TERM: Summer 2022-23

I. Course Core and Title: EEE 2103: ELECTRONIC DEVICES

II. Credit: 3 credit hours (4 hours of theory per week)

III. Nature: Core Course for EEE AND CSE

IV. Prerequisite: Electrical Circuits 2 (AC) [EEE] &
Introduction to Electrical Circuits [CSE]

Chapter # 01

SEMICONDUCTOR DEVICES

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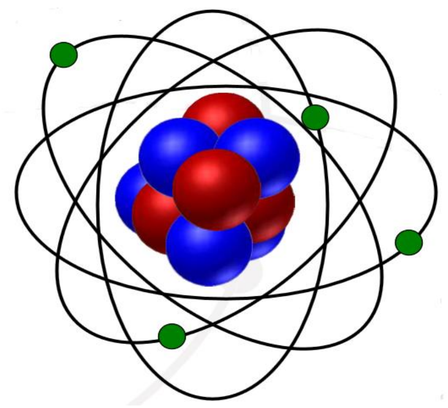
ATOMS

- What is an atom?
  - ✓ Atoms are the smallest particles of matter. It makes up everything around us.
  - ✓ Compounds are made up of different types of atoms.

- What are the components of an atom?
  - ✓ At the center of all atoms is the Nucleus.
  - ✓ The nucleus contains PROTONS and NEUTRONS.
  - ✓ Orbiting around the nucleus are the ELECTRONS.



- **The atomic number is equal to the number of protons in the nucleus of an atom.**
- The atomic number identifies the element.

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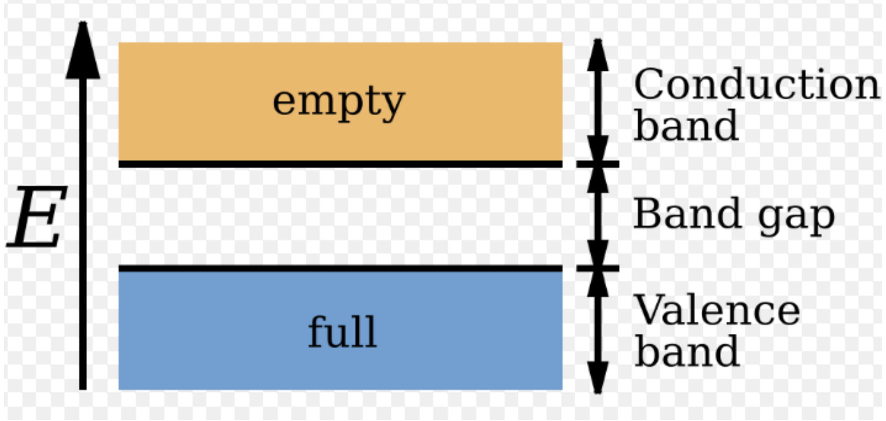
ENERGY BAND

- The materials can be classified by the energy gap between their valence band (VB) and the conduction band (CB).
- The energy level which holds a fair number of electrons is called the **valence level**.
- The level just above the valence level is called the **conduction level**. This is because electrons here help material to be able to conduct electricity.



- Separating these two bands is an energy gap in which no electrons can normally exist.
- Conduction takes place when an electron jumps from VB to CB.
- Wider the gap between the valence and conduction bands, higher the energy it requires for shifting an electron from valence band to the conduction band.

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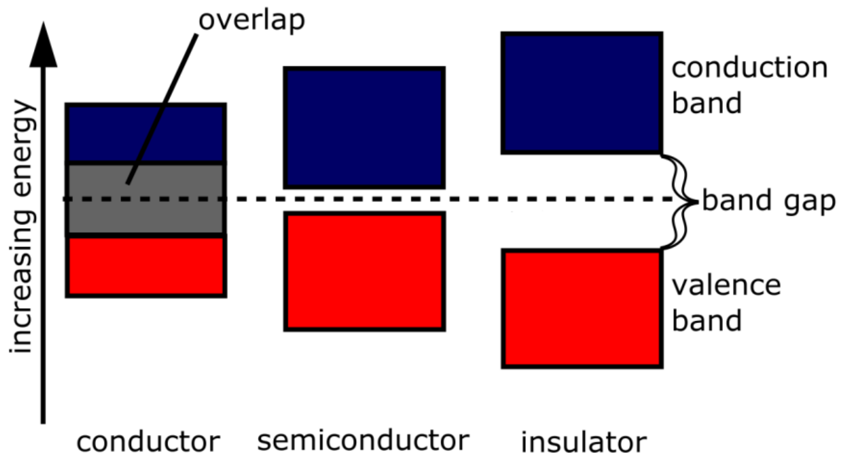
CLASSIFICATION OF MATERIALS

- Based on the energy gap, materials are of three types: **CONDUCTORS**, **INSULATORS** and **SEMI-CONDUCTORS**.

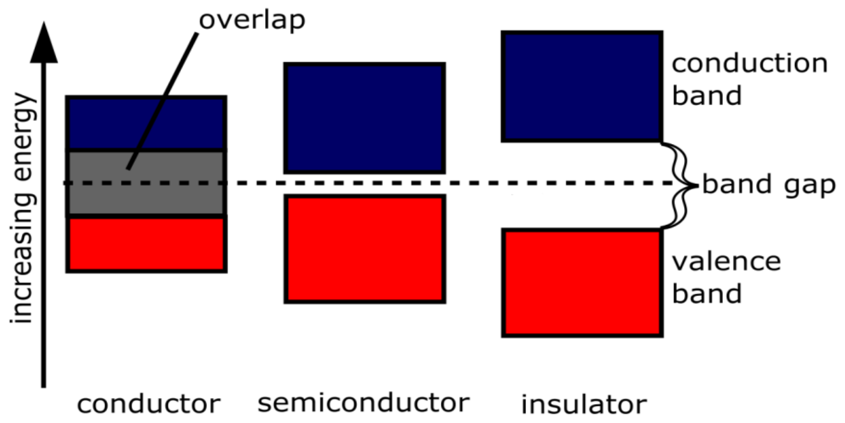
- **For Conductors**, this energy gap is absent or in other words, CB and VB overlaps each other. Thus, electron requires minimum energy to jump from valence band. The typical examples of conductor are Silver, Copper, and Aluminum.



- **In Insulators,** this gap is vast. Therefore, it requires a significant amount of energy to shift an electron from VB to CB. Mica and Ceramic are the well-known examples of insulation material.

CLASSIFICATION OF MATERIALS (CONT.)

- **Semiconductors** have an energy gap which is in between that of conductors and insulators. Thus one electron requires energy more than conductors but less than insulators for shifting valence band to conduction band.
- Semiconductor Materials:
  - ✓ **Germanium** is the first semiconductor used.
  - ✓ **Silicon** is today's most important semiconductor material.



  - ✓ **Gallium Arsenide and Indium Phosphate** are popular for opto-electronic applications.
  - ✓ **Silicon Germanium and Gallium Arsenide** are good for RF applications.

CLASSIFICATION OF SEMI-CONDUCTORS

- Semiconductor materials are of two types: single-crystal and compound-crystal.

  ✓ **Single-crystal semiconductors** such as GERMANIUM (Ge) and SILICON (Si) have a repetitive crystal structure.

  ✓ **Compound-crystal semiconductors** such as GALLIUM ARSENIDE (GaAs), CADMIUM SULFIED (CdS) and GALLIUM ARSENIDE PHOSPHIDE (GaAsP) are constructed of two or more semiconductor materials of different atomic structures.

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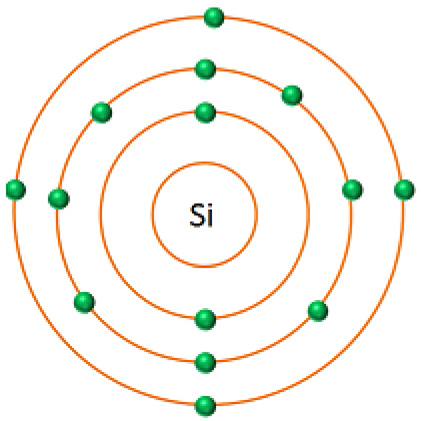
Ge, Si and GaAs

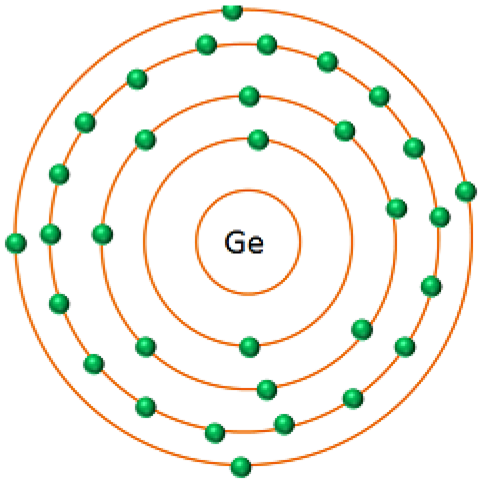
- The three semiconductors used most frequently in the construction of electronic devices are **Si, Ge and GaAs**.
- Reasons for using Ge and Si mostly:
  - Maximum purification possible.
  - Easily available.
  - The periodic structure of Si and Ge does not change much due to doping.
- Why Si is better than Ge?
  - Si has the advantages of being readily available at low-cost, good temperature characteristics and excellent breakdown voltage levels compare to the Ge.

ATOMIC STRUCTURE OF Si AND Ge

- **Covalent Bonding**: In a pure Si or Ge crystal, the four valance electrons of one atom form a bonding arrangement with four adjoining atoms. This bonding of atoms sharing by the electrons is called covalent bonding.
- Atomic number of Si is 14 and Ge is 32. Both Si and Ge are of elements of IV group, i.e., both elements have four valance electrons in the outer shell. So both form covalent bond with neighboring atom.



Silicon



Germanium

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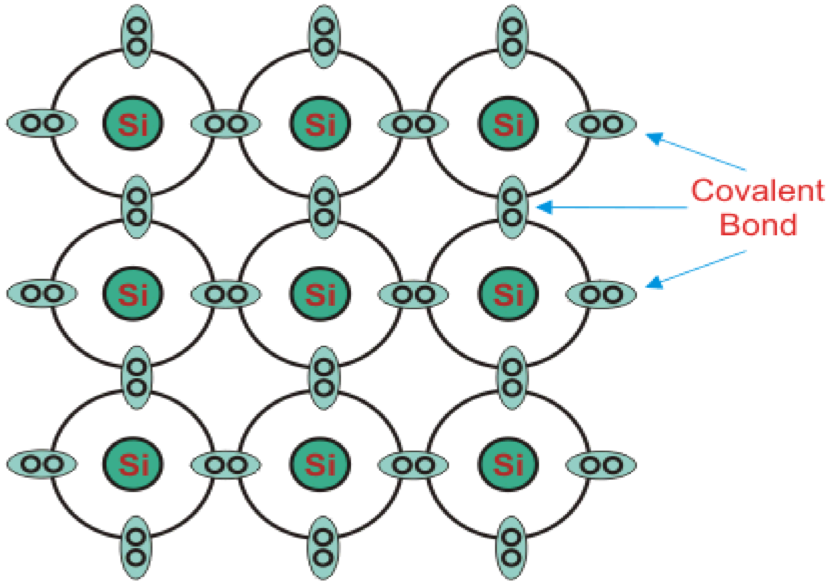
INTRINSIC AND EXTRINSIC SEMI-CONDUCTORS

- Semiconductor in its pure form is called as intrinsic semiconductor. In pure semiconductor number of electrons (n) is equal to number of holes (p).



2D Representation of Pure Si Crystal

HOLES

- The lowest levels are normally filled with tightly held electrons.
- The higher energy levels may be empty, but an electron on a lower orbit must obtain some extra energy as a cover price to move to a higher orbit.
- An electron traveling from the valence level leaves behind a hole, and thus an overall positive charge for the atom.
- The holes don’t really exist, but materials behave as if they did.
- It has no mass, occupies space (+ve charge carrier).

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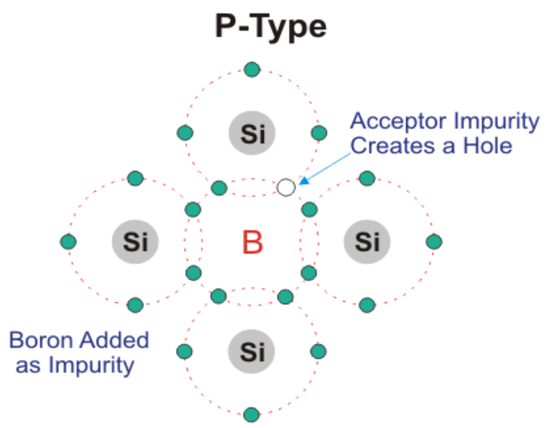
INTRINSIC AND EXTRINSIC SEMI-CONDUCTORS (CONT.)

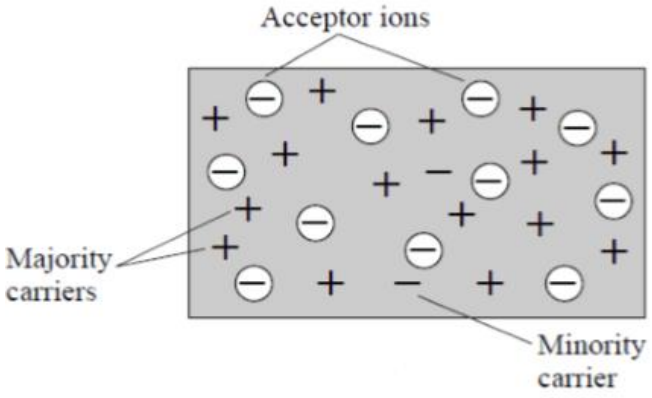
- Impure semiconductors are called <u>extrinsic semiconductors</u>.
- Extrinsic semiconductor is formed by adding a small amount of **<u>IMPURITY</u>**.
- Adding impurity or foreign atoms to a crystal to increase the amount of electrons and holes is called **<u>DOPING</u>**.
- The impurity or foreign atom is called **<u>DOPANT</u>** (Ex: Boron, Phosphorus).
- Depending on the type of impurity added, we have two types of semiconductors: **<u>N-TYPE AND P-TYPE SEMICONDUCTORS</u>.**
- In 100 million parts of semiconductor one part of impurity is added.

P-Type and N-Type Semi-conductors

- **P- type semiconductor** is formed by adding **trivalent** (three valence electrons) impurity in pure semiconductor crystal, e.g. **B, Al, Ba**.
- Three of the four valence electron of tetravalent impurity forms covalent bond with Si atom. This leaves an **empty space** which is referred to as **hole**.



- When temperature is raised, electron from another covalent bond jumps to fill this empty space. This leaves a hole behind. In this way, conduction takes place.
- P- type impurity accepts electron and is called **acceptor atom**.



- In this type of semiconductor **majority carriers are holes** and **minority carriers are electrons**.

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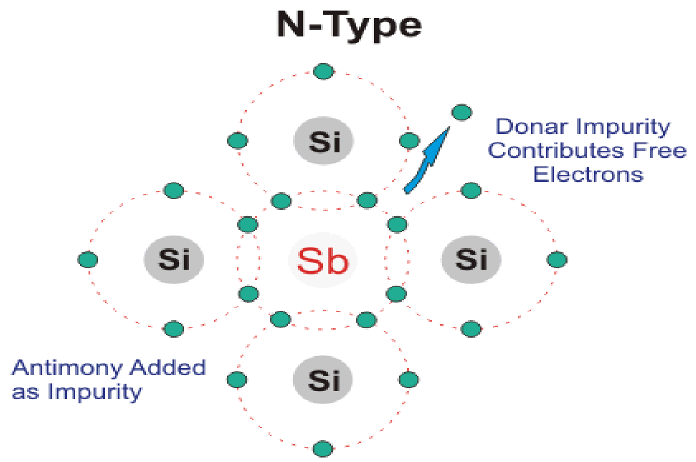
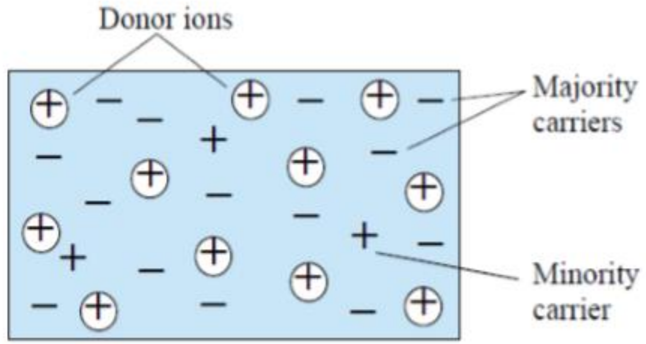
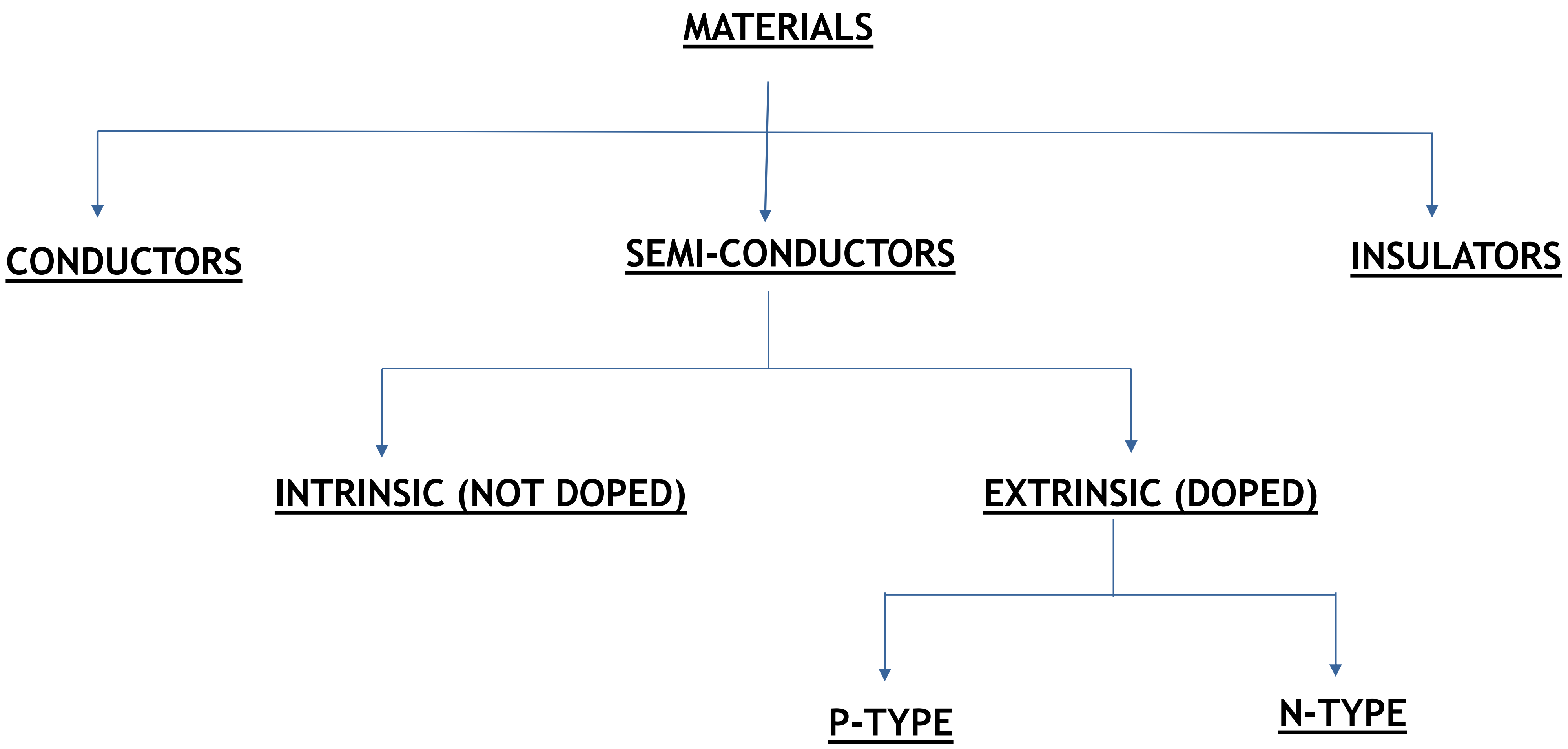
P-Type and N-Type Semi-conductors (Cont.)

- **N - type semiconductor** is formed by adding pentavalent (five valence electrons) impurity in pure semiconductor crystal, e.g. **P, As, Sb**.
- Four of the five valence electron of pentavalent impurity forms covalent bond with Si atom and the remaining electron is free to move anywhere within the crystal.
- Pentavalent impurity donates electron to Si that's why N-type impurity atoms are known as **donor atoms**.
- In this type of semiconductor **majority carriers are electrons and minority carriers are holes**.







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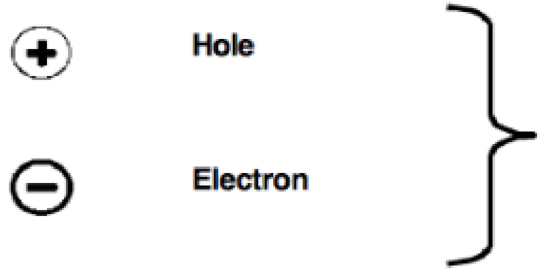
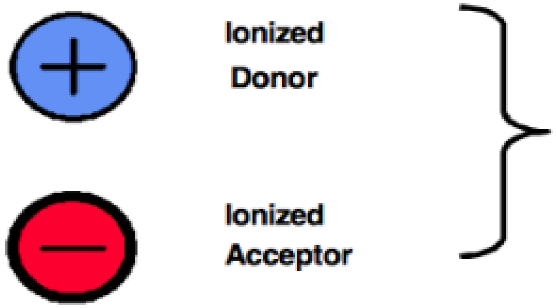
- Semiconductors with both acceptor and donor atoms has the following four kind of charge carriers:



<u>Mobile Charge Carriers:</u> They contribute to current flow when electric field or external voltage is applied.



<u>Immobile Charges:</u> They do not contribute to current flow when electric field is applied. However, they affect to local electric field or breakdown voltage.

- The conductivity is a function of the dopant concentration.

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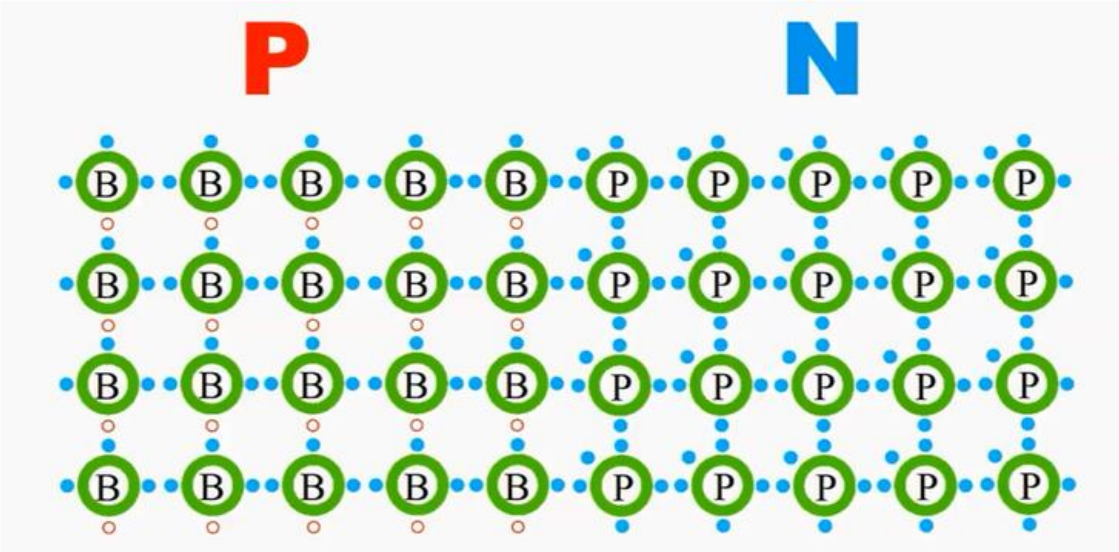
P-N Junction

- P-Type and N-Type semiconductors taken separately are of very limited use.

- If a piece of P type material is joined to a piece of N type material so that they can touch, a **PN JUNCTION** is formed.



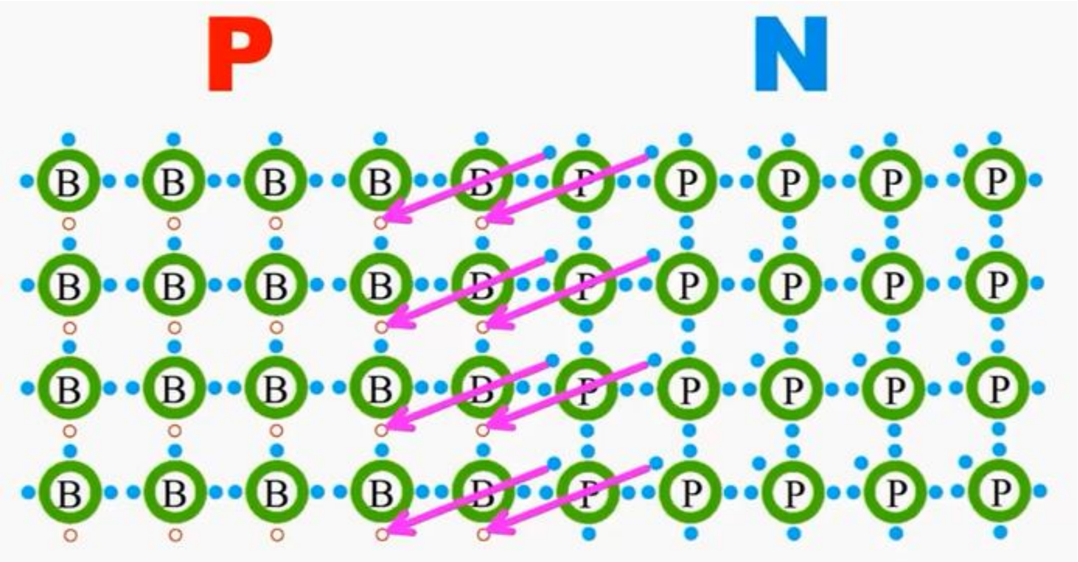
- It can function as-
  - Rectifiers
  - Amplifiers
  - Switches
  - And other operations in electronic circuits.

*** Dopant atoms are this concentrated for easier visualization.

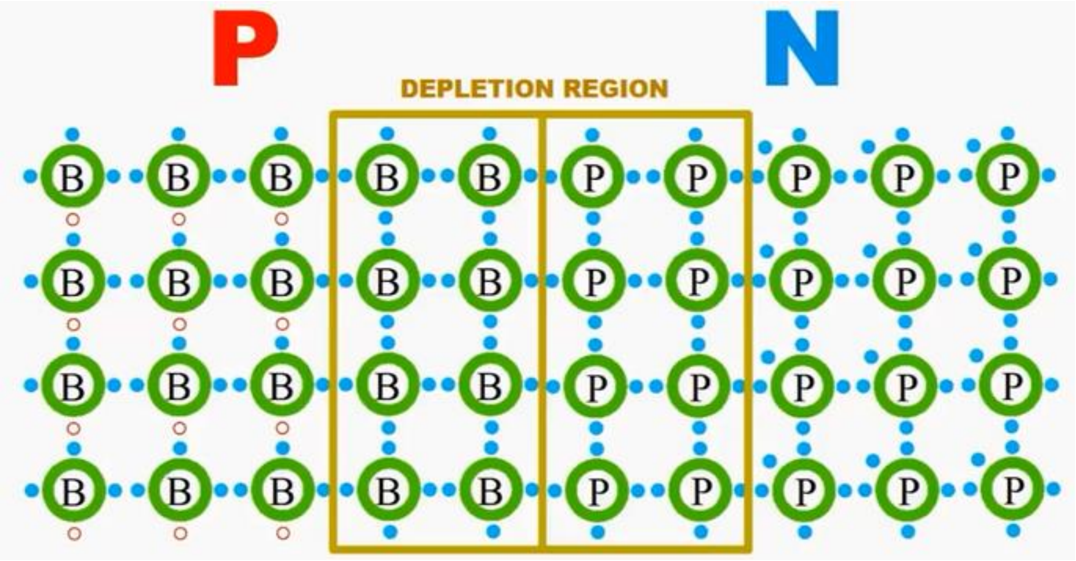
*** In real life, almost all of these atoms would be Si.

What happens inside a P-N Junction?

- At the border between N type and P type, the extra electrons from the N type Silicon jump over into the holes of the P type Silicon and fill those out.

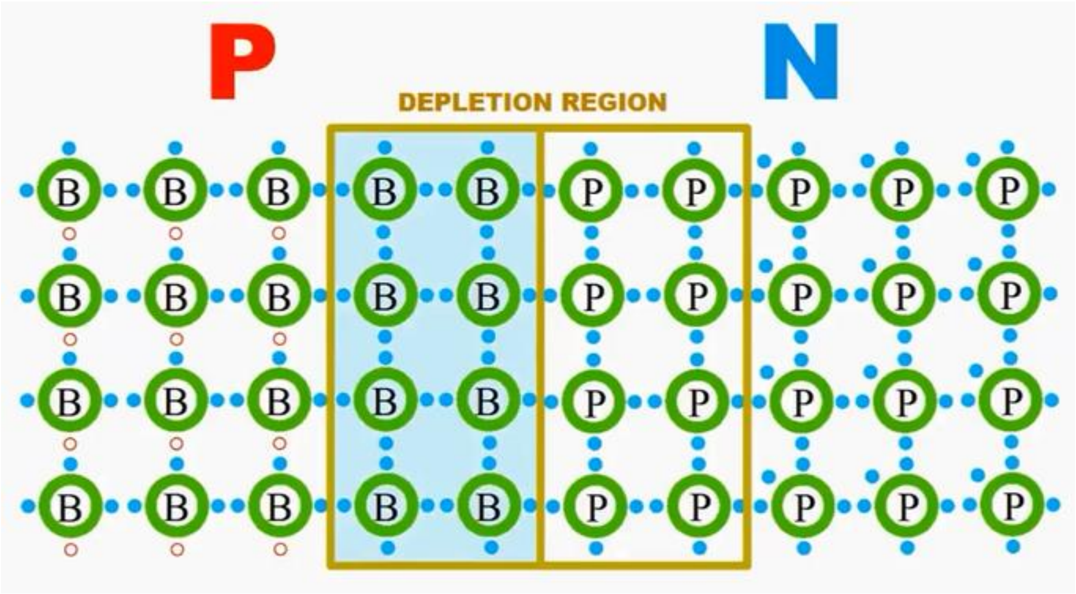


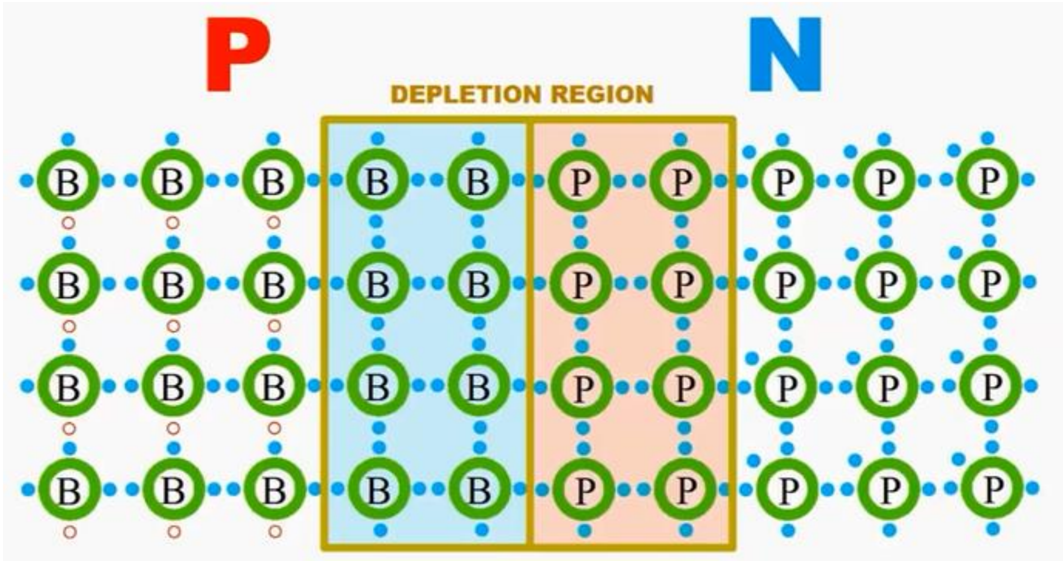
- Because of this, a **depletion region** formed and creates a barrier between the two crystals.



What happens inside a P-N Junction? (Cont…)

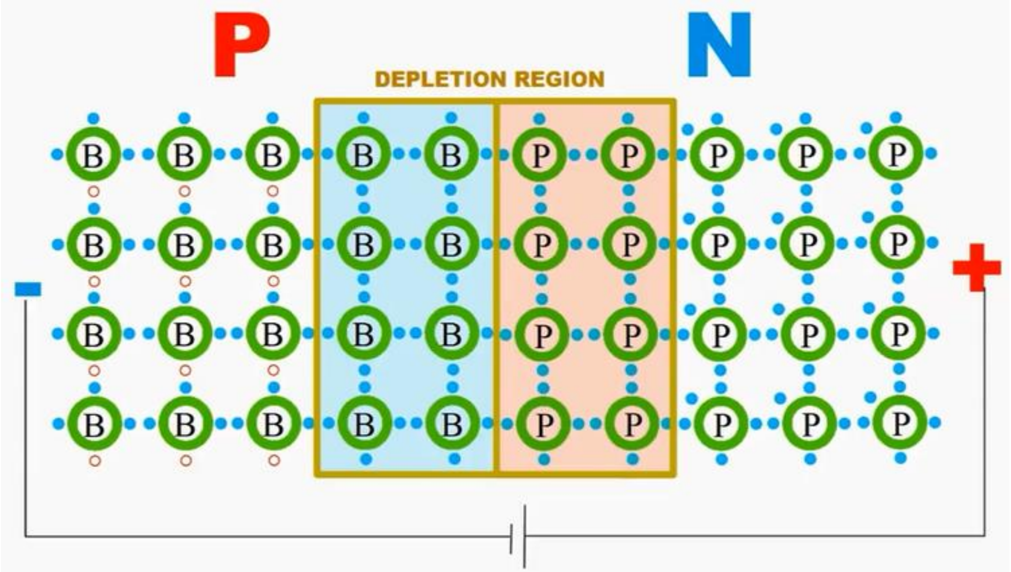
- There is a layer of P type Silicon now has extra electrons filling its holes (acceptor atoms) and makes this area **negatively charged**.
- On the other side, the layer of N type Silicon just had its electrons leave (donor atoms) and makes this area **positively charged**.
- The layer of atoms at the border are ionized and depleted of charge carriers.
- This prevents any currents from flowing.



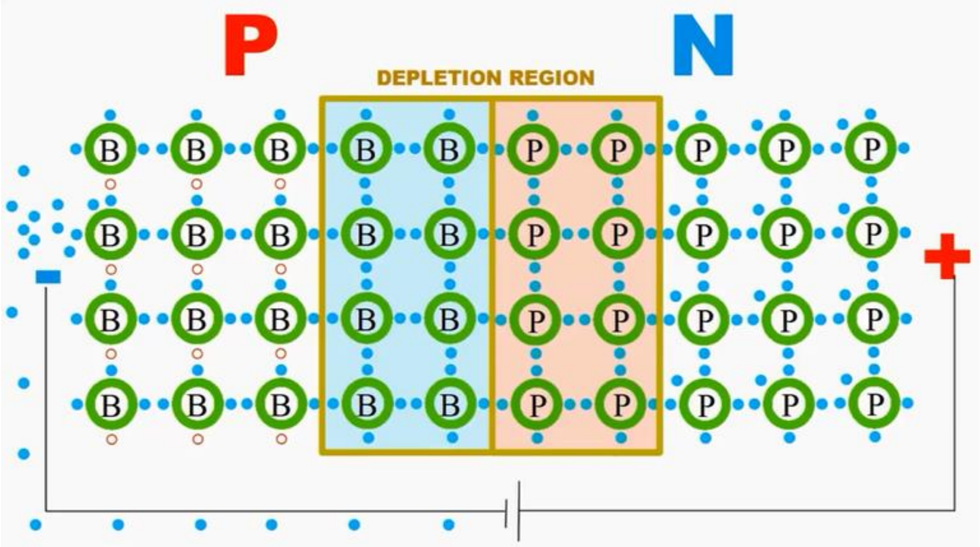


Reverse Bias

- When positive terminal of a voltage source is connected to the N type region and the negative terminal of the source is connected to the P type region, then the PN junction is said to be in reverse biased condition.



- The negative side adds electrons to the P type Silicon.



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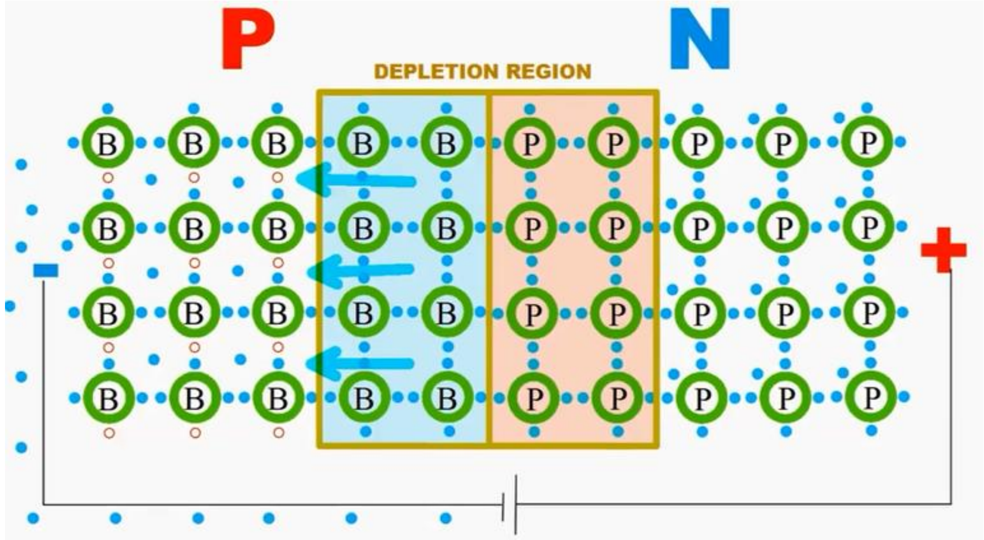
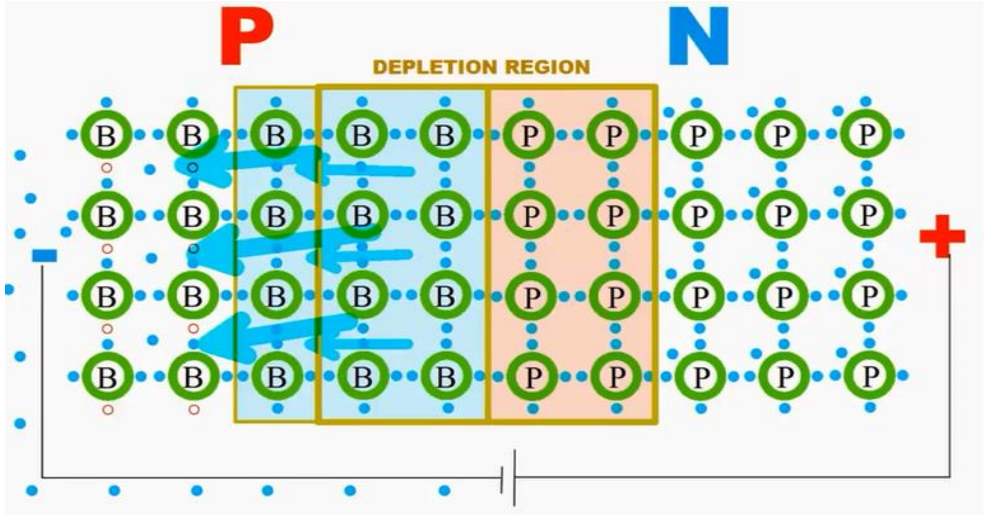
Reverse Bias (Cont…)

- The first electrons want to cross the depletion region, but they are repelled by the extra electrons already there.
- They stop and drop into the hole created by the Boron and cancel them out.
- The Boron atoms become negatively charged because of the extra electrons.
- This **widens** the depletion region and repels more electros.
- This completely stops any current from flowing.





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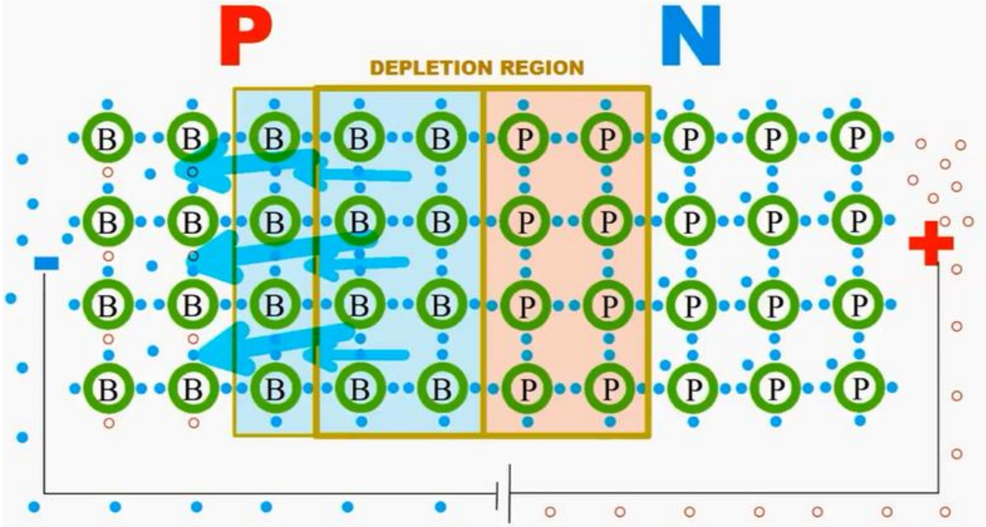
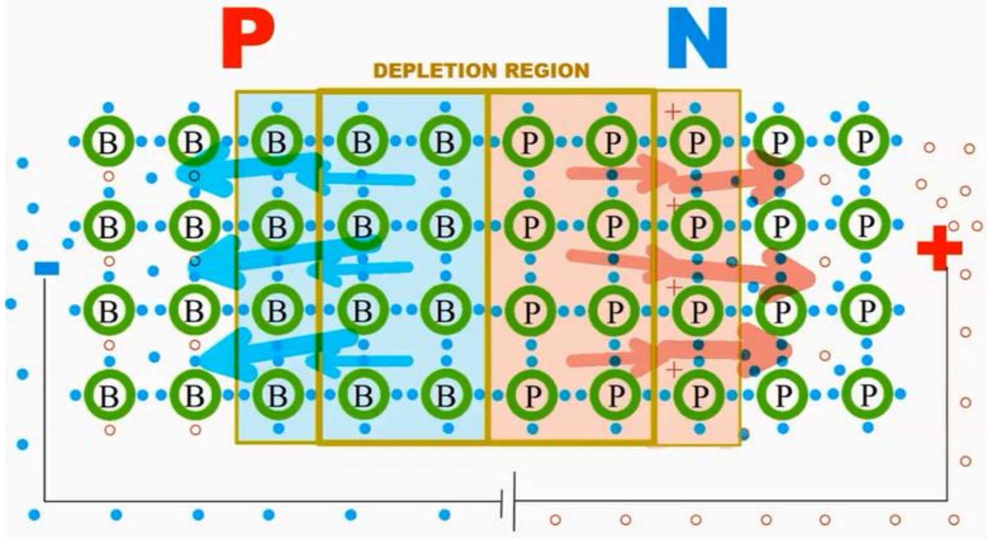
Reverse Bias (Cont…)

- On the other side, positive holes are added to the N type Silicon.
- Just like the electrons, the holes want to cross the barriers but are repelled by the positive side of the depletion region.
- They stop and replace the electrons and make this atoms positively charged.
- This widens the depletion region and repels even more holes.
- This again completely stops any current from flowing.
- So no current can flow for this bias.





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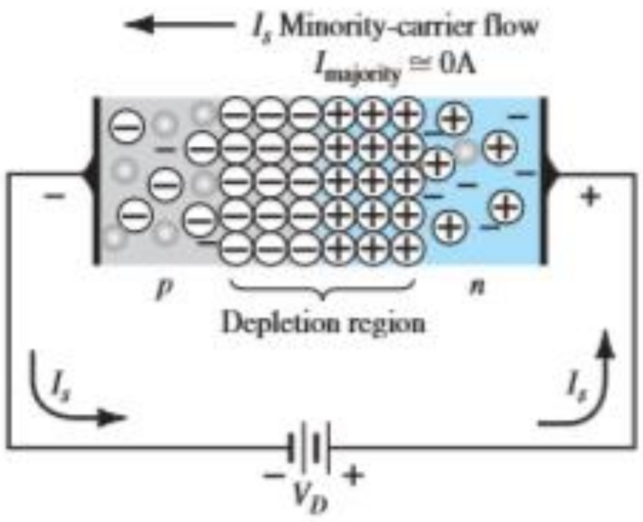
Reverse Bias (Cont.)

- However, p-n junction diode **allows the minority charge carriers**. The positive terminal of the battery pushes the holes (minority carriers) towards the p-type semiconductor. In the similar way, negative terminal of the battery pushes the free electrons (minority carriers) towards the n-type semiconductor.
- The positive charge carriers (holes) which cross the p-n junction are attracted towards the negative terminal of the battery. On the other hand, the negative charge carriers (free electrons) which cross the p-n junction are attracted towards the positive terminal of the battery. Thus, **the minority charge carriers carry the electric current in reverse biased p-n junction diode**.



- **The electric current carried by the minority charge carriers is very small (μA range). Hence, minority carrier current is considered as negligible.**

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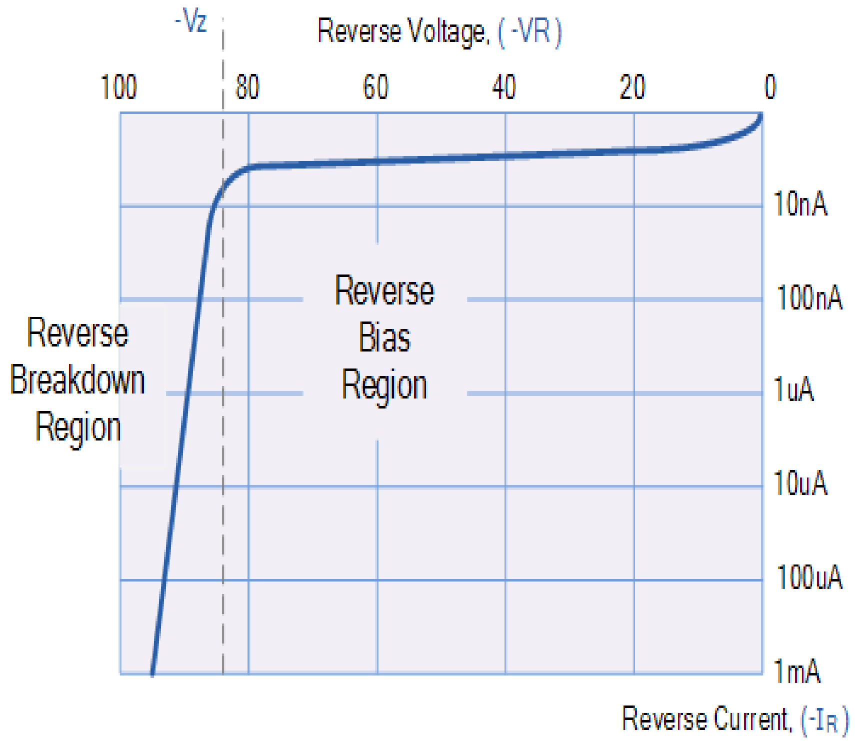
Reverse Bias (Cont.)

- Here the interesting thing to note is that, diode does not conduct with change in applied voltage. The current **remains constant at a negligibly small value (ideally zero) for a long range of change in applied voltage**.
- When the voltage is raised above a particular point, say 80 volts, the current suddenly shoots (increases suddenly). This is called as **"reverse saturation current" (I_S)** and this particular value of applied voltage, where reverse current through diode increases suddenly is known as **"break down voltage" or Peak Inverse Voltage (PIV)**.



- **If the reverse current exceeds this maximum rating, the diode will get damaged**.

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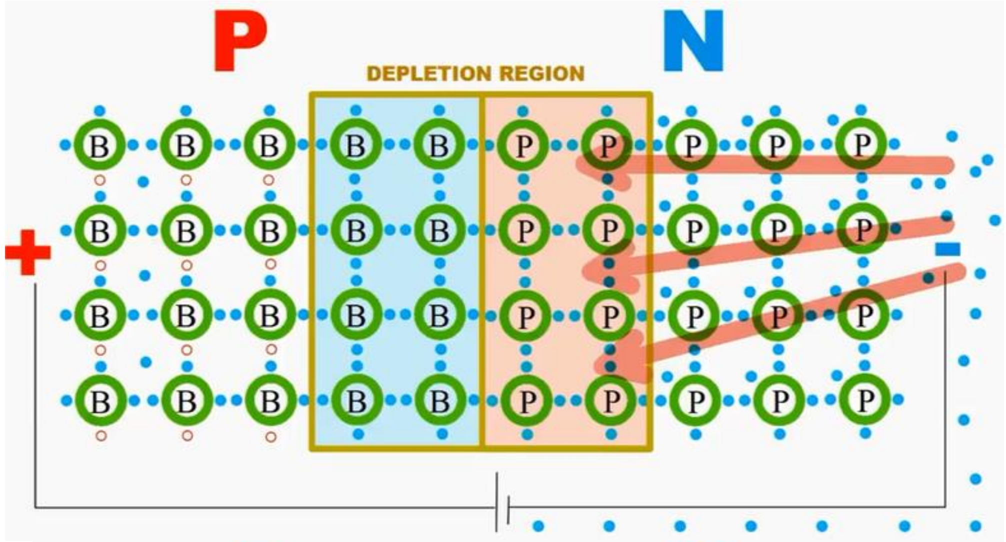
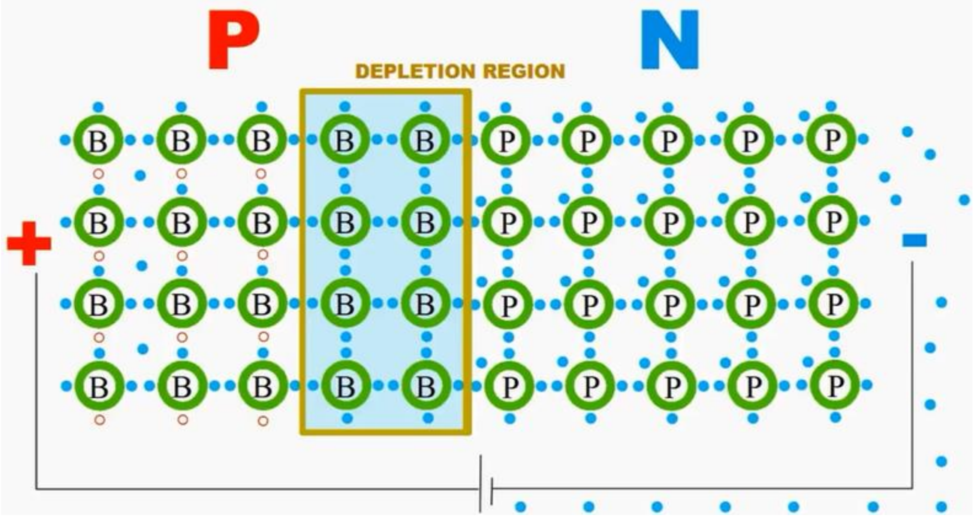
Forward Bias

- When we connect p-type region of a junction with the positive terminal of a voltage source and n-type region with the negative terminal of the voltage source, then the junction is said to be forward biased.
- This time the negative side adds electrons to the N type Silicon.
- The N type Si now has a massive excess of electrons which are all attracted to the massive number of holes in the depletion region.
- So it comes to those holes, drop down into them and cancel them out.
- The depletion region gets smaller and might almost disappear if there are enough electrons coming through at once.





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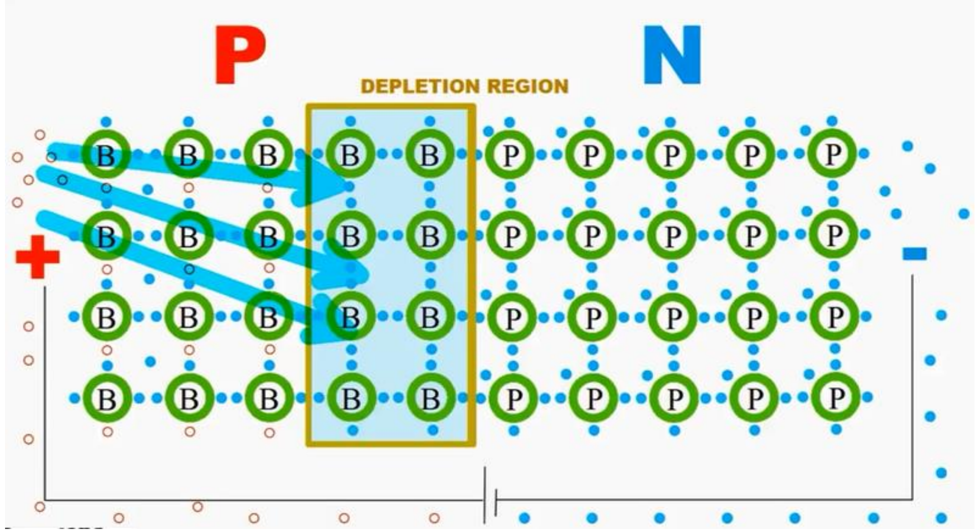
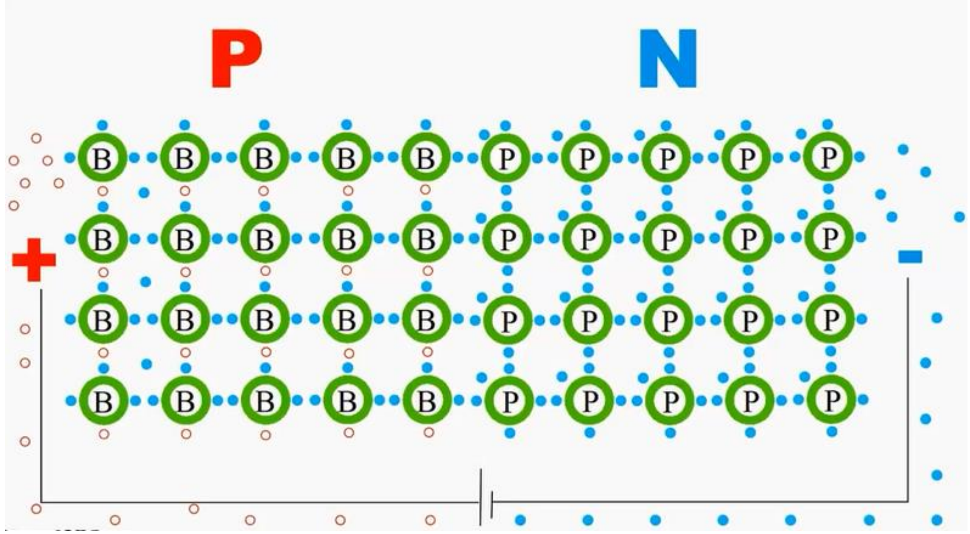
Forward Bias (Cont…)

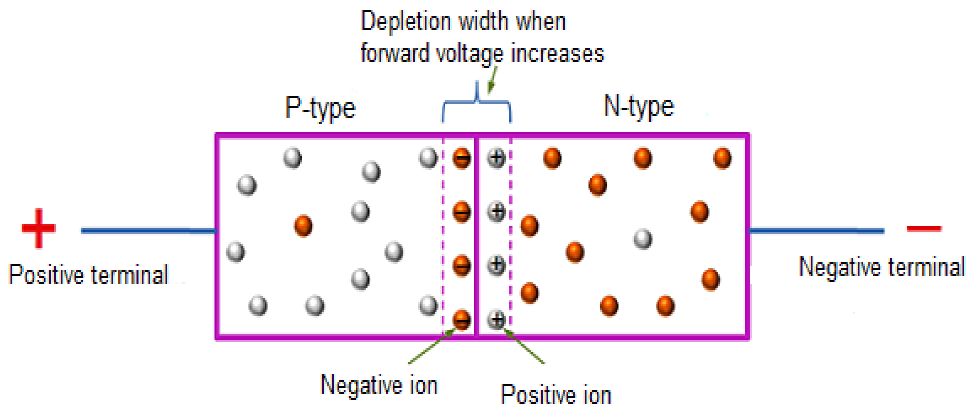
- Meanwhile the positive side adds holes to the P type Si.
- The P type crystal now has a massive excess of holes which re all attracted to the massive number of electrons in the depletion region.
- So the extra holes come to the electrons and the electrons hop over to the previously neutral atoms to the extra positive holes, then cancel them out and the depletion region gets smaller and might almost disappear with large enough current.

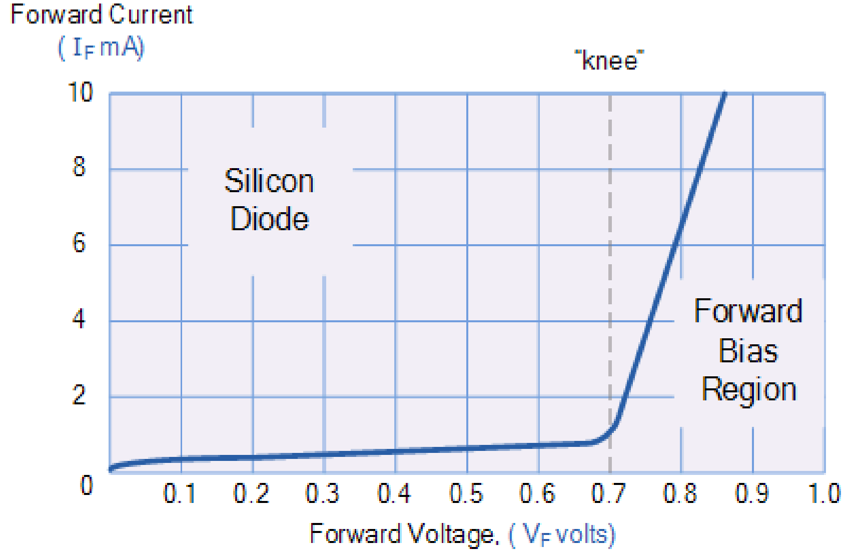




Forward Bias (Cont.)

- Thus in the forward bias, the width of the depletion layer starts reducing.
- With the increase in the applied forward voltage, the depletion layer will further reduce.
- If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome, that means, the depletion region vanishes and current will start to flow.





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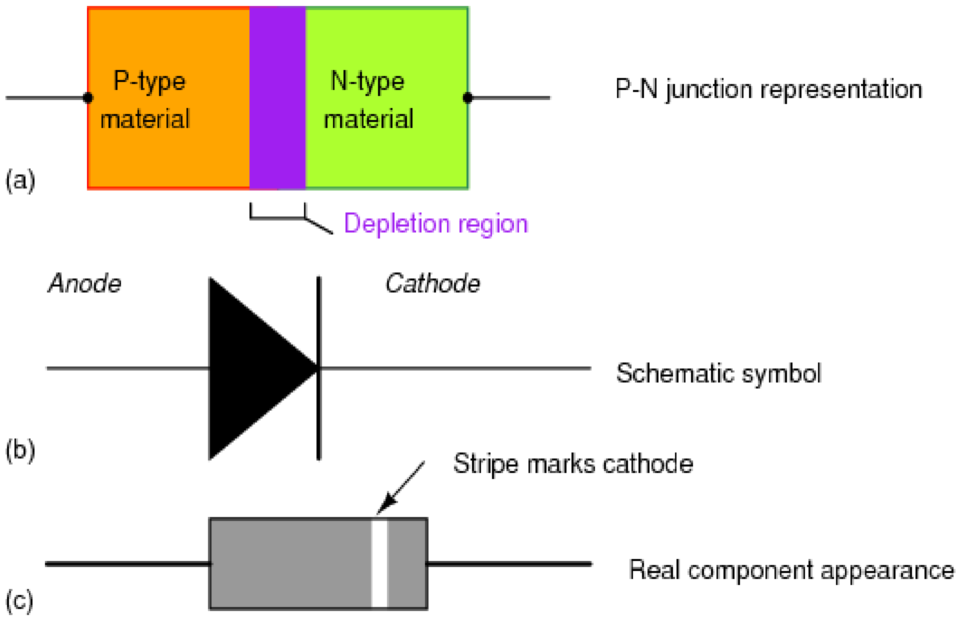
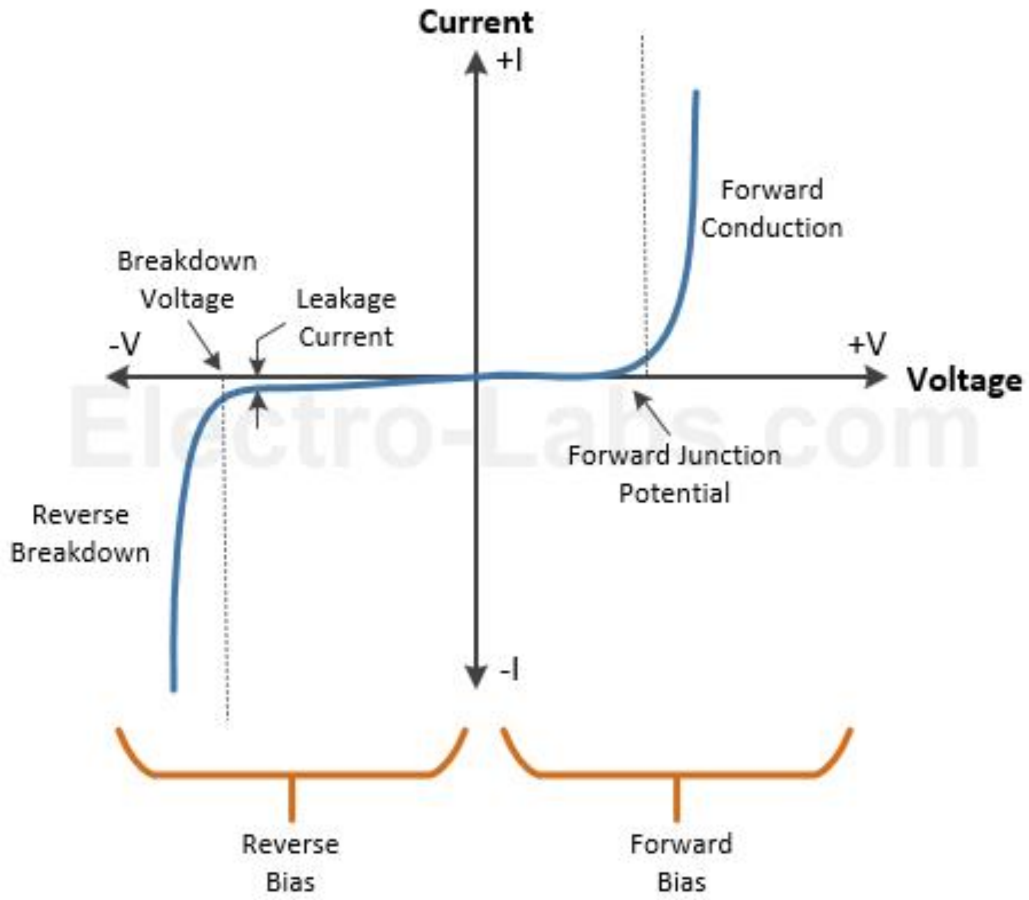
P-N Junction Diode Symbol and I-V Characteristics





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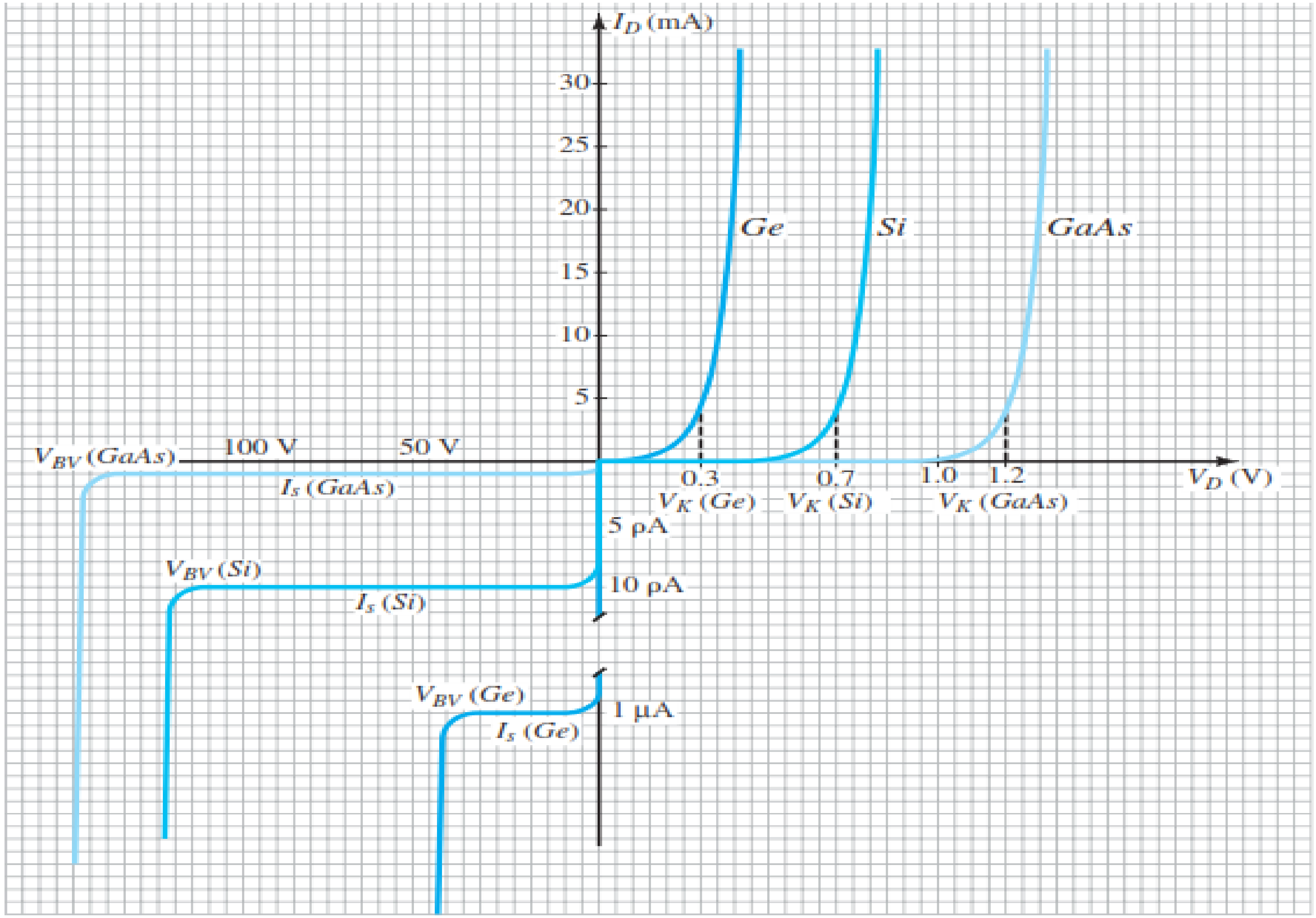
Comparison of Ge, Si, and GaAs Diodes



Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

Silicon	Germanium
Higher *PIV (≈ 1000V)	Lower PIV (≈ 400V)
Higher current rating	Lower current rating
Wider temperature range (up to 200⁰C)	Narrow temperature range (lower than 100⁰C)
Higher forward-bias voltage (0.7V)	Lower forward-bias voltage (0.3V)

** PIV = peak inverse voltage*

Shockley's equation

- The general characteristics of a semiconductor diode can be defined by the following equation, referred to as Shockley's equation, for the forward and reverse-bias regions:

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)}$$

where,

$\boldsymbol{I_S}$ = reverse saturation current

$\boldsymbol{V_D}$ = applied forward-bias voltage across the diode

$\boldsymbol{n}$ = ideality factor (assume 1 if not given)

$\boldsymbol{V_{\mathrm{T}}}$ = thermal voltage

- The equation of $\boldsymbol{V_{\mathrm{T}}}$ is given below:

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

where,

$\boldsymbol{k}$ = Boltzmann's constant

$\mathbf{T_K}$ = absolute temperature in kelvins

$\mathbf{q}$ = magnitude of electronic charge = $\mathbf{1.6\ X\ 10^{-19}}$ C

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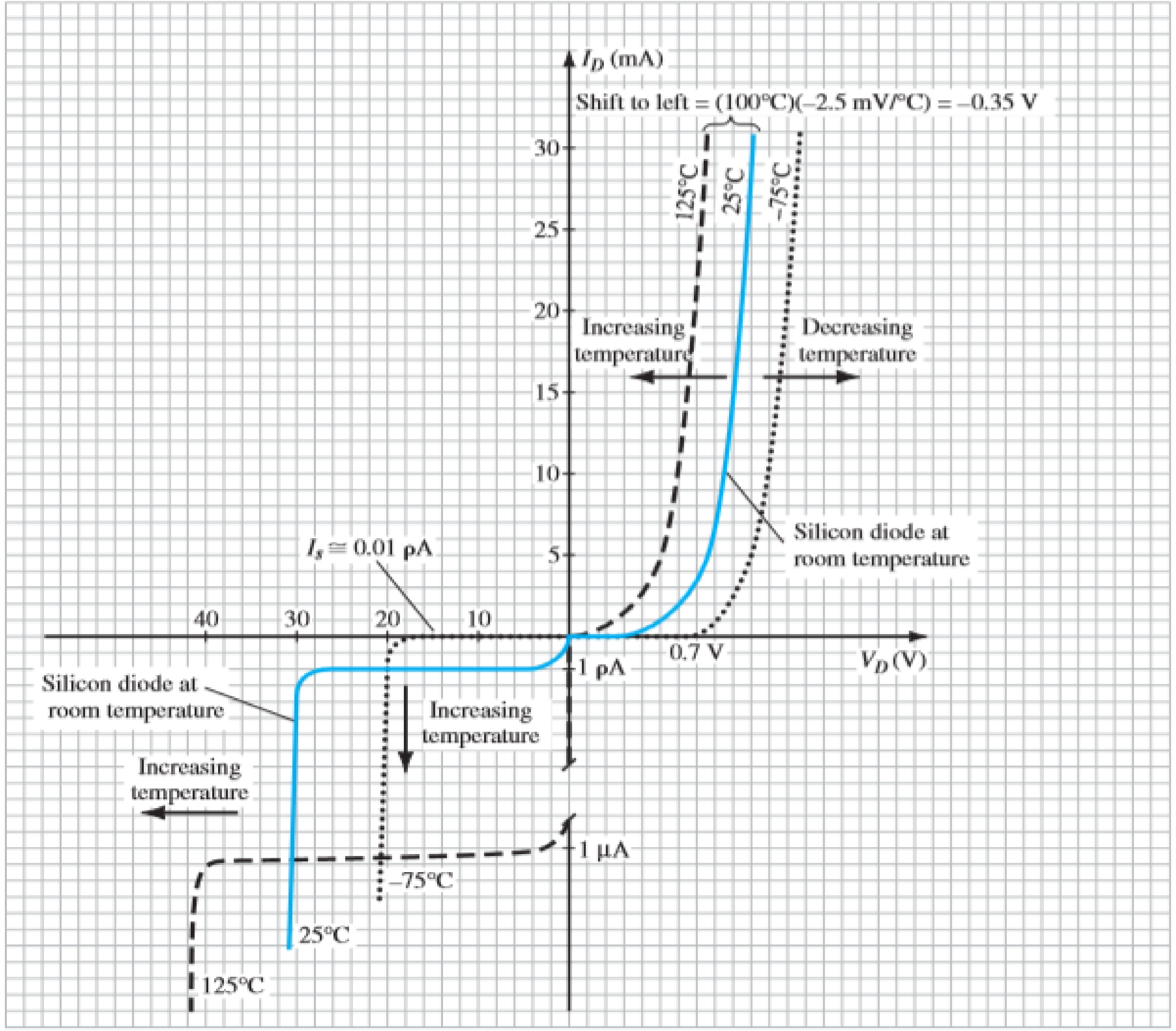
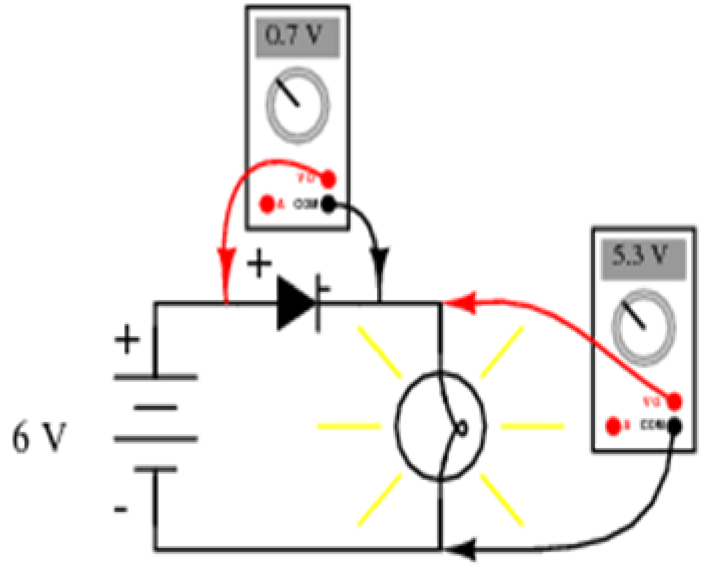
Temperature Effects

- In the forward-bias region the characteristics of a silicon diode **shift to the left at a rate of 2.5 mV per centigrade degree increase** in temperature.

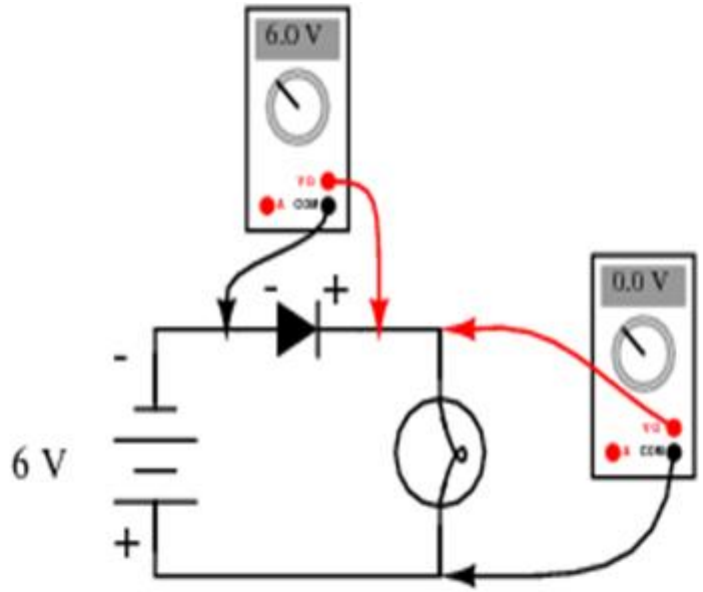
- In the reverse-bias region, the **reverse current of a silicon diode doubles for every 10˚C rise in temperature**.



Forward and Reverse Bias Test



(a)
Forward Bias



(b)
Reverse Bias

* Assume the diode as a Silicon diode.

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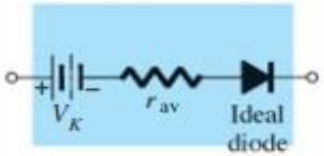
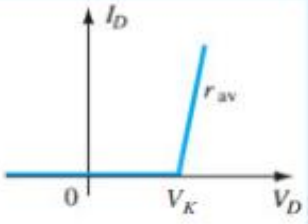
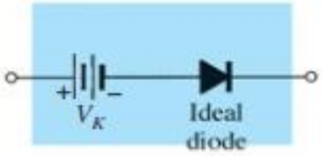
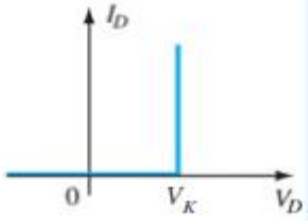
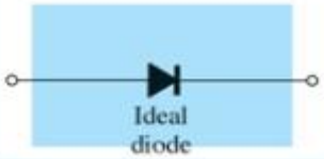
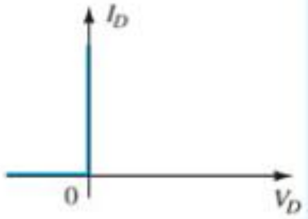
Diode Equivalent Circuits

- An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device in a particular operating region.

- In other words, once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit can be inserted in its place without severely affecting the actual behavior of the system.

Type	Conditions	Model	Characteristics
Piecewise-linear model			
Simplified model	$R_{network} \gg r_{av}$		
Ideal device	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

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RESISTANCE LEVELS

- As the operating point of a diode moves from one region to another, the resistance of the diode will also change due to the nonlinear shape of the characteristic curve. The type of applied voltage or signal will define the resistance level.

- Semiconductors act differently for DC and AC conditions. There are 3 types of resistances:

  - ✓ DC or Static Resistance
  - ✓ AC or Dynamic Resistance
  - ✓ Average AC Resistance

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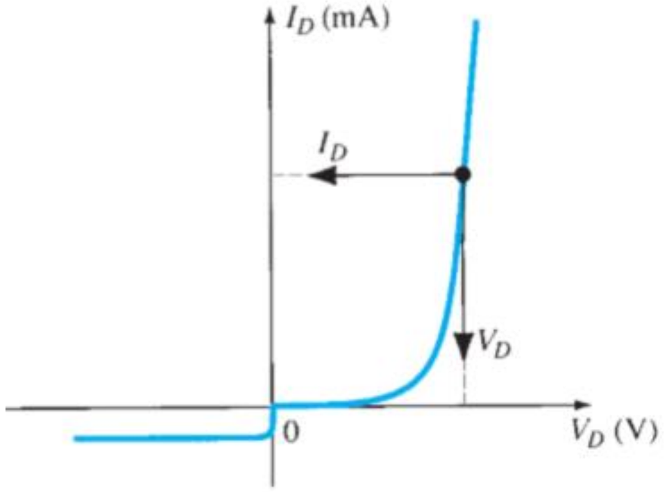
DC or Static Resistance

- The resistance of a diode at a particular operating point is called the dc or static resistance diode. It can be determined using equation:

$$R_D = \frac{V_D}{I_D}$$



- The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics.
- The resistance levels in the reverse-bias region will naturally be quite high.
- In general, therefore, the higher the current through a diode, the lower is the dc resistance level.
- Typically, the dc resistance of a diode in the active (most utilized) will range from about **<u>10 Ω to 80 Ω</u>**.

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AC or Dynamic Resistance

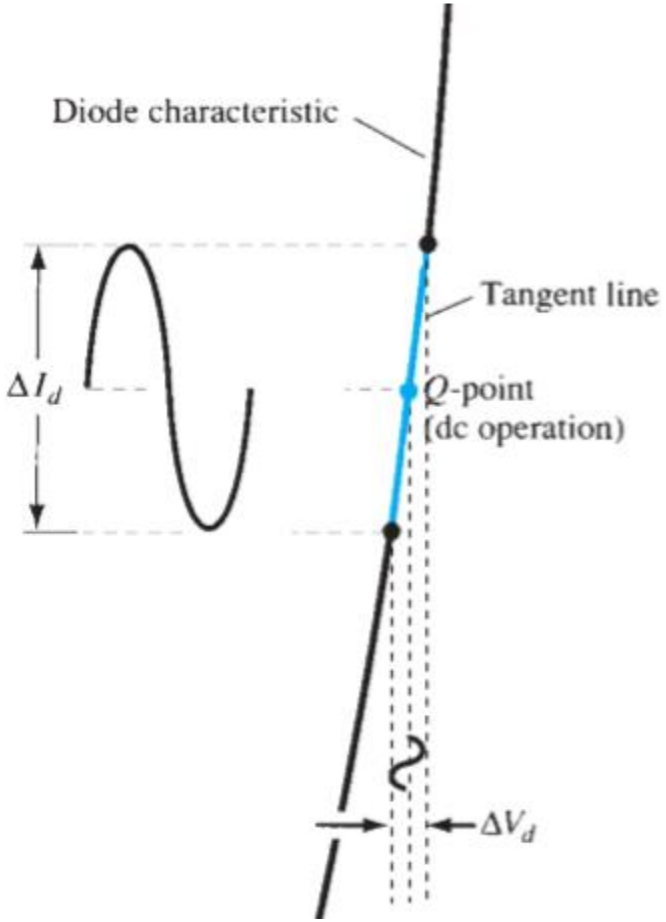
- If a sinusoidal rather than a dc input is applied, the situation will change completely.

- The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage.

- In equation form,

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}}$$

where Δ signifies a finite change in the quantity.



AC or Dynamic Resistance (Cont.)

- We have found the dynamic resistance graphically, but there is a basic definition in differential calculus that states: "**<u>The derivative of a function at a point is equal to the slope of the tangent line drawn at that point</u>**".
- The general characteristics of a semiconductor diode can be defined by the following equation, referred to as Shockley's equation:

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)}$$

Taking the derivative of the following equation with respect to the applied bias will result in:

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}[I_s(e^{V_D/nV_T} - 1)]$$

$$\downarrow$$

$$\frac{dI_D}{dV_D} = \frac{1}{nV_T}(I_D + I_s)$$

In general, $I_D > I_s$

So,

$$\frac{dI_D}{dV_D} \cong \frac{I_D}{nV_T} \longrightarrow \frac{dV_D}{dI_D} = r_d = \frac{nV_T}{I_D}$$

The equation of $\boldsymbol{V}_{\mathrm{T}}$ from slide 31 is:

$$\boxed{V_T = \frac{kT_K}{q}} \cong 26\,\mathrm{mV}$$

Substituting n=1 and V_T =26 mV results in:

$$\boxed{r_d = \frac{26\,\mathrm{mV}}{I_D}}$$

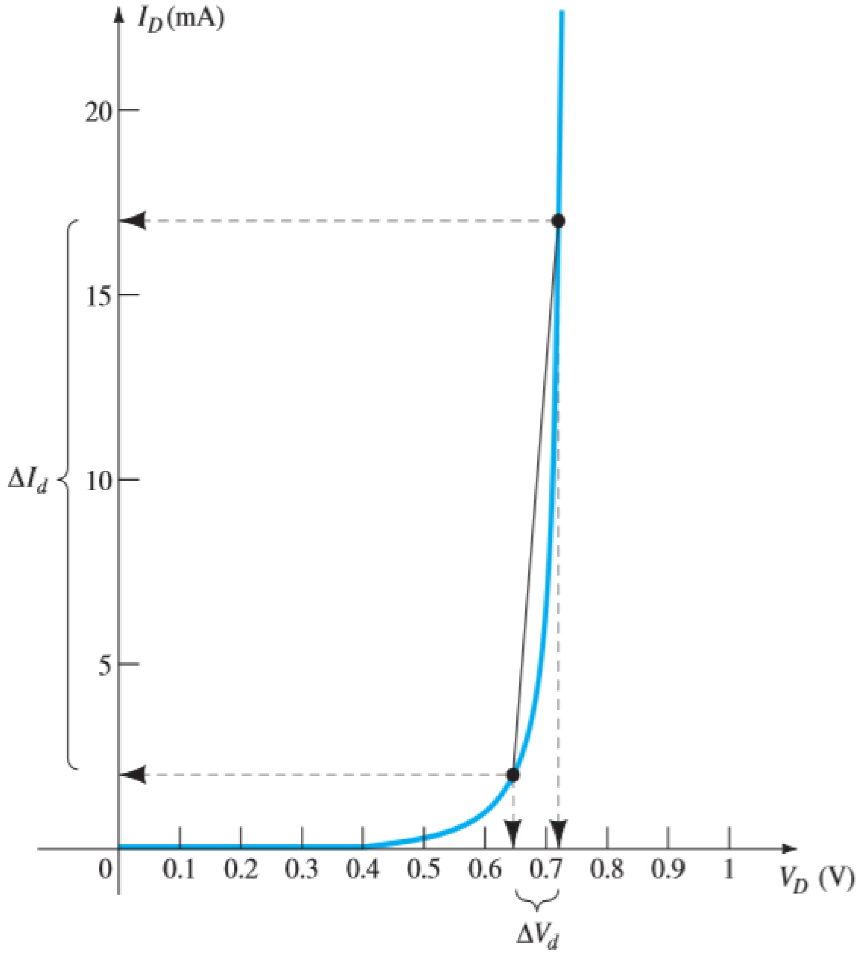
It implies that the dynamic resistance can be found simply by substituting the quiescent value of the diode current into the equation.

Average AC Resistance

- If the input signal is sufficiently large to produce a broad swing such as indicated in the figure, the resistance associated with the device for this region is called the average ac resistance.
- The average ac resistance can be determined by picking 2 points on the characteristic curve developed for a particular circuit.
- In equation form:

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}}$$

where Δ signifies a finite change in the quantity.



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REFERENCES

Robert. L. Boylestad & Louis Nashelky, "Electronics Devices and Circuit Theory", 11th edition, Prentice Hall

THANK YOU !!!