NUST
SCHOOL OF ELECTRICAL ENGINEERING
& COMPUTER SCIENCE

- Course: **EE383 Instrumentation and Measurements**
- Session: Fall 2022

- **Lectures: Week 7**
- Course Instructor: Dr. Shahzad Younis

Week 7

- **Chapter 5**

  Transducers

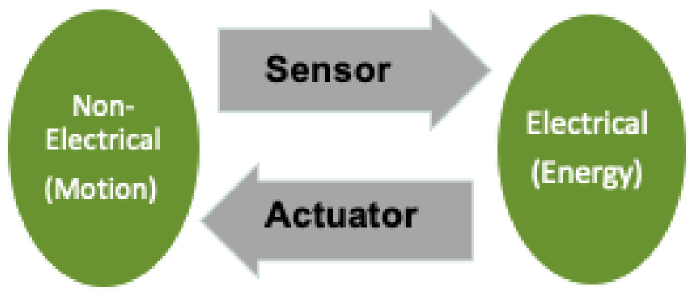
Book: Introduction to Measurements and Instrumentation, Arun K. Ghosh

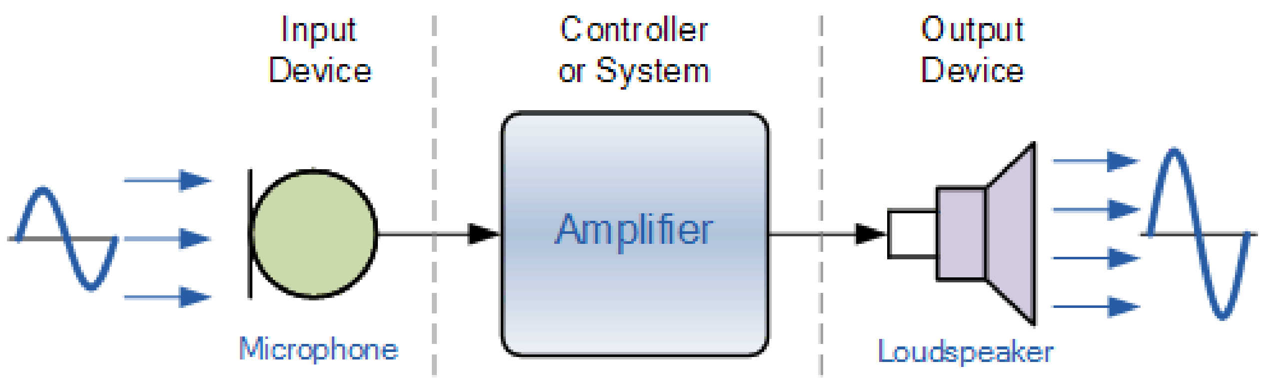
Recall: Instrument

- ❑ **Transducer**

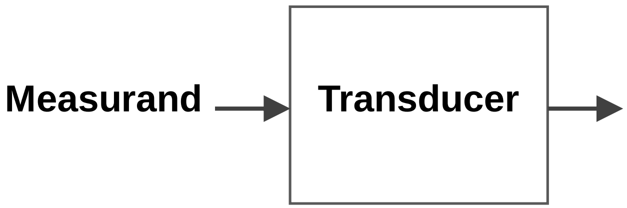
Instrument

- **Transducer**





Instrument

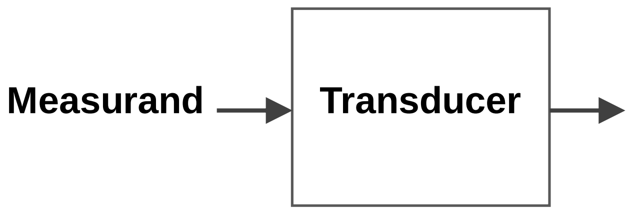


❑ **Transducer**

- **Conversion of the physical variable to be measured into a suitable signal (preferably electrical one)**

Instrument

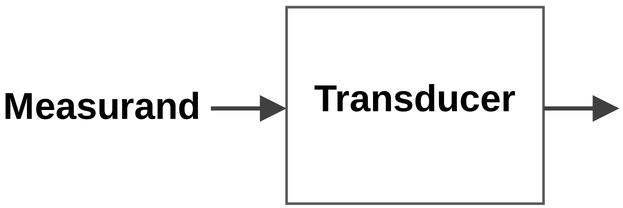
- **Measurement system**



- **Transducer**
  - **Output as a function of the measurand**
  - **Output is in a suitable form; electrical**
  - **Piezoelectric strain sensor, thermocouple etc.**

Instrument

- **Measurement system**

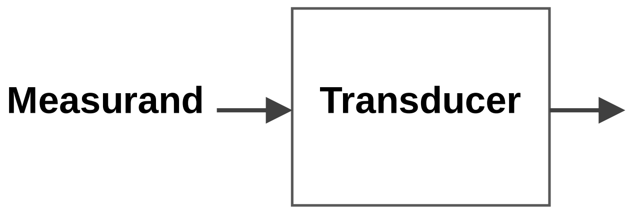


Is transduction perfect?

- **It also extracts energy from the measurand, so disturbs measurement**

Instrument

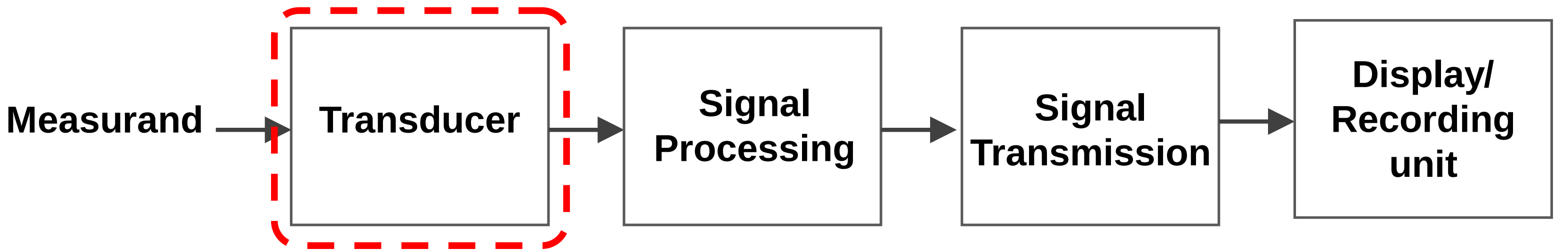
- ❑ **Measurement system**



- ❑ **CH 5, Ch 6-11**

Instrument

- **Measurement system**



Transducers

- **Electrical measurements (I and V)**
  - **Only signal conditioning and display**
  - **Transducers are not required**

Transducers

- **non-electrical measurements (temperature, pressure, ….)**
  - **transducers are the first step of the instrumentation**
  - **Transducers/sensors/detectors**

Transducers

- **What is a transducer?**

Transducers

Transducer is a device which receives energy in one form and converts it into another convenient form preferably an electrical form.

Example:

A **thermocouple** produces an electrical output, i.e., voltage across its terminals in response to change in temperature.

Heat Energy → Electrical Energy

Voltage is **convenient to measure** instead of temperature.

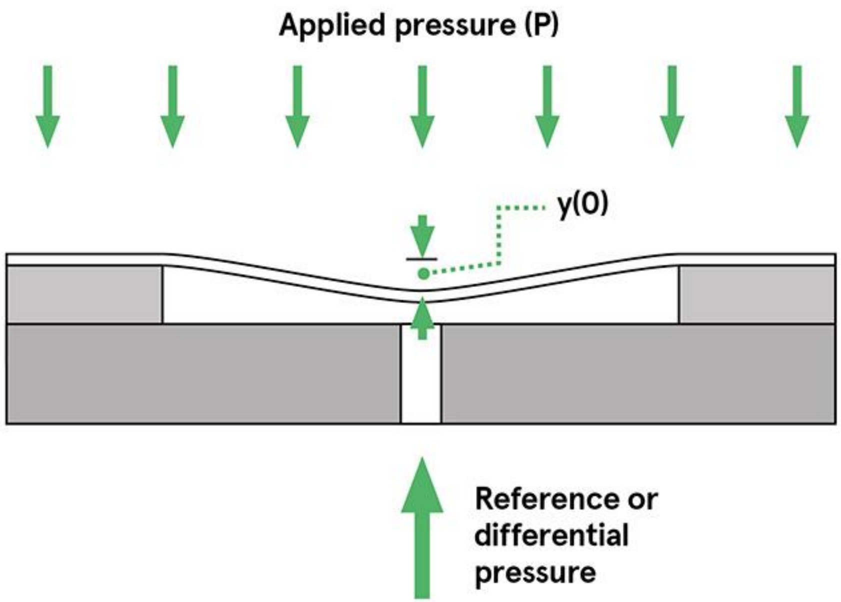
Thermocouple is a **temperature transducer**.

Transducers

- **What is a transducer?**
  - **converts energy from one form or state to a convenient form or state**
  - **change of the form of energy is not always necessary**

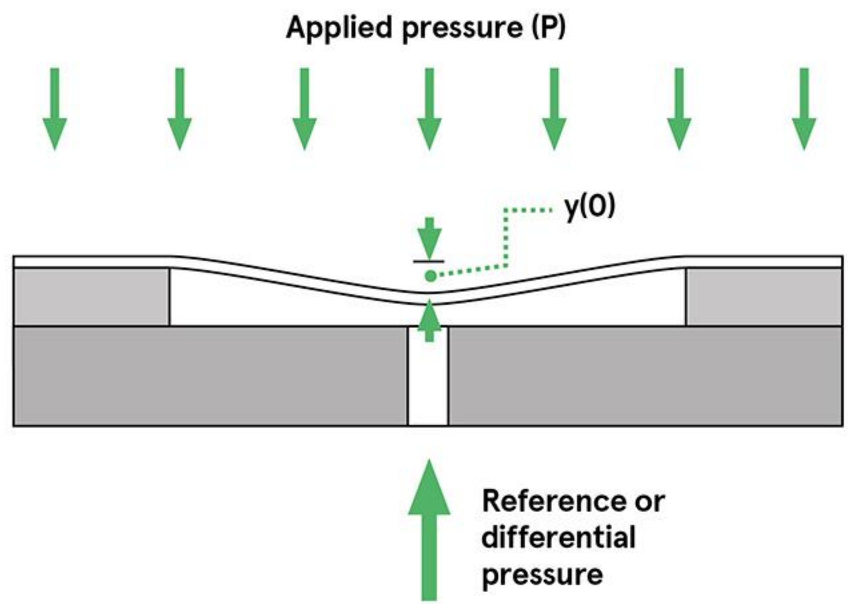
Transducers

- **diaphragm (dai·uh.fram)**
  a pressure transducer



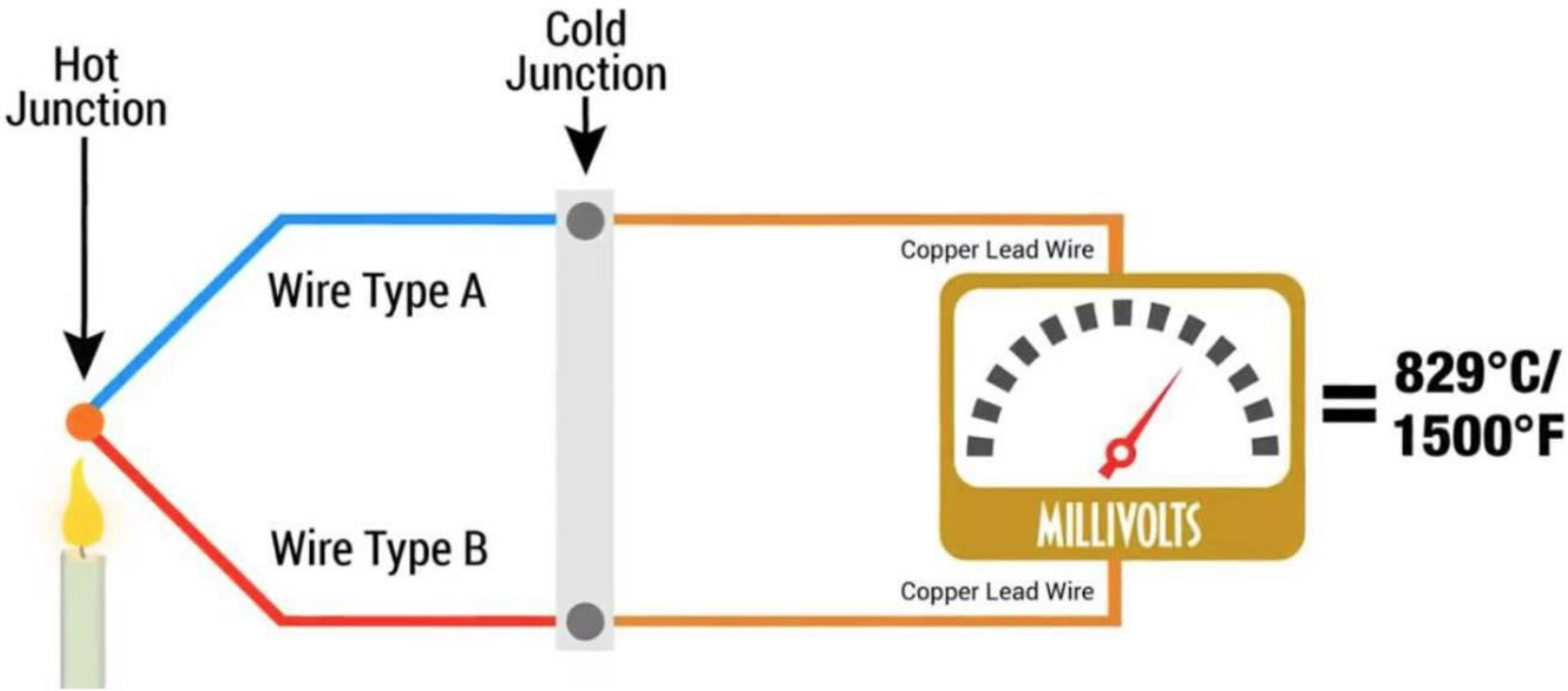
Transducers

- diaphragm- a pressure transducer
  - pressure to displacement
    - both are mechanical energies
    - displacement being convenient for measurement
  - only change in the energy state



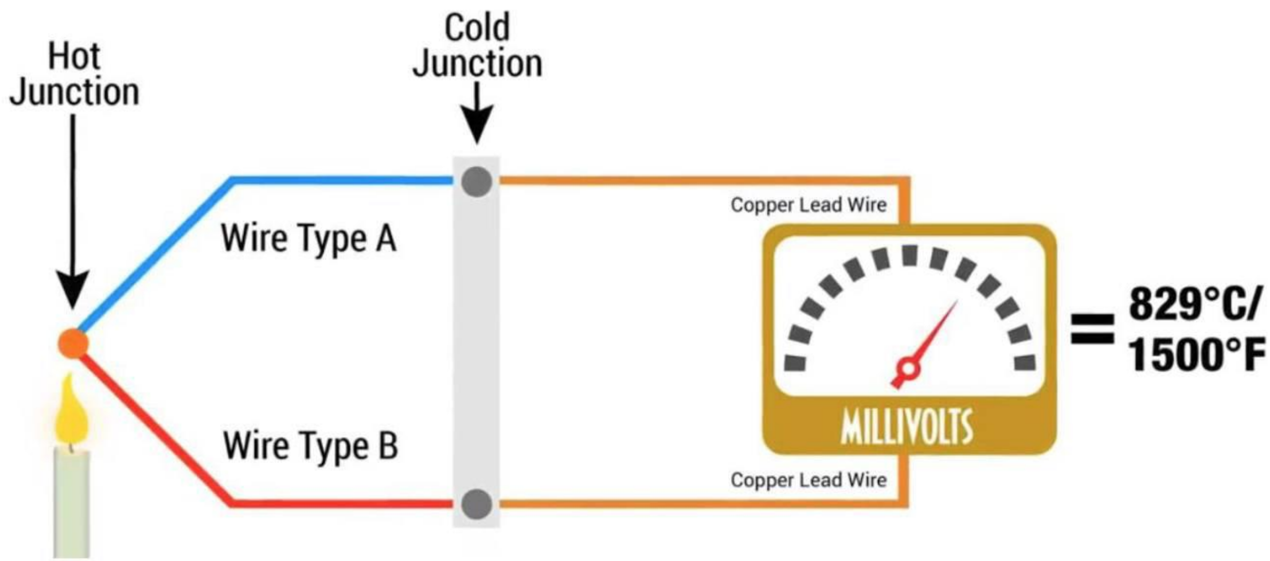
Transducers

- thermocouple:- a temperature transducer
  - junction of dissimilar metals



Transducers

- thermocouple:- a temperature transducer
  - temperature change to electrical output
    - electrical being more convenient for measurement
    - change in the form of energy



Transducers

- **Why electrical output is preferred?**

Transducers

- **Why electrical output is preferred?**

1. The signal can be conditioned, i.e. modified, amplified, modulated, etc.
2. A remote operation as well as multiple readout is possible
3. Devices, such as op-amps are available to ensure a minimal loading of the system
4. Observer-independent data acquisition and minute control of the process with the help of microprocessors

Classification of Transducers

1. **Active and passive transducers**
2. **Analogue and digital transducers**
3. **Primary and secondary transducers**
4. **Direct and inverse transducers**

Classification of Transducers

1. **Active and passive transducers**
2. **Analogue and digital transducers**
3. **Primary and secondary transducers**
4. **Direct and inverse transducers**

Transducers Classification: Active and Passive

- ❑ **Active Transducers**
  - ❑ Generate energy by themselves
    - ❑ Conversion of energy from one form to another
    - ❑ No external source of energy is necessary to excite them
  - ❑ Thermoelectric, Piezoelectric, Photovoltaic, Electromagnetic, Galvanic etc.

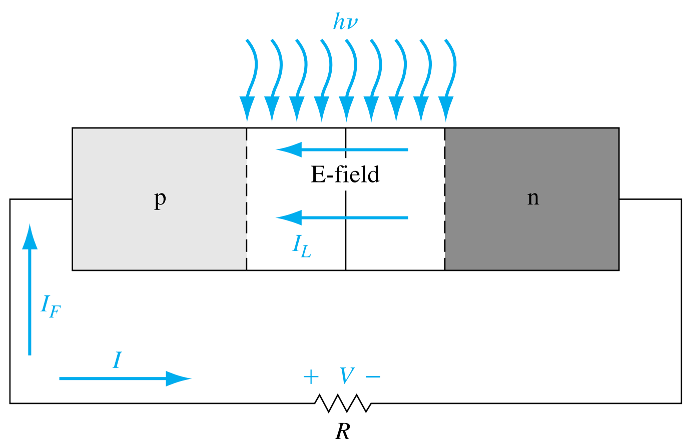


Figure 14.6 | A pn junction solar cell with resistive load.

Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

❖ **Photovoltaic transducer**

Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Active Transducers

Table 5.1 Active transducers

Property used	*Device*	*Application in the measurement of*
Thermoelectricity generation	Thermocouple	Temperature
	Thermopile	Radiation pyrometry or temperature of distant objects
	Thermocouple gauge	Low pressure
Piezoelectricity generation	Piezoelectric transducer	Pressure
Photoelectricity generation	Photodiode in combination with a diaphragm	Pressure
Electricity generation by moving a coil in a magnetic field	Electromagnetic pick-up	Flow

Transducers Classification: Active and Passive

- **Passive Transducers**
  - Do not generate energy
    - Measurand changes their electrical state/property
    - Need to be excited by external electrical energy
  - Resistive, Inductive, Capacitive, Photoconductive, Thermoresistive, etc.

Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

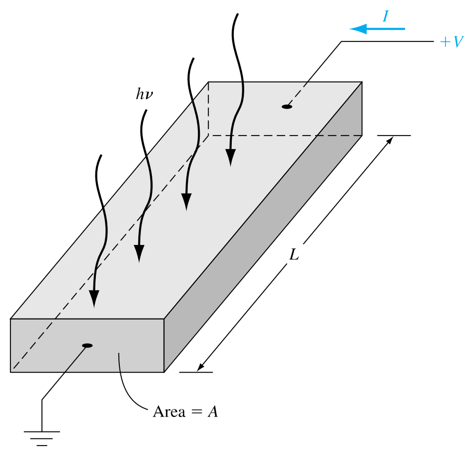


Figure 14.16 | A photoconductor.

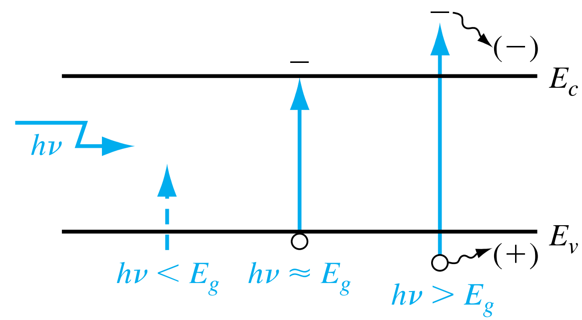


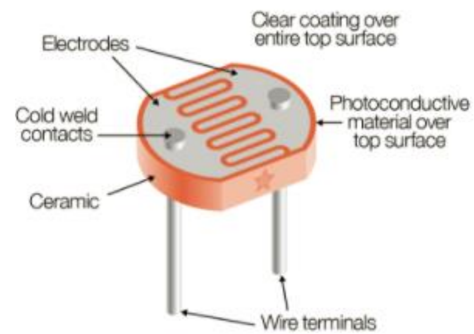
Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

❖ **Photoconductive transducer**

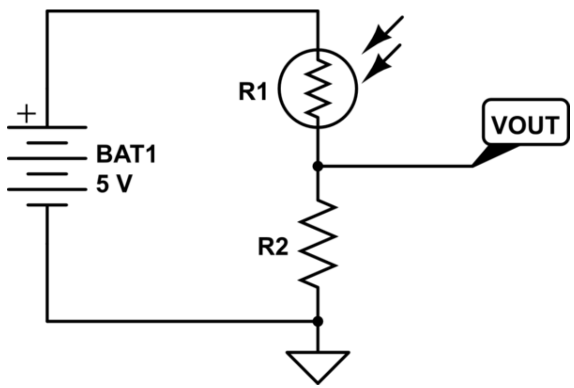
Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

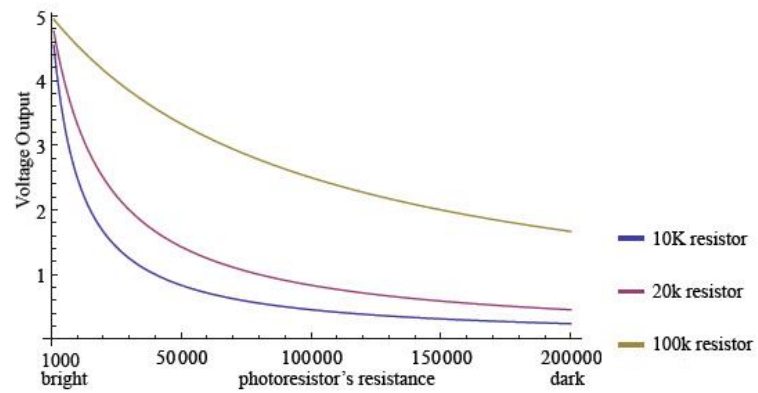
Passive Transducers
Photoresistor

A **photoresistor** (also known as a light-dependent resistor, LDR, or photo-conductive cell) is a passive component that decreases resistance with respect to receiving luminosity (light) on the component's sensitive surface.



can be excited by an emf from a cell and the voltage against the photoresistor can be measured. When exposed to a light of certain intensity (measurand) its resistance changes, thus changing the voltage across it.





Passive Transducers

Table 5.2 Passive transducers

Property used	*Device*	*Application in the measurement of*
Resistance variation	Potentiometer	Displacement
	Strain gauge	Small displacement useful in the measurement of strain, pressure, force, torque
	Pirani gauge	Low pressure
	Hot-wire anemometer	Flow
	Platinum resistance thermometer	Temperature
	Thermistor	Temperature
	Photoconductive cell or light-dependent-resistor (LDR) in combination with a diaphragm	Pressure
Inductance variation	Linear variable differential transformer (LVDT)	Displacement
	Synchro	Angular displacement
	Eddy-current gauge	Displacement
Capacitance variation	Capacitor gauge	Displacement, pressure
	Dielectric gauge	Liquid level, thickness (which are basically displacements)

Active and Passive Transducers

Active transducers are **self generating** devices. No external energy source is required to excite them.

Example:

Thermocouple.

Depending on principle of operation, active transducers can be.

1- Thermoelectric.

2- Piezoelectric.

3- Photovoltaic.

4- Electromagnetic.

Passive transducers **do not generate energy.** They need to be excited by application of external electrical energy source.

Example:

Photoresistor/ Potentiometer.

Depending on principle of operation, passive transducers can be.

1- Resistive. (Potentiometer, Strain gauge)

2- Inductive. (LVDT)

3- Capacitive. (Capacitor gauge)

Classification of Transducers

1. Active and passive transducers
2. **Analogue and digital transducers**
3. Primary and secondary transducers
4. Direct and inverse transducers

Transducers Classification: Analogue and Digital

- **Analogue transducer**
  - Analogue output
    - Thermocouple, photovoltaic transducer, piezoelectric devices, ….
- **Digital transducer**
  - Discrete output
    - Push button switch

Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Analogue and Digital Transducers

Analogue transducers have a continuous output.

Example:

PV cell for measurement of light intensity will have an output range from **0 → 5V.**

Potentiometer can measure displacement continuously in its range of operation.

Digital transducers produce output in discrete form.

Example:

Push button switch.

Classification of Transducers

1. Active and passive transducers

2. Analogue and digital transducers

3. **Primary and secondary transducers**

4. Direct and inverse transducers

Transducers Classification: Primary and Secondary

- **Primary transducer**
  - Applied signal is directly sensed by it
    - A transducer producing output in the electrical format
    - Thermocouple, photovoltaic transducer, piezoelectric devices, ….

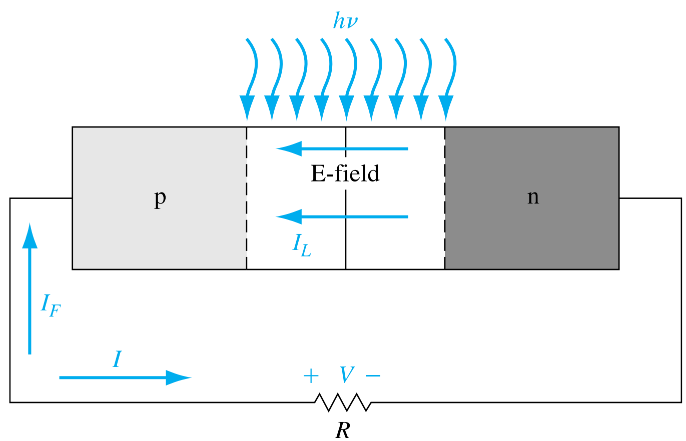


Figure 14.6 | A pn junction solar cell with resistive load.

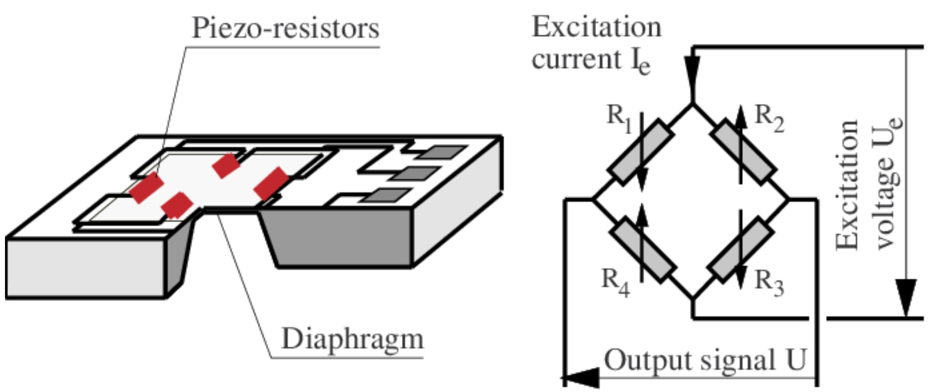
Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

❖ **Photovoltaic transducer**

Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Transducers Classification: Primary and Secondary

- **Secondary transducer**
  - If the output of the sensor is non-electrical, secondary transducer converts it into electrical form
  - Pressure measurement



❖ **Diaphragm pressure sensor**

Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Primary and Secondary Transducers

If a transducer senses the signal and produce and electrical output in response, it will be called primary transducer.

An additional transducer is not required in such case.

Example:

PV cell for **light intensity** measurement.

Thermocouple for **temperature** measurement.

Sometimes the primary transducer does not produce an electrical output.

An additional sensor called secondary transducer is required to convert its output to electrical format.

Example:

Primary transducer: A **diaphragm for pressure** measurement produces displacement. → Secondary transducer: An additional **displacement sensor** such a potentiometer maybe used to produce electrical output.

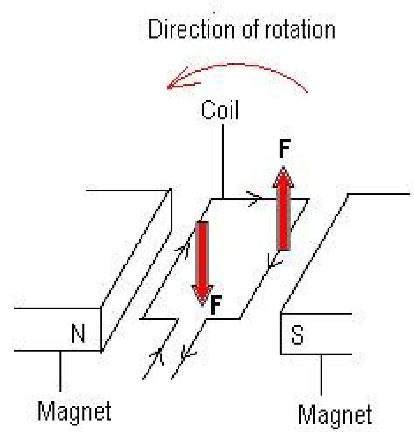
Classification of Transducers

1. Active and passive transducers
2. Analogue and digital transducers
3. Primary and secondary transducers
4. **Direct and inverse transducers**

Transducers Classification: Direct and Inverse

- **Direct transducer**
  - Receives energy in one form or state and transfers it to an electrical signal
    - Thermocouple, photovoltaic transducer, piezoelectric devices, ….

- **Inverse transducer**
  - Converts electrical quantity into a non-electrical quantity
  - A current carrying coil in a magnetic field
    - Output is force which causes translational or rotational displacement.



Ref. Ch. 5: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Direct and Inverse Transducers

Direct transducers converts physical energy to electrical energy.

Physical Energy → Electrical Energy

Example:

PV cell convert light energy to electricity.

Thermocouple convert heat energy to electricity.

Inverse transducers converts electrical energy to physical energy.

Electrical Energy→ Physical Energy

Example:

An **analogue ammeter** converts current flowing through it to mechanical rotation of a pointer.

Physical Phenomenon for Transducers

Working of transducers are based on the following physical phenomenon.

1- Magnetic effects

2- Piezoresistivity

3- Piezoelectricity

4- Surface acoustic wave

5- Optical effects

Physical Phenomenon for Transducers

Working of transducers are based on the following physical phenomenon.

1- Magnetic effects

2- Piezoresistivity

3- Piezoelectricity

4- Surface acoustic wave

5- Optical effects

Magnetic Effects

Table 5.3 Magnetic effects used in transducers

Effect	*Year of discovery*	*What it is*	*Application*
Faraday effect	1831	Generation of electricity in a coil with the change in the ambient magnetic field	Reluctance based transducers
Joule effect (Magnetostriction)	1842	Change in shape of a ferromagnetic body with magnetisation	In combination with piezoelectric elements for magnetometers and potentiometers
ΔE effect	1846	Change in Young's modulus with magnetisation	Acoustic delay line components for magnetic field measurement
Matteucci effect	1847	Torsion of a ferromagnetic rod in a longitudinal field changes magnetisation	Magnetoelastic sensors
Thomson effect	1856	Change in resistance with magnetic field	Magnetoresistive sensors
Wiedemann effect	1858	A torsion is produced in a current carrying ferromagnetic rod when subjected to a longitudinal field	Torque and force measurement Displacement measurement Level measurement
Villari effect	1865	Effect on magnetisation by tensile or compressive stress	Magnetoelastic sensors
Hall effect	1879	A current carrying crystal produces a transverse voltage when subjected to a magnetic field vertical to its surface	Magnetogalvanic sensors
Skin effect	1903	Displacement of current from the interior of material to surface layer due to eddy currents	Distance and proximity sensors
Josephson effect	1962	Quantum tunnelling between two superconducting materials with an extremely thin separating layer	SQUID magnetometers

Magnetic Effects

One of the following magnetic effects is most commonly used in modern magnetic sensors.

1- Joule Effect

2- Villari Effect

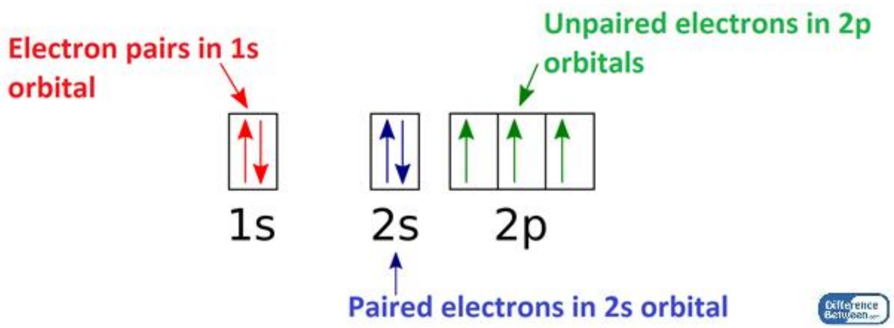
3- Wiedemann Effect

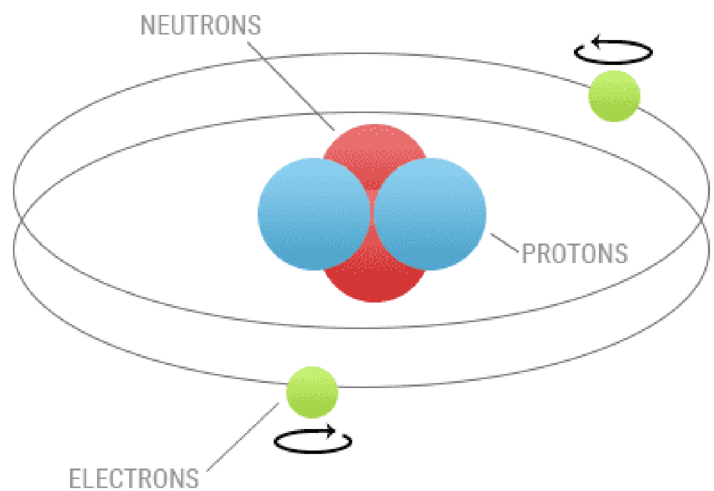
4- Matteucci Effect

5- Hall Effect

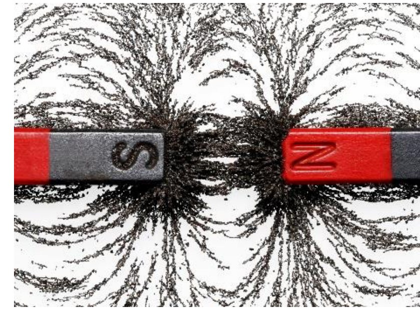
Magneto elastic Effects

Recall
Few Basic Concepts of Magnetism?

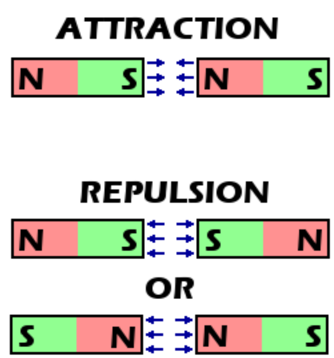




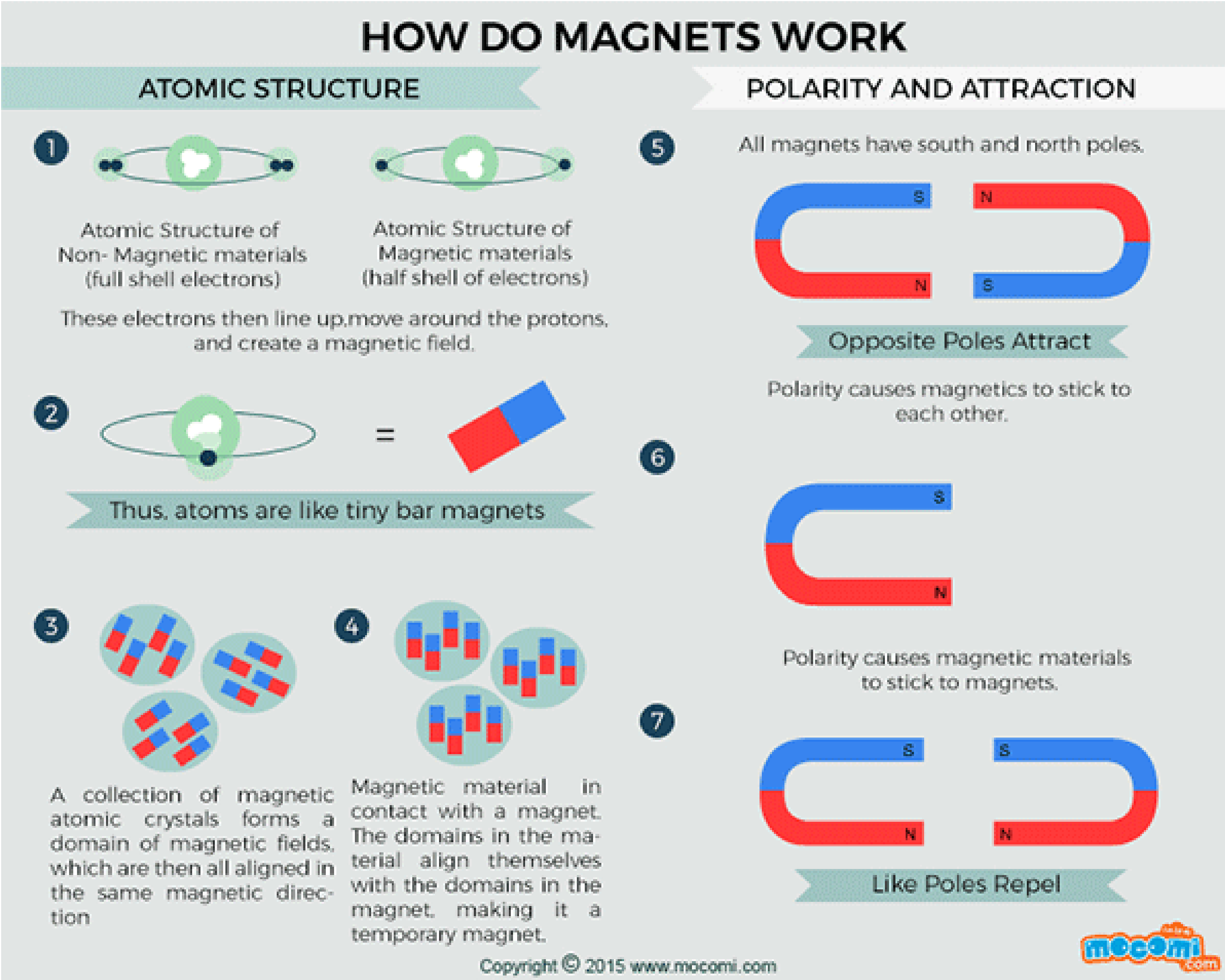
Basic Concepts: Magnetism?



- Magnetism is the force of attraction or repulsion of a magnetic material due to the arrangement of its atoms, particularly its electrons.
- Substances that can alter the value of the magnetic field in which they are placed are magnetic materials.



https://asia.ipitaka.com/blogs/news/15-things-you-didn-t-know-about-magnets-but-will-do-shortly


HOW DO MAGNETS WORK
ATOMIC STRUCTURE
POLARITY AND ATTRACTION
1
Atomic Structure of Non- Magnetic materials (full shell electrons)
Atomic Structure of Magnetic materials (half shell of electrons)
These electrons then line up,move around the protons, and create a magnetic field.
2
=
Thus, atoms are like tiny bar magnets
3
A collection of magnetic atomic crystals forms a domain of magnetic fields, which are then all aligned in the same magnetic direction
4
Magnetic material in contact with a magnet. The domains in the material align themselves with the domains in the magnet, making it a temporary magnet.
5
All magnets have south and north poles.
S
N
N
S
Opposite Poles Attract
Polarity causes magnetics to stick to each other.
6
S
N
Polarity causes magnetic materials to stick to magnets.
7
S
S
N
N
Like Poles Repel
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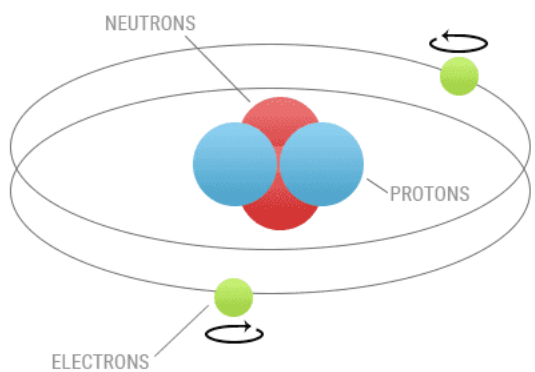
Basic Concepts: Magnetism?

- The magnetic behaviour of a material is determined by its number of unpaired electrons in each atom.

- In the atoms of most elements electrons exist in pairs with each electron spinning in a different direction causing them to cancel out each other's magnetic field, therefore no net magnetic field exists.

- However, some materials have unpaired electrons which will generate a net magnetic field and therefore have a greater reaction to an external magnetic field.

- Most materials are classified either as
  - **Ferromagnetic,**
  - **Diamagnetic or**
  - **Paramagnetic.**



Basic Concepts: Magnetism?

- atoms with 1 or more *unpaired electrons* are ***paramagnetic***, ***(attracted by a magnetic)***

- atoms with all spins *paired* are ***diamagnetic*** ***(repelled by magnet)***

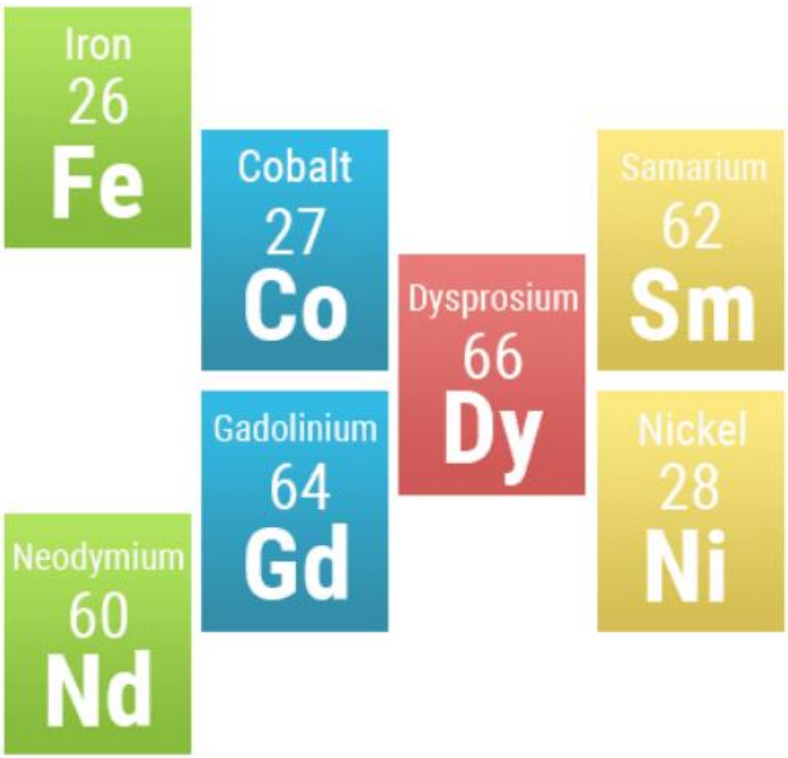
He $\boxed{\uparrow\downarrow}$ → ***diamagnetic***

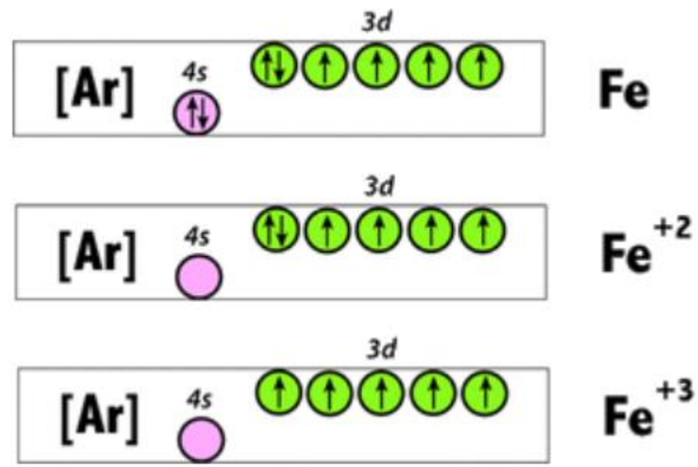
$1s^2$

Li $\boxed{\uparrow\downarrow}$ $\boxed{\uparrow}$ → ***paramagnetic***

$1s^2$ $2s^1$

Basic Concepts: Magnetism?

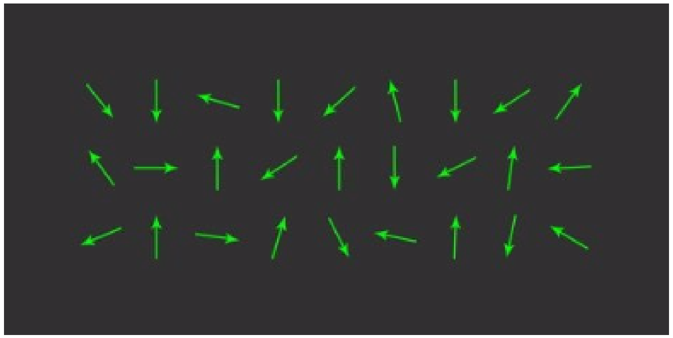




Electronic structures of neutral (Fe), ferrous (Fe^{+2}), and ferric (Fe^{+3}) iron. Ferric iron has 5 unpaired electrons while the others have only 4. [Ar] = argon base structure.

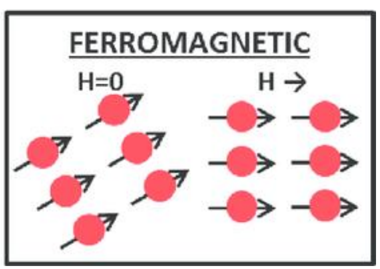
https://www.first4magnets.com/magnetic-materials-i156

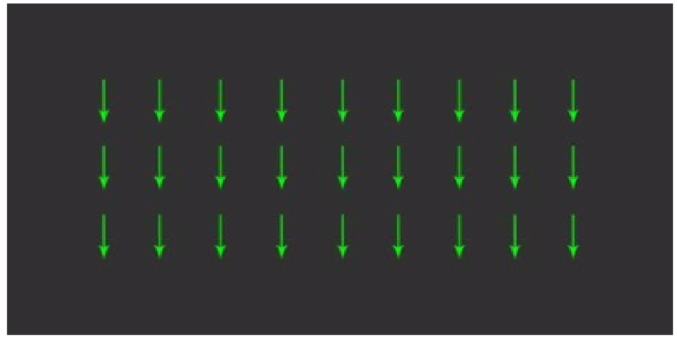
CLASSIFICATION OF MAGNETIC MATERIALS



FERROMAGNETIC

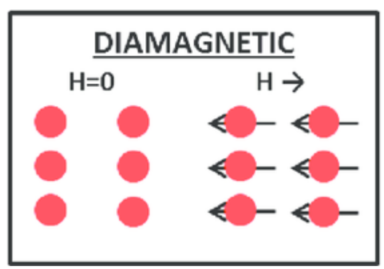
Ferromagnetic materials have some unpaired electrons in their atoms and therefore generate a net magnetic field, albeit a very weak one. This is because the individual atoms or groups of atoms, known as magnetic domains, are randomly aligned cancelling each other out. When an external magnetic field is applied to the ferromagnetic material the individual domains are forced into alignment which they maintain once the external field is removed therefore maintaining their magnetism, known as remanence. Iron, nickel and cobalt are all ferromagnetic materials.

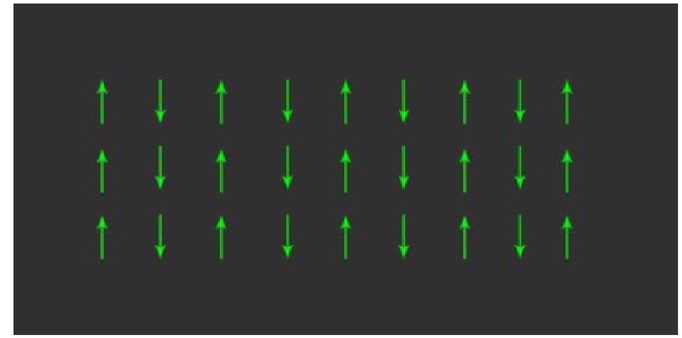




DIAMAGNETIC

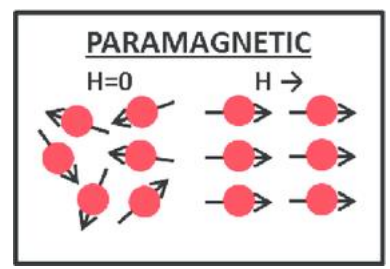
Diamagnetic materials repel any externally applied magnetic field. This occurs because their magnetic domains realign to oppose an externally applied magnetic field when influenced by a magnetic field. All materials show some diamagnetic properties, however, in most materials the effect is extremely weak and unnoticed. All the electrons within the atoms of diamagnetic materials are paired, therefore they do not generate their own net magnetic field. Most elements in the periodic table are diamagnetic.

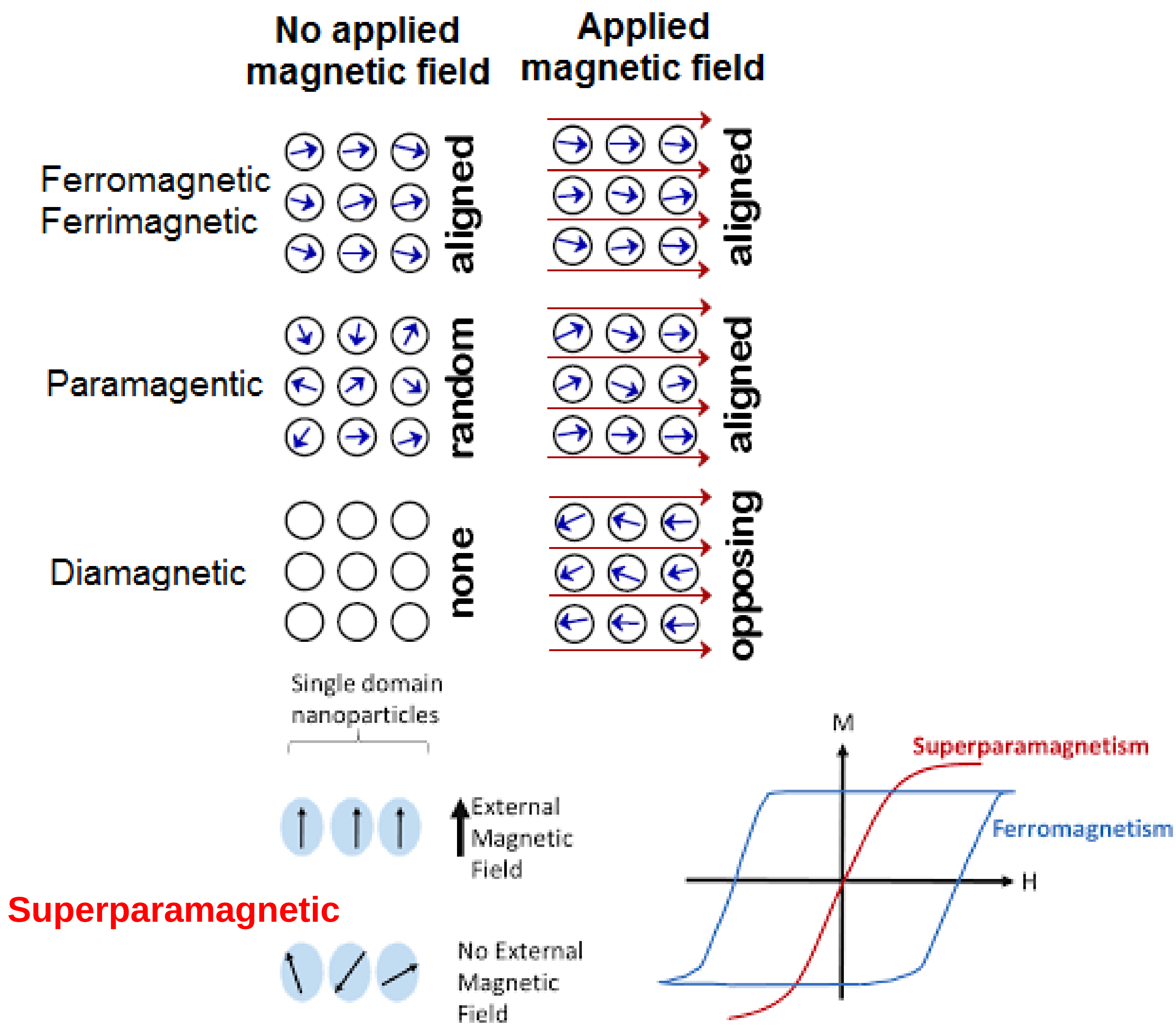




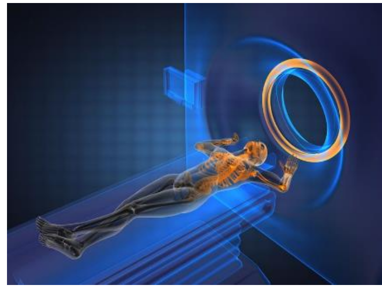
PARAMAGNETIC

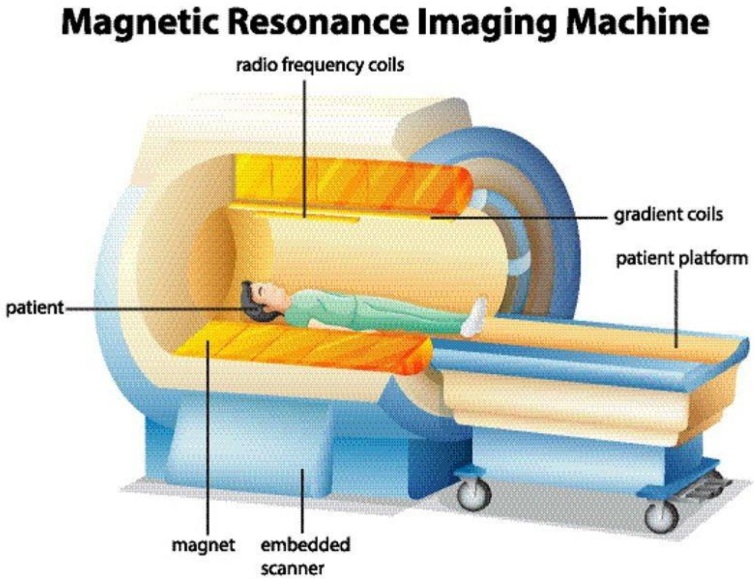
Paramagnetic materials have a small susceptibility to magnetic fields meaning that they are slightly attracted by a magnetic field. However, unlike ferromagnetic materials they do not maintain their magnetic properties once the external magnetic field is removed. Most elements are paramagnetic, however, because their attractive force is many thousands of times weaker than ferromagnetic material they are also generally considered as 'non-magnetic'.

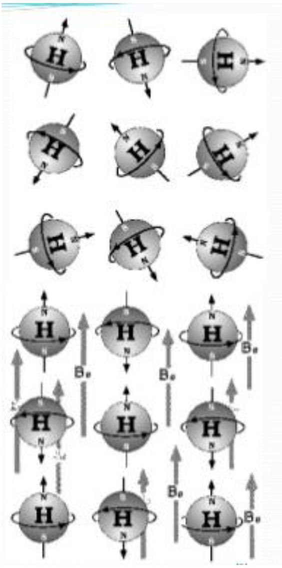


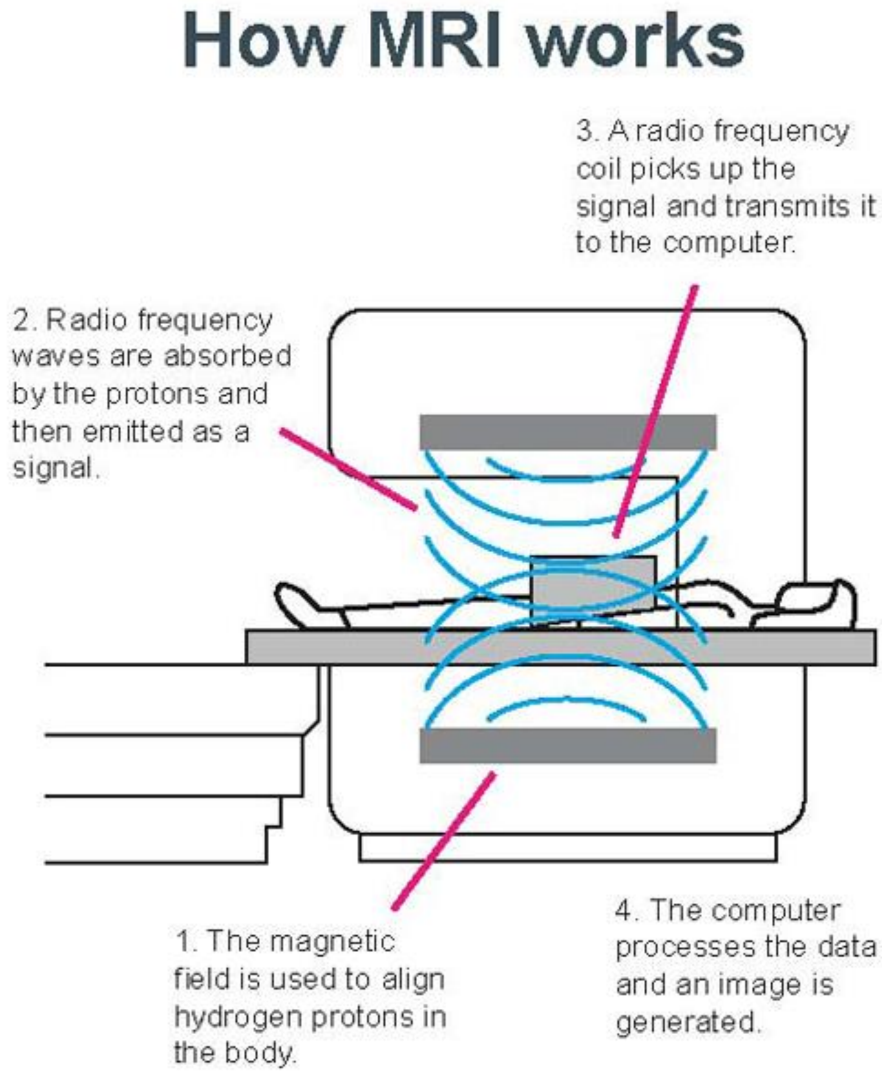

No applied magnetic field
Applied magnetic field
Ferromagnetic
Ferrimagnetic
aligned
aligned
Paramagentic
random
aligned
Diamagnetic
none
opposing
Single domain nanoparticles
External Magnetic Field
Superparamagnetic
No External Magnetic Field
M
H
Superparamagnetism
Ferromagnetism

Application?







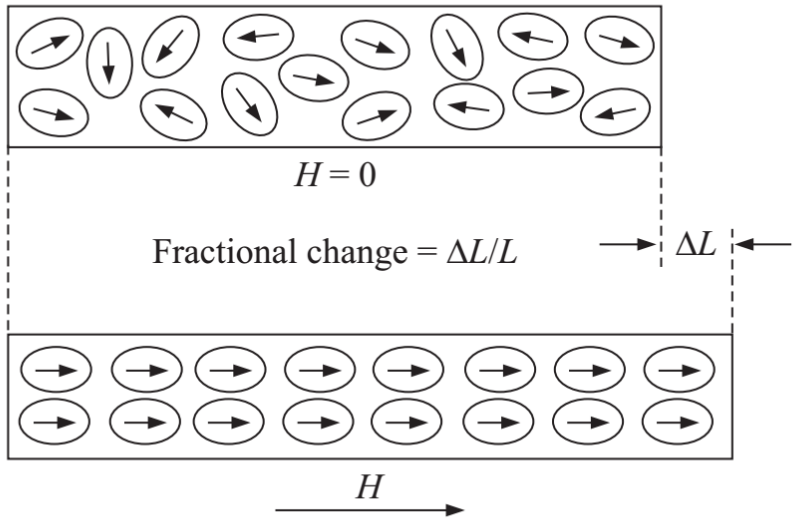


Magnetoelastic Effects

- Coupling between the magnetisation of the ferromagnetic materials and their elasticity
  - Several effects which have application for sensing,

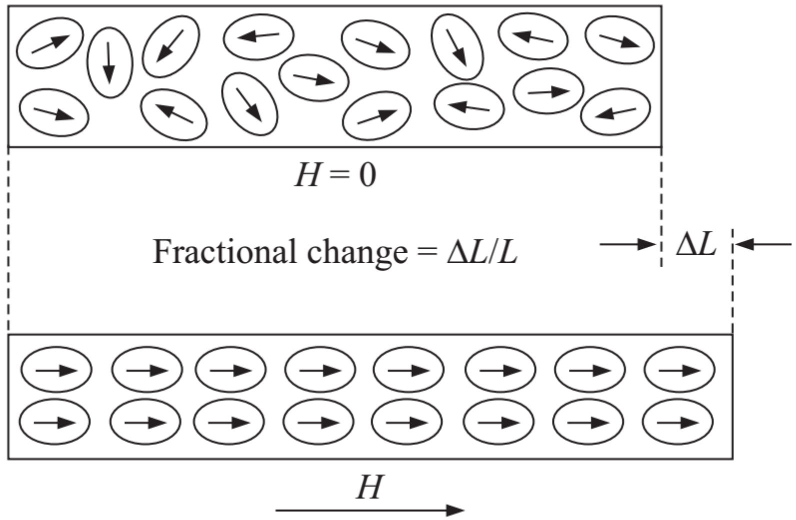
Direct effect	*Inverse effect*
Joule effect	Villari effect
Wiedemann effect	Matteucci effect

Joule Effect- Magnetostriction



- **How does this happen?**
  - The first process is dominated by the migration of domain walls within the material in response to external magnetic fields
  - The second is the rotation of the domains

Joule Effect- Magnetostriction



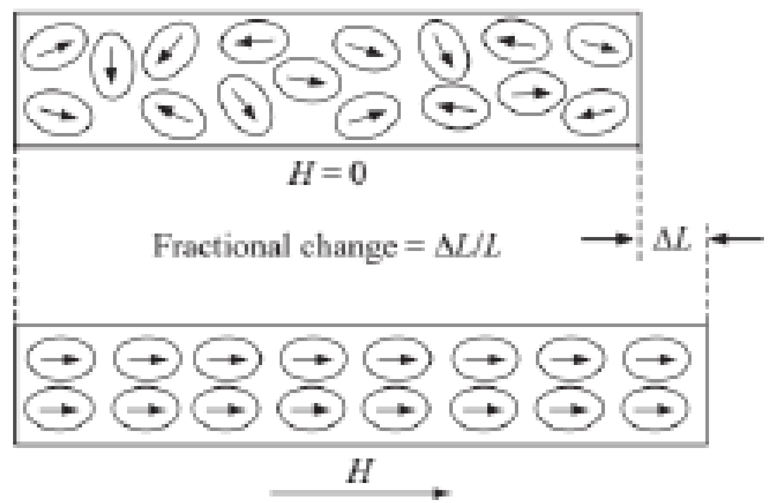
- Change in shape of material due to magnetization is called magnetostriction
- The deformation is isochoric
  - volume is conserved (V=Constant)
  - there is an opposite dimensional change in the orthogonal direction

Joule Effect

Change in length of a material due to applied magnetic filed is called joule effect.

When a magnetic field is applied to a ferromagnetic material, rotation and movement of magnetic domains cause its length to change. Correspondingly there is a change in its width, therefore the volume of ferromagnetic material remains constant.

Change in shape of material due to magnetization is called magnetostriction.



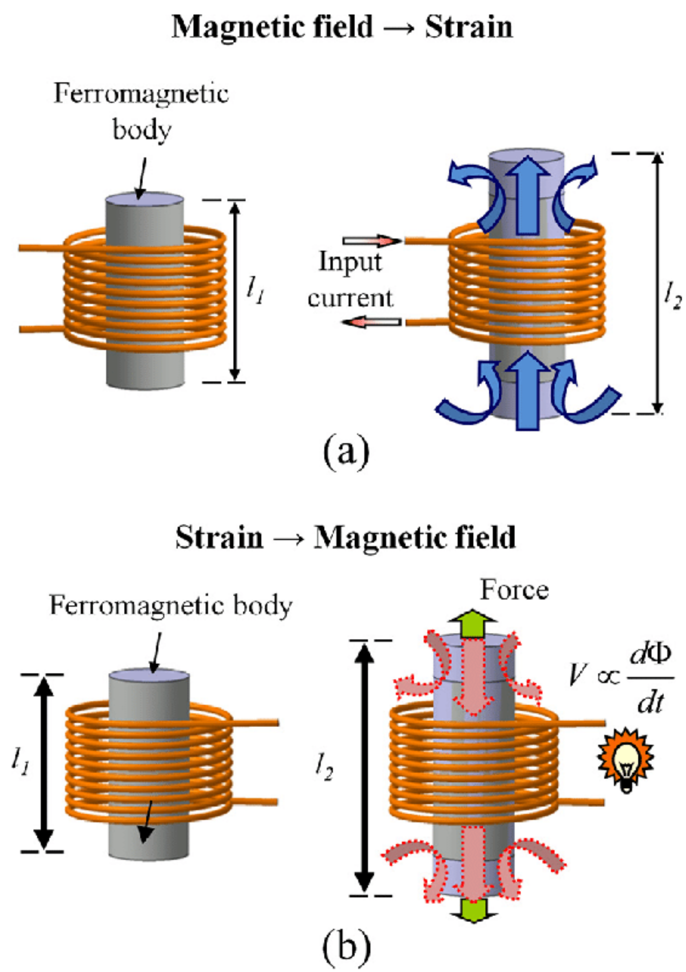
Joule Effect- Magnetostriction

❑Humming sound from a transformer?

We hear a humming sound emitted from a transformer or a fluorescent tube choke. This is caused by magnetostriction. 50 Hz ac generates magnetic fields in transformers causing the core to change the maximum length twice per cycle thus producing the familiar and sometimes annoying 100 Hz (or higher harmonics) hum.

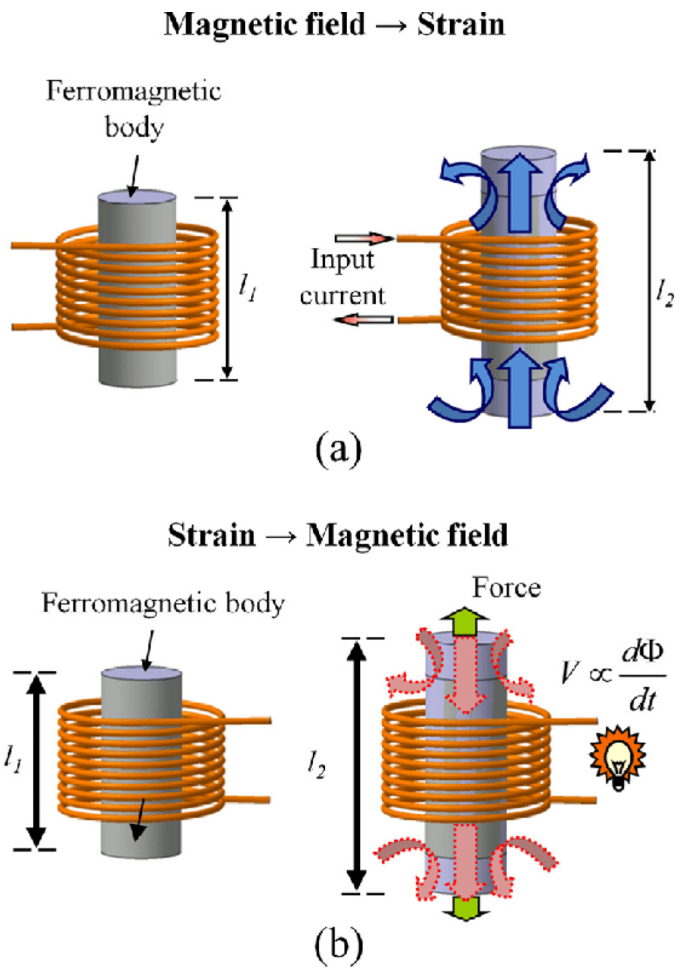
Villari Effect

- An inverse effect to Joule effect
- A stress induced in the material causes a change in the magnetization
  - stress or force sensing



Villari Effect

- ❑ **Villari reversal**
  - ❑ **change in sign of the magnetostriction coefficient**



Villari (inverse of Joule)Effect

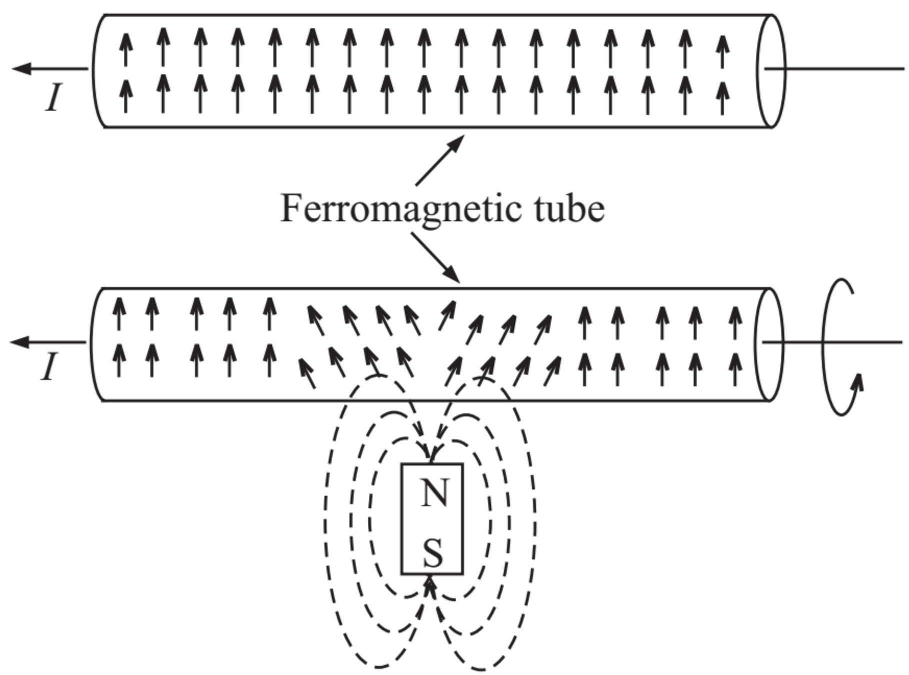
A **stress (σ = F/A)** induced on the ferromagnetic material causes a **change in its magnetization**.

Change in magnetization is then measured and calibrated to measure the **applied stress or force**.

The Joule effect and Villari effect are utilized in producing magnetostrictive displacement sensors and level sensors.

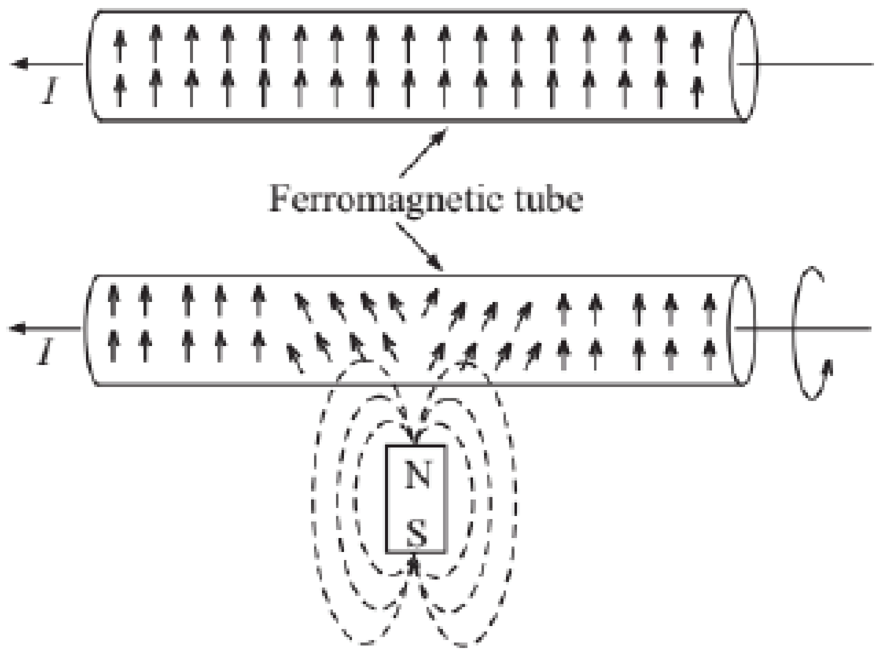
Wiedemann Effect

- Twisting due to interaction between the magnetic field due to the current and the external axial magnetic field (from usually the permanent magnet)
  - Magnetostrictive material



Wiedemann Effect

When an axial magnetic field is applied to a current carrying magnetostrictive wire a twisting occurs at the location of axial magnetic field.



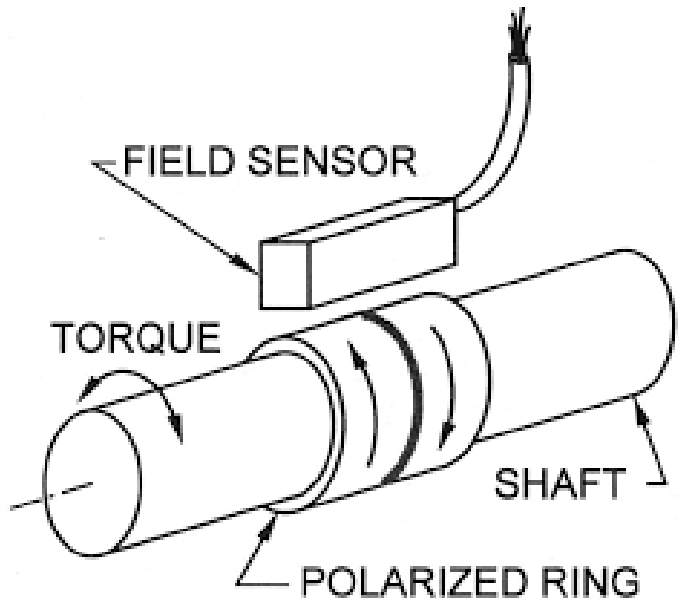
Mateucci Effect

- Inverse of Wiedemann effect
- Change in magnetization of a magnetostrictive/magnetized wire due to twisting

Mateucci Effect

❑Any application?

- ❑ **Magnetoelastic torque sensors**



Matteucci (inverse Wiedemann) Effect

When a wire made of magnetostrictive material is twisted, its magnetization changes.

The change in magnetizaton can be measured and related to external torque that twisted it.

This effect can be employed in torque sensor.

Magnetostriction Coefficient

- Fractional change in length as the magnetisation increases from zero to its saturation value

$$\lambda = \left.\frac{\Delta L}{L}\right|_{\text{saturated } \mathbf{B}}$$

where, L is the original length of the material and ΔL is the change in length

- positive for expansion and negative for contraction

Magnetostriction Coefficient

Table 5.4 Magnetostriction coefficients for different materials

Material	*Crystal axis*	*Magnetostriction coeficient* λ ($\times 10^{-5}$)
Iron	100	$+1.1$ to $+2.0$
	111	-1.3 to -2.0
	Polycrystalline	-0.8
Nickel	100	-5.0 to -5.2
	111	-2.7
	Polycrystalline	-2.5 to -4.7
Cobalt	Polycrystalline	-5.0 to -6.0
Terfenol-D ($Tb_xDy_{1-x}Fe_y$)	Polycrystalline	2000

Magnetostriction Coefficient

- **Magnetic strain energy**

$\sigma = F/A$

In the case of a single stress σ applied on a single magnetic domain, the magnetic strain energy density E_σ can be expressed as:

$$E_\sigma = \frac{3}{2}\lambda_s \sigma \sin^2\theta$$

where, λ_s is the magnetostrictive coefficient at saturation

θ is the angle between the saturation magnetisation and the stress direction

For λ_s and $\sigma > 0$ (like in iron under tension), E_σ is minimum for $\theta = 0$ i.e., when the tension is aligned with the saturation magnetisation. Consequently, the magnetisation is increased by tension.

Applications

1. Transferring magnetic energy to mechanical energy
2. Transferring mechanical energy to magnetic energy

Applications

- **Transferring magnetic energy to mechanical energy**

The first mode is used to design

1. Actuators for generating motion and/or force
2. Sensors for detecting states of magnetic field

Applications

- **Transferring Mechanical energy to magnetic energy**

The second mode is used to design

1. Sensors for detecting motion and/or force
2. Devices for inducing change in the magnetic state of a material
3. Passive damping devices, which dissipate mechanical energy as magnetically and/or electrically induced thermal losses

Applications of Magnetoelastic Transducers

Applications. The existence of both direct and reciprocal Joule and Wiedemann effects leads to two modes of operation for magnetostrictive transducers:

1. Transferring magnetic energy to mechanical energy
2. Transferring mechanical energy to magnetic energy

The first mode is used to design

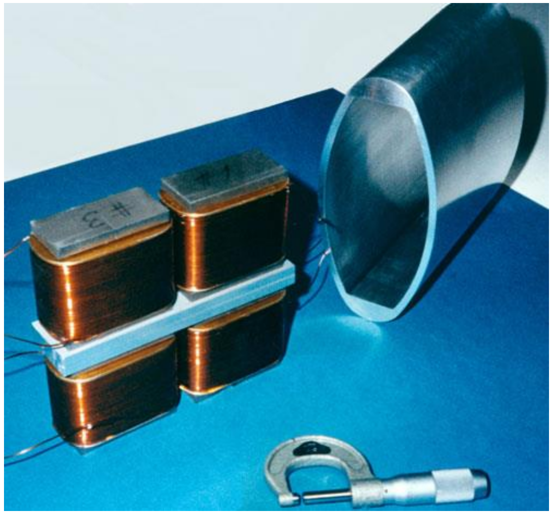
1. Actuators for generating motion and/or force
2. Sensors for detecting states of magnetic field

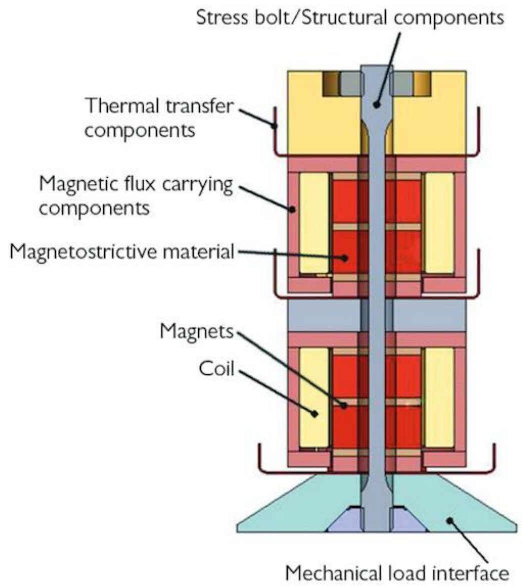
The second mode is used to design

1. Sensors for detecting motion and/or force
2. Devices for inducing change in the magnetic state of a material
3. Passive damping devices, which dissipate mechanical energy as magnetically and/or electrically induced thermal losses

Applications

- **Terfenol-D sonar transducer**





As with many other transducer technologies such as electromagnetic (moving coils) and piezoelectricity, a magnetostrictive transducer has the ability to both actuate and sense simultaneously. Applications such as the telephone, scanning sonar and others make use of this dual mode. For example, a Terfenol-D sonar transducer can be used as either a transmitter or a receiver or both at the same time. Another potential use of dual mode operation is in active vibration and acoustic control. One transducer can be used to sense deleterious structural vibrations and provide the actuation force to suppress them.

It is also utilised to produce ultrasonic vibrations either as a sound source or as ultrasonic waves in liquids which can act as a cleansing agent in ultrasonic cleaning devices.

Concepts? Coupling Diagram

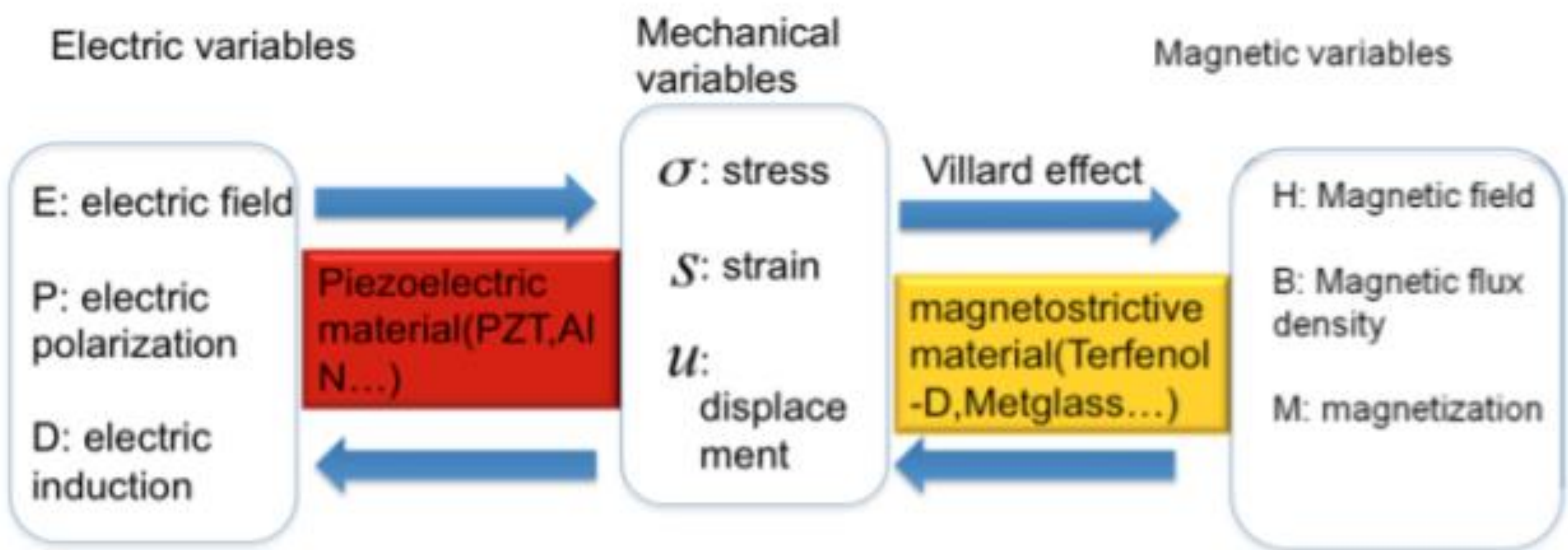


Figure 1.1 Composite material conversion mechanisms

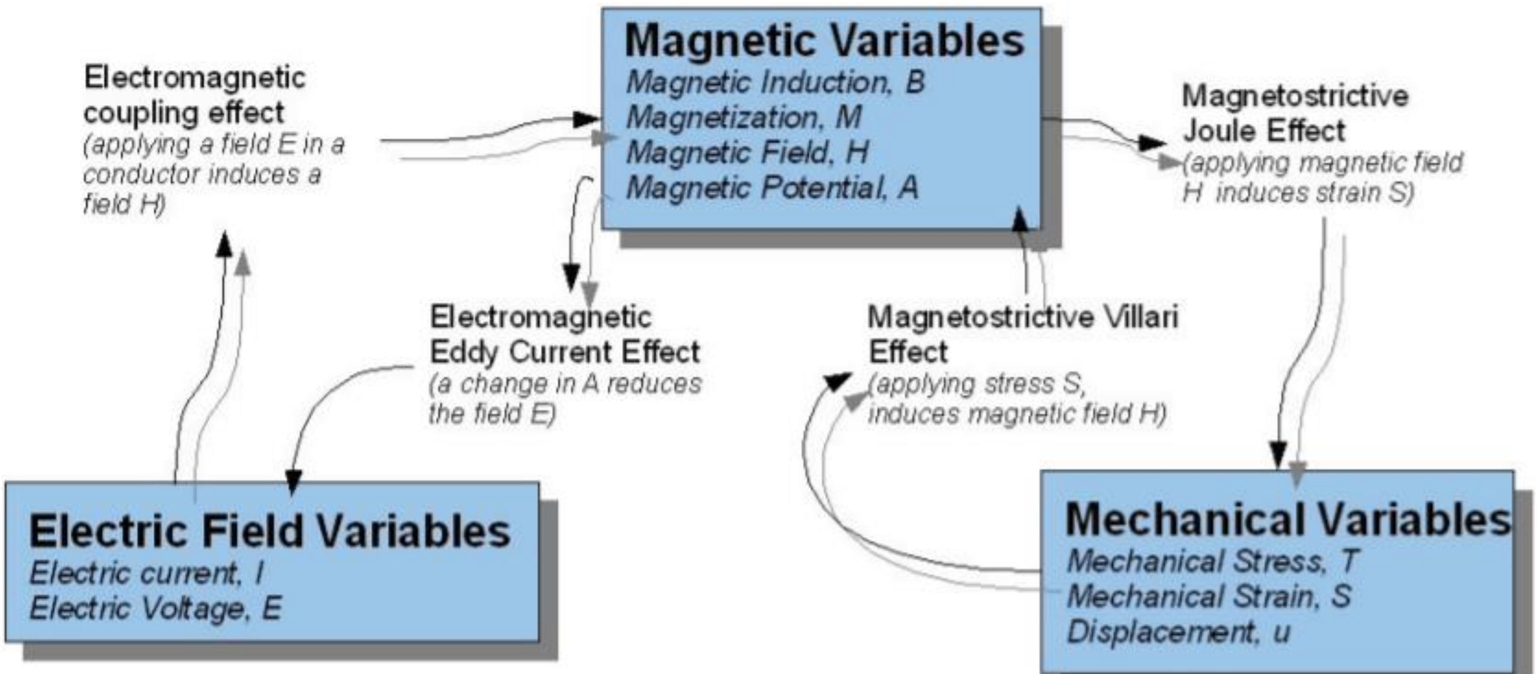
https://tel.archives-ouvertes.fr/tel-01630261/document

Summary

The magnetostrictive materials will change shape when it is subjected to a magnetic field. This occurs because magnetic domains in the material align with the magnetic field. Similarly, when the material is strained (stretched or compressed), its magnetic energy changes. This phenomenon is reversible and for this matter it can be use to build actuators, sensors or to make energy conversion.

It is possible to simplify the processes into two reversible energy conversion steps:

- from electric to magnetic;
- from magnetic to mechanical.



http://www.elkraft.ntnu.no/eno/Papers2008/Martino.pdf

Magnetic Effects

One of the following magnetic effects is most commonly used in modern magnetic sensors.

1- Joule Effect

2- Villari Effect

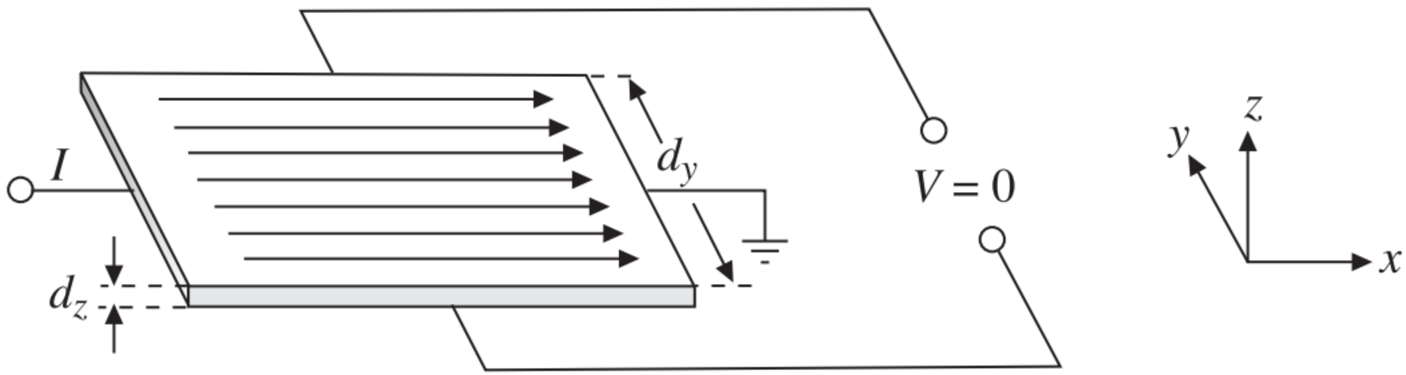
3- Wiedemann Effect

4- Matteucci Effect

5- Hall Effect

Magneto elastic Effects

Hall Effect



Hall Effect

Hall voltage (V_H) is generated in a

- Current I carrying conductor is placed in a magnetic field B
- Perpendicular to both I and V

$$V_H \propto \mathbf{I} \times \mathbf{B}$$

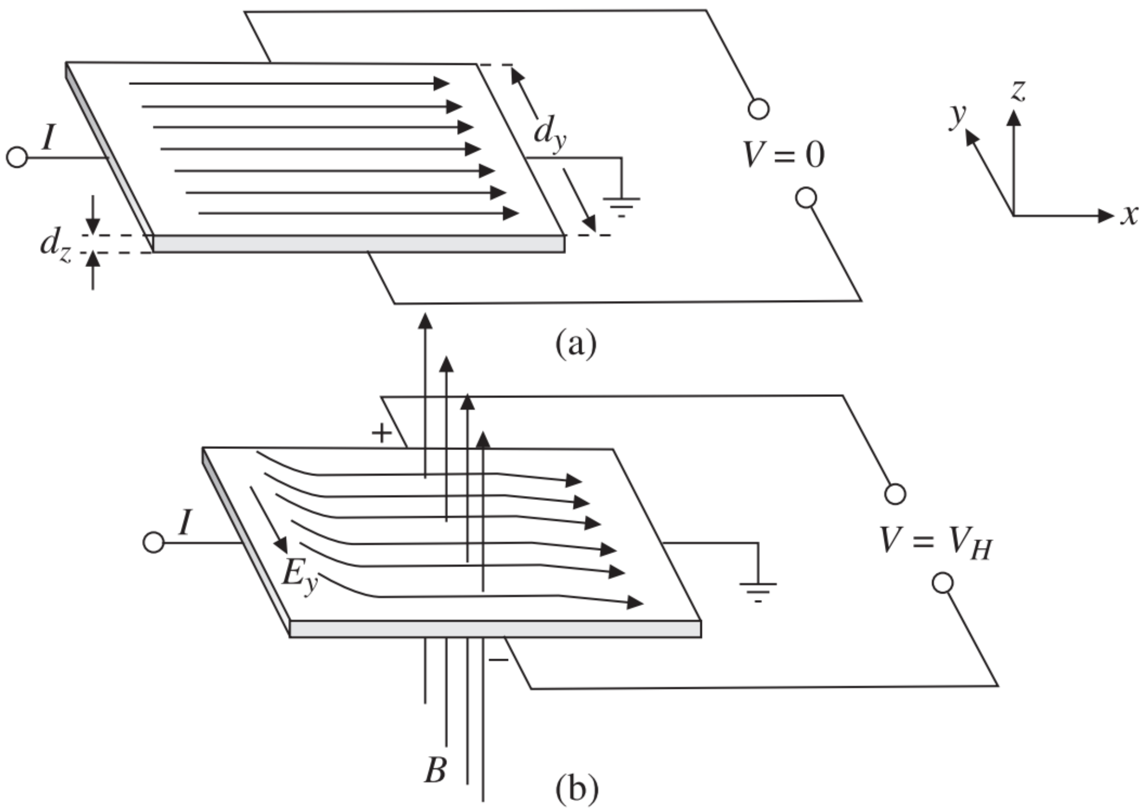


Fig. 5.3 Hall voltage generation principle: (a) no magnetic field and (b) magnetic field present.

Hall Effect

❑Why?

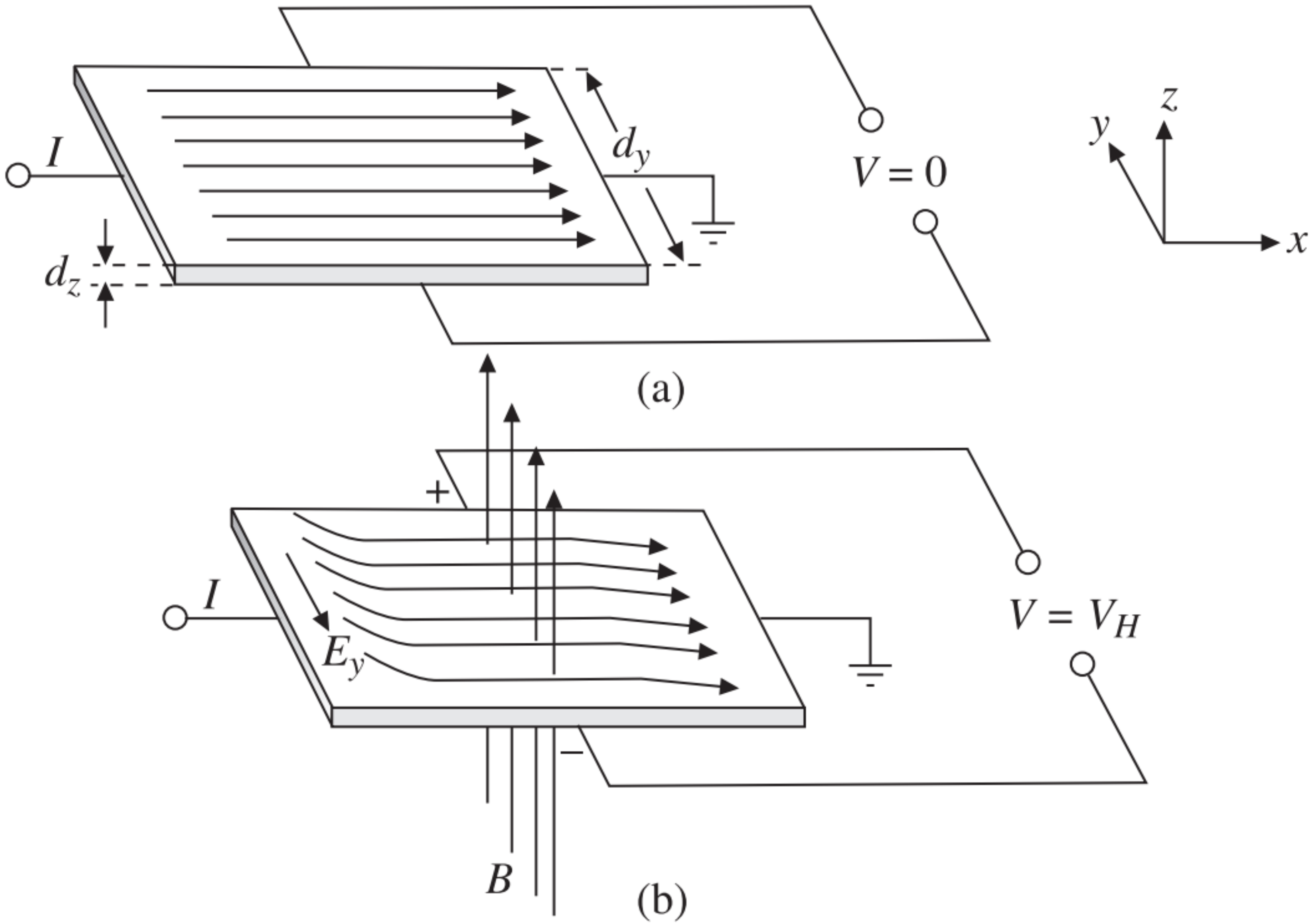
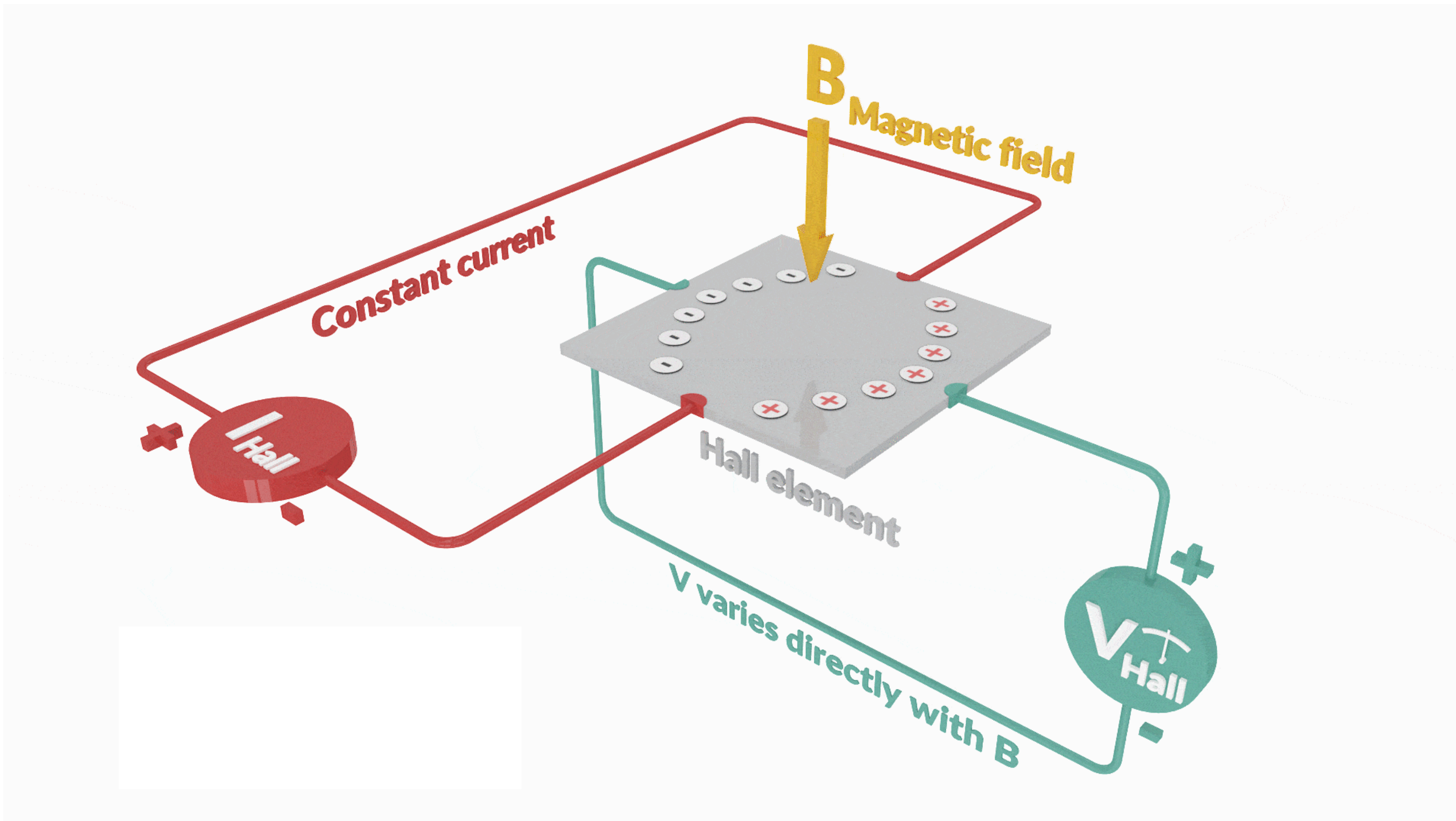


Fig. 5.3 Hall voltage generation principle: (a) no magnetic field and (b) magnetic field present.

Hall Effect

- **Why?**
  - Lorentz force law



Hall Effect

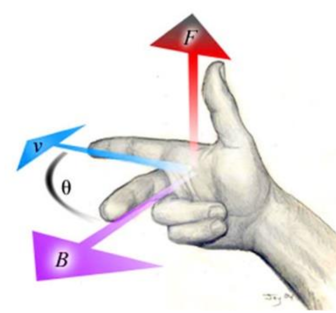
$$V_H \propto \mathbf{I} \times \mathbf{B}$$

If e is the electronic charge
$\mathbf{v}$ is the velocity of carriers
$\mathbf{E}$ is the electric field

then the Lorentz force $\mathbf{F}$ experienced by charge carriers due to the combined electric and magnetic fields is given by

$$\mathbf{F} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{5.1}$$

$$\vec{F} = \underset{\text{Electric force}}{q\vec{E}} + \underset{\text{Magnetic force}}{q\vec{v}\; x\; \vec{B}}$$

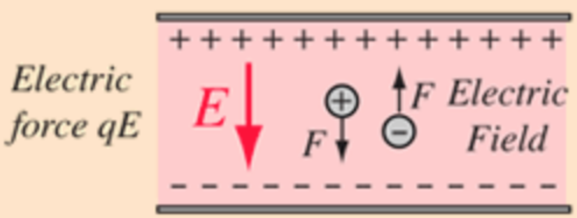


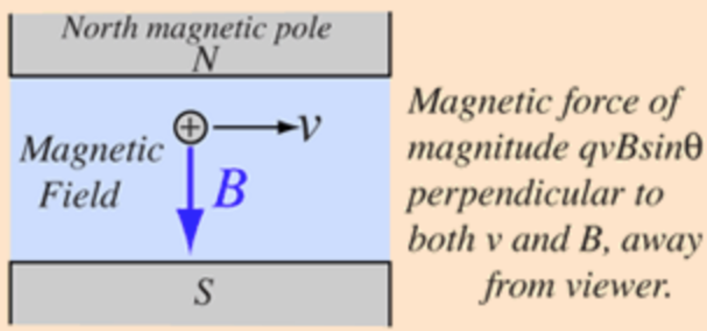
Lorentz Force Law

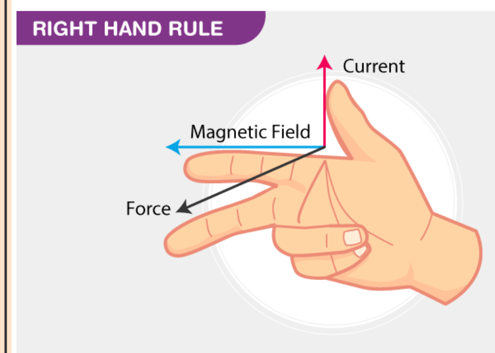
Both the electric field and magnetic field can be defined from the Lorentz force law:

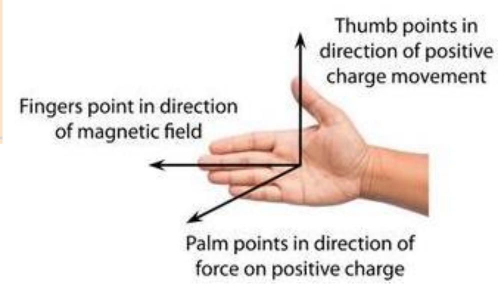
$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

The electric force is straigtforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.



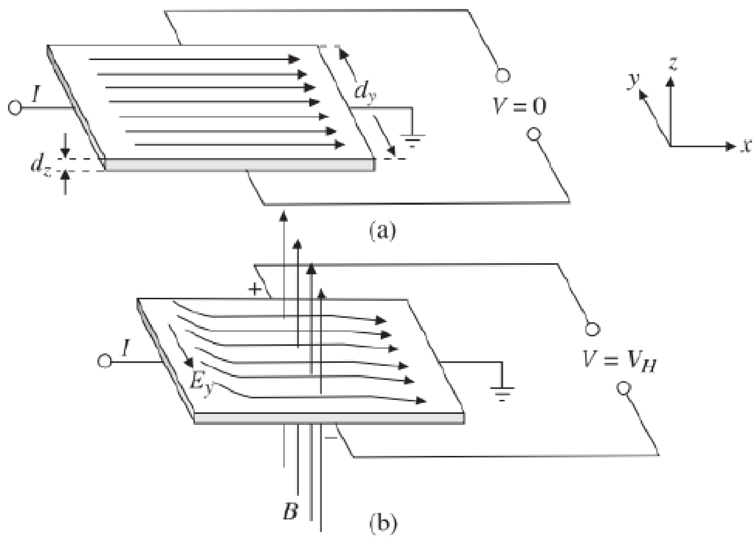






Hall Effect

Figure 5.3 illustrates the basic principle of the Hall effect. It shows a thin sheet of semiconducting material (Hall element) through which a current is passed. The output connections are perpendicular to the direction of current.

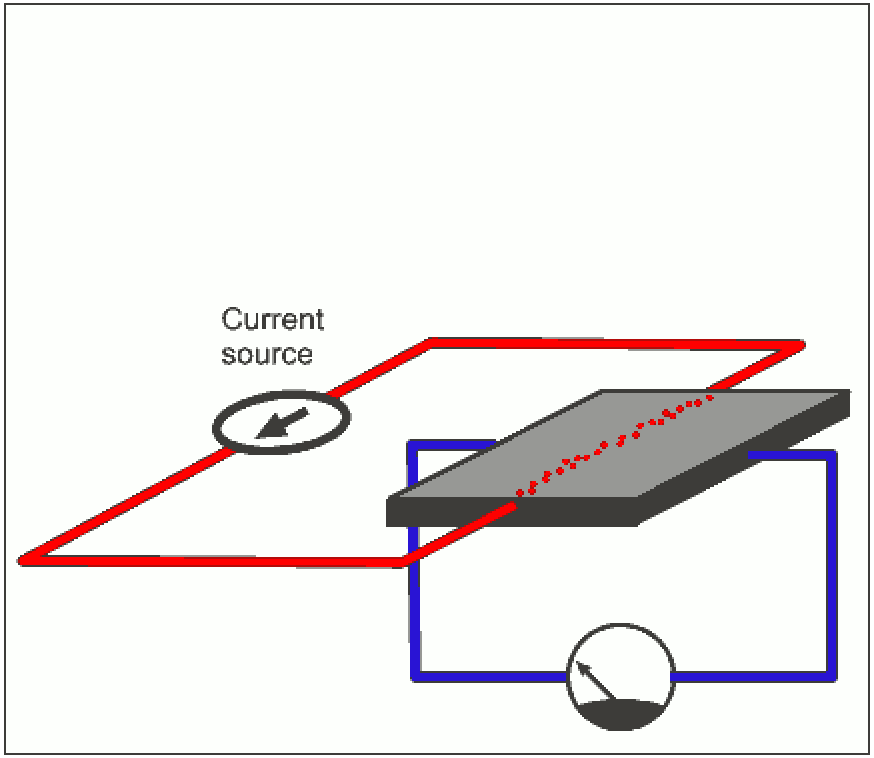


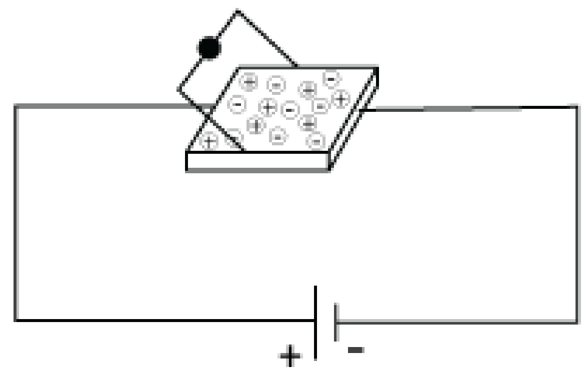
When no magnetic field is present the current flows in straight path. The current distribution through the material is uniform and no potential difference is seen across the output.

When perpendicular magnetic field is applied, moving charges experience a Lorrentz force. The moving charges accumulate on one face of material. Equal and opposite charges are accumulated on the opposite face.

Electric field is established inside the material perpendicular to motion of charge and the magnetic field. A steady electric potential called hall voltage is built up.

Hall Effect





Hall Effect in Metals

$$V_H = -\frac{IB}{ned_z}$$

Hall voltage

$$R_H = \frac{V_H d_z}{IB} = -\frac{1}{ne}$$

Hall Coefficient

Table 5.5 Hall coefficients at room temperature for metals

Metal	*Hall coefficient* (m^3/C)[a]
Gold	−0.72
Copper	−0.55
Aluminium	−0.30
Magnesium	−0.94
Tin	−0.04

[a] Source: *American Institute of Physics Handbook*, New York (1985).

- ❑ **Hall coefficients for metals are too low to serve any useful purpose**
  - ❑ **The Hall voltage in semiconductors is appreciable**

Hall Effect in Semiconductors

If n is the concentration of electrons
p is the concentration of holes
μ_e is the drift mobility of electrons
μ_h is the drift mobility of holes
E is the electrostatic field

then,

$$\begin{aligned} \text{the drift velocity of electrons } v_e &= \mu_e E \\ \text{the drift velocity of holes } v_h &= \mu_h E \end{aligned} \tag{5.6}$$

definition of Hall coefficient ➡ $$R_H = \frac{p\,\mu_h^2 - n\mu_e^2}{e\left(p\,\mu_h + n\mu_e\right)^2} = \frac{p - nb^2}{e(p + nb)^2} \tag{5.18}$$

where $b = \mu_e/\mu_h$. The following conclusions can be drawn from Eq. (5.18):

1. R_H depends on both the drift mobility ratio and the concentrations of holes and electrons
2. R_H is positive for $p > nb^2$
3. R_H is negative for $p < nb^2$
4. Equation (5.5) for metals is obtained by substituting $p = 0$

Let us now work out an example to see what is the value of the Hall coefficient of a semiconductor.

Hall Effect in Semiconductors

Example 5.1
The following are the data for the intrinsic Si: $n = p = n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$, $\mu_h = 450\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$, and $\mu_e = 1350\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$. Calculate R_H.

Solution
From the given data we have

$$n = p = 1.5 \times 10^{16}\ \text{m}^{-3}$$

$$b = \frac{\mu_e}{\mu_h} = \frac{1350\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}}{450\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}} = 3$$

Therefore,

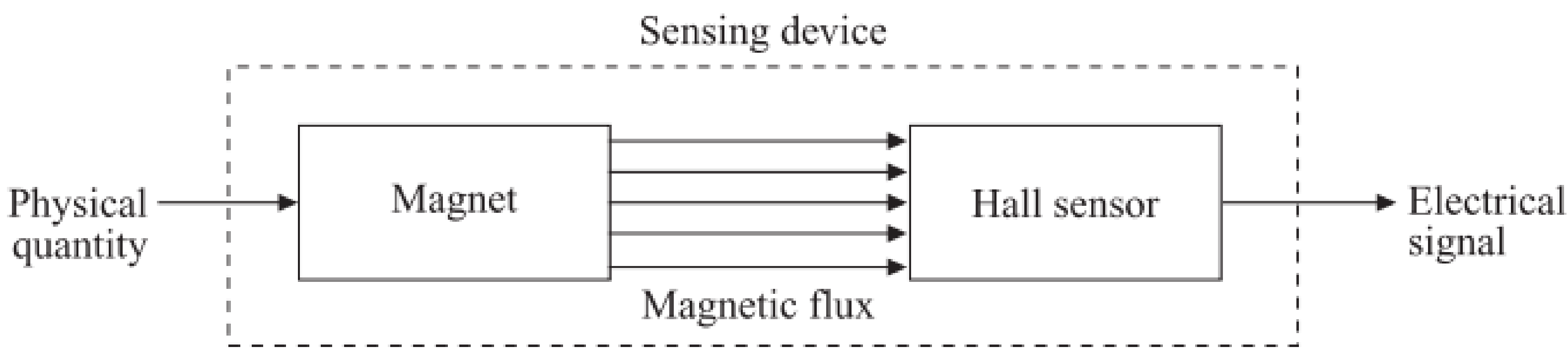
$$R_H = \frac{(1.5 \times 10^{16}) - (1.5 \times 10^{16})(3)^2}{(1.6 \times 10^{-19})\left[(1.5 \times 10^{16}) + (1.5 \times 10^{16})(3)^2\right]}\ \text{m}^3/\text{C}$$

$$= -208.3\ \text{m}^3/\text{C}$$

Thus, it is evident that the Hall coefficient of a semiconductor is orders of magnitude higher than that for typical metals. This is why all Hall devices use a semiconductor rather than a metal element.

Basic Hall Effect Sensors

- ❑ **Hall effect: converts magnetic field into an electrical signal**



- ❑ Physical quantities
  - ❑ temperature, pressure, position, speed,…
    - ❑ first, inducing a motion in the magnetic field

Many physical parameters can be measured by inducing the motion of a magnet. For example, both temperature and pressure can be sensed through the expansion and contraction of a bellows to which a magnet is attached.

Signal Conditioning

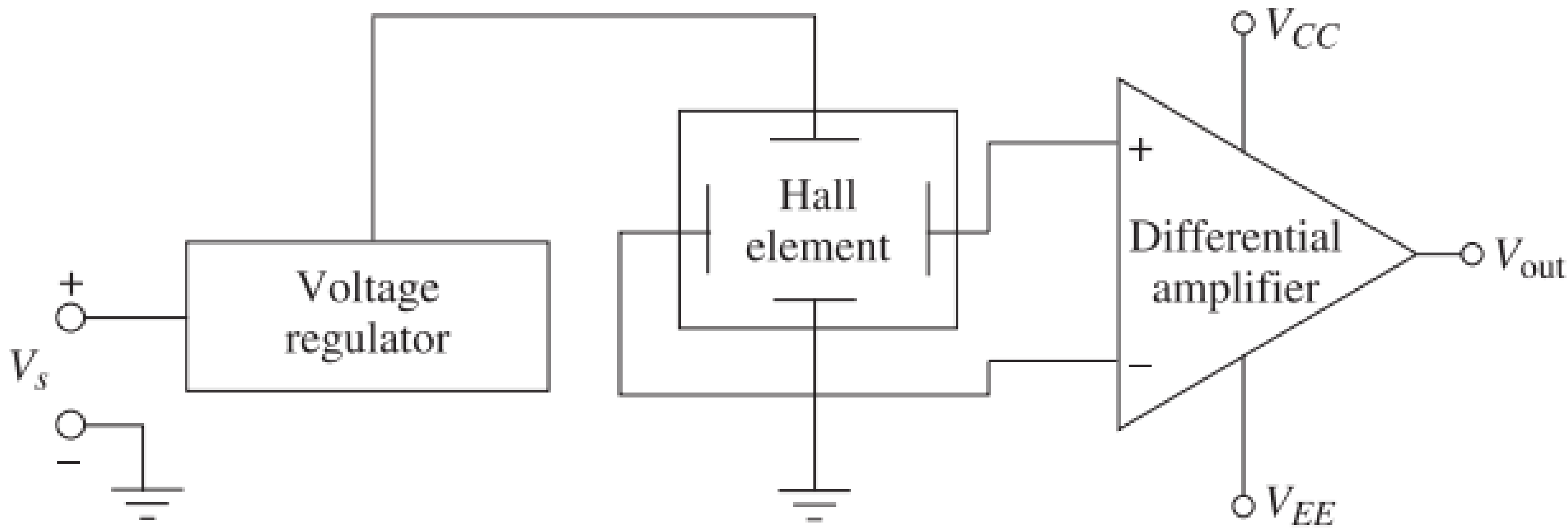


Fig. 5.7 Schematic diagram of a basic Hall effect sensor.

- ❑ **Voltage regulator**
  - ❑ to keep current contact as Hall voltage is dependent on current
- ❑ **Differential amplifier**
  - ❑ Hall voltage is ~ micro V
    - ❑ High input resistance, low noise and moderate gain

Transfer Characteristics

- Relates output to the input

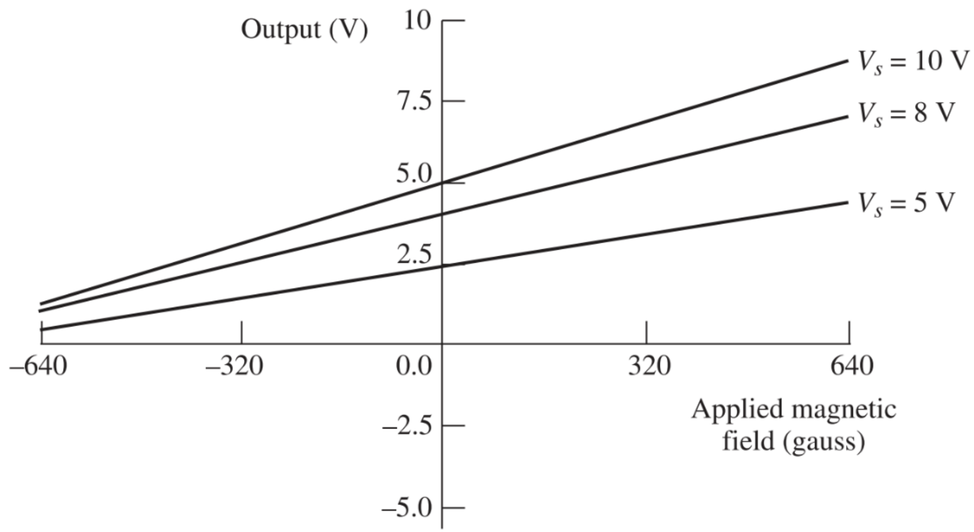


Fig. 5.8 Transfer characteristics of a typical Hall device.

$$V_{\text{out}}\ (\text{volt}) = 6.25 \times 10^{-4} V_s B + 0.5 V_s$$

where, B is the magnetic field strength and V_s, the supply voltage.

The transfer characteristic of a Hall sensor is specified by the following properties:

1. Sensitivity
2. Null offset
3. Span

Transfer Characteristics

- Relates output to the input

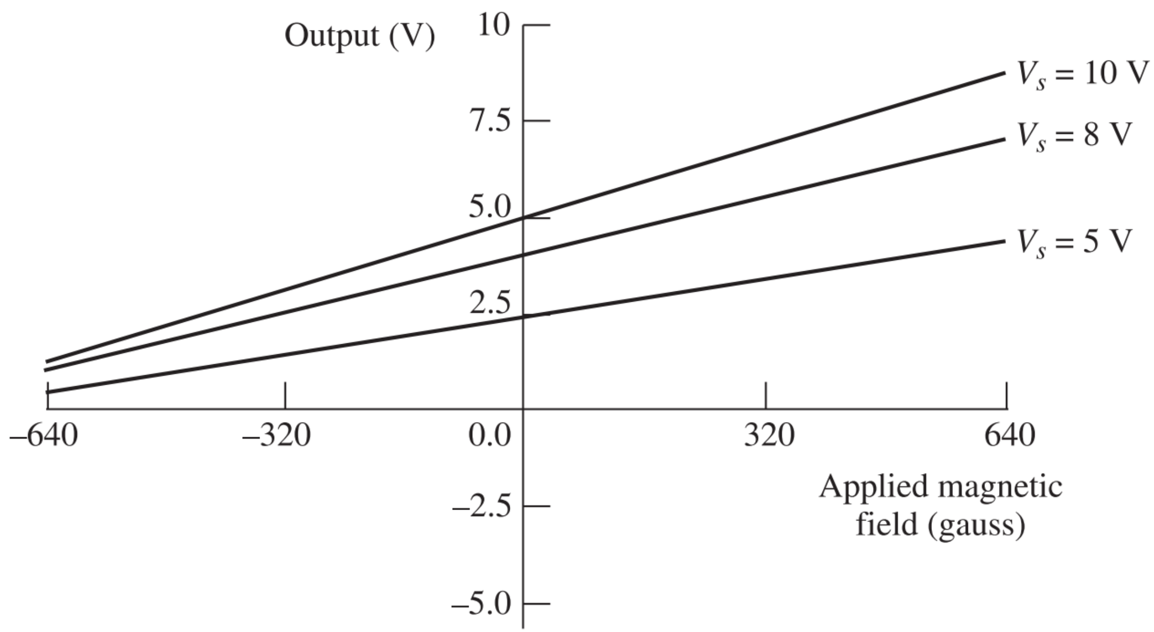


Fig. 5.8 Transfer characteristics of a typical Hall device.

Sensitivity. By definition, the sensitivity is the ratio of the change in output resulting from a given change in input. In this case, it is

$$S = \left|\frac{\Delta V_{\text{out}}}{\Delta B}\right| = 6.25 \times 10^{-4} V_s \text{ volt/gauss)} \qquad [\text{ From Eq. (5.19)}]$$

Transfer Characteristics

- Relates output to the input

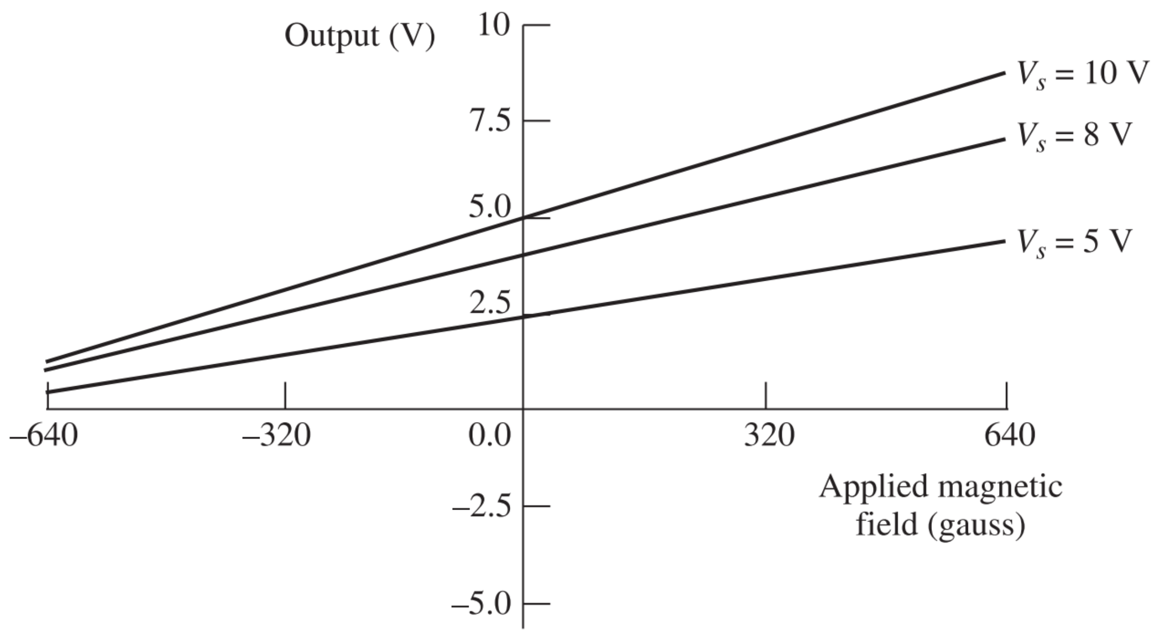


Fig. 5.8 Transfer characteristics of a typical Hall device.

Null offset. The null offset is the output from a sensor with no magnetic field excitation. Therefore, substituting $B = 0$ in Eq. (5.19), we get

$$\text{Null offset} = 0.5V_s$$

The imperfection in the fabrication process of the sensor may give rise to the null offset.

Transfer Characteristics

- **Relates output to the input**

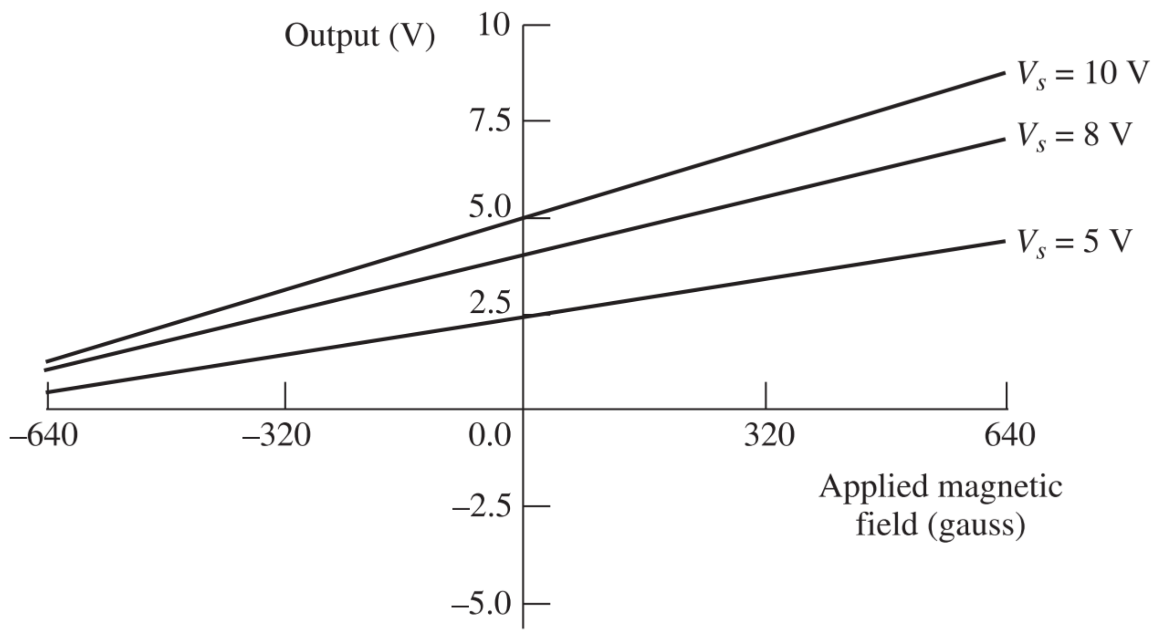


Fig. 5.8 Transfer characteristics of a typical Hall device.

Span. The span, defined as the difference between the maximum output and the minimum output, is

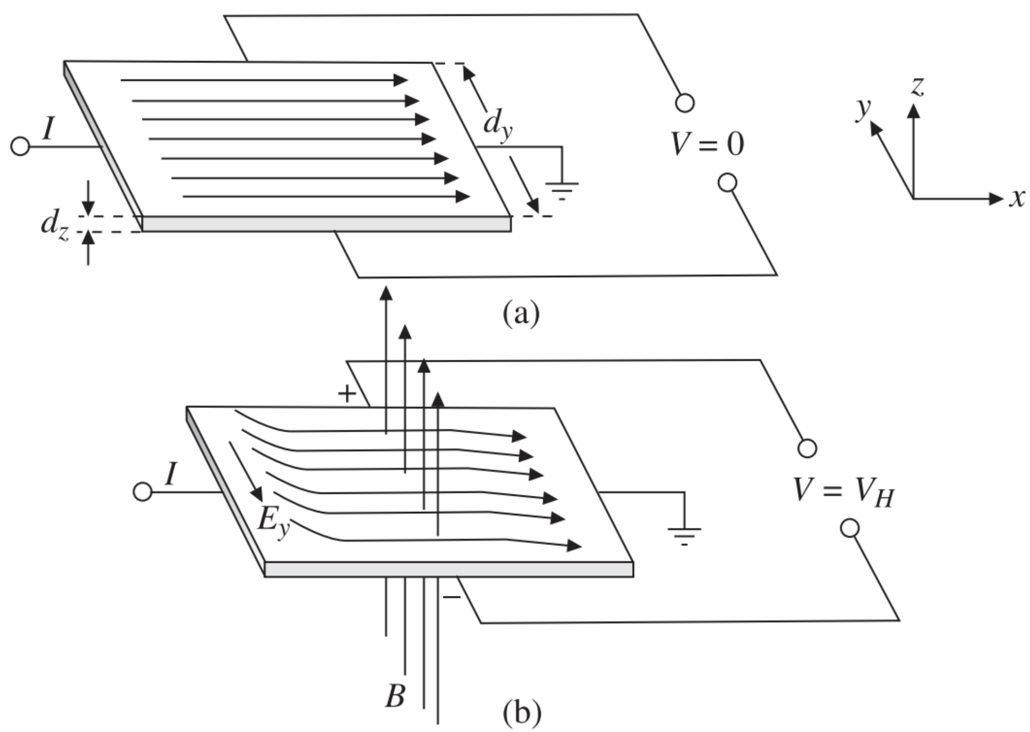
$$\text{Span} = V_{\text{out}}\big|_{\max B} - V_{\text{out}}\big|_{\min B}$$

for a given supply voltage V_s.

Magnetoresistance

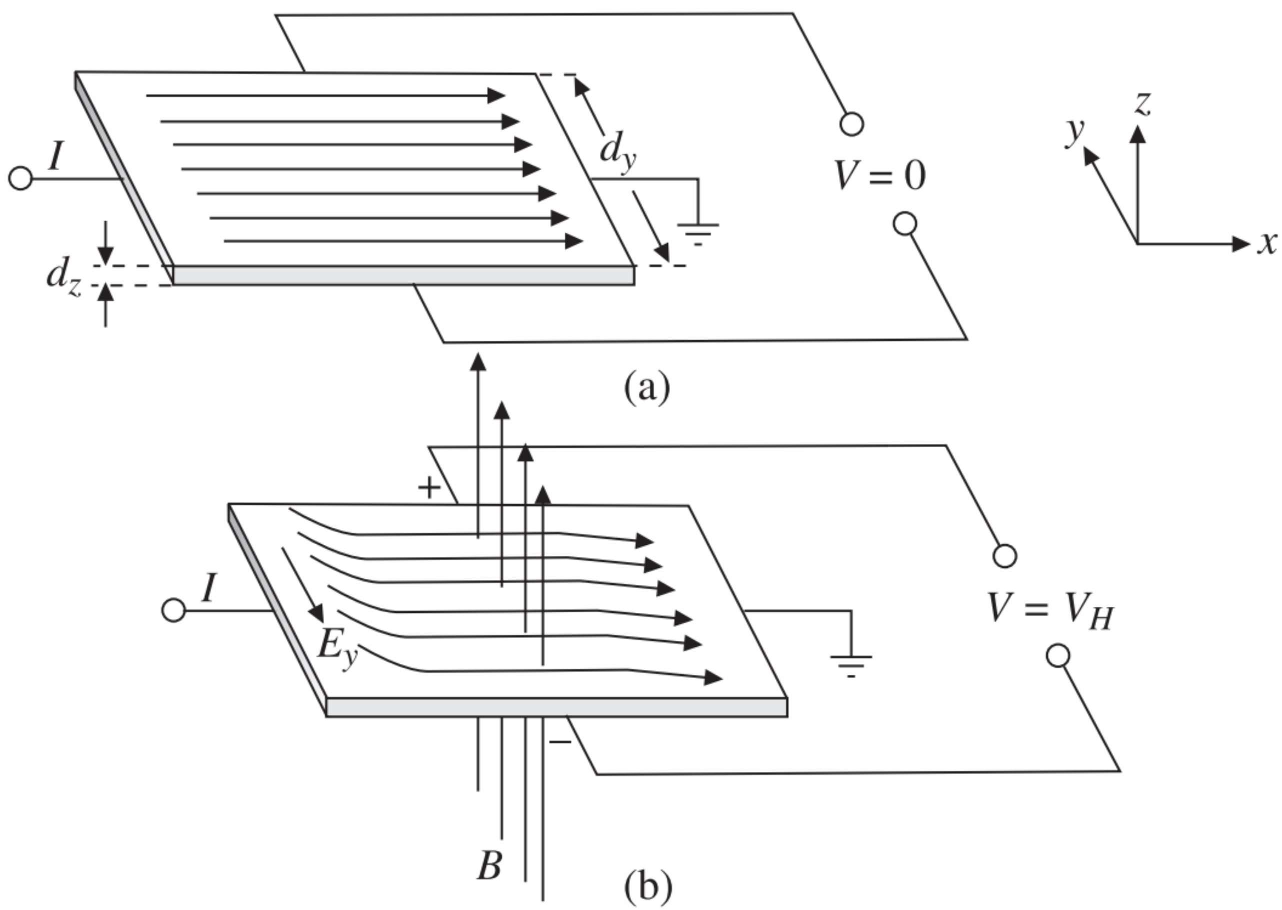
The magnetoresistance effect is closely associated with Hall effect transducers.

Suppose, in Fig. 5.3 if d_y of the Hall element is made much shorter than d_x, the Hall voltage can be almost short-circuited. As a consequence, the charge carriers move at the Hall angle to the x-direction. The increase in path length for the carriers causes an increase in resistance of the device. This increase in resistance of the Hall element owing to the application of a magnetic field is known as the geometrical *magnetoresistance effect*.



Magnetoresistance

- Applied magnetic field causes deviation of some charge carriers from their path
  - there is a current decrease, with an increased electric resistance



Magnetoresistance

Magnetoresistors offer following advantages as compared to magnetic sensors

1. A magnetoresistor is a zero order system while inductive sensors are first order systems because their response depends on the time derivative of the magnetic flux density.
2. Hall effect sensors also are zero order systems. But magnetoresistors show increased sensitivity, temperature range, and frequency passband (from dc to several megahertz) compared with 25 kHz for Hall effect sensors.

Construction. Magnetoresistors are usually manufactured from permalloy, which is an alloy of approximately 20% iron and 80% nickel. Also Ni-Fe-Co and Ni-Fe-Mo alloys have been tried.

Magnetoresistance

- Applied magnetic field causes deviation of some charge carriers from their path
  - there is a current decrease, with an increased electric resistance

Table 5.6 Applications of magnetoresistive effect

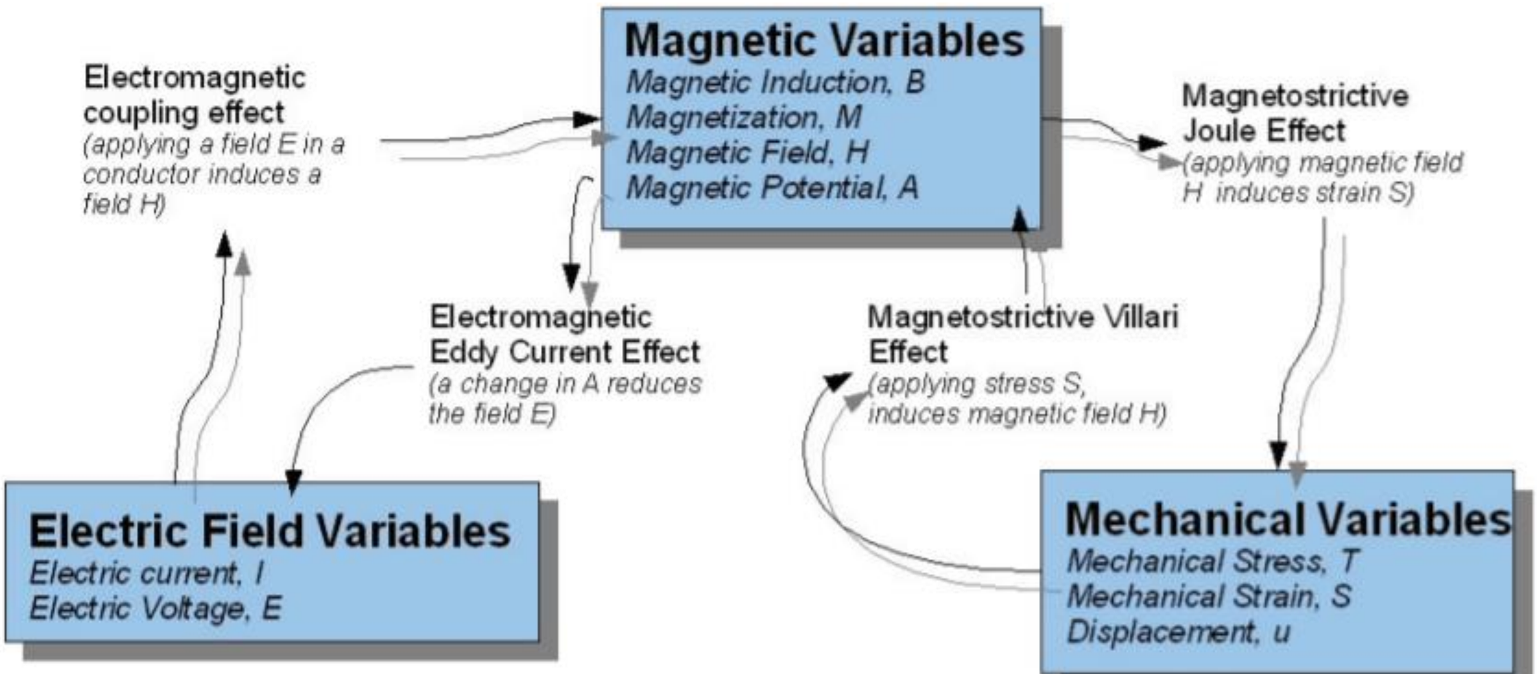
Principle	*Application*
Direct measurement of magnetic fields	Magnetic audio recording Reading machines for credit cards, magnetically coded price tags
Measuring magnetic field variation[a]	Measurement of linear and angular displacement Proximity switches Position measurement Angular velocity of ferrous gear wheels

Summary

The magnetostrictive materials will change shape when it is subjected to a magnetic field. This occurs because magnetic domains in the material align with the magnetic field. Similarly, when the material is strained (stretched or compressed), its magnetic energy changes. This phenomenon is reversible and for this matter it can be use to build actuators, sensors or to make energy conversion.

It is possible to simplify the processes into two reversible energy conversion steps:

- from electric to magnetic;
- from magnetic to mechanical.



http://www.elkraft.ntnu.no/eno/Papers2008/Martino.pdf

Physical Phenomenon for Transducers

Working of transducers are based on the following physical phenomenon.

1- Magnetic effects

2- Piezoresistivity

3- Piezoelectricity

4- Surface acoustic wave

5- Optical effects

Concepts Check?
Piezoresistive Vs Piezoelectric

Recall..Coupling Diagram

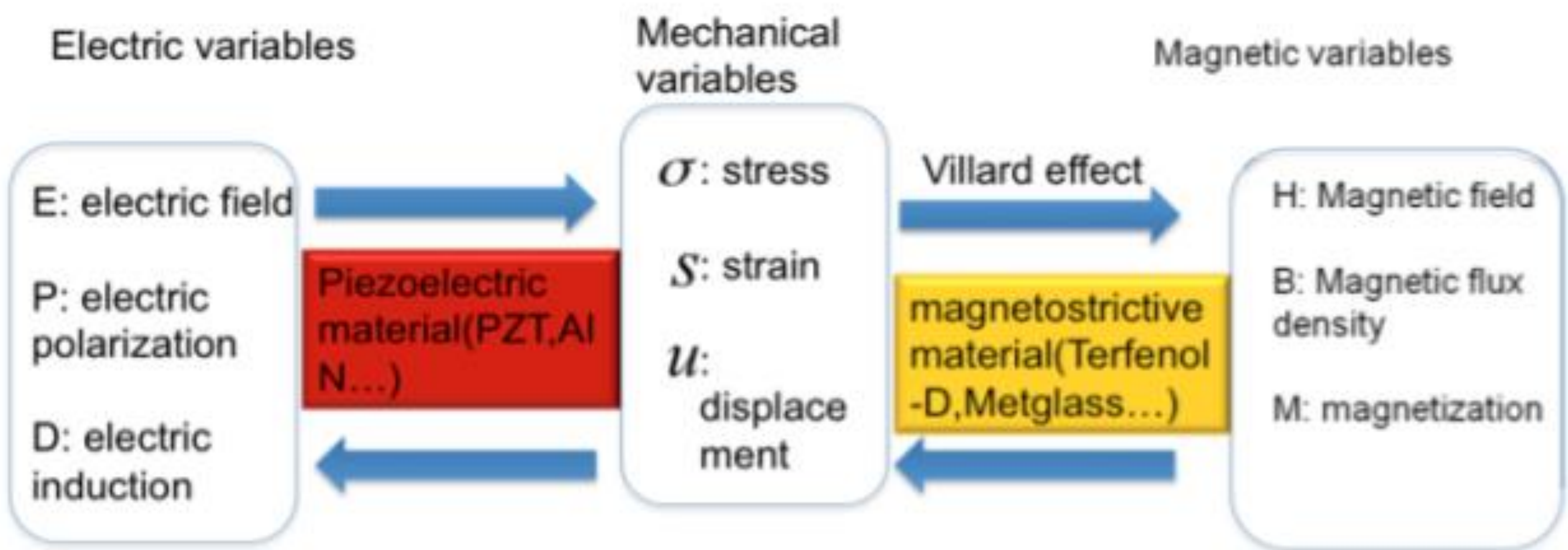
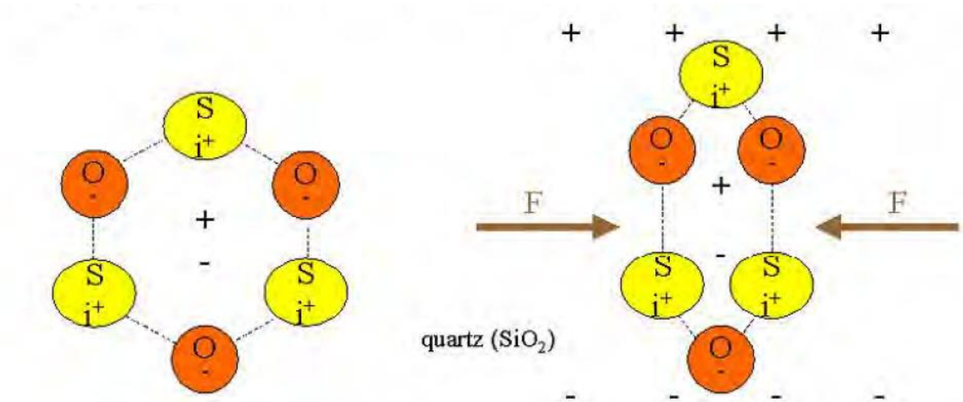
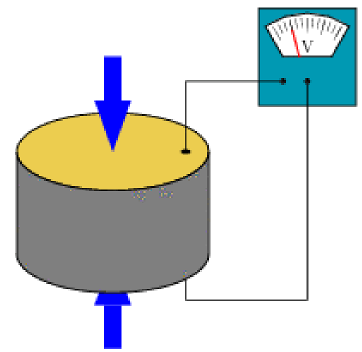


Figure 1.1 Composite material conversion mechanisms

https://tel.archives-ouvertes.fr/tel-01630261/document

Concepts Check?





No center of symmetry!

Piezoelectric Materials

Piezoelectric *materials convert mechanical energy to electrical energy and vice versa, while* ***piezoresistive*** *devices convert mechanical energy to resistance values and that's it. They do not work in reverse like their piezoelectric counterparts*

Concepts Check

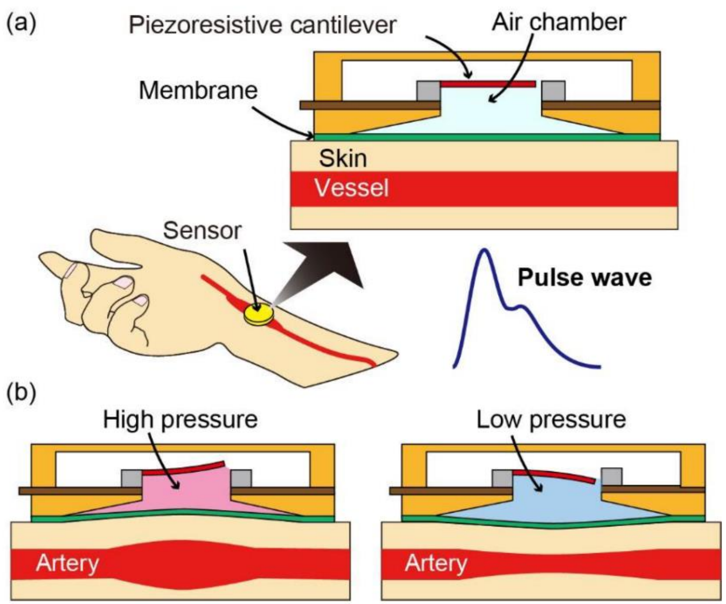
Piezoresistive Vs Piezoelectric

- The **piezoresistive** effect is a change in the electrical resistivity of a semiconductor or metal when mechanical strain is applied.
- In contrast to the piezoelectric effect, the **piezoresistive** effect causes a change only in electrical resistance, not in electric potential.

- **Piezoelectric** components convert mechanical energy to electrical energy and vice versa, while **piezoresistive** devices convert mechanical energy to resistance values and that's it. *They do not work in reverse like their piezoelectric counterparts.*

Piezoresistivity

- Change of electric resistivity of the material caused by an applied mechanical stress



Bio-NEMS/MEMS Sensor

Piezoresistivity

- Change of electric resistivity of the material caused by an applied mechanical stress
- Semiconductors are well-knows for “Piezoresistive effect”

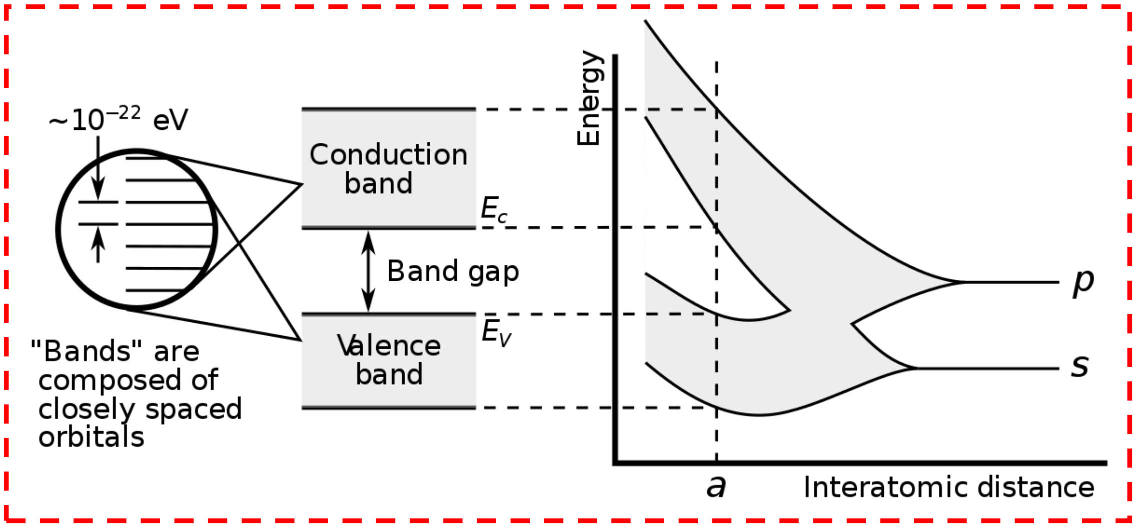
Piezoresistivity

- **Origin of piezoresistivity**
  - **Change in resistivity of the semiconductor when strained ?**

Piezoresistivity

❑ Origin of piezoresistivity

When a semiconducting material is stressed, the interatomic spacings within the material change. This eventually changes the bandgaps in each atom making it easier (or harder depending on the material and strain) for electrons to be raised into the conduction band. A higher or lower electron population in the conduction band results in a change in resistivity of the semiconductor.



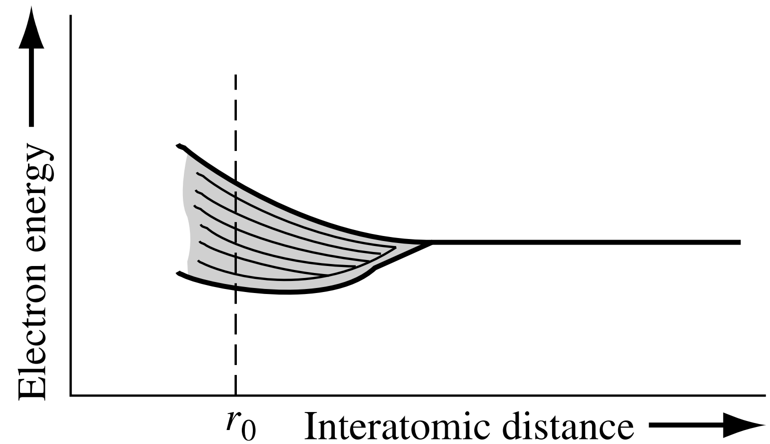


Figure 3.2 | The splitting of an energy state into a band of allowed energies.

Piezoresistivity

- **Origin of piezoresistivity**
  - Change in resistivity of the semiconductor when strained
    - When strained, the interatomic spacing within the material change
    - The change in the interatomic spacing eventually changes the bandgaps in each atom

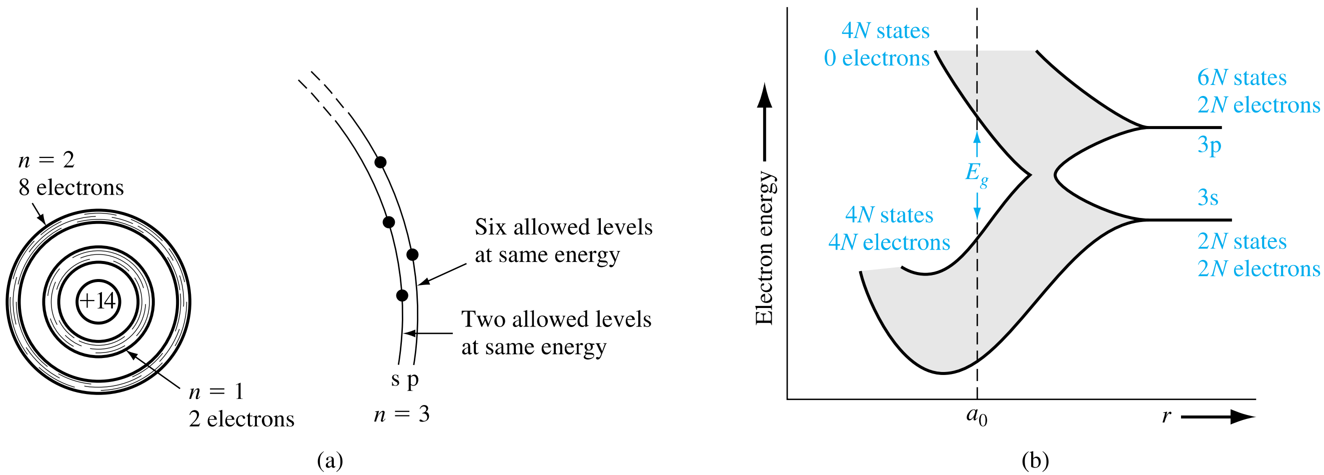
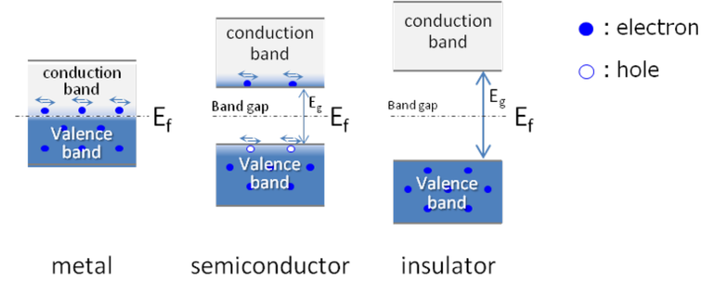


Figure 3.4 | (a) Schematic of an isolated silicon atom. (b) The splitting of the 3s and 3p states of silicon into the allowed and forbidden energy bands.
(From Shockley [6].)

Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

Piezoresistivity



- ❑ **Origin of piezoresistivity**
  - ❑ Change in resistivity of the semiconductor when strained
    - ❑ Change in the interatomic spacing changes the atomic bandgaps
    - ❑ Band gaps change makes it easier (or harder depending on the material and strain) for electrons to be raised into the conduction band

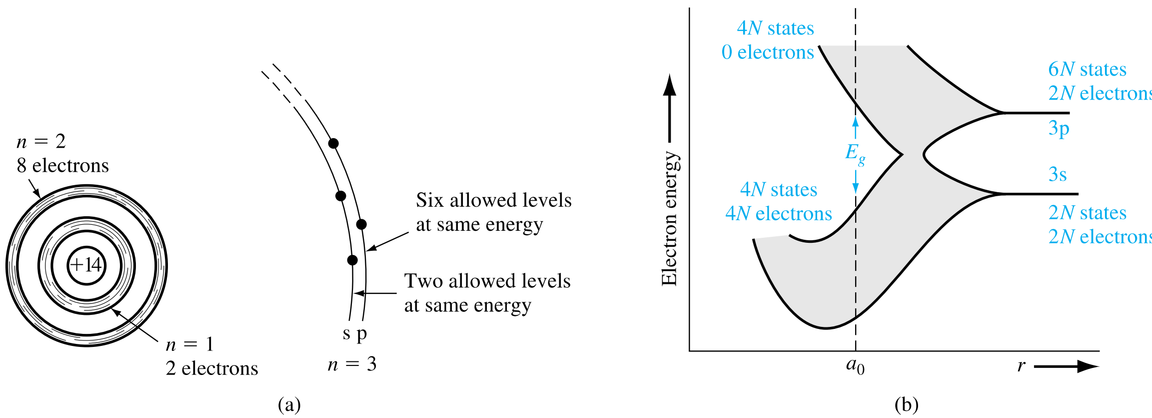
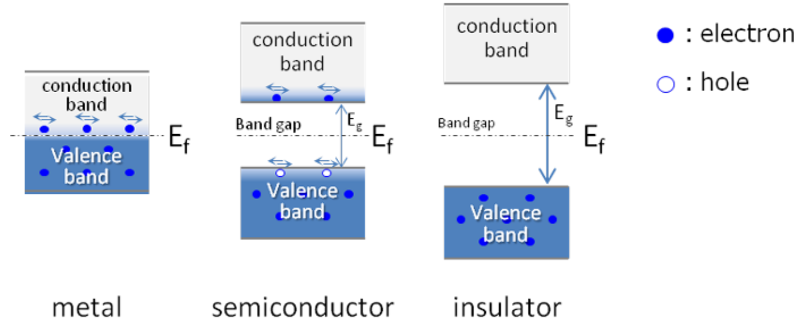


Figure 3.4 | (a) Schematic of an isolated silicon atom. (b) The splitting of the 3s and 3p states of silicon into the allowed and forbidden energy bands.
(From Shockley [6].)

Piezoresistivity



$$R = \rho \frac{l}{A}$$

where ρ is the resistivity of the material of the conductor
l is the length of the conductor
A is the area of cross-section of the conductor.

- **Metals**
  - *Resistivity ρ* is more or less a constant at a given temperature because their conduction bands are already sufficiently populated with electrons

- **Semiconductors**
  - In semiconductors, the conduction bands are not so well populated. Their resistivity changes when they are stressed.

$$\rho_\sigma = \frac{d\rho/\rho}{\varepsilon}$$

where $d\rho$ is the change in resistivity
ρ is the original resistivity
ε is the strain

Piezoresistivity

- **Semiconductors**
  - *Resistivity ρ* can be varied by stress as conduction bands of semiconductors are not so populated normally
  - *Piezoresistivity*

$$\rho_\sigma = \frac{d\rho/\rho}{\varepsilon}$$

where $d\rho$ is the change in resistivity
ρ is the original resistivity
ε is the strain

- ✓ Geometric effect: change in the length and the cross-sectional area
- ✓ Piezoresistive effect is several orders of magnitude higher than the geometric effect
- ✓ This effect is prominent in Germanium, polycrystalline silicon, amorphous silicon, silicon carbide, and single crystal silicon

Piezoresistors

- Piezoresistors are fabricated using a wide variety of piezoresistive materials
  - The simplest form: silicon based diffused resistors
    - Two contacts diffused n or p-well within a p or n-substrate
    - The additional p + or n + diffusions facilitate ohmic contacts to the device

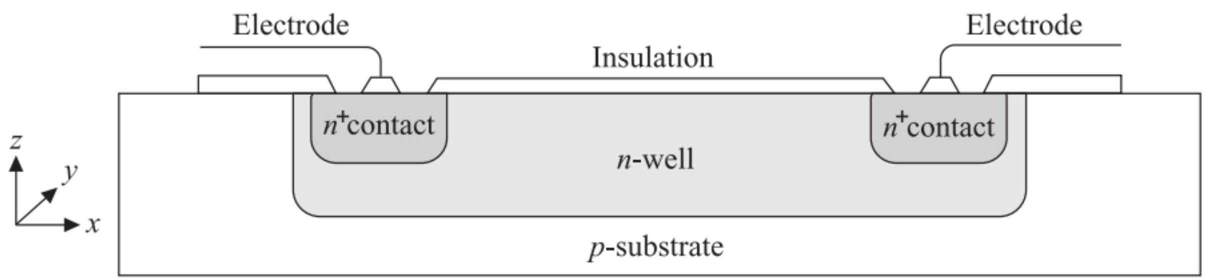


Fig. 5.23 Schematic cross-section of an elementary silicon *n*-well piezoresistor.

Piezoresistors

Nonlinearity. The variation of piezoresistivity with strain at moderate doping is far from linear. For example, the fractional resistivity variation of lightly doped p-Si at moderate tensile stress and at the room temperature can be written as

$$\frac{d\rho}{\rho} = 175\varepsilon + 72625\varepsilon^2$$

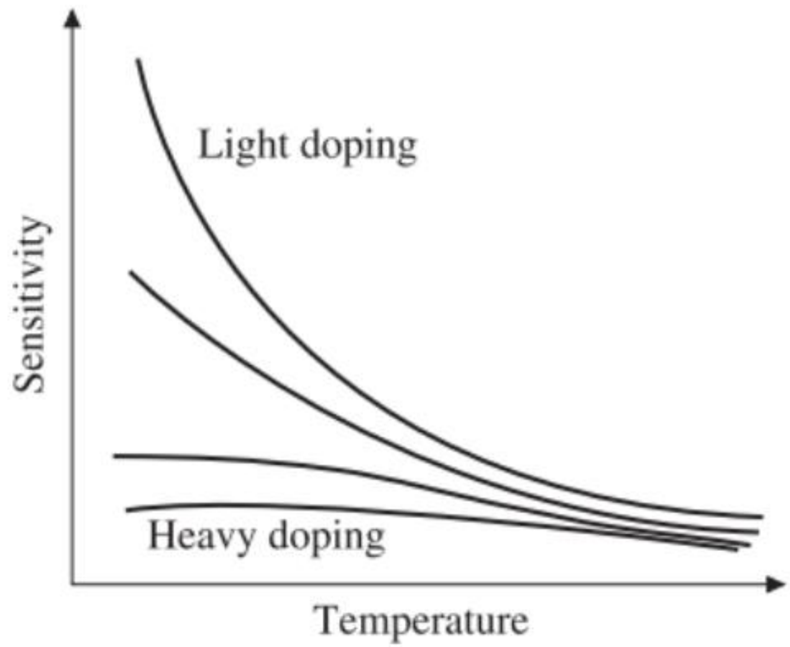
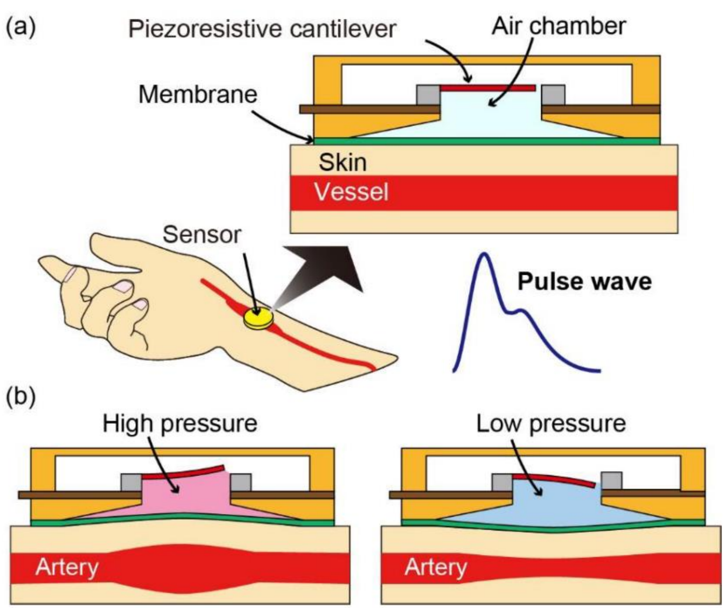


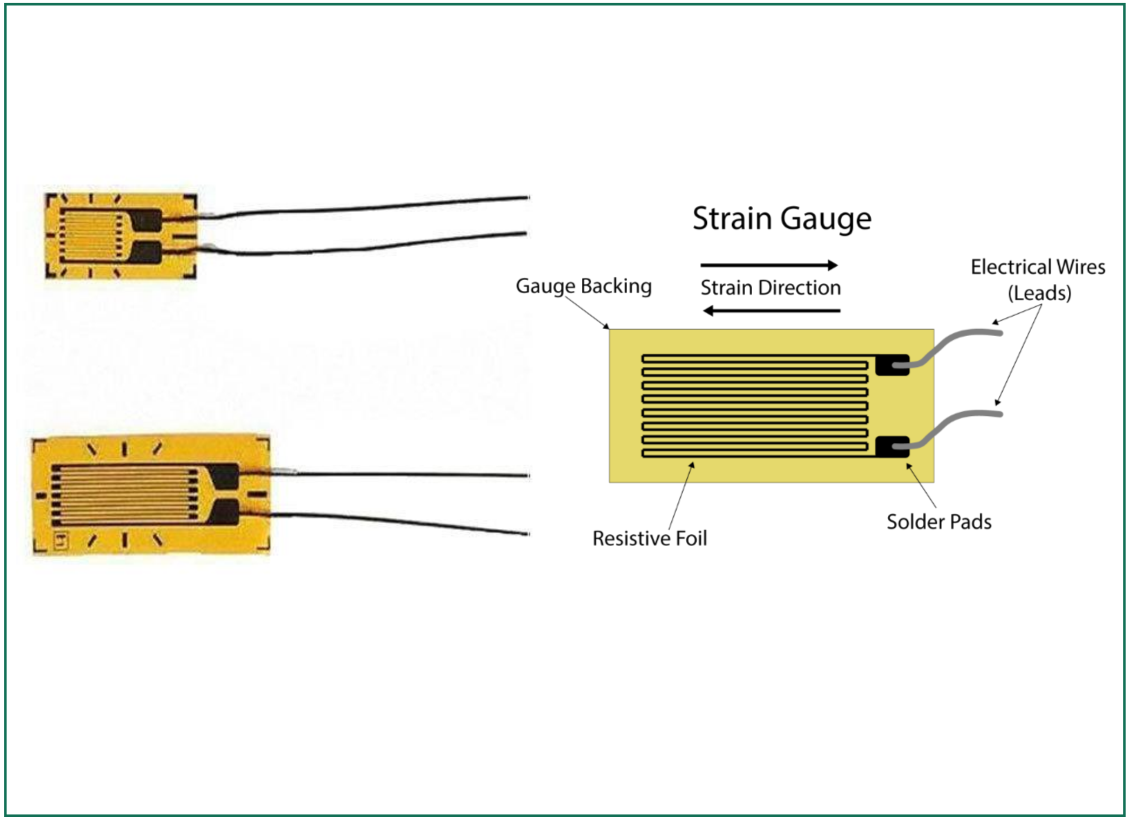
Fig. 5.24 Sensitivity vs. temperature plots for p-Si at different degrees of doping.

Piezoresistivity Applications

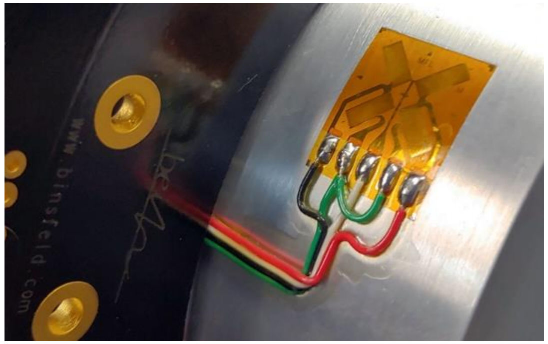
- ❑ Piezoresistive effect is typically used in strain gauge.
- ❑ Strain gauges have application in pressure transducers and accelerometers.



Bio-NEMS/MEMS Sensor



Piezoresistivity Application
Strain Gauge?



$$Strain = \frac{\Delta L}{L}$$

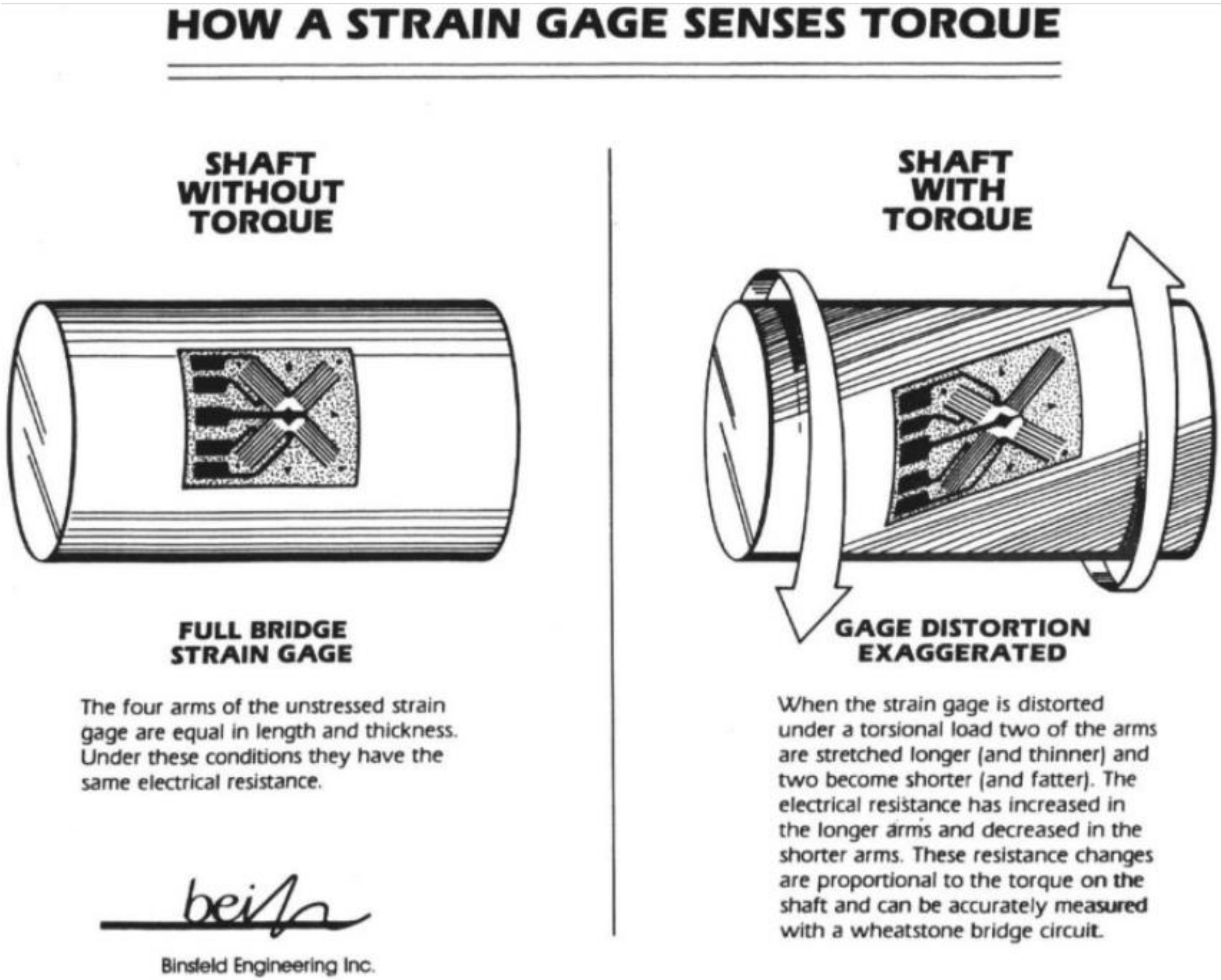
What is a Strain Gage?

A strain gage works to measure the amount of strain on a given object. At its most basic form, a strain gage converts a change in dimension to a change in electrical resistance. The ratio of mechanical strain to electrical resistance is what is known as the Gage Factor, and is specific to the type/lot of strain gage used. Strain gages can be used to sense expansion as well as contraction and produce positive or negative signals to distinguish between the two.

How Does a Strain Gage Work?

In general, a strain gage makes use of very fine wire or metallic foil arranged in a grid pattern. The electrical resistance of the strain gage's metallic grid changes in proportion to the amount of strain experienced by the object, offering the operator a clear, accurate measurement of strain, e.g. how much the item is stretched or twisted.

Strain gages come in many different shapes, sizes, and patterns depending on the parameter being measured. A strain gage designed for torque measurement is shown below.



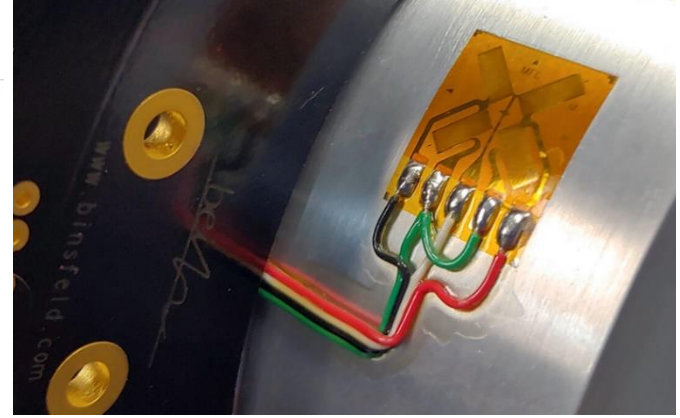


Figure 4. How a strain gage senses torque.

https://binsfeld.com/what-is-a-strain-gage-and-how-does-it-work/

Queries

Thanks!