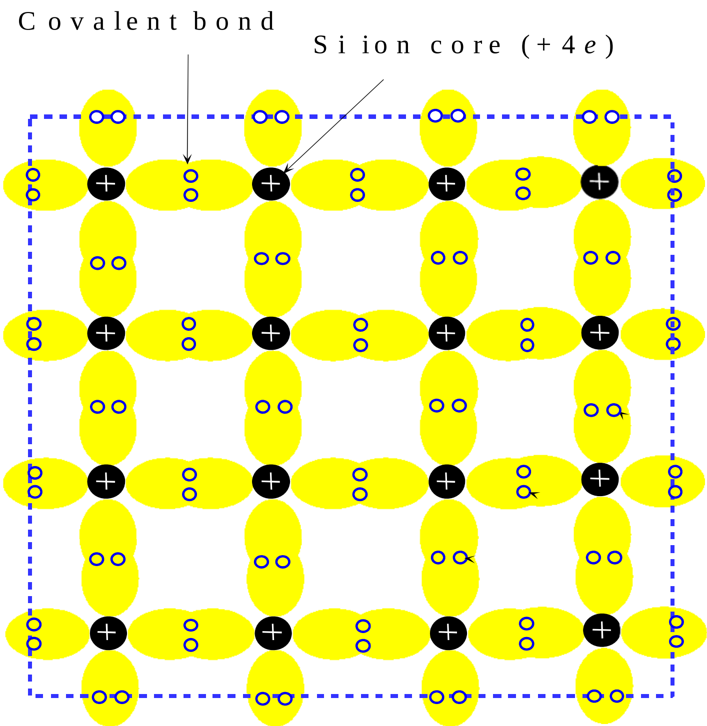
Lect. 21: Semiconductors

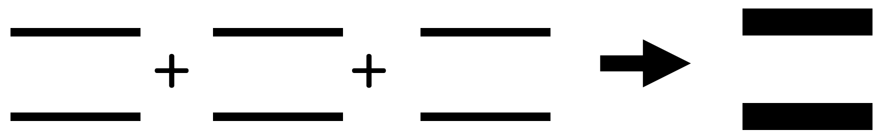
Si lattice structure



Electron energy levels in semiconductors

Electrons in each Si atom have discrete energy levels.

But in Si crystal, energy bands are formed.



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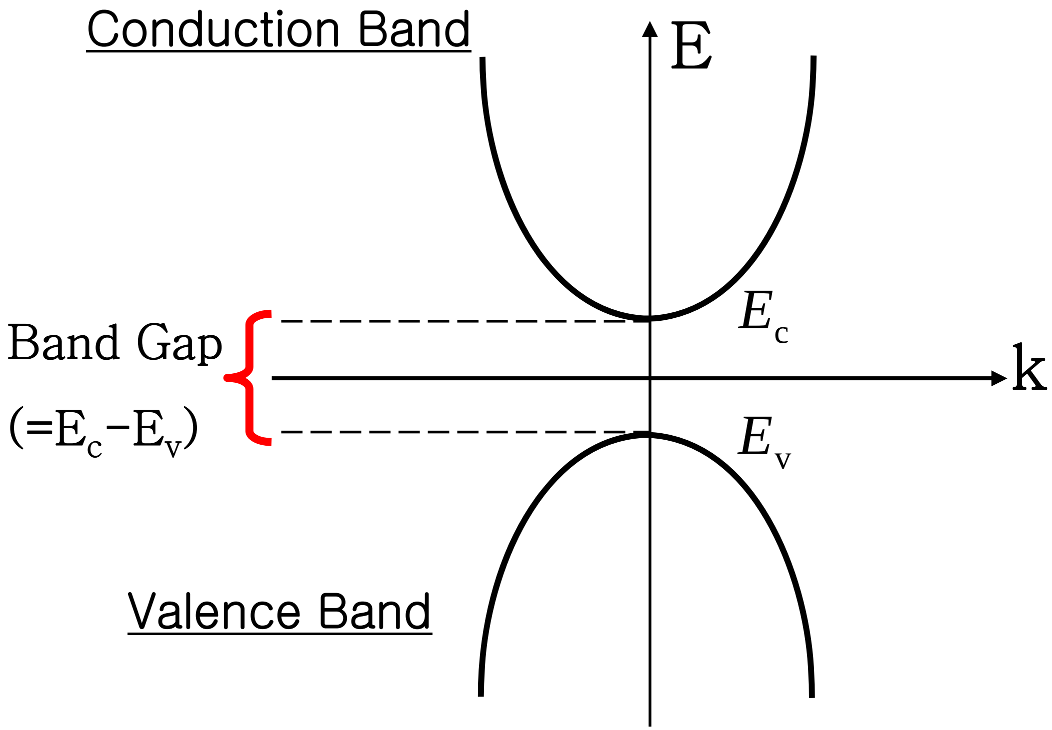
Band diagram

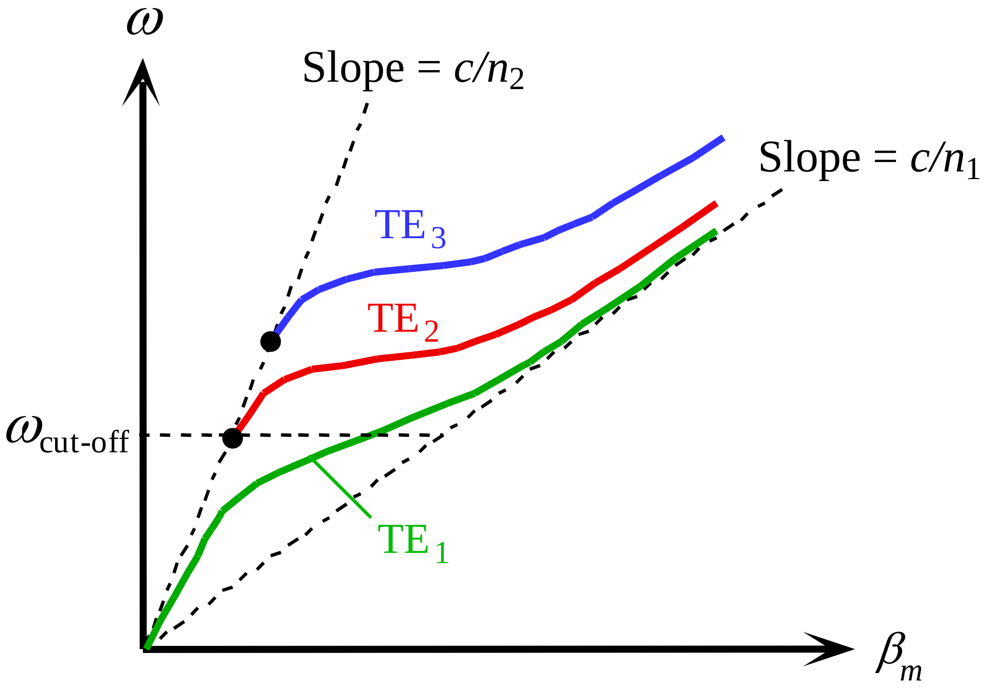


E vs k ?

$$E = h\nu = \frac{h}{2\pi}\omega = \hbar\omega$$

ω vs k : Fourier transform domain descripton of t vs $\overline{\mathrm{r}}$

Often used for ‘wave’ characterization

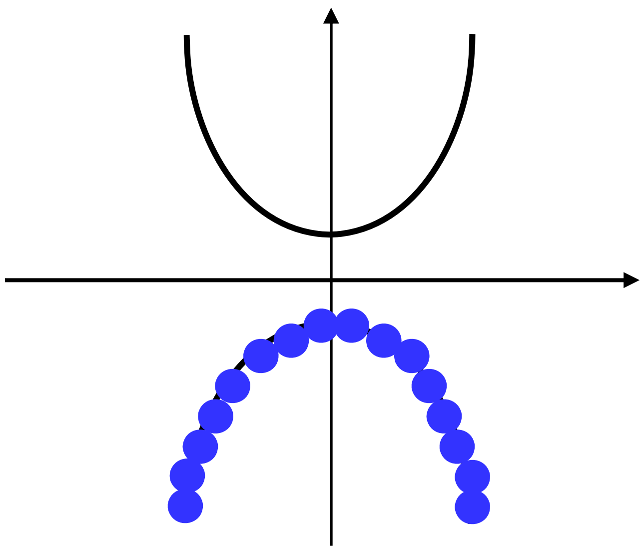


EM waves in a dielectric waveguide

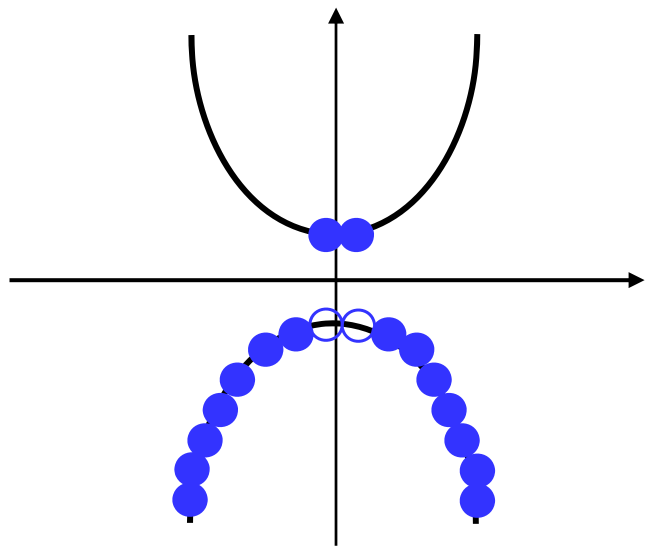
Lect. 21: Semiconductors

Where are electrons?

T=0 K



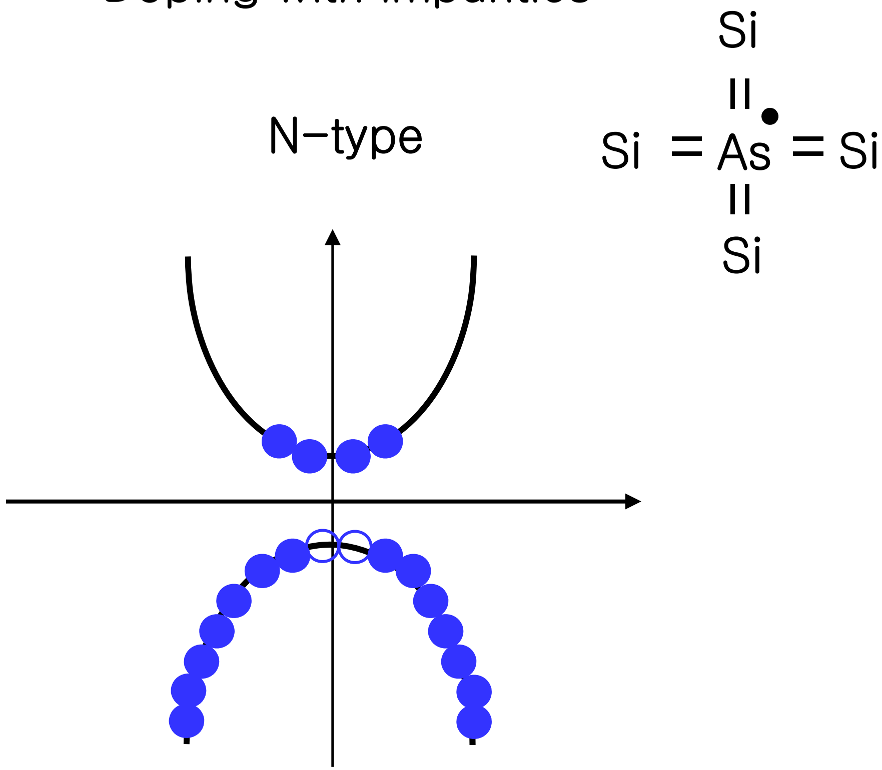
T > 0 K



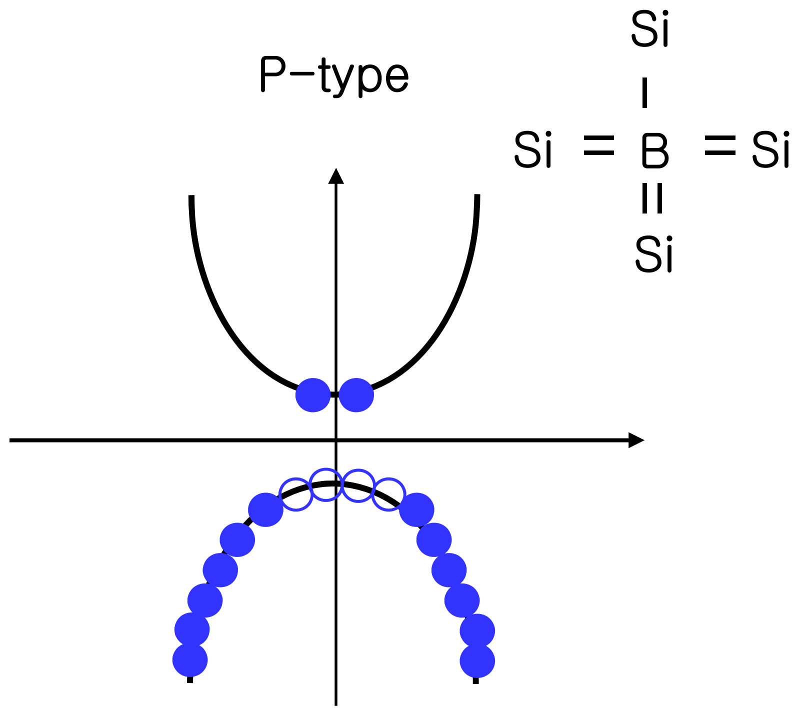
no electrons in conduction band
➔ many holes in conduction band

same number of electrons in conduction band as holes in valence band

Doping with impurities



More electrons in conduction band than holes in valence band



More holes in valence band than electrons in conduction band

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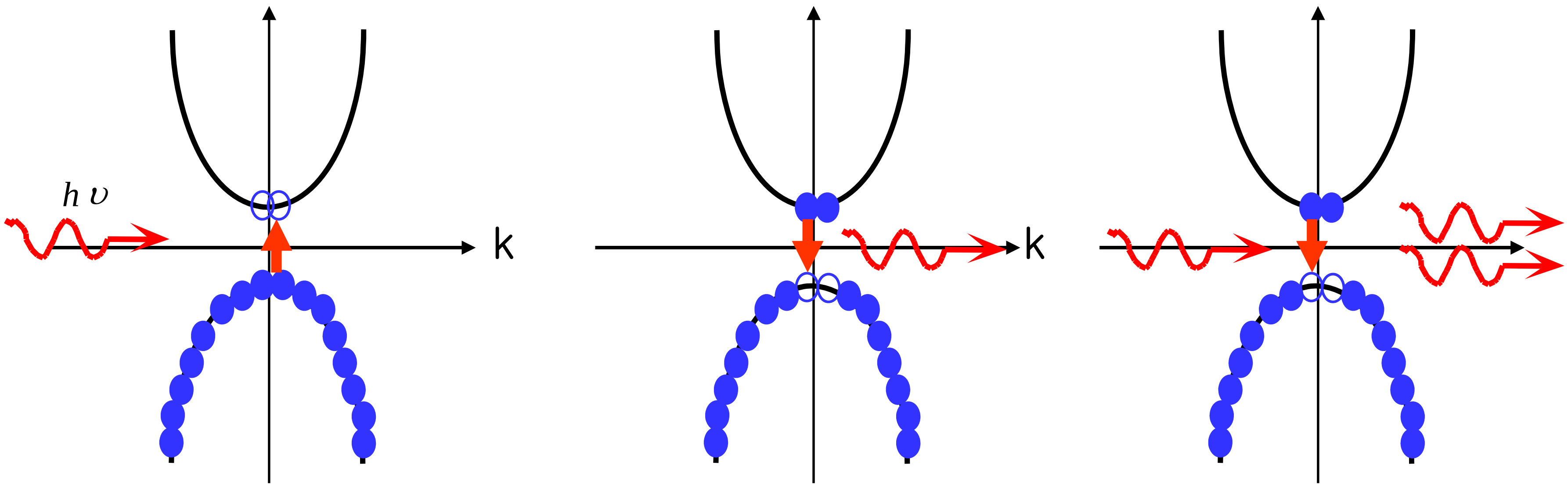
Interaction of light with semiconductor

Absorption | Spontaneous Emission | Stimulated Emission

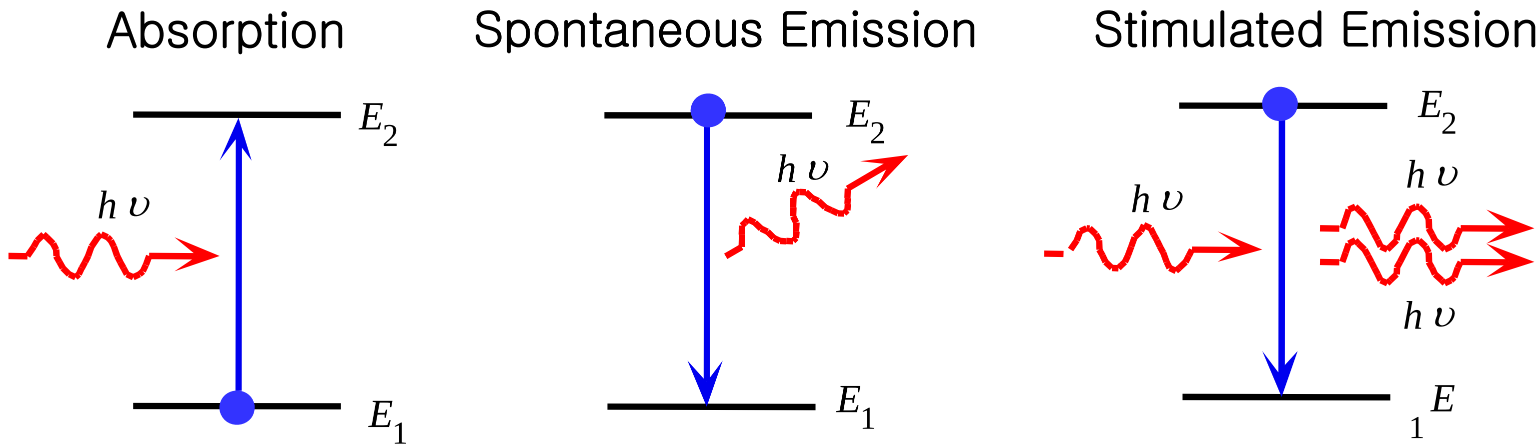


hν > Eg

Momentum (k) conservation required for photon emission

Lect. 21: Semiconductors

Remember



$$R_{12} = B_{12} \cdot N_1 \cdot \rho \qquad R_{sp} = A_{21} \cdot N_2 \qquad R_{21} = B_{21} \cdot N_2 \cdot \rho$$

ρ : photon density

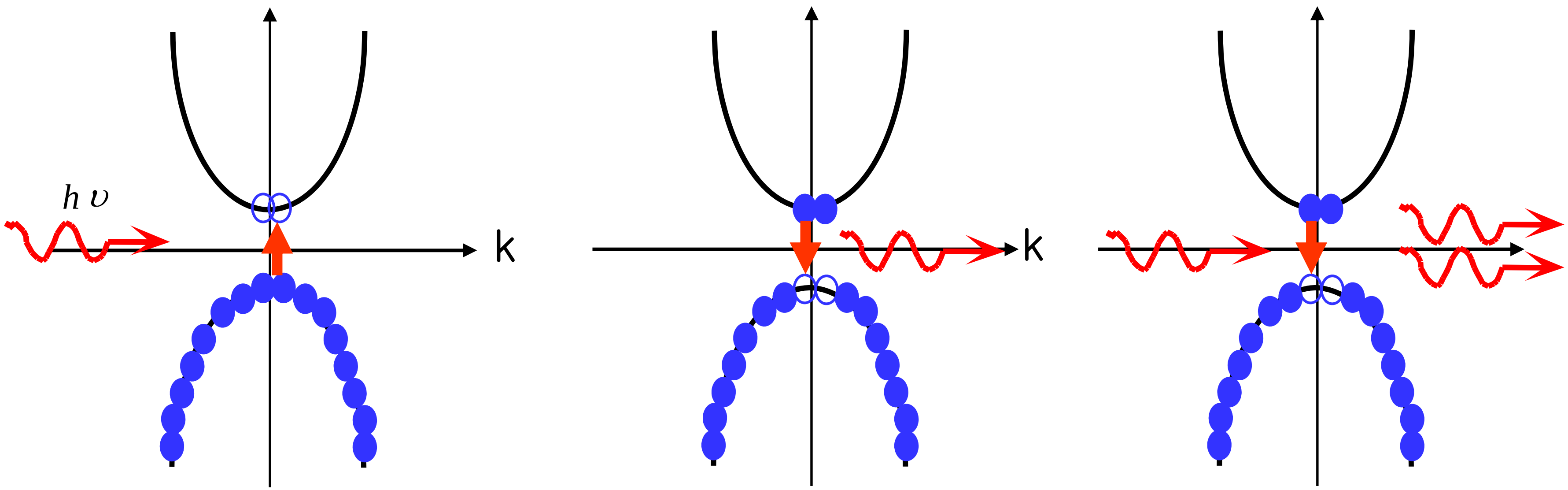
$N_{1,2}$: electron density at $E_{1,2}$

B_{12}, B_{sp}, B_{21} : constants

For population inversion, $\dfrac{N_2}{N_1} > 1$

Lect. 21: Semiconductors

Absorption | Spontaneous Emission | Stimulated Emission



$R_{12}(h\nu) = B_{12} \cdot N_1(E_1) \cdot P_2(E_2) \cdot \rho(h\nu)$ $R_{sp}(h\nu) = A_{21} \cdot N_2(E_2) \cdot P_1(E_1)$ $R_{21}(h\nu) = B_{21} \cdot N_2(E_2) \cdot P_1(E_1) \cdot \rho(h\nu)$

Optical gain for $E_{ph} = E_2 - E_1$ is proportional to $N_2(E_2) \cdot P_1(E_1) - N_1(E_1) \cdot P_2(E_2)$

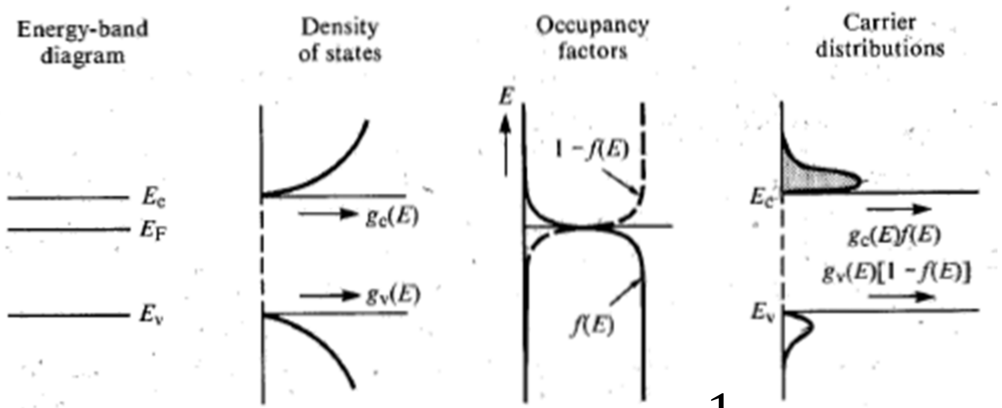
Population inversion:

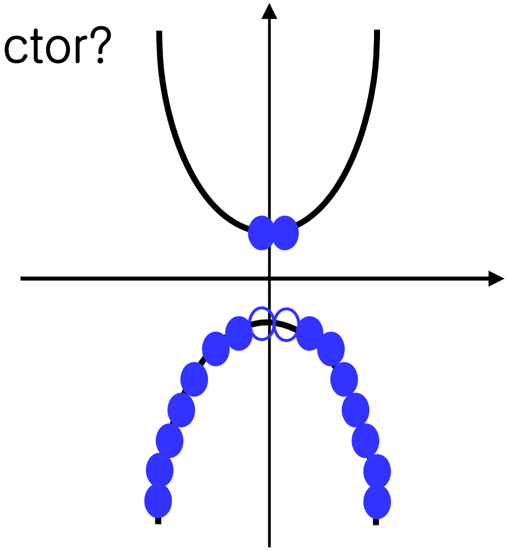
$$\frac{N_2(E_2) \cdot P_1(E_1)}{N_1\left(E_1\right) \cdot P_2(E_2)} > 1$$

Electron and hole injection needed

Lect. 21: Semiconductors

What determines electron/hole concentrations in semiconductor?





Fermi factor (equilibrium) $f(E) = \dfrac{1}{1+e^{(E-E_F)/kT}}$;

With carrier pumping (non-equilibrium) $f_n(E) = \dfrac{1}{1+e^{(E-E_{Fn})/kT}}$, $f_p(E) = \dfrac{1}{1+e^{(E-E_{Fp})/kT}}$

➔ Quasi Fermi factor

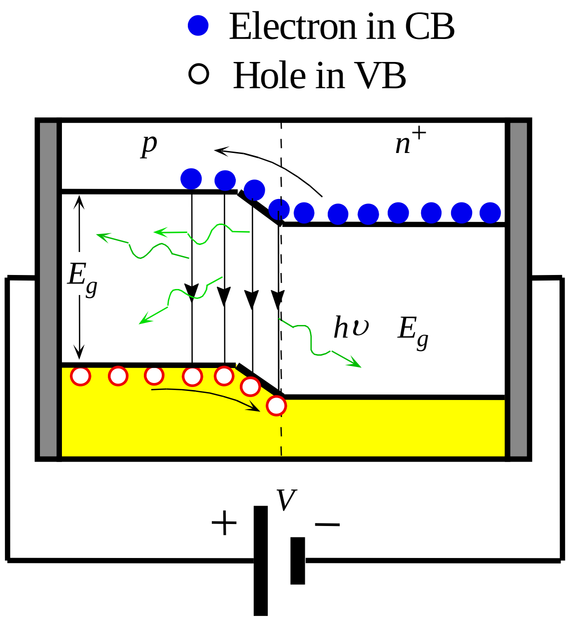
$$N = \int_{E_c}^{\infty} g_c(E) f_n(E)\, dE \quad P = \int_{-\infty}^{E_v} g_v(E)\left[1 - f_p(E)\right] dE$$

Optical Gain for g(E_{ph}= E_2−E_1) $\sim \left[N_2(E_2)\cdot P_1(E_1) - N_1(E_1)\cdot P_2(E_2)\right]$

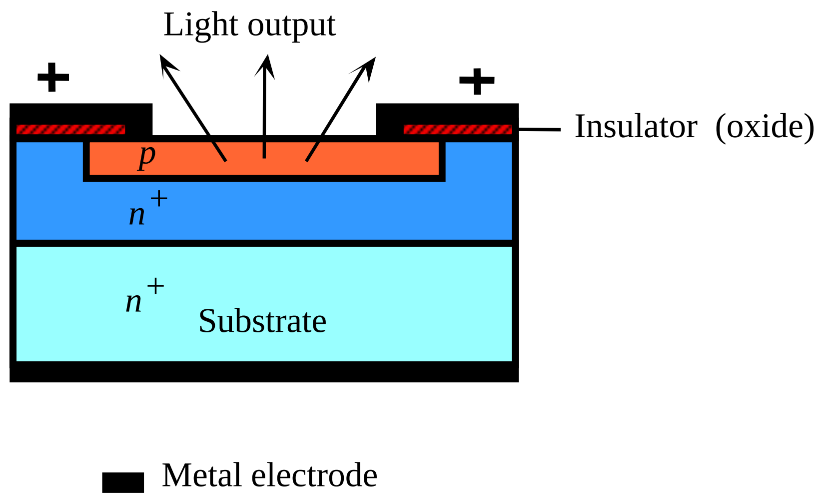
$$= g_c(E_2) f_n(E_2) g_v(E_1)\left[1 - f_p(E_1)\right] - g_v(E_1) f_n(E_1) g_c(E_2)\left[1 - f_p(E_2)\right]$$

Lect. 21: Semiconductors

How to pump electrons and holes into a semiconductor? Forward-bias PN junction



Light emitting diode (LED)



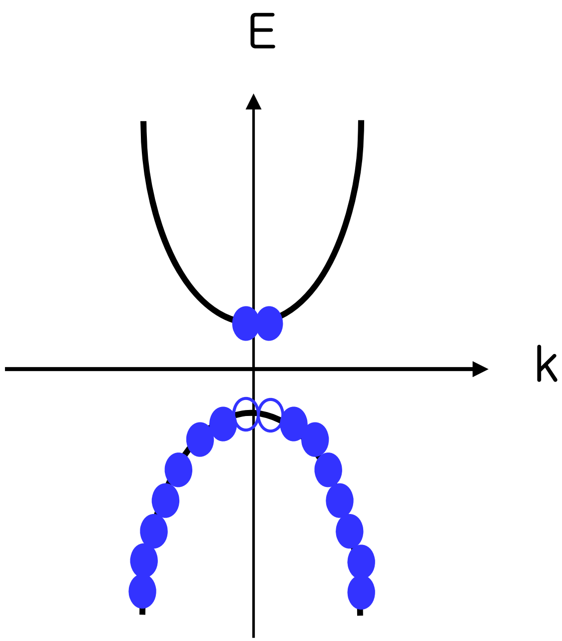
Light emission by spontaneous emission

Does any semiconductor emit light?

What determines the color of LED?

Lect. 21: Semiconductors

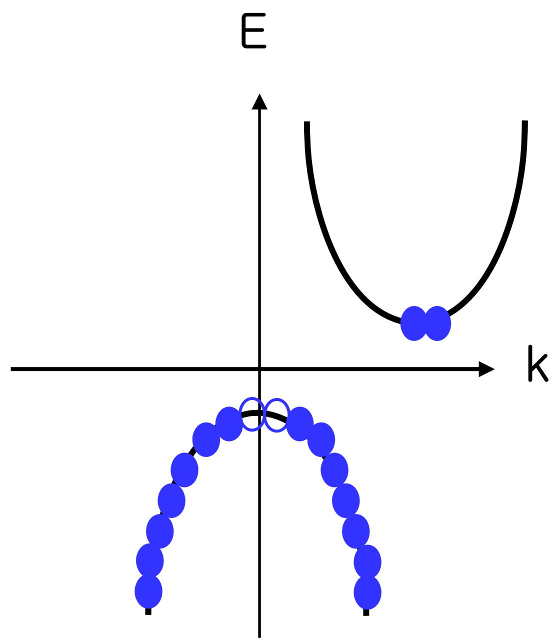
Direct semiconductor



K-selection rule:

$k_{photon} = k_i - k_f \ \ (k_i \sim k_f)$

Indirect Semiconductor

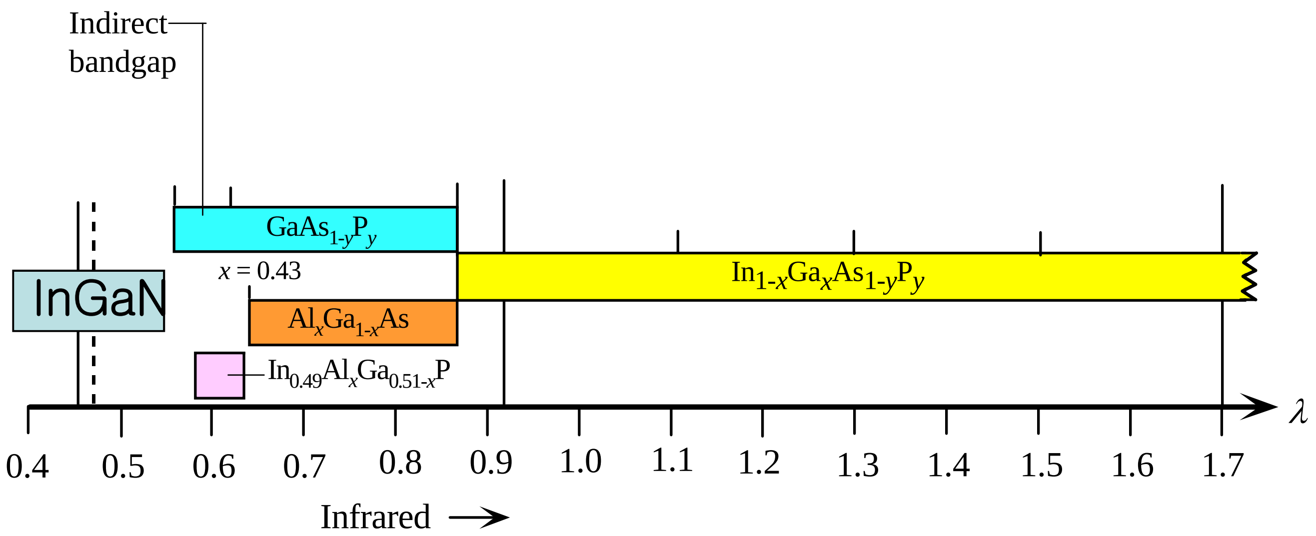


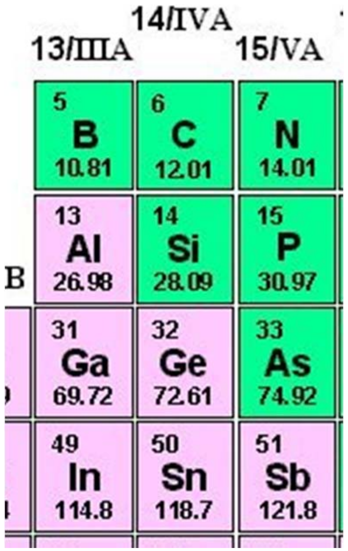
Momentum conservation not possible by photon emission

=> No emission (Example: Si)

Lect. 21: Semiconductors

Bandgap energies for major LED materials: III-V compound semiconductor





Lect. 21: Semiconductors

The Nobel Prize in Physics 2014

Photo: Yasuo Nakamura/Meijo University

Isamu Akasaki

Prize share: 1/3

Photo: Nagoya University

Hiroshi Amano

Prize share: 1/3

Ill. N. Elmehed. © Nobel Media 2014

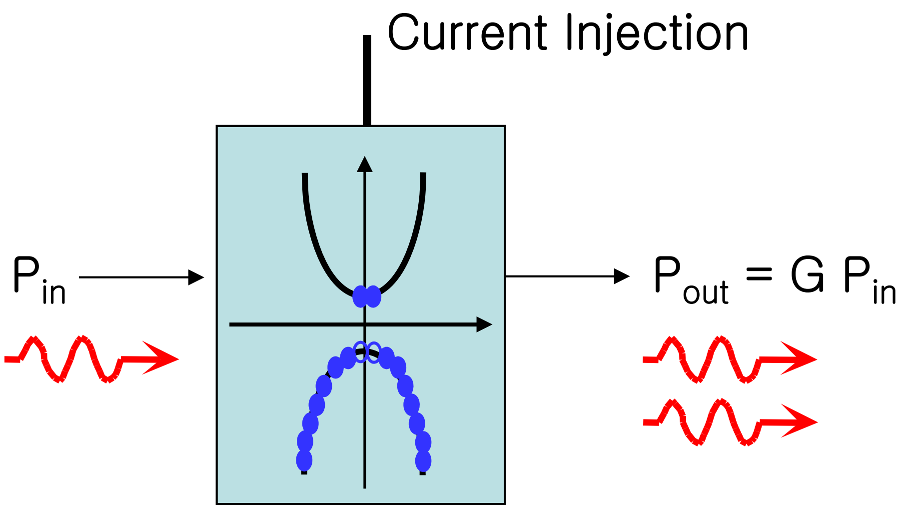
Shuji Nakamura

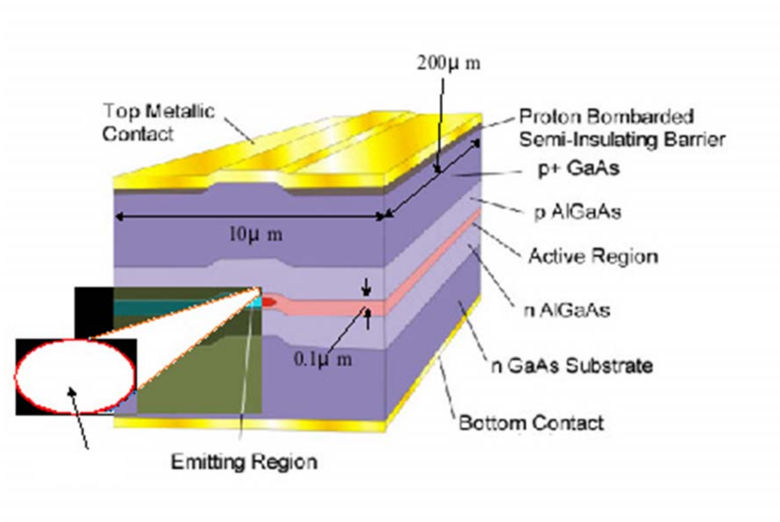
Prize share: 1/3

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*.

Lect. 21: Semiconductors

Current injection into PN Junction can be used for Semiconductor Optical Amplifier



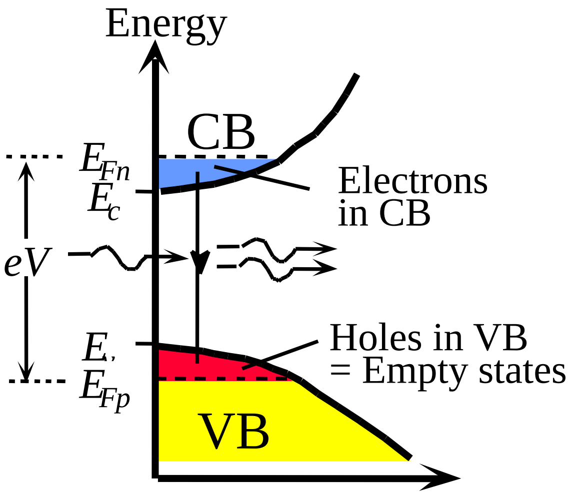


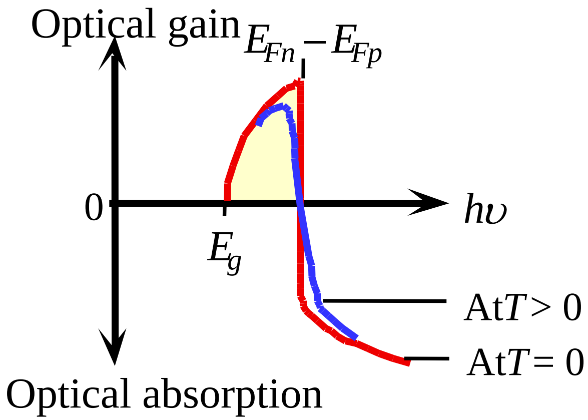
W.-Y. Choi

Lect. 21: Semiconductors

Gain spectrum

$$g(E_2 - E_1) \sim g_c(E_2) f_n(E_2) g_v(E_1)\left[1 - f_p(E_1)\right] - g_v(E_1) f_n(E_1) g_c(E_2)\left[1 - f_p(E_2)\right]$$





- 0 gain for $E_2 - E_1 < E_g$
- For $E_2 - E_1 > E_g$, gain increases until around $h\nu = E_{Fn} - E_{Fp}$
- Gain < 0 for $h\nu > E_{Fn} - E_{Fp}$
- Sharper transition at lower T

Lect. 21: Semiconductors

Homework:

Assume the optical gain coefficient in semiconductor is given as
$g=a(N-N_0)$ [1/cm], where $a=10^{-17}cm^2$, $N_0=10^{18}cm^{-3}$ for $\lambda = 1\mu m$.

If 0.5cm long SOA is made up of above semiconductor,
what is the required carrier density in order to achieve SOA power gain of 20dB
for $\lambda = 1\mu m$ input signal?