Optical Properties

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Contents

1) Basic concepts

2) Optical properties of metals

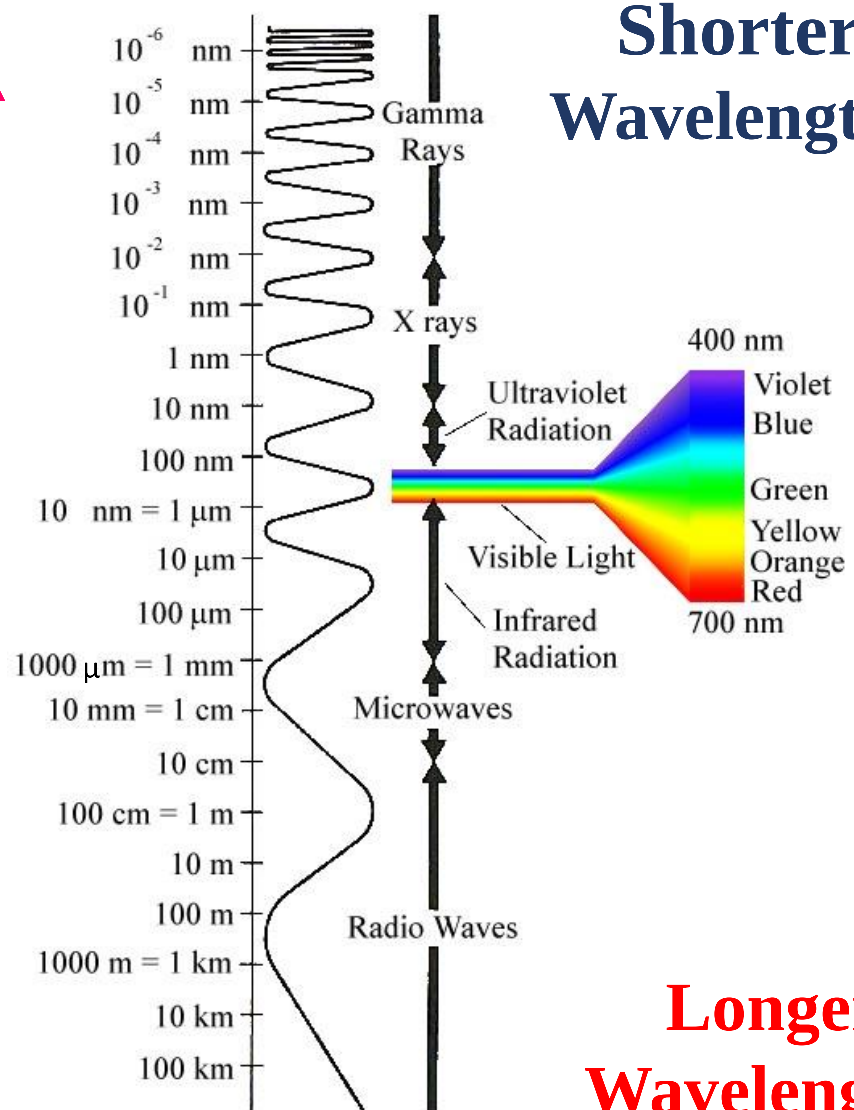
3) Optical properties of non-metals

4) Applications of optical phenomenon

The Electromagnetic Spectrum

Increasing Photon Energy (eV)

Shorter Wavelengths



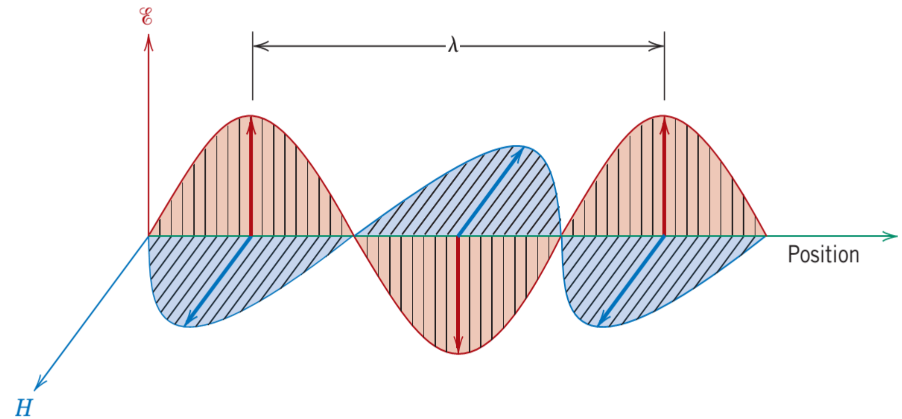
Longer Wavelengths

Color & Energy

- Violet ~ 3.17eV
- Blue ~ 2.73eV
- Green ~ 2.52eV
- Yellow ~ 2.15eV
- Orange ~ 2.08eV
- Red ~ 1.62eV

Electromagnetic Radiation

- ***Each electromagnetic radiation*** **is characterized by a combination** of a **time-varying *electric field* (E)** & **a time-varying magnetic field (H)** propagating through space and having specific range of wavelengths.



- All electromagnetic radiation traverses a **vacuum** at the **same velocity** (3×10^8 m/s).

$$\boxed{Velocity, c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}}$$

ϵ_o = Electric permittivity of vacuum = 8.854×10^{-12} Farad/meter
μ_o = Magnetic permittivity of vacuum = 1.257×10^{-6} Henry/meter

$$\boxed{Energy, E = h\vartheta = h\frac{c}{\lambda}}$$

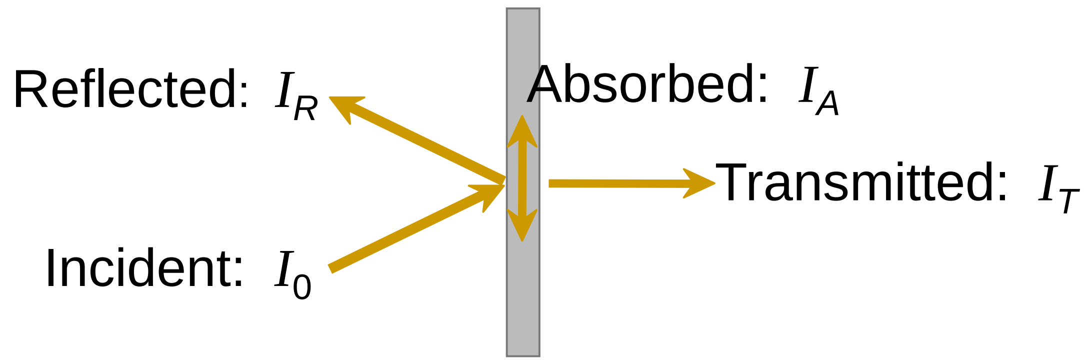
h = Planck's constant = 6.634×10^{-34} J-s
ϑ = Frequency (Hz or s^{-1})
λ = Wavelength (m)
C = velocity (m/s)

Reference: W.D Callister, 7 Ed.

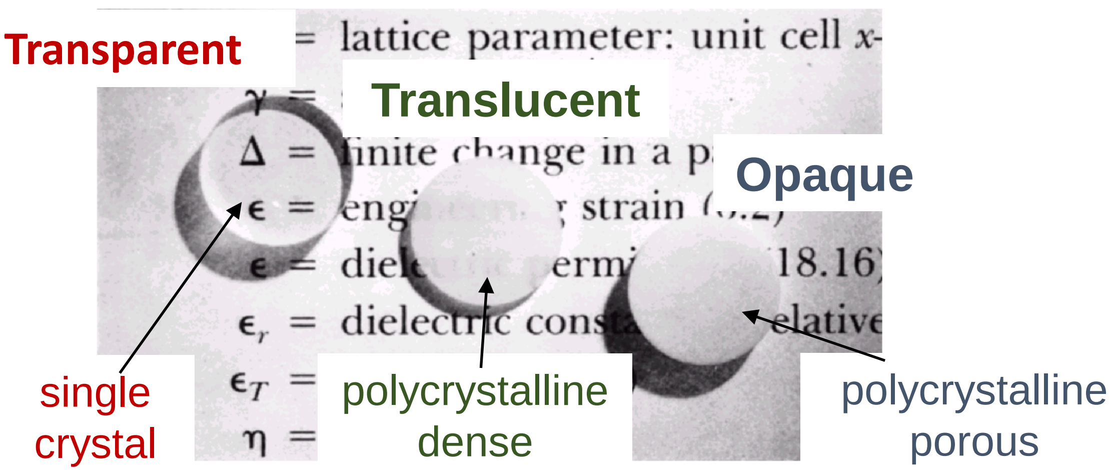
Light Interactions with Solids

- Incident light is reflected, absorbed, scattered, and/or transmitted.

$$I_0 = I_T + I_A + I_R$$



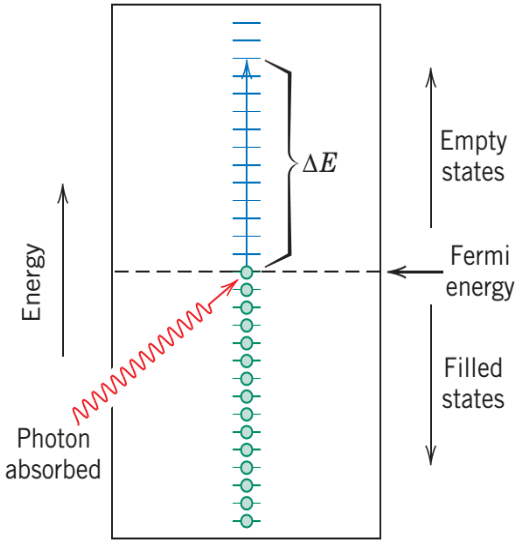
- Optical classification of materials:



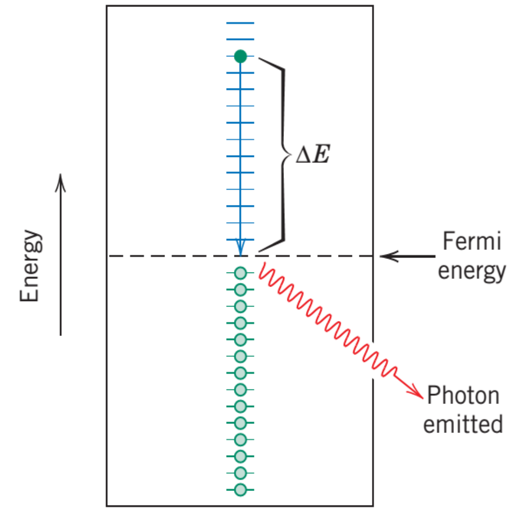
Reference: W.D Callister, 7 Ed.

Optical properties – Metals

- All frequencies of visible light are absorbed by metals because of the continuously available empty electron states, which permit electron transitions.
- The incident radiation having frequencies within the visible range excites electrons into unoccupied energy states above the Fermi energy. So, the **incident radiation is absorbed**. Hence **metals** are **opaque**.
- The Fermi energy is the maximum energy occupied by an electron at 0K.
- The change in energy of the electron ΔE is equal to the energy of the photon.
- **Reemission** of a photon of light takes place by the direct **transition** of an **electron** from a **high to a low energy state**.
- **Metals are opaque** to **low frequency** radiation (radiowaves to about some middle of UV rays).
- **Metals** are **transparent** to **high frequency** (x-ray and γ-ray) radiation.



Photon absorption

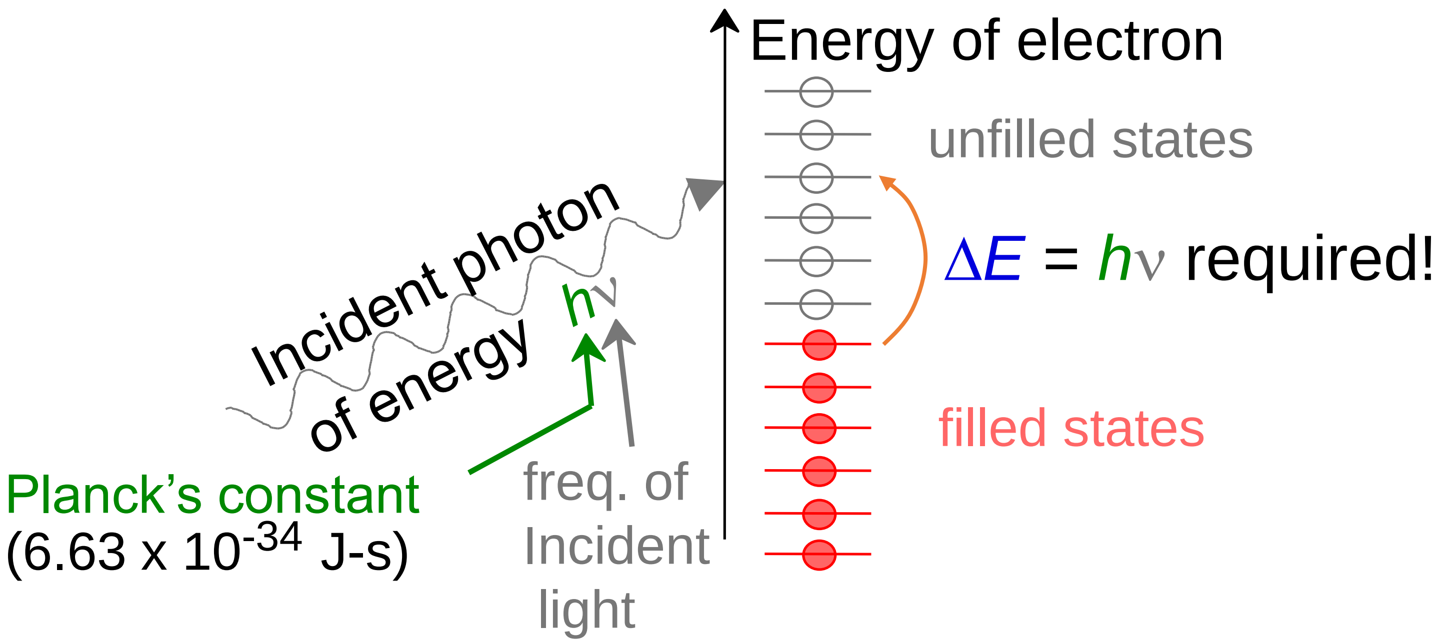


Photon Reemission

Reference: W.D Callister, 7 Ed.

Optical Properties of Metals: Absorption

- Photons are absorbed by electron transitions.

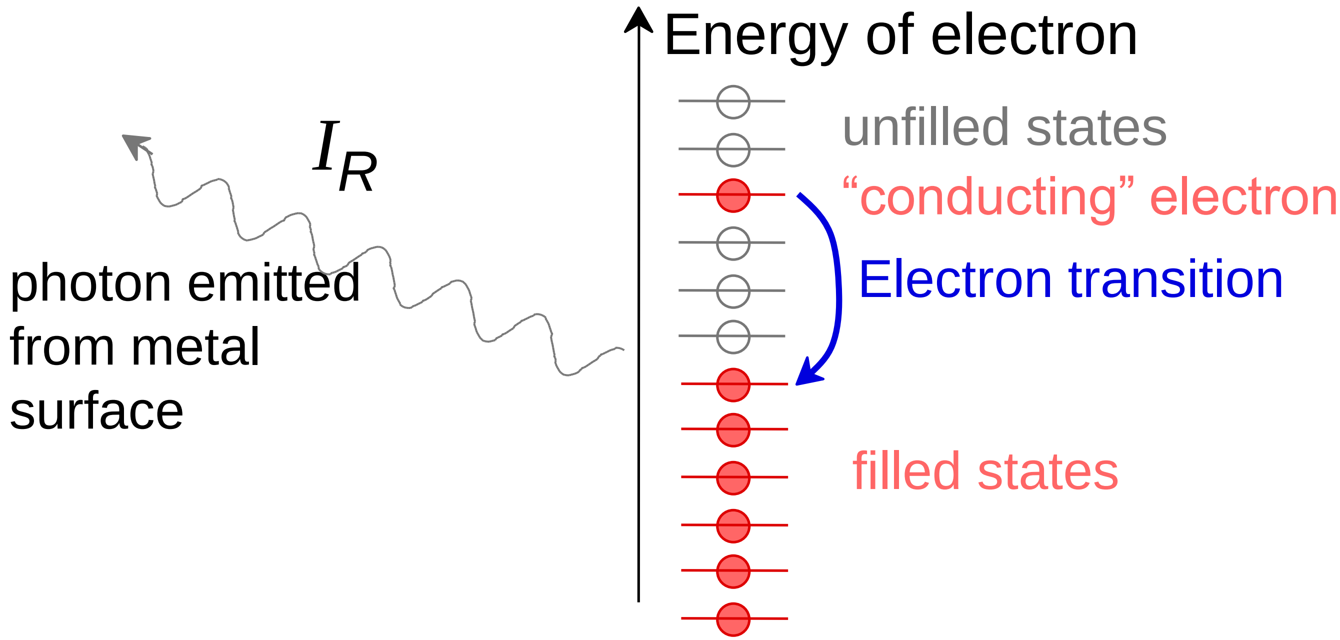


- Unfilled electron states are adjacent to filled states
- Near-surface electrons absorb visible light.

Reference: Callister & Rethwisch 8e.

Optical Properties of Metals: REFLECTION

- Most of the **absorbed radiation** is **reemitted** from the surface in the form of visible light of the **same wavelength**, which appears as **reflected light**.
- **Electron transition** from an **excited state** produces a **photon**.



- Metals Reflectivity = I_R / I_0 is between 0.90 and 0.95.

Reference: Callister & Rethwisch 8e.

Optical Properties of Non-metals

With regard to non-metals all four optical phenomenon are important:

- Refraction
- Reflection
- Absorption
- Transmission

Refraction

- When light photons are transmitted through a material, they causes polarization of the electrons and in turn the speed of light is reduced and the beam of light changes direction.

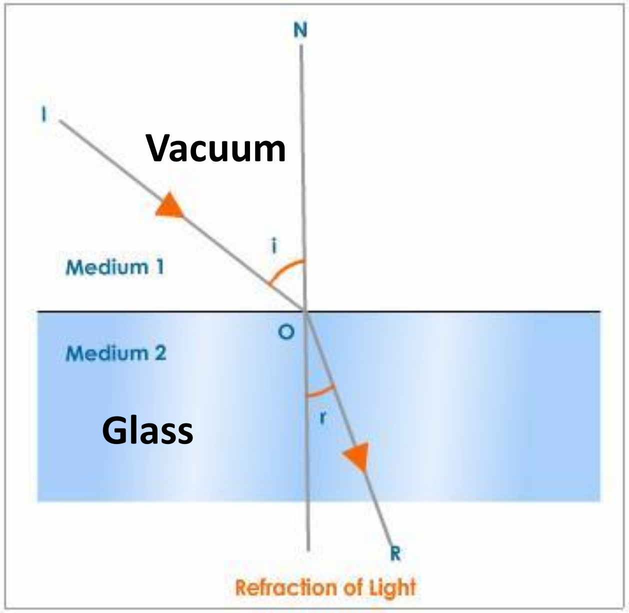
$$\boxed{Refractive\ Index, n = \frac{Speed\ of\ light\ in\ a\ vacuum\ (c)}{Speed\ of\ light\ in\ a\ Medium\ (v)}}$$

$$Speed\ of\ light\ in\ a\ Medium\ (v) = \frac{1}{\sqrt{\in \mu}}$$

where, $\in$ and μ are the permittivity and permeability of the medium.

$$\boxed{n = \frac{c}{v} = \frac{\sqrt{\in \mu}}{\sqrt{\epsilon_o \mu_o}} = \sqrt{\epsilon_r \mu_r}}$$

where, ϵ_r and μ_r are the relative permittivity and permeability of the medium.



- Using **Snell's law**

$$\boldsymbol{n_1 sin\theta_i = n_2 sin\theta_r}$$

Refractive Index

Material	*Average Index of Refraction*
Ceramics	
Silica glass	1.458
Borosilicate (Pyrex) glass	1.47
Soda–lime glass	1.51
Quartz (SiO_2)	1.55
Dense optical flint glass	1.65
Spinel ($MgAl_2O_4$)	1.72
Periclase (MgO)	1.74
Corundum (Al_2O_3)	1.76
Polymers	
Polytetrafluoroethylene	1.35
Polymethyl methacrylate	1.49
Polypropylene	1.49
Polyethylene	1.51
Polystyrene	1.60

Reference: W.D Callister, 7 Ed.

Reflection

- Reflectivity is defined as fraction of light reflected at an interface.

$$R = \frac{I_R}{I_o}$$

- If the light is normal (or perpendicular) to the interface, then

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

Where n_1 and n_2 are the refractive indices of two media

- **Higher the refractive index** of the solid, the **greater** is the **reflectivity**.
- In **metals**, the reflectivity is typically on the order of **0.90-0.95**, whereas for **glasses** it is close to **0.05**.
- The **high reflectivity** of **metals** is one reason that they are **opaque**.

Absorption

- When a light beam in impinged on a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material.

The amount of light absorbed by a material is calculated using **Beer's Law**

$$I_T = I_0 e^{-\beta \ell}$$

β = absorption coefficient, cm^{-1}
ℓ = sample thickness, cm
I_0 = incident light intensity
I_T = transmitted light intensity

$$I_0 = I_T + I_A + I_R$$

- Materials that have large β values are considered to be highly absorptive.

Absorption mechanisms

Rayleigh scattering:

- Photon interacts with the electrons, it is deflected without any change in its energy.
- Example - Blue color in the sunlight gets scattered more than other colors in the visible spectrum and thus making sky look blue.

Tyndall effect

- Scattering occurs from particles which are much larger than the wavelength of light.
- Example - Clouds look white.

Compton scattering

- Interacting photon knocks out an electron loosing some of its energy during the process.

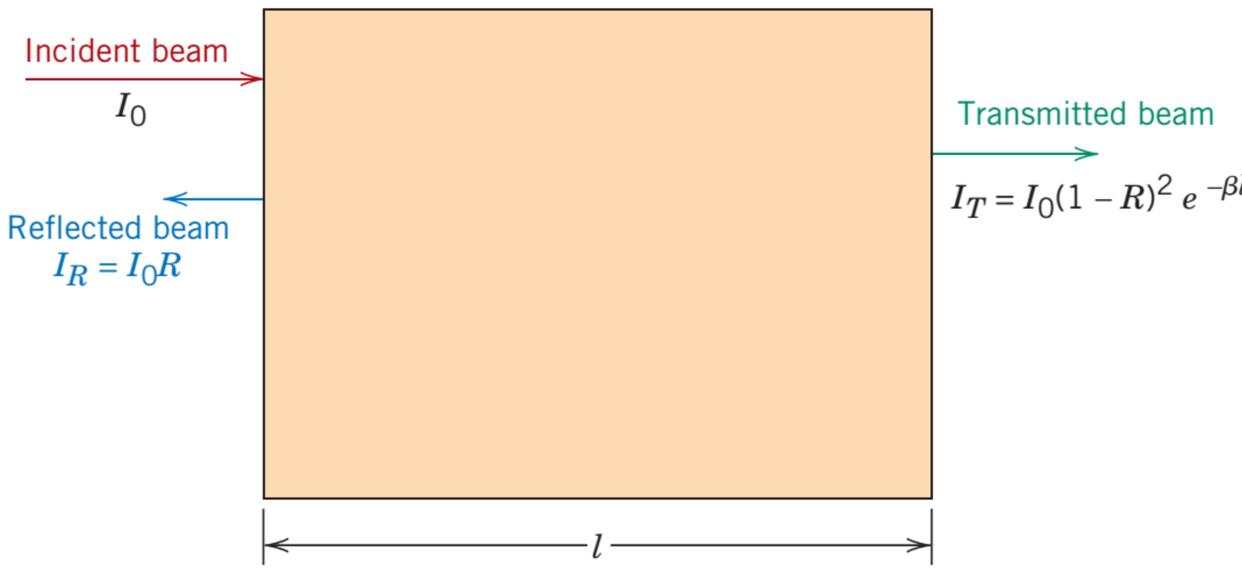
Photoelectric effect

- When photon energy is consumed to release an electron from atom nucleus.

Transmission

- Fraction of light beam that is not reflected or absorbed is transmitted through the material.

$$I_T = I_o(1 - R)^2 e^{-\beta l}$$



Reference: W.D Callister, 7 Ed.

Applications of Optical Phenomena

1. Luminescence

- ✓ It is the process where a material absorbs energy and then immediately emits visible radiation.
- ✓ It consists of electron excitation and then dropping down to lower energy states.
- ✓ If the emission of radiation occurs **within 10^{-8} sec** after excitation, the luminescence is called **Fluorescence**, and if it takes **longer than 10^{-8} sec**, it is known as **Phosphorescence.**
- ✓ Ordinarily pure materials do not display this phenomenon but some special materials called **Phosphors** have this capacity, such as $BaMgAl_{10}O_{17}$,Y_2O_3, ZnS, CdS.
- ✓ **Applications:** Fluorescent lamps, CRT (Cathode ray tube), plasma video display screens, white LEDs.

2. Photo-conductivity

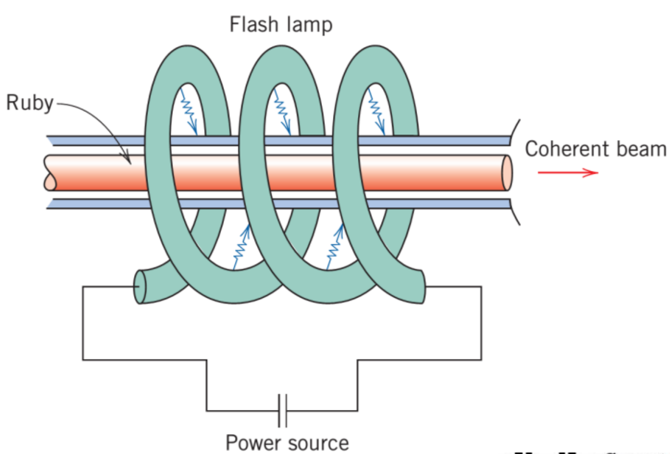
- Bombardment of semiconductors by photons, with **energy** equal to greater than the **band gap**, may result in **creation** of **electron-hole pairs** that can be used to generate current. This process is called Photoconductivity.
- It is different from photo-electric effect in the sense that an electron-hole pair is generated whose energy is related to the band gap energy instead of free electron alone whose energy is related to the Fermi level.
- The current produced in photo-conductivity is directly related to the incident light intensity.
- This phenomenon is utilized in photographic light meters. Cadmium sulfide (CdS) is commonly used for the detection of visible light, as in light meters.
- Solar cells are also based on Photoconductivity.

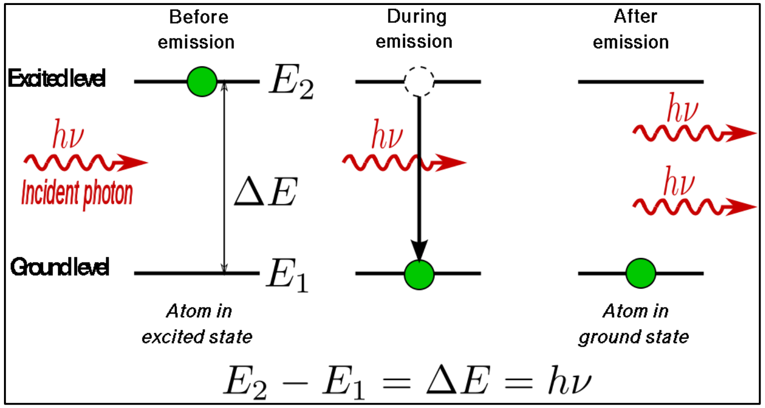
Photographic light meters

Solar cells

3. Lasers

- Laser : **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- Unlike luminescence, which produce incoherent light, the light produced by **laser emission** is **coherent** (constant phase difference and the same frequency).
- This is based on the fact that in certain materials, electrons excited by a stimulus produce photons which in turn excite additional photons of identical wavelength.
- Example - **Ruby** (Single crystal of Al_2O_3 doped with little amount of Cr_2O_3); Yttrium aluminium garnet ($Y_3Al_5O_{12}$ – **YAG**) doped with neodymium, Nd; **He-Ne laser**; some semiconductors like GaAs and InGaAsP.
- **Applications** - welding, metal cutting, heat treatment, surgery, reading compact disks, etc.





Reference: W.D Callister, 7 Ed.

Image: Wikipedia

In the **next lecture**, we will study another application:

- ✓ Optical fibres
- ✓ Its principle, types and applications

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