DEPARTMENT OF

ELECTRONICS AND COMMUNICATION ENGINEERING

ELECTRONIC DEVICES AND CIRCUITS

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COURSE OBJECTIVES

◉

- To acquire fundamental knowledge and expose to the field of semiconductor theory and devices and their applications.
- To introduce different types of semiconductor devices, viz., diodes and special diodes.
- To explain application of diodes as rectifiers, clippers, clampers and regulators.
- To describe operation and characteristics of Bipolar Junction Transistor& Field Effect Transistor.
- To analyze the various biasing circuits using BJTs & FETs.

Course Outcomes

- After the completion of the course students will able to
- **CO1: Understand principle, operation, characteristics and applications of Bipolar Junction**
- Transistor and Field Effect Transistor (L1)
- **CO2: Describe basic operation and characteristics of various semiconductor devices. (L2)**
- **CO3: Analyze diode circuits for different applications such as rectifiers, clippers and clampers**
- also analyze low frequency and high frequency models of BJT and FET. (L3)
- **CO4: Design various biasing circuits for BJT and FET. (L4)**
- **CO5: Compare the performance of various semiconductor devices. (L5)**

SYLLABUS

UNIT-I

SEMICONDUCTOR DIODE

CONTENTS

1. **Semiconductor Diode**
2. Open circuited PN junction,
3. PN junction as a rectifier, Current components in a PN diode,
4. Diode Equation and its mathematical derivation, Volt-Ampere Characteristics,
5. Energy band diagram of PN diode,
6. Temperature dependence of Volt-Ampere Characteristics,
7. Diode resistance (Static and Dynamic resistance),
8. Transition capacitance,
9. Diffusion capacitance, Step graded junction.

- WHAT IS ELECTRONICS

- APPLICATIONS

Atomic Structure

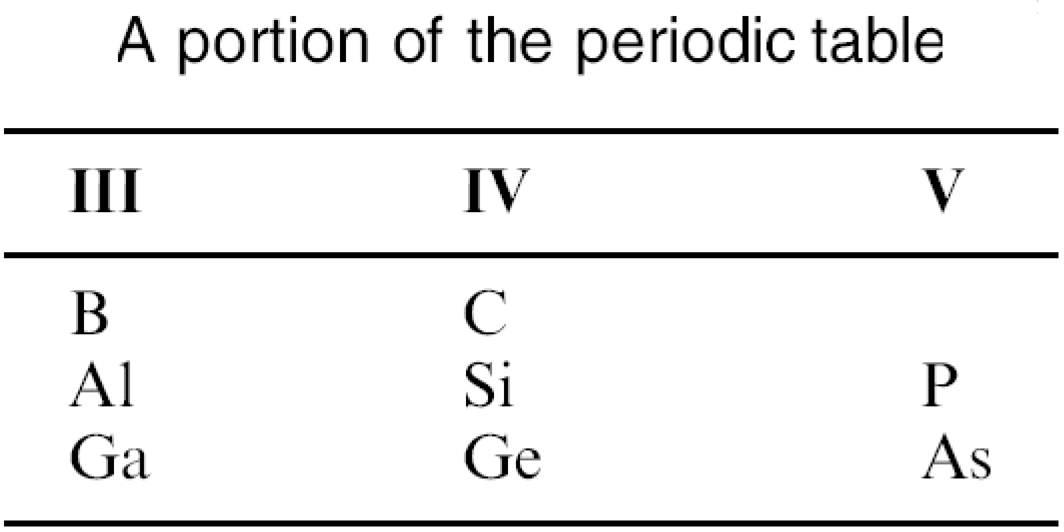
An atom is composed of :

- Nucleus (which contains positively charged protons and neutral neutrons)
- Electrons (which are negatively charged and that orbit the nucleus)

Valence Electrons

- Electrons are distributed in various shells at different distances from nucleus
- Electron energy increases as shell radius increases.
- Electrons in the outermost shell are called valence electrons
- Elements in the period table are grouped according to the number of valence electrons

Valence Electrons



A portion of the periodic table

III	IV	V
B	C	
Al	Si	P
Ga	Ge	As

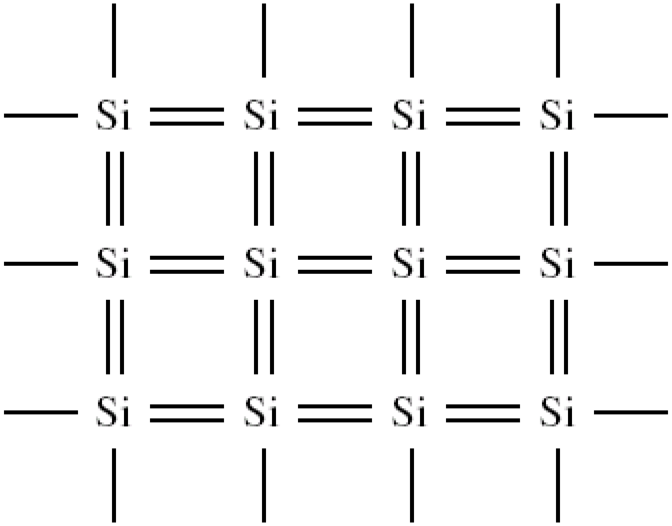
Elemental/Compound Semiconductor

- Silicon (Si) and Germanium (Ge) are in group IV, and are **elemental semiconductors**
- Galium arsenide (GaAs) is a goup III-V **compound semiconductor**

Silicon Crystal

- → At 0°K, each electron is in its lowest possible energy state, and each covalent bounding position is filled.
- →If a small electric field is applied, the electrons will not move → silicon is an **insulator**

Silicon Atom Diagram at 0°K

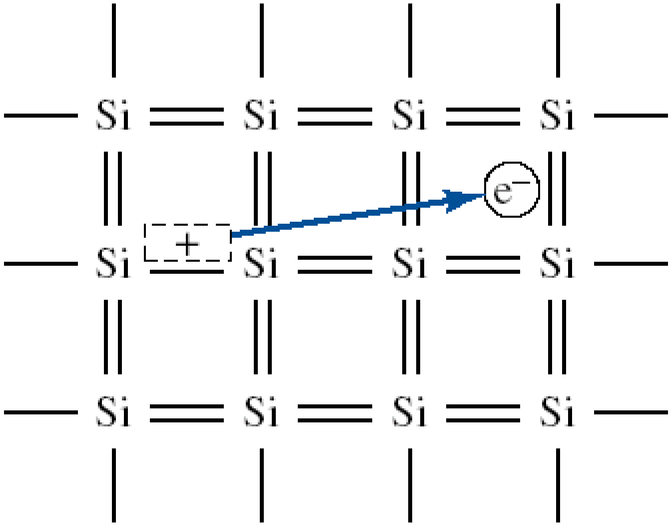


Two-dimensional representation of the silicon crystal at $T = 0\,^{\circ}\mathrm{K}$

Intrinsic Silicon

- → If the temperature increases, the valence electrons will gain some thermal energy, and breaks free from the covalent bond → It leaves a positively charged hole
- → In order to break from the covalent bond, a valence electron must gain a minimun energy ***Eg***: **Bandgap energy**

Silicon Atom Diagram at Ambiant Temp



The breaking of
a covalent bond for $T > 0\,^{\circ}$K

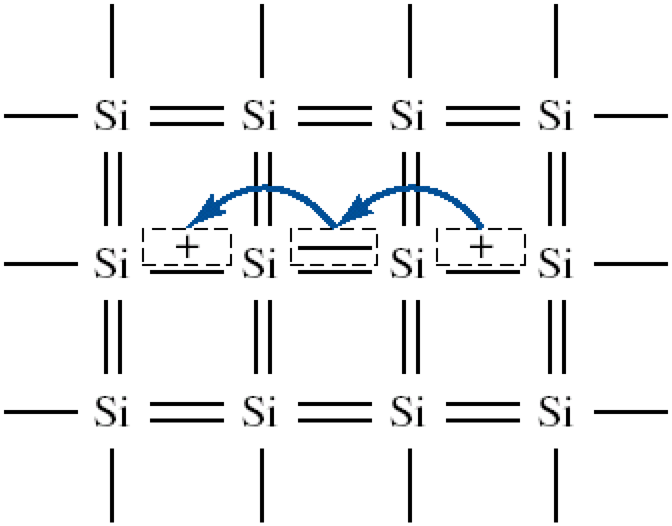
Insulators/Conductors

- Materials that have large bandgap energies (in the range of 3 to 6 electron-volts (eV)) are **insulators**, because at room temperature, essentially no free electron exists in the material
- Materials that contain very large number of free electrons at room temperature are **conductors**

Semiconductors

- → In a semiconductor, the bandgap energy is in the order of 1 eV. The net flow of free electrons causes a current.
- → In a semiconductor, two types of charged particles contribute to the current: the negatively charged electrons and the positively charged holes

Movement of Holes



A two- dimensional representation of the silicon crystal showing the movement of the positively charged hole

Semiconductor Constants

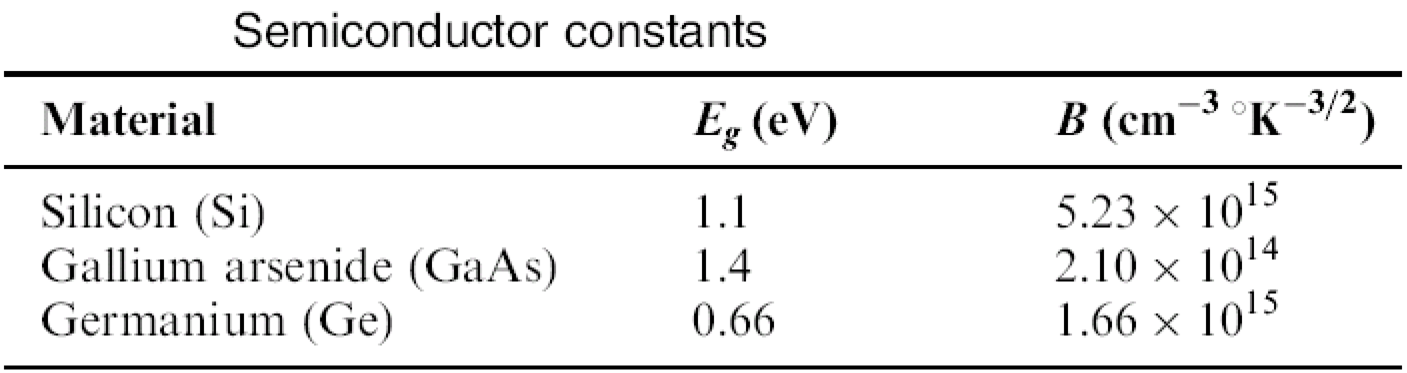
- The concentration of electrons and holes directly influence the magnitde of the current
- In an intrinsic semiconductor (a single crystal semiconductor) the densities of holes and electrons are equal.

ni: intrinsic carrier concentration for free electrons (same for holes)

$$n_i = BT^{3/2} e^{\left(\frac{-E_g}{2kT}\right)}$$

B: constant related to specific semiconductor material
Eg: Bandgap energy (eV)
T: Temperature (°K)
K: Boltzman Constant (86 E-06 eV/°K)

Semiconductor Constants



Semiconductor constants

Material	E_g (eV)	B (cm^{-3} °K$^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

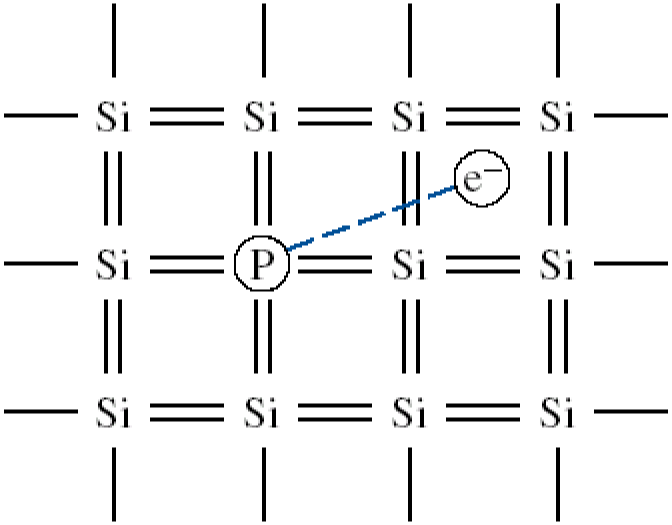
Extrinsic Semiconductor / Doping

- The electron or hole concentration can be greatly increased by adding controlled amounts of certain impurities
- For silicon, it is desirable to use impurities from the group III and V.
- An N-type semiconductor can be created by adding phosphorus or arsenic

Extrinsic Semiconductor/Doping

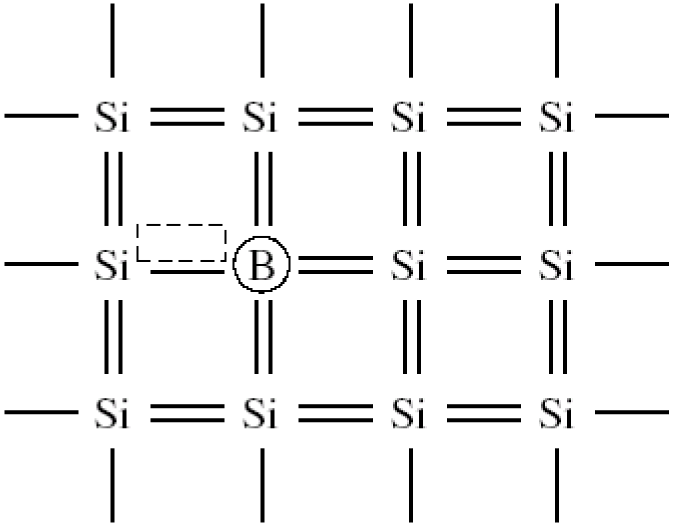
- The phosphorus (group **V**) atom is called **donor impurity** because it donates an electron that is free to move
- The boron (group **III**) has accepted a valence electron (or donated a hole), it is therefore called **acceptor impurity**

N-Type Semiconductor



Two-dimensional representation of a silicon lattice doped with a phosphorus atom

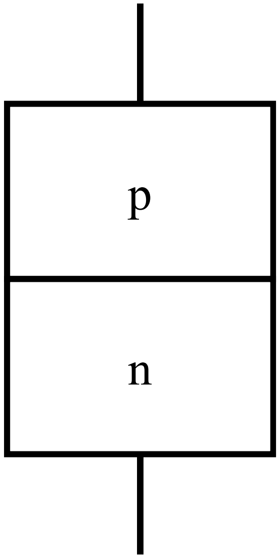
P-Type Semiconductor

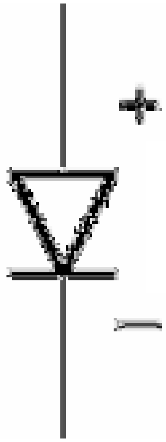


Two-dimensional representation of a silicon lattice doped with a boron atom

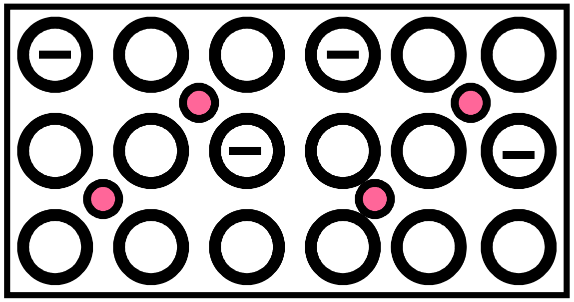
Introduction to Semiconductor Devices

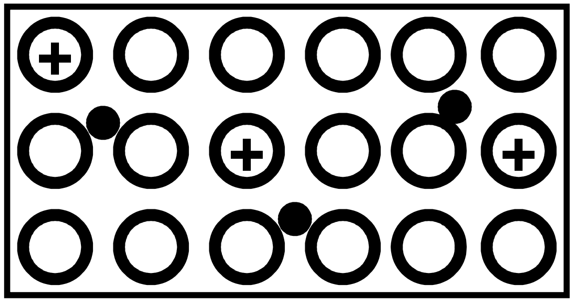
Semiconductor p-n junction diodes





p-n junction formation





p-type material

Semiconductor material doped with **acceptors**.

Material has high hole concentration

Concentration of free electrons in p-type material is very low.

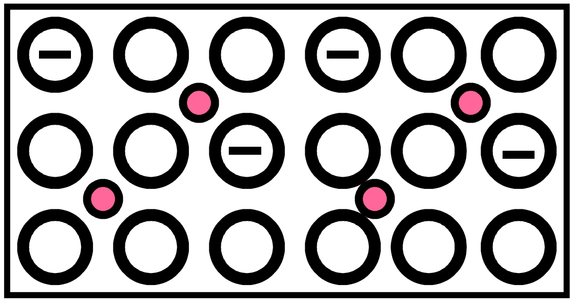
n-type material

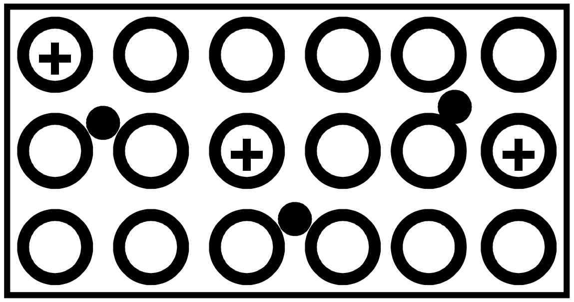
Semiconductor material doped with **donors**.

Material has high concentration of free electrons.

Concentration of holes in n-type material is very low.

p-n junction formation





p-type material

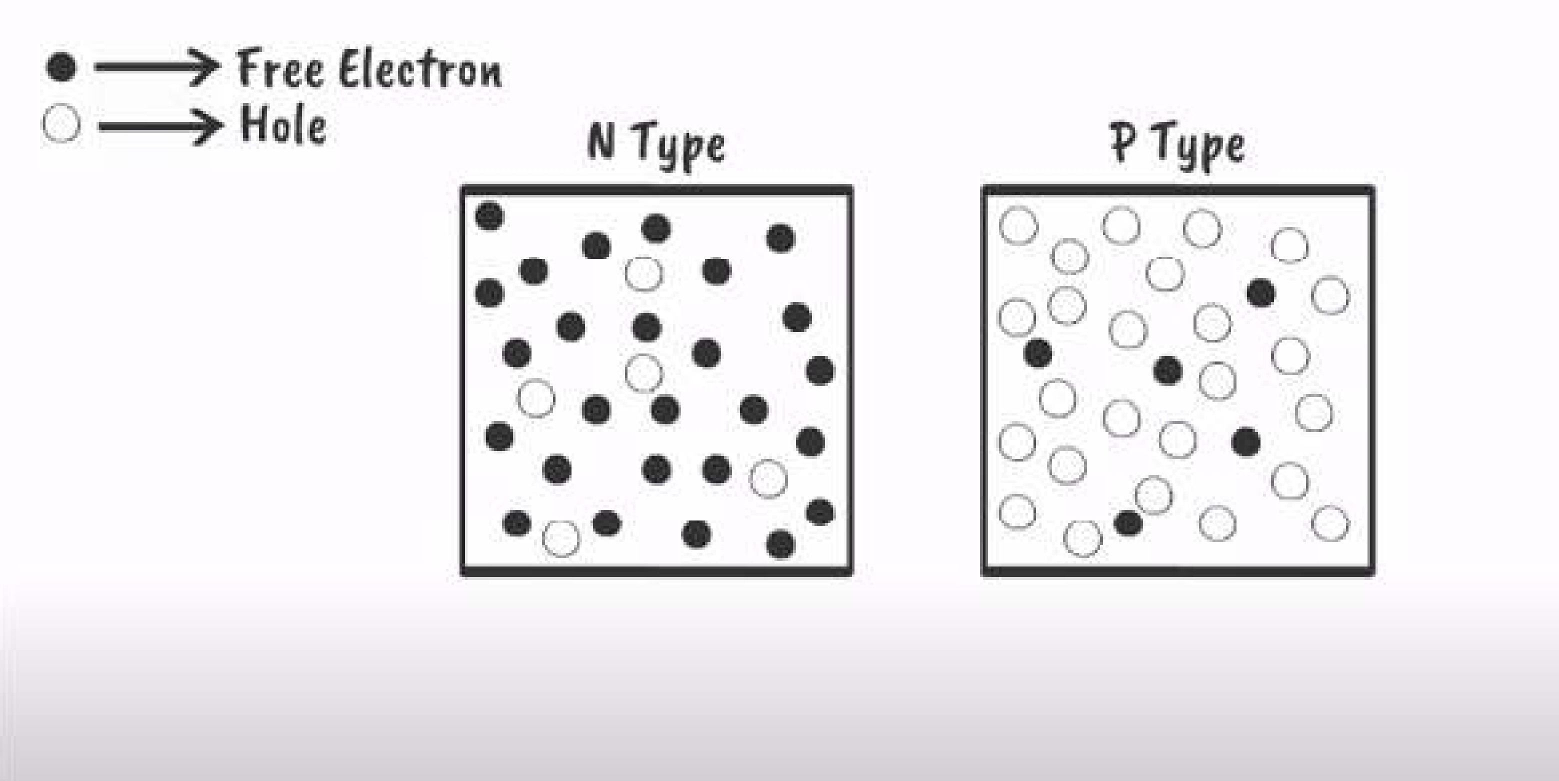
Contains NEGATIVELY charged acceptors (immovable) and POSITIVELY charged holes (free).

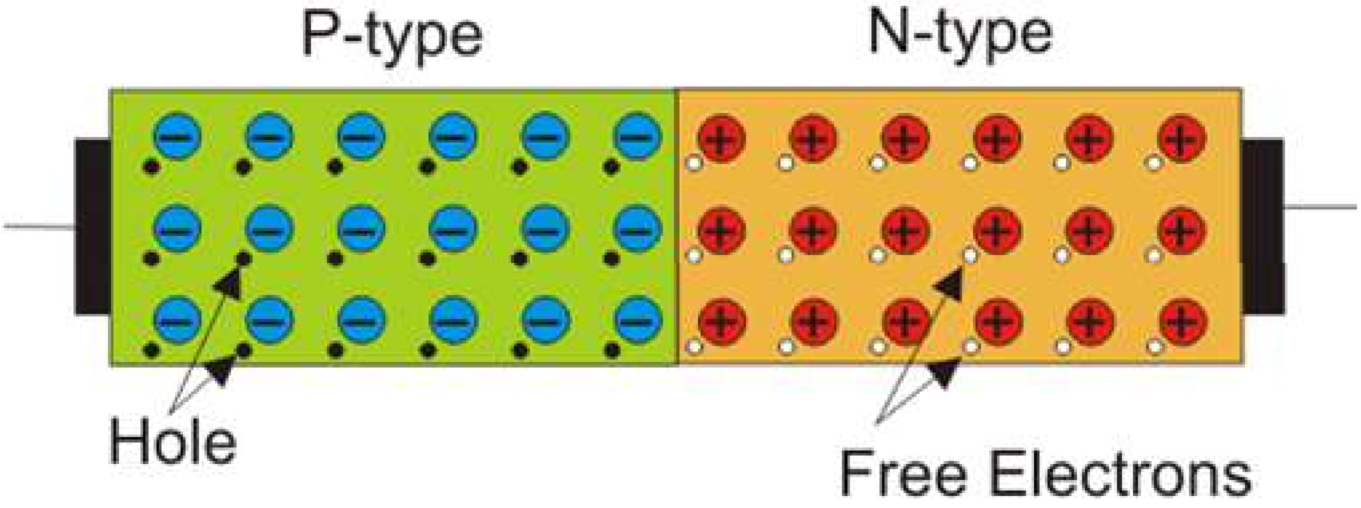
Total charge = 0

n-type material

Contains POSITIVELY charged donors (immovable) and NEGATIVELY charged free electrons.

Total charge = 0

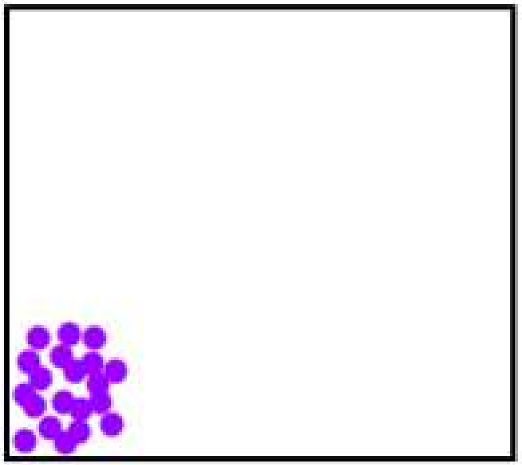

● → Free Electron
○ → Hole
N Type
P Type

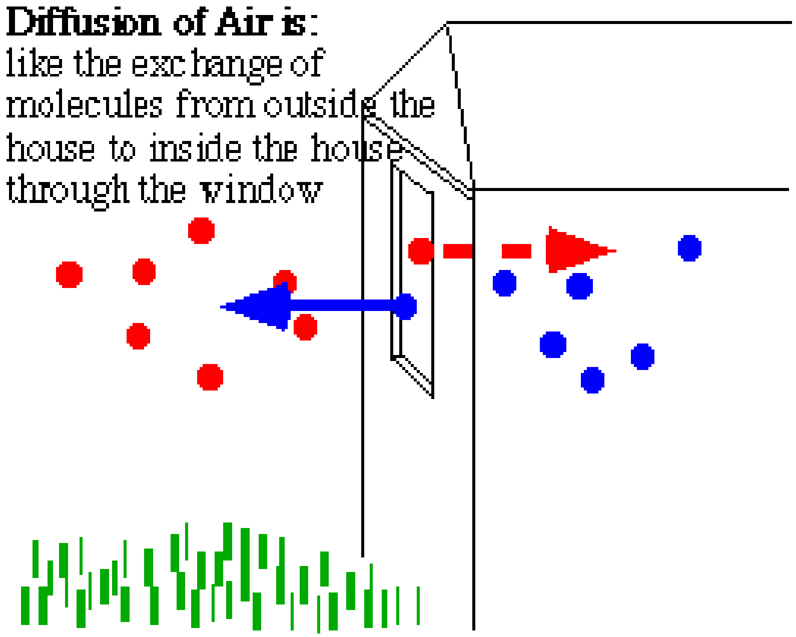


n type material is electrically neutral => free electrons = positive donor ions

p type material is electrically neutral => holes = negative acceptor ions

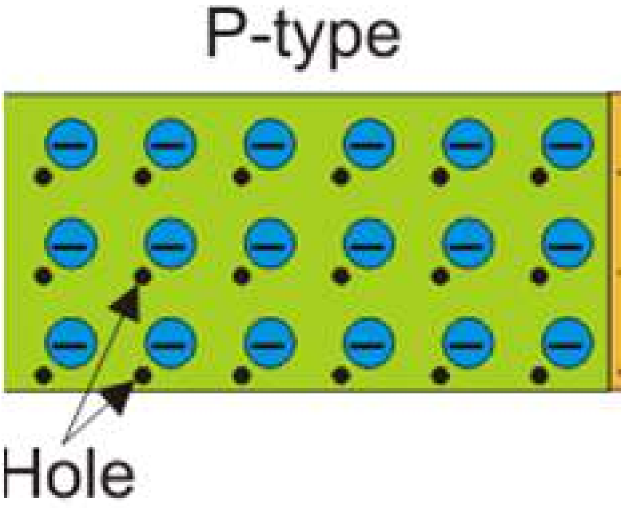
Diffusion

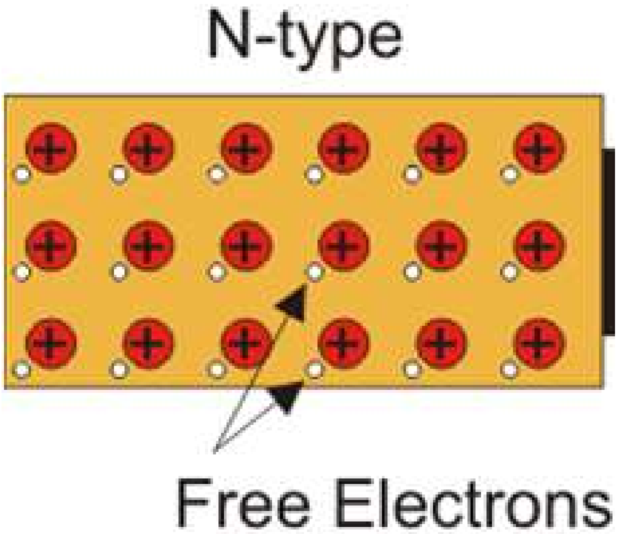




Diffusion of Air is:
like the exchange of molecules from outside the house to inside the house through the window

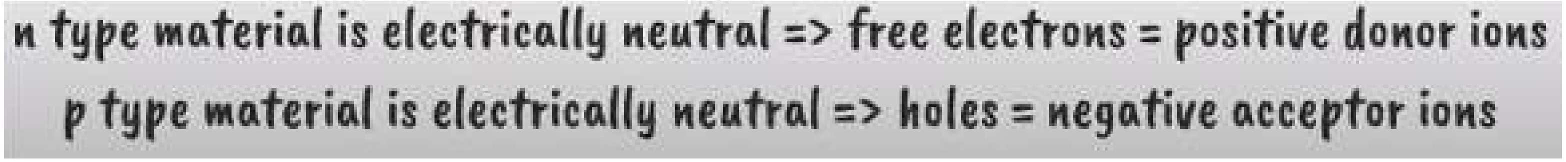
As a result of diffusion, the molecules or other free particles distribute uniformly over the entire volume





A p-type semiconductor has a high concentration of holes and a low concentration of free electrons. Holes in the p-type semiconductor are majority charge carriers, and free electrons in the p-type semiconductor are minority charge carriers.

An n-type semiconductor has plenty of free electrons and a very few numbers of holes. Free electrons in the n-type semiconductor are referred to as majority charge carriers, and holes in the n-type semiconductor are referred to as minority charge carriers.

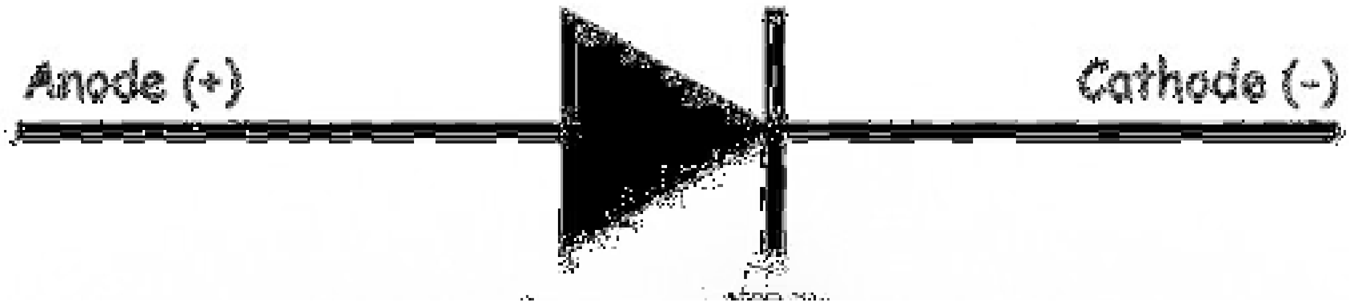

n type material is electrically neutral => free electrons = positive donor ions
p type material is electrically neutral => holes = negative acceptor ions

SEMICONDUCTOR DIODE OR PN JUNCTION DIODE

A **diode** is defined as a two-terminal electronic component that only conducts current in one direction (so long as it is operated within a specified voltage level). An ideal diode will have zero resistance in one direction, and infinite resistance in the reverse direction.

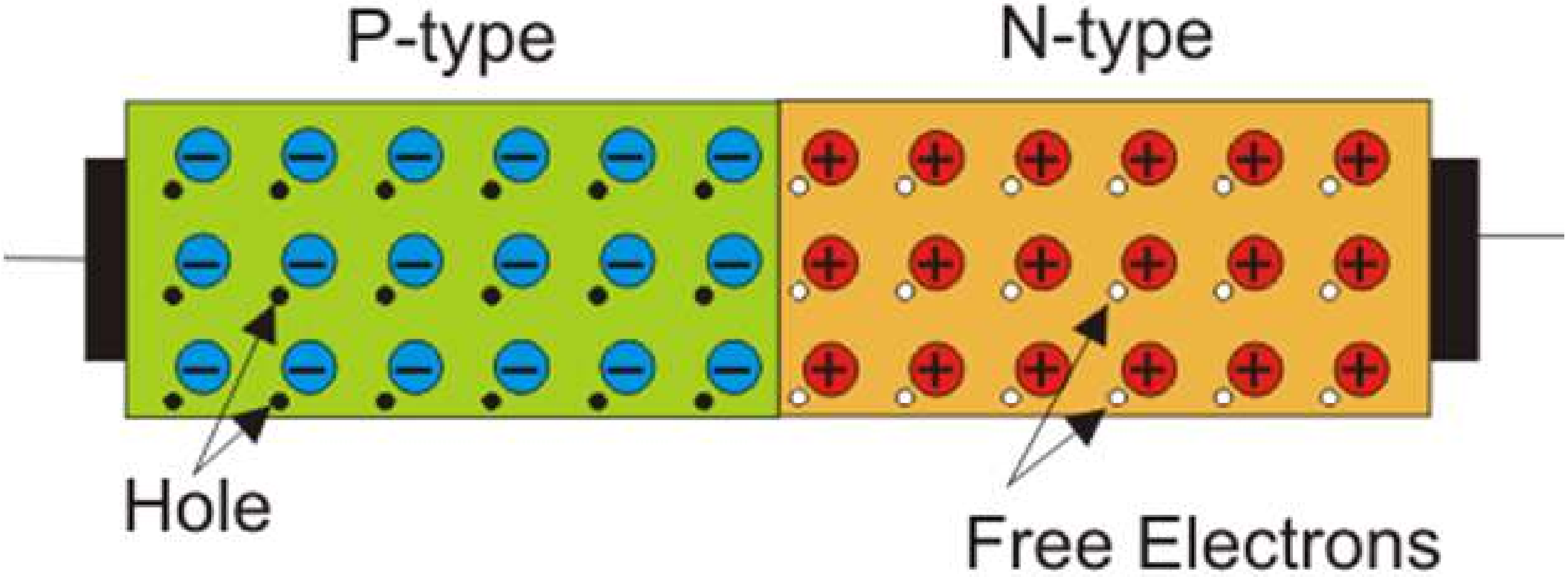
In the real world, diodes can not achieve zero or infinite resistance. Instead, a diode will have negligible resistance in one direction (to allow current flow), and very high resistance in the reverse direction (to ***prevent*** current flow).

Diode Symbol



The arrowhead points in the direction of conventional current flow in the forward biased condition

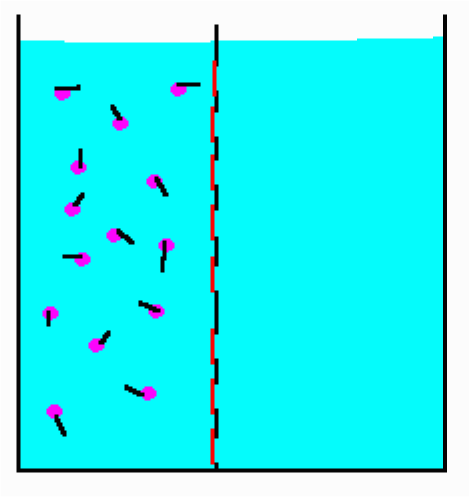
OPEN CIRCUITED DIODE

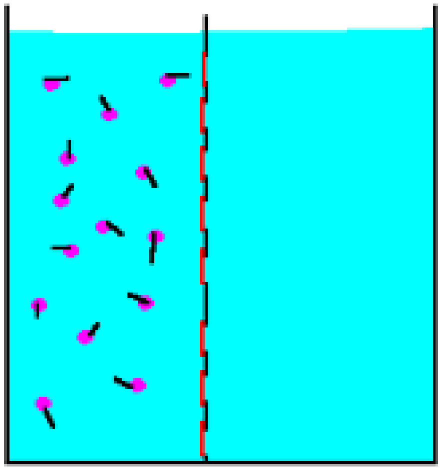


What all phenomena occurs during formation of a PN junction?

1) Diffusion
2) Formation of space charge
3) Drift

Diffusion

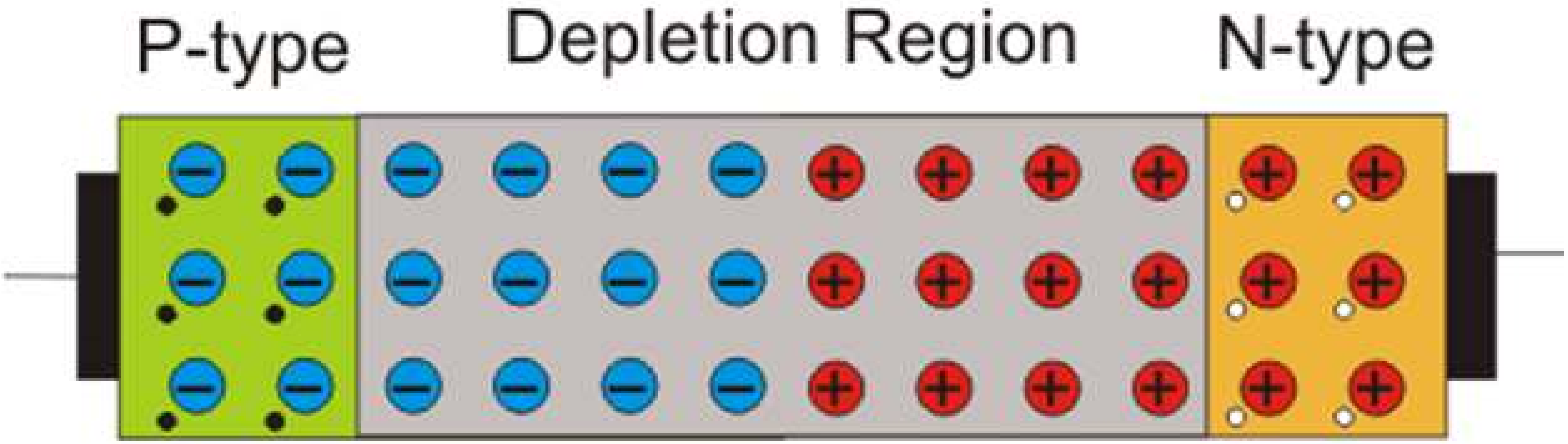




A substance, the purple dots, in solution. A membrane prevents movement of the water and the molecules from crossing from one side of the beaker to the other.

Now that the gates have been opened, the random movements of the molecules have caused, overtime, the number of molecules to be equal on the two sides of the barrier.

DEPLETION REGION



The diffusion forms a dipole charge layer at the p-n junction interface

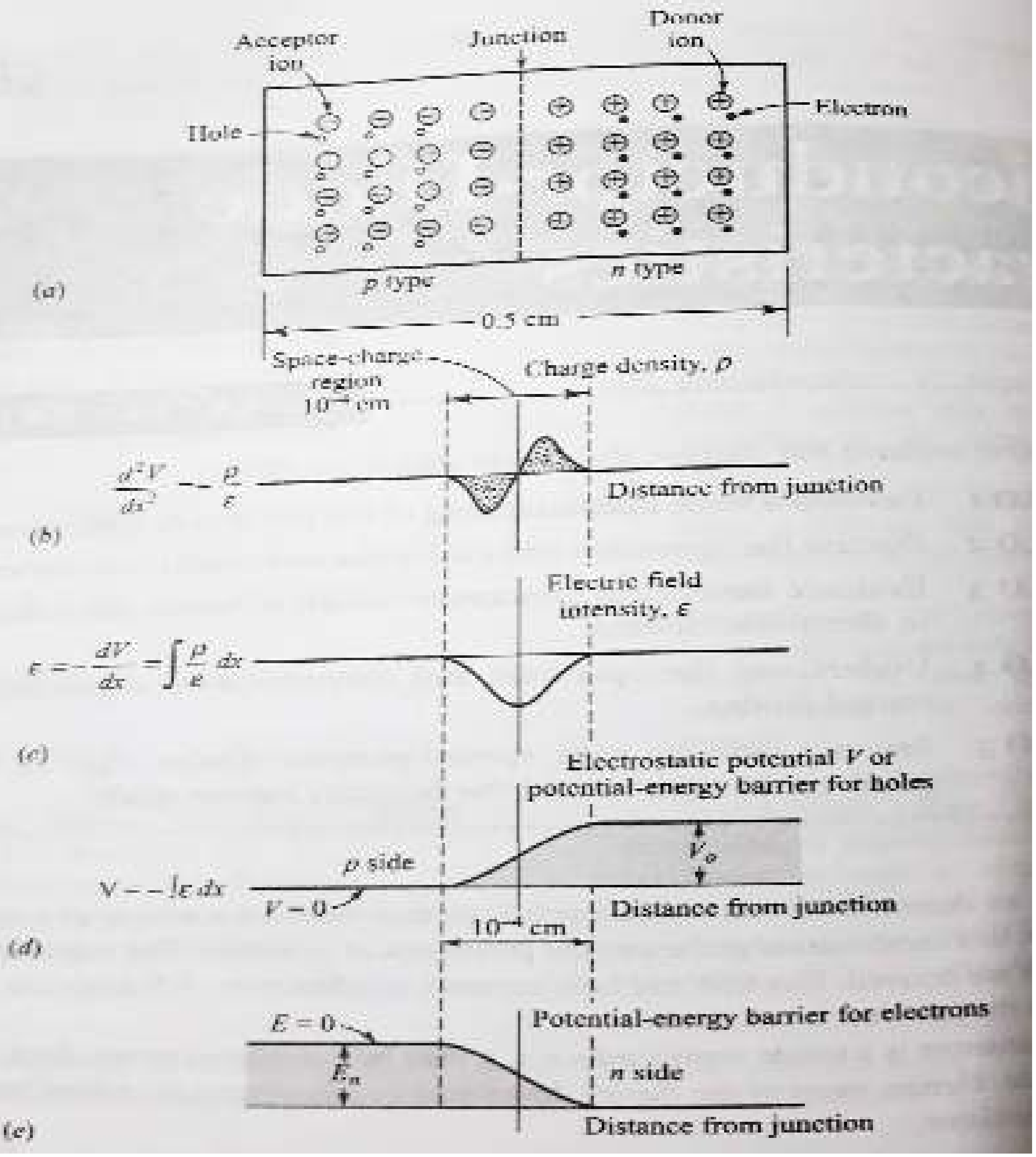
There is a “built-in” VOLTAGE at the p-n junction interface that prevents penetration of electrons into the p-side and holes into the n-side.

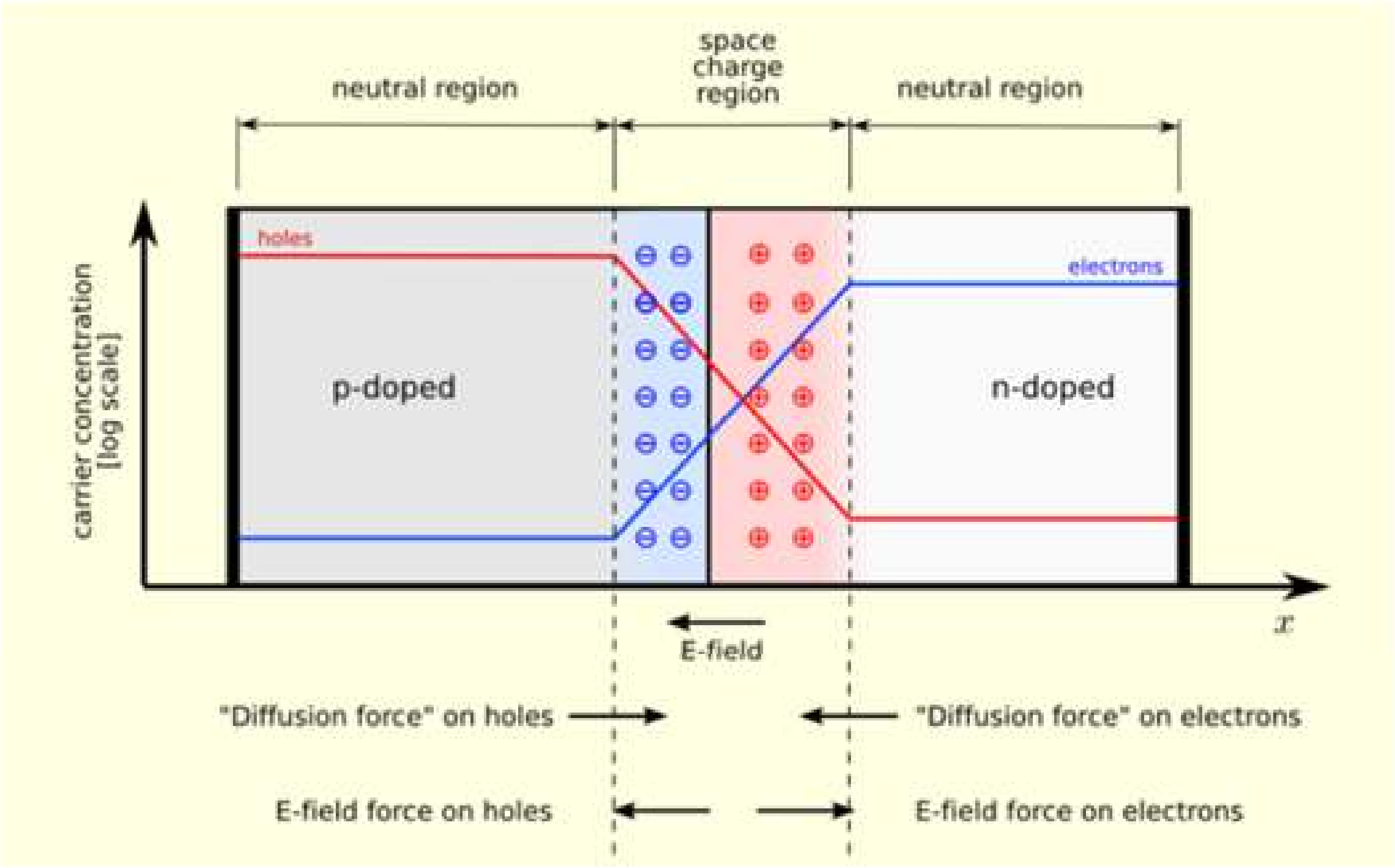
When the voltage applied is lower than the built-in voltage, the current is still nearly zero

When the voltage exceeds the built-in voltage, the current can flow through the p-n junction

DRIFT

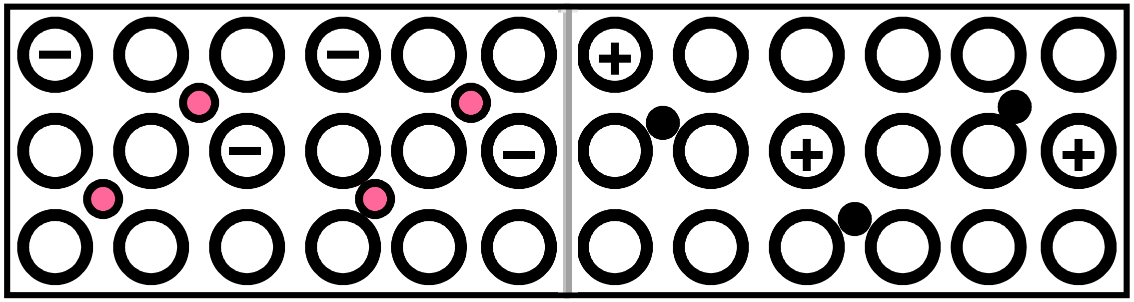
formation of an electric field directed from positive charge to negative charge. This electric field causes electrons to move from p side to n side (p–>n) and the holes to move from n side to p side (n–>p). This motion of charge carriers due to electric field is known as **“drift”**
The current resulting from the flow of electrons and holes due to this electric field (generated by depletion region) is known as **“drift current”**.
drift current is opposite in direction to the diffusion current.


Acceptor ion
Junction
Donor ion
Hole
Electron
(a)
p type
n type
0.5 cm
Space-charge region 10^{-4} cm
Charge density, ρ
$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$
Distance from junction
(b)
Electric field intensity, $\mathcal{E}$
$\mathcal{E} = -\frac{dV}{dx} = \int \frac{\rho}{\varepsilon}\,dx$
(c)
Electrostatic potential V or potential-energy barrier for holes
p side
$V = -\int \mathcal{E}\,dx$
$V = 0$
V_o
Distance from junction
10^{-4} cm
(d)
$E = 0$
E_n
Potential-energy barrier for electrons
n side
Distance from junction
(e)


neutral region
space charge region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration [log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

p- n junction formation

What happens if n- and p-type materials are in close contact?



Being free particles, **electrons** start diffusing from n-type material into p-material

Being free particles, **holes,** too**,** start diffusing from p-type material into n-material

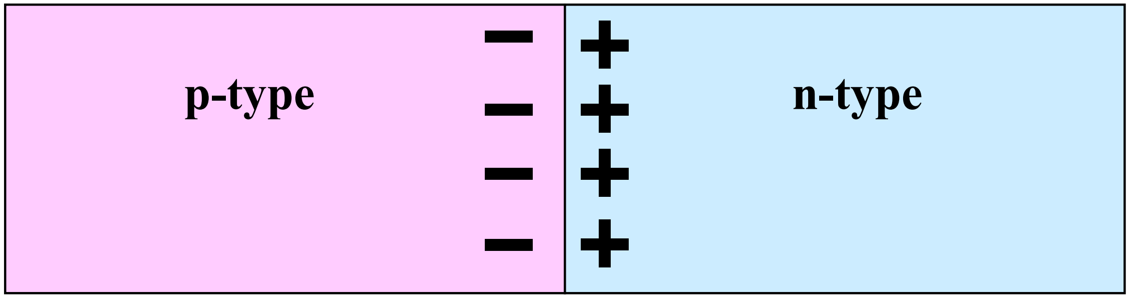
Have they been NEUTRAL particles, eventually all the free electrons and holes had uniformly distributed over the entire compound crystal.

However, every electrons transfers a negative charge (-q) onto the p-side and also leaves an uncompensated (+q) charge of the donor on the n-side.

Every hole creates one positive charge (q) on the n-side and (-q) on the p-side

p- n junction formation

What happens if n- and p-type materials are in close contact?



Electrons and holes remain staying close to the p-n junction because negative and positive charges attract each other.

Negative charge stops electrons from further diffusion

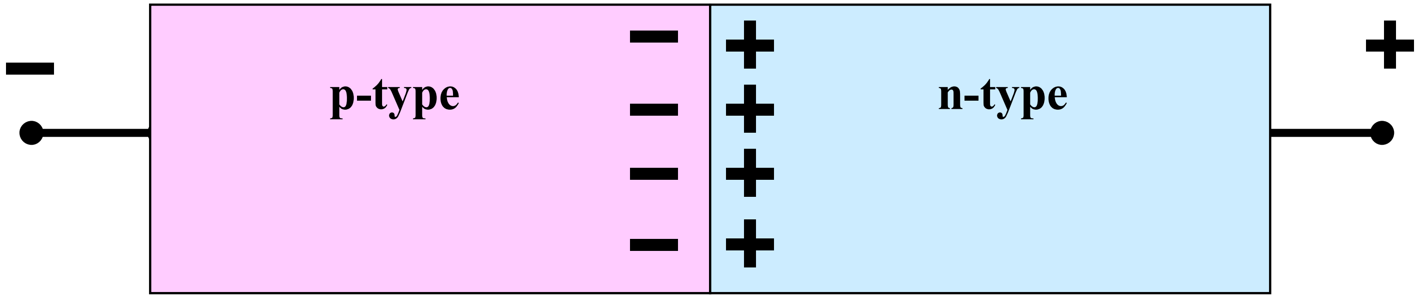
Positive charge stops holes from further diffusion

The diffusion forms a dipole charge layer at the p-n junction interface.

There is a “built-in” VOLTAGE at the p-n junction interface that prevents penetration of electrons into the p-side and holes into the n-side.

p- n junction current – voltage characteristics

What happens when the voltage is applied to a p-n junction?



The polarity shown, attracts holes to the left and electrons to the right.

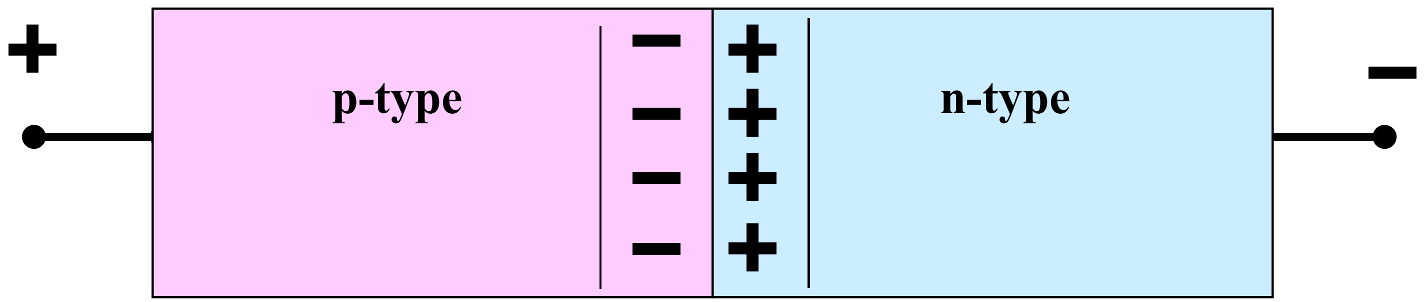
According to the **current continuity law,** the current can **only** flow if all the charged particles move forming a closed loop

However, there are very few holes in n-type material and there are very few electrons in the p-type material.
There are very few carriers available to support the current through the junction plane

For the voltage polarity shown, the current is nearly zero

p- n junction current – voltage characteristics

What happens if voltage of opposite polarity is applied to a p-n junction?



The polarity shown, attracts electrons to the left and holes to the right.

There are plenty of electrons in the n-type material and plenty of holes in the p-type material.

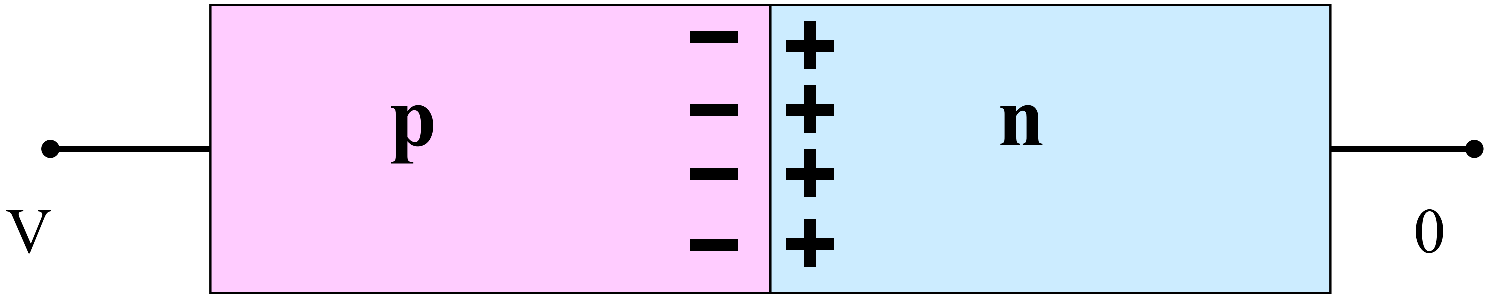
There are a lot of carriers available to cross the junction.

When the voltage applied is lower than the built-in voltage, the current is still nearly zero

When the voltage exceeds the built-in voltage, the current can flow through the p-n junction

Diode current – voltage (I-V) characteristics

Semiconductor diode consists of a p-n junction with two
contacts attached to the p- and n- sides



$$I = I_S\left[\mathbf{exp}\left(\frac{qV}{kT}\right)-1\right]$$

I_S is usually a very small current, $I_S \approx 10^{-17} \ldots 10^{-13}$ A

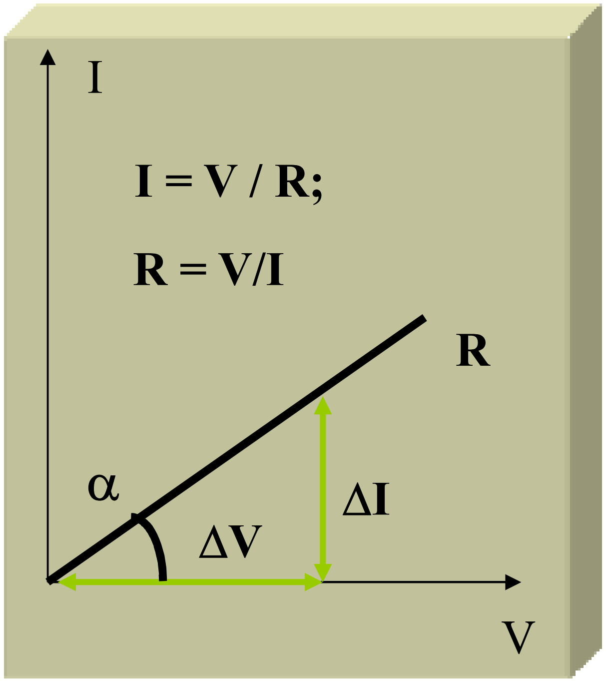
When the voltage V is negative (“reverse” polarity) the exponential term ≈ -1;
The diode current is ≈ I_S (very small).

When the voltage V is positive (“forward” polarity) the exponential term increases rapidly with V and the current is high.

Graphing the I-V characteristics of electronic components.

The I-V plot represents is the dependence of the current I through the component on the voltage V across it.

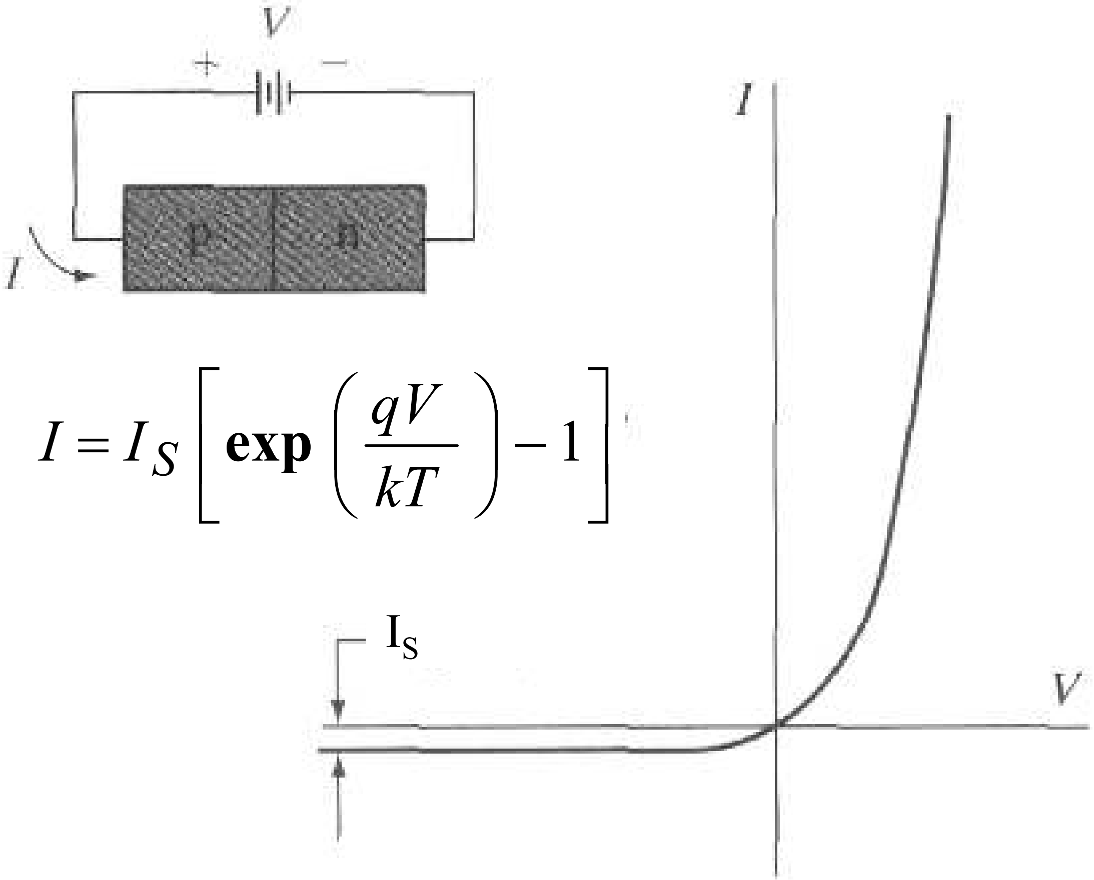
Resistor $$V = I \times R; \; => \; I = \left(\frac{1}{R}\right) \times V$$



tg(α) = 1/R

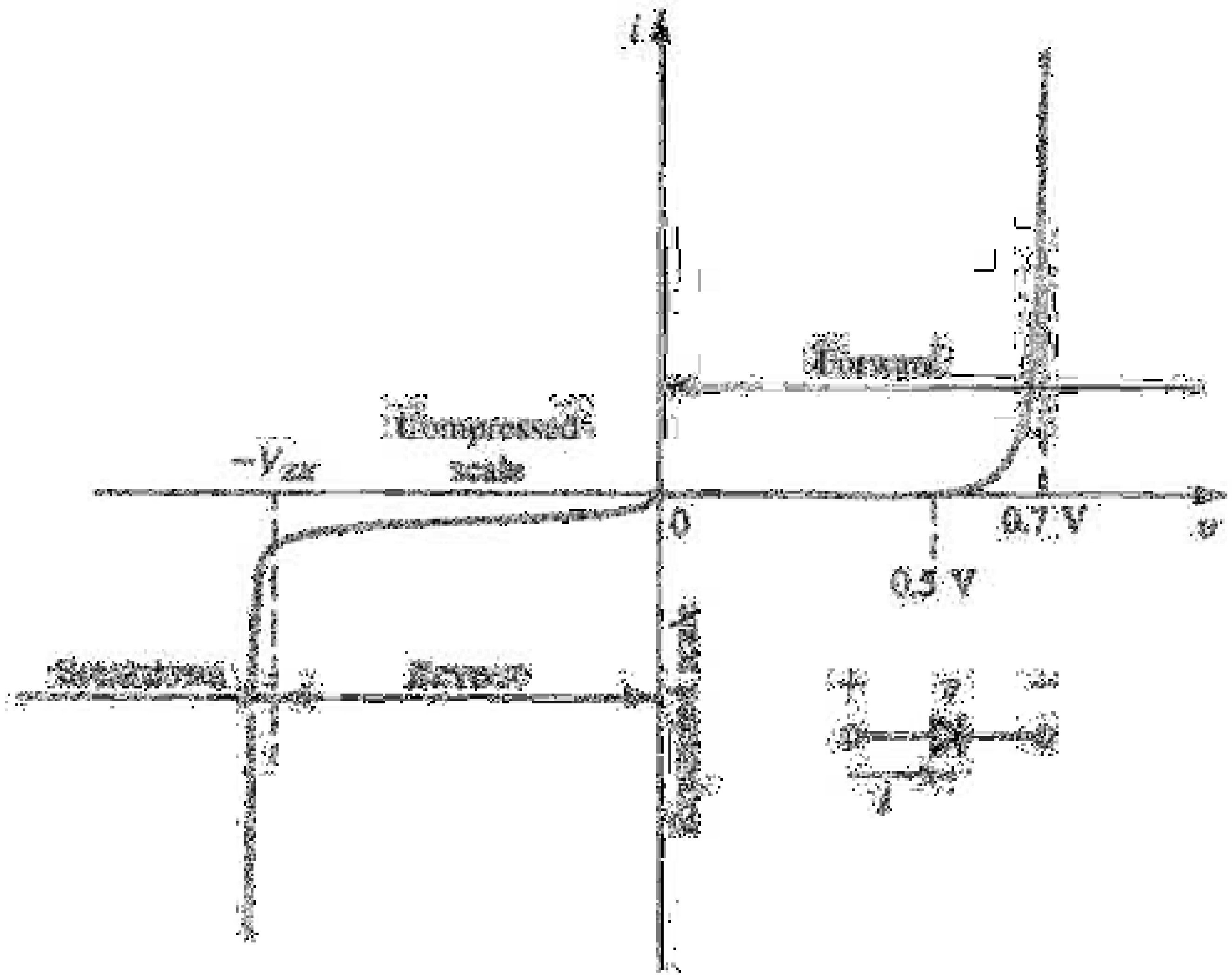
The I-V characteristic of the resistor

The I-V characteristic of the diode



$$I = I_S\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

The experimental V-I characteristic of a Si diode



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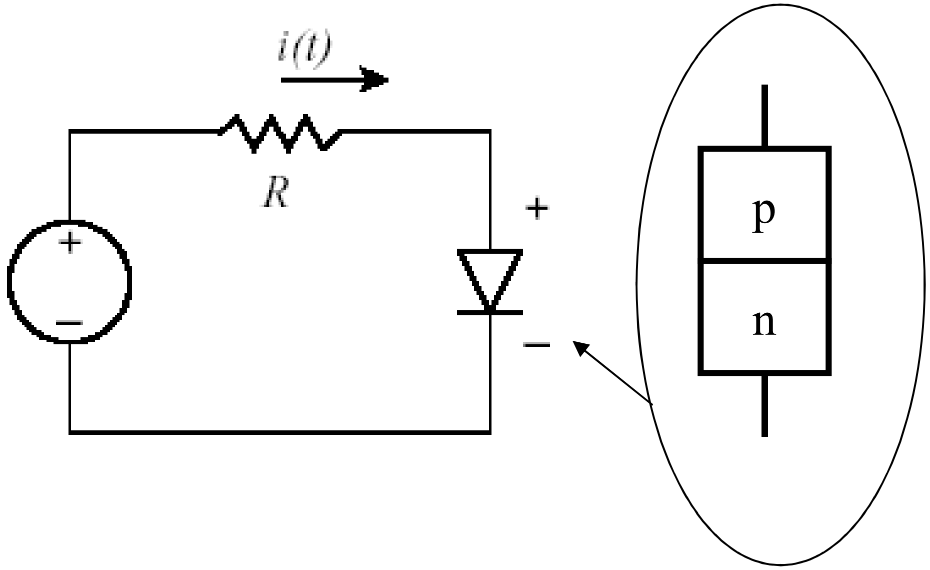
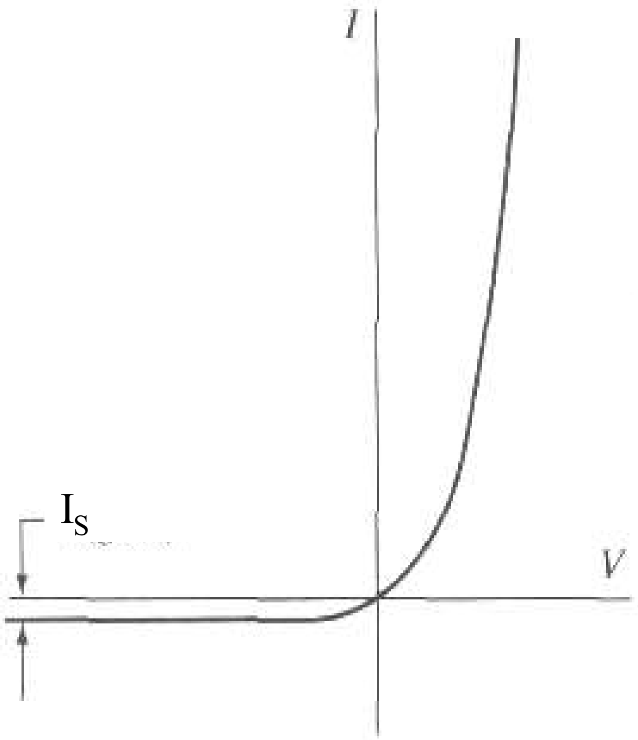
p-n diode circuit notation



When "plus" is applied to the p-side, the current is high. This voltage polarity is called FORWARD.

When "plus" is applied to the n-side, the current is nearly zero. This voltage polarity is called REVERSE.



Resistance Levels

Semiconductors act differently to DC and AC currents.
There are 3 types of resistances.

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

- 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 (1.1):

$$R_D = V_D/I_D \qquad (1.1)$$

Example : DC or Static Resistance – refer Figure 1.1

Ideal diode			Si diode		
I_D(A)	V_D(V)	R_D(Ω)	I_D(A)	V_D(V)	R_D(Ω)
20m	0	0	20m	0.8	40
2m	0	0	2m	0.5	250

dc resistance of forward-bias region decrease when higher currents and voltage.

Ideal diode			Si diode		
I_D(A)	V_D(V)	$R_D(\Omega)$	I_D(A)	V_D(V)	$R_D(\Omega)$
0	-10	∞	-2µ	-10	5M

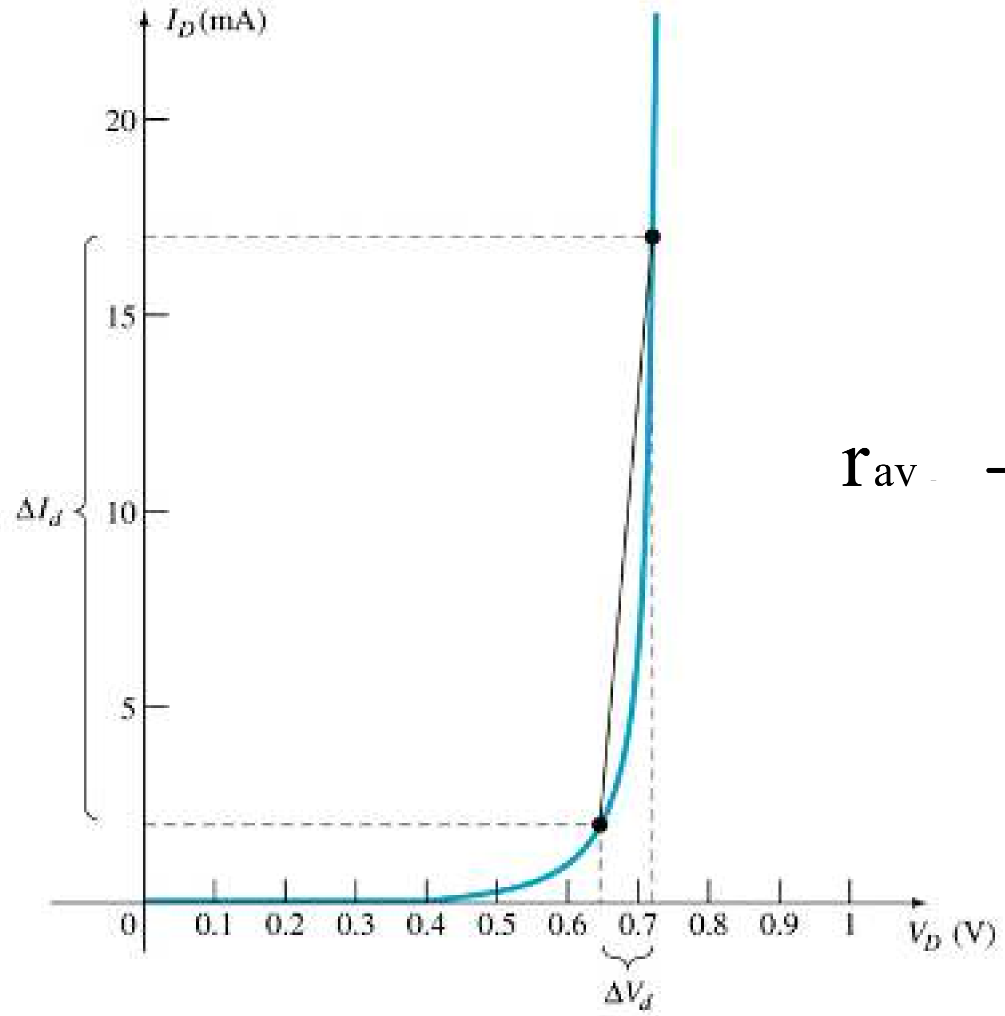
- dc resistance of reverse-bias region, its open-circuit equivalent.

- AC or Dynamic Resistance

- Static resistance is using dc input. If the input is sinusoidal the scenario will be change.
- The varying input will move instantaneous operating point UP and DOWN of a region.
- Thus the specific changes in current and voltage is obtained. It can be determined using equation (1.2)

$$r_d = \Delta V_D / \Delta I_D \qquad (1.2)$$

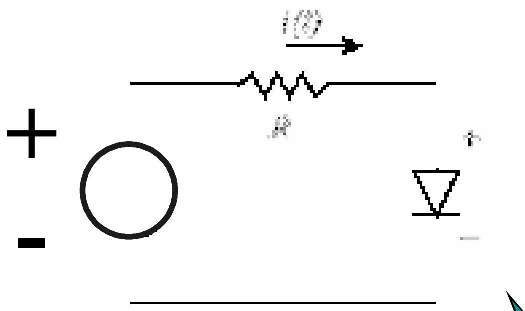
•Average AC Resistance



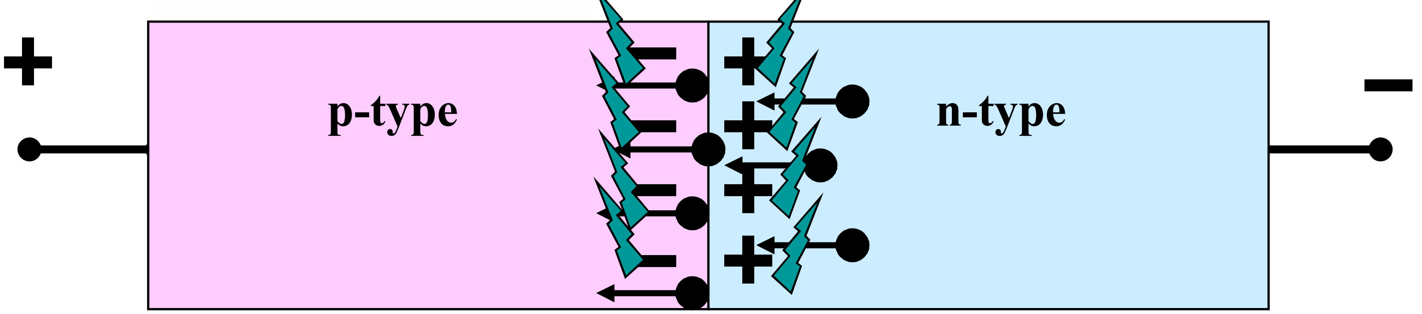
$$r_{av} \quad \frac{Vd}{Id} \text{(point to point)}$$

AC resistance can be determined by picking 2 points on the characteristic curve developed for a particular circuit.

p- n diode applications: Light emitters



P-n junction can emit the light when forward biased



Electrons drift into p-material and find plenty of holes there. They “RECOMBINE” by filling up the “empty” positions.

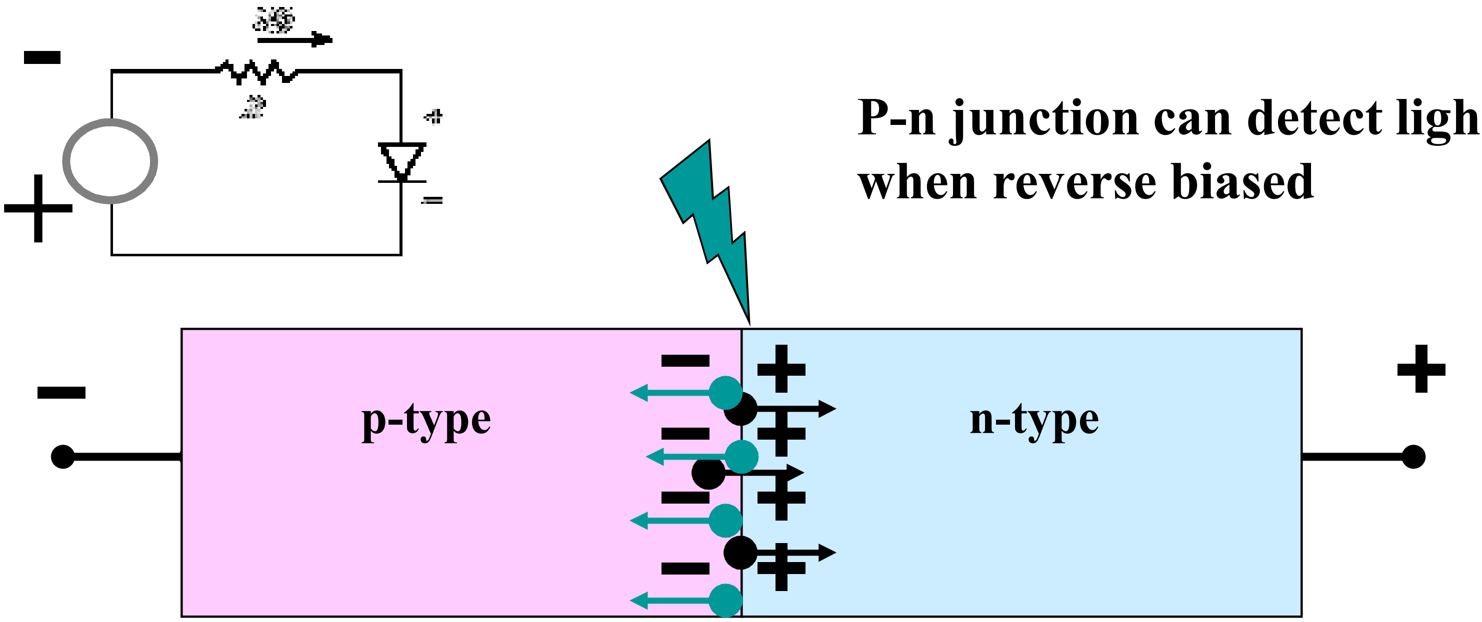
Holes drift into n-material and find plenty of electrons there. They also “RECOMBINE” by filling up the “empty” positions.

The energy released in the process of “annihilation” produces

PHOTONS – the particles of light

p- n diode applications: Photodetectors

P-n junction can detect light when reverse biased



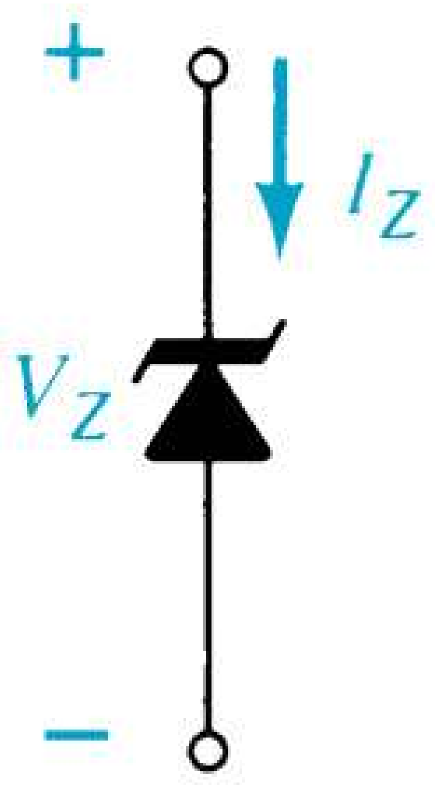
When the light illuminates the p-n junction, the photons energy RELEASES free electrons and holes.

They are referred to as PHOTO-ELECTRONS and PHOTO-HOLES

The applied voltage separates the photo-carriers attracting electrons toward “plus” and holes toward “minus”

As long as the light is ON, there is a current flowing through the p-n junction

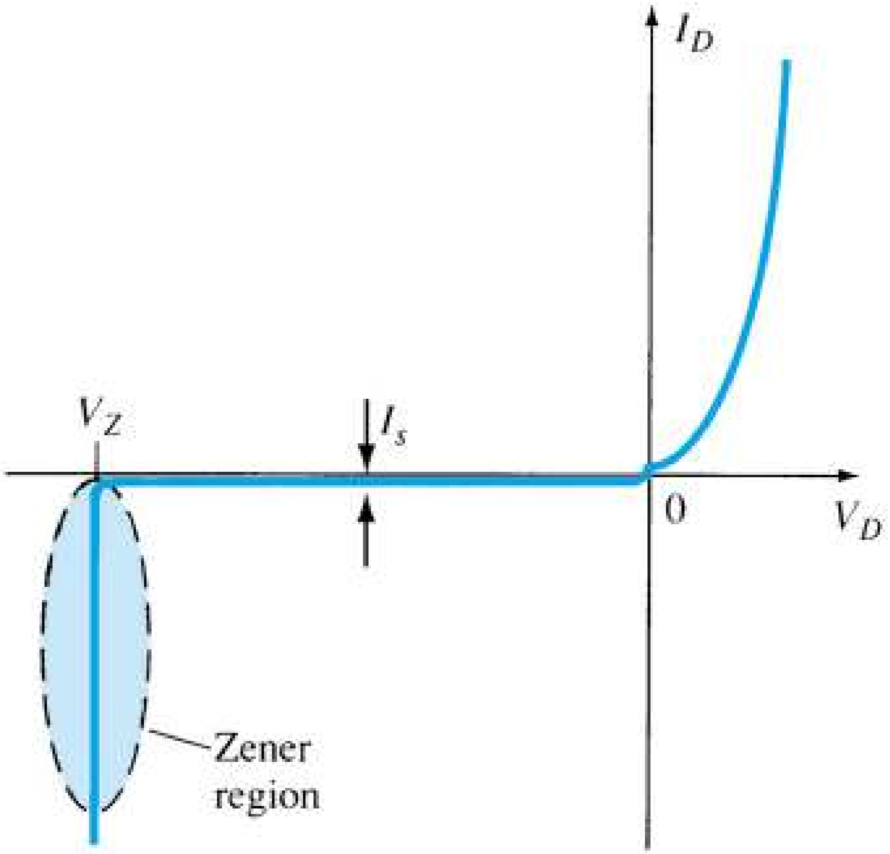
Zener Diode



(a)

- A Zener is a diode operated in reverse bias at the Peak Inverse Voltage (PIV) called the Zener Voltage (V_Z).
- Common Zener Voltages: 1.8V to 200V

Zener Region



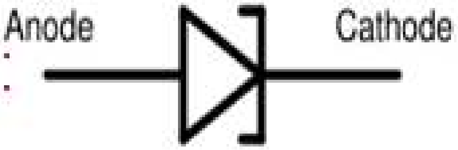
The diode is in the reverse bias condition.
At some point the reverse bias voltage is so large the diode breaks down.
The reverse current increases dramatically.
This maximum voltage is called ***avalanche breakdown voltage*** and the current is called ***avalanche current.***

NEGATIVE RESISTANCE DEVICE

- It is a device which exhibits a negative incremental resistance over a limited range of V-I characteristic.
- It is of two types :-
    1. Current controllable type : V-I curve is a multi valued function of voltage and single valued function of current .eg:- UJT, p-n-p-n diode
    2. Voltage controllable type : V-I curve is a multi valued function of current and single valued function of voltage. eg:- SCS, Tunnel diode -

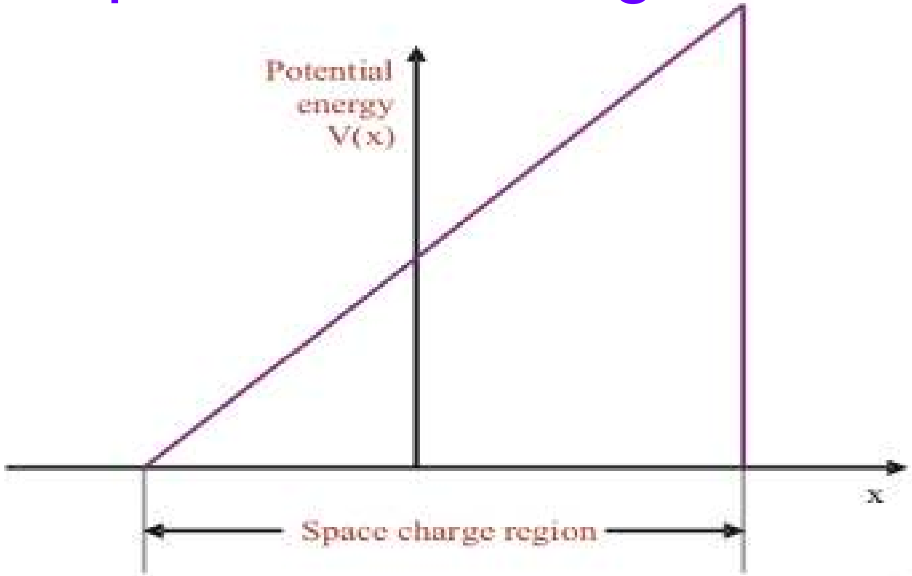
TUNNEL DIODE (Esaki Diode)

- It was introduced by Leo Esaki in 1958.
- Heavily-doped p-n junction
  - Impurity concentration is 1 part in 10^3 as compared to 1 part in 10^8 in p-n junction diode
- Width of the depletion layer is very small (about 100 A).
- It is generally made up of Ge and GaAs.
- It shows tunneling phenomenon.
- Circuit symbol of tunnel diode is :



WHAT IS TUNNELING

- **Classically**, carrier must have energy at least equal to potential-barrier height to cross the junction .
- But according to **Quantum mechanics** there is finite probability that it can penetrate through the barrier for a thin width.
- This phenomenon is called **tunneling** and hence the Esaki Diode is know as **Tunnel Diode**.



Triangular potential barrier approximation of the potential barrier in the tunnel diode.

CHARACTERISTIC OF TUNNEL DIODE

Ip:- Peak Current

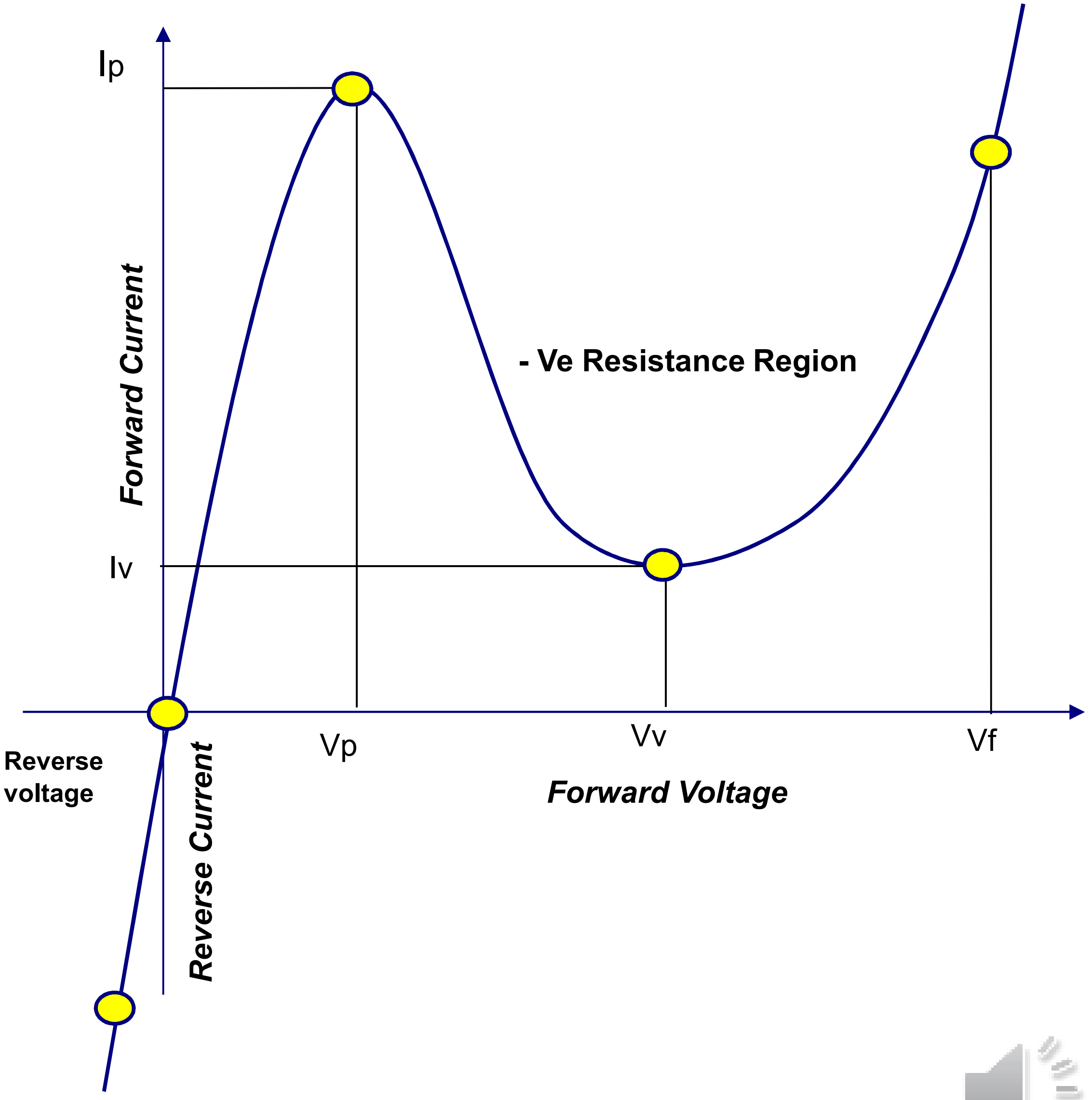
Iv :- Valley Current

Vp:- Peak Voltage

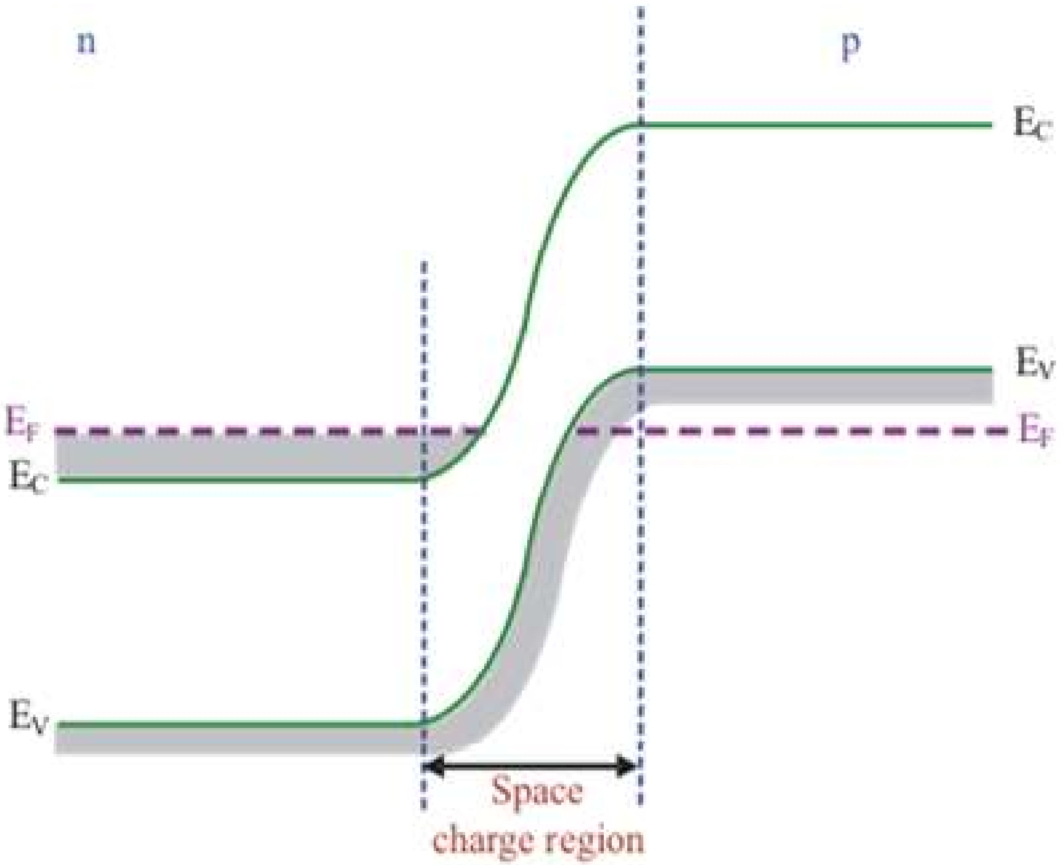
Vv:- Valley Voltage

Vf:- Peak Forward

Voltage

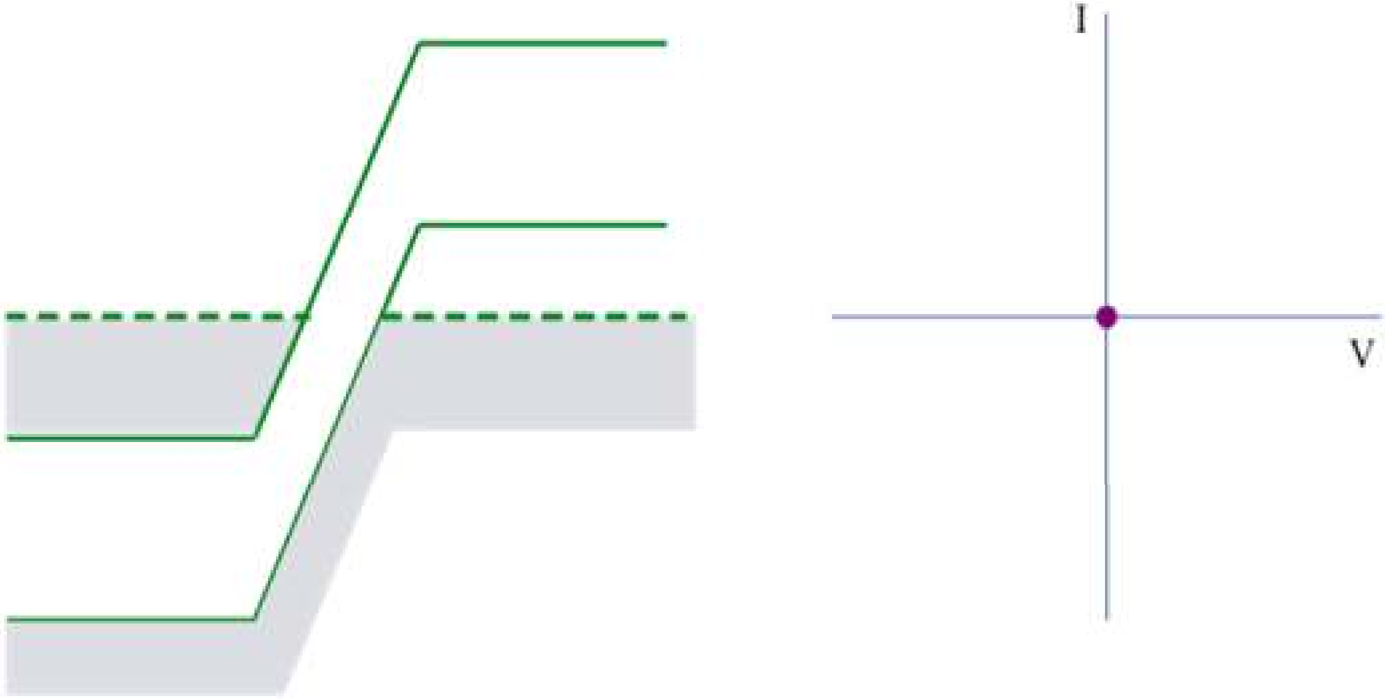


ENERGY BAND DIAGRAM



Energy-band diagram of pn junction in thermal equilibrium in which both the n and p region are degenerately doped.

AT ZERO BIAS

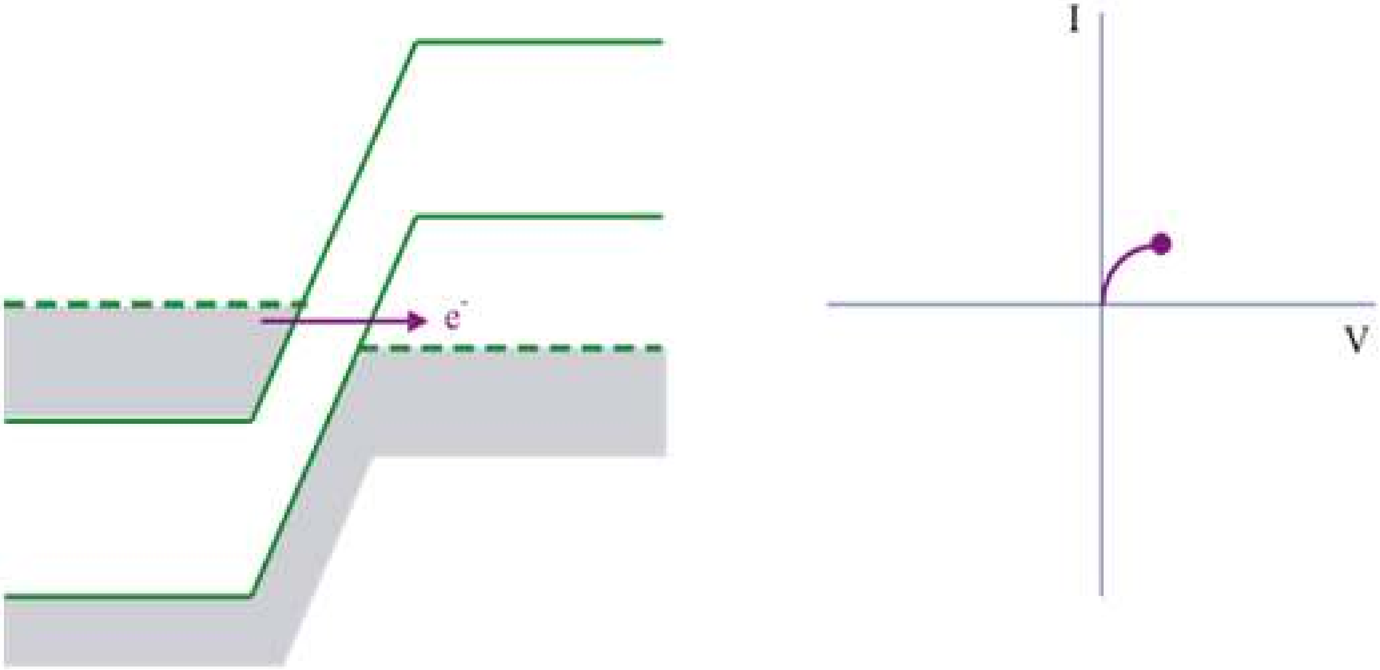


Simplified energy-band diagram and I-V characteristics of the tunnel diode at zero bias.

-Zero current on the I-V diagram;

-All energy states are filled below E_F on both sides of the junction;

AT SMALL FORWARD VOLTAGE

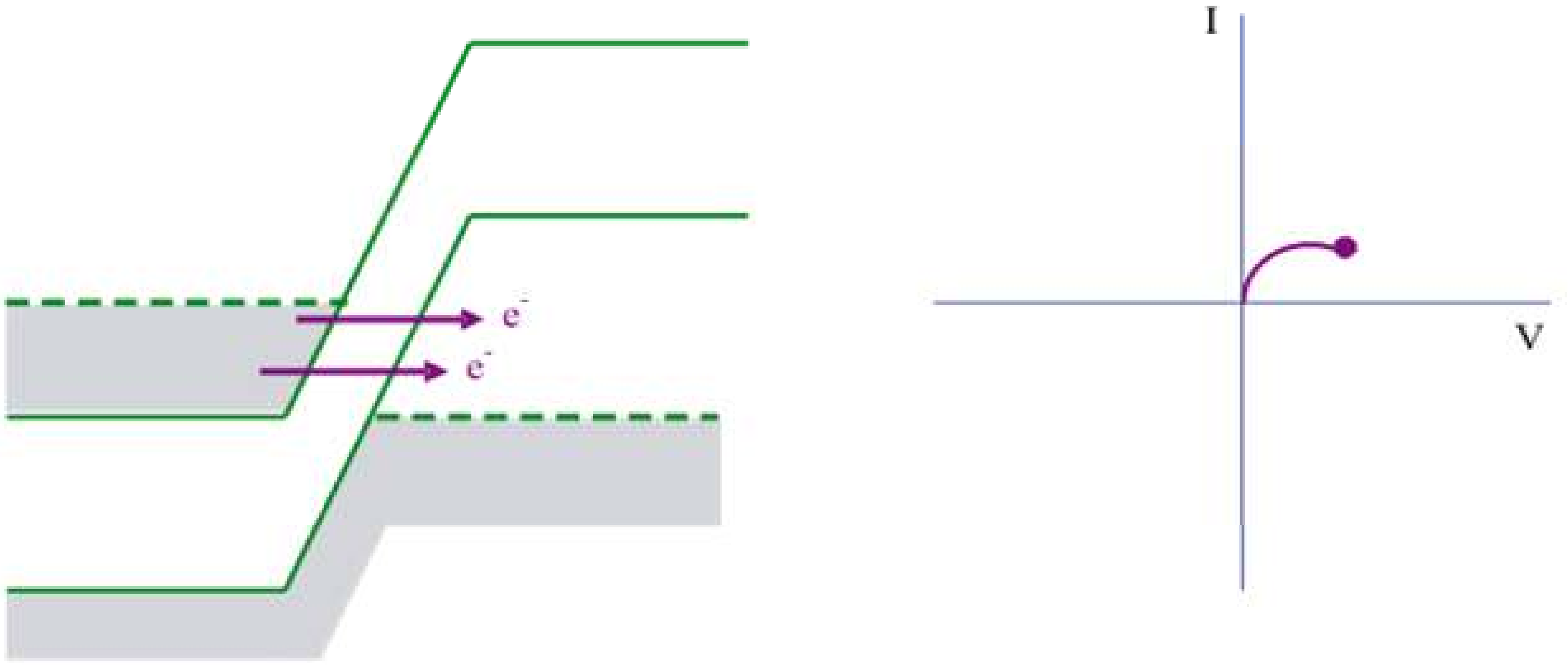


Simplified energy-band diagram and I-V characteristics of the tunnel diode at a slight forward bias.

-Electrons in the conduction band of the n region are directly opposite to the empty states in the valence band of the p region.

-So a finite probability that some electrons tunnel directly into the empty states resulting in forward-bias tunneling current.

AT MAXIMUM TUNNELING CURENT

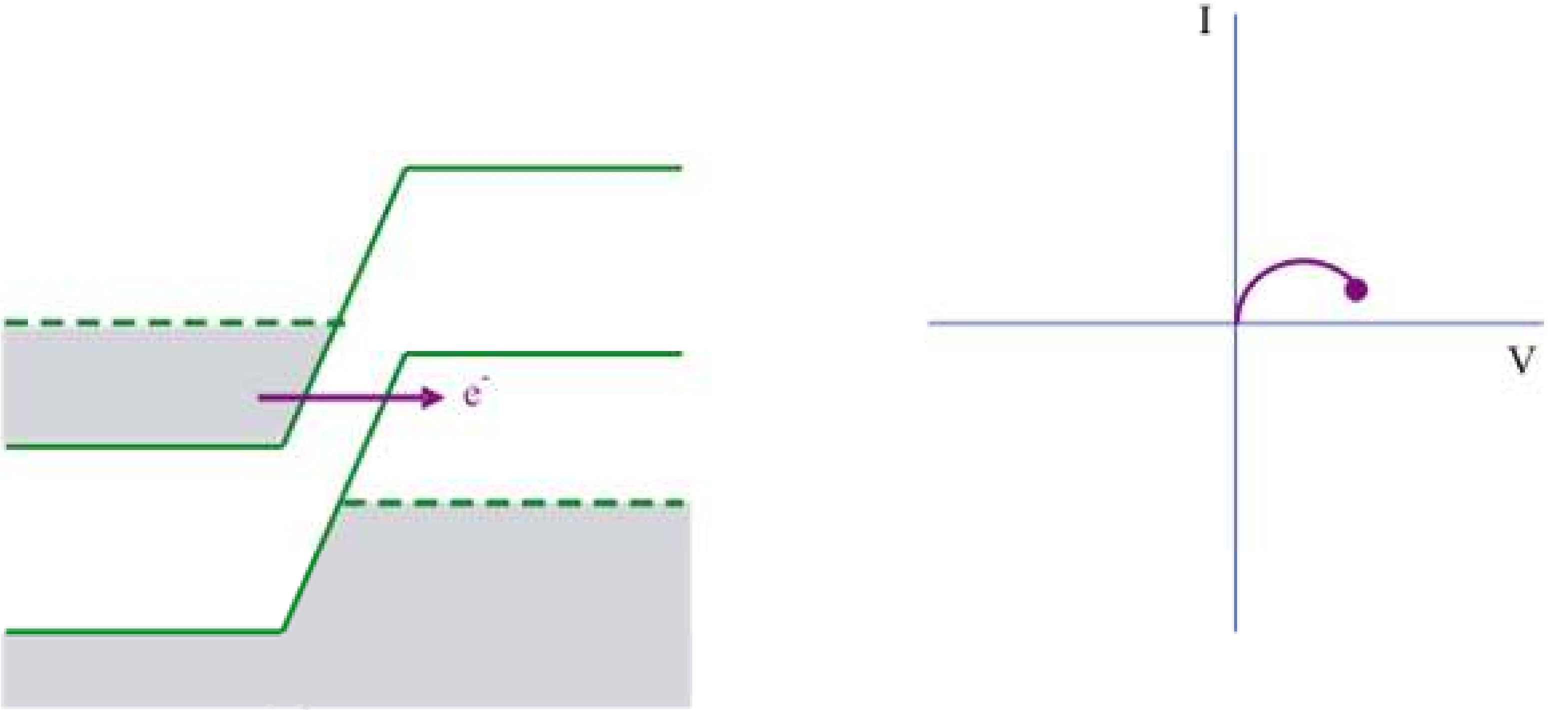


Simplified energy-band diagraam and I-V characteristics of the tunnel diode at a forward bias producing maximum tunneling current.

-The maximum number of electrons in the n region are opposite to the maximum number of empty states in the p region.

- Hence tunneling current is maximum.

AT DECREASING CURRENT REGION

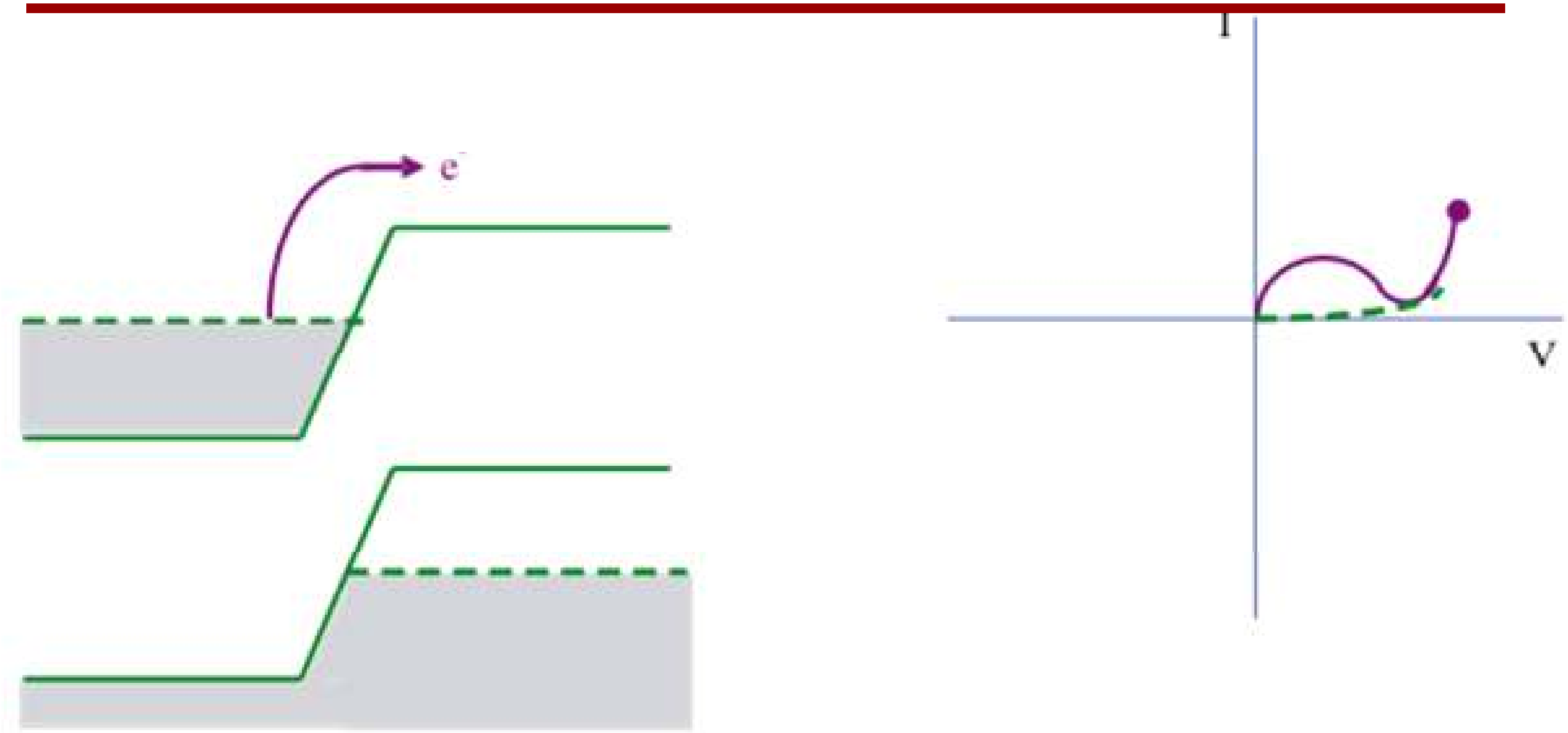


Simplified energy-band diagram and I-V characteristics of the tunnel diode at a higher forward bias producing less tunneling current.

-The forward-bias voltage increases so the number of electrons on the n side, directly opposite empty states on the p side decreases.

- Hence the tunneling current decreases.

AT HIGHER FORWARD VOLTAGE



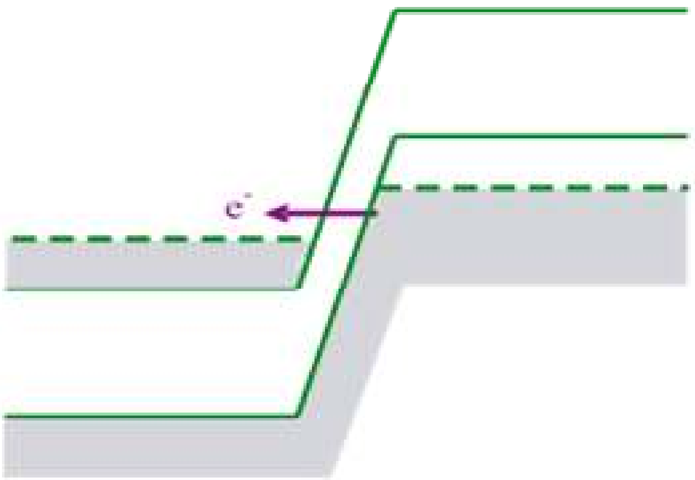
Simplified energy-band diagram and I-V characteristics of the tunnel diode at a forward bias for which the diffusion current dominates.

-No electrons on the n side are directly opposite to the empty states on the p side.

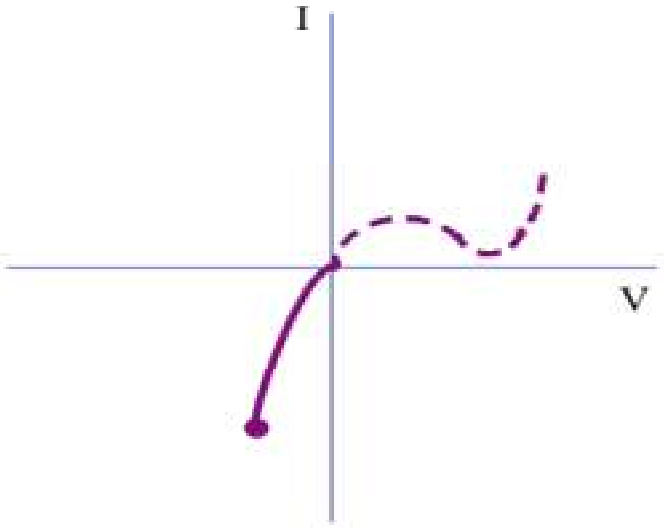
- The tunneling current is zero.

-The normal ideal diffusion current exists in the device.

AT REVERSE BIAS VOLTAGE



A simplified energy-band diagram of a tunnel diode with a reverse bias voltage



I-V characteristic of a tunnel diode with a reverse-bias voltage.

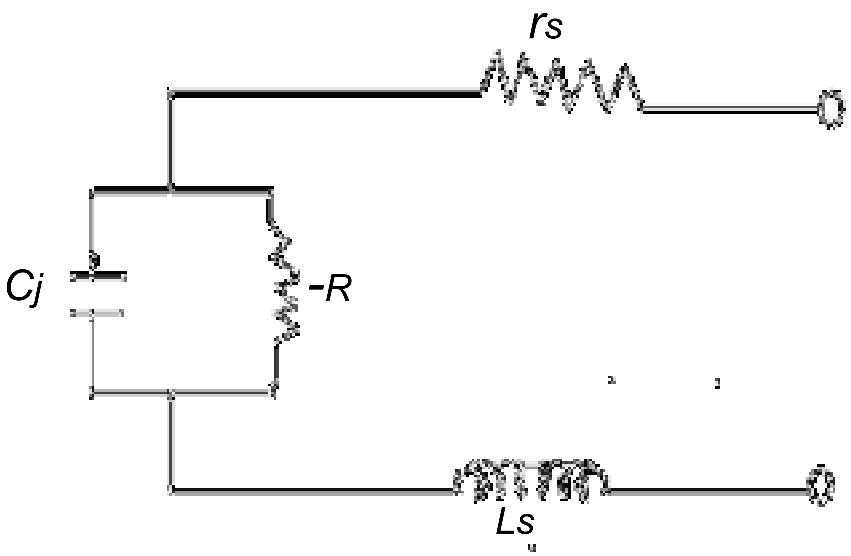
- Electrons in the valence band on the p side are directly opposite to empty states in the conduction band on the n side.

-Electrons tunnel directly from the p region into the n region.

- The reverse-bias current increases monotonically and rapidly with reverse-bias voltage.

TUNNEL DIODE EQUIVALENT CIRCUIT

- This is the equivalent circuit of tunnel diode when biased in negative resistance region.

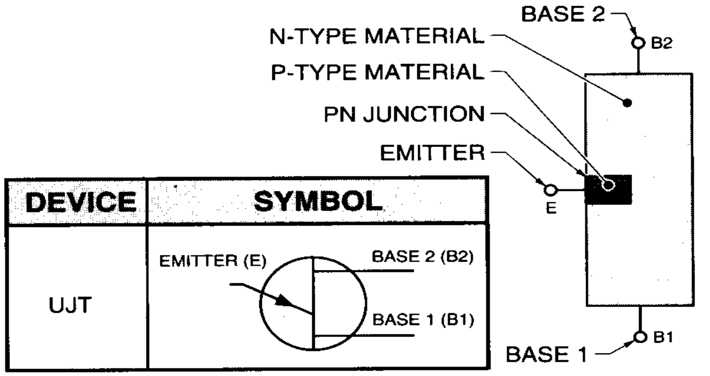


- At higher frequencies the series R and L can be ignored.

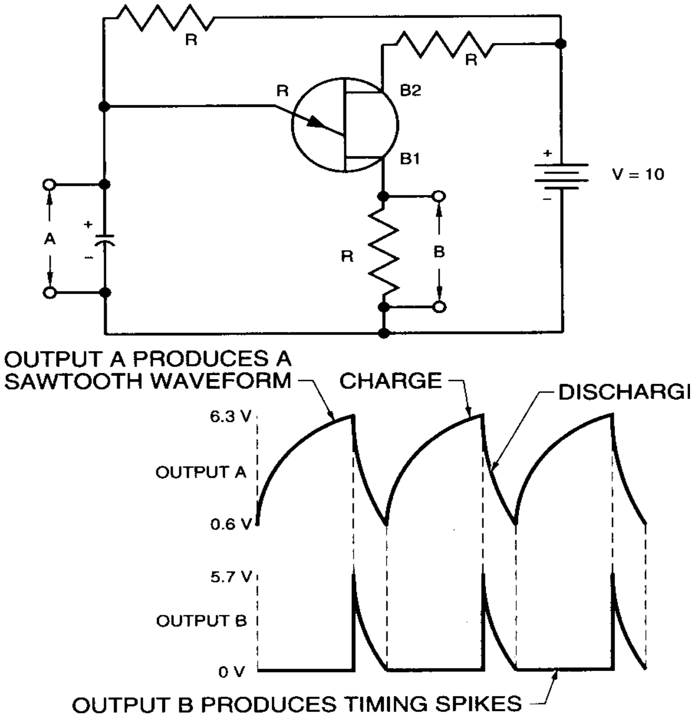
- Hence equivalent circuit can be reduced to parallel combination of junction capacitance and negative resistance.

Uni Junction Transistor (UJT)

- Simple two layer transistor
- Operates using the principle of avalanche breakdown producing a saw tooth output
- Used to trigger an SCR or TRIAC
- Also used within pulse circuitry
- Output from photocells, thermistors, and other transducers can be used to trigger

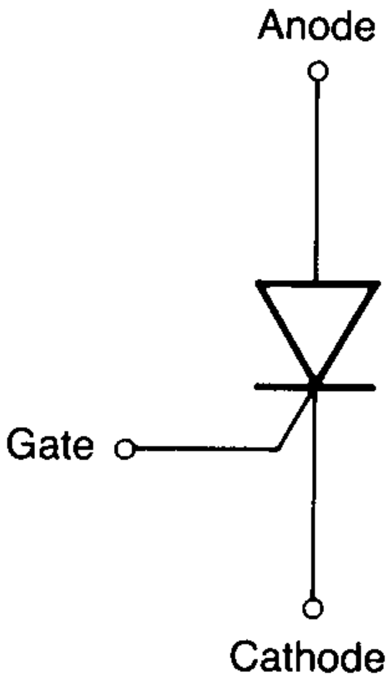


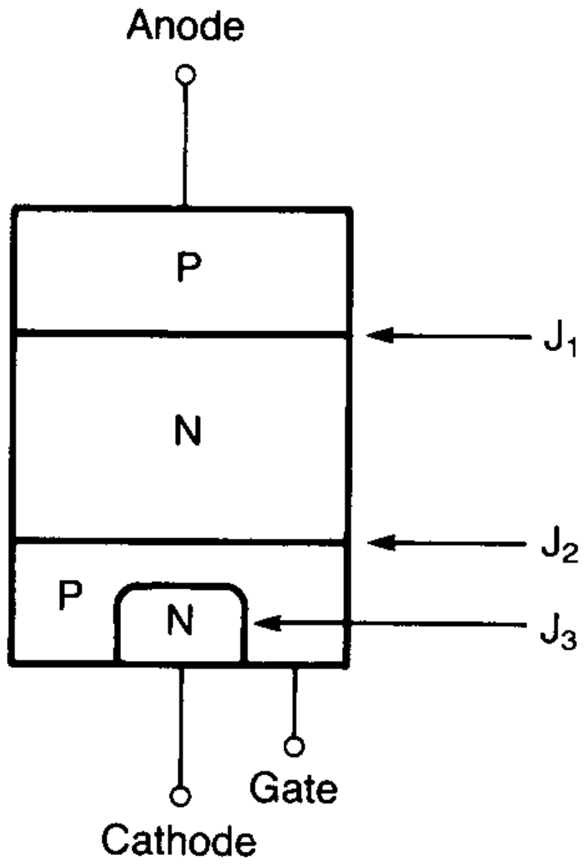
DEVICE	SYMBOL
UJT	EMITTER (E) BASE 2 (B2) BASE 1 (B1)



UJT APPLICATION

Silicon Controlled Rectifier (SCR)





Three terminals
- anode - P-layer
- cathode - N-layer (opposite end)
- gate - P-layer near the cathode

Three junctions - four layers

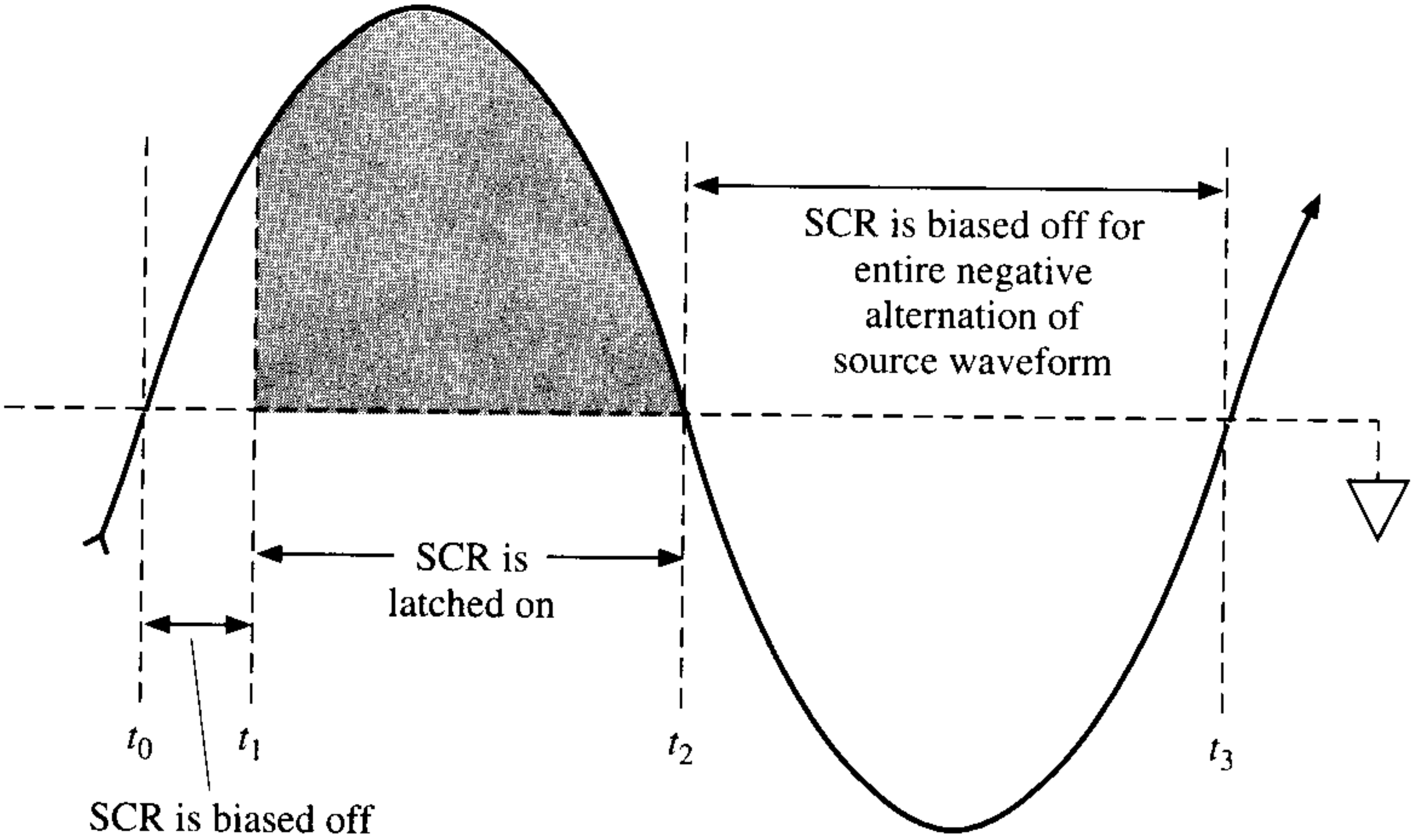
Connect power such that the anode is positive with respect to the cathode - no current will flow

NOTE: Blocked by the reverse bias of junction 2

- **Positive potential applied to the gate**
  - **Current will flow - TURNED-ON**
  - **Once turned on, gate potential can be removed and the SCR still conducts**

CALLED LATCHING

- **Holding current maintains latch**


SCR is biased off for entire negative alternation of source waveform
SCR is latched on
t_0
t_1
t_2
t_3
SCR is biased off