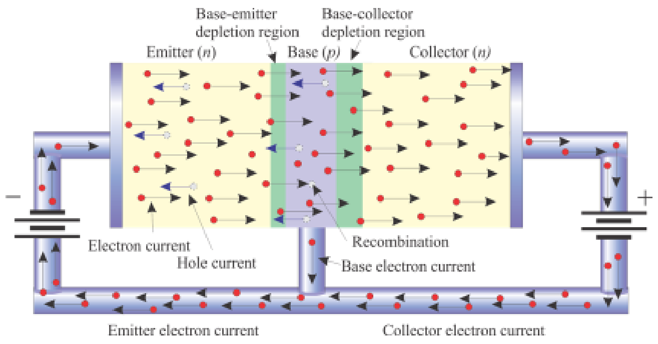
**UNIT-4**

# Fundamental of Semiconductor Devices



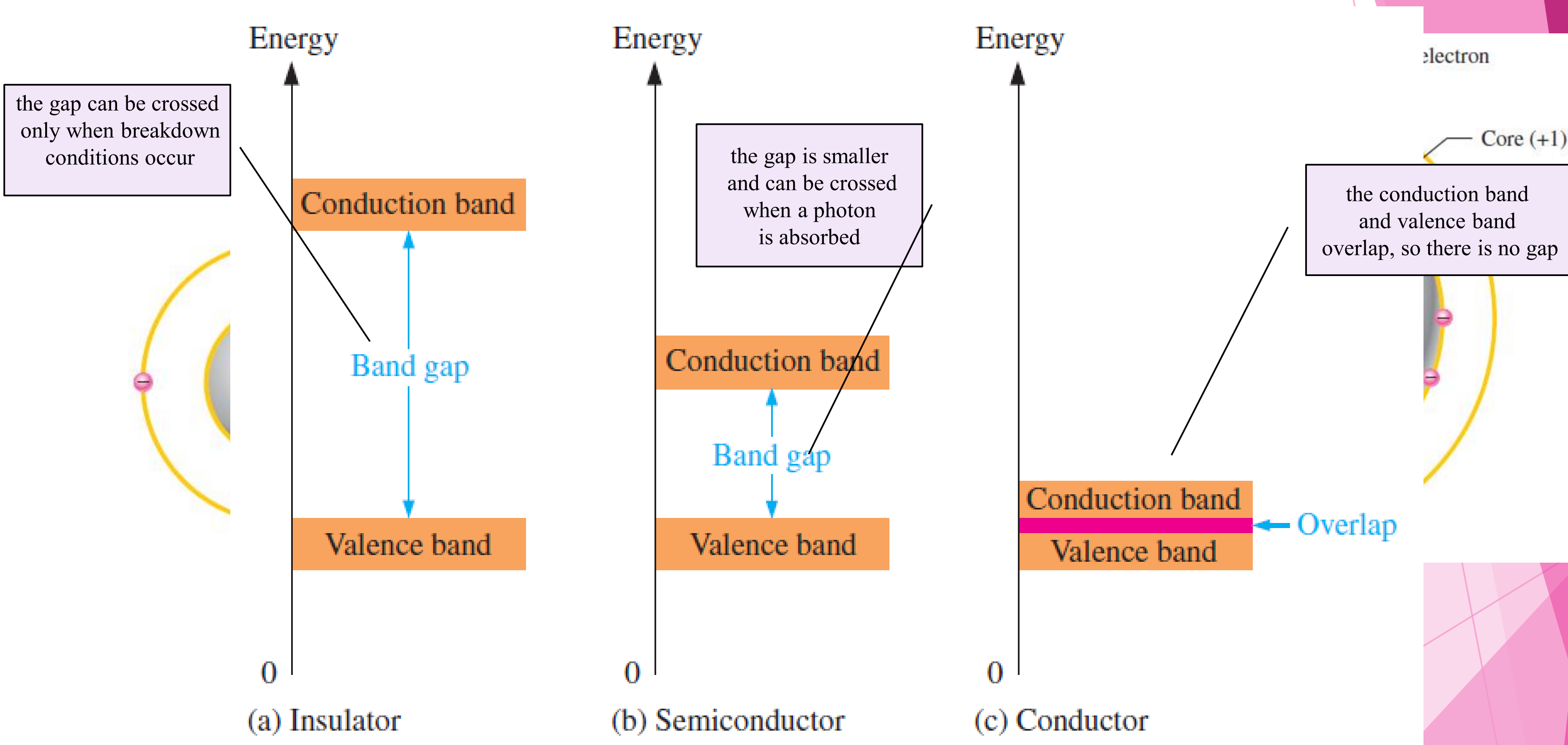
# Semiconductor Devices

- Introduction to Semiconductor Materials
  - Conductor and Insulators.
  - N-type, P-Type, electron, and hole current
  - PN junction, depletion region, potential barrier.

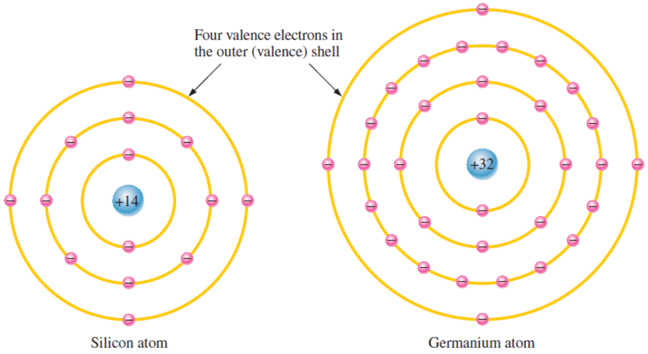
- Diodes

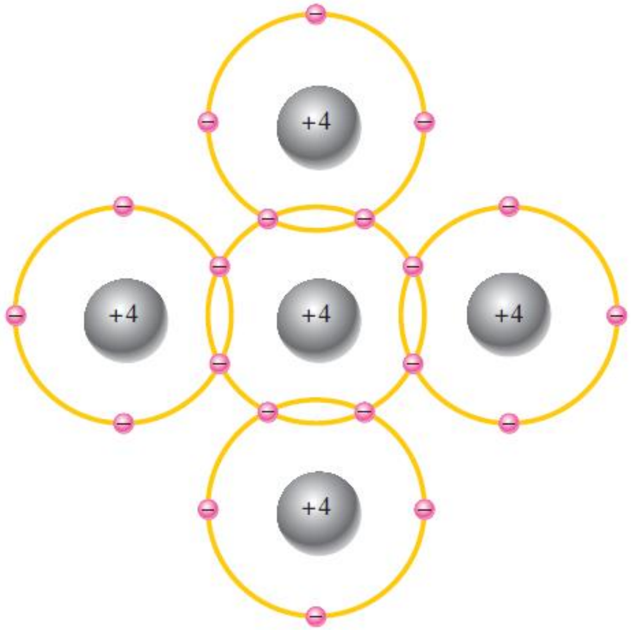
  - Forward Bias, reverse bias
  - semiconductor diode characteristics
  - analysis of diode circuits
  - clamping circuit
  - testing of diodes
  - Diode applications
  - Special Diodes:
  - Light Emitting Diodes
  - Zener Diodes
  - Photo Diodes

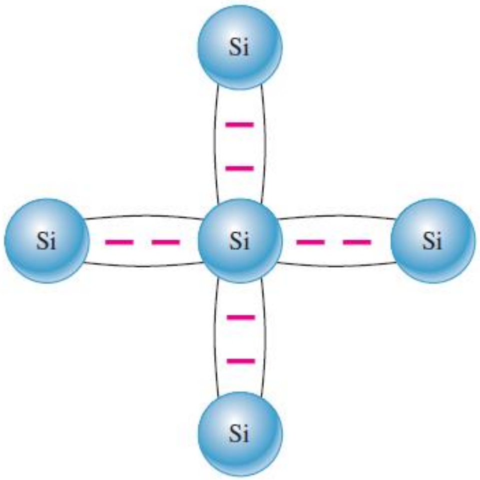
# Conductor and Insulators.
## Atomic Model



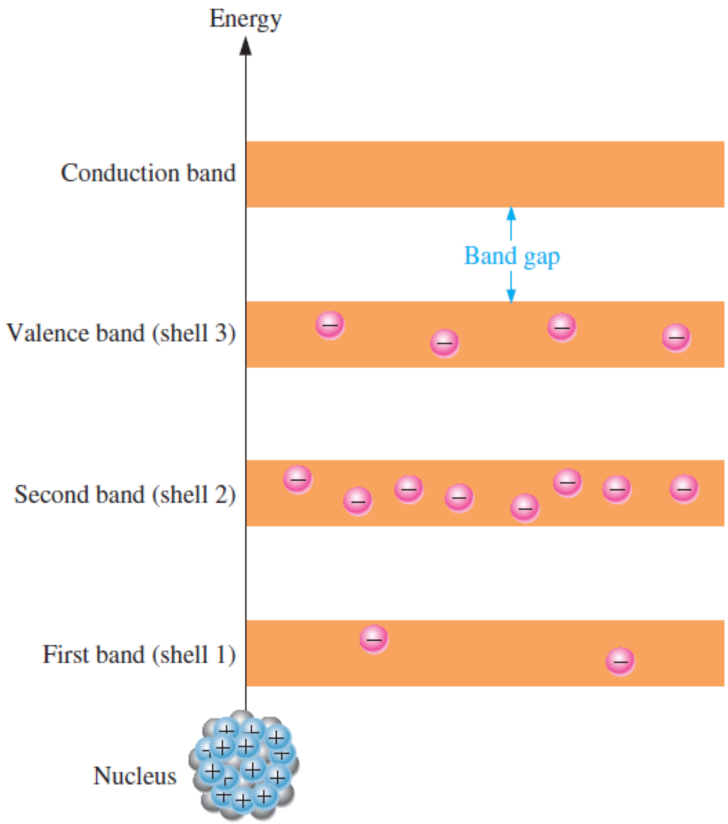
# Silicon and Germanium

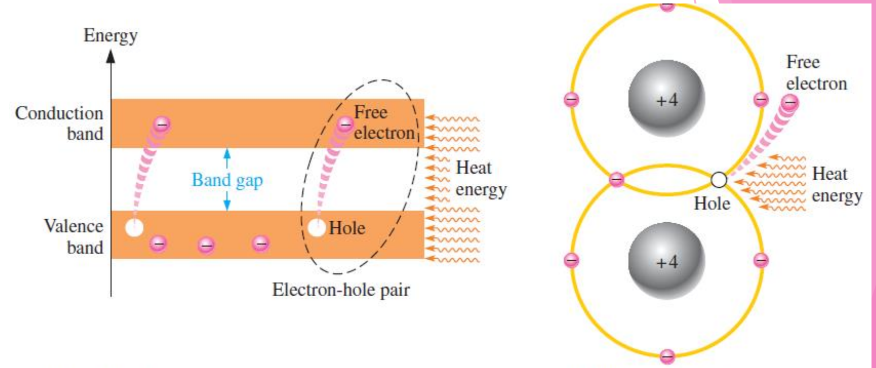


# Conduction Electron and Holes.




(a) Energy diagram

(b) Bonding diagram

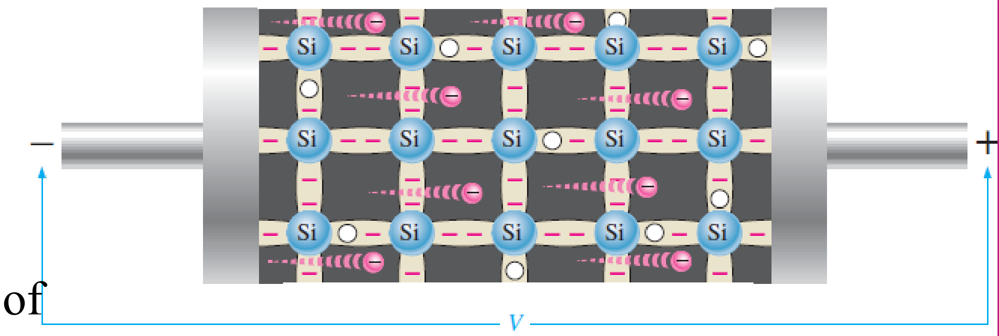
An intrinsic (pure) silicon crystal at room temperature has sufficient heat energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electron called '**Conduction Electron**'

It leaves a vacancy in valance band, called **hole**.

Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

# Electron Hole Current.

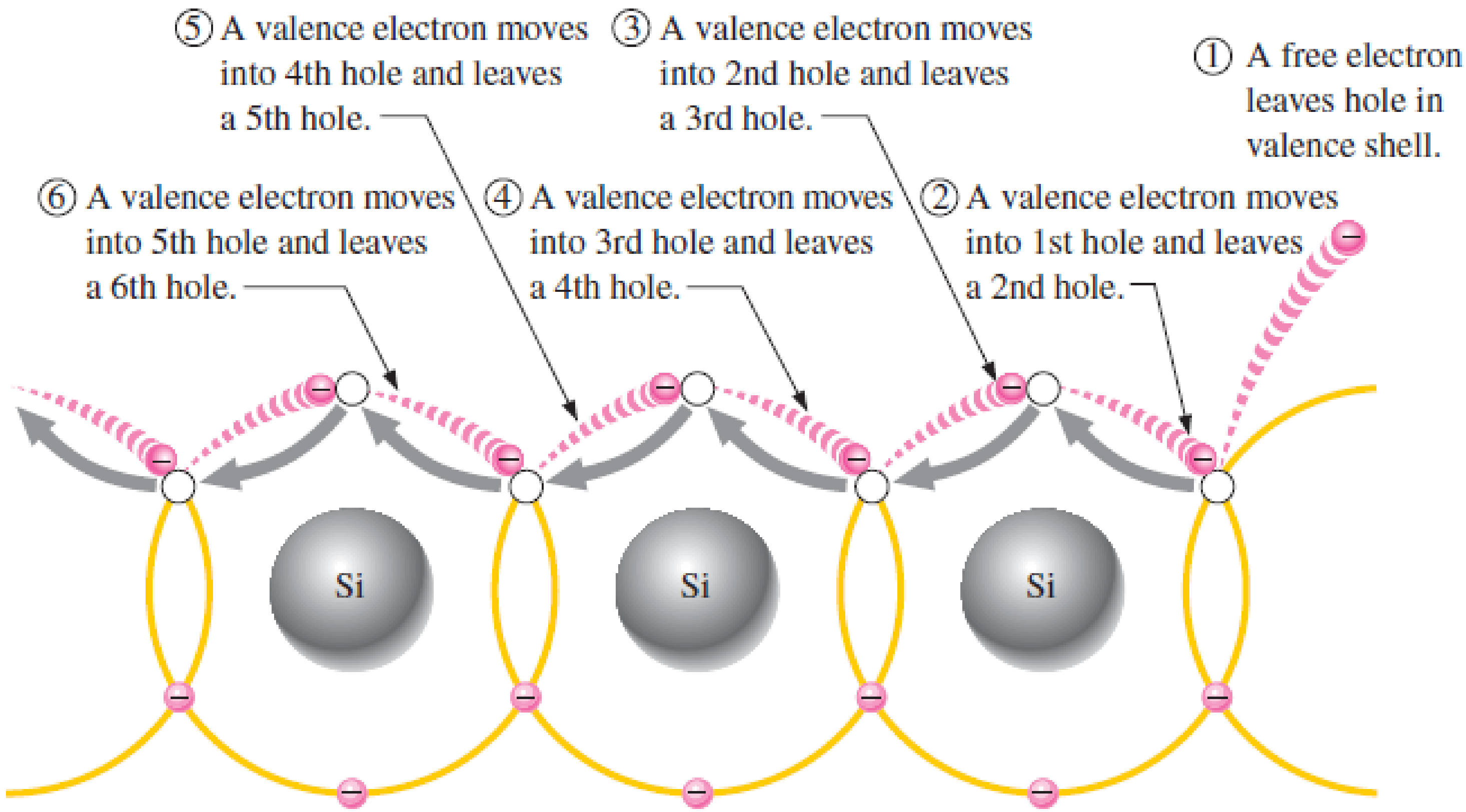
**In conduction band :** When a voltage is applied across a piece of intrinsic silicon, the thermally generated free electrons in the conduction band, are now easily attracted toward the positive end.




This movement of free electrons is one type of current in a semiconductive material and is called ***electron current.***

**In valance band:** In valance band holes generated due to free electrons. Electrons in the valance band are although still attached with atom and not free to move, however they can move into nearby hole with a little change in energy, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure. It is called ***hole current.***

# Electron Hole Current.




When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

# N-type semiconductor

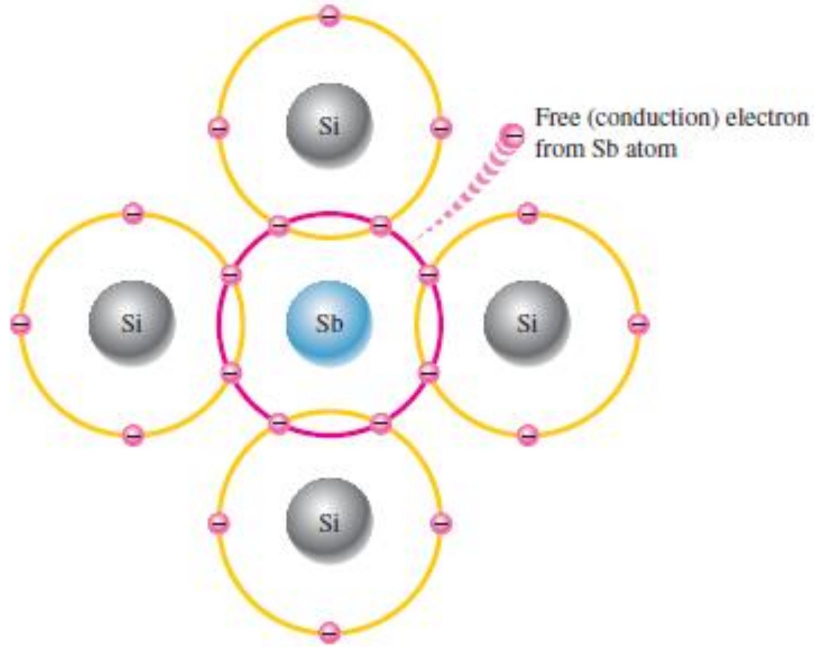
Electrons in the conduction band and holes in the valence band make the semiconductive material to conduct but they are too limited to make it a very good conductor..

Adding impurities in materials like Si or  Ge can drastically increase the conductivity of material. The process is called ***doping.***

Addition of  a penta-valent material icnreases the number of conduction  electrons.

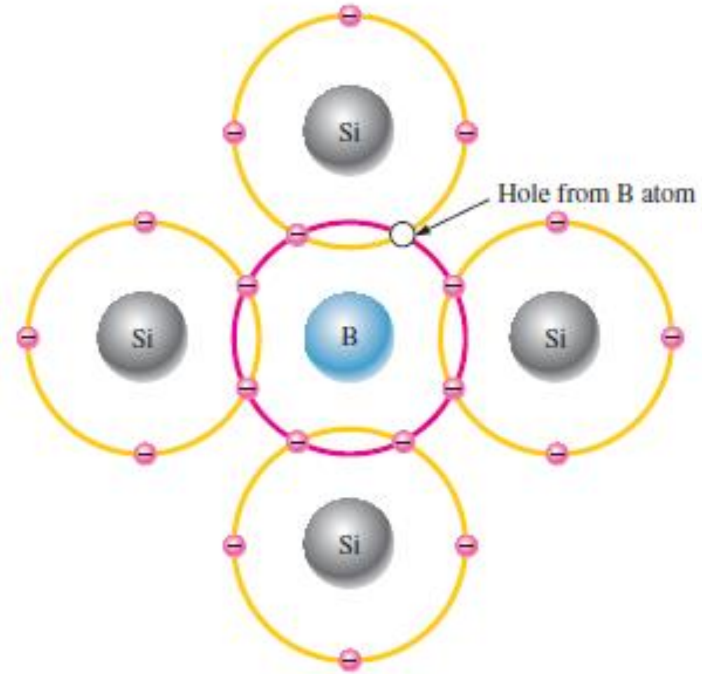
Majority carrier: electrons
Minority carriers: holes

Material is called ***N-type*** semiconductor




An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

# P-type semiconductor.




Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

Intrinsic semiconductors are those

A. Which are made of semiconductor material in its purest form

B. Which have zero energy gap

C. Which have more electrons than holes

D. Which are available locally

A.Which are made of semiconductor material in its purest form

Intrinsic semiconductor at room temperature will have, ................. available for conduction

A. Electrons
B. Holes
C. Both electrons and holes
D. None of the above

C.Both electrons and holes

A pure semiconductor behaves like an insulator at $0^0$ K because

A. There is no recombination of electrons with holes
B. Drift velocity of free electrons is very small
C. Free electrons are not available for current conduction
D. Energy possessed by electrons at that low temperature is almost zero

C.Free electrons are not available for current conduction

Which of the following is a semi-conductor

A. Diamond
B. Arsenic
C. Phosphorous
D. Gallium arsenide

D.Gallium arsenide

The energy gap is much more in silicon than in germanium because

A. It has less number of electrons
B. It has high atomic mass number
C. Its crystal has much stronger bonds called ionic bonds
D. Its valence electrons are more tightly bound to their parent nuclii

D.Its valence electrons are more tightly bound to their parent nuclii

A semiconductor in its purest form is called.......

A. Insulator
B. Superconductor
C. Intrinsic semiconductor
D. Extrinsic semiconductor

# C.Intrinsic semiconductor

A P-type semiconductor results when

A. A pentavalent impurity is added to an intrinsic semiconductor

B. A trivalent impurity is added to an intrinsic semiconductor

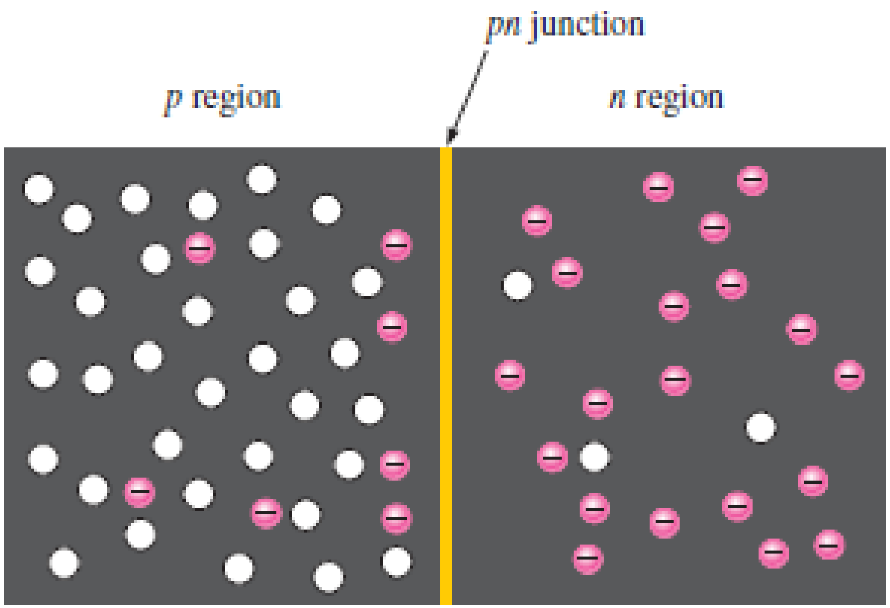
C. Either a pentavalent or trivalent impurity is added to an intrinsic semiconductor

D. None of the above

B.A trivalent impurity is added to an intrinsic semiconductor

# PN Junction

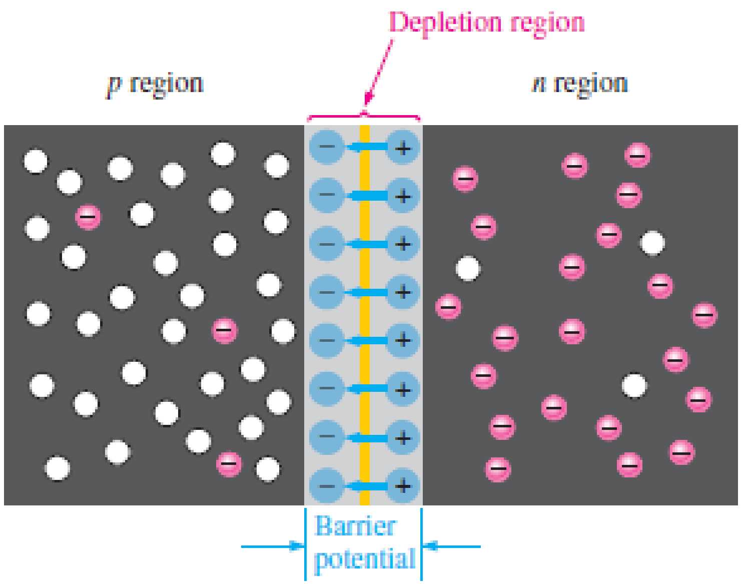
Although P-type material has holes in excess and N-type material has a number of free conduction electron however the net number of proton and electron are equal in each individual material keeping it just neutral.




The basic silicon structure at the instant of junction formation showing only the majority and minority carriers.

Free electrons in the *n region near the pn junction begin to diffuse across the* junction and fall into holes near the junction in the *p region.*

# PN Junction

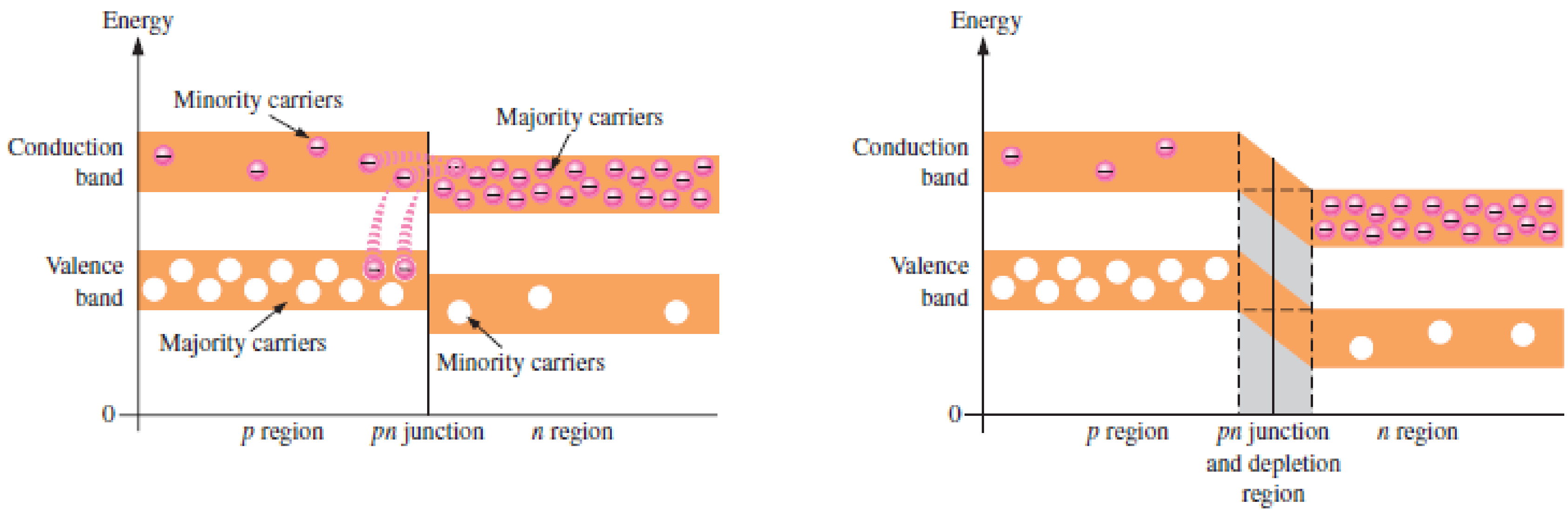



For every electron that diffuses across the junction and
combines with a hole, a positive charge is left in the *n region* and a negative charge is created in the *p region, forming a* barrier potential.

This action continues until the voltage of the barrier repels further diffusion.

The blue arrows between the positive and negative charges in the depletion region represent the electric field.

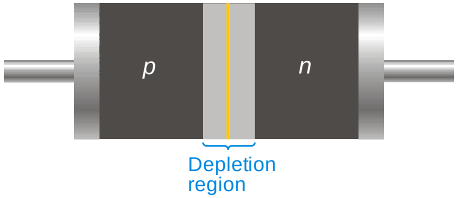
# Energy band and potential barrier

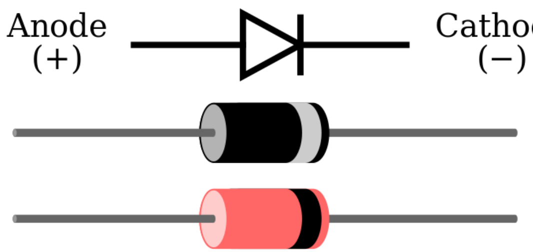


# Diodes

- Diode, semiconductor material, such as silicon, in which half is doped as p-region and half is doped as n-region with a pn-junction in between.

- The p region is called **anode** and n type region is called **cathode.**




Diode symbol

# Diodes

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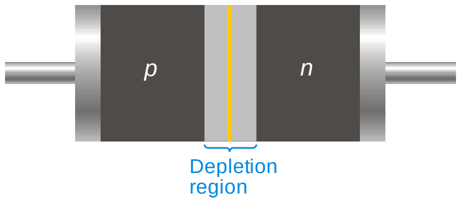
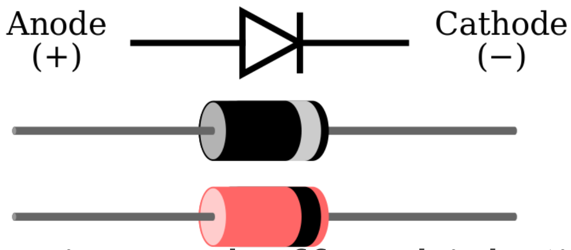


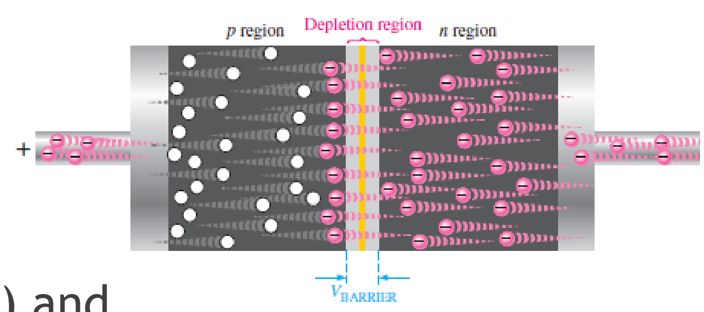




Diode symbol

- It conducts current in one direction and offers high (ideally infinite) resistance in other direction.

# Forward Biased

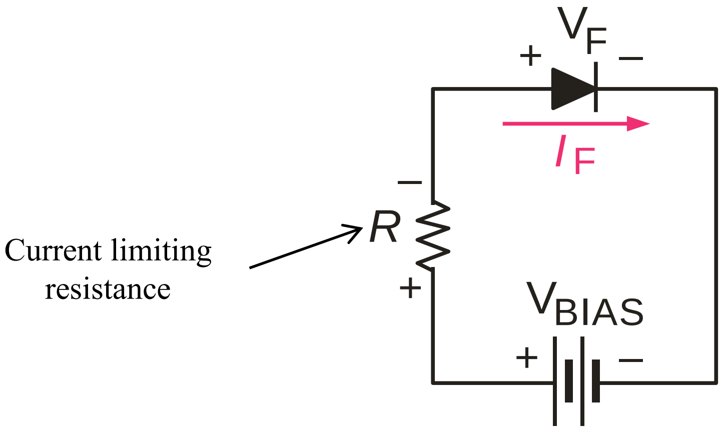
- Forward bias is a condition that allows current through pn junction.

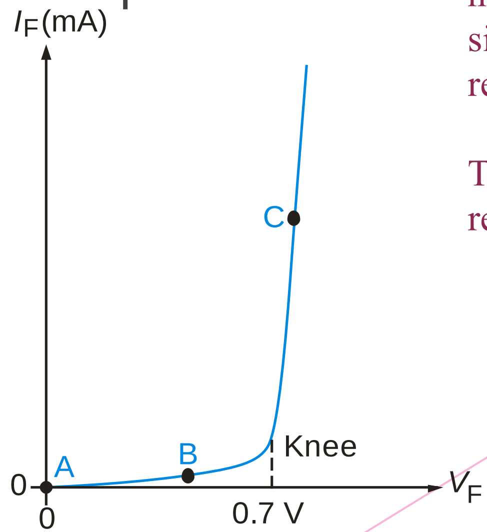



  - A dc voltage ($V_{bais}$) is applied to bias a diode.
  - Positive side is connected to p-region (anode) and negative side is connected with n-region.
  - $V_{bais}$ must be greater than 'barrier potential'

As more electrons flow into the depletion region reducing the number of positive ions and similarly more holes move in reducing the positive ions.

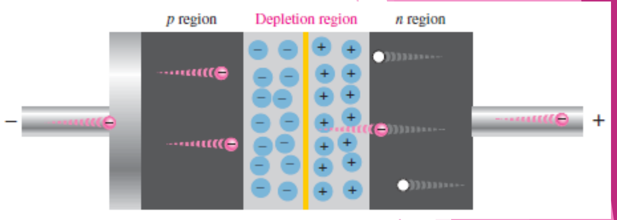
This reduces the width of depletion region.



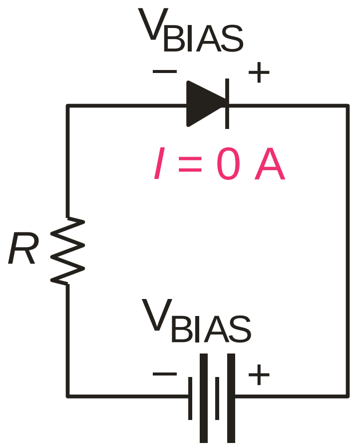
# Reverse Biased

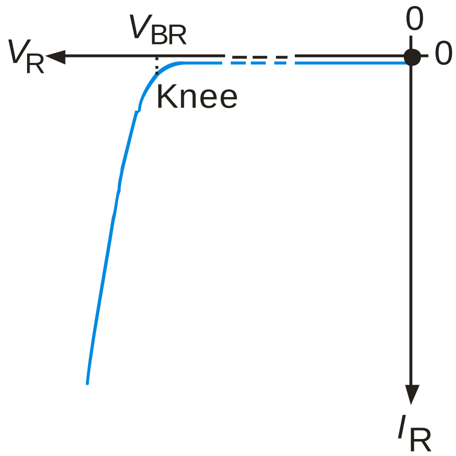
- Reverse bias is a condition that prevents current through junction.
- Positive side of $V_{bias}$ is connected to the n-region whereas the negative side is connected with p-region.
- Depletion region get wider with this configuration.



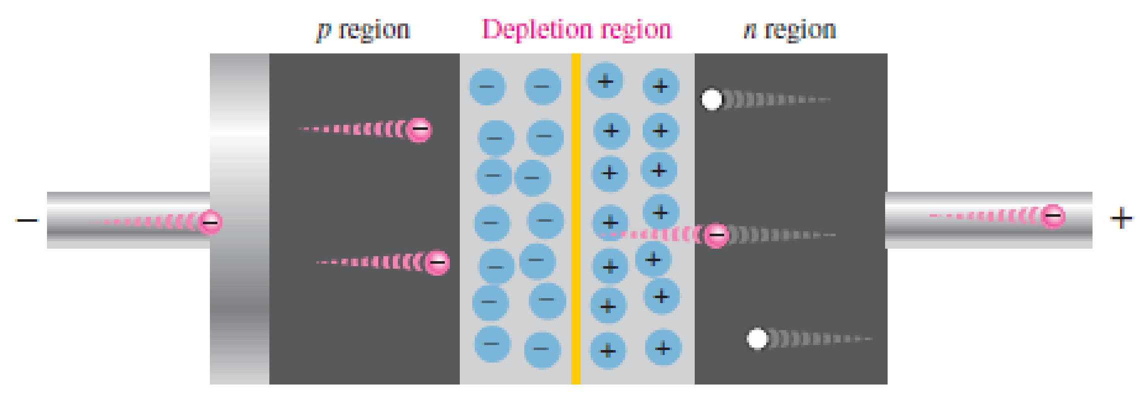

The positive side of bias voltage attracts the majority carriers of n-type creating more positive ions at the junction.

This widens the depletion region.



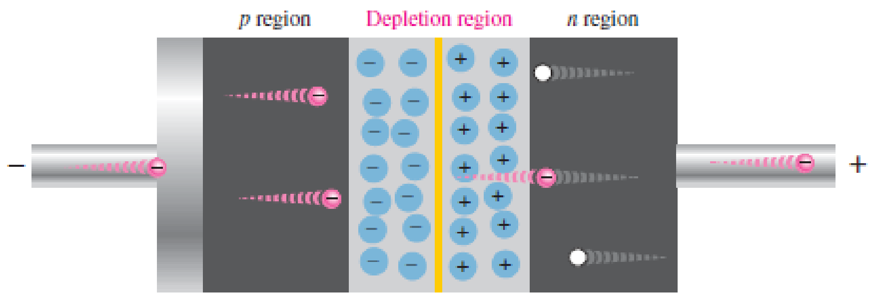



# Reverse Current




- A small amount current is generated due to the minority carriers in p and n regions.
- These minority carriers are produced due to thermally generated hole-electron pairs.
- Minority electrons in p-region pushed towards +ve bias voltage, cross junction and then fall in the holes in n-region and still travel in valance band generating a hole current.

# Reverse Breakdown

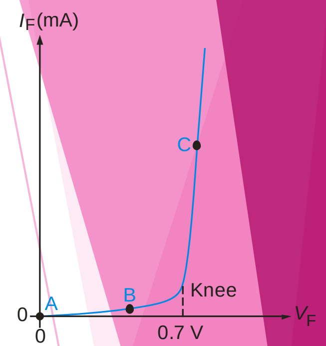


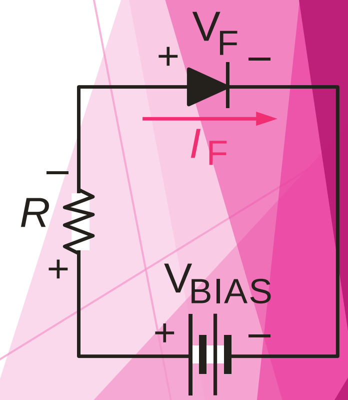

- If the external bias voltage is increased to a value call *breakdown voltage* the reverse current can increase drastically.
- Free minority electrons get enough energy to knock valance electron into the conduction band.
- The newly released electron can further strike with other atoms.
- The process is called ***avalanche effect***.

# Diode V-I Characteristic

- **VI Characteristic for forward bias.**

  - The current in forward biased called *forward current* and is designated $I_f$.
  - At 0V ($V_{bias}$) across the diode, there is no forward current.
  - With gradual increase of $V_{bias}$, the forward voltage and forward current increases.
  - A resistor in series will limit the forward current in order to protect the diode from overheating and permanent damage.
  - A portion of forward-bias voltage drops across the limiting resistor.
  - Continuing increase of $V_f$ causes rapid increase of forward current but only a gradual increase in voltage across diode.

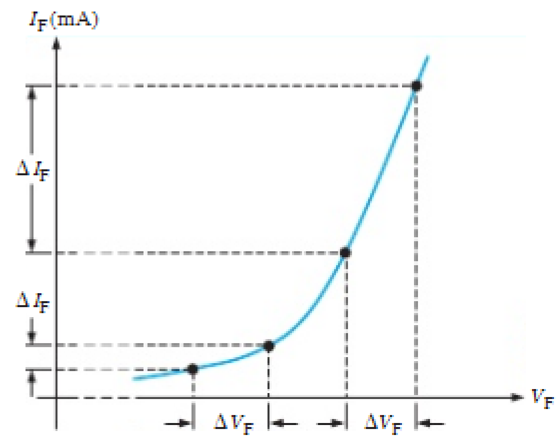


# Diode V-I Characteristic

❖ **Dynamic Resistance:**

- The resistance of diode is not constant but it changes over the entire curve. So it is called dynamic resistance.

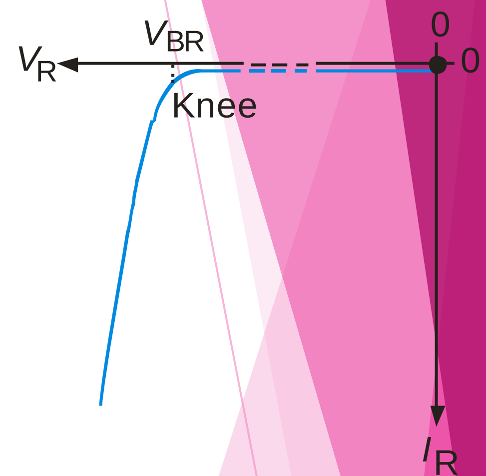



The dynamic resistance $r'_d$ decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F / \Delta I_F$.

# Diode V-I Characteristic

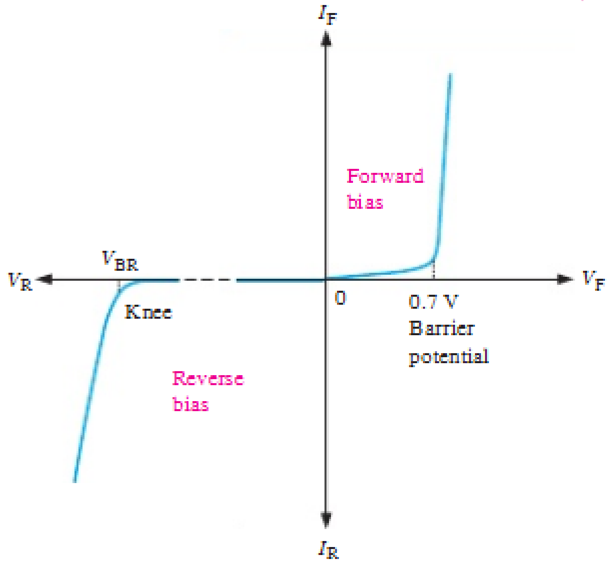
## VI Characteristic for reverse bias.

- With 0V reverse voltage there is no reverse current.
- There is only a small current through the junction as the reverse voltage increases.
- At a point, reverse current shoots up with the break down of diode. The voltage called break down voltage. This is not normal mode of operation.
- After this point the reverse voltage remains at approximately $V_{BR}$ but $I_R$ increase very rapidly.
- Break down voltage depends on doping level, set by manufacturer.



# Diode V-I Characteristic

- The complete V-I characteristic curve




The complete *V-I* characteristic curve for a diode.

The knee voltage of a diode approximately is equal to the

A. Breakdown voltage
B. Barrier potential
C. Applied voltage
D. Forward voltage

## B.Barrier potential

The peak inverse voltage (PIV) is applied across a diode when it is

A. Forward-biased
B. Reversed-biased
C. On a heat sink
D. ON

B.Reversed-biased

The turn-on voltage of a Ge junction diode is

A. 1.0 V
B. 0.3 V
C. 0.7 V
D. 0.1 V

B.0.3 V

In reverse biased diode, as the reverse voltage decreases the depletion region

A. Remains same
B. Decreases
C. Increases
D. Depends on doping

B.Decreases

The forward region of a semiconductor diode characteristic curve is where diode appears as

A. An OFF switch
B. A capacitor
C. A constant current source
D. An ON switch

D.An ON switch

For a PN diode, the number of minority carriers crossing the junction mainly depends on

A. Potential barrier
B. Forward bias voltage
C. Rate pf thermal generation of electron holes pairs
D. None of the above

C.Rate pf thermal generation of electron holes pairs

Which of the following are least mobile?

A. Electrons
B. Holes
C. Ions
D. None of the above

C.Ions

The current in reverse bias, in a P-N junction diode may be,

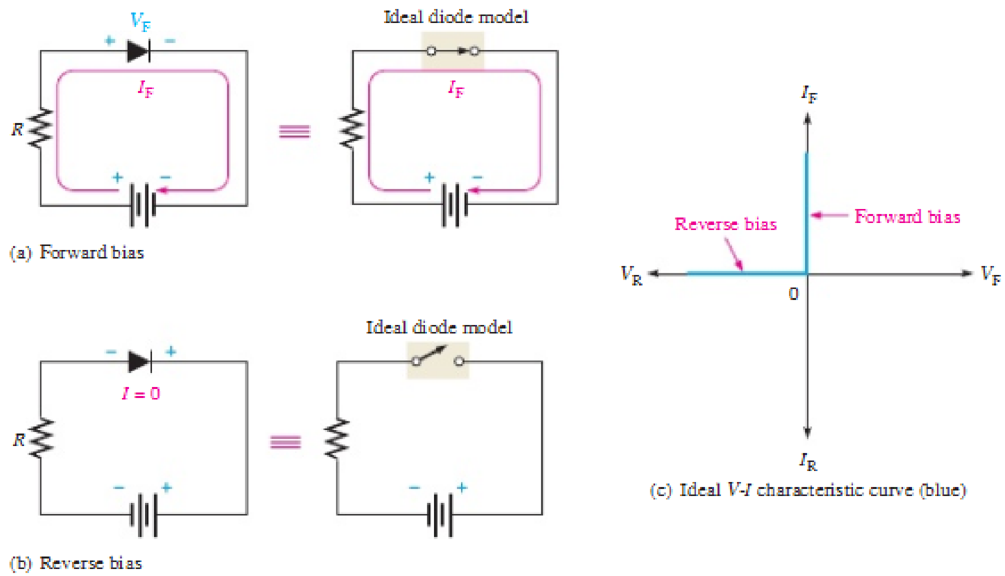
A. Few micro or nano amperes
B. Few miliamperes
C. Between 0.2 A and 2 A
D. None of the above

A.Few micro or nano amperes

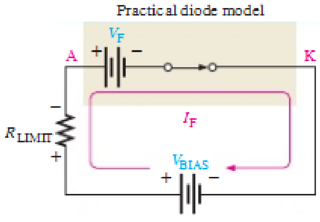
# Diode models

- **Ideal Diode Model**

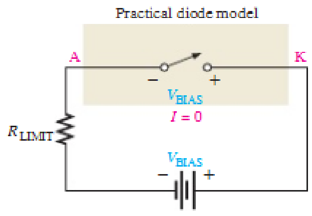
- Barrier potential, the forward dynamic resistance and reverse current all are neglected.



# Diode models




(a) Forward bias

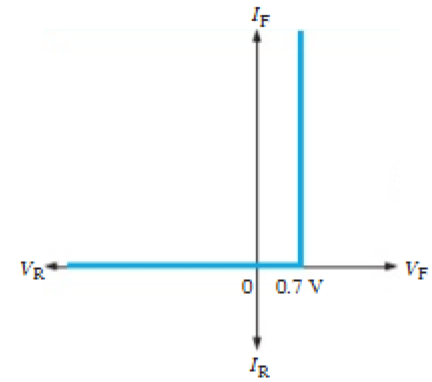



(b) Reverse bias

$V_F = 0.7V$

- **Practical Diode Model**

- Barrier potential, the forward dynamic resistance and reverse current all are neglected.




(c) Characteristic curve (silicon)

- Forward current $I_F$ is determined using Kirchhoff's voltage as follows:

$$V_{BIAS} - V_F - V_{R_{LIMIT}} = 0$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT}$$

Substituting and solving for $I_F$, $$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

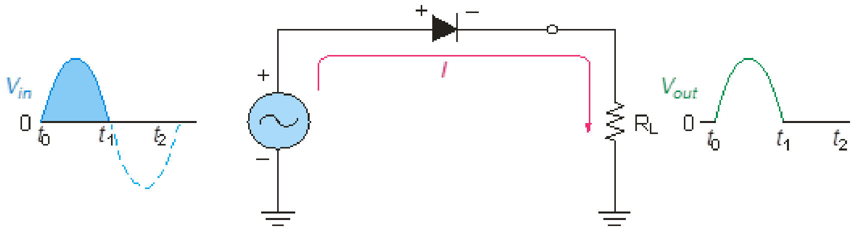
Ex)


$V > 0{,}7\,V \rightarrow$ Diode conducts $\rightarrow V_D = 0{,}7\,V$

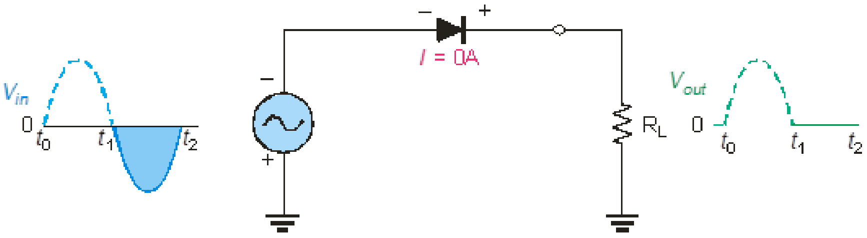
$$I = \frac{V_R}{R} = \frac{5 - 0{,}7}{1k} = \frac{4{,}3}{1k} = 4{,}3\ mA$$

# Half wave Rectifiers

- As diodes conduct current in one direction and block in other.
- When connected with ac voltage, diode only allows half cycle passing through it and hence convert ac into dc.
- As the half of the wave get rectified, the process called half wave rectification.

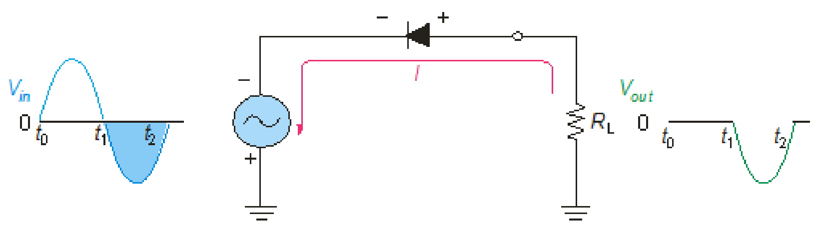



- A diode is connected to an ac source and a load resistor forming a half wave rectifier.
- Positive half cycle causes current through diode, that causes voltage drop across resistor.



# Diode as Rectifiers

- Reversing diode.




- Average value of Half wave output voltage:

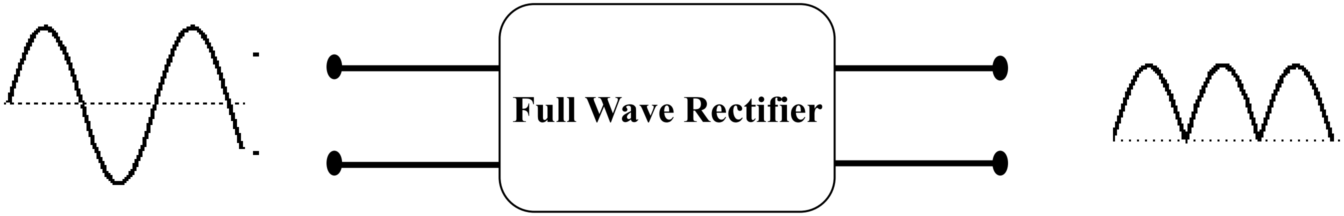
$$V_{AVG} = V_P \;/\; pi$$

- $V_{AVG}$ is approx 31.8% of $V_p$

- PIV: Peak Inverse Voltage = $V_p$

# Full wave rectifiers

- A full wave rectifier allows unidirectional current through the load during the entire 360 degree of input cycle.



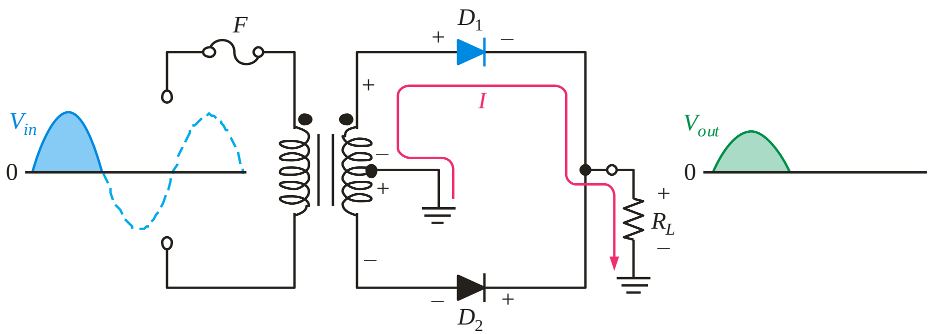

- The output voltage have twice the input frequency.

$$V_{AVG} = 2V_P / pi$$

- $V_{AVG}$ is 63.7% of Vp

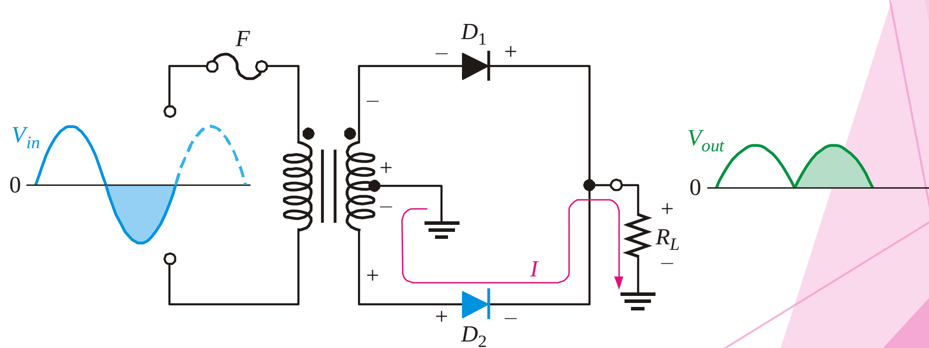
# The Center-Tapped Full wave rectifiers

- A center-tapped transformer is used with two diodes that conduct on alternating half-cycles.



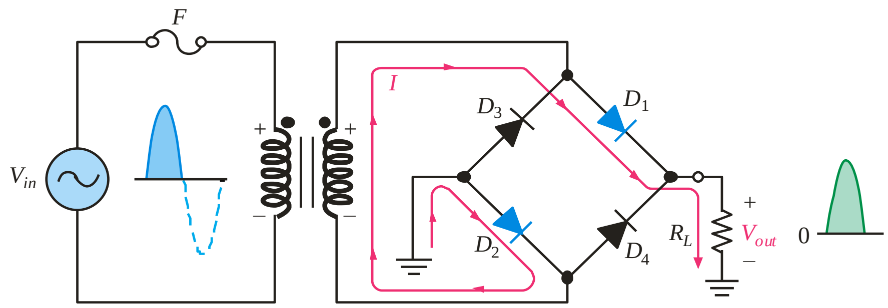

During the positive half-cycle, the upper diode is forward-biased and the lower diode is reverse-biased.

During the negative half-cycle, the lower diode is forward-biased and the upper diode is reverse-biased.



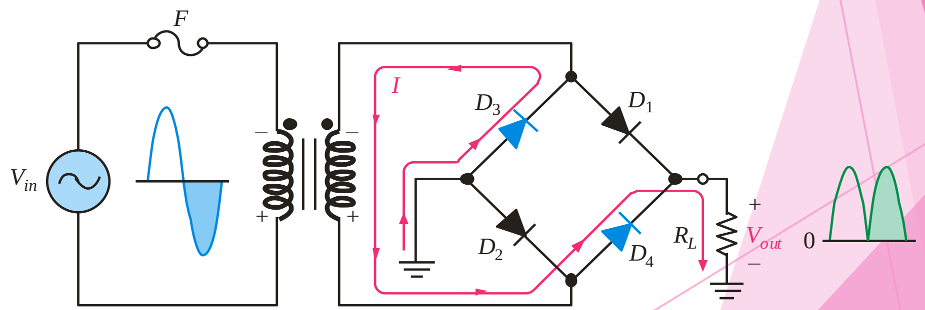
# The Bridge Full-wave rectifiers

- The Bridge Full-Wave rectifier uses four diodes connected across the entire secondary as shown.




Conduction path for the positive half-cycle.

Conduction path for the negative half-cycle.



# The Bridge Full-Wave Rectifier

**Example:**

Determine the peak output voltage and current in the 3.3 kΩ load resistor if $V_{sec} = 24\ \text{V}_{rms}$. Use the practical diode model.

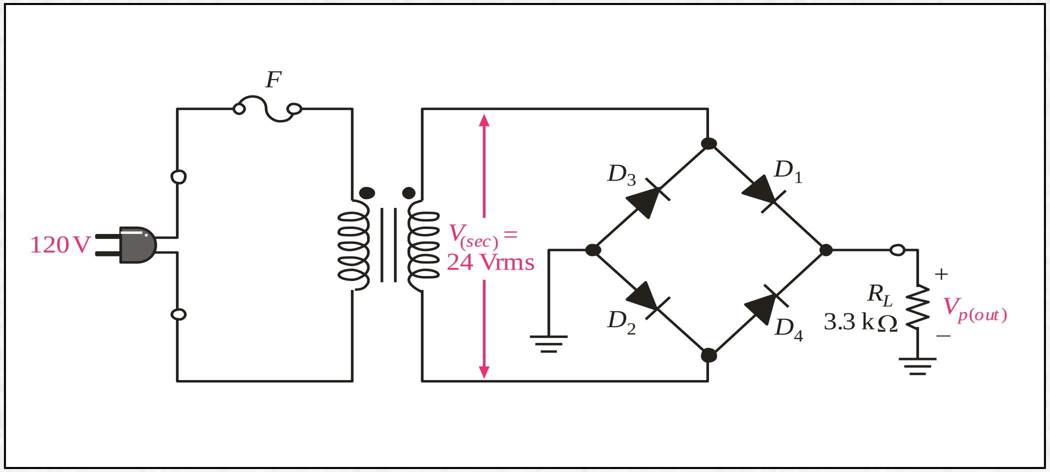
**Solution:**

The peak output voltage is:

$$V_{p(sec)} = 1.41 V_{rms} = 33.9\ \text{V}$$

$$V_{p(out)} = V_{p(sec)} - 1.4\ \text{V}$$

$$= 32.5\ \text{V}$$

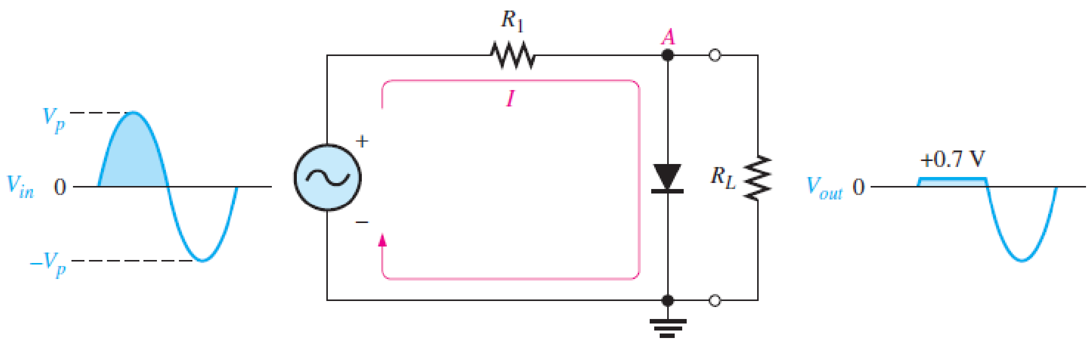



Applying Ohm's law,

$$I_{p(out)} = 9.8\ \text{mA}$$

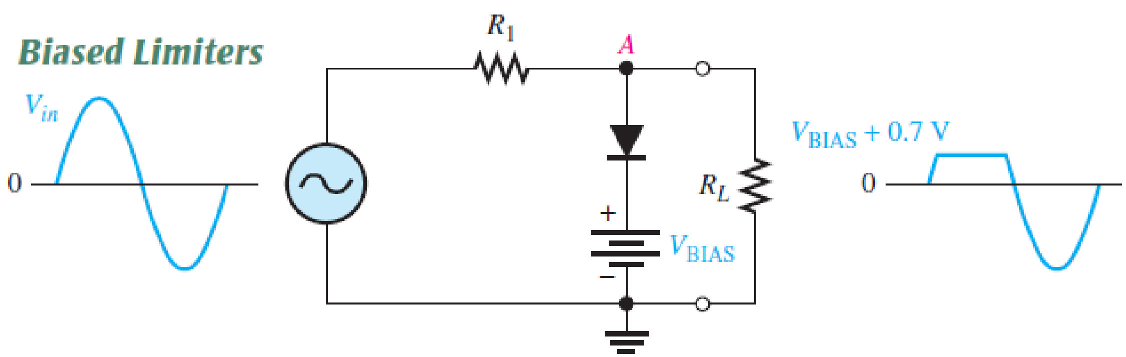
# Diode Limiters

- Diode circuits, called limiters or clippers, are used to clip off portions of signal voltages above or below certain levels.

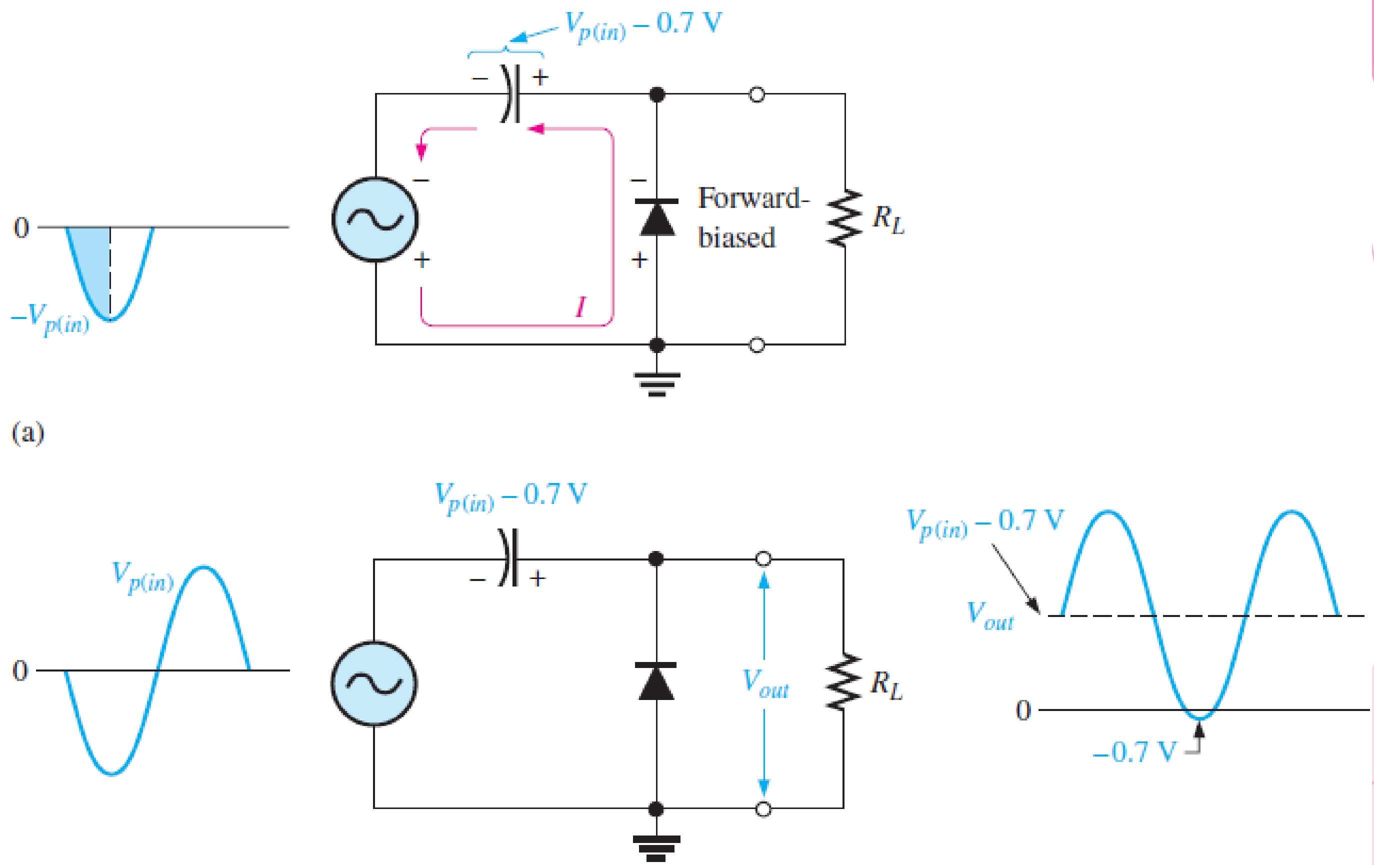



$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right)V_{in}$$

**Biased Limiters**

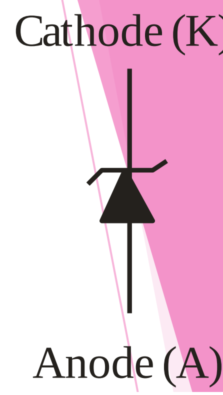


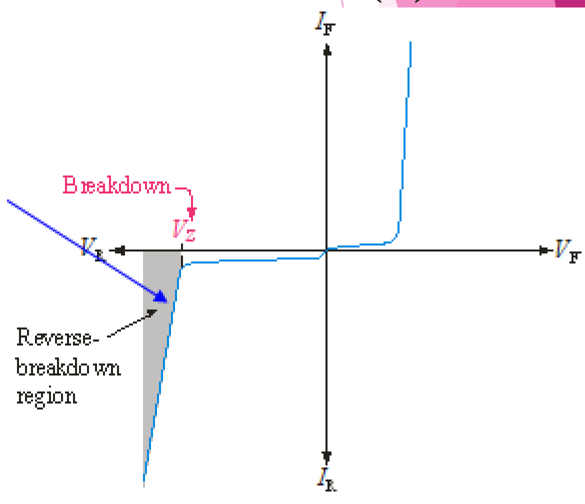
# Diode Clampers



# Zener Diodes

- A Zener diode is a silicon pn junction that is designed for operation in reverse-breakdown region
- When a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is key to the Zener diode operation.
- 

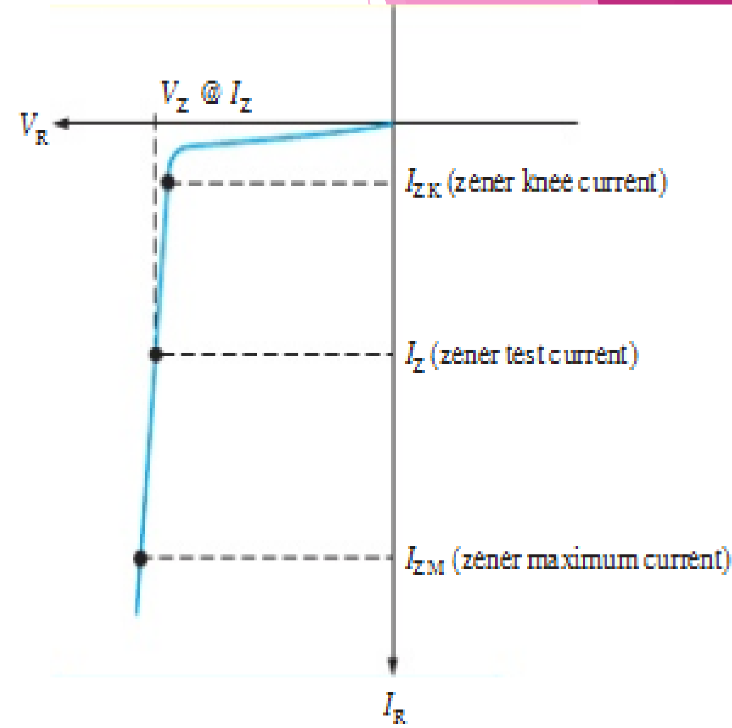



Characteristic curve

# Zener Breakdown Characteristic

- As the reverse voltage ($V_R$) increases, the reverse current($I_R$) remains extremely small up to the knee of the curve.
- Reverse current is also called Zener current($I_Z$).
- At knee point the breakdown effect begins, the internal Zener resistance ($Z_Z$) begins to decrease.
- The reverse current increase rapidly.
- The Zener breakdown ($V_Z$) voltage remains nearly constant.

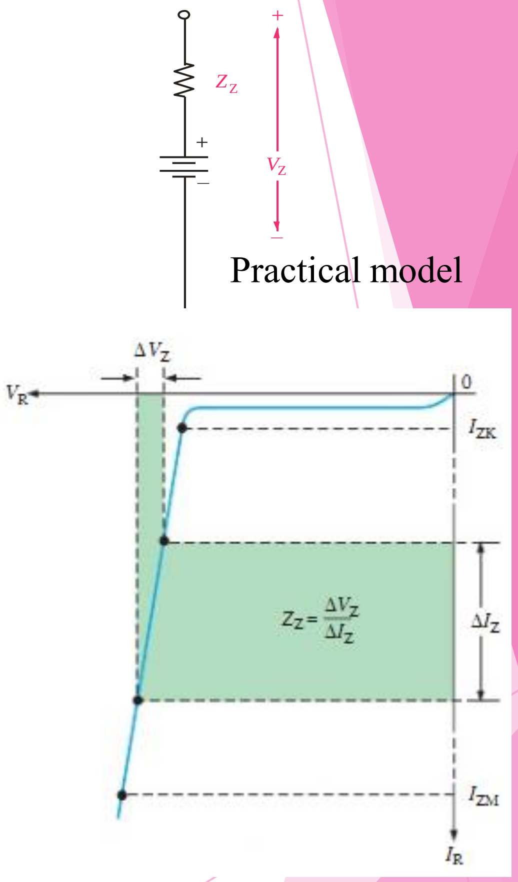



Reverse characteristic of a zener diode. $V_Z$ is usually specified at a value of the zener current known as the test current.

# Zener Diode Impedence

- The zener impedance, $Z_Z$, is the ratio of a change in voltage in the breakdown region to the corresponding change in current:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$




What is the zener impedance if the zener diode voltage changes from 4.79 V to 4.94 V when the current changes from 5.00 mA to 10.0 mA?

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{0.15\text{ V}}{5.0\text{ mA}} = 30\ \Omega$$

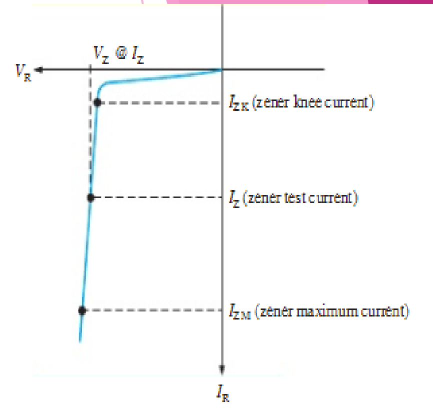
# Zener Regulation

- The ability to keep the reverse voltage constant across its terminal is the key feature of the Zener diode.

- It maintains constant voltage over a range of reverse current values.

- A minimum reverse current $I_{ZK}$ must be maintained in order to keep diode in regulation mode. Voltage decreases drastically if the current is reduced below the knee of the curve.

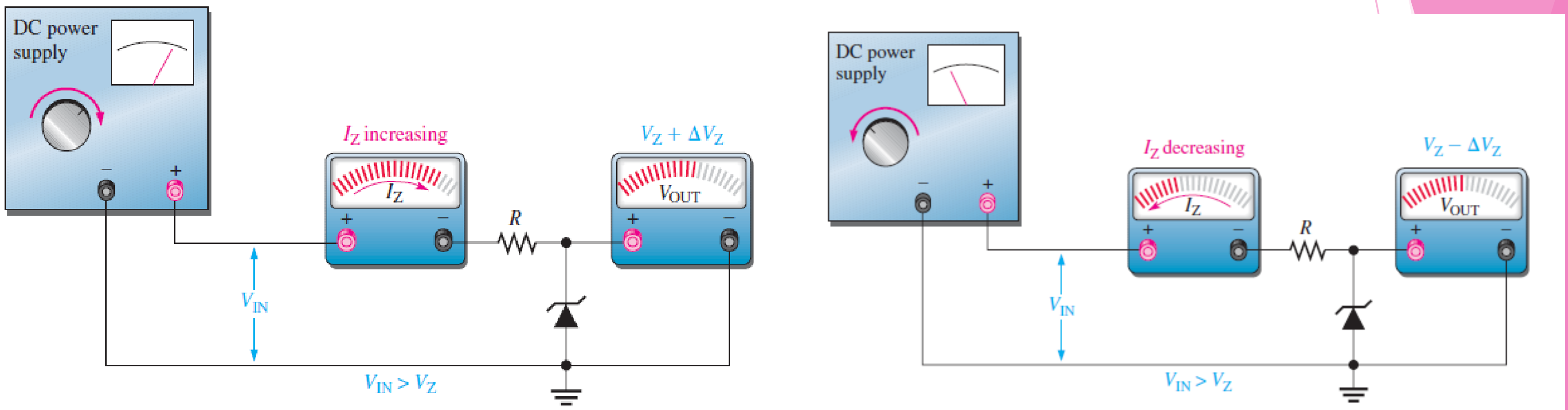
- Above $I_{ZM}$, max current, the Zener may get damaged permanently.




Reverse characteristic of a zener diode. $V_Z$ is usually specified at a value of the zener current known as the test current.

# Zener Regulation

- Zener Regulation with variable input voltage:

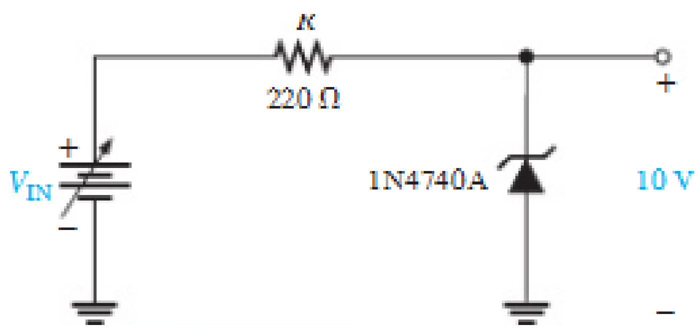



As the input voltage changes, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

# Zener Regulation

❖ Zener Regulation with variable input voltage

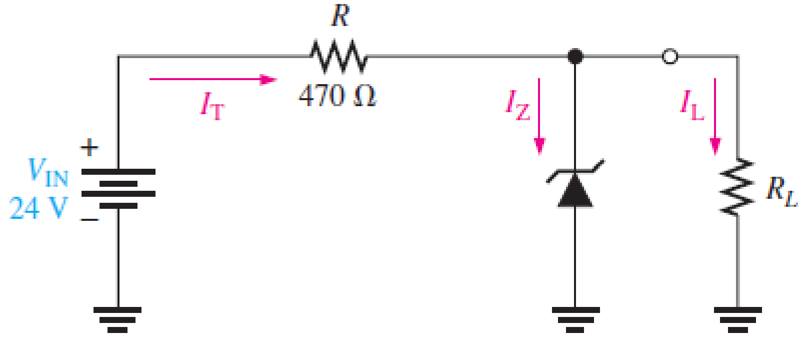
- Ideal model of IN4047A
- $I_{ZK}$ = 0.25mA
- $V_Z$ = 10V
- $P_{D(max)}$ = 1W




Vin(min) = 10.55V
Vin(max) = 32V

# Zener Regulation

- Zener Regulation with variable load




It maintains voltage a nearly constant across RL as long as Zener current is within IZK and IZM.

$V_Z = 12$ V,
$I_{ZK} = 1$ mA,
$I_{ZM} = 50$ mA.

Zener diode is a

A. Reserve biased diode
B. Variable voltage source
C. Constant current source
D. Forward biased diode

A.Reserve biased diode

When biased correctly, a zener diode

A. Never overheats
B. Has a constant voltage across it
C. Has a constant current passing through it
D. Acts as a fixed resistance

B.Has a constant voltage across it

When the temperature of a P-N junction rises........will increase

A. Reverse leakage current
B. Width of depletion layer
C. Junction barrier voltage
D. All of the above

## A.Reverse leakage current

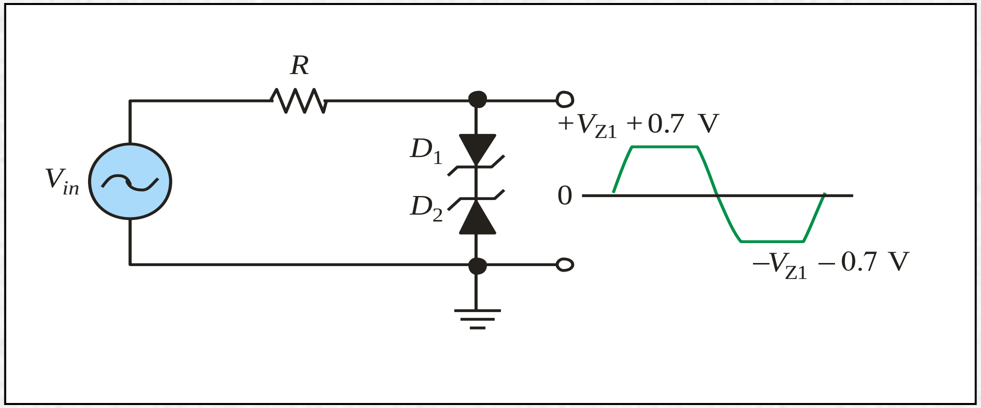
Application of forward bias to a junction diode

A. Reduces forward current
B. Reduces minority carrier current
C. Reduces potential barrier height
D. All of the above

C.Reduces potential barrier height

## Zener Diode Applications

Zeners can also be used as limiters. The back-to-back zeners in this circuit limit the output to the breakdown voltage plus one diode drop.




**Question:**

What are the maximum positive and negative voltages if the zener breakdown voltage is 5.6 V?

$\pm 6.3$ V

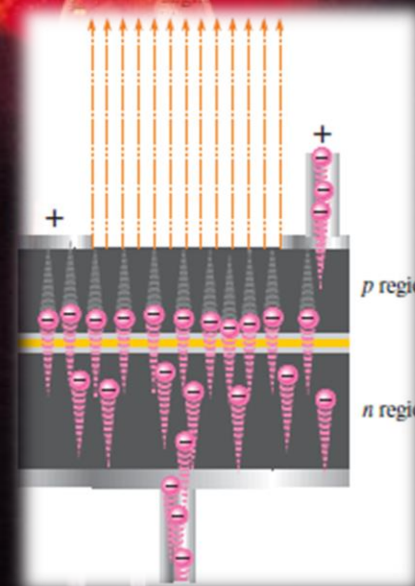
# Optical Diodes

- *Light Emitting Diodes* (LEDs): Diodes can be made to emit light electroluminescence) or sense light.

- When forward biased electrons form n-region cross the junction and recombines to holes with the emission of  photons.

- Various impurities are added during the doping process to establish the wavelength of the emitted light.

- The process is called electroluminescence.



# Light Emitting Diodes

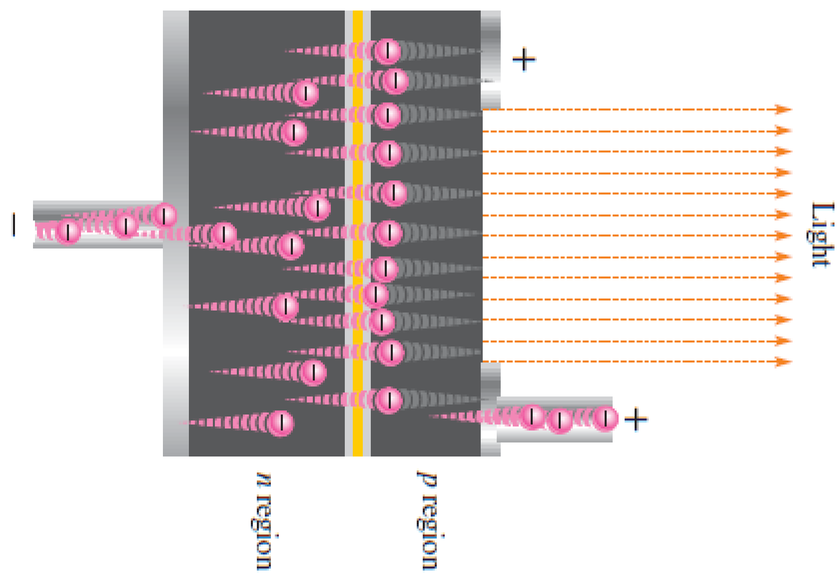
- LEDs vary widely in size and brightness – from small indicating lights and displays to high-intensity LEDs that are used in traffic signals, outdoor signs, and general illumination.

- LEDs are very efficient light emitters, and extremely reliable, so domain of uses getting wider.

# Light Emitting Diodes

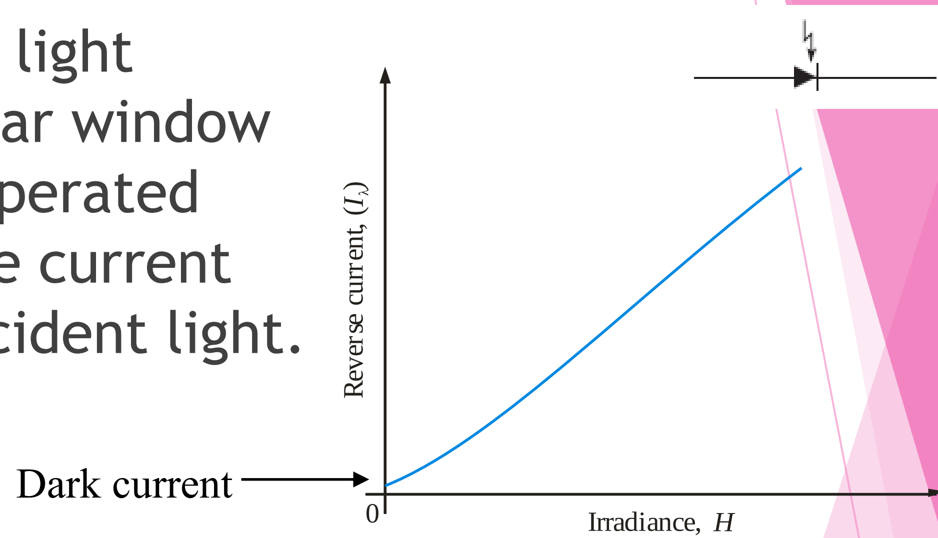
- When the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material.

- The difference in energy between the electrons and the holes corresponds to the energy of visible light

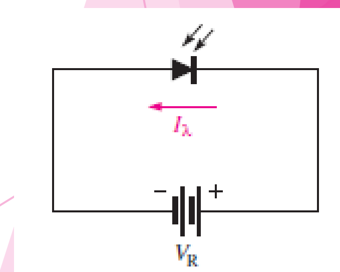


# Photo Diode

- A **photodiode** is a special light sensitive diode with a clear window to the *pn* junction. It is operated with reverse bias. Reverse current increases with greater incident light.



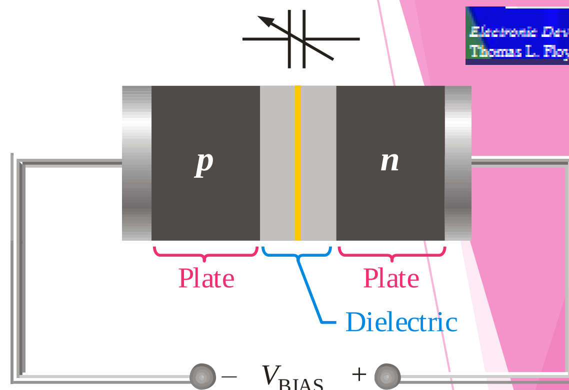

- The tiny current that is present when the diode is not exposed to light is called **dark current**



# Varactor Diode

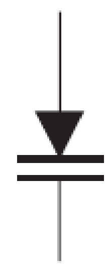
- A **varactor diode** is a special purpose diode operated in reverse-bias to form a voltage-controlled capacitor. The width of the depletion region increases with reverse-bias.

- Varactor diodes are used in tuning applications. The applied voltage controls the capacitance and hence the resonant frequency.




*Electronic Devices, 9th edition*
Thomas L. Floyd

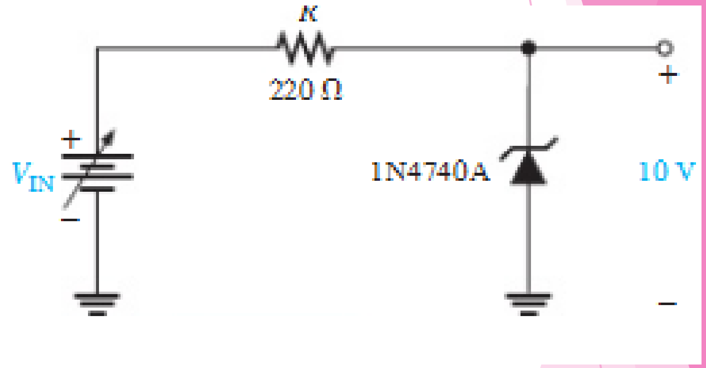
$$C = \frac{A\epsilon}{d}$$



# Zener Regulation

- Zener Regulation with variable input voltage

  - Ideal model of IN4047A
  - $I_{ZK}$ = 0.25mA
  - $V_Z$ = 10V
  - $P_{D(max)}$ = 1W, $I_{ZM}$ = 1W / 10V = 100mA




For the minimum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZK}R = (0.25\ \text{mA})(220\ \Omega) = 55\ \text{mV}$$

Since $V_R = V_{IN} - V_Z$,

$$V_{IN(min)} = V_R + V_Z = 55\ \text{mV} + 10\ \text{V} = 10.055\ \text{V}$$

For the maximum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZM}R = (100\ \text{mA})(220\ \Omega) = 22\ \text{V}$$

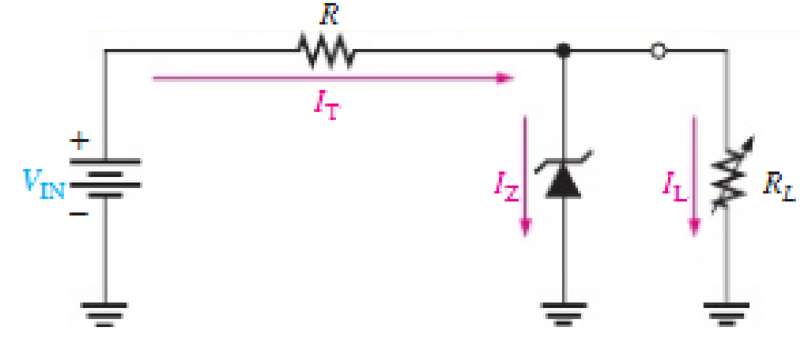
Therefore,

$$V_{IN(max)} = 22\ \text{V} + 10\ \text{V} = 32\ \text{V}$$

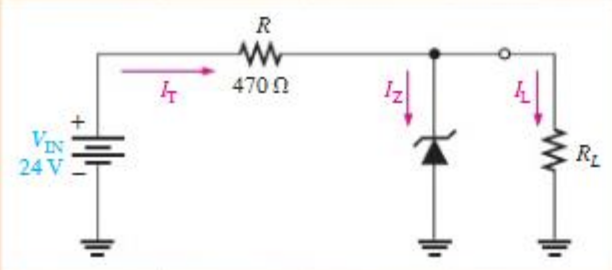
This shows that this zener diode can ideally regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output. The output will vary slightly because of the zener impedance, which has been neglected in these calculations.

# Zener Regulation

- Zener Regulation with variable load
  - It maintains voltage a nearly constant across RL as long as Zener current is within IZK and IZM.




Determine the minimum and the maximum load currents for which the zener diode in Figure 3–14 will maintain regulation. What is the minimum value of $R_L$ that can be used? $V_Z = 12\text{ V}$, $I_{ZK} = 1\text{ mA}$, and $I_{ZM} = 50\text{ mA}$. Assume an ideal zener diode where $Z_Z = 0\ \Omega$ and $V_Z$ remains a constant 12 V over the range of current values, for simplicity.




When $I_L = 0\text{ A}$ ($R_L = \infty$), $I_Z$ is maximum and equal to the total circuit current $I_T$.

$$I_{Z(max)} = I_T = \frac{V_{IN} - V_Z}{R} = \frac{24\text{ V} - 12\text{ V}}{470\ \Omega} = 25.5\text{ mA}$$

If $R_L$ is removed from the circuit, the load current is 0 A. Since $I_{Z(max)}$ is less than $I_{ZM}$, 0 A is an acceptable minimum value for $I_L$ because the zener can handle all of the 25.5 mA.

$$I_{L(min)} = \mathbf{0\ A}$$

The maximum value of $I_L$ occurs when $I_Z$ is minimum ($I_Z = I_{ZK}$), so

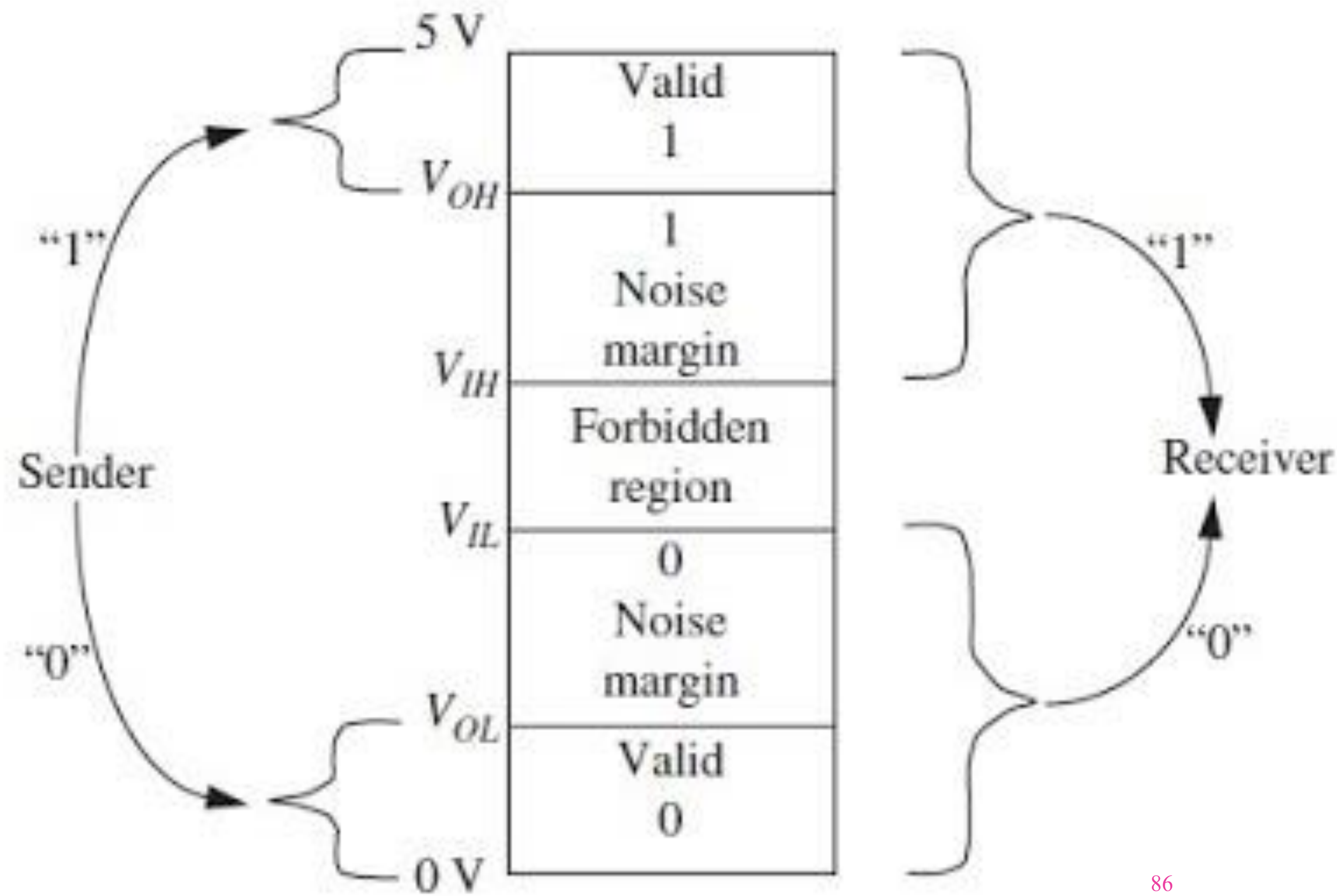
$$I_{L(max)} = I_T - I_{ZK} = 25.5\text{ mA} - 1\text{ mA} = \mathbf{24.5\ mA}$$

The minimum value of $R_L$ is

$$R_{L(min)} = \frac{V_Z}{I_{L(max)}} = \frac{12\text{ V}}{24.5\text{ mA}} = \mathbf{490\ \Omega}$$

Therefore, if $R_L$ is less than 490 Ω, $R_L$ will draw more of the total current away from the zener and $I_Z$ will be reduced below $I_{ZK}$. This will cause the zener to lose regulation. Regulation is maintained for any value of $R_L$ between 490 Ω and infinity.

# Voltage Levels and Static Discipline



- To send a logical 0, the sender must produce an output voltage value that is less than VOL. Correspondingly, the receiver must interpret input voltages below VIL as a logical 0.
- Similarly, to send a logical 1, the sender must produce an output voltage value that is greater than VOH. Further, the receiver must interpret voltages above VIH as a logical 1.
- Noise Margin: The absolute value of the difference between the prescribed output voltage for a given logical value and the corresponding forbidden region voltage threshold for the receiver is called the noise margin for that logical value.
- NM0 = VIL − VOL
- NM1 = VOH − VIH
- The static discipline is a specification for digital devices. The static discipline requires devices to interpret correctly voltages that fall within the input thresholds (VIL and VIH). As long as valid inputs are provided to the devices, the discipline also requires the devices to produce valid output voltages that satisfy the output thresholds (VOL and VOH).