FoP 3B Part II

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Room 151

Lecture 6: pn junction (II)

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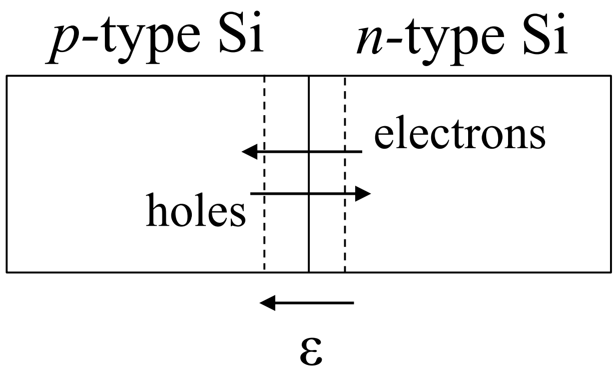
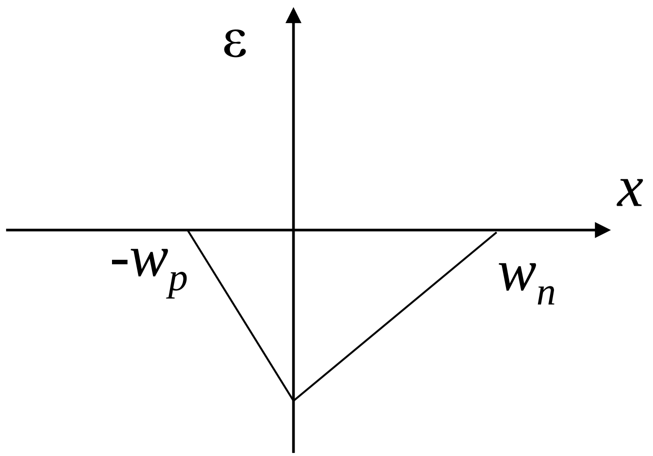
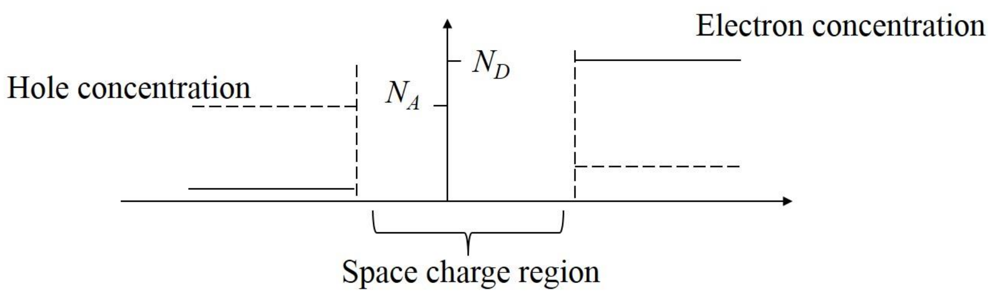
Summary of Lecture 5



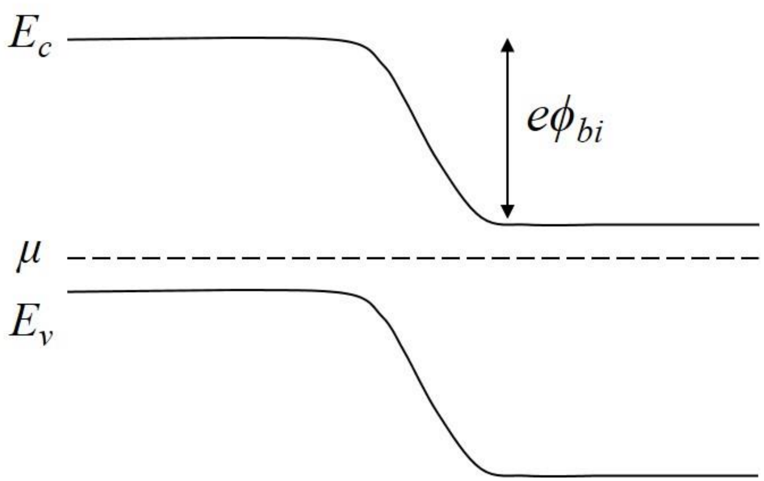
Electric field:



Depletion approximation:



Band bending:



Aim of today's lecture

► Complete analysis of the pn-junction under equilibrium and describe behaviour under electrical biasing

Key concepts:

- -Calculate built-in potential and space charge region widths
- -Forward and reverse bias: rectification
- -Solar cell and light emitting diode devices

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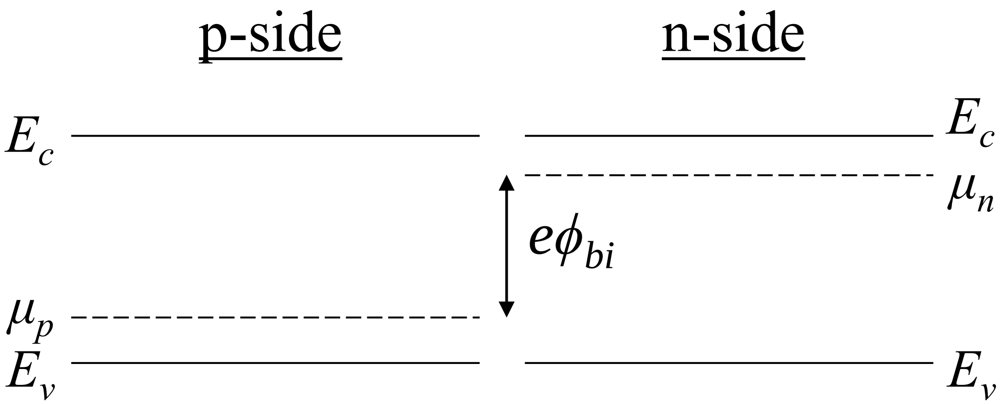
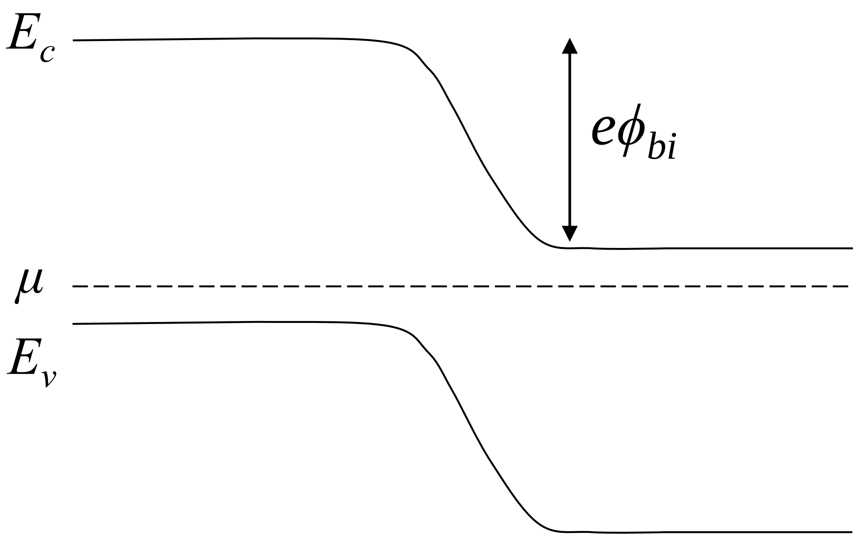
Energy level diagram for pn-junction



Before contact



After contact

$$\phi_{bi} = (\mu_n - \mu_p)/e$$

From lectures 3 and 4:

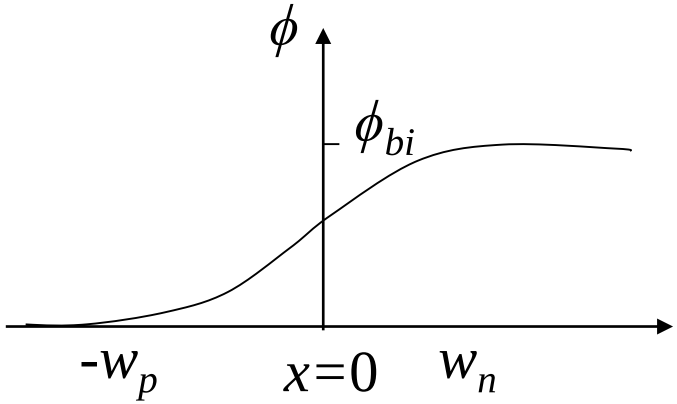
$$\mu_n = E_c - kT\ln\left(\frac{N_c}{N_D}\right)$$

$$\mu_p = E_v + kT\ln\left(\frac{N_v}{N_A}\right)$$

$$np = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

$$\boxed{\therefore\ \phi_{bi} = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

Space charge region widths



$$\phi(x) = \begin{cases} \dfrac{eN_A}{2\epsilon_r\epsilon_0}\left(x + w_p\right)^2 & -w_p < x < 0 \\ \phi_{bi} - \dfrac{eN_D}{2\epsilon_r\epsilon_0}(x - w_n)^2 & 0 < x < w_n \end{cases}$$

Since the potential is continuous at $x = 0$ and using the fact that $N_A w_p = N_D w_n$ (charge conservation) gives:

$$w_n = \left[\frac{2\epsilon_r\epsilon_0\phi_{bi}}{e}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

$$w_p = \left[\frac{2\epsilon_r\epsilon_0\phi_{bi}}{e}\left(\frac{N_D}{N_A}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

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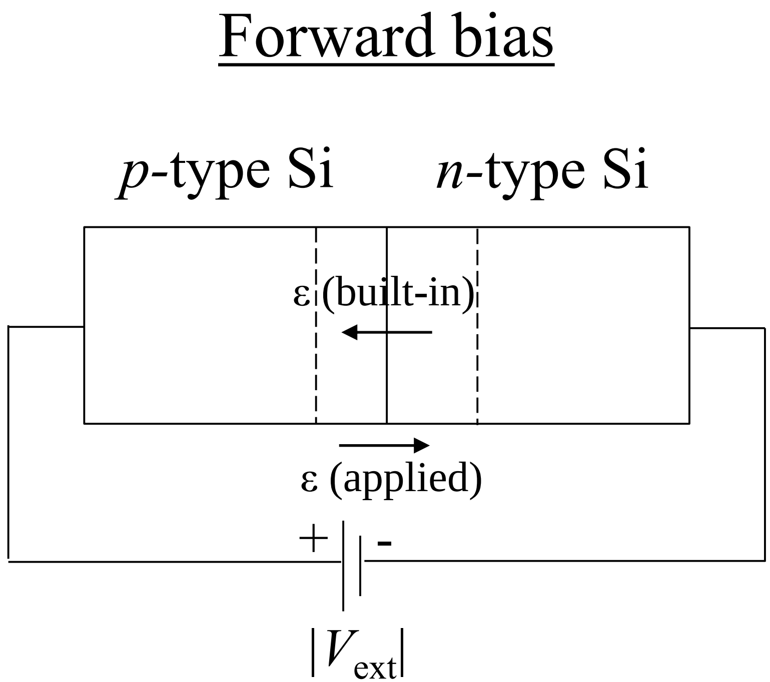
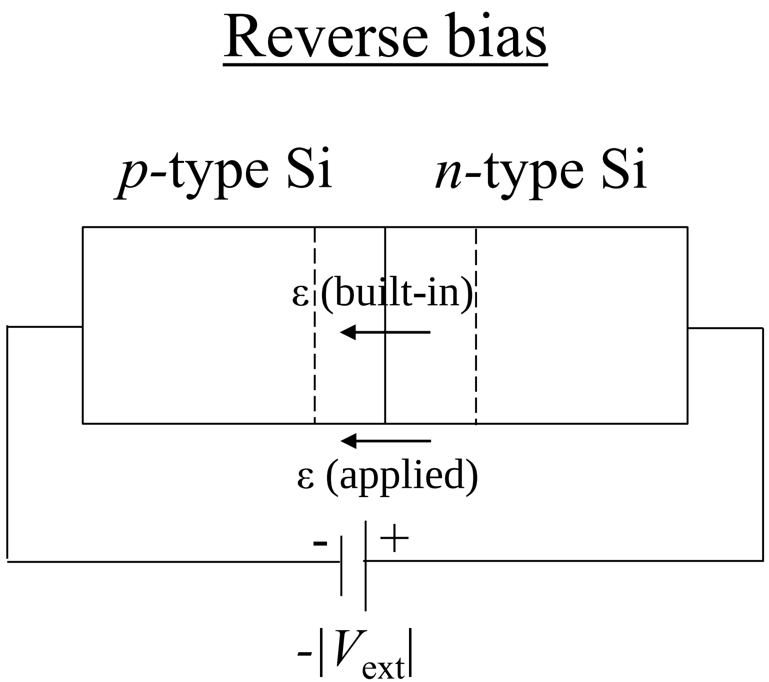
What happens when we electrically bias the pn-junction?





- Applied electric field concentrated in space charge region.
- Net electric field smaller under forward bias and vice-versa for reverse bias.

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Space charge widths under biasing

In equilibrium ϕ_{bi} is given by:

$$\phi_{bi} = \frac{kT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Under bias replace ϕ_{bi} with $(\phi_{\text{bi}} - V_{\text{ext}})$. Note that for forward bias V_{ext} is positive and negative for reverse bias.

Therefore:

$$w_n = \left[\frac{2\epsilon_r \epsilon_0 (\phi_{bi} - V_{ext})}{e} \left(\frac{N_A}{N_D}\right) \left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

$$w_p = \left[\frac{2\epsilon_r \epsilon_0 (\phi_{bi} - V_{ext})}{e} \left(\frac{N_D}{N_A}\right) \left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

Space charge region is *narrower* under forward bias and *wider* for reverse bias.

Electric field and potential under biasing

$$\varepsilon(x) = \begin{cases} -N_A e(x+w_p)/\epsilon_r\epsilon_0 & -w_p < x < 0 \\ N_D e(x-w_n)/\epsilon_r\epsilon_0 & 0 < x < w_n \\ 0 & \text{elsewhere} \end{cases}$$

Similar equations as equilibrium, but use new values for w_p and w_n

$$\phi(x) = \begin{cases} \dfrac{eN_A}{2\epsilon_r\epsilon_0}(x+w_p)^2 & -w_p < x < 0 \\ (\phi_{bi}-V_{ext}) - \dfrac{eN_D}{2\epsilon_r\epsilon_0}(x-w_n)^2 & 0 < x < w_n \end{cases}$$

Similar equations as equilibrium, but use new values for w_p, w_n and replace ϕ_{bi} with $(\phi_{\mathrm{bi}} - V_{\mathrm{ext}})$

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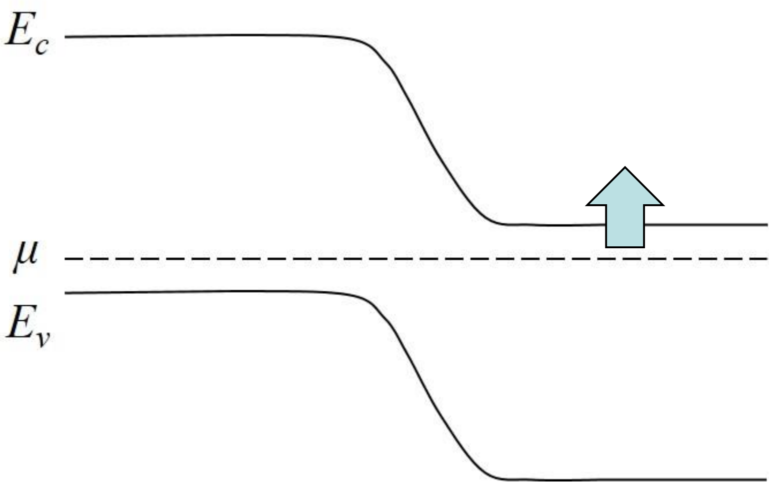
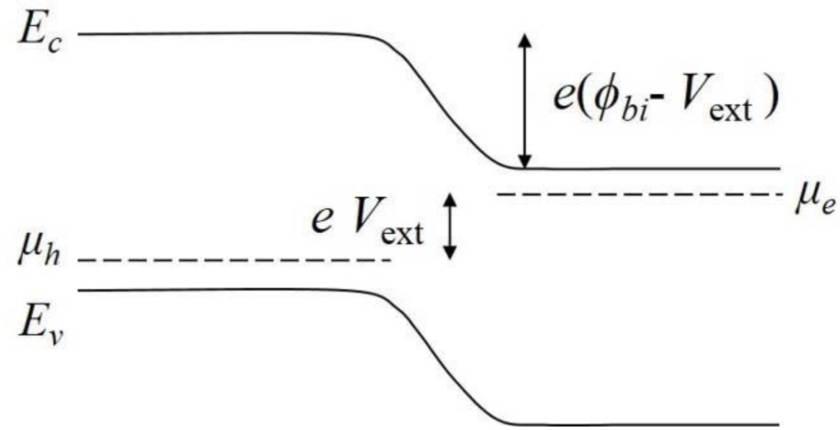
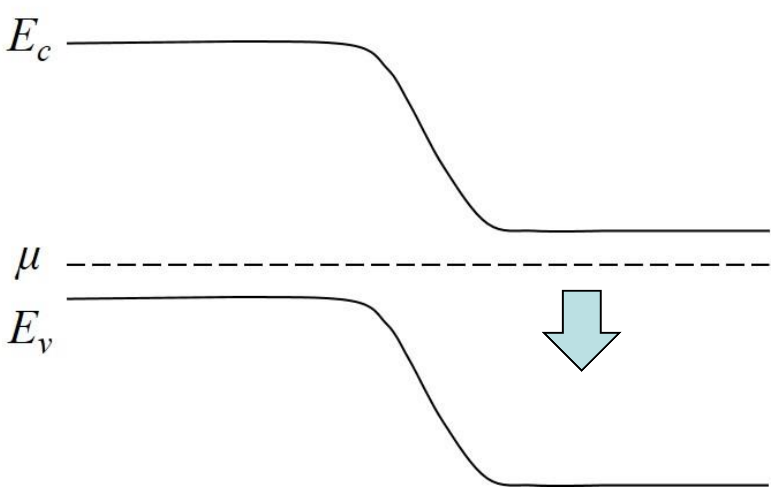
Energy level diagram under biasing



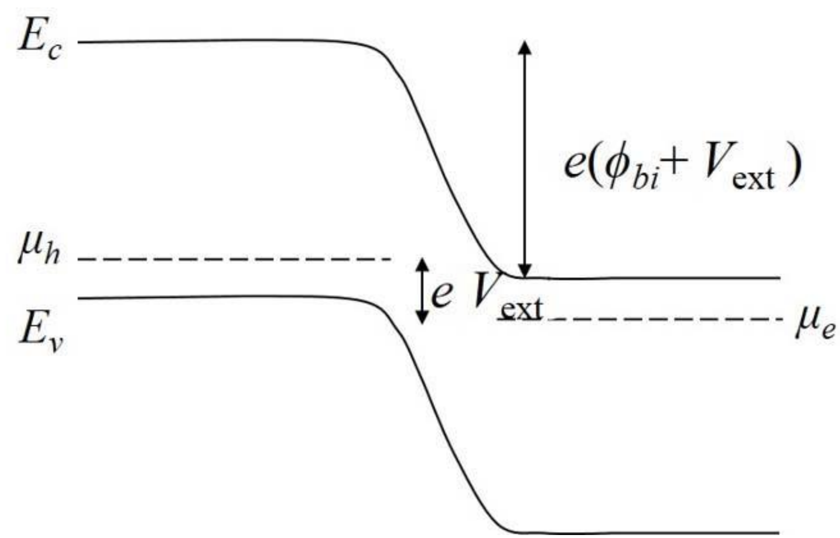
Equilibrium



Forward bias



Equilibrium



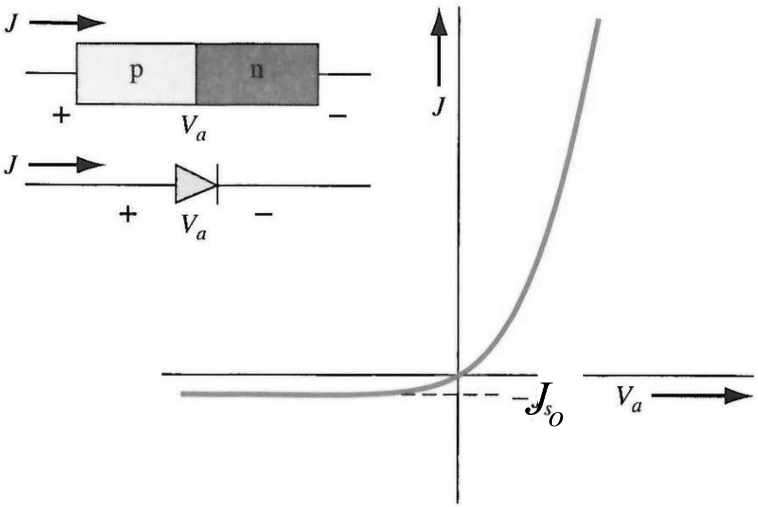
Reverse bias

$J(V)$ behaviour- rectification

Current density (J):

$$\boxed{J = J_o\left[\exp\left(\frac{eV_{ext}}{kT}\right) - 1\right]}$$

$J_o =$ reverse saturation current density



⇨ Current conduction only in forward bias direction

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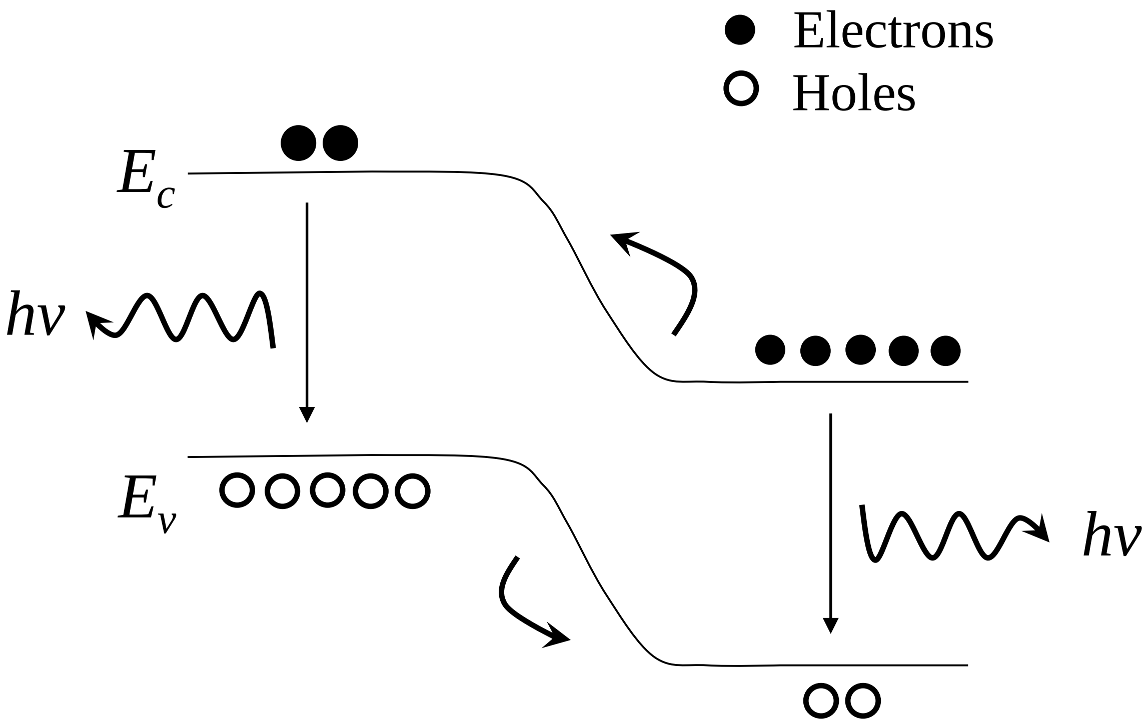
pn junction devices- light emitting diodes

-In forward bias electrons/holes injected across space charge region.

-This creates excess *minority carriers* in the quasi-neutral regions.

-Recombination of excess minority carriers with majority carriers emits light.



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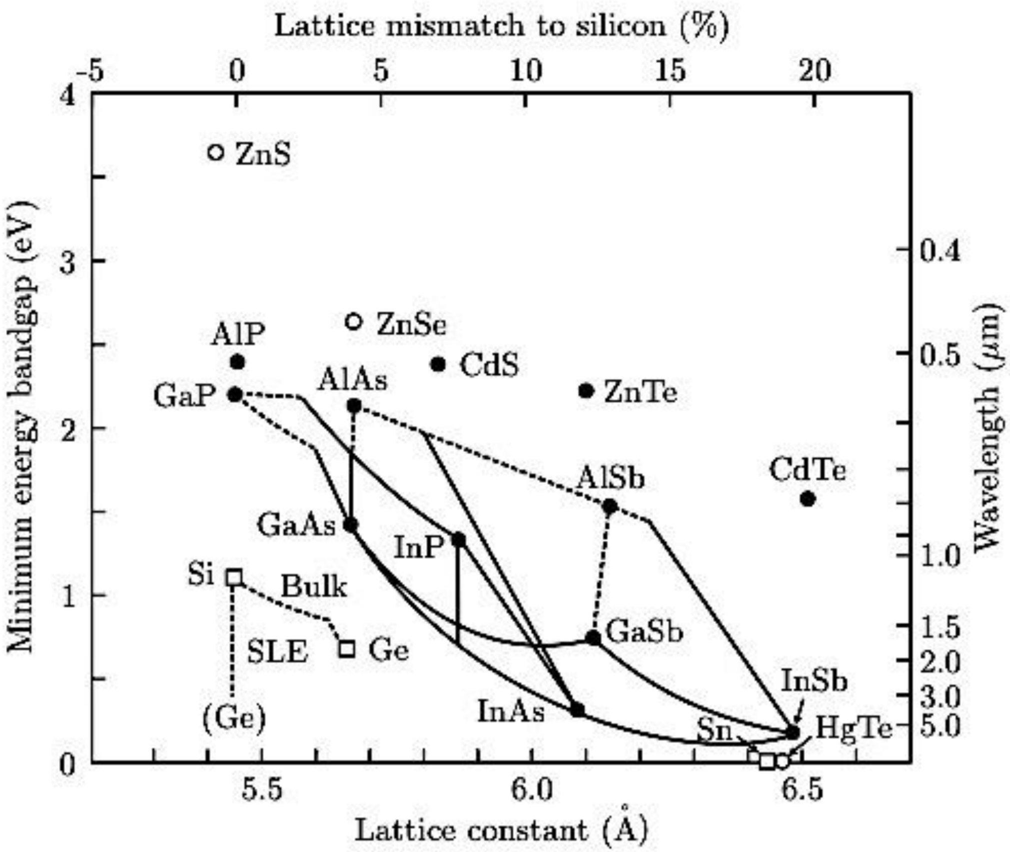
pn junction devices- light emitting diodes



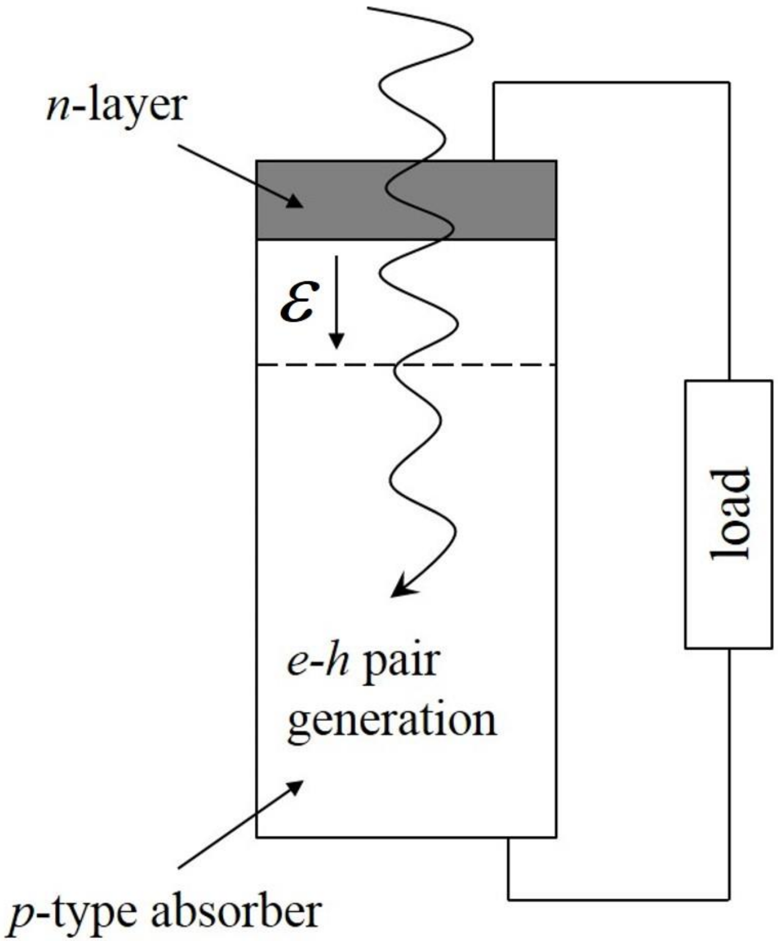
Example LED materials:

AlGaInP alloy: red emission
InGaN: green-blue emission

Organic LEDs also widely used (e.g. OLED TVs)

-Band gap of semiconductor LED must be matched with the photon energy.
-Direct band gap semiconductor required for high efficiency

pn junction devices- solar cells



-Light absorption in *p*-layer generates electron-hole pairs due to promotion of valence band electron into conduction band.

-Excess electrons and holes diffuse randomly and do not produce a net electric current

-However, *minority carriers* diffusing into the space charge region can be extracted by the built-in electric field to produce an electric current.

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