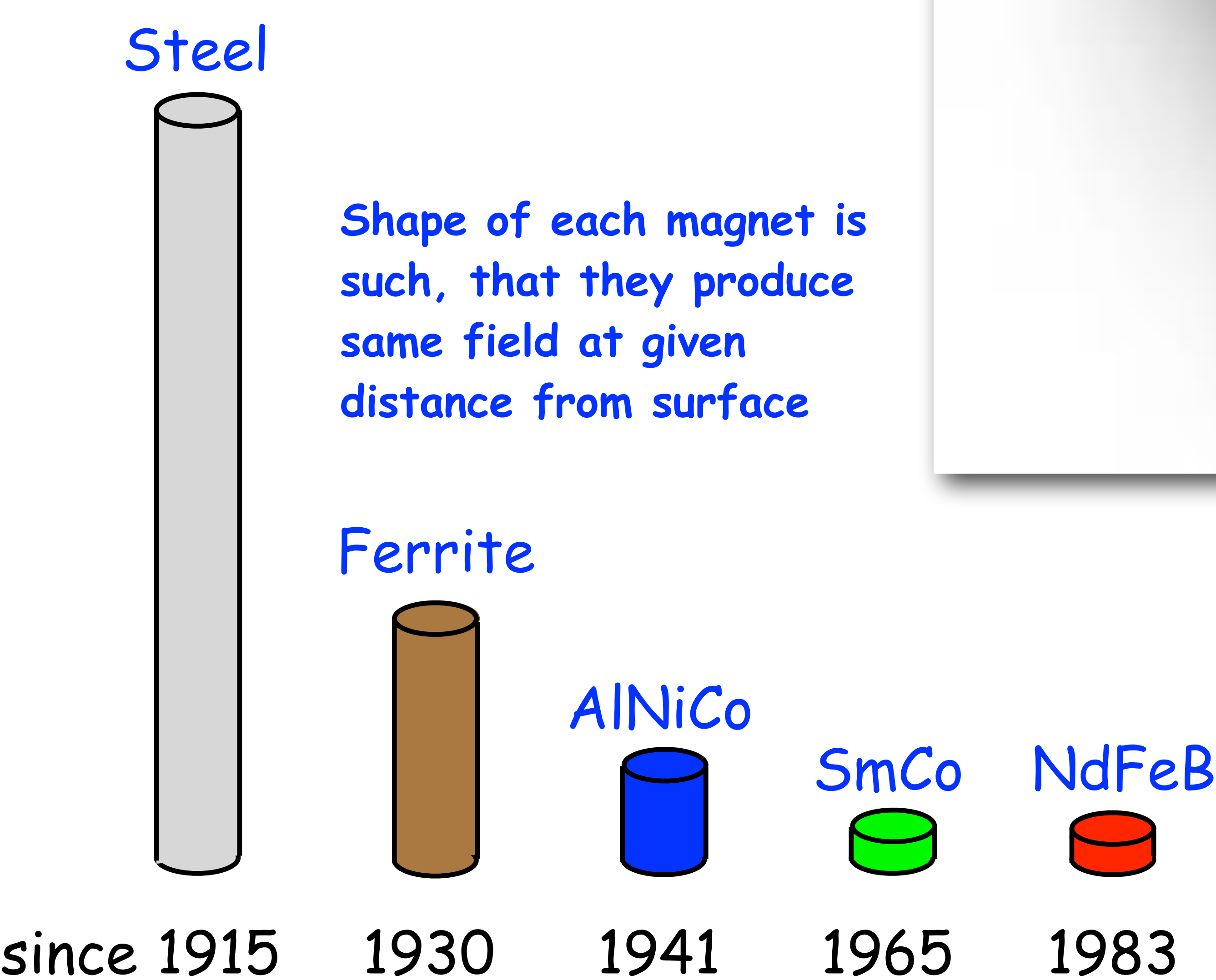




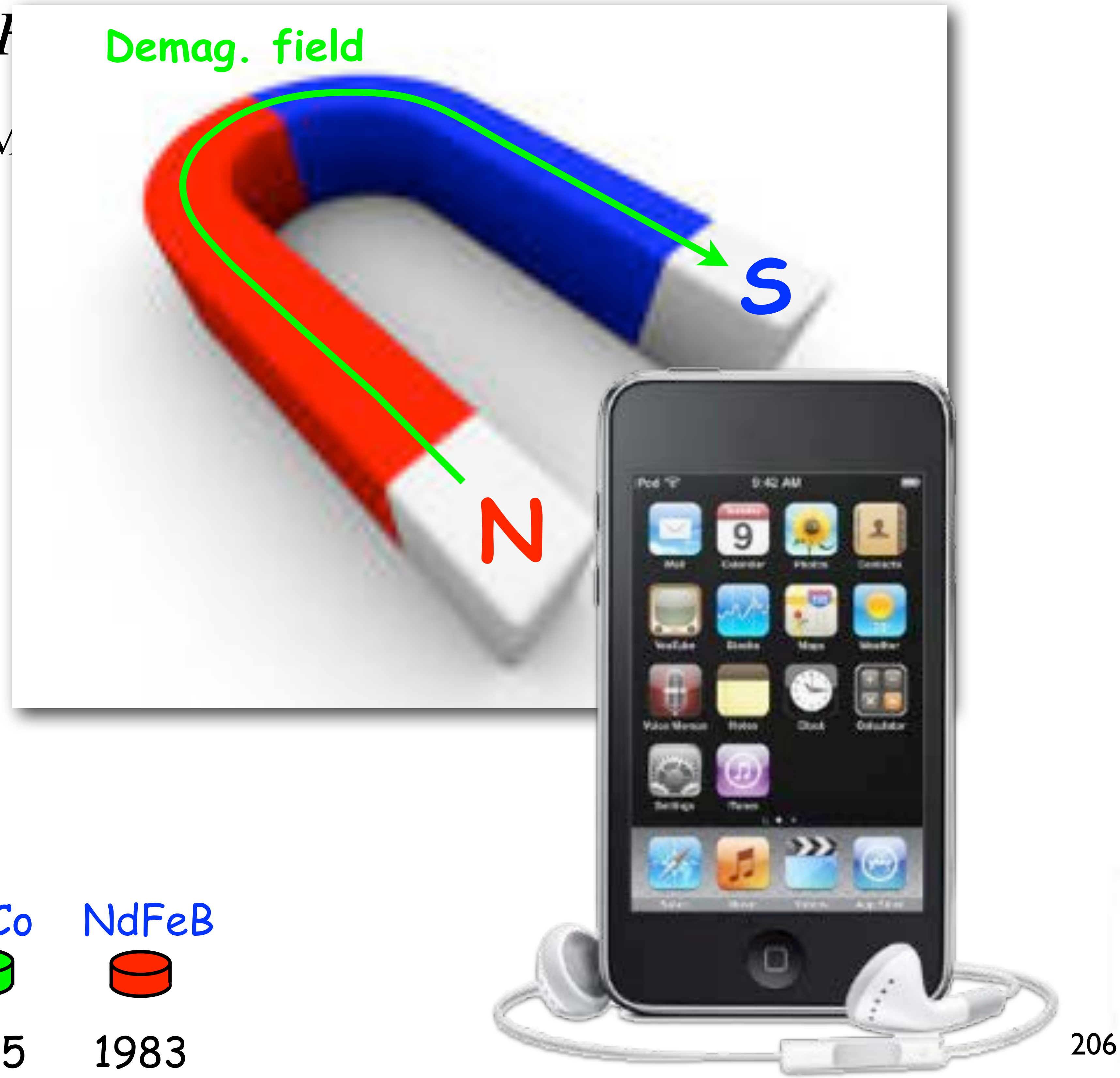
Hardmagnetic materials, basics

The non-ideal magnet…

- Assumption: square $M(H$
- $(BH)_{max} = (M_r - {}_M H_c) \cdot {}_M$
- $N_{opt} = H_c / M_r < 1/2$
- Examples: steel, Alnico

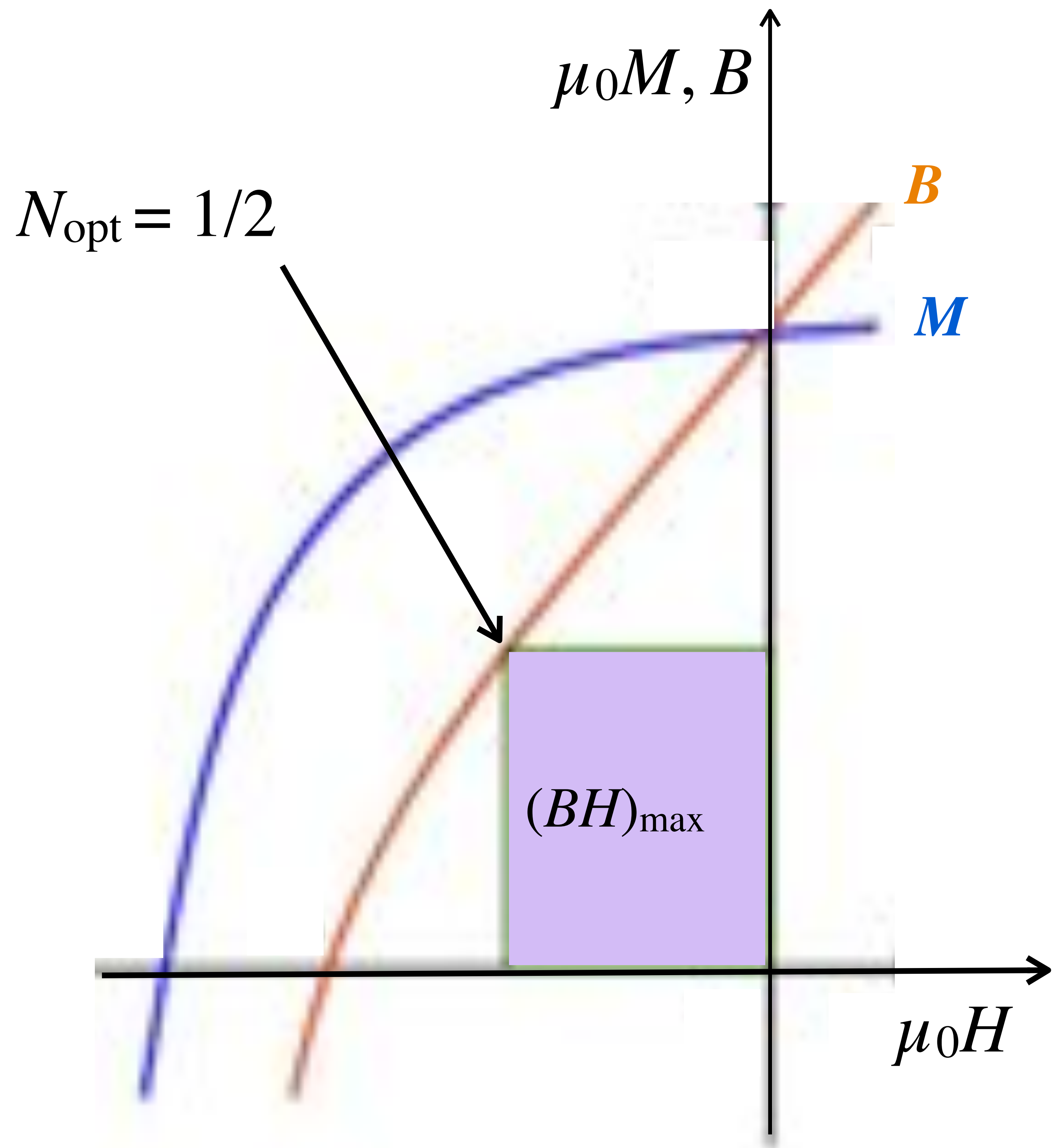


Shape of each magnet is such, that they produce same field at given distance from surface



Hardmagnetic materials, basics

Shape and energy product

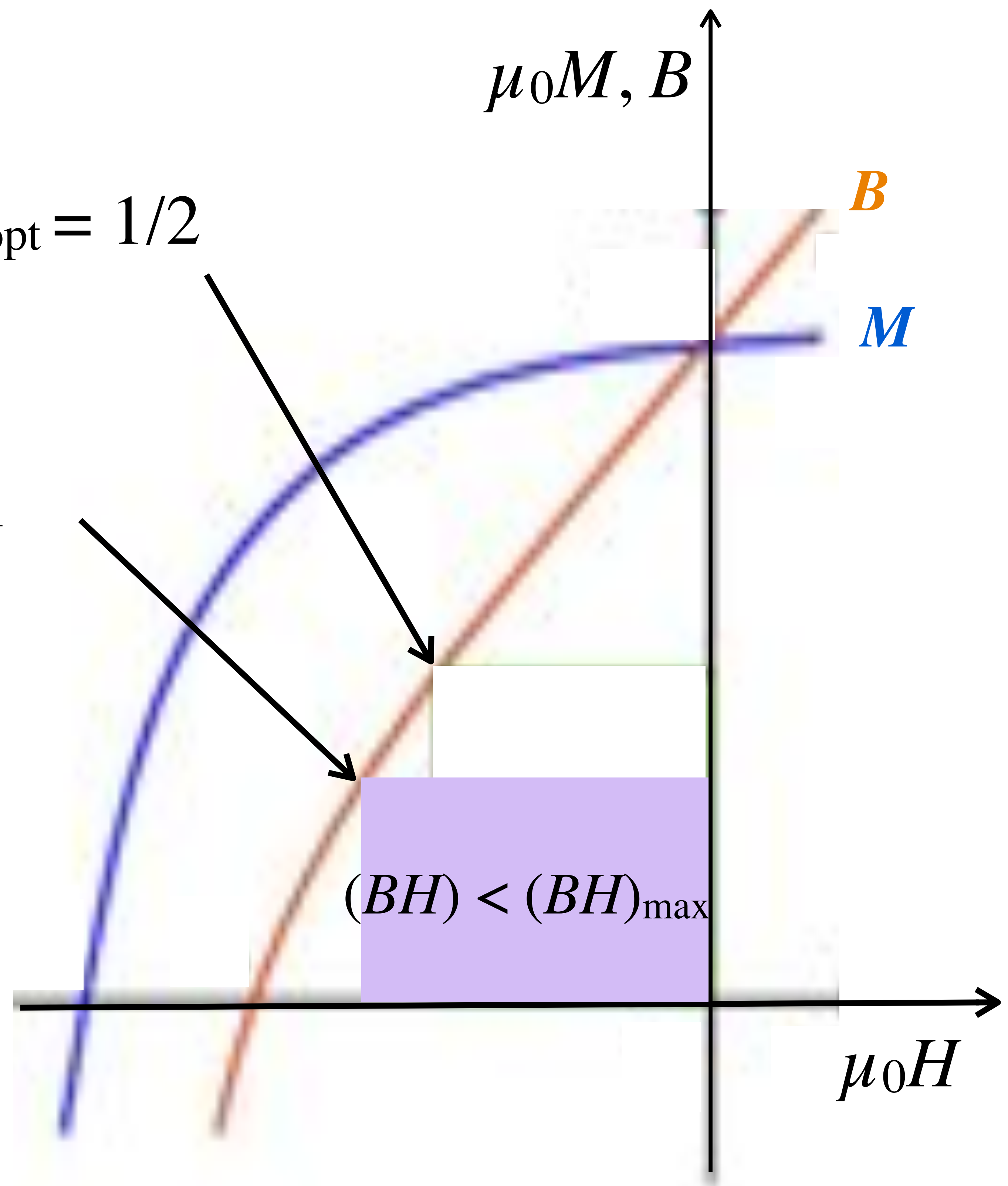


Hardmagnetic materials, basics

Shape and energy product

$N_{opt} = 1/2$

$1/2 < N < 1$

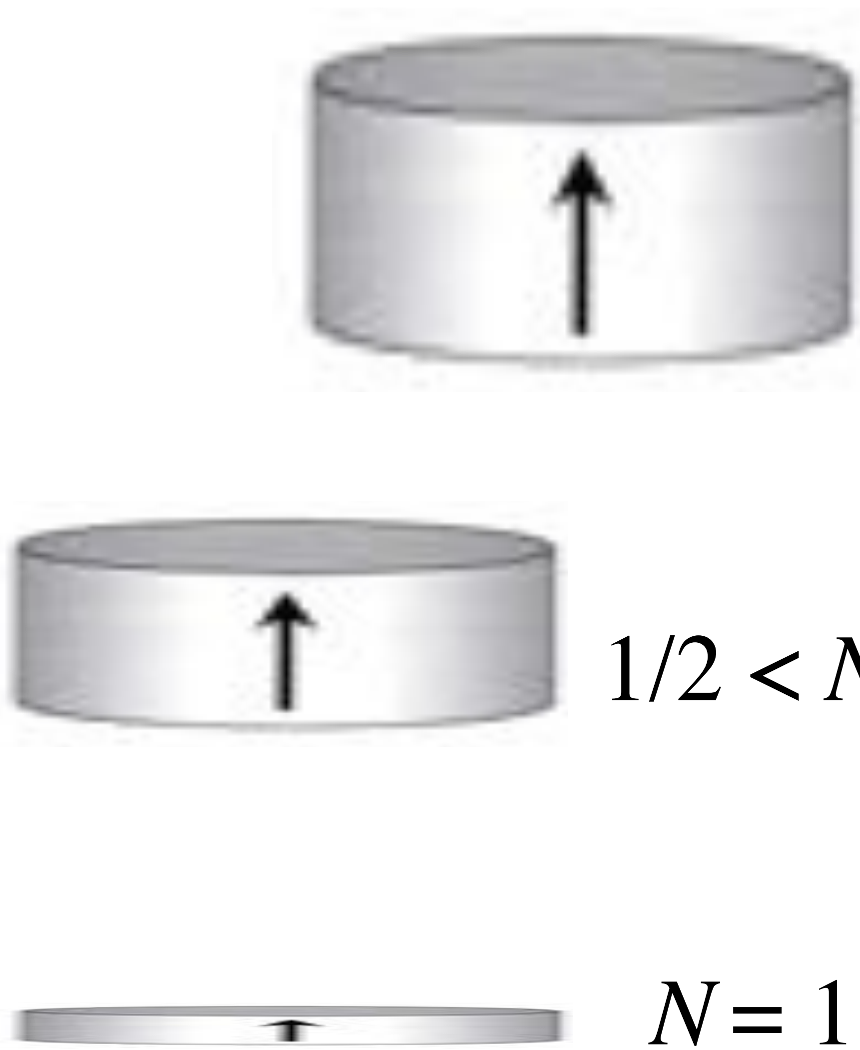


Load line

$$B_m = -\frac{1-N}{N}\mu_0 H_m$$

Hardmagnetic materials, basics

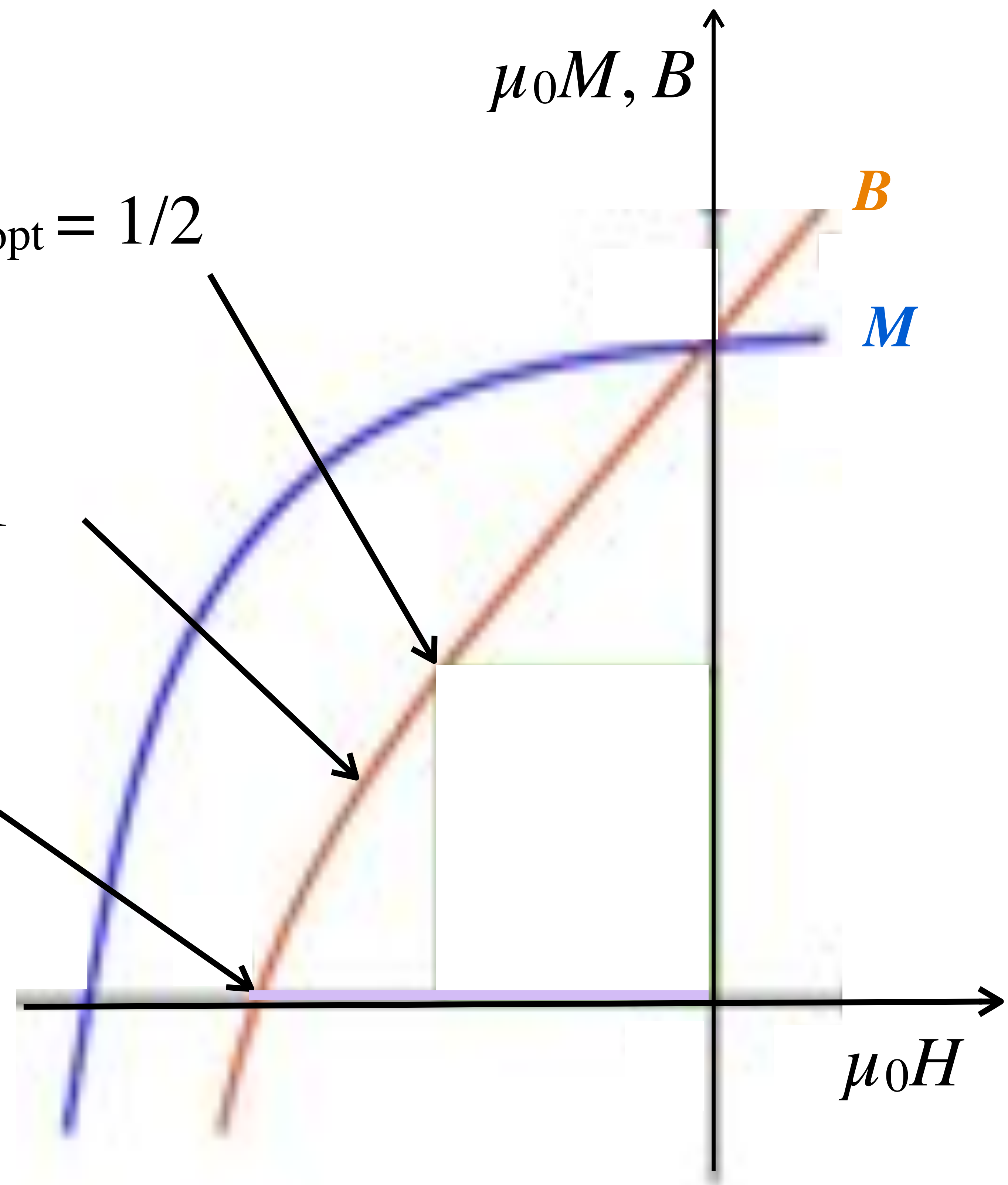
Shape and energy product



$N_{opt} = 1/2$

$1/2 < N < 1$

$N = 1$



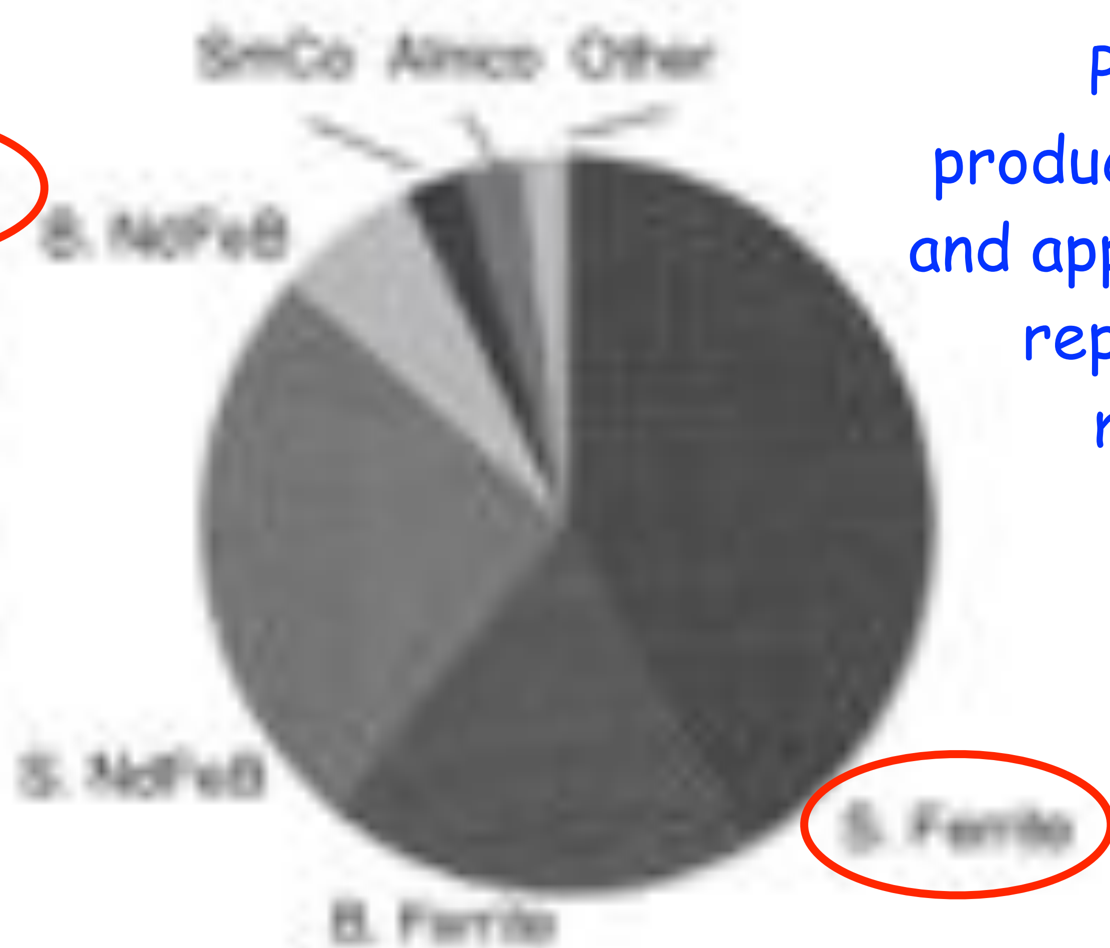
$(BM) = 0$ for plate or film with perpendicular anisotropy → must be made 3D (nanodot)

Permanent magnets, Summary

Permanent magnets: Summary

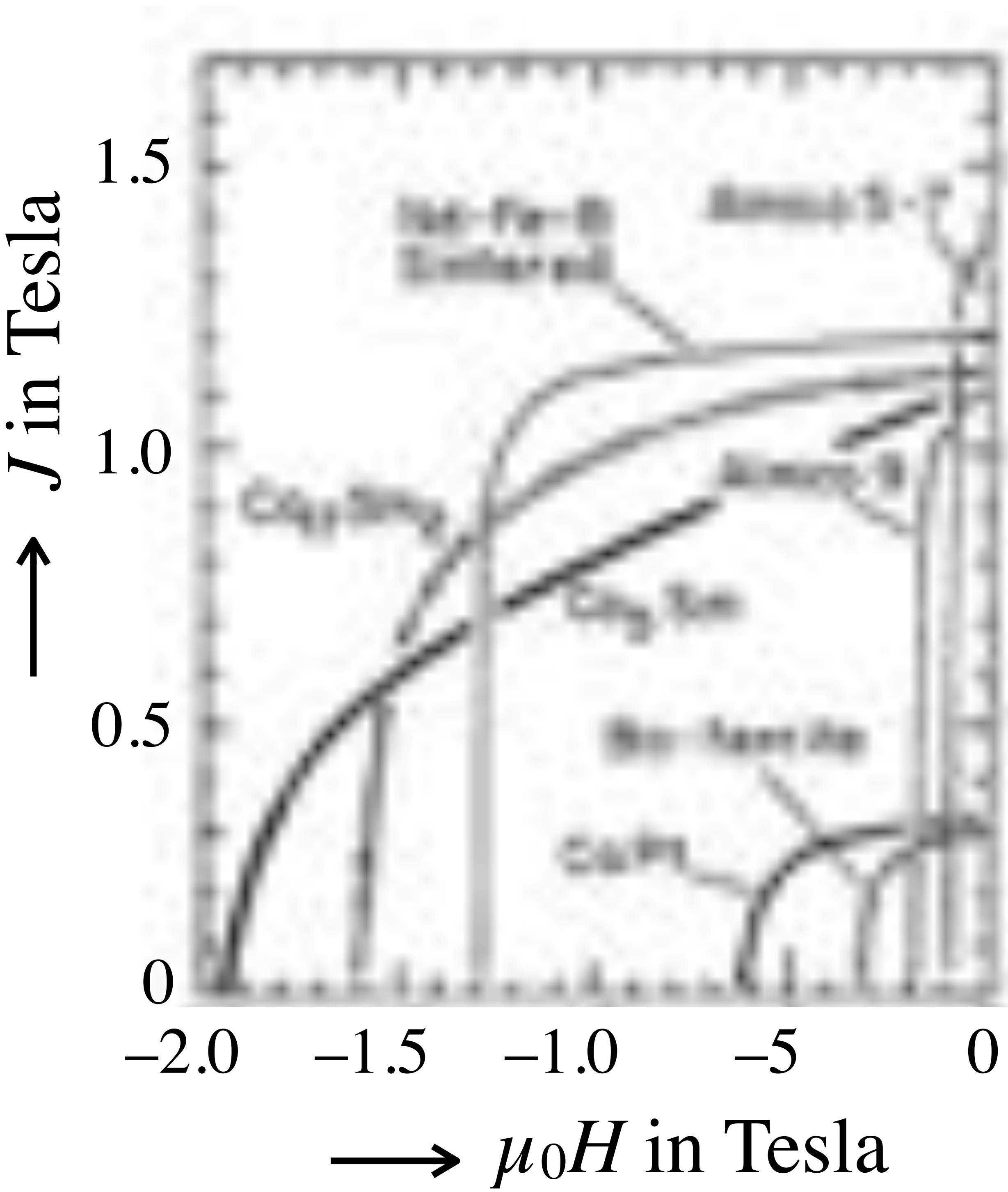
Properties of commercial oriented permanent magnets

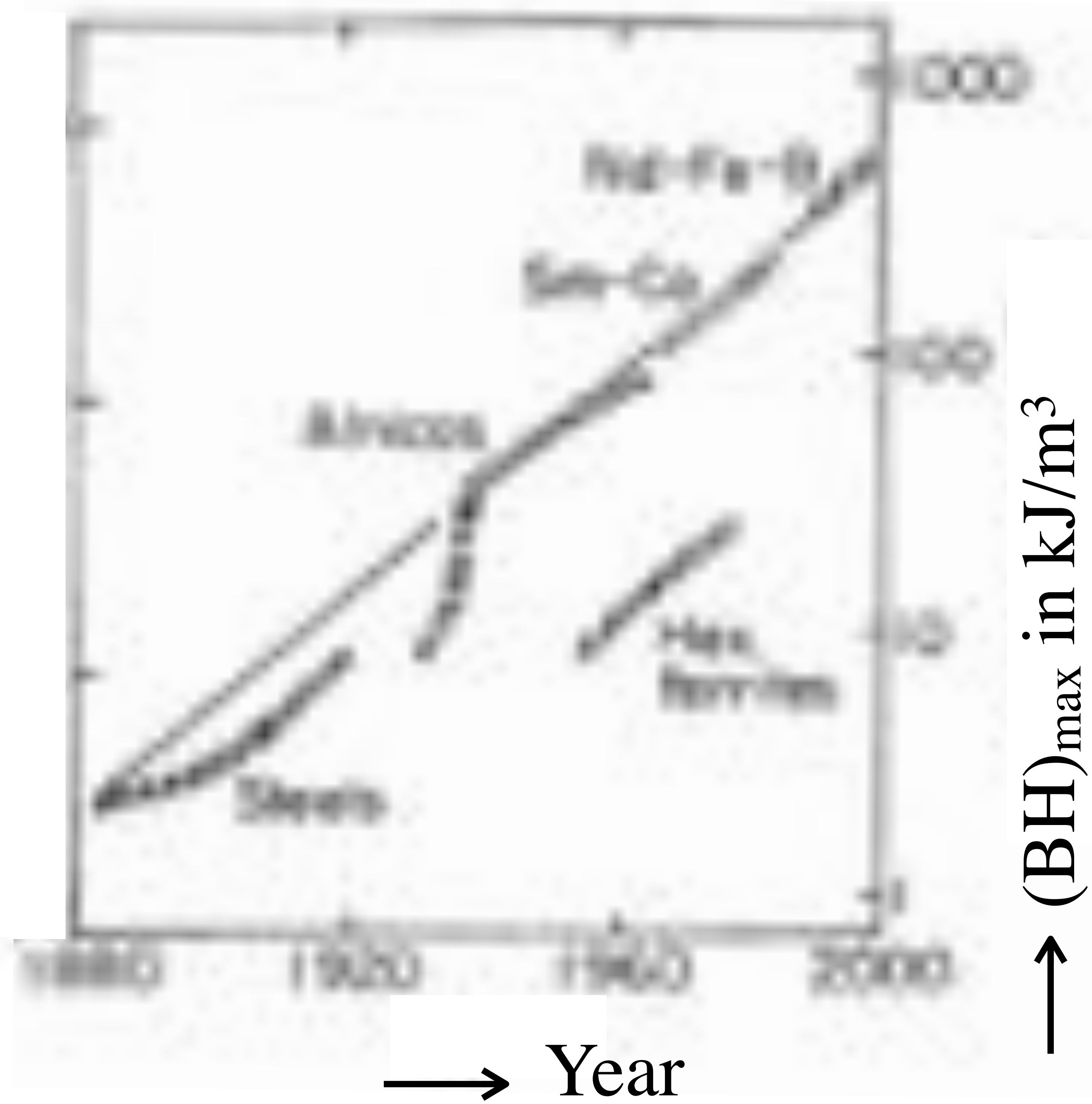
	$\mu_0 M_r$ (T)	J_s (T)	$_jH_c$ (kA m^{-1})	$_BH_c$ (kA m^{-1})	$(BH)_{max}$ (kJ m^{-3})	$\mu_0 M_s^2/4$ (kJ m^{-3})
$SrFe_{12}O_{19}$	0.42	0.47	275	265	34	35
Alnico 5	1.25	1.40	54	52	43	310
$SmCo_5$	0.88	0.95	1700	700	150	154
Sm_2Co_{17}*	1.08	1.15	1100	800	220	232
$Nd_2Fe_{14}B$	1.28	1.54	1000	900	350	326



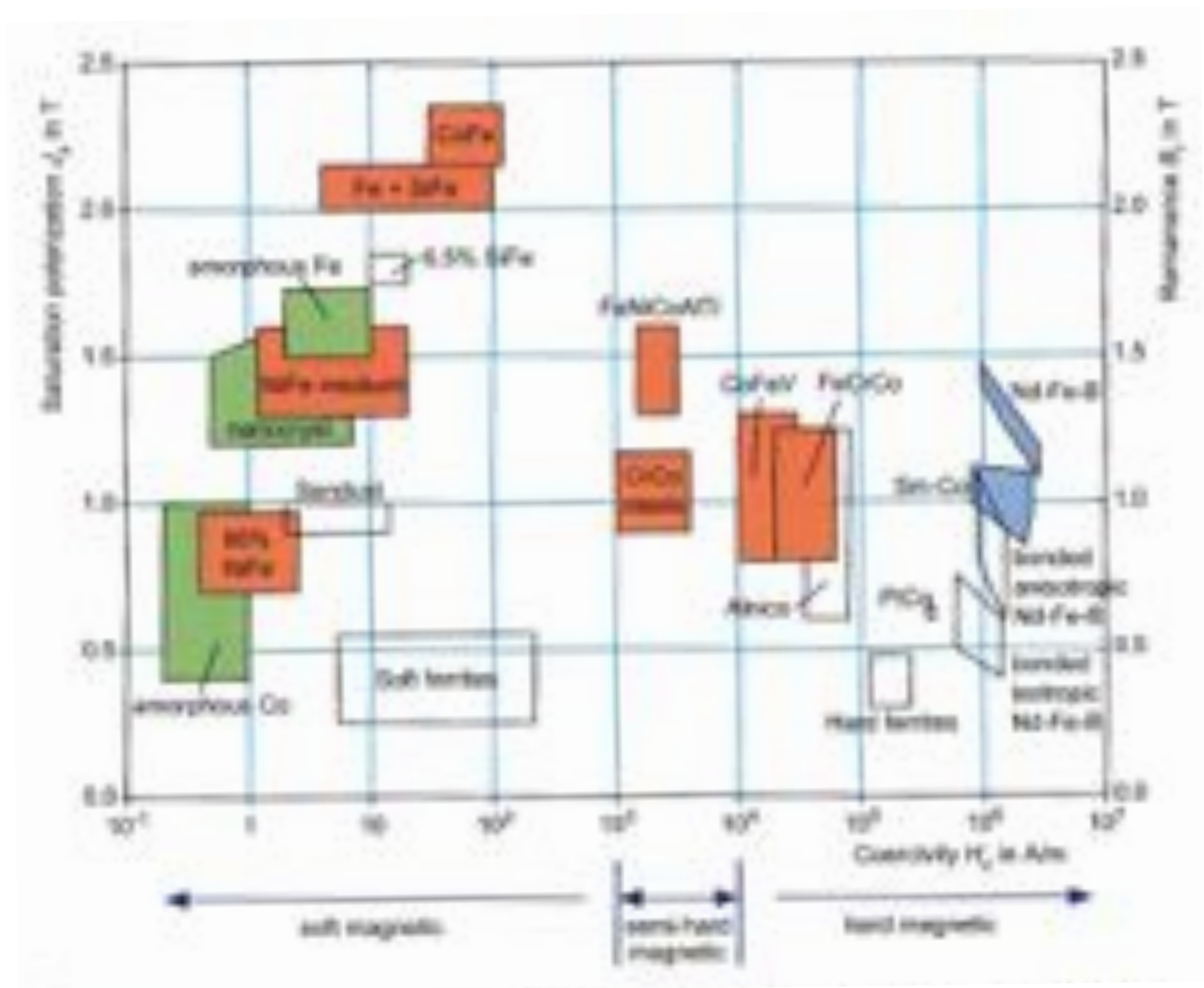
Permanent magnet production by materials and applications. The pie represents an annual market of about 6 Billion Dollars

Permanent magnets: Summary





Summary
hard and soft magnetic materials


amorphous Fe
6.5% SiFe
CoFe
FeNiCo(AlTi)
CoFeV
FeCrCo
Nd-Fe-B
Sm-Co
Alnico
Soft ferrites
Hard ferrites
amorphous Co
bonded anisotropic Nd-Fe-B
bonded isotropic Nd-Fe-B
Coercivity H_c in A/m
soft magnetic
semi-hard magnetic
hard magnetic

There is much more on Magnetic Materials...

3.
Magnetic Materials with special functions

Materials for Spintronic Applications

see lecture by Jian-Ping Wang

Materials for Magnetic Data Storage

see lecture by Kaizhong Gao

Materials for Biomedical Applications

see lecture by Tim St. Pierre

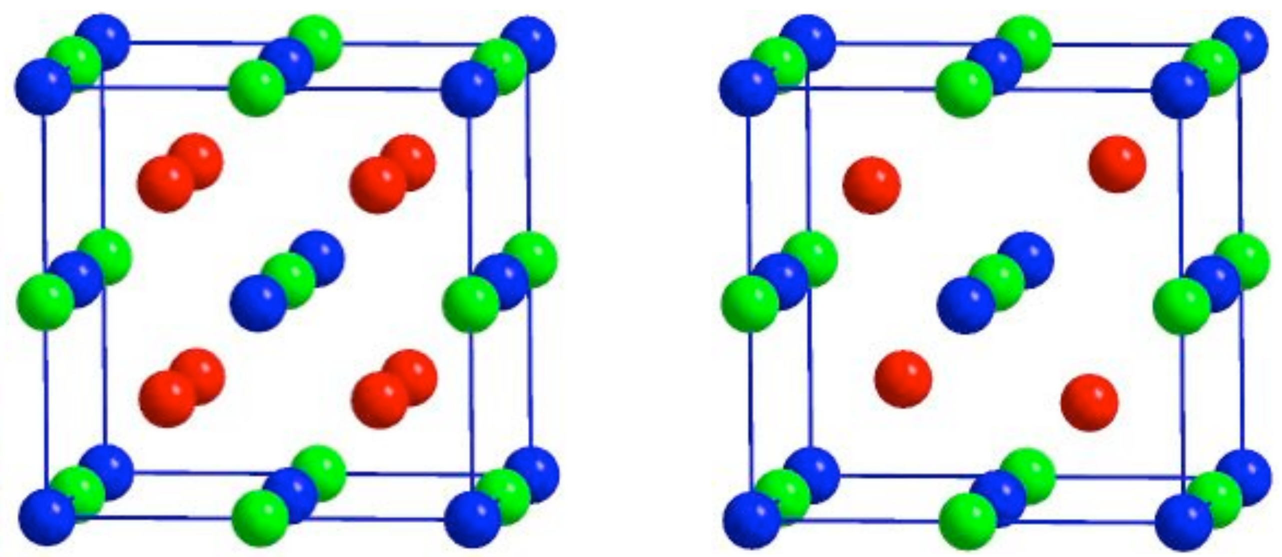
Heusler alloys

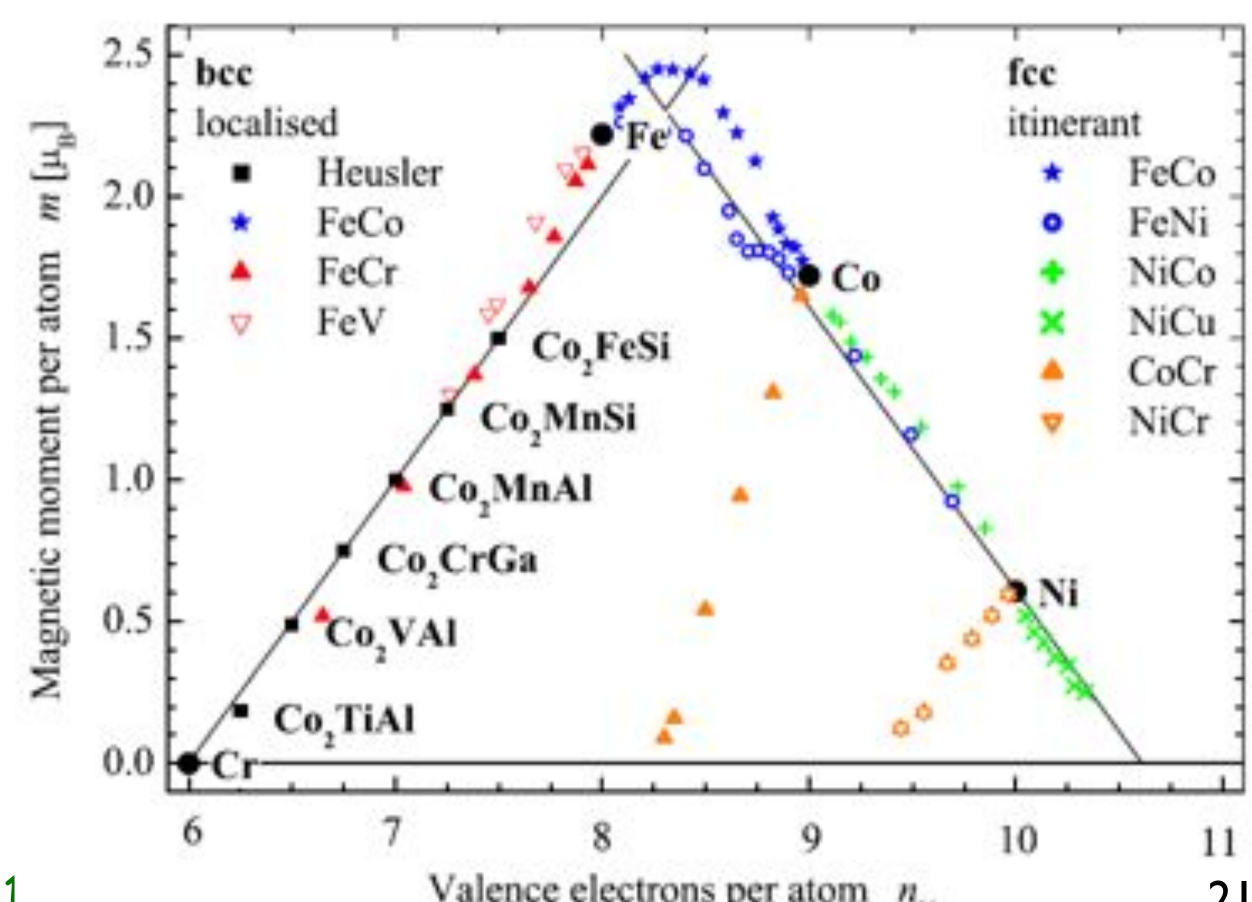
Heusler alloys

Ternary, intermetallic materials

$L2_1$ structure X_2YZ (Protoype: Cu_2MnAl)

$C1_b$ structure XYZ (Protoype: LiAlSi)



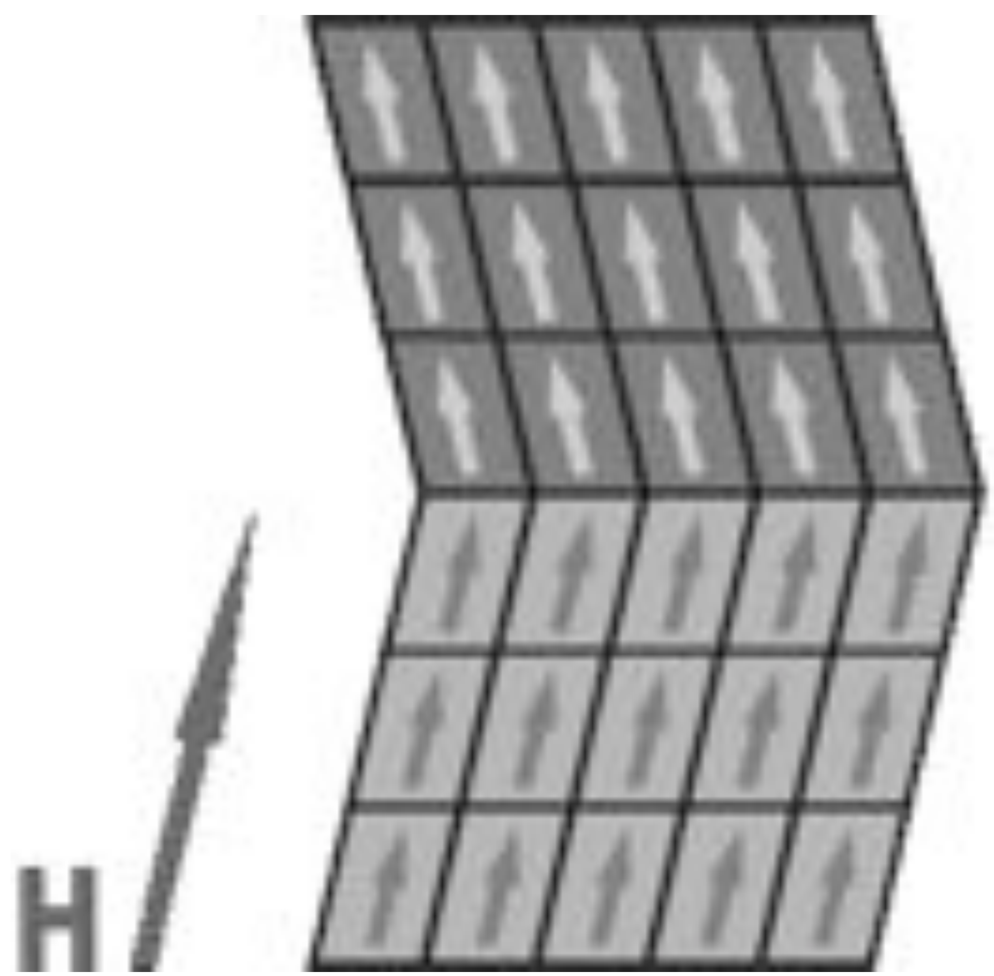


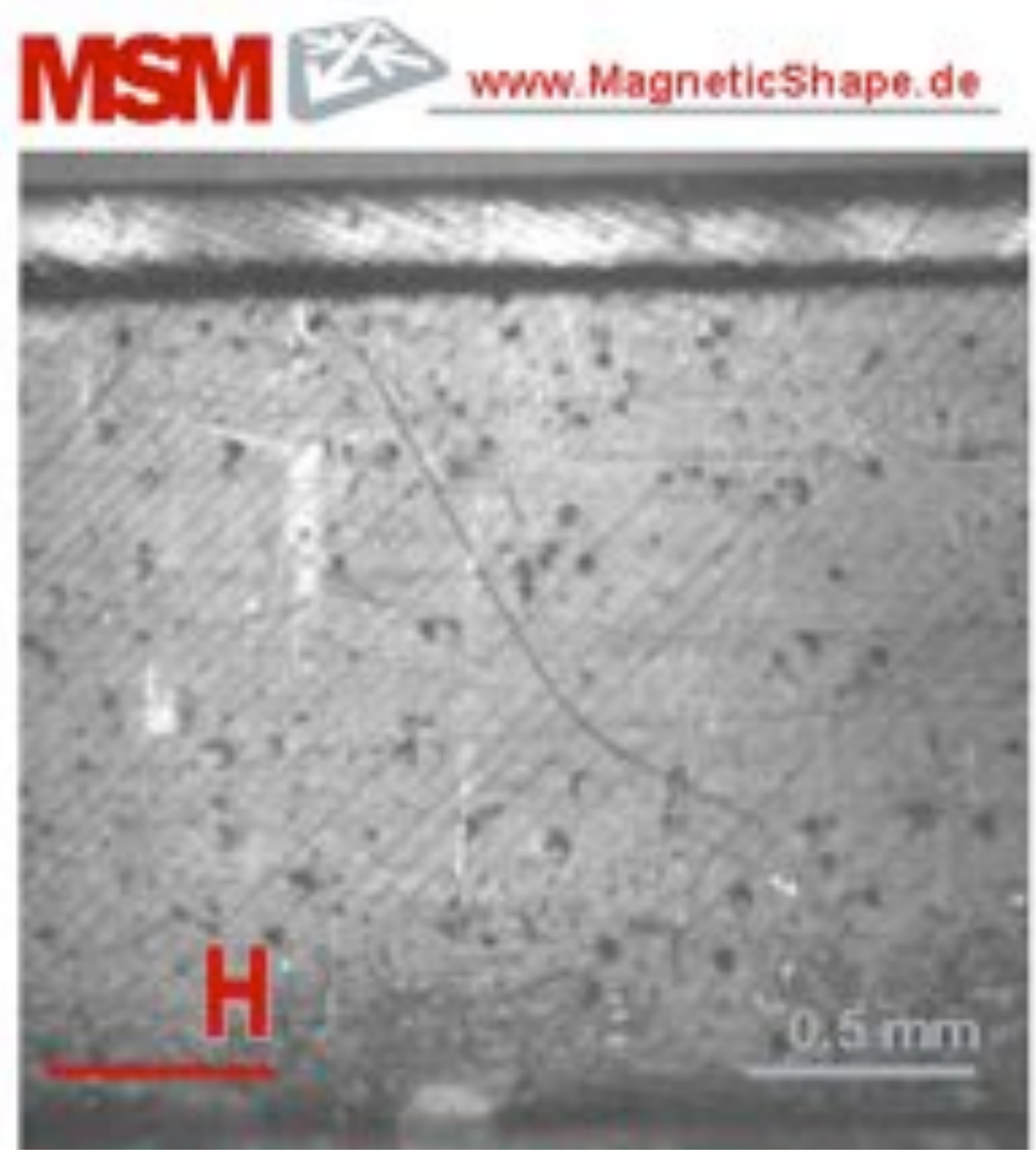
Graf, Felser, Parkin, Progress in Solid State Chemistry 39 (2011,

Magnetic Shape Memory Materials

Magnetic Shape Memory Materials

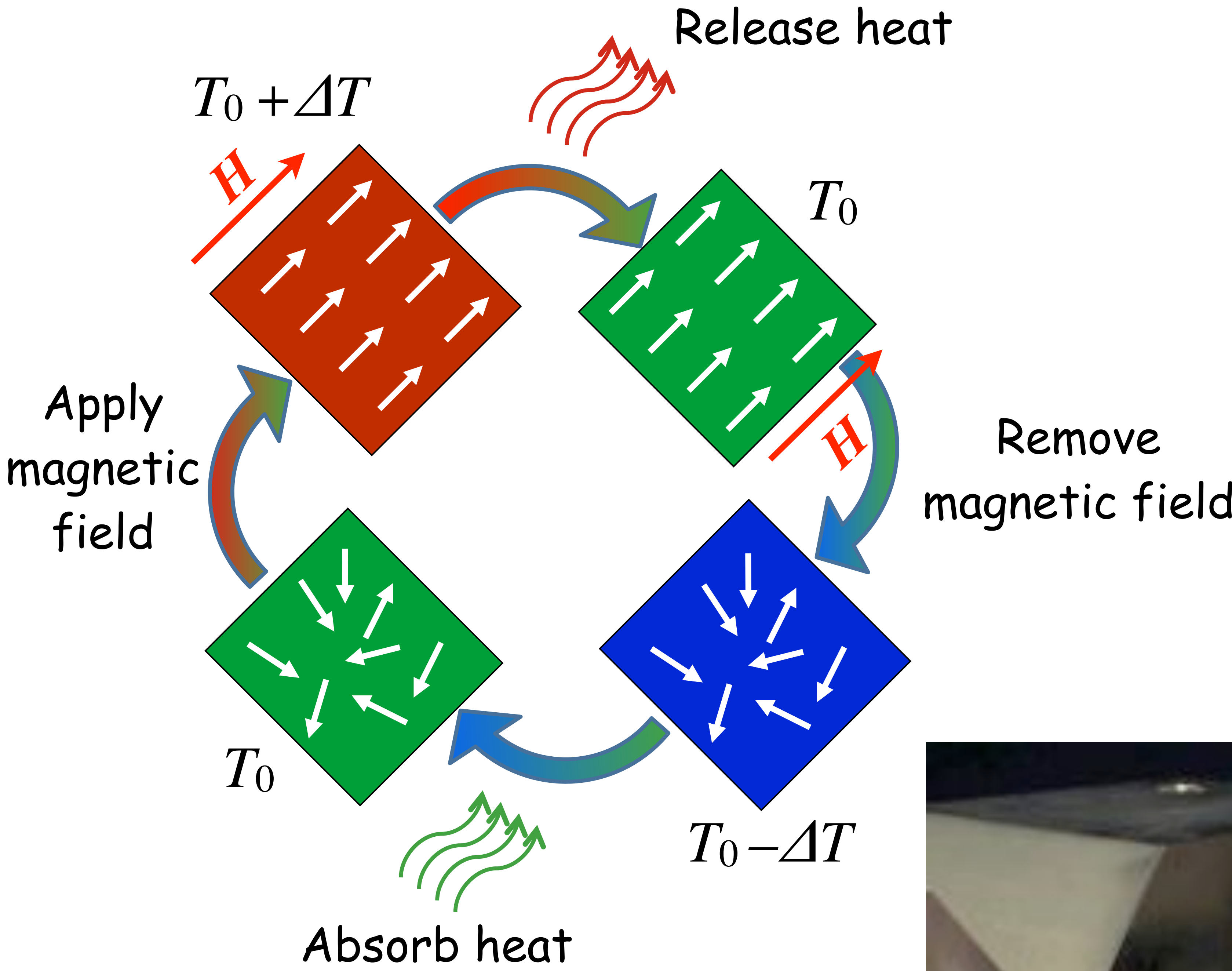
- Magnetically-induced reorientation of crystal structure, elongation up to 10%
- Twin boundary movement in martensitic phase (no phase transition, affects only microstructure)
- **Typical: 5M Ni-Mn-Ga (Heusler alloy)**
- Application: compact actuators

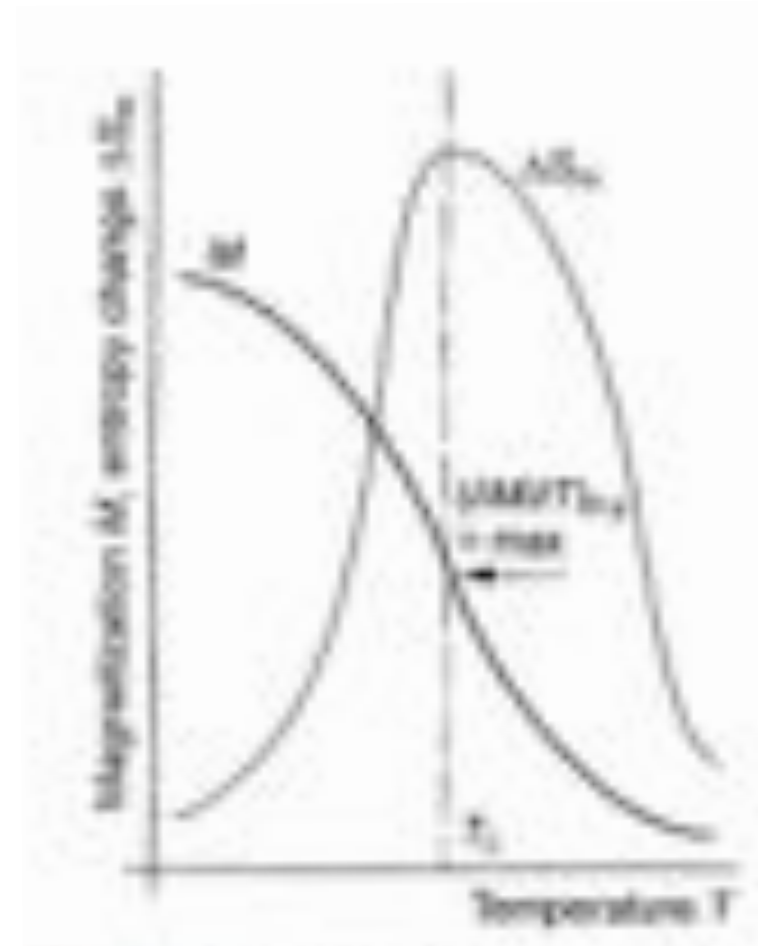




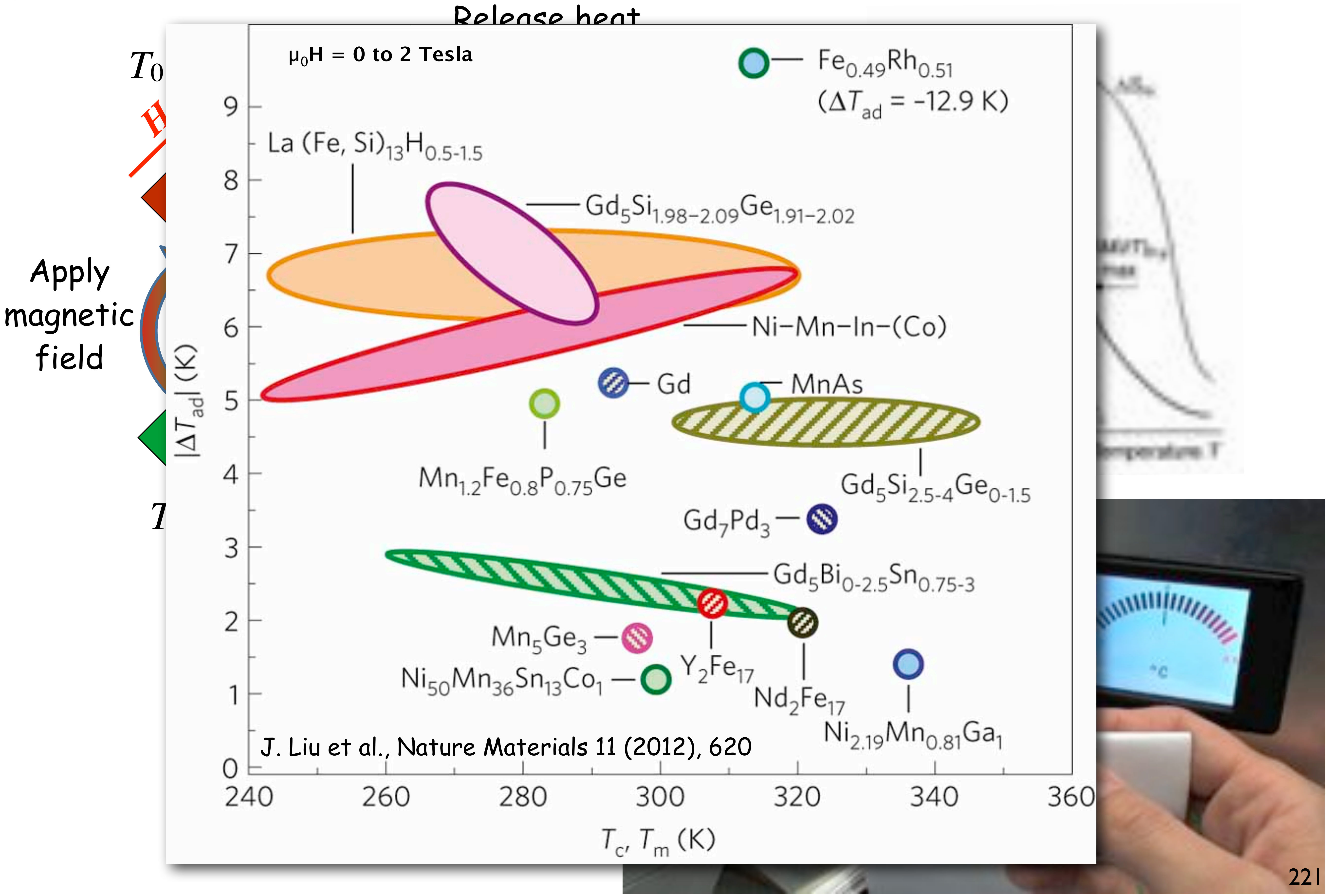
Magnetocaloric Materials

Magnetocaloric Materials





Magnetocaloric Materials



Multiferroics

Multiferroics

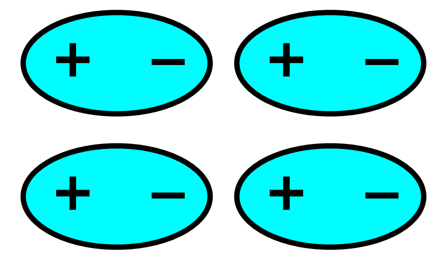
Multiferroics: two or more of the primary ferroic properties are united

→ Electric control of magnetic order

→ Magnetic control of electric order

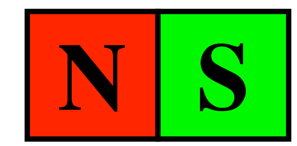
Ferroelectricity

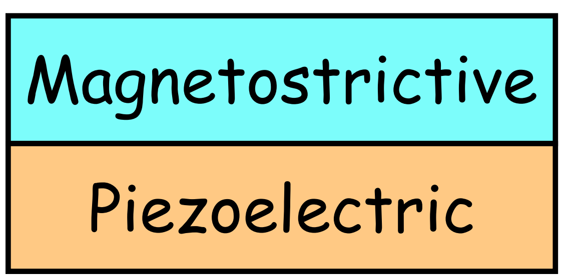
spontaneous polarization



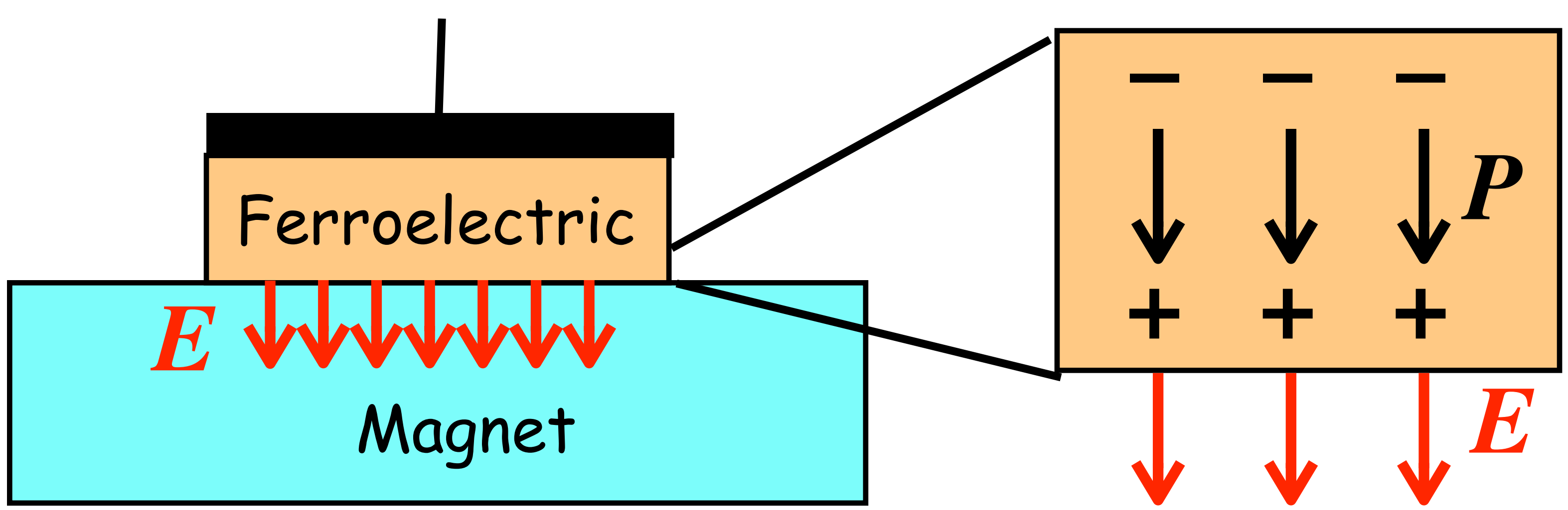
Ferromagnetsm

spontaneous magnetization





Piezoelectric material exerts elasitic strain on magnetic material: Control of magnetic properties (anisotropy, Curie temperature, magnetic moment, magnetic phase etc.)



Field-effect-type charge density control within the screening length of the magnet

Applied in magnetic tunnel junction with ferroelectric tunnel barrier

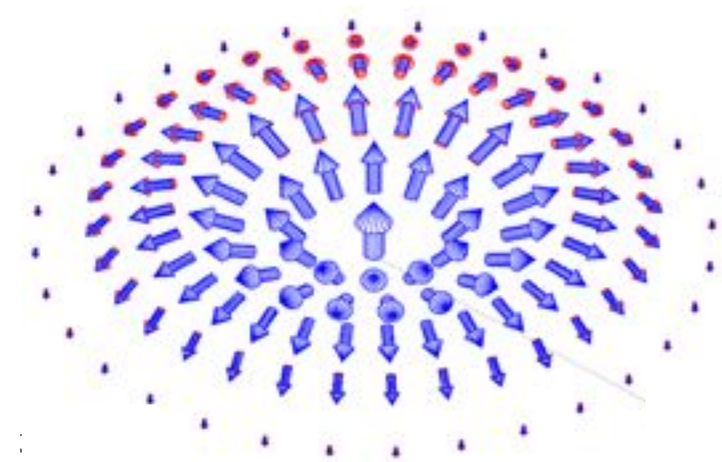
H. J. A. Molegraaf et al., Adv. Mater. 21, 3470 (2009)
V. Garcia et al., Science 327, 1106 (2010)

Helical magnets, Skyrmios

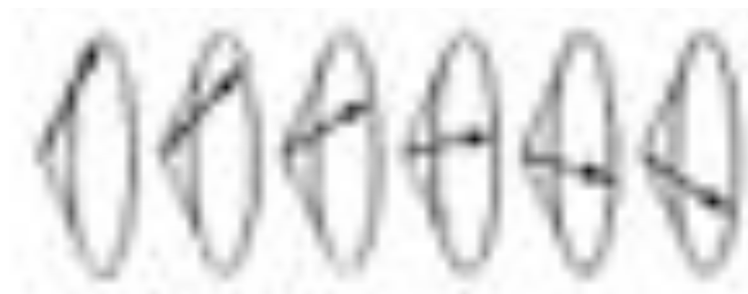
Helical magnets, Skyrmios

Competition: $J\ (\mathbf{S}_1 \cdot \mathbf{S}_2)$ — Heisenberg (direct exchange); $\mathbf{D} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$ — Dzyaloshinskii, Moriya (antisymmetric exchange)

Skyrmoins



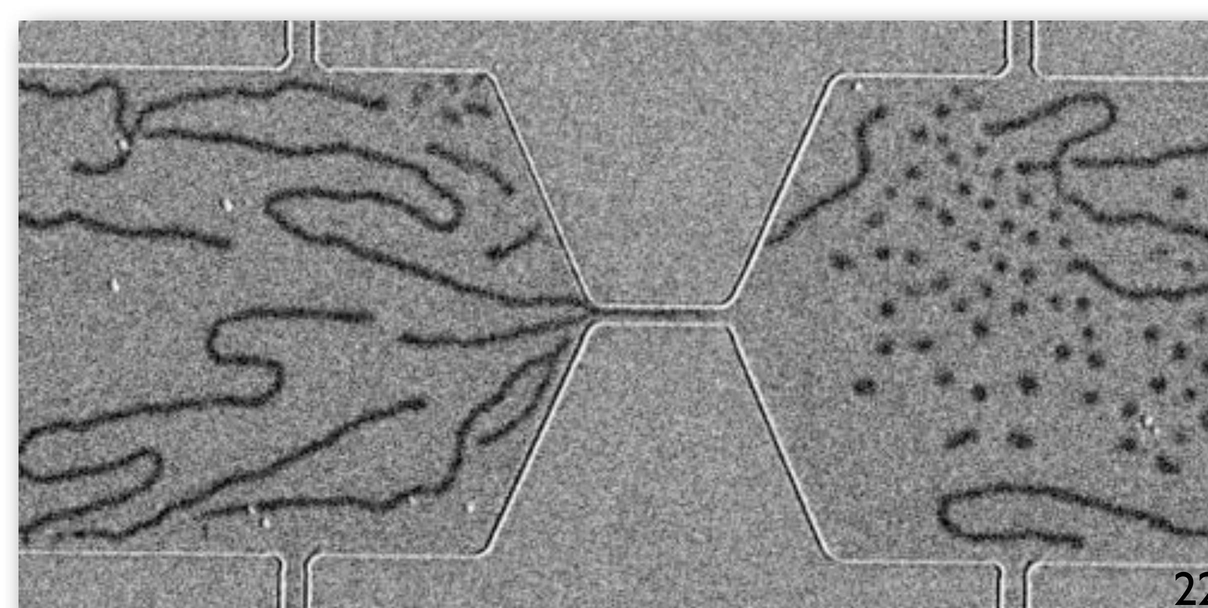
Spin spirals and skyrmions:



Materials:

- **Non-centrosymmetric magnetic crystals**
  - B20-metals: helimagnets MnSi, FeGe…
  - $Cr_{1/3}NbSe_2$
  - $CuFeS_2$ chalcopyrite structure
  - $CsCuCl_3$ …
  - $CePt_3Si$, UIr
  - UPdSn
  - $Ba_2CuGe_2O_7$, $K_2V_3O_8$
  - $BiFeO_3$, $TbFe_3(BO_3)_4$, multiferroics
  - ect. …
- **Thin magnetic films:**
  - Surfaces break inversion symmetry

CoFeB film with perpendicular anisotropy
Courtesy: Axel Hofmann, Argonne



etc.