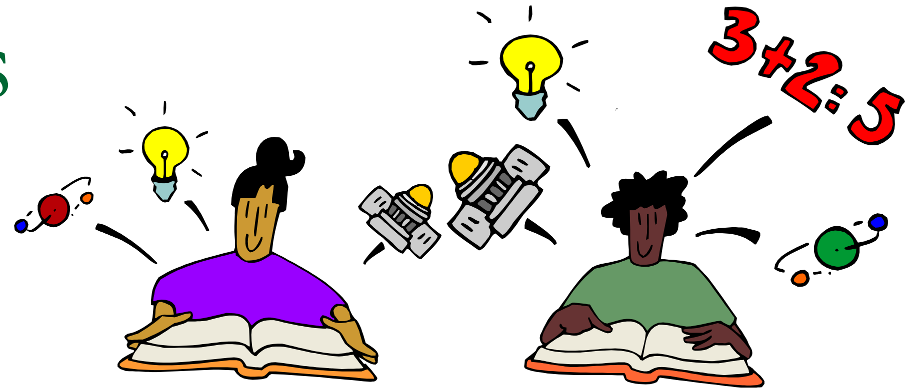
ECEG-2131 (AEI): Carrier Transport and PN junction

Addis Ababa Institute of Technology (AAIT) School of Electrical and Computer Engineering

Addis Ababa University (Since 1950)

Learning Outcomes

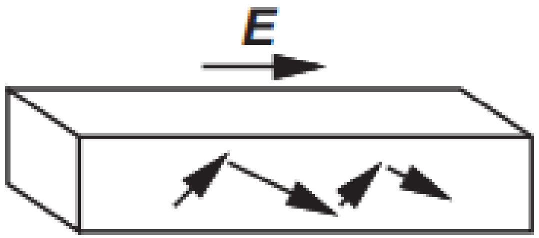


- At the end of the lecture, students should be able to know about:
  - Drift Current.
  - Diffusion Current
  - Resistivity of a material
  - Conductivity of a material
  - The PN junction

Carrier Transport

- Having studied charge carriers and the concept of doping, we are ready to examine the movement of charge in semiconductors, i.e., the mechanisms leading to the flow of current.
- ***Current = Drift + Diffusion***

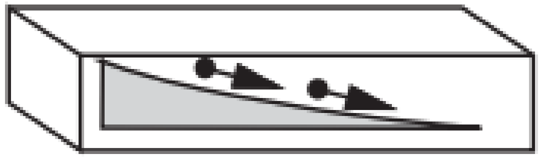
Drift Current



$$J_n = q n \mu_n E$$

$$J_p = q p \mu_p E$$

Diffusion Current

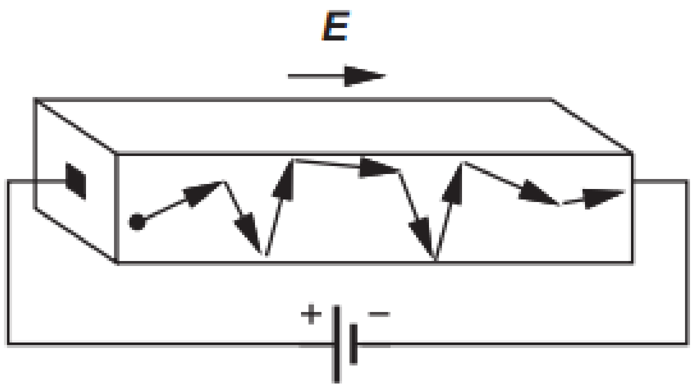


$$J_n = q D_n \frac{dn}{dx}$$

$$J_p = -q D_p \frac{dp}{dx}$$

Drift

- ***Drift*** it is the movement of charge carriers due to an electric field.



- Charge carriers are accelerated by the field and accidentally collide with the atoms in the crystal, eventually reaching the other end and flowing into the battery.
- The acceleration due to the field and the collision with the crystal counteract, leading to a constant velocity for the carriers.

Drift

- We expect the velocity, *v*, to be proportional to the electric field strength, *E*:

$$v \propto E,$$

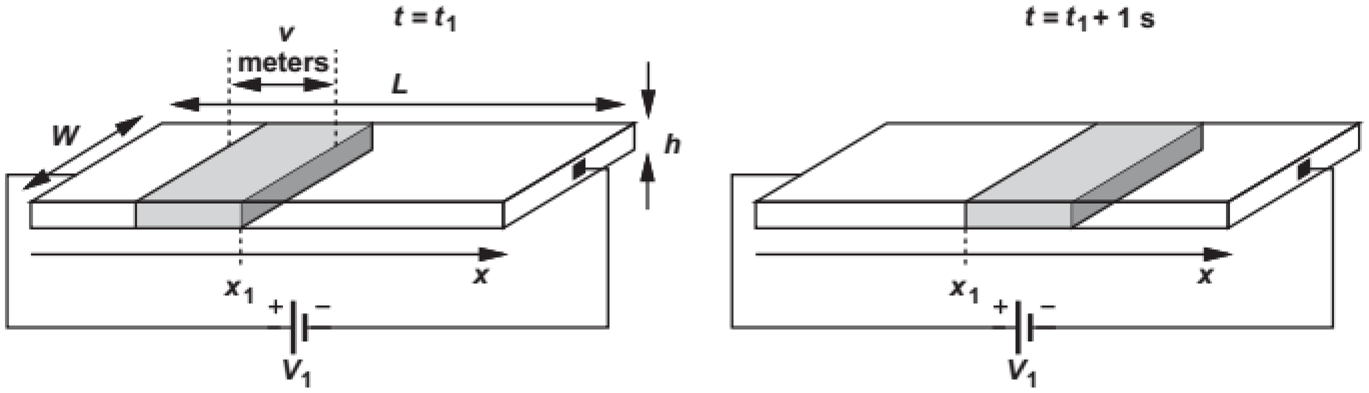
$$v = \mu E,$$

- Where μ is called the "mobility". For example in silicon, the mobility of electrons, μ_n = 1350 cm^2/(V·s), and that of holes, μ_p = 480 cm^2/(V·s).
- For electrons and holes, we can rewrite the formula as follows:

$$\vec{v_e} = -\mu_n \vec{E}.$$
$$\vec{v_h} = \mu_p \vec{E}.$$

- So, how can we calculate the current due to drift based on the drift velocity?

Drift



- We can calculate the total charge passing through in 1 second as follows,

$$I = -v \cdot W \cdot h \cdot n \cdot q$$

- The corresponding current density due to electrons is given by,

$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$

$$= q(\mu_n n + \mu_p p)E.$$

The conductivity σ of a semiconductor $\sigma = nq_n\mu_n + pq_p\mu_p$

Exercise

- Compute the conductivity of an intrinsic Silicon. Assuming $n = p = n_i = 1.5 \times 10^{16}$ carriers/m^3, $\mu_n = 0.14$ m^2/(V · s) and $\mu_p = 0.05$ m^2/(V · s)

$$\sigma = nq_n\mu_n + pq_p\mu_p$$

$$\sigma = n_i q(\mu_p + \mu_n)$$

$$\sigma = (1.5 \times 10^{16})(1.6 \times 10^{-19})(0.14 + 0.05)$$

$$\sigma = 4.56 \times 10^{-4} S/m$$

Exercise

- A bar of silicon with intrinsic electron density 1.4×10^{16} electrons/m^3 is doped with impurity atoms until the hole density is 8.5×10^{21}holes/m^3.
- Find the electron density of the extrinsic material

$$n = \frac{n_i^2}{p} = \frac{(1.4 \times 10^{16})^2}{8.5 \times 10^{21}} = 2.3 \times 10^{10} electronss/m^3$$

- Is the extrinsic material n-type or p-type

Since $p > n$, the material is p-type.

- Find the extrinsic conductivity

$$\sigma = nq_n\mu_n + pq_p\mu_p$$

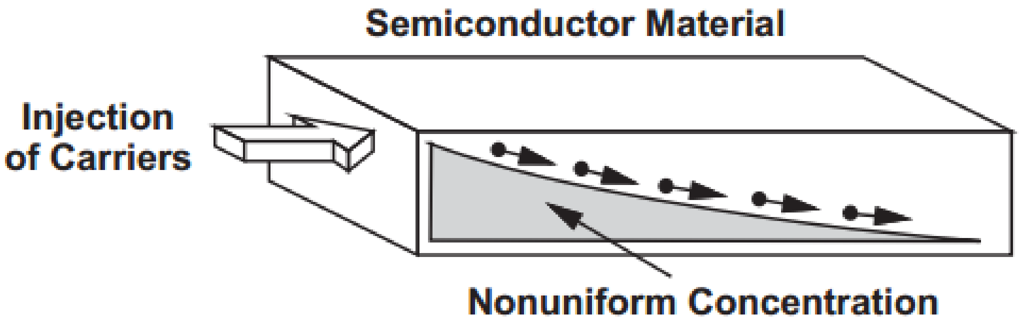
$$\sigma = (2.3 \times 10^{10})(0.14)(1.6 \times 10^{-19}) + (8.5 \times 10^{21})(0..05)(1.6 \times 10^{-19})$$

$$\sigma = 5.152 \times 10^{-10} + 68 \approx 68 S/m$$

Diffusion

- In addition to drift, another mechanism can lead to current flow.
- If charge carriers are “dropped” (injected) into a semiconductor it creates a nonuniform density of charge carriers.
- This high concentration of the injected carriers tend to flow from the region of high concentration to regions of low concentration.
- This mechanism is known as “**diffusion**”.
- Even in the absence of an electric field, the carriers move toward regions of low concentration, thereby carrying an electric current so long as the nonuniformity is sustained.

Diffusion



- From what we know qualitatively, the more nonuniform the concentration the more the current. Hence,

$$I \propto \frac{dn}{dx}$$

- We call dn/dx the concentration gradient with respect to x. If each carrier has a charge equal to q and the semiconductor has a cross sectional area of A,

$$I \propto Aq\frac{dn}{dx}.$$

Diffusion

- Therefore the total current will be given by,

$$I = AqD_n \frac{dn}{dx},$$

- Where D_n is a proportionality factor called the "diffusion constant".
- In intrinsic Silicon, D_n = 34cm^2/s (for electrons), and D_p = 12cm^2/s (for holes).
- The corresponding current density then becomes:

$$J_n = qD_n \frac{dn}{dx}. \qquad J_p = -qD_p \frac{dp}{dx}.$$

$$J_{tot} = q\left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right).$$

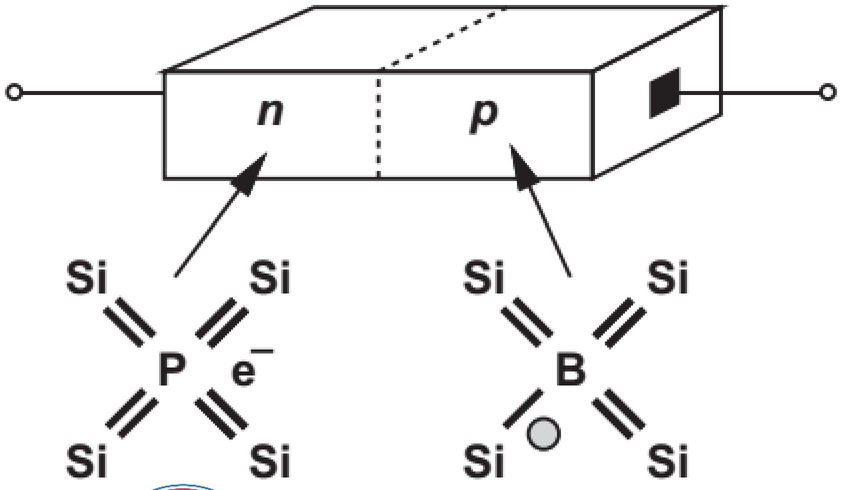
Einstein Relation

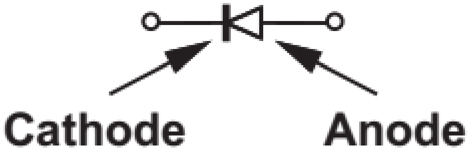
- From our discussions, we have seen two types of currents of a semiconductor.
- These have introduced factors μ_n (or μ_p) and D_n (or D_p) for drift and diffusion respectively.
- They can be related using the Einstein relation,

$$\frac{D}{\mu} = \frac{kT}{q}$$

pn Junction

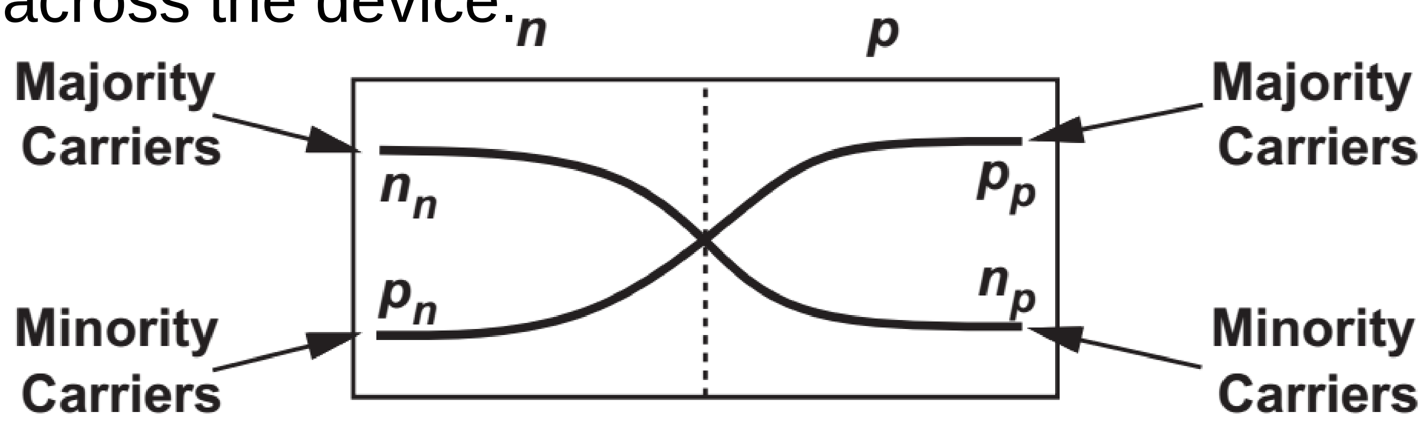
- An interesting situation arises when we introduce n-type and p-type dopants into two adjacent sections of a piece of semiconductor.
- We can only build this device on a single crystal, i.e. we can't bring a separate n-type material and p-type material together.
- This device finds applications in many electronic devices





pn junction in equilibrium

- With no external connections, i.e. the terminals are open and no voltage is applied across the device.

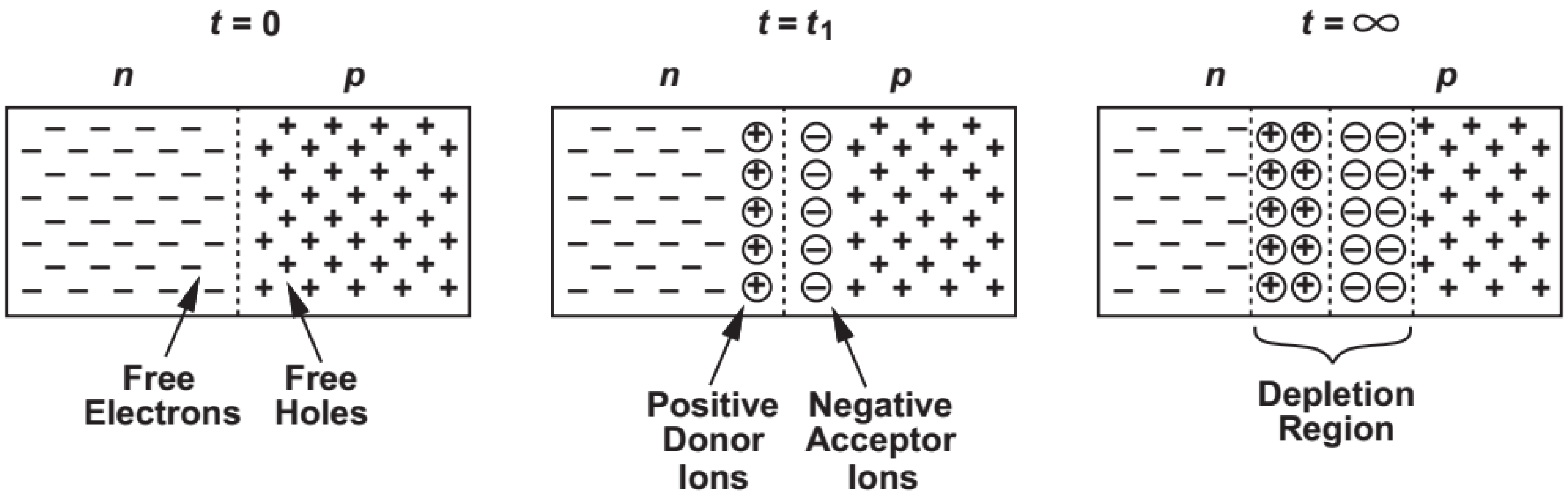


n_n : Concentration of electrons on n side
p_n : Concentration of holes on n side
p_p : Concentration of holes on p side
n_p : Concentration of electrons on p side

- There is an initial diffusion of majority carriers from both sides.

pn junction in equilibrium

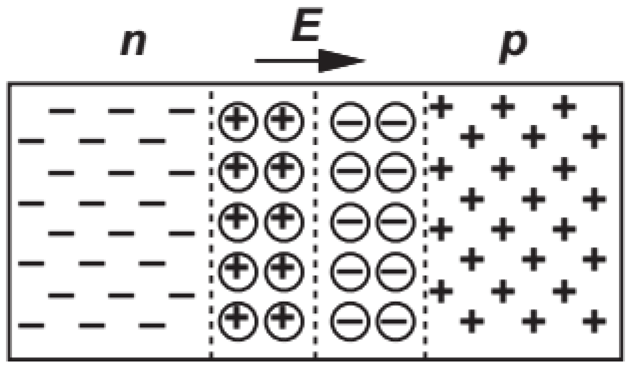
- Initially there is a diffusion of carriers from both sides.



- This diffusion eventually decays to zero.
- For every electron that departs from the n side, a positive ion is left behind.
- The immediate vicinity of the junction is depleted of free carriers and hence called the “depletion region”.

pn junction in equilibrium

- Because of the ions left in the depletion region, an electric field is generated.
- Hence, we have a drift current which opposes the diffusion current.



- The junction reaches equilibrium once the electric field is strong enough to completely stop the diffusion current.

pn junction in equilibrium

- In equilibrium, we must impose this condition,

$$|I_{\text{drift},p}| = |I_{\text{diff},p}|$$

$$|I_{\text{drift},n}| = |I_{\text{diff},n}|.$$

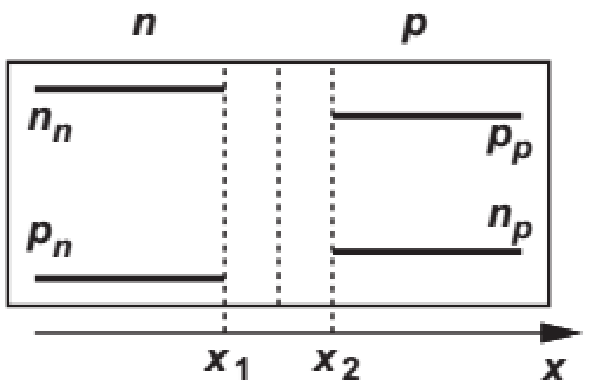
- From this, we get:

$$q\mu_p pE = qD_p \frac{dp}{dx}$$

- Finally,

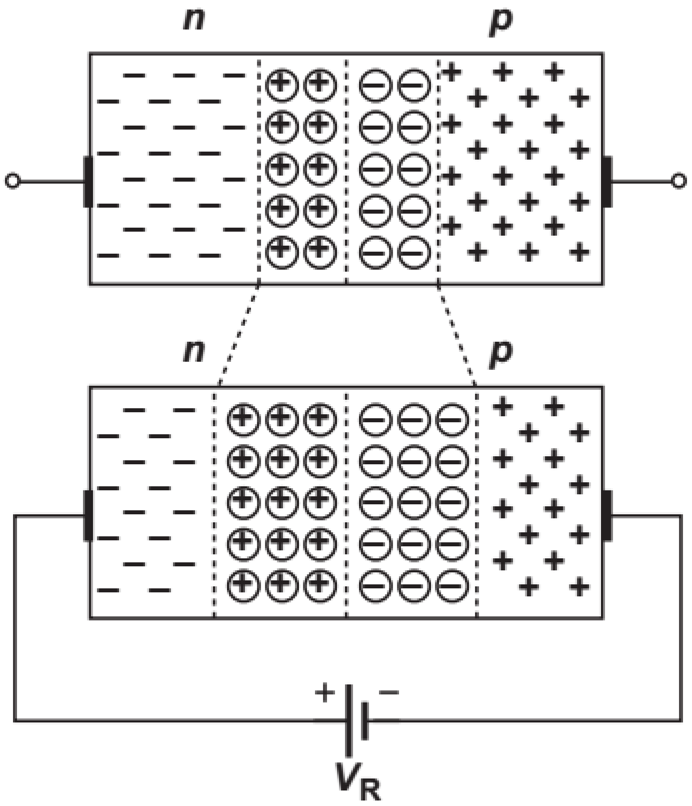
$$V(x_2) - V(x_1) = -\frac{D_p}{\mu_p} \ln \frac{p_p}{p_n}.$$

$$|V_0| = \frac{kT}{q} \ln \frac{p_p}{p_n}$$ or $$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

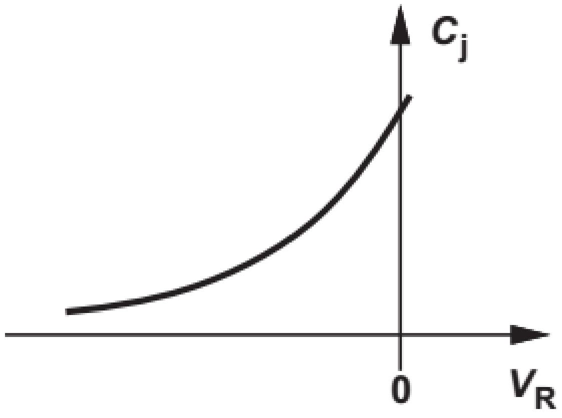


pn junction under reverse bias

- We first apply a voltage source that makes the n side more positive and the p side more negative, i.e. reverse bias

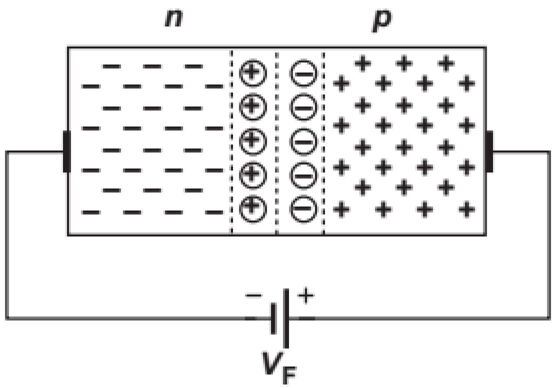


$$C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V_R}{V_0}}}$$



pn junction under forward bias

- We can also apply a voltage that makes the p side more positive and the n side more negative, i.e. forward bias



- This is also known as the diode.

What to Do This Week?

- Reading Assignment
  - Diode modeling
  - Diode circuits
  - Diode applications