Magnetic sensors

Magnetic field:
- *H* : Magnetic field strength. Unit: A/m)
- *B* : Magnetic flux density (magnetic induction) Unit: **Tesla** (T)
  Non-SI unit, still commonly used: **Gauss**: 1 Gauss = 100 μT

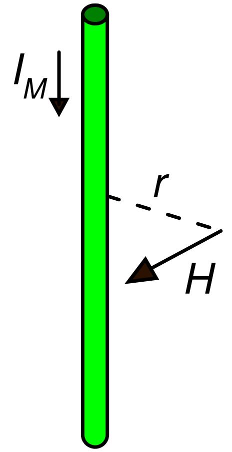
In a medium of magnetic permeability μ:

$$B = \mu H$$

Vacuum permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m (H=Henry).

Example of electric field magnitude

Earth's magnetic field: 25 to 65 μT



Magnetic field produced by a current

$$H = \frac{I_M}{2\pi r}$$

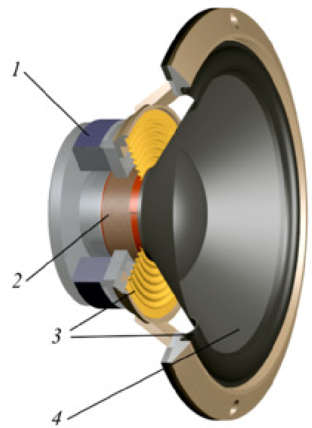
$$B = \mu H$$

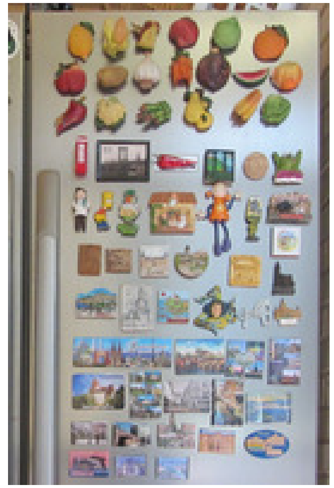
Example:
$\mu=\mu_0$ (air, vacuum ...)
I_M=1 A, r=10 cm

B=20 μT

General purpose permanent magnets (e.g. "refrigerator magnets") B=5-20 mT

Inside the gap of loudspeaker magnets: ~ 1 T





Refrigerator magnets

Applications of magnetic sensors

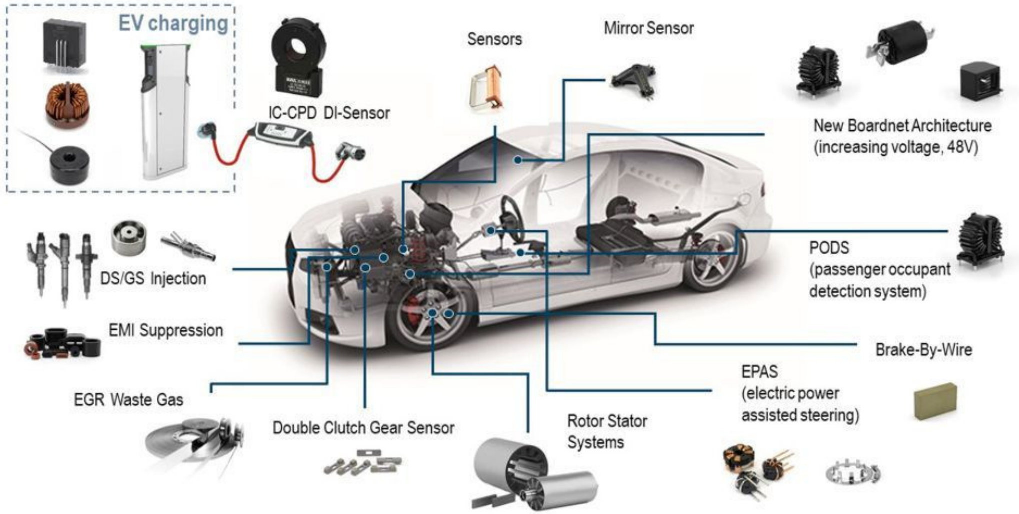
Magnetic compass:

- Aid to navigation
- Orientation finding
- Accuracy improvement of IMUs (inertial measurement units)

Proximity sensors

Angular position sensors

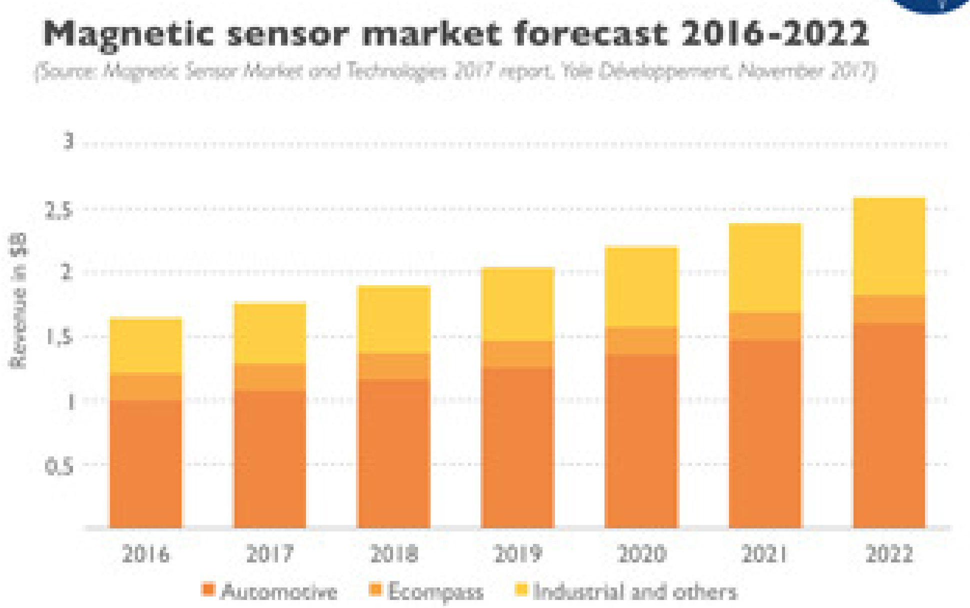
Contactless current measurements

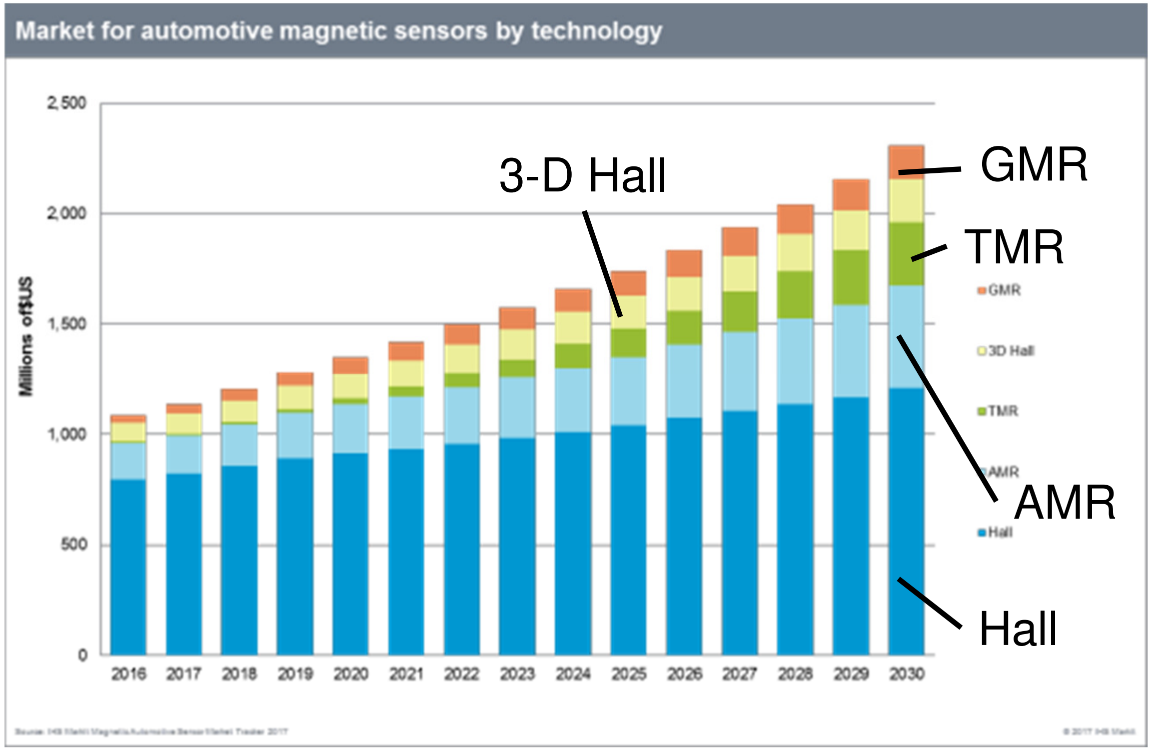


Magnetic sensors: market

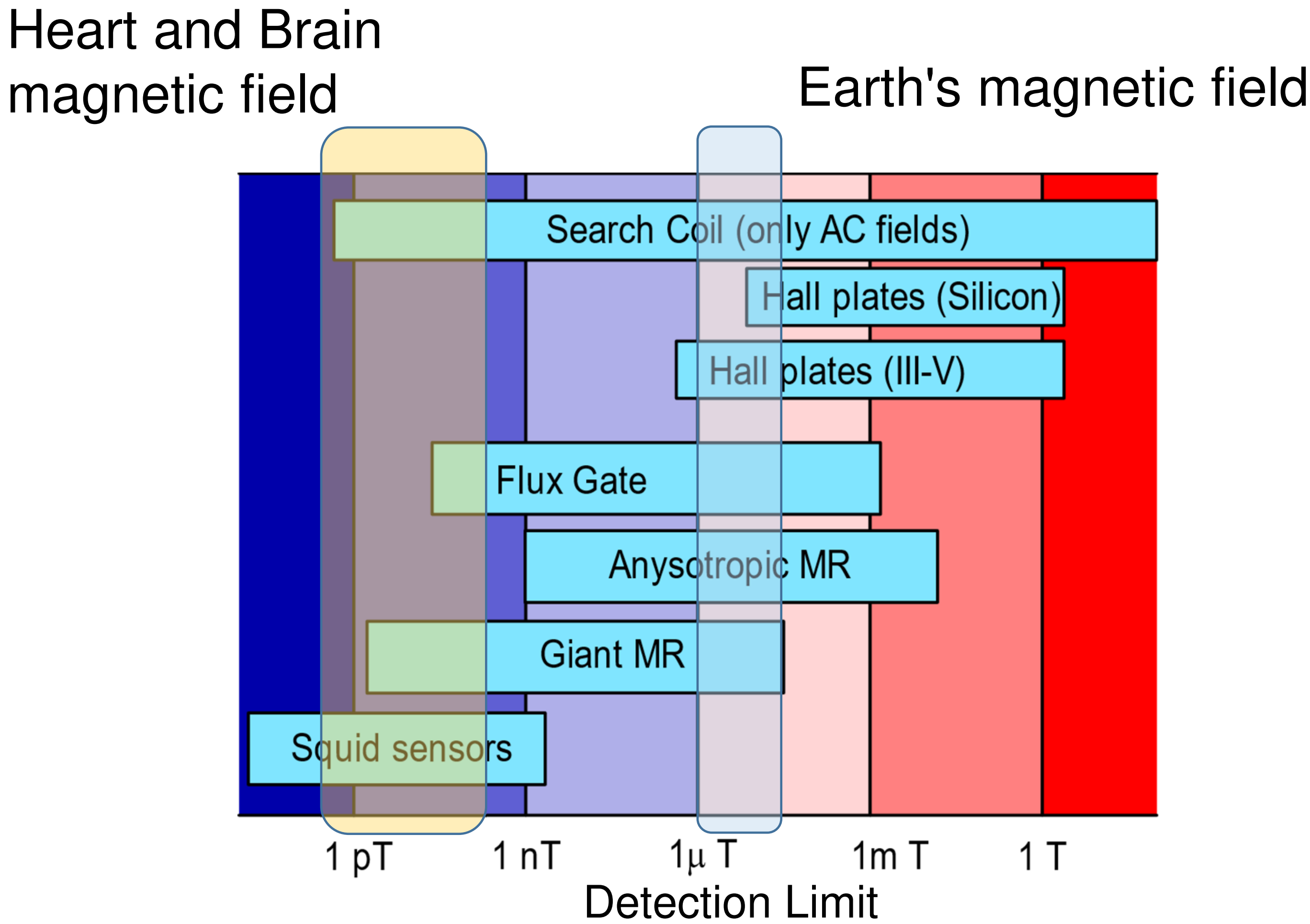
By Type (in automotive)

By Application

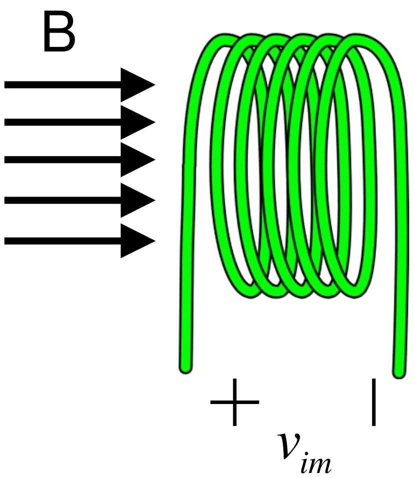


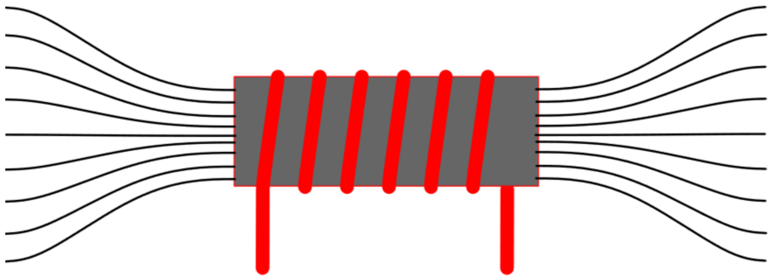


Types of magnetic sensors



Search Coil





A ferromagnetic nucleus can be used to concentrate the field lines, increasing the sensitivity

$$v_{im} = -\frac{d\Phi}{dt} \cong N \cdot A \frac{dB}{dt}$$

AC Fields only!

$$B = B_M \cos(\omega t) \qquad v_{im} = -B_M N \cdot A\omega \sin(\omega t)$$

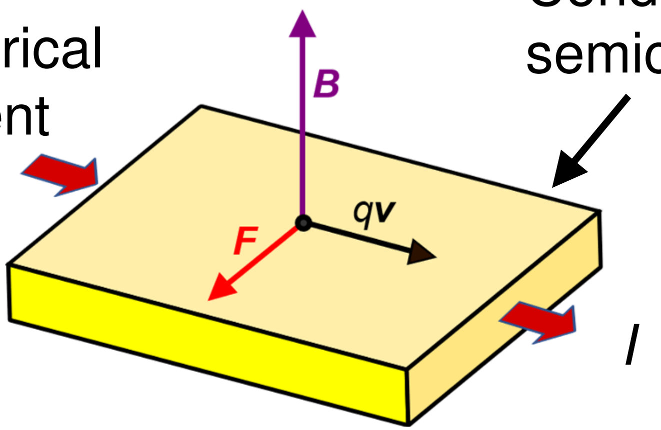
The search coil needs the magnetic flux to be variable. Constant magnetic fields can be measured only mechanically rotating or vibrating the coil.

Hall sensors

Basic Hall effect:
Discovered by Edwin Hall in 1879

Electrical current

Conductor or semiconductor plate

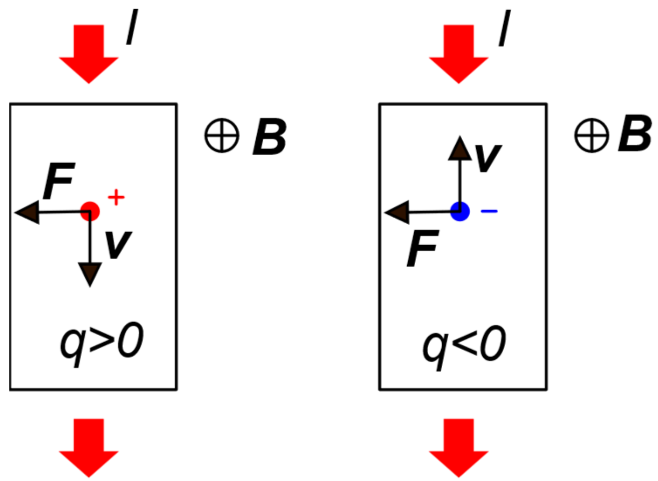


$\boldsymbol{F}$: Lorentz Force

$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

Positive charge carriers

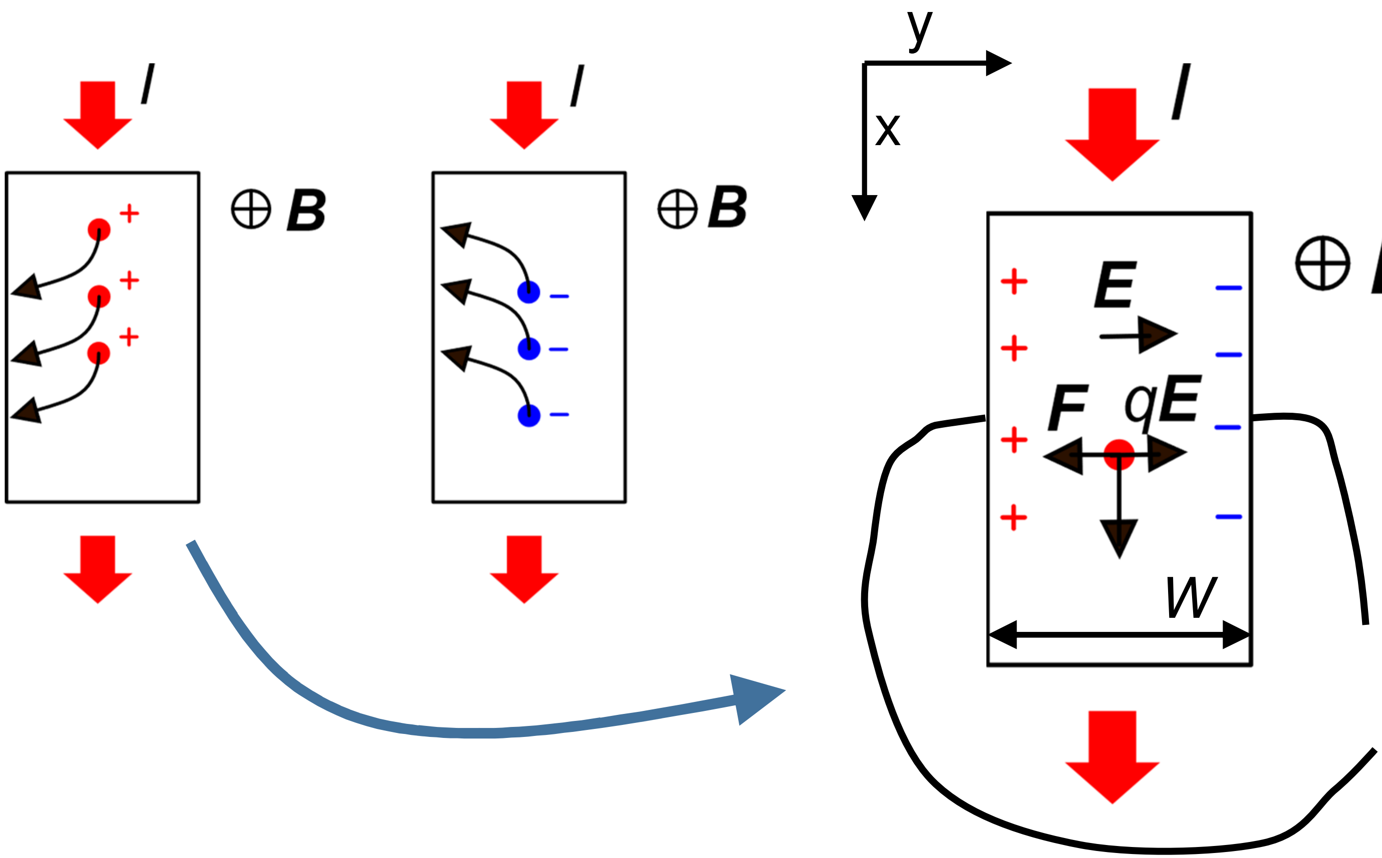
Negative charge carriers



q: charge of the charge carrier (can be positive or negative)
$\boldsymbol{v}$: charge carrier velocity
$\boldsymbol{B}$: Magnetic induction field

The force has the same direction

Hall effect: formation of the Hall voltage



$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

$$F = qvB$$

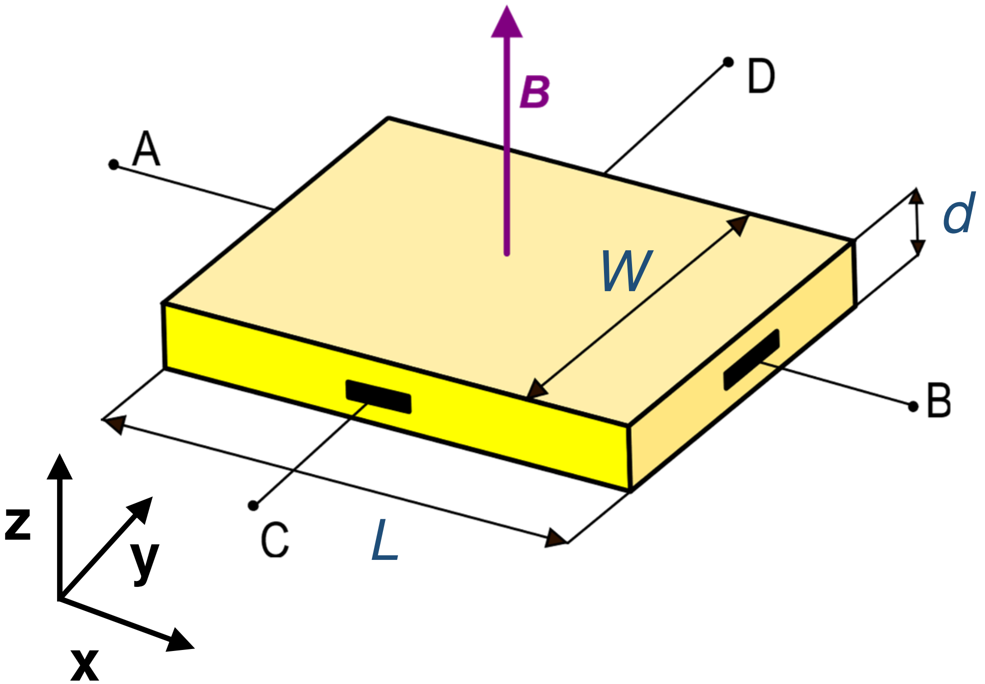
Stationary conditions:

$$qE_Y = F$$

$$E_Y = vB$$

$$\overset{+}{\underset{-}{V_H}} = E_Y W = vBW$$

Hall Voltage



$$V_{CD} = V_H = E_Y W = vBW$$

$$v = \mu E_X$$

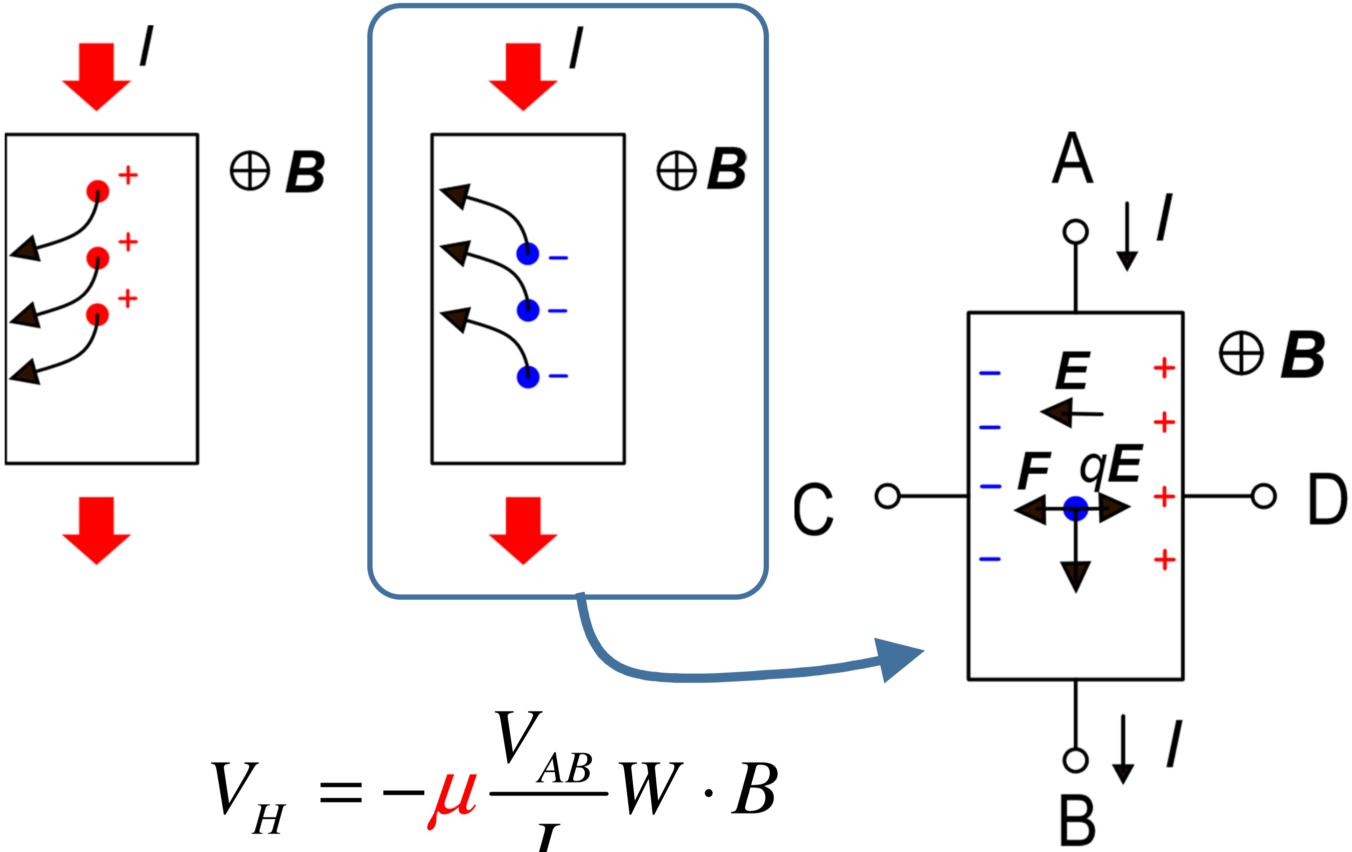
$$V_H = \mu E_X W \cdot B$$

$$E_X = \frac{V_{AB}}{L}$$

$$V_H = \mu \frac{V_{AB}}{L} W \cdot B$$

The Hall effect can be used to determine the carrier mobility μ

Case of negative charges:

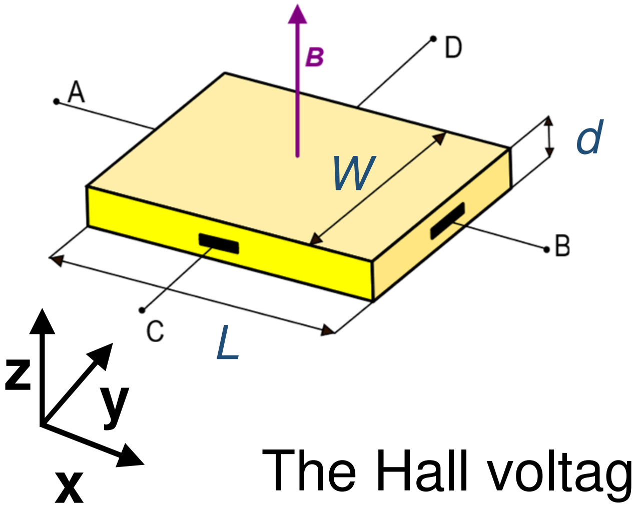


$$V_H = -\mu \frac{V_{AB}}{L} W \cdot B$$

The Hall voltage change sign if the sign of the charge charrier is changed

The Hall effect can be used to determine if the main charge carries are **holes** or **electrons**

Hall Voltage: a more practical expression



$$V_H = vBW \qquad J = \frac{I}{Wd} = qnv$$

$$V_H = \frac{I}{qnd}B \qquad v = \frac{J}{qn} = \frac{I}{qnWd}$$

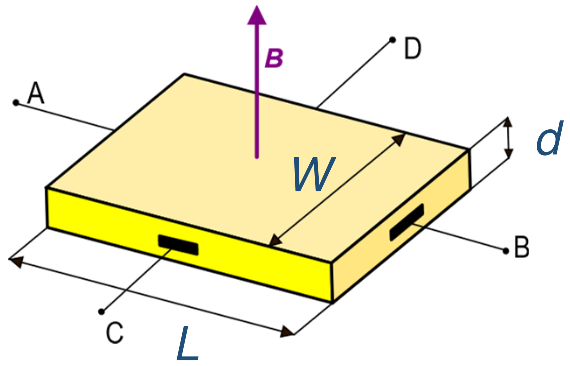
The Hall voltage is proportional to both the magnetic field (B) and the bias current (I)

For this reason, the sensitivity is generally expressed in:

V / (A T)

"Volt per Ampere Tesla"

Examples of Hall voltage magnitude



d=1 μm (possible thickness of an interconnection layer in an Integrated circuit)

$$V_H = \frac{1}{qnd} I \cdot B$$

Copper: $n \sim 8 \times 10^{22}\ \mathrm{cm^{-3}} = 8 \times 10^{28}\ \mathrm{m^{-3}}$

$$\frac{1}{qnd} = \frac{1}{1.6\times10^{-19} \cdot 8\times10^{28} \cdot 10^{-6}} \cong 78\ \mu\mathrm{V/A/T}$$

n-Si with $N_D=10^{-16}\ \mathrm{cm^{-3}}$: n= $N_D = 1 \times 10^{22}\ \mathrm{m^{-3}}$ $\quad \frac{1}{qnd} = 625\ \mathrm{V/A/T}$