Electronic Circuits for Mechatronics (ELCT 609)

Spring 2021

Lecture 1: PN Junctions Physical Structure

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GUC
German University in Cairo
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Electronic (Semiconductor) Devices

P-N Junctions (Diodes): Physical Structure & I-V Characteristics

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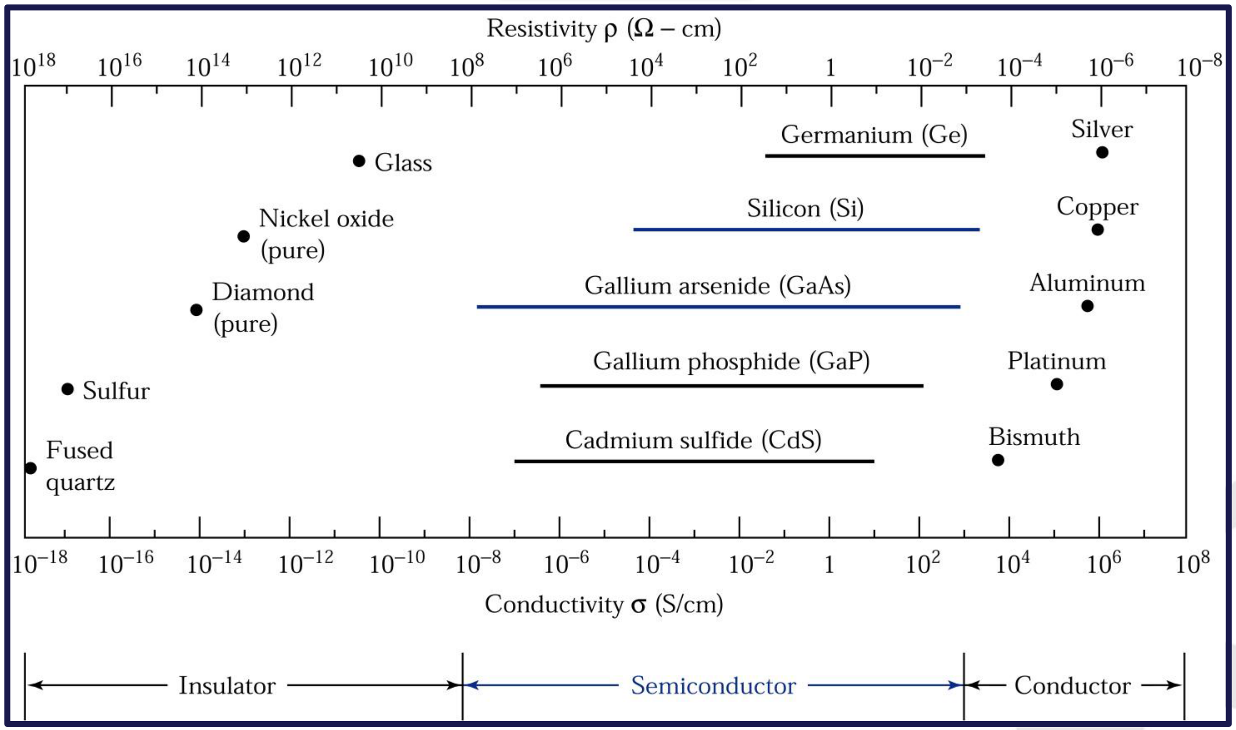
Introduction to Semiconductors

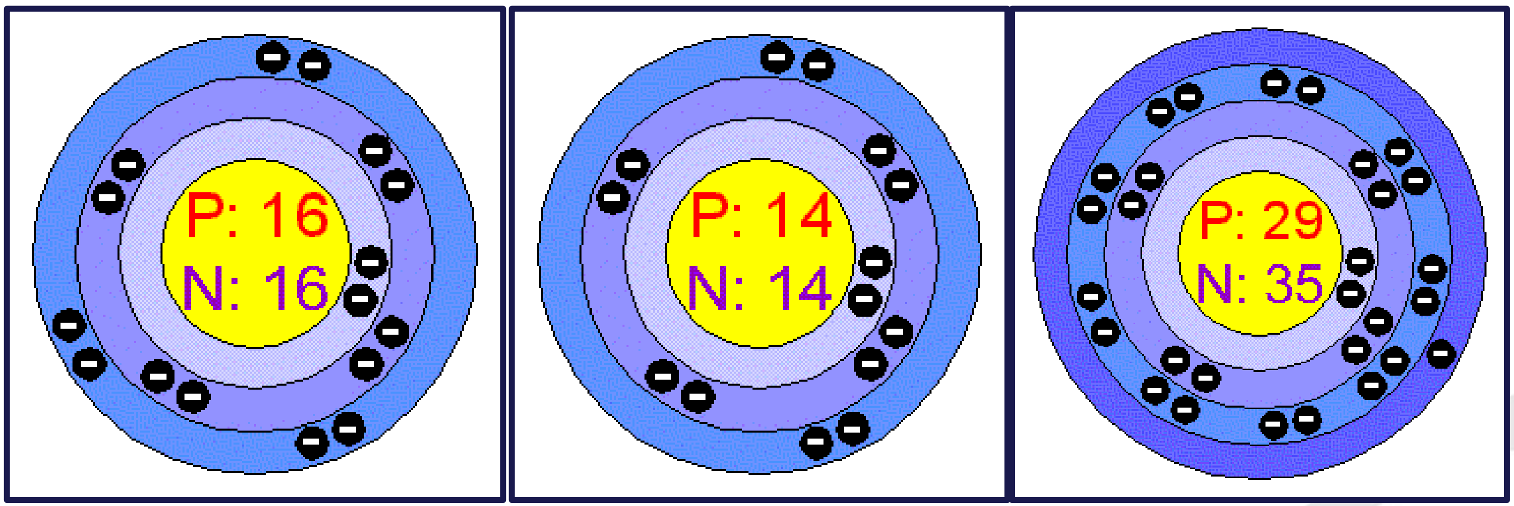
Solid-state Materials

- Insulators
- Semiconductors
- Conductors



Introduction to Semiconductors

- ❑ What is the reason for Conductivity Variation?
  - ❑ Outer Shell Electrons inside the material's atom



Sulfur (Insulator)	Silicon (Semiconductor)	Copper (Conductor)

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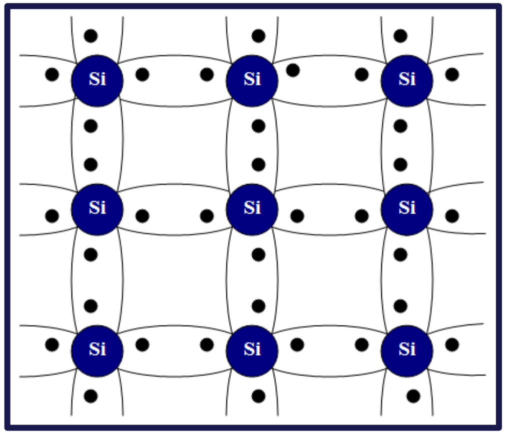
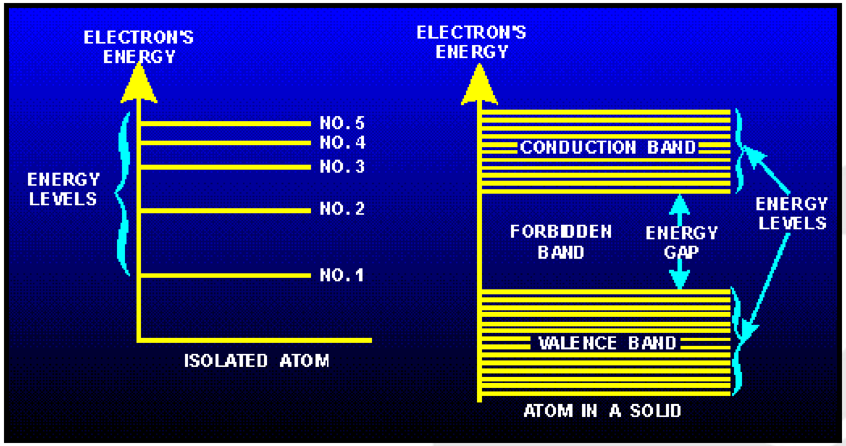
Introduction to Semiconductors

- Silicon atoms form a crystal (**Intrinsic Semiconductor**)
- Si atoms outer shells overlap, then split into two Energy bands:
  - Conduction Band
  - Valence Band



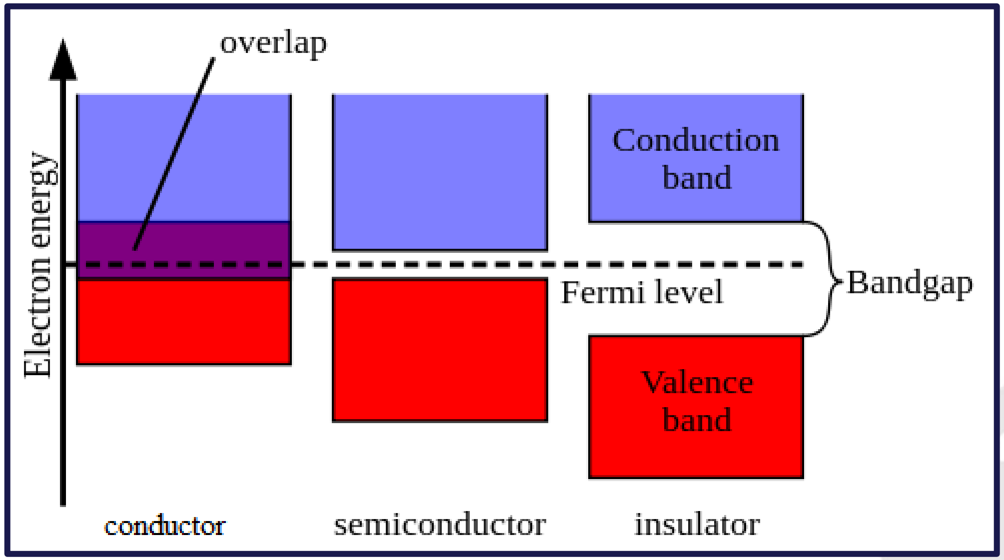
Pure Silicon Crystal
(Semiconductor)



Energy Band Diagram for Silicon
(Band theory for Solids)

Material's Conductivity

- Free electrons (Charges) exist in **Conduction Band**
- Electrons tied with the atom nucleus exist in **Valence Band**
- **No. of Electrons** in Conduction Band indicates the material **Conductivity**



Material’s Conductivity

- Metals have a large number of electrons in Conduction band (Overlapping bands)
  - Electrons can move freely with the **smallest energy** gain
- Insulators have no electrons in Conduction band
  - Electrons need to gain **high energy** to be able to move freely
  - $(E_{gap} = 9\ eV = 1.44196e - 18\ J)$
- Semiconductors have no electrons in Conduction band at Zero Kelvin Temp.
  - Electrons need to gain **small energy** to be able to cross from the valence to the conduction band
  - $(E_{gap} = 1\ eV = 1.6e - 19\ J)$

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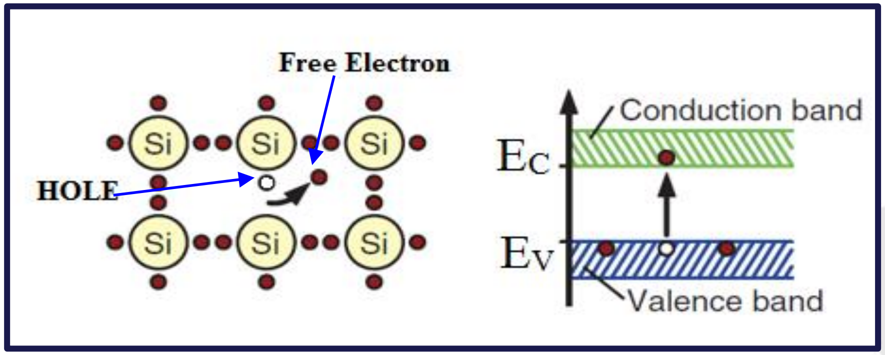
Semiconductor Conductivity

- What happens to a Silicon Crystal at room Temp.?
  - Electrons gain thermal energy enough to break a covalent bond
  - Electron leaves a **HOLE** in the outer shell
    - **Electron-hole pair generation**
  - Free electron existence increases the Si Conductivity
  - **<u>Can we add more free Electrons and Holes to enhance the Si Conductivity?</u>**

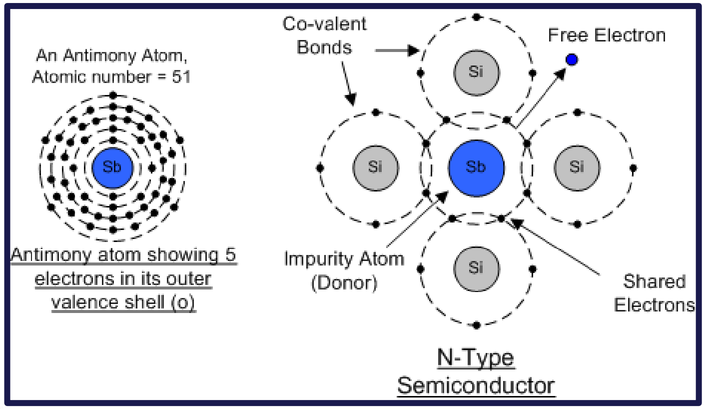


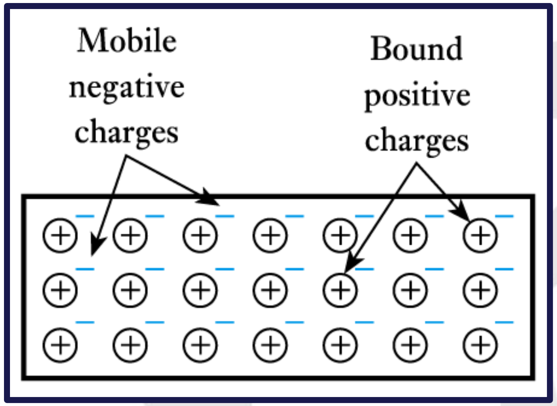
Semiconductor Conductivity

- **<u>Can we add more free Electrons to enhance the Silicon Conductivity?</u>**
  - Yes, by adding new materials to the silicon crystal (**Extrinsic Semiconductor**)

- Add penta-valent element
- Materials with **<u>5</u>** electrons in their outer shell
- Ex: Arsenic “As”, antimony “Sb”, and Phosporus

N-Type Semiconductor





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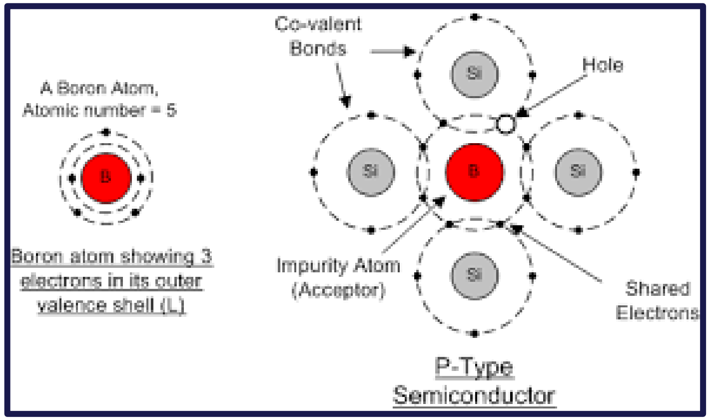
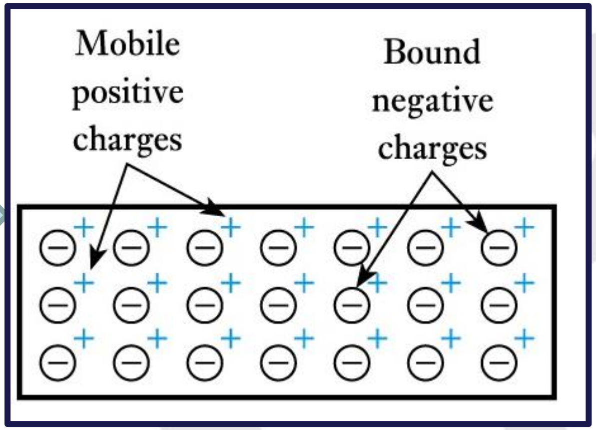
Semiconductor Conductivity

- **Can we add more Holes to enhance the Silicon Conductivity?**
  - Yes, by adding new materials to the silicon crystal (**Extrinsic Semiconductor**)

- Add Tri-valent element
- Materials with **3** electrons in their outer shell
- Ex: Aluminum "**Al**", Boron "**B**", and Gallium "**Ga**"

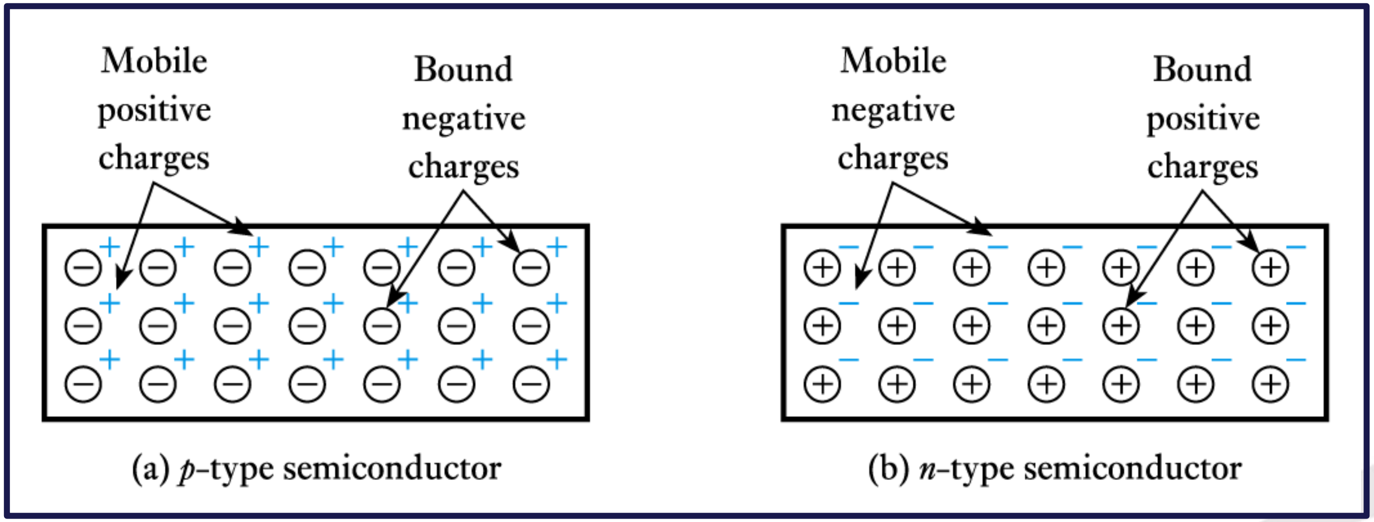
P-Type Semiconductor





Semiconductor Conductivity

- **Extrinsic Semiconductors**



P-Type
Majority Charge Carries (Holes)
Minority Charge Carriers (Electrons)

N-Type
Majority Charge Carries (Electrons)
Minority Charge Carriers (Holes)

Semiconductor Conductivity

- **Summary:**
  - Intrinsic Si Crystal is a bad conductor at 0 Kelvin
  - At room Temp., some electrons gain energy and can move inside Si crystal (in small numbers)
    - Electron-Hole Pairs are generated
  - When an electron break free from a covalent bond it leaves a hole (a positive free charge)
  - Extrinsic Si Crystals contain free charges in large numbers (Doping Process)
    - **N-Type** has negative free charges (**electrons are the majority current carriers**)
    - **P-Type** has positive free charges (**Holes are the majority current carriers**)

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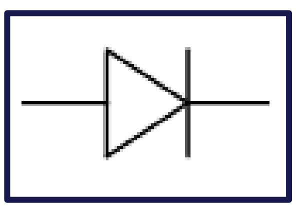
Semiconductor Devices

- **<u>What is the use of Extrinsic Semiconductors?</u>**
  - Extrinsic Si Crystals contain free charges in large numbers
  - Both N and P types can be used as conducting materials, **However still conducting elements will have higher conductivity**
- **<u>What is the importance of Extrinsic Semiconductors then?</u>**
  - Manufacturing different types of N and P types together creates new devices with electrically controllable conductivity
    - Ex: **P-N Junction**

P-N Junction Structure

- **<u>What happens when we put a P-Type and N-Type in contact?</u>**
- Electrons/holes diffuse in P/N type semiconductor
  - We call this charge motion **Diffusion Current**
  - Does the holes and electrons diffusion cancel the net current?

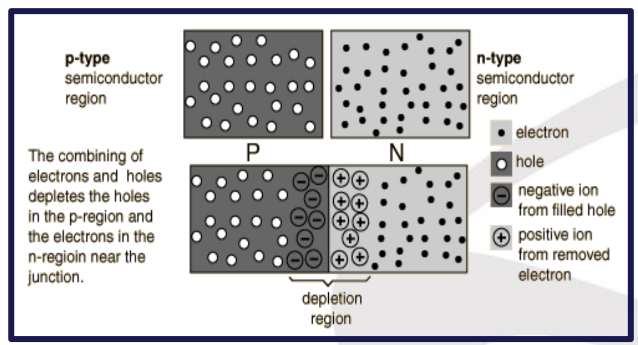
P-N Junction Circuit Symbol



Holes

Electrons

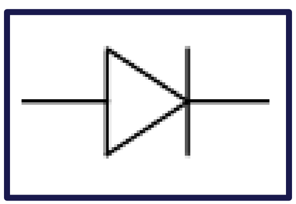
Diffusion Current

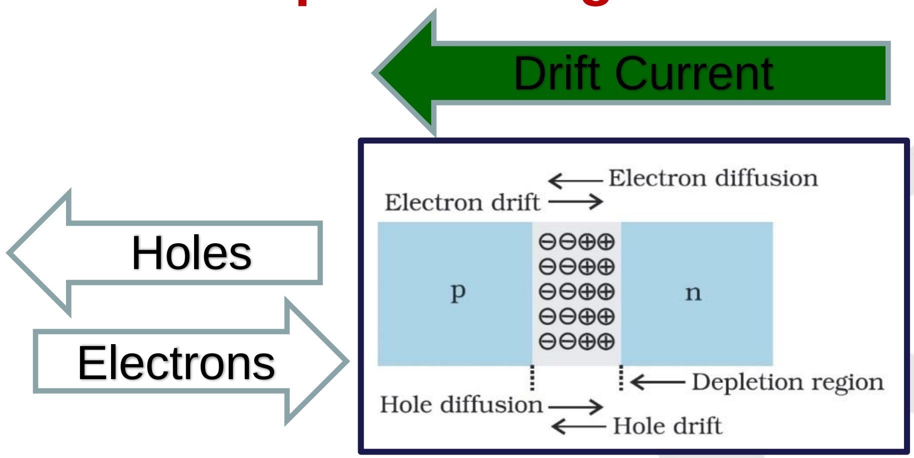


P-N Junction Structure

- <u>**What happens when we put a P-Type and N-Type in contact?**</u>
- Minority carriers drift in the junction
  - We call this charge motion **Drift Current**
- At thermal equilibrium the total current is Zero
- A free charge region called **Depletion Region**

P-N Junction Circuit Symbol





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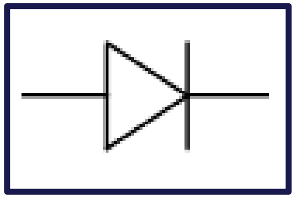
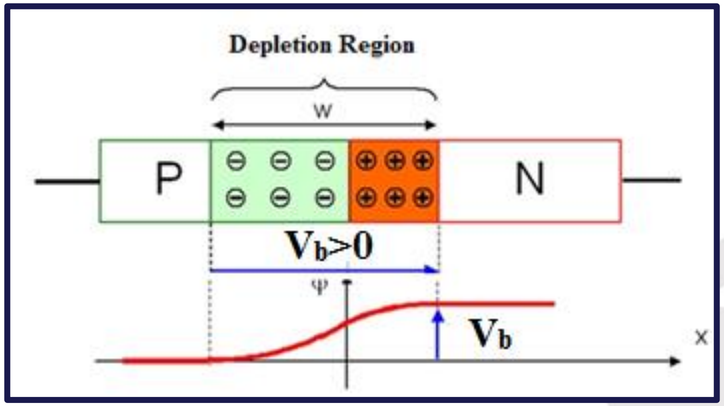
P-N Junction Structure

- **Will the electron-hole recombination happens for all charge carriers?**
- **No**, as the ions in the depletion region creates an **Electric Field**
- This field will oppose the holes and electrons from moving
  - A potential barrier is created

P-N Junction Circuit Symbol





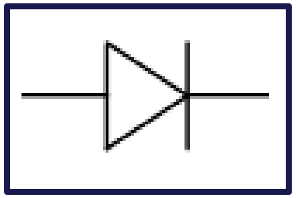
P-N Junction Biasing

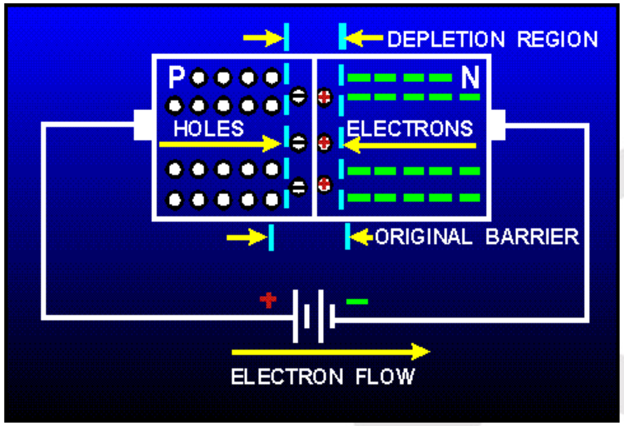
- The potential barrier (V_b) will keep the free charges (holes & electrons) from diffusing
- What would happen if we connected a voltage Source across the P-N junction??

- If the Voltage across the P-N junction is greater than V_b, then the majority carriers gain enough energy to surpass the depletion region
- Depletion region width decreases
- High Diffusion Current
- Low Drift Current
- High Current flows from P-Type to N-Type,

$I_D>0$

P-N Junction Circuit Symbol





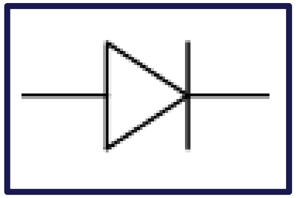
P-N Junction Biasing

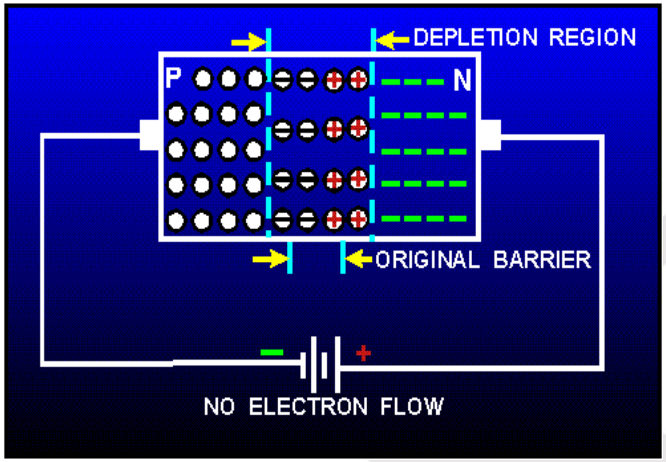
- What will happen if we connected a voltage Source across the P-N junction, with the P-Type less than N-Type??

- **If the Voltage across the P-N junction is less than V_b, then the majority carriers doesn't have enough energy to surpass the depletion region**
- **Depletion region width increases**
- **No Diffusion Current**
- **Small drift Current**
- **Very low Current flowing from N-Type to P-Type**
- **This current can be neglected and considered Zero (Reverse Saturation Current I_s)**

$I_D \approx 0$

P-N Junction Circuit Symbol

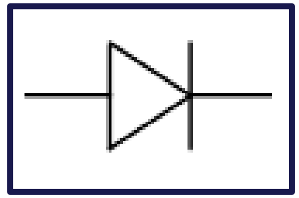


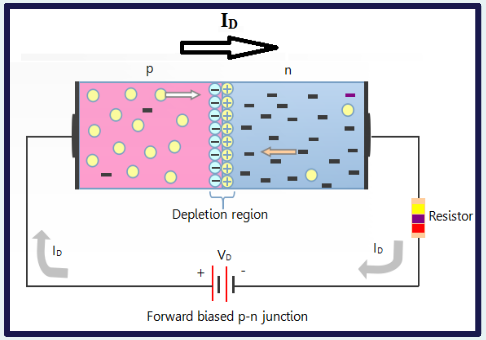
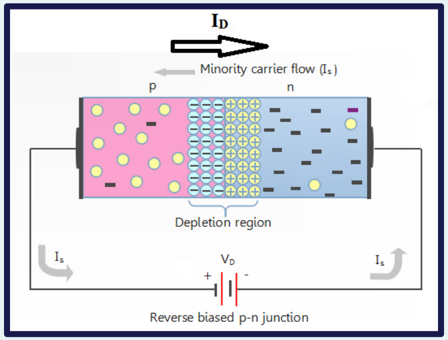


P-N Junction Biasing

- P-N junction Modes of Operation

P-N Junction Circuit Symbol

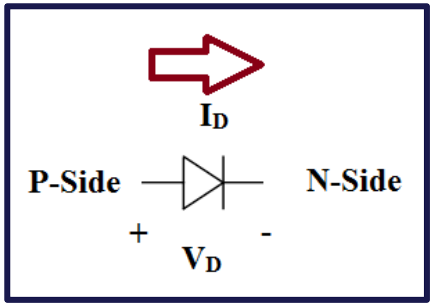


Forward Biased	Reverse Biased
	
$V_D = V_P - V_N$ $V_D > V_b$	$V_D = V_P - V_N$ $V_D < V_b$
$I_D > 0$	$I_D = -I_s \cong 0$

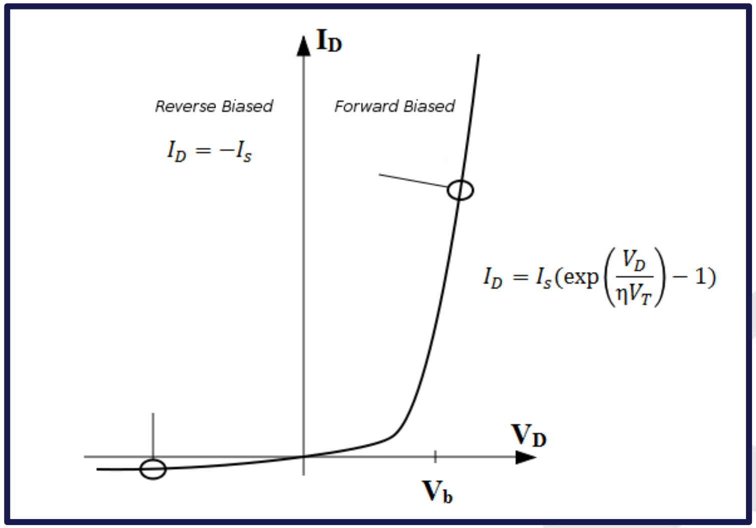
P-N Junction I-V Characteristics

- **Can we model I_D versus V_D?**

$$I_D = I_s\left(\exp\left(\frac{V_D}{\eta V_T}\right) - 1\right)$$



I_S :Reverse Saturation Current [nA]
V_T :Thermal voltage [mV]
η :ideality factor (1 ~ 2)



P-N Junction I-V Characteristics

- **Notes:**
  - V_D is the diode voltage, always take P-side minus N-side
  - I_D is the diode current, flowing from P-side to N-side
  - Thermal voltage is defined by:

$$\boxed{V_T = \frac{kT}{q}}$$

k :Boltzmann's Constant
T :Absolute Temperature in Kelvin
q :electron Charge

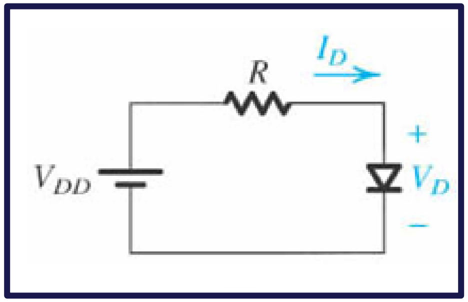
  - At room temp., V_T=25mV
  - We can make the following approximations:

Forward Biased	Reverse Biased
$\boxed{I_D \cong I_s \exp\left(\frac{V_D}{\eta V_T}\right)}$	$\boxed{I_D = -I_s \cong 0}$

Example

- Find the diode voltage and current for the Circuit Shown?
  - Given: V_{DD}=1V, R=100Ω
  - Solution:
    - We need two equations to get V_D and I_D
    - First equation KVL in the loop

$$\boxed{V_{DD} = I_D R + V_D} \quad \boxed{I_D = \frac{V_{DD} - V_D}{R}}$$



    - Second Equation: we use the I-V Characteristic of the diode
      - Which one? Forward or Reverse Biased equation?
        - We **will assume** one mode and **verify our assumption**!
        - <u>Since V_{DD} drive the current in the loop from P side to N-Side, we will assume Forward Biased</u>

Example

- ❑ Find the diode voltage and current for the given Circuit?
  - ❑ Forward biased equation:

$$\boxed{I_D \cong I_s \exp\left(\frac{V_D}{\eta V_T}\right)}$$

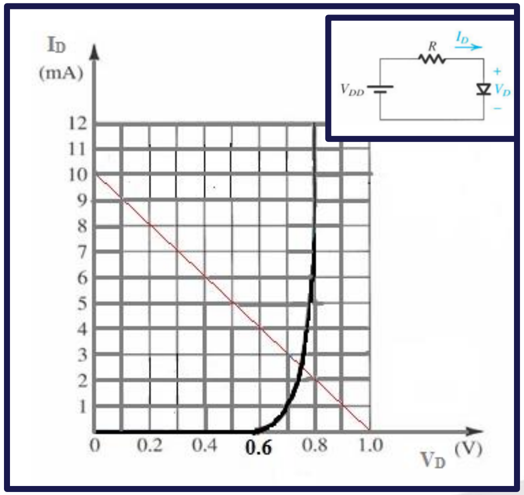
  - ❑ Solving the two equations together?

$$\boxed{I_D = \frac{V_{DD} - V_D}{R}}$$

    - ❑Linear and nonlinear equation!!!!!!
      - ❑Use **Iteration**? Too **complicated!**
      - ❑Use graphical Solution
        - ❑Draw both equations and their intersection is the solution

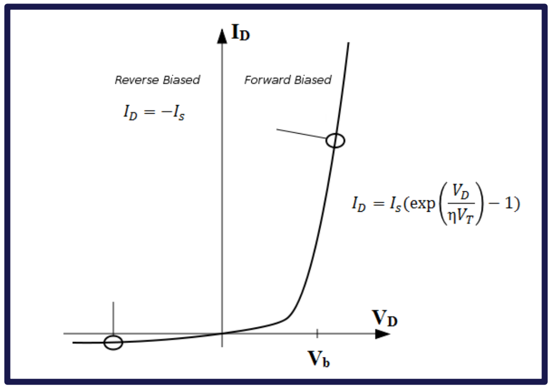
$$V_D = 0.75V, I_D = 2.5V$$

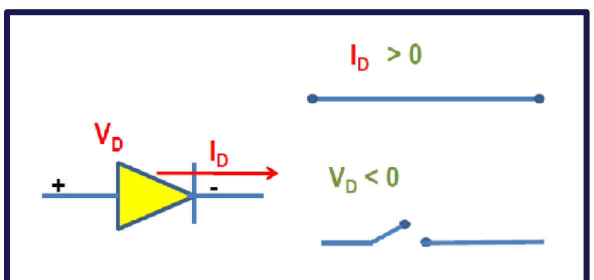
  - ❑ Check assumption $I_D > 0$, **Is there an easier solution?**

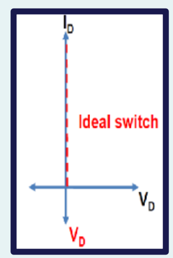


PN Junctions I-V Modeling

- **We can exchange the exponential equation with a linear one**
  - By approximating I-V Characteristics **(Ideal Diode)**

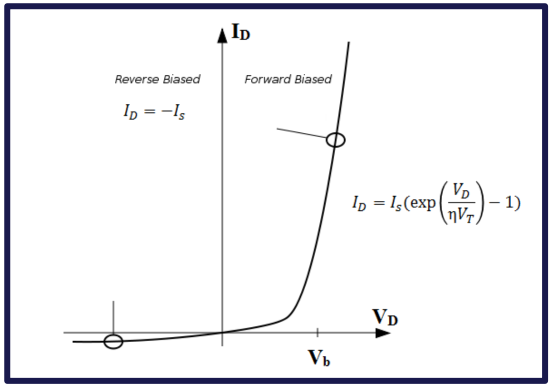


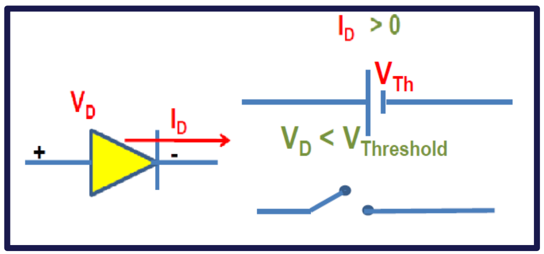


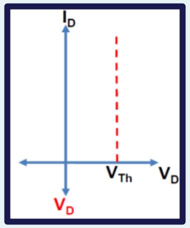
Ideal Diode Model (Switch)	Forward Biased	Reverse Biased
	Assume $V_D = 0$ Verify $I_D > 0$	Assume $I_D = 0$ Verify $V_D < 0$

PN Junctions I-V Modeling

- **We can exchange the exponential equation with a linear one**
  - By approximating I-V Characteristics **(Battery)**

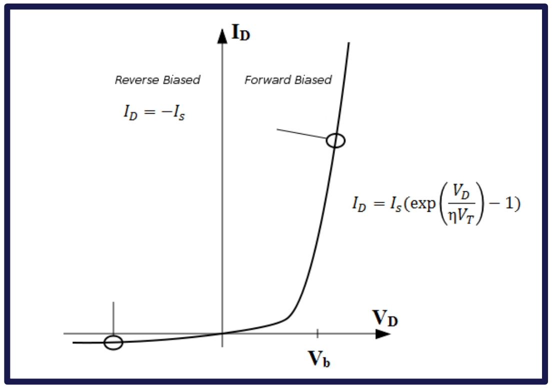


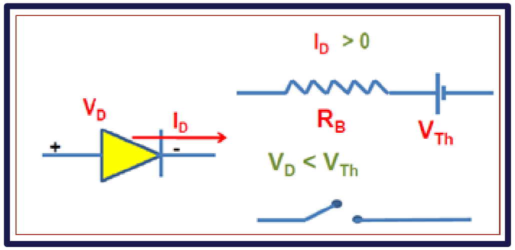


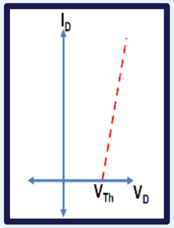
Battery Model	Forward Biased	Reverse Biased
	**Assume** $V_D = V_{Th}$ **Verify** $I_D > 0$	**Assume** $I_D = 0$ **Verify** $V_D < V_{Th}$

PN Junctions I-V Modeling

- **We can exchange the exponential equation with a linear one**
  - By approximating I-V Characteristics **(Battery and Resistor)**





Battery and R Model	Forward Biased	Reverse Biased
R_B is the slope of the line 	Assume $V_D = V_{Th}$ Verify $I_D > 0$	Assume $I_D = 0$ Verify $V_D < V_{Th}$

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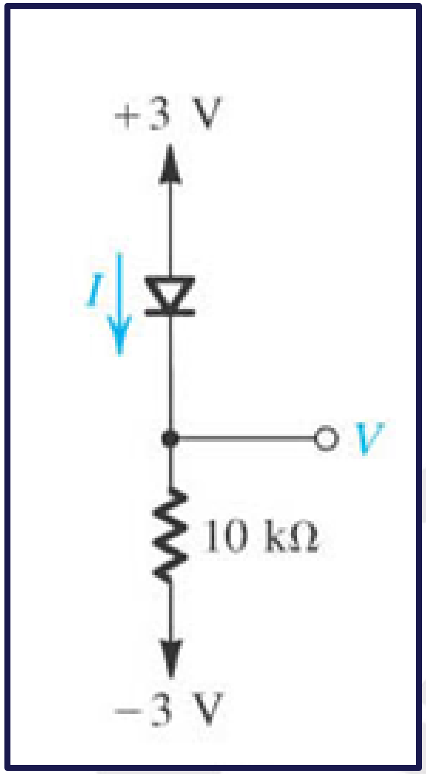
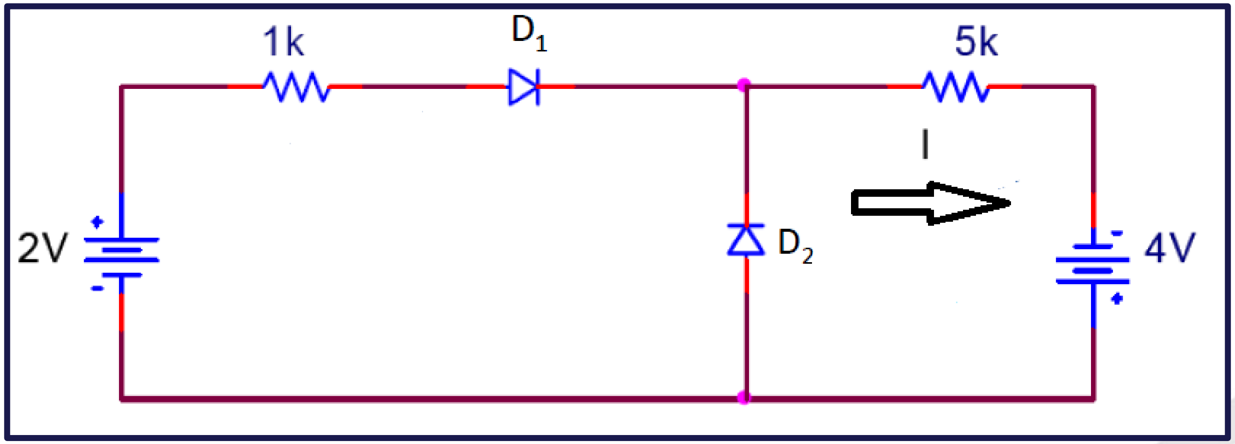
Example

- Find the circuit voltage and current? Assuming:
  - Ideal Diode
  - (Final answer **I=0.6mA, V=+3V**)



Example

- Find the current I ? Assuming:
  - V_{Th}=0.6V (Final answer **I=0.9mA**)



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