Junctions and Barriers

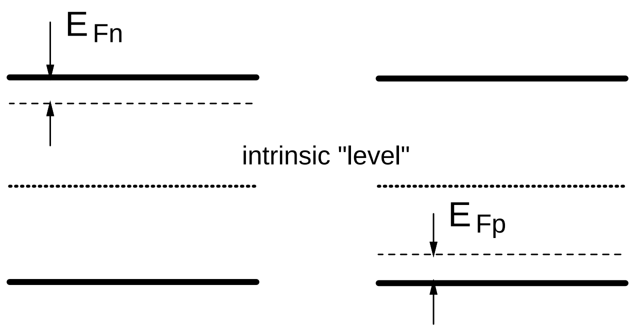


Figure 1: *n*- and *p*-type semiconductors

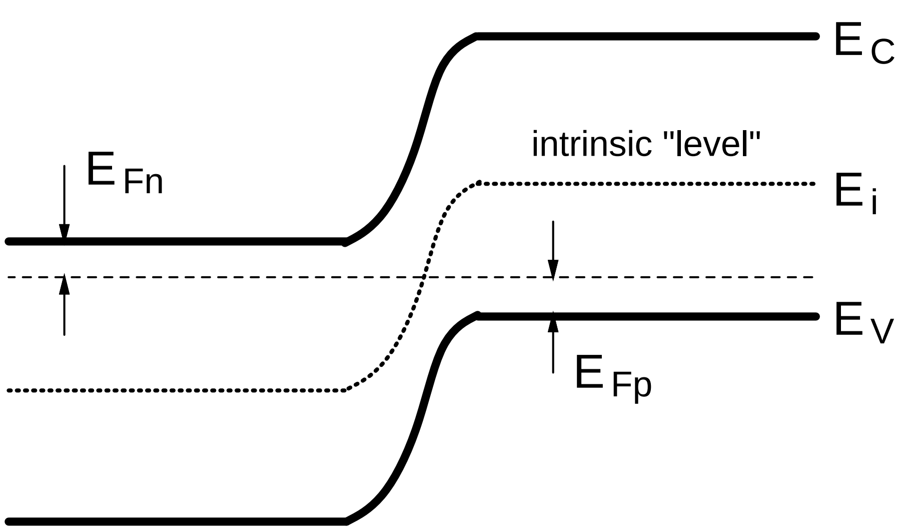


Figure 2: Metallurgical junction of two materials

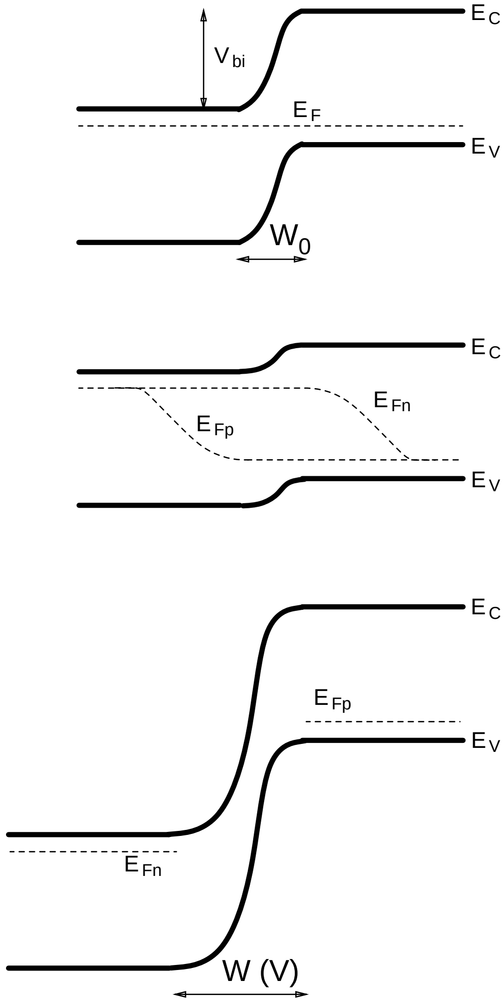


Figure 3: In forward bias, electrons flood the *p*-region and the holes flood the *n* region; this phenomenon is called ***injection***. The region where the substantial amount of minority carriers reside is 0.ds 0 √ determined by the ***diffusion length*** $L_D =$.

In reverse bias, there are 2 components of the current (in the ideal *pn* junction): ***generation*** current ($\propto n_i \times W(V)$) and ***diffusion*** current [$\propto (n_i^2 / N_A) \times L_D / \tau$].

Diffusion. distance covered from home in time t on average is

$$L \ =$$

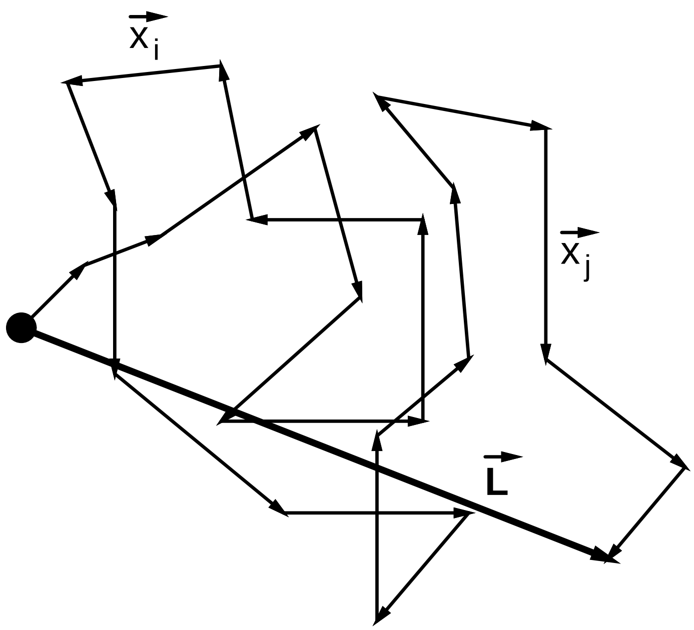


Figure 4: Random walk problem

$$\vec{L} = \vec{x}_1 + \vec{x}_2 + \vec{x}_3 + \cdots$$
$$L^2 = \sum_{i,j} x_i \, x_j$$
$$<L^2> = \sum_i <x_i^2> + \sum_{i \neq j} <x_i \, x_j> = N <x^2>$$
$$\bar{L} \equiv \bar{x}$$

If $t = \tau$ is the lifetime, $L = L_D$ is called the diffusion length,

$$L_D \ =$$

L_D is a characteristic of the material. It is long (can be millimeters) in indirect materials (where τ is slow) and short in direct-gap III-V compounds (typically, several microns). L_D depends very much on traps, dislocations, grain boundaries, etc., which all affect primarily τ.

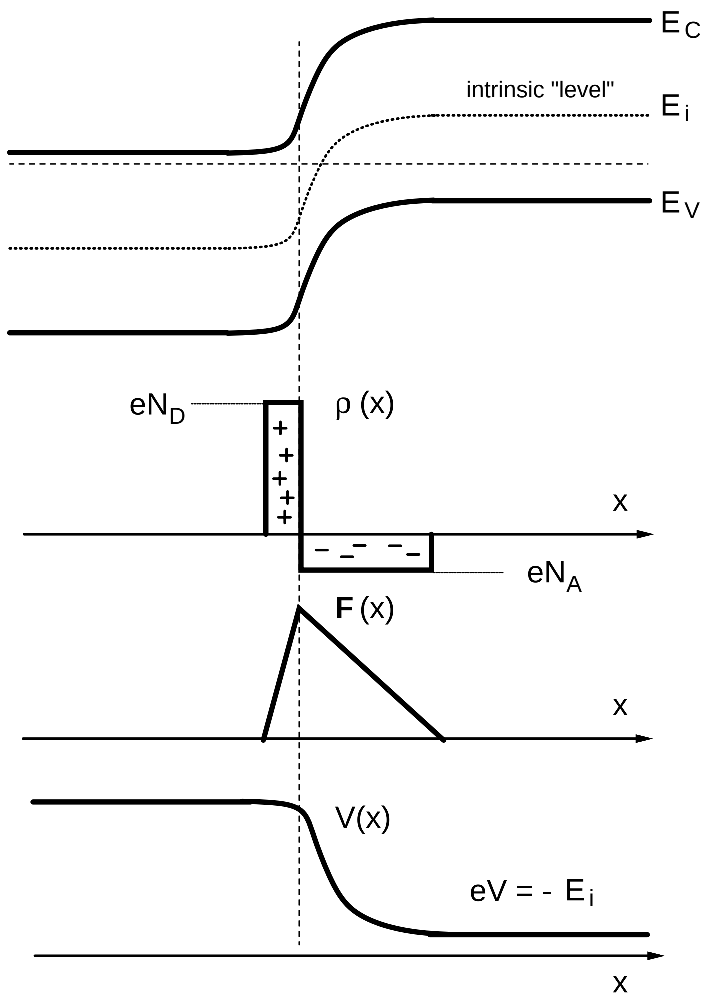


Figure 5: Charge, Field, and Potential profiles in a *pn*-junction

$$\frac{\mathrm{d}F}{\mathrm{d}x} = \frac{\rho}{\varepsilon} \qquad \text{Poisson}$$

$$\frac{\mathrm{d}V}{\mathrm{d}x} = -F \qquad \text{definition of potential}$$

$$\frac{\mathrm{d}E_C}{\mathrm{d}x} = eF \qquad \text{definition of potential energy}$$

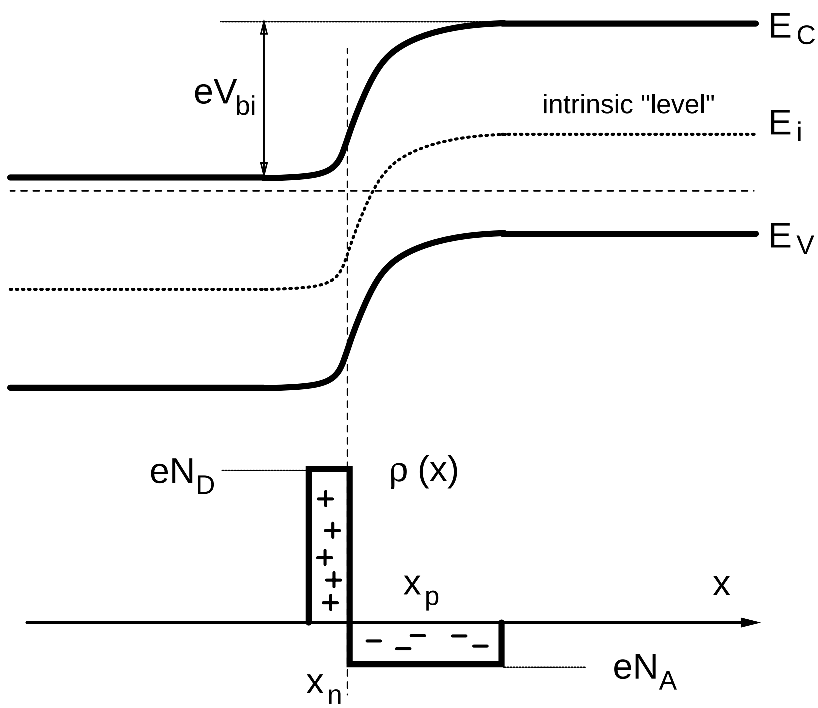


Figure 6: One-sided *pn*-junction ($N_D \gg N_A$)

Neutrality: $N_A x_p = N_D x_n$

Build-in voltage: $V_{bi} = kT \ln \frac{N_D N_A}{n_i^2}$

intrinsic concentration: $n_i^2 = N_C N_V e^{-E_G/kT}$

In equilibrium everywhere: $n p = n_i^2$

To determine the electrostatic state of a *pn* junction
(in equilibrium or under bias V)

1. Calculate or look up n_i
   [characteristic of the material, $n_i(T)$]

2. From N_D, N_A calculate V_{bi}

$$V_{bi} = kT \ln \frac{N_D N_A}{n_i^2}$$

3. Calculate x_n and x_p from

$$\frac{e N_D x_n^2}{2\varepsilon} + \frac{e N_A x_p^2}{2\varepsilon} = V_{bi} \pm V \qquad \text{(from Poisson's eq.)}$$

$$N_D x_n = N_A x_p \qquad \text{neutrality}$$

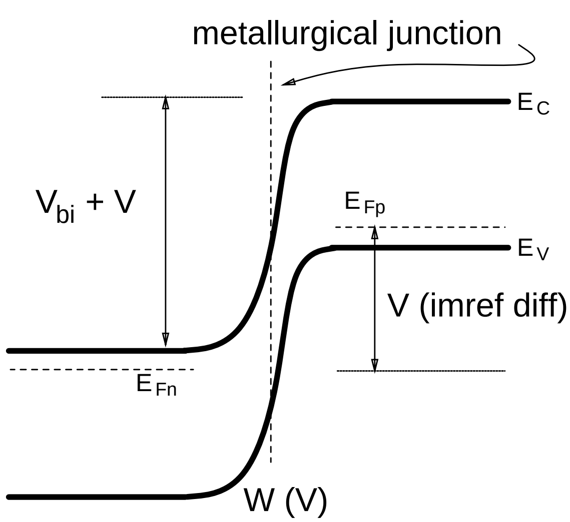
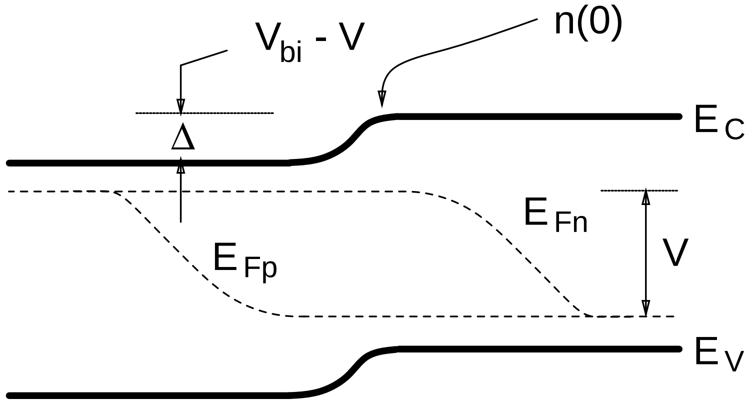


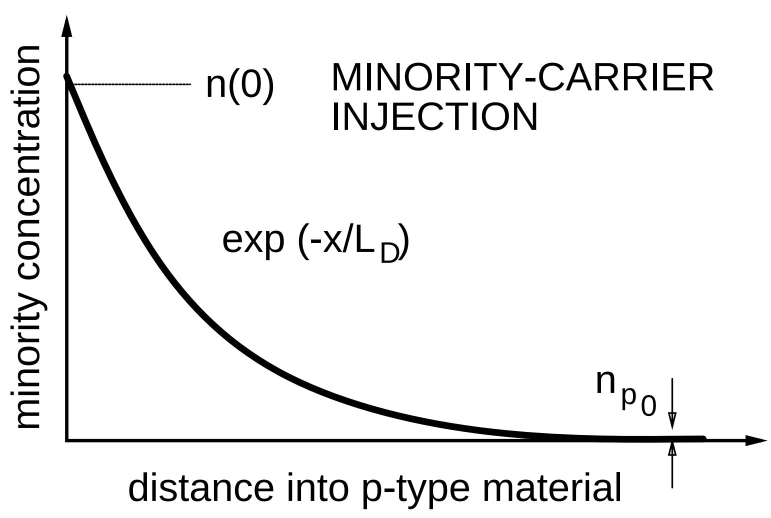
Figure 7: Reverse-biased *pn*-junction

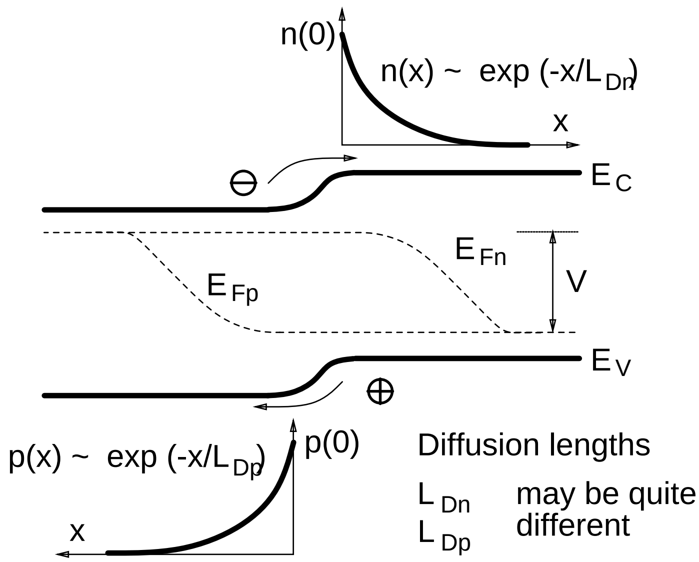
***pn* junction under forward bias**

$$n(0) = n_{p0}\, e^{V/kT} \qquad \text{where} \quad n_{p0} \approx \frac{n_i^2}{N_A}$$

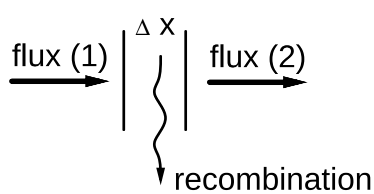
$$n(0) = n_{n0}\, e^{-\Delta/kT} \qquad \text{where} \quad n_{n0} \approx N_D$$







CONTINUITY EQUATION



$$\frac{\mathrm{d}(n\,\Delta x)}{\mathrm{d}t} = D\,\frac{\mathrm{d}n\,(1)}{\mathrm{d}x} - D\,\frac{\mathrm{d}n\,(2)}{\mathrm{d}x} - \frac{n - n_{p0}}{\tau}\,\Delta x$$

☛ $$D\,\frac{\mathrm{d}^2 n}{\mathrm{d}\,x^2} = \frac{n}{\tau} \qquad \text{(in steady state)}$$

$$n'' = \frac{n}{L_{\mathrm{D}}^2} \qquad \text{where} \quad L_{\mathrm{D}} \equiv$$

Solutions: $\mathrm{e}^{\pm x/L_{\mathrm{D}}}$ (in general, $A\,\mathrm{e}^{x/L_{\mathrm{D}}} + B\,\mathrm{e}^{-x/L_{\mathrm{D}}}$)

Physical choice: $(n - n_{p0}) = [\,n\,(0) - n_{p0}\,]\,\mathrm{e}^{-x/L_{\mathrm{D}}}$

Electron Diffusion Current:

$$n - n_{p0} = [n(0) - n_{p0}]\, e^{-x/L_D}$$

$$e D \frac{dn}{dx} = \frac{e D}{L_D} [n(0) - n_{p0}]\, e^{-x/L_D}$$

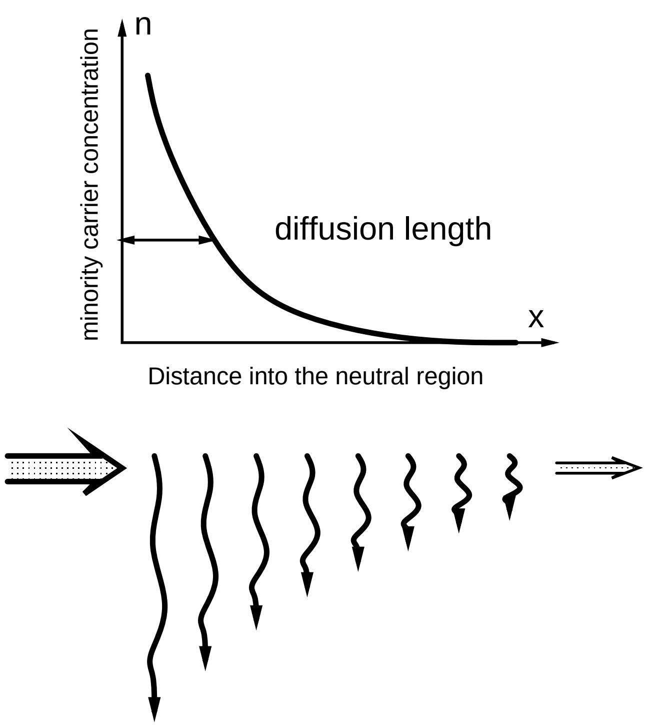
$$= e\, n_{p0} [e^{eV/kT} - 1]\, e^{-x/L_D}$$

Conservation of charge:

$$\frac{d\rho}{dt} = 0 \quad ☛ \quad \vec{\nabla} \cdot \vec{J} = 0$$

Hence

$$J_n + J_p = \text{Const} \quad (\text{independent of } x)$$



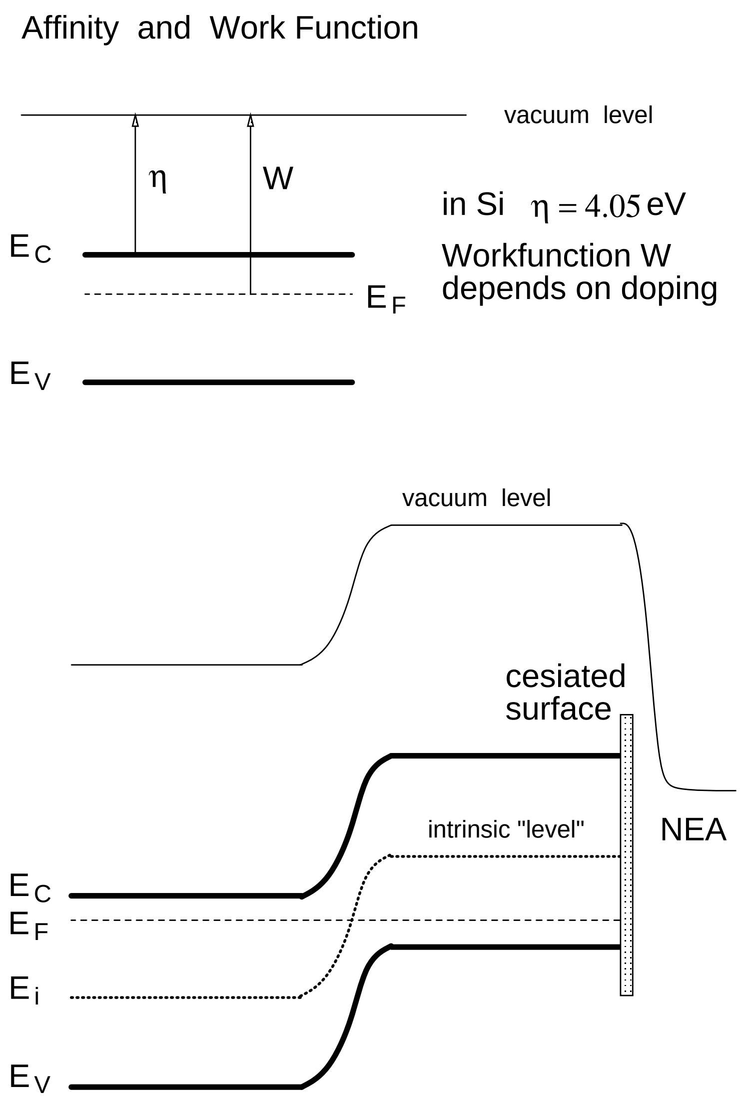


Figure 10: Illustration of electron affinity and the workfunction. Certain surface treatments (e.g., Cs or Cs oxide) produce surfaces with workfunctions as low as 1 or 2 eV. For a sufficiently widegap *p*-type semiconductor, this may result in a *negative affinity* (NEA) of the material near the surface.

Such a surface works as an "electron gun" or "cold cathode", shooting out any minority electrons injected in the region near the surface. Minority electrons can be injected by forward-biasing the *pn* junction.

Junction Capacitance

$$\frac{C}{A} = \frac{\varepsilon}{W} = \frac{\varepsilon}{x_n + x_p}$$

Exercise: small-signal derivation *Check that the same result is obtained!*

$$\frac{C}{A} = \frac{\delta Q}{\delta V}$$

where

$$\delta Q = e\,\delta x_n\,N_\mathrm{D} = e\,\delta x_p\,N_\mathrm{A}$$