

# ECE321 – Electronics I

## Lecture 4: Physics of Semiconductor Diodes

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## *Review of Last Lecture*

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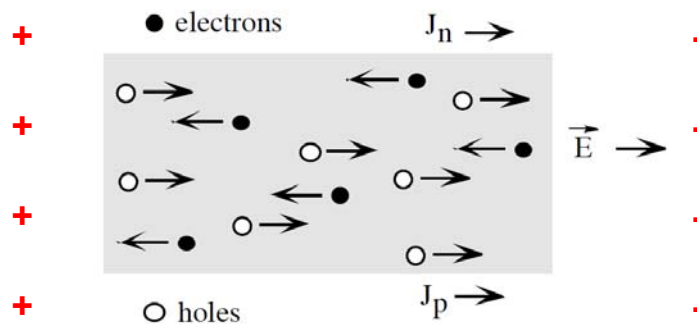
- Electrical Property of Materials
- Energy Band Diagrams
- Semiconductor Materials
- n-Type and p-Type Semiconductor Materials
- Mass Action Law

## Today's Lecture

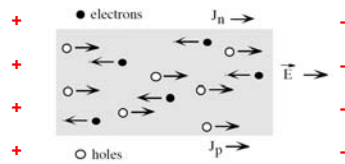
- Carrier Transport in Semiconductors
- Drift Current
- Diffusion Current
- PN Junction
- Depletion Region
- Reverse Biased PN Junction
- Forward Biased PN Junction

## Drift Current Due to Electric Field

- This is what happens in a typical resistors
- Direction of electrons and holes under externally applied electric field ( $E$ ) is shown below



## Drift Current Equations in Semiconductor



$$J = \mu_n q E n_o + \mu_p q E p_o$$

*n*-type silicon has  $n_o \approx N_D = 10^{17}$  (atoms/cm<sup>3</sup>) at 300 K,  $\mu_n = 1350$  cm<sup>2</sup>/V•s,  $\mu_p = 480$  cm<sup>2</sup>/V•s, and the electric field is 10 V/cm. (a) What is the minority hole carrier density  $p_o$ ? (b) What is the total current density  $J$ ? (c) What is the resistivity of the material?

Solution

$$(a) \quad p_o = \frac{n_i^2}{n_o} = \frac{(1.062 \times 10^{10})^2}{10^{17}} = 1.128 \times 10^3 \left( \frac{\text{holes}}{\text{cm}^3} \right)$$

$$(c) \quad J = \sigma E = \frac{1}{\rho} E$$

$$216 = 10 / \rho \rightarrow \rho = 46.3 \text{ m}\Omega\cdot\text{cm}$$

$$\text{Ref: } \rho_{\text{cu}} = 1.7 \text{ }\mu\Omega\cdot\text{cm}$$

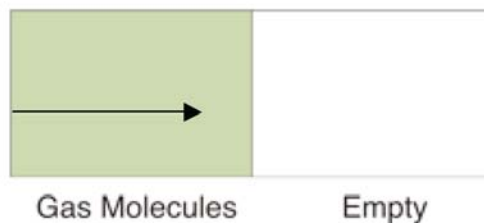
(b)

$$J = (1350)(1.6 \times 10^{-19})(10)(10^{17}) + (480)(1.6 \times 10^{-19})(10)(1.128 \times 10^3)$$

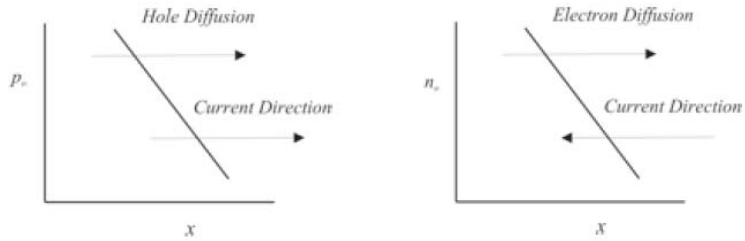
$$= 216 + 8.7 \times 10^{-13} = 216 \left( \frac{\text{A}}{\text{cm}^2} \right)$$

## Diffusion Current Due to Density Gradient

- This happens when the carrier concentration is different from one side to the other side
- An analogous case happens in gas container below, where the gas molecules “diffuses” from higher density to lower density



## Diffusion Current Equations



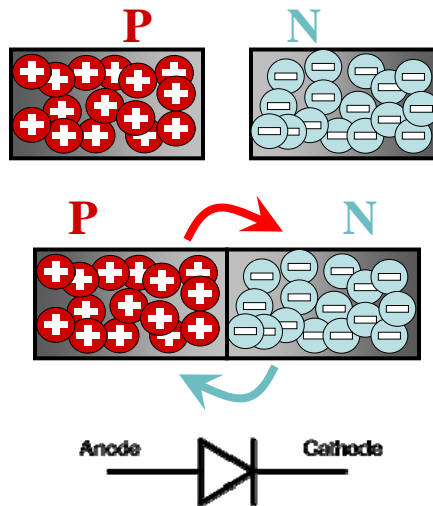
$$J_{pdiff} = qD_p \frac{dp_0}{dx}$$

$$J_{ndiff} = qD_n \frac{dn_0}{dx}$$

$D_n$  and  $D_p$  are the electron and hole “diffusion constants”

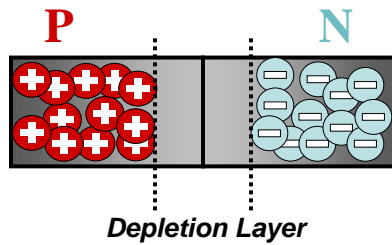
## PN Junction

- What does happen when P-Type semiconductor meets N-Type Semiconductor?



## PN Junction

- ❑ Some electrons will cross the junction and fill holes. A pair of ions is created each time this happens.
- ❑ As this ion charge builds up, it prevents further charge migration across the junction.
- ❑ The junction goes into equilibrium when the barrier potential prevents further diffusion.
- ❑ At 25 degrees C, the barrier potential for a silicon pn junction is about 0.5 to 0.7 volts.



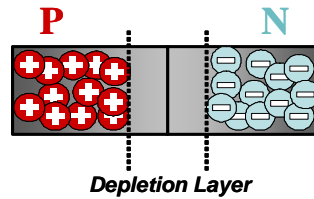
## Depletion Region in Equilibrium

- ❑ The barrier potential across depletion region is computed as:

$$V_{bi} = V_{th} \ln \left( \frac{N_A \cdot N_D}{n_i^2} \right) \qquad V_{th} = \frac{kT}{q}$$

- ❑ The width of depletion region is computed as:

$$W = \sqrt{\frac{2\epsilon_{si}}{q} \frac{N_A + N_D}{N_A \cdot N_D} V_{bi}}$$

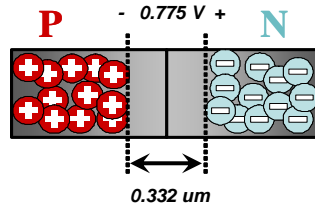


## Example: Depletion Region

- Calculate the built-in potential and depletion width at 300K in a diode if  $n_i = 1.062 \times 10^{10} \text{ cm}^{-3}$ ,  $\epsilon_{\text{si}} = 1.04 \times 10^{-12} \text{ F/cm}$ ,  $N_A = 10^{16} \text{ cm}^{-3}$ , and  $N_D = 10^{17} \text{ cm}^{-3}$ .

$$V_{bi} = V_{th} \ln \left( \frac{N_A \cdot N_D}{n_i^2} \right) = 0.026 \ln \left( \frac{10^{16} \cdot 10^{17}}{(1.062 \times 10^{10})^2} \right) = 0.775 \text{ V}$$

$$W = \sqrt{\frac{2\epsilon_{\text{si}}}{q} \frac{N_A + N_D}{N_A \cdot N_D} V_{bi}} = \sqrt{\frac{2 \times 1.04 \times 10^{-12}}{1.609 \times 10^{-19}} \frac{10^{16} + 10^{17}}{10^{16} \cdot 10^{17}}} \times 0.775 = 3.32 \times 10^{-5} \text{ cm} = 0.332 \mu\text{m}$$



## Depletion Region Phenomena

- The depletion region is so named because it is formed by removal of all free charge carriers leaving none to carry a current.
- Depletion region is therefore an **insulator** region within a conductive material.
- Many modern semiconductor devices function based on “depletion region” phenomena.
- Example: Diodes, Solar cells, Bipolar Transistors, and MOS Transistors, Variable Capacitance Diodes

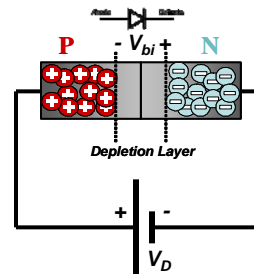
## PN Junction Under Applied Voltage

- ❑ The applied external voltage,  $V_D$ , on the diode will directly affect the built-in potential
  - In reverse bias, the external voltage adds up to the built-in potential increasing the effect of  $V_{bi}$
  - In forward bias, the external voltage is against the built-in potential reducing the effect of  $V_{bi}$
- ❑ Depletion region width also depends on the voltage applied to the diode.

❑ Review:

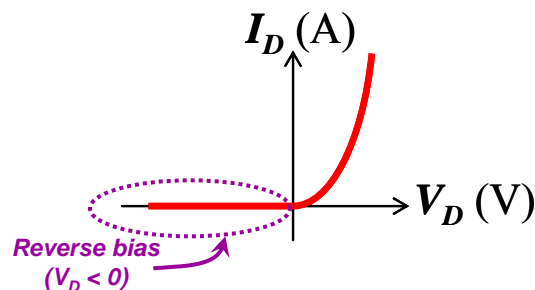
$$W = \sqrt{\frac{2\epsilon_{si}}{q} \frac{N_A + N_D}{N_A \cdot N_D} (V_{bi} - V_D)}$$

$$V_{bi} = V_{th} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \quad V_{th} = \frac{kT}{q}$$



## Reverse Biased PN Junction

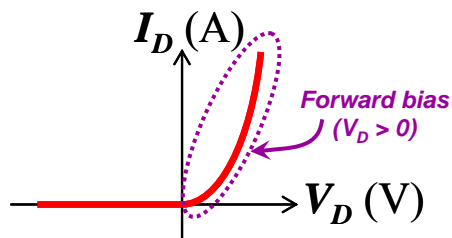
- ❑ In CMOS transistors, that are currently used in semiconductor industry, all PN junctions are normally in reverse bias condition.
- ❑ When  $V_D < 0$  the width of depletion region increases which results in no conduction.



## Forward Biased PN Junction

- ❑ When  $0 < V_D < V_{bi}$  the width of depletion region decreases.
- ❑ Once  $V_D \geq V_{bi}$ , then depletion region disappears and the diode starts conducting.
- ❑ The current in a diode can then be approximated as:

$$I_D = I_S \left( e^{V_D/V_{th}} - 1 \right) \quad V_{th} = \frac{kT}{q}$$



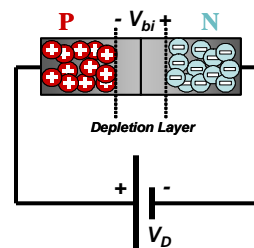
## Diode's Parasitic Capacitance

- ❑ The depletion region, which act as an insulator, behaves like a capacitor in a PN junction.
- ❑ The "junction capacitance" can be calculated as:

$$C_j = \frac{\epsilon_{si} A}{W} = \frac{\epsilon_{si} A}{\sqrt{\frac{2\epsilon_{si}}{q} \frac{N_A + N_D}{N_A \cdot N_D} (V_{bi} - V_D)}} = \frac{A \sqrt{\frac{q\epsilon_{si}}{2} \frac{N_A \cdot N_D}{N_A + N_D} V_{bi}}}{\sqrt{1 - \frac{V_D}{V_{bi}}}} = \frac{C_{j0}}{\sqrt{1 - \frac{V_D}{V_{bi}}}}$$

Where:

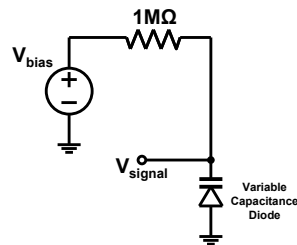
$$V_{bi} = V_{th} \ln \left( \frac{N_A \cdot N_D}{n_i^2} \right) \quad V_{th} = \frac{kT}{q}$$



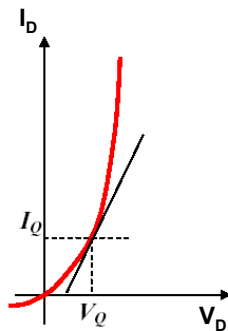


## Variable Capacitance Diode (Varactor)

- ❑ Generally, the junction capacitance in a diode is undesirable because it slows down the switching of the diode.
- ❑ Sometimes, we make a good use of this “parasitic capacitance”.
- ❑ The capacitance of a reverse bias diode can be adjusted by the amount of bias on a diode.
- ❑ If the AC input signal is small enough, the reverse bias diode can be seen as a capacitor, whose value can be adjusted by its reverse bias voltage.



## Small Signal Model for Diodes



$$I_D = I_S \left( e^{V_D/V_{th}} - 1 \right) \quad V_{th} = \frac{kT}{q}$$

### Dynamic (Small Signal) Conductance

$$g_d = \left( \frac{dI_D}{dV_D} \right)_{V_D=V_Q} = \frac{I_S}{V_{th}} e^{V_Q/V_{th}} \approx \frac{I_Q}{V_{th}}$$

### Dynamic (Small Signal) Resistance

$$r_d = \frac{1}{g_d} = \frac{V_{th}}{I_Q}$$