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Magnetic field sensors

SENSOR SYSTEMS

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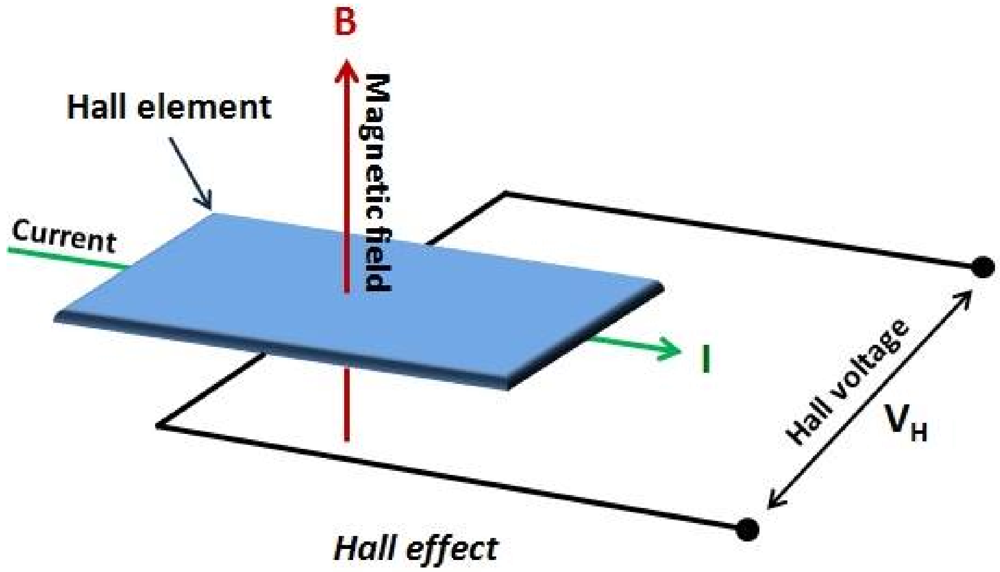
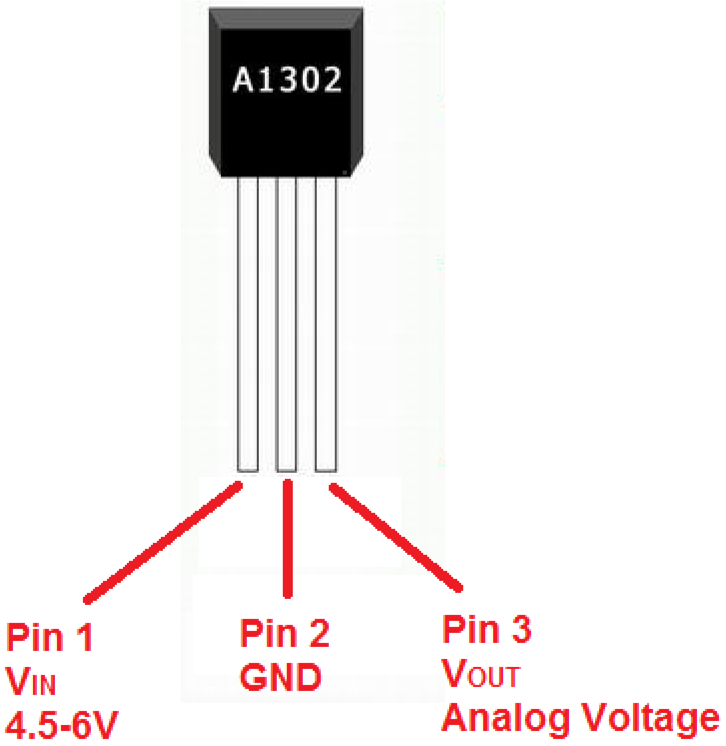
- Hall sensors
- Magneto-resistive sensors





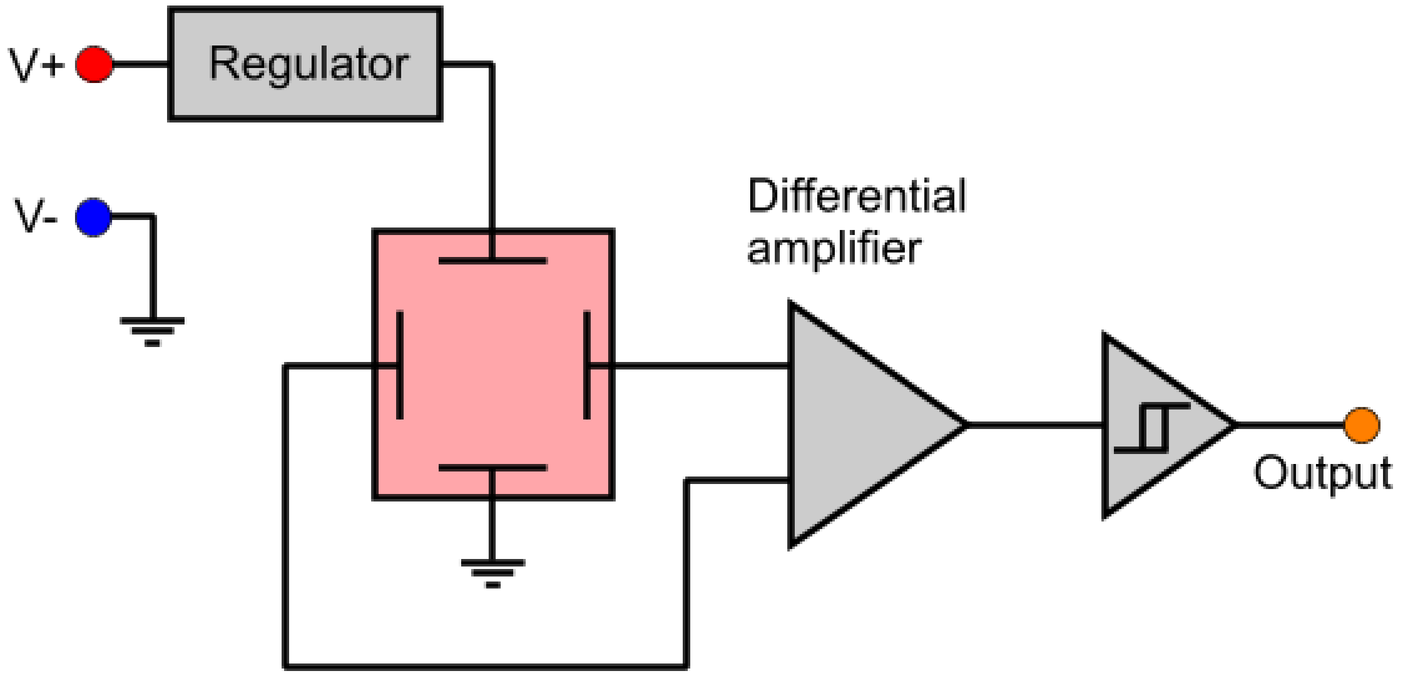
WeBeep: 10 – Hall sensors

Hall sensor system

Thin sheet of conductive (or semiconductor) material with output connections perpendicular to the direction of current flow.

When subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength.

The voltage output is very small (µV) and requires additional electronics to achieve useful voltage levels.

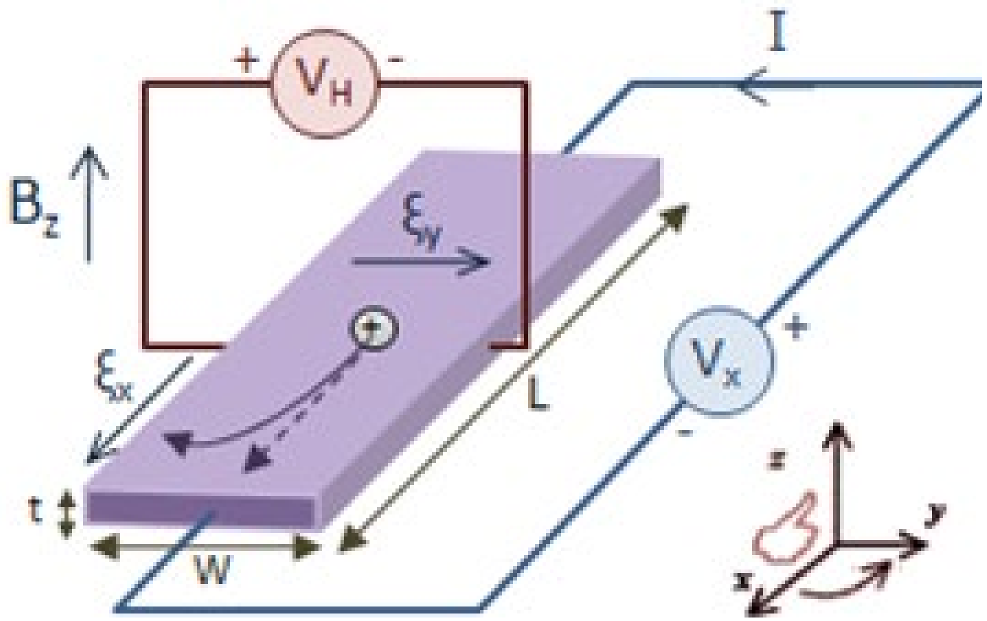


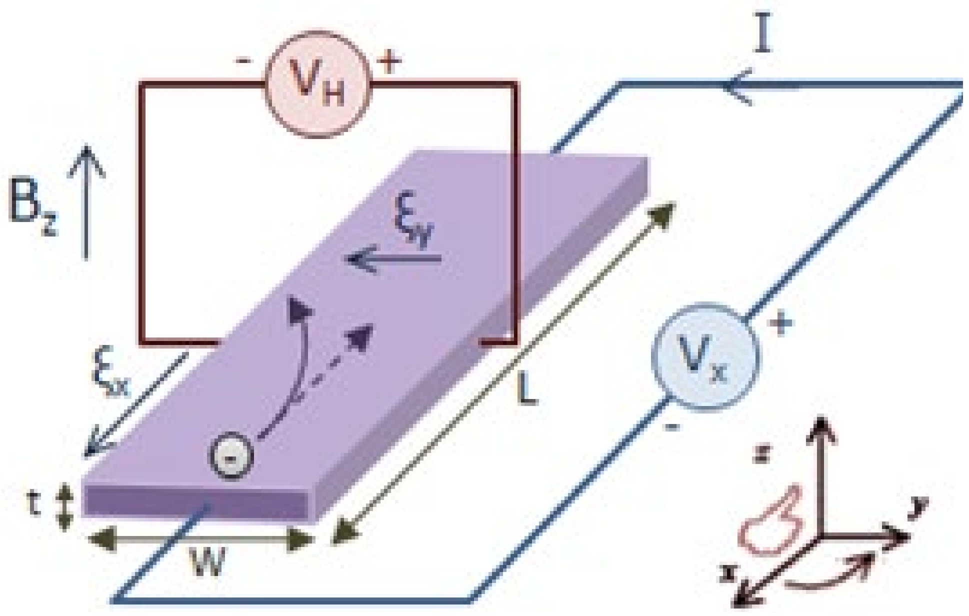
Coulomb Force and Lorentz Force:

$$\boldsymbol{F} = q(\boldsymbol{E}_y + \boldsymbol{v}_x \times \boldsymbol{B}_z)$$

The Hall voltage is recorded perpendicular to the direction of current flow.

→ Opposite effect depending on the majority carrier (holes or electrons)





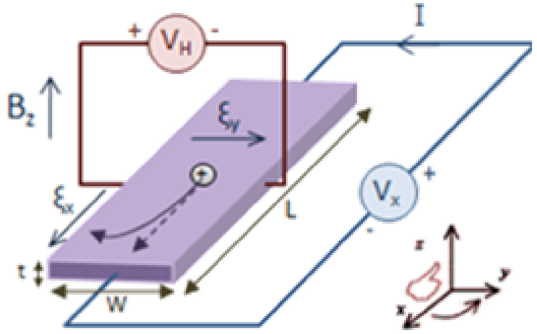
At equilibrium (considering modulus of the vectors):

$$E_y = vB$$

Being: $E_y = \dfrac{V_H}{w}$

$v = \dfrac{J}{qn}$ (J current density due to V_x)

→ $V_H = \dfrac{1}{qn} JwB = R_H JwB$

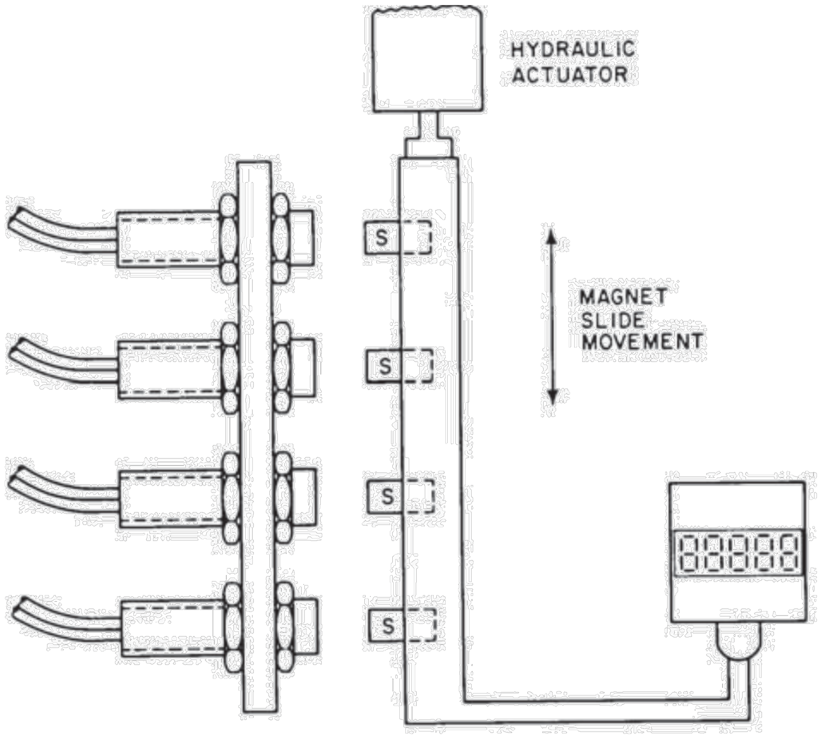


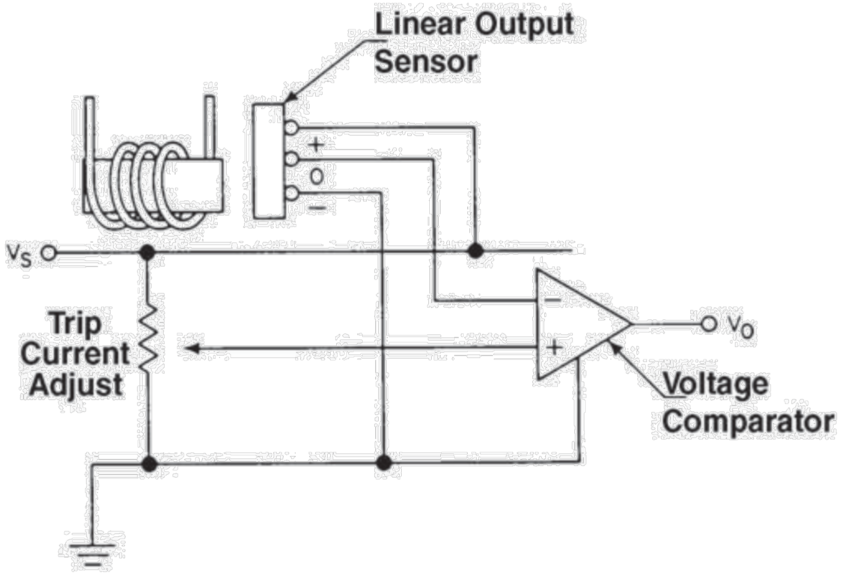
$\boldsymbol{F} = q\left(\boldsymbol{E}_y + \boldsymbol{v}_x \times \boldsymbol{B}_z\right)$

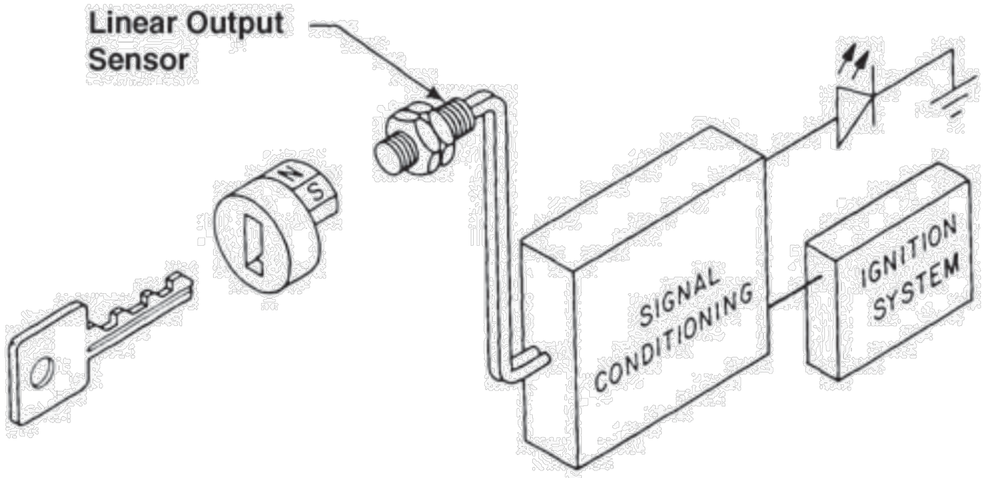
R_H = Hall constant

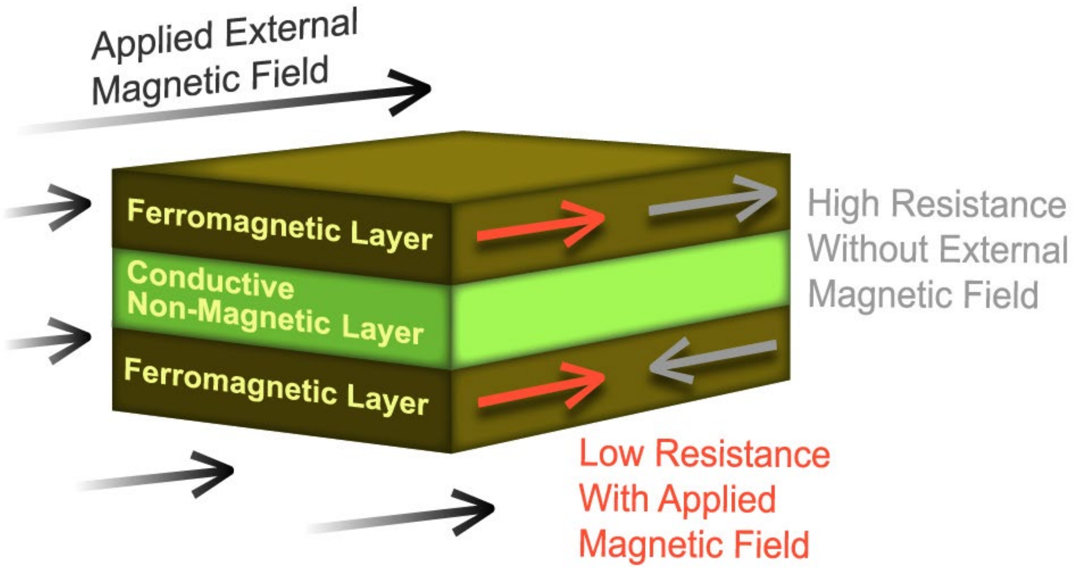
- negative for electrons (n-doped semiconductors)
- positive for holes (p-doped semiconductors)

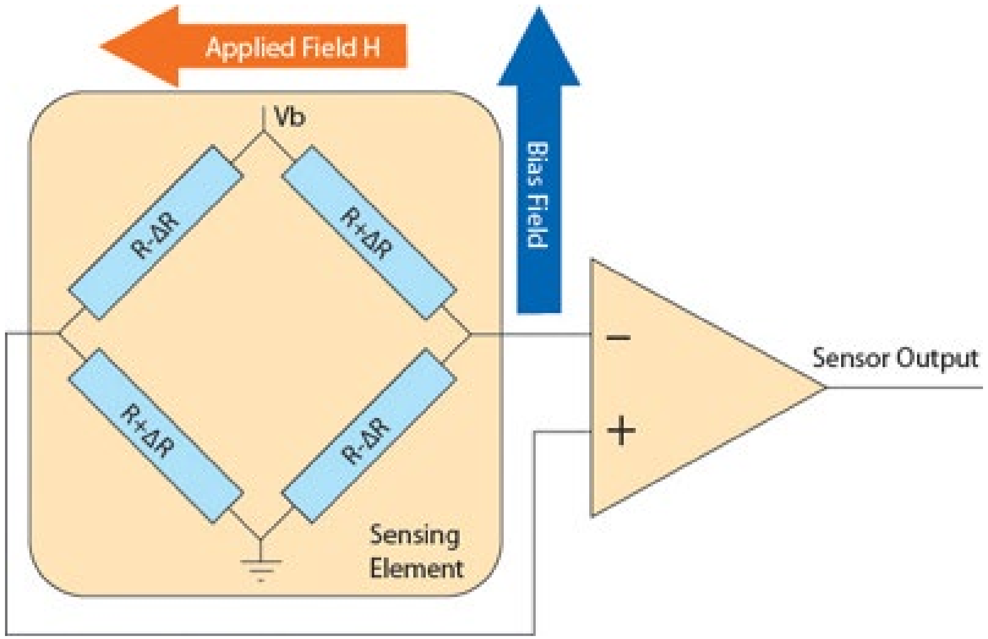
- Proximity / displacement sensors
- Magnetic switches
- Doors interlock
- Magnetic encoders
- Current measurements
- Compass











Beep: 11 – Magnetoresistance

Magnetoresistance = the property of a material or system of materials that results in a change of resistance when exposed to a magnetic field.

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solid-state magnetic sensors:

- can replace more expensive wire-wound sensors
- more sensitive than Hall sensors

Figure of merit for magnetoresistance is the MR ratio defined by:

$$MR = \frac{R_{max} - R_{min}}{R_{min}}$$

The MR ratio indicates the maximum signal that can be obtained from the sensor.

Ordinary Magnetoresistance (OMR)

All conductors exhibit a weak MR effect too feeble to be of use in sensors.

Anisotropic Magnetoresistance (AMR) MR = 1-2%

Many magnetic materials exhibit a larger magnetoresistive effect, which is significant enough to be used in sensors.

Giant Magnetoresistance (GMR) MR = 20-50%

Tunneling Magnetoresistance (TMR) MR = 50-60%

Recent advances in thin film deposition technology has allowed researchers to create nanostructured multilayer devices with successively larger effects.

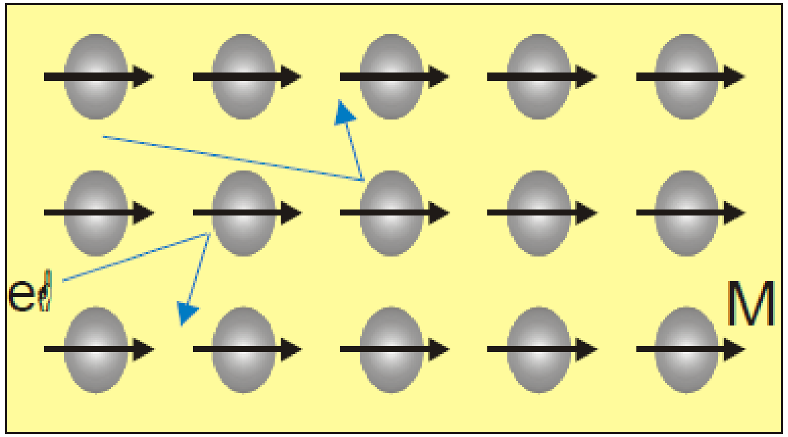
Anisotropic Magnetoresistance (AMR)

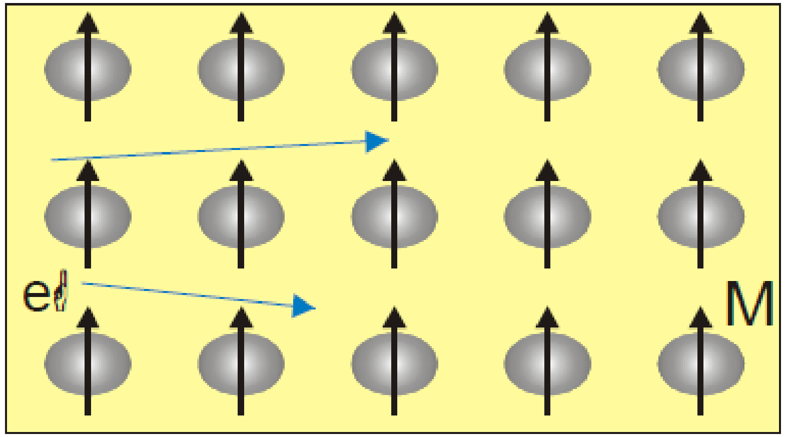
Anisotropic because its properties depend on the angle between the electric current and the magnetization direction

AMR effect = change in the scattering cross section of atomic orbitals distorted by the magnetic field:

- Magnetization parallel to current (i.e. 0° or 180°)
  → resistance produced by scattering is maximum

- magnetization perpendicular to current (i.e. 90° or 270°)
  → resistance produced by scattering is minimum

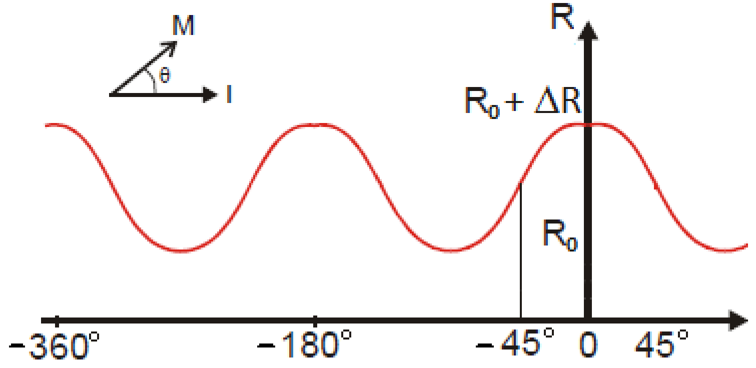




$$R = R_0 + \Delta R \cdot \cos^2\theta$$

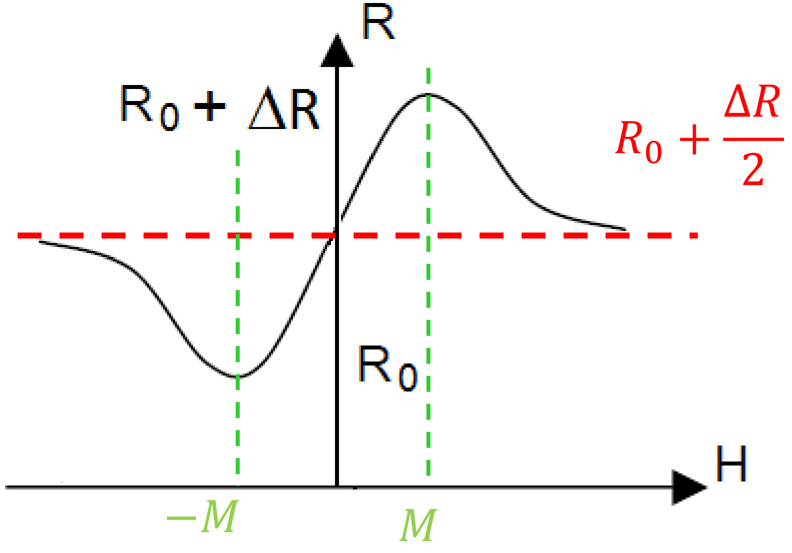
Resistance is given as a function
of angle between magnetization and current.

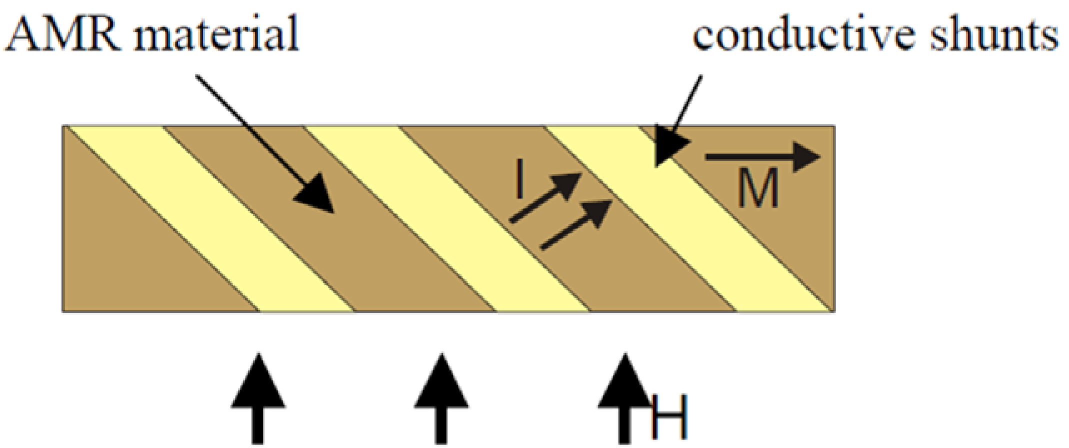
→ θ = 45º maximum sensitivity and linearity.



45º alignment by patterning diagonal stripes of highly conductive metal onto the more resistive AMR material.

Application of an external magnetic field
→ rotate the magnetization with a resulting change in resistance.





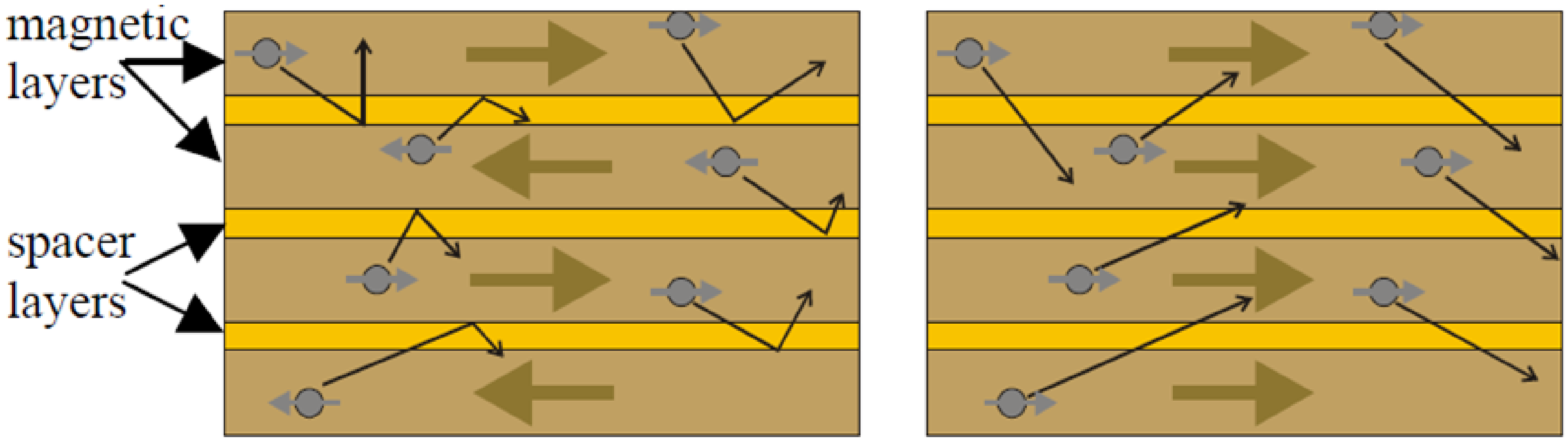
$$B = \mu_0 \mu_r (H + M)$$

Giant magnetoresistance because their MR far exceeds that of any AMR devices.

Two or more layers of ferromagnetic metal separated by ultra-thin non-magnetic metal spacer layers.

Spacer layers allow the magnetic directions of the layers to differ while still permitting the passage of electrons.

- magnetic layers aligned in opposite direction
  → electrons are blocked from the adjacent layers (high resistance)
- magnetic layers aligned in same direction
  → electrons pass freely through other layers (low resistance)



GMR working principle

With thin spacer layers (few atoms)

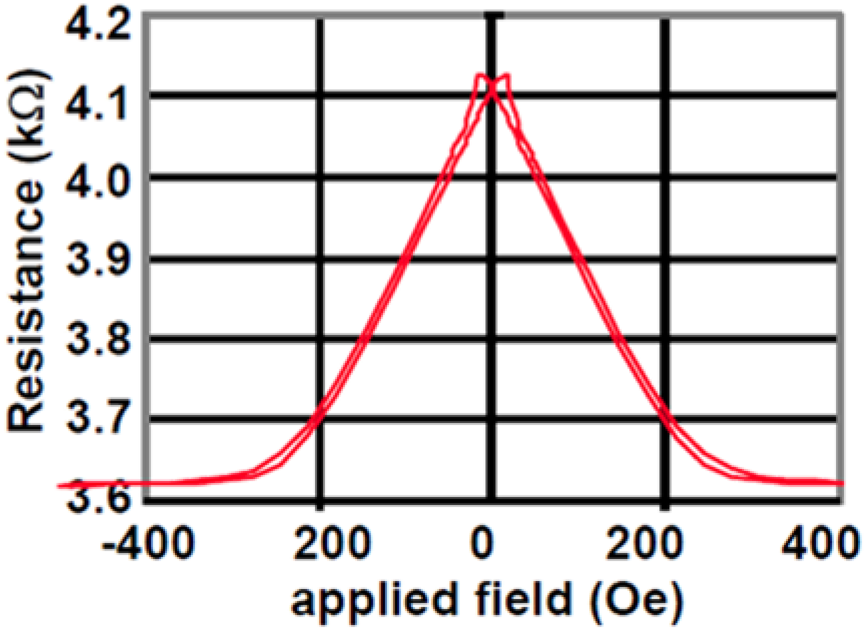
→ strong "exchange coupling" favors antiparallel alignment

(high resistance)

When an external magnetic field overcomes the interlayer coupling

→ force all of the layers to align

(low resistance)

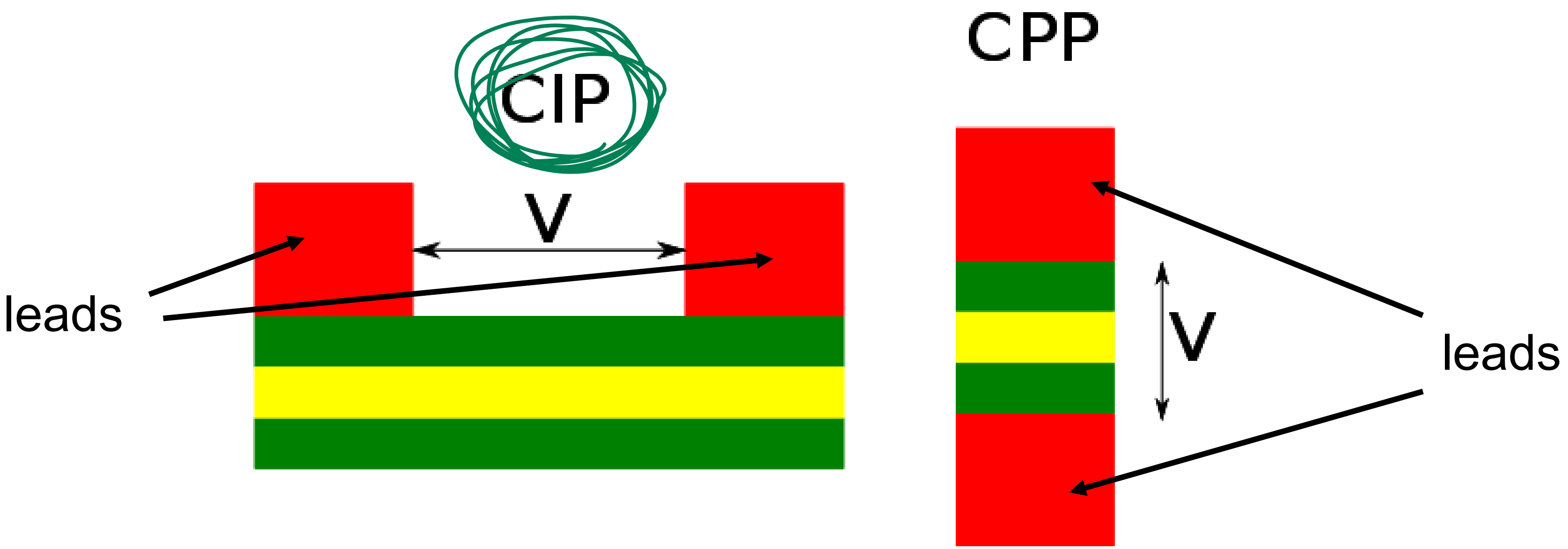


Magnetic field in either direction causes alignment of the magnetizations

→ R vs. H curve = even function

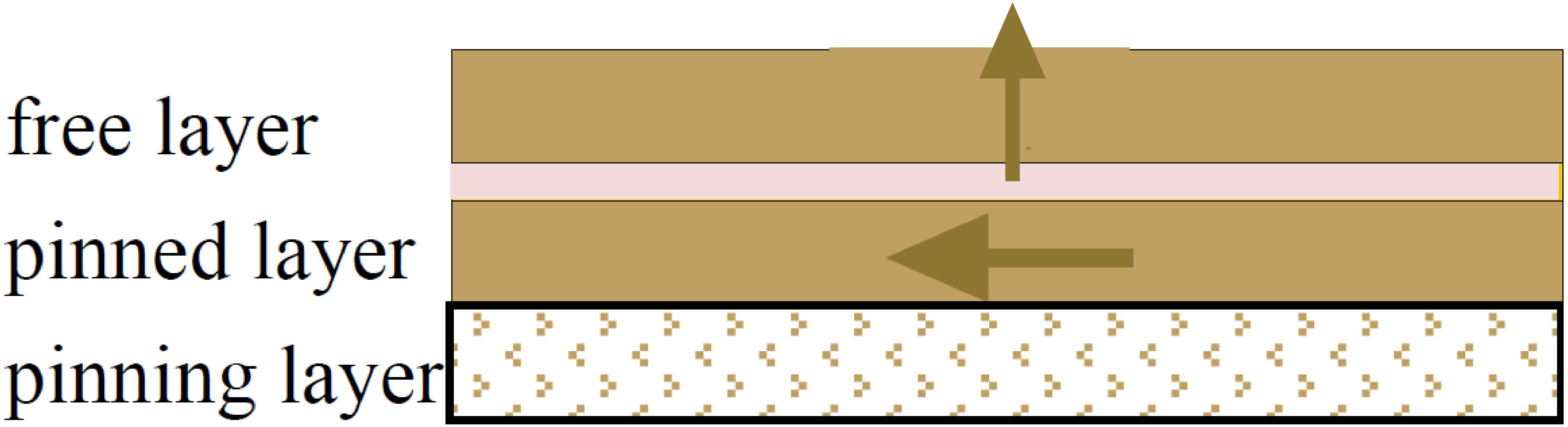
- current-in-plane of the films (CIP)
  MR is reduced because of current shunting through the layers

- current-perpendicular-to-plane (CPP)
  resistance that is too low for practical circuit applications



TMR uses two magnetic layers with an ultra-thin insulating layer in the middle:

- bottom layer deposited on top of an antiferromagnetic “pinning” layer
  (no net magnetization, but hold the magnetization of the adjacent ferromagnetic layer fixed in one direction)
- top layer is free to rotate its magnetic field in response to an external field
  (its rest position is made to be perpendicular to the pinned layer)

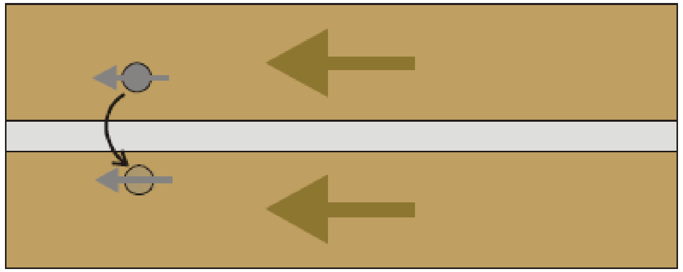


Quantum mechanical tunneling:
electrons pass from one layer to the other through the insulator

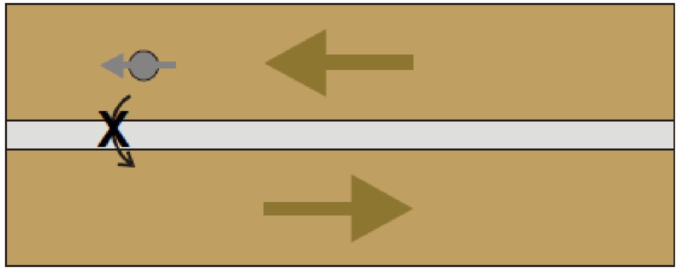
The ease of tunneling between the two magnetic layers is modulated by the angle between the magnetization vectors in the two layers (spin-dependent tunneling):

- **Magnetic layers aligned in the same direction**
  → many states are available in the bottom layer for spin-polarized electrons from the top layer to tunnel into (**low resistance**)

- **Magnetic layers in opposite directions**
  → the spin polarized electrons are prevented from tunneling because they have the wrong orientation to enter the bottom layer (**high resistance**)



High tunneling probability



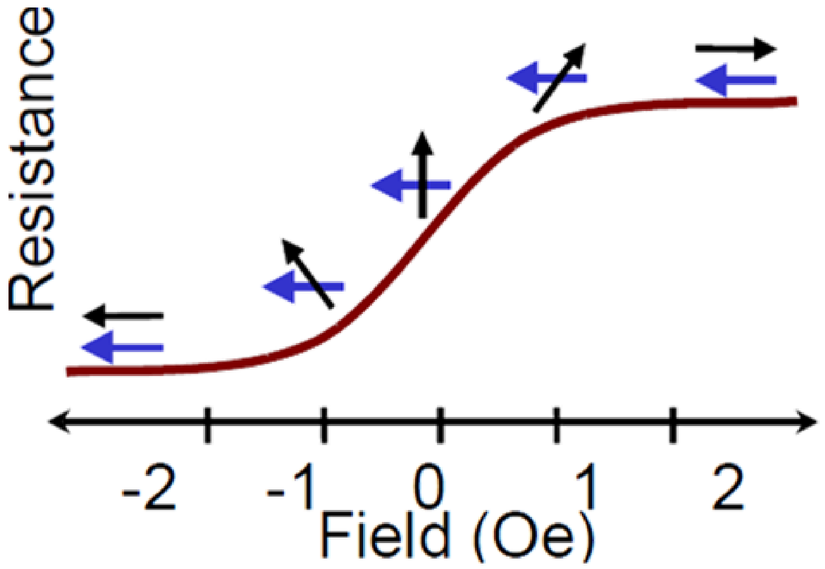
Low tunneling probability

TMR working principle (2/2)

Absence of an applied field
→ direction of magnetization of the free layer is perpendicular to that of the pinned layer

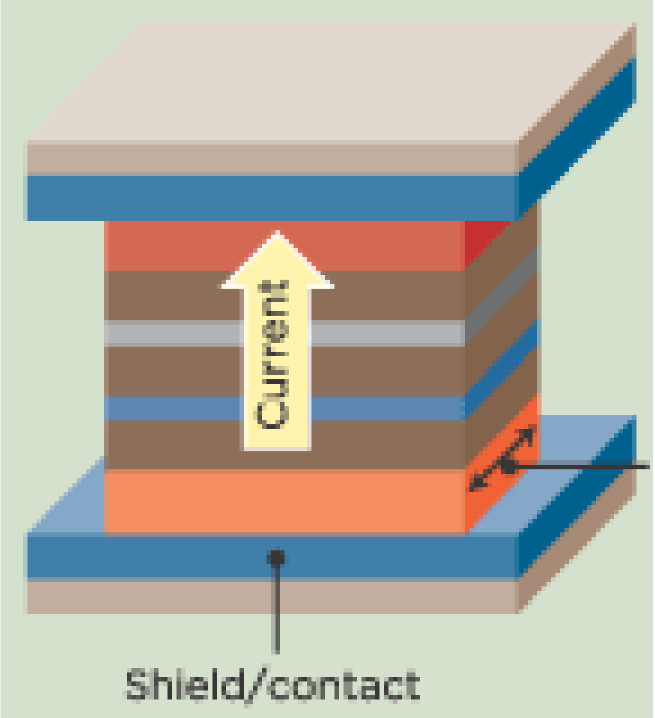
Fields parallel to the pinned layer
→ decrease the angle making the layers more parallel and decrease the resistance

Fields in the opposite direction
→ increase the angle and increase the resistance



TMR devices are operated in **current-perpendicular-to-plane** (CPP) configuration with contacts on top and bottom of the film stack.

Multiple TMR devices are often electrically connected in series to increase the overall resistance and limit the voltage at each tunnel barrier (voltages above a few hundred mV may damage the thin insulator).



Application that requires high sensitivity:

- Eddy currents sensing
  (to detect cracks or flaws into materials)
- Stray field sensing
  (to detect defects and non-uniformities in magnetic materials)
- Remote monitoring of stresses
  in embedded steel reinforcements and fasteners
  (magnetoelastic effects)
- Displacement encoders