Chapter 3

Semiconductor Physics

Course Content

- Basic concepts in Electronics
- Semiconductor: p-type, n-type; p-n junction diode, its characteristics, half wave, full wave and bridge type rectifiers, basic filter circuits, Zener diode characteristics, Zener diode as a voltage regulator.

Semiconductor Physics

- At the end of this lecture, student will be able to :
  - Define a semiconductor
  - Classify semiconductor, insulator and conductor
  - Define intrinsic and extrinsic semiconductor
  - Explain P-type and N-type semiconductor
  - Illustrate conduction in semiconductor

Topics

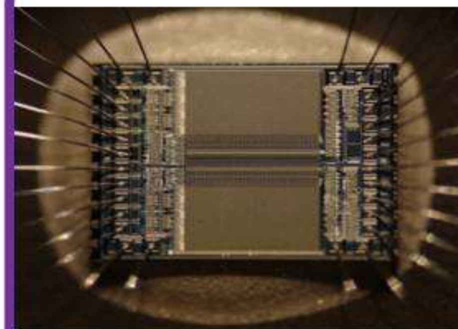
- Insulators, Semiconductors, and Conductors comparison
- Semiconductors
- Intrinsic and extrinsic semiconductor
- P type and N type semiconductor
- Conduction in Semiconductors

Introduction

Insulators, Semiconductors, and Conductors

Insulators, Semiconductors, and Conductors

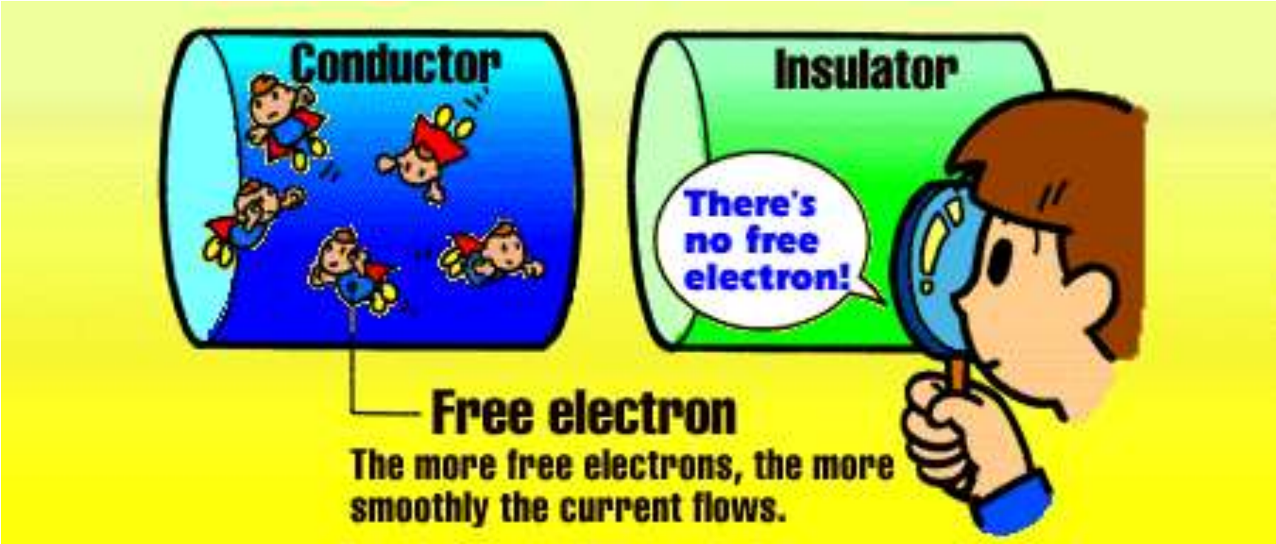
Conductors



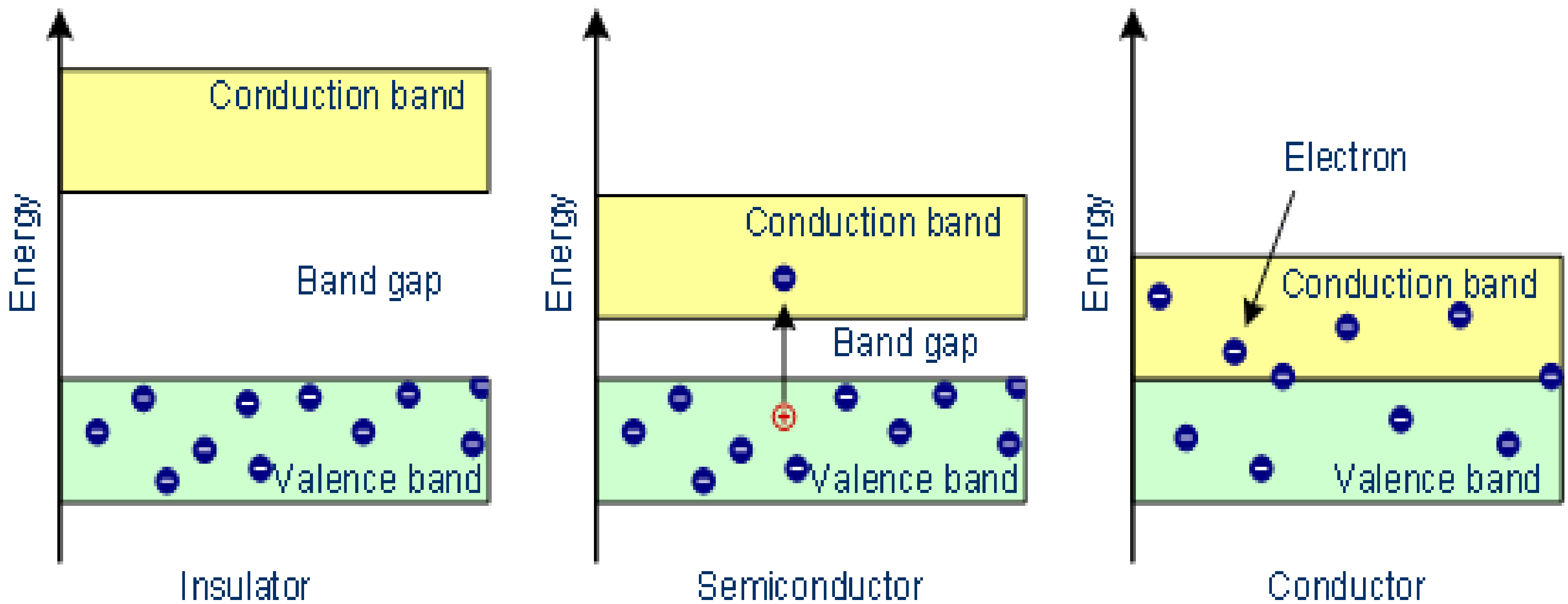
Semi-conductors

Insulators

Insulators, Semiconductors, and Conductors Continued..



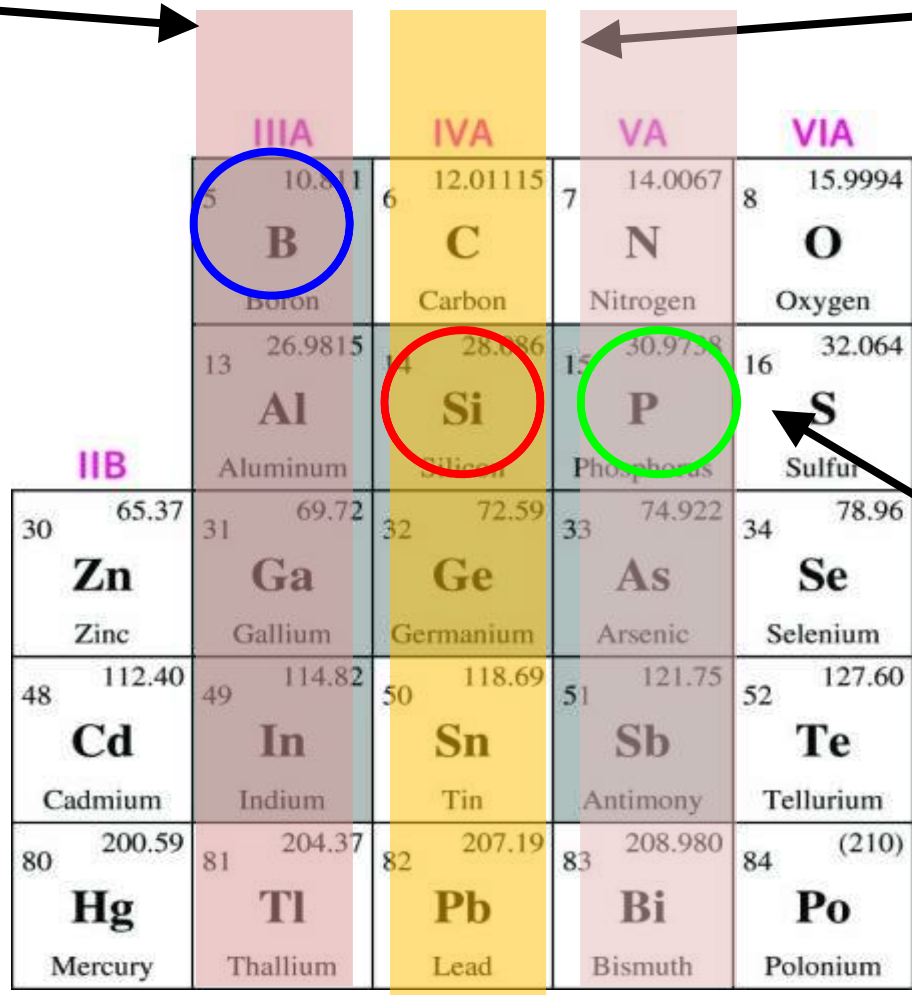
Insulators, Semiconductors, and Conductors Continued..



Periodic Table

Column 3 Elements have 3 electrons in the Valence Shell

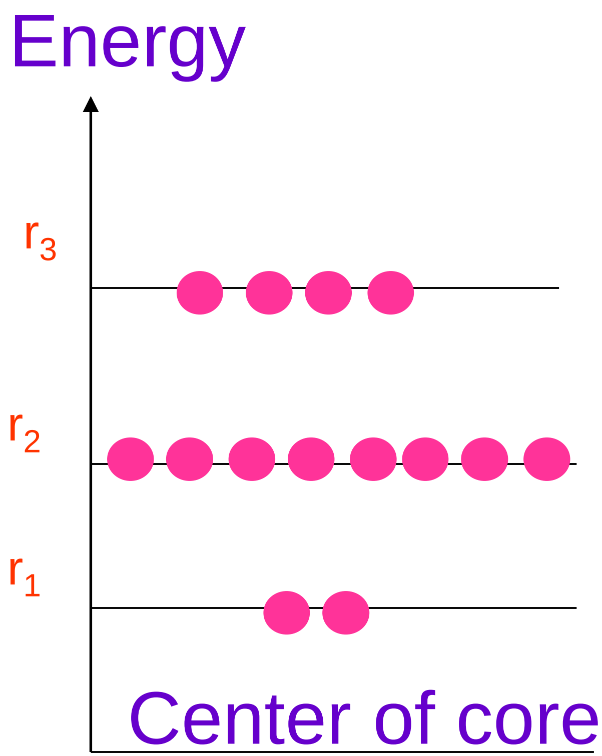
Column 4 Elements have 4 electrons in the Valence Shell



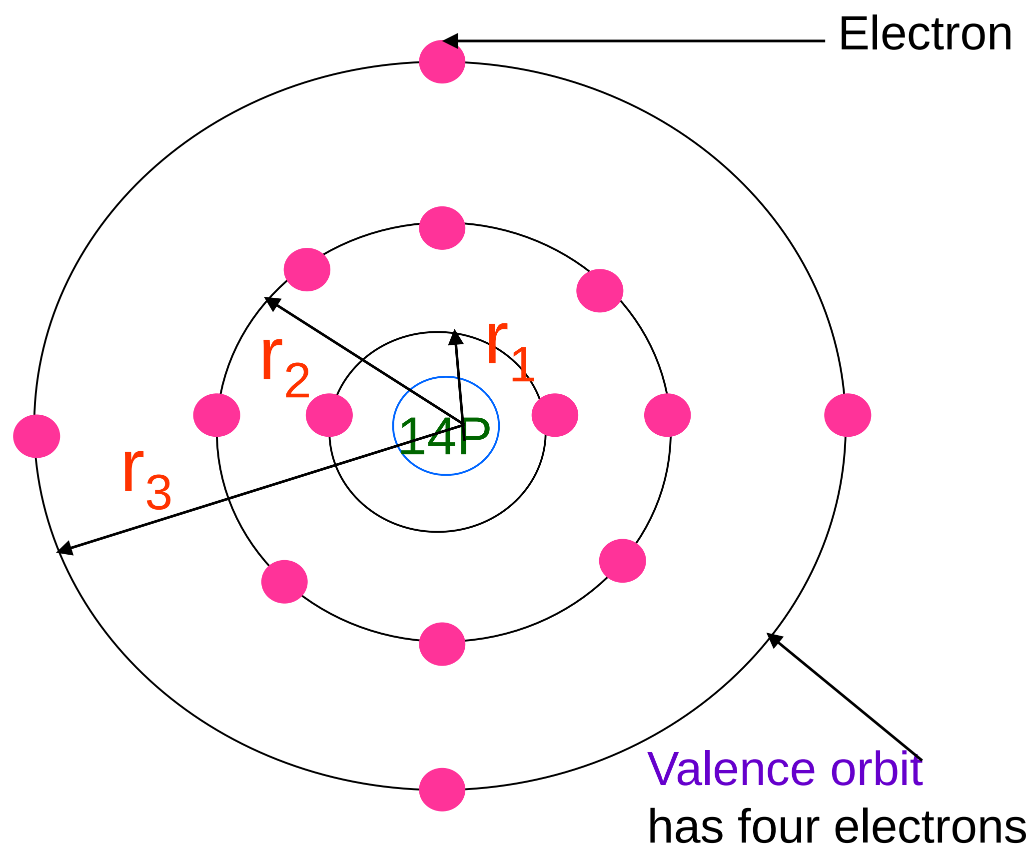
Column 5 Elements have 5 electrons in the Valence Shell

Position of semiconductors in Periodic Table

Semiconductor



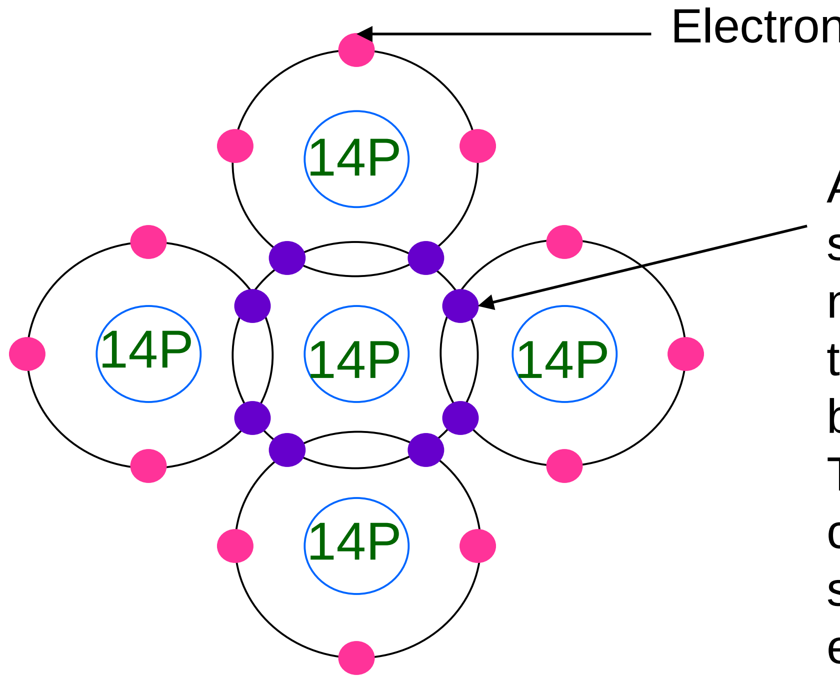
Energy levels in a single atom



Isolated silicon atom

Electrons in the same orbit has same energy

Covalent Bond



Silicon Crystal

An electron shared by two neighboring atoms to form a covalent bond.
This way an atom can have a stable structure with eight valence band electrons.

Types of Semiconductors

Semiconductors can be classified as:

1. Intrinsic Semiconductor
2. Extrinsic Semiconductor

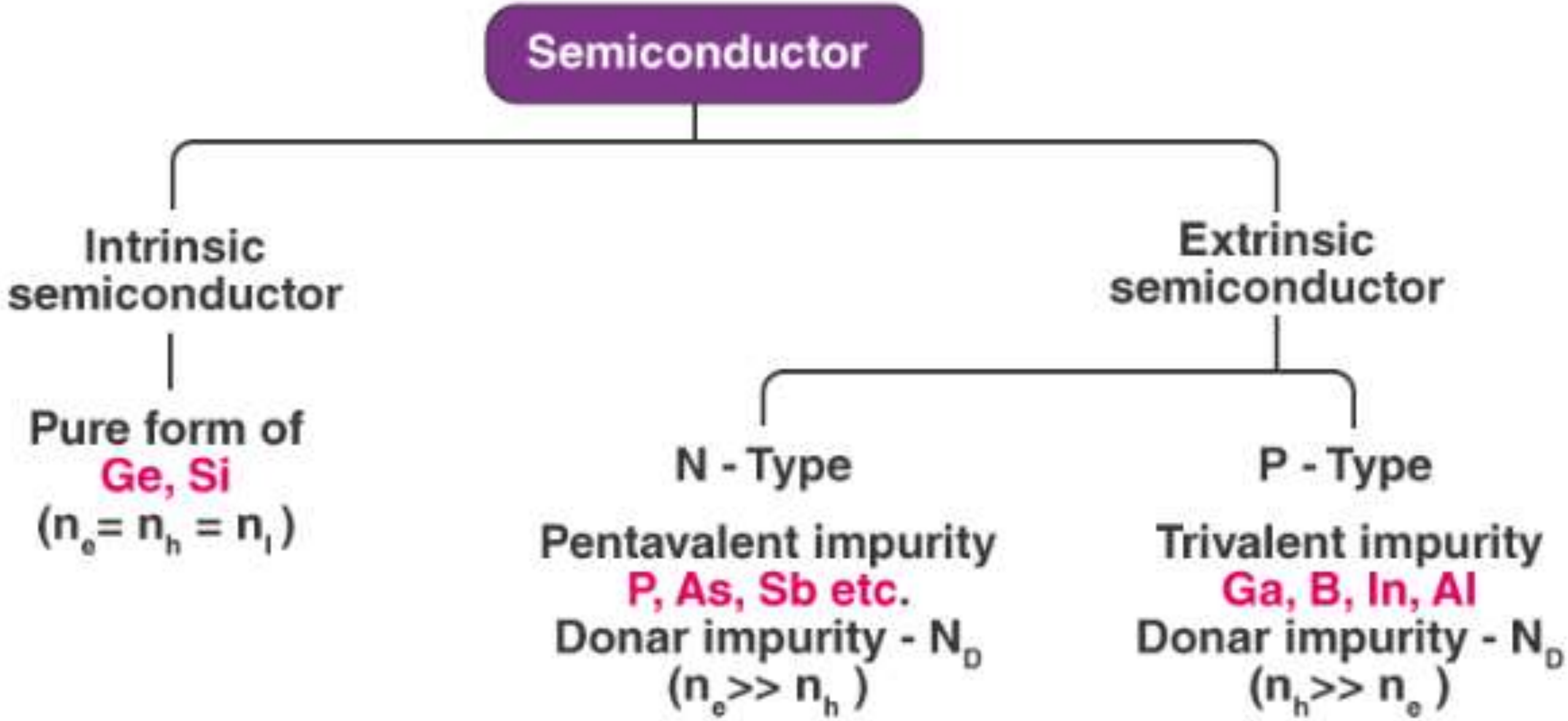
Extrinsic Semiconductors are further classified as:

a. n-type Semiconductors

b. p-type Semiconductors

Semiconductors can be classified as follows:

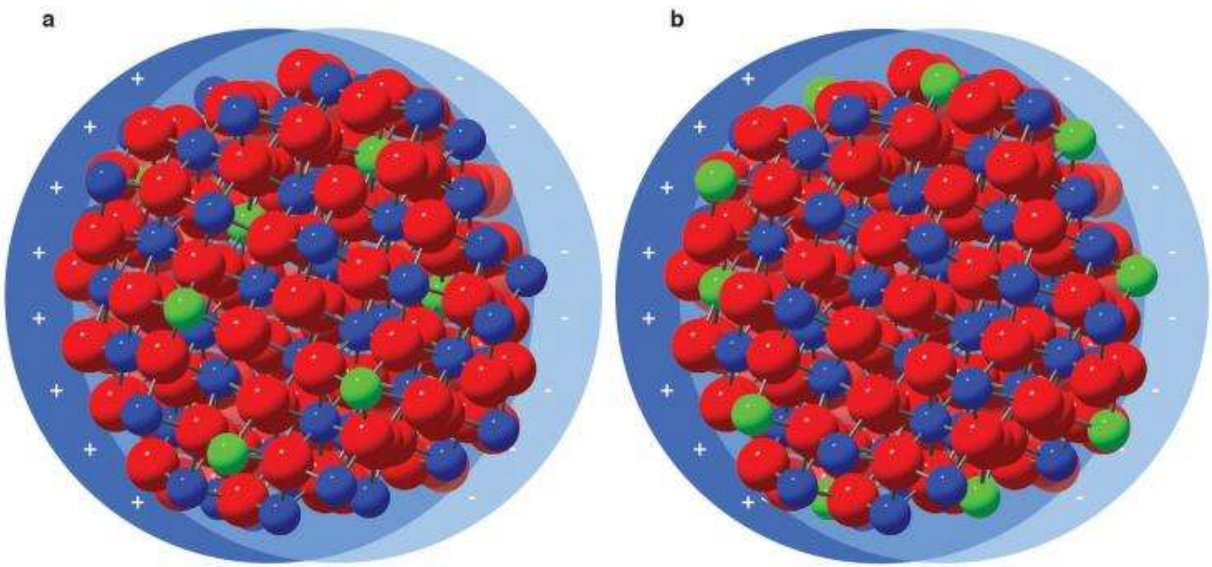
- **Intrinsic Semiconductor**
- **Extrinsic Semiconductor**



Classification of Semiconductors

Doping

- Doping means mixing a pure semiconductor with impurities to
  - increase its electrical conductivity



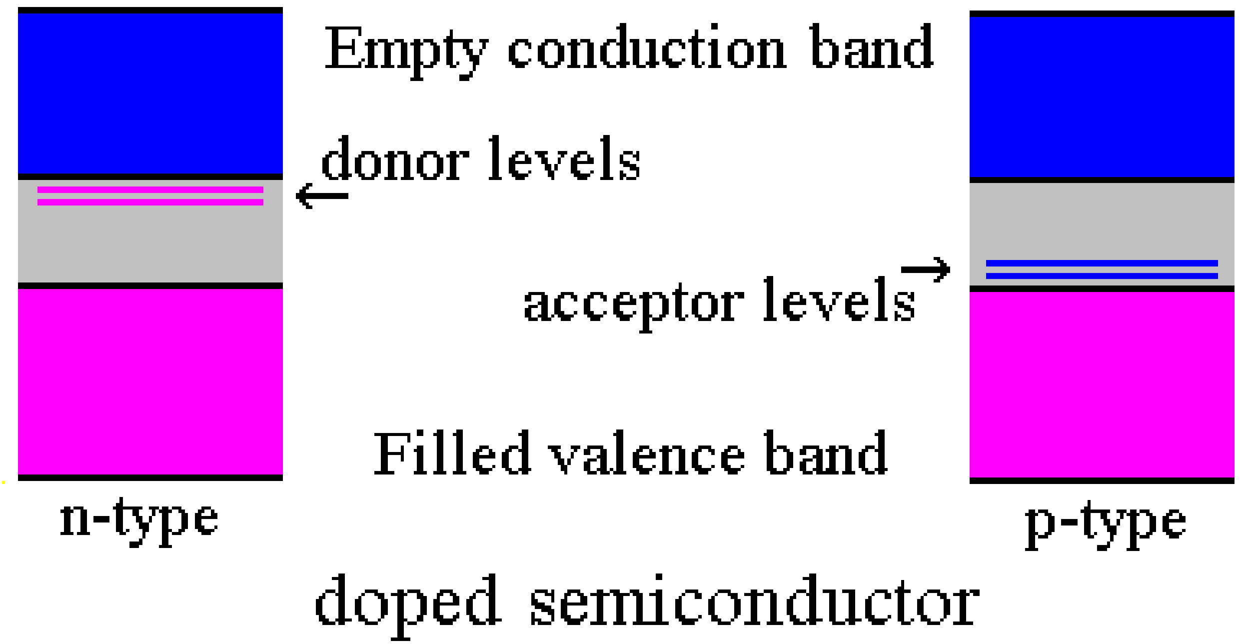
Doping Ways

- Doping Can be done in two ways
  - By mixing pentavalent elements such as phosphorous, arsenic, antimony
  - By mixing Trivalent elements such as aluminum, boron, gallium and Indium

Extrinsic Semiconductor

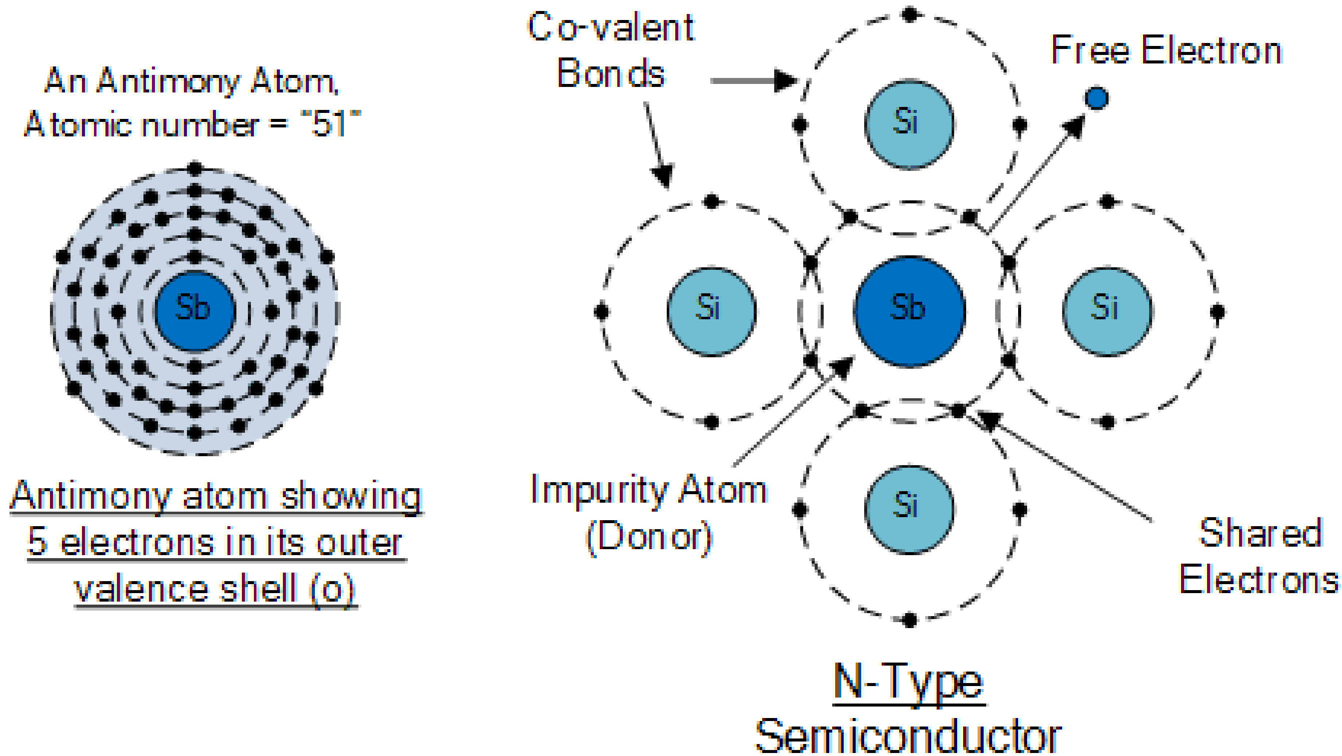
[Extrinsic Semiconductors]

Extrinsic Semiconductor Energy Band Diagram

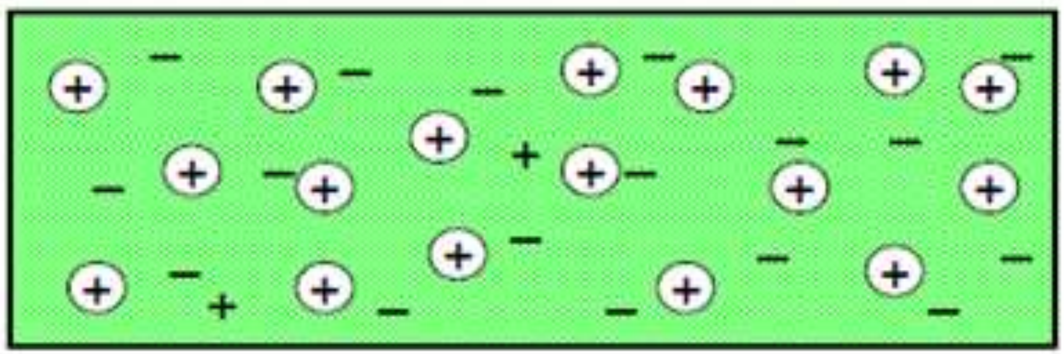


n-type semiconductor

Has many free electrons in conduction band and few holes In valence band



n-type Semiconductor



Shorthand Notation

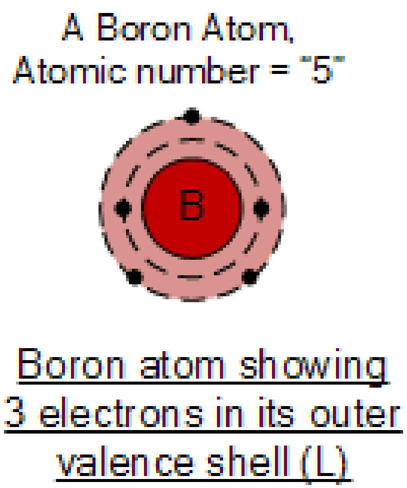
⊕ Positively charged ion; immobile

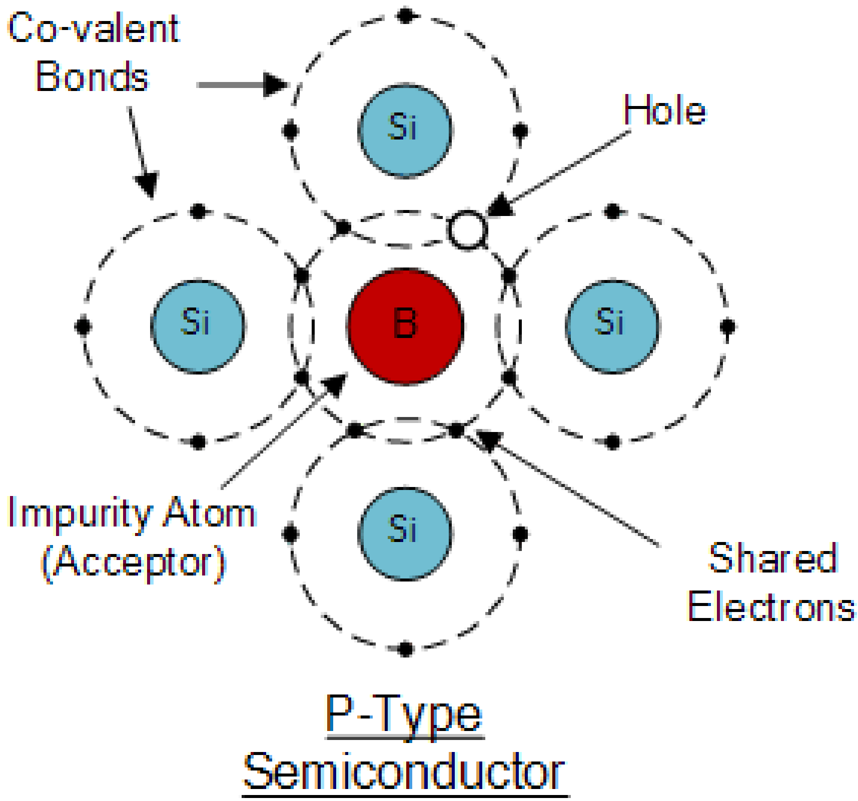
− Negatively charged e-; mobile;
Called “majority carrier”

\+ Positively charged h+; mobile;
Called “minority carrier”

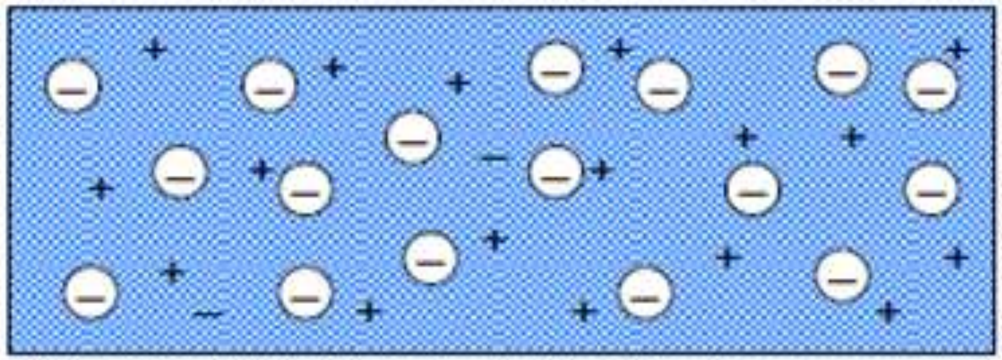
p-type Semiconductor

Has few free electrons in conduction band and many holes
In valence band





p-type Semiconductor



<u>Shorthand Notation</u>

⊖ Negatively charged ion; immobile

\+ Positively charged h+; mobile;
Called "majority carrier"

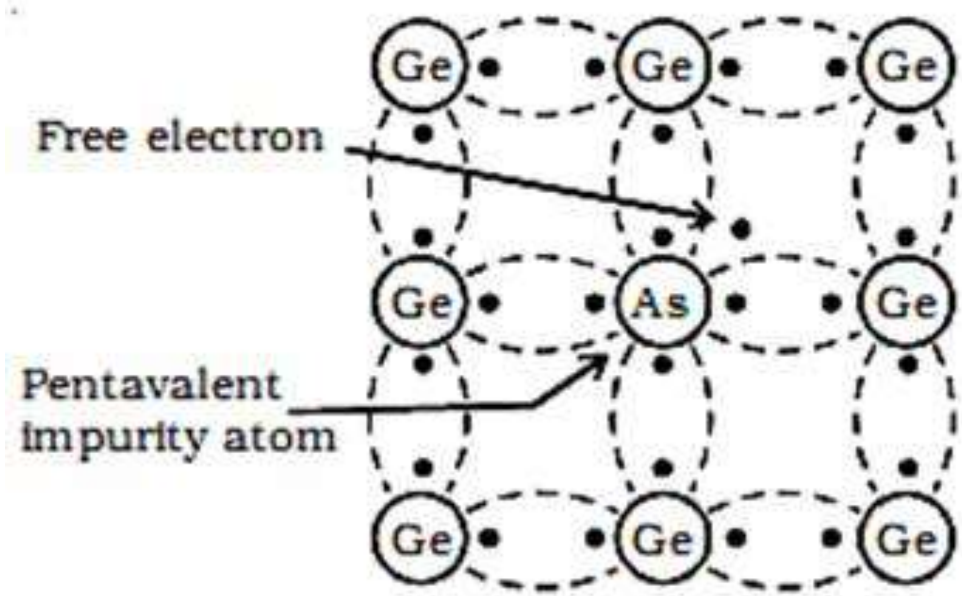
– Negatively charged e-; mobile;
Called "minority carrier"

Comparison of Semiconductors

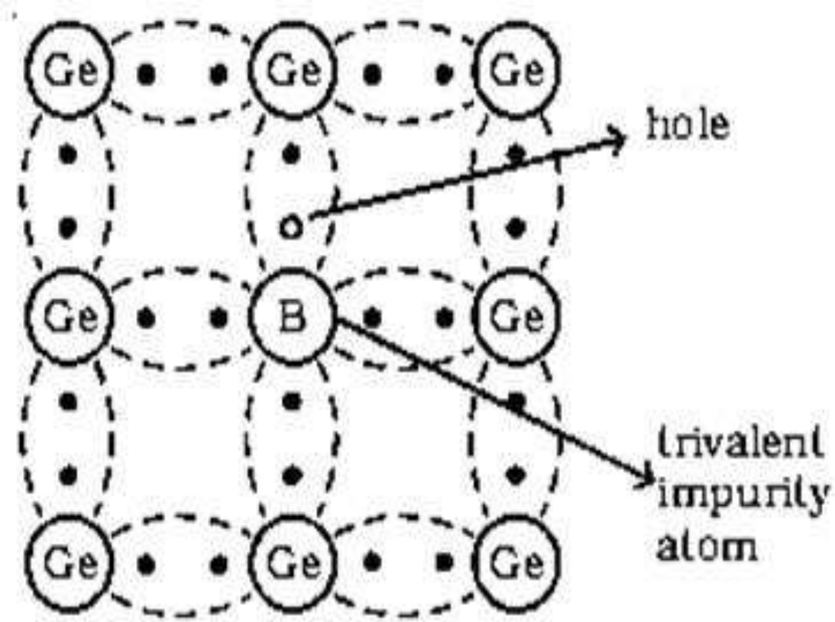
Intrinsic Semiconductor	Extrinsic Semiconductor
Pure semiconductor	Impure semiconductor
The density of electrons is equal to the density of holes	The density of electrons is not equal to the density of holes
Electrical conductivity is low	Electrical conductivity is high
Dependence on temperature only	Dependence on temperature, as well as on the amount of impurity
No impurities	Trivalent impurity and pentavalent impurity

Comparison Between n-type and p-type Semiconductors

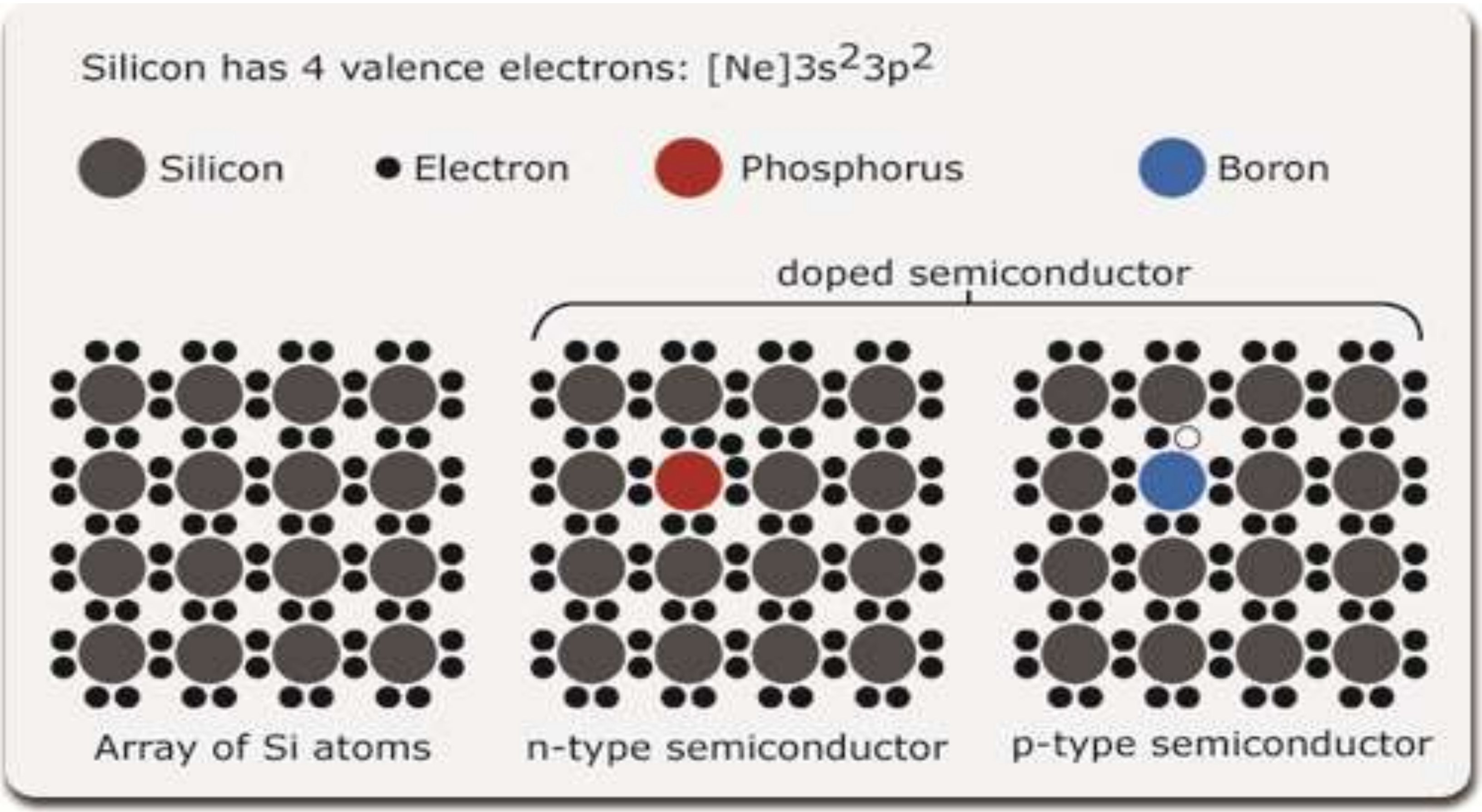
n-type



p-type



Comparison Between n-type and p-type Semiconductors continued..



Summary

- Silicon and Germanium are the most commonly used semiconductors.
- Semiconductor in the extreme pure form is known as intrinsic semiconductors.
- Doping with pentavalent impurity will result in n-type and with trivalent impurity will result in p- type.
- P-type and n-type semiconductors are electrically neutral.
- Conduction in semiconductors is through Drift and Diffusion

p-n Junction Diode

- At the end of this lecture, student will be able to :
  - Illustrate how p-n junction diode is formed
  - Define depletion region and potential barrier
  - Explain the Working of diode under forward and reverse bias

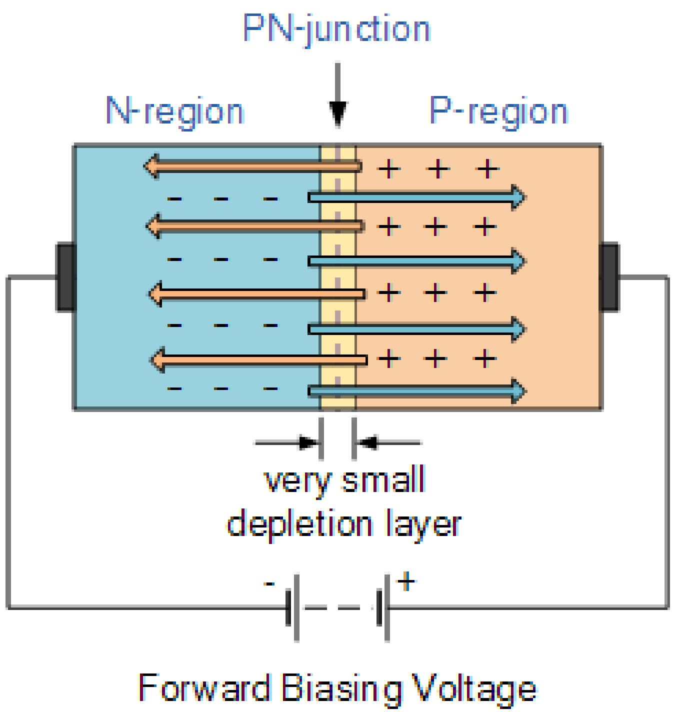
Topics

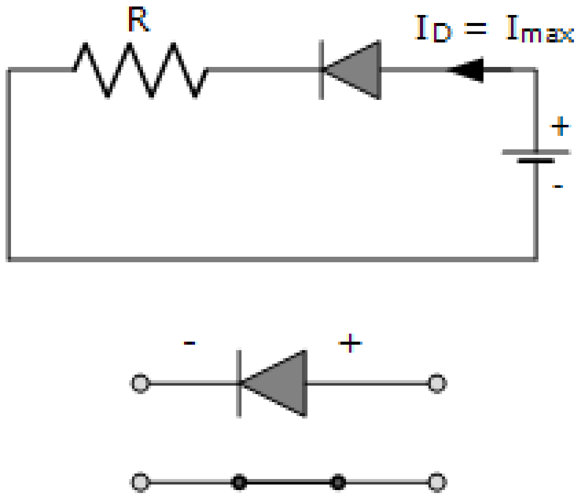
- p-n junction diode
- p-n junction working forward bias and reverse bias
- Junction properties

p-n Junction Diode

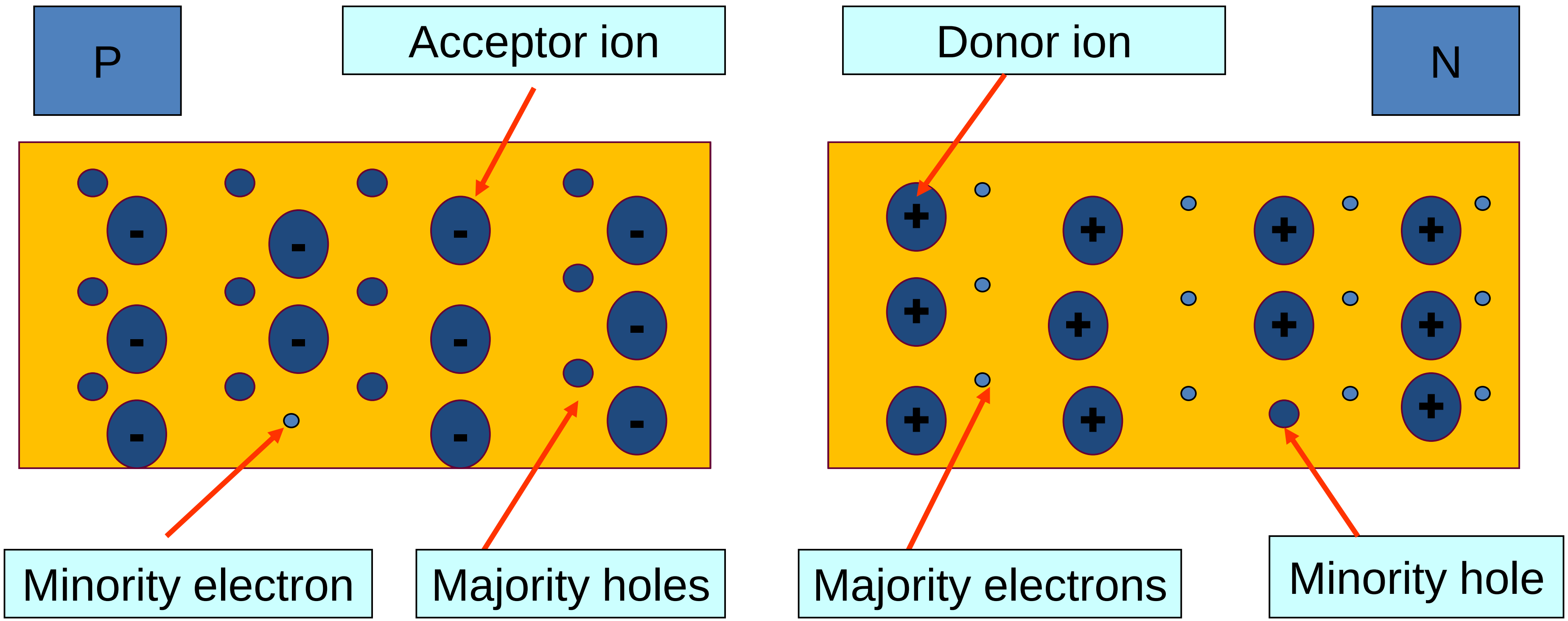
PN Junction Diode

A PN-junction diode is formed when a p-type semiconductor is fused to an n-type semiconductor creating a potential barrier voltage across the diode junction





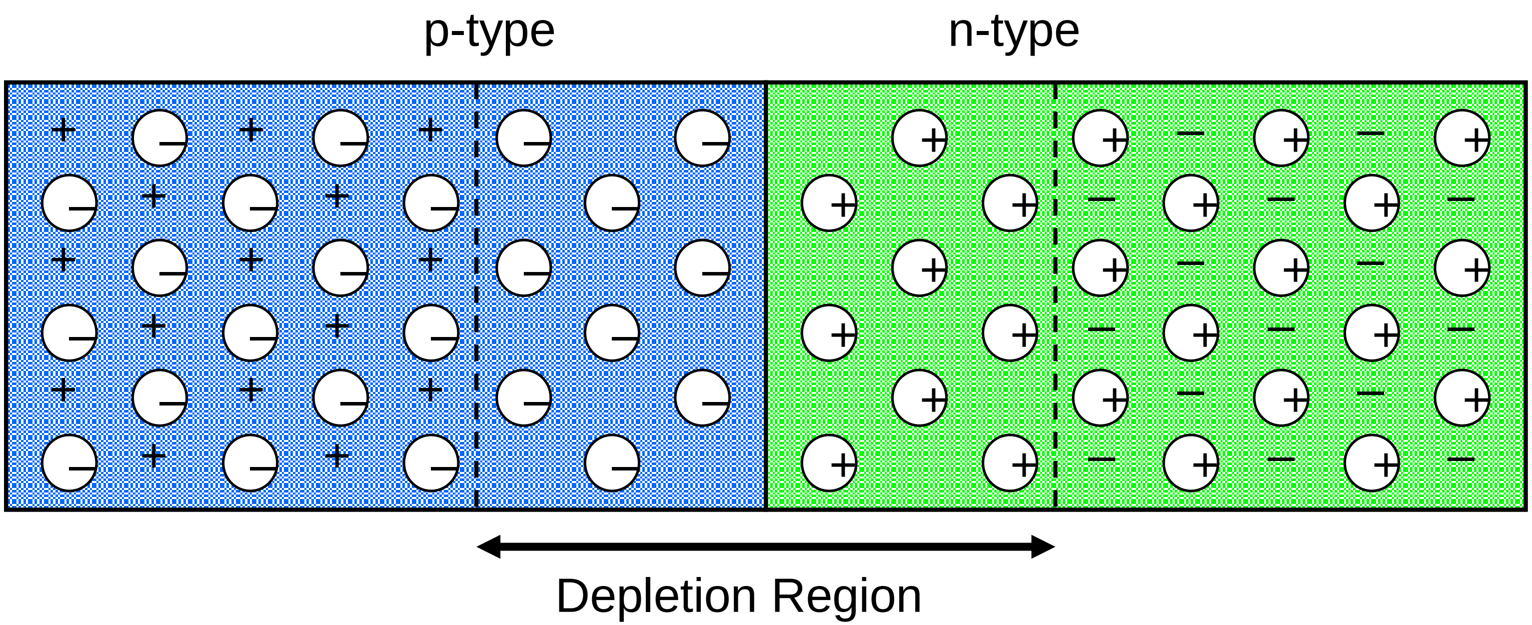
p and n type Semiconductors

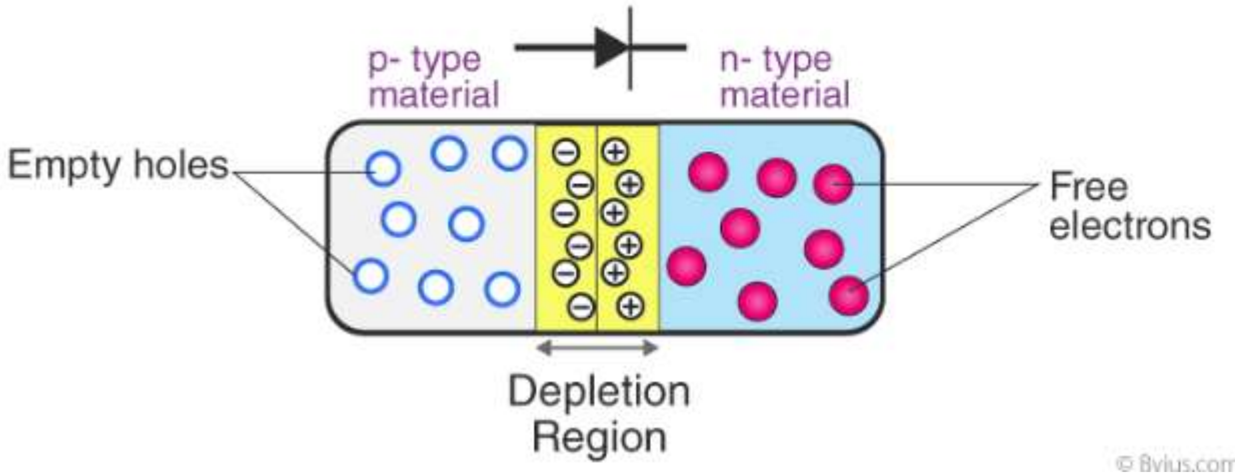


P-type semiconductor

N-type semiconductor

p-n Junction


p-type
n-type
Depletion Region


p- type material
n- type material
Empty holes
Free electrons
Depletion Region
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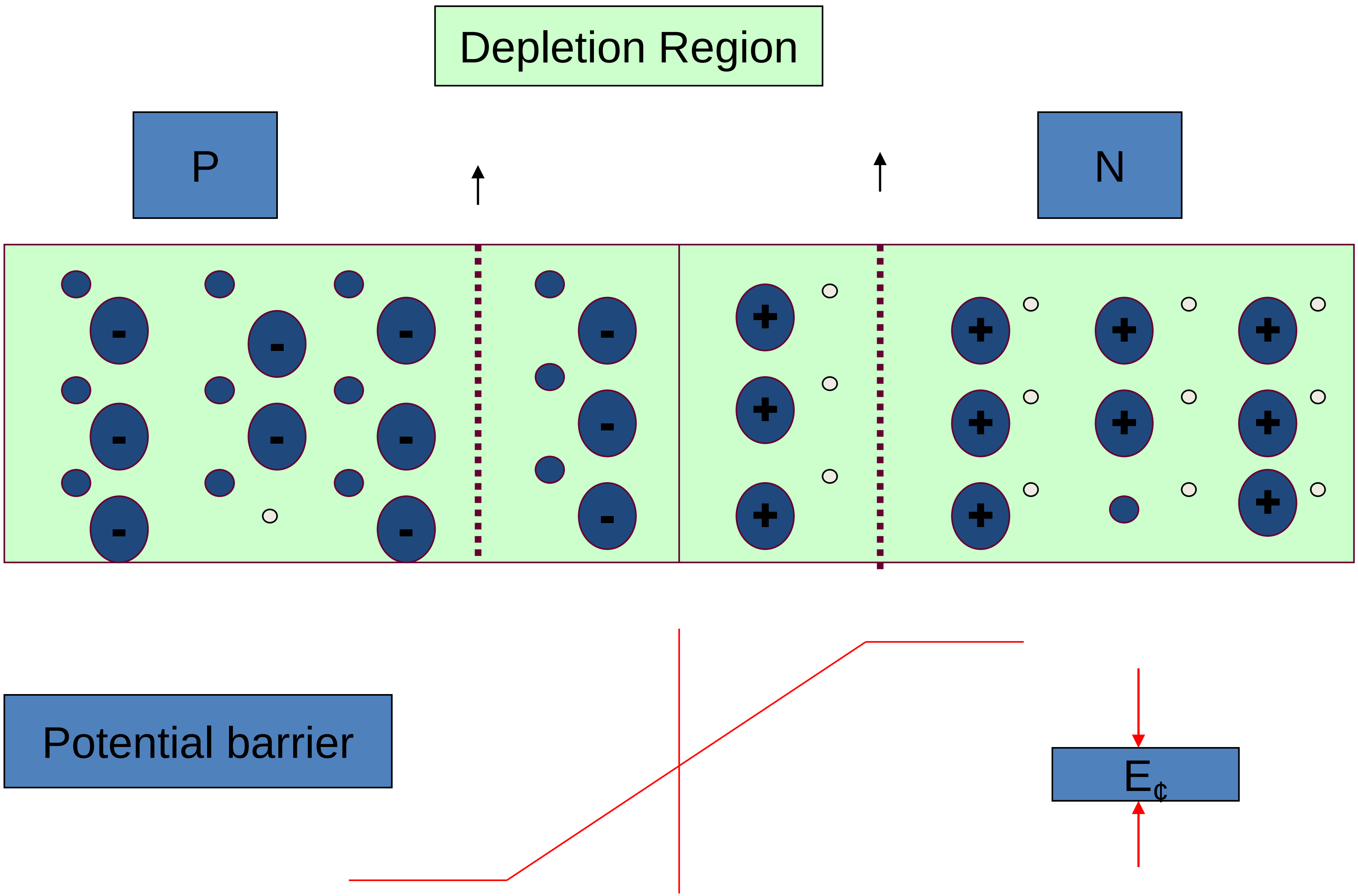
p-n Junction Diode Formation

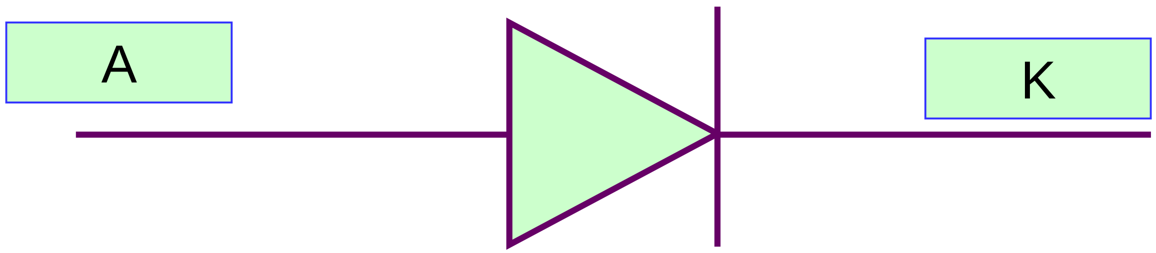
[Formation of p-n junction diode]

Formation of p-n Diode

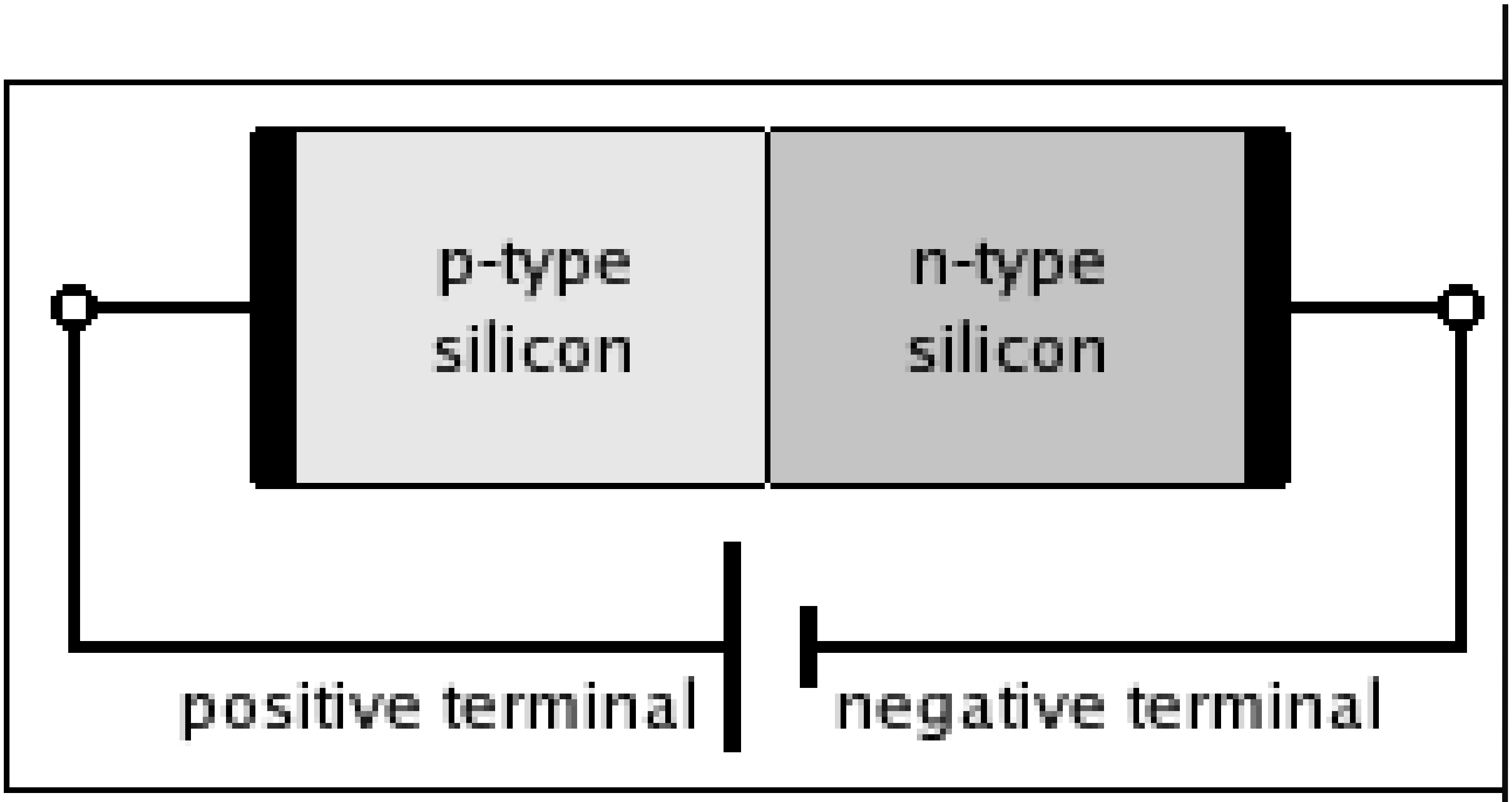


Circuit Symbol of p-n Diode

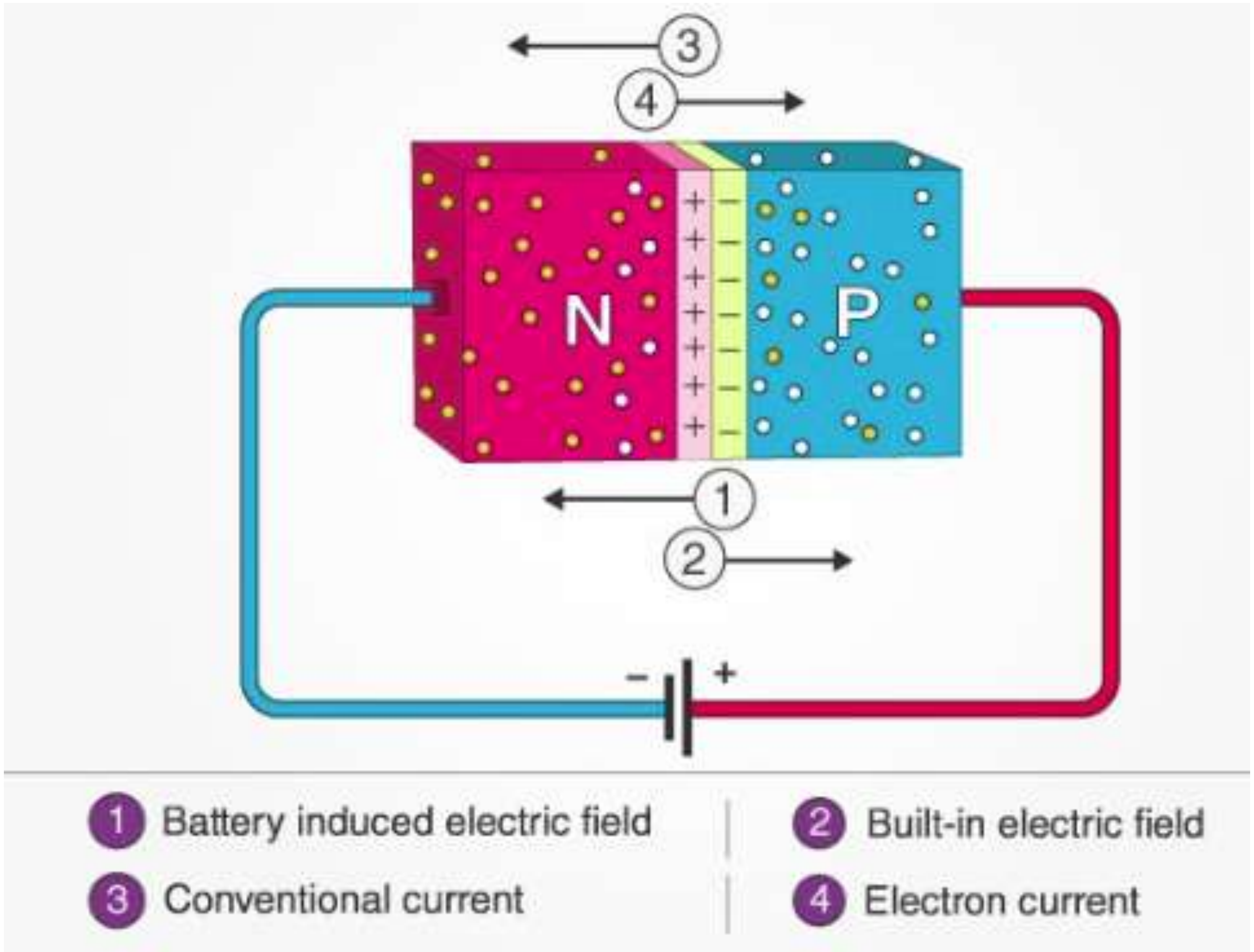
- Arrow head indicates the direction of conventional current flow.



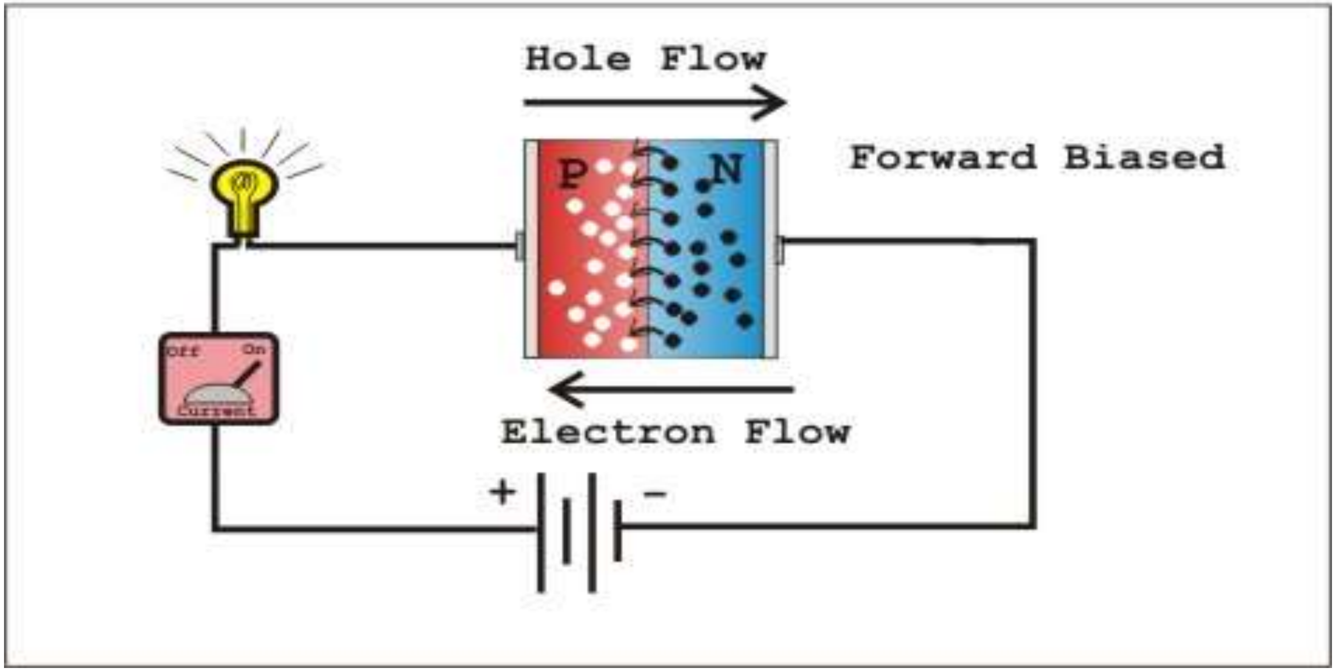
p-n Junction Diode - Forward Biasing



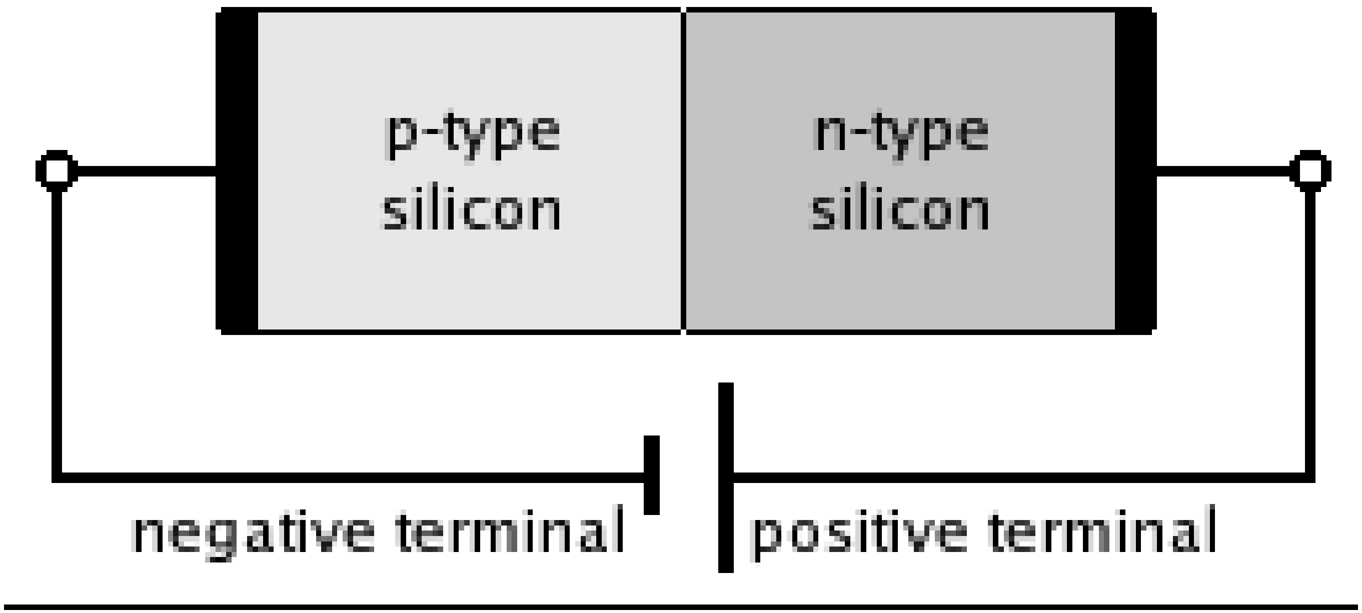
Working of p-n Junction under FB



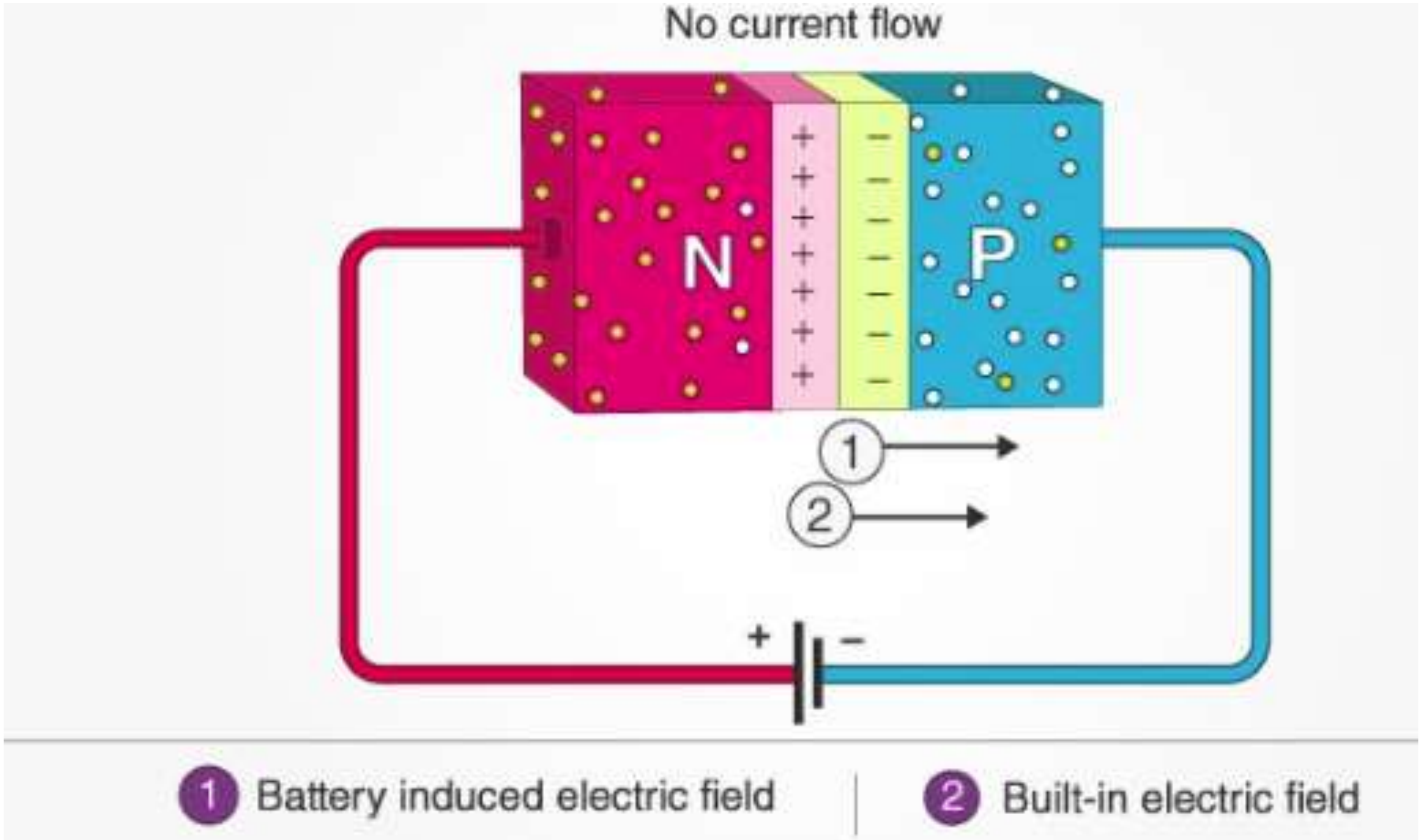
p-n Junction Forward Bias



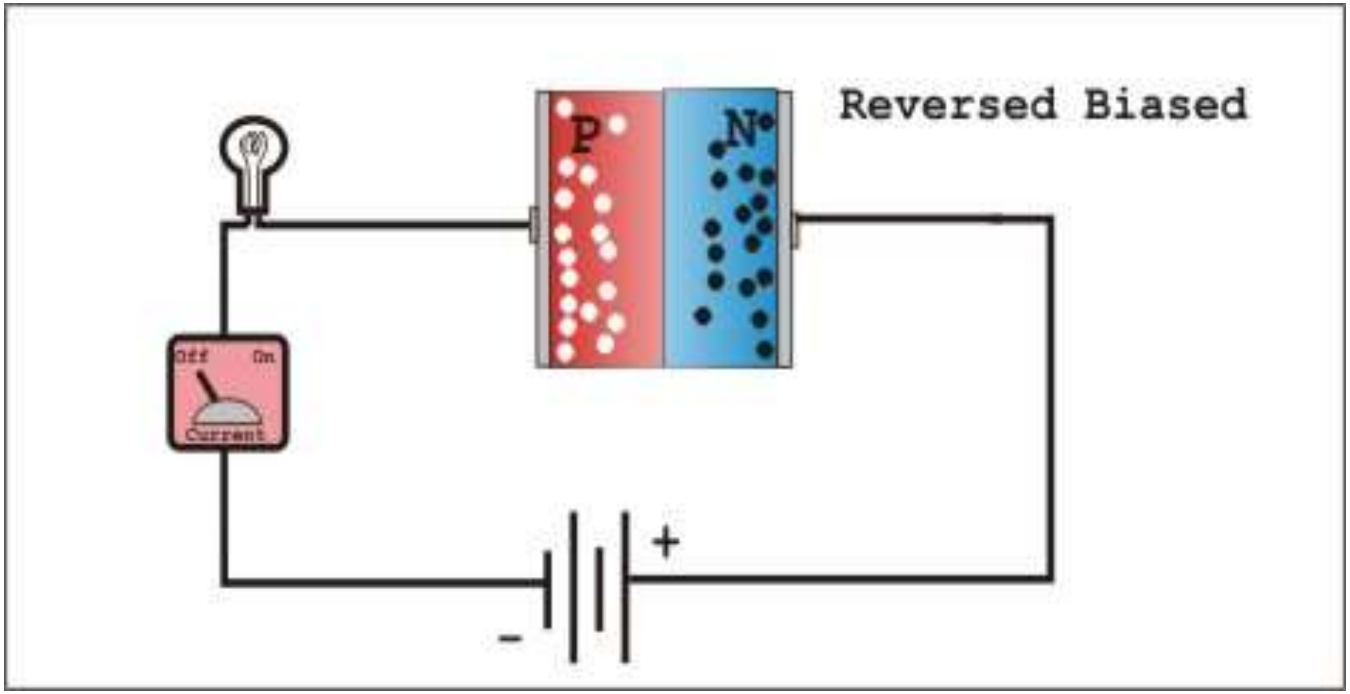
p-n Junction Diode- Reverse Biasing



P-N Junction Working Under Reverse Bias



p-n Junction Reverse Bias



Junction Properties

- The junction contains immobile ions i.e. this region is depleted of mobile charges.
- This region is called the depletion region, the space charge region, or transition region.
- It is in the order of 0.5-1 micron width.
- The cut-in voltage is 0.3v for Ge, 0.6v for Si
- The reverse saturation current doubles for every 10 degree Celsius rise in temperature.
- Forward resistance is in the order ohms, the reverse resistance is in the order mega ohms.
- The Transition region increases with reverse bias this region also considered as a variable capacitor and known as Transition capacitance

Summary

- Diode is formed by putting a n-type and p-type semiconductor together.
- Migration of holes from p to n and electrons from n to p causes a formation of depletion layer. This gives rise to barrier potential preventing further migration of holes and electrons
- The diode behaves like a ‘ON’ switch in forward bias
- Current flow in forward bias is due to diffusion.
- The diode behaves like a ‘OFF’ switch in reverse bias mode.
- Current flow in reverse bias is due to drift.
- Fermi energy levels get redistributed according to the applied bias .

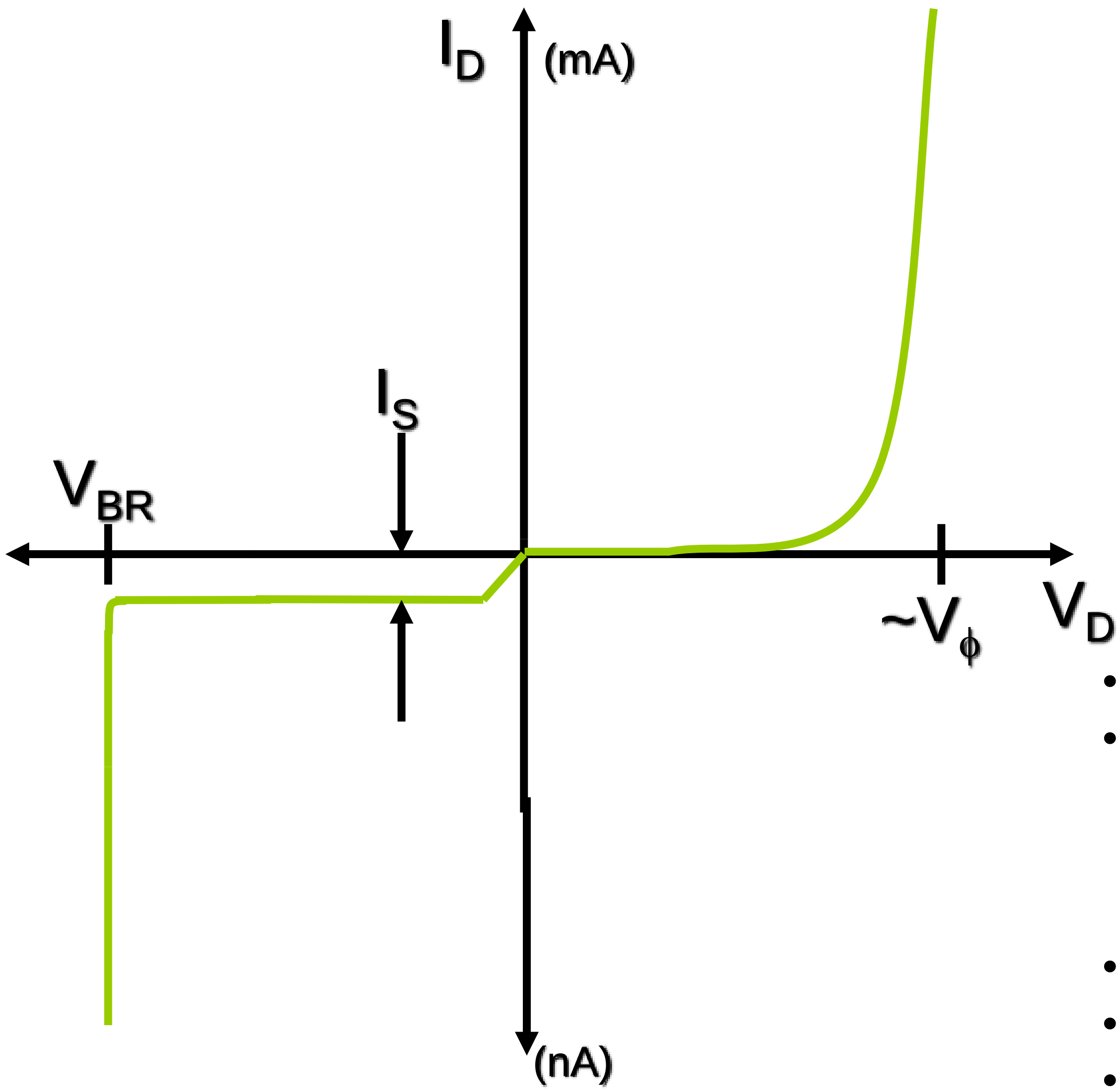
Diode Characteristics

- At the end of this lecture, student will be able to :
  - Explain working of different diode models and their characteristics
  - Draw the characteristics of the diode.
  - Draw the load line and derive the operating point of diode
  - Calculate the diode resistance

Topics

- Diode Characteristics
- Diode models
- DC load line of diode
- Zener and Avalanche breakdown

Diode Characteristic



- V_D = Bias Voltage
- I_D = Current through Diode. I_D is Negative for Reverse Bias and Positive for Forward Bias
- I_S = Saturation Current
- V_{BR} = Breakdown Voltage
- V_ϕ = Barrier Potential Voltage

Diode Equation

$$I_D = I_S(e^{V_D/\eta V_T} - 1)$$

- I_D is the current through the diode,
- I_S is the saturation current and V_D is the applied biasing voltage.
- V_T is the thermal equivalent voltage and is approximately 26 mV at room temperature.

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

$k = 1.38 \times 10^{-23}$ J/K   T = temperature in Kelvin $q = 1.6 \times 10^{-19}$ C

- η is the emission coefficient for the diode. For a silicon diode η = 2 for low currents and goes down to about 1 at higher currents

Problem

Example 1.1

- At a temperature of 300K, a certain junction diode has i_D = 0.1mA for v_D = 0.6V. Assume that n is unity and use $\boldsymbol{V_T}$ = 0.026V. find the value of the saturation current I_s.

$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right]$$

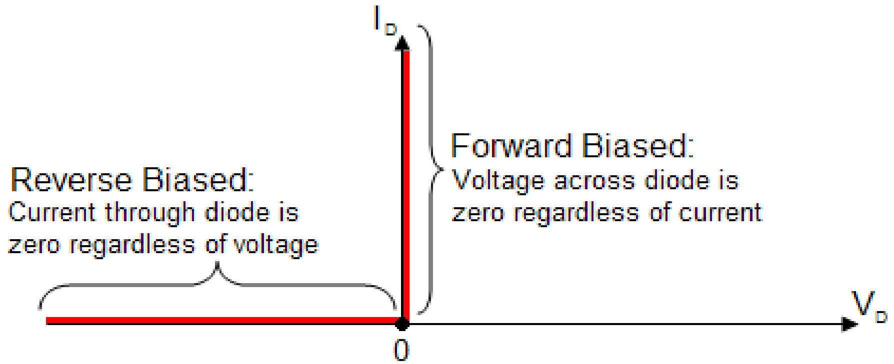
$$Is = \frac{i_D}{\exp(v_D / nV_T) - 1}$$

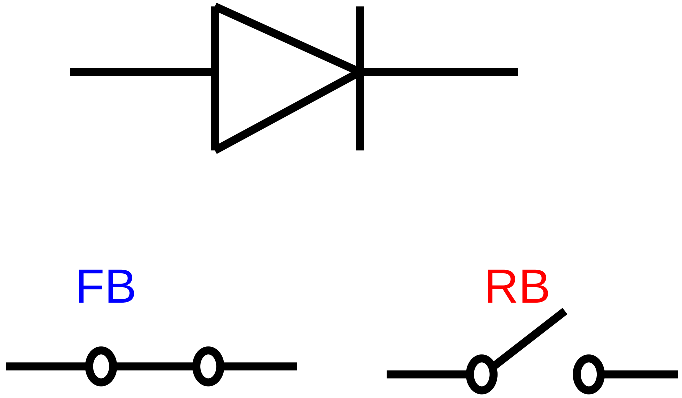
$$= \frac{10^{-4}}{\exp(0.6/0.026) - 1}$$

$$= 9.502 \times 10^{-15} A$$

Diode Circuit Models

1.Ideal Diode Model





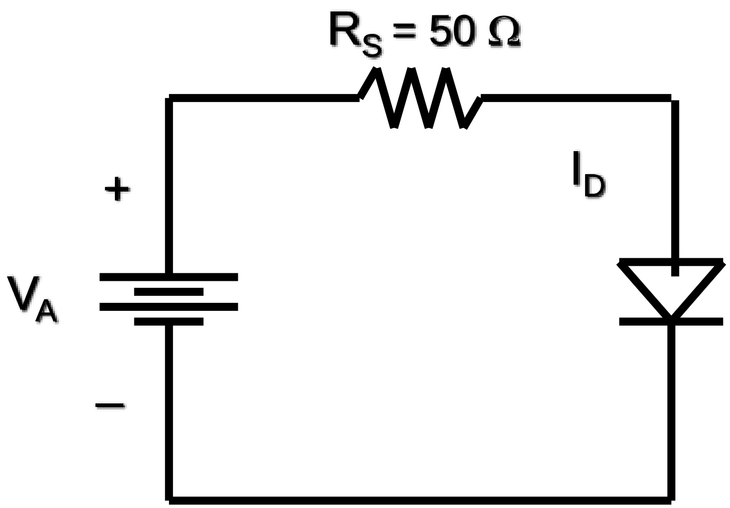
V-I characteristic of Ideal diode and its equivalent circuit representation

- The diode is designed to allow current to flow in only one direction
- Under forward bias V=0 and I>0
- Under reverse bias V<0 and I=0

Problem

Example 1.2

•Assume the diode in the circuit below is ideal. Determine the value of I_D if a) V_A = 5 volts (forward bias) and b) V_A = -5 volts (reverse bias)

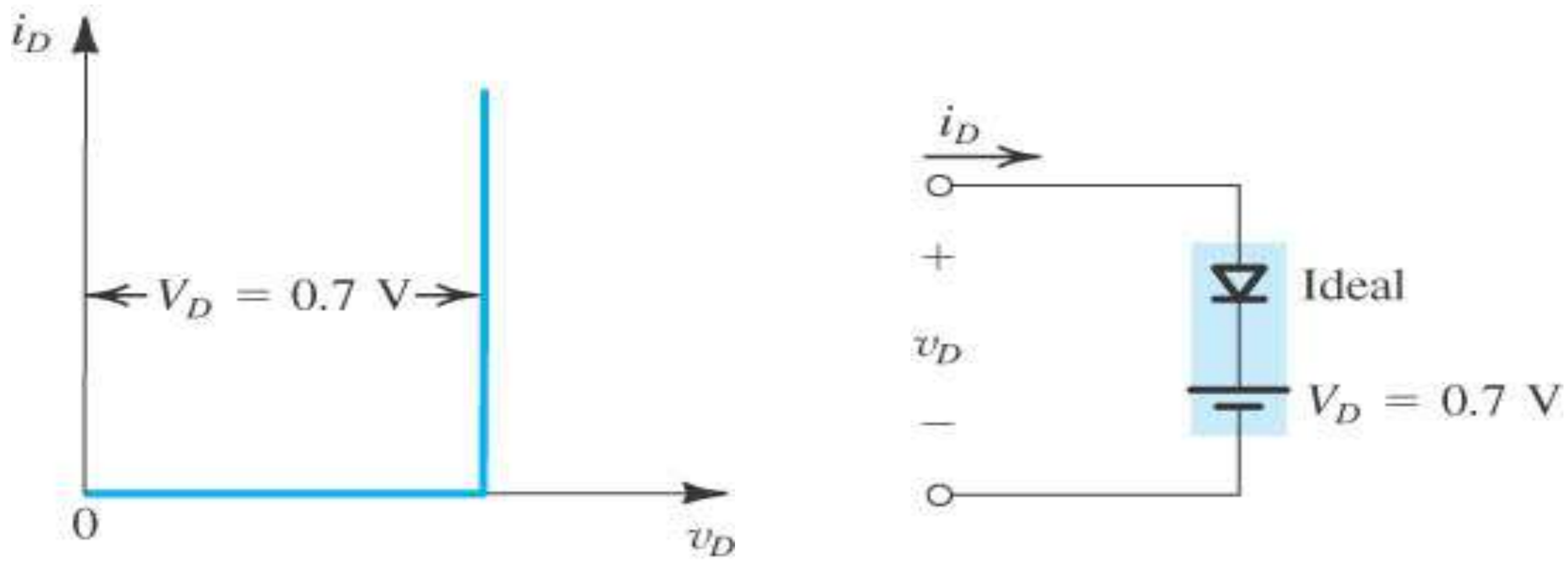


a) With $V_A > 0$ the diode is in forward bias and is acting like a perfect conductor so:

$$I_D = V_A/R_S = 5\text{ V} / 50\ \Omega = 100\text{ mA}$$

b) With $V_A < 0$ the diode is in reverse bias and is acting like a perfect insulator, therefore no current can flow and $I_D = 0$.

2. Constant Voltage Drop model

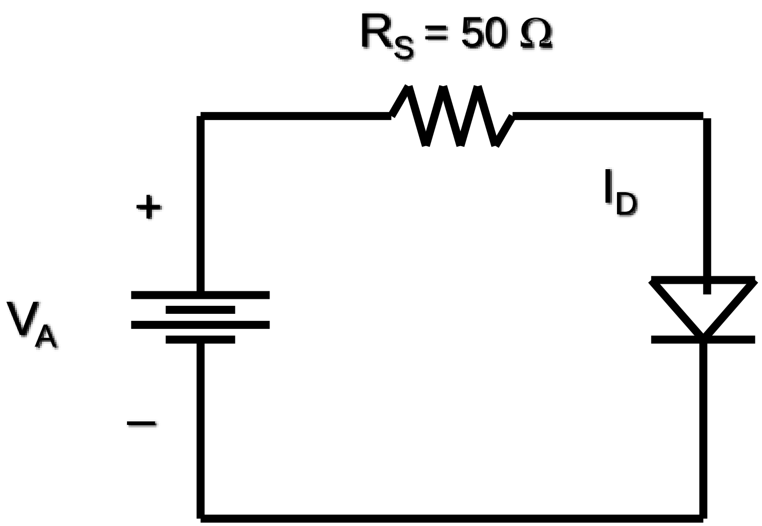


(a) (b)

Problem

Example 1.3

- Assume V_ϕ = 0.3 volts (typical for a germanium diode) Determine the value of I_D if V_A = 5 volts (forward bias).

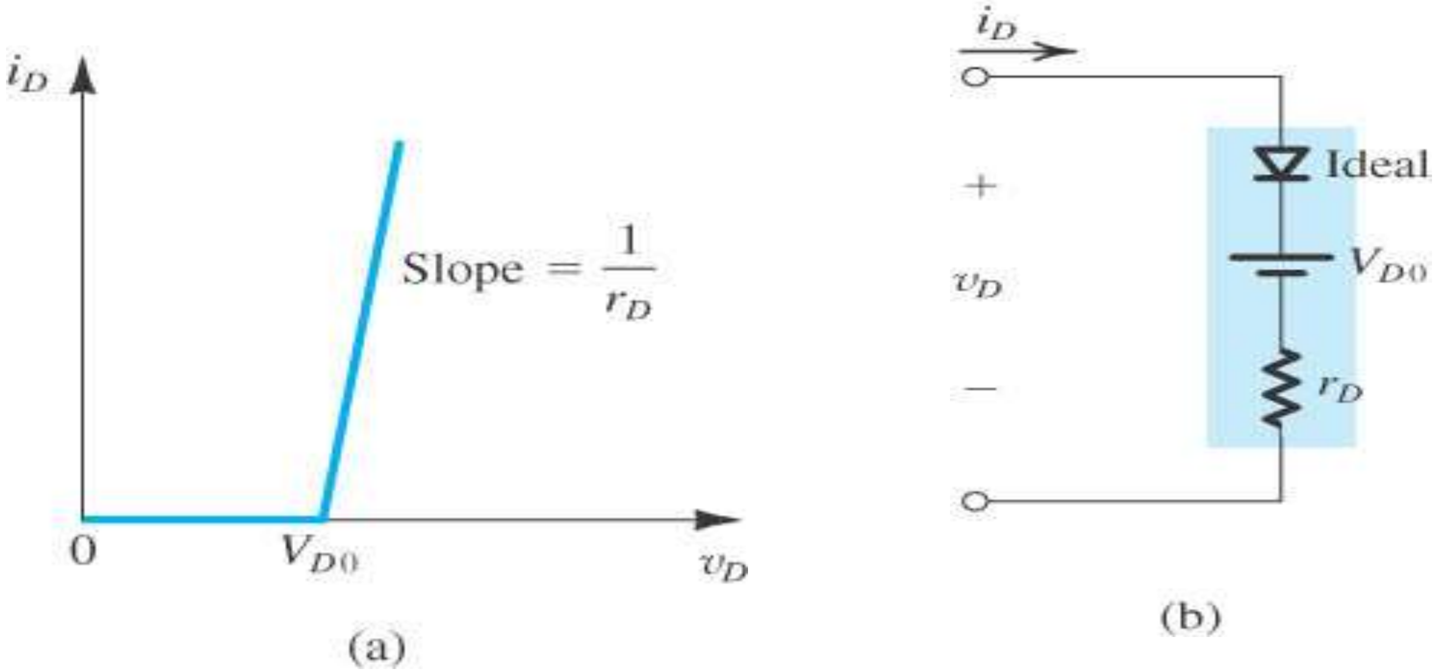


With $V_A > 0$ the diode is in forward bias and is acting like a perfect conductor so write a KVL equation to find I_D:

$$0 = V_A - I_D R_S - V_\phi$$

$$I_D = \frac{V_A - V_\phi}{R_S} = \frac{4.7\ \text{V}}{50\ \Omega} = 94\ \text{mA}$$

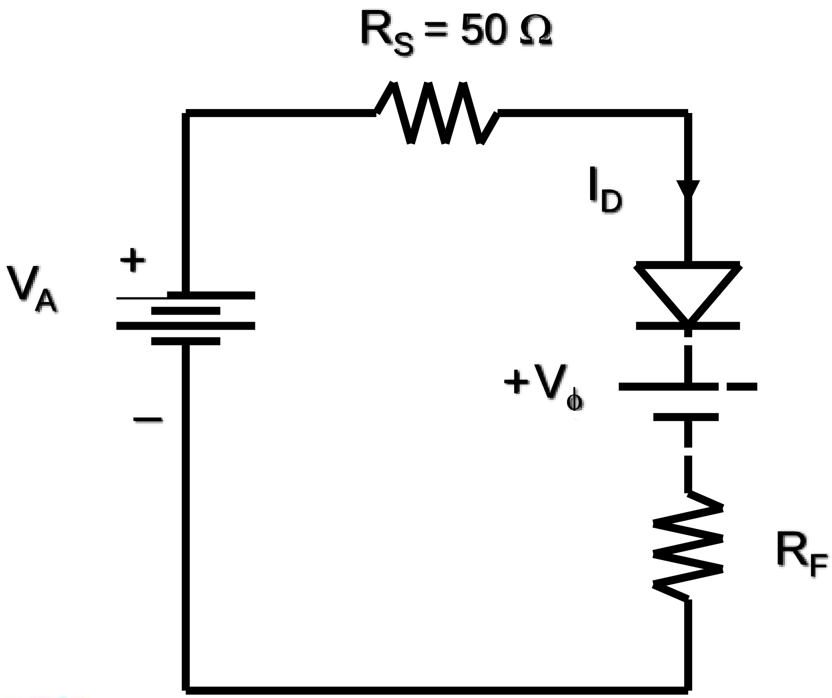
3. Piecewise Linear Model



Problem

Example 1.4

•Assume the diode is a low-power diode with a forward resistance value of 5 ohms. The barrier potential voltage is still: V_ϕ = 0.3 volts (typical for a germanium diode) Determine the value of I_D if V_A = 5 volts.



Once again, write a KVL equation for the circuit:

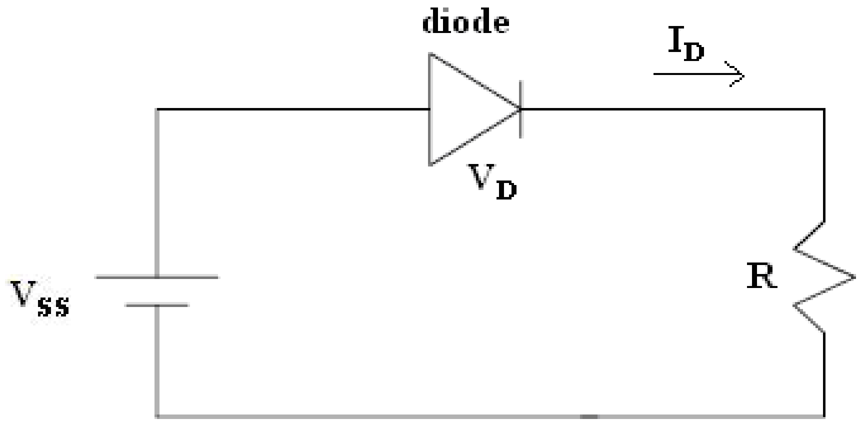
$$0 = V_A - I_D R_S - V_\phi - I_D R_F$$

$$I_D = \frac{V_A - V_\phi}{R_S + R_F} = \frac{5 - 0.3}{50 + 5} = 85.5 \text{ mA}$$

I_D for the Three Different Diode Circuit Models

	Example 1.2	Example 1.3	Example 1.4
	1.2 Ideal Diode Model	Ideal Diode Model with Barrier Potential Voltage	Ideal Diode Model with Barrier Potential and Linear Forward Resistance
I_D	100 mA	94 mA	85.5 mA

Diode Load Line Analysis



Diode circuit

From Kirchoff's Voltage Law (KVL),

$$V_{ss} = I_D R + V_D$$

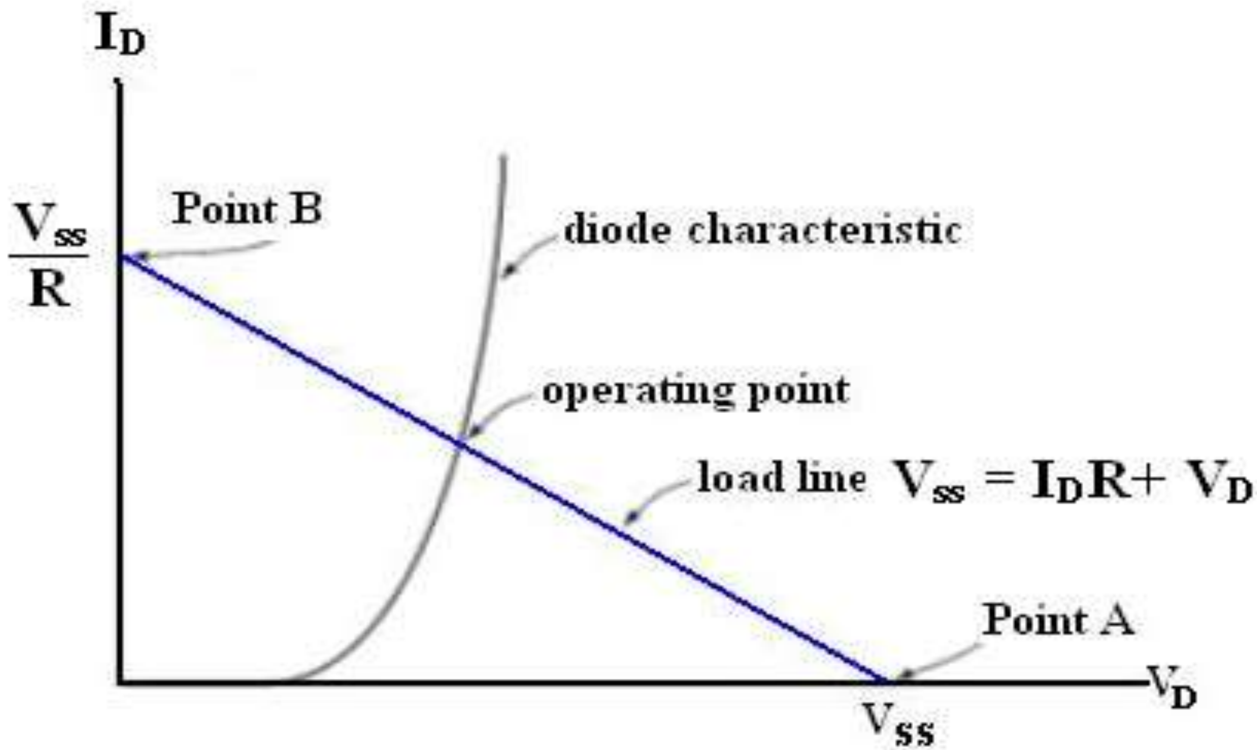
Plot this equation to I_D-V_D graph

Diode Characteristic and Load Line

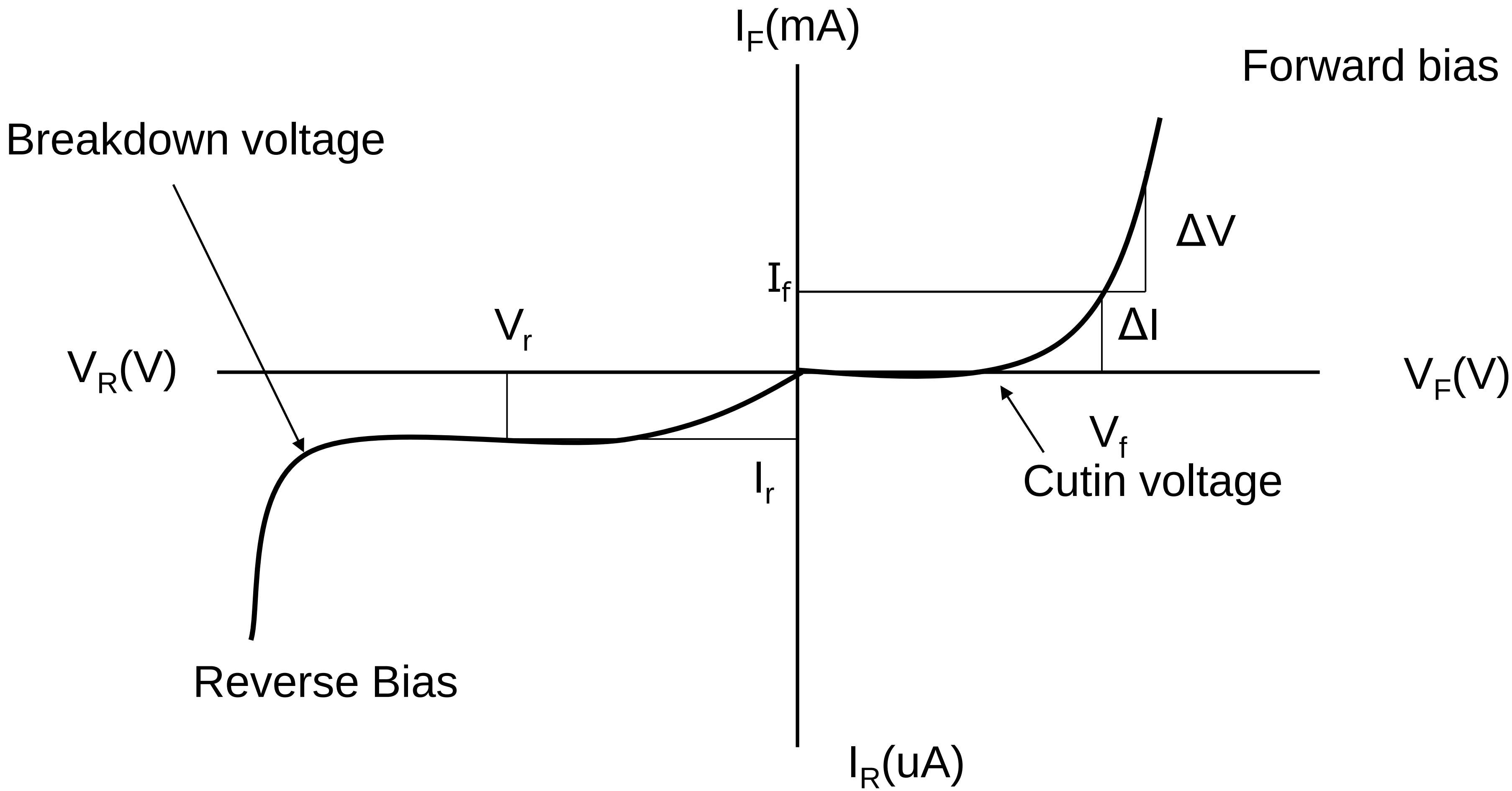
$$V_{ss} = I_D R + V_D$$

If $I_D=0$, $V_D=V_{ss}$

If $V_D=0$, $I_D=V_{ss}/R$



Resistance Calculation



Forward Resistance

1. Dynamic resistance (r_f)= $\Delta V / \Delta I$ Ω.

   Where ΔV, ΔI are incremental voltage and current values on Forward characteristics

2. Static resistance (R_f)= V_f / I_f Ω.

   Where $V_{f,}$ I_f are voltage and current values on Forward characteristics.

Reverse Resistance

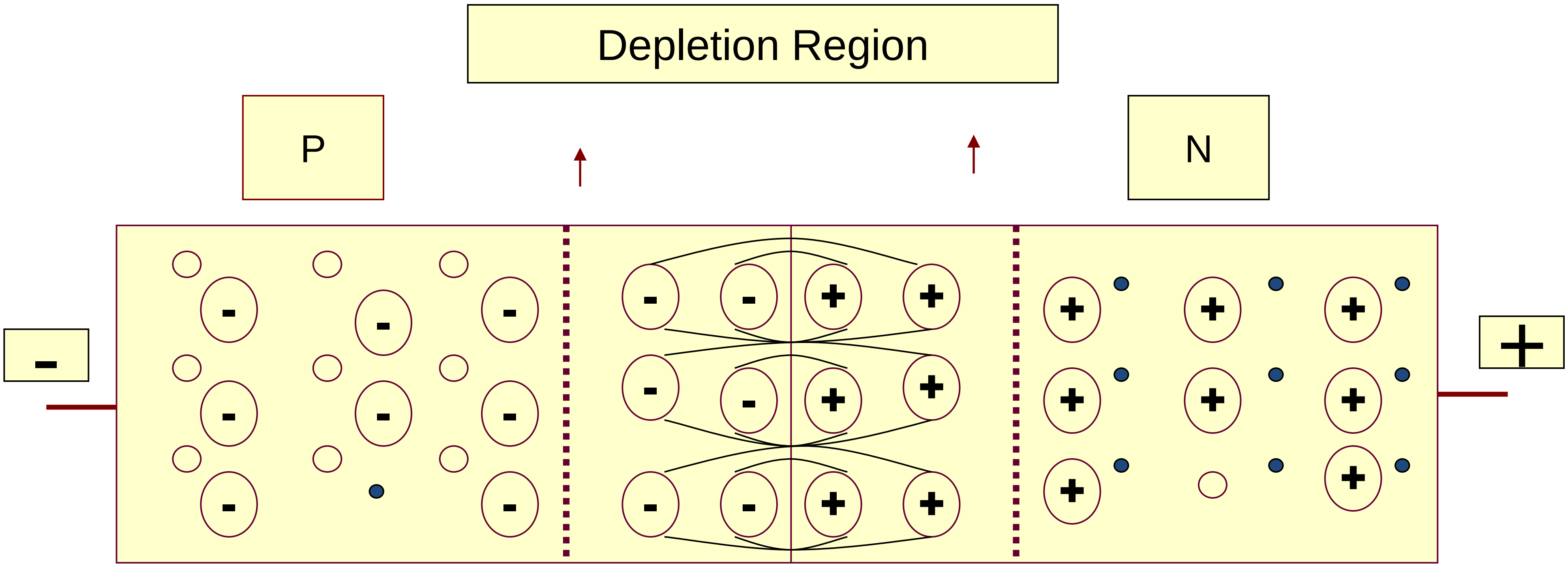
- Static resistance (R_r) = V_r / I_r Ω

  Where V_r, I_r are voltage and current values on Reverse characteristics.

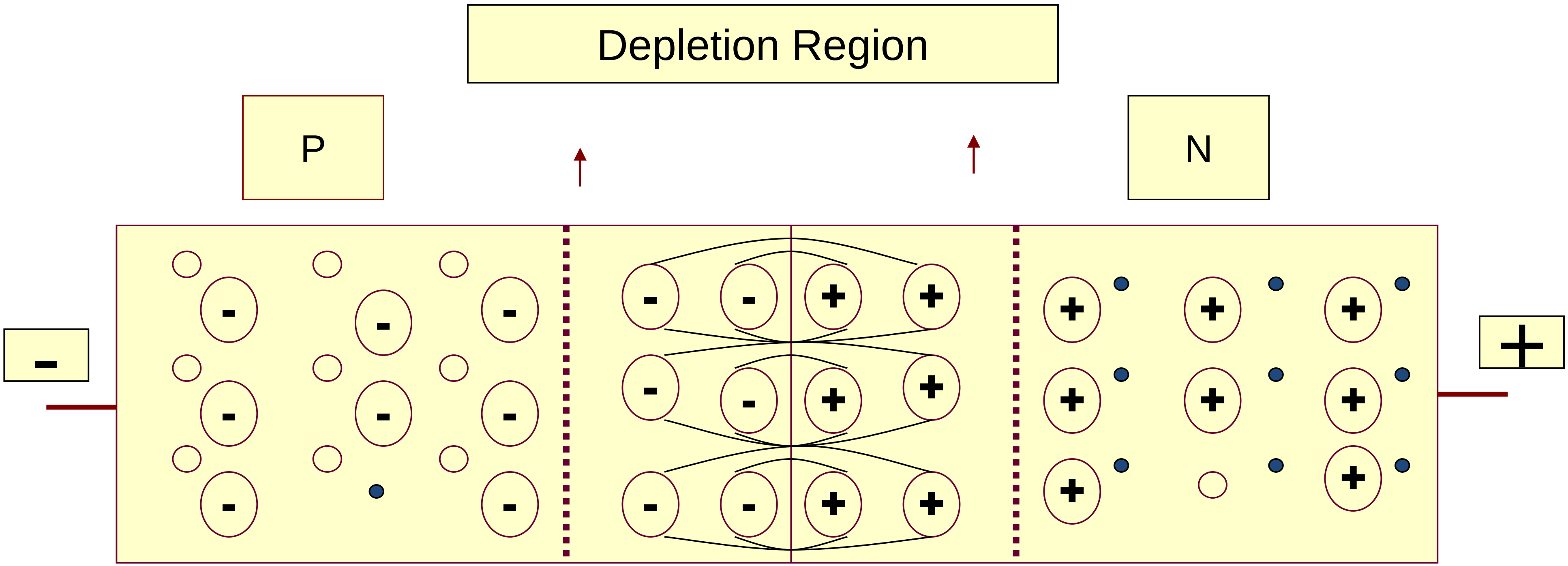
Zener Break Down

- Break down in Zener Diode.
- In heavily doped diode field intensity is more at junction.
- Applied reverse voltage setup strong electric field.
- Thin depletion region in Zener diode.
- Applied field enough to break covalent bonds in the depletion region.
- Extremely large number of electrons and holes results.
- Produces large reverse current.
- Known as Zener Current I_Z.
- This effect is called “Ionization by an Electric field”.

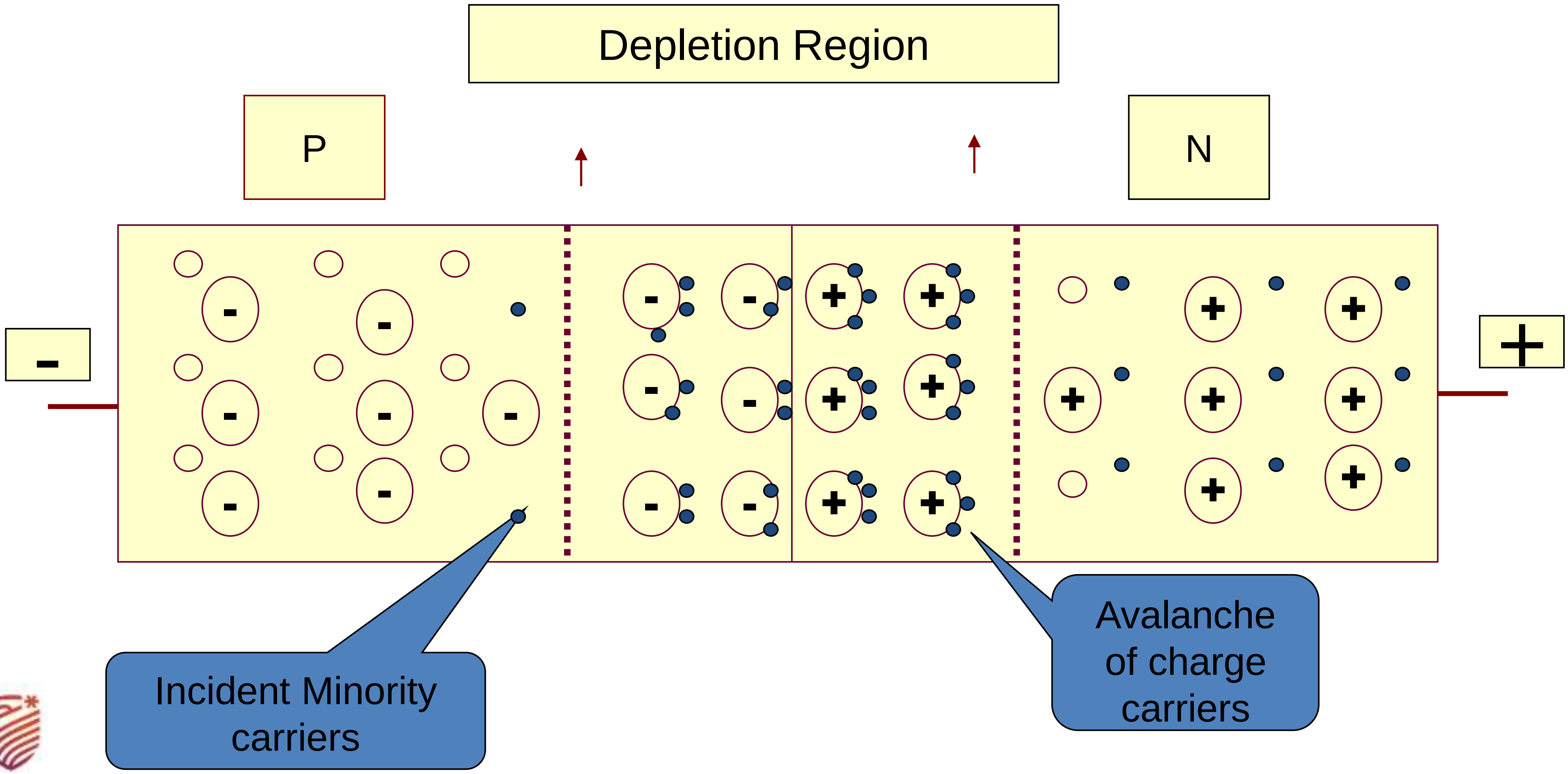
Zener Break Down Mechanism



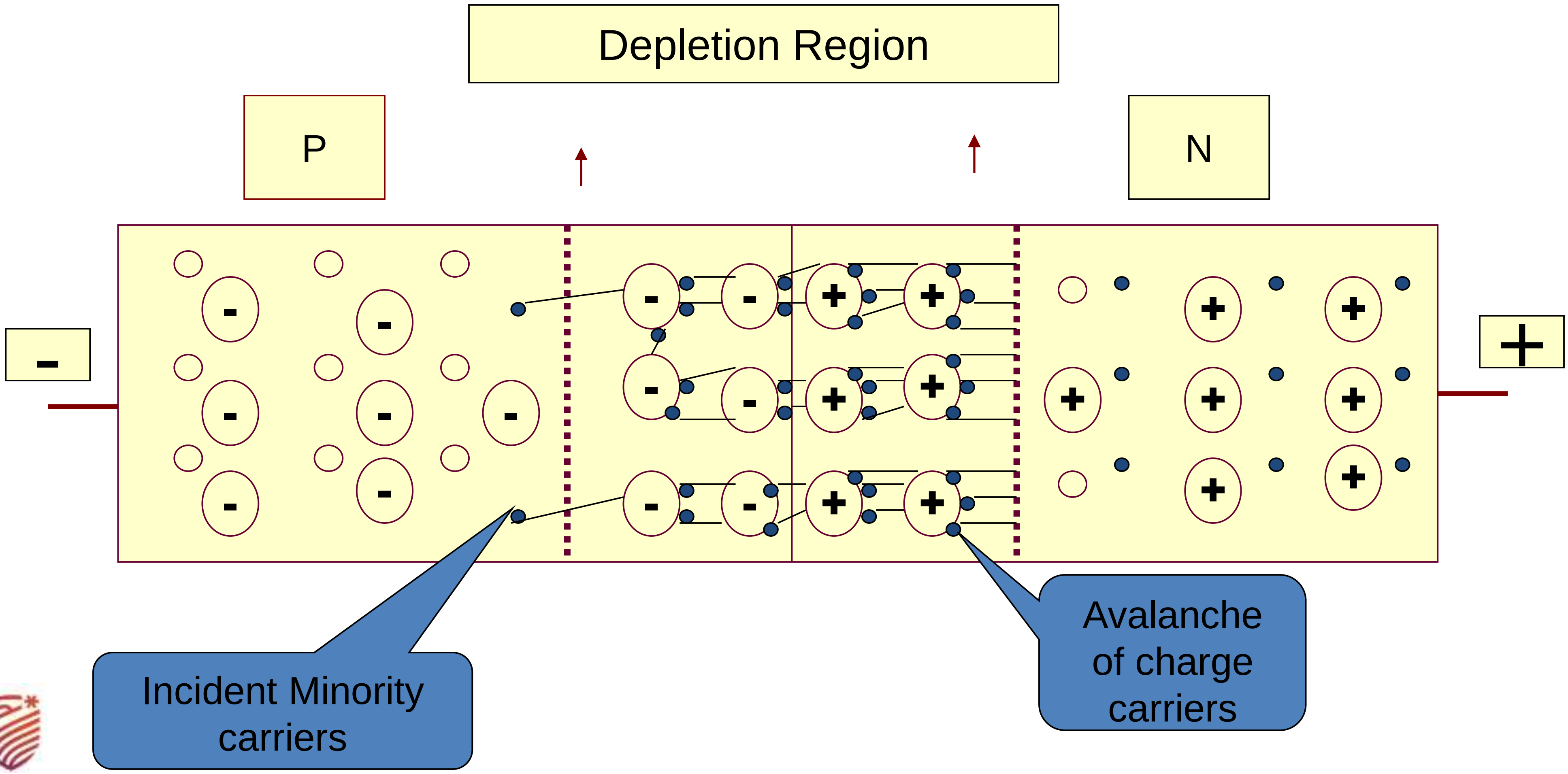
Zener Break Down Mechanism continued..



Avalanche Break Down Mechanism



Avalanche Break Down Mechanism Continued..



Differences Between Zener & Avalanche Breakdowns

Zener break down

1. Occurs in heavily doped diodes.
2. Ionization takes place by electric field.
3. Occurs even with less than 5V.
4. After the breakdown voltage across the Zener diode is constant.

Avalanche break down

1. Occurs in lightly doped diodes.
2. Ionization takes place by collisions.
3. Occurs at higher voltages.
4. After breakdown voltage across the p-n diode is not constant.

Summary

- Diode allows current flow only in one direction.
- Barrier potential voltage is the voltage at which appreciable current starts to flow in a diode
- Diode model with barrier potential and forward resistance is the accurate diode model.
- In FB diode current increases exponentially.
- Zener break down occurs in heavily doped diodes
- Avalanche break down occurs at a higher voltages.

Half Wave Rectifier

- At the end of this lecture, student will be able to :
  - Define rectification
  - Illustrate need for rectifiers
  - Explain the working of half wave rectifier

Topics

- Rectifiers
- Half wave rectifier circuit diagram
- Half wave rectifier waveforms
- Half wave rectifier working

Rectifiers

Rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which is in only one direction, a process known as rectification.

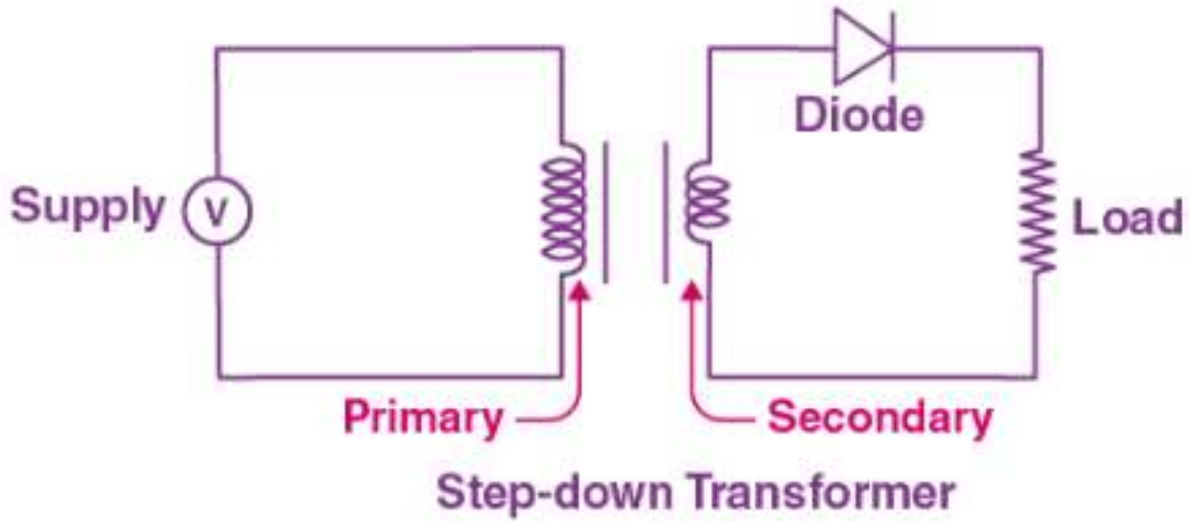
Types of Rectifiers

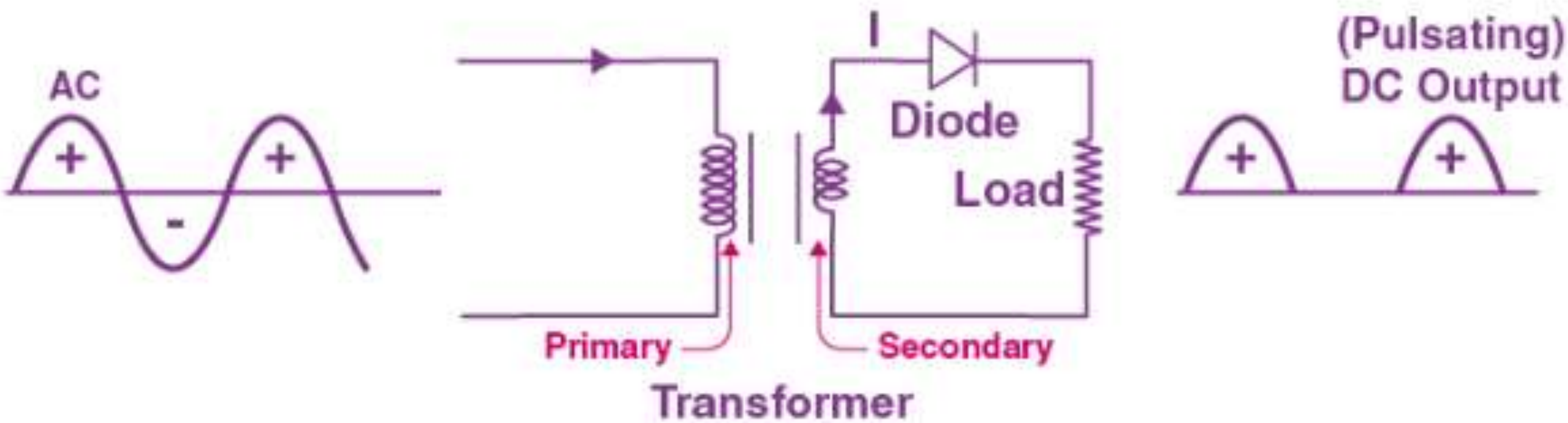
- Half wave Rectifier
- Full wave Rectifier
- Bridge Rectifier

Half Wave Rectifier

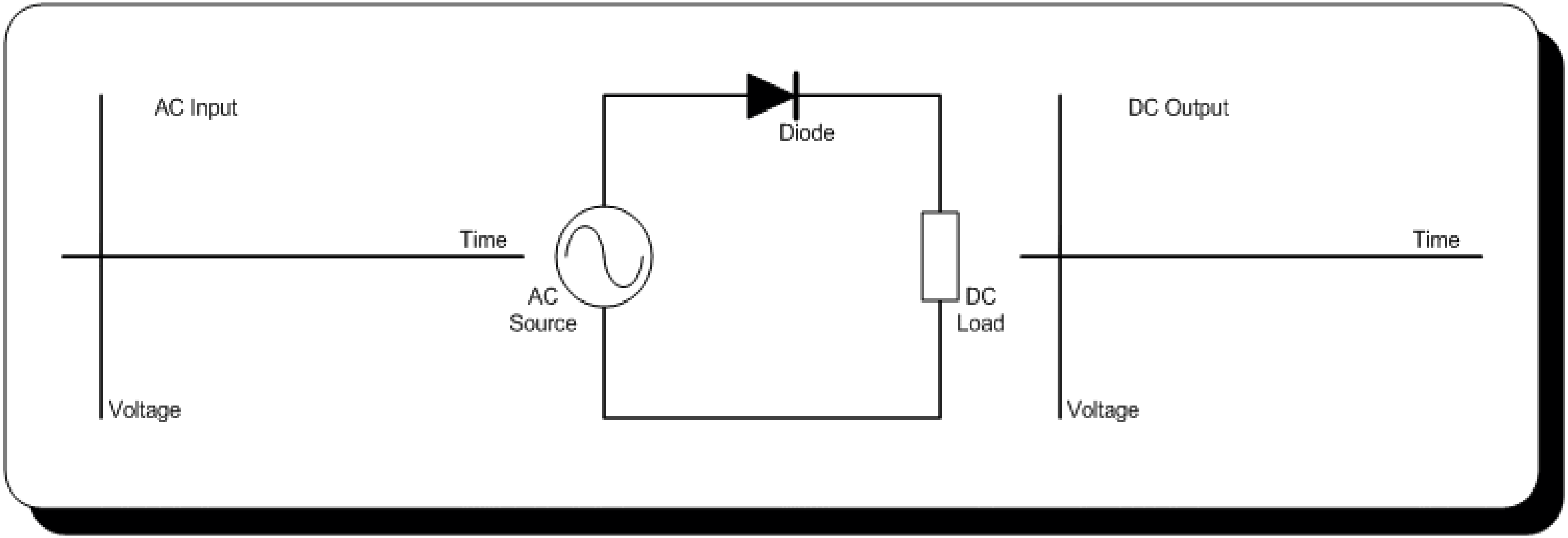
- A half wave rectifier is defined as a type of rectifier that allows only one-half cycle of an AC voltage waveform to pass while blocking the other half cycle.
- In half wave rectification, either the positive or negative half of the AC wave is passed, while the other half is blocked.
- Since only one half of the input waveform reaches the output, it is very inefficient if used for power transfer.

Half Wave Rectification

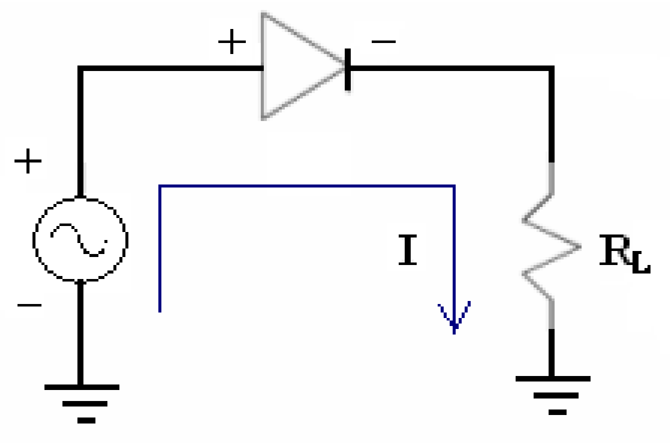


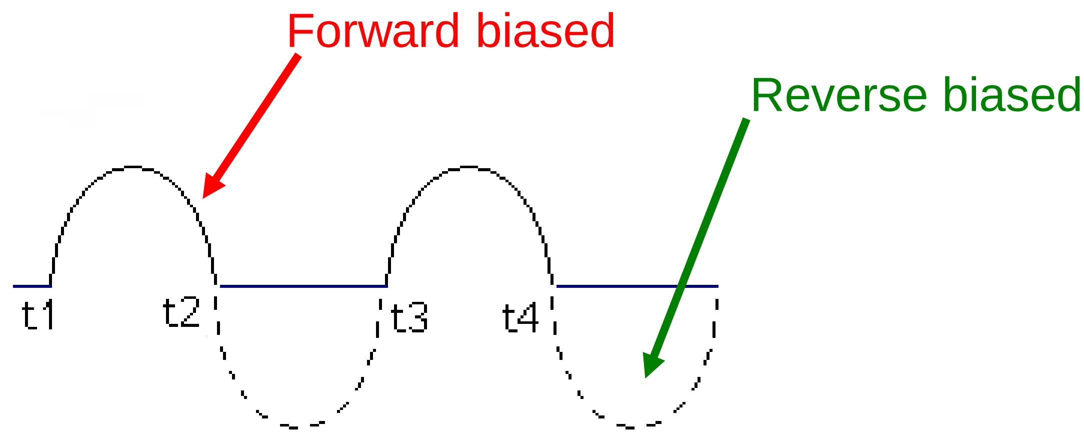


Working of Half Wave Rectifier

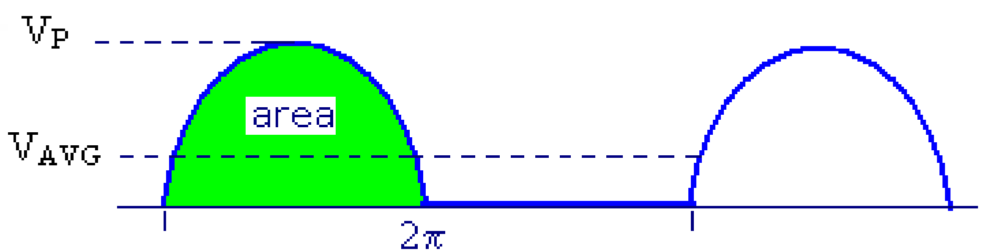


Output DC Voltage of HWR





Average value:



$$V_{AVG} = \frac{V_P}{\pi}$$

Half Wave Rectifier Analysis

- Peak Inverse Voltage(PIV)
  - Maximum voltage a rectifying diode can withstand during the reverse bias period.
  - PIV of half wave rectifier=V_M

Output DC Voltage/Average Voltage

- The average voltage is a measure of the efficiency of the rectifier circuit
- The "straight line" dc equivalent of the pulsating dc created by half wave rectification
- The value you would measure on a dc voltmeter

Output DC Voltage/Average Voltage Continued ..

$$V_{ave} = \int_0^T v_o.dt = \int_0^{T/2} V_m \sin(\omega t).dt + \int_{T/2}^T 0.dt$$

$$= \frac{2V_m}{\omega T}\left[\cos 0 - \cos\frac{\omega T}{2}\right] = \frac{2V_m}{2\pi}[\cos 0 - \cos \pi]$$

$$\text{Or,} \quad V_{ave} = \frac{V_m}{\pi}$$

- **Average Load current**

$$I_L = \frac{V_{ave}}{R_L}$$

Root Mean Square (RMS) Voltage

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{\pi} V_m^{\,2}\sin^2\omega t\, d(\omega t)\right]^{1/2}$$

$$= V_m\left[\frac{1}{4\pi}\int_0^{\pi}(1-\cos 2\omega t)\, d(\omega t)\right]^{1/2} = \frac{V_m}{2}$$

$V_{rms} = V_m/2$

Ripple Factor

- Ripple factor determines how well a half wave rectifier can convert AC voltage to DC voltage
- It is the ratio of RMS value of ac component to the dc component in the output.

Ripple factor $r = \dfrac{RMS\ value\ of\ the\ ac\ componen.}{dc\ value\ of\ the\ component}$

$$\gamma = \frac{Vr_{rms}}{V_{dc}}$$

$$V\gamma_{rms} = \sqrt{V_{rms}^{\ 2} - V_{dc}^{\ 2}}$$

$$r = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

$$r = \sqrt{\left(\frac{V_m/2}{V_m/\pi}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2} = \underline{\underline{1.21}}$$

Efficiency (η)

η is the ratio of DC output power to AC input power

$$\eta = \frac{dc\ output\ power}{ac\ input\ power} = \frac{P_{dc}}{P_{ac}}$$

$$\frac{V_{dc}^{2}/R_L}{V_{rms}^{2}/R_L} = \frac{\left[V_m/\pi\right]^2}{\left[V_m/2\right]^2} = 4/\pi^2 = 0.406 = \underline{\underline{40.6\%}}$$

Form Factor

- The form factor is the ratio between RMS value and average value and is given by the formula

$$Form\ factor = \frac{rms\ value}{average\ value}$$

$$= \frac{\left(V_m \big/ 2 \right)}{\left(V_m \big/ \pi \right)} = \frac{\pi}{2} = \underline{\underline{1.57}}$$

Transformer Utilization Factor

$$TUF = \frac{P_{dc}}{P_{ac\ rated}}$$

$$TUF = \frac{\left(\frac{I_m^2}{\pi^2}R_L\right)}{\left(\frac{V_m}{\sqrt{2}}\frac{I_m}{2}\right)} = \frac{\left(\frac{V_m^2}{\pi^2}\frac{1}{R_L}\right)}{\left(\frac{V_m}{\sqrt{2}}\frac{V_m}{2R_L}\right)} = \frac{2\sqrt{2}}{\pi^2} = \underline{\underline{0.287}}$$

Advantages of Half Wave Rectifier

- Cheep
- Simple
- Easy to construct

Disadvantages of Half Wave Rectifier

- Ripple factor is high and an elaborate filtering is required to give steady dc output.

- The power output and rectification efficiency is quite low. This is due to the fact that power is delivered only during one half cycle of the input alternating voltage.

- Transformer utilization factor is low

- DC saturation of transformer core resulting in magnetizing current and hysteresis losses and generation of harmonics.

Summary

- A rectifier converts AC signal to DC signal
- In half wave rectifier only one half of the input waveform reaches the output.
- A HWR is cheep, simple and easy to construct.
- RMS voltage of HWR is $V_m/2$
- Average value of voltage in a HWR is V_m/π
- Efficiency of a HWR is only 40.6%

Full Wave and Bridge Rectifiers

- At the end of this lecture, student will be able to :
  - Explain the working of centre tapped full wave rectifier
  - Explain the working of bridge rectifier

Topics

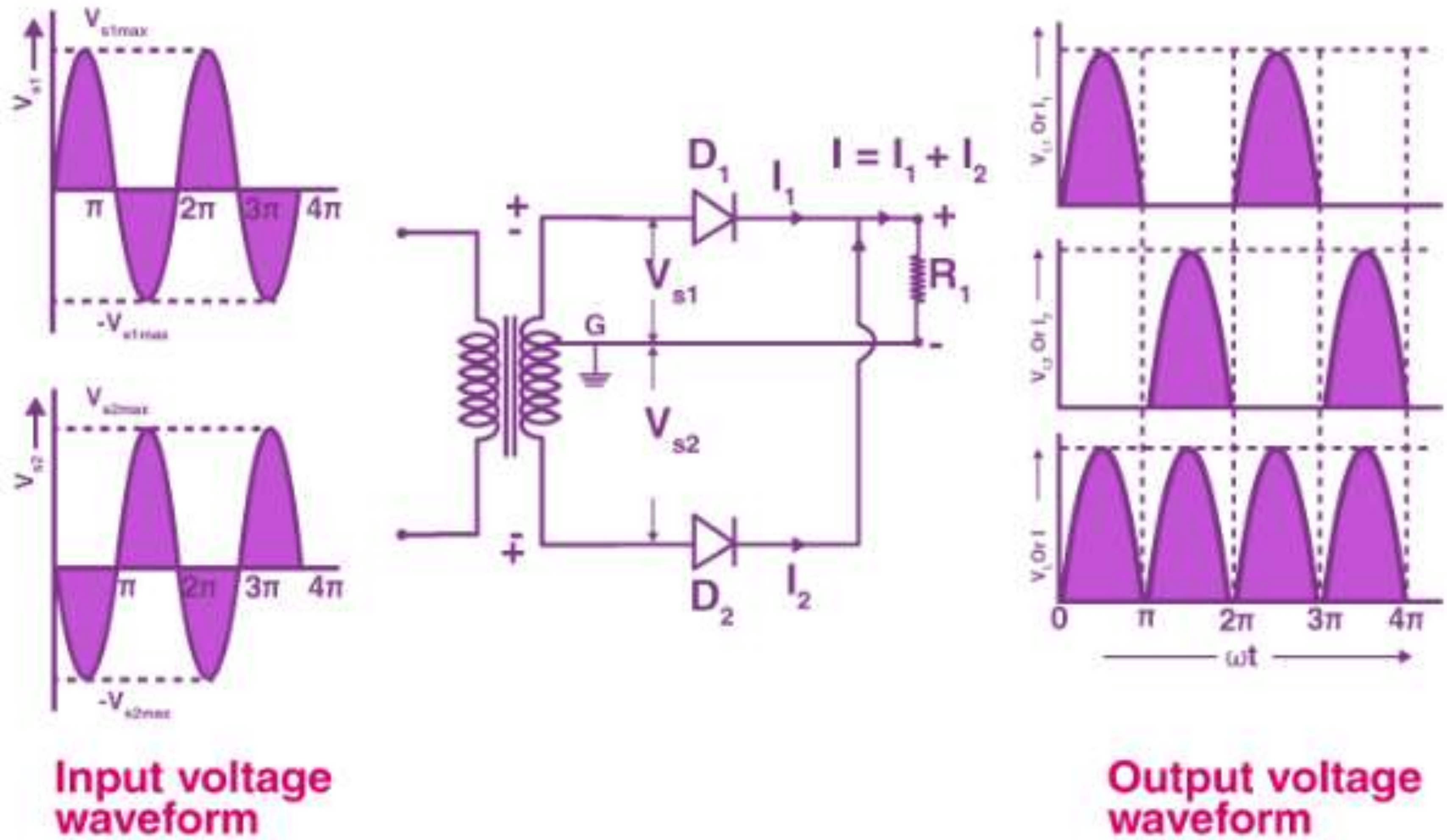
- Full wave rectifier-Circuit diagram and working
- Bridge rectifier-Circuit diagram and working

Full Wave Rectifier

- A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output.

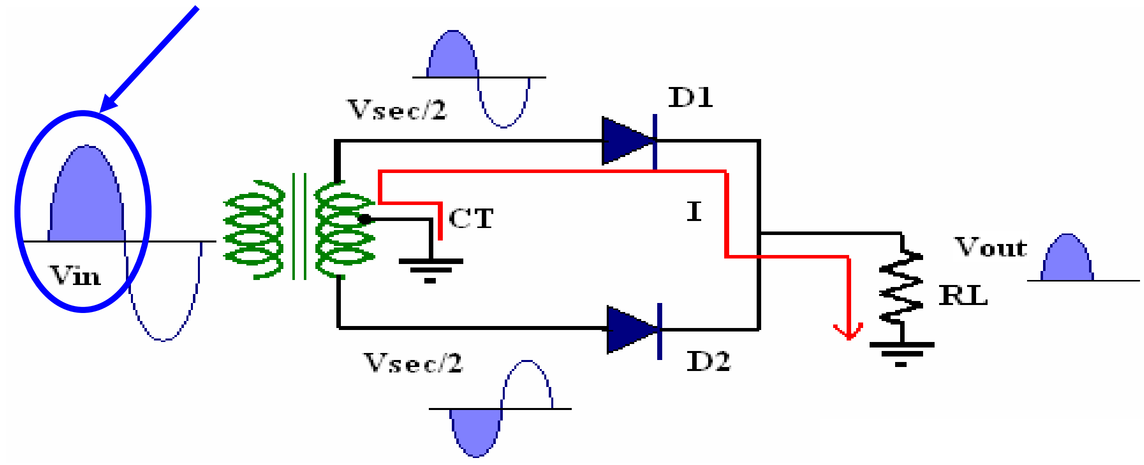
- Full-wave rectification converts both polarities of the input waveform to DC (direct current), and is more efficient.

Full Wave Rectifier Using Two Diodes

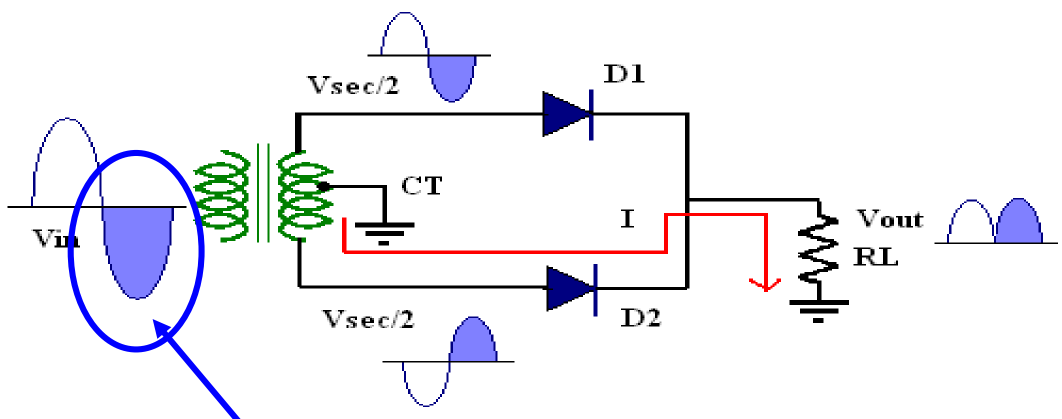


Centre tapped Full-wave Rectifier

Positive half-cycle



(a)



Negative half-cycle

(b)

Full Wave Rectifier Analysis

- **Peak Inverse Voltage(PIV).**
  - PIV of Full wave rectifier=$2V_M$

- **DC/ average voltage**
  - Average voltage of Full wave rectifier

$$V_{ave} = \frac{2V_m}{\pi}$$

Full Wave Rectifier Analysis Continued ..

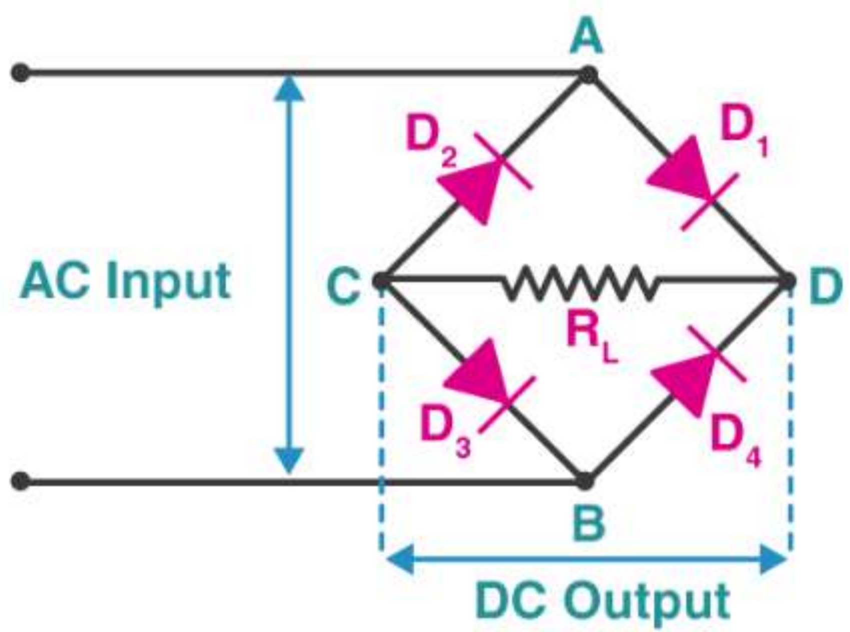
- **RMS voltage**
  - V_{rms} of full wave rectifier= $\frac{V_M}{\sqrt{2}}$
- **Ripple factor**
  - Ripple factor of full wave rectifier= 0.48
- **Efficiency**
  - Efficiency of full wave rectifier= 81.2%

Full Wave Rectifier Analysis Continued ..

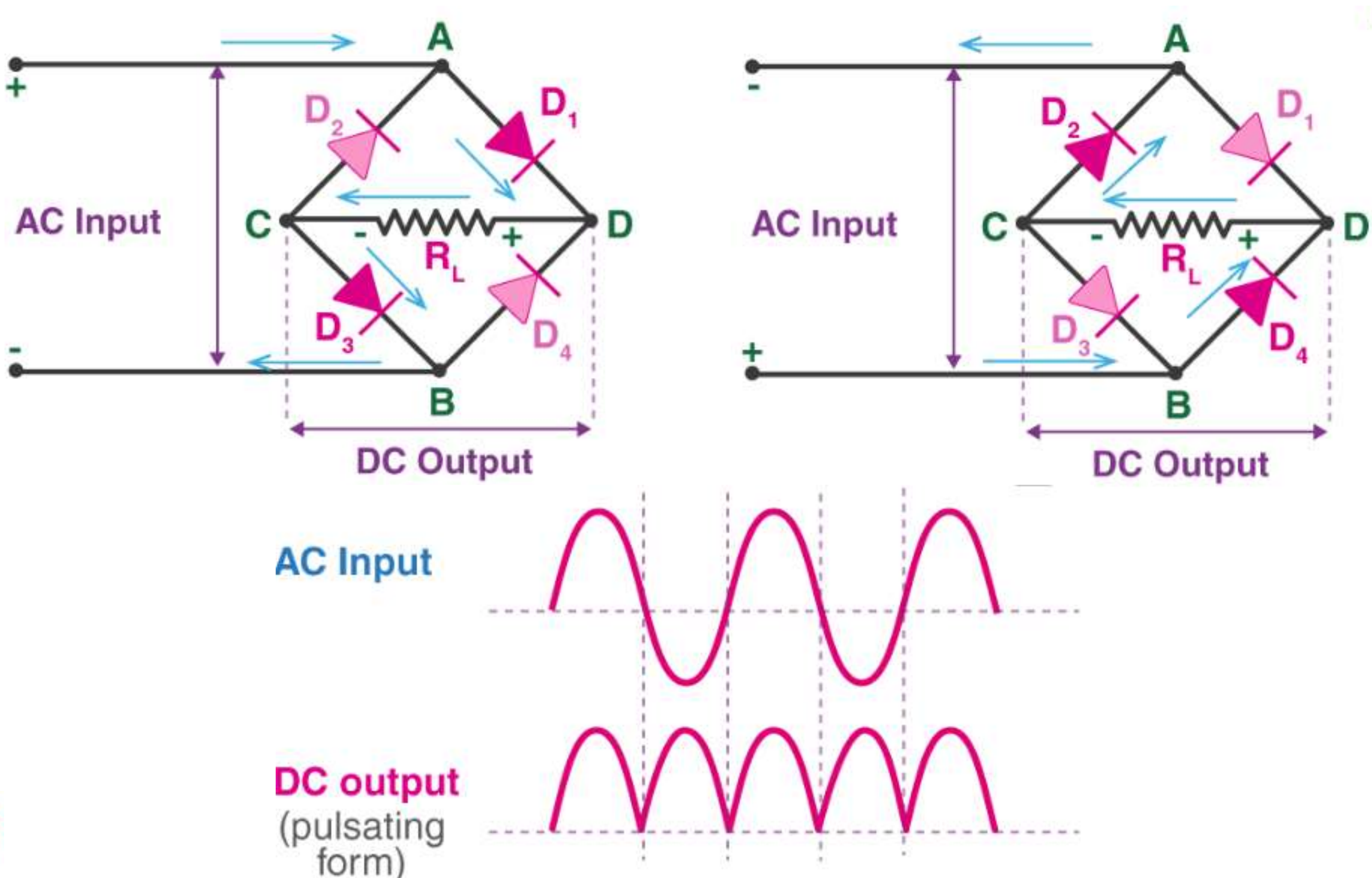
- **Form factor**
  - Form factor of full wave rectifier = 1.11
- **Transformer Utilization factor**
  - Transformer Utilization factor of full wave rectifier= 0.693

Bridge Rectifier

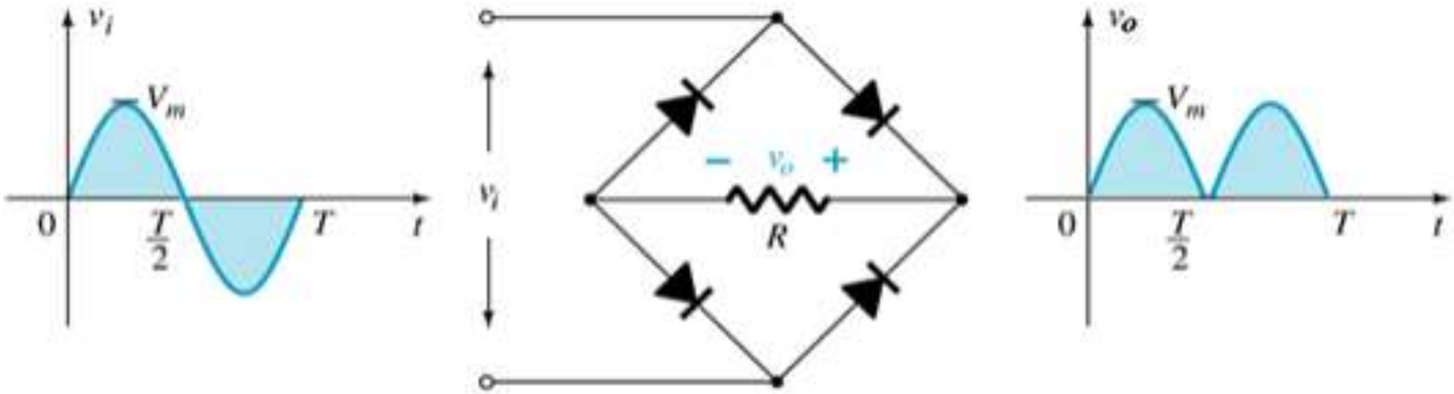
- The bridge rectifier circuit is made of four diodes D_1, D_2, D_3, $D_{4,}$ and a load resistor R_L
- The four diodes are connected in a closed-loop configuration to efficiently convert the alternating current (AC) into Direct Current (DC).

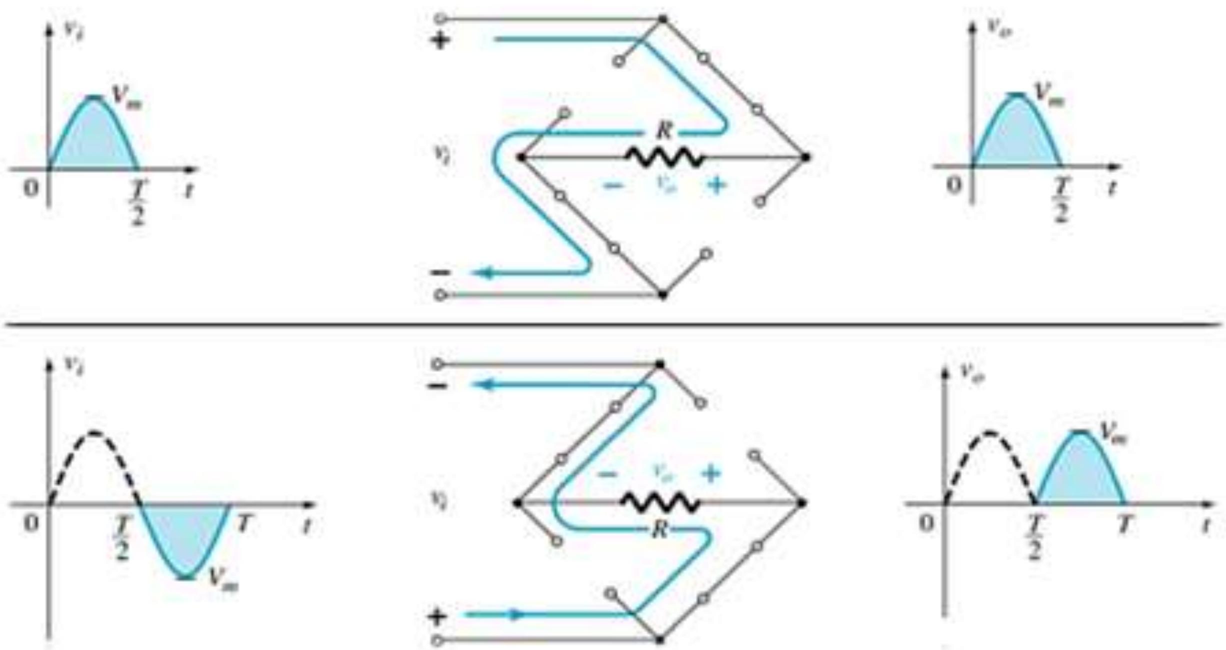


Bridge Rectifier Working

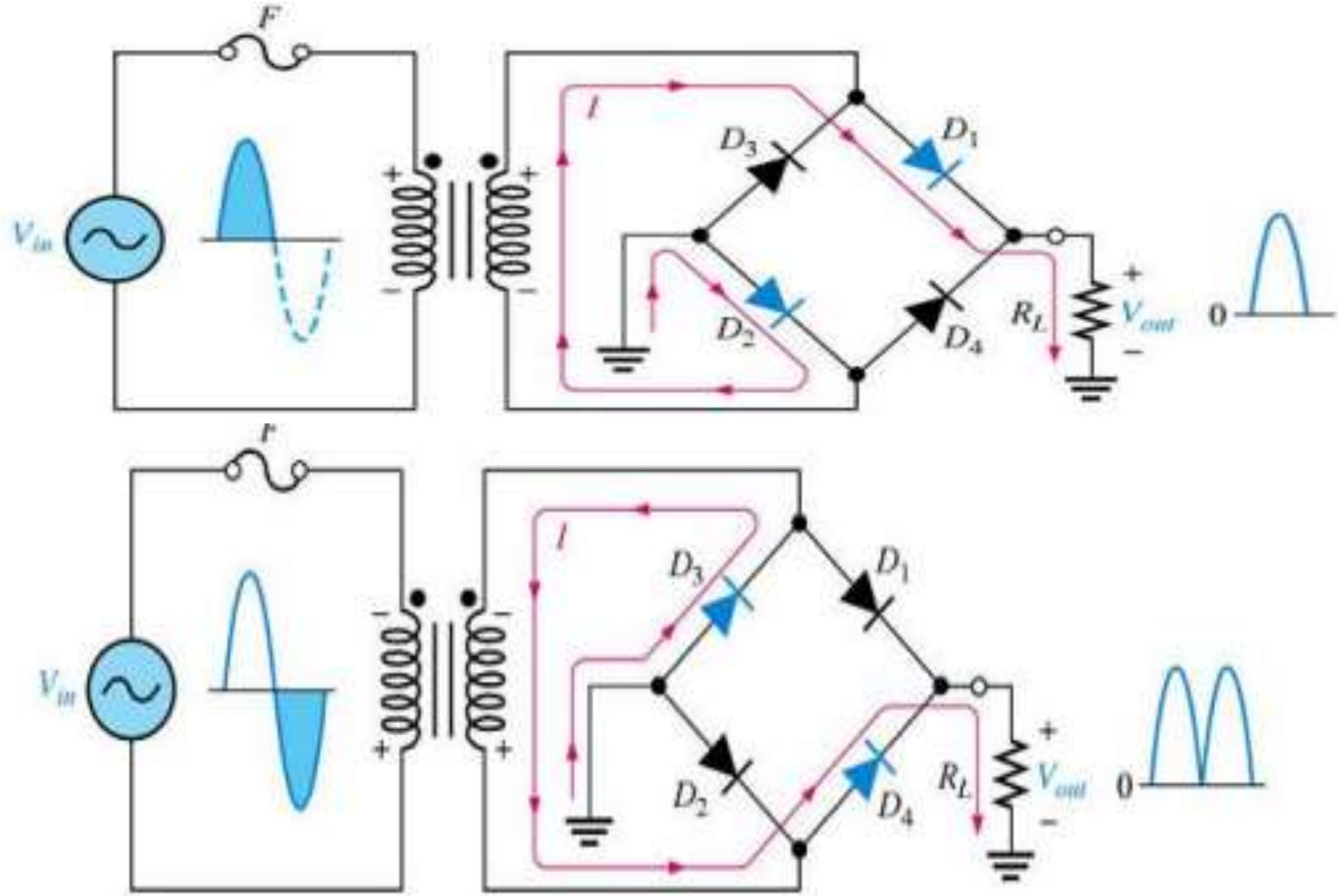


Bridge Rectifier Working





Bridge Rectifier Working Continued..



Bridge Rectifier with transformer

Bridge Rectifier Analysis

- **Peak Inverse Voltage(PIV).**
  - PIV of bridge rectifier=V_M

- **DC/ average voltage**
  - Average voltage of bridge rectifier

$$V_{ave} = \frac{2V_m}{\pi}$$

Bridge Rectifier analysis continued ..

- **RMS voltage**
  - V_{rms} of Bridge rectifier=$\frac{V_M}{\sqrt{2}}$
- **Ripple factor**
  - Ripple factor of Bridge rectifier= 0.48
- **Efficiency**
  - Efficiency of Bridge rectifier= 81.2%

Bridge Rectifier Analysis Continued ..

- **Form factor**
  - Form factor of full wave rectifier=1.11
- **Transformer Utilization factor**
  - Transformer Utilization factor of full wave rectifier= 0.812

Advantages of Full Wave Rectifier

- Efficiency is high
- Ripple factor is very less
- TUF is high

Disadvantages of Full Wave Rectifier

- More components used
- Bulky
- Cost is high

Rectifier Comparison

Parameter	*HWR*	*FWR-CT*	*FWR-bridge*
$V_{OUT\ DC}$	V_{max}/π	$2V_{max}/\pi$	$2V_{max}/\pi$
$V_{OUT\ RMS}$	$V_{max}/2$	$V_{max}/\sqrt{2}$	$V_{max}/\sqrt{2}$
PIV	V_{max}	$2V_{max}$	V_{max}
γ	1.21	0.48	0.48
η_{max}	40.6%	81.2%	81.2%
No. of diodes	1	2	4

Summary

- Full wave rectifier uses centre tapped transformer and two diodes.
- RMS voltage of FWR is $V_m/\sqrt{2}$
- Average value of voltage in a HWR is $2V_m/\pi$
- Efficiency of a HWR is only 81.2%
- Full wave rectifier with 4 diodes is known as bridge rectifier.
- PIV of full wave rectifier with centre tap is $2V_{m.}$
- PIV of bridge rectifier is V_m