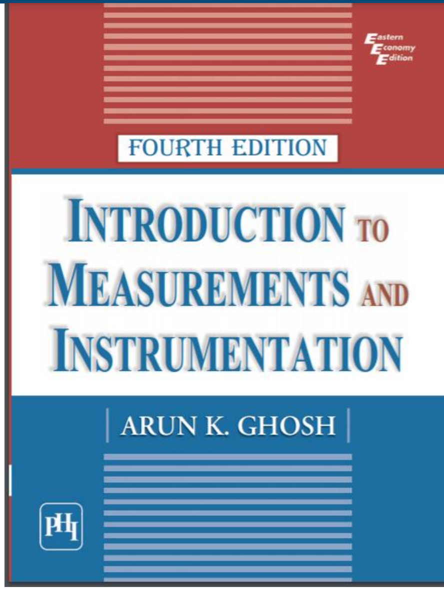
NUST
SCHOOL OF ELECTRICAL ENGINEERING
& COMPUTER SCIENCE

- Course: **EE383 Instrumentation and Measurements**

- **Lectures: Week 8**
- Course Instructor: Dr. Shahzad Younis

SCHOOL OF ELECTRICAL ENGINEERING
& COMPUTER SCIENCE

INSTRUMENTATION
& MEASUREMENT



Week 8

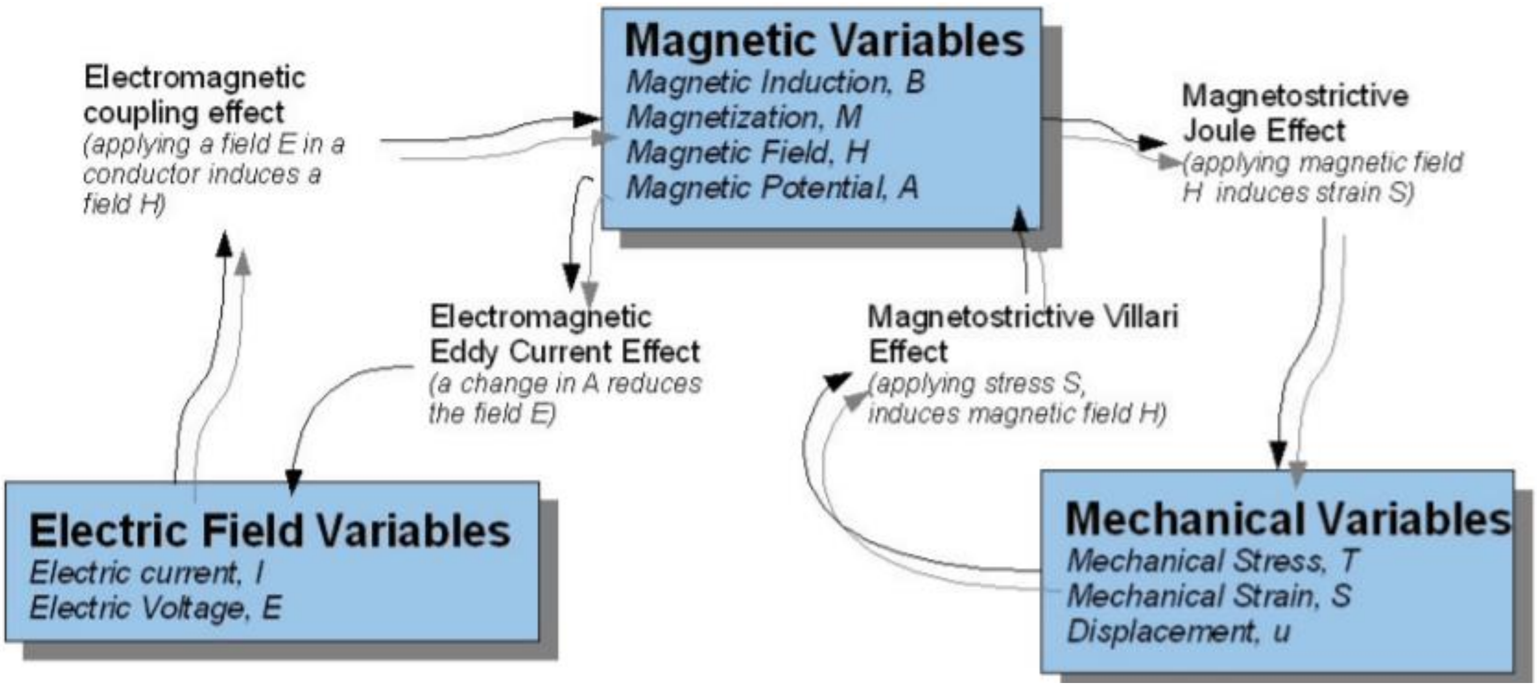
- **Chapter 5**

  Transducers

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

- **Transducer**

Conversion of Variables?



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

Physical Phenomenon for Transducers

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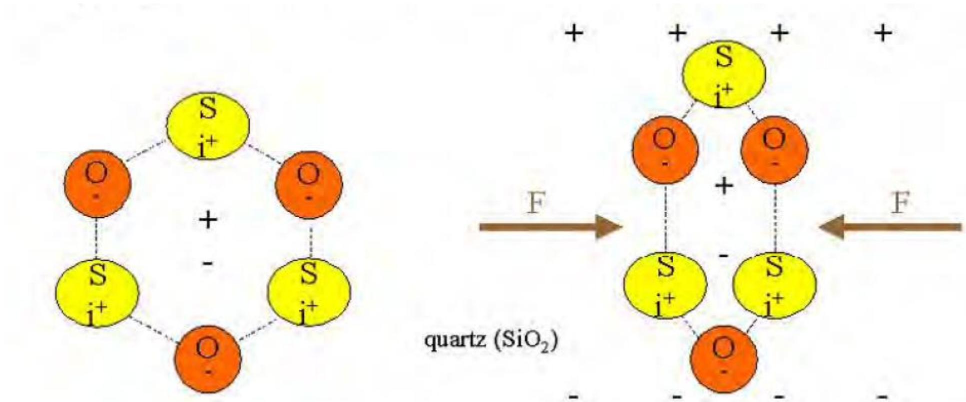
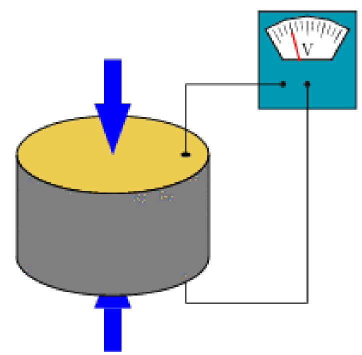
Recall.



No center of symmetry!

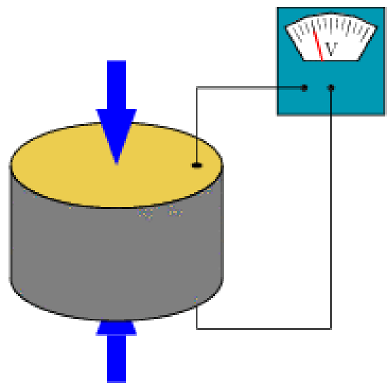


Piezoelectric Materials

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*

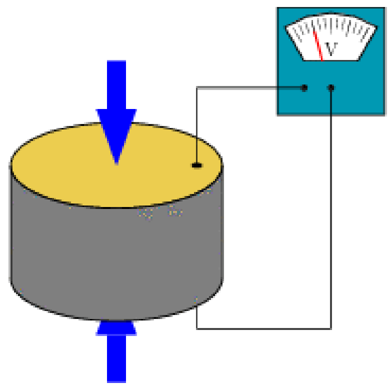
Piezoelectricity

- ❑ **Coupling of piezo (strain/squeeze) and electricity**



Piezoelectricity

- Piezoelectric effect: Certain materials, especially the crystalline ones, produce an emf when deformed by an application of pressure along the specific axes



Piezoelectricity

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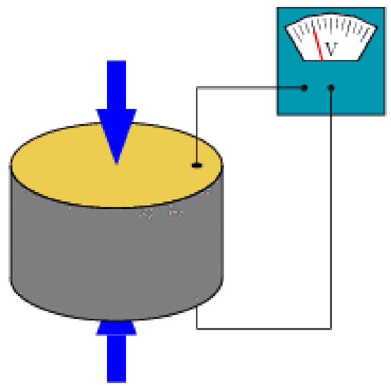


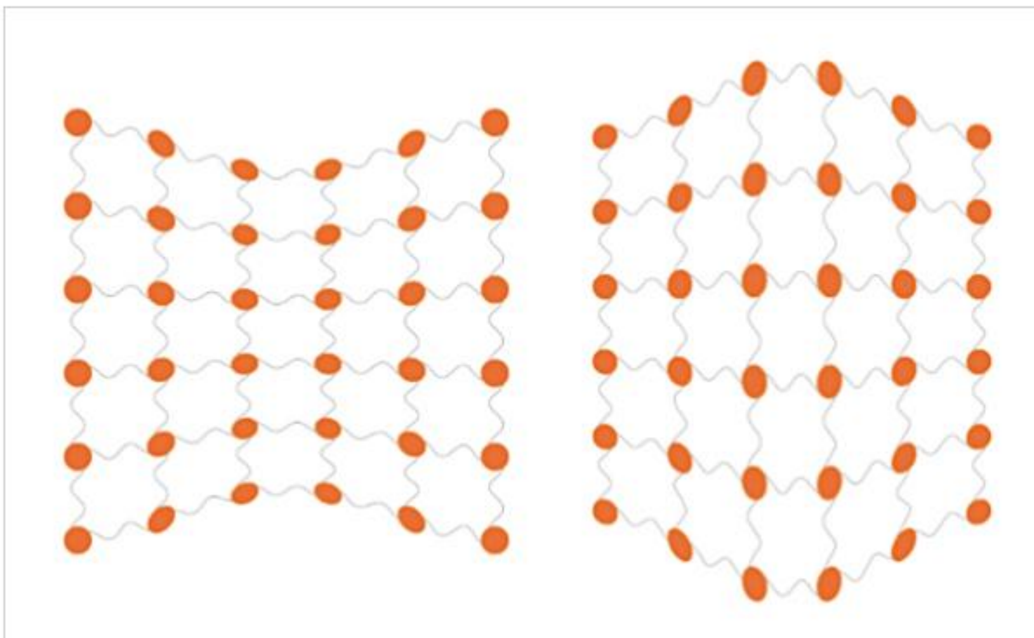
- **What is the origin of piezoelectricity?**

Piezoelectric Effect

Certain materials will generate a measurable potential difference when they are made to expand or shrink in a particular direction.

Increasing or decreasing the space between the atoms by squeezing, hitting, or bending the crystal can cause the electrons to redistribute themselves and cause electrons to leave the crystal, or create room for electrons to enter the crystal. A physical force on the crystal creates the electromotive force that moves charges around a circuit.

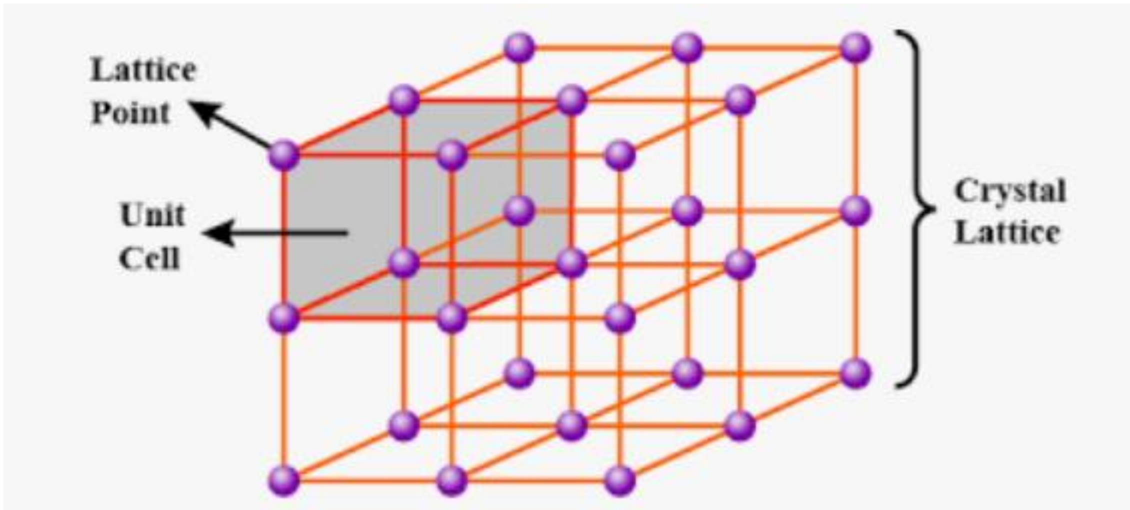
The opposite is true as well: Applying an electric field to a piezoelectric crystal leads to the addition or removal of electrons, and this in turn causes the crystal to deform and thereby generate a small physical force.



Representation of a compressed (left) and stretched (right) crystalline structure.

Origin of Piezoelectricity?

- ❑ Unit cell: the basic repeating unit of a material

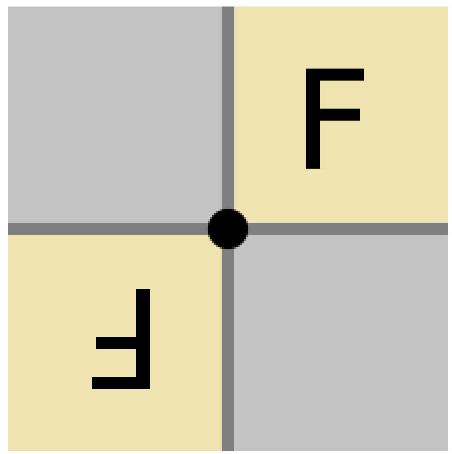


1. When the unit cell is symmetrical around the center (i.e., centrosymmetric), the material is NON piezoelectric
2. When the unit cell is not symmetrical around the center (i.e. non centrosymmetric), the material is piezoelectric

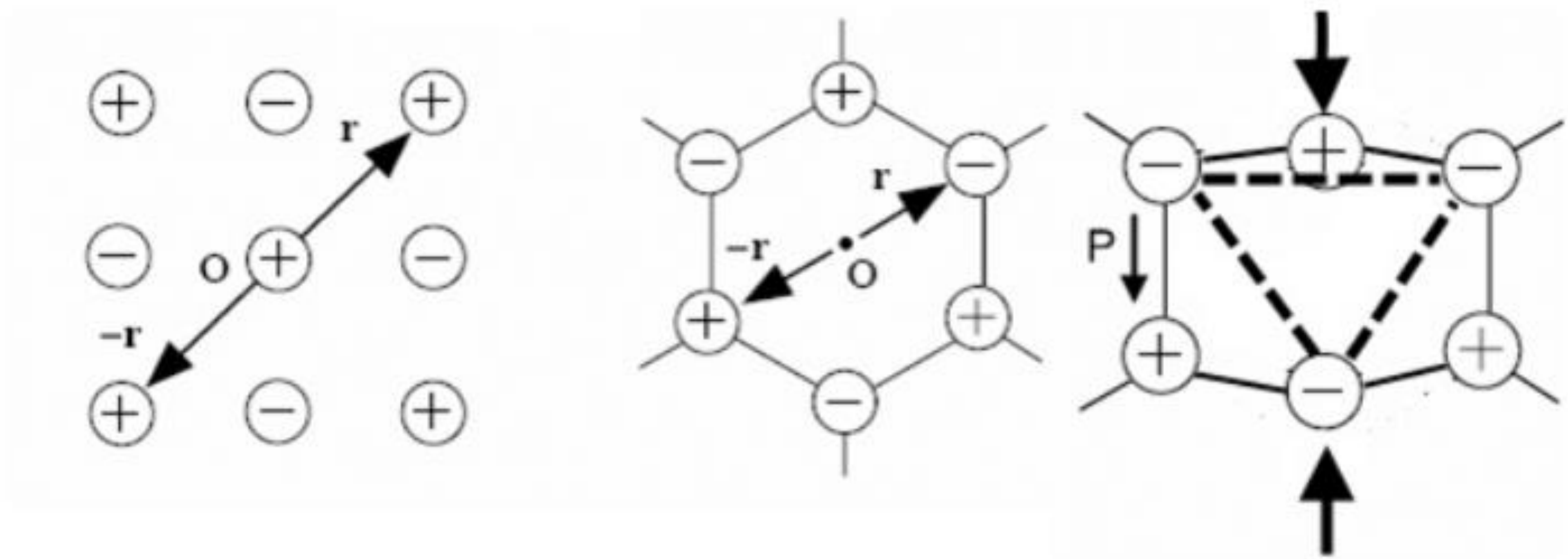
Centro-symmetric & Non-centrosymmetric

- Symmetric with respect to a central point.

- A centre of symmetry is a point through which the (crystal) structure displays inversion symmetry. Mathematically, if there is an atom at (x,y,z) relative to the centre of symmetry, there must also be an atom at (-x,-y,-z); this is true for all x, y and z.



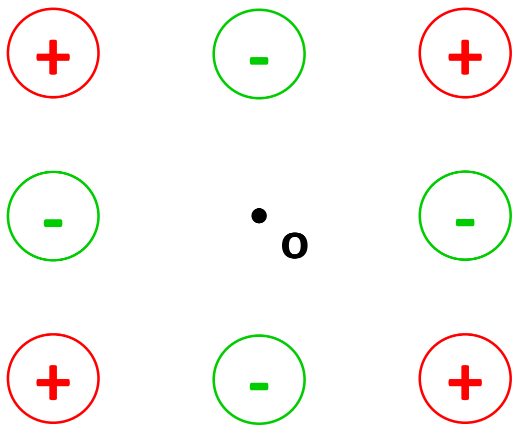
Centro-symmetric & Non-centrosymmetric

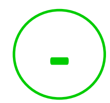


Left-a centrosymmetric unit cell (NaCl) with centre of mass O, Centre-A noncentrosymmetric, unstressed hexagonal unit cell with centre of mass O, Right-Showing the displacement of positive and negative charge, resulting in a shift of mass centre. 1

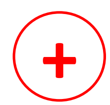
Origin of Piezoelectricity

- Let us consider a *fictitious* unit cell





negatively charged atom

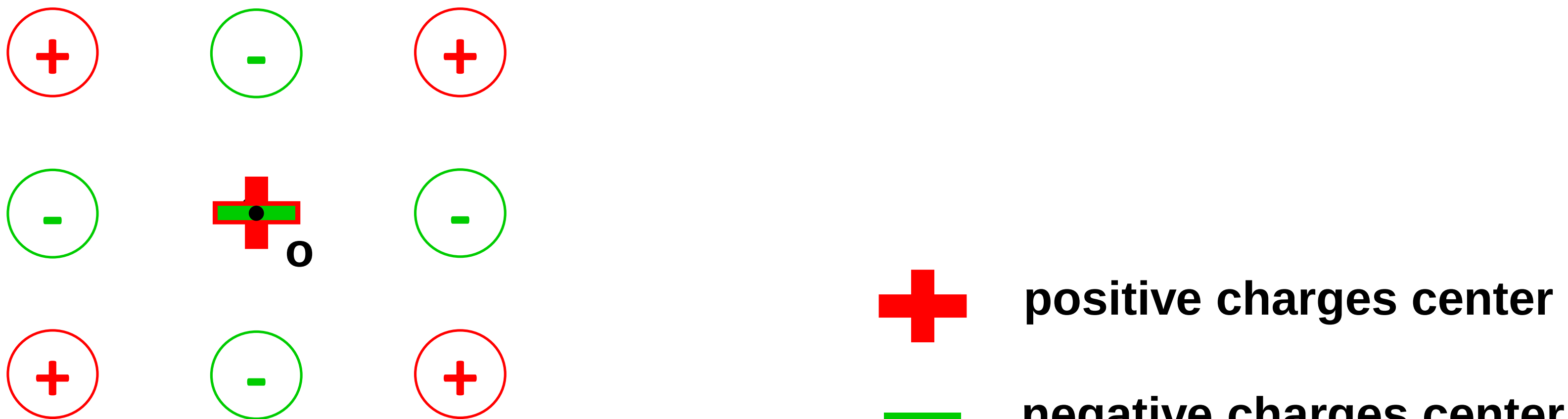


positively charged atom

- It is symmetrical around the center, O
  - ✓ known as, centro-symmetric unit cell

Origin of Piezoelectricity

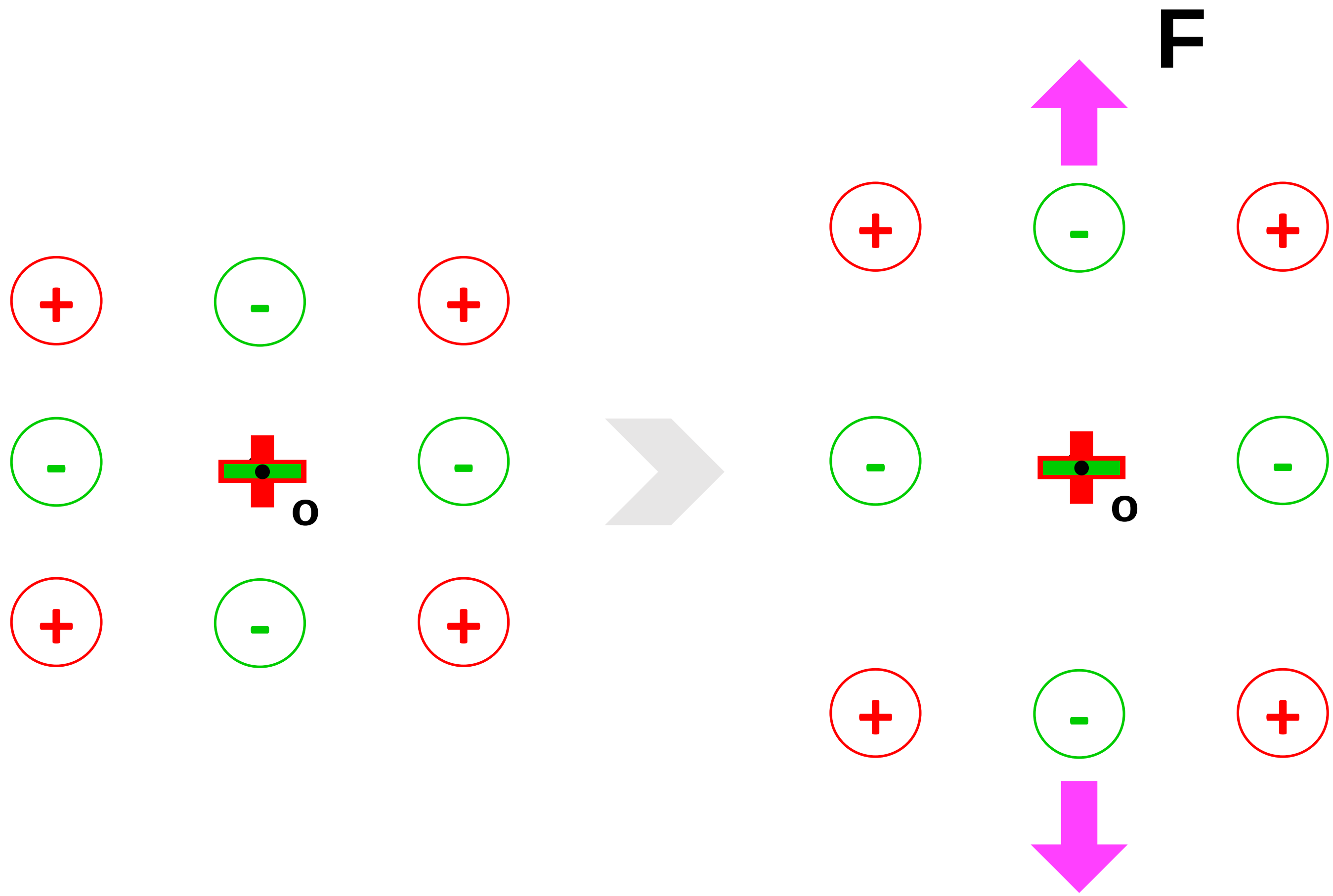
- Fictitious centro-symmetric unit cell



- Center of the positive charges and negative charges coincide
  - non-polar

Origin of Piezoelectricity

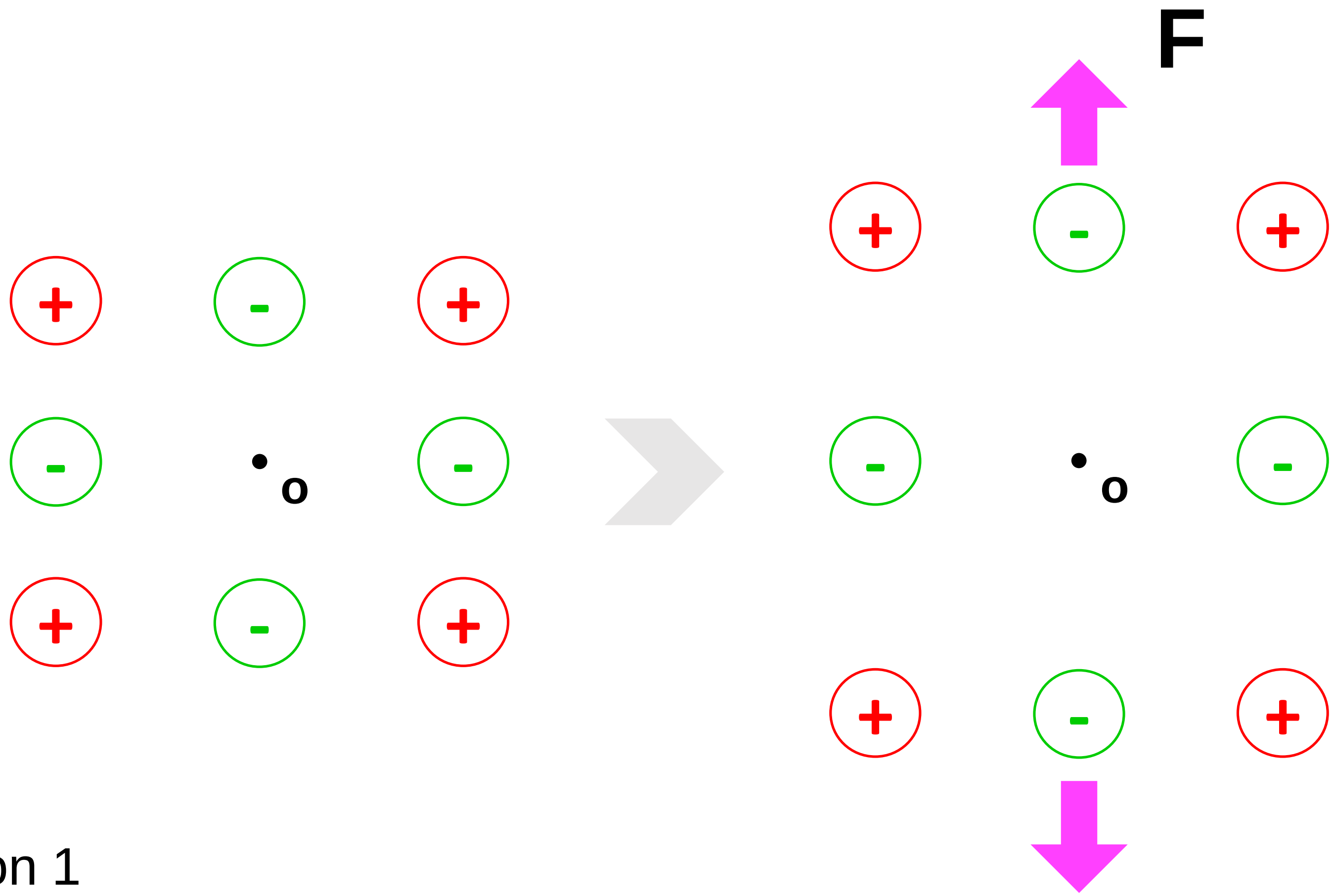
- Let us apply a force F to the fictitious centro-symmetric unit cell



- Though atoms displaced, center of positive and negative charges still coincide
  - Non polar:- no polarization:- no piezoelectric effect

Origin of Piezoelectricity

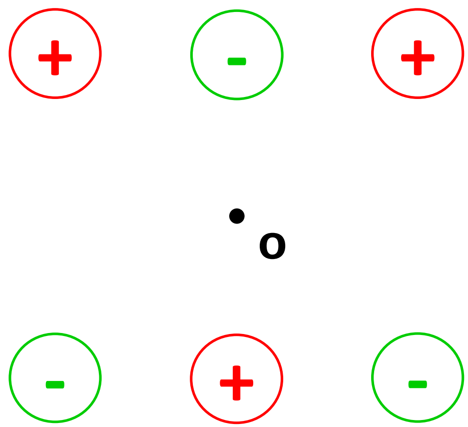
- A force F to the fictitious centro-symmetric unit cell

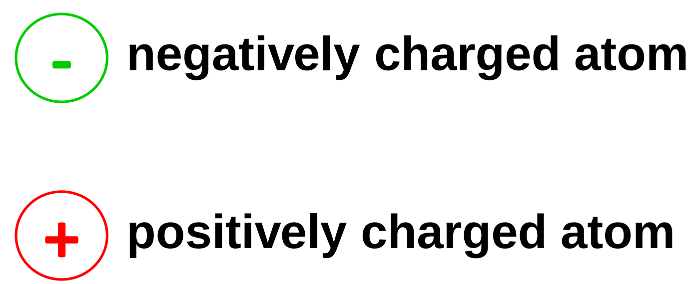


- Conclusion 1
  - When the unit cell is symmetrical around the center (i.e., centrosymmetric), the material is NON piezoelectric

Origin of Piezoelectricity

- ❑ Let us consider a fictitious unit cell which is not symmetrical around the center

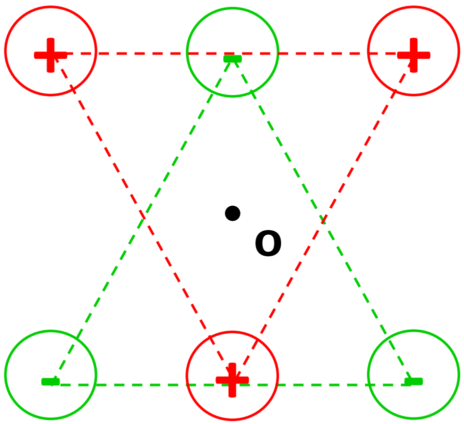




- ❑ It is not symmetrical around the center, O
  - ✓ known as, **<u>non centro-symmetric unit cell</u>**

Origin of Piezoelectricity

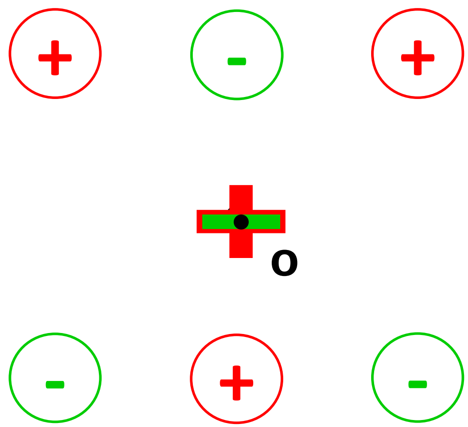
- A fictitious non centrosymmetric unit cell



- This is like two (oppositely charged) triangles in inverted form

Origin of Piezoelectricity

- non centrosymmetric fictitious unit cell



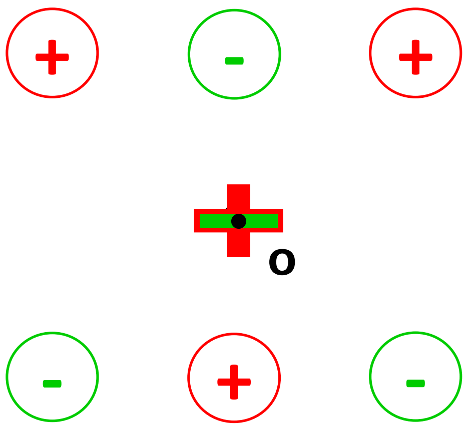
positive charges center

negative charges center

- Center of the positive charges (triangle) and negative charges (triangle) coincide
  - without external stress, no polarization

Origin of Piezoelectricity

- ❑ **non centrosymmetric fictitious unit cell**

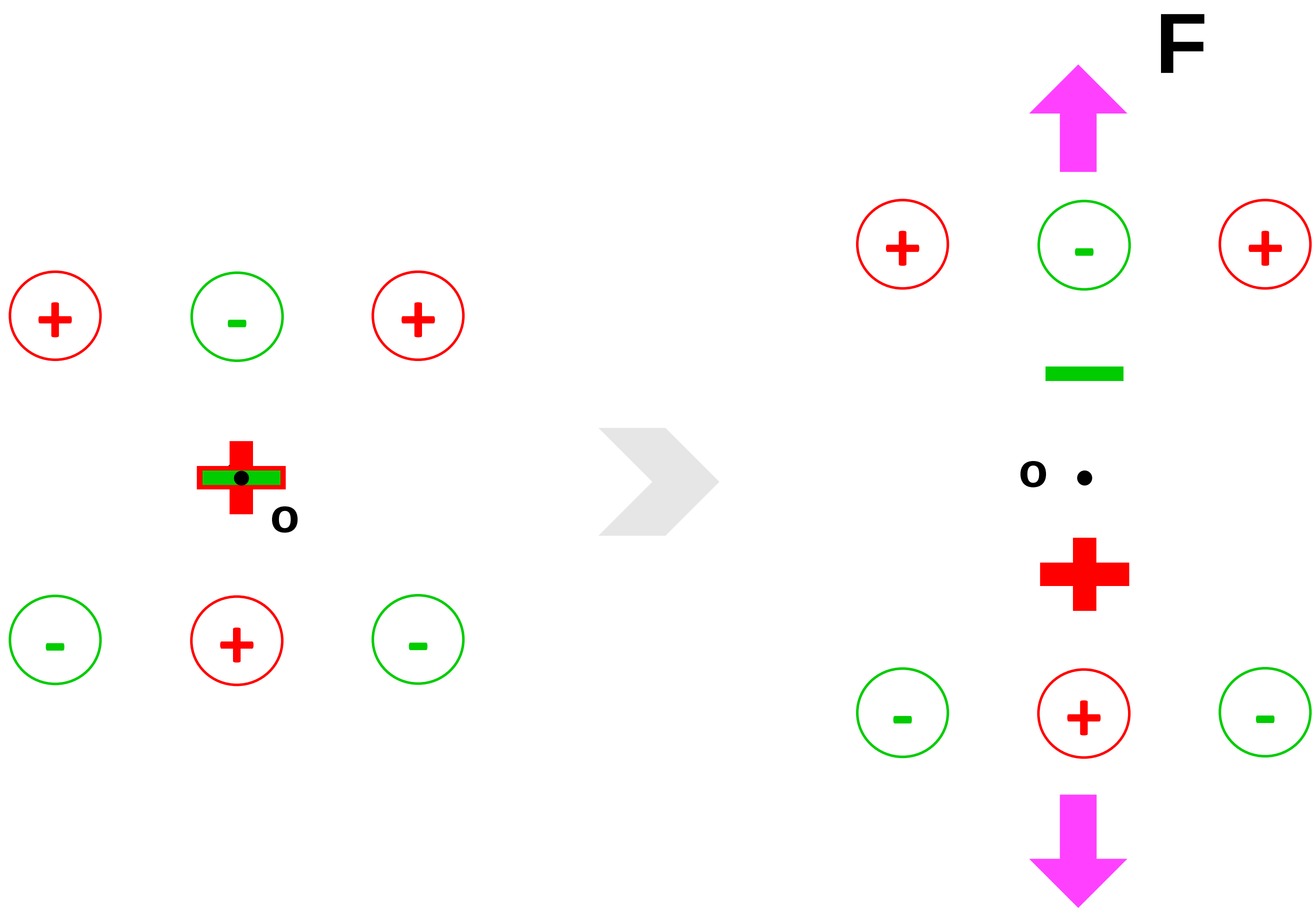


- ❑ **Non-polar**

❑ But, what will happen when we apply a force ?

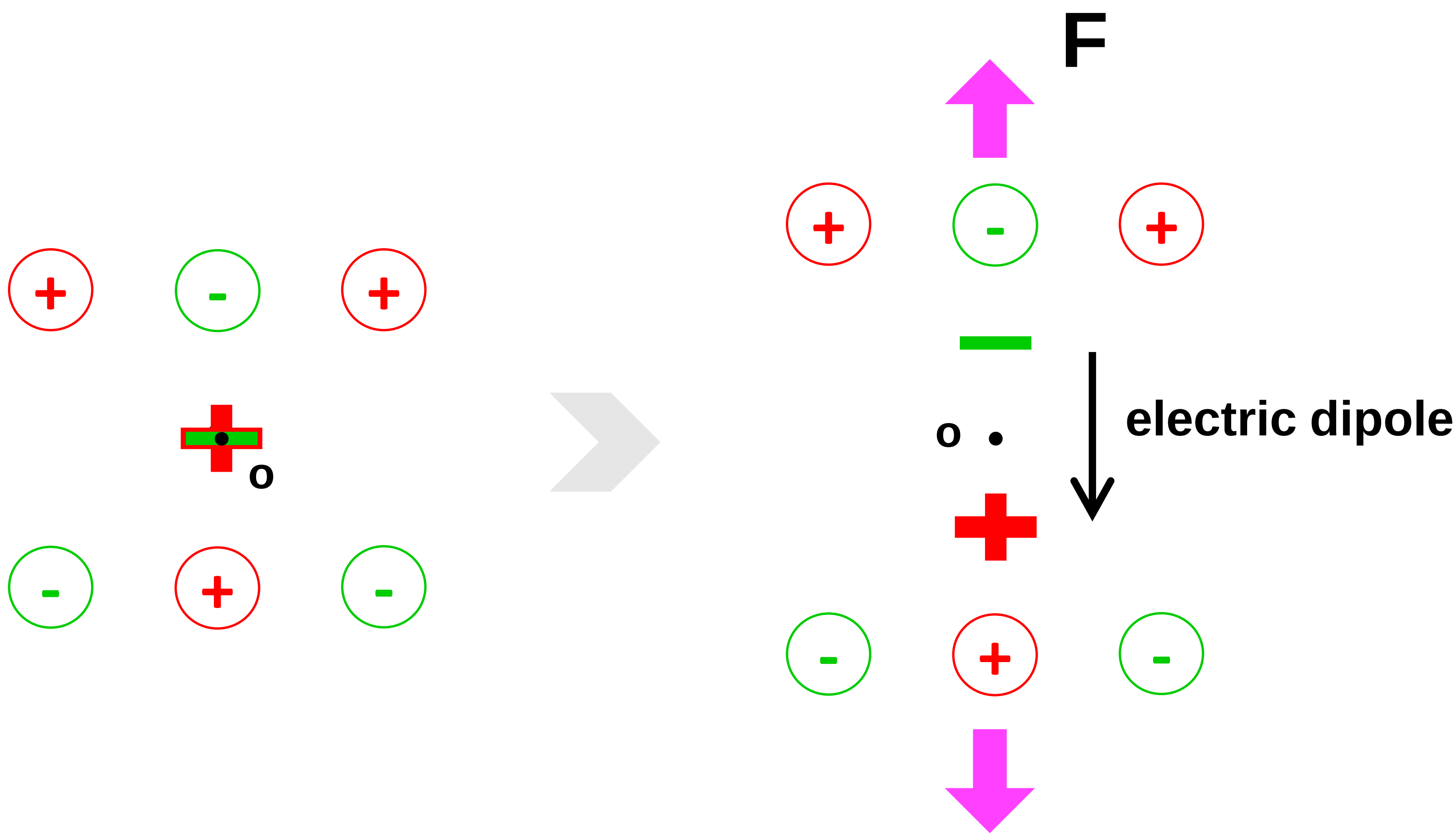
Origin of Piezoelectricity

- let us apply a force F to the fictitious non centrosymmetric unit cell



Origin of Piezoelectricity

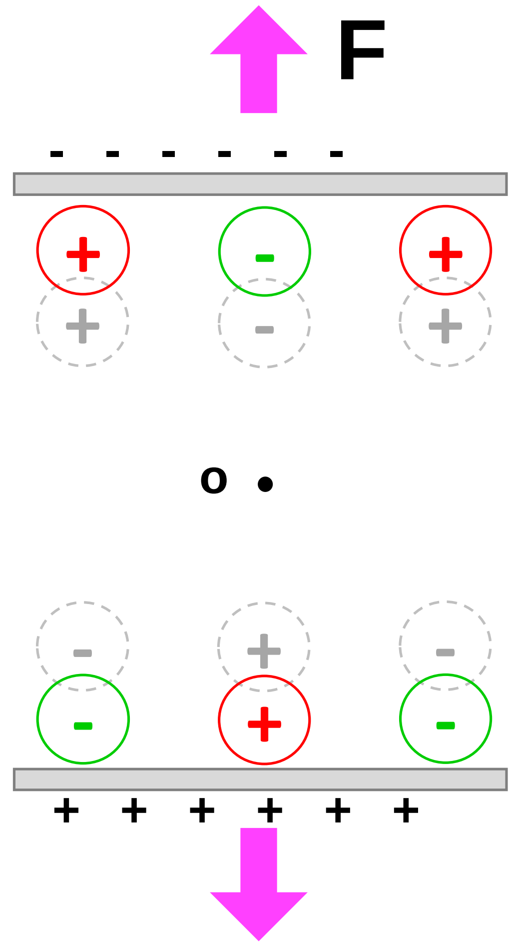
- **a force F applied to the fictitious non centrosymmetric unit cell**



- Center of the positive charges (triangle) and negative charges (triangle) separate
  - <u>creating an electric dipole:- polarization:- *piezoelectric effect*</u>

Origin of Piezoelectricity

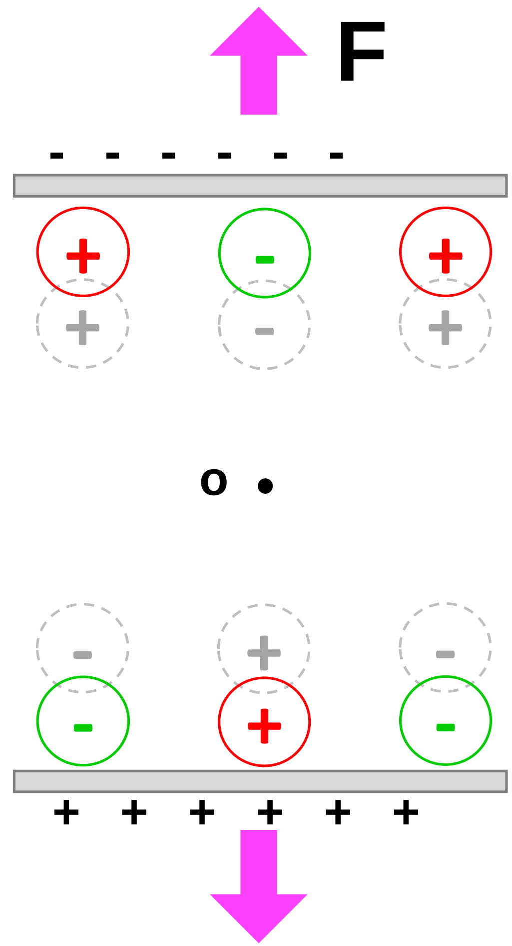
❖ *let us consider it in another perspective*



- Effectively one face gets positively charged and other face is negatively charged
- This will electrostatically induce current in any external circuit when connected
    - *Piezoelectricity or piezoelectric effect*

Origin of Piezoelectricity

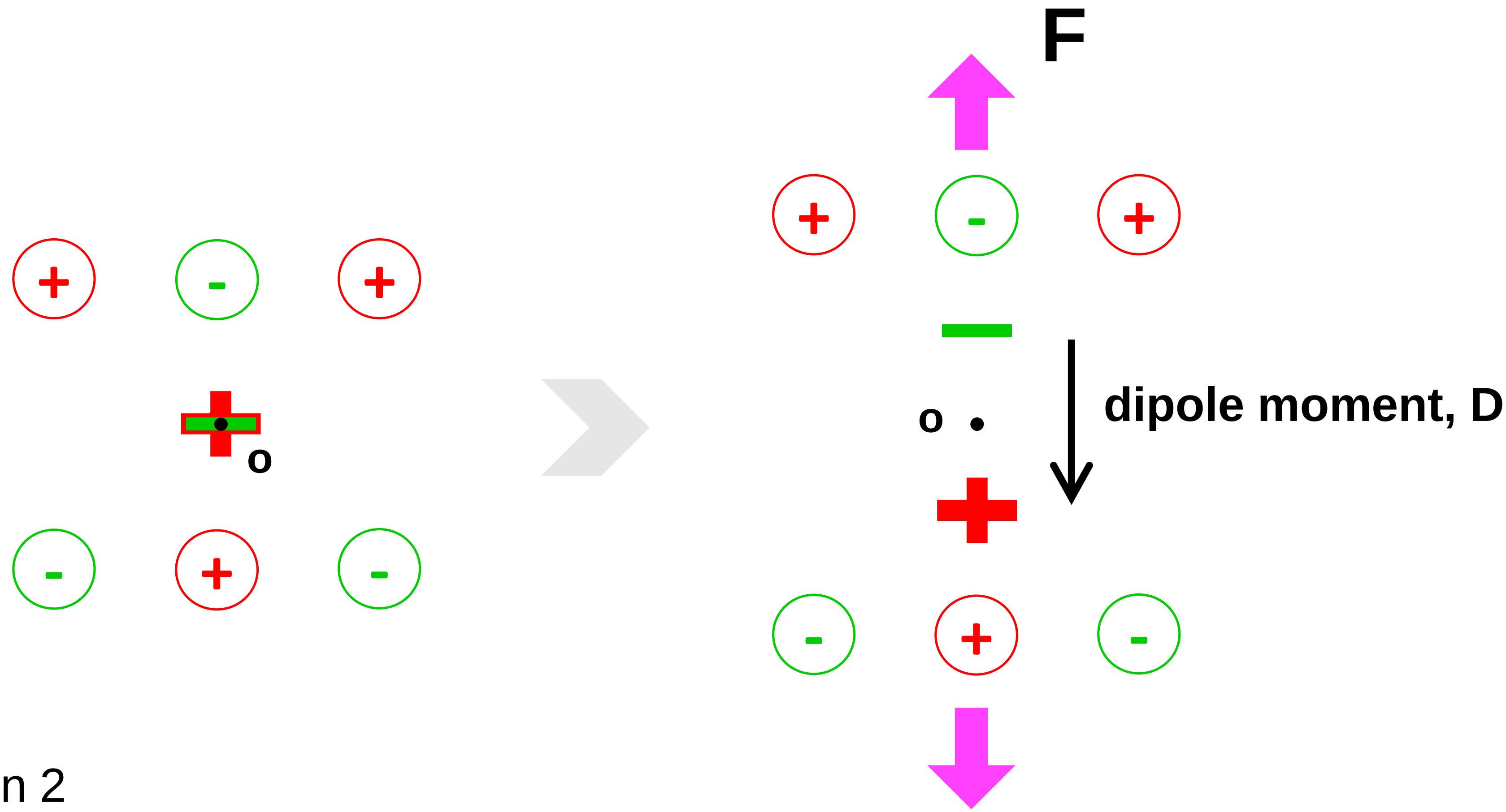
- *let us consider it in another perspective*



- How will the current flow in an external circuit?

Origin of Piezoelectricity

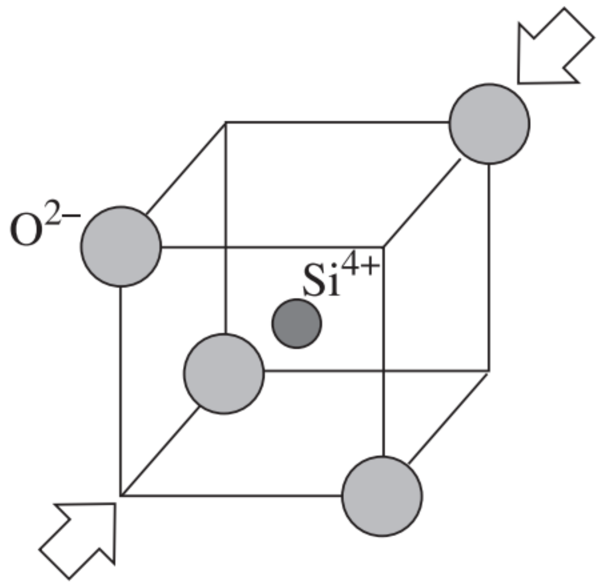
- a force F applied to the fictitious non centrosymmetric unit cell



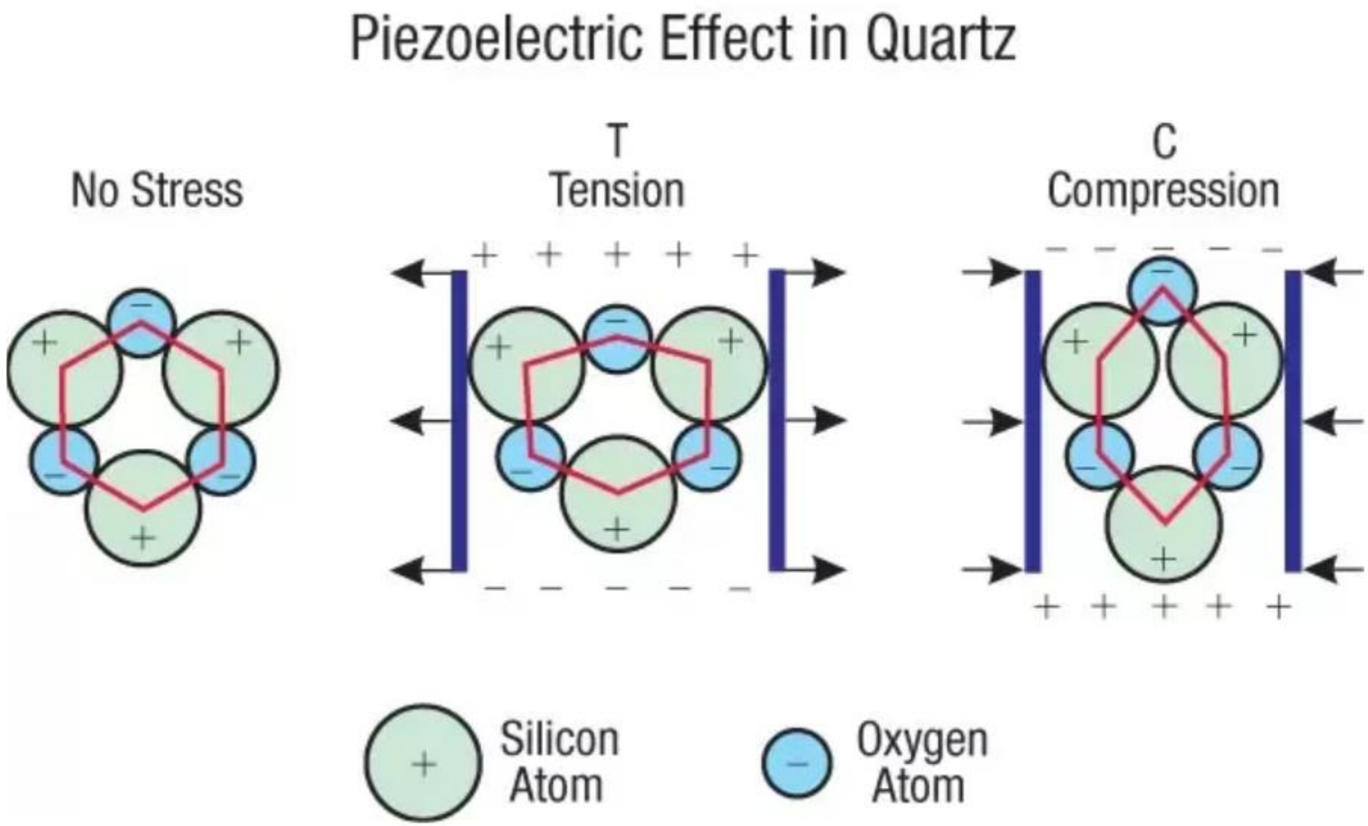
- Conclusion 2
  - When the unit cell is non symmetrical around the center (i.e., non centrosymmetric), the material is piezoelectric

Origin of Piezoelectricity

- A quartz (SiO_2) tetrahedron: a well known piezoelectric material
  - a (real) non centrosymmetric unit cell



- When pressure is applied, a displacement of the positive ion charge towards the center of the negative ion charges occurs
  - outer faces of such a piezoelectric element gets charged



- Piezoelectricity is the generation of an electrical charge as a result of applied mechanical stress. It is caused by relative motion of ions in the crystal structure, changing the dipole moment.

- It <u>cannot occur in centrosymmetric materials</u> since in these materials, there is no way for mechanical stress to generate a dipole moment. Any motion of an ion is reflected by symmetry to an equal and opposite motion that cancels out the dipole moment.

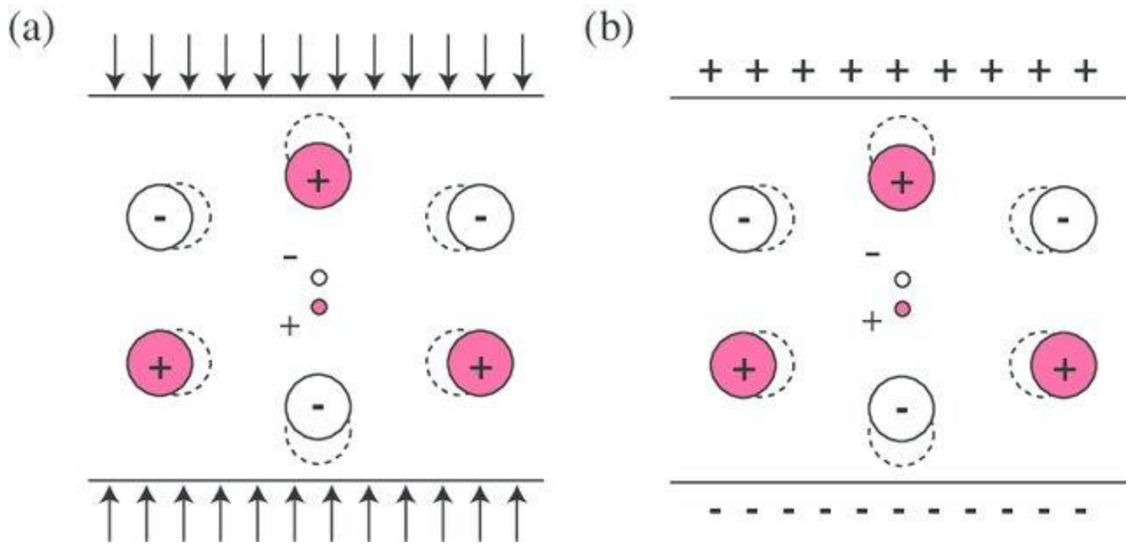
Origin of Piezoelectricity

- ***Two conclusions***

1. When the unit cell is symmetrical around the center (i.e., centrosymmetric), the material is NON piezoelectric
2. When the unit cell is not symmetrical around the center (i.e. non centrosymmetric), the material is piezoelectric

Piezoelectricity

- **Inverse piezoelectric effect**
  - an electric field is applied to a piezoelectric crystal, a mechanical strain is produced in it



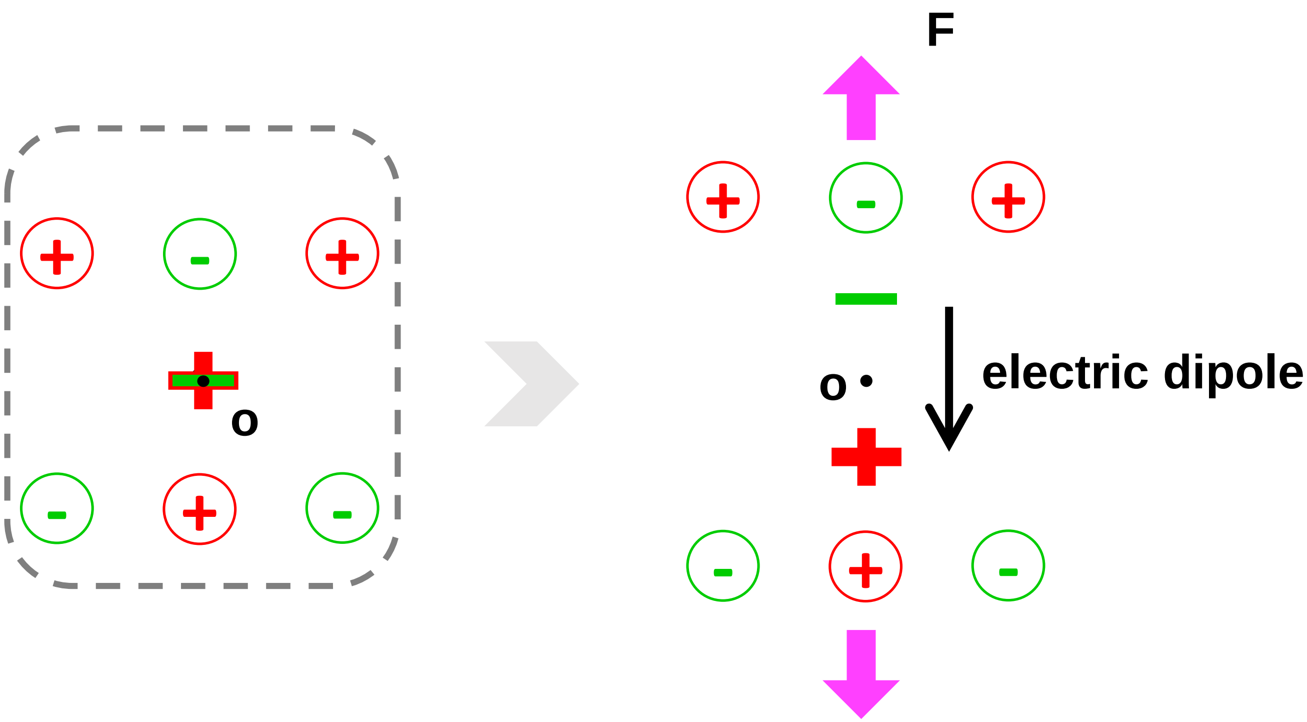
piezoelectric effect **Inverse piezoelectric effect**

Piezoelectric Materials

Category	*Examples*
Naturally occurring single crystals	Quartz Tourmaline Topaz Cane Sugar Rochelle salt (potassium sodium tartrate tetrahydrate, $KNaC_4H_4O_6$, $4H_2O$)
Man-made crystals	Gallium Orthophosphate ($GaPO_4$) Langasite ($La_3Ga_5SiO_{14}$)— both quartz analogous crystals
Man-made polycrystalline ceramic materials	Barium Titanate ($BaTiO_3$) Lead Zirconate Titanate ($Pb[Zr_xTi_{1-x}]O_3$ where $0 < x < 1$)—more commonly known as PZT Lead Titanate ($PbTiO_3$) Potassium Niobate ($KNbO_3$) Lithium Niobate ($LiNbO_3$) Lithium Tantalate ($LiTaO_3$) Sodium Tungstate ($NaWO_3$)
Man-made polymers	PolyVinyliDene Fluoride (PVDF)

Piezoelectricity

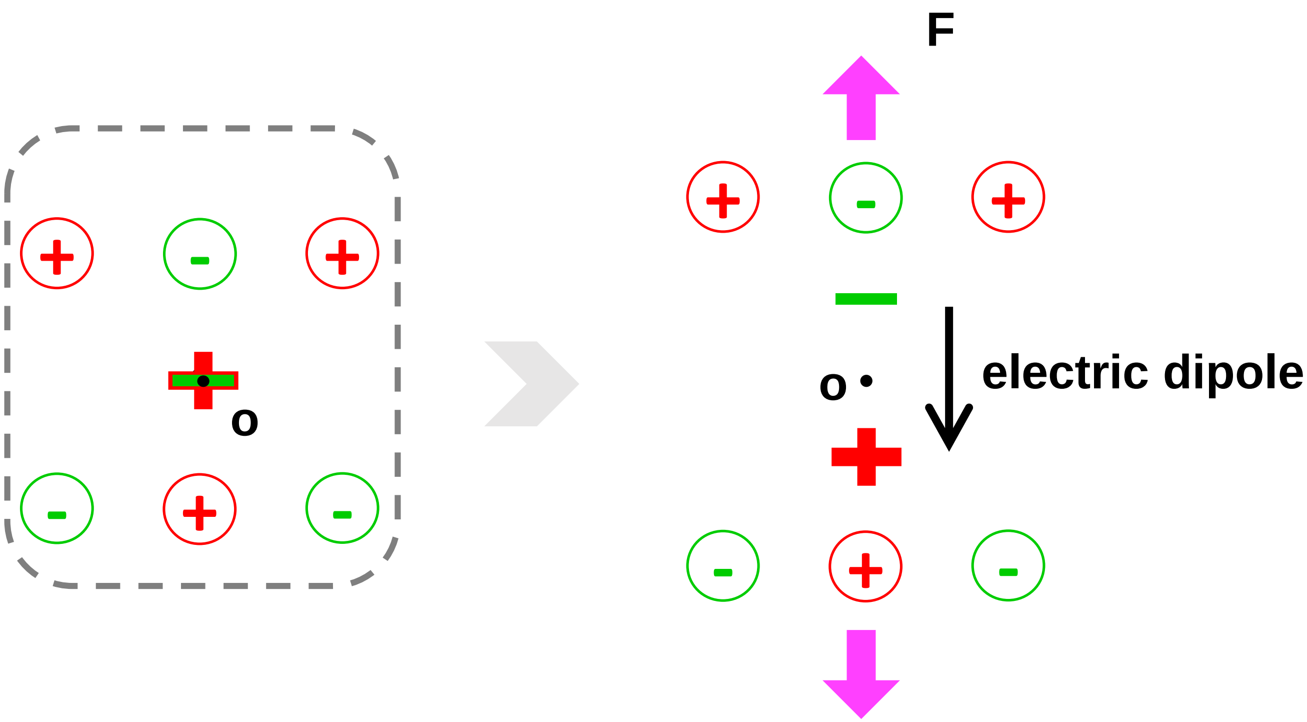
- Non centrosymmetric crystal



- Without stress, there is no electric dipole or polarisation

Piezoelectricity

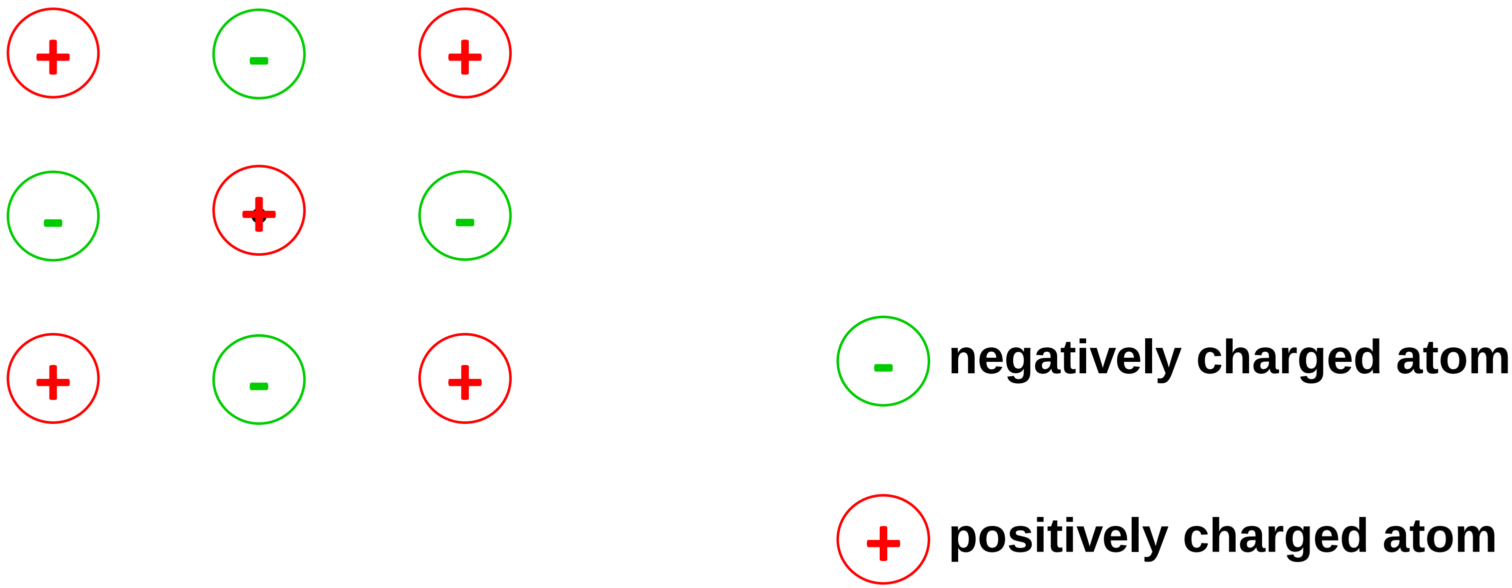
- Non centrosymmetric crystal



- Without stress, there is no electric dipole or polarization
- **Is there any material that has polarization without stress?**
  - **Ferroelectric materials**

Piezoelectricity

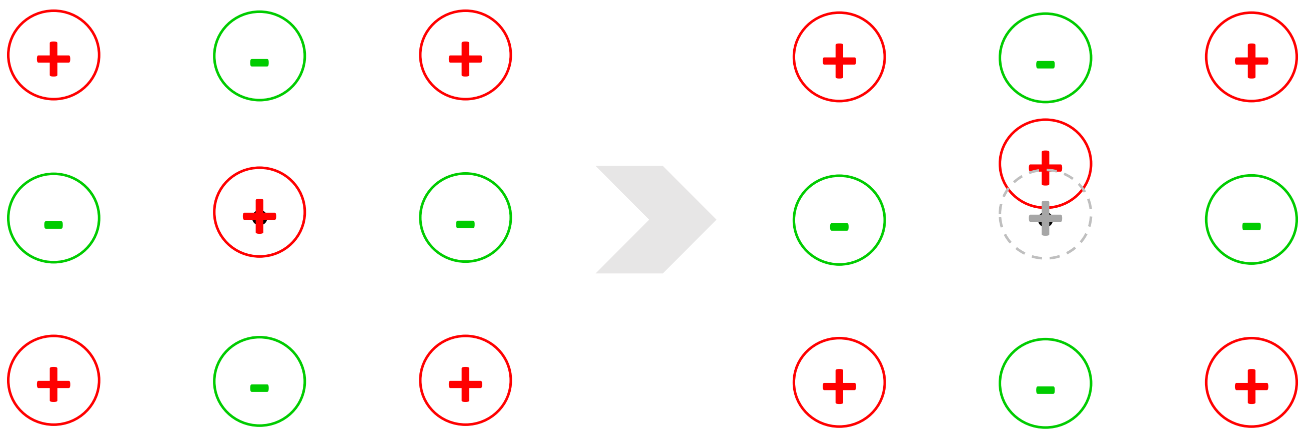
- let us again consider a *fictitious* unit cell



- non-polar as the center of positive charges and negative charges coincide
  - non-piezoelectric

Piezoelectricity

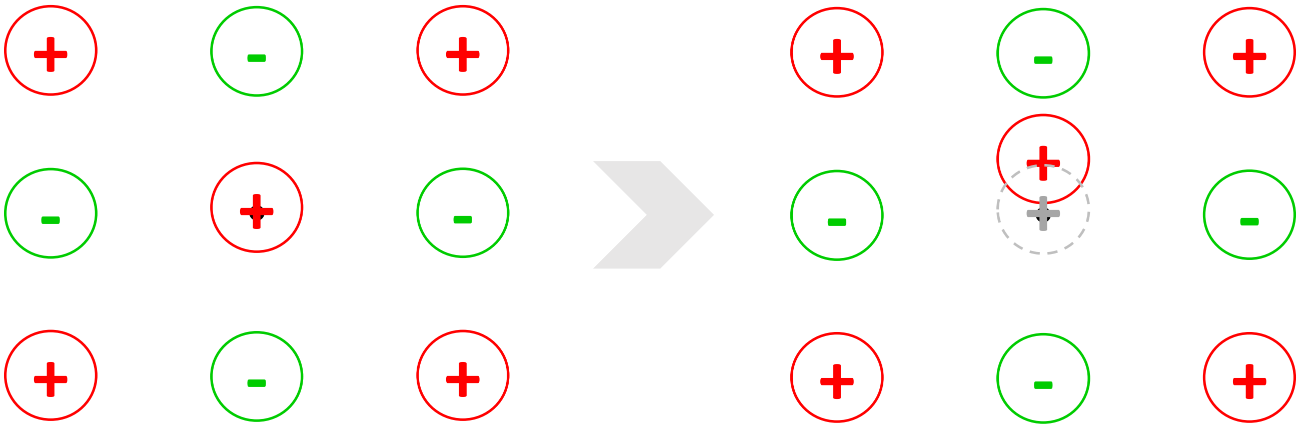
- *fictitious* unit cell



- What if the central positive atom displaces upward due to some thermodynamic reasons?

Piezoelectricity

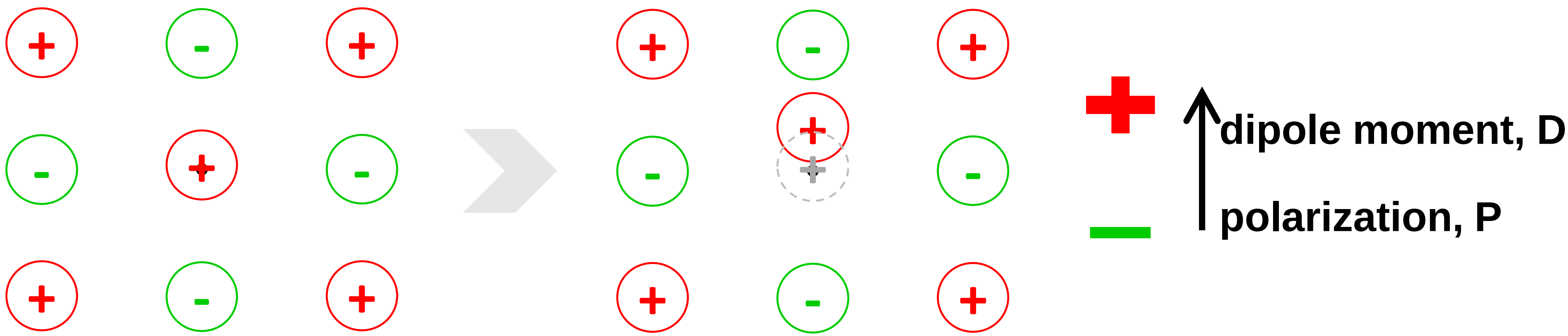
- *fictitious* unit cell



- What if the central positive atom displaces upward due to some thermodynamic reasons?
  - it becomes non centrosymmetric

Piezoelectricity

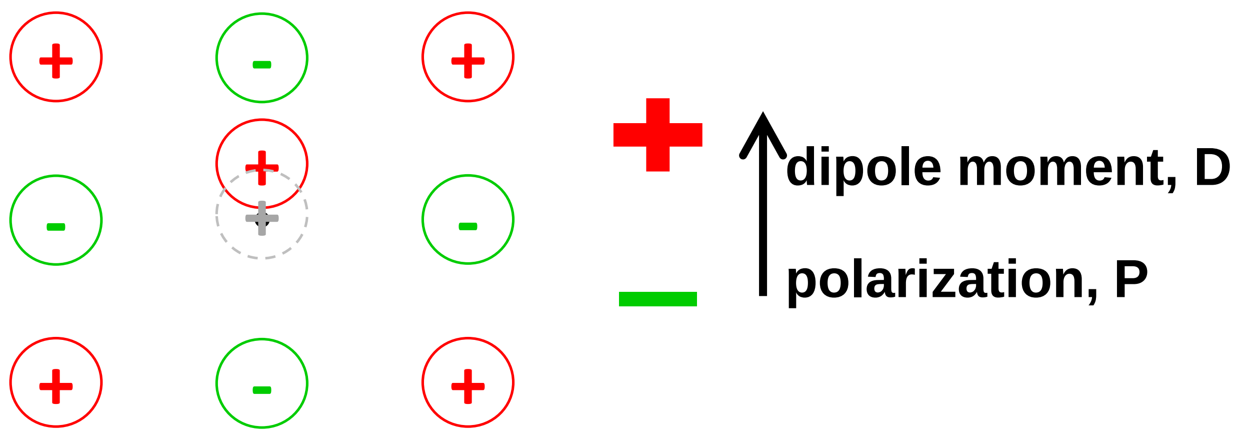
- ***fictitious* unit cell**



- What if the central positive atom displaces upward due to some thermodynamic reasons?
    - upper part gets effectively positively charged and, as a result, the lower part effectively gets negatively charged

Piezoelectricity

- ❑ ***fictitious* unit cell**



- ❑ Non polar material
  - ❑ there is an electric dipole or polarization without strain
  - ❑ known as, spontaneous polarization

Piezoelectric Materials

- ❑ **PZT(lead zirconate titanate (Pb[Zr(x)Ti(1-x)]O3))'s unit cell**

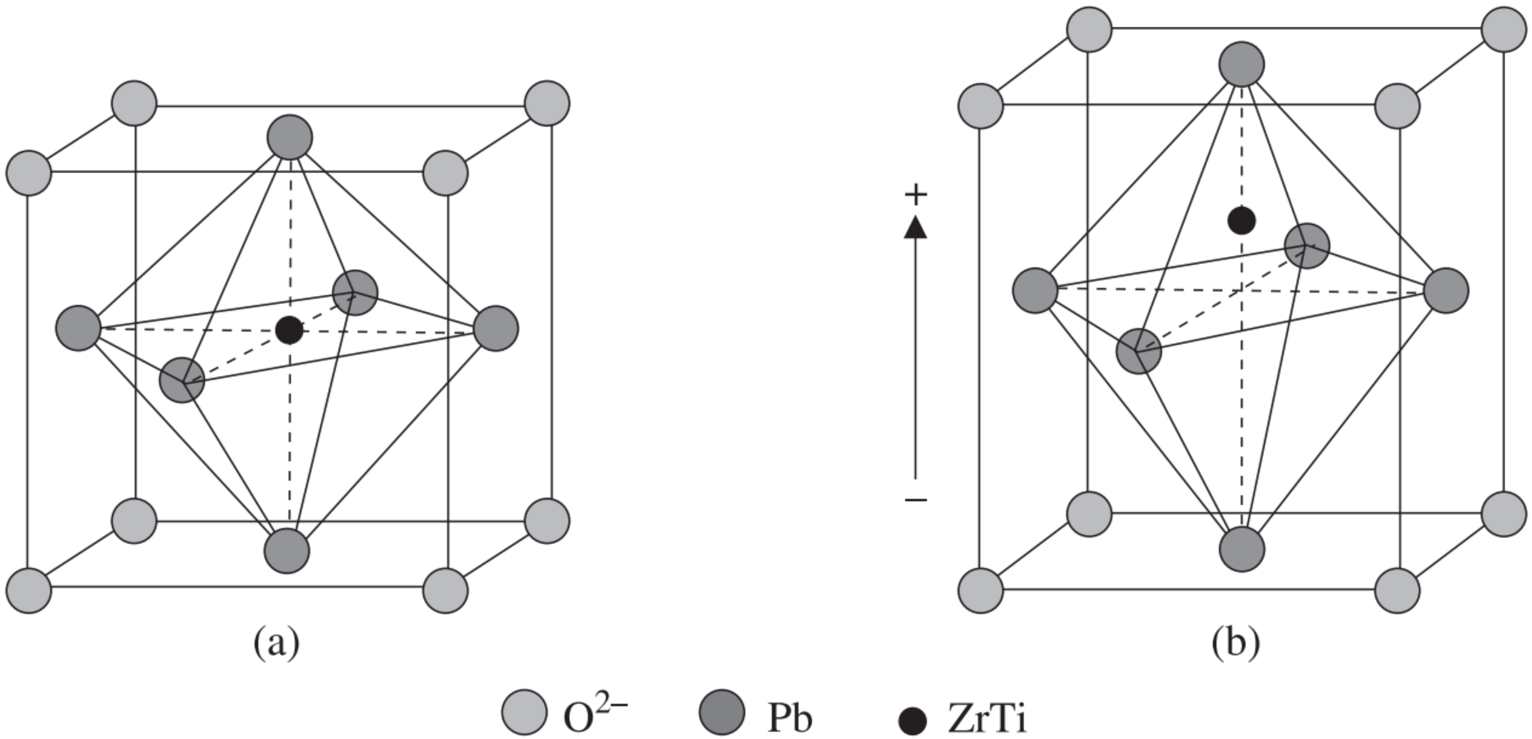


Fig. 5.11 PZT unit cell: (a) Perovskite-type PZT unit cell in the symmetric cubic state above the Curie temperature, and (b) tetragonally distorted unit cell below the Curie temperature.

- ❑ Spontaneous polarization
  - ❑ without stress, there exists a dipole moment, polarization

Piezoelectric Effect (pg 322- Morris & Langari)

When a force is applied to piezoelectric material an output voltage is produced.

When a voltage is applied to piezoelectric material it gets deformed/ produces force.

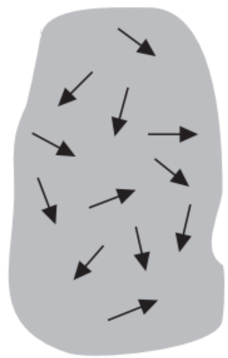
For rectangular block of piezoelectric material, the induced voltage is given by.

$$V = \frac{kFd}{A}$$

k: piezoelectric constant
F: Force, g
d: thickness of material, mm
A: Area of the material, mm^2

Piezoelectric Materials

- **Domains- ferroelectrics**
  - Groups of unit cells with same orientation of the polarization are akin to Weiss domains



- Unpoled: no macroscopic piezoelectric behavior

Piezoelectric Materials

- ❑ **Domains- ferroelectrics**

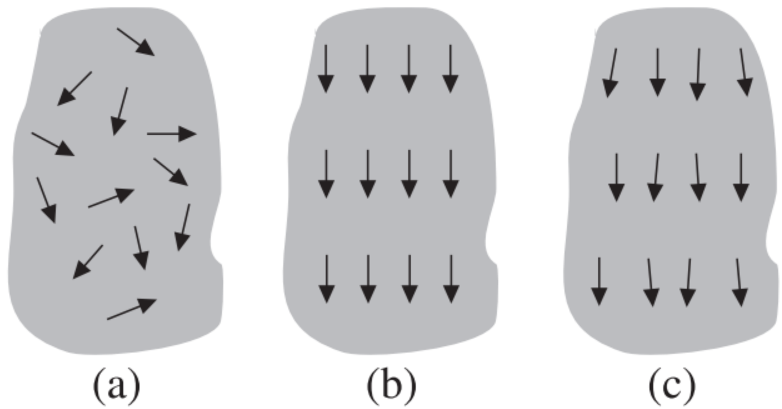
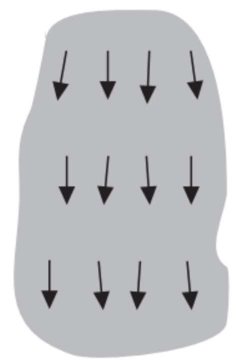


Fig. 5.12 Electric dipoles in domains: (a) unpoled ferroelectric ceramic, (b) during poling and (c) after poling (piezoelectric ceramic).

- ❑ Poling: permanent alignment of the different domains using a strong electric field
  - ❑ Remnant polarization

Piezoelectric Materials

- Polled ferroelectrics
  - Another class of piezoelectric materials

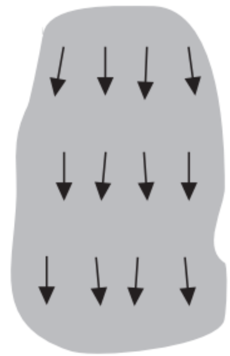


(c)

- direct piezoelectric effect: external force (strain) will change the net polarization
- inverse piezoelectric effect: external electric field will cause a change in the dimension

Piezoelectric Materials

- Polled ferroelectrics
  - Another class of piezoelectric materials

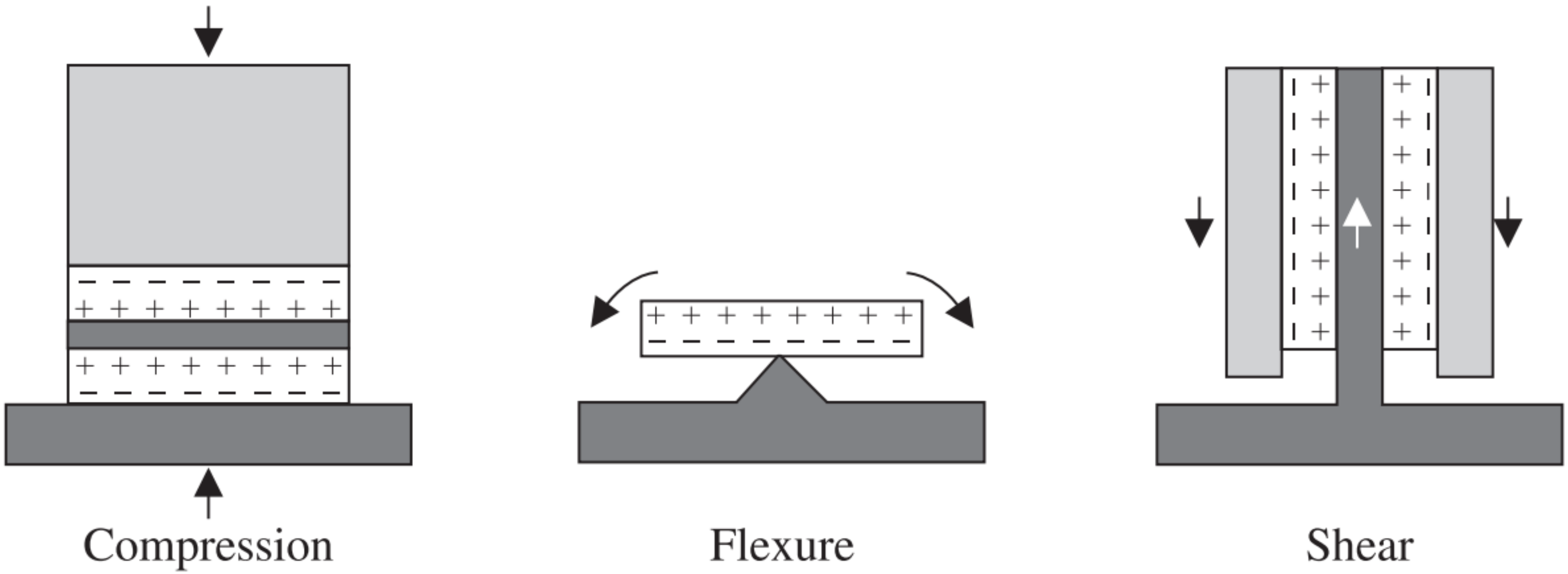


(c)

- direct piezoelectric effect: external force (strain) will change the net polarization
- inverse piezoelectric effect: external electric field will cause the change the dimension

- **How? think about it!**

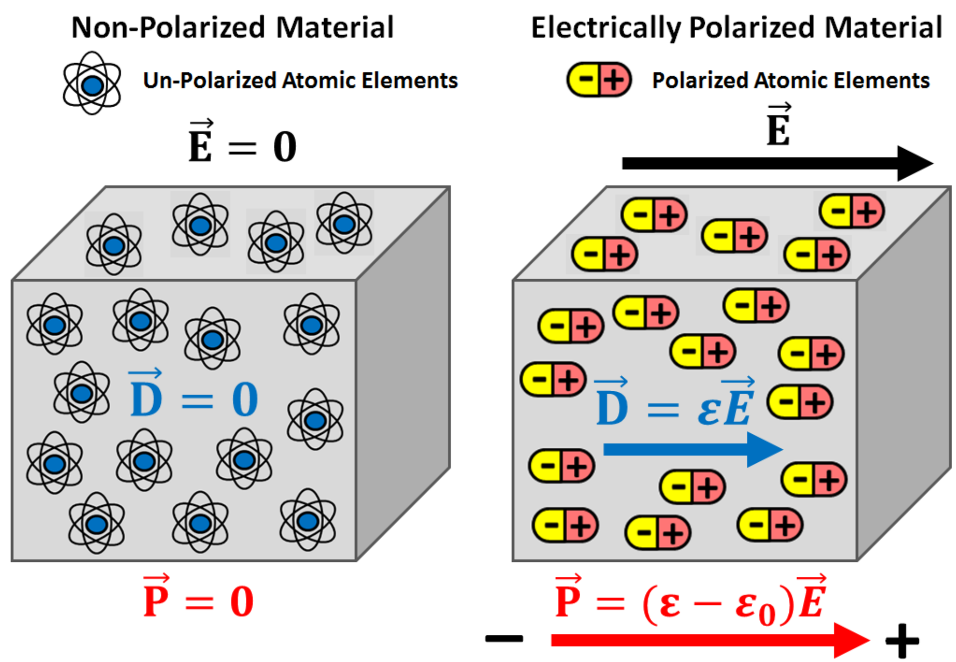
Modes of utilizing piezoelectricity



Configuration	*Advantages*	*Disadvantages*
Compression	High rigidity, making it useful for implementation in high frequency pressure and force sensors	Somewhat sensitive to thermal transients
Flexure	Simplicity of design	Narrow frequency range and low overshock survivability
Shear	Offers a well balanced blend of wide frequency range, low off-axis sensitivity, low sensitivity to base strain and low sensitivity to thermal inputs	Rather complicated design

Piezoelectric effect: useful equations

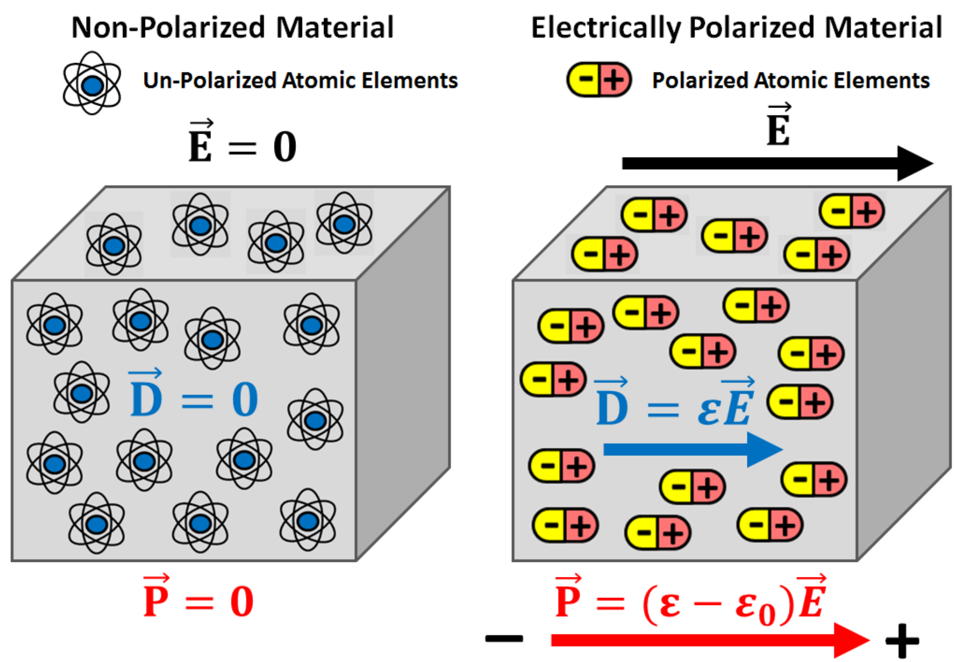
- Electric behavior
- When an electric field E is applied to a dielectric medium of permittivity ε, the bound electrical charges tend to separate
  - material undergoes polarization



Piezoelectric effect: useful equations

- **Electric behavior**
- The dielectric displacement D
  - (measure of the charge displacement, polarization)

$$D = \varepsilon E$$

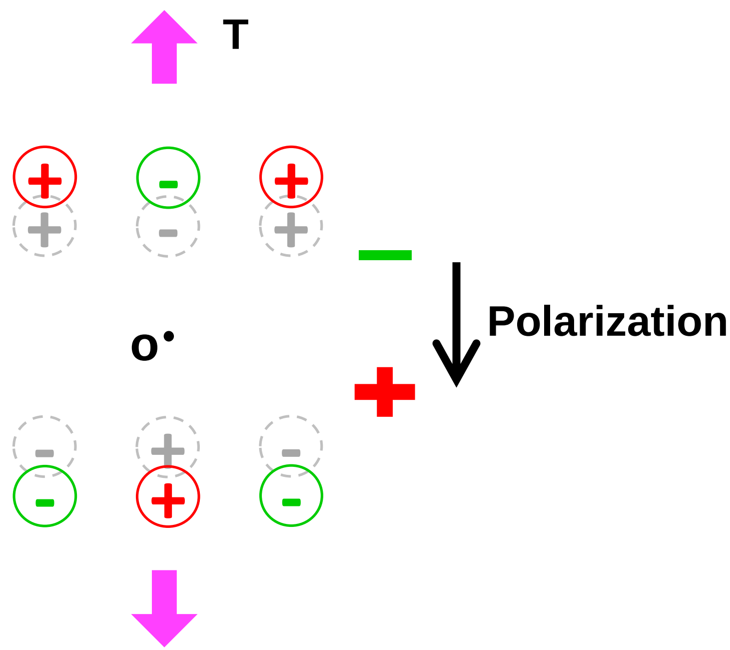


Piezoelectric effect: useful equations

- ❑ for a piezoelectric material, the applied stress T causes a dielectric displacement D (i.e. induces polarization)

$$D = d\,T$$

- ❑ d is piezoelectric coefficient
  - ✓ a measure of sensitivity



Piezoelectric effect: useful equations

Dielectric displacement due to electric field $= \varepsilon E$

Dielectric displacement due to stress $= d\,T$

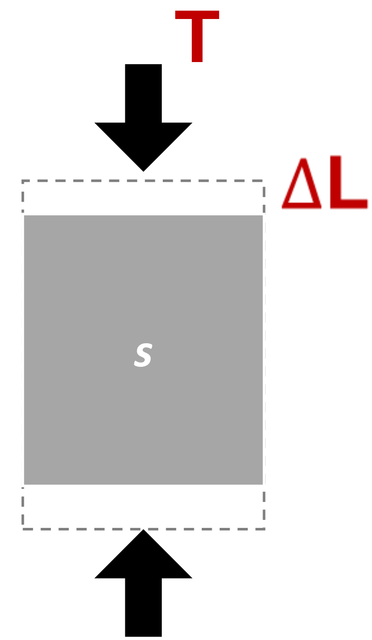
- **For a piezoelectric material, general equation for dielectric displacement D [C/m^2]**

$$D = \varepsilon E + d\,T \quad \text{......................} \quad (1)$$

Piezoelectric effect: useful equations

- **Elastic behavior**
- If T is the applied stress, S is the strain, *s* is the material's compliance.
  - By Hooke's law

$$S = s\,T$$



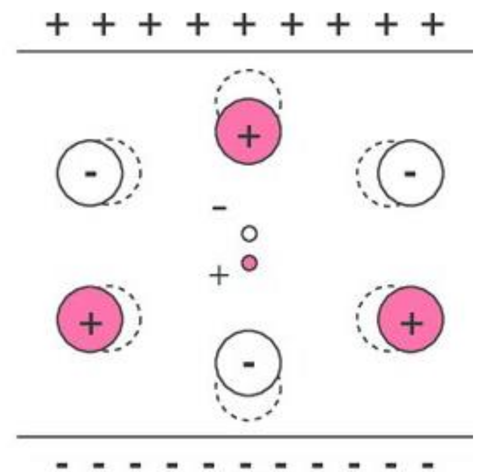
- **compliance *s* is the reciprocal of Young's modulus**

Piezoelectric effect: useful equations

- for a piezoelectric material, the applied stress E also causes a strain S

$$\mathbf{S = d\ E}$$

- d is a piezoelectric coefficient
  - ✓ a measure of sensitivity



Inverse piezoelectric effect

Piezoelectric effect: useful equations

Strain due to electric field $= d\ E$

Strain due to stress $= s\ T$

- **For a piezoelectric material, general equation for strain S**

$$S = d\,E + s\,T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Piezoelectric effect: useful equations

- constitutive equations

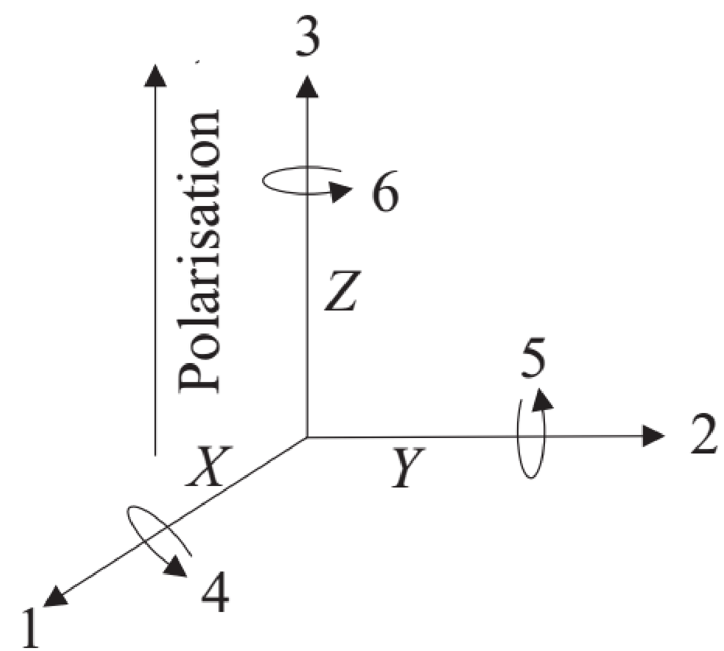
$$\mathbf{D} = \varepsilon\, \mathbf{E} + \mathbf{d}\, \mathbf{T} \quad \text{..................} \quad (1)$$

$$\mathbf{S} = d^{t}\, \mathbf{E} + \mathbf{s}\, \mathbf{T} \quad \text{..................} \quad (2)$$

- d is known as piezoelectric charge coefficient or charge constant
  - ✓ it is a matrix
  - ✓ it is, indeed, transposed (matrix function) in eq. 2.

Piezoelectric Coefficients

- **Piezoelectric effects are dependent on direction**
  - **The axes 4, 5 and 6 identify rotations (shear)**



Piezoelectric Material Characterization

Piezoelectric materials are characterised by d, g, h, e coefficients as well as a coupling parameter k. We will discuss them after we talk about the notations used in defining them.

Apart from the piezoelectric coefficients, piezoelectricity is also affected by

1. Electric properties like permittivity and pyroelectricity[20]
2. Elastic property like the Young's modulus
3. Thermal property like the Curie temperature

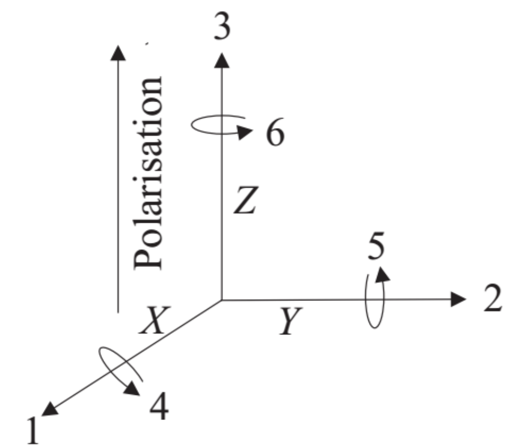
Table 5.8 Significance of superscripts used to specify piezoelectric material constants

Superscript	*Implication*	*Meaning*
T	Stress = constant	Mechanically free
E	Electric field = 0	Short circuited
D	Charge displacement (i.e. current) = 0	Open circuit
S	Strain = constant	Mechanically clamped

Notations

Generally represented as double subscripts

- The first indicated the direction of stimulus and
- Second represents the reaction of the system



For example, d_{33} applies when the electric field is along the polarisation axis (direction 3) and the strain (deflection) is along the same axis. d_{31} applies if the electric field is in the same direction as before, but the deflection of interest is that along axis 1 (perpendicular to the polarisation axis).

In addition, piezoceramic material constants may be written with a *superscript* which specifies either a mechanical or electrical boundary condition. The superscripts are T, E, D and S are explained in Table 5.8.

Piezoelectric effect: useful equations

- constitutive equations

$$\mathbf{D} = \varepsilon\,\mathbf{E} + \mathbf{d}\,\mathbf{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

$$\mathbf{S} = \mathbf{d}^{t}\,\mathbf{E} + \mathbf{s}\,\mathbf{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

- d is known as piezoelectric charge coefficient or charge constant
  - ✓ it is a matrix
  - ✓ it is, indeed, transposed (matrix function) in eq. 2.

Piezoelectric effect

- **Constitutive equations**

D = d T + ε E

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11}^T & \varepsilon_{12}^T & \varepsilon_{13}^T \\ \varepsilon_{21}^T & \varepsilon_{22}^T & \varepsilon_{23}^T \\ \varepsilon_{31}^T & \varepsilon_{32}^T & \varepsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Here T_1, T_2, T_3 denote longitudinal stress in 1, 2 and 3 directions while T_4, T_5, T_6 indicate shear stress along 23, 31, 12 directions as defined earlier.

d_{ij} ; i stands for the electrical quantity and j stands for mechanical quantity

Piezoelectric effect

- **Constitutive equations**

$$\mathbf{D = d\ T + \varepsilon\ E}$$

- for the poled piezoelectric ceramic PZT,

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11}^T & 0 & 0 \\ 0 & \varepsilon_{22}^T & 0 \\ 0 & 0 & \varepsilon_{33}^T \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Piezoelectric coefficients

***d* coefficient.** The piezoelectric charge coefficient (aka *charge constant*), d_{ij}, is defined as follows:

Direct effect

$$d_{ij} = \left.\frac{\text{Charge density developed in } i\text{-direction}}{\text{Applied stress in } j\text{-direction}}\right|_{E=0} \text{C/N} \qquad \left[\text{from } \frac{\text{C/m}^2}{\text{N/m}^2}\right] \tag{5.20}$$

Inverse effect

$$d_{ij} = \left.\frac{\text{Developed strain in } j\text{-direction}}{\text{Applied electric field in } i\text{-direction}}\right|_{T=\text{const.}} \text{m/V} \qquad \left[\text{from } \frac{\text{m/m}}{\text{V/m}}\right] \tag{5.21}$$

Note: The directions i and j are inverted in the inverse effect—the j-direction is in the numerator in this case.

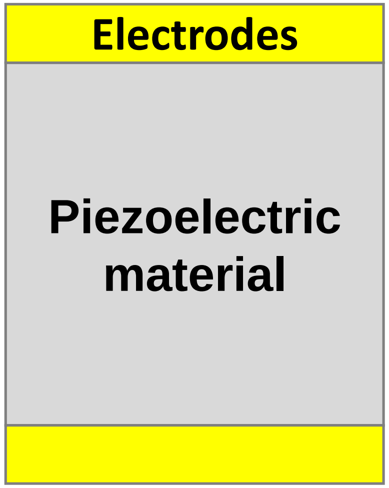
$$d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_j}{\partial E_i}\right)^T$$

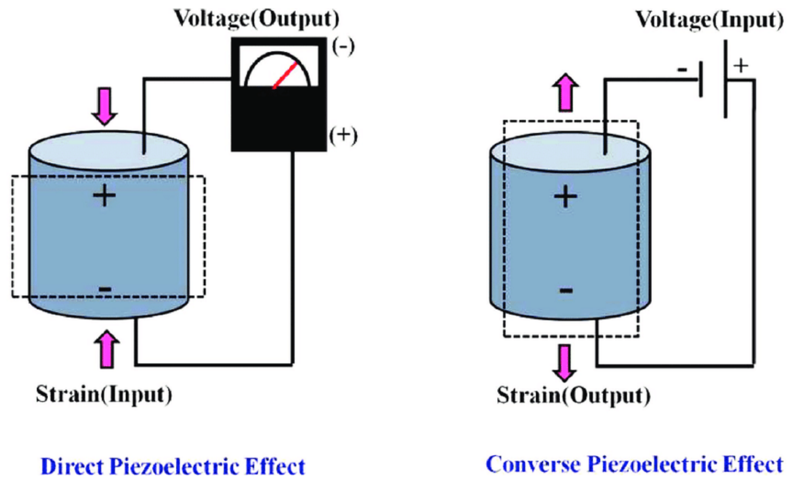
Piezoelectric coefficients

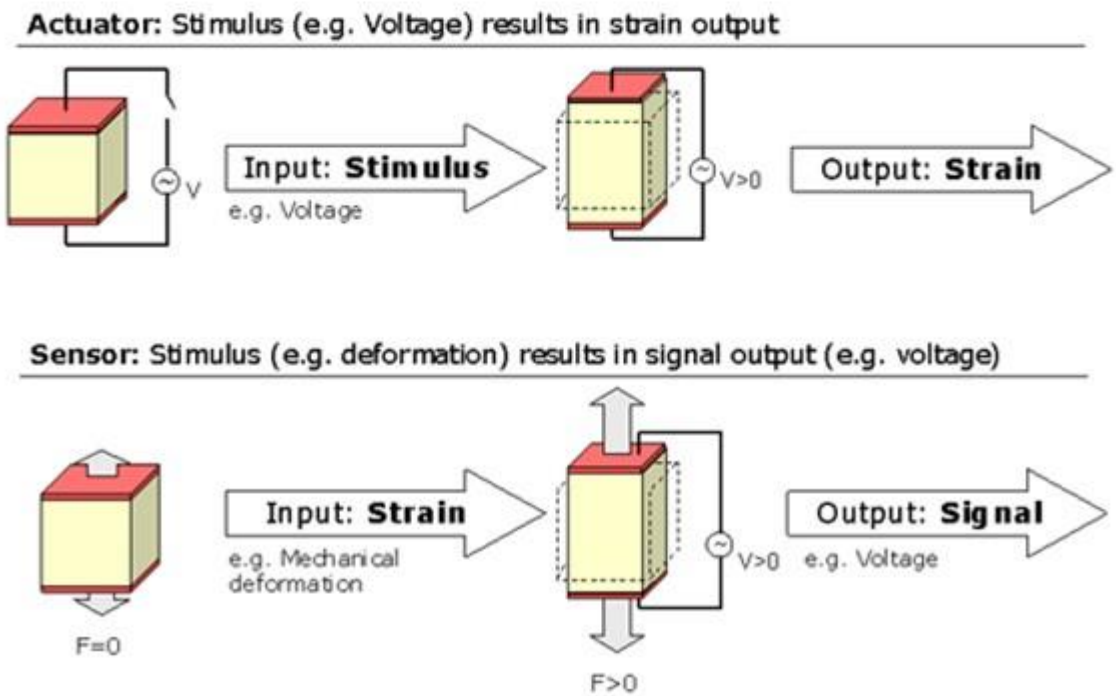
Table 5.9 Useful data of piezoelectric materials

Material	*d* (C/N) $\times 10^{-12}$	ε_r	*Young's modulus* (N/m) $\times 10^{9}$	*Max. Temp.* (°C)	*Humidity* range (%)
Quartz	2.3	4.5	80	550	0–100
Tourmaline	1.9	6.6	160	1000	0–100
Rochelle salt	550	350	19	45	40–70
Lithium sulphate	13.5	10.3	46	75	0–95
Ammonium dihydrogen phosphate	48	15.3	19.3	125	0–94
PZT	356	1750	59	285	
Barium titanate	150	1412	86	100	

Piezoelectric devices





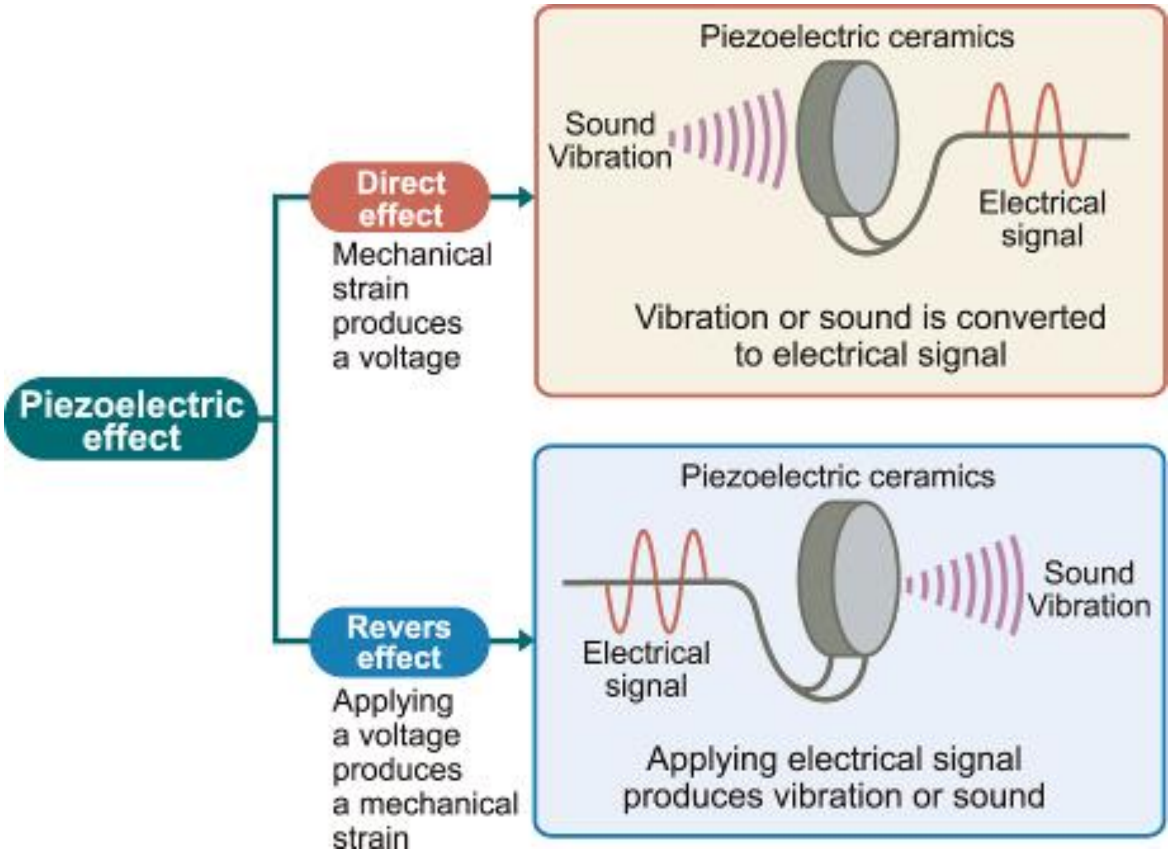


Piezoelectric effect

- for sensing applications, direct piezoelectric effect
- for actuation applications, inverse piezoelectric effect

Piezoelectric Transducers

- **Application**
  - Ultrasonic transmitters and receivers



Piezoelectric Transducers

❑ Application

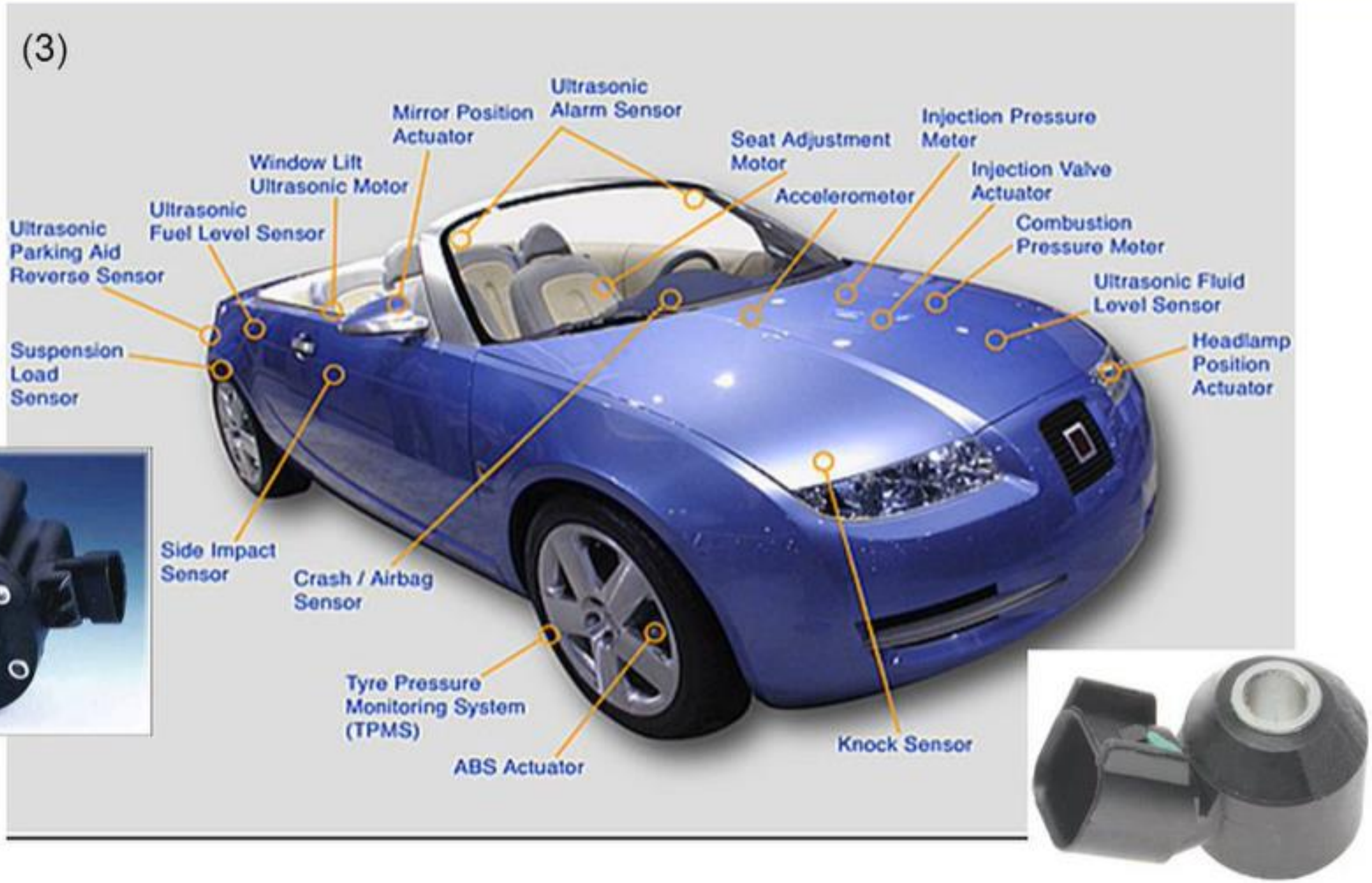
The piezo materials are available in a variety of shapes and sizes such as discs, plates, bars, rings, rods, tubes, etc. Some of their typical applications as transducers are as follows:

1. Vibration and shock measurement
2. Accelerometers
3. Ultrasound flow meters
4. Dynamic force and pressure measurement
5. NDT (non-destructive testing) transducers[23]

Other applications include

1. Stable oscillation frequency generators
2. High voltage generators tor gas lighters
3. Fuses for explosives
4. Nebulisers
5. SONAR
6. Deepwater hydrophones[24]
7. Actuators/translators
8. Ultrasonic cleaners, welders

Piezoelectric effects



Physical Phenomenon for Transducers

Working of transducers are based on the following physical phenomenon.

1- Magnetic effects

2- Piezoelectricity

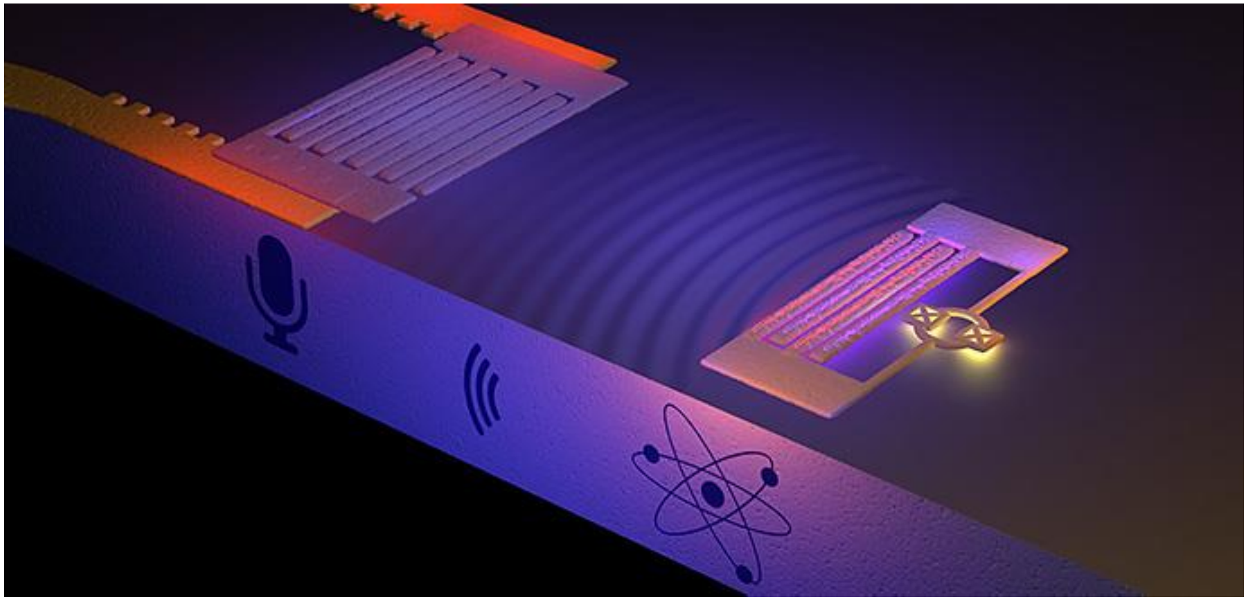
3- Piezoresistivity

4- Surface acoustic wave

5- Optical effects

Surface Acoustic Waves (SAW)

- An acoustic wave is a type of mechanical wave where pressure variation propagates through a material.
- Mechanical waves that once created on the surface of a piezoelectric material travel along it's surface



The wave has a velocity that is nearly 5 orders of magnitude less than the corresponding electromagnetic wave, making Rayleigh surface waves among the slowest to propagate in solids. The wave amplitudes are typically around 10 Å and the wavelengths range from 1–100 μm.

Surface Acoustic Waves (SAW)

- **SAW device/sensor design**

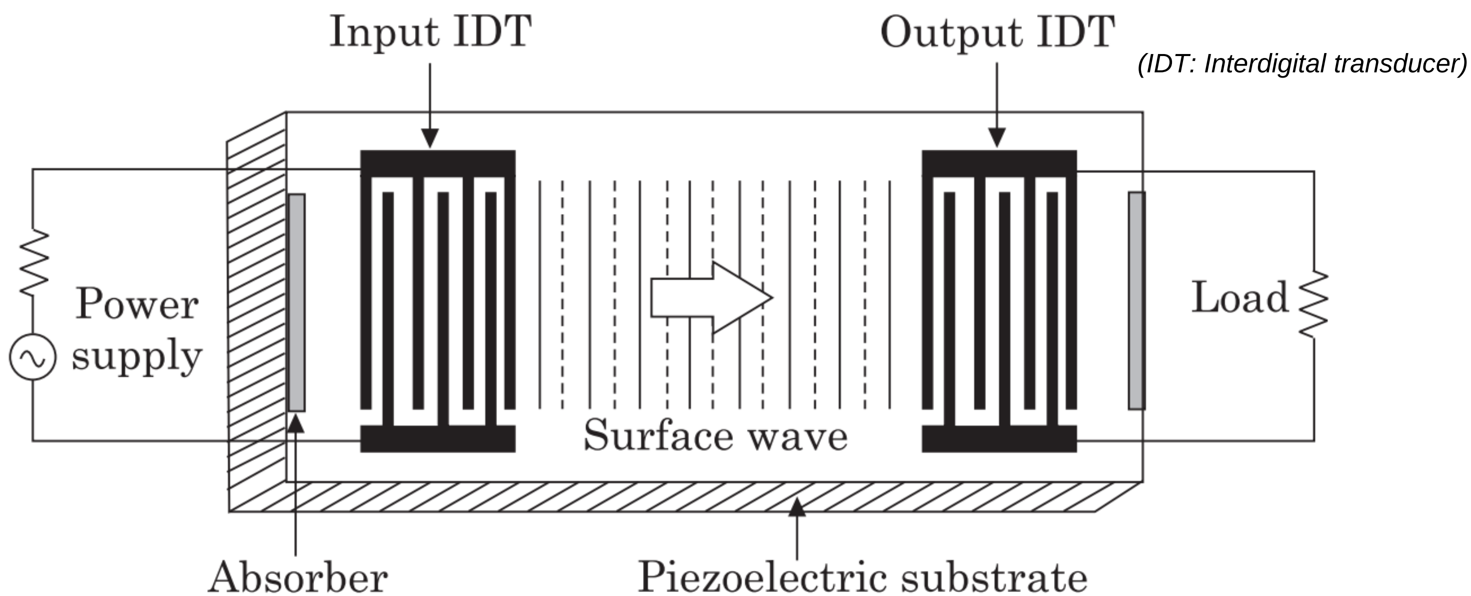
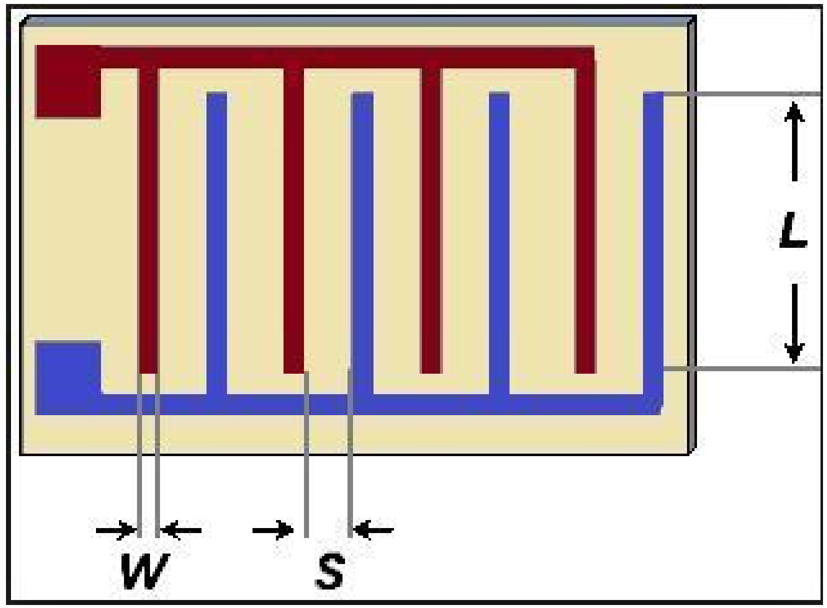


Fig. 5.26 Diagram of a surface acoustic wave sensor.

- **Fabrication**
  - **Photolithographic process**

Among the piezoelectric materials chosen for the substrate, the most common are quartz (SiO_2), lithium tantalate ($LiTaO_3$), and, sometimes, lithium niobate ($LiNbO_3$).

Surface Acoustic Waves (SAW)



- Interdigital electrodes

Surface Acoustic Waves (SAW)

- **SAW device/sensor design**

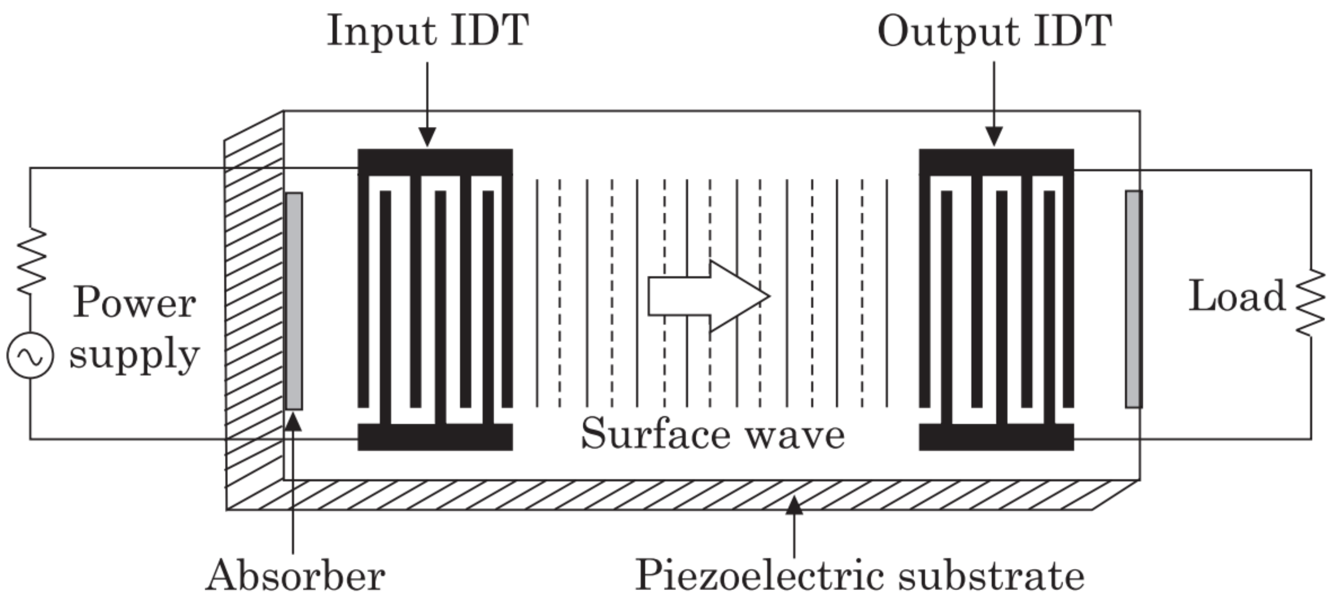


Fig. 5.26 Diagram of a surface acoustic wave sensor.

- at input, the applied electric field generates the SAW waves due to inverse piezoelectric effect
- at output, the SAW are converted to voltage due to direct piezoelectric effect

Surface Acoustic Waves (SAW)

- **SAW device/sensor design**

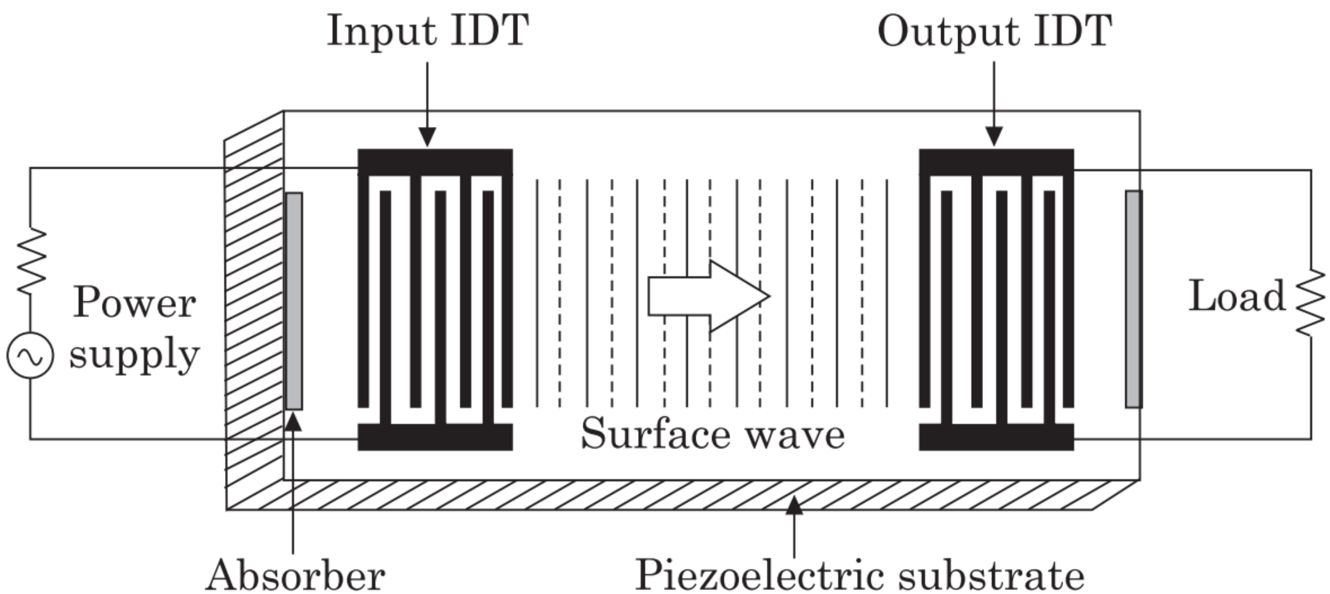


Fig. 5.26 Diagram of a surface acoustic wave sensor.

- **Sensing mechanism**
  - SAW wave propagation and, so the output, is influenced by the medium/substance on top of the SAW device

Surface Acoustic Waves (SAW)

- **Applications**

- *Pressure, torque, shock, and force detectors* under an applied stress that changes the dynamics of the propagating medium.
- *Mass, or gravimetric, sensors* when particles are allowed to come in contact with the propagation medium thus changing the stress on it.
- *Vapour sensors* when a coating is applied that absorbs only specific chemical vapours and changes the mass of the coating.
- *Biosensors*, if the coating absorbs specific vapours of biological fluids.

Physical Phenomenon for Transducers

Working of transducers are based on the following physical phenomenon.

1- Magnetic effects

2- Piezoelectricity

3- Piezoresistivity

4- Surface acoustic wave

5- Optical effects

Optical Effects

- **Light detection/measurement**

Optical Effects

- **Optical detectors**

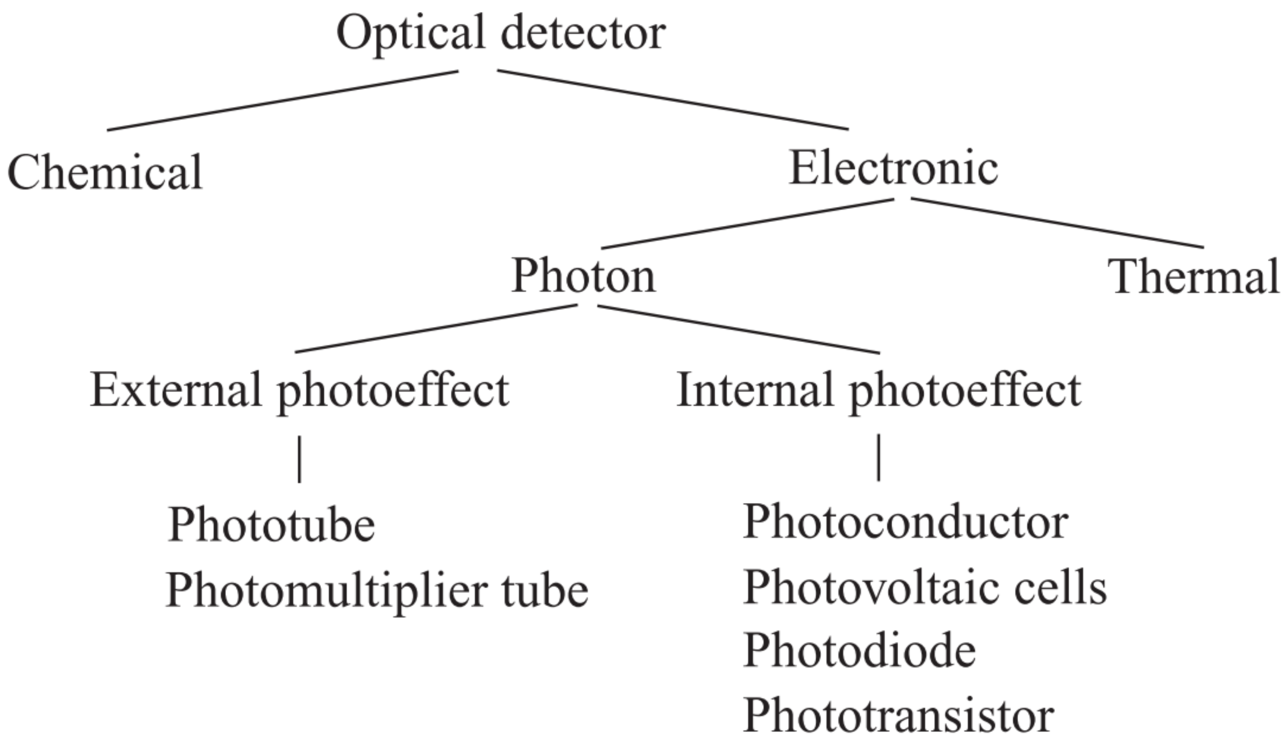


Fig. 5.27 Optical detectors tree.

Optical Effects

- **Chemical**
  - do not give a signal output as do the other types
  - e.g., photographic film, photopolymers

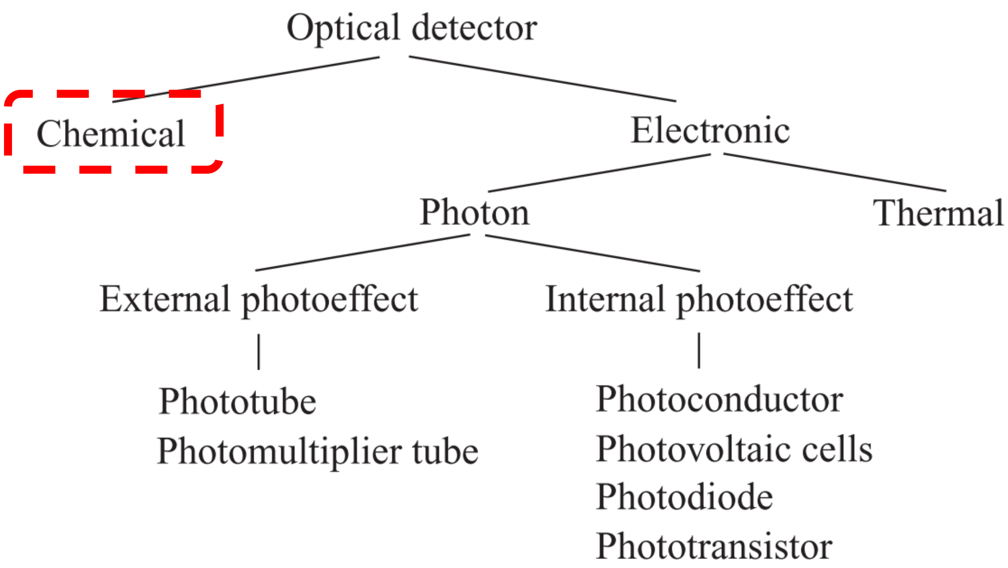
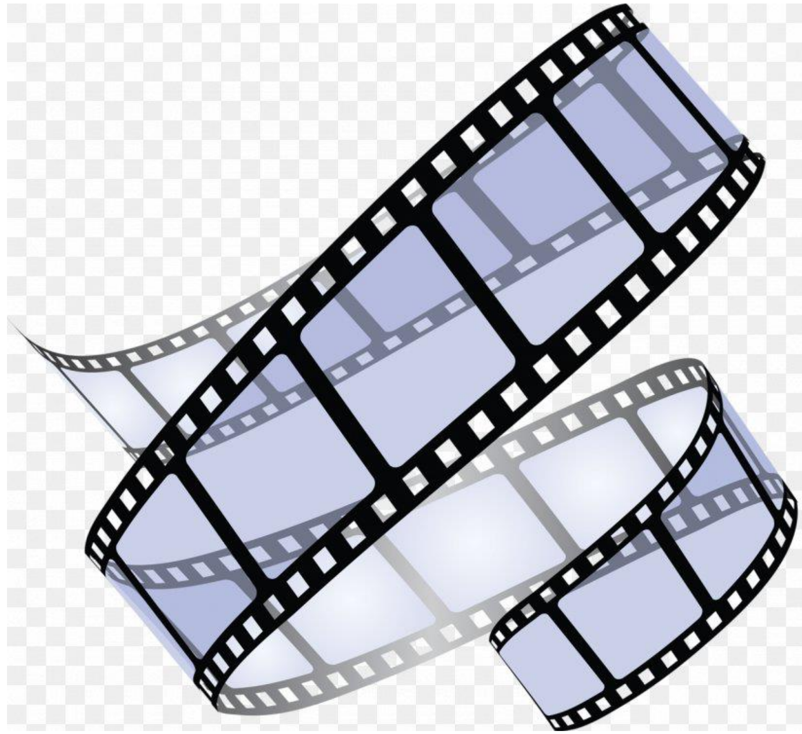


Fig. 5.27 Optical detectors tree.



Photographic film

Optical Effects

- Thermal detectors
  - the absorption of light raises the temperature of the device and this, in turn, results in changes in some temperature-dependent parameter (e.g. electrical conductivity)
  - Thermocouple, Pyroelectric detectors

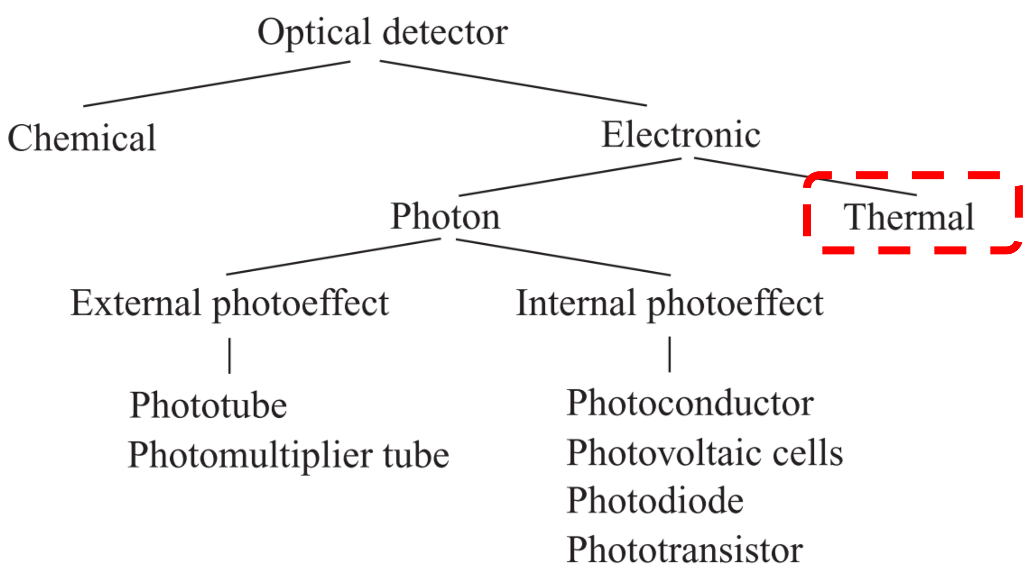
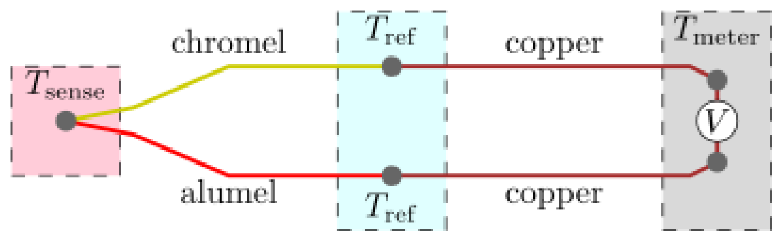


Fig. 5.27 Optical detectors tree.



Thermocouple

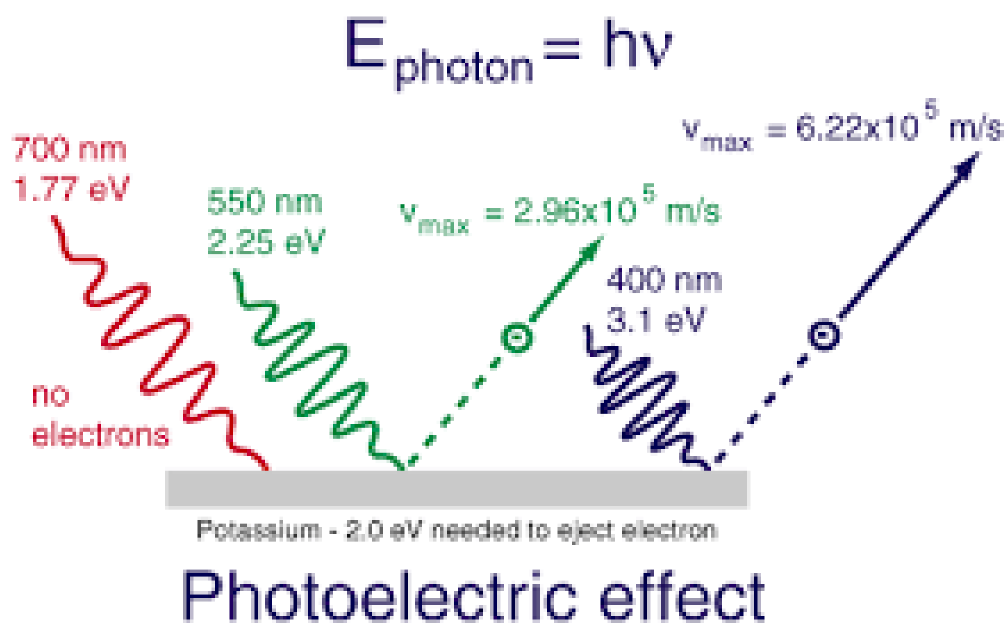
Concepts Checks

What is Photon?

A photon is a piece of energy
has no mass
moves at the speed of light
acts like a particle
has momentum
The energy of a photon is quantized

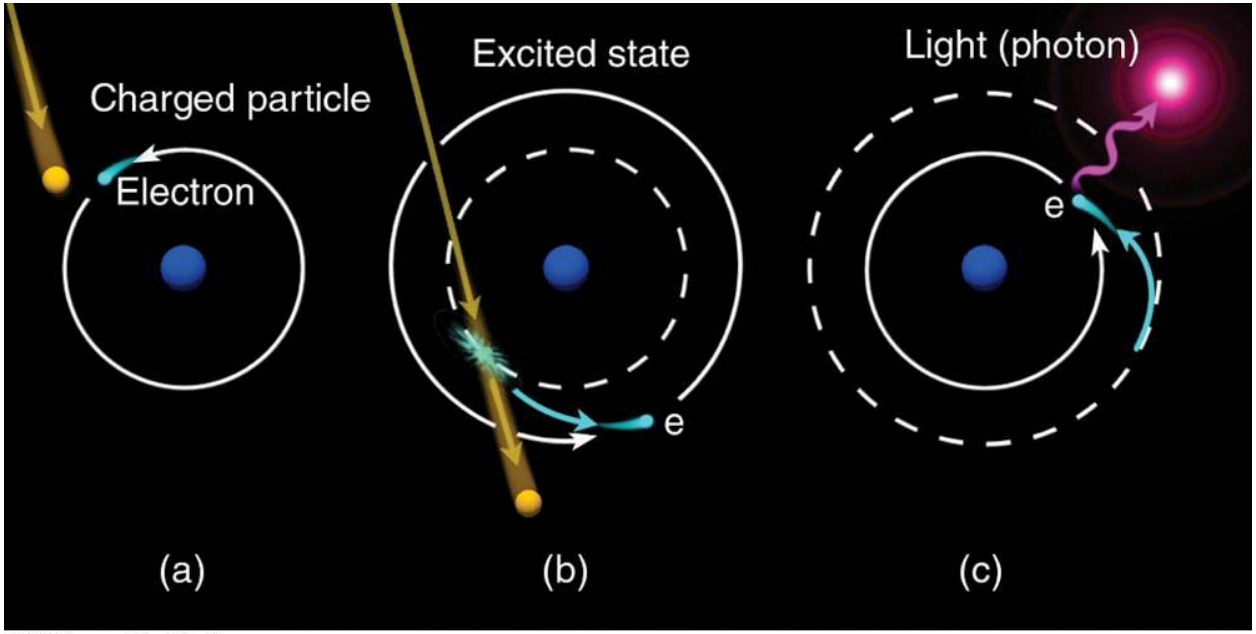
Photoelectric Effect?

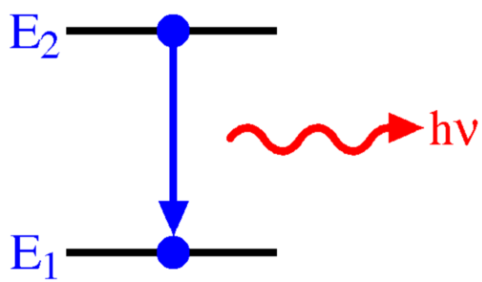
- It is the emission of electrons when electromagnetic radiation, such as light (photons) hits a material. Electrons emitted in this manner are called photoelectrons.



What are Photons?

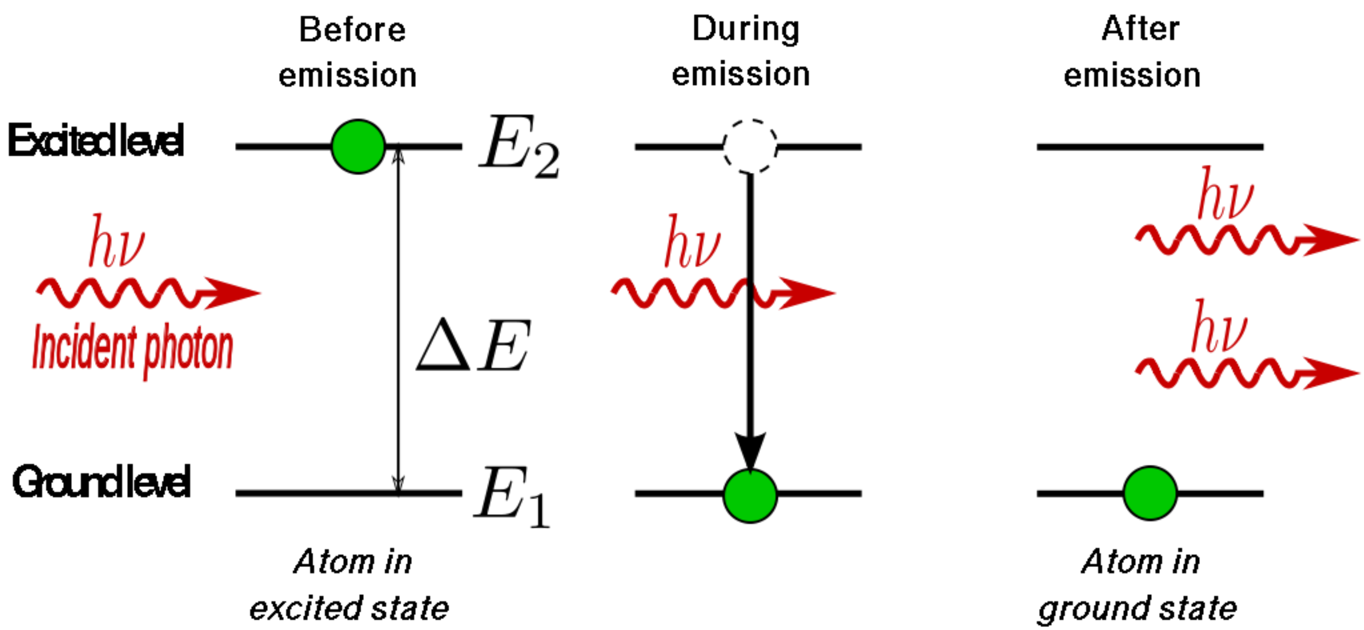
- A **photon** is a tiny elementary particle that comprises waves of electromagnetic radiation.
- **Photons** have no charge, no resting mass, and travel at the speed of light.
- Einstein believed light is a **particle** (**photon**) and the flow of **photons** is a **wave**.





Wikipedia

What are Photons?



$$E_2 - E_1 = \Delta E = h\nu$$

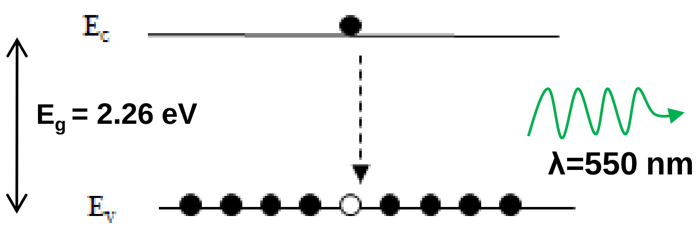
Photon Frequency?

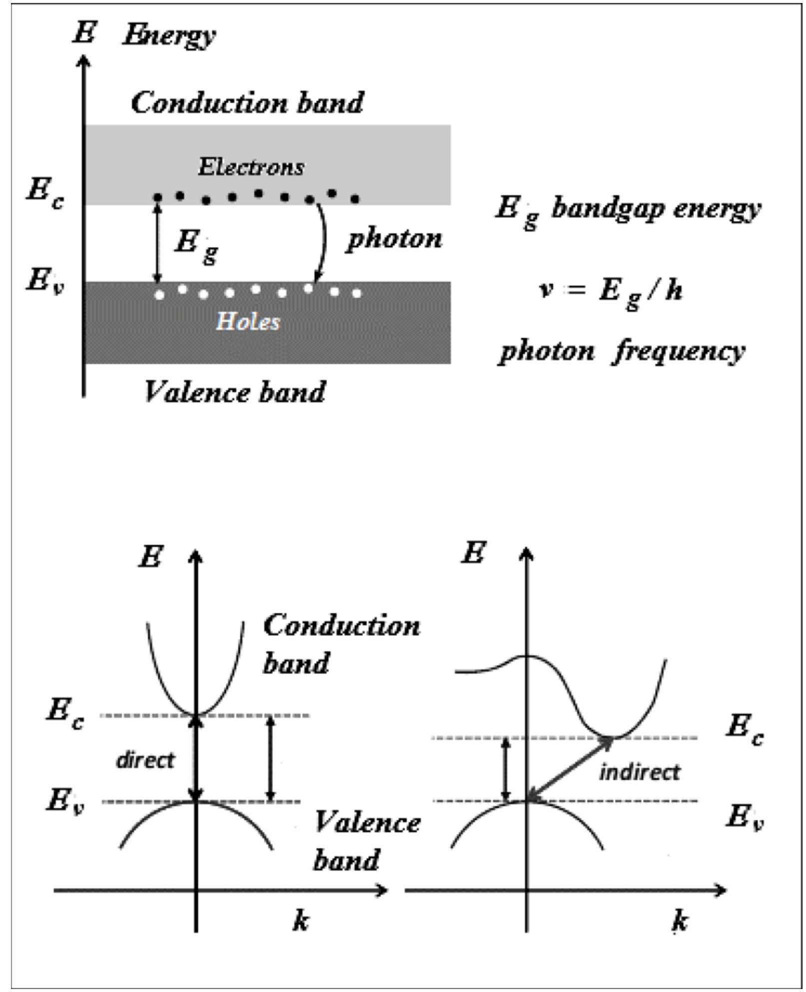
GaP, a material commonly used for green LEDs, has an intrinsic band gap of 2.26 eV. Carrier recombination across the gap results in the emission of 550 nm light.

$$E = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{E}$$

$$\lambda = \frac{(4.136 * 10^{-15}\ \mathrm{eV \cdot s})(2.998 * 10^{8}\ \mathrm{m/s})}{2.26\ \mathrm{eV}}$$

$$\lambda \cong 550\ \mathrm{nm}$$





Optical Effects

- **Photon detectors:**
  - Photoeffect
    - External photoeffect
    - Internal photoeffect

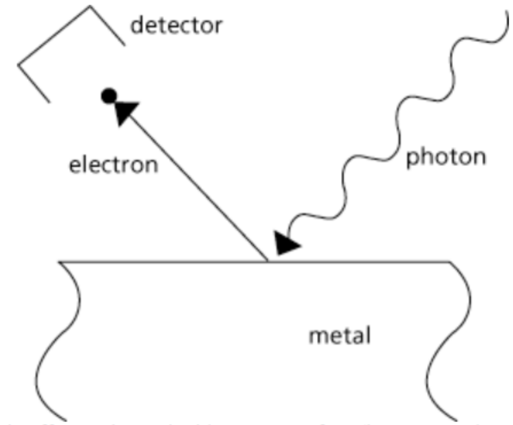


Figure 1. In the photoelectric effect a photon incident on a surface (here, a metal surface in vacuum) transfers its energy to an electron, which leaves the surface and is detected. The photoelectric effect demonstrates the particle nature of light.

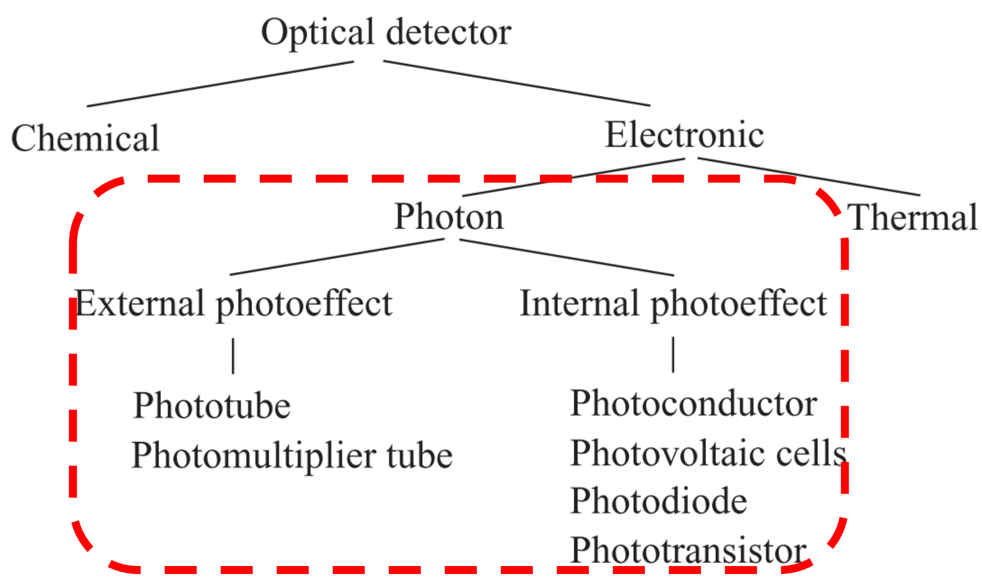


Fig. 5.27 Optical detectors tree.

External Photoeffect: Photoemission

- **Photoelectric effect or Photoemissive effect**
  - When irradiated by electromagnetic radiation of very short wavelength, such as visible or ultraviolet light, electrons are emitted from the matter

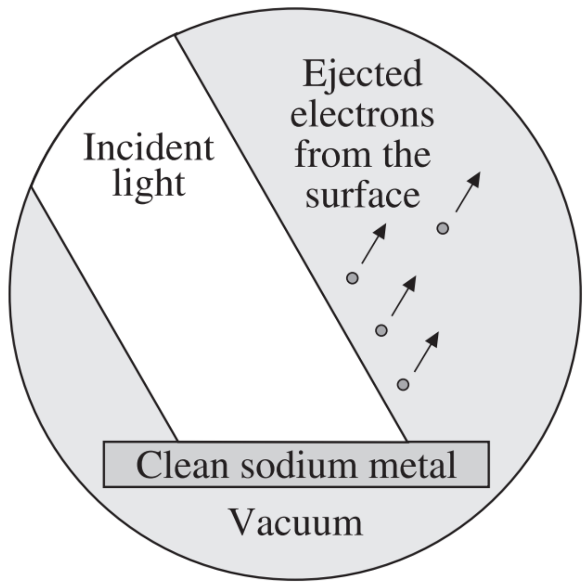
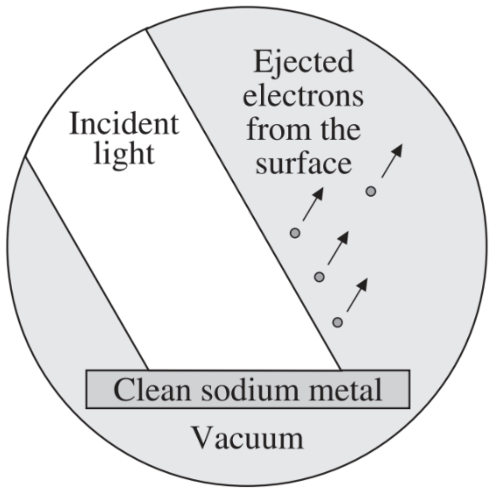


Fig. 5.28 Schematic diagram showing emission of photoelectrons.

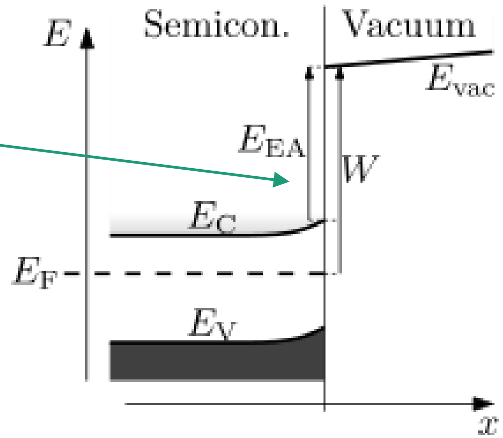
External Photoeffect: photoemission

- Photoelectric effect or photoemissive effect



$$E_{\text{max}} = h\nu - \varphi$$

- Max kinetic energy of photoelectron (Einstein equation)
  - φ is the work function: energy consumed by the electron to escape the material
  - *h* is plank's constant and *v* the frequency
  - The incoming radiation should be thought of as quanta of energy *hv*



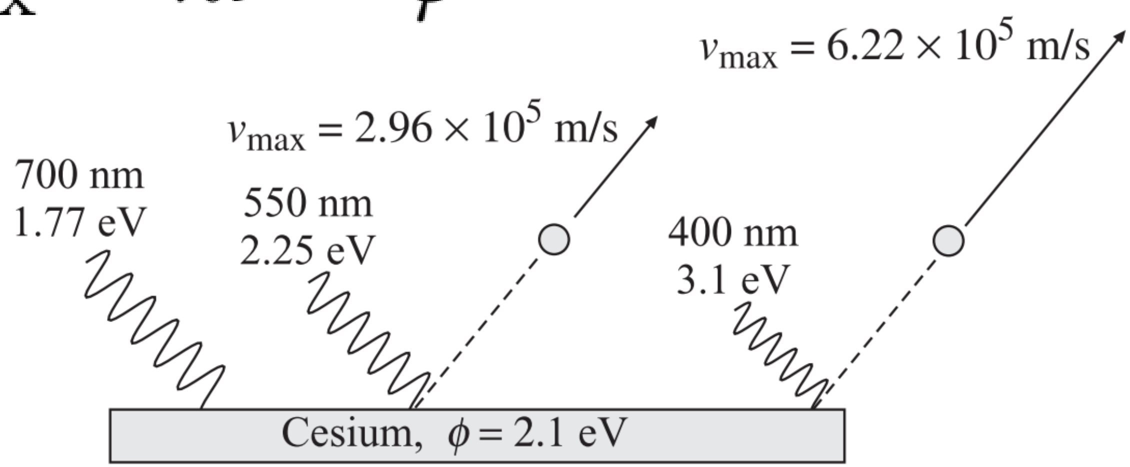
*DOI: 10.1039/C5MH00160A (Focus) Mater. Horiz., 2016, **3**, 7-10*

External Photoeffect: photoemission

Observations. The remarkable aspects of the photoelectric effect are:

1. The electrons are emitted immediately. There is no time lag between the irradiation of the substance and the ejection of electrons from it.
2. If the intensity of the light is increased, the number of photoelectrons also increases, but not their maximum kinetic energy.
3. An impinging red light ($\lambda = 700$ nm) will not cause the ejection of electrons, no matter whatever its intensity is. A green ($\lambda = 550$ nm) or violet ($\lambda = 400$ nm) light will eject electrons. But their maximum velocities are greater the shorter the wavelength (Fig. 5.29).

$$E_{\mathrm{max}} = h\nu - \varphi$$



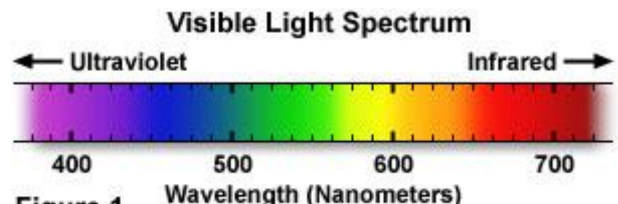


Figure 1

External Photoeffect: photoemission

- **Photoemissive materials**

Table 5.12 Work functions and threshold wavelengths for a few common elements

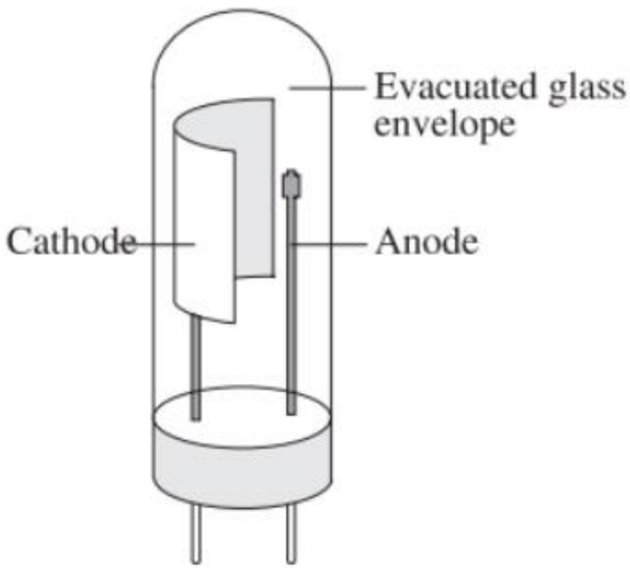
Element	φ (eV)	λ_0 (μm)	*Element*	φ (eV)	λ_0 (μm)
Aluminum	4.08	0.3025	Magnesium	3.68	0.3354
Beryllium	5.0	0.2468	Mercury	4.5	0.2742
Cadmium	4.07	0.3032	Nickel	5.01	0.2463
Calcium	2.9	0.4256	Niobium	4.3	0.2870
Carbon	4.81	0.2566	Potassium	2.3	0.5366
Cesium	2.1	0.5877	Platinum	6.35	0.1943
Cobalt	5.0	0.2468	Selenium	5.11	0.2415
Copper	4.7	0.2626	Silver	4.73	0.2609
Gold	5.1	0.2420	Sodium	2.28	0.5413
Iron	4.5	0.2742	Uranium	3.6	0.3428
Lead	4.14	0.2981	Zinc	4.3	0.2870

External Photoeffect: photoemission

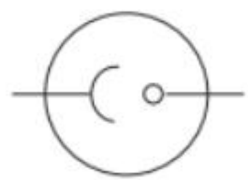
- **Photoemissive transducers**
  - Phototube
  - Photomultiplier tube

Phototube

- An electric current proportional to the photon flux incident on the cathode
  - Vacuum tube
  - Incident light causes cathode to emit electrons
  - under external voltage, electrons are collected at anode to make a current



(a)



(b)

The *quantum yield* K_λ is defined as

$$K_\lambda = \frac{\text{Number of electrons released}}{\text{Number of photons absorbed}}$$

Fig. 5.30 (a) Schematic diagram of a phototube, (b) symbolic representation of a phototube.

Photomultiplier

- Convert small intensities of light into electrical current using multiplication
  - Dynodes for secondary electron generation
  - Dynodes are usually made of materials like MgO and GaP

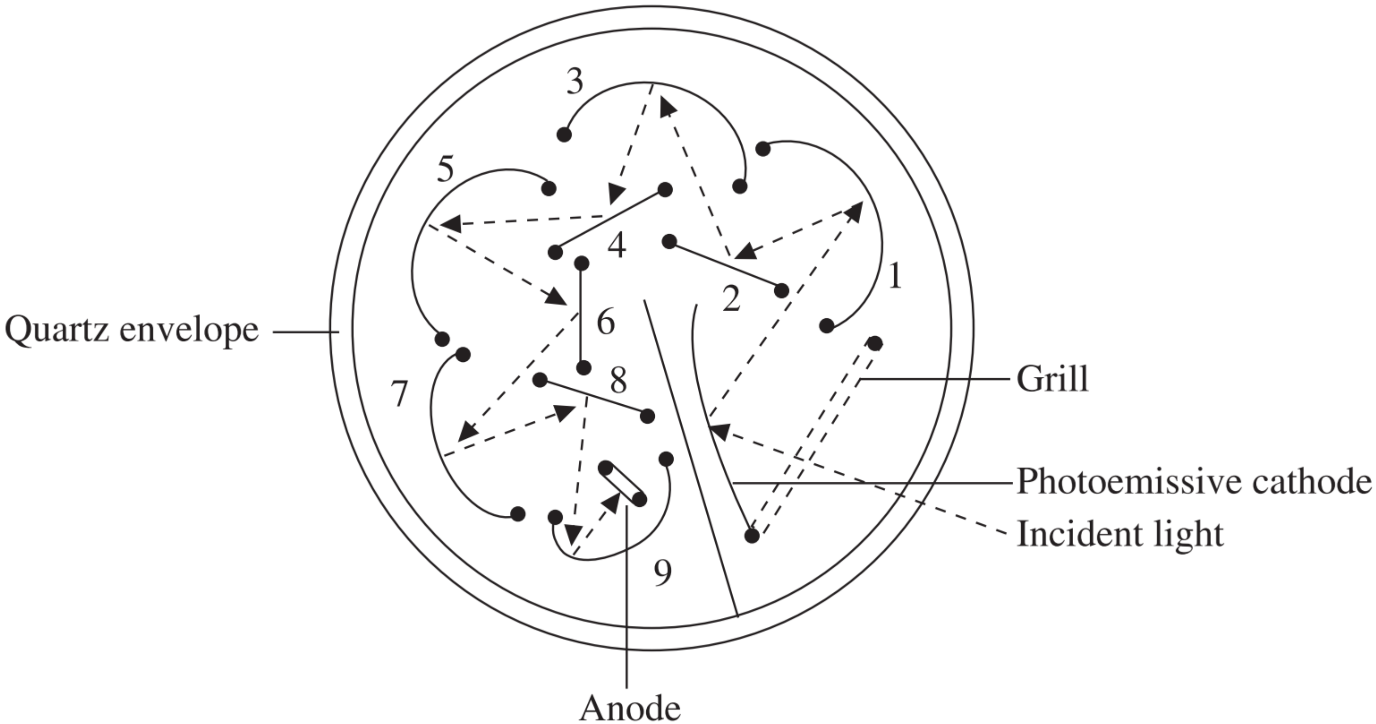


Fig. 5.32 Diagram of a photomultiplier tube. The numbers 1, 2, 3, . . . indicate dynodes.

Internal Photoeffect

- In the internal photoeffect, the photoexcited carriers (electrons and holes) remain within the material

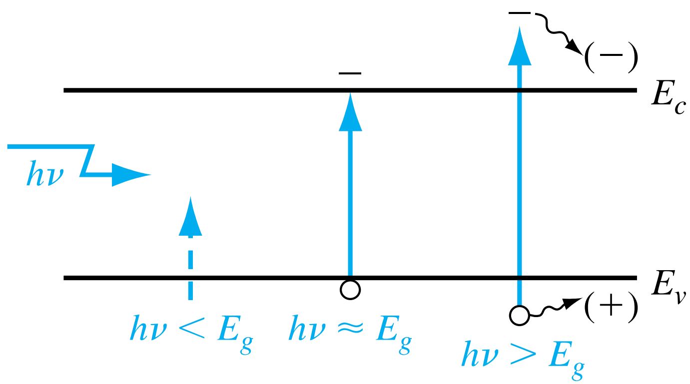
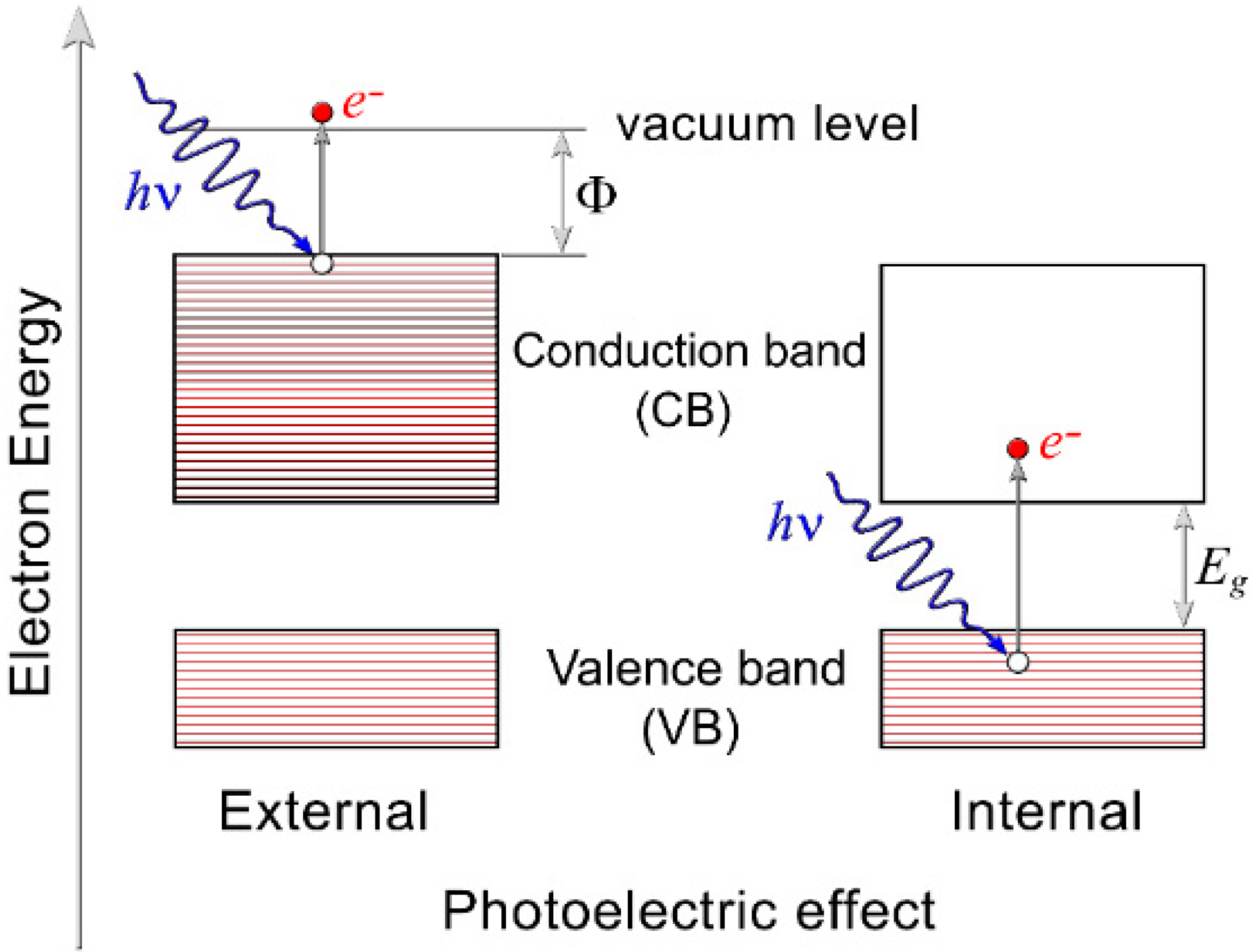


Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

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

Concepts Checks?
How…Internal Photoeffect



Optical Effects

- **Photon detectors:**
  - Photoeffect
    - External photoeffect
    - **Internal photoeffect**

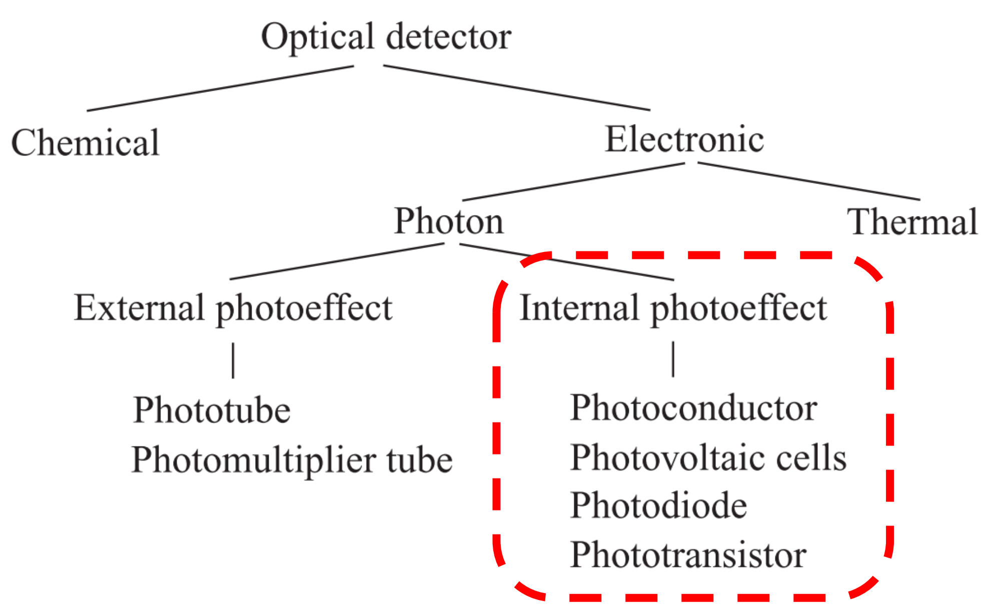


Fig. 5.27 Optical detectors tree.

Internal Photoeffect

- **Transducers**

  1. Photoconductor
  2. Photovoltaic transducer
  3. Photodiode
  4. Phototransistor

Photoconductor

- Light-induced increase in the conductivity, an effect exhibited by almost all semiconductors when irradiated by light of suitable waveband band, UV, IR,..
- Electron-hole pair generation due to the photon absorption

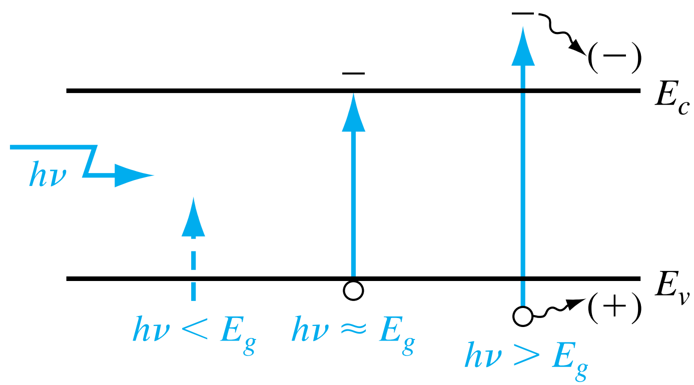


Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

Photoconductor

- Light-induced increase in the conductivity, an effect exhibited by almost all semiconductors

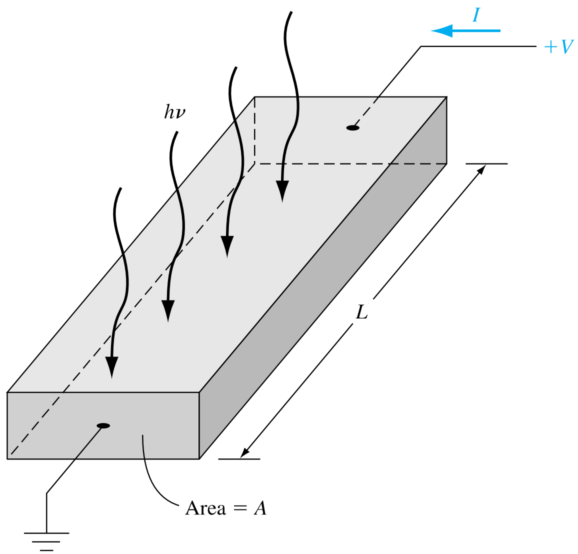


Figure 14.16 | A photoconductor.

- An external voltage source connected to the material causes the electrons and holes to move, resulting in a detectable electric current

Photoconductor

- ❑ Light-induced increase in the conductivity, an effect exhibited by almost all semiconductors

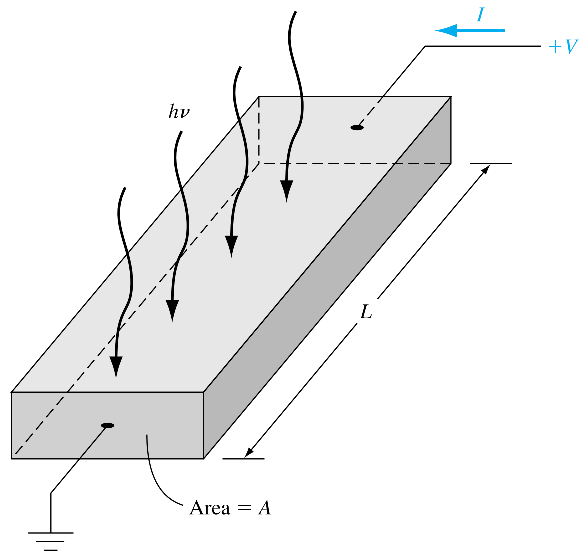


Figure 14.16 | A photoconductor.

- ❑ Known as photoresistor, or a photoconductor or sometimes a light dependent resistor (LDR)

Photoconductor

- Thin films of photoconductive substances deposited on a glass or plastic substrate

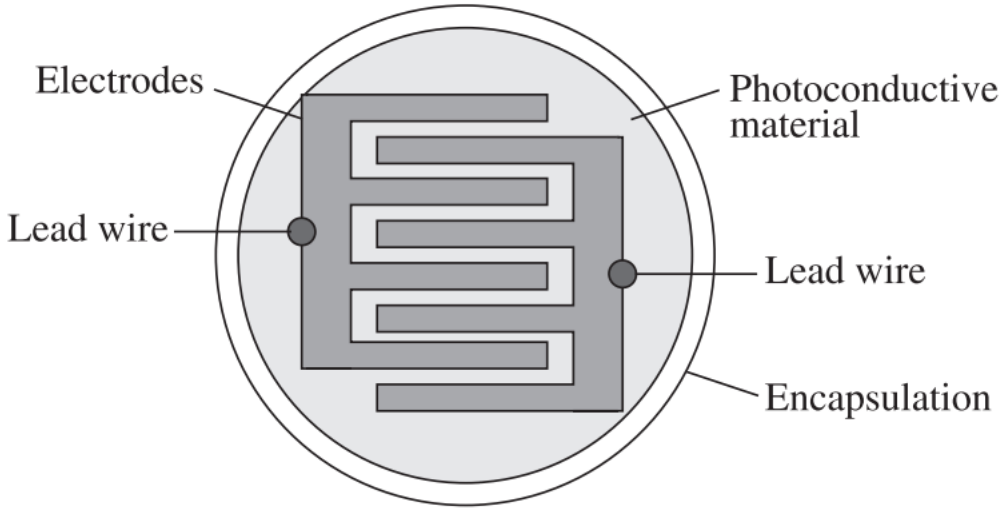


Fig. 5.34 Photoconductor.

- Interdigital electrodes
  - Resistance control using the number of fingers and spacing
- Ohmic contacts
- Materials: cadmium sulfide, lead sulfide, indium antimonide,…

Photoconductor: Applications

- Camera Light meters (CdS LDRS)
- Clock Radios
- Burglar Alarms
- Automatic ON/OFF street lights

Photovoltaic transducer

- The photovoltaic cell is a p–n junction structure where photons absorbed in the depletion layer generate electron-hole pairs
- Due to the local electric field within that layer, the two carriers drift in opposite directions and an electric current is induced in the external circuit.

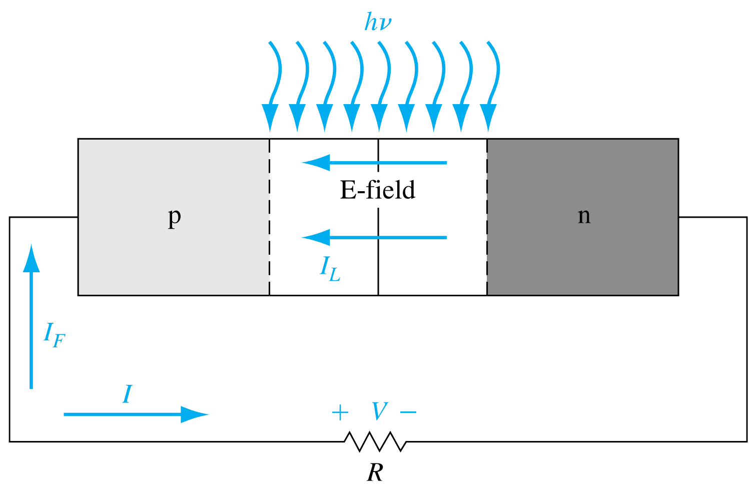


Figure 14.6 | A pn junction solar cell with resistive load.

- Photovoltaic Cells (PV) or Solar cells

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Photovoltaic transducer

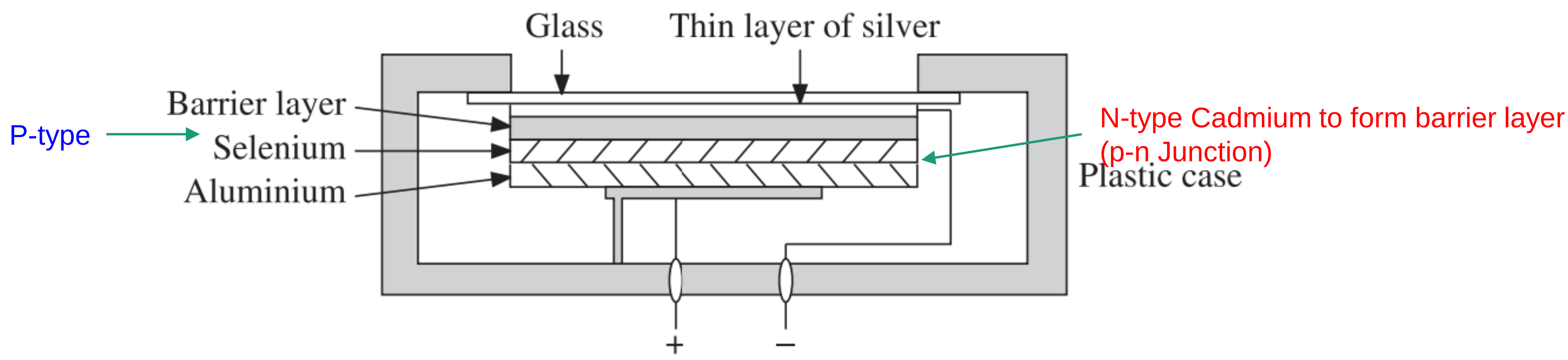

Fig. 5.35 Schematic diagram of a photovoltaic cell.

- ❑ Semiconductor materials: Se, Si, Cu_2O as well as from ternary and quaternary compound semiconductors such as InGaAs, HgCdTe and InGaAsP
- ❑ Sandwiched between two different metal electrodes

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

Multijuntion Solar Cells (Tandem Cells)

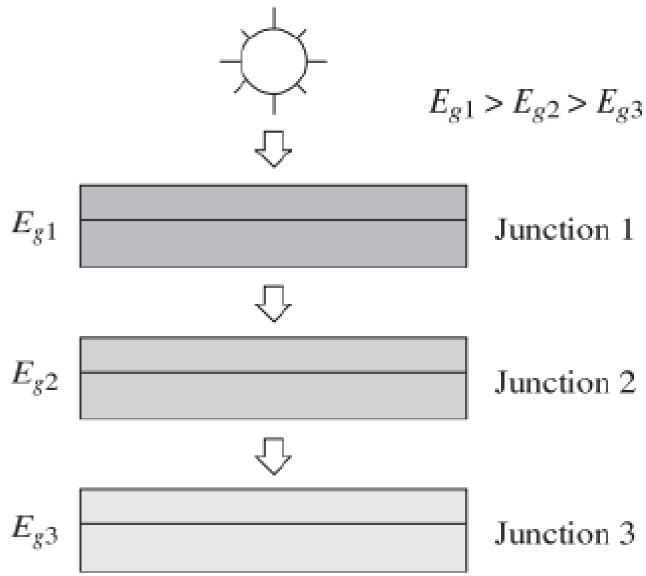

Fig. 5.36 Functioning of a multijunction cell.

Multijunction solar cell. In a single-junction photovoltaic cell, only photons whose energy is equal to or greater than the band gap of the junction can free an electron-hole pair for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used.

- Solution: more than one band gap and more than one junction (cascade)

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Photo Diodes

- A p–n junction is operated in reverse bias
- Output current is a function of the amount of incident light

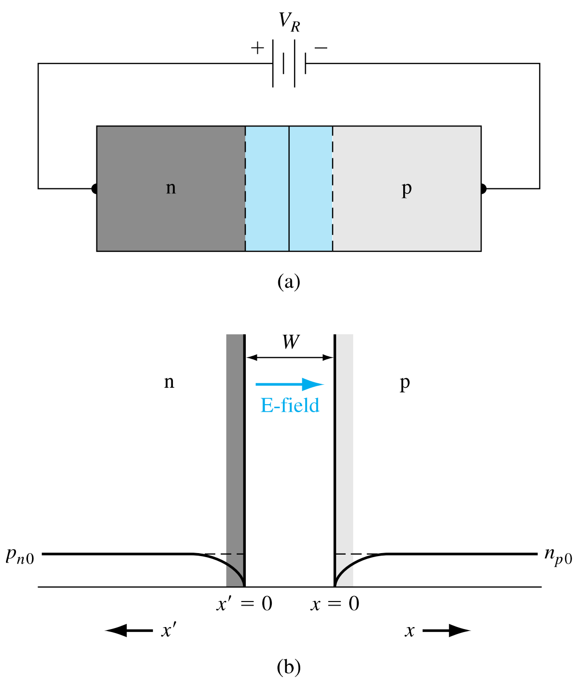

Figure 14.17 | (a) A reverse-biased pn junction. (b) Minority carrier concentration in the reverse-biased pn junction.

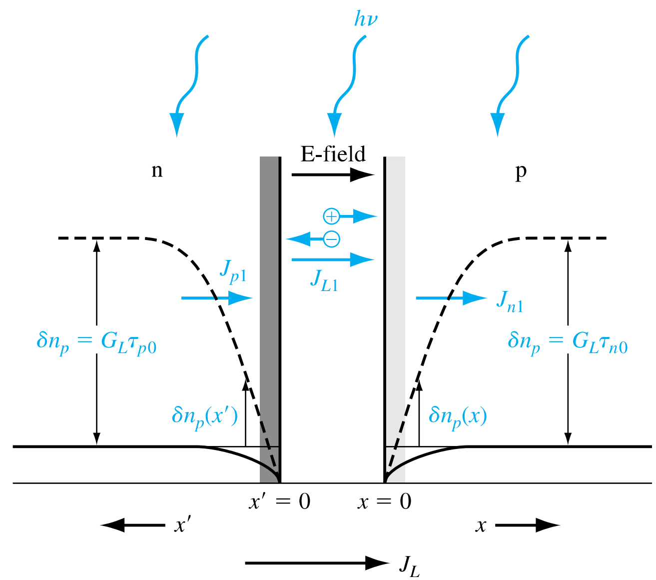

Figure 14.18 | Steady-state, photoinduced minority carrier concentrations and photocurrents in a "long" reverse-biased pn junction.

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Photo Diodes

- ❑ **Output current is a function of the amount of incident light**

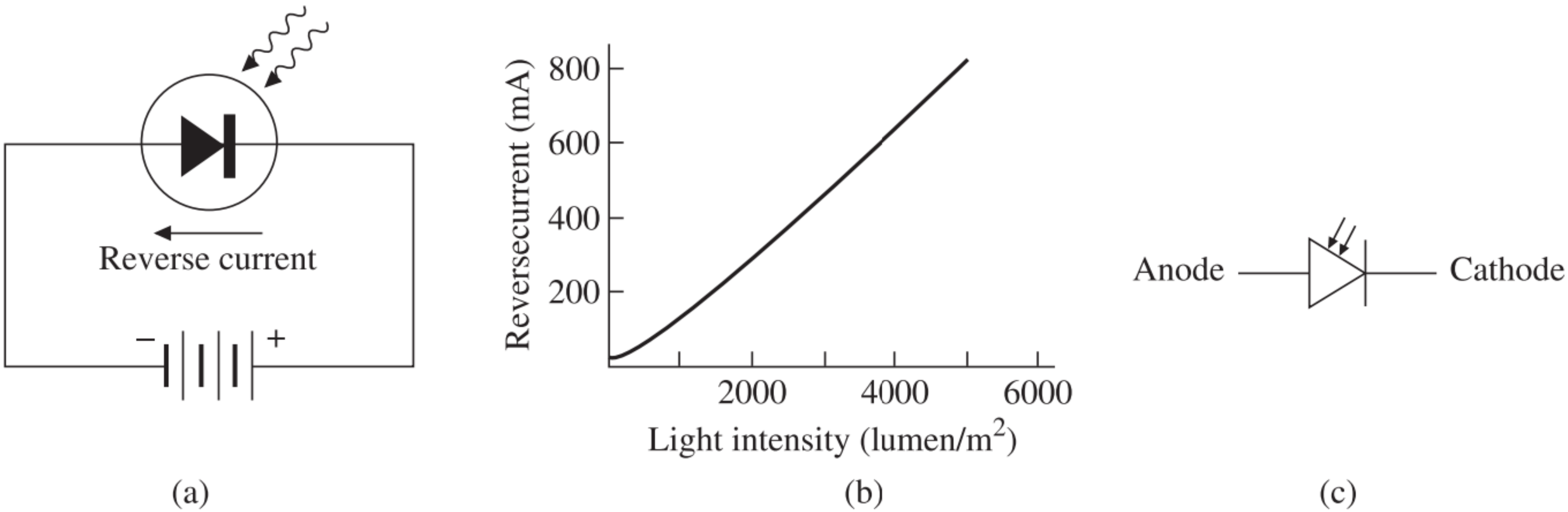

Fig. 5.37 Photodiode: (a) operation, (b) response curve, and (c) symbol.

- ❑ The photodiode response is fast—on the order of nanoseconds
- ❑ Linearity of response

Phototransistor

- ❑ Electrons and holes generated in the reverse-biased B–C junction produce a photocurrent I_L
- ❑ Holes are swept into the p-type base, making the base positive with respect to the emitter
- ❑ Since the B–E becomes forward-biased, electrons will be injected from the emitter back into the base, leading to the normal transistor action.

✓ **When light strikes the base, a voltage is applied to the base. So, a phototransistor amplifies variations in the light striking it.**

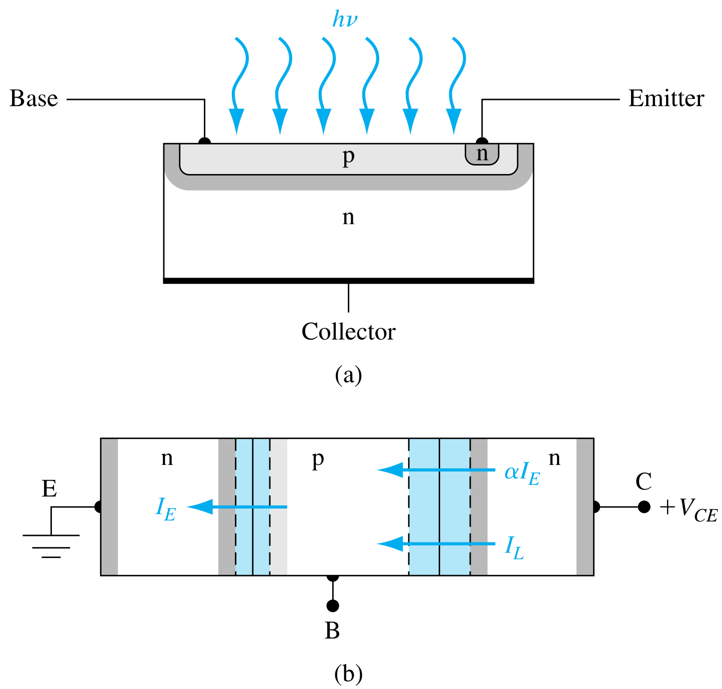

Figure 14.20 | (a) A bipolar phototransistor. (b) Block diagram of the open-base phototransistor.

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Phototransistor

- **Light Detectors: phototransistor**
  - A combination of a photodiode and a transistor that not only detects the light intensity like a photodiode, but also amplifies the generated current.

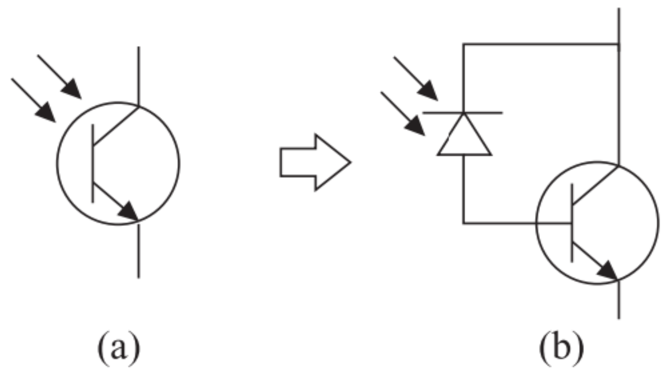

Fig. 5.38 (a) Phototransistor and (b) an equivalent circuit with a photodiode.

  - High gain makes it more sensitive to light than a photodiode, but has a slower response time

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Comparison of Different Photon Detectors

Table 5.14 Typical characteristics of photon detectors

Type	$D^{*\,a}$ (cm Hz$^{1/2}$ W^{-1})	$R_\lambda{}^b$	*Linear range* (decades)	*Spectral range* (nm)	*Rise time*^{c} (ns)	*Output*
Phototube	10^8–10^{10}	0.001–0.1^d	5	200–1000	1–10	Current
Photomltiplier tube	10^{12}–10^{17}	10–$10^{5\,d}$	6	110–1000	1–10	Current, charge
Photoconductive cell	10^9–10^{12}	10^4–$10^{6\,e}$	5	750–6000	50–10^6	Resistance change
Photovoltaic cell	10^8–10^{11}	100–$10^{6\,e}$	3	400–5000	10^3	Current, voltage
Si Photodiode	10^{10}–10^{12}	0.05–0.5^d	5–7	250–1100	1–10	Current

^{a} Measure of minimum detectability: $D = 1/\Phi_n$; D^* is normalised D for area A (cm^2) and bandwidth Δf (Hz) $[DA^{1/2}(\Delta f)^{1/2}]$.

^{b} Values indicate range for several different types.

^{c} Time for output to rise from 10–90% of final value for instantaneous increase in radiant power.

^{d} A/W

^{e} V/W

Queries

Thanks!