Magnetic Sensors

2024 European School of Magnetism

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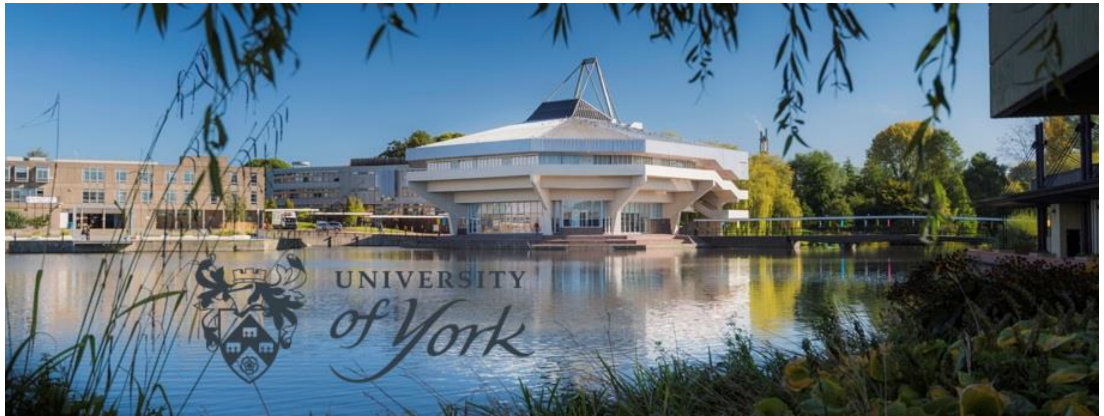


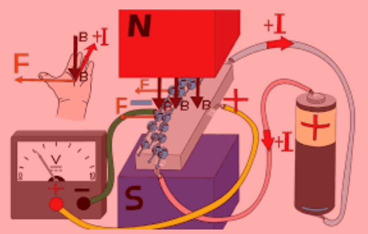
Introduction

- A sensor is *a device which detects or measures a physical property and records, indicates, or otherwise responds to it.*

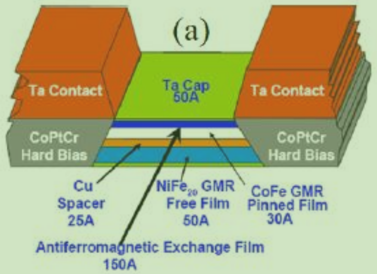
- Magnetic sensors are those associated with the laws and effects of magnetic or electromagnetic fields.

Inductive

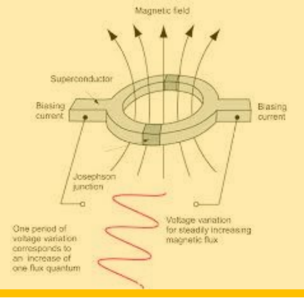
Hall Effect



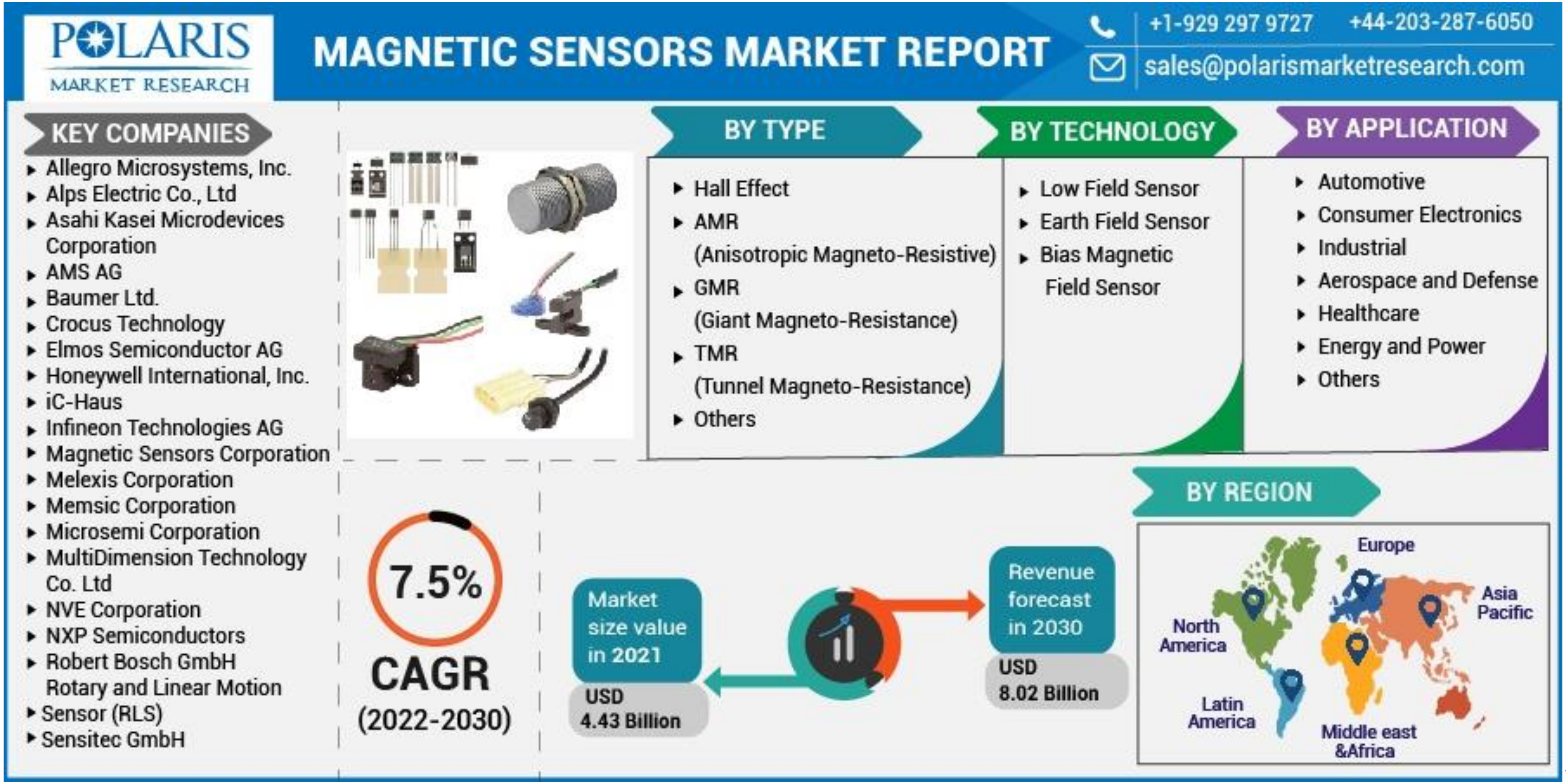
Magneto Resistive



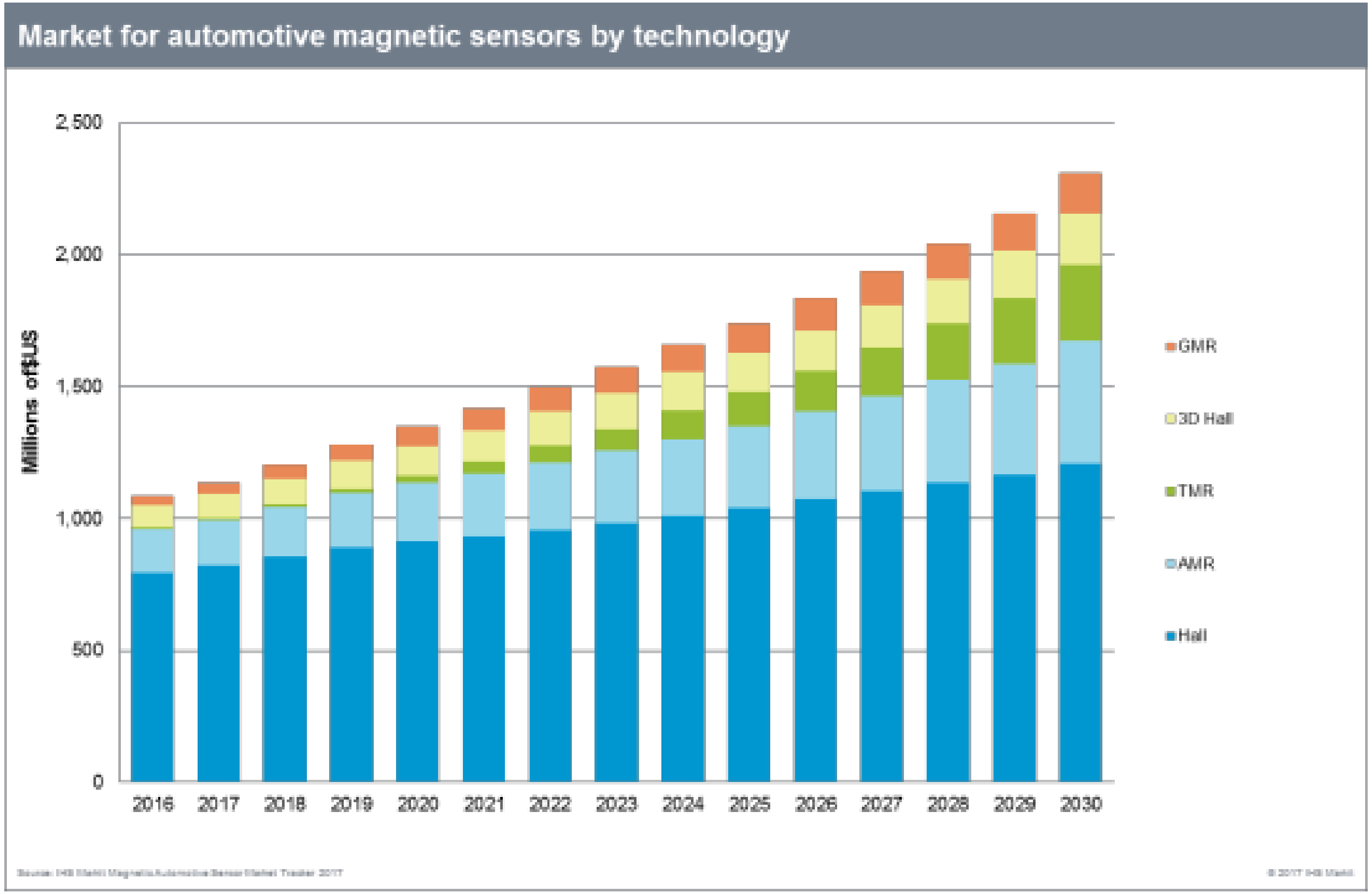
SQUID



Magnetic Sensors Market



Automotive Sector



https://www.greencarcongress.com/2018/07/20180724-sensors.html

Inductive Sensors

- They are based on Faraday's law of induction and are the most fundamental type of magnetic sensing.

- When a magnet is brought closer to a coil, the magnetic flux density in the coil rises, resulting in opposing forces in the form of induced electromotive force (emf) and induced current.

- The coil's output voltage is proportional to the rate of change of the magnetic field.

$$\boldsymbol{\varepsilon = -N\frac{d\phi}{dt}}$$

ε = induced voltage
N = number of turns
$d\phi$ = change in the magnetic flux
dt = change in time

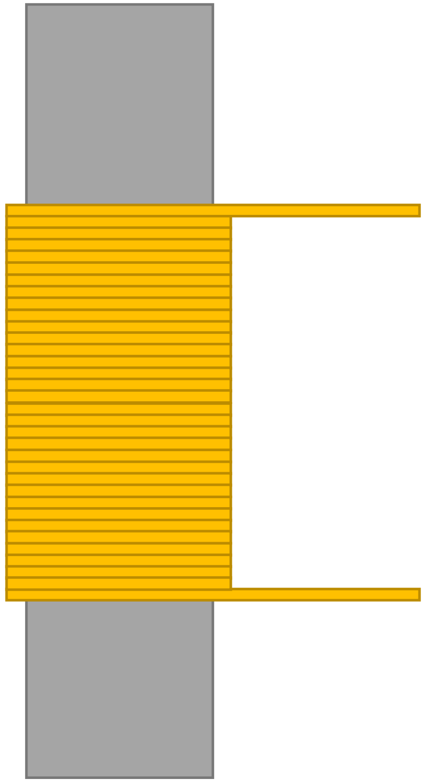
Fluxgate Sensor

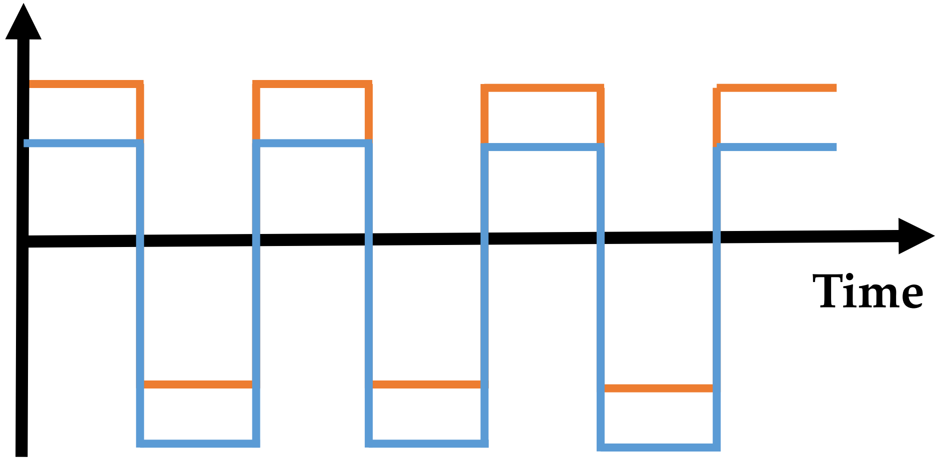
- These type of sensors are especially important in detecting weak magnetic fields.

- The structure mainly consists of excitations windings, core and sensing windings.

- To date they have been applied to many fields, e.g. geophysics, wearable electronic devices and non-destructive testing.

Fluxgate Sensor: simple picture



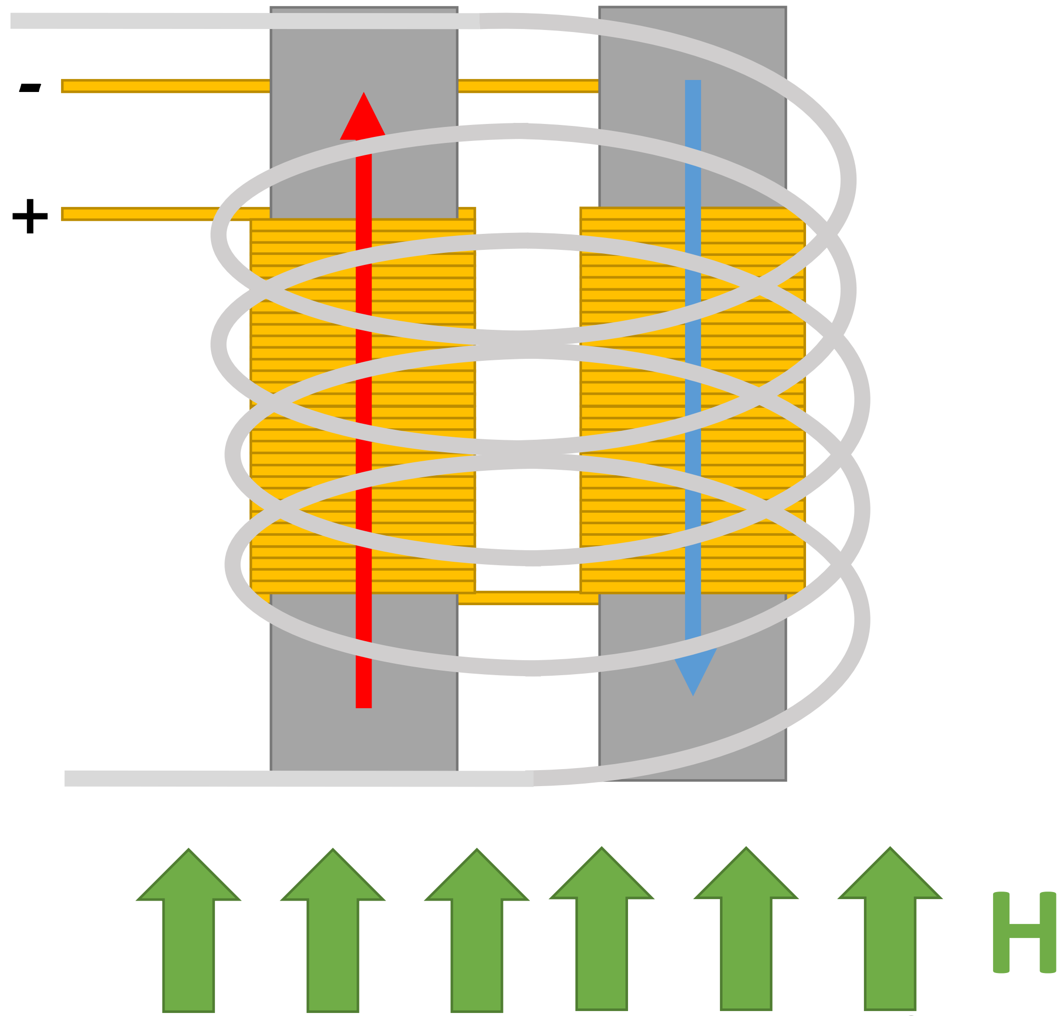


- By combining multiple fluxgate sensors you can measure magnetic fields in 3D

Fluxgate Sensor: common configuration

- You can now have two bar magnets connected in series but wound in opposition.

- A current passing through this primary coil will magnetise the bar magnets but each will generate a field in opposite directions.



Fluxgate Sensor: modern application

- Lymph nodes are small round organs that are part of the body's lymphatic system.

- It consists of a network of vessels and organs that contains lymph, a clear fluid that carries infection-fighting white blood cells as well as fluid and waste products from the body's cells and tissues.

- In a person with cancer, lymph can also carry cancer cells that have broken off from the main tumour.

- A sentinel lymph node is defined as the first lymph node to which cancer cells are most likely to spread from a primary tumour.

Sentinel Lymph Biopsies

- A sentinel lymph node biopsy (SLNB) is a procedure in which the sentinel lymph node is identified, removed, and examined to determine whether cancer cells are present. It is used in people who have already been diagnosed with cancer.

- A negative SLNB result suggests that cancer has not yet spread to nearby lymph nodes or other organs.

- A positive SLNB result indicates that cancer is present in the sentinel lymph node and that it may have spread to other organs.

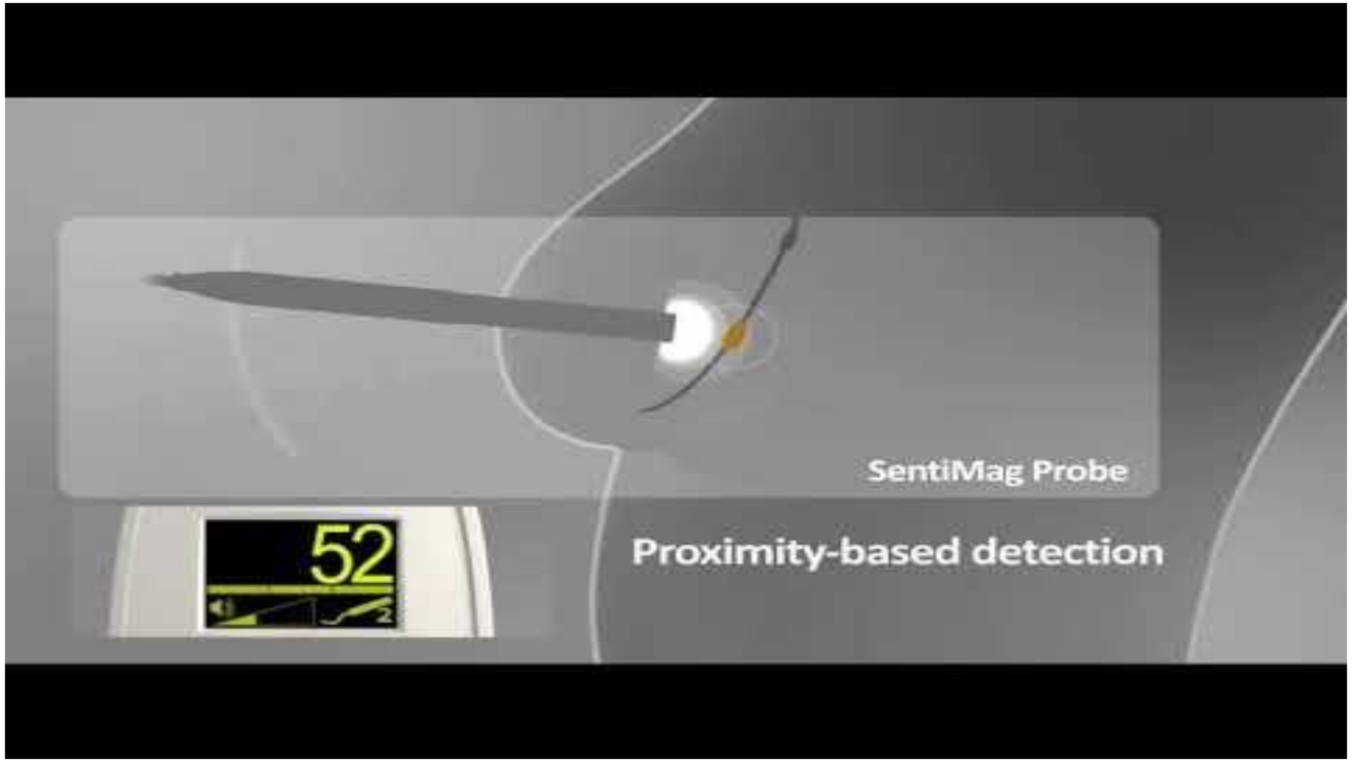
- This information can be used to diagnose the stage of the cancer.

Conventional Method

- First, the sentinel nodes need to be located.
- This is usually done by injecting a radioactive substance, a blue dye, or both near the tumour.
- The surgeon then uses a device to detect lymph nodes that contain the radioactive substance or looks for lymph nodes that are stained with the blue dye.
- One the location is known, an incision is made and the node removed.
- The node is then sent for analysis.

Magnetic Location of Nodes

endomag

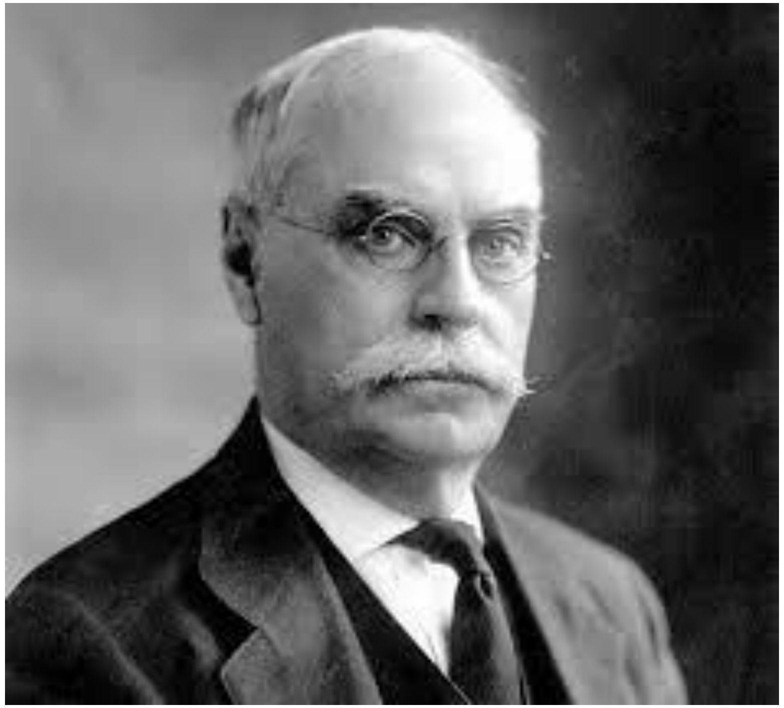


Hall Effect

- It is the most common method of measuring magnetic fields.

- It refers to the generation of a potential difference across an electrical conductor when a magnetic field is applied perpendicular to that of the flow of the current.

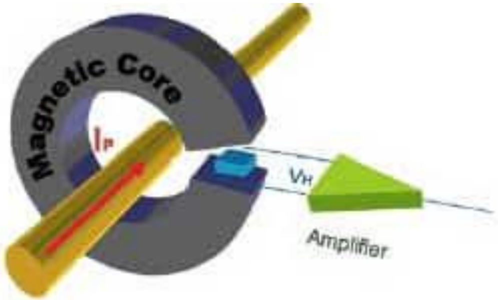
- Discovered in 1879 by Edwin Hall while working as a PhD student.



Hall Effect Sensors Applications

Proximity Sensors

3D Printers



Current Sensors

Antilock Braking System

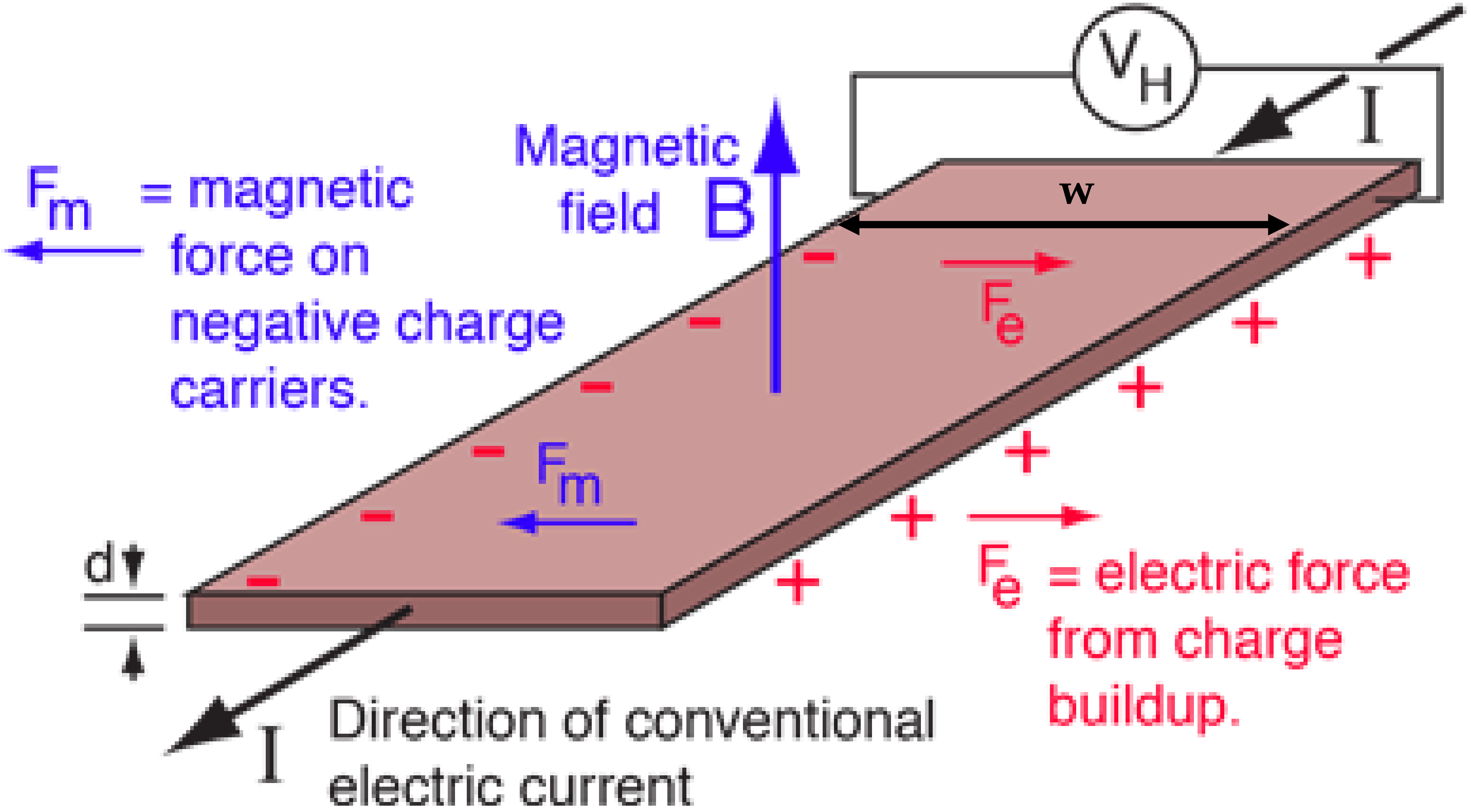
Tablets

Electric Treadmill

Positioning Sensors

Automatic Fuel Level Indicators

How it Works



http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html

Mathematically

$$F_m = qv_d B$$

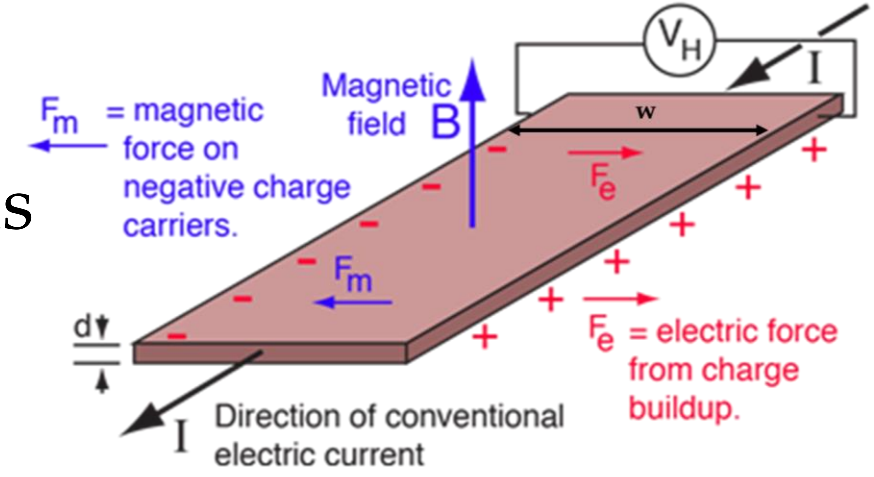
$$F_m = F_e \rightarrow qvdB = qE_H \rightarrow vdB = E_H$$

$$F_e = qE_H$$

- Since $V_H = E_H w$, where w is the width of the conductor.

$$v_d B = \frac{V_H}{w} \Rightarrow V_H = v_d B w$$

Mathematically



- This can be rewritten in terms of the current as

$$V_H = \frac{wBI}{neA}$$

- Where n is is the number of electrons per unit volume and A is the cross sectional area of the conductor.

$$V_H = \frac{BI}{ned}$$

- The Hall constant is defined as: $R_H = \frac{1}{ne}$ so $V_H = \frac{R_H B}{d} I$

Hall Probe Sensor

- Since $V_H \propto B$ the Hall voltage changes linearly with the magnitude of the magnetic field

$$V_H = \frac{R_H B}{d} I; \; R_H = \frac{1}{ne}$$

Question: do you think it’s practical to use metals in such devices?

The answer is ‘no’ as n is very large for these materials, making V_H very small

- The development of semiconductors allowed for the value of n to be set at an optimum value so that Hall probes became a convenient method of measuring magnetic fields.

Hall Effect in Semiconductors

- Although they have lower room temperature conductivity than conductors, their conductivity increases as temperature increases.

- Both electrons and positive carriers (‘holes’) contribute to the conductivity.

- Semiconductors can be chemically ‘doped’ so that there is an excess of either electrons or holes participating in conduction.

- Doping alters the conductivity of the semiconductor and offers many possibilities to control the behaviour of the material and is the main reason for the importance of semiconductors in modern electronic devices.

Hall Effect in Intrinsic Semiconductors

- For intrinsic semiconductors the Hall constant is given by:

$$R_H = \frac{p\mu_H^2 - n\mu_e^2}{e(p\mu_H + n\mu_e)^2}$$

n is the electron concentration
p is the hole concentration
μ_e is the mobility of the electrons
μ_H is the mobility of the holes
e is the elementary charge

Applications

- Classifying materials
- Measure magnetic fields i.e. magnetometer
- Position sensing
- IC as Hall effect sensors

Hall Effect in Extrinsic Semiconductors

- Extrinsically doped semiconductors, n-type and p-type, behave quite differently compared to intrinsic semiconductors in the Hall Effect.

- When dopants are introduced into the semiconductors, the charge carrier density becomes predominantly one type → much stronger Hall Effect.

- The Hall coefficient for n-type semiconductors is given $R_H = -1/ne$ where n is the dopant concentration and e is the charge of an electron.

- In p-type superconductors the current flows in the direction opposite to the electron flow with $R_H = 1/pe$

Typical Materials Used

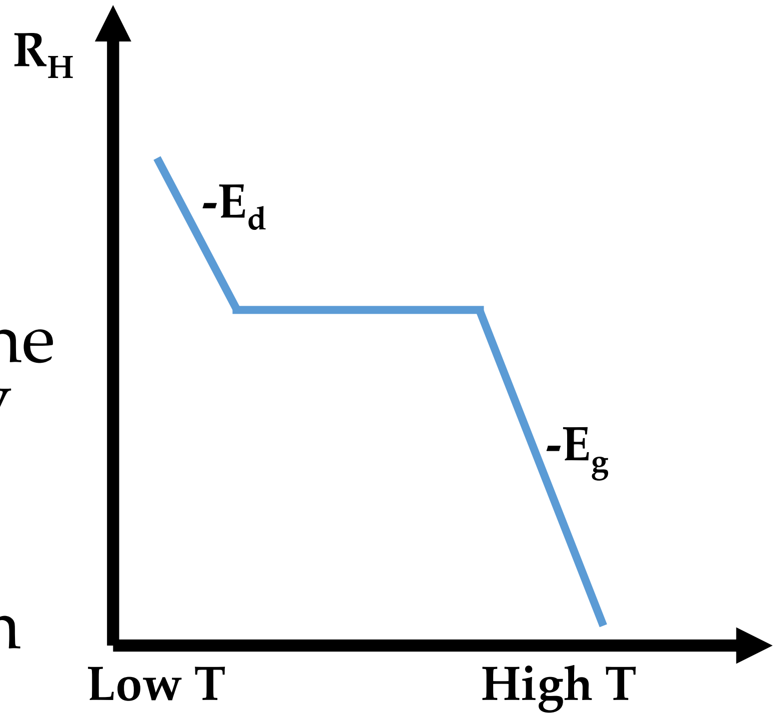
- **Germanium:** when doped with As it becomes an n-type semiconductor while doping with Ga results in a p-type semiconductor → Ge has a higher carrier mobility than Si so more prominent Hall effect.

- **Silicon:** while it has a lower carrier mobility than Ge, it has as a higher threshold for intrinsic conduction, making it suitable for a broader range of temperatures.

- **Gallium Arsenide:** this is a III-V direct bandgap semiconductor. It has the highest electron mobility among prevalent semiconductors, making it ideal for high-frequency applications.

Temperature Variation

- It varies depending on the type of material.
- For instance, when one carrier dominates $R_H = 1/ne$.
- The temperature dependence of R_H is controlled by the temperature dependence of the charge carrier density n(T).
- At low T, thermal energy can only excite carriers from donor levels (E_d) close to the conduction band.
- At high T, carriers can be excited across the band gap (E_g) .



Non linearity

In principle: $V_H = \frac{R_H B}{d} I$

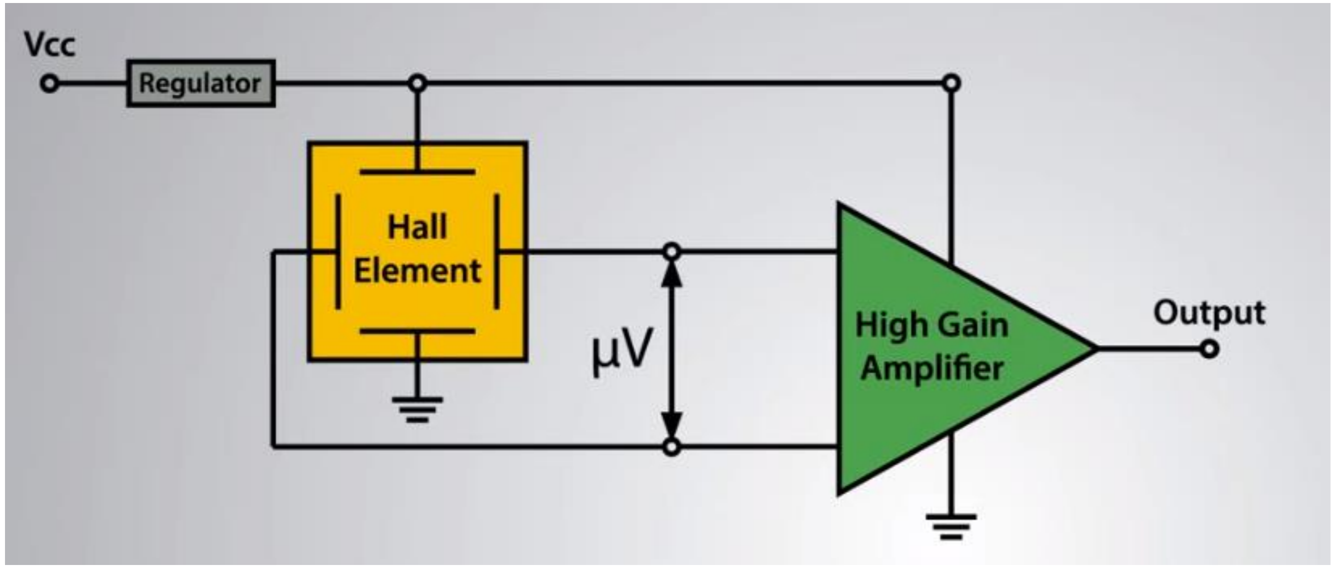
In practice: $V_H = \frac{G R_H(B) B}{d} I$

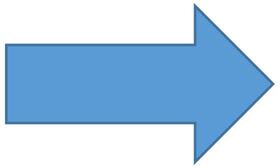
G – geometrical correction factor

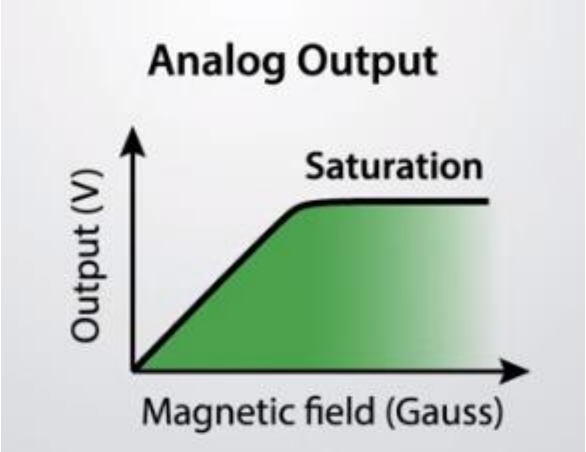
- **Material** – at high fields you don't have to worry as much but at low fields (most sensing cases) R_H depends on the magnitude of the applied field.
- **Geometrical** (G) – due to short circuiting effects by the sensor contacts.
- Material and geometrical non-linearities are opposite in sign → a Hall element can be designed so that they compensate each other.
- They are proportional to the square of the magnetic induction and but independent of the bias current.

Analog vs Digital Sensors

- Analog sensors are suitable to measure proximity because of their continuous linear output.

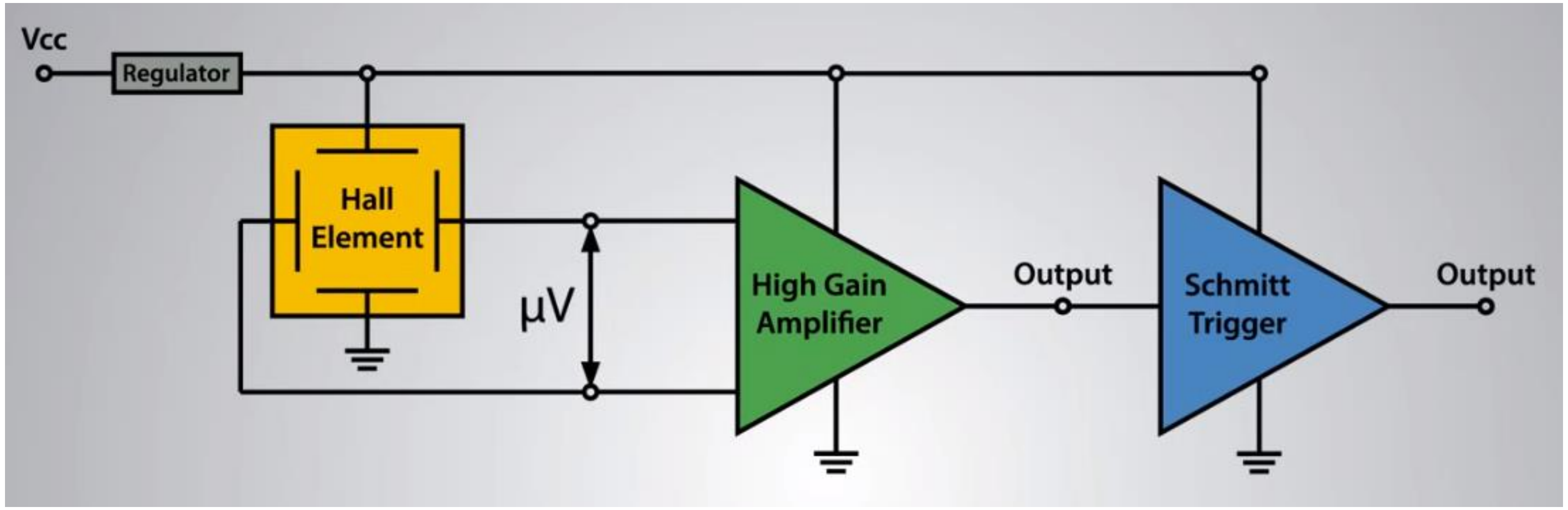


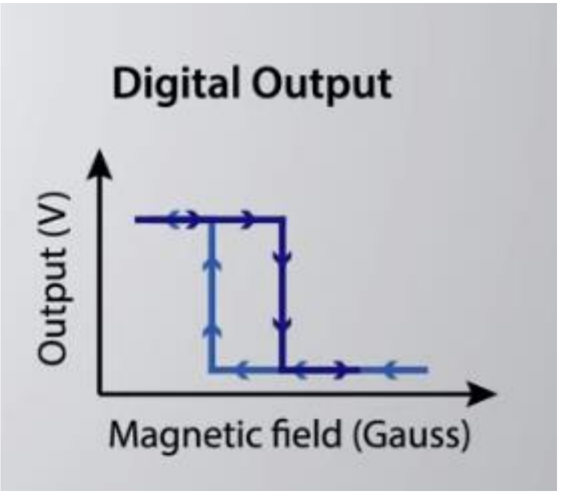




Analog vs Digital Sensors (II)

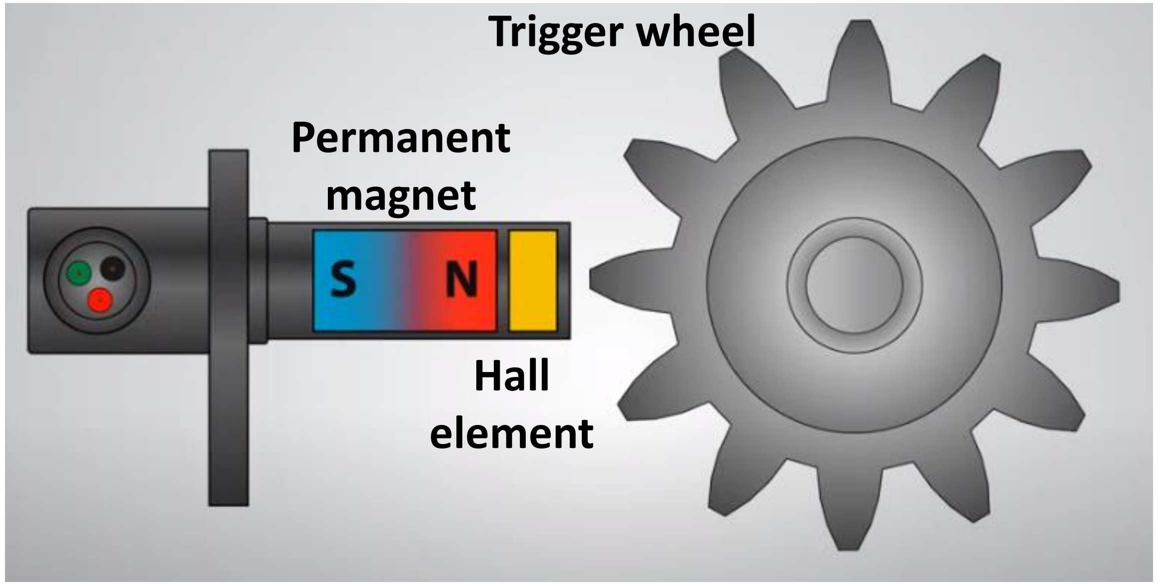
- Digital sensors have an additional element which provides hysteresis or two threshold levels so the output is high/low.

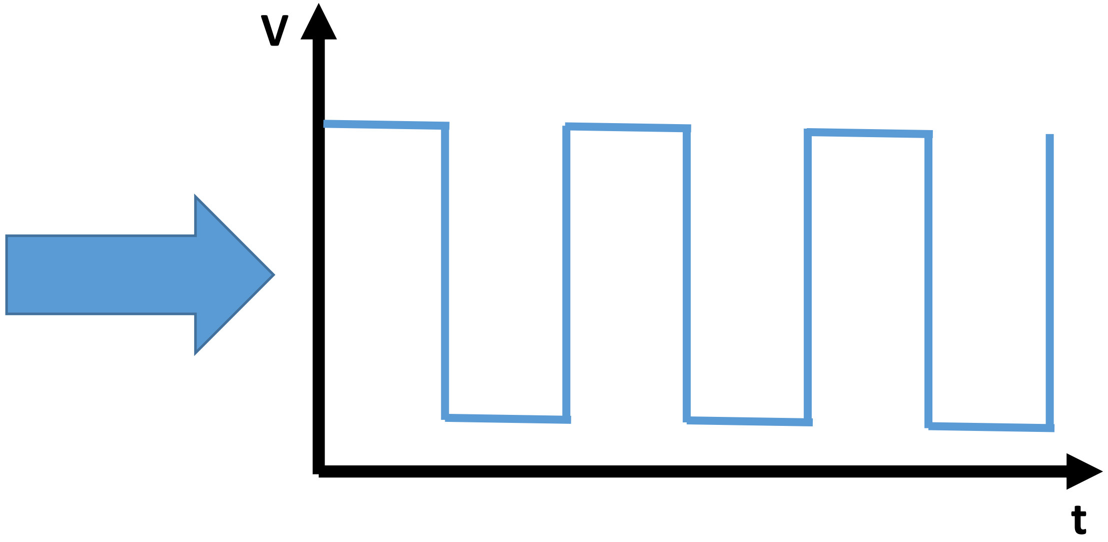




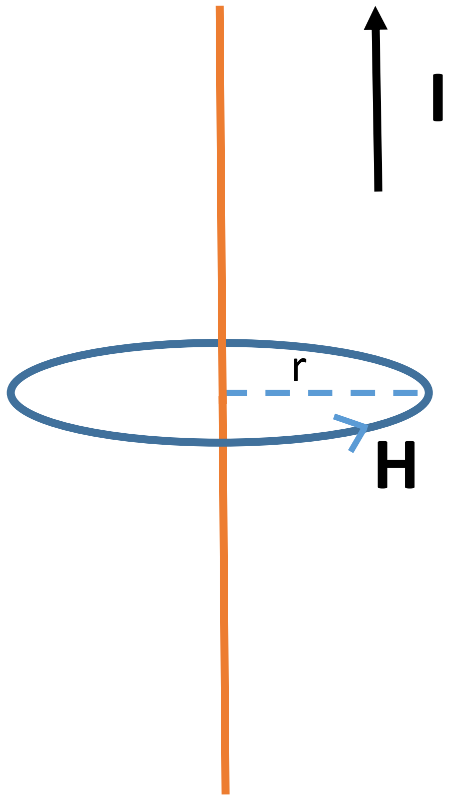
Applications Digital sensors

- Hall effect switch: e.g. limit switchers for example in 3D printers.
- Detection/positioning in industrial automation systems.
- Wheel speed as well as determining position of crankshaft in engine systems.





Hall Effect Current Sensor



- $\oint H dl = nI$
- l = 2π r
- $B = \mu_0 \mu_r H$ where $\mu_0 = 4\pi 10^{-7}$ A/m

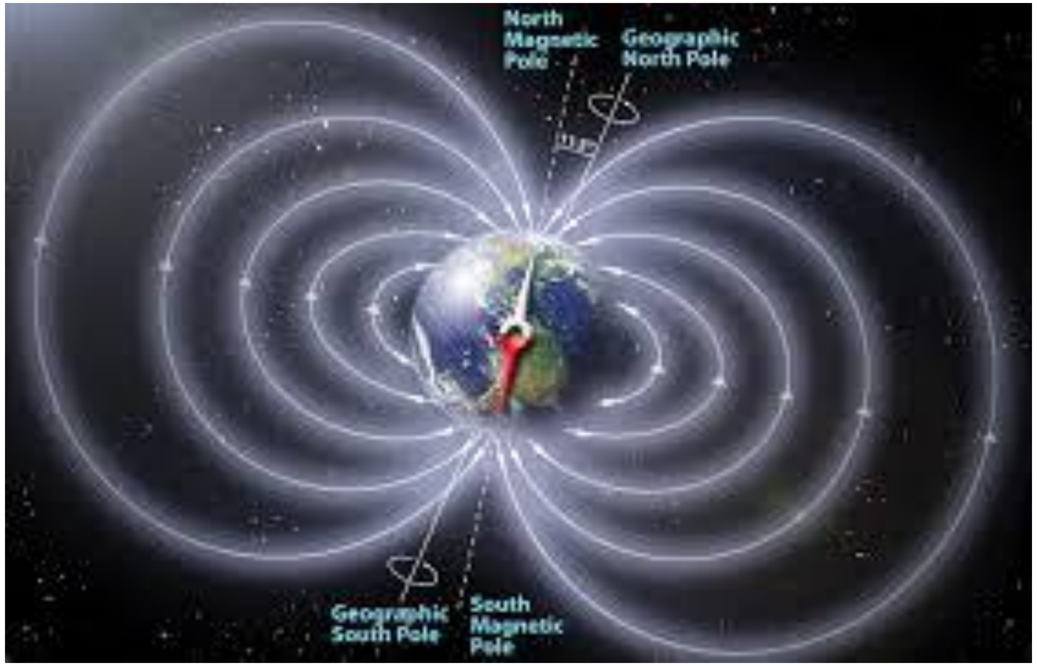
Example

Let's assume r = 1.5 mm → l = 2πr ~ 1 cm.

If n = 1 and I = 1 A

H = I/l = 100 A/m → B = = $4\pi 10^{-7}\ 10^{2}$ = 1.2 10^{-4} T = 1.2 G

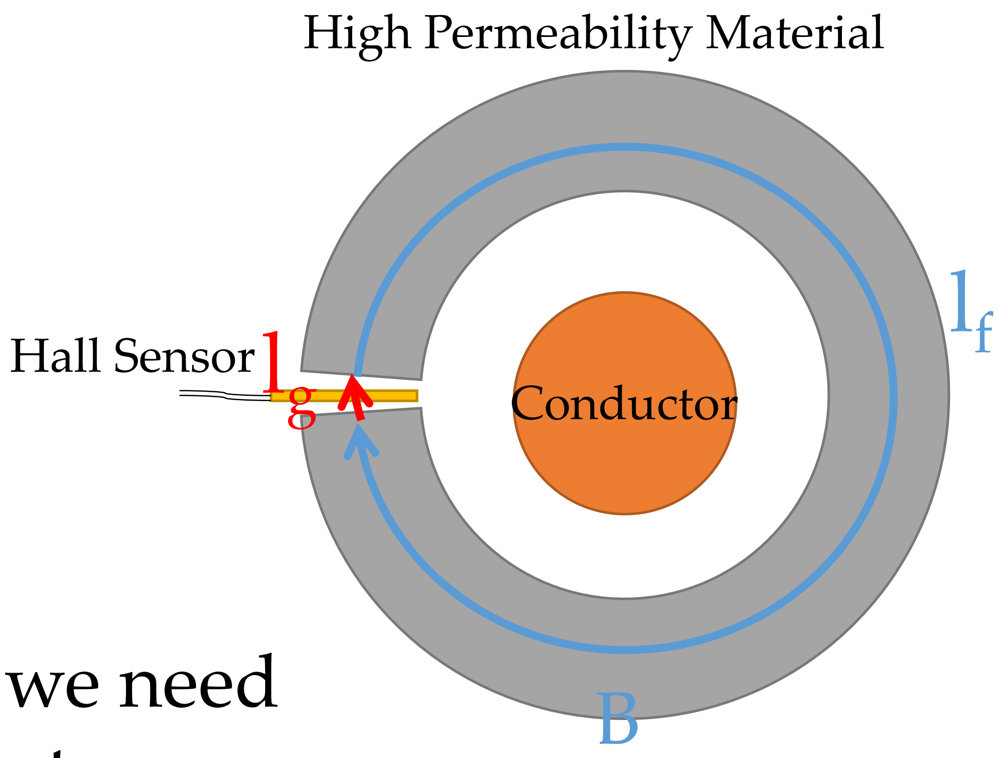
But…



0.5 G vs 1.2 G → Problem when detecting low currents. Potential interference with other components.

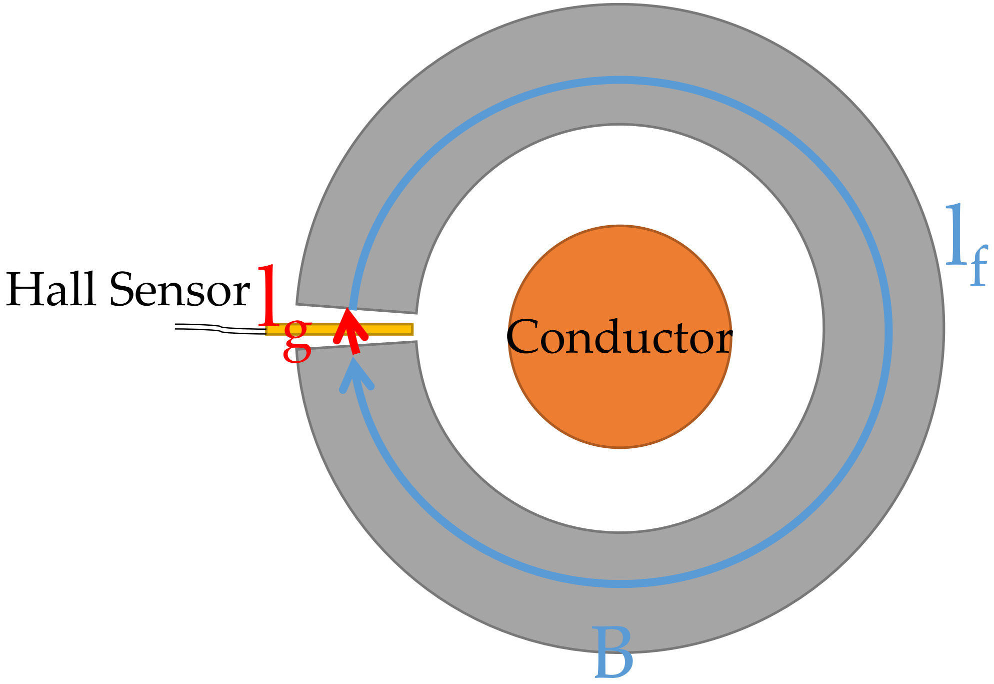
Solution: Use a concentrator

- Most common method in non intrusive current sensing
- $\oint H dl = I$
- H (no core) = $\frac{I}{l_f + l_g}$
- When a ferromagnet is in place we need to break the integral into two parts:
- $H_g l_g + H_f l_f = I$



Solution: Use a concentrator

- $B = \mu_0 \mu_r H$
- Assuming the gap is small B is constant. Hence:
- $\mu_0 H_g = \mu_0 \mu_r H_f$ → $$H_f = \frac{H_g}{\mu_r}$$



- $H_g l_g + H_f l_f = I$ → $H_g l_g + \frac{H_g}{\mu_r} l_f = I$ → $H_g \left(l_g + \frac{l_f}{\mu_r} \right) = I$

Solution: Use a concentrator

$$H_g\left(l_g + \frac{l_f}{\mu_r}\right) = I$$

- If $\mu_r = 1$ we get the same solution we got before.
- If $\mu_r \neq 1$

$$H_g = \frac{I}{\left(l_g + \frac{l_f}{\mu_r}\right)}$$

- If $l_g >> l_f/\mu_r$

$$H_g \sim \frac{I}{l_g}$$

This will hold as long as $\mu_r >> l_f/l_g$

Solution: Use a concentrator

- So without a concentrator:

$$H \sim \frac{I}{l}$$

- And with a concentrator: If $\mu_r = 1$ we get the same solution we got before.

$$H_g \sim \frac{I}{l_g}$$

- The gap can be x100 smaller than l so a much higher signal is achieved in the Hall sensor region.

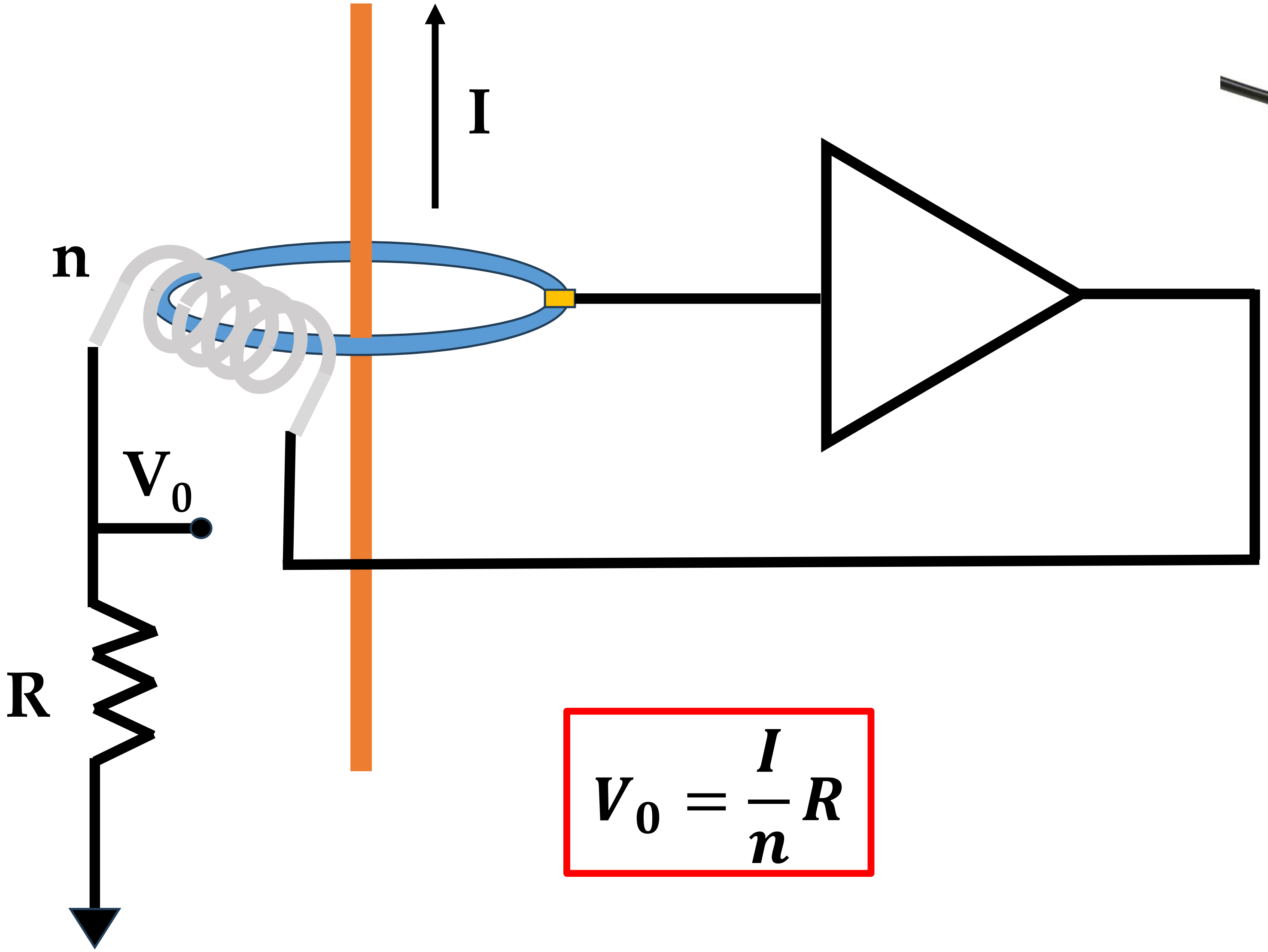
Example

- Let's assume l_f = 3 cm, l_g = 3 mm and μ_r = 3000.

- $H_g \sim \frac{I}{3 \cdot 10^{-3}}$ → 10 times larger than without the concentrator.

- $B = \mu_0 H_g = 4\pi 10^{-7} \frac{I}{3 \cdot 10^{-3}} \sim 4 \cdot 10^{-4} I\ T = 4I\ G$ → about 4 times larger than without the concentrator.

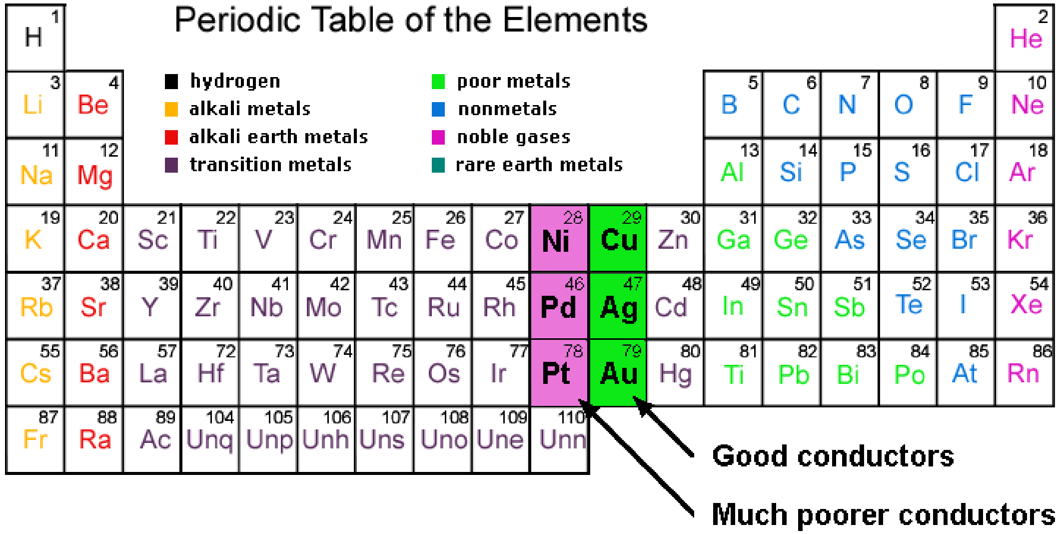
Closed loop operation



$$V_0 = \frac{I}{n} R$$

Question

Why certain transition metals – Ni, Pd, Pt – are much poorer conductors than their immediate neighbors in the Periodic Table, Cu, Ag and Au?



Answer

In transition metals the current is conducted by electrons from the *d*-bands and *s*-bands

Electron in the *d*-bands are more tightly bound and less mobile. But the *s*-band electrons may be scattered by defects (always present) or by phonons, and may end up in the *d*-band, losing mobility and increasing the resistance.

In copper, however, the 3d band is completely filled, so such scattering cannot occur – therefore, copper is an excellent conductor!

However, in nickel, copper's next-door neighbour, the situation is different.

The d band is not completely full so that s→d scattering may occur → Ni is a poorer conductor.

Magneto Resistance

- The first observation of magnetoresistance (MR) in a magnetic material was made by Lord Kelvin in 1857.
- This observation predates the formal discovery of the electron by J. J. Thomson by 40 years.
- In bulk materials this effect is known as anisotropic MR.

Anisotropic Magneto Resistance (I)

- In a completely demagnetised material electrons will be scattered evenly irrespective of the direction of the spin of the electrons forming the current density.

- If the material is now saturated then all the electrons will to some degree experience a Hall effect which will cause them to circle around the direction of the magnetisation.

- That orbit will result in significantly longer electron paths resulting in an increased probability for scattering thereby increasing the effective resistance of the material.

Anisotropic Magneto Resistance (II)

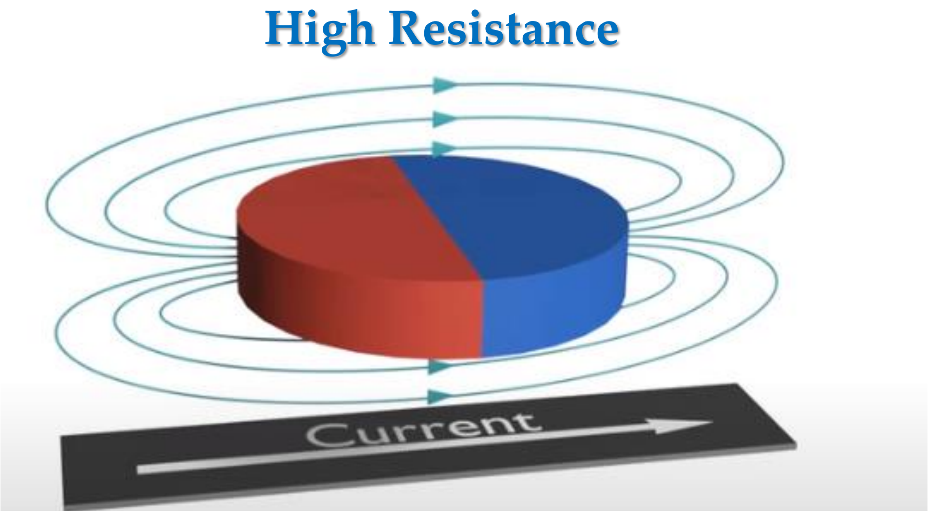
- In general the value of anisotropic magneto-resistance is very small. For example in Ni it is of the order of 2.5%, for Fe 0.8% and for Co in an hcp phase it is 3% along the c-axis.

- It should be noted that these values for magneto-resistance are those for single crystal materials.

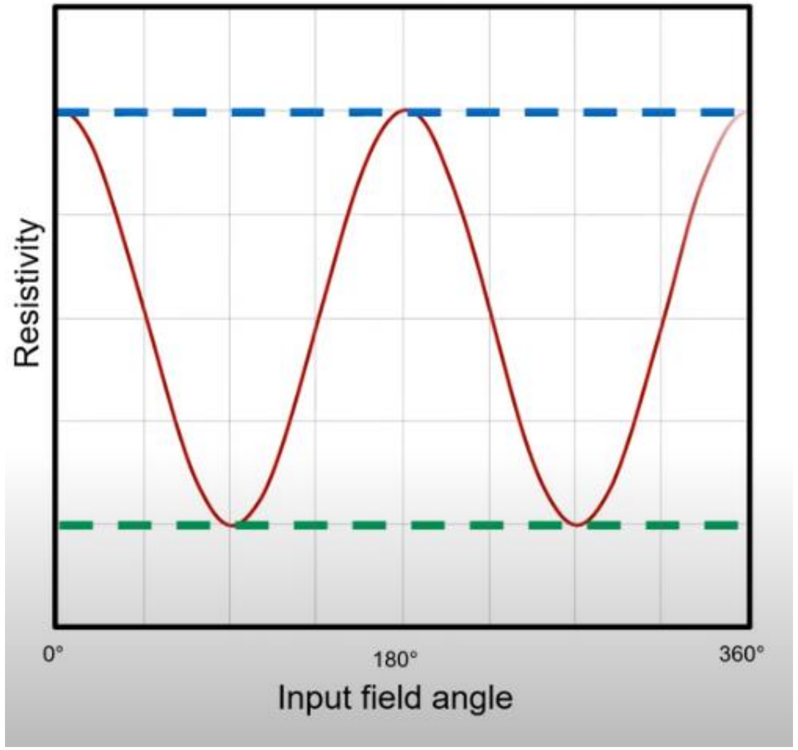
- In amorphous materials there is no significant effect due to the lack of long-range crystallographic order.

- The increased grain boundary scattering, if very small grains are present, swamps any magnetoresistive effect that may be present.

How Does it Manifest Itself



$$\rho(\theta) = \rho_{\parallel} + (\rho_{\parallel} - \rho_{\perp})cos^2(\theta)$$



Applications

- Because of its simple construction, AMR is frequently utilized in low power magnetic switches.
- Angle sensing (more about this later).
- Laptop computers – control of power supply of LCD linked to open/close operation.
- Despite these very small values of magneto-resistance it is worth noting that early magnetic recording systems and in particular those used in early hard disk drives, did use magneto-resistive thin film read heads.
- This was due to the fact that they could be defined by the relatively crude lithographic processes available at that time.
- However with the advent of the discovery of giant magneto-resistance (GMR) and subsequently tunnelling magnetoresistance (TMR) there is almost no use at all for materials exhibiting AMR.

Giant Magneto Resistance (GMR)

- With the development of quantum mechanics and in particular the concept of electron spin, it was realised that there could be significant scattering of conduction electrons due to the presence of electron spin when they pass through a magnetised region of a ferromagnetic material.

- Macroscopically, GMR can be envisioned very simply through a resistor network model.

- Sir Neville Mott in Cambridge published an almost defining work on the subject in 1936 in which he described the existence of two resistive channels in a ferromagnet which depend on the orientation of the electron spin.

- This concept of two different resistive channels led to significant further work on spin dependent scattering in ferromagnets most notably by Fert and Campbell (1968 and 1976).

Mott Model

- The electrical conductivity in metals can be described in terms of two largely independent conducting channels, corresponding to the up-spin and down-spin electrons.
- Electrical conduction occurs in parallel for the two channels.
- In ferromagnetic metals the scattering rates of the up-spin and down-spin electrons are different.
- Let's assume that the scattering is strong for electrons with spin antiparallel to the magnetization direction and weak for electrons with spin parallel to the magnetization direction.
- By applying an external magnetic field, the specimen's resistance can be changed, as had originally been observed by Lord Kelvin.

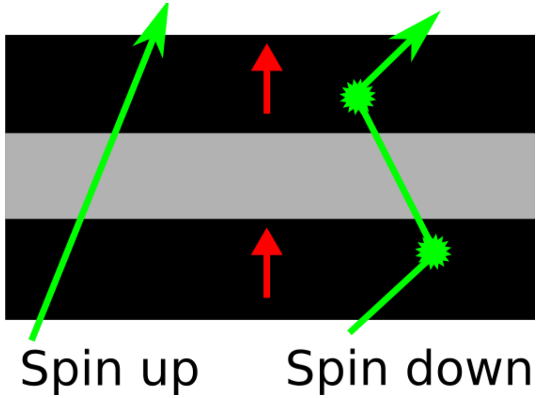
Mott Model

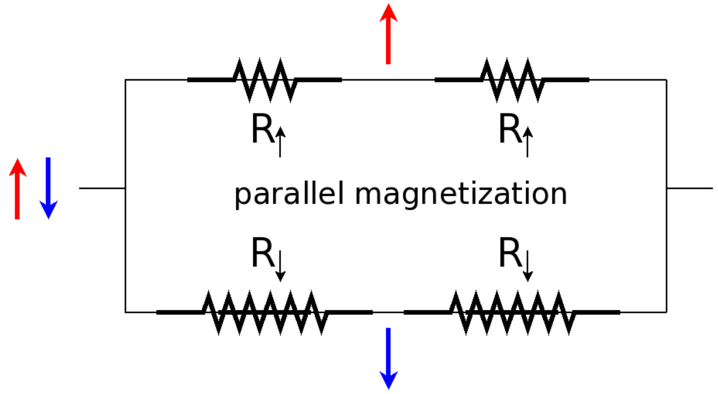
- Parallel magnetization

- Up-spin electrons experience small resistance, down-spin electrons experience large resistance.

- Total resistance is

$$R_{para} = \frac{2R_{\uparrow}R_{\downarrow}}{R_{\uparrow} + R_{\downarrow}}$$





Mott Model

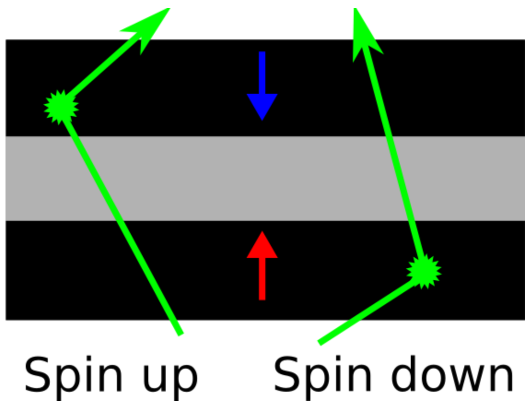
- Antiparallel magnetization

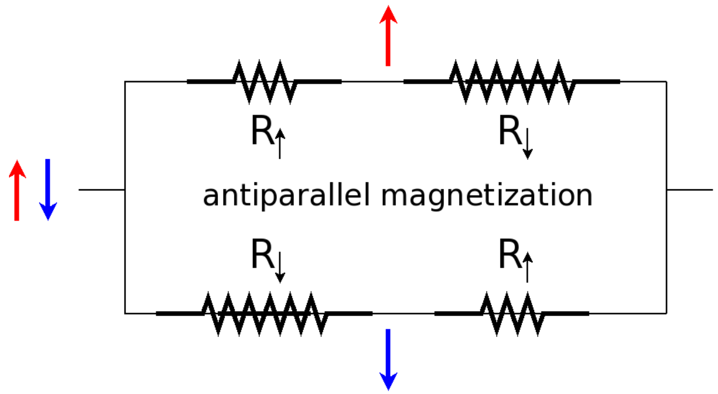
- Both electron spins experience small resistance in one layer and large resistance in the other.

$$R_{antpara} = \tfrac{1}{2}(R_\uparrow + R_\downarrow)$$

- Total resistance is

$$\Delta R = R_{para} - R_{antipara} = -\frac{1}{2}\frac{(R_\uparrow - R_\downarrow)^2}{(R_\uparrow + R_\downarrow)}$$





Discovery of Fert & Grunberg

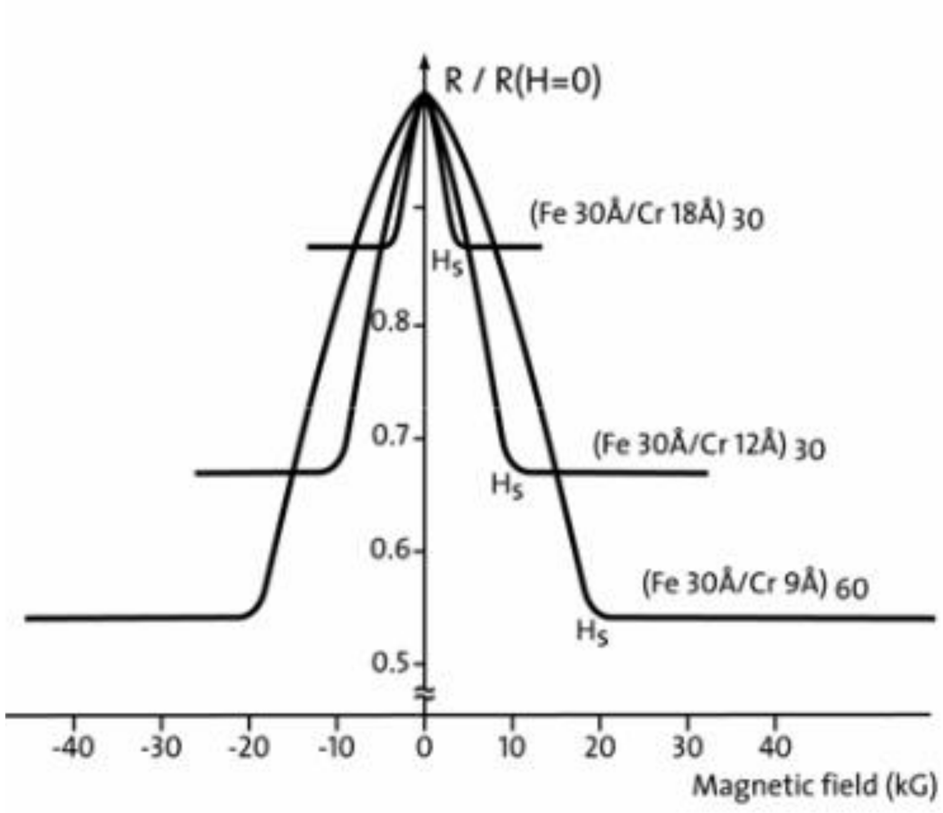
- GMR was discovered independently by Prof. Albert Fert of Université Paris-Sud in France and Prof. Peter Grünberg of Forschungszentrum in Jülich, Germany.

- Both groups submitted papers to *Physical Review* in the summer of 1988

http://www.nobelprize.org/nobel_prizes/physics/laureates/2007/

Original Data (Fert)

- 60-bilayers of Fe-Cr deposited by MBE.
- Resistance measured at 4.2 K.
- Nearly 50% drop in resistance observed!!

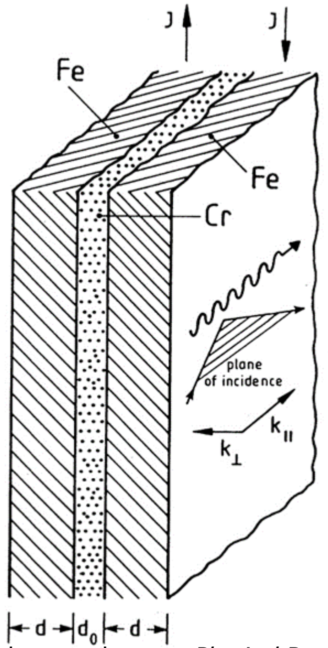


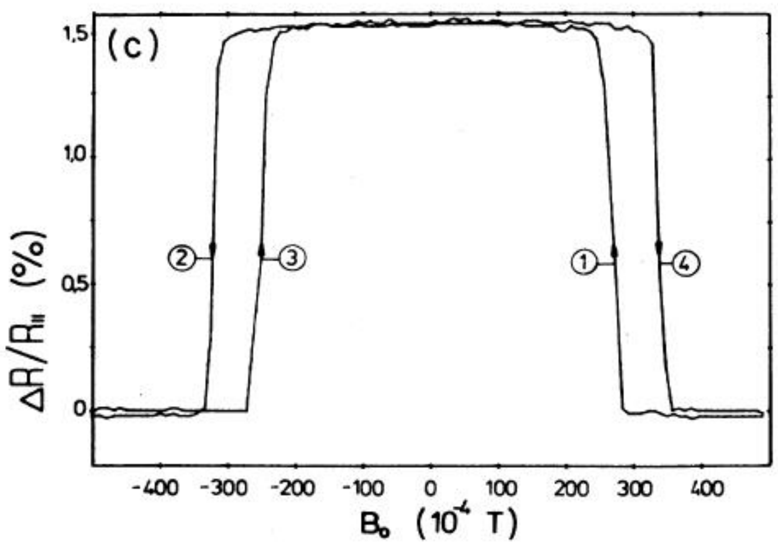
M. N. Baibich et. al. Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices. *Physical Review Letters,* 39, 4828 (1988).

Original Data (Grunberg)

- Fe-Cr-Fe trilayer measured at room temperature.

- A 1.5% drop in resistance was reported.

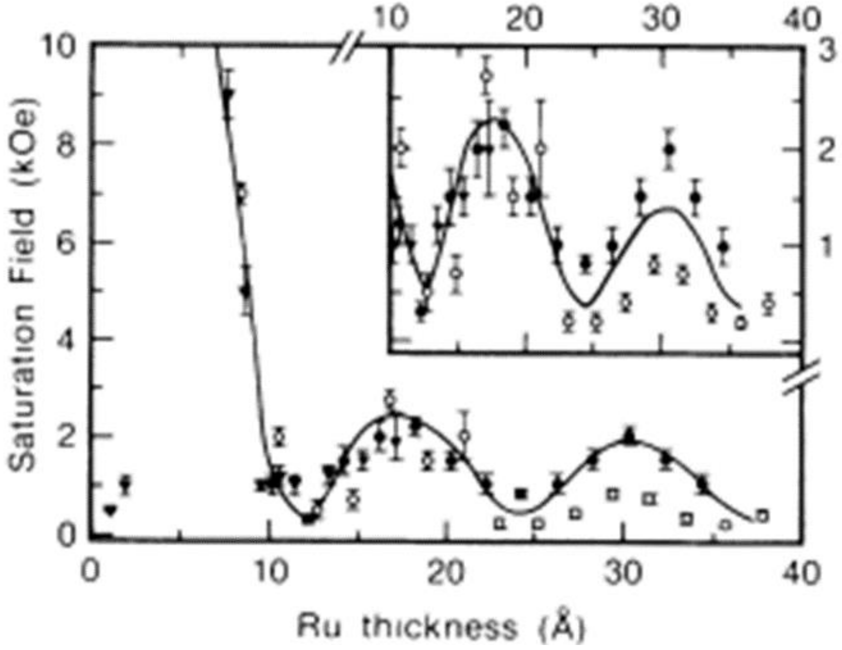




G. Binasch et. al. Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange. *Physical Review B*, 61, 2472 (1989).

Discovery by IBM

- Stuart Parkin of IBM attempted to reproduce the effect using the sputtering technique.
- Fert and Grünberg used molecular beam epitaxy, a more precise but slower and more expensive method.
- Parkin's group succeeded, observing GMR in the first multilayer sample's produced.
- Parkin's group began experimenting with various sample compositions and layer thicknesses to better understand GMR and how to integrate it into magnetic storage.



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Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr, and Fe/Cr

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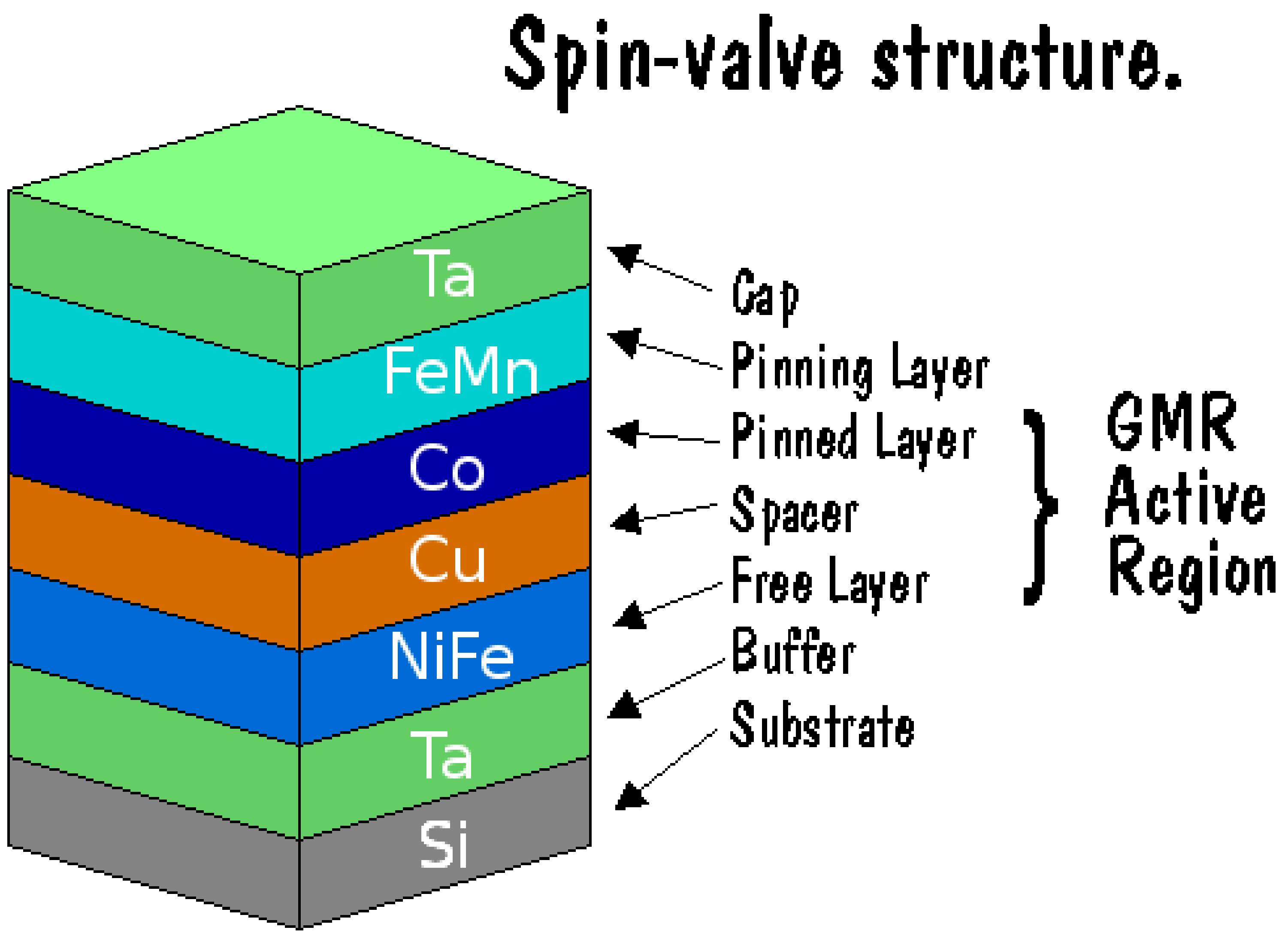
(Received 27 November 1989)

We report the discovery of antiferromagnetic interlayer exchange coupling and enhanced saturation magnetoresistance in two new metallic superlattice systems, Co/Cr and Co/Ru. In these systems and in Fe/Cr superlattices both the magnitude of the interlayer magnetic exchange coupling and the saturation magnetoresistance are found to oscillate with the Cr or Ru spacer layer thickness with a period ranging from 12 Å in Co/Ru to ≃18–21 Å in the Fe/Cr and Co/Cr systems.

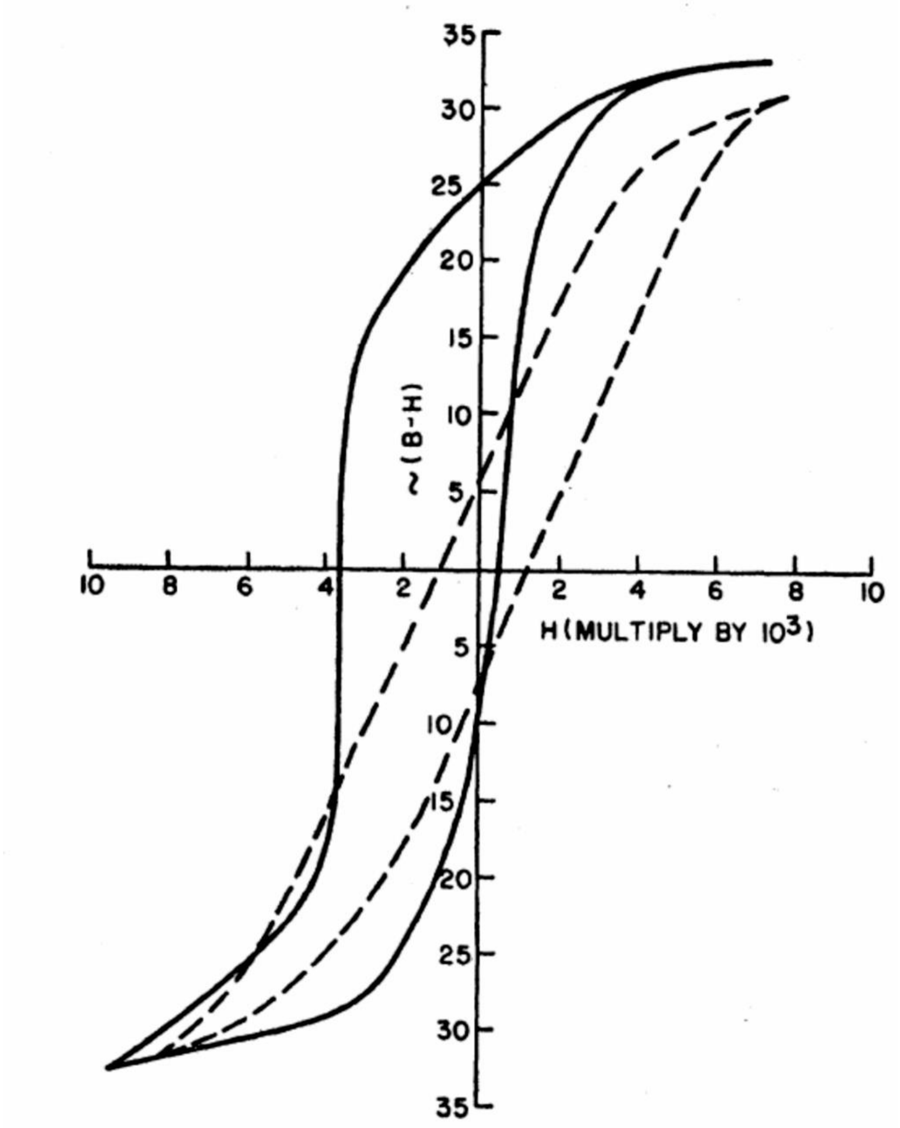
PACS numbers: 75.50.Rr, 72.15.Gd, 75.70.Cn

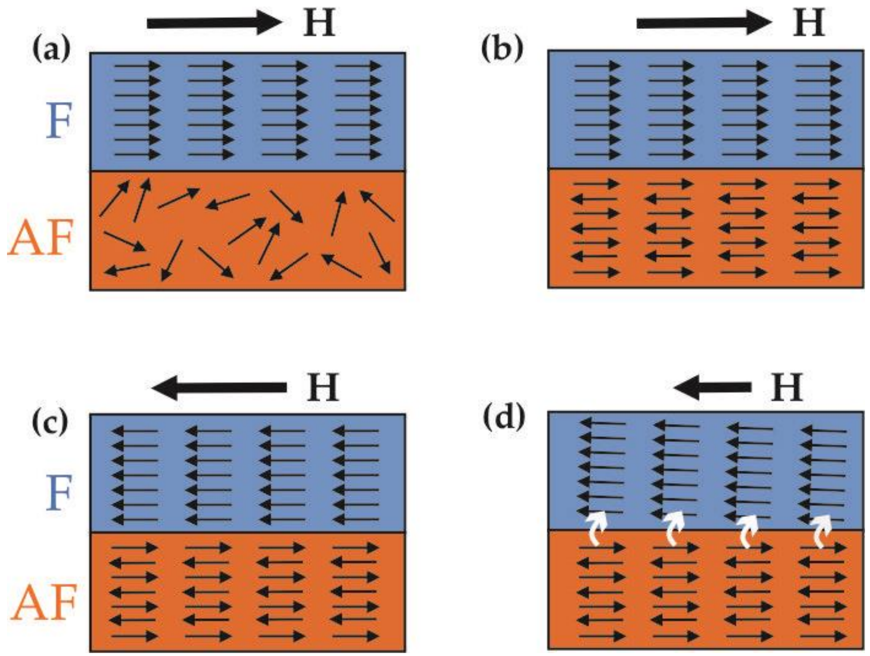
Spin-Valve

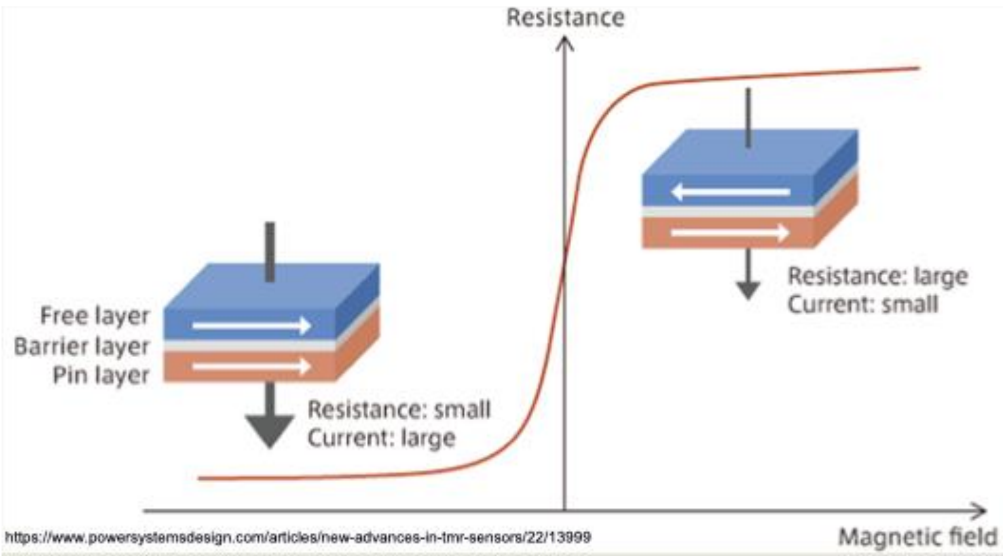


Spin-valve structure.
Ta
FeMn
Co
Cu
NiFe
Ta
Si
Cap
Pinning Layer
Pinned Layer
Spacer
Free Layer
Buffer
Substrate
GMR Active Region

Exchange Bias Effect

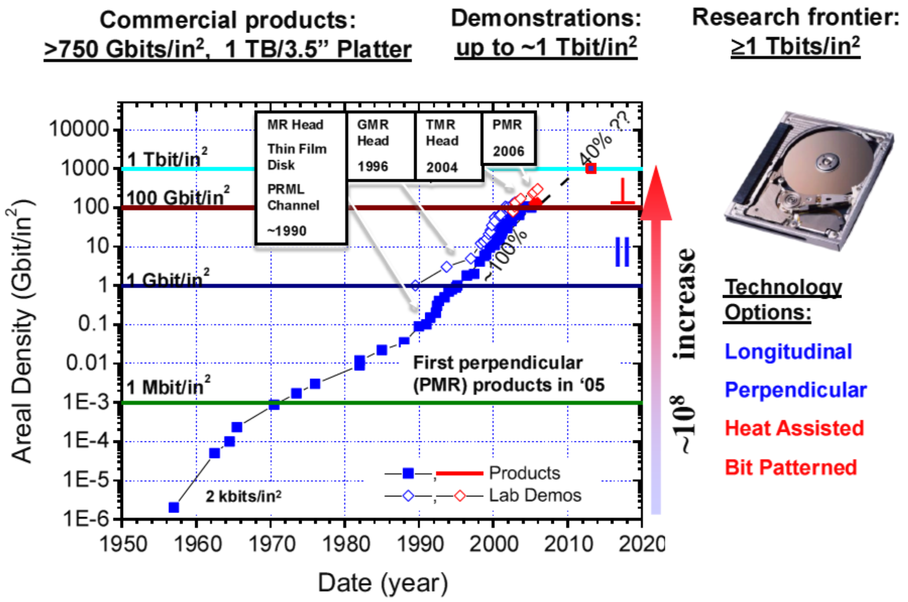


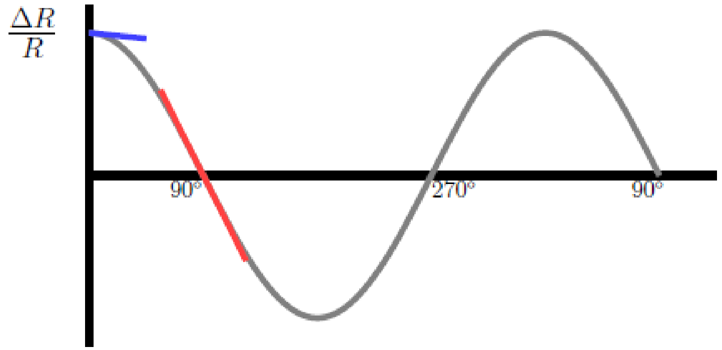




HDD Read-Head

- Read-heads detect tiny fields resulting from a bit of stored information.
- Biasing permanent magnet materials were incorporated either side of the stack so that the orientation of the free layer was as close as possible to 90 degrees.
- If the reference and free layer were antiparallel the field that is being sensed needs to overcome the total AF coupling in the SAF.
- By biasing the free layer, very small fields will generate a signal, even for small deflections.





Antiferromagnets of Choice

- The first antiferromagnetic material used in a GMR head was NiO.
- It was soon replaced by FeMn.
- Around the mid 90s FeMn was replaced by IrMn.
- Another material that has had some use due to its high magnetocrystalline anisotropy is PtMn.

0.03 parts per billion of the Earth's crust
Price in 2000: $13k/kg
Price in 2021: $163k/kg

GMR Sensors Applications (other than read-heads)

- They have a small footprint and are capable of sensing the Earth's magnetic field, which makes them attractive for orientation, navigation and inertial positioning applications.

- GMR sensors are more accurate and reliable than other types of touch screen sensors, such as resistive touch sensors → high end touch screens.

- They are used in crankshaft and camshaft positions, which is crucial for engine timing.

- Also in robotics to sense position and orientation of objects.

- And many more!

Tunnelling Magneto Resistance (TMR)

- Now imagine that you substitute the non magnetic metallic spacer by an insulator.
- If the insulating layer is thin enough then electrons can tunnel from one F layer to another.
- This is strictly a quantum mechanical effect.
- The effect was discovered by M Jullière in 1975 in Fe/Ge-O/Co junctions at 4.2K.
- The relative change in resistance was quite modest at 14% and did not attract a lot of attention.

However…

- In 1991 T. Miyazaki (Tohoku University) found an effect of 2.7% at room temperature.

- In 1994 Miyazaki found 18% in junctions separated by an amorphous aluminium oxide insulator.

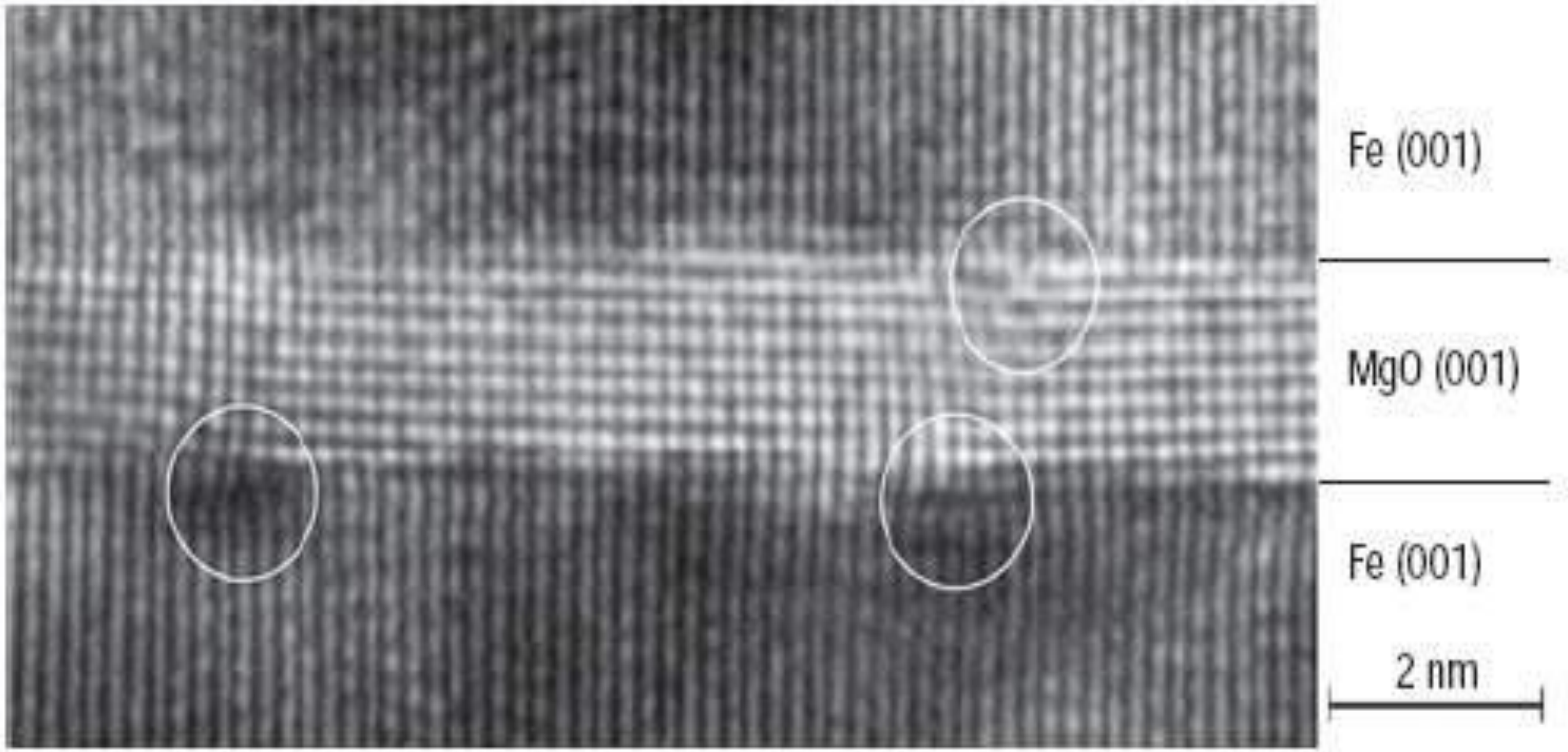
- Jagadeesh Moodera from MIT found 11.8% in junctions with Co and CoFe electrodes.

- Values of up to 70% TMR at room temperature have been observed using an alumina tunnel barrier.

MgO Barriers

- Since the year ~2000 interest focused on crystalline MgO tunnel barriers.
- This was motivated by theoretical predictions that using Fe as the F and MgO as the insulator could result in TMR values of several thousand %.
- Bowen at al. reported the first experiments showing significant TMR ratios in an MgO based MTJ.
- The material studied was Fe/MgO/FeCo(001).
- In 2004 Parkin and Yuasa managed to achieve TMR ratios >200% at RT.
- In 2008, values >600% (RT) and >1000% (4.2K) were reported by the group of Hideo Ohno (Tohoku University).

Typical TEM Image

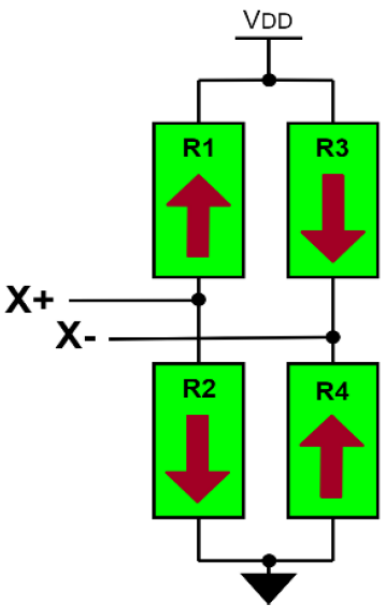


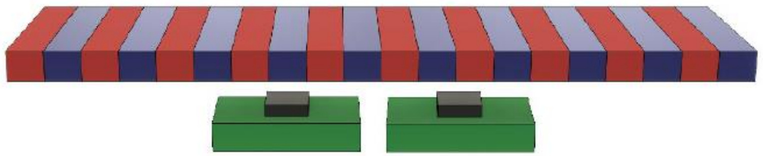
Yuasa et al, Fe/MgO/Fe

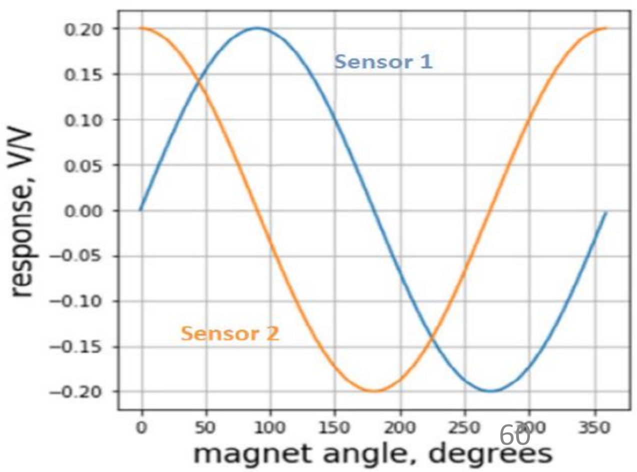
Nature Mat. 2005 $\Delta R/R = (R_{AP}\text{-}R_P)/\ R_P \approx$ **200%** at RT

TMR 1D Linear Sensor (I)

- Linear sensors work in the linear range of the TMR characteristics.
- The output from both sensors will produce two wave forms that are 90 degrees out of phase from each other.
- Since the dynamic range can be ±20 mT it is important to select the correct magnetic strip.
- Excessive distance and/or weak magnets might produce unreliable results.
- Gap between strip and TMR sensors also key.



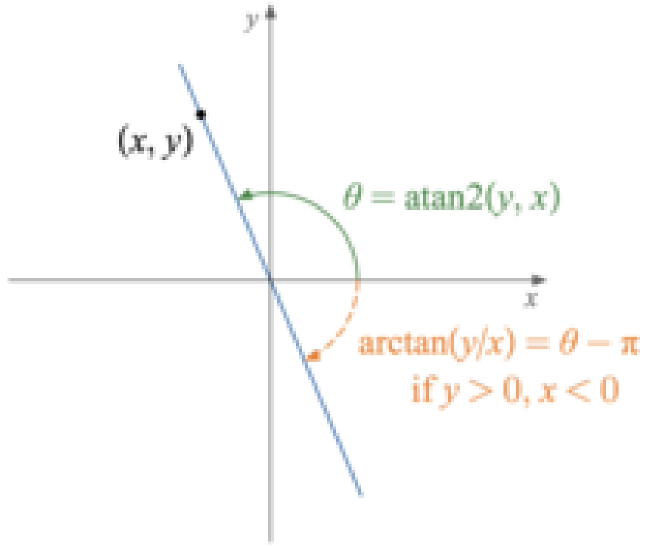




https://www.mouser.com/pdfDocs/AN121-TMR-for-Linear-Motion-Sensing-Rev01.pdf?srsltid=AfmBOopUobZWf-5eqaRU0_YnH0uqzzdU7_JK3UpH76nA4Dd3Wdk_Z5pW

TMR 1D Linear Sensor (II)

- Change in position of the magnetic strip is calculated using the previous output voltage and applying th arctan2 function.



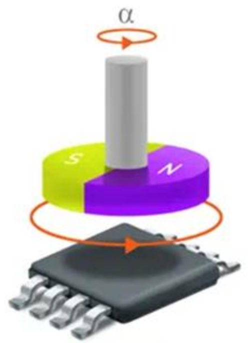
- By definition atan2(y,x) is the angle measured in radians between the positive x axis and the ray fro the origin to the point (x,y) in the Cartesian plane.
- If:
  - The pitch of the magnetic strip is 2 mm.
  - Sensor 1 last/current measured voltage = +0.2079/+0.2249 V
  - Sensor 2 last/current measured voltage = +0.9781/+0.9722 V

atan2(0.2079,0.9781) = 1.34390
atan2(0.2249,0.9722) = 1.32645

$$d = \frac{1.3490 - 1.32645}{\pi} \cdot 2mm = +0.0111\ mm$$

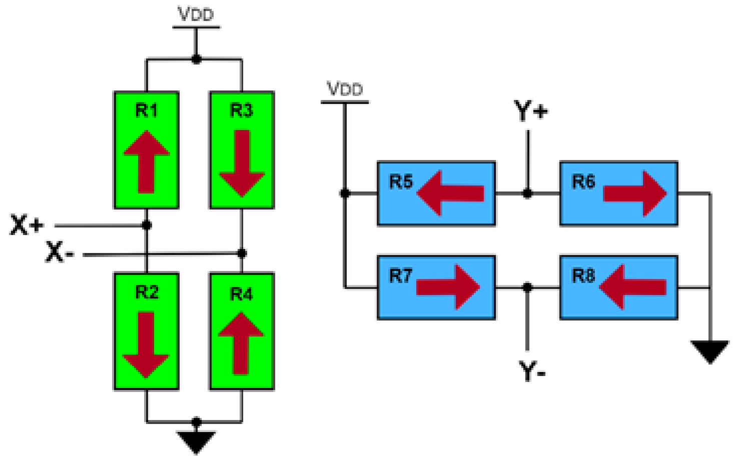
https://en.wikipedia.org/wiki/Atan2

2D TMR Angular Sensors

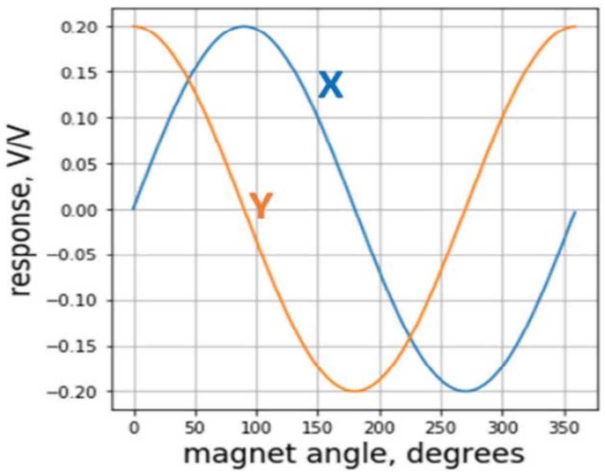


- On the other hand angular sensors work in the saturated region.

- For this reason TMR angular sensors cannot operate at low magnetic fields (typical ranges 20-100 mT).



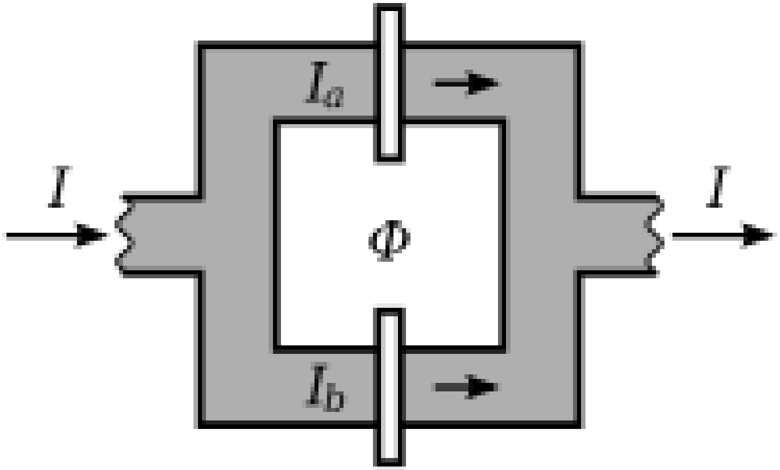
- Steering angle measurement.
- Rotor position measurement for motor communication in a brushless-DC (BLDC) motors.
- Speed sensing for wheel speed measurements (ABS sensor).
- Crank shaft speed and position sensing with direction data.



angle = atan(Y/X)

SQUID sensors

- Very sensitive magnetometers used to measure extremely weak magnetic fields, based on superconducting loops containing Josephson junctions.



- They can measure fields as low as 10^{-14} T.

- RF SQUIDS also available: only use one junction but less sensitive (quite useful in biomagnetism).

- Widespread use has been somewhat hampered by the inherent complexity of its operating principles (the additional complications associated with the use of cryogens).

https://en.wikipedia.org/wiki/SQUID#:~:text=In%20the%20clinical%20environment%20SQUIDs,for%20diagnosis%20and%20risk%20stratification.

Applications

- Most common commercial use is in magnetic property measurement system (MPMS).
- Due to their sensitivity they are ideal for studies in biology where very small fields are involved.
- Useful in magnetoencephalography (MEG)– neural activity inside the brain.
- They can operate at frequencies much higher than the highest temporal frequency of interest in the signals emitted by the brain (kHz) → MEG achieves good temporal resolution.

Conclusions

- Magnetic sensors are everywhere and it is very unlikely that they will go away!

- The obvious difference between the Hall sensor and MR sensor is the relative orientation of the measured magnetic field vector to the sensor chip.

- Cor ... ve and ... stro ...

Technology	Power Consumption	Sensitivity	Resolution	Cost
Hall	High	Low	Low	Cheap
AMR	Mid	Mid	High	Cheap
GMR	Mid	Mid	Mid	Not so cheap
TMR	Low	High	High	More expensive

- TM ... e.