# EELE408 Photovoltaics
## Lecture 07: Absorption of Light

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## Complex index of refraction

- The optical properties of a material depend on the complex index of refraction:
- n is the real part of the complex index of refraction used in optical design

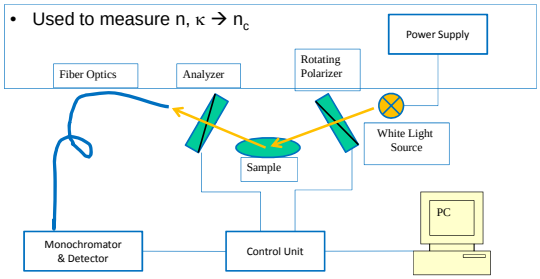
$$n_c = n - i\kappa$$

- κ is the extinction coefficient, the imaginary part of the complex index of refraction
- The extinction coefficient implies there is a loss or absorption of photons



## Ellipsometry

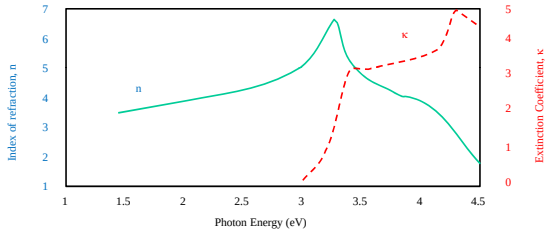
- Used to measure n, κ → $n_c$






## Optical Constants for Silicon

At photon energies below 3 eV the extinction coefficient is below 0.006 and the index of refraction is about 3.5





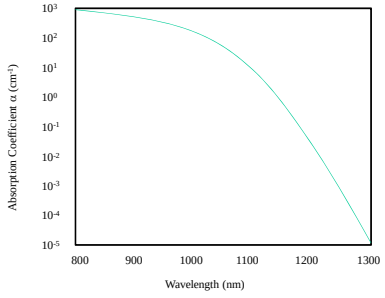

## Absorption Coefficient

- The extinction coefficient is related to the absorption coefficient by:

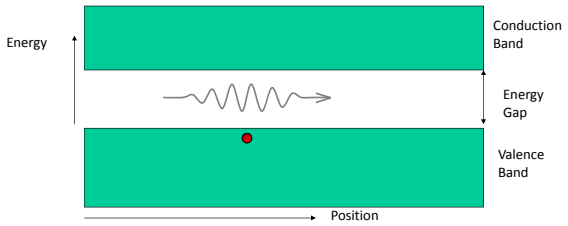
$$\alpha(\lambda) = \frac{4\pi\kappa(\lambda)}{\lambda}$$



## Silicon Optical Absorption



## $E_{ph}<E_G$

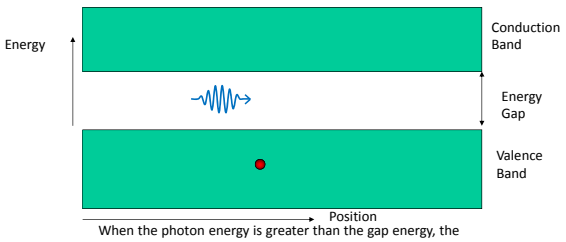



When the photon energy is less than the gap energy, the photon is not absorbed and the photon passes straight through the semiconductor



## $E_{ph}>E_g$

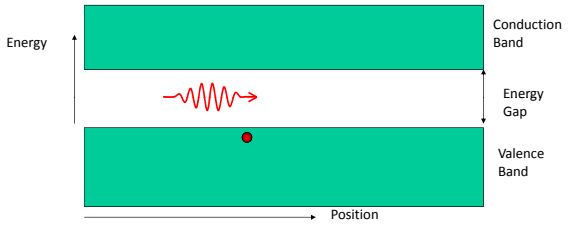
The electron and hole looses thermal energy to the lattice by collisions and moves to the edge of the bands. Part of the photon energy is lost as heat.




When the photon energy is greater than the gap energy, the photon is absorbed and an electron breaks from the lattice and moves from the valence band into the conduction band.



## $E_{ph}=E_G$




When the photon energy is equal to the gap energy, the photon is again absorbed but no thermal energy is generated.

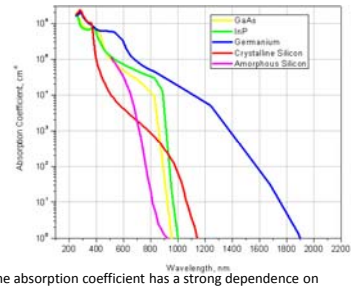


## Photon Absorption

- The absorption photons create both majority and minority carriers, but the light generated carriers are orders of magnitude less than the concentration of majority carriers that are already there.
- Typically the minority carriers are significantly increased that the concentration of minority carriers can be approximated by the photo-generated minority carriers.



## Absorption Coefficient (α)




The absorption coefficient has a strong dependence on wavelength of the light.



## Generation Rate

- The intensity of the light reduces as it passes through the material

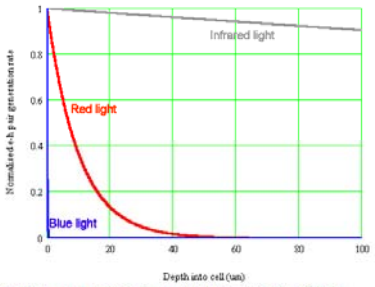
$$I = I_0 e^{-\alpha x}$$

  - $I_0$ is the light intensity at the top surface
  - $\alpha$ is the absorption coefficient ($cm^{-1}$)
- The light interacts with the material creating electron hole pairs (EHP)
- The EHP generation rate is related to the change in the light intensity as it passes through the material

$$G = \alpha N_0 e^{-\alpha x}$$

$N_0$ is the photon flux at the surface (# of photons/area/second)

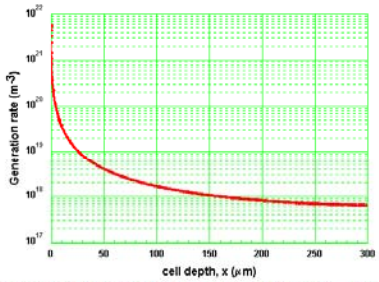
## Generation is wavelength dependent




The generation rate in silicon for several wavelengths of light.



## EHP Generation Rate




Generation rate of electron-hole pairs in a piece of silicon as a function of distance into the cell. The cell front surface is at 0 μm and is where most of the high energy blue light is absorbed.

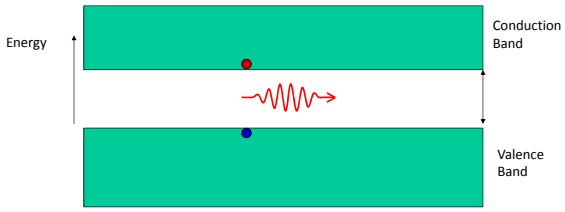


## Recombination

- Electrons in the excited state will eventually decay from the conduction band back to the valence band this is called recombination
- The electron and hole recombine giving up energy
- Types of Recombination
  - Radiative
  - Auger
  - Shockley-Read-Hall



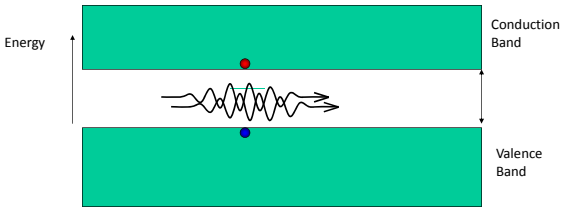
## Band to Band Recombination




- Dominate effect in lasers and LED's
- In Si PV devices relatively unimportant since Si is an indirect material



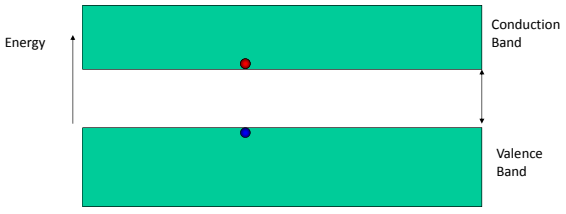
## Recombination through defects (traps)




- Two step process electron releases photon as moves to midgap energy level
- The electron and hole recombine releasing another low energy photon



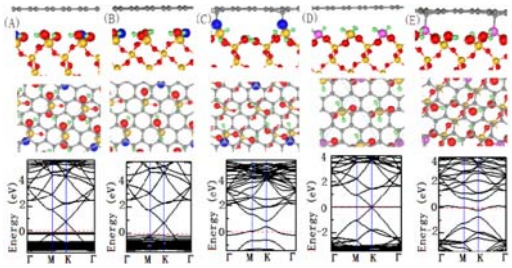
## Auger Recombination




- Involves two electrons colliding transferring kinetic energy
- One electron recombines with a hole and the other is pushed higher into the conduction band where it looses its kinetic energy via collisions to thermal energy

## Surface defects

- Any defects or impurities within the solid or at the surface promote recombination





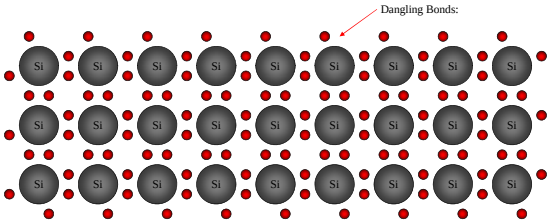

## Surface Sites


- Surface Sites



## Dangling Bonds at Surface

- The surface is a severe disruption of the silicon lattice, hence a locale of high recombination





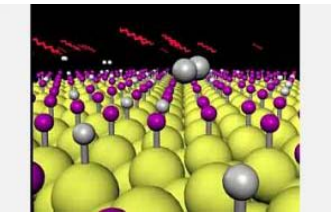

## Surface Recombination Velocity

- High recombination rate at surface depletes minority carriers
- Diffusion causes movement of minority carriers to this region
- Surface recombination rate is limited by the rate in which the minority carriers can move to the surface (Surface Recombination Velocity (cm/sec))
  - Min = 0 for no recombination at surface
  - Max = $10^7$ cm/sec limited by max velocity of carriers in the semiconductor



## Surface Passivation

- The reduction of the dangling bonds reduces the surface recombination
- Usually oxide is grown on the surface of silicon to tie up these dangling bonds. This is called **surface passivation**





## Improved Absorption Efficiency

- Reduction of unwanted materials from silicon lattice (remove trapping sites)
  - Use very pure materials
- Passivate surface to reduce dangling bonds
  - Oxidize the surfaces