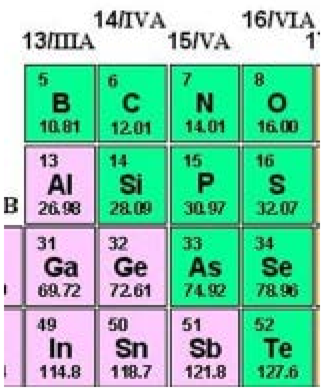
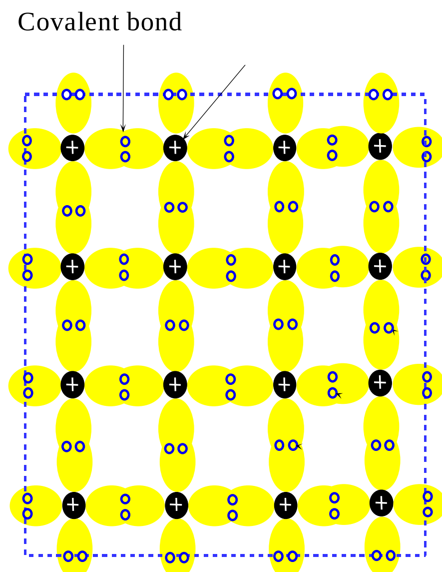
Lect. 23: Optical Gain in Semiconductor

Electron energy levels in semiconductors?

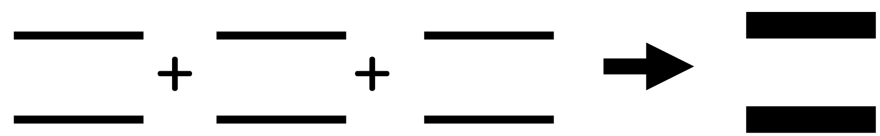
GaAs (III-V Semiconductor)





Electrons in each atom have discrete energy levels.

But in a semiconductor crystal, energy bands are formed.



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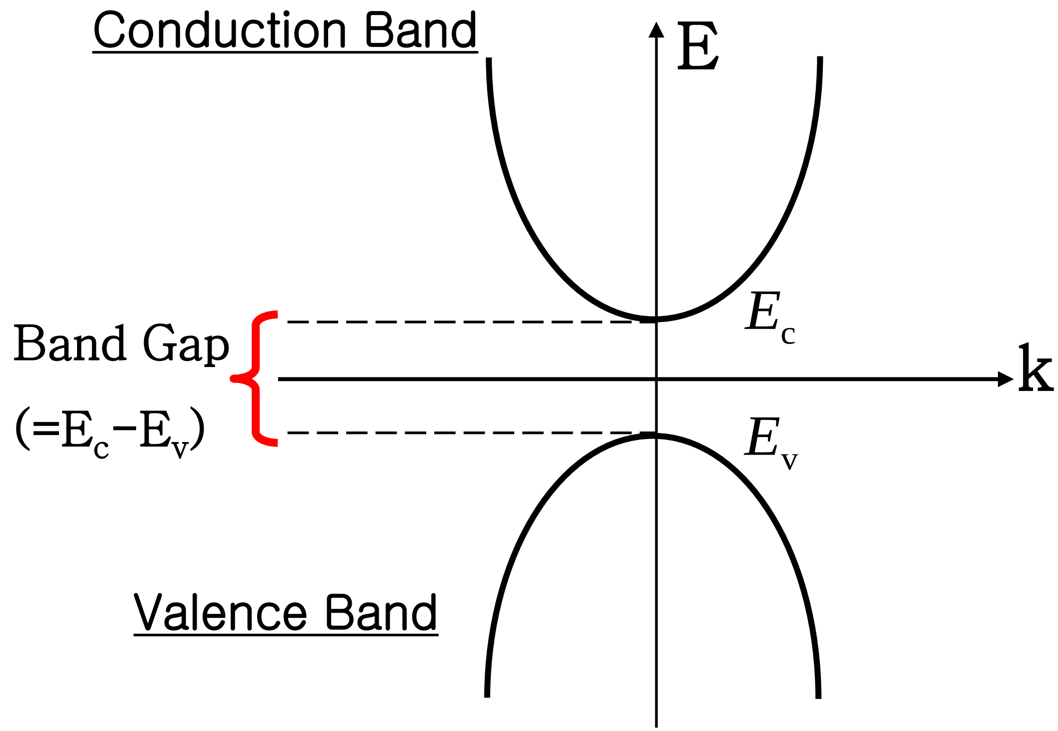


E vs k ?

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

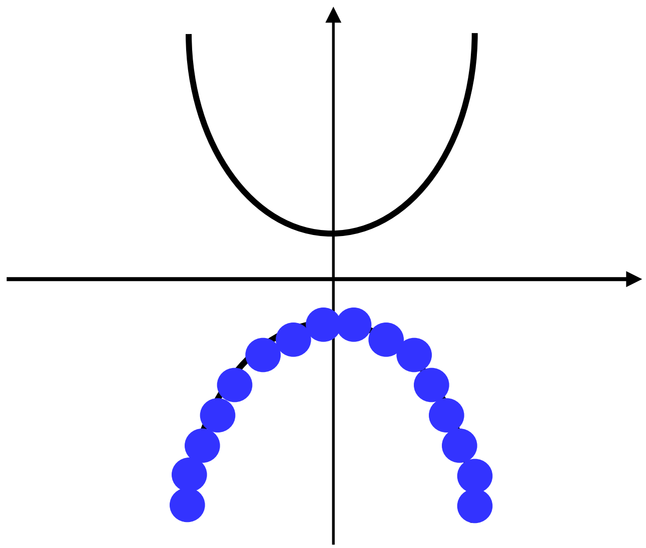
ω vs k : Fourier transform domain descripton of t vs $\bar{r}$

Often used for representing 'wave' characteristics

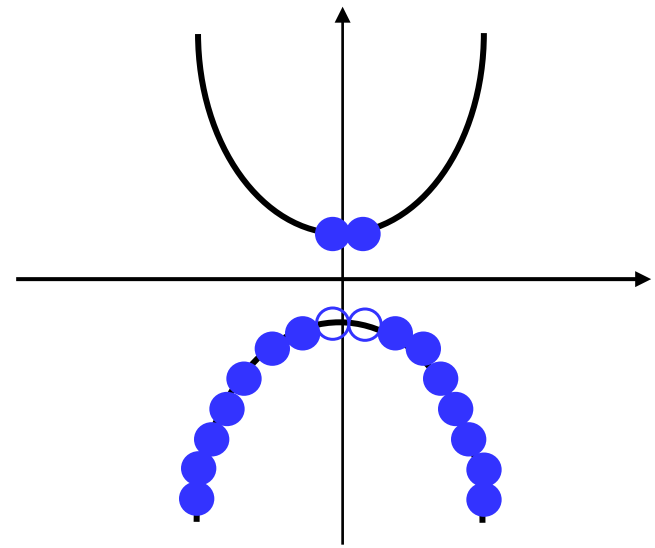
Lect. 23: Optical Gain in Semiconductor

Where are electrons?

T=0 K



T > 0 K



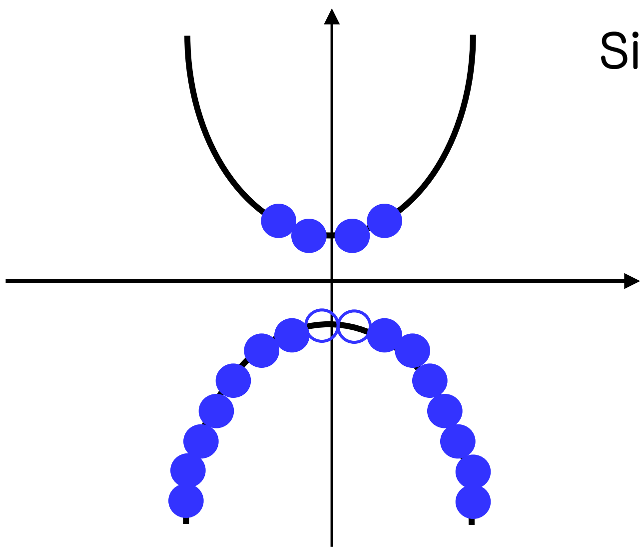
no electrons in conduction band
➔ many holes in conduction band

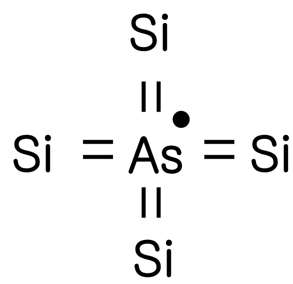
same number of electrons in conduction band
as holes in valence band

Lect. 23: Optical Gain in Semiconductor

Doping with impurities

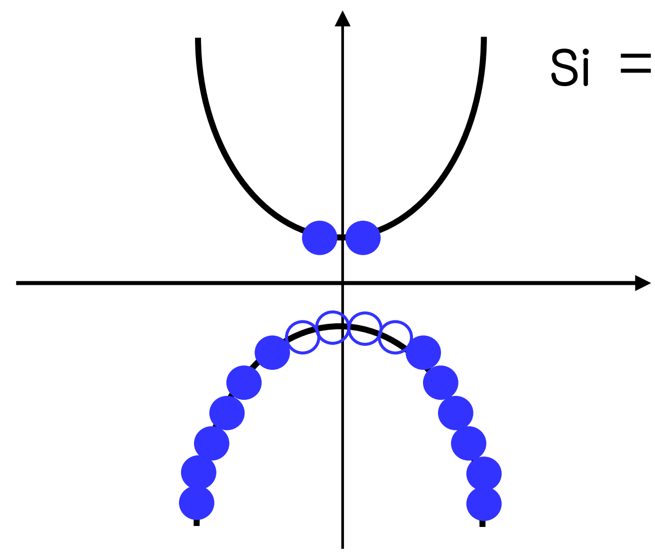
N−type

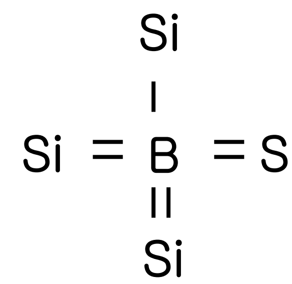




More electrons in conduction band
than holes in valence band

P−type



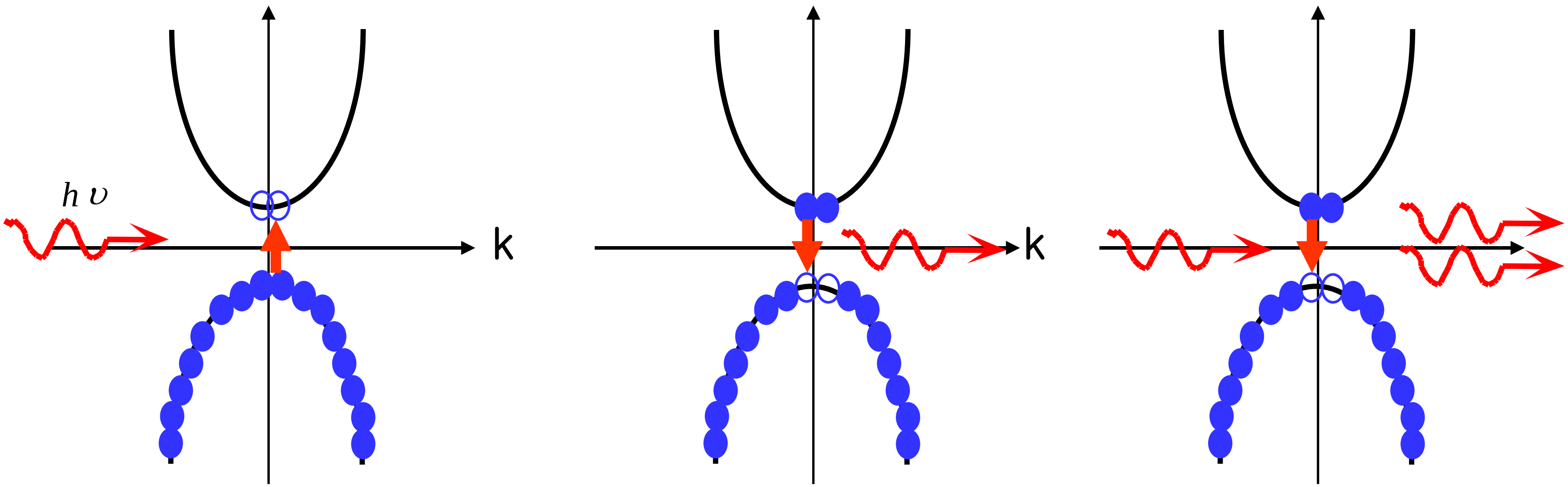


More holes in valence band
than electrons in conduction band

Lect. 23: Optical Gain in Semiconductor

Interaction of light with semiconductor

Absorption | Spontaneous Emission | Stimulated Emission

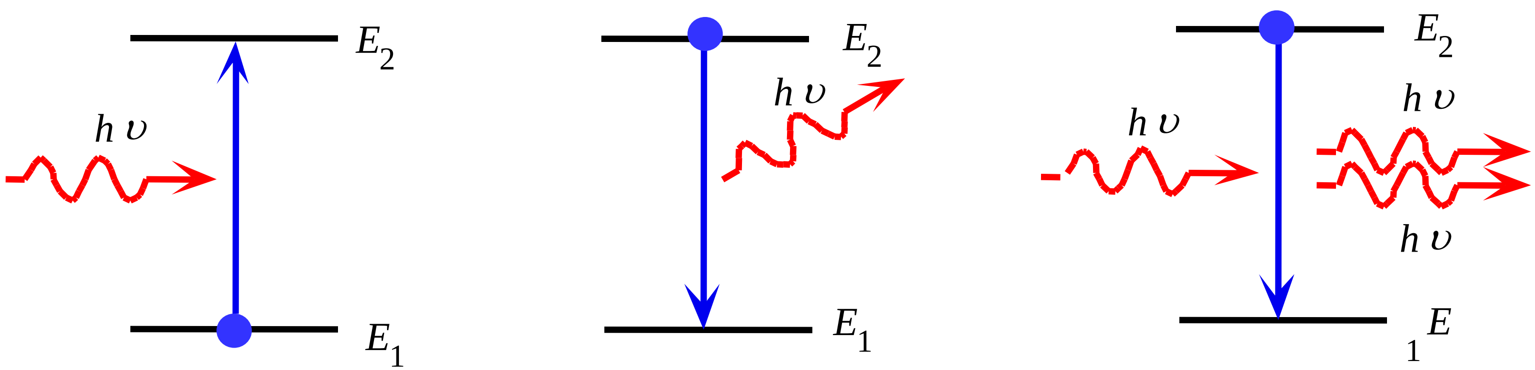


hν > Eg

Momentum (k) conservation required for photon emission

Remember

Absorption | Spontaneous Emission | Stimulated Emission



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

ρ : photon density

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

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

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

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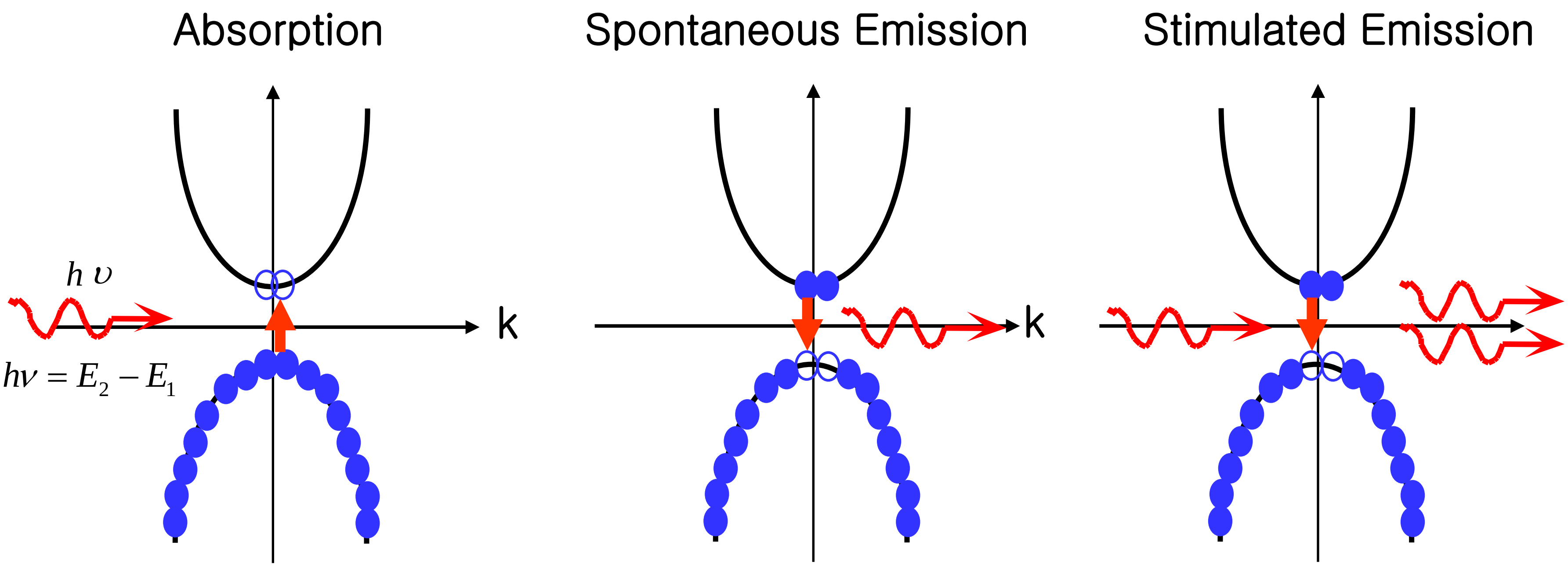
Lect. 23: Optical Gain in Semiconductor



$R_{12}(h\nu) = B_{12} \cdot N_1(E_1) \cdot P_2(E_2) \cdot \rho(h\nu)$

$R_{sp}(h\nu) = A_{21} \cdot N_2(E_2) \cdot P_1(E_1)$

$R_{21}(h\nu) = B_{21} \cdot N_2(E_2) \cdot P_1(E_1) \cdot \rho(h\nu)$

Interaction for photons having many different energies are possible

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:

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

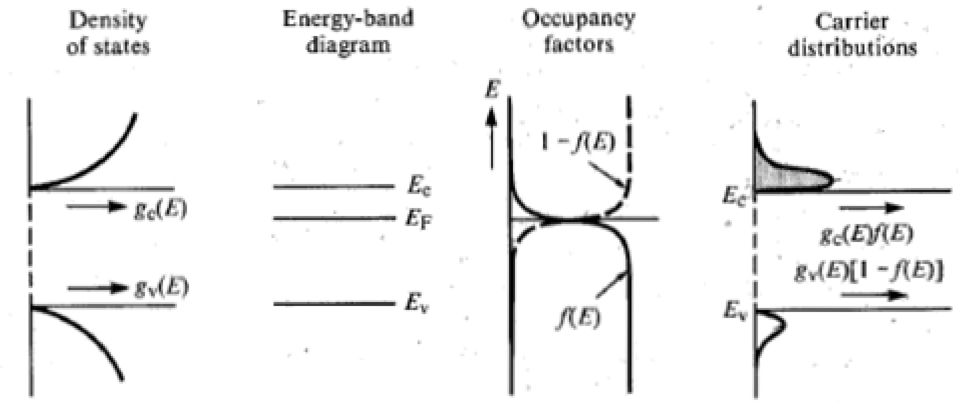
Electron and hole injection (pumping) needed

Lect. 23: Optical Gain in Semiconductor

What determines electron/hole concentrations in semiconductor?

Density of States (DOS) and Fermi factor

DOS: Number(Density) of states an electron can exist
at a given energy. Proportional to sqrt(E).



$$N = \int_{E_c}^{\infty} g_c(E) f(E)\, dE$$

$$P = \int_{-\infty}^{E_v} g_v(E)\left[1 - f(E)\right] dE$$

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

Probability for an electron to exist at a given energy level

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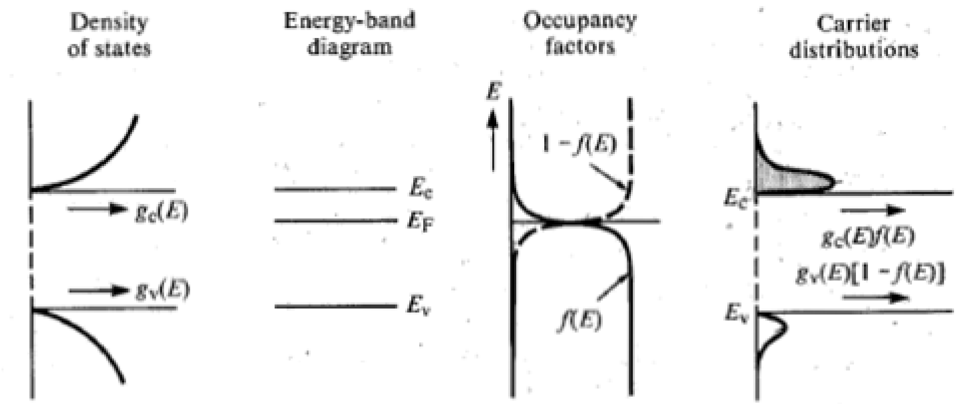
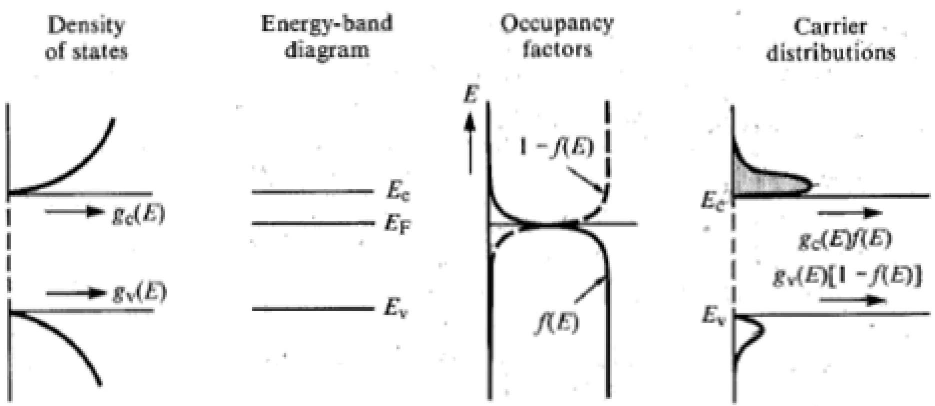


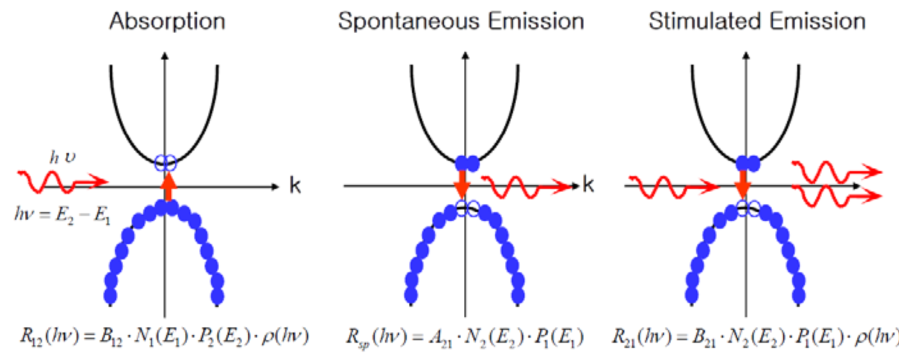
What happens with pumping?

Separate Fermi factors for electrons and holes (Quasi Fermi factor)

$$f_n(E) = \frac{1}{1 + e^{(E - E_{Fn})/kT}}, \quad f_p(E) = \frac{1}{1 + e^{(E - E_{Fp})/kT}}$$

Lect. 23: Optical Gain in Semiconductor





Optical Gain for $E_{ph} = E_2 - E_1$

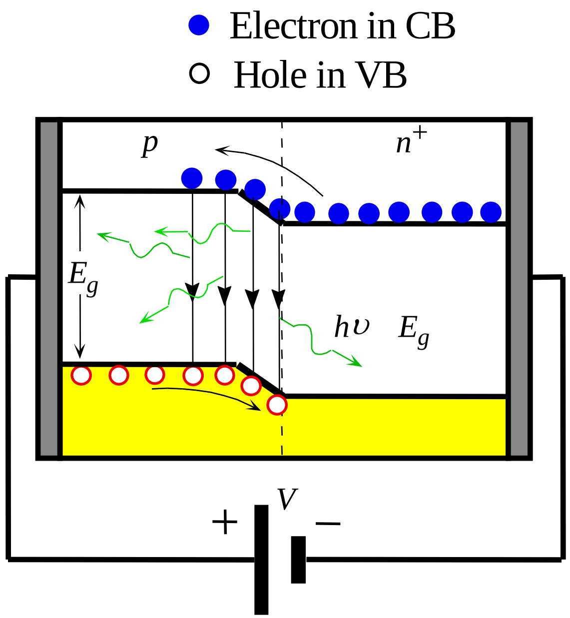
$$g(E_2 - E_1) \sim \left[N_2(E_2) \cdot P_1(E_1) - N_1(E_1) \cdot P_2(E_2) \right]$$

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

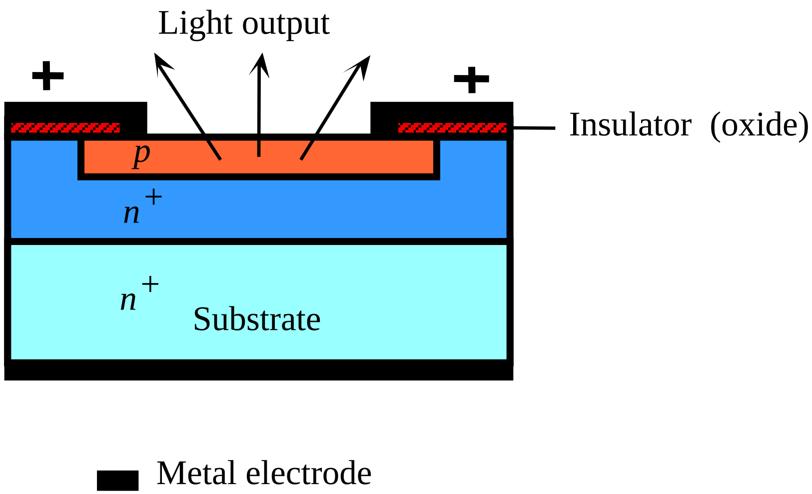
Lect. 23: Optical Gain in Semiconductor

How to pump electrons and holes into a semiconductor?

Forward-bias PN junction



Light emitting diode (LED)



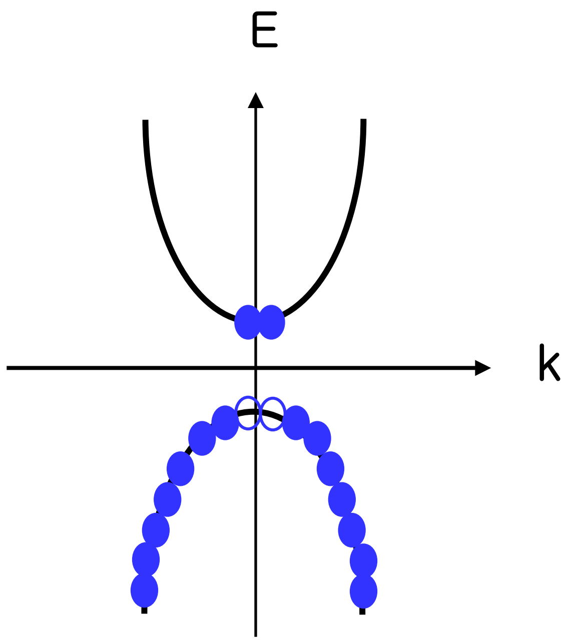
Light emission by spontaneous emission

Does any semiconductor emit light?

What determines the color of LED?

Lect. 23: Optical Gain in Semiconductor

Direct semiconductor

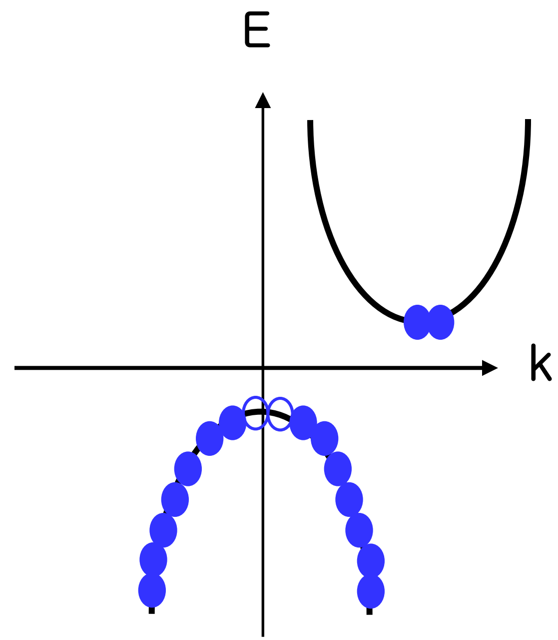


K-selection rule:

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

=> Light emission (Example: GaAs)

Indirect Semiconductor

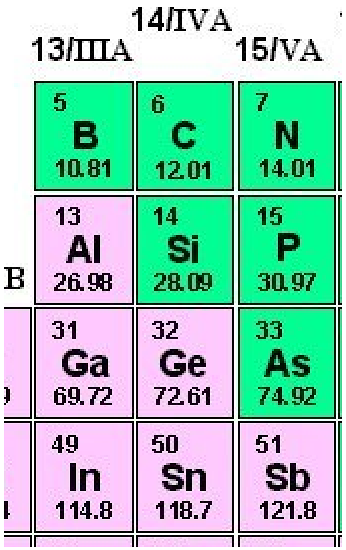


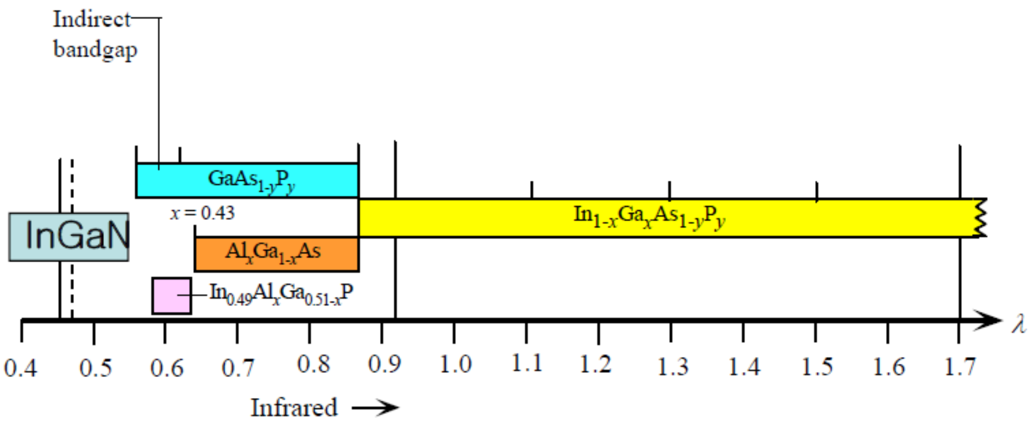
Momentum conservation not possible by photon emission

=> No emission (Example: Si)

Lect. 23: Optical Gain in Semiconductor

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





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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

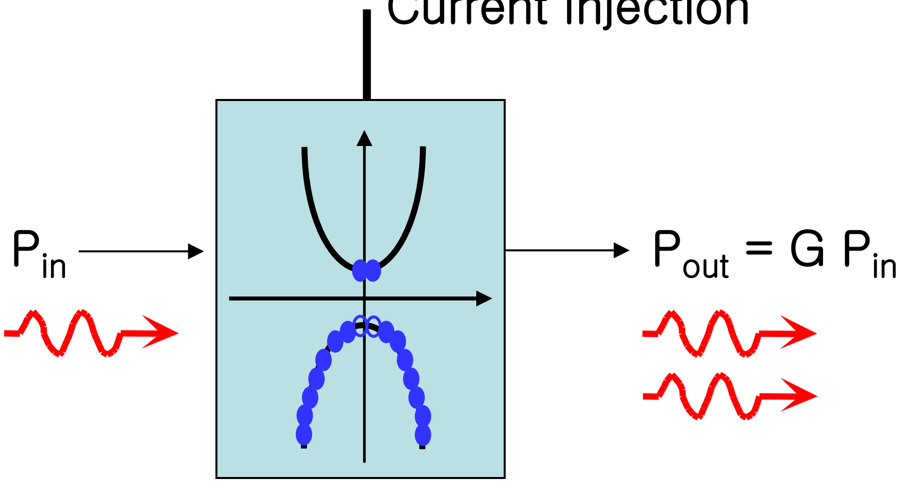
Shuji Nakamura

Prize share: 1/3

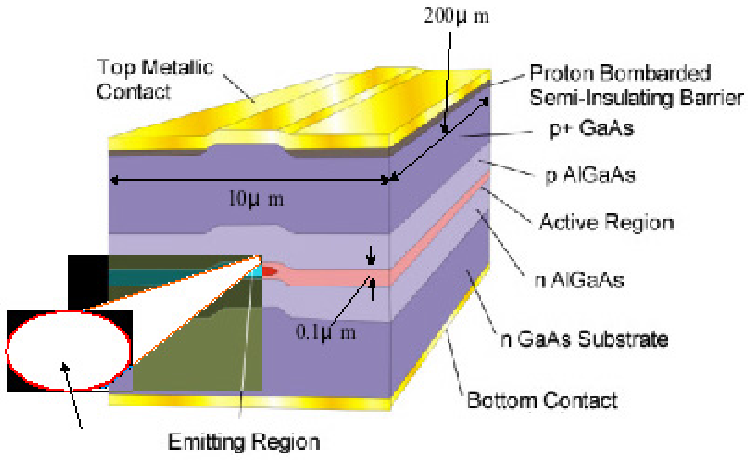
The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources".*

Lect. 23: Optical Gain in Semiconductor

Semiconductor Optical Amplifier: Forward-biased PN Junction



Vertical PN junction with
lateral optical input and output



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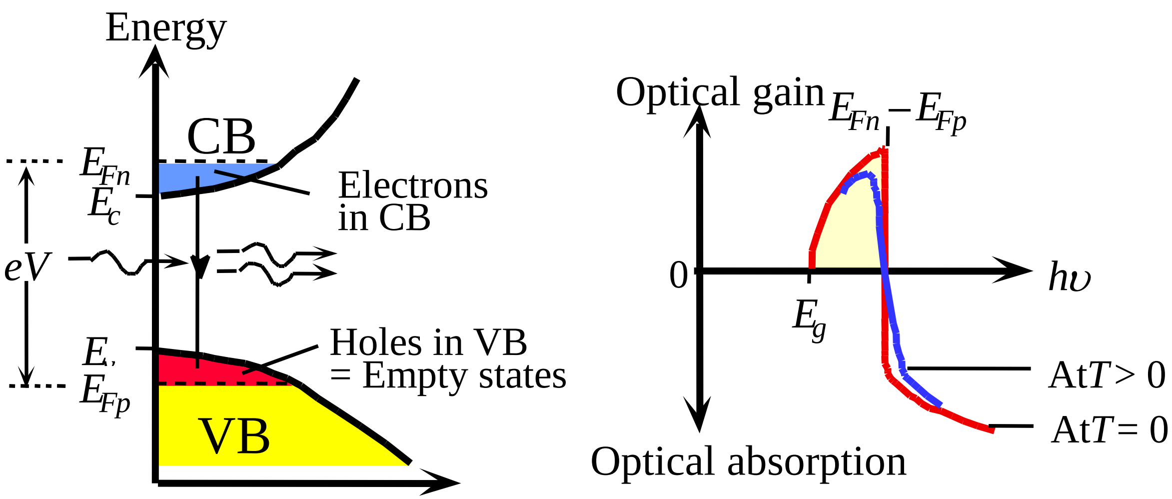
Lect. 23: Optical Gain in Semiconductor

Gain spectrum for optical amplifier

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



- 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

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Homework:

Show that in a semiconductor population inversion is achieved for photons having hν if

$$E_{Fn} - E_{Fp} \geq E_2 - E_1, \text{ where } E_2 - E_1 = h\nu$$

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