MAGNETIC SENSORS

Content:

Hall probes
Magnetoresistances
Electromagnetic induction

Magnetic field

- Charge generates electric and magnetic fields according to their motion.
  - Still charge → electric field; moving charge → electric field and magnetic field; accelerated charge → electromagnetic field.
- Sensors of magnetic fields are used for direct evaluation of magnetic fields
  - Terrestrial magnetic field (compass), biomagnetism,..
- Or for indirect measurements
  - E.g. position sensors

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Magnetic fields sensors are based:
  On the interaction with charges in motion (electric current)
    Hall effect, magnetoresistors, magnetodiodes, MagFET…
  On the interaction with electron spin
    Anisotropy Magneto-Resistances, Giant Magneto-Resistance
  On the interaction between magnetic fields
    Fluxgate magnetometers

Magnetic field measurement units and typical values

	MKS	CGS
Induced magnetic field B	Tesla [V s m^{-2}]	Gauss [1 T=10^4 G]
Magnetic field H	Ampere per metro [A/m]	Oersted [1Oe=79A/m]

$$B = \mu \cdot H \qquad \mu = \mu_r \cdot \mu_0 \quad magnetic\ \ permeability \qquad \mu_0 = 4\pi \cdot 10^{-7} \frac{V \cdot s}{m \cdot A}$$

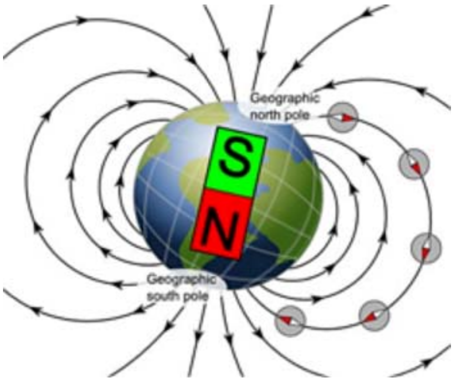
Practical unit: gamma $1\gamma = 10^{-5} G = 10^{-9} T$

Terrestrial magnetic field	≈ 0.5 G
Magnetic field at 1 cm from a conductor carrying a current of 1 A	≈ 0.2 G
Heart magnetic field	≈ 10^{-6} G = 0.1 γ
Brain magnetic field	≈ 10^{-10} G = 10 μγ

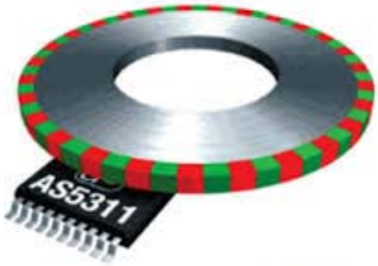
Main applications

Compass for navigation

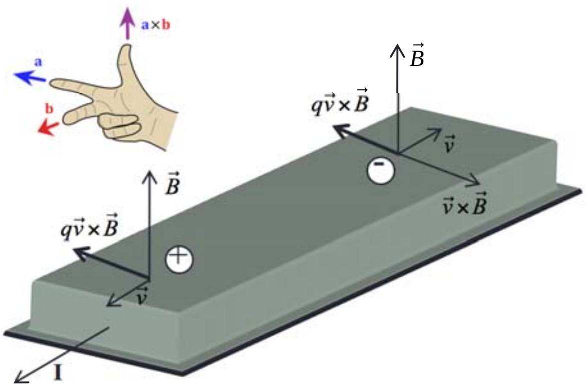
B_{earth}~50 μT



Position sensors



Hall effect



In a current-carrying conductor the Lorentz force is balanced by a transversal electric field created by the charges displacement (Hall electric Field).

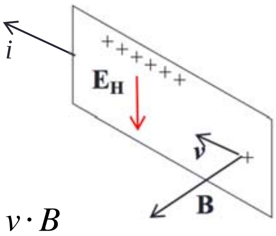
$$\vec{F}_L = q\vec{v}\times\vec{B};\quad \vec{F}_E = q\vec{E}_H$$

$$q\cdot v\cdot B = q\cdot E_H \Rightarrow E_H = v\cdot B$$

Positive charge carriers

$$\vec{F}_L = +q(+\vec{v})\times\vec{B}$$

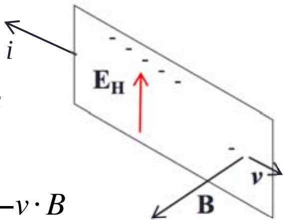
$$q\cdot E_H = q\cdot v\cdot B \Rightarrow E_H = v\cdot B$$



Negative charge carriers

$$\vec{F}_L = -q(-\vec{v})\times\vec{B}$$

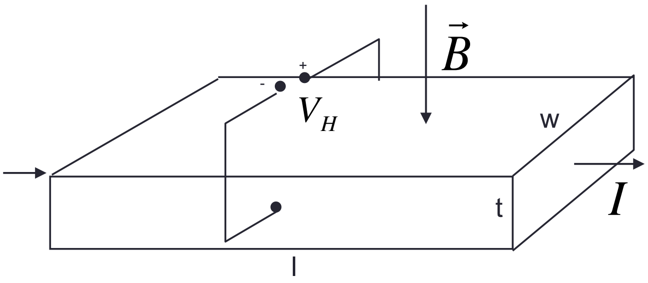
$$-q\cdot E_H = q\cdot v\cdot B \Rightarrow E_H = -v\cdot B$$



The direction of the Hall electric Field depends on the sign of the charge carriers.
Discrimination between N and P type semiconductors.

Hall effect based magnetic sensor

- The voltage drop across the section of the conductor is proportional to the magnetic field.



A: cross-section of the conductor A=w t
n: charge carriers concentration
q: elementary charge

$$I = q\cdot v\cdot n\cdot A \;\Rightarrow\; v = \frac{I}{q\cdot n\cdot A} = \frac{I}{q\cdot n\cdot w\cdot t}$$

$$V_H = w\cdot E_H = w\cdot v\cdot B$$

$$V_H = w\cdot\frac{I}{q\cdot n\cdot w\cdot t}\cdot B \Rightarrow V_H = \frac{I}{q\cdot n\cdot t}\cdot B$$

Hall coefficient: $R_H = \frac{1}{qn} = \frac{V_H\cdot t}{I\cdot B}$

Sensitivity is inversely proportional to the carriers concentration and to the thickness of the conductor. The largest sensitivity is achieved by semiconductor thin films.

Hall effect in metals and semiconductors

- Numerical examples
  - metal

$$t = 0.2\,mm$$

$$n = 8.5\times10^{28}\ m^{-3}$$

$$I = 1\,A$$

$$S_H = \frac{I}{q\cdot n\cdot t} = \frac{1}{1.6\times10^{-19}\cdot 8.5\times10^{28}\cdot 2\times10^{-4}} = 0.37\ \frac{\mu V}{T}$$

  - Doped semiconductor

$$t = 0.2\,mm$$

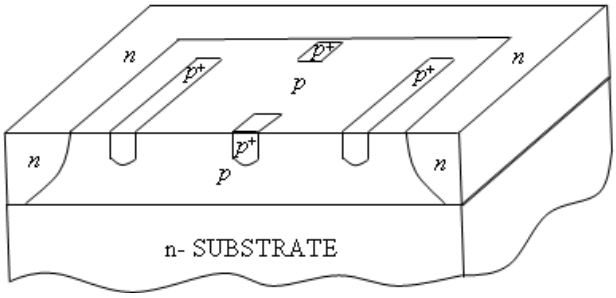
$$n = 1\times10^{20}\ m^{-3}$$

$$I = 10\,mA$$

$$S_H = \frac{I}{q\cdot n\cdot t} = \frac{10^{-2}}{1.6\times10^{-19}\cdot 1\times10^{21}\cdot 2\times10^{-4}} = 0.31\ \frac{V}{T}$$

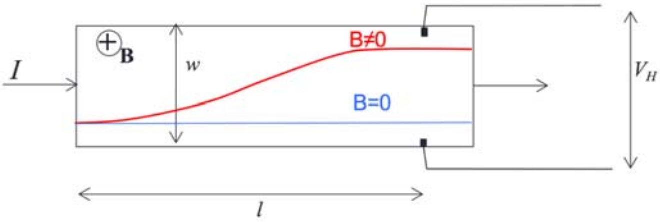
Hall probe

- The hall probe is a thin semiconductor with four orthogonal contacts.
- It can be fabricated either as a thin film on a insulating substrate or as an implanted layer on a semiconductor wafer.
- Doping is light because the sensitivity is inversely proportional to the carriers concentrations
- Most used materials are InSb, InAs, GaAs, Si, and Ge. Composite semiconductors are characterized by a large mobility, but silicon is preferred for integrated sensors.
- Typical sensitivities are of the order of 100 V/A*T but up to1000 V/A*T can be achieved.
- Resolution can be of the order of 10 mG.

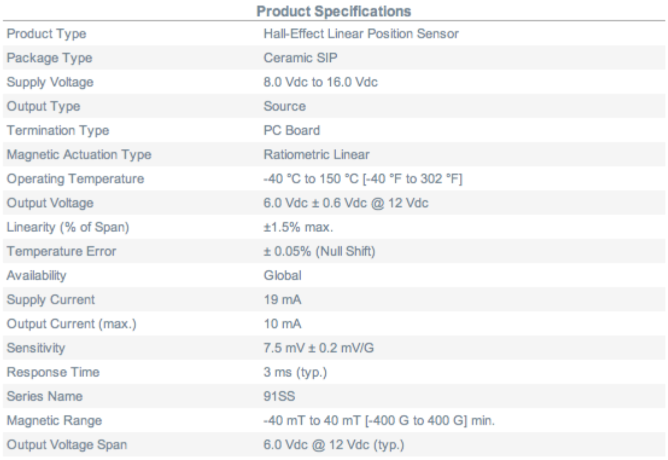


Size effect.

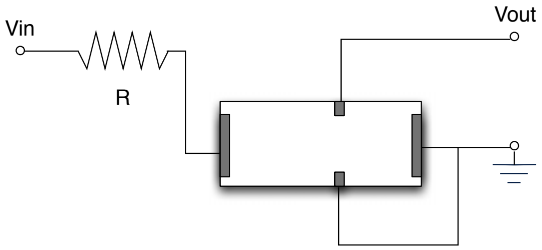
- If l is too short, the charges reach the electrode with a small deflection and then the electric field is not in equilibrium with the Lorentz force.
- To consider this effect a geometrical factor is introduced (G<1) proportional to l/w. In pratice, G=1 when l>3 w.

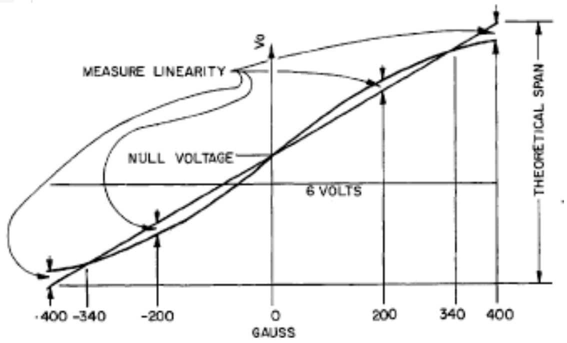


Honeywell 91SS12



Product Specifications	
Product Type	Hall-Effect Linear Position Sensor
Package Type	Ceramic SIP
Supply Voltage	8.0 Vdc to 16.0 Vdc
Output Type	Source
Termination Type	PC Board
Magnetic Actuation Type	Ratiometric Linear
Operating Temperature	-40 °C to 150 °C [-40 °F to 302 °F]
Output Voltage	6.0 Vdc ± 0.6 Vdc @ 12 Vdc
Linearity (% of Span)	±1.5% max.
Temperature Error	± 0.05% (Null Shift)
Availability	Global
Supply Current	19 mA
Output Current (max.)	10 mA
Sensitivity	7.5 mV ± 0.2 mV/G
Response Time	3 ms (typ.)
Series Name	91SS
Magnetic Range	-40 mT to 40 mT [-400 G to 400 G] min.
Output Voltage Span	6.0 Vdc @ 12 Vdc (typ.)

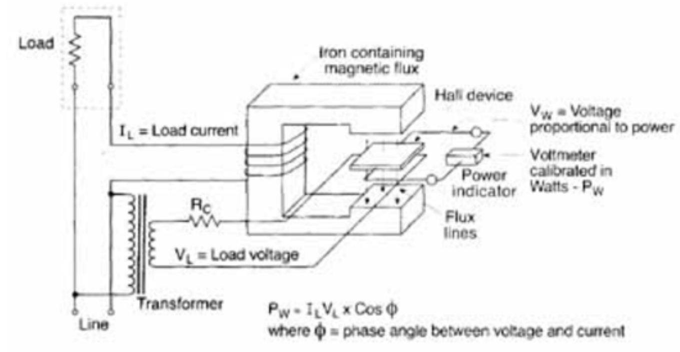




Wattmeter with a Hall sensor

- Hall sensors can enable the product of currents and voltages.
- For instance, Hall sensors can be used to measure the power of a a.c. signal

P=V*I V_L provides the current to the sensor and I_L generates the magnetic field



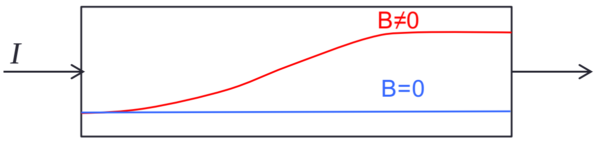
$$B=\mu\cdot N_S\cdot I_L;$$

$$I_H=\frac{V_L}{R_C+R_S}$$

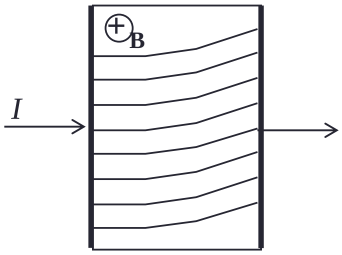
$$V_H=S_H\cdot I_H\cdot B=S_H\cdot\frac{V_L}{R_C+R_S}\cdot\mu\cdot N_S\cdot I_L=K\cdot P$$

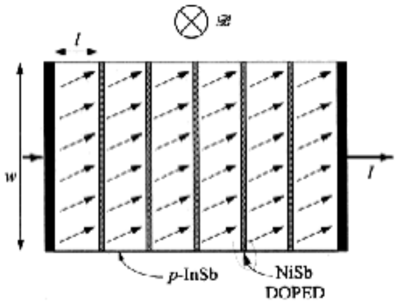
$$K=S_H\cdot\frac{\mu\cdot N_S}{R_C+R_S}$$

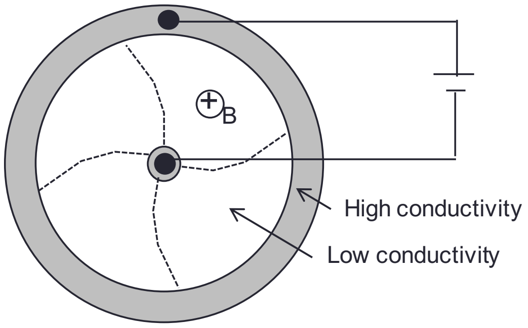
Magnetoresistance



- Electric resistance is proportional to the path travelled by the charges.
- The magnetic field deflects the trajectories of the charges and then it increases the electric resistance.
- The effect is more intense if the Lorentz force is not equilibrated by the Hall electric field. This happens in conductors where the length is almost 3 times smaller than the width (l<3 w).
- To maximize the effects subtle layers of conductors are sandwiched between metallic conductors.







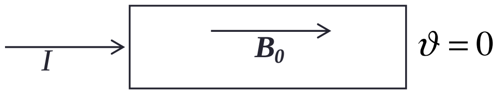
Corbino disk: the circular structure avoids the formation of the Hall electric field.

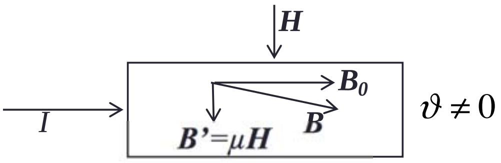
Interaction with electronic spin
Anisotropic MagnetoResistance (AMR)

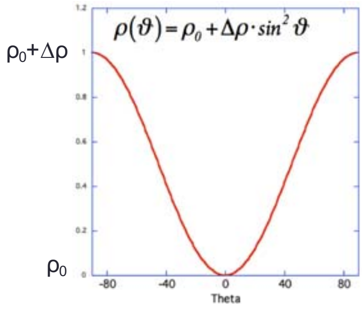
- In ferromagnetic materials the probability of charge scattering, and then the resistivity, is a function of the angle between the current vector (**J**) and the magnetic field (**B**).

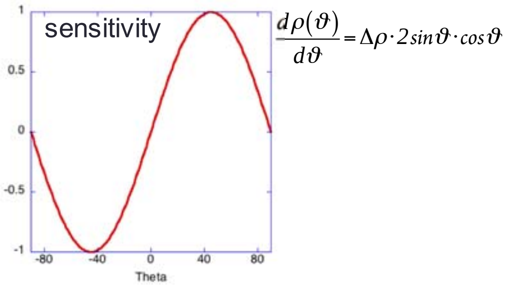
$$\rho(\vartheta) = \rho_0 + \Delta\rho \cdot \sin^2 \vartheta$$

- The AMR is formed by a thin film with a ordered magnetization vector ($\mathbf{B_0}$).
- The internal magnetic field sums with an external magnetic field. This results in a change of the resistance. $\Delta\rho$ is of the order of 1%.

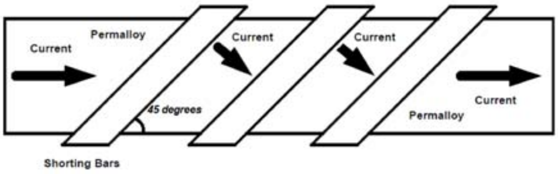




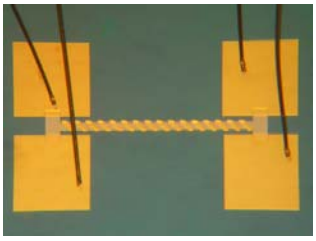


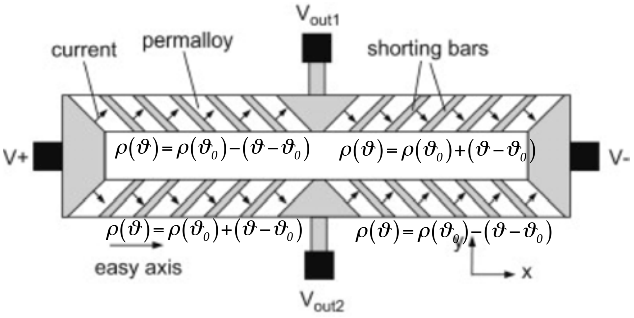


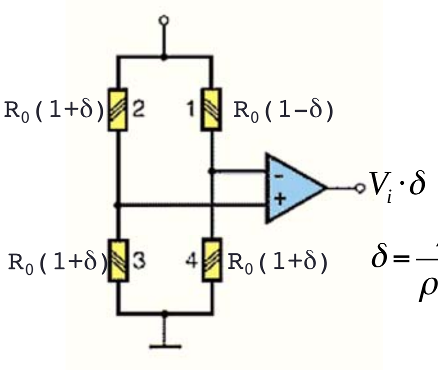
Barber pole AMR



- The sensitivity is maximum when the current direction is ±45° with respect to the magnetization direction.
  - Permalloy (80% Ni, 20% Fe) ferromagnetic material.
  - Metallic shorting bar redirects the current at 45°C.
- Changing the direction of the shorting bars the sign of the sensitivity is changed. So a sensor with positive and negative sensitivities can be designed.
- This feature is exploited in a full Wheatstone bridge.

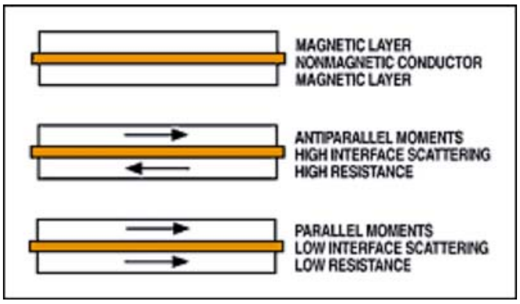




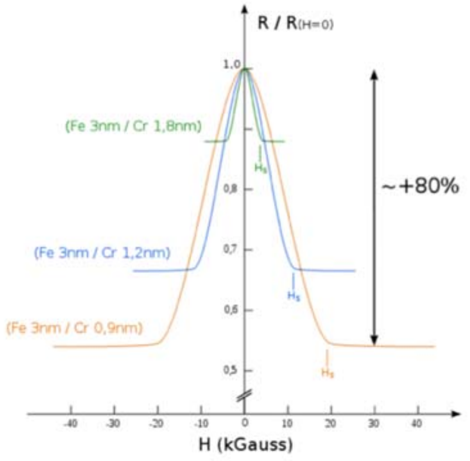


$$\delta=\frac{\Delta\vartheta}{\rho(\vartheta_0)}$$

Giant MagnetoResistance (GMR)

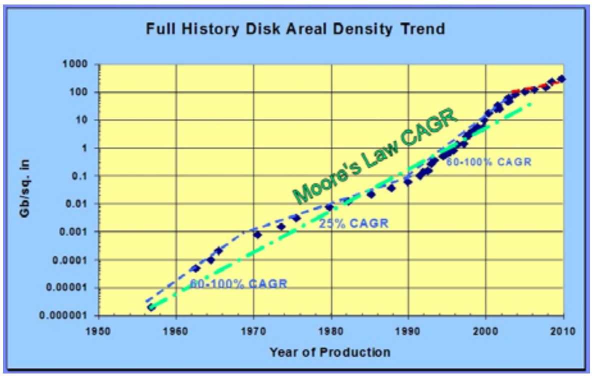


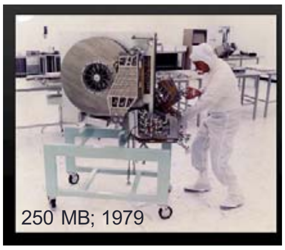
- It is observed in structures formed by two ferromagnetic materials separated by a ultrathin (<1nm) non magnetic layer.
- The electric resistance strongly depends on the magnetic dipoles orientation of the two ferromagnetic materials.
- The application of an external magnetic field to one of the ferromagnetic switches the magnetic moment changing the resistance.



Hard disks

- GMR allows for the miniaturization of magnetic sensors. For instance, for the compression of bit area in hard disks.

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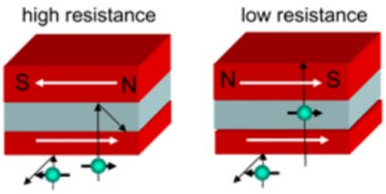
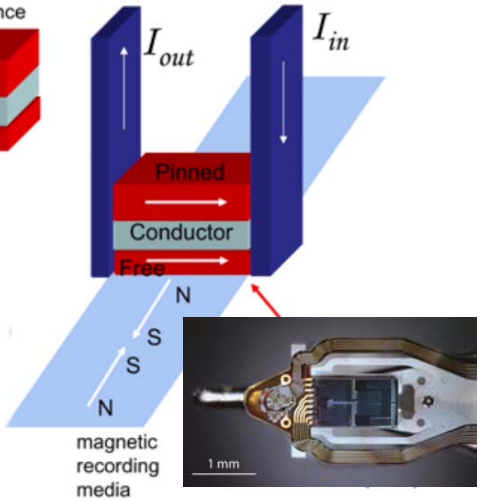
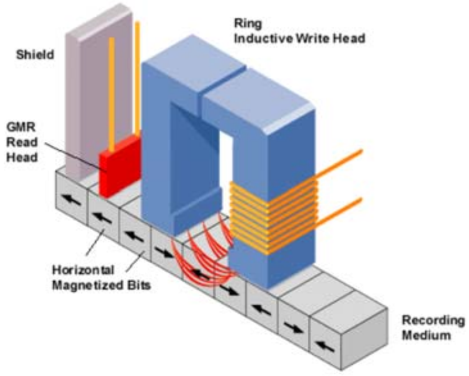
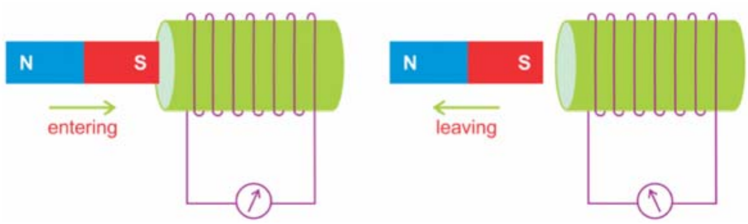






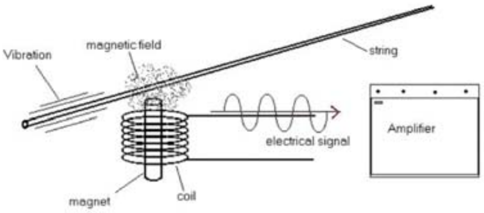
Electromagnetic induction

A variable magnetic fields
induces a current in a coil



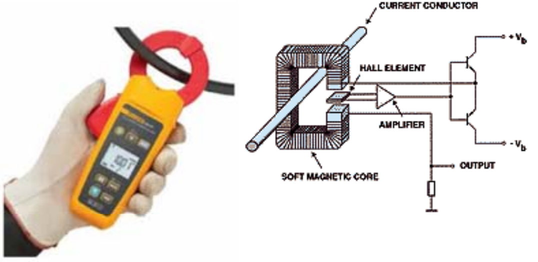
$$\Delta V = -\frac{d\Phi_B}{dt}$$

$$\Phi_B = \int_{\Sigma} B \cdot dl$$



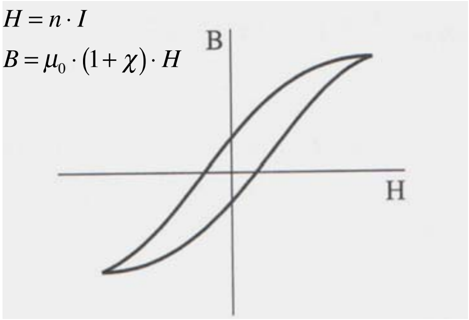
Current (a.c.) clamp
Variable B is generated by a a.c. current

$$B(r) = \frac{\mu_0}{2\pi}\frac{I}{r}$$



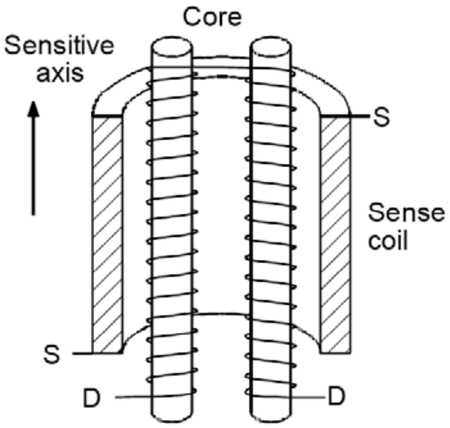
Fluxgate magnetometer

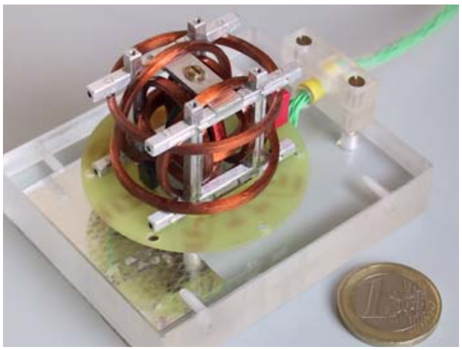
- Two core coils oppositely folded are surrounded by a larger single coil (Sense coil).
- The current applied to the core coils induces two opposite fields that cancel each other.
- In presence of an external magnetic field, the equilibrium is broken and the net magnetic field inside the larger coil induces a current in the sense coil.
- Fluxgates achieves resolutions of the order of 10^{-5} G (100 times better than Hall sensors).



$$H = n \cdot I$$

$$B = \mu_0 \cdot (1 + \chi) \cdot H$$



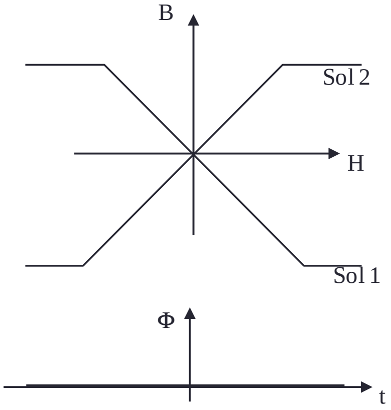


3 axis magnetometer

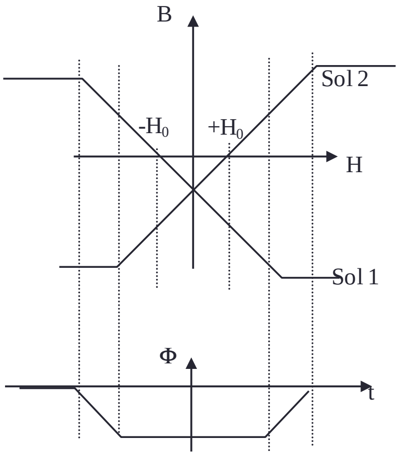
Fields, fluxes and voltages

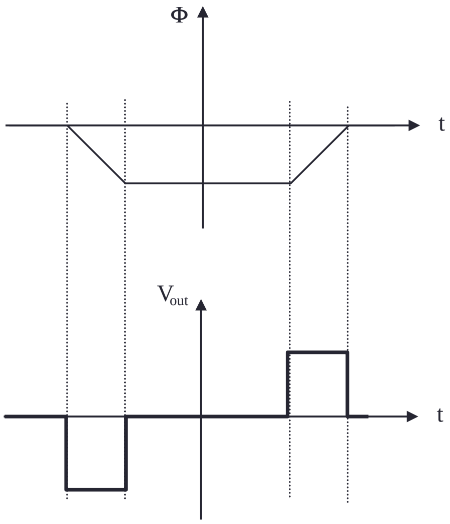
For sake of simplicity, let us suppose a linear hysteres

H_{ext}=0



H_{ext}=H_0





$$V_{out} = n \cdot \frac{d\phi}{dt}$$