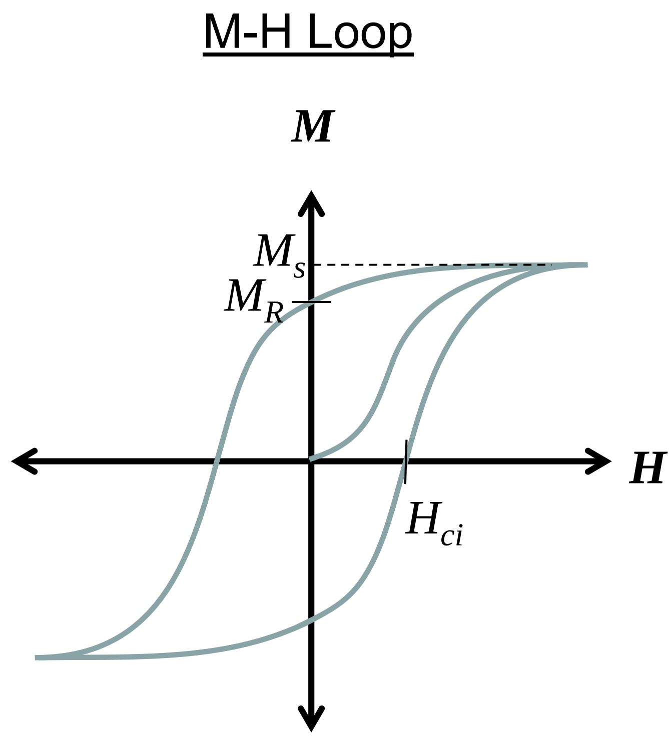
Fundamentals of Magnetism

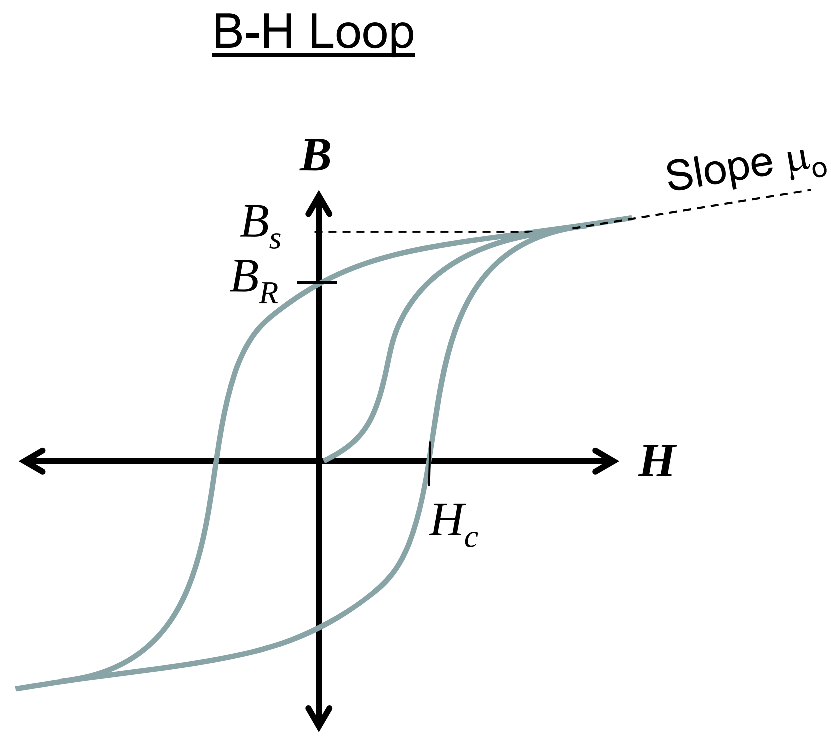
Part II

Albrecht Jander

Oregon State University

Real Magnetic Materials, Bulk Properties





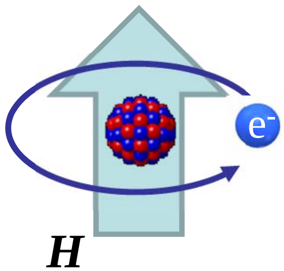
M_S - Saturation magnetization
H_{ci} - Intrinsic coercivity
M_R - Remanent magetization

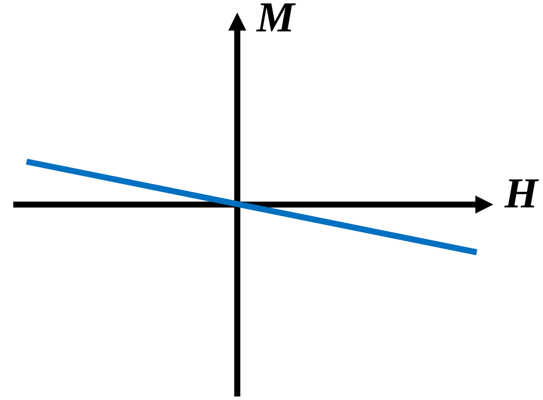
B_s - Saturation flux density
B_R - Remanent flux density
H_c - Coercive field, coercivity

Note: these two figures each present the same information because $B=\mu_o(H+M)$

Diamagnetism

- Atoms without net magnetic moment





χ is small and negative

Diamagnetic substances:

Ag		-1.0×10^{-6}
Be		-1.8×10^{-6}
Au		-2.7×10^{-6}
H_2O*		-8.8×10^{-6}
NaCl		-14×10^{-6}
Bi		-170×10^{-6}
Graphite		-160×10^{-6}
Pyrolitic	(⊥)	-450×10^{-6}
graphite	(∥)	-85×10^{-6}

Atomic number

Orbital radius

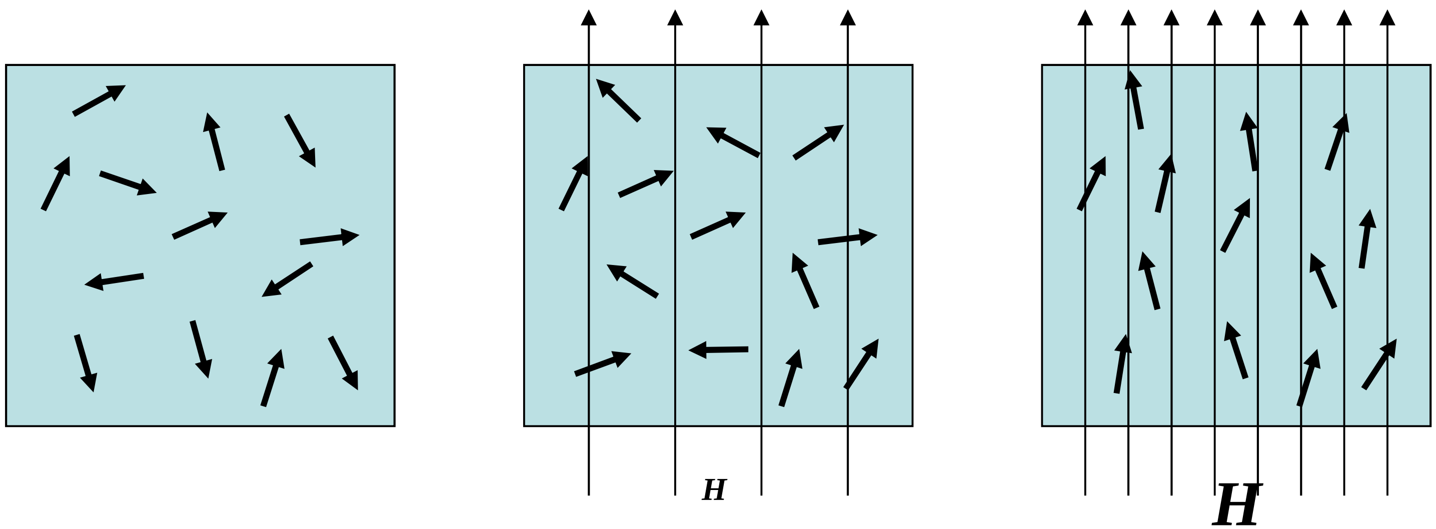
Atomic density

$$\chi = -\frac{N_A \rho}{W_A}\frac{\mu_0 Z e^2 r^2}{6 m_e}$$

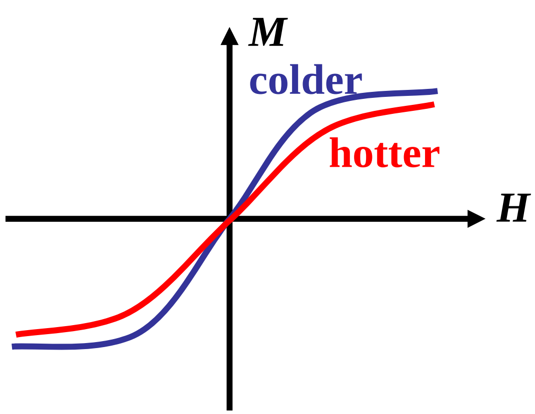
* E.g. humans, frogs, strawberries, etc.
See: http://www.hfml.ru.nl/froglev.html

Paramagnetism

- Consider a collection of atoms with independent magnetic moments.
- Two competing forces: spins try to align to magnetic field but are randomized by thermal motion.

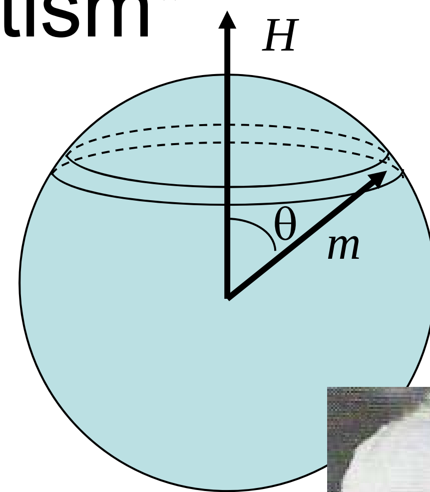


$\mu_0 mH << k_B T$ $\mu_0 mH > k_B T$



- Susceptibility is small and positive
- Susceptibility decreases with temperature.
- Magnetization saturates (at low T or very large H)

Langevin Theory of Paramagnetism*



- Energy of a magnetic moment, m, in a field, H

$$E = -\mu_0 \vec{m} \cdot \vec{H} = -\mu_0 m H \cos(\theta)$$

- Independent moments follow Boltzmann statistics

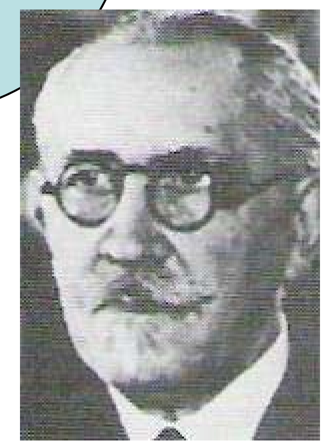
$$P(E) = e^{-E/k_B T} = e^{\mu_0 m H \cos(\theta)/k_B T}$$

- The "density of states" on the sphere is

$$dn = 2\pi r^2 \sin(\theta) d\theta$$

- So the probability of a moment pointing in direction θ to $\theta + d\theta$ is

$$p(\theta) = \frac{e^{\mu_0 m H \cos(\theta)/k_B T} \sin(\theta)}{\int_0^\pi e^{\mu_0 m H \cos(\theta)/k_B T} \sin(\theta) d\theta}$$



Paul Langevin
(1872-1946)

- The magnetization of a sample with N moments/volume will be

$$M = Nm\langle \cos(\theta) \rangle = Nm \int_0^\pi \cos(\theta) p(\theta) d\theta = Nm \frac{\int_0^\pi e^{\mu_0 m H \cos(\theta)/k_B T} \cos(\theta) \sin(\theta) d\theta}{\int_0^\pi e^{\mu_0 m H \cos(\theta)/k_B T} \sin(\theta) d\theta}$$

- Which any fool can see is just:

$$M = Nm\left[\coth\left(\frac{\mu_0 m H}{k_B T}\right) - \frac{k_B T}{\mu_0 m H}\right]$$

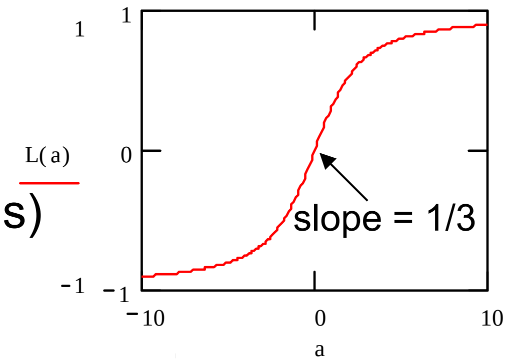
*Langevin, P., Annales de Chem. et Phys., 5, 70, (1905).

Curie's Law*

- Langevin paramagnetism:

$$M = Nm\left[\coth\left(\frac{\mu_0 mH}{k_B T}\right) - \frac{k_B T}{\mu_0 mH}\right]$$

$$L(a) = \coth(a) - \frac{1}{a}$$



Pierre Curie
(1859-1906)

- For $\mu_o mH << k_B T$ (most practical situations)

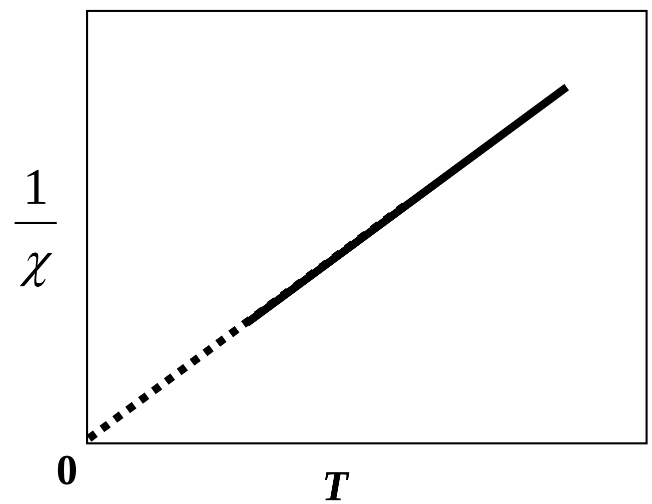
$$M = \mu_0 \frac{Nm^2}{3k_B T} H$$

- Which gives Curie's Law:

$$\chi = \frac{M}{H} = \mu_0 \frac{Nm^2}{3k_B T} = \frac{C}{T}$$

Curie constant

Curie's Law



Note: quantization of the magnetic moment requires a correction to the above classical result which assumes all directions are allowed:

$$\chi = \frac{M}{H} = \mu_0 \frac{Ng^2 \mu_B^2 J(J+1)}{3J^2 k_B T} = \frac{C}{T}$$

*Curie, P., Ann. Chem. Phys., **5,** 289 (1895)

Paramagnetic Substances

<u>Paramagnetic susceptibility:</u>

Sn	0.19×10^{-6}
Al	1.65×10^{-6}
O_2 (gas)	1.9×10^{-6}
W	6.18×10^{-6}
Pt	21.0×10^{-6}
Mn	66.1×10^{-6}

Liquid oxygen

Curie-Weiss* Law

Pierre Weiss (1865–1940)

- Consider <u>interactions</u> among magnetic moments:

$$E = -\mu_0 \vec{m} \cdot (\vec{H} + \alpha \vec{M})$$

where M represents the average orientation of the surrounding magnetic moments. ("Mean field theory") and α is the strength of the interactions

- The Langevin equation then becomes:

$$M = Nm\left[\coth\left(\frac{\mu_0 m(H+\alpha M)}{k_B T}\right) - \frac{k_B T}{\mu_0 m(H+\alpha M)}\right]$$

- Again for $\mu_o mH << k_B T$

$$M = \mu_0 \frac{Nm^2}{3k_B T}(H + \alpha M)$$

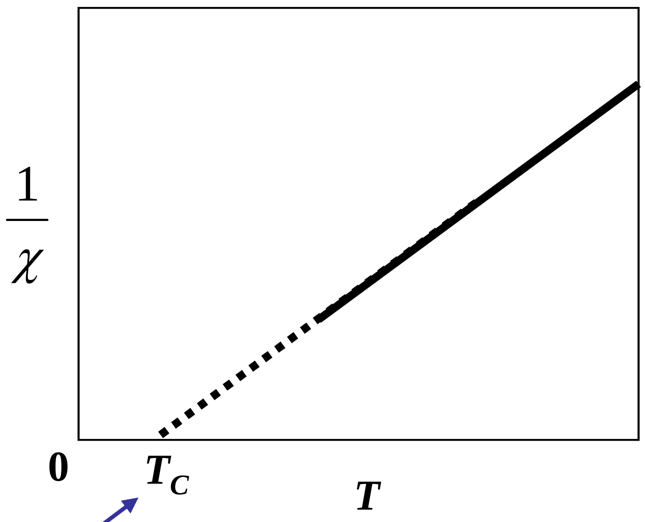
- Which gives the Curie-Weiss Law:

$$\chi = \frac{M}{H} = \frac{C}{T - \alpha C} = \frac{C}{T - T_C}$$

$$T_C = \mu_0 \frac{\alpha N m^2}{3k_B}$$

Curie Temperature

Curie-Weiss Law

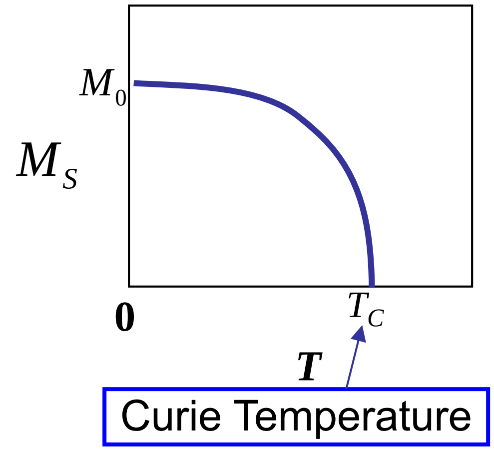


*Weiss, P., J. de Phys., **6,** 661 (1907)

Weiss Theory* of Ferromagnetism

- Starting with the Langevin equation with "mean field" interactions

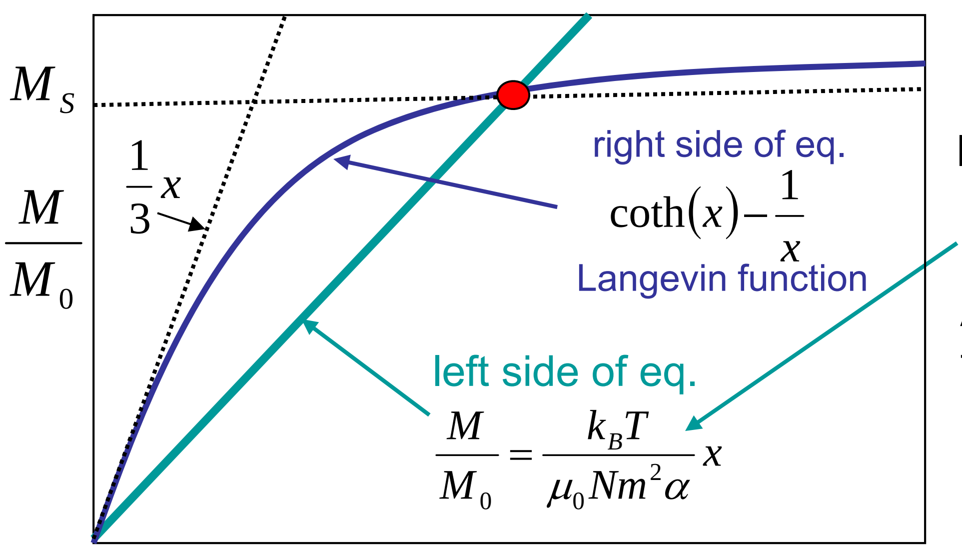
$$M = Nm\left[\coth\left(\frac{\mu_0 m(H+\alpha M)}{k_B T}\right) - \frac{k_B T}{\mu_0 m(H+\alpha M)}\right]$$



- Set the external field to zero, $H=0$

$$M = Nm\left[\coth\left(\frac{\mu_0 m(\alpha M)}{k_B T}\right) - \frac{k_B T}{\mu_0 m(\alpha M)}\right]$$

- This can be solved for M graphically:



$$x = \frac{\mu_0 m \alpha M}{k_B T}$$

Plot both sides of the equation as a function of

$$x = \frac{\mu_0 m \alpha M}{k_B T}$$

Intersection is spontaneous magnetization, M_s

Note: line with slope proportional to T

Asymptote of Langevin function is 1/3 so the only solution for M_S is zero when

$$\frac{k_B T}{\mu_0 N m^2 \alpha} > \frac{1}{3}$$

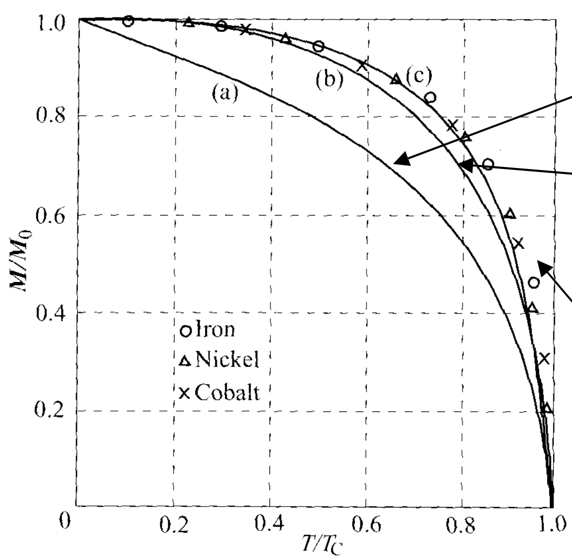
Spontaneous magnetization decreases with temperature and vanishes at:

$$T_C = \frac{\mu_0 N m^2 \alpha}{3 k_B}$$

*Weiss, P., J. de Phys., **6,** 661 (1907)

Weiss Theory of Ferromagnetism

- Fits data very well!
- Again, corrections need to be made for quantization of magnetic moments



(a) Classical result using Langevin function

(b) Quantum result using Brilloun function

$$M = Nm \tanh\left(\frac{\mu_0 m(H + \alpha M)}{k_B T}\right)$$

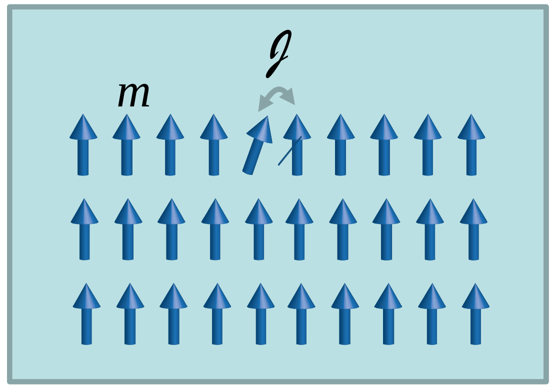
(c) Measurements

Points to remember:
- Ferromagnets have spontaneous magnetization, M_S even in zero field
- M_S goes to zero at the Curie temperature, T_C
- Above T_C material is paramagnetic.

Ferromagnetic Materials

Material:	M_s [A/m]	T_C [°C]
Ni	0.49×10^6	354
Fe	1.7×10^6	770
Co	1.4×10^6	1115
Gd		19
Dy		-185
NdFeB		310
NiFe	$\sim 0.8 \times 10^6$	447
FeCoAlO	1.9×10^6	

Ferromagnetic Exchange Interaction

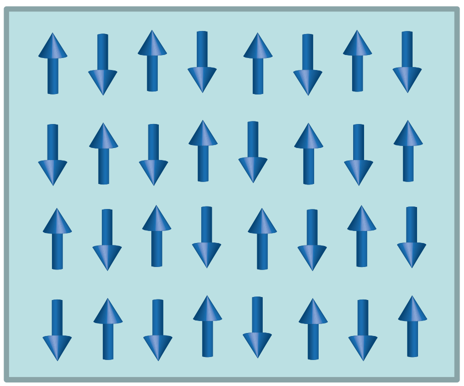


$$E_{m_i, m_{i+1}} = -\mu_0 \mathcal{J} m^2 \cos(\Delta\theta)$$

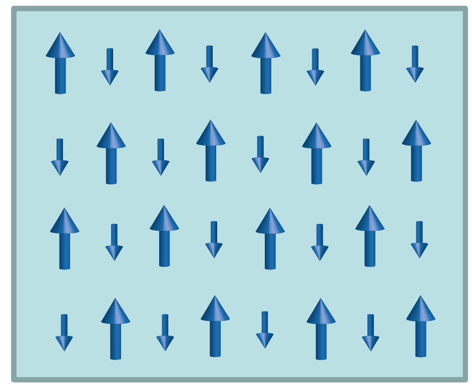
Antiferromagnetic and Ferrimagnetic Materials

Negative exchange coupling:

Antiferromagnet

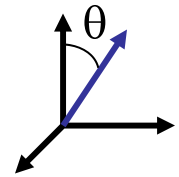


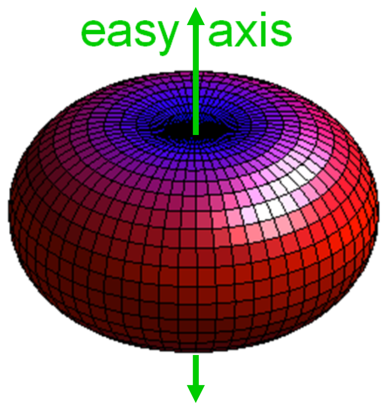
Ferrimagnet



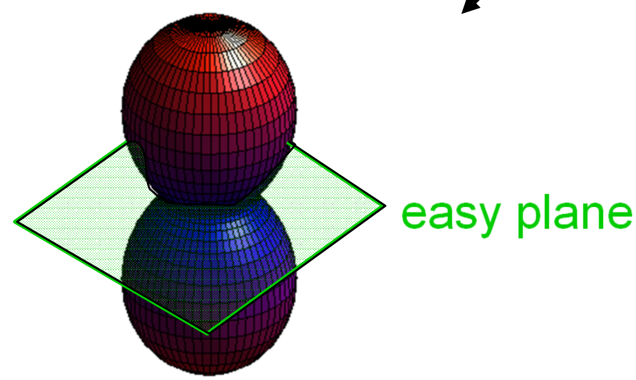
Crystalline Anisotropy

- **Uniaxial:** $E = K_u \sin^2\theta + K_2 \sin^4\theta + \ldots$



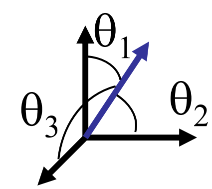


$K_u > 0$

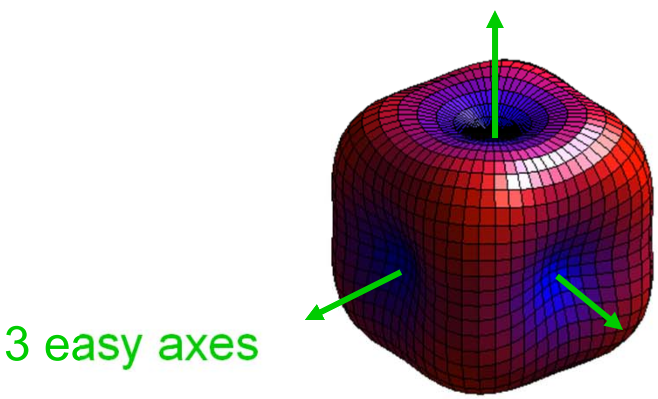


$K_u < 0$

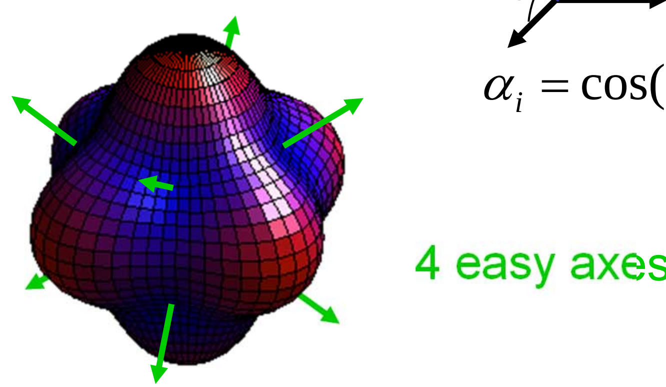
- **Cubic:** $E = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \ldots$



$\alpha_i = \cos(\theta_i)$



$K_1 > 0$



$K_1 < 0$

Crystalline Anisotropies of Some Magnetic Materials

Material	Structure	A [J/m] x10^{-11}	K_1 [J/m^3] x10^5	K_2 [J/m^3] x10^5
Cobalt	hcp	1.5	4.1	1.5
Iron	bcc	1.5	0.48	-0.1
Nickel	fcc	1.5	-0.045	-0.023
$SmCo_5$		2.4	170	

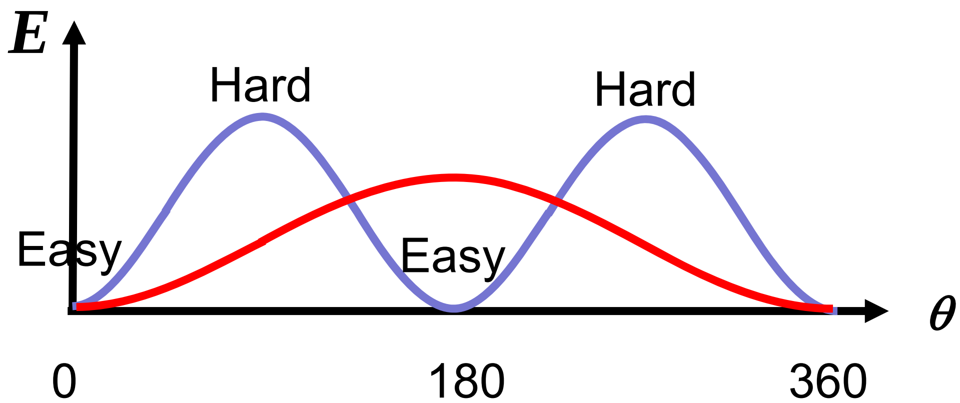
Stoner-Wohlfarth Theory*

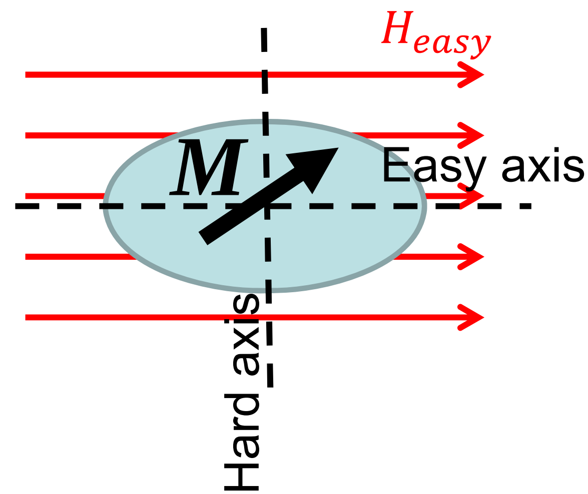
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

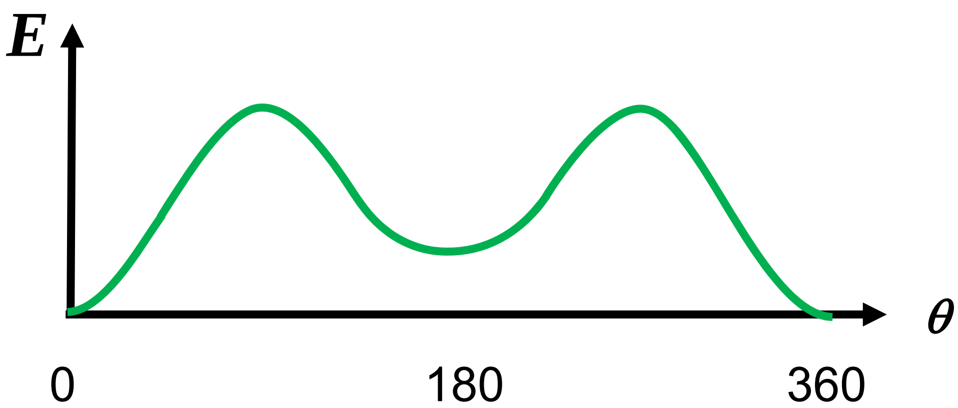
Magnetostatic energy

$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$





Total energy (Magnetic field along easy axis)



* E. Stoner and P. Wohlfarth, "A Mechanism of Magnetic Hystereisis in Heterogeneous Alloys", IEEE Trans. Magn., **27**, 3475, 1991

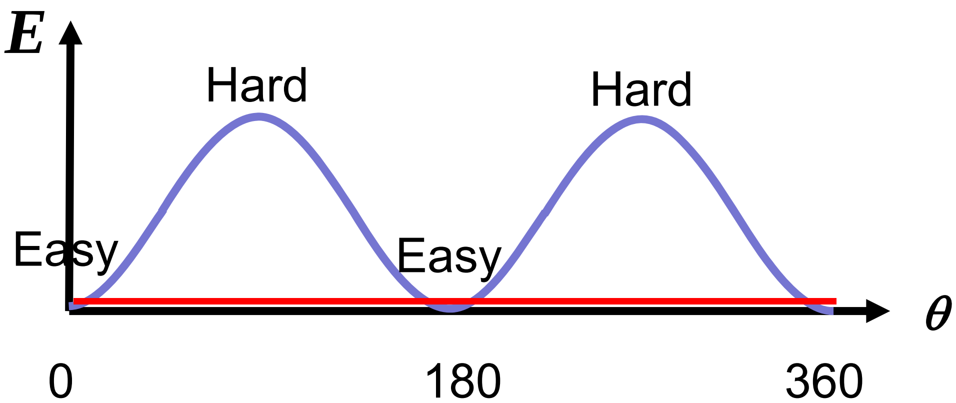
Stoner-Wohlfarth Theory*

Anisotropy energy

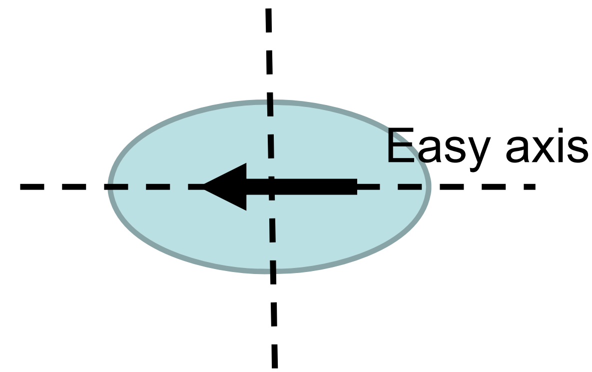
$$E_{anis} = K_u V sin^2(\theta)$$

Magnetostatic energy

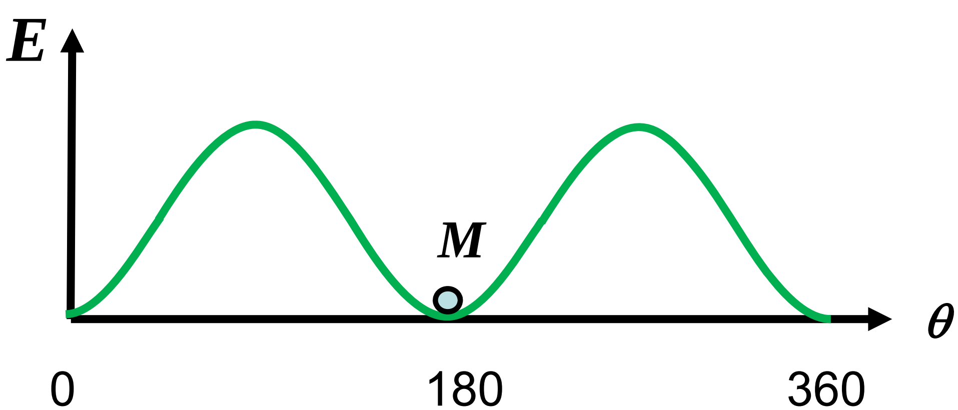
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$

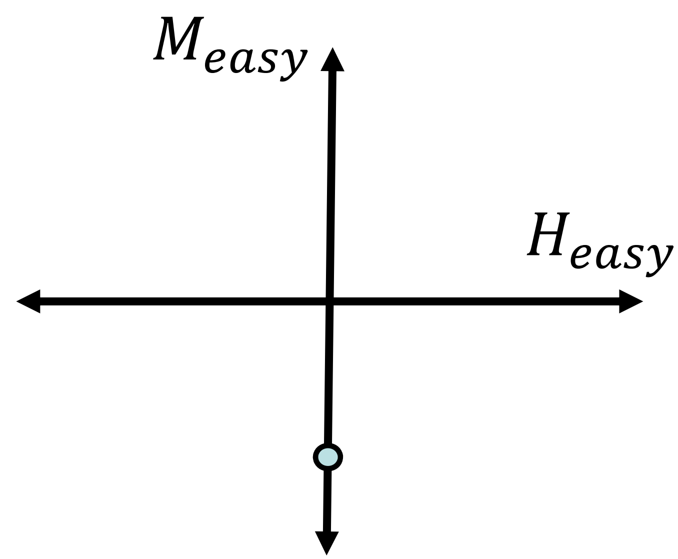


H_{easy} = 0



Total energy (Magnetic field along easy axis)





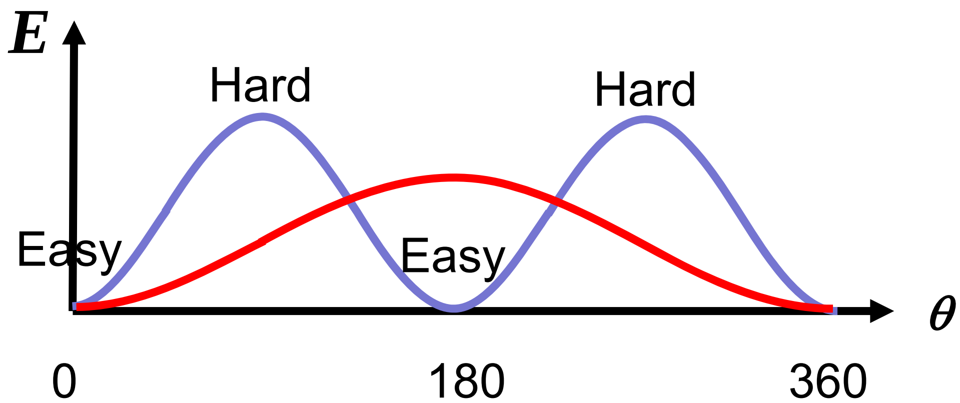
Stoner-Wohlfarth Theory*

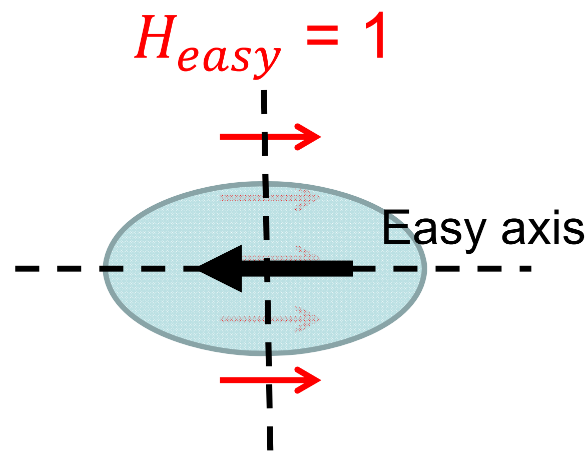
<u>Anisotropy energy</u>

$$E_{anis} = K_u V sin^2(\theta)$$

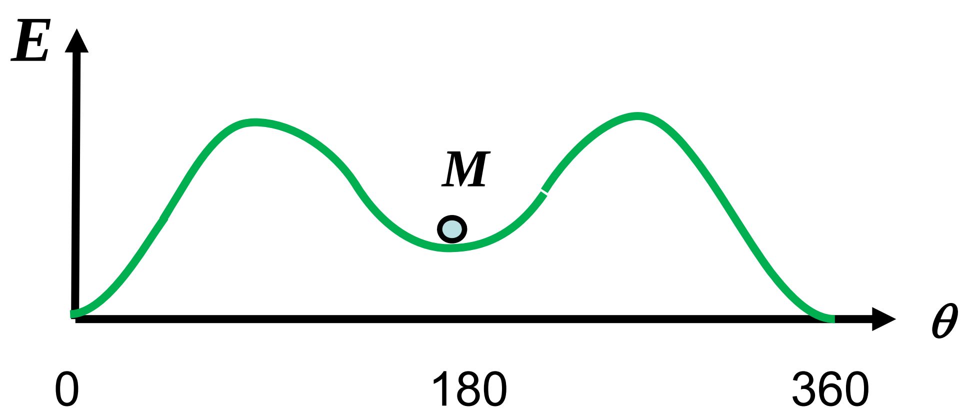
<u>Magnetostatic energy</u>

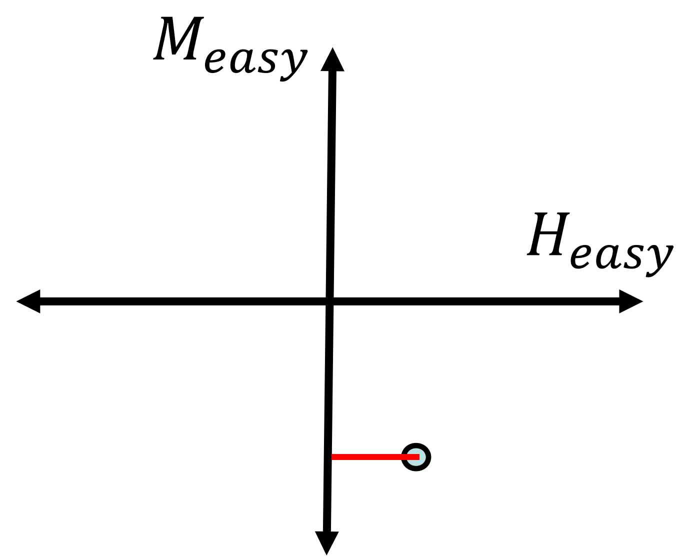
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$





Total energy (Magnetic field along <u>easy axis</u>)





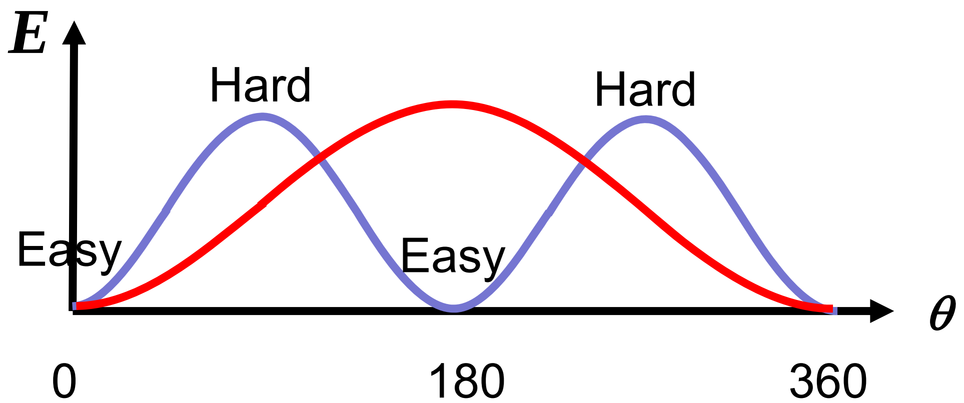
Stoner-Wohlfarth Theory*

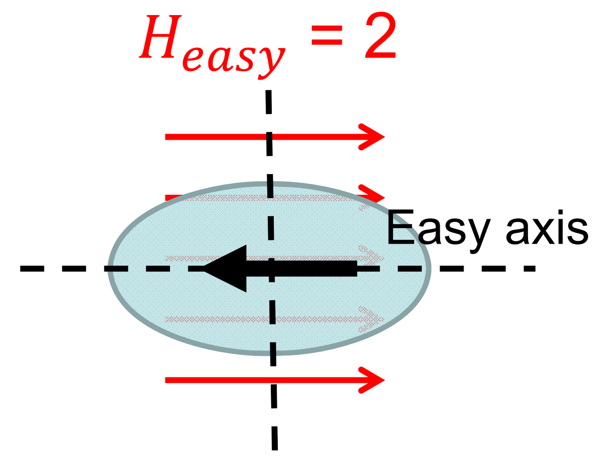
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

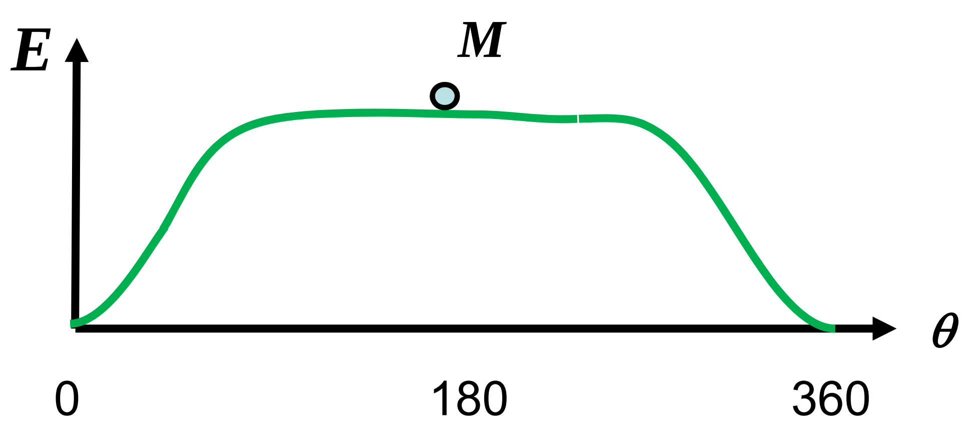
Magnetostatic energy

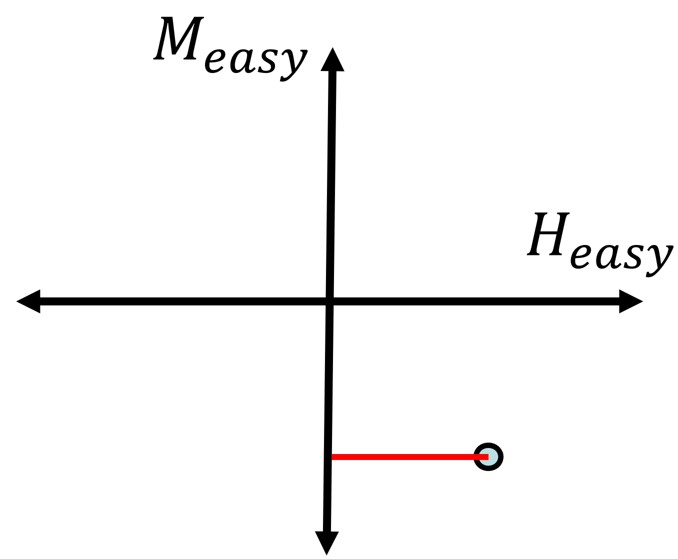
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$





Total energy (Magnetic field along easy axis)





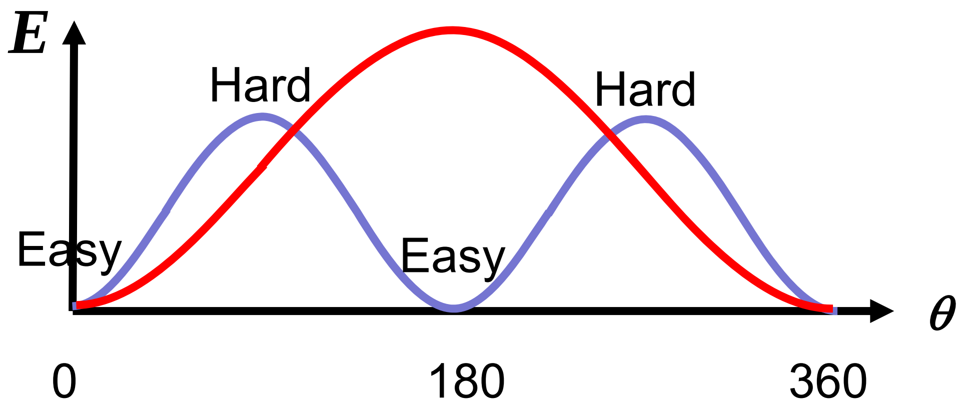
Stoner-Wohlfarth Theory*

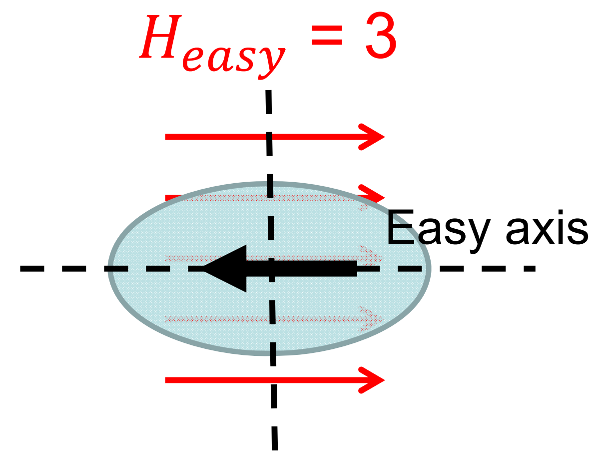
<u>Anisotropy energy</u>

$$E_{anis} = K_u V sin^2(\theta)$$

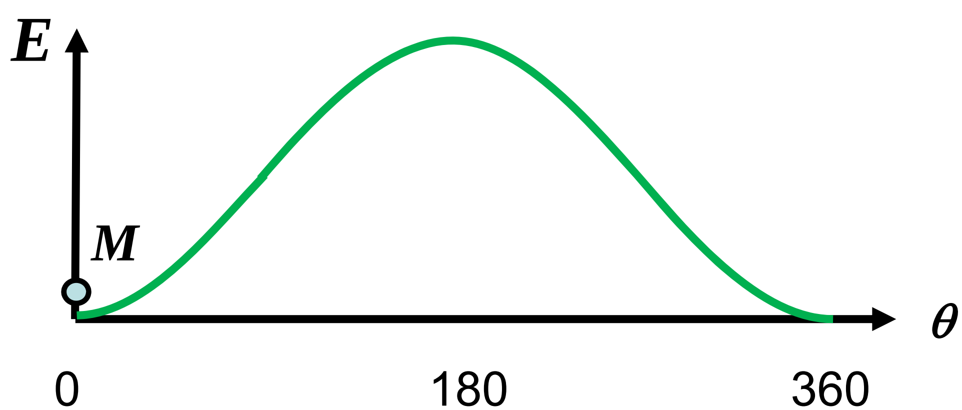
<u>Magnetostatic energy</u>

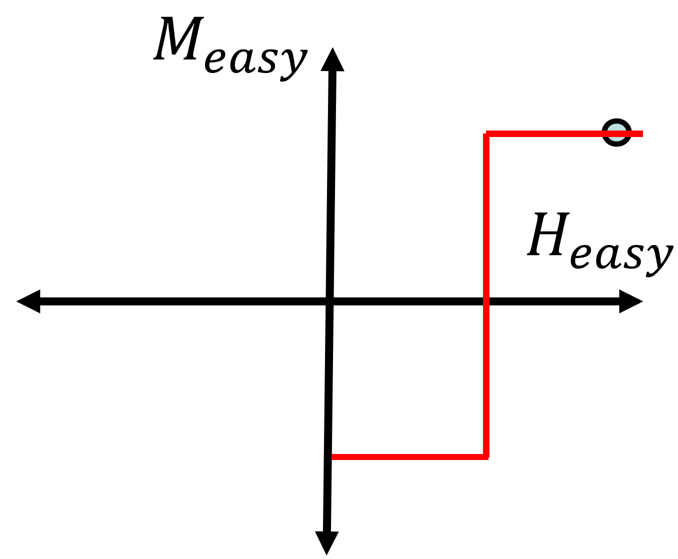
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$





Total energy (Magnetic field along <u>easy axis</u>)





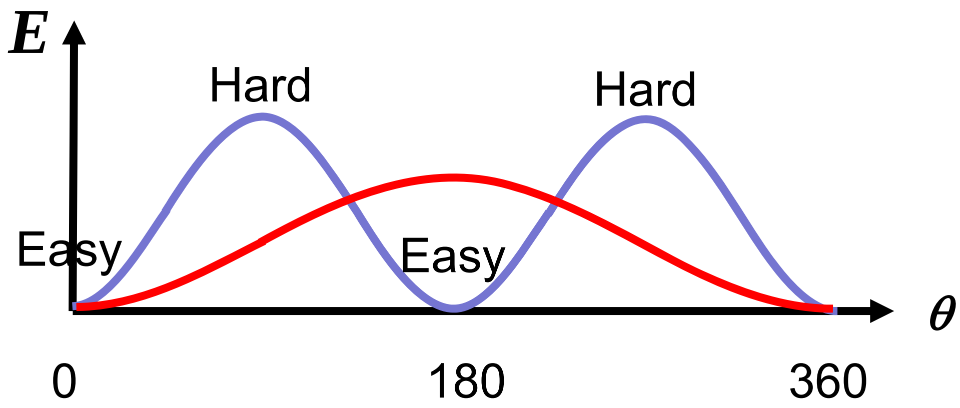
Stoner-Wohlfarth Theory*

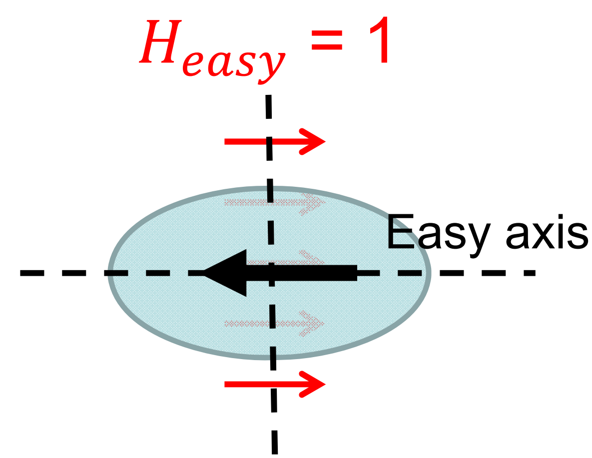
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

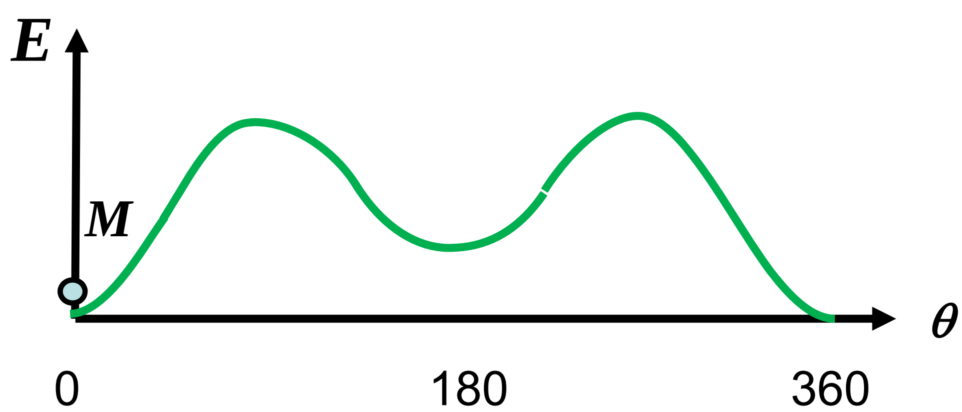
Magnetostatic energy

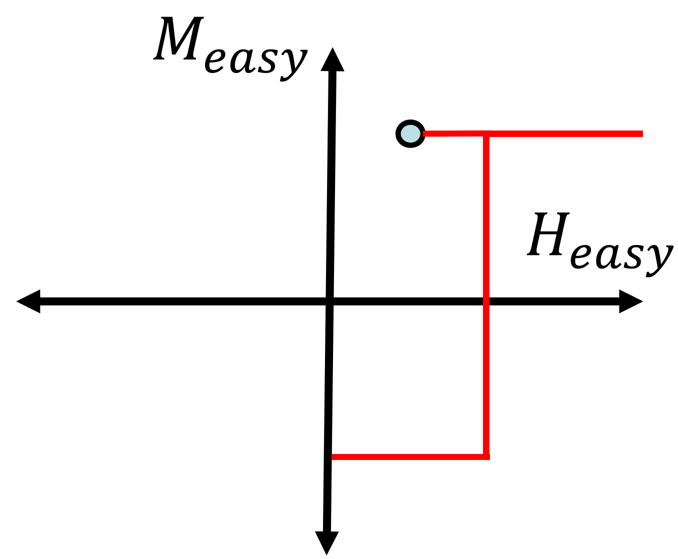
$$E_{ms} = H_{easy} M_s V sin\,(\theta)$$





Total energy (Magnetic field along easy axis)

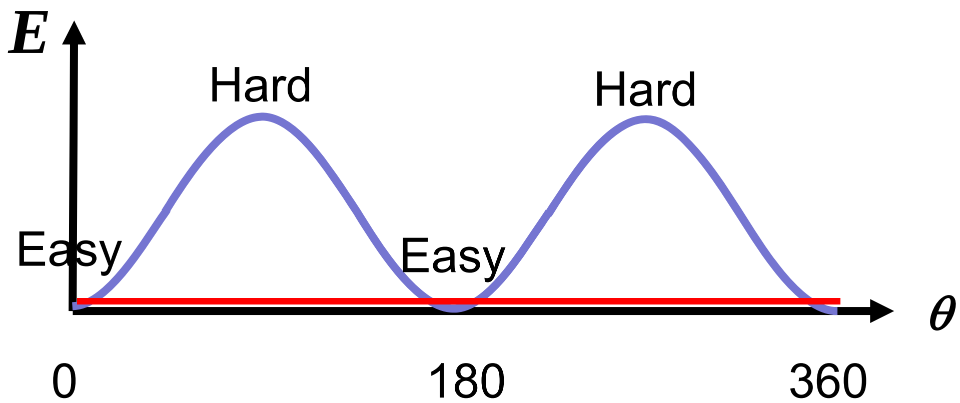




Stoner-Wohlfarth Theory*

Anisotropy energy

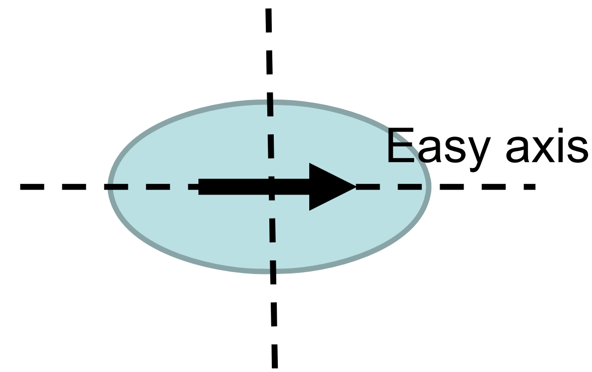
$$E_{anis} = K_u V sin^2(\theta)$$



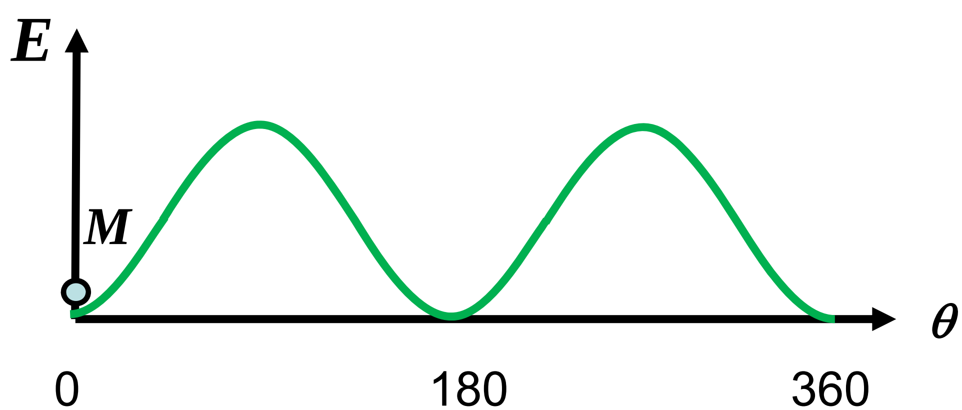
Magnetostatic energy

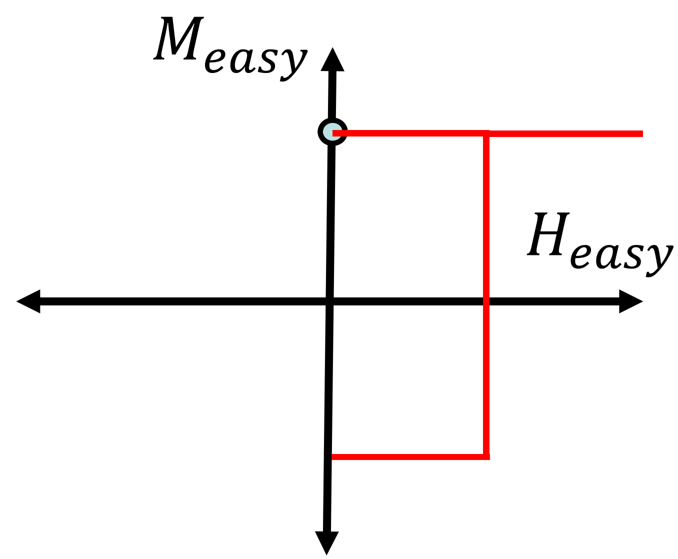
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$

H_{easy} = 0



Total energy (Magnetic field along easy axis)





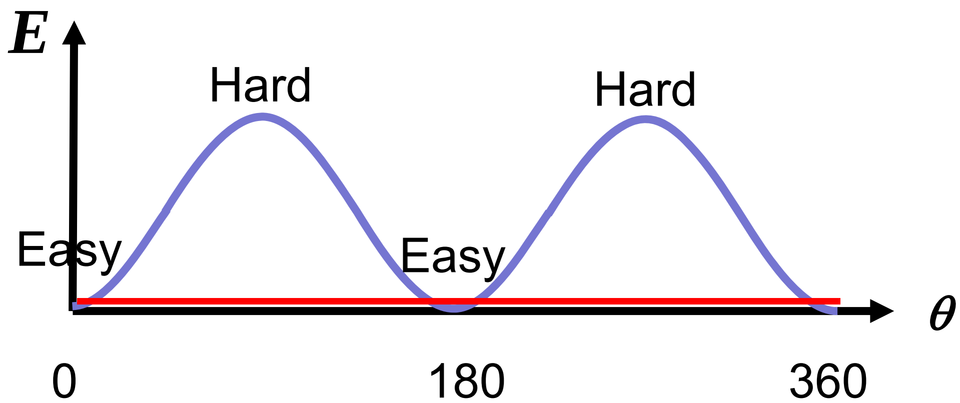
Stoner-Wohlfarth Theory*

Anisotropy energy

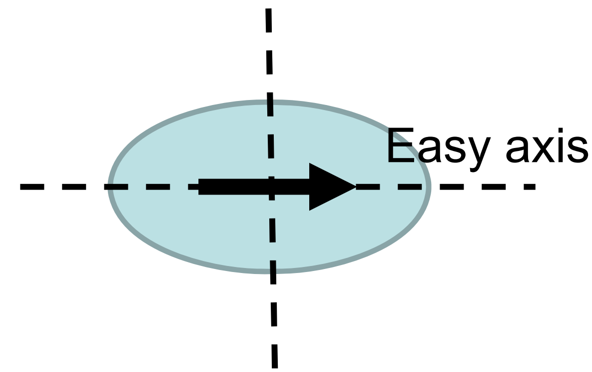
$$E_{anis} = K_u V sin^2(\theta)$$

Magnetostatic energy

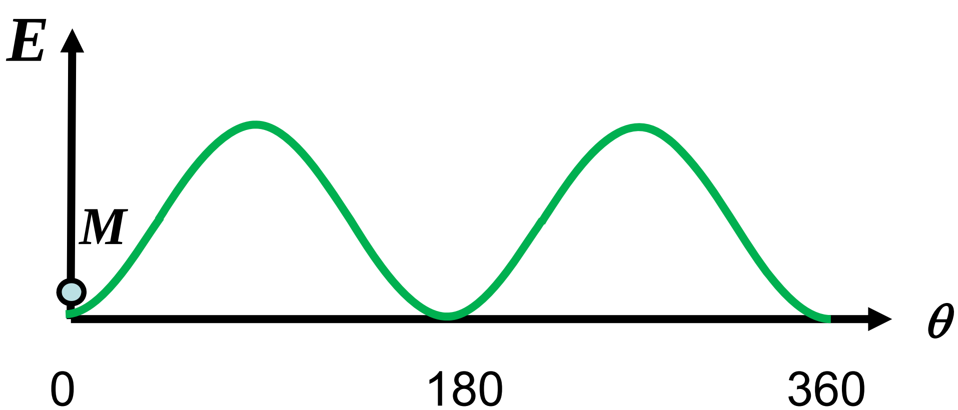
$$E_{ms} = H_{easy} M_s V cos\,(\theta)$$

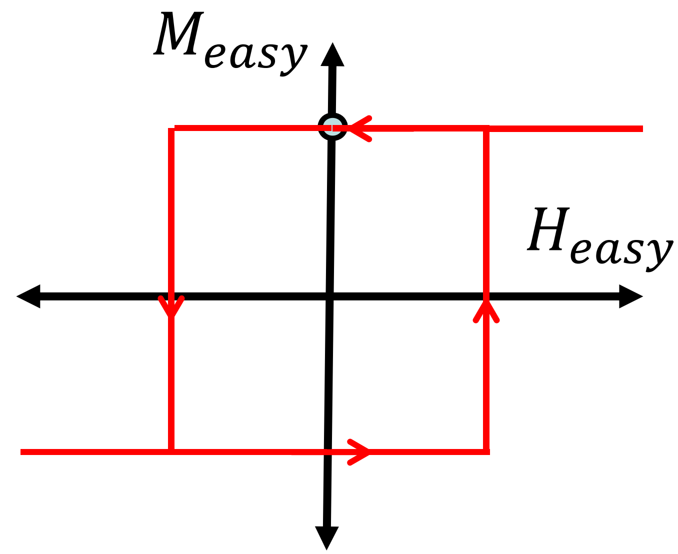


H_{easy} = 0



Total energy (Magnetic field along easy axis)





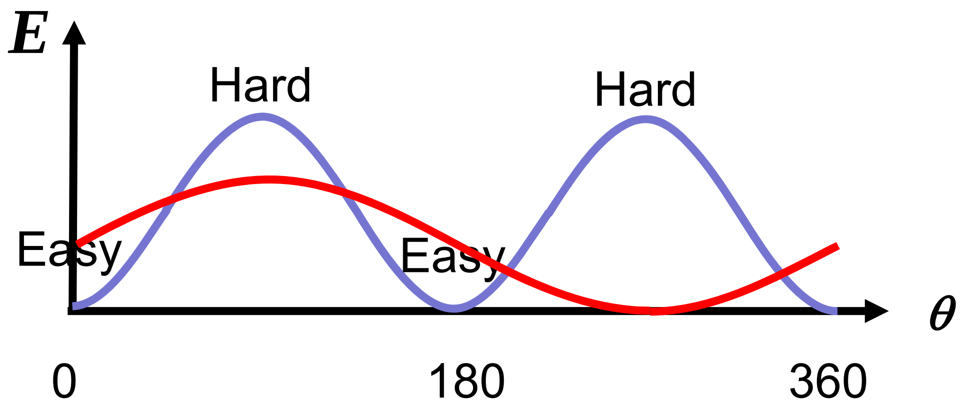
Stoner-Wohlfarth Theory*

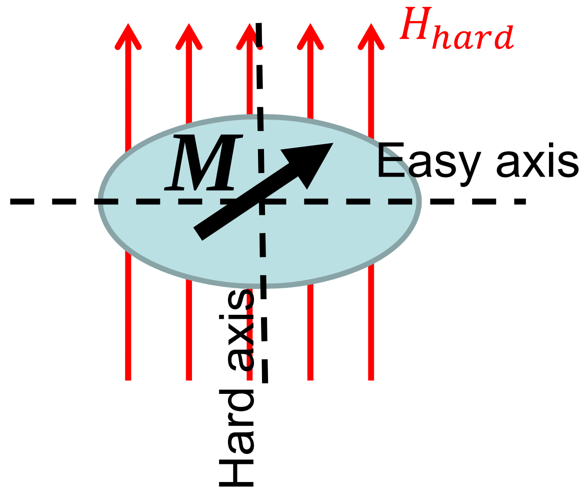
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

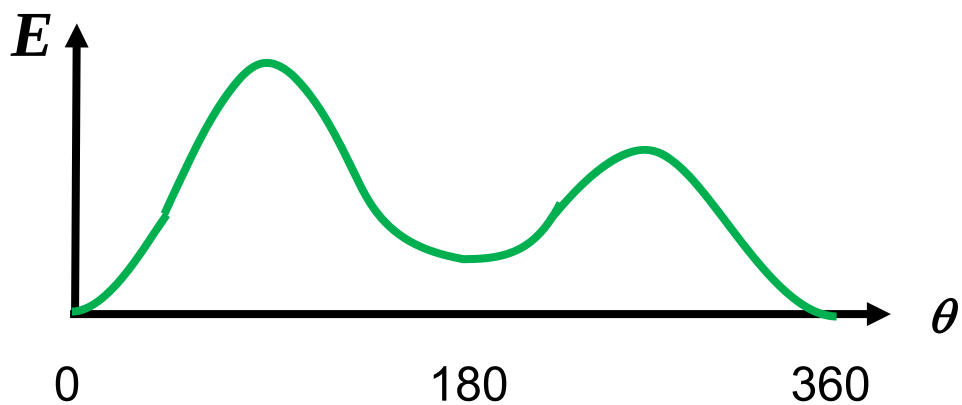
Magnetostatic energy

$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$





Total energy (Magnetic field along easy axis)



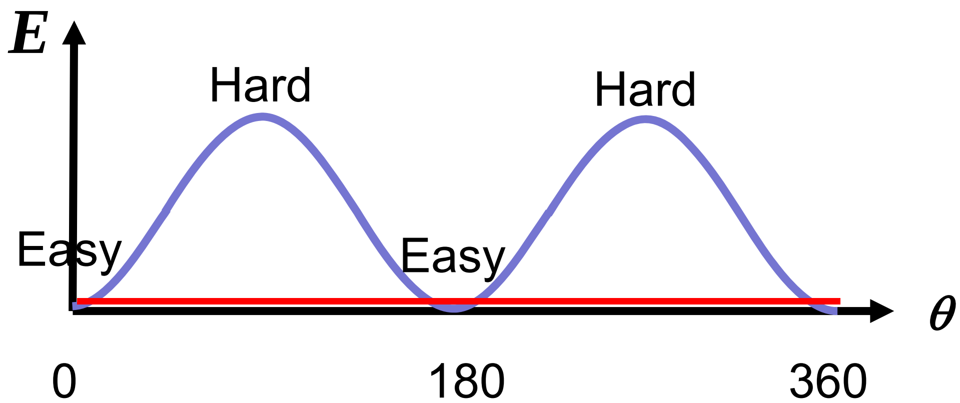
Stoner-Wohlfarth Theory*

Anisotropy energy

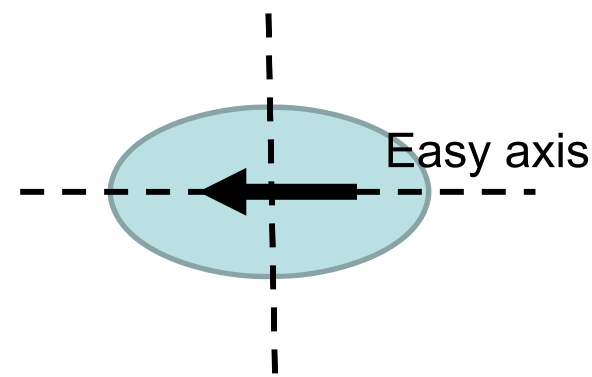
$$E_{anis} = K_u V sin^2(\theta)$$

Magnetostatic energy

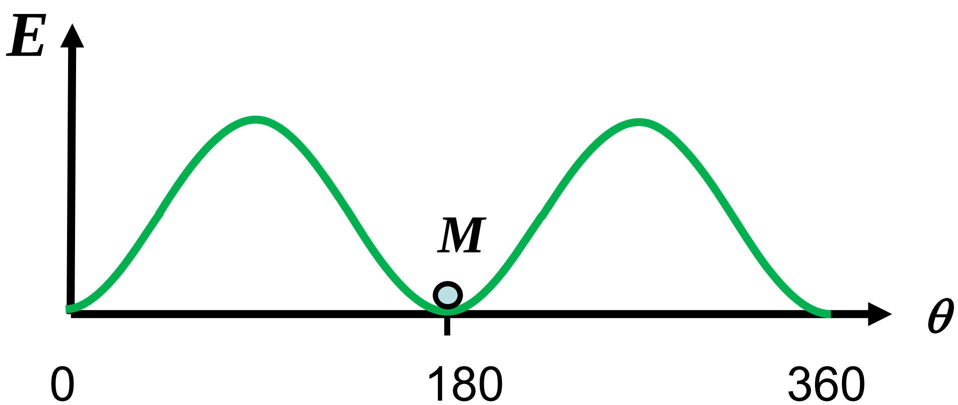
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$

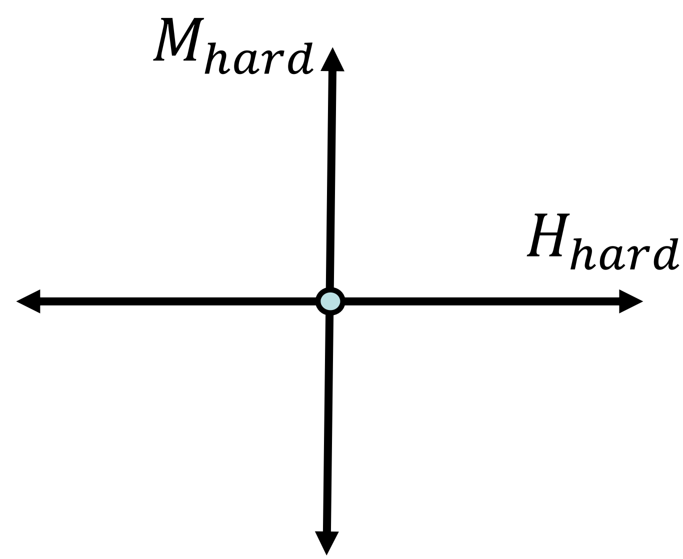


H_{hard} = 0



Total energy (Magnetic field along easy axis)





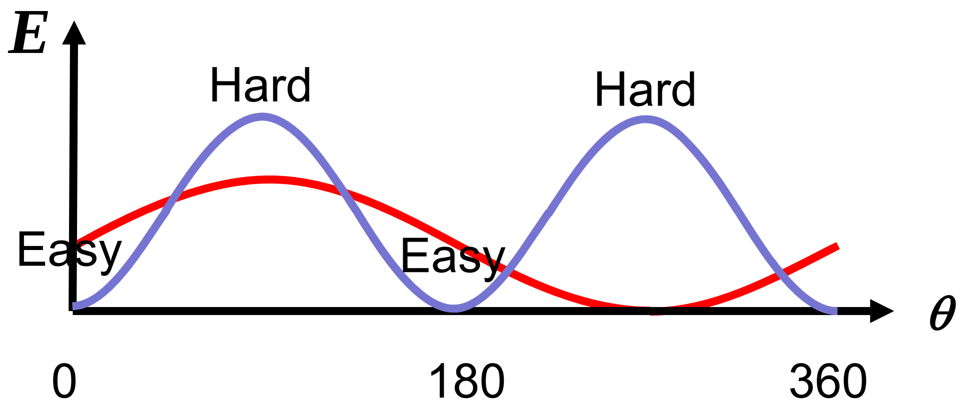
Stoner-Wohlfarth Theory*

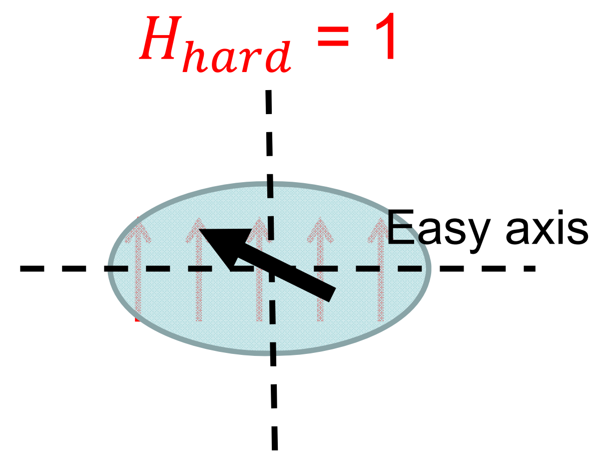
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

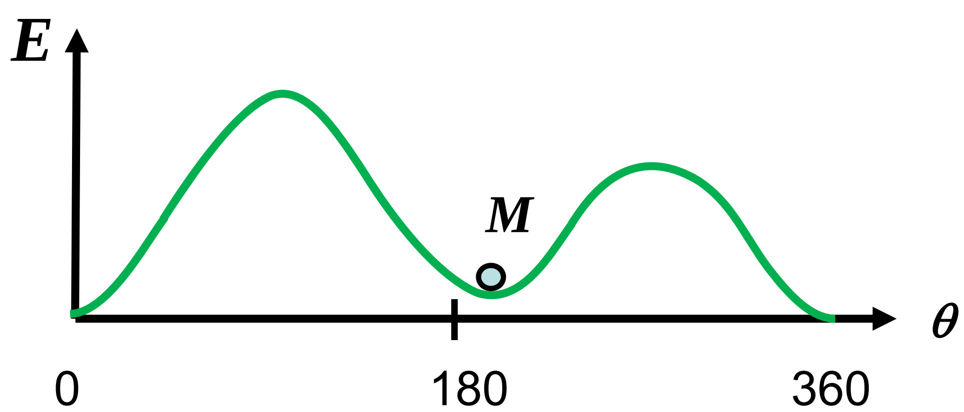
Magnetostatic energy

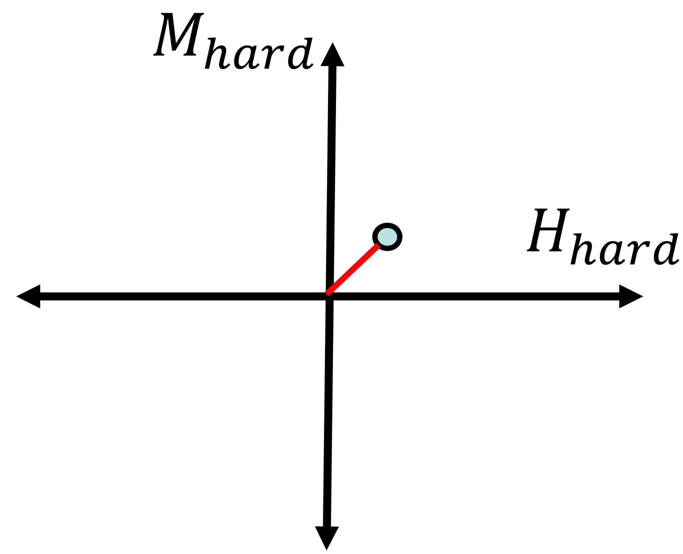
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$





Total energy (Magnetic field along easy axis)





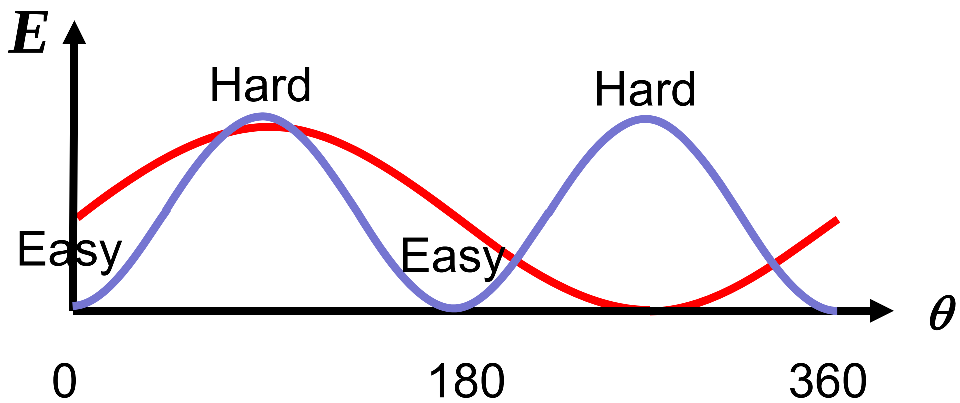
Stoner-Wohlfarth Theory*

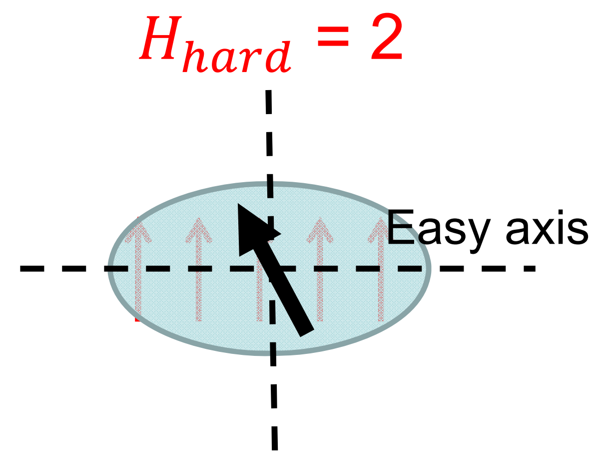
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

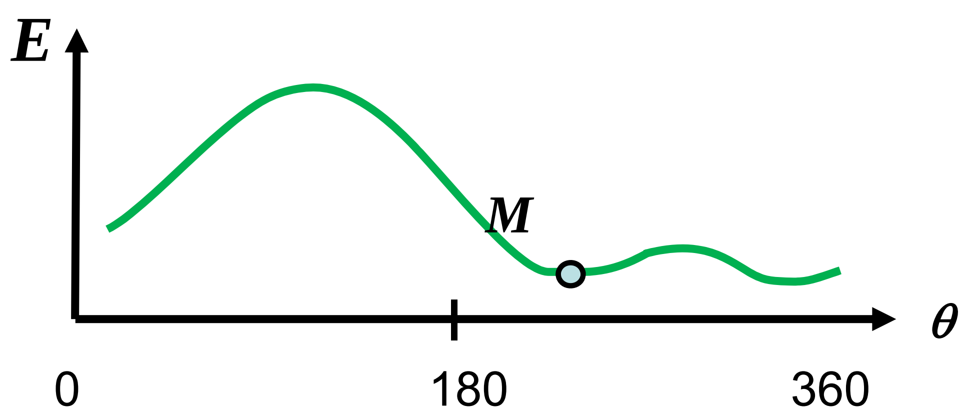
Magnetostatic energy

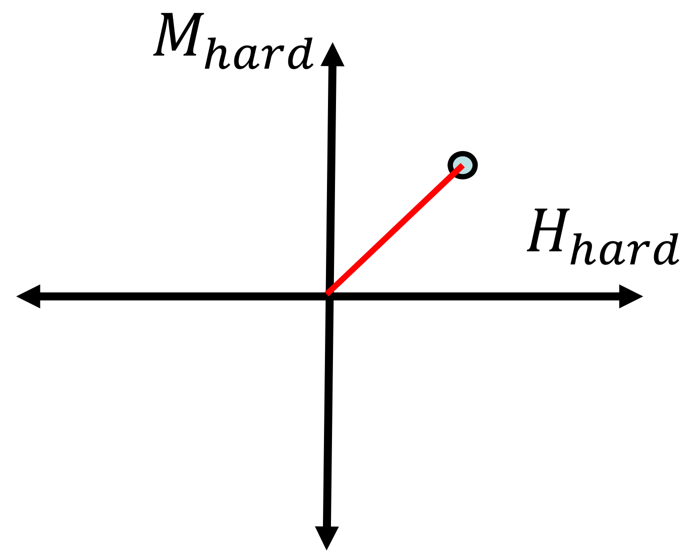
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$





Total energy (Magnetic field along easy axis)





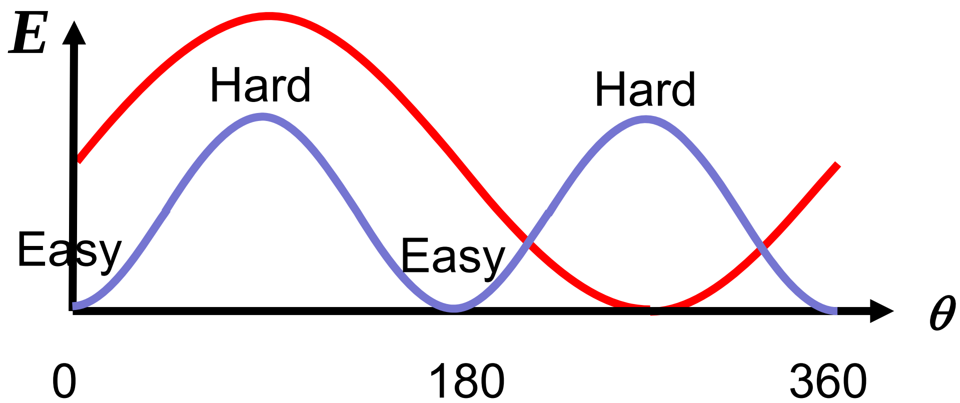
Stoner-Wohlfarth Theory*

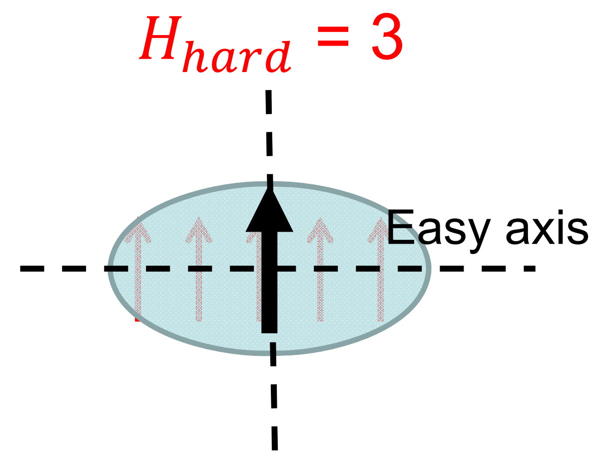
Anisotropy energy

$$E_{anis} = K_u V sin^2(\theta)$$

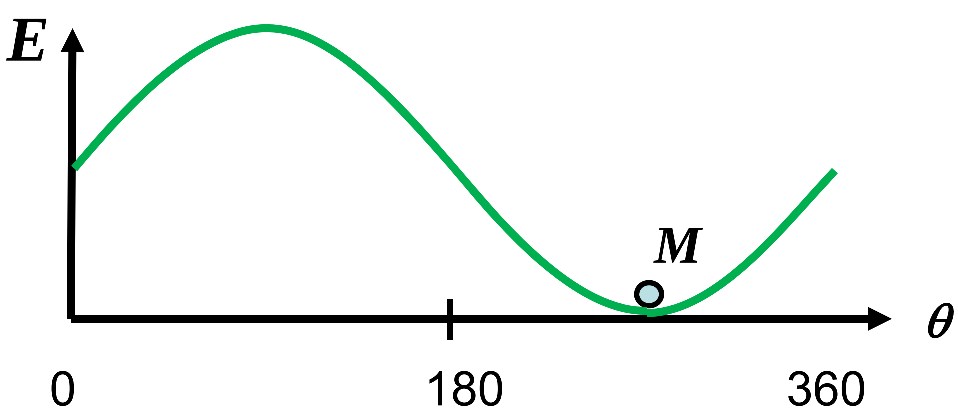
Magnetostatic energy

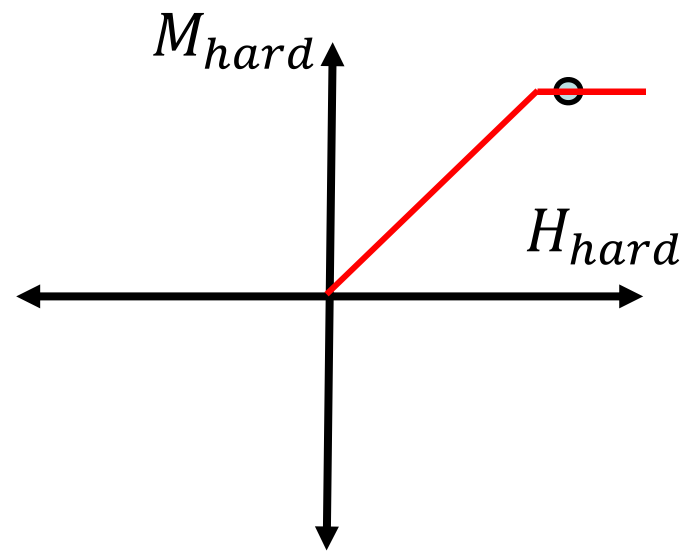
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$





Total energy (Magnetic field along easy axis)





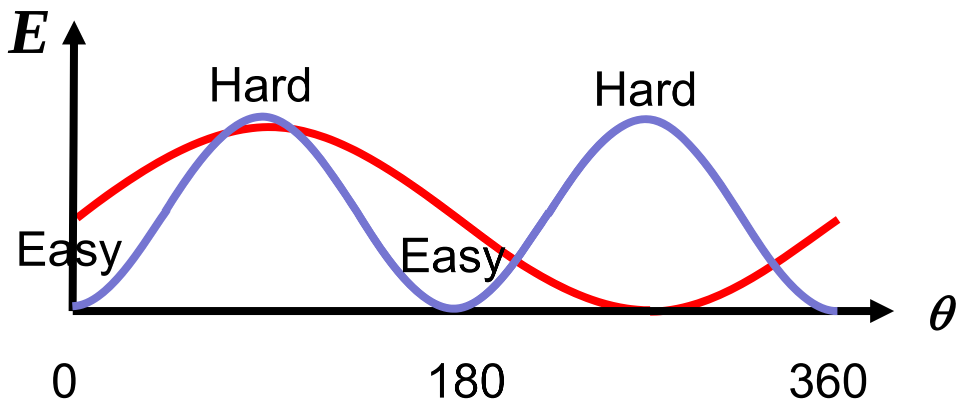
Stoner-Wohlfarth Theory*

<u>Anisotropy energy</u>

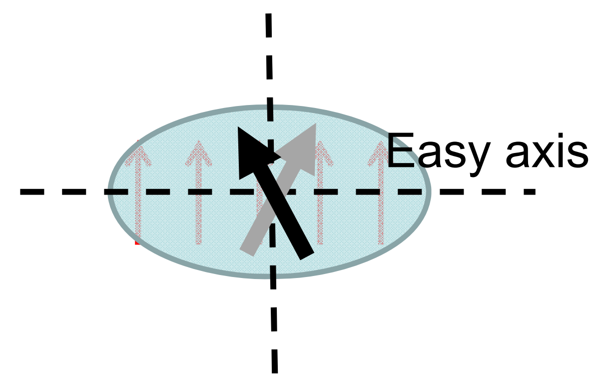
$$E_{anis} = K_u V sin^2(\theta)$$

<u>Magnetostatic energy</u>

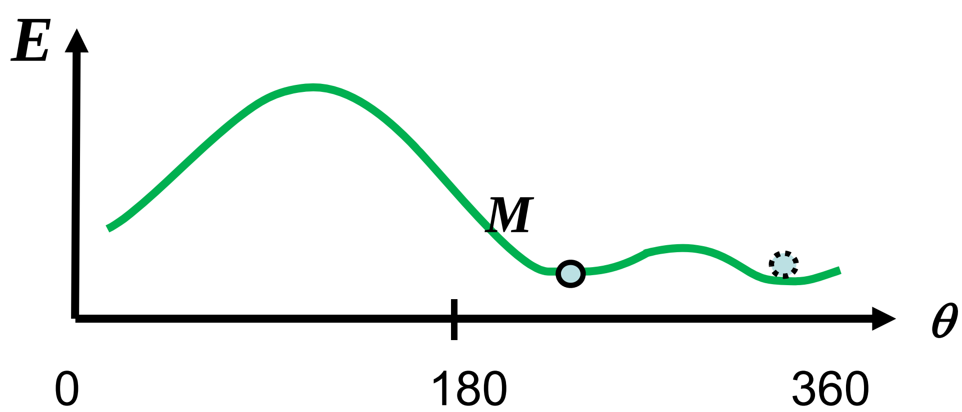
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$

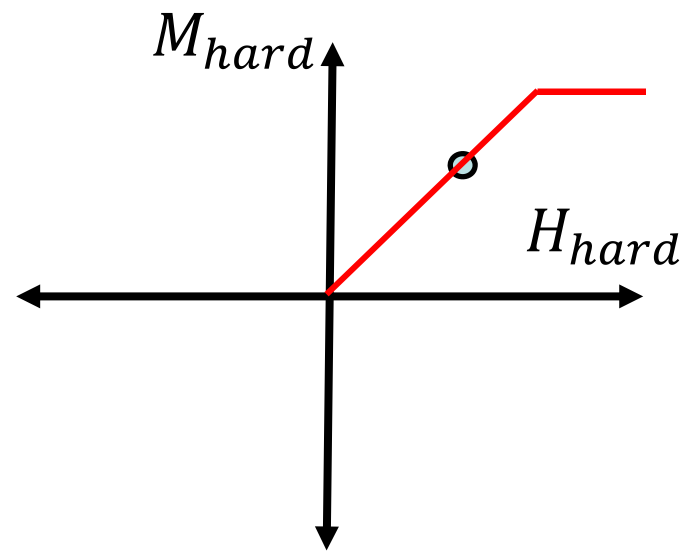


H_{hard} = 2



Total energy (Magnetic field along <u>easy axis</u>)





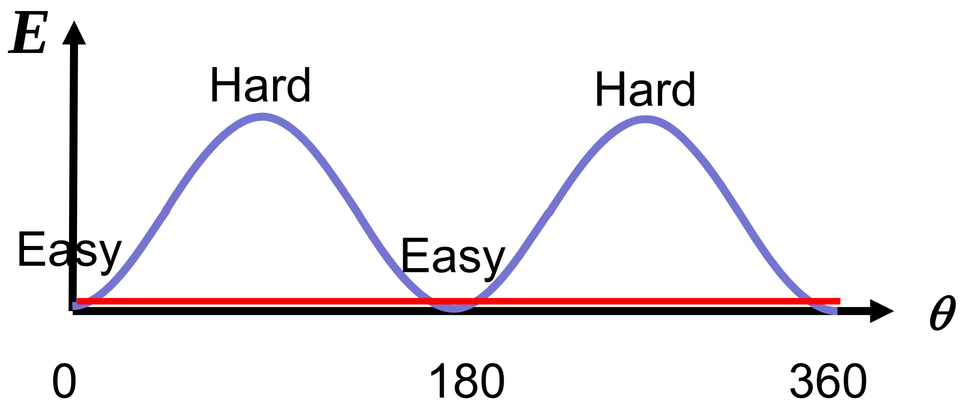
Stoner-Wohlfarth Theory*

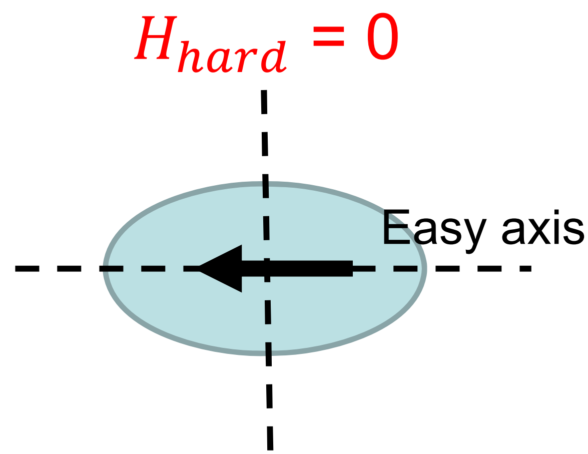
<u>Anisotropy energy</u>

$$E_{anis} = K_u V sin^2(\theta)$$

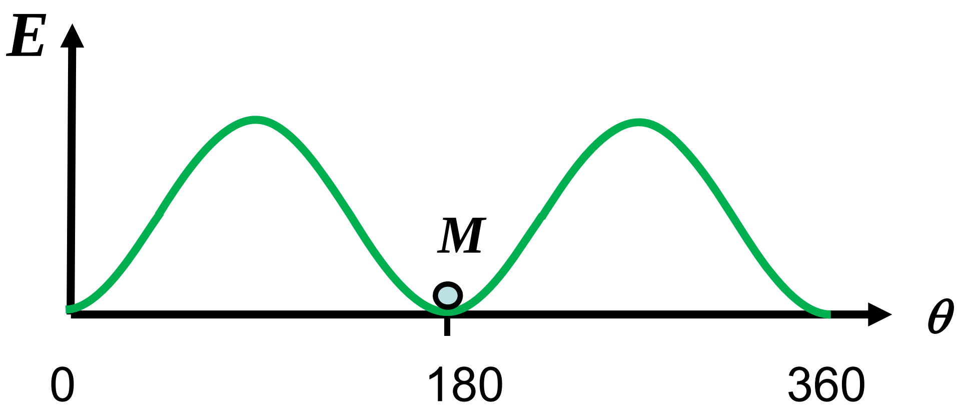
<u>Magnetostatic energy</u>

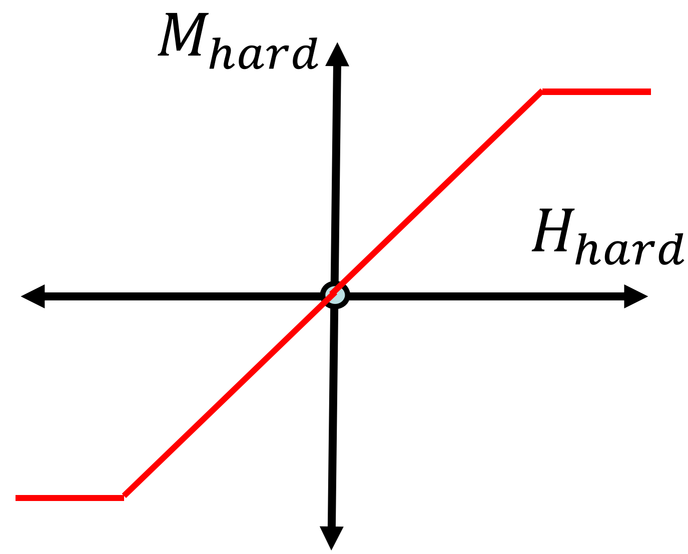
$$E_{ms} = H_{hard} M_s V sin\,(\theta)$$



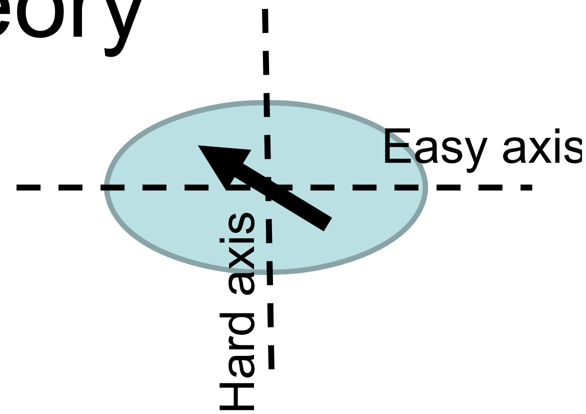


Total energy (Magnetic field along <u>easy axis</u>)



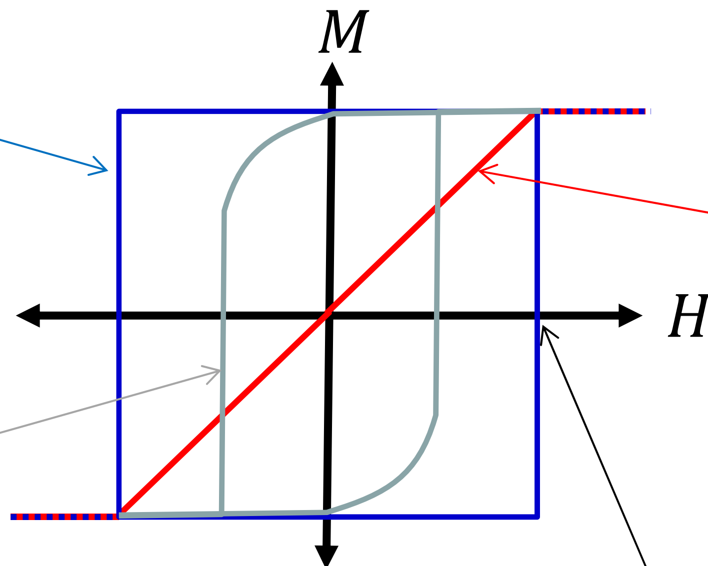


Stoner-Wohlfarth Theory



Easy axis loop

- “Hard” magnet
- Permanent magnets
- Data storage



Hard axis loop

- “Soft” magnet
- Transformers/inductors
- Flux guides
- Recording heads

45° loop

- Lowest switching field
- MRAM

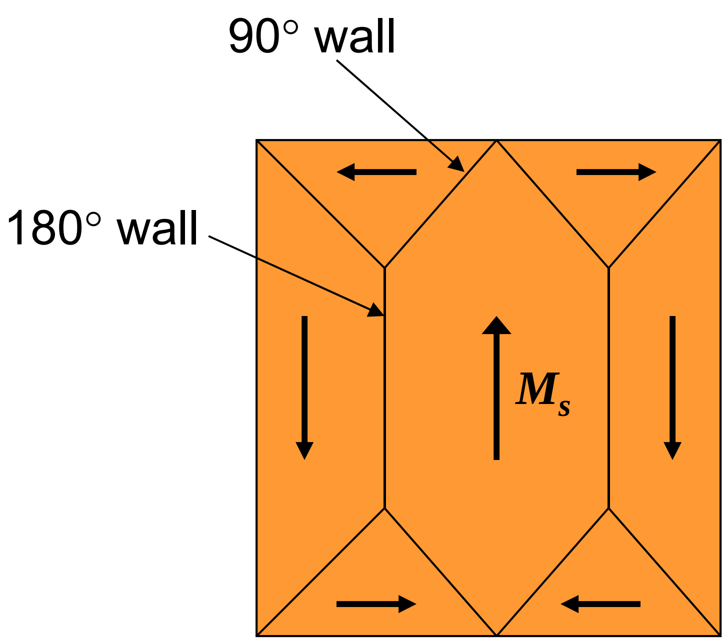
Anisotropy field

$$H_K = \frac{2K_u}{M_S}$$

Magnetic Domains

Domain Walls

Domain walls are the boundary between to regions with different magnetization direction.

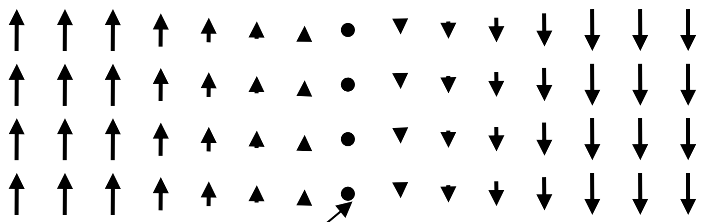


- A ferromagnet with net magnetization less than saturation breaks into domains due to demagnetizing fields.
- Domains form to reduce the magnetostatic energy.
- Within a domain, the magnitude of magnetization is the "spontaneous magnetization", M_s
- The direction of magnetization varies from domain to domain.

Two Types of Domain Walls

•<u>Bloch wall</u>

magnetization rotates around axis normal to wall

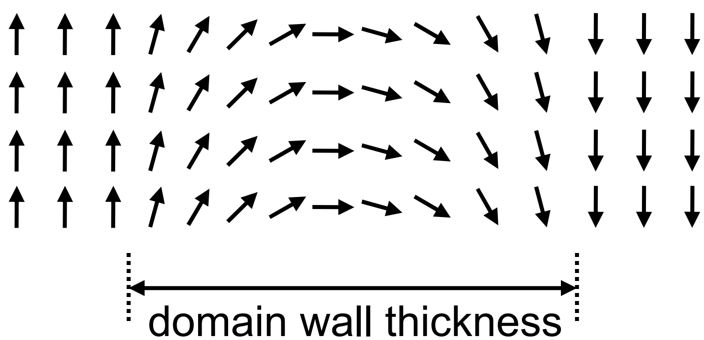


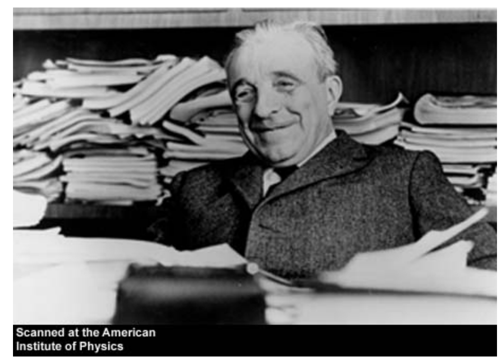
M pointing at you !

$$\mathrm{div}(M) = 0 \quad \Rightarrow \quad \text{nopoles in bulk}$$

Felix Bloch
(1905-1983)

•<u>Néel wall</u>





Louis Néel
(1904-2000)

$$\mathrm{div}(M) \neq 0 \quad \Rightarrow \quad \text{distributed poles in bulk}$$

Domain Wall Exchange Energy

- Assume linear transition over N lattice points

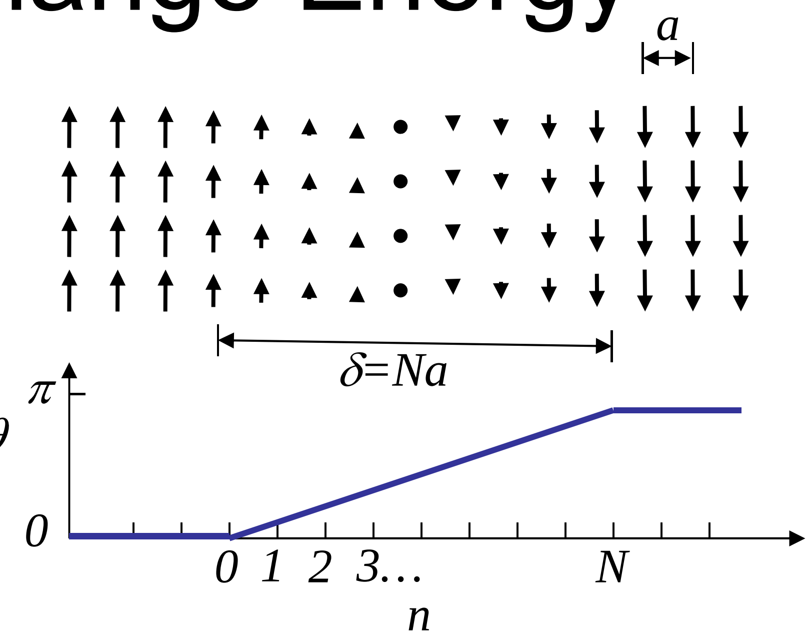
$$\theta(n) = \pi \frac{n}{N} \qquad for\ n = 0..N$$

- Angle between adjacent moments is

$$\Delta\theta = \frac{\pi}{N}$$

- Exchange energy between adjacent moments

$$E_{m_i, m_{i+1}} = -\mu_0 \mathcal{J} m^2 \cos(\Delta\theta) \cong -\mu_0 \mathcal{J} m^2 \left(1 - \frac{(\Delta\theta)^2}{2}\right)$$



- Summing through wall thickness

$$\sum_{n=0..N} E_{m_n, m_{n+1}} = \frac{N \mu_0 \mathcal{J} m^2 (\Delta\theta)^2}{2} + C$$

$$= \frac{\mu_0 \mathcal{J} m^2 \pi^2}{2N} + C$$

- Summing over wall area:

$$E_{exch} = \frac{\text{Area}}{a^2} \frac{\mu_0 \mathcal{J} m^2 \pi^2}{2N} + C$$

- Using $\delta = Na$:

$$\frac{E_{exch}}{\text{Area}} = \frac{\mu_0 \mathcal{J} m^2 \pi^2}{2a} \frac{1}{\delta}$$

- Exchange energy favors thick walls.

Domain Wall Anisotropy Energy

- Assume linear transition over N lattice points

$$\theta(n) = \pi \frac{n}{N} \qquad for\ n = 0..N$$

- Anisotropy energy penalty for each moment:

$$E_{m_i} = K_u \sin^2(\theta) a^3$$

uniaxial anisotropy energy / volume

- Summing through wall thickness

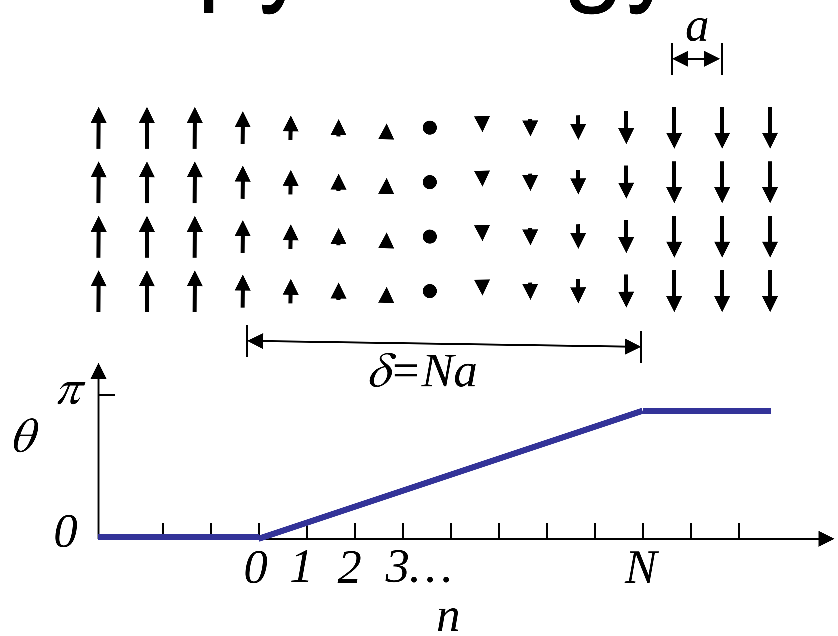
$$\sum_{n=0..N} E_{m_n} \cong \frac{N}{\pi}\int_0^{\pi} K_u \sin^2(\theta) a^3 d\theta = \frac{K_u N a^3}{2}$$

- Summing over wall area:

$$E_{anis} = -\frac{\text{Area}}{a^2}\frac{K_u N a^3}{2}$$

Or,

$$\frac{E_{anis}}{\text{Area}} = \frac{K_u}{2}\delta$$



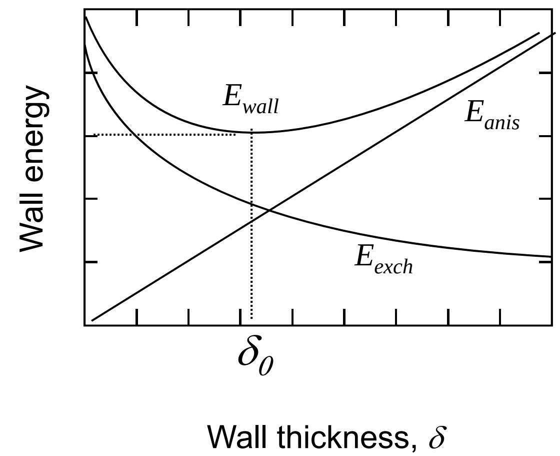
- Anisotropy energy favors thin walls.

Domain Wall Thickness

• Domain wall thickness is determined by a balance between anisotropy and exchange energy:

$$\frac{E_{anis}}{\text{Area}} = \frac{K_u}{2}\delta \qquad\qquad \frac{E_{exch}}{\text{Area}} = \frac{\mu_0 \mathcal{J} m^2 \pi^2}{2a}\frac{1}{\delta}$$

• Define exchange stiffness: $A = \dfrac{\mu_0 \mathcal{J} m^2}{a}$



• Total wall energy is:

$$\frac{E_{wall}}{\text{Area}} = \frac{K_u}{2}\delta + \frac{\pi^2 A}{2\delta}$$

• The minimum energy is achieved at:

$$\frac{dE_{wall}}{d\delta} = \frac{K_u}{2} - \frac{\pi^2 A}{2\delta^2} = 0 \quad \Rightarrow \quad \delta_0 = \pi\sqrt{\frac{A}{K_u}}$$

• Where the wall energy is:

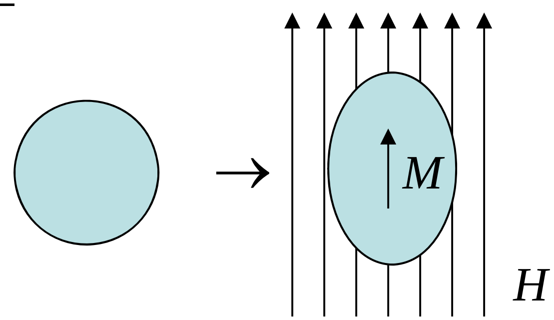
$$E_{wall} = \pi\sqrt{K_u A}\ \text{Area}$$

Magnetostriction

Random crystal orientation:

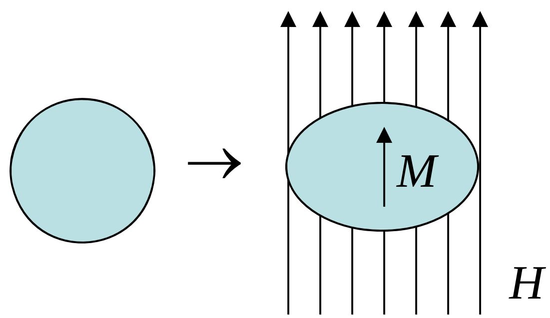
$$\frac{\Delta l}{l} = \frac{3}{2}\lambda_s(\cos^2\theta - \frac{1}{3})$$

$\lambda_s > 0$



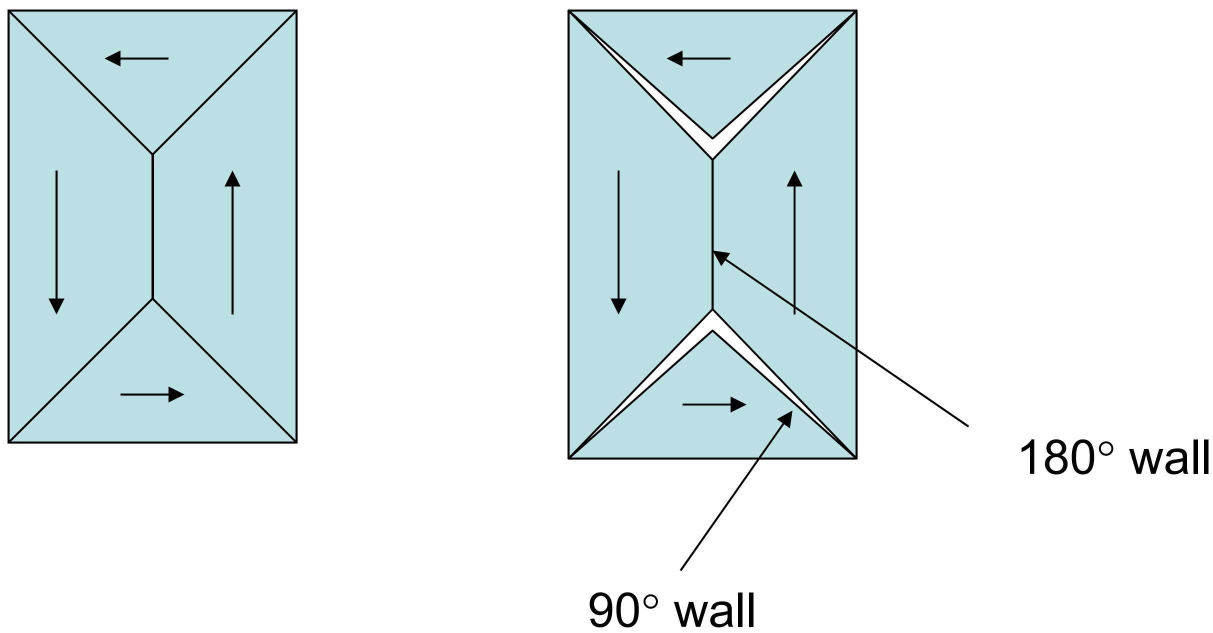
E.g. “Terfenol”
$TbFe_2$: λ_s = 1753x10^{-6}

$\lambda_s < 0$



E.g.
Ni (fcc): λ_s = -34x10^{-6}
Fe (bcc): λ_s= -7x10^{-6}

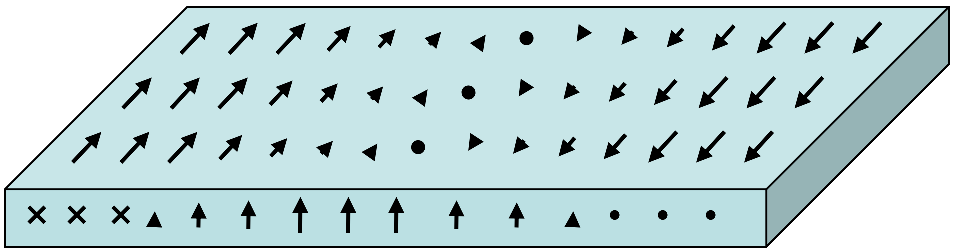
Magnetostrictive Effect on Domain Walls



- Magnetostrictive strain energy favors 180 degree walls.

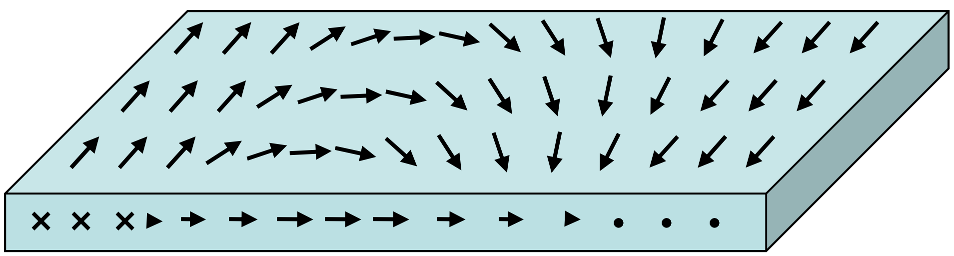
Domain Walls in Thin Films

- <u>Bloch wall</u>

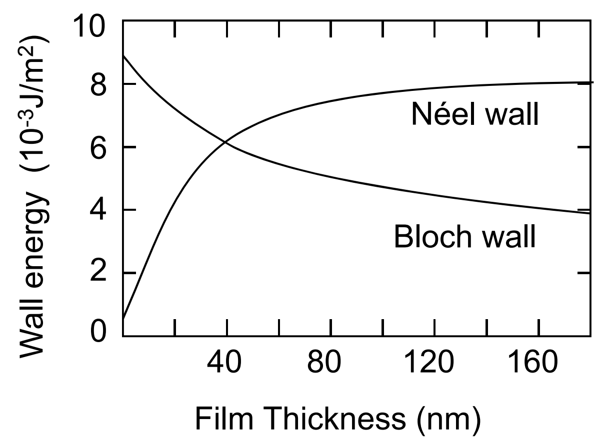


Magnetic poles on surface

- <u>Néel wall</u>



Magnetic poles in bulk

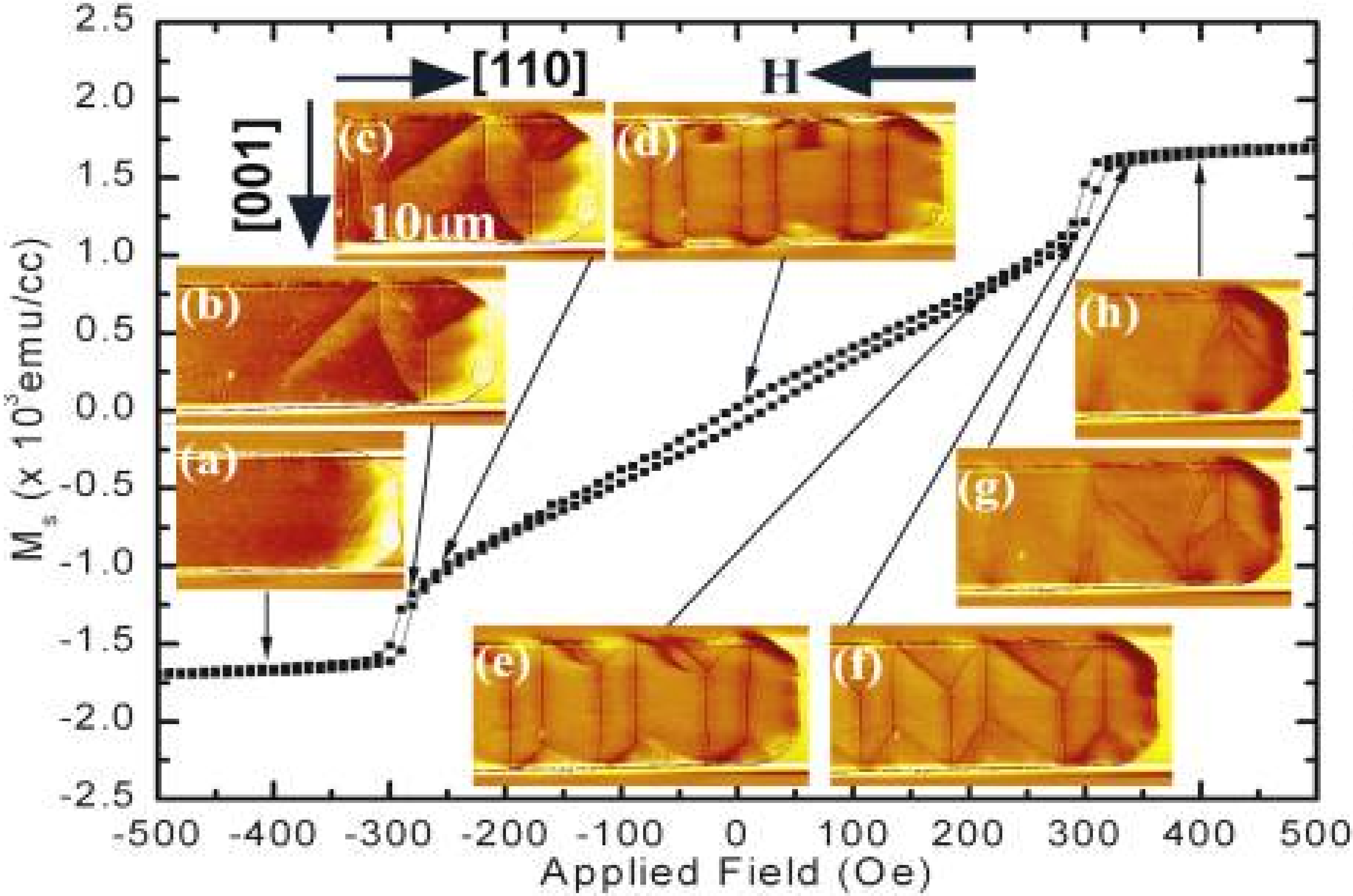


For A = 10^{-11} J/m, B_s = 1 T and K = 100 J/m^3
from O'Handley, <u>Modern Magnetic Materials</u>

Domain Configuration

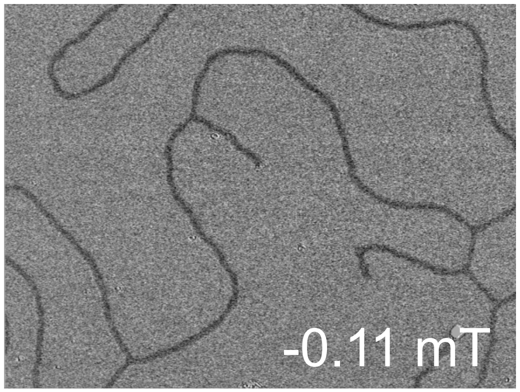
- Balance of energy between:
  - Magnetostatic self energy (demag. field -> try to reduce magnetic poles)
  - Domain wall energy (exchange and anisotropy -> reduce wall area)
  - Strain energy (magnetostriction -> favor 180° walls)
  - Magnetostatic energy in applied field ($E=-m \cdot B$ -> favors alignment with field)

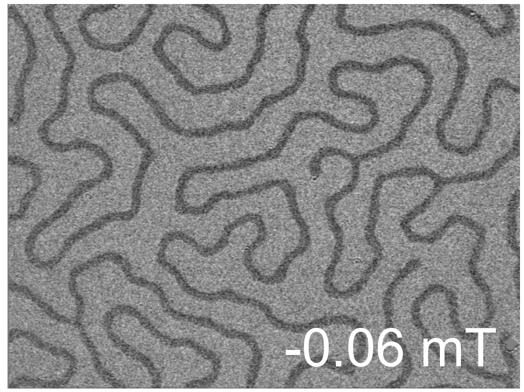
Domains in Fe film

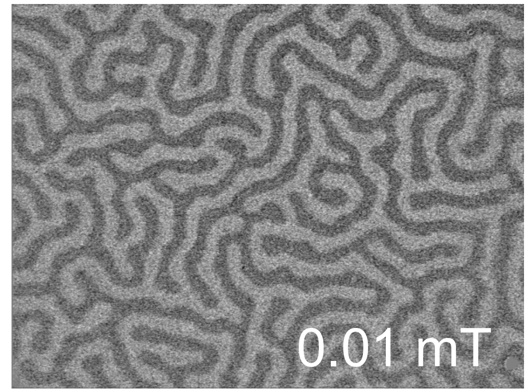


MFM images From: http://physics.unl.edu/~shliou/ResearchActivity/research3.htm

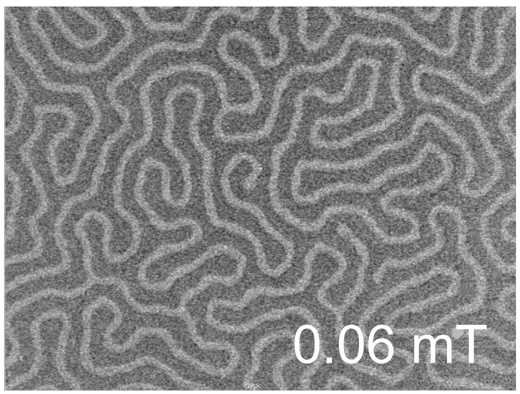
Stripe domains in CoFeB thin film with Perpendicular Anisotropy

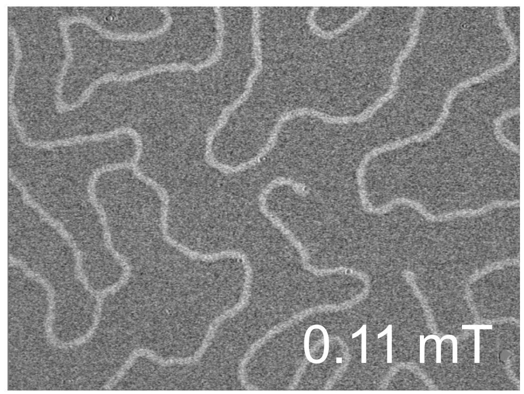






25 μm

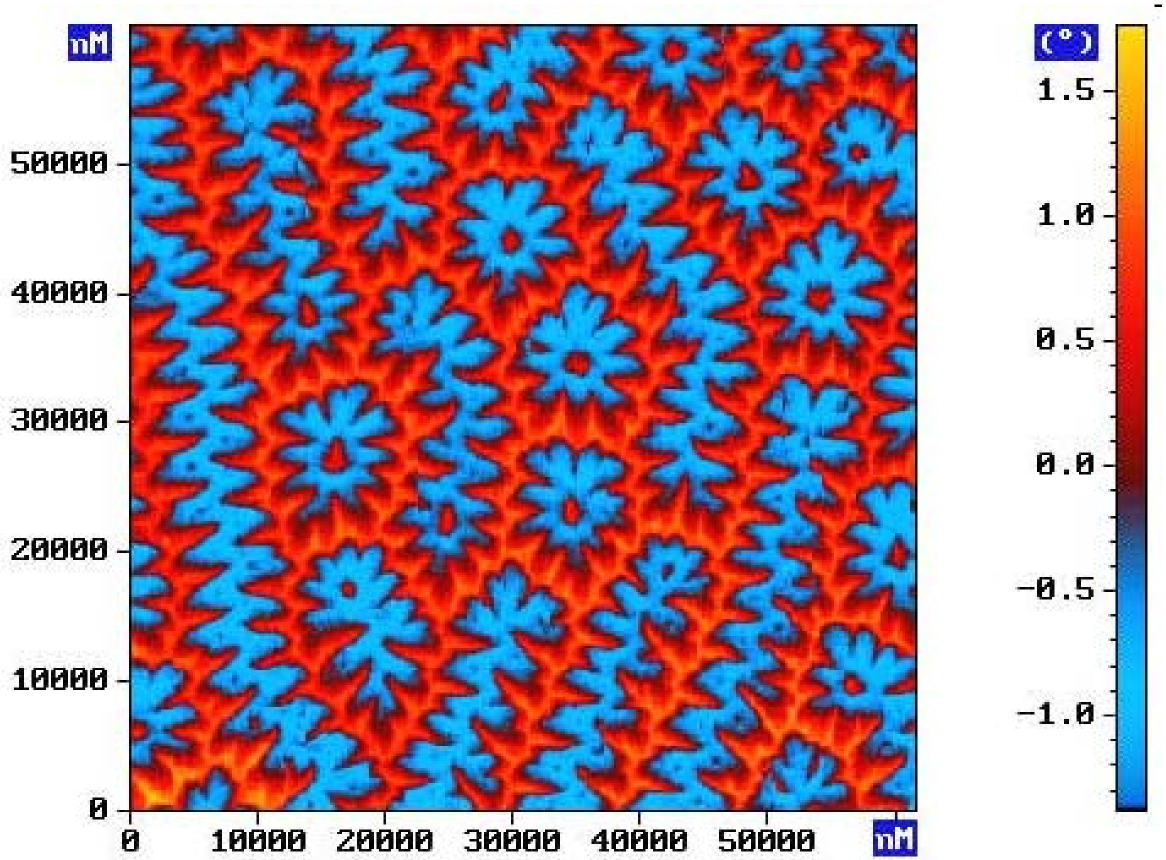




Polar Kerr images.

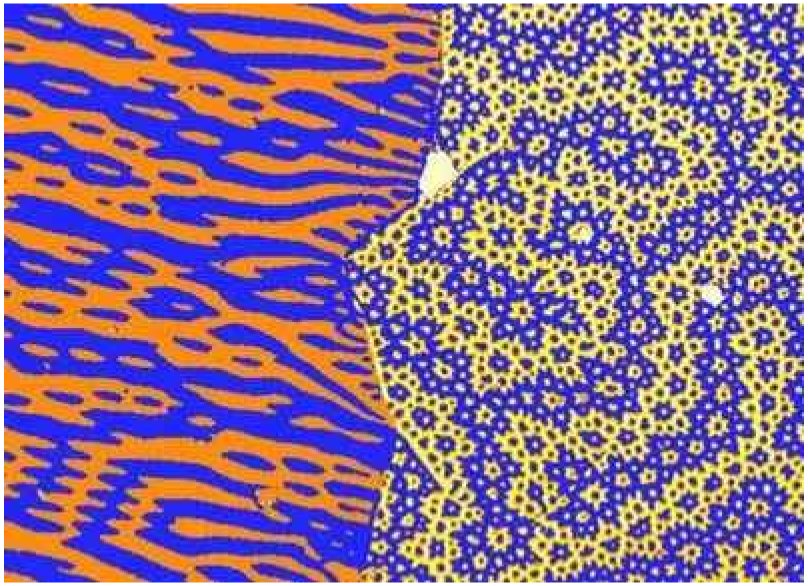
Flower Domains in YIG

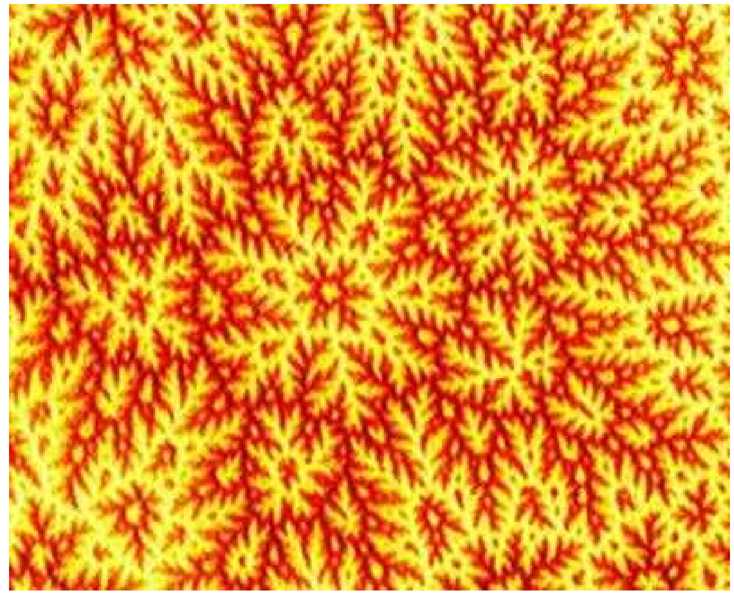
MFM Image



From: http://www.nanoworld.org/russian/s_11.html

Pretty Domain Patterns



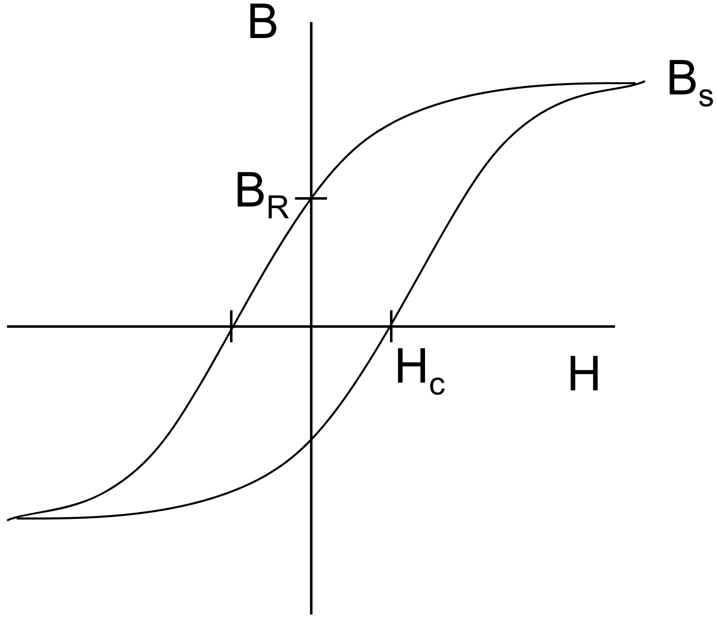


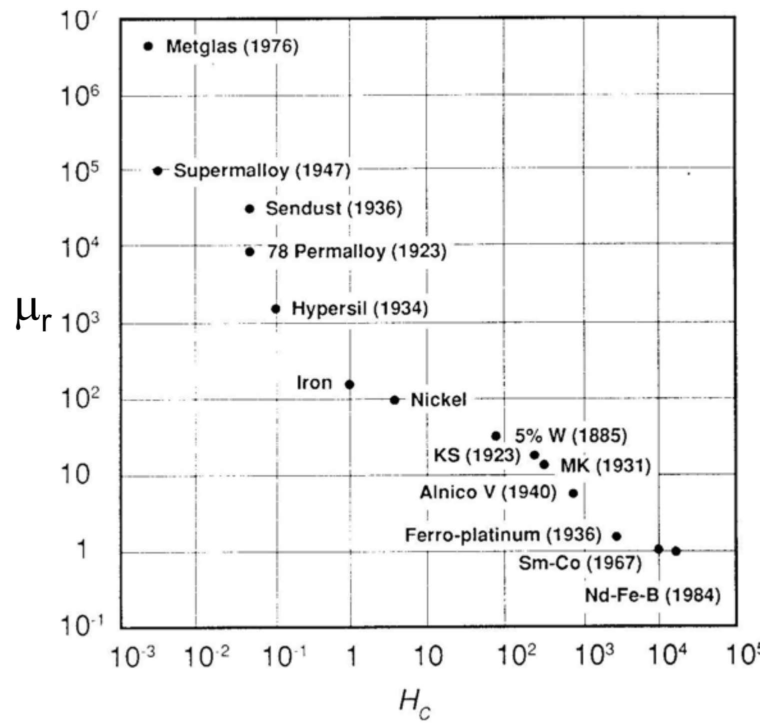
Magnetic Materials

Magnetic materials are typically classified as “hard” or “soft” depending on the intended application.

Soft magnets have low coercivity and high permeability.

Hard magnets have high coercivity and high remanent magnetization.





Soft Iron

- Inexpensive, high coercivity material
- $\mu_r \sim 1000 - 5000$
- Used in DC/low frequency applications

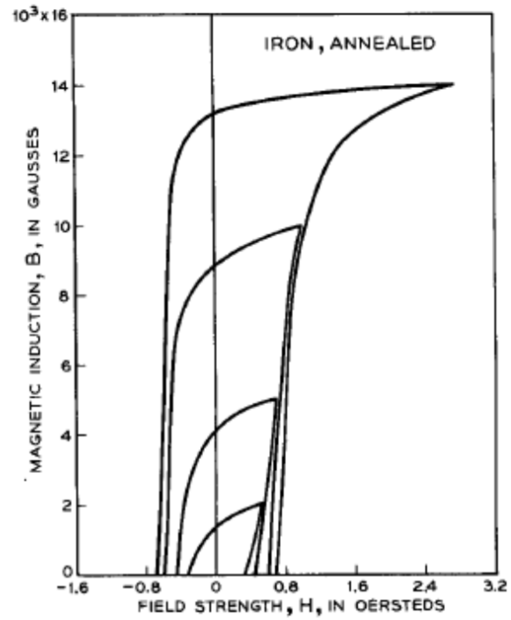
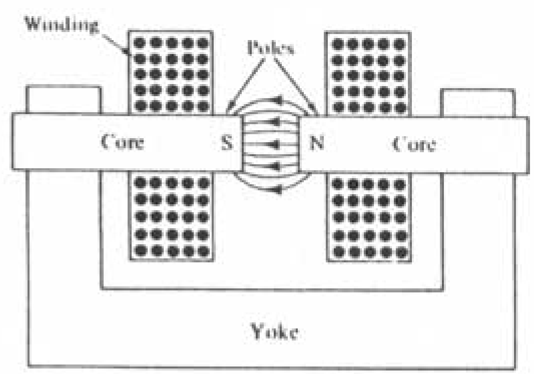


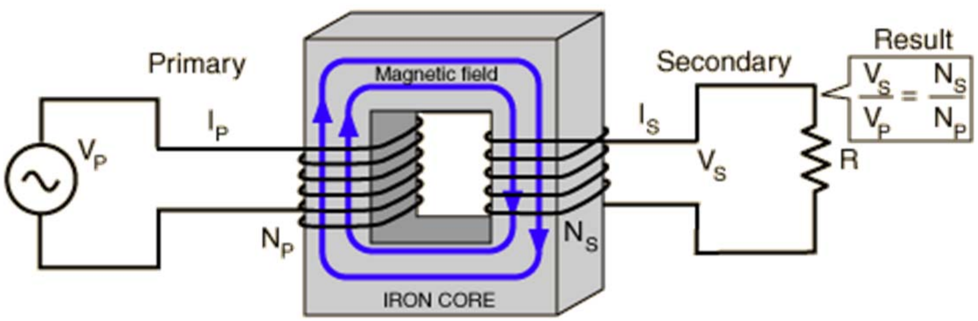
Fig. 3-5. Upper halves of hysteresis loops of ordinary annealed iron



Silicon Steel ("Electrical Steel")

- Most common in power (50/60 Hz) applications
- Adding Si, Al increases resistivity, permeability and reduces coercivity.
- Bad effects: reduces B_s, T_c and increases brittleness

- Higher resistivity and lower coercivity -> less losses
- Higher permeability -> better coupling
- Si limited to 3-4%, material gets too brittle.



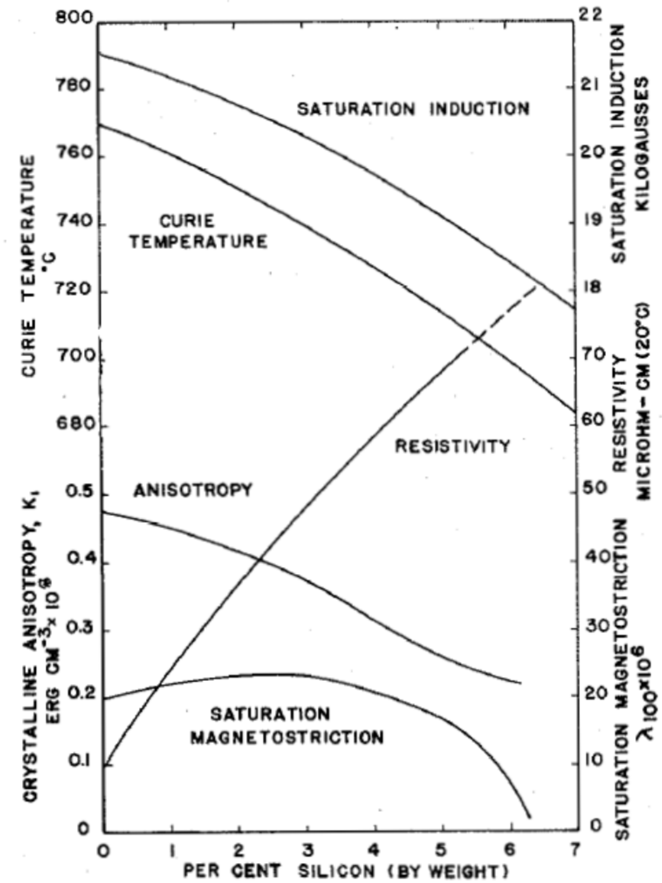
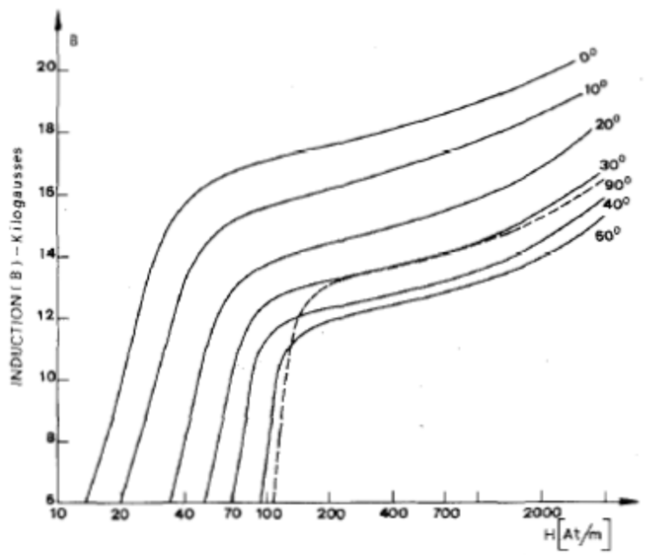


Fig. 1. Variation of important properties of silicon–iron alloys with composition.

Littmann, M.; Iron and silicon-iron alloys,
IEEE Transactions on Magnetics, 7, 48 - 60 (1971)

Cold-rolled Grain-Oriented Steel (CRGO)

- Reduces hysteresis further by orienting grains:

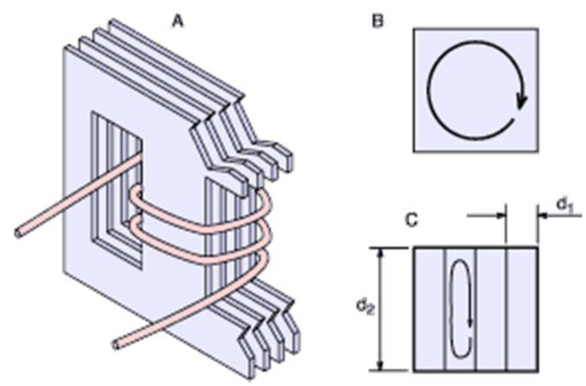


*

Fig. 2. AC excitation curve, induction at various angles to rolling direction.

	Losses (W/kg)
Commercial iron	5-10
Si-Fe hot rolled	1-3
Si-Fe CRGO	0.3-0.6

Lamination reduces eddy currents:



*Di Napoli, A.; Paggi, R.; A model of anisotropic grain-oriented steel, IEEE Transactions on Magnetics 19, 1557, (1983)

Ni-Fe Alloys (Permalloys)

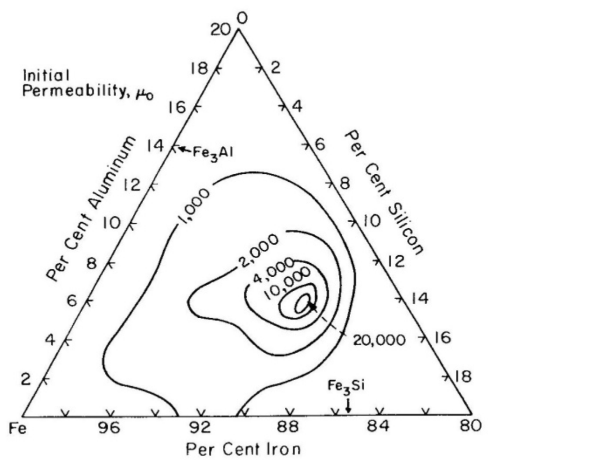
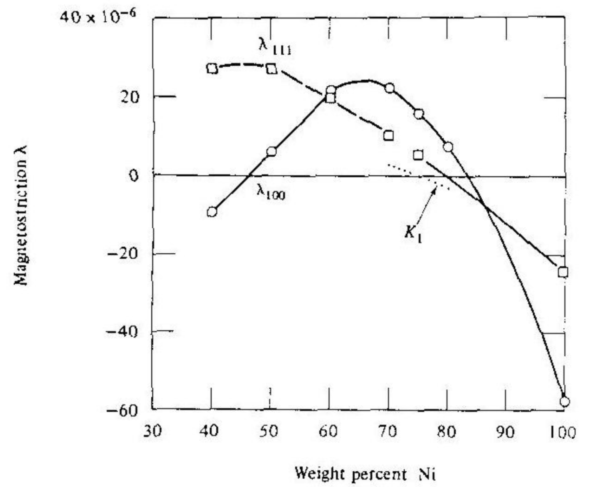


Figure 10.11 Contours of initial permeability on same Fe-Si-Al ternary diagram as ... Figure 10.10 (Bozorth, IEEE Press, copyright 1994).



2.12 Dependence of magnetostriction coefficients λ_{100} and λ_{111} with nickel conte... nickel alloys.

Zero magnetostriction at 80%

Zero anisotropy at 78%

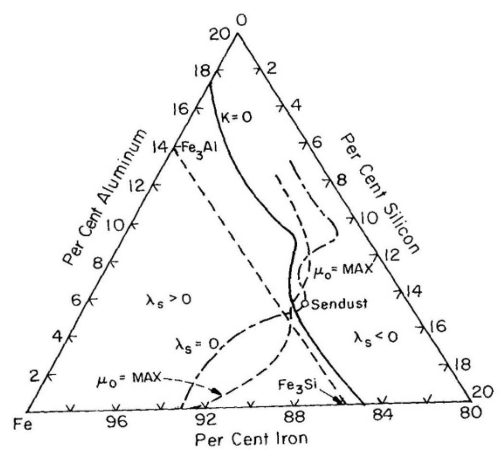


Figure 10.10 Iron-rich corner of ternary Fe-Si-Al diagram (wt%) showing fields of p... tive and negative magnetostriction, the courses of the zero-anisotropy line and maxim... permeability line. The Sendust composition is defined by the intersection of the λ_s = and $K = 0$ lines (Bozorth, IEEE Press, copyright 1994).

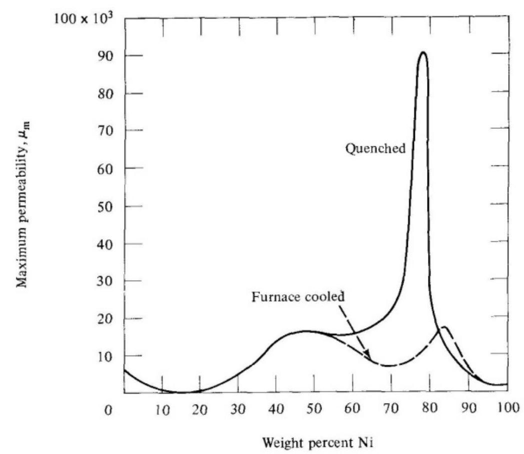


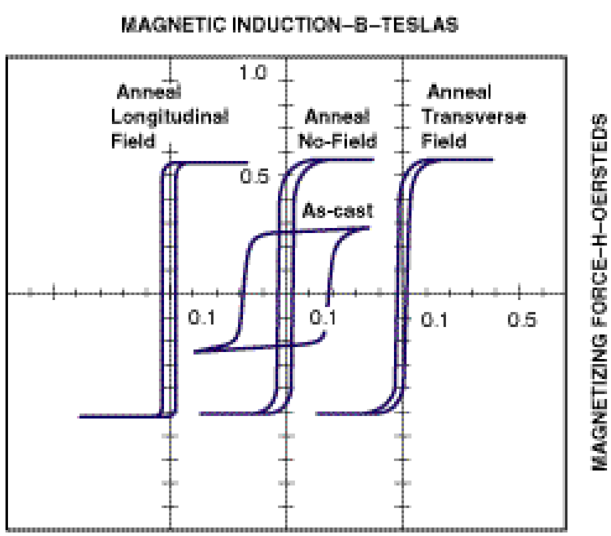
Fig. 13.26 Maximum permeabilities of iron-nickel alloys. Bozorth [13.30].

Amorphous Alloys, “Metglas” (Metallic Glasses)

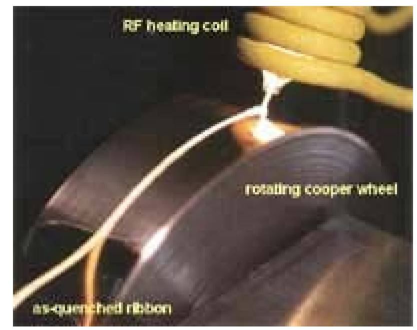
- No crystalline anisotropy

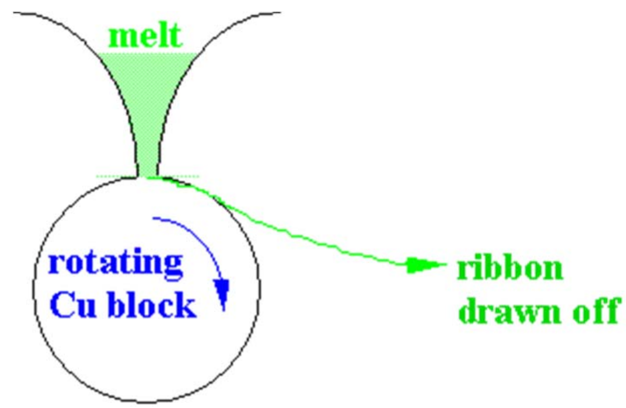
- Ultra-low coercivity and super-high permeability

- Available in thin ribbons only:



- Rapid quenching: melt spinning





Some Soft Magnetic Materials

Material	Composition	Relative Permeability μ_i	μ_{max}	H_c (kA/m)	B_s (T)
Iron	100% Fe	150	5000	80	2.15
Silicon-iron (non-oriented)	96% Fe 4% Si	500	7000	40	1.97
Silicon-iron (grain oriented)	97% Fe 3% Si	1500	40,000	8	2.0
78 Permalloy	78% Ni 22% Fe	8000	100,000	4	1.08
Hipernik	50% Ni 50% Fe	4000	70,000	4	1.60
Supermalloy	79% Ni, 16% Fe 5% Mo	100,000	1,000,000	0.16	0.79
Mumetal	77% Ni, 16% Fe 5% Cu, 2% Cr	20,000	100,000	4	0.65
Permendur	50% Fe 50% Co	800	5000	160	2.45
Hiperco	64% Fe, 35%Co 0.5% Cr	650	10,000	80	2.42
Supermendur	49% Fe, 49%Co 2% V	-	60,000	16	2.40
Metglass (amorphous)	1.6%Ni,4.4%Fe, 8.6%Si,82%Co, 3%B	-	1,000,000	0.01	0.57

Ferrites

Ceramic materials of type $MO \cdot Fe_2O_3$ where M = transition metal

Magnetic properties are not as good as metals.
But, high resistivity makes them useful for high frequency applications.

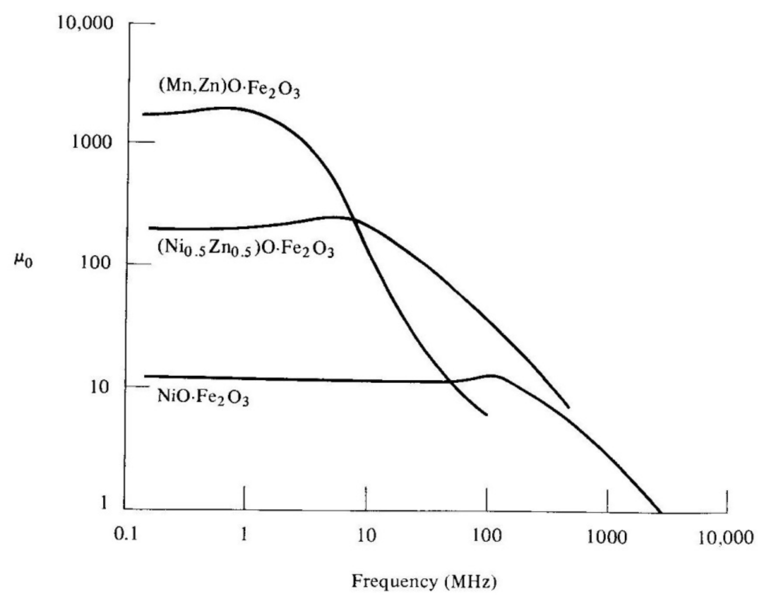


Fig. 13.42 Variation of initial permeability μ_0 with frequency for three ferrites.

Skin depth:

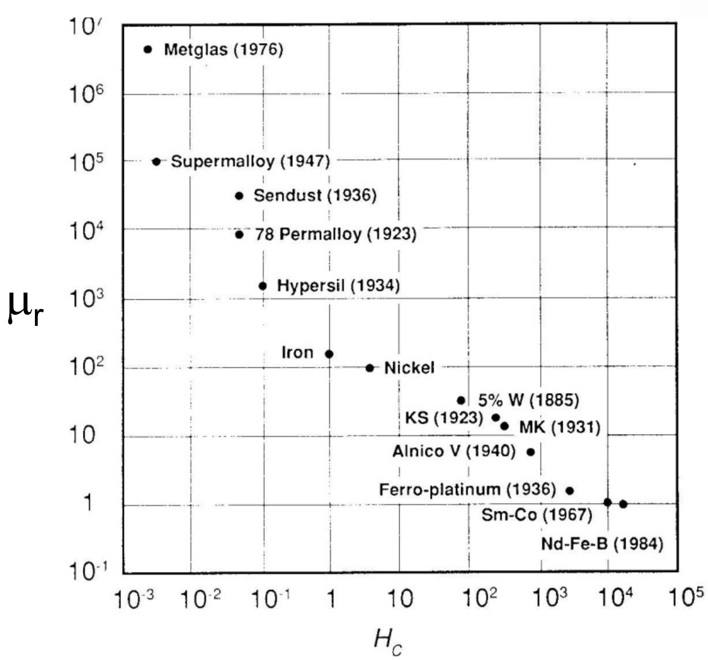
$$\delta = \frac{1}{\sqrt{\mu \sigma \pi f}}$$

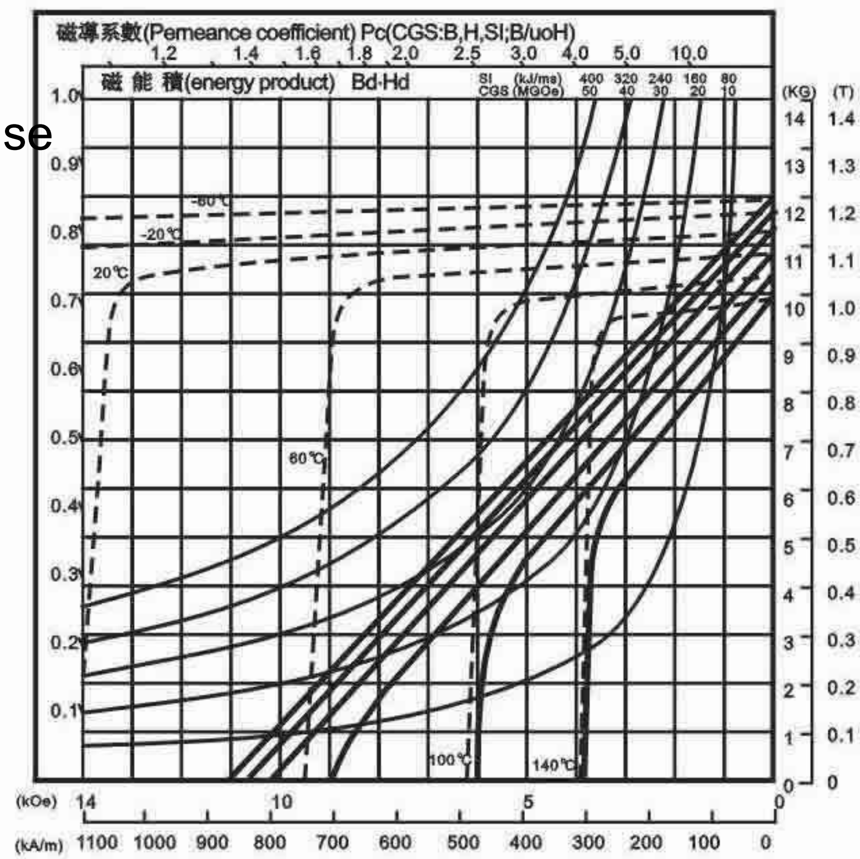
= 8.6 mm for Cu at 60 Hz

= 3 mm for Si-Fe at 60 Hz.

Hard Magnetic Materials

- Permanent magnet materials.
- Manufacturers typically provide data in the form of second quadrant B-H response or "demagnetisation curves"
- Often B and $\mu_0 M$ are plotted on same axis and often in CGS units.
- These days often in Chinese.

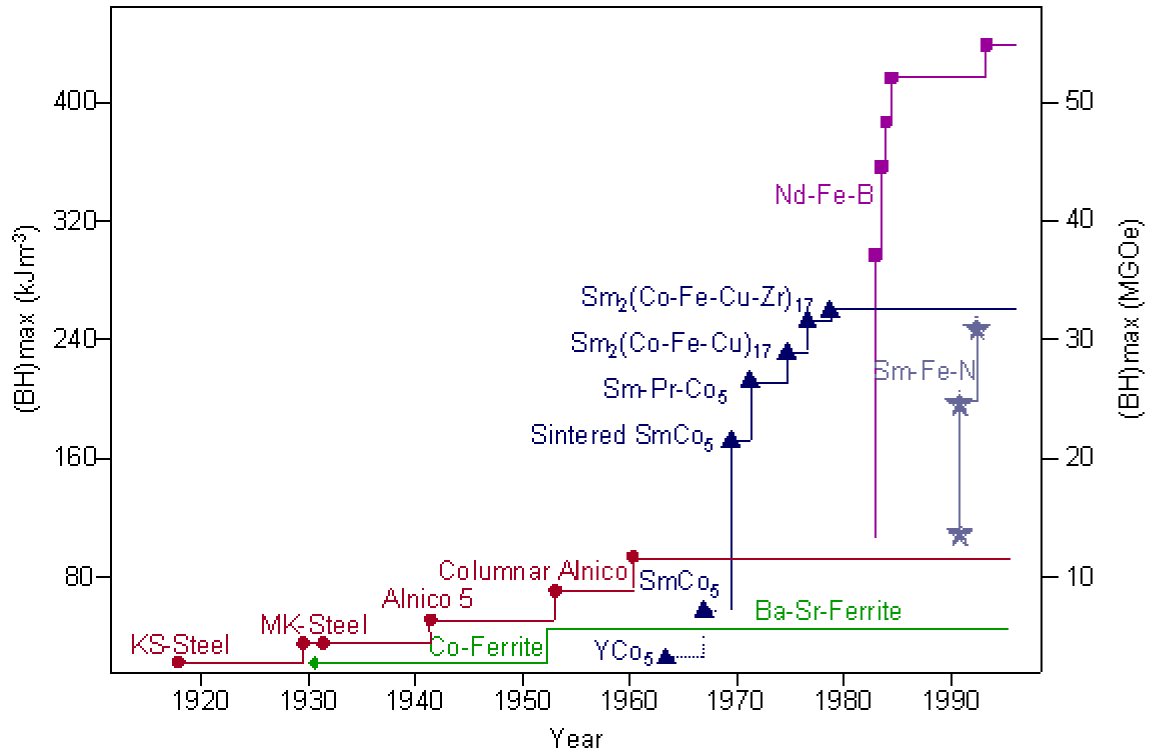




N-30

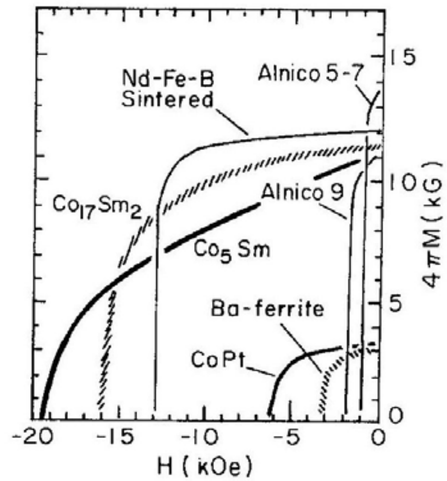
Demagnetization curves of sintered magnet N30 at different temperatures

Advances in Permanent Magnet Materials



http://www.aacg.bham.ac.uk/magnetic_materials/history.htm

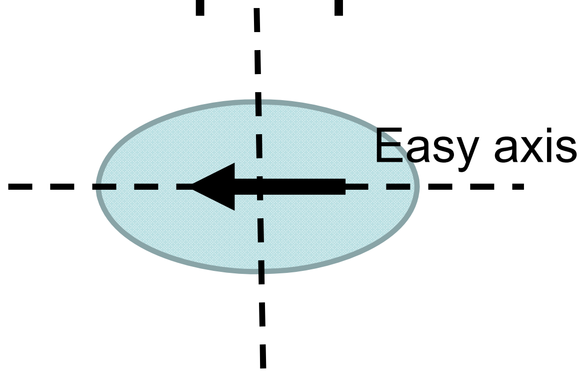
Common Permanent Magnet Materials



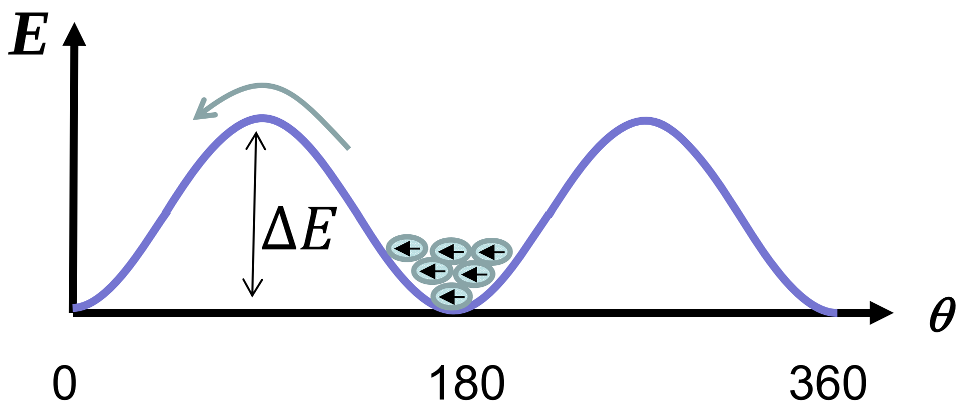
Material	B_r (T)	H_c (kA/m)	$(BH)_{max}$ (kJ/m^3)	T_c of B_r (%/°C)	T_{max} (°C)	T_{curie} (°C)	Cost (relative)	Notes
SmCo	1.05	730	206	-0.04	300	750	Highest (100)	Hard, brittle
NdFeB	1.28	980	320	-0.12	150	310	High (50)	Corrodes easily
Alnico	1.25	50	45	-0.02	540	860	Medium (30)	
Ferrite	0.39	250	28	-0.20	300	460	Low (5)	
Bonded	0.25	160	11	-0.19	100	-	Low (1)	Injection molded

Thermal Decay of Magnetization

Superparamagnetism



For H_a=0:



$$\Delta E \quad = K_u V$$

$$M(t) = M_0 e^{-t/\tau}$$

$$\tau = \tau_0 e^{-\Delta E / k_B T}$$

τ_0 = attempt period ~ 1ns

"Superparamagnetic" if $K_u V < k_B T$