TECHNISCHE UNIVERSITÄT CHEMNITZ

Guest Lecture „Magnetic Functional Materials“ within the AFM module„Facets of Materials“

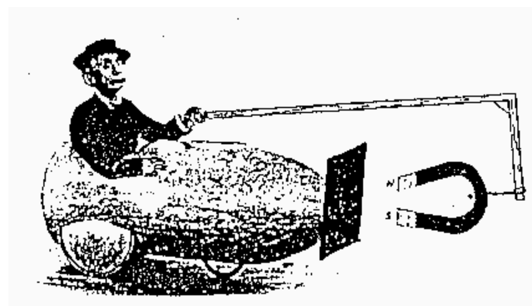
Feedback Session I (the basics)

Prof. Dr. Olav Hellwig

Lehrstuhl für Magnetische Funktionsmaterialien

Sommersemester 2021

Fridays
9:15 – 10:45 Uhr



Magnetic Functional Materials • TUC • HZDR

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MAIN

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Sorry, the first couple of slides in the recorded lecture were presented in German, since the lecture was originally recorded for the German physics module „Komplexe Materialien“!

I will show the corresponding English slides here in the review session and will once more go through the outline of the recorded lecture.

Content

Ferromagnetic (Functional) Materials

- **Introduction**
- **Energies und energy densities of a ferromagnetic sample**
  - **Exchange Interaction**
  - **Stray field or demagnetization energy, shape anisotropy**
  - **Additional anisotropy energies (except for shape anisotropy = demagnetization energy)**
  - **Zeemann energy, external fields**
- **Mutual competition between the different magnetic energy terms**
- **Hysteresis-effects, Stoner-Wohlfarth model, basis for binary magn. data storage)**
- **Magnetic functional materials for data storage**
  - **Development of the hard disk drive: from magnetic Micro-systems to Nano-systemes**
  - **GMR (Giant magnetoresisance) and TMR effects for high sensitivity magnetic read heads**
  - **Future hard disk drive technologies**
  - **New effects in the magnetic nano-world: Spin tranfer torque in Nano-contacts**
  - **Separation of charge and spin currents: Spin orbit torque in thin films systems**
  - **New applications Magnetic Random Access Memory (MRAM)**
  - **Spin waves as new information carriers (HZDR-movie)**

Ferromagnetische (Funktionale) Materialien

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

- Total lecture time 3:08:55

Questions ?

We can go to the corresponding slide and discuss !

Lecture Review

- 12 +2 questions about the last lecture …

Do you remember?

Question 1

Which elements are ferromagnetic at room temperature?

A: Fe, Cr, Mn

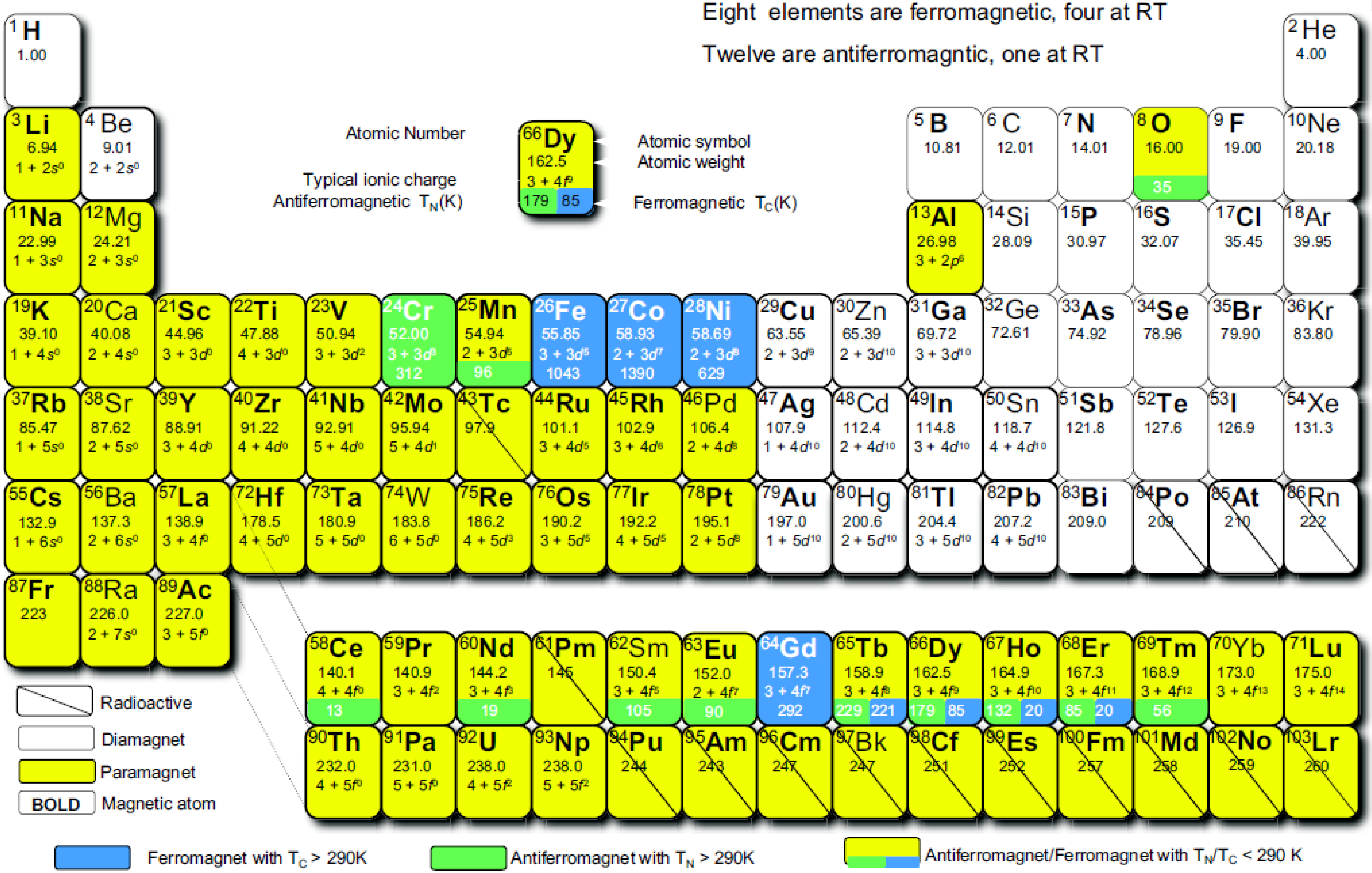
B: Co, Fe, Cr

C: Ni, Fe, Co

D: Co, Ni, Fe, Tb

E: Gd, Fe, Co, Ni

Magnetic Elements



Question 2

Which material has the highest Curie Temperature T_C?

A: Fe

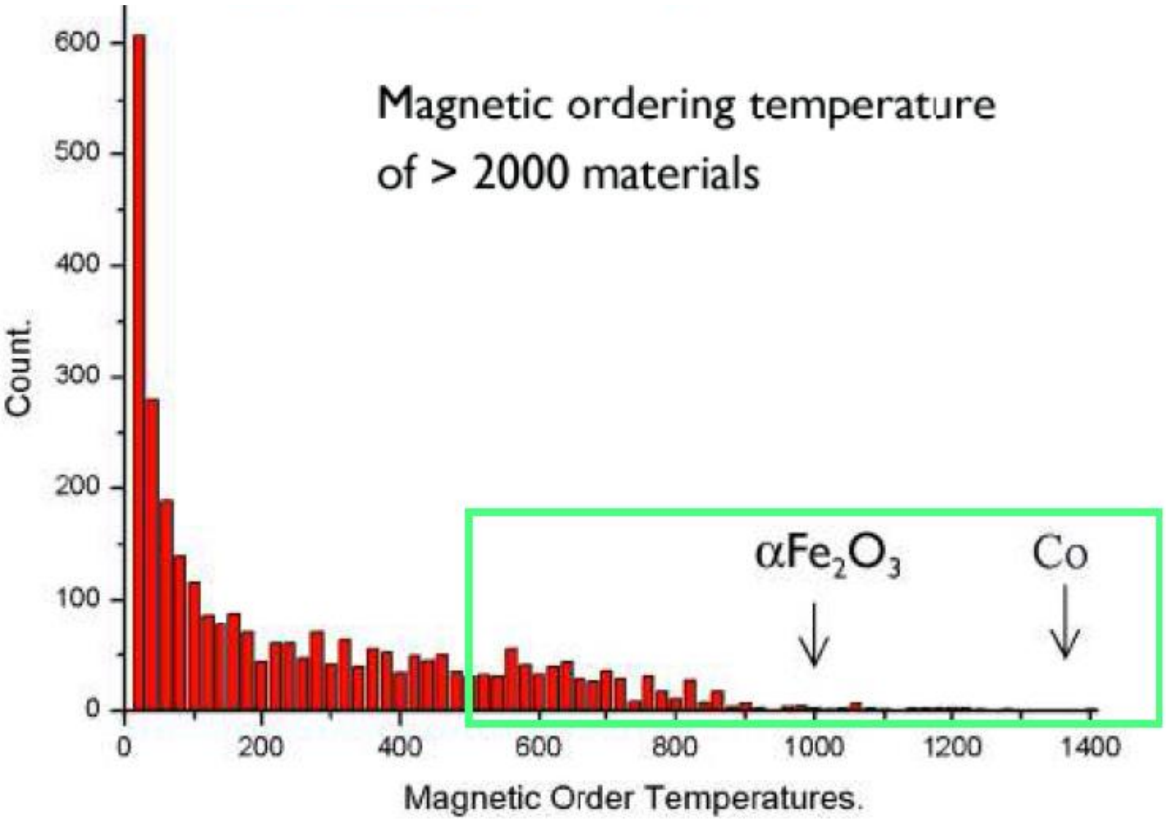
B: Co

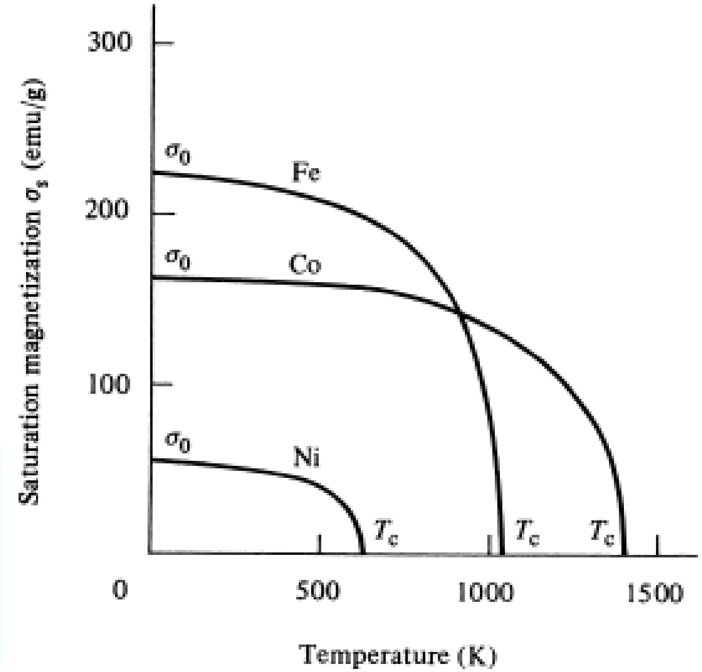
C: Ni

D: Fe_2O_3

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

T_C of magnetic materials





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

The Curie temperature needs to be > 500 K

Co has the highest T_C of all magnetic materials

Question 3

Which magnetic energy is the most short range?

A: Zeeman energy

B: Anisotropy Energy

C: Demagnetization energy

D: Exchange energy

E: Stray field energy

Question 4

Which magnetic energy is the most long range?

A: Shape anisotropy energy

B: Stray field energy

C: Demagnetization energy

D: all of the above

E: none of the above

Question 5

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

A: Zeeman energy

B: Anisotropy Energy

C: Demagnetization energy

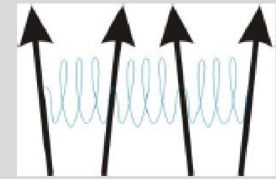
D: Exchange energy

E: Stray field energy

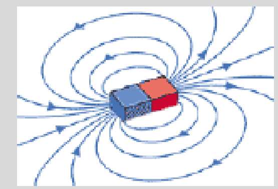
How much vary stray fields, exchange and ansiotropy across useful magnetic materials?

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

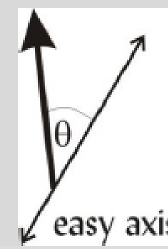
$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$



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



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



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

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

largest variations in anisotropy

Question 6

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

A: Fe

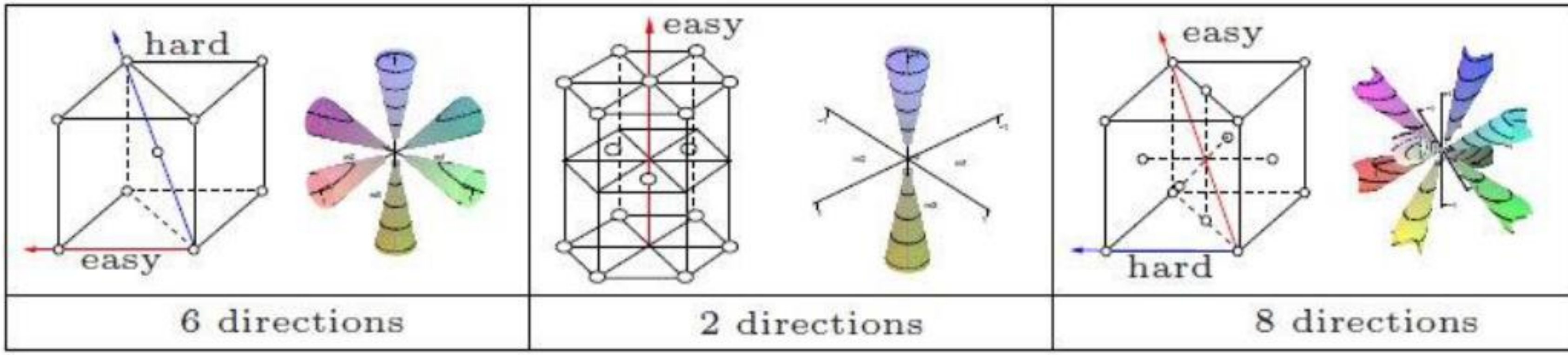
B: Co

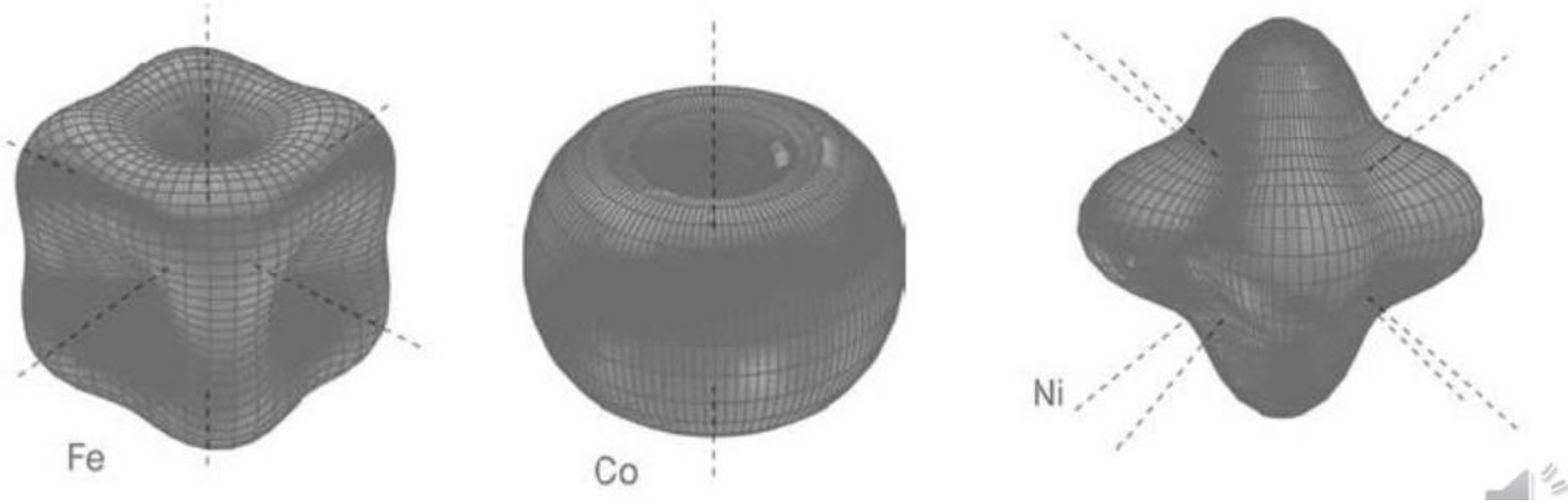
C: Ni

D: all of the above

E: None of the above

Fe bulk	Co bulk	Ni bulk





Question 7

Which of the following statements is true?

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

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

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

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

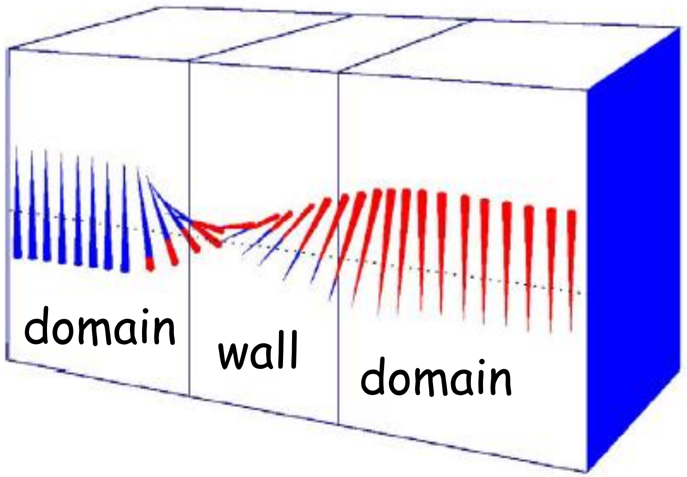
E: The larger the stray field energy, the shorter the domain wall width

Domain wall width and energy

walls $\sigma_w = exchange + anisotropy$

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

How do we define where the domain wall ends?



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

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

anisotropy K (energy density) up to 100 000

$$\sigma_w = 4\sqrt{AK} \quad and \quad \delta_w = \pi\sqrt{A/K}$$

domain wall energy density — domain wall width

exchange stiffness A less than 10

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

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

Now take all three energies and compare ….

Question 8

What energy dominates in the image? Why?

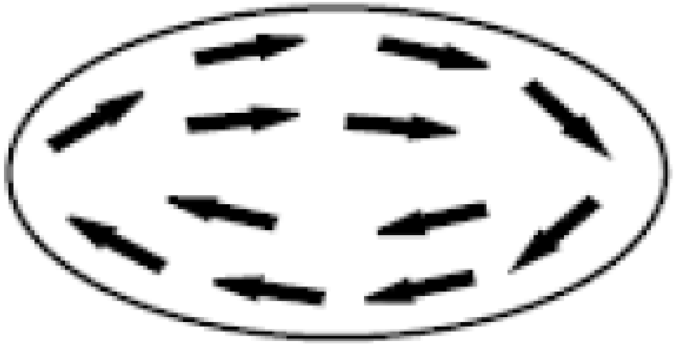
A: Shape anisotropy energy

B: Stray field energy

C: Demagnetization energy

D: all of the above

E: none of the above



Question 9

What energies determine the magnetic state in the image?

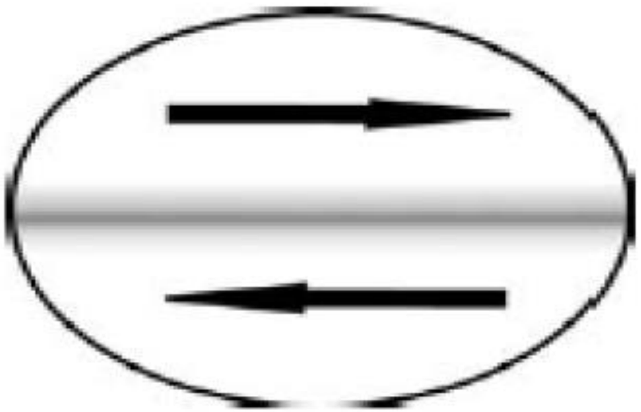
A: Uniaxial anisotropy energy

B: Stray field energy

C: Exchange energy

D: all of the above

E: none of the above



Question 10

What micromagnetic energies are considered in the Stoner Wohlfarth model?

A: external magnetic field and exchange energies

B: external magnetic field and stray field energies

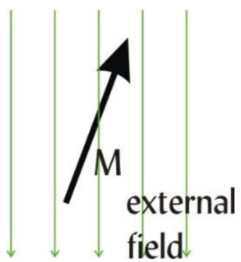
C: external magnetic field and anisotropy energies

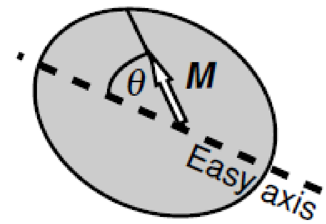
D: exchange and anisotropy energies

E: stray field and anisotropy energies

Stoner-Wohlfarth-Model

Simplest possible reversal: Consider only Zeeman and anisotropy energy
Simplest analytical model that exhibits hysteresis, Stoner-Wohlfarth-Model

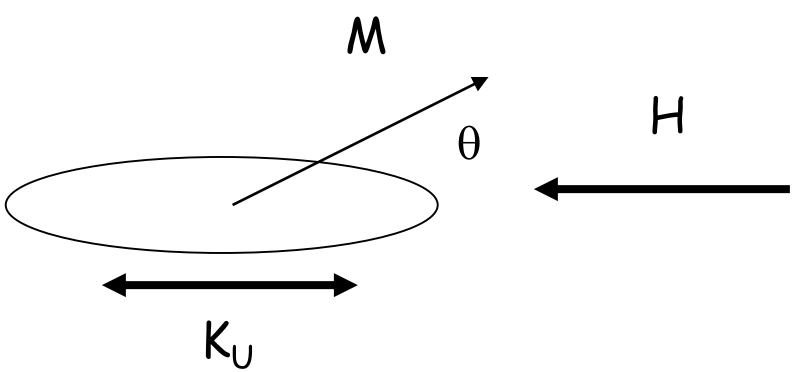




$$E_{external} = -\vec{H} \cdot \vec{M}$$

$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



$$E = -MH\cos\theta + K\sin^2\theta$$

H term is uni-directional, K term is uniaxial

Question 11

What assumptions go into the Stoner Wohlfarth model, as a macro spin model?

A: Exchange energy is neglected

B: Exchange energy is infinitely strong

C: Stray field energy is neglected

D: Stray field energy is infinitely strong

E: Both, B and C

Question 12

At which angle of external field axis and anisotropy axis do we get the lowest reversal field in the Stoner Wohlfarth model?

A: When the external field is applied along the easy axis

B: When the external field is applied along the hard axis

C: When the external field is applied at 45 degrees, i.e. exactly in between the easy axis and the hard axis

D: When the external field is applied at 30 degrees

E: none of the above

Stoner-Wohlfarth-Model at arbitrary angles

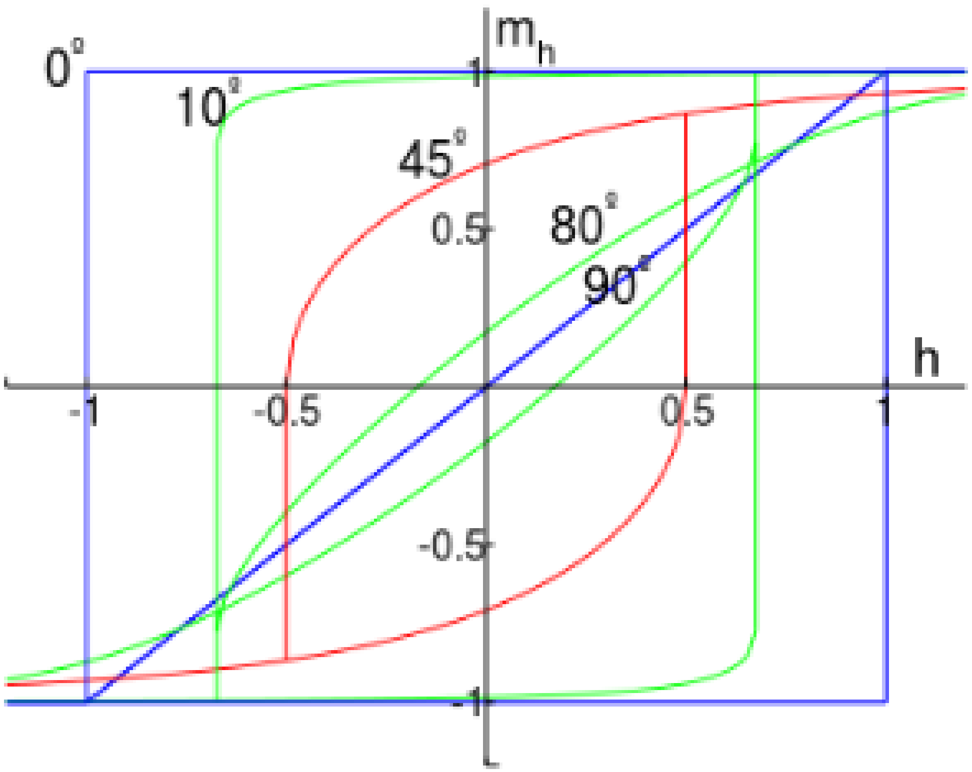


Figure 3. Some hysteresis loops predicted by the Stoner–Wolhfarth model for different angles between the field and easy axis.

https://www.youtube.com/watch?v=_KkzQuWA06A

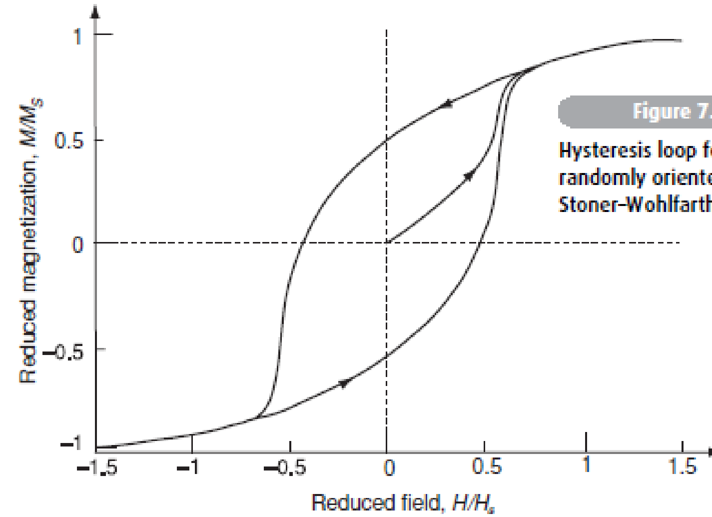
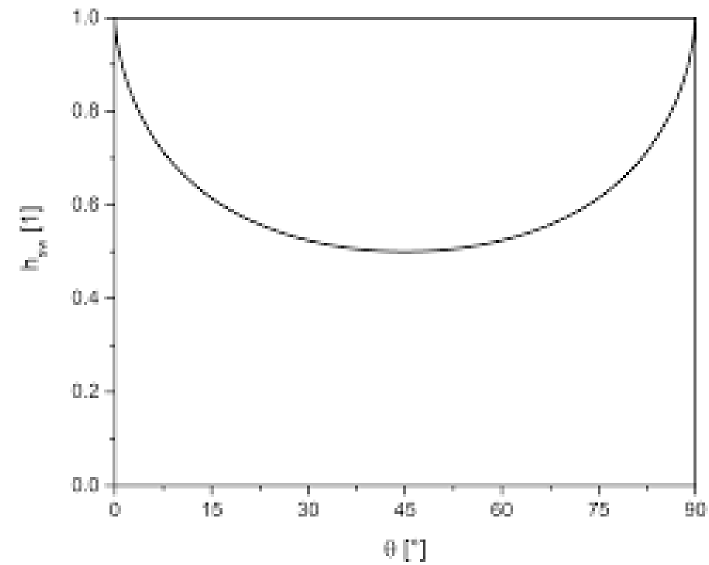


Figure 7.12
Hysteresis loop for a randomly oriented array of Stoner–Wohlfarth particles.



Reversal movies for 0,15,30,45,60,75, 85 and 90 degrees

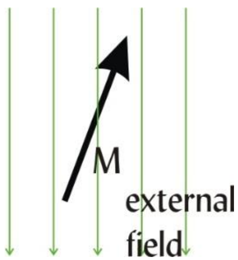
Some open questions …

Which magnetic energy terms do they belong to ?

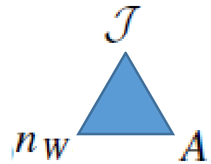
1. M
2. A
3. J
4. K
5. H

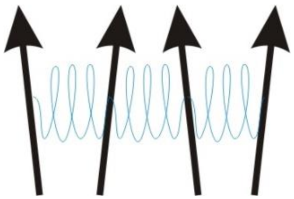
A: Exchange energy
B: Zeeman energy
C: Anisotropy energy
D: Stray field energy

Micromagnetic Energies determining the magnetic state of a sample



$$E_{external} = -\vec{H} \cdot \vec{M}$$



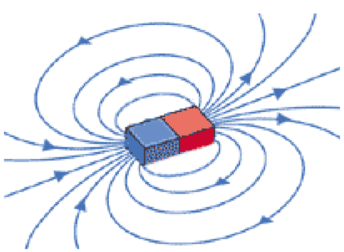


$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$

very short range,
nearest neighbor interactions only

$$E_{total} = \int_\Omega (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

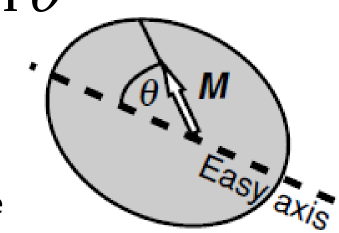
$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



long range,
everything interacts,
takes most computational
resources in micro-magnetics

$$E_{anisotropy} = g(\theta)$$

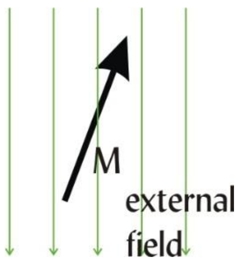
$$= K_U \sin^2\theta$$

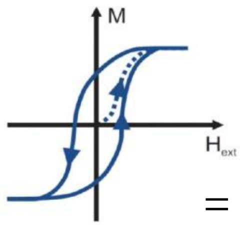


directionally varying energy,
source is often the crystal structure

Closer look at Anisotropy energy (biggest knob)
(Exchange and stray field energy should be known ….)

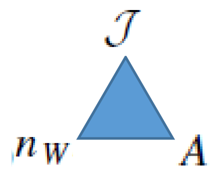
Micromagnetic Energies determining the magnetic state of a sample





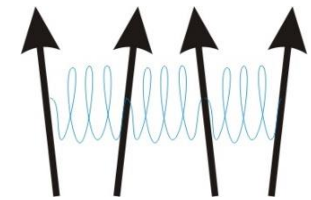
$= - H\,M \cos\theta$

$$E_{external} = -\vec{H} \cdot \vec{M}$$



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

very short range,
nearest neighbor interactions only

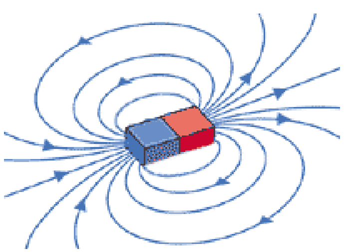


exchange integral

$$\mathcal{H} = -2\sum_{i>j} \mathcal{J}_{ij}\,\boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

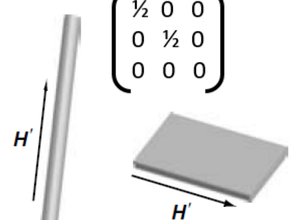
$$E_{total} = \int_\Omega (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

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



long range,
everything interacts,
takes most computational resources in micro-magnetics

$$\begin{pmatrix} \tfrac{1}{2} & 0 & 0 \\ 0 & \tfrac{1}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

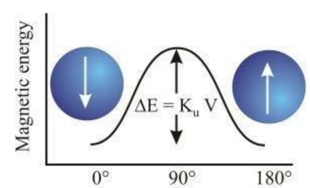


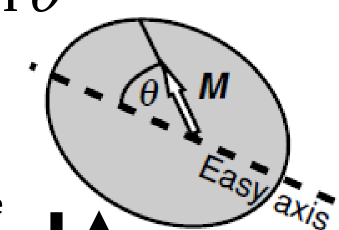
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$E_{anisotropy} = g(\theta)$$

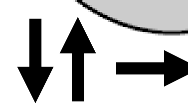
$$= K_U \sin^2\theta$$





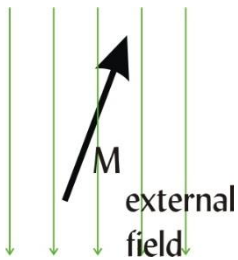
directionally varying energy,
source is often the crystal structure

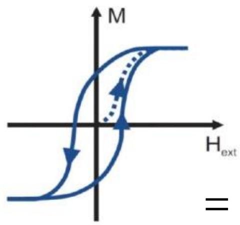
simplest case = uni-axial



Closer look at Anisotropy energy (biggest knob)
(Exchange and stray field energy should be known ….)

Micromagnetic Energies determining the magnetic state of a sample

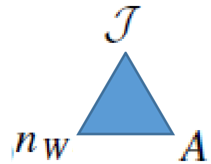




$$= - H\, M \cos\theta$$

$$E_{external} = -\vec{H} \cdot \vec{M}$$

H earth ≈ 50µT=0.00005 T, H electromagnet ≈ 2.5 T
H superconducting ≈ 15 T, H pulsed ≈ 100 T (factor 10^7)



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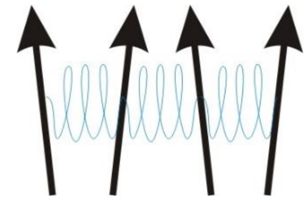


exchange integral

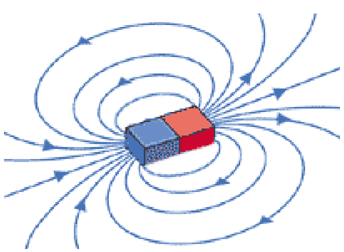
$$\mathcal{H} = -2\sum_{i>j} \mathcal{J}_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

***A* varies by a factor of less than 10**

$$E_{total} = \int_\Omega (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

M varies by a factor of ~10 (for useful, large M materials)

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



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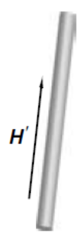
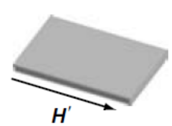


$$\begin{pmatrix} ½ & 0 & 0 \\ 0 & ½ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



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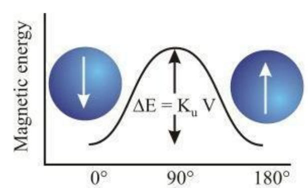
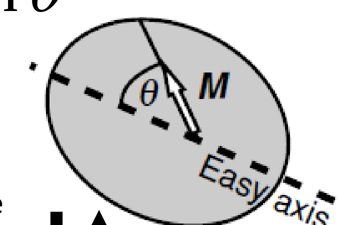
$$E_{magnetostatics} = -\frac{1}{2}\int_{sample} \vec{H}_d \cdot \vec{M} dV = -\frac{1}{2}\int_{sample} N\vec{M}^2 dV = -\frac{1}{2} N\vec{M}^2 V$$

K_u varies by a factor of 100 000 or more …

$$E_{anisotropy} = g(\theta)$$



$$= K_U \sin^2\theta$$



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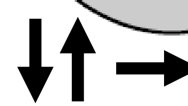

Closer look at Anisotropy energy (biggest knob)
(Exchange and stray field energy should be known ….)

Some open questions …

Which magnetic energy (energy density) terms do belong to which characteristic magnetic parameter

1. Exchange energy
2. Anisotropy energy
3. Demagnetization or stray field energy (shape anisotropy)

A: The magnetic hardness parameter κ (or Q-factor)
B: The domain wall energy σ_W
C: The exchange length l_{ex}

Magneto-crystalline anisotropy energy

(across all magnetic materials)

Table 7.1. Domain wall parameters for some ferromagnetic materials

	M_s stray/demag $(\mathrm{MA\ m^{-1}})$	A exchange $(\mathrm{pJ\ m^{-1}})$	K_1 anisotropy $(\mathrm{kJ\ m^{-3}})$	δ_w exchange vs anisotropy (nm)	γ_w $(\mathrm{mJ\ m^{-2}})$	anisotropy vs stray fields κ	exchange vs stray l_{ex} (nm)
$Ni_{80}Fe_{20}$	0.84	10	0.15	2000	0.01	0.01	3.4
Fe	1.71	21	48	64	4.1	0.12	2.4
Co	1.44	31	410	24	14.3	0.45	3.4
CoPt	0.81	10	4900	4.5	28.0	2.47	3.5
$Nd_2Fe_{14}B$	1.28	8	4900	3.9	25	1.54	1.9
$SmCo_5$	0.86	12	17 200	2.6	57.5	4.30	3.6
CrO_2	0.39	4	25	44.4	1.1	0.36	4.4
Fe_3O_4	0.48	7	−13	72.8	1.2	0.21	4.9
$BaFe_{12}O_{19}$	0.38	6	330	13.6	5.6	1.35	5.8
	magnetization	exchange stiffness	anisotropy (energy density)	domain wall width	domain wall energy	hardness parameter	exchange length
Variation across materials	less than 5	less than 10	up to 100 000	up to 1000	up to 6000	up to 500	~ factor 3
				$\delta_w = \pi\sqrt{A/K}$	$\gamma_w = 4\sqrt{AK}$	$\kappa = \sqrt{\lvert K_1\rvert / \mu_0 M_s^2}$	$l \approx \sqrt{A}/M$

factor 1000!

largest variations in anisotropy

stray field energy = shape anisotropy energy

exchange

stray field ↔ anisotropy

Discussion about and feedback on the lecture recordings