# UESTC 3002/HN3008: Electronic Devices

## Lecture 2.1: *p-n Junction (2)*

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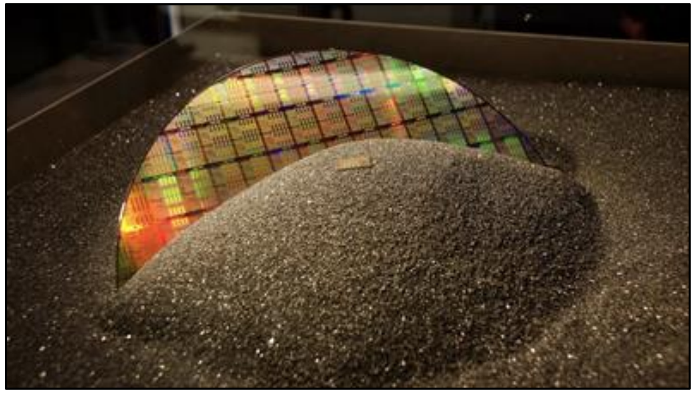
Reading: Chapter 5, Solid State Electronic Devices 7E, Ben G. Streetman, Sanjay K. Banerjee

# In today's lesson



- Junction Capacitance
- Carrier action: diffusion and drift current
- Net Carrier Current in Semiconductors
- Class Task: Exploring Carrier Currents (Teams of 4 - 5)

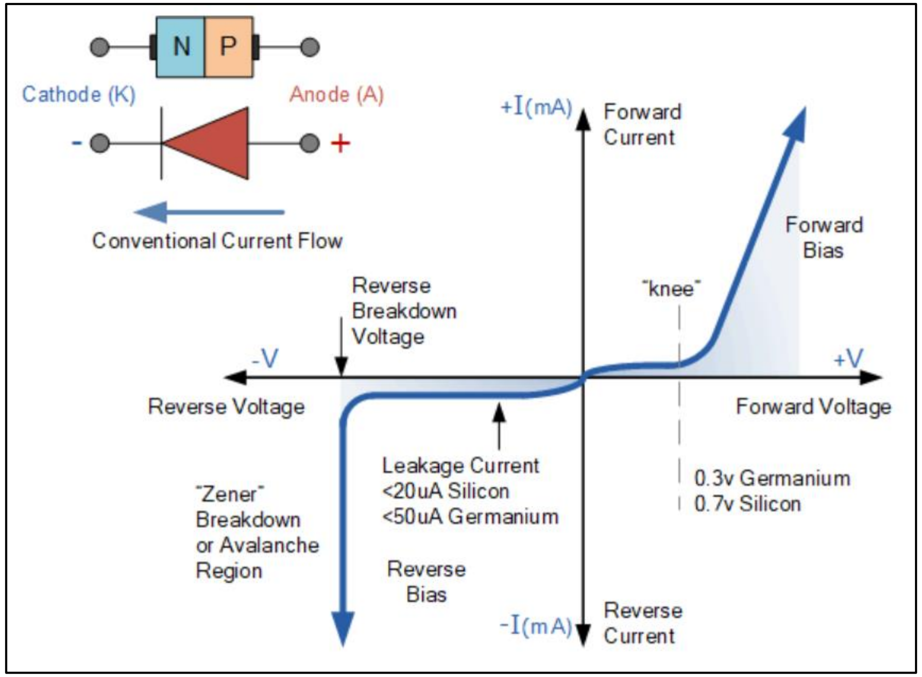
Source: newport.com

# Revision - Key Parameters of p-n Junction

Built-in Voltage: $V_{bi} = \frac{kT}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$

Depletion Width: $W = \sqrt{\frac{2\epsilon_0\epsilon_r\,(V_{bi} - V)}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$

Ideal Diode Equation: $I_{diode} = I_0\left(e^{qV/kT} - 1\right)$

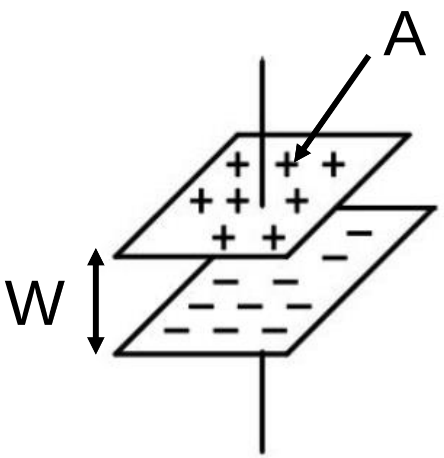



Source: electronics-tutorials.ws

# Junction Capacitance

Separation of charge leads to Capacitance

$$C = A\sqrt{\frac{q\varepsilon}{2(V_{bi} - V)}\left(\frac{N_D N_A}{N_D + N_A}\right)}$$




For $p^+$-n junction $N_a >> N_d$

$$C = A\sqrt{\frac{q\varepsilon}{2(V_{bi} - V)} N_D}$$

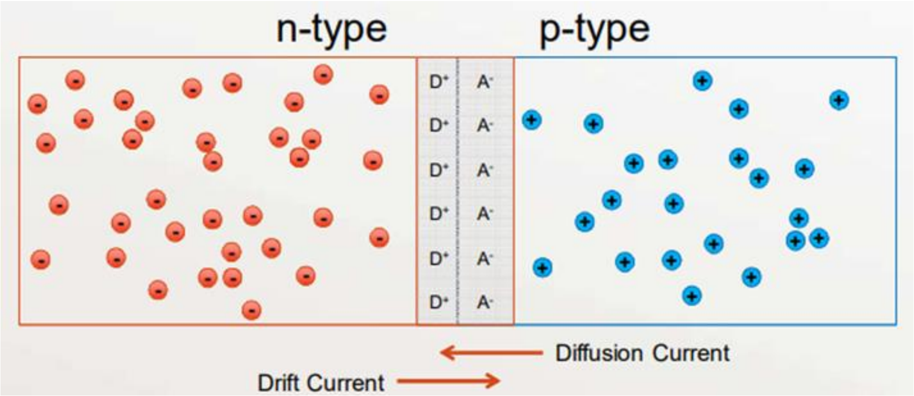
Measuring C will help extracting $N_D$ - a common approach in manufacturing industry

# Carrier Transport

Primary types of carrier action occur inside a semiconductor:

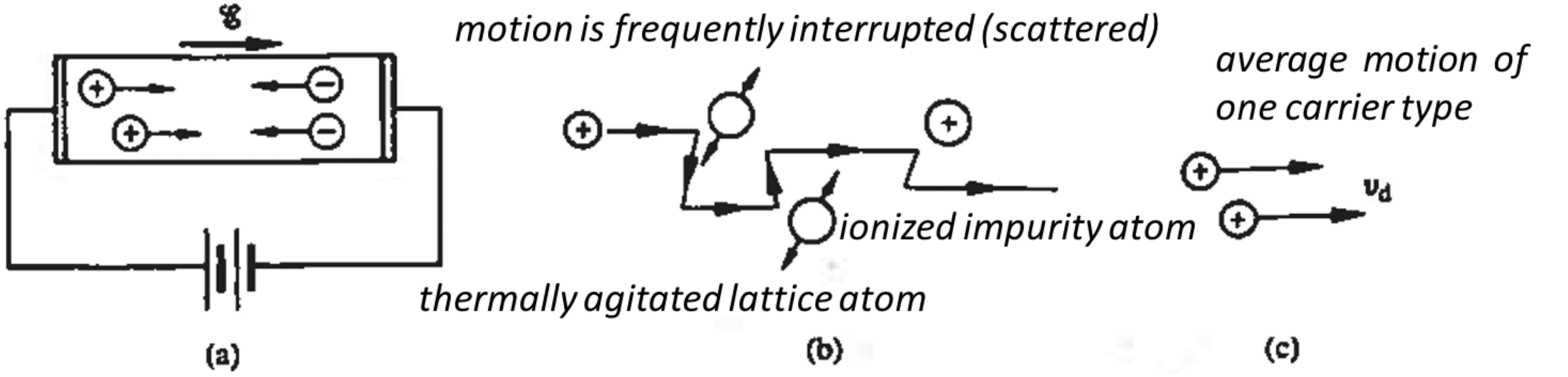
Drift: Charged particle motion under the influence of an electric field.

Diffusion: Particle motion due to concentration gradient or temperature gradient.



# Drift

- E is applied across a semiconductor, the resulting force on the carriers tends to accelerate the +q charged holes in the direction of E and the -q charged electrons in the direction opposite to E.
- This force superimposes on the random motion of electrons. Can be viewed as particles moving at a constant average drift velocity $v_d$.



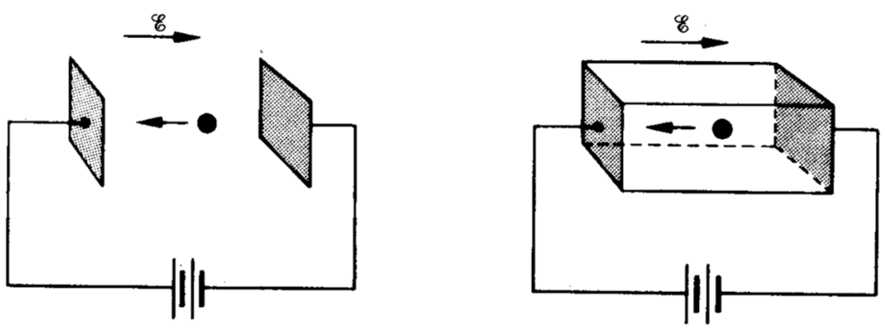

Visualization of carrier drift: (a) motion of carriers within a biased semiconductor bar; (b) drifting hole on a microscopic or atomic scale; (a) carrier drift on a microscopic scale.

Source: Semiconductor device fundamentals, Robert F. Pierret

# Drift

- When electrons and holes are placed in E, they accelerate because of the force applied.
- Force on a charged particle: F = *q*E
- The force causes acceleration: a = F/m
- The electric field causes the particle to accelerate depending on its charge and effective mass

**In vacuum** | **In semiconductor**




$F = (-q)E = m_o a$

$F = (-q)E = m_n^* a$

where

$m_n^*$ is the electron effective mass

Source: Semiconductor device fundamentals, Robert F. Pierret, scientificamerican.com

# Drift

- **Drift velocity** ($v_d$) is the velocity of charge carriers in a material when an electric field is applied. At low electric field:

$$v_d = \mu E$$

- μ is the mobility of the charge carriers (how easily they move through the material).

- The mobility of electrons ($\mu_e$) and holes ($\mu_h$) differ and depend on temperature, doping concentrations and other factors.

- **Drift current density** ($J$) refers to the flow of electric current per unit area due to the movement of charge carriers in a semiconductor under the influence of an electric field.

$$J_n = qnv_d = qn\mu_n E \qquad J_p = qpv_d = qp\mu_p E$$

- Each type of carrier contributes to the total current density based on its concentration and drift velocity.

$$J_{drift} = J_{n,drift} + J_{p,drift}$$

# Conductivity and Resistivity

- **Conductivity ($\sigma$):** It is defined as the coefficient of proportionality between the current density ($J$) and the electric field ($E$) applied across the material. The overall conductivity of a semiconductor:

$$\boldsymbol{\sigma = q(n\mu_n + p\mu_p)}$$

- **Resistivity** measures how strongly a material opposes the flow of electric current. It is influenced by the number of charge carriers and how easily they move through the material.

$$\boldsymbol{\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\ \mu_p)}}$$

# Diffusion

- **Diffusion** is caused by the random thermal motion of charge carriers, leading to a net flow from areas of higher concentration to lower concentration.

- The diffusion current density (*J*) of electrons and holes is described by Fick's Law:

$$J_{n,diffusion} = -qD_n \frac{dn}{dx} \qquad J_{p,diffusion} = qD_p \frac{dp}{dx}$$

- The diffusion current depends on the concentration gradient and the diffusion coefficients for the respective charge carriers.

- $\frac{dn}{dx}$ is the concentration gradient of electrons (change in electron concentration with distance).

- **Diffusion coefficient ($D_n$ $D_p$)** describes how readily charge carriers move from regions of high concentration to low concentration due to a concentration gradient.

- It reflects the ease with which these carriers spread out within the material.

# Diffusion

- D is related to its mobility via the Einstein relation:

$$D_n = \mu_n \frac{kT}{q} \qquad\qquad D_p = \mu_p \frac{kT}{q}$$

- Both depend on carrier mobility and temperature, and higher mobility leads to higher diffusion rates.

- This relation connects the thermal motion of charge carriers (diffusion) to their response to an electric field (drift).

# Net Carrier Current in Semiconductors

- The total or net carrier current in a semiconductor arises as the combined result of drift and diffusion currents.
- The total current density is the result of adding the contributions from each carrier type.

$$J = J_n + J_p = J_{n,drift} + J_{n,diffusion} + J_{p,drift} + J_{p,diffusion}$$

# ED Class Task
# Exploring Carrier Currents

Teams of 4-5: 15-20 minutes

Research and identify one **real-world application** of semiconductor devices where drift and diffusion currents play a critical role (e.g., solar cells, diodes, transistors). [8 – 12 min]

- Prepare to share how these currents affect the **device’s performance**.

Probable Questions:

- How do temperature and doping levels affect drift and diffusion currents?
- In what scenarios would one current dominate over the other?

Share with the Class! [6 – 8 min]

# In next Lecture

- Band Diagrams
- Reverse Breakdown
- Problems Exercise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# Supplementary

# Electron & Hole Concentration

The general equation for the conductivity of a semiconductor, depends on **n**, the electron concentration, and **p**, the hole concentration.

How do we determine these quantities?

The procedure involves multiplying **density of states $g_{cb}(E)$** by the **probability of a state being occupied f(E)** and **integrating over the entire CB for n** and over the entire **VB for p**.

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# Electron & Hole Concentration

Integrating this from the **bottom (Ec)** to the **top  (Ec + x)** of the **CB** gives the **electron concentration (n)**, which is the number of electrons per unit volume in the CB.

$$n = \int_{E_c}^{E_c+\chi} n_E(E)\,dE = \int_{E_c}^{E_c+\chi} g_{cb}(E)\,f(E)\,dE$$

$$\downarrow$$

$$n_E\,dE = g_{cb}(E)\,f(E)\,dE$$

# Electron & Hole Concentration

Note that the <u>Fermi function</u> gives the probability of occupying an available energy state,

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

Now that we have introduced he Fermi function, we should define the <u>**Density of States,**</u> which is the ***number of available energy states*** to determine how many electrons would reach the <u>conduction band</u>. The density of states is given by:

$$g_{cb}(E) = \frac{(\pi 8\sqrt{2}) m_e^{*3/2}}{h^3} (E - E_c)^{1/2}$$

# Electron & Hole Concentration

Effective mass of electron, $m_e$*= 9.1exp-31 kg

$$n \approx \frac{(\pi 8\sqrt{2})m_e^{*3/2}}{h^3} \int_{E_c}^{\infty} (E - E_c)^{1/2} \exp\left[-\frac{(E - E_F)}{kT}\right] dE$$

which leads to

$$n = N_c \exp\left[-\frac{(E_c - E_F)}{kT}\right]$$

where

$$N_c = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}$$

# Electron & Hole Concentration

We can carry out a similar analysis for the concentration of holes in the VB. Multiplying the density of states $g_{vb}(E)$ in the VB with the probability of occupancy by a hole [1 – f(E)].

Remember that the probability that an electron is absent gives p, the hole concentration per unit energy. Integrating this over the VB gives the hole concentration.

The hole concentration can therefore be expressed as:

$$p = \int_0^{E_v} p_E \, dE = \int_0^{E_v} g_{vb}(E)[(1 - f(E)] \, dE$$

With the assumption that $E_F$ is a few $kT$ above $E_v$, the integration simplifies to

$$p = N_v \exp\left[-\frac{(E_F - E_v)}{kT}\right]$$

where $N_v$ is the effective density of states at the VB edge and is given by

$$N_v = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}$$

# Intrinsic Carrier Concentration

Using the expressions for hole and electron concentrations, we can therefore express the **intrinsic** carrier concentration as:

$$np = N_c \exp\left[-\frac{(E_c - E_F)}{kT}\right] N_v \exp\left[-\frac{(E_F - E_v)}{kT}\right] = N_c N_v \exp\left[-\frac{(E_c - E_v)}{kT}\right]$$

or

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

# Intrinsic Carrier Concentration

An **intrinsic semiconductor** is a pure semiconductor crystal in which the electron and hole concentrations are equal. By pure we mean virtually no impurities in the crystal. In an intrinsic semiconductor, the Fermi-level is in the middle of the bank gap, as previously shown.

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