The p-n Junction (The Diode)

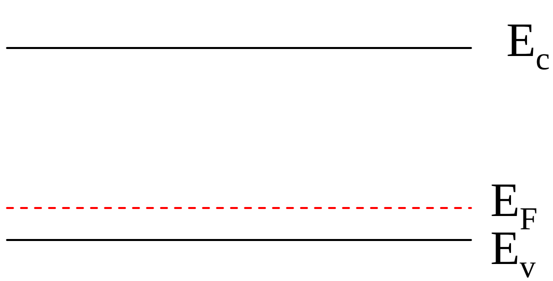
- Derivation of ideal diode equation covered in the SMA Device Course
- Development here introduces the fundamental materials concepts

<u>p-type material in equilibrium</u>

$p \sim N_a$

$n \sim n_i^2/N_a$

$$E_F = -k_b T \ln\left(\frac{N_a}{N_V}\right)$$

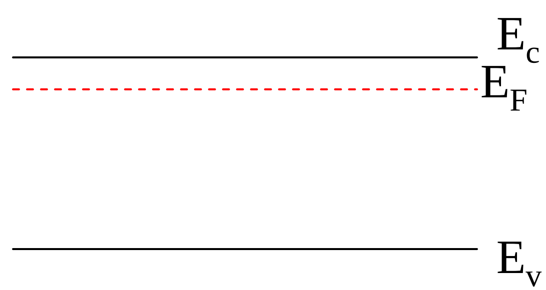


<u>n-type material in equilibrium</u>

$n \sim N_d$

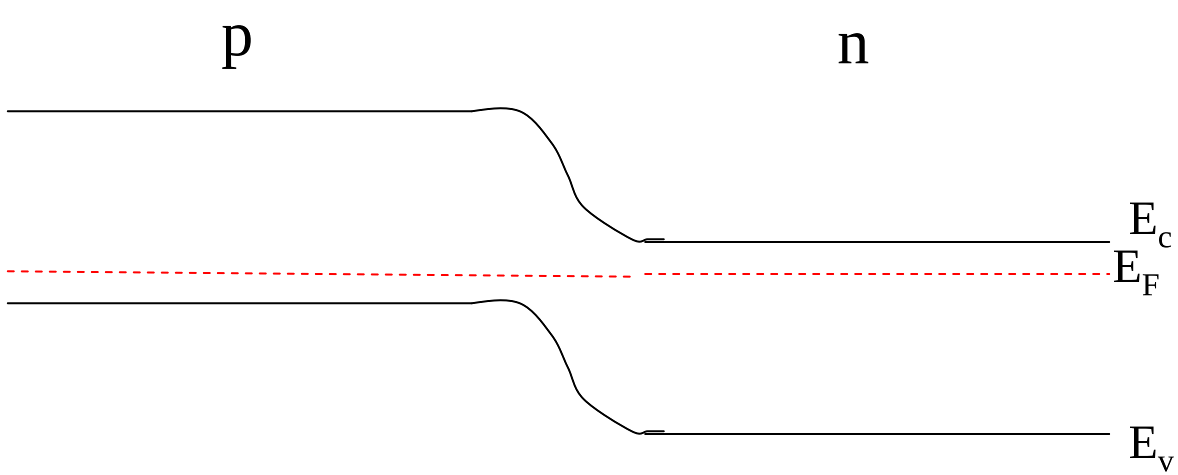
$p \sim n_i^2/N_d$

$$E_F = E_g + k_b T \ln\left(\frac{N_d}{N_C}\right)$$

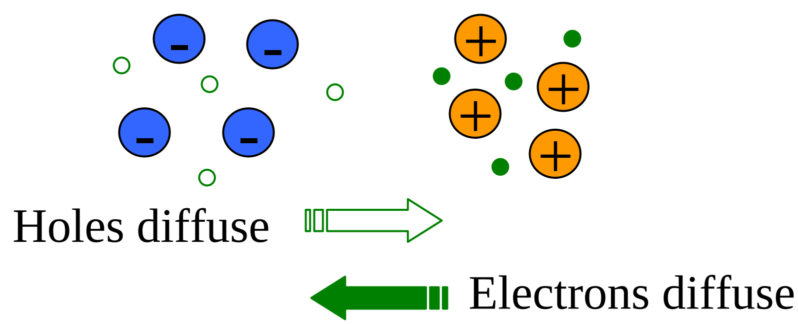


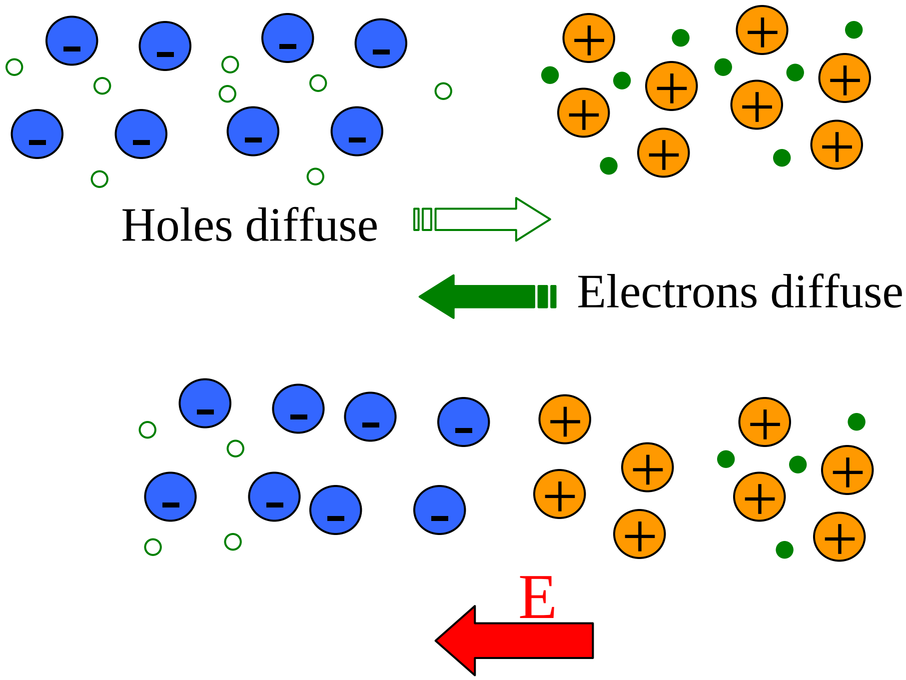
What happens when you join these together?

Joining p and n



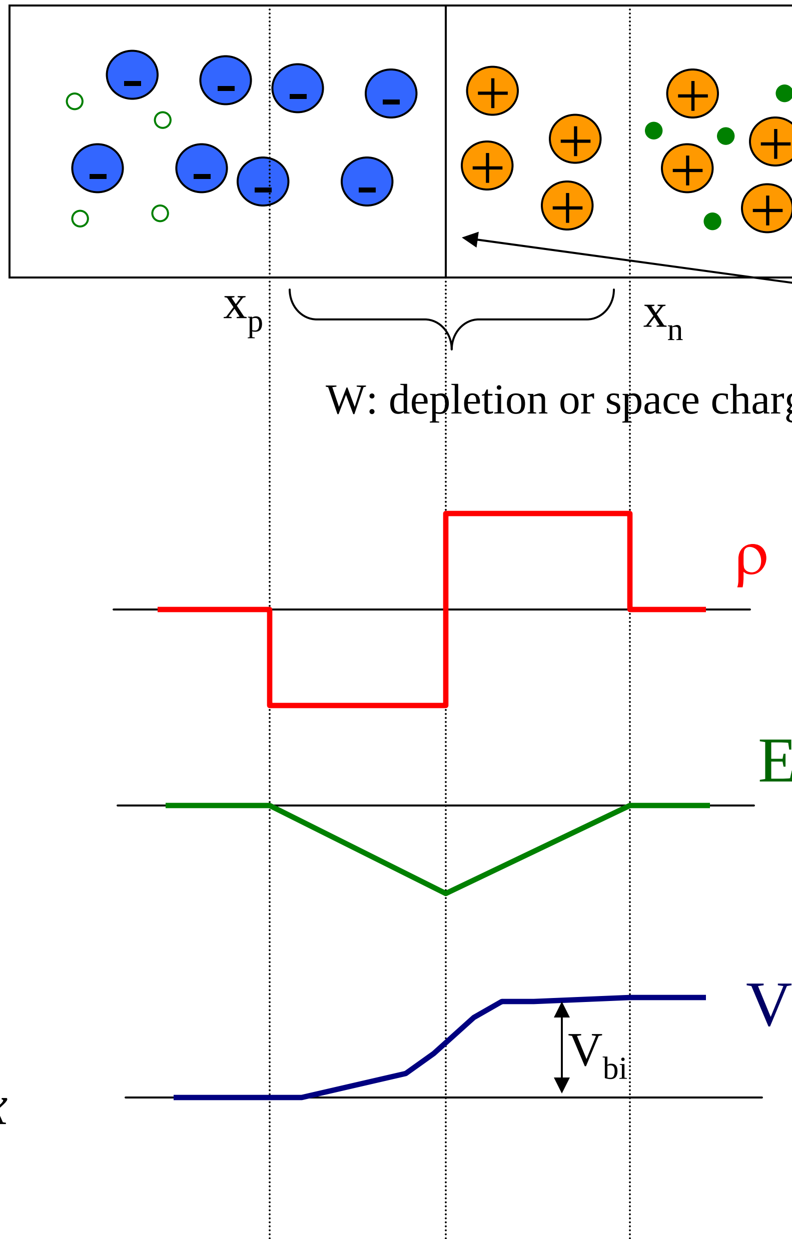
Carriers flow under driving force of diffusion until E_F is flat





An electric field forms due to the fixed nuclei in the lattice from the dopants

Therefore, a steady-state balance is achieved where diffusive flux of the carriers is balanced by the drift flux



$$N_d x_n = N_a x_p$$

$$E = \int \frac{\rho(x)}{\varepsilon} dx$$

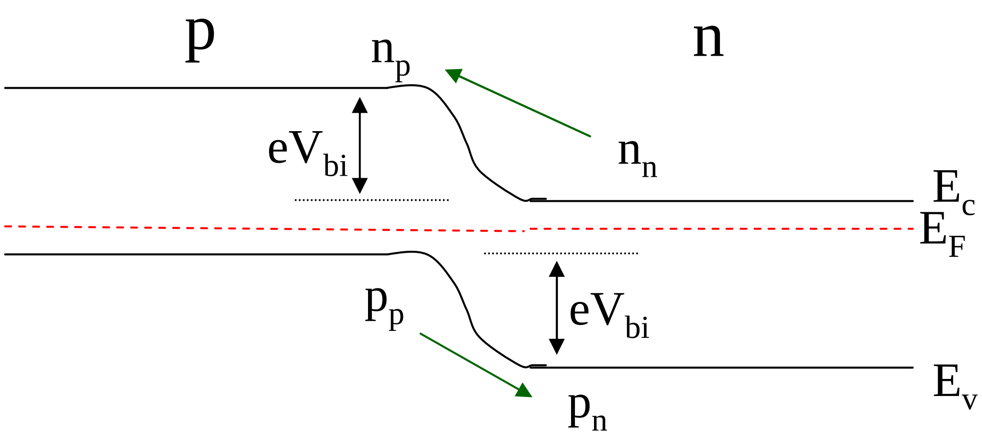
$$x_p = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_d}{N_a (N_d + N_a)}}$$

$$x_n = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_a}{N_d (N_d + N_a)}}$$

$$V = \int E(x) dx$$

$$W = \sqrt{\frac{2\varepsilon_r \varepsilon_o V_{bi}}{e} \frac{N_a + N_d}{N_d N_a}}$$

What is the built-in voltage V_{bi}?



$$eV_{bi}=E_{Fn}-E_{Fp}$$

$$E_{Fp} = -k_b T \ln\left(\frac{p}{N_V}\right) = -k_b T \ln\left(\frac{N_a}{N_V}\right) \qquad E_{Fn} = -k_b T \ln\left(\frac{p_n}{N_V}\right) = -k_b T \ln\left(\frac{n_i^2}{N_V N_d}\right)$$

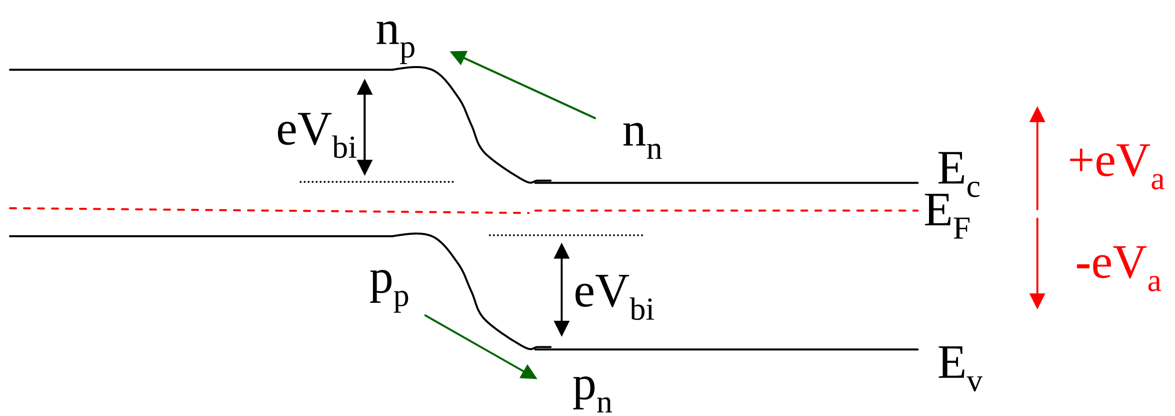
$$\therefore V_{bi} = \frac{k_b T}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

We can also re-write these to show that eV_{bi} is the barrier to minority carrier injection:

$$p_n = p_p e^{\frac{-eV_{bi}}{k_b T}} \qquad n_p = n_n e^{\frac{-eV_{bi}}{k_b T}}$$

Qualitative Effect of Bias

- Applying a potential to the ends of a diode does NOT increase current through drift
- The applied voltage upsets the steady-state balance between drift and diffusion, which can unleash the flow of diffusion current
- "Minority carrier device"

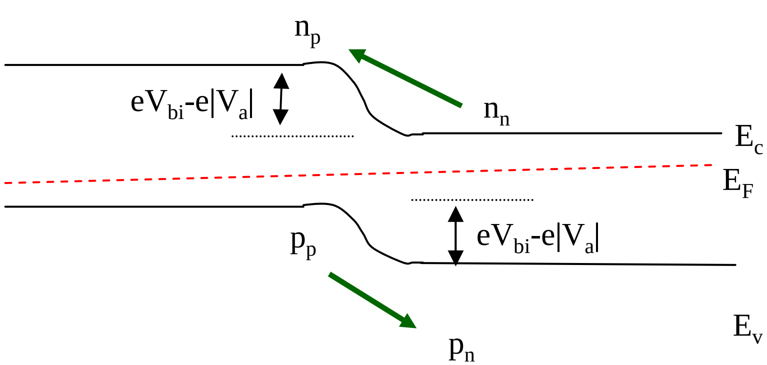


$$n_p = n_n e^{\frac{-e(V_{bi}-V_a)}{k_b T}} \qquad p_n = p_p e^{\frac{-e(V_{bi}-V_a)}{k_b T}}$$

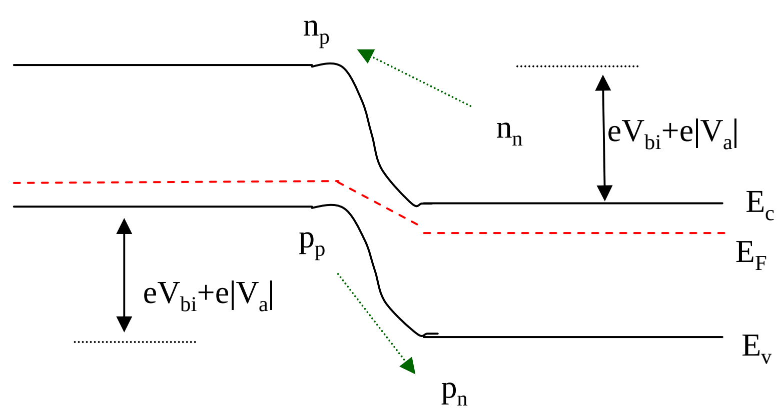
Qualitative Effect of Bias

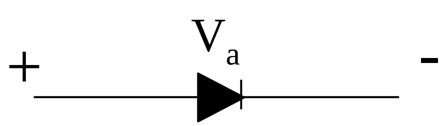
- Forward bias (+ to p, - to n) decreases depletion region, increases diffusion current exponentially
- Reverse bias (- to p, + to n) increases depletion region, and no current flows ideally

Forward Bias



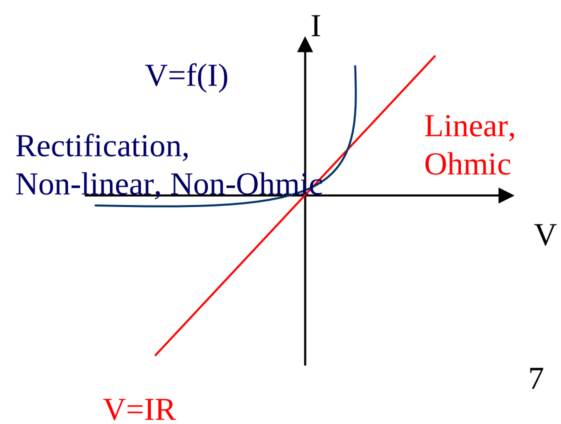
Reverse Bias





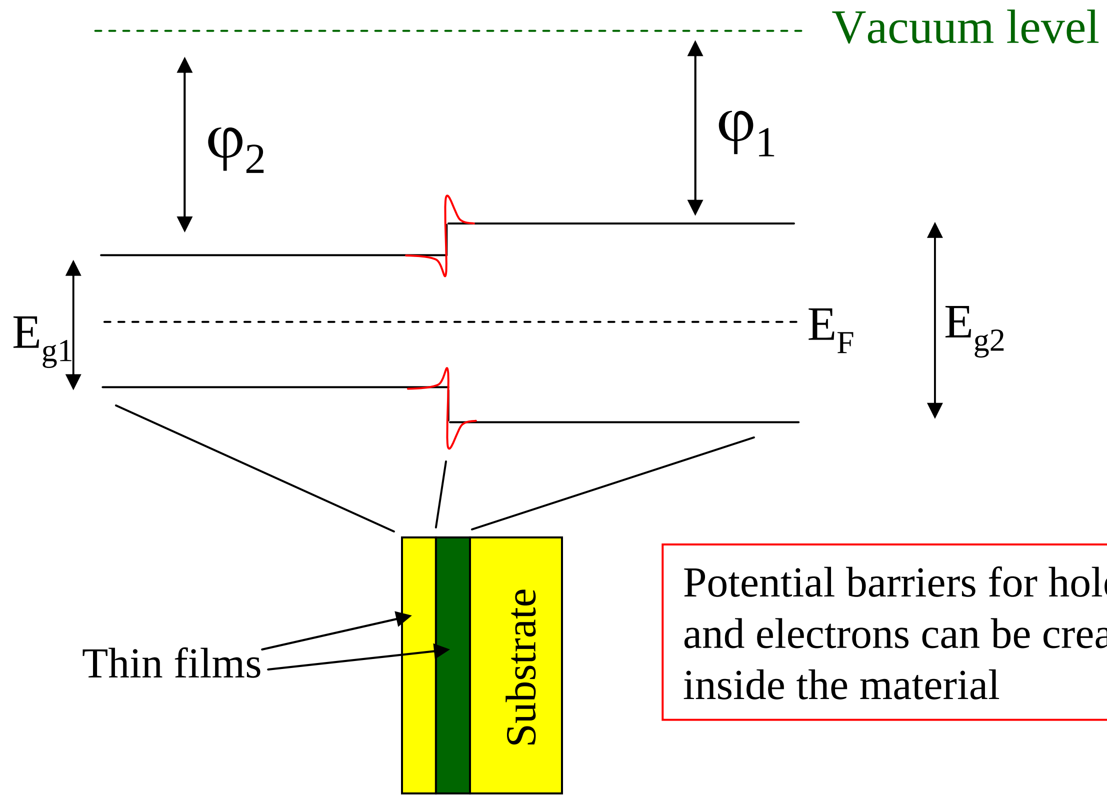
$$J = q\left(\frac{D_e}{L_e}\frac{n_i^2}{N_a} + \frac{D_h}{L_h}\frac{n_i^2}{N_d}\right)\left(e^{\frac{qV_a}{k_bT}} - 1\right) = J_o\left(e^{\frac{qV_a}{k_bT}} - 1\right)$$

$$\frac{D_i}{\mu_i} = \frac{k_bT}{q} \qquad L_i = \sqrt{D_i\tau_i}$$



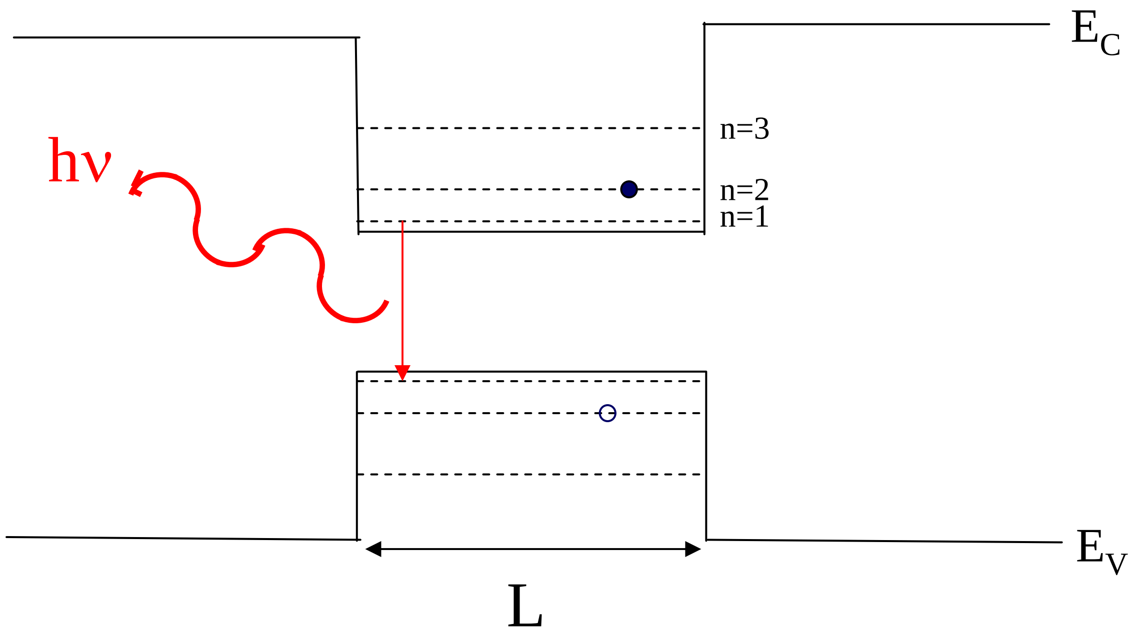
Other means to create internal potentials: Heterojunctions

- Different semiconductor materials have different band gaps and electron affinity/work functions
- Internal fields from doping p-n must be superimposed on these effects: Poisson Solver ($dE/dx=V=\rho/\varepsilon$)



Potential barriers for holes and electrons can be created inside the material

Quantum Wells



If we approximate well as having infinite potential boundaries:

$$k = \frac{n\pi}{L}$$ for standing waves in the potential well

$$E = \frac{\hbar^2 k^2}{2m^*} = \frac{h^2 n^2}{8m^* L^2}$$

We can modify electronic transitions through quantum wells