Chapter 3-2. Diffusion and band bending

We will learn two new topics in this lecture:

Diffusion – a process whereby particles tend to spread out or redistribute as a result of their random thermal motion, migrating on a macroscopic scale from regions of high particle concentration to region of low particle concentration.

Examples of diffusion:

Perfume in a room

Ink drop in a bottle of water

Hot point probe measurements

Band bending – resulting from the presence of electric field inside a semiconductor. No band bending means the electric field is zero.

Hot-point probe measurement

This is a commonly used technique for determining whether a semiconductor is p-type or n-type.

Carriers diffuse more rapidly near the *hot* probe. This leads to a *particle* current away from the hot probe and an *electrical* current away (p-type) or towards (n-type) the hot probe.

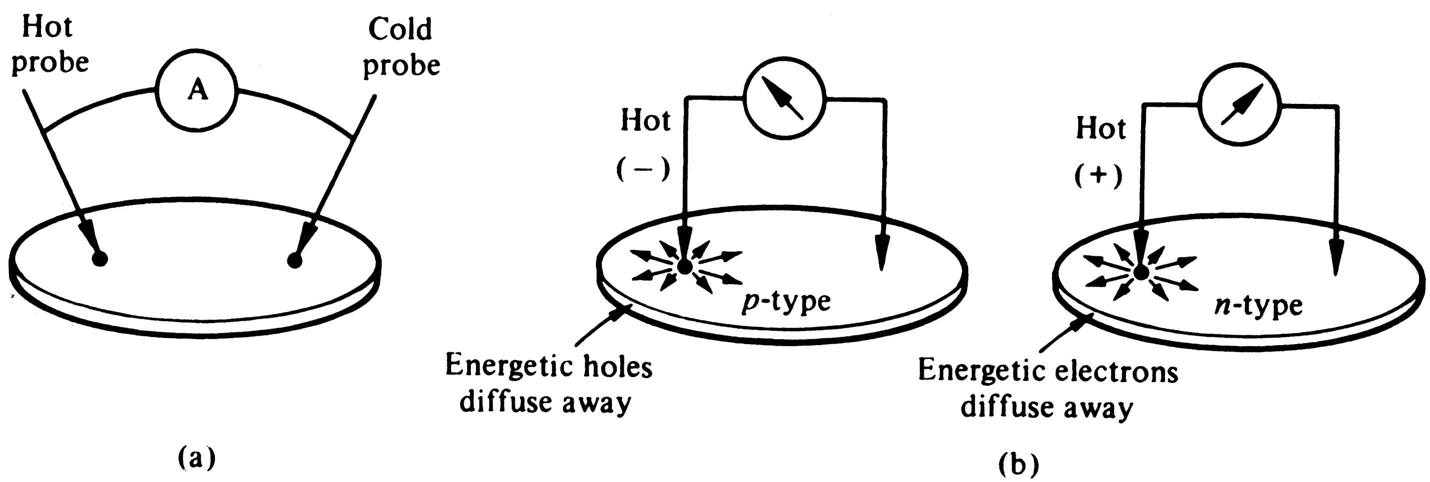


Figure 3.13

Diffusion current

- For diffusion to occur, there must be a concentration gradient.
- Logically, greater the concentration gradient, greater the flux of particles diffusing from higher concentration region to lower concentration region.

If F is the flux (i.e. the # of particles / (cm^2 s) crossing a plane perpendicular to the particle flow, then,

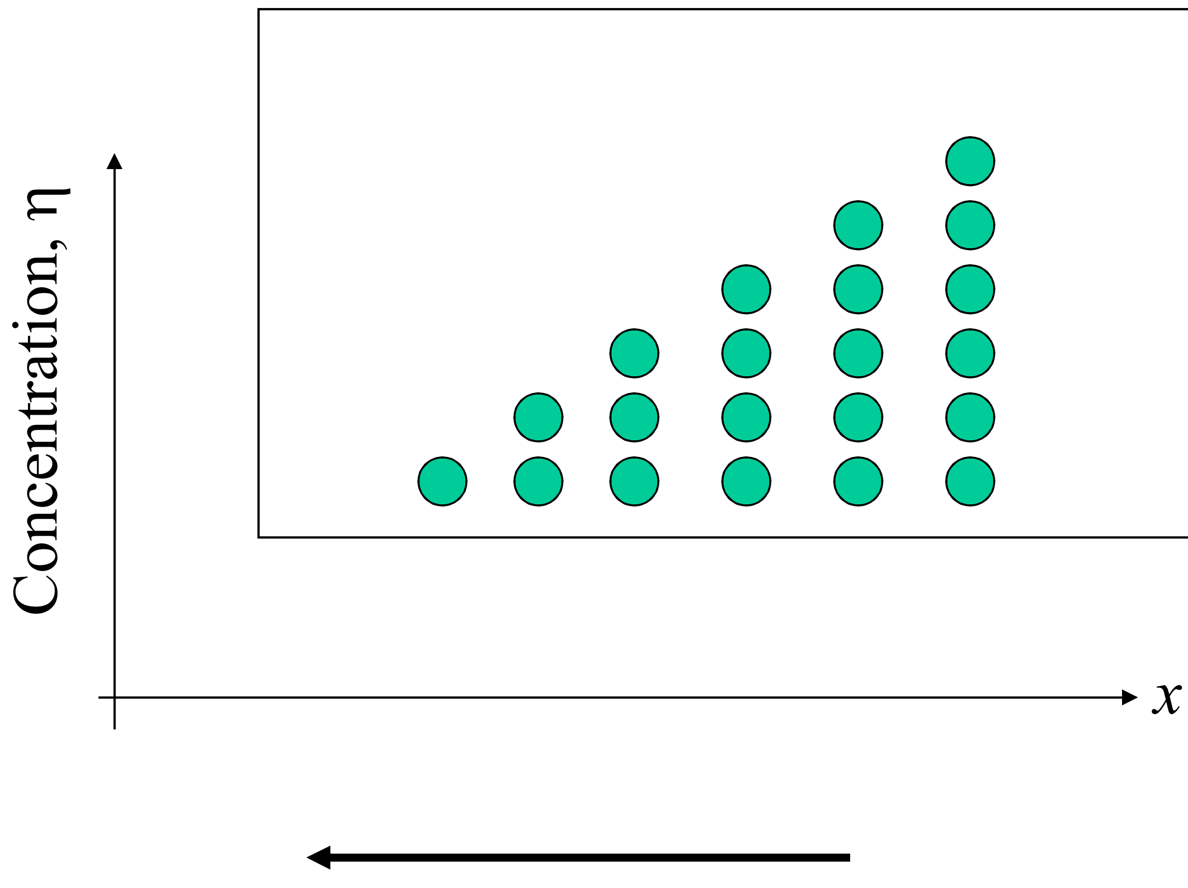
$$F = -D \frac{d\eta}{dx}$$

η = particle concentration

where D is called the diffusion coefficient. The (–) sign appears because for positive concentration gradient, $d\eta/dx$, the particles diffuse along the negative x direction.

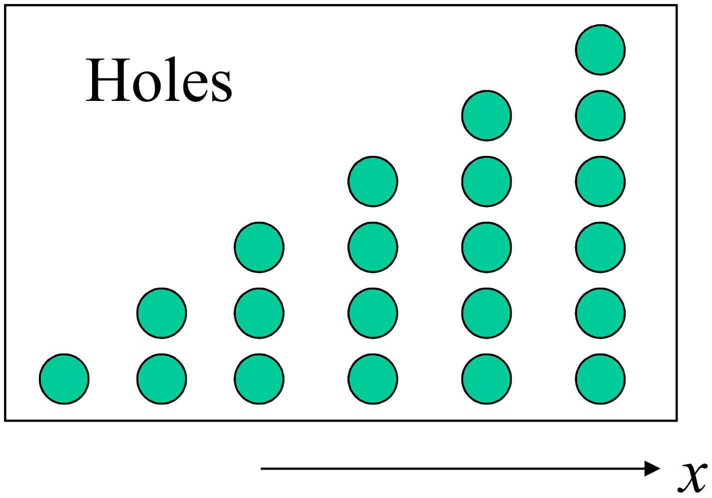
Particle diffusion

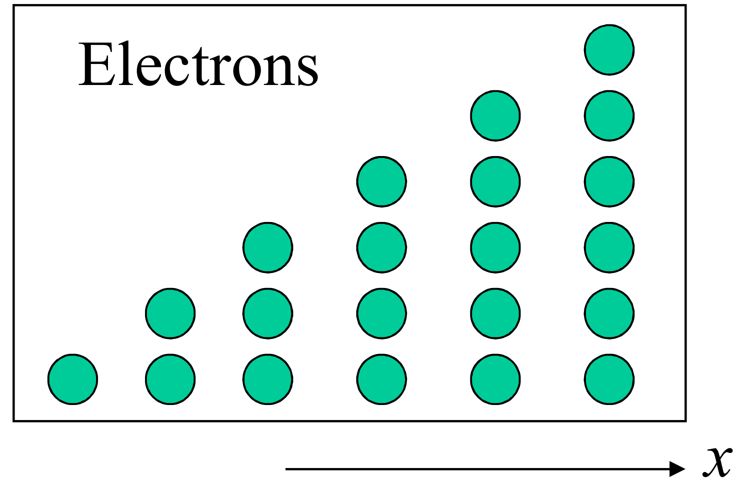
Concentration gradient, $d\eta/dx$ = positive



Particles flow along $-x$ direction

Diffusion current





hole flux $\leftarrow$

hole diffusion current $\leftarrow$

electron flux $\leftarrow$

electron diffusion current $\rightarrow$

$$J_{p\,|\,\mathrm{diff}} = -\,q\,D_p\,(\mathrm{d}p\,/\,\mathrm{d}x)$$

$$J_{n\,|\,\mathrm{diff}} = +\,q\,D_n\,(\mathrm{d}n\,/\,\mathrm{d}x)$$

What is the unit of diffusion coefficient, *D*?

Total currents

$$J_{\mathrm{p}} = J_{\mathrm{p|drift}} + J_{\mathrm{p|diff}} = [q\mu_{\mathrm{p}} p\mathcal{E}] + [-qD_{\mathrm{p}} \frac{\mathrm{d}p}{\mathrm{d}x}]$$

drift $\updownarrow$ $\qquad$ diffusion $\updownarrow$

$$J_{\mathrm{n}} = J_{\mathrm{n|drift}} + J_{\mathrm{n|diff}} = [q\mu_{\mathrm{n}} n\mathcal{E}] + [qD_{\mathrm{n}} \frac{\mathrm{d}n}{\mathrm{d}x}]$$

The total current flowing in semiconductor is given by:

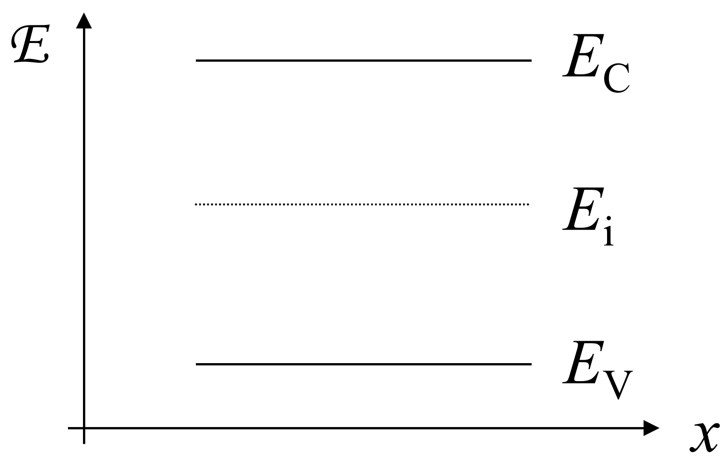
$$J = J_{\mathrm{n}} + J_{\mathrm{p}}$$

Band bending

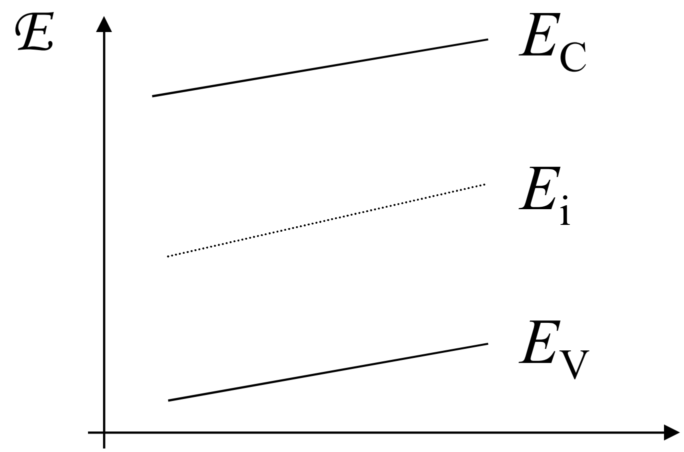
Band diagram represents energies of electrons – so far we have drawn it as independent of position.

When $\mathcal{E}$*-field* is present, E_C and E_V change with position - called "band-bending".

This is a way to represent that an $\mathcal{E}$-field is present.



No $\mathcal{E}$*-field*



indicates presence of $\mathcal{E}$*-field*

Band bending and electrostatic variables

Diagram represents total energy of electrons with x

K.E. = $E - E_C$ for electrons

P.E. = $E_C - E_{ref}$ for electrons

From elementary physics
P.E. = $-q\,V$ for electrons
$V = -(1/q)\,(E_C - E_{ref})$

$\mathcal{E} = -(\mathrm{d}V/\mathrm{d}x) = (1/q)\,(\mathrm{d}E_C/\mathrm{d}x)$

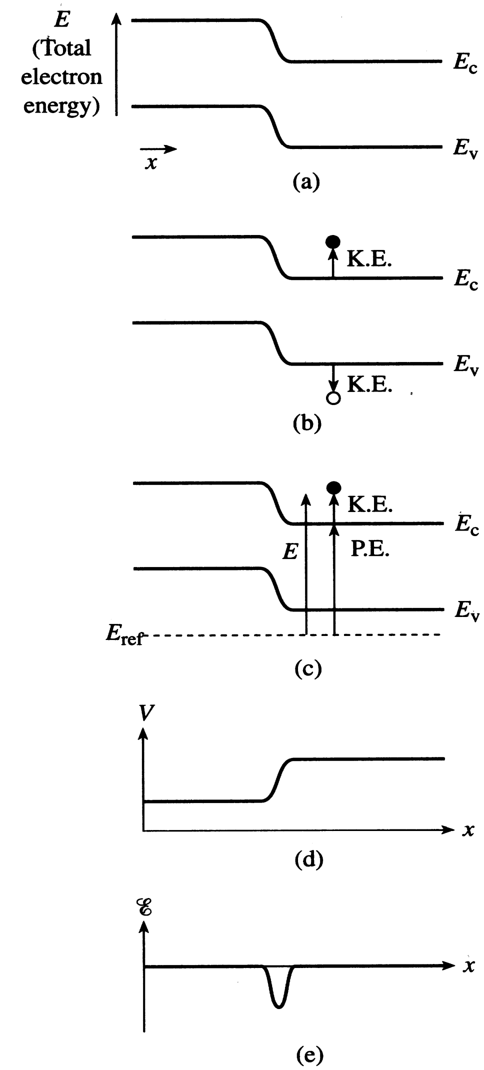


Figure 3.10

Band bending

Crudely, inverting E_C (in eV) versus x diagram results in electrostatic potential V (in Volts) versus x diagram. Similar to potential energy, V is relative with respect to some arbitrary reference.

$$V = -\frac{1}{q}(E_C - E_{ref})$$

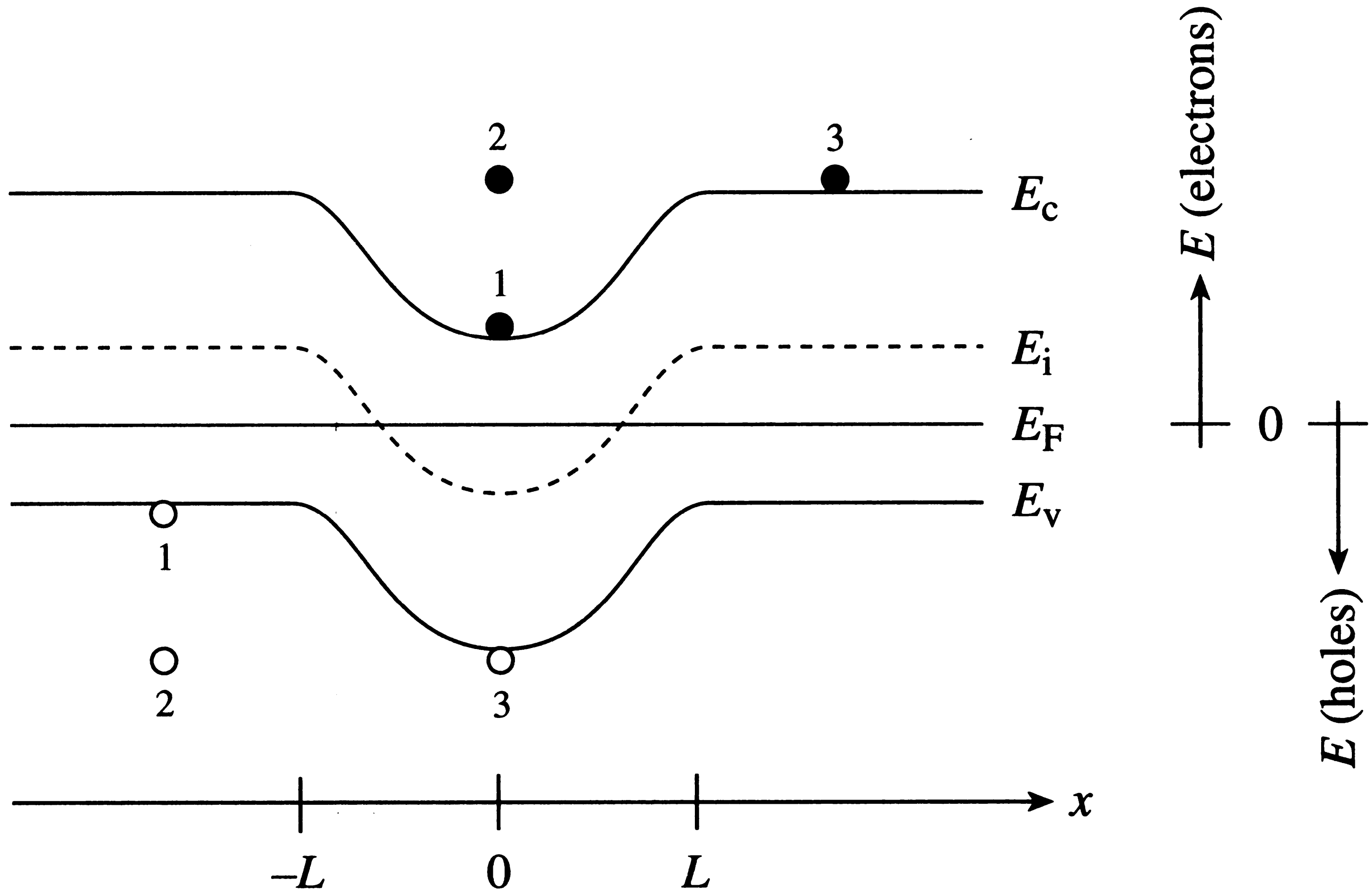
If $E_C - E_{ref}$ is given in eV, we use e = 1.6×10^{-19} C to convert from eV to Joules. Thus, values of V in Volts are numerically equal to $E_C - E_{ref}$ expressed in eV.

The slope of E_C (energy in eV) versus x diagram gives the $\mathcal{E}$-*field* versus x plot.

$$\mathcal{E} = \frac{1}{q}\frac{dE_C}{dx} = \frac{1}{q}\frac{d\,E_V}{dx} = \frac{1}{q}\frac{d\,E_i}{dx}$$

$\mathcal{E}$-*field* expressed in V/cm will be numerically equal to dE_i/dx if E_i is in eV and x in cm

Example 1: (Exercise 3.2) Plot electrostatic potential, V, **and** $\mathcal{E}$-*field*, $\mathcal{E}$, versus x for the case shown below.



Review

$$\boxed{\rho = \frac{1}{qp\mu_p + qn\mu_n}}$$

Resistivity formula

$$\boxed{J_{drift} = J_{n|\,drift} + J_{p|drift} = q\left(\mu_n n + \mu_p p\right)\mathcal{E}}$$

Drift current density

$$\boxed{J_{n|\,diff} = qD_n \frac{dn}{dx} \quad \text{and} \quad J_{p|\,diff} = -qD_p \frac{dp}{dx}}$$

Diffusion current density

$$\boxed{\begin{aligned} J_p &= J_{p|drift} + J_{p|diff} = qp\mathcal{E} \quad + \quad (-)qD_p \frac{dp}{dx} \\ J_n &= J_{n|drift} + J_{n|diff} = qn\mathcal{E} \quad + \quad qD_n \frac{dn}{dx} \end{aligned}}$$

Total hole and electron current density

$$\boxed{J = J_n + J_p}$$

Total current density