

#### 4.1.4 Summary to: Magnetic Materials - Definitions and General Relations

The **relative permeability**  $\mu_r$  of a material "somehow" describes the interaction of magnetic (i.e. more or less all) materials and magnetic fields  $H$ , e.g. vial the equations  $\Rightarrow$

- $B$  is the **magnetic flux density** or **magnetic induction**, sort of replacing  $H$  in the Maxwell equations whenever materials are encountered.
- $L$  is the inductivity of a linear solenoid (also called coil or inductor) with length  $l$ , cross-sectional area  $A$ , and number of turns  $t$ , that is "filled" with a magnetic material with  $\mu_r$ .
- $n$  is *still* the index of refraction; a quantity that "somehow" describes how electromagnetic fields with extremely high frequency interact with matter.  
For all practical purposes, however,  $\mu_r = 1$  for optical frequencies

$$B = \mu_0 \cdot \mu_r \cdot H$$

$$L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot w^2}{l}$$

$$n = (\epsilon_r \cdot \mu_r)^{1/2}$$

Magnetic fields inside magnetic materials polarize the material, meaning that the vector sum of magnetic dipoles inside the material is no longer zero.

- The decisive quantities are the **magnetic** dipole moment  $\underline{m}$ , a vector, and the **magnetic** Polarization  $\underline{J}$ , a vector, too.
- Note: In contrast to dielectrics, we define an additional quantity, the **magnetization**  $\underline{M}$  by simply including dividing  $\underline{J}$  by  $\mu_0$ .
- The magnetic dipoles to be polarized are either already present in the material (e.g. in **Fe**, **Ni** or **Co**, or more generally, in all **paramagnetic** materials, or are induced by the magnetic fields (e.g. in **diamagnetic** materials).
- The dimension of the magnetization  $\underline{M}$  is **[A/m]**; i.e. the same as that of the magnetic field.

$$B = \mu_0 \cdot H + J$$

$$\underline{J} = \mu_0 \cdot \frac{\sum \underline{m}}{V}$$

$$\underline{M} = \frac{J}{\mu_0}$$

The magnetic polarization  $\underline{J}$  or the magnetization  $\underline{M}$  are *not* given by some magnetic surface charge, because  $\Rightarrow$ .

There is no such thing as a **magnetic monopole**, the (conceivable) counterpart of a negative or positive electric charge

The equivalent of "Ohm's law", linking current density to field strength in conductors is the **magnetic** Polarization law:

- The decisive material parameter is  $\chi_{mag} = (\mu_r - 1) =$  **magnetic susceptibility**.
- The "classical" induction  $B$  and the magnetization are linked as shown. In essence,  $\underline{M}$  only considers what happens in the material, while  $\underline{B}$  looks at the total effect: material plus the field that induces the polarization.

$$\underline{M} = (\mu_r - 1) \cdot H$$

$$\underline{M} := \chi_{mag} \cdot H$$

$$\underline{B} = \mu_0 \cdot (H + \underline{M})$$

Magnetic polarization mechanisms are formally similar to dielectric polarization mechanisms, but the physics can be entirely different.

**Atomic mechanisms of magnetization are not directly analogous to the dielectric case**

Magnetic moments originate from:

- The intrinsic magnetic dipole moments  $m$  of elementary particles with spin is measured in units of the Bohr magneton  $m_{\text{Bohr}}$ .
- The magnetic moment  $m^e$  of the electron is  $\Rightarrow$
- Electrons "orbiting" in an atom can be described as a current running in a circle thus causing a magnetic dipole moment; too

$$m_{\text{Bohr}} = \frac{h \cdot e}{4\pi \cdot m^* e} = 9.27 \cdot 10^{-24} \text{ Am}^2$$

$$m^e = \frac{2 \cdot h \cdot e \cdot s}{4\pi \cdot m^* e} = 2 \cdot s \cdot m_{\text{Bohr}} = \pm m_{\text{Bohr}}$$

▶ The total magnetic moment of an atom in a crystal (or just solid) is a (tricky to obtain) sum of all contributions from the electrons, and their orbits (including bonding orbitals etc.), it is either:

- **Zero** - we then have a **diamagnetic material**.

**Magnetic field induces dipoles, somewhat analogous to electronic polarization in dielectrics. Always very weak effect (except for superconductors) Unimportant for technical purposes**

- In the order of a few Bohr magnetons - we have a essentially a **paramagnetic material**.

**Magnetic field induces some order to dipoles; strictly analogous to "orientation polarization" of dielectrics. Always very weak effect Unimportant for technical purposes**

▶ In some **ferromagnetic** materials spontaneous ordering of magnetic moments occurs below the Curie (or Neél) temperature. The important families are

- Ferromagnetic materials  $\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow$  large  $\mu_r$ , **extremely important**.
- Ferrimagnetic materials  $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow$  still large  $\mu_r$ , **very important**.
- Antiferromagnetic materials  $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow$   $\mu_r \approx 1$ , unimportant

**Ferromagnetic materials: Fe, Ni, Co, their alloys "AlNiCo",  $\text{Co}_5\text{Sm}$ ,  $\text{Co}_{17}\text{Sm}_2$ , "NdFeB"**

▶ There is characteristic temperature dependence of  $\mu_r$  for all cases

**Questionnaire**  
Multiple Choice questions to all of 4.1