Devices and Basic Circuits [Diode Circuits]

Overview

- Introduction
- What are P-type and N-type semiconductors??
- What are Diodes?
- Forward Bias & Reverse Bias
- Characteristics Of Ideal Diode
- Shockley Equation
- I – V Characteristics of Diodes

Introduction

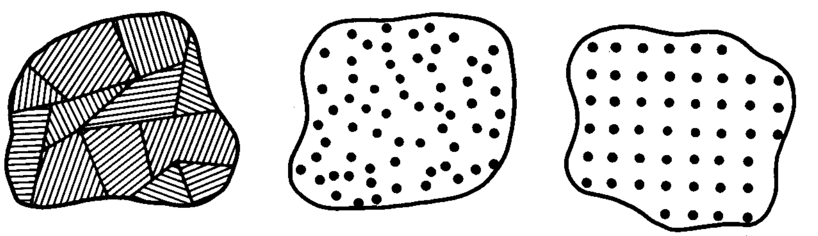
Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

Ex : Silicon and Germanium

What is a Semiconductor ?

- **V=IR , If we measure the current I flowing through a bar of a homogenous material with uniform cross section, when a voltage V is applied across it. R=V/I**
- **Resistivity is a basic property of the material is related to the resistance of bar by a geometric ratio: $\rho=RA/L$**

- Low resistivity => "conductor" $10^{-6}\,\Omega$ cm (Al, Cu…)
- High resistivity => "insulator" non-crystalline 10^{16} -$10^{18}\,\Omega$ cm SiO_2….)
- Intermediate resistivity => "semiconductor"
  - conductivity lies between that of conductors and insulators
  - generally crystalline in structure for IC devices
    - In recent years, however, semiconductors have become commercially very important



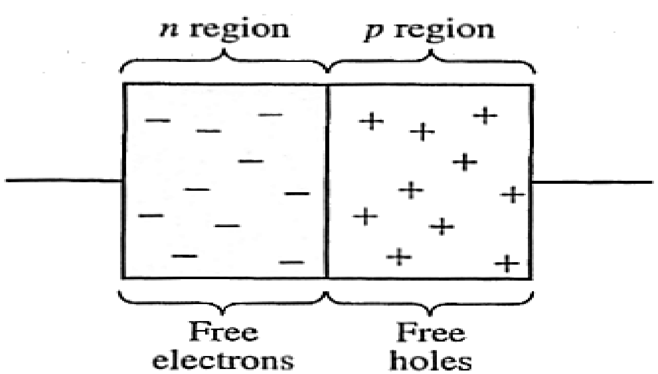
polycrystalline amorphous crystalline

What are P-type and N-type ?

- Semiconductors are classified in to P-type and N-type semiconductor
- P-type: A P-type material is one in which holes are majority carriers i.e. they are positively charged materials (++++)
- N-type: A N-type material is one in which electrons are majority charge carriers i.e. they are negatively charged materials (-----)

Diodes:

Electronic devices created by bringing together a *p*-type and *n*-type region within the same semiconductor lattice. Used for rectifiers, LED etc

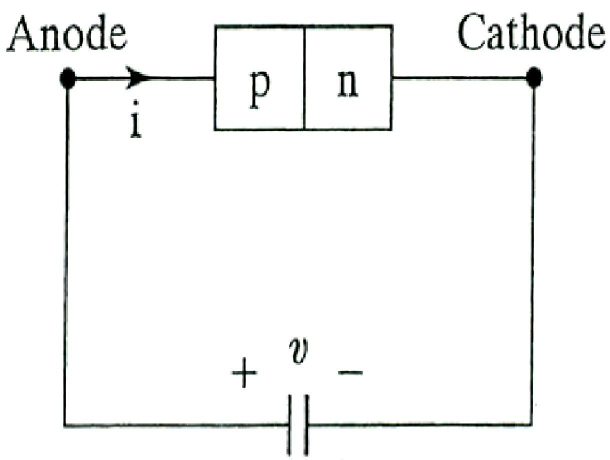


DIODE CIRCUITS AND THEIR APPLICATIONS

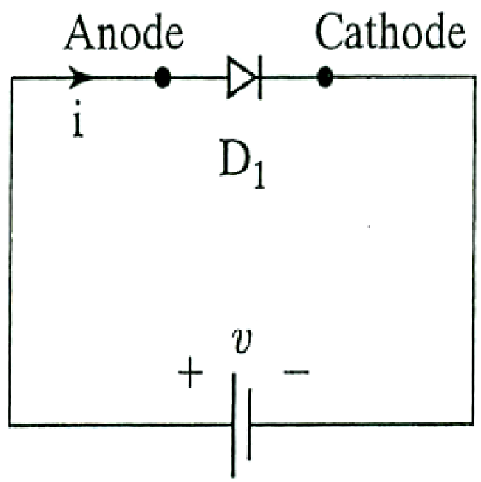
- **A diode is a two-terminal pn-junction device.**

- **A diode can be considered to be an electrical one-way valve.**

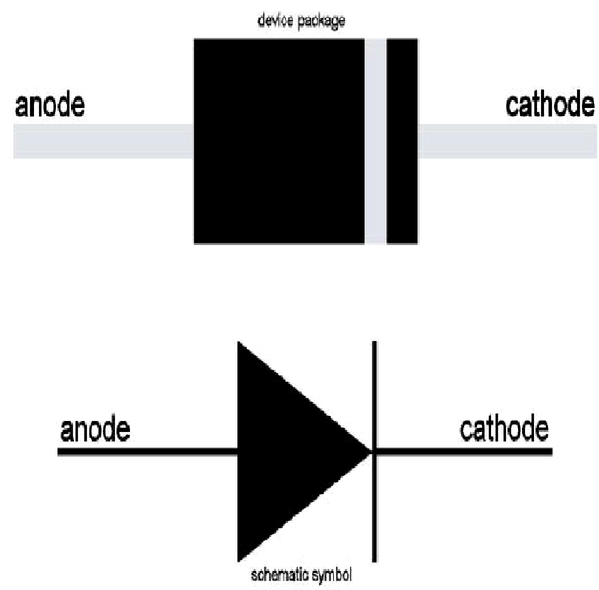
- **They are made from a large variety of materials including silicon, germanium, gallium arsenide, silicon carbide …**



(a) pn-junction

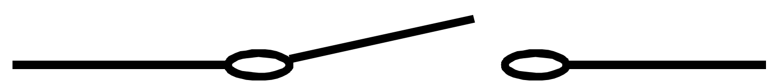


(b) Diode symbol

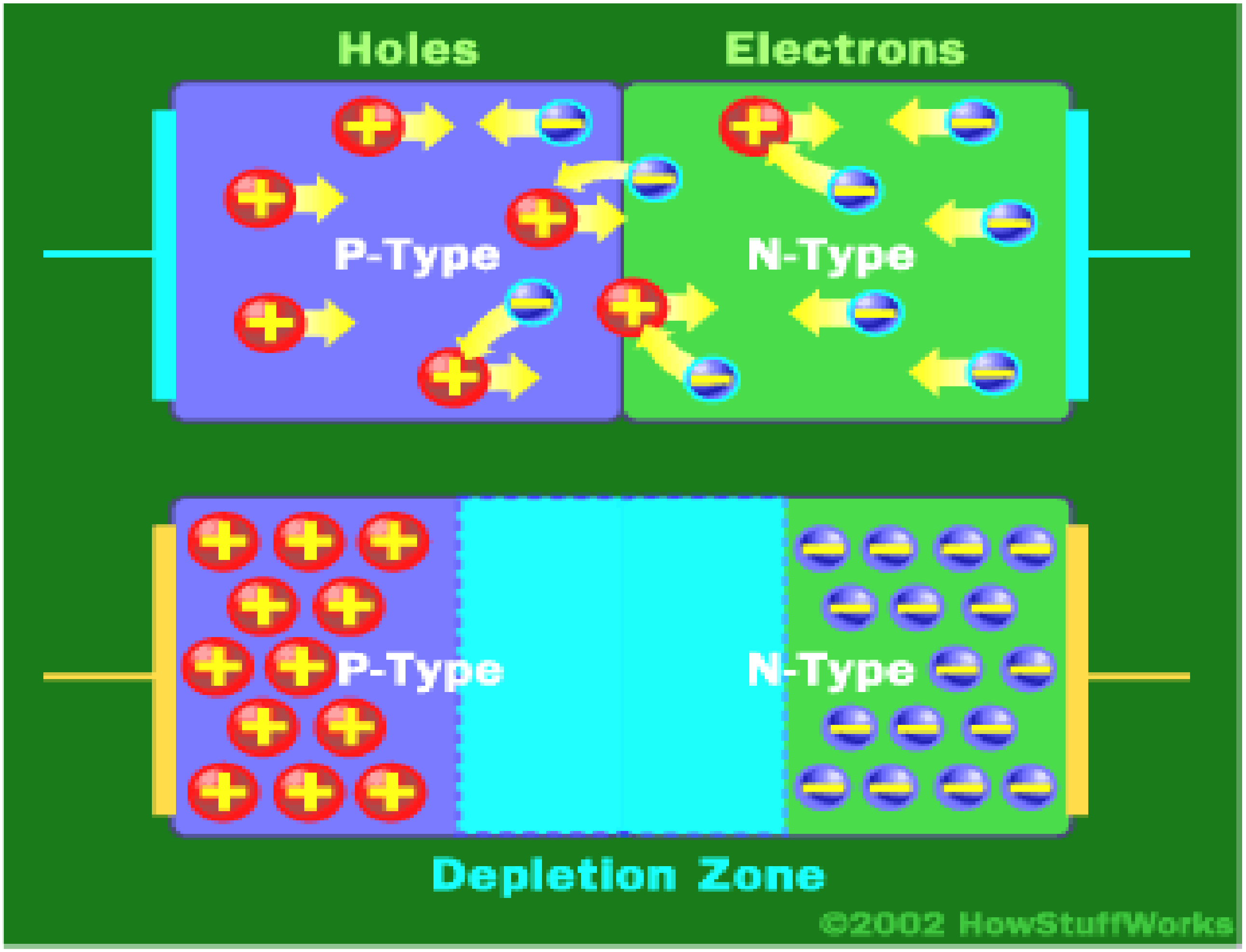


Forward biased

Reverse biased



How Diodes Work

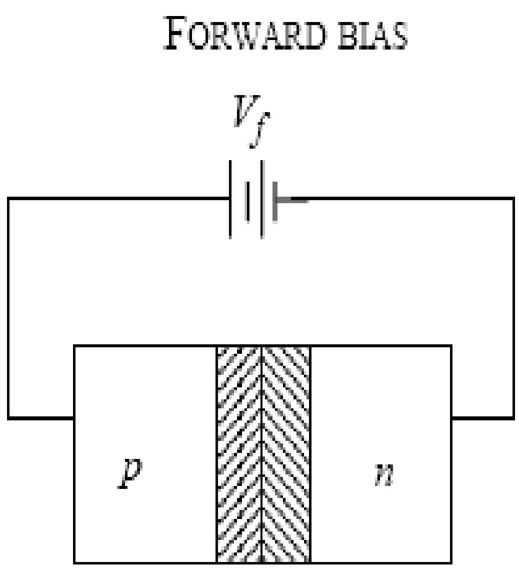


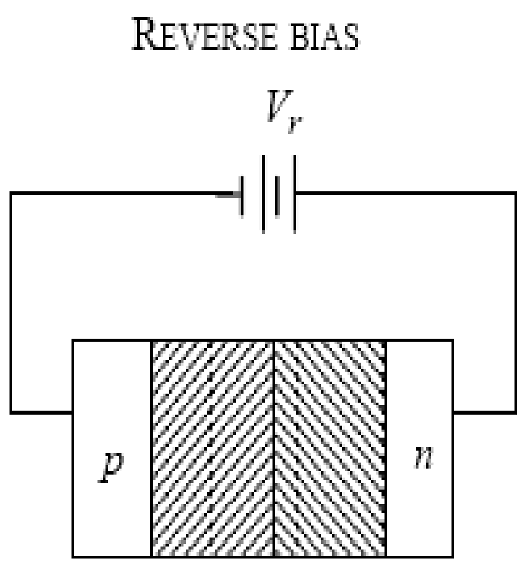
At the junction, free electrons from the N-type material fill holes from the P-type material. This creates an insulating layer in the middle of the diode called the depletion zone.

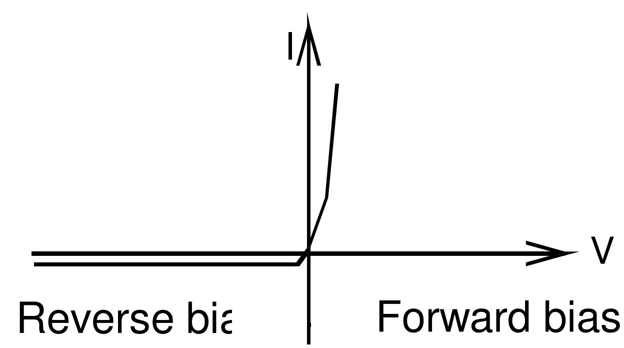
Forward Bias and Reverse Bias

- Forward Bias : Connect positive of the Diode to positive of supply…negative of Diode to negative of supply

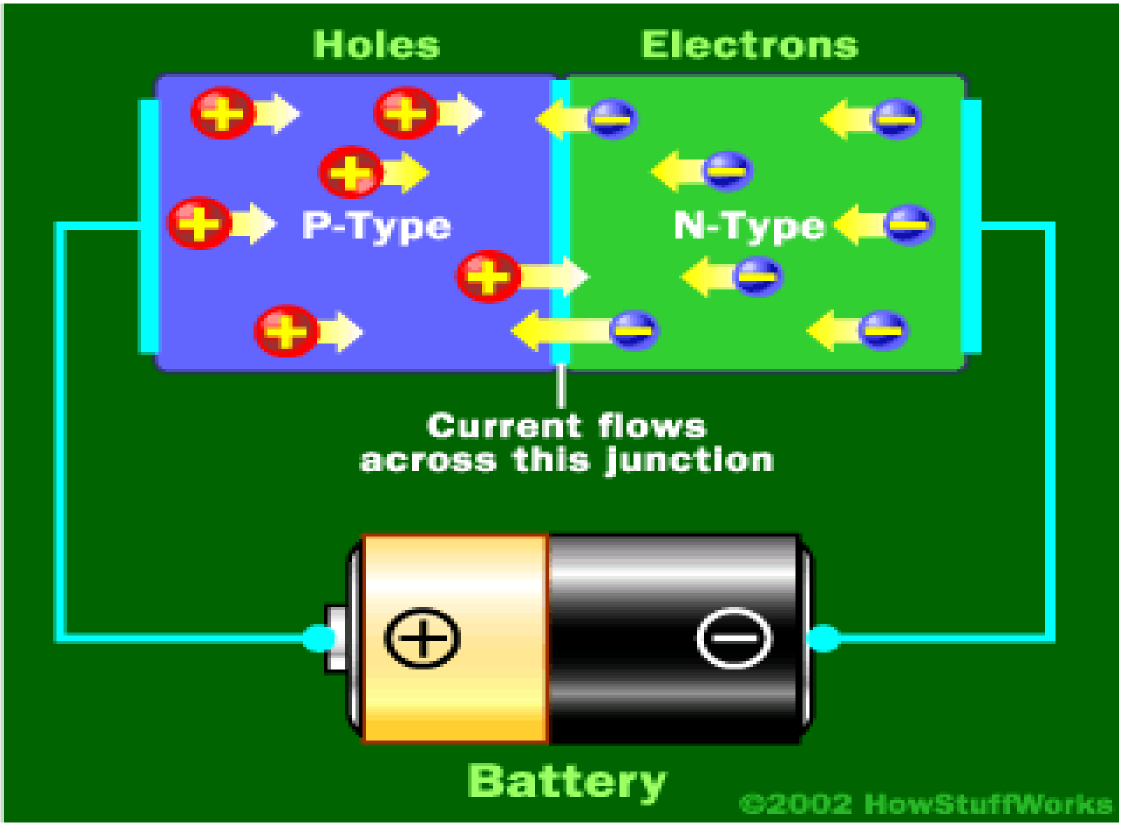
- Reverse Bias: Connect positive of the Diode to negative of supply…negative of diode to positive of supply.





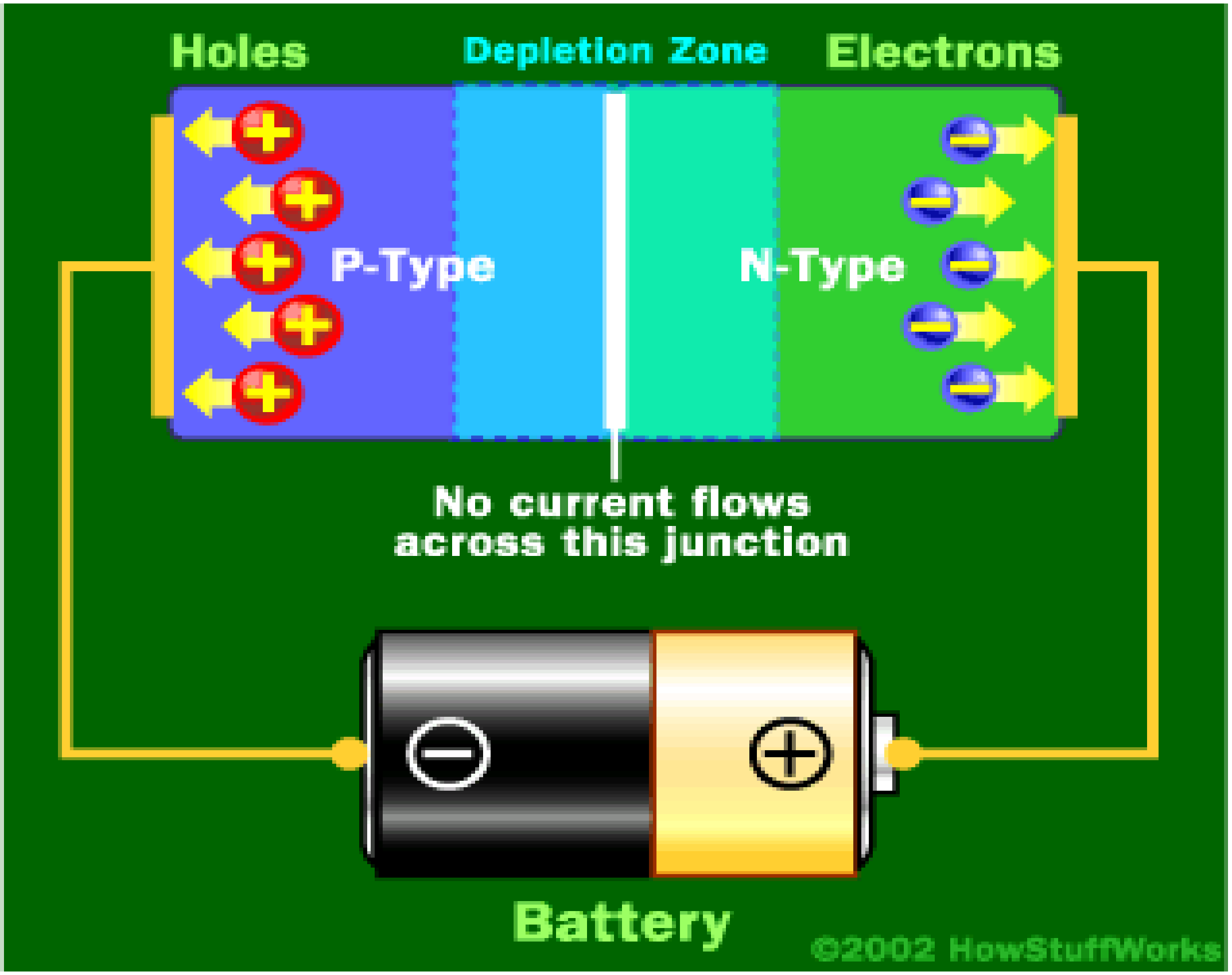


Forward-Biased P-N Junctions



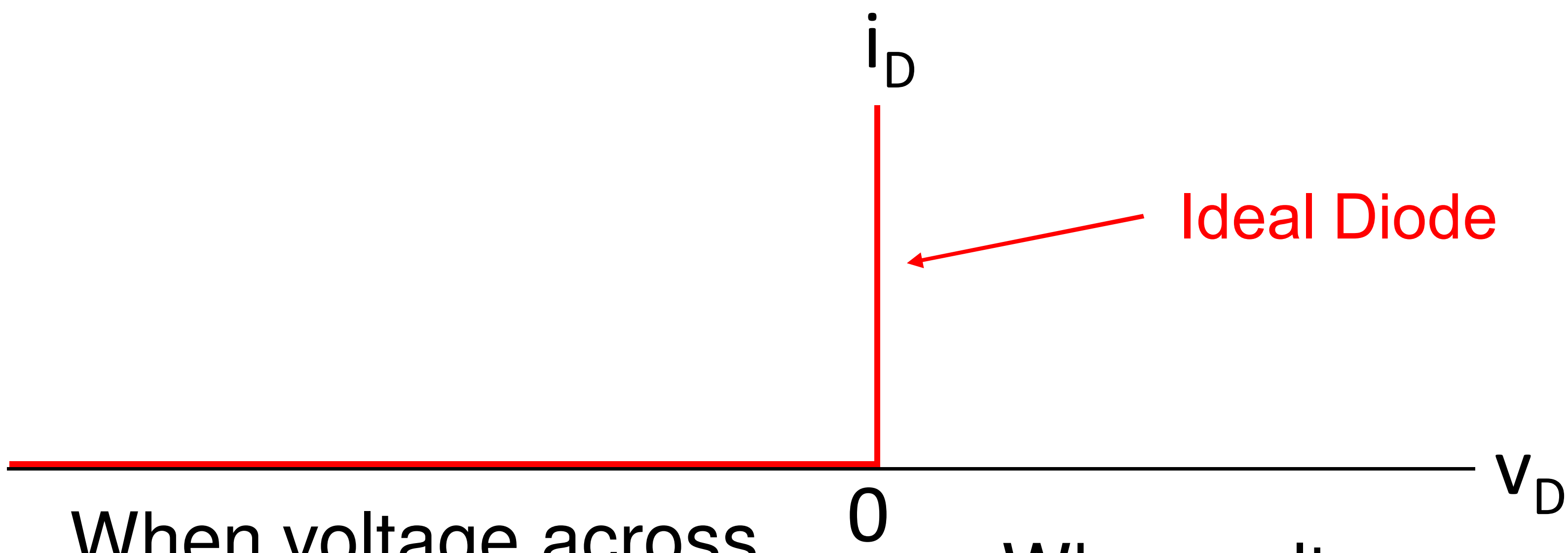
When the negative end of the circuit is hooked up to the N-type layer and the positive end is hooked up to P-type layer, electrons and holes start moving and the depletion zone disappears.

Reversed-Biased P-N Junctions



When the positive end of the battery is hooked up to the N-type layer and the negative end is hooked up to the P-type layer, free electrons collect on one end of the diode and holes collect on the other. The depletion zone gets bigger and no current flows.

I-V characteristic for an ideal diode

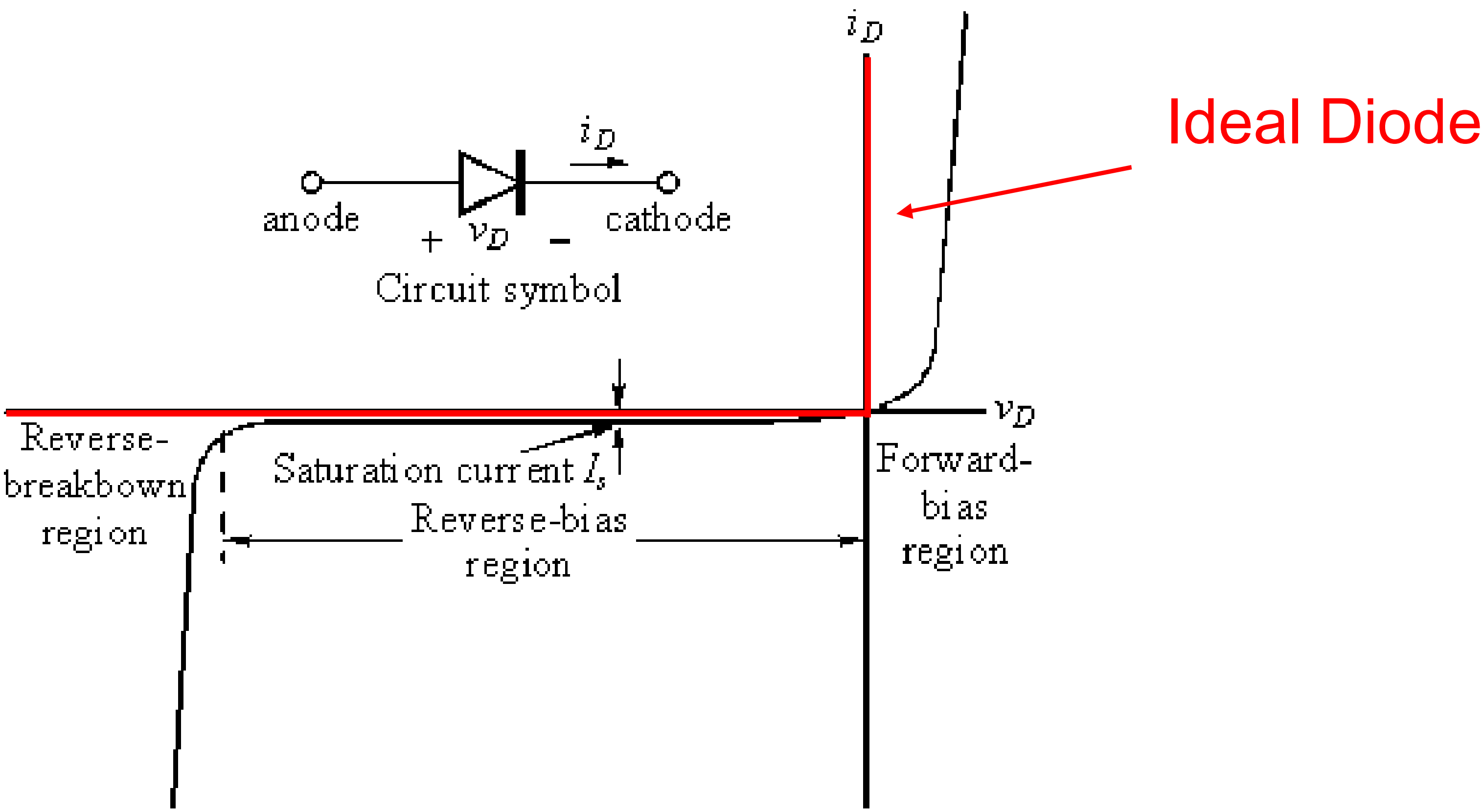


When voltage across the diode is negative, the diode looks like an open circuit.

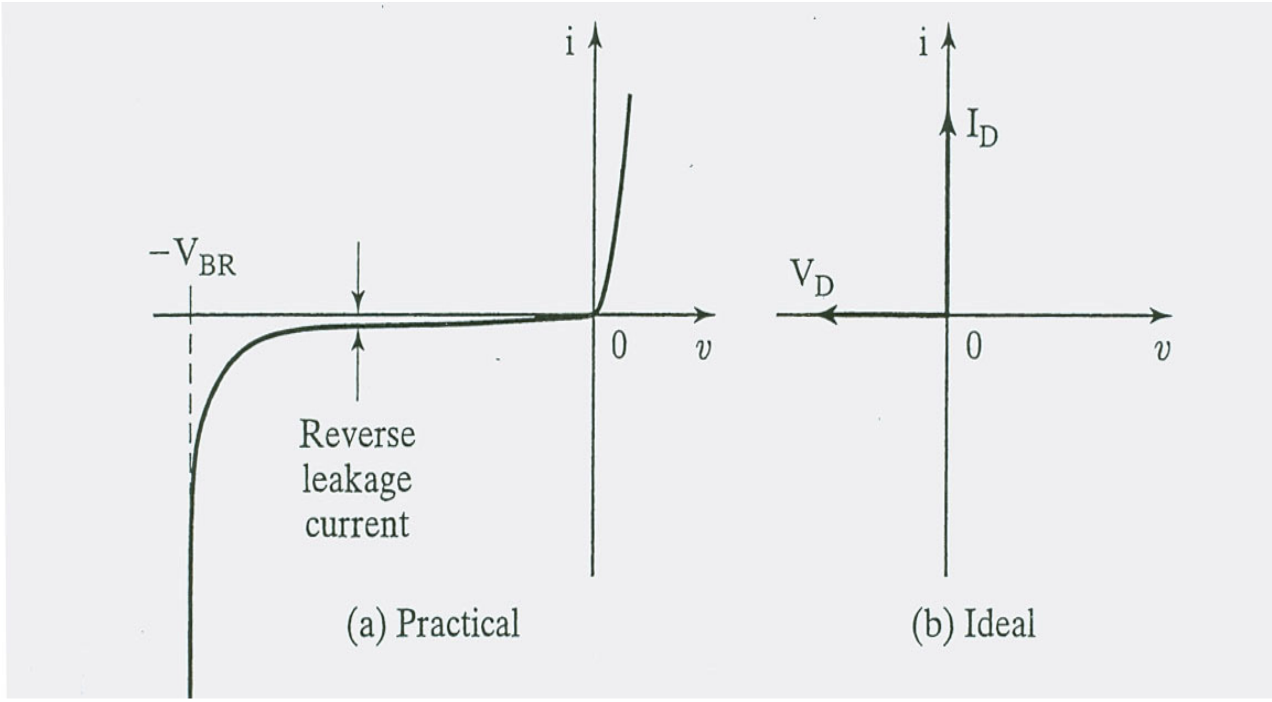
When voltage across the diode is positive, the diode looks like a short.

The I-V characteristics of a diode is shown below:

- **Real diode is close to ideal**



The I-V characteristics of a diode is shown below:



- **This characteristic can be expressed by an equation known as Schockley diode equation:**

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

I_D= Majority charge carriers Current
I_S= Minority charge carriers Current

- **V_T is a constant called thermal voltage and is given by:**

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

$$V_T \cong 26\,\mathrm{mV}$$

I_s is the saturation current ~10^{-14}
V_D is the diode voltage
n – emission coefficient (varies from 1 - 2)
$k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant
$q = 1.60 \times 10^{-19}$ C is the electrical charge of an electron.
At a temperature of 300 K,

- The diode characteristic of the figure can be divided into three regions:
  - Forward-biased region: $V_D > 0$
  - Reverse-biased region: $V_D < 0$
  - Breakdown region: $V_D < -V_{BR}$

Forward-Biased Region

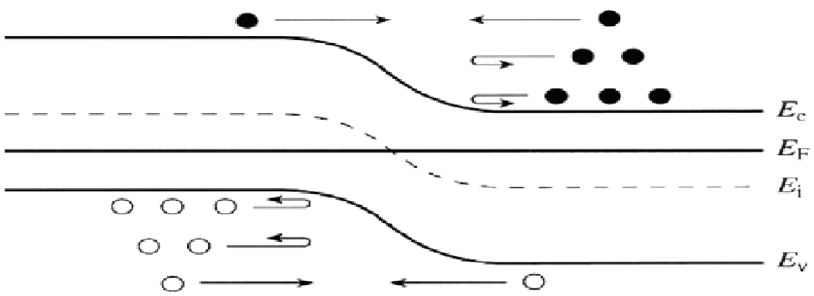
$$I_D = I_s(e^{V_D / nV_T} - 1) = I_s e^{V_D / nV_T}$$

$$\text{when } \mathrm{v_D} \geq\approx 0.1\mathrm{V},\ i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)$$

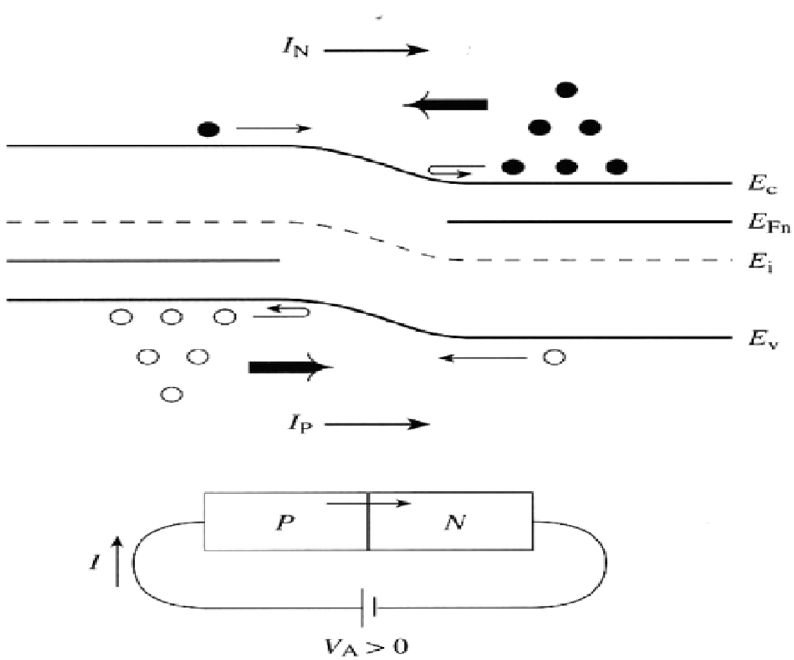
Reverse-Biased Region

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

Band diagram and carrier flow under bias



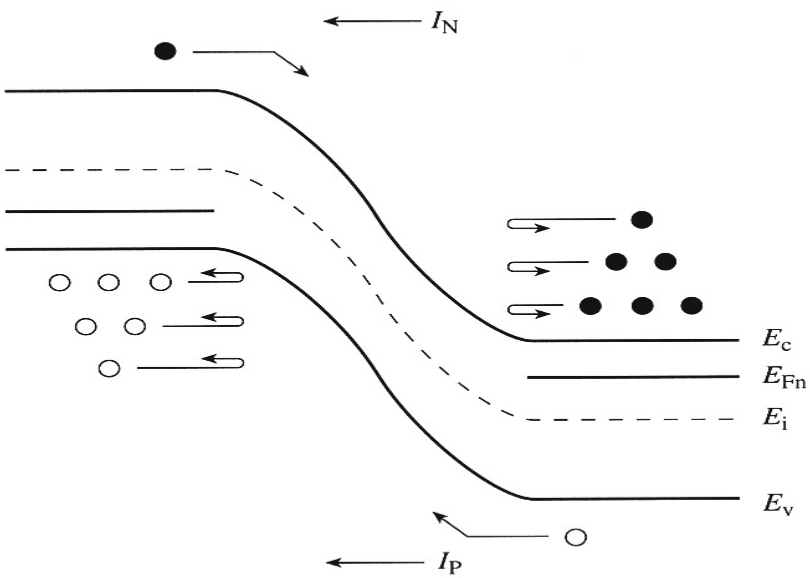
(a) Equilibrium ($V_A = 0$)



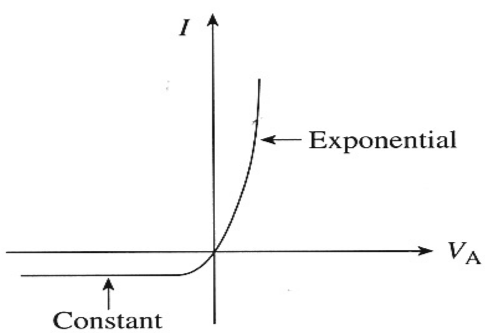
(b) Forward bias ($V_A > 0$)
Fig. 6.1(Pierret, 1996)

- When the diode forward-bias-voltage is increased, the barrier for electron and hole diffusion current decreases linearly. See the band diagram.
- Since the carrier concentration decreases exponentially with energy in both bands, diffusion current increases exponentially as the barrier is reduced.
- As the reverse-bias-voltage is increased, the diffusion current decreases rapidly to zero, since the fall-off in current is exponential.

Band diagram and carrier flow under bias



(c) Reverse bias ($V_A < 0$)



(d)

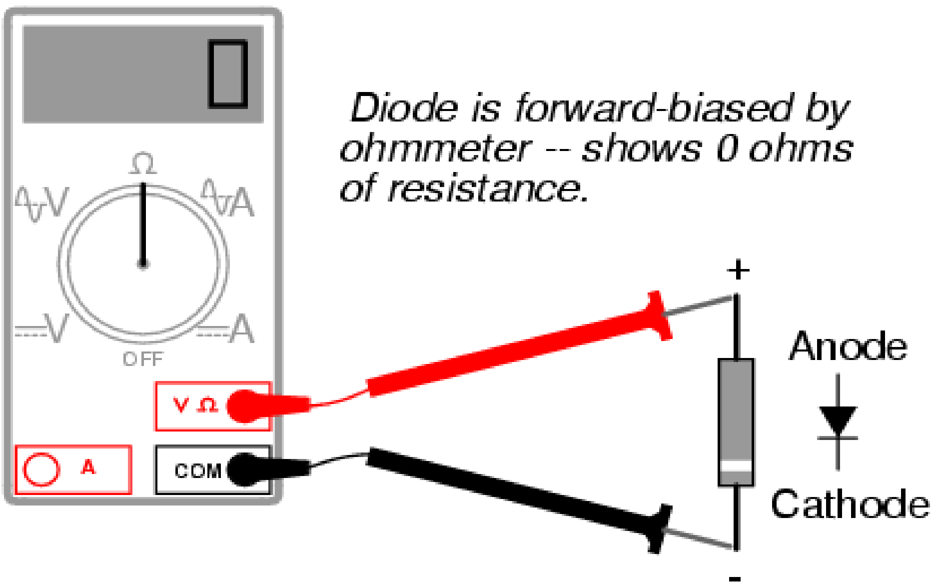
Figure 6.1 *Continued.*

When the reverse-bias-voltage is increased, the net electric field increases, but drift current *does not* change. In this case, drift current is limited NOT by HOW FAST carriers are swept across the depletion layer, but rather HOW OFTEN.

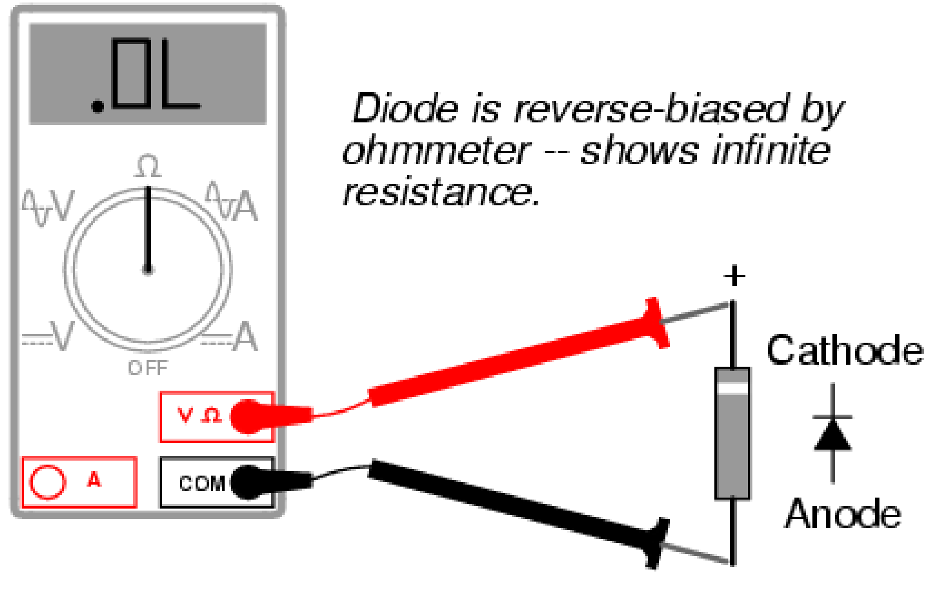
The number of carriers drifting across the depletion layer is small because the number of minority carriers that diffuse towards the edge of the depletion layer is small.

To a first approximation, the drift current does not change with the applied voltage.

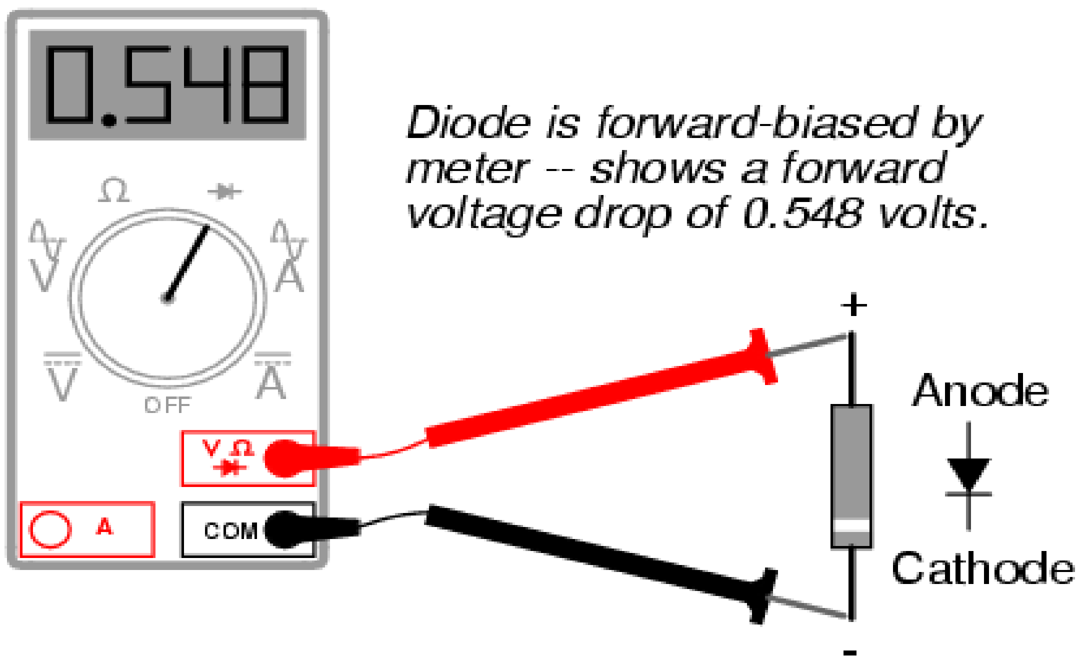
Diode – Characteristic



Diode is forward-biased by ohmmeter -- shows 0 ohms of resistance.

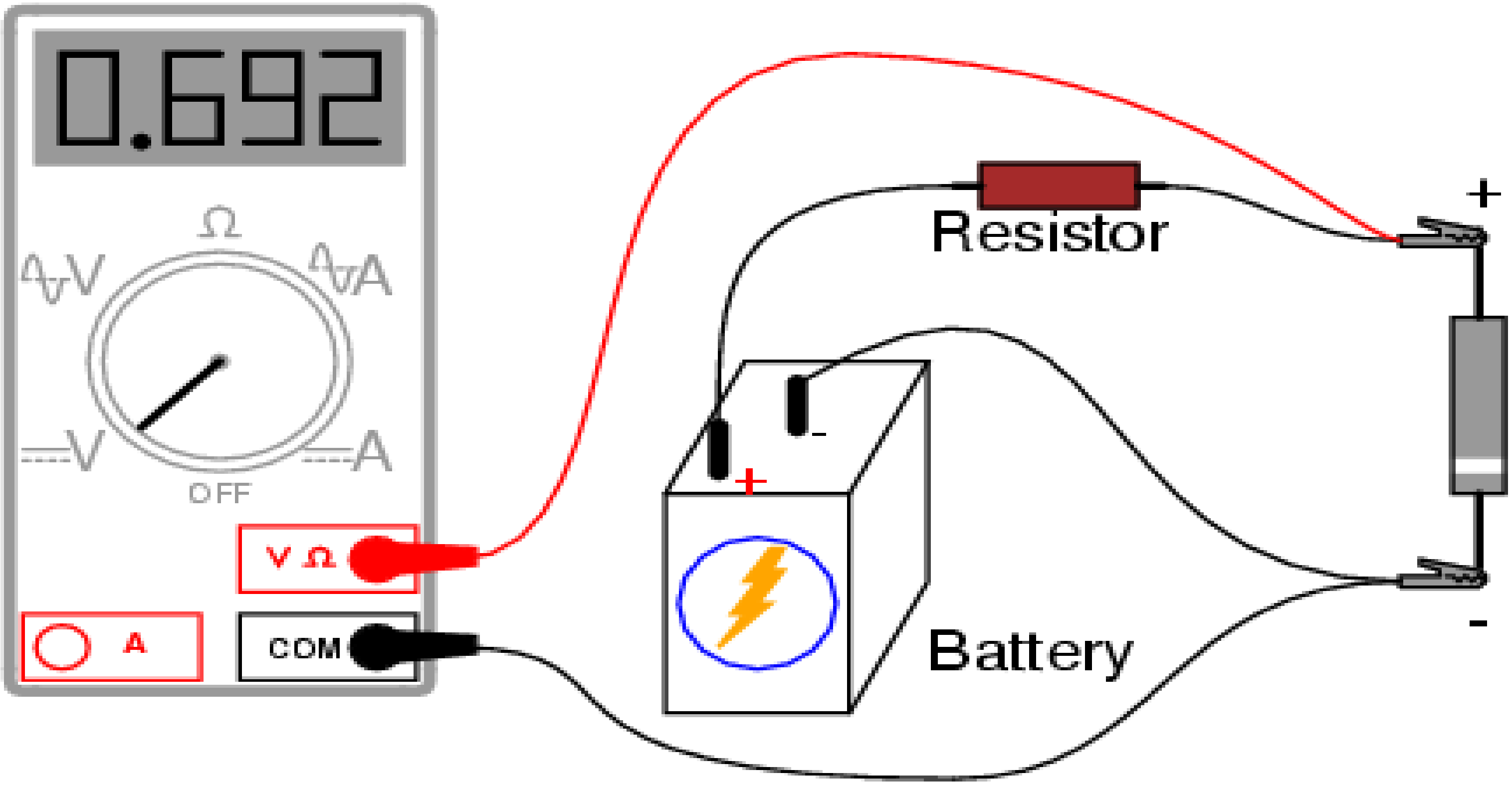


Diode is reverse-biased by ohmmeter -- shows infinite resistance.

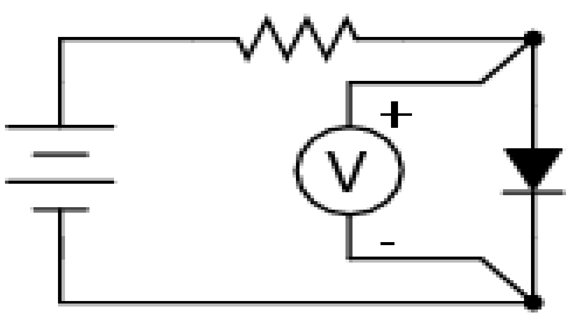


Diode is forward-biased by meter -- shows a forward voltage drop of 0.548 volts.

Diode – Characteristic :



Schematic diagram



Resistor sized to obtain diode current of desired magnitude.

Diodes – Load-Line Analysis of Diode Circuits

Load-Line Analysis of Diode Circuit

$$We\ can\ use\ v = iR,\ i = C\frac{dv}{dt},\ v = L\frac{di}{dt},\ldots$$

$$but\ when\ there\ is\ a\ diode:\ i_D = I_s\left[exp\left(\frac{v_D}{nV_T}\right) - 1\right]$$

It is difficult to write KCL or KVL equations.

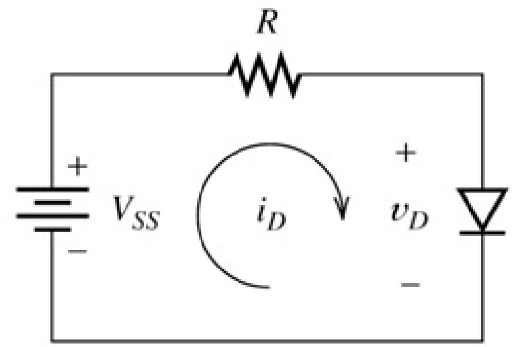


Figure Circuit for load-line analysis.

For the circuit shown,

KVL gives:

$$V_{SS} = R\,i_D + v_D$$

If the I-V curve of the diode is given, we can perform the

$$\boxed{\text{" Load - Line Analysis"}}$$

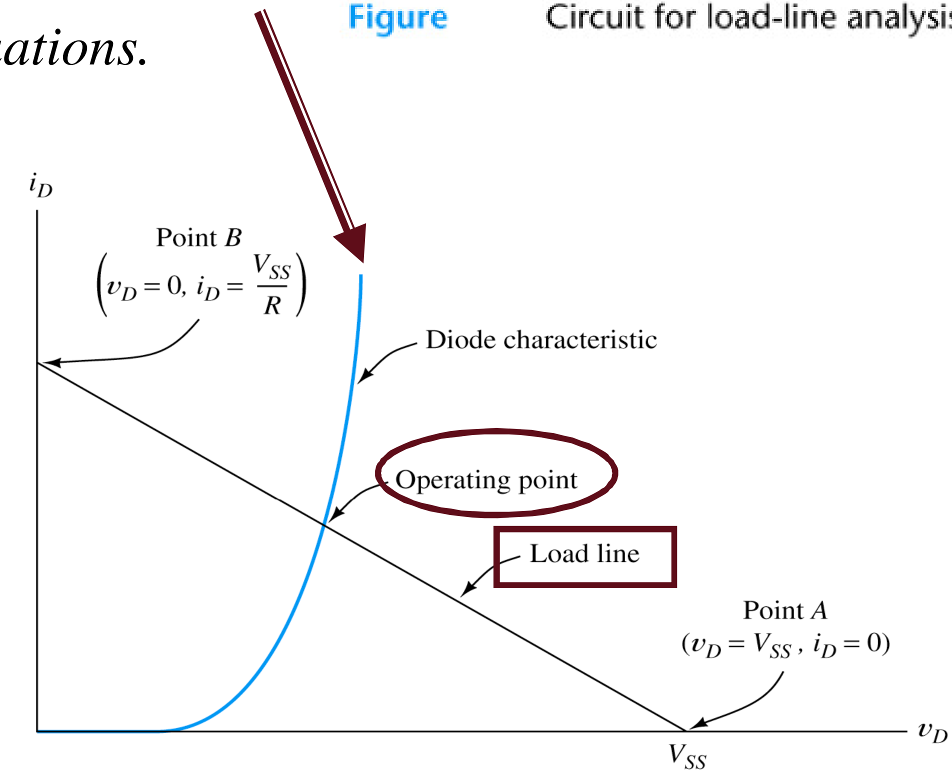
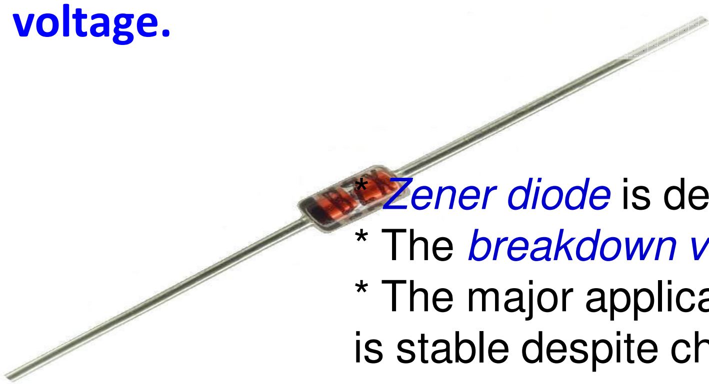
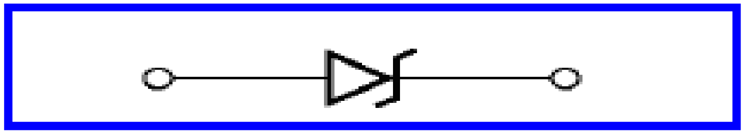


Figure 10.6 Load-line analysis of the circuit of Figure 10.5.

Zener diode

A zener diode is a p-n junction device which is designed for a specific *reverse breakdown* voltage.

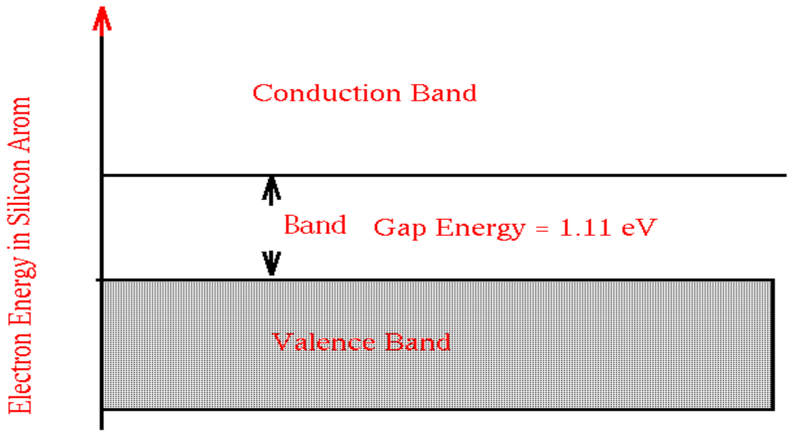




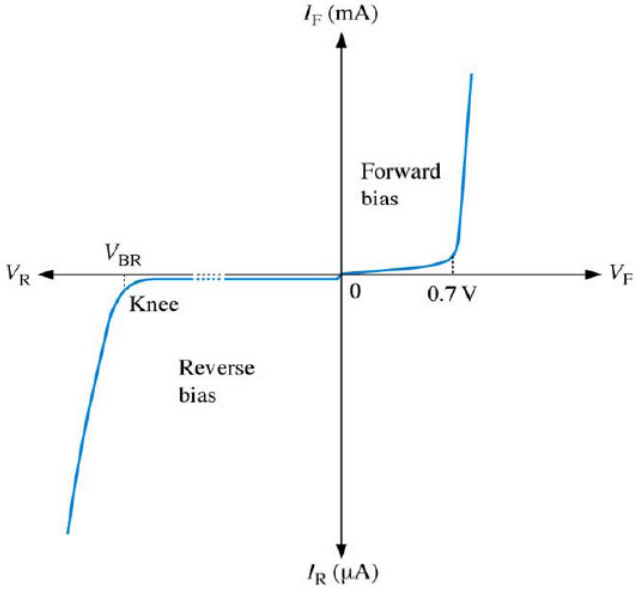
* *Zener diode* is designed for operation in the reverse-breakdown region.
* The *breakdown voltage* is controlled by the doping level *(-1.8 V to -200 V)*.
* The major application of Zener diode is to provide an output reference that is stable despite changes in input voltage – power supplies, voltmeter,…

Zener effect:

High reverse voltages can provide electrons enough energy to “jump” from valence band to conduction band, thus creating free electrons. Hence, the diode conducts a high current under rever



Energy band in Silicon Atom



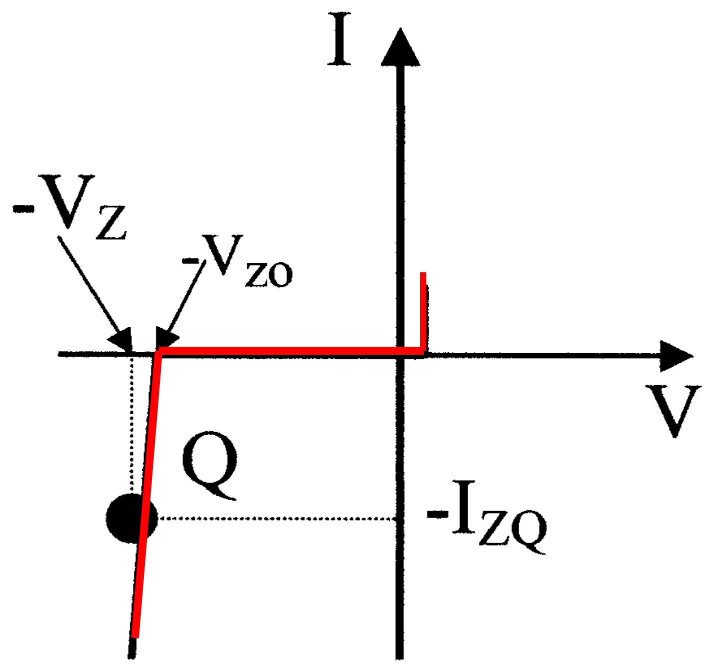
Zener Diode

- The slope of the line at Q is $1/r_Z$
- r_Z is called the incremental resistance of the zener diode
- This is exaggerated for clarity in the figure. In practice r_Z is small (a few ohms) and the breakdown voltage is approximately constant irrespective of the reverse current.

•Zener breakdown occurs when the electric field in the depletion layer increases to the point where it can break covalent bonds and generate electron-hole pairs.

•Electrons generated in this way are swept by the electric field into the n side.

•Holes generated in this way are swept by the electric field into the p side.



- These electrons and holes constitute a reverse current through the junction.

- Once the zener effect starts a large number of carriers can be generated with negligible increase in the junction voltage.

- In the breakdown region the reverse current is thus determined by the external circuit, the reverse voltage across the diode remains close to the rated breakdown voltage.

- The other breakdown mechanism is avalanche breakdown.

- This occurs when minority carrier in the depletion layer gain sufficient kinetic energy to break covalent bonds in atoms when they collide.

- Avalanche breakdown.

- Carriers liberated may have or gain sufficient energy to cause other carriers to be generated.

- This process continues in the fashion of an ‘avalanche’

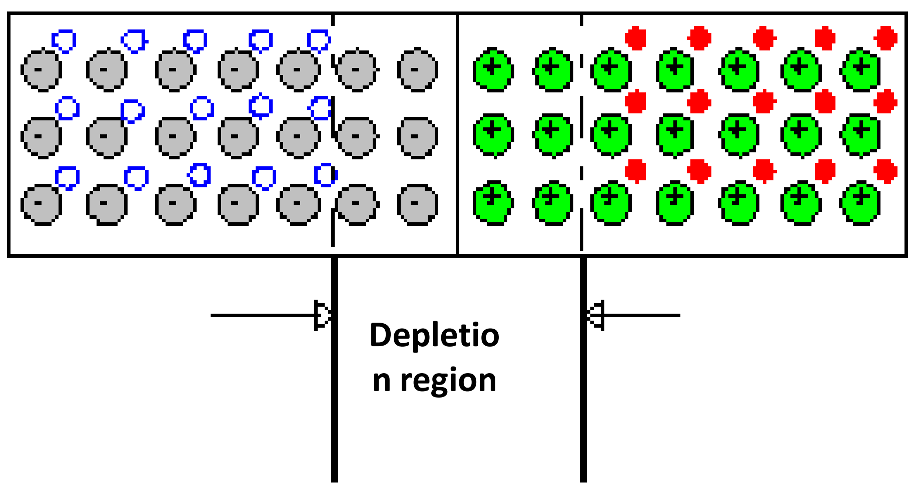
•Many carriers can be created to support any reverse current determined by the external current.

•The device is operated in reverse bias.

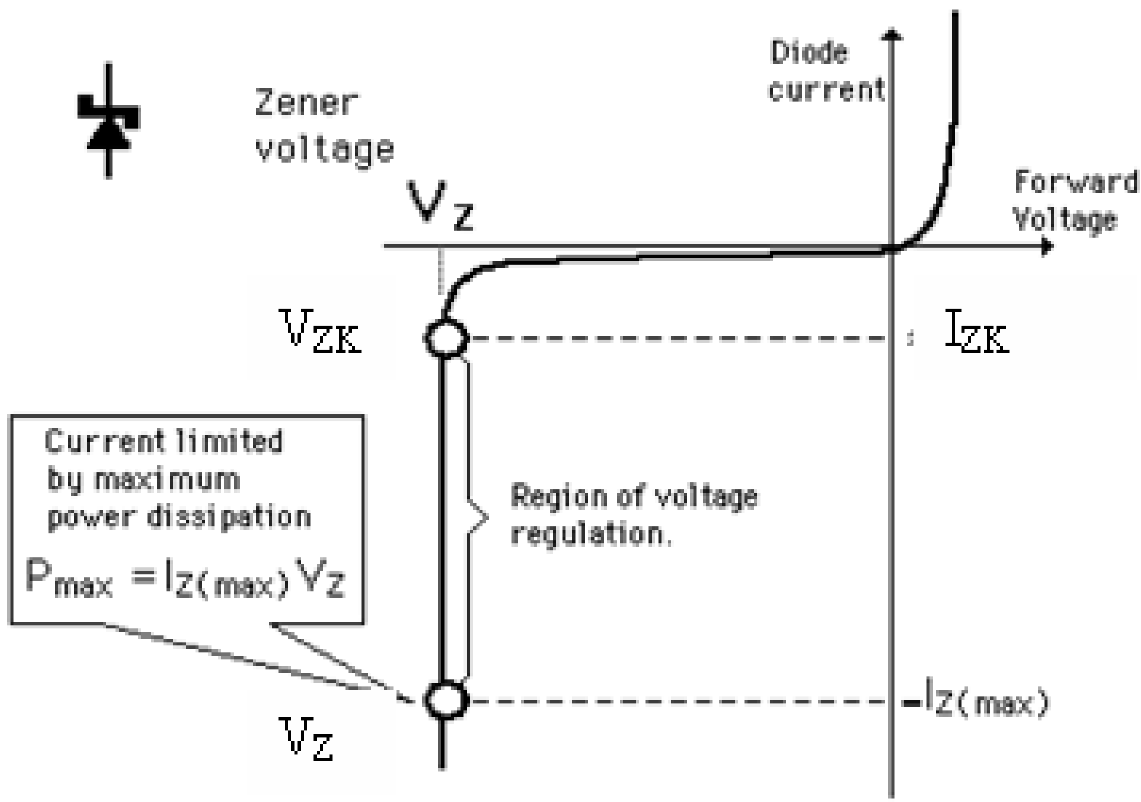
•Thus we reverse the sign notation that we normally use for diode voltages and currents, as shown on the next slide

Avalanche effect:

Minority carriers in the depletion region are strongly accelerated by the electric field, thus creating electron-hole pairs by impact ionization. The increase of free carriers increases the current, which provides more carriers to create impact ionization



I-V characteristic of zener diode



The Zener diode is used to provide a stable reference voltage in the face of a varying supply voltage.