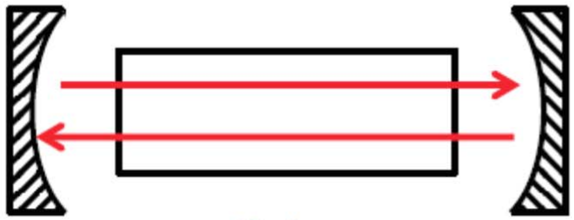
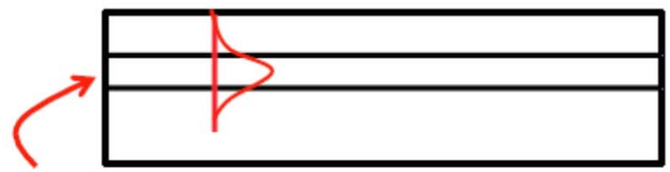
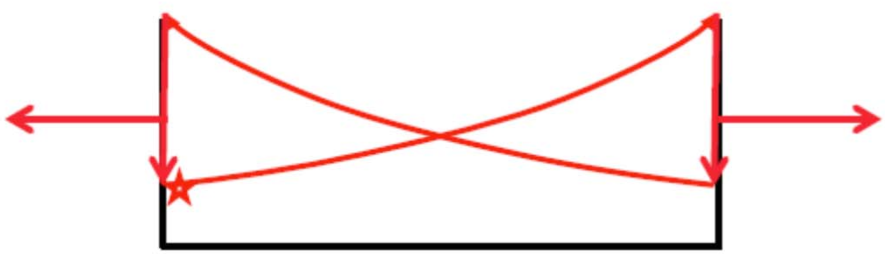
Basic Concept of Lasers

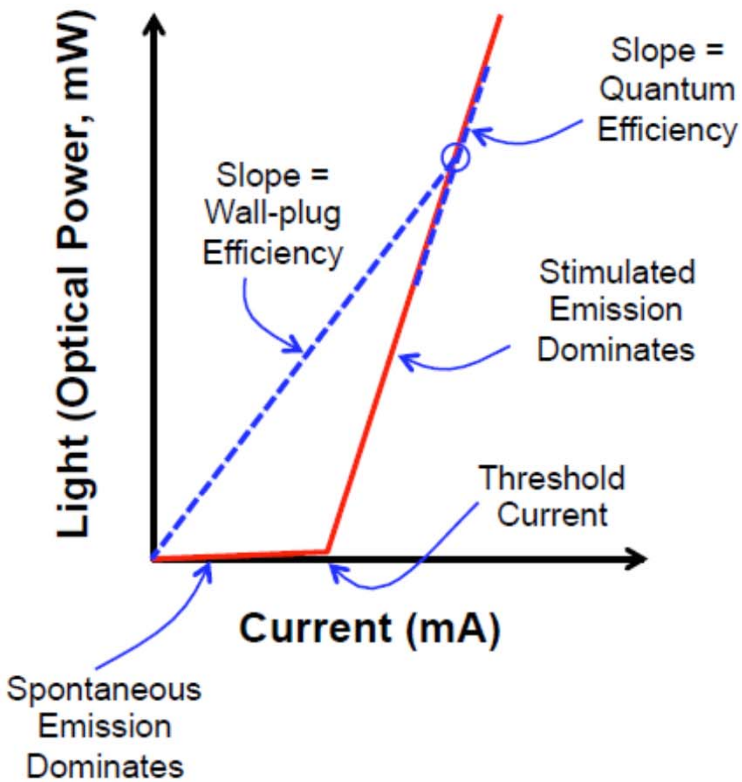






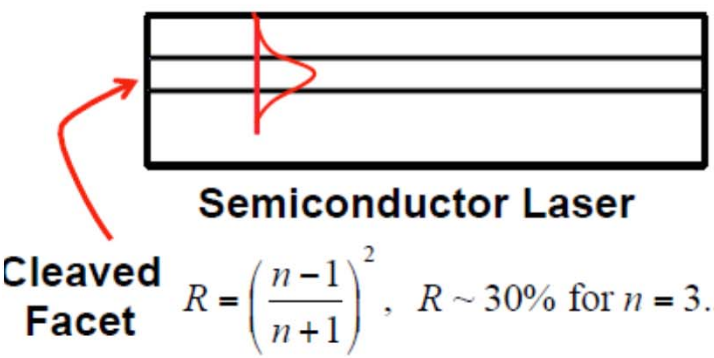
- Laser:
  - **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- Basic elements:
  - Gain media
  - Optical cavity
- Threshold condition:
  - Bias point where laser starts to "lase"
  - Gain (nearly) equals loss

L-I Curve of Semiconductor Lasers

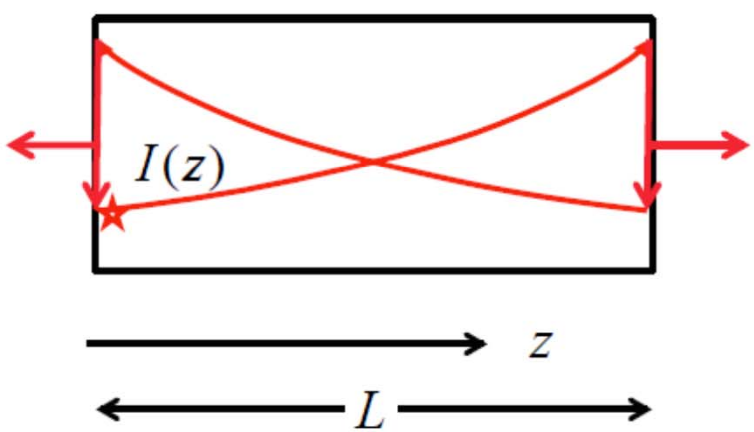


- Distinctive threshold (at least in classical lasers)
- Semiconductor laser is a forward-biased p-n junction, so mainly a current-biased device
- Threshold current :
  - Minimum current at which the laser starts to "lase"
- Quantum efficiency
  - "Differential" electrical-to-optical conversion efficiency, i.e., how many photons generated by injected electrons beyond threshold
- Wall-plug efficiency
  - Total electrical-to-optical conversion efficiency

“Edge-Emitting” Semiconductor Lasers



$R = \left(\frac{n-1}{n+1}\right)^2$, $R \sim 30\%$ for $n = 3.5$



g : gain coefficient [cm^{-1}]

Light ampflication: $I(z) = I_0 e^{\Gamma g z}$

Γ: confinement factor

(fraction of energy in gain media)

Threshold condition:

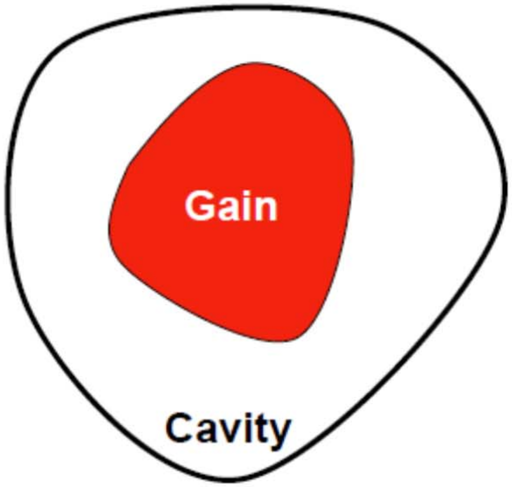
Round-trip gain = 1

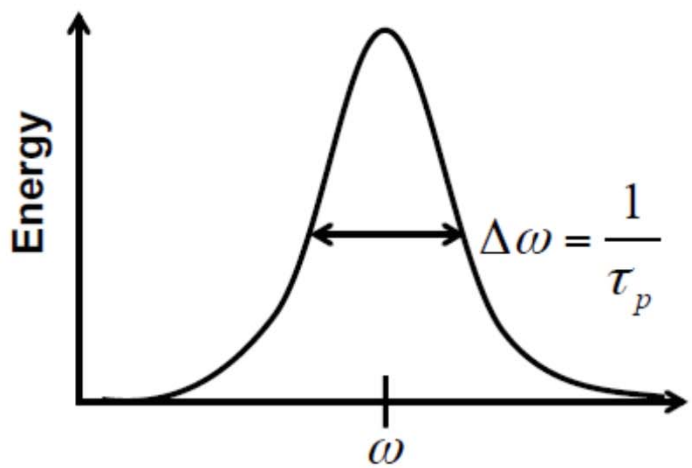
$$e^{\Gamma g L - \alpha_i L} R_1 e^{\Gamma g L - \alpha_i L} R_2 = 1$$

$$g = g_{th} = \frac{\alpha_i}{\Gamma} + \frac{1}{2\Gamma L}\ln\left(\frac{1}{R_1 R_2}\right) = \frac{\alpha_i + \alpha_m}{\Gamma}$$

$$\begin{cases} \alpha_i \text{ : intrinsic loss} \\ \alpha_m = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) : \text{ mirror loss (i.e., output light)} \end{cases}$$

Generic Description of Optical Cavity





Quality Factor:

$$Q = \frac{\text{Energy Stored}}{\text{Energy Dissipated per Cycle}}$$

$$Q = \frac{\omega}{\Delta\omega}$$

$$\Delta\omega = \frac{1}{\tau_p}$$

τ_p : photon lifetime [sec]

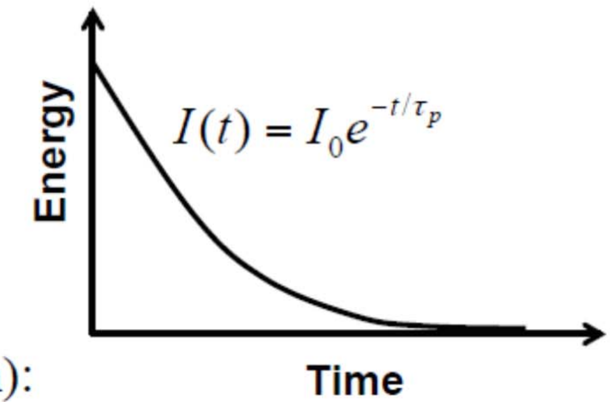
$$\frac{1}{\tau_p} = \alpha \frac{c}{n} \qquad \begin{pmatrix} \alpha\text{: loss rate per cm} \\ 1/\tau_p\text{: loss rate per sec} \end{pmatrix}$$

$$\boxed{Q = \omega\tau_p}$$

Photon Lifetime and Spectral Width

Decay of optical energy when input is turned off (ring-down measurement):

$$I(t) = I_0 e^{-t/\tau_p} \quad \text{for } t \geq 0$$

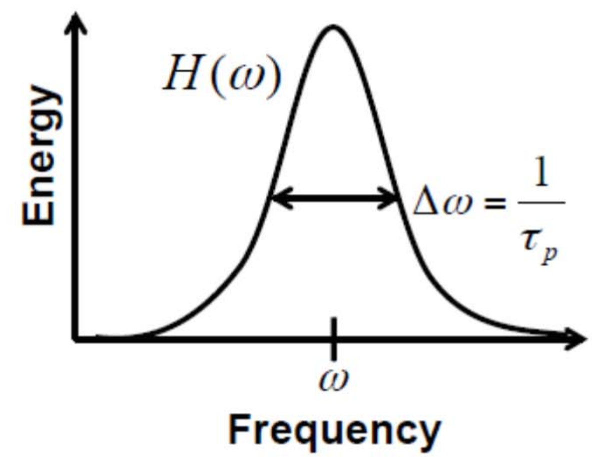


Electrical (optical) field:

$$E(t) = E_0 e^{j\omega_0 t} e^{-t/2\tau_p} \quad \text{for } t \geq 0$$

Frequency domain response (Fourier transform):

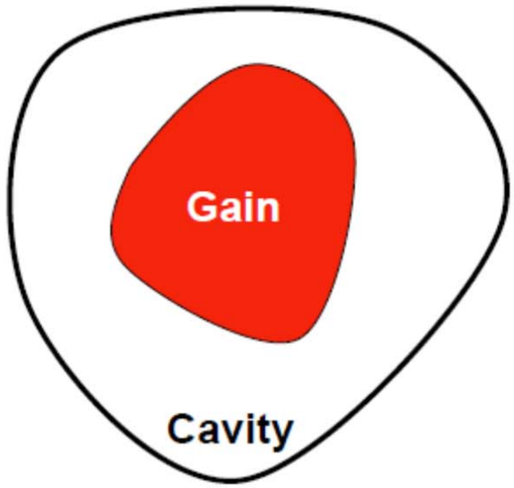
$$H(\omega) = \int_0^\infty e^{j\omega_0 t} e^{-t/2\tau_p} e^{-j\omega t} dt = \frac{1}{j(\omega - \omega_0) + 1/2\tau_p}$$



FWHM of $|H(\omega)|^2$: $\quad \omega - \omega_0 = \pm \frac{1}{2\tau_p}$

$$\boxed{\Delta\omega = \frac{1}{\tau_p}}$$

Threshold Condition of Generic Lasers

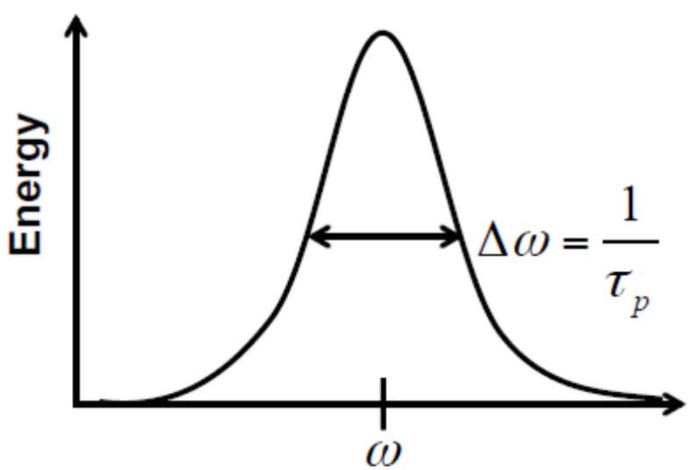


Gain = Loss

(rate of gain = rate of loss)

$$\Gamma g_{th} \frac{c}{n} = \frac{1}{\tau_p} = \frac{\omega}{Q}$$

$$\boxed{g_{th} = \frac{\omega}{Q} \frac{n}{\Gamma c}}$$



Quantum efficiency:

$$\eta = \frac{\alpha_m}{\alpha_m + \alpha_i} = \frac{Q_{rad}^{-1}}{Q_{rad}^{-1} + Q_{loss}^{-1}} = \frac{Q_{rad}^{-1}}{Q^{-1}}$$

$$\boxed{\eta = \frac{Q}{Q_{rad}}}$$

Typical Q of Semiconductor Laser

Edge-emitting laser:

$L = 100\mu m,\;\; R = 30\%,\;\; \omega \sim 100THz\;,\; \tau_p \sim 1ps,\;\; Q \sim 600$

Vertical Cavity Surface-Emitting Laser (VCSEL)

$L = 1\mu m, R = 99\%,\;\; Q \sim 700$

Microdisk (Whispering Gallery Mode or WGM) Laser

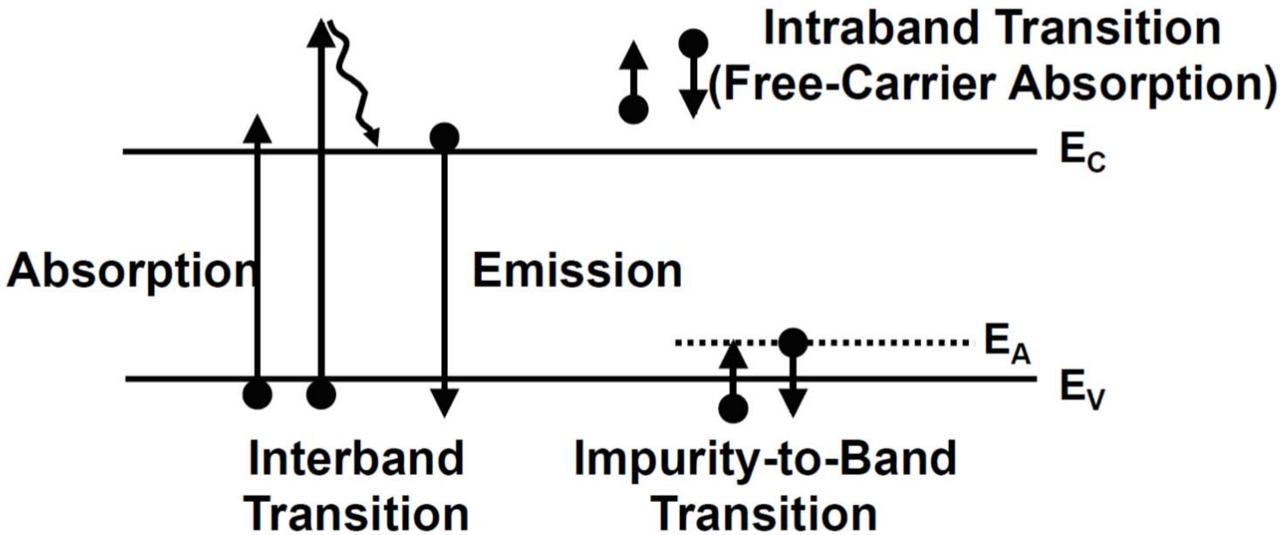
$Q \sim 1000$ (up to 10^{11} possible in low loss materials)

Photonic crystal laser: $Q \sim 1000$ (up to 10^6 possible)

Metal cavity laser (plasmonic laser): $Q \sim 10$ to 100

The gain medium

Optical Properties of Semiconductors



Optical transitions

- Absorption: exciting an electron to a higher energy level by absorbing a photon
- Emission: electron relaxing to a lower energy state by emitting a photon

Band-to-Band Transition

Since most electrons and holes are near the band -edges, the photon energy of band-to-band (or interband) transition is approximately equal to the bandgap energy:

$$h\nu = E_g$$

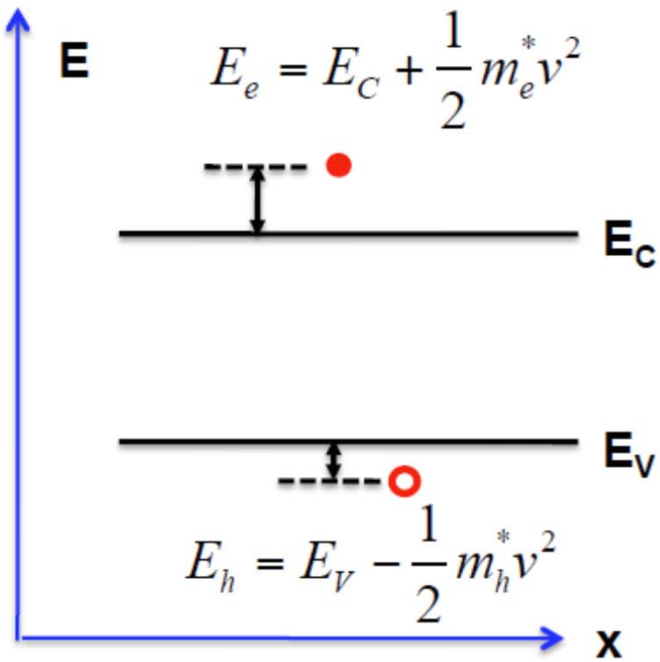
The optical wavelength of band-to-band transition can be approximated by

$$\lambda = \frac{c}{\nu} = \frac{hc}{E_g} \approx \frac{1.24}{E_g}$$

λ : wavelength in μm

E_g : energy bandgap in eV

Energy Band Diagram in Real Space and k-Space



$$E_e = E_C + \frac{1}{2} m_e^* v^2$$

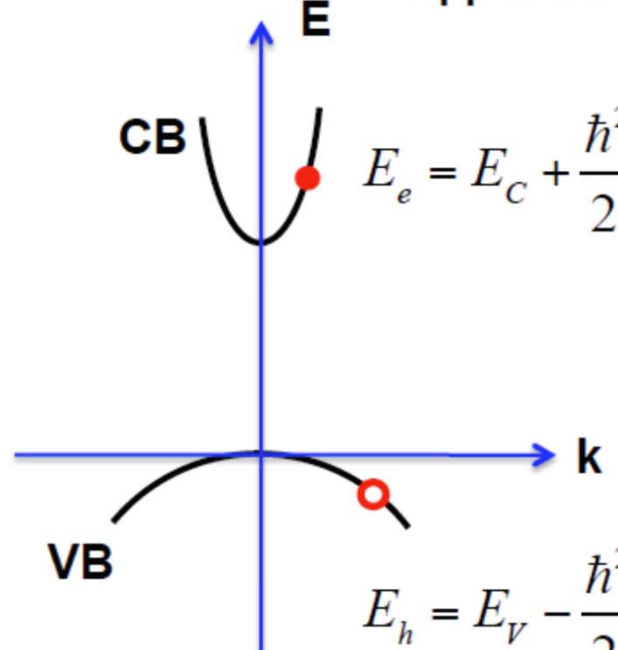
$$E_h = E_V - \frac{1}{2} m_h^* v^2$$

Real Space

Momentum:

$$\hbar k = m_e^* v_e$$

Effective Mass Approximation

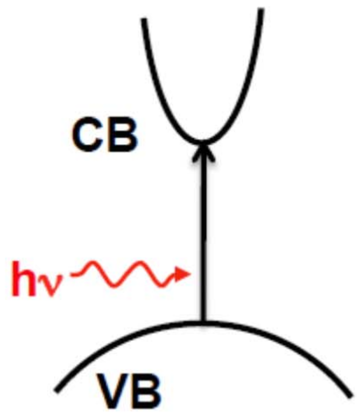


$$E_e = E_C + \frac{\hbar^2 k^2}{2m_e^*}$$

$$E_h = E_V - \frac{\hbar^2 k^2}{2m_h^*}$$

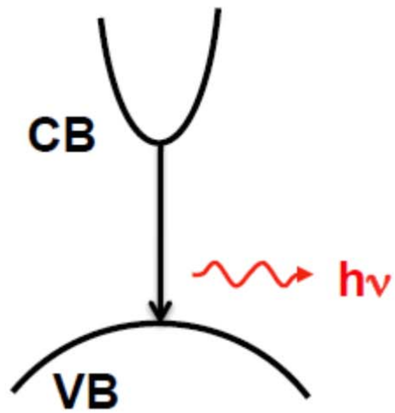
K-Space

Band-to-Band Transition



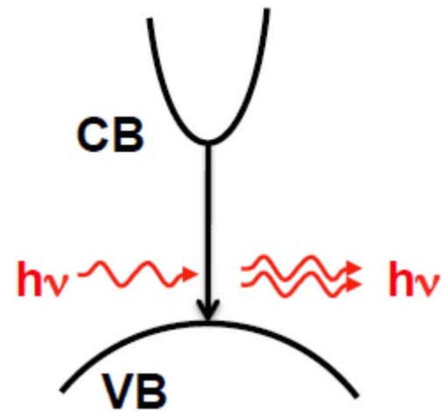
Absorption

Photodetectors;
Solar Cells



Spontaneous
Emission

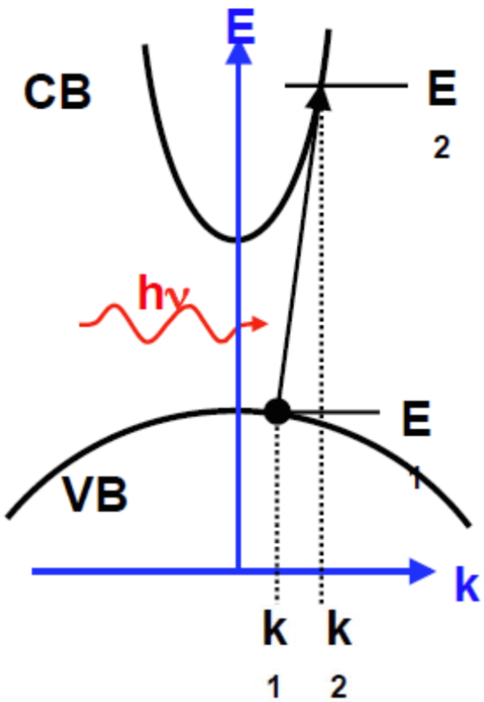
LED



Stimulated
Emission

Optical Amplifiers;
Semiconductor Lasers

Conservation of Energy and Momentum



Optical transitions are "vertical" lines

- Conditions for optical absorption and emission:
  - Conservation of energy

$$\boxed{E_2 - E_1 = h\nu}$$

  - Conservation of momentum

$$k_2 - k_1 = k_{h\nu}$$

$$k_2, k_1 \sim \frac{2\pi}{a}$$

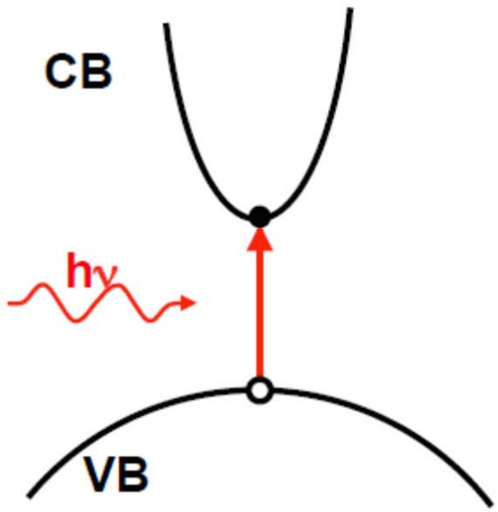
$$k_{h\nu} \sim \frac{2\pi}{\lambda}$$

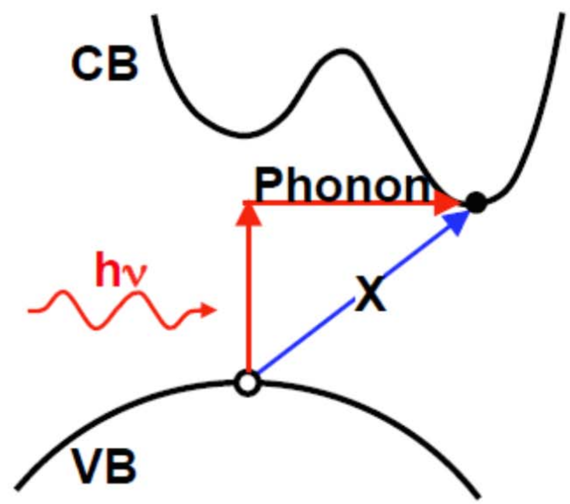
$$(a \sim 0.5nm) << (\lambda \sim 1\mu m)$$

Lattice Constant

$$\Rightarrow \boxed{k_2 = k_1}$$

Direct vs Indirect Bandgaps





- Direct bandgap materials
  - CB minimum and VB maximum occur at the same k
  - Examples
    - GaAs, InP, InGaAsP
    - $(Al_xGa_{1-x})As$, $x < 0.45$
- Indirect bandgap materials
  - CB minimum and VB maximum occur at different k
  - Example
    - Si, Ge
    - $(Al_xGa_{1-x})As$, $x > 0.45$
  - Not "optically active"