Chapter 11. Magnetic Properties

Magnetic Properties

: Interaction between magnetic field and magnetic moments.

- Two sources for magnetic moment

(1) Orbital angular momentum of electrons in atoms

(2) Intrinsic electron angular momentum

- If an electric field is applied to a polarizable material, a polarization (P), electric dipole moment per volume, is set up.
  $p = qd$

- If an electric filed is applied at an angle to the dipole moment, a torque(T) is developed.

  $T = p \times \varepsilon$

- When p is parallel to ε, minimum energy can be obtained. The dipole should line up parallel to the ε.

  $V = -p \cdot \varepsilon$

Magnetic dipole: $\mu = \mu_0 IA$

Torque: $T = p \times \varepsilon$

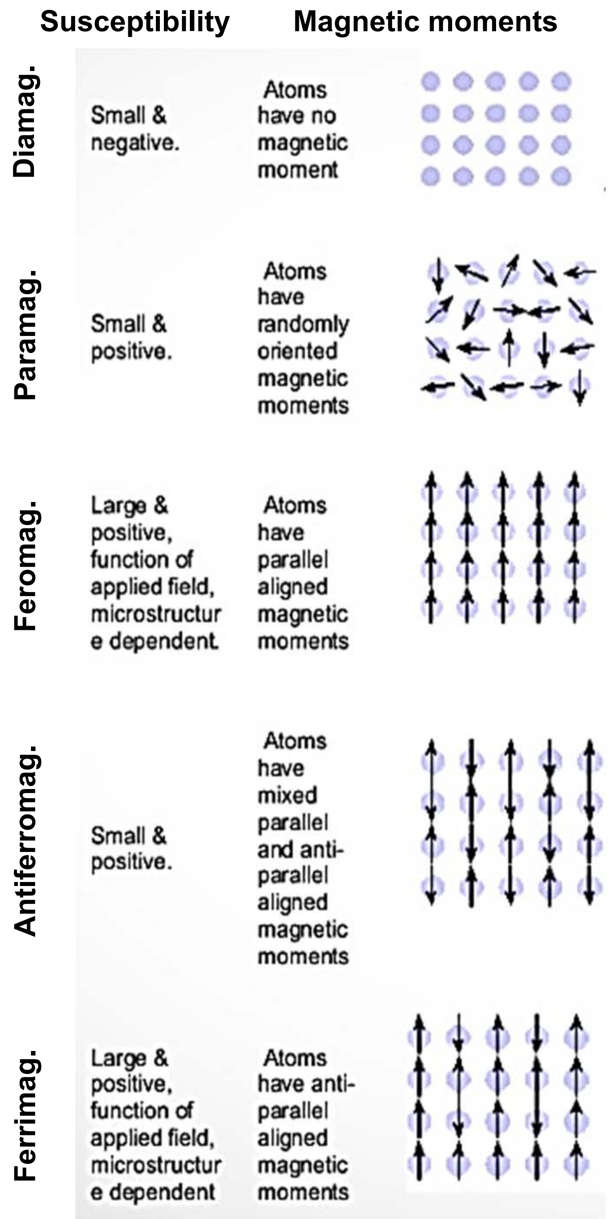
Energy: $V = -\mu \cdot \mathrm{H}$

Magnetization: $M = \sum \mu$

Types of magnetism

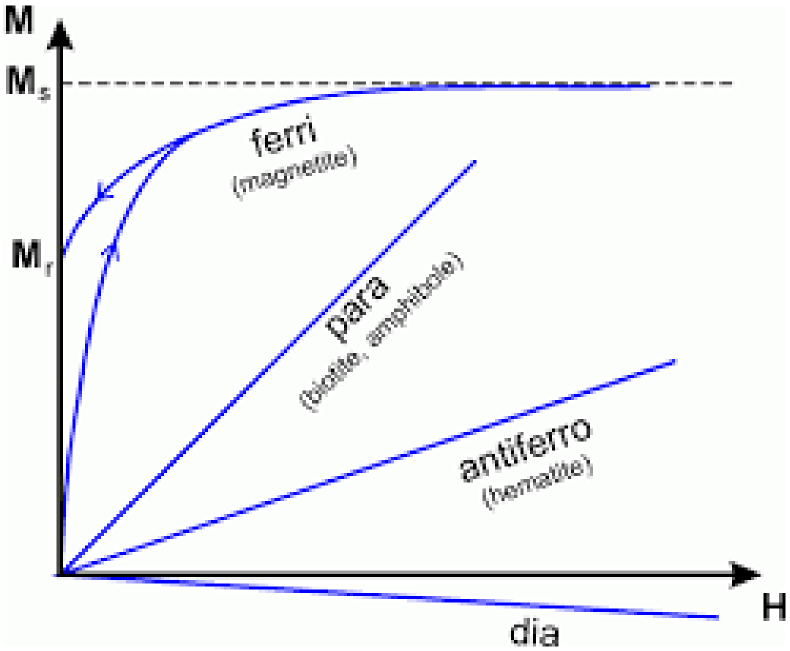
The magnetic susceptibility (x) is defined by $M = xH$, where M is the magnetization of the material (the magnetic dipole moment per unit volume) and H is the magnetic field strength.

Diamegnetism: If a magnetic field is applied to a material without a magnetic moment, a magnetic field is set up from slight repulsion of a material by a magnetic field.
Paramagnetism: The magnetic moments that are present in the absence of magnetic field line up with the magnetic field to decrease total energy. The paramagnetism decreases with increasing temperature due to thermal motion of the atoms.
Ferromagnetism: The presence of a large magnetic moment that persists in the absence of a magnetic field due to spontaneous ordering of the moments by direct interaction below Curie temperature.
Antiferromagnetism: The magnetic moments on neighboring planes are oppositely oriented. (total magnetic moments over finite volume = 0) Antiferromagnetic ordering is destroyed above Néel temperature.
Ferrimagnetism: Ordered structure similar to antiferromag. The number of atoms with opposite spin are unequal so that ferrimagnetic material has a net magnetic moment.

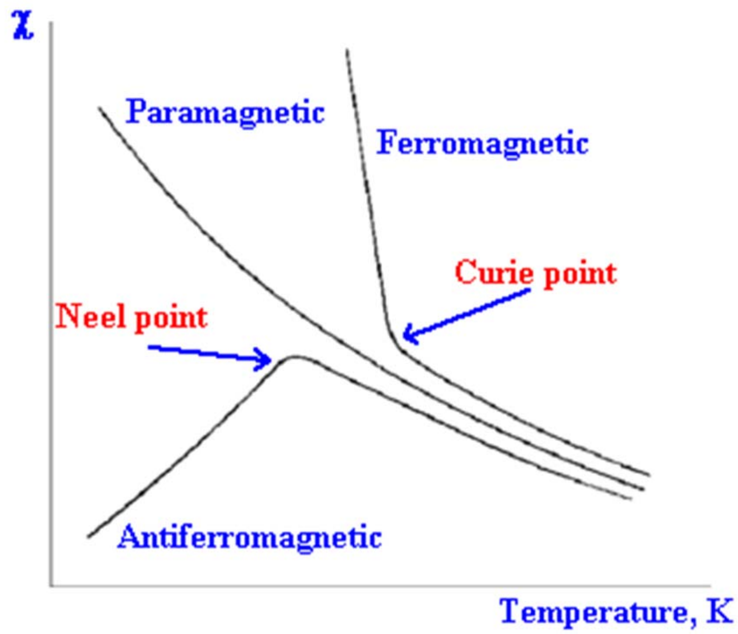


Types of magnetism

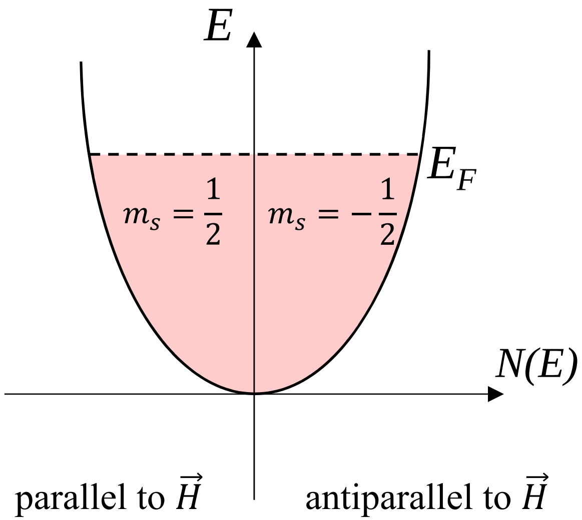
Magnetization



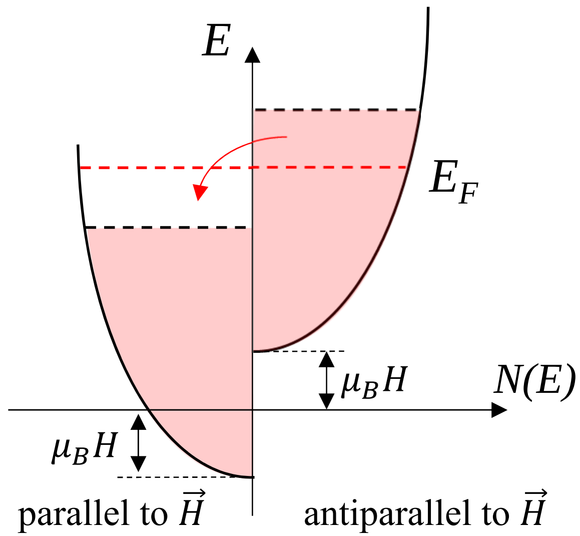
T-dependence of susceptibility



Free electron paramagnetism



$\vec{H} = 0$



$\vec{H} > 0$

In no magnetic field, all the orbital states of lowest energy are occupied by two electrons with opposite spins.

In a magnetic field, electrons with spin magnetic moment in the direction of the magnetic field have their energy lowered by $\mu_B H$ and the electrons with opposite spin have their energy increased by $\mu_B H$.

Free electron paramagnetism

Application of H produces more electrons of $2\mu_\mathrm{B}HN(E_F)$ with spin parallel to H than with spin opposite to H.

- Induced magnetic moment per unit volume
  $M = 2{\mu_\mathrm{B}}^2 HN(E_F)/v$

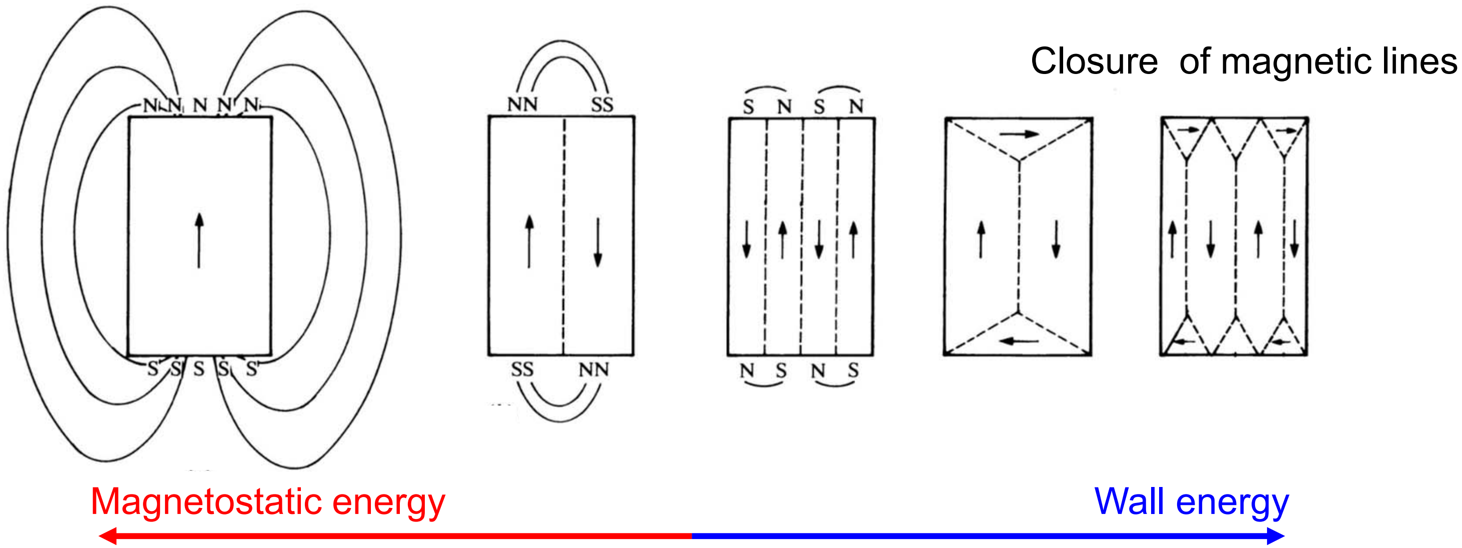
- Magnetic susceptibility
  $k = 2{\mu_\mathrm{B}}^2 N(E_F)/v$
  $\because\ N(E_F) = (vm/2\pi^2\hbar^2)(3\pi^2 n)^{1/3}$ (eq. 6.19)

$$k = ({\mu_\mathrm{B}}^2 m/\pi^2\hbar^2)(3\pi^2 n)^{1/3}$$

$\Rightarrow$Free-electron paramagnetism is proportional to $n^{1/3}$ and T-independent.

Ferromagnetic domains

- All practical ferromagnetic materials consist of magnetic domain in the absence of an applied magnetic field.
- Domain exist in magnetic material in order to minimize the total magnetic energy which has several different contributions.

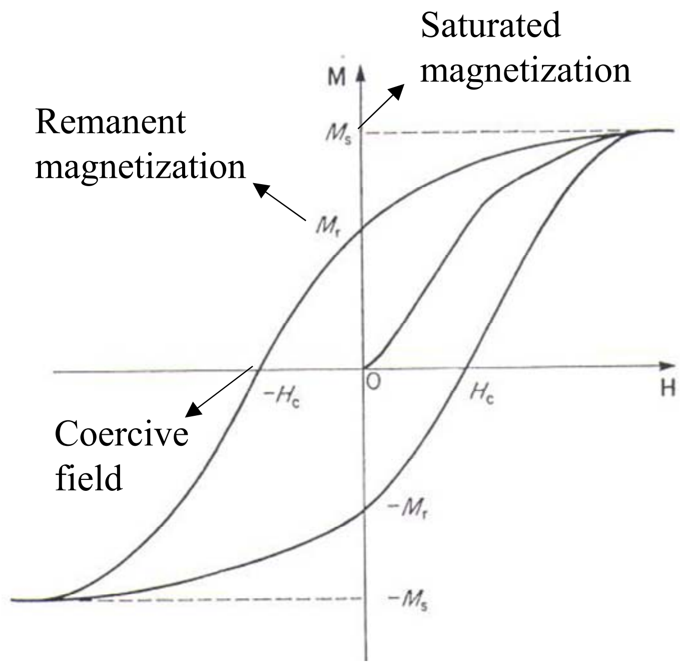


The spontaneous parallel alignment of magnetic moments with in a crystal results in a large saturation magnetization (M_s). The aligned magnetic moments also produce a large external magnetic field. There is a substantial energy associated with the external field (*magnetostatic energy*) that should be reduced. Formation of magnetic domains with the crystal eliminates the external field and thereby lowers the magnetostatic energy. However, more (smaller) domains increases the *wall energy*. At equilibrium of minimum total energy of magnetostatic and wall energy, single domain size is 10-100 nm.

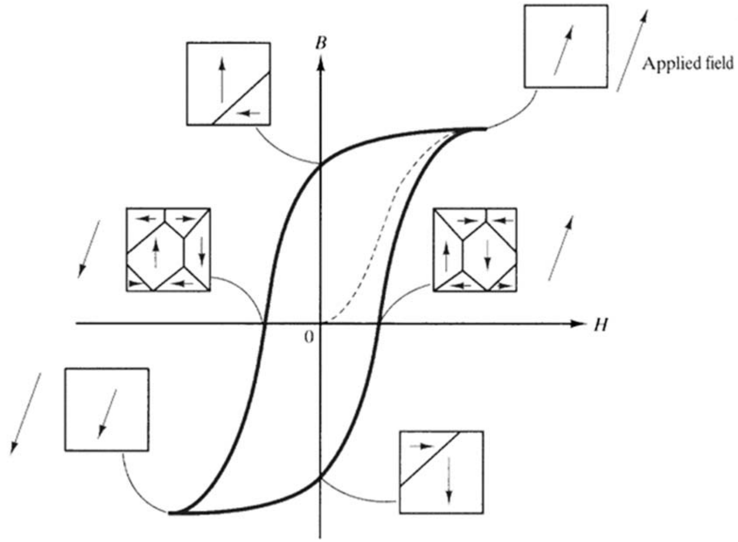
Ferromagnetic Hysteresis

- Origin ~ defects and inclusions

  Many defects in domains → large hysteresis



- "Hard" magnetic materials
  - High M_r, High H_c
  - Many defects
  - Useful as permanent magnet



- "Soft" magnetic materials
  - Smaller M_r, Smaller H_c
  - Few defects and inclusions
  - Useful for transformer cores or for electromangnets