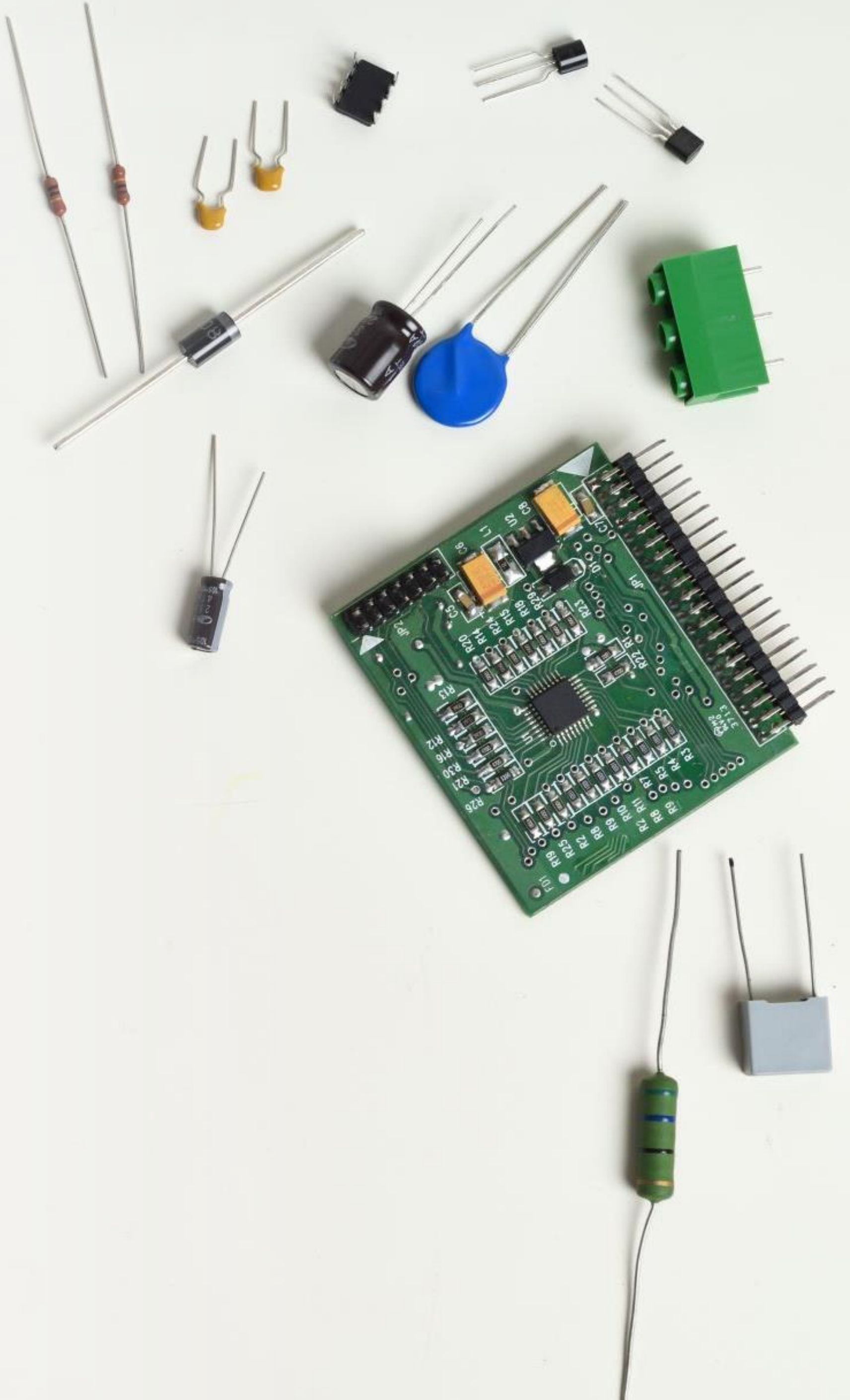
104010 : BASIC ELECTRONICS ENGINEERING

UNIT I

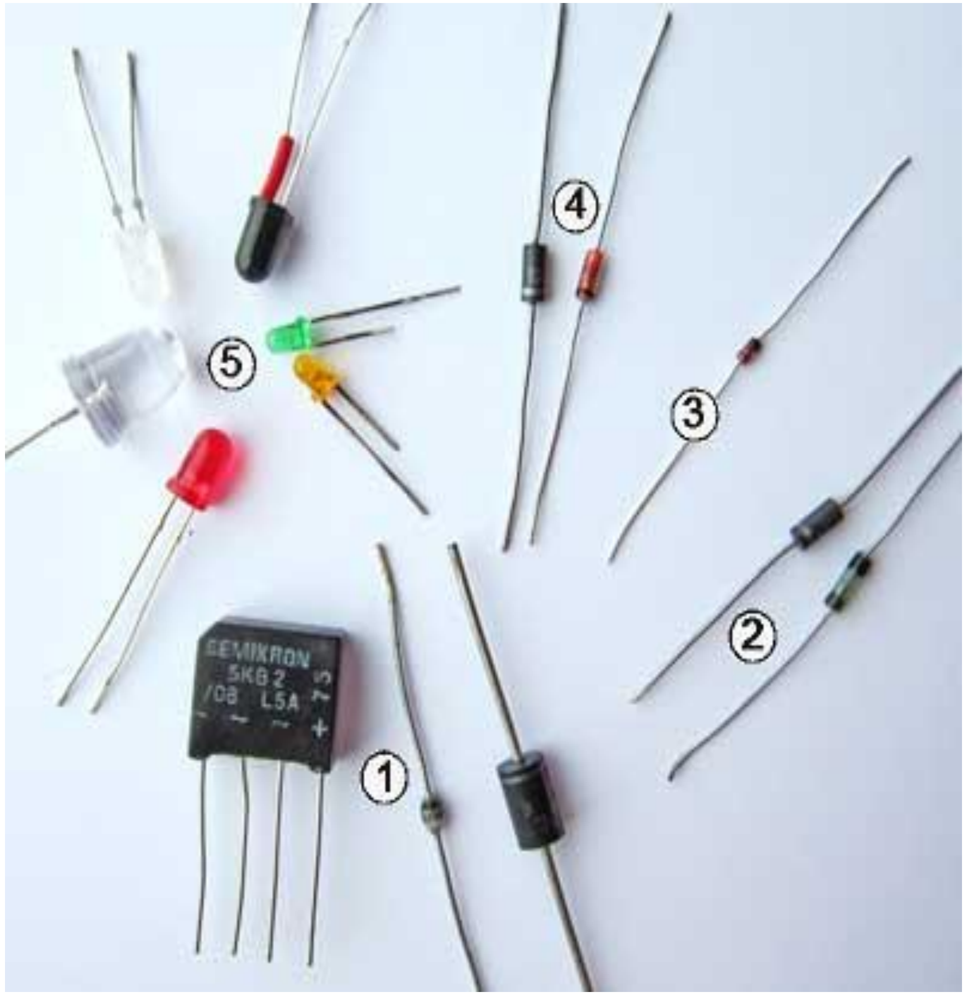
Introduction to Electronics



Diodes

The image shows a selection of common wire ended diodes as follows:

1. Three power rectifiers, (a Bridge rectifier for use with mains (line) voltages, and two mains voltage rectifier diodes).
2. A point contact diode (with glass encapsulation) and a Schottky diode.
3. A small signal silicon diode.
4. Zener Diodes with glass or black resin encapsulation.
5. A selection of light emitting diodes. Counter-clockwise from red: Yellow and green indicator LEDs, an infra-red photodiode, a 5mm warm white LED and a 10mm high luminosity blue LED.

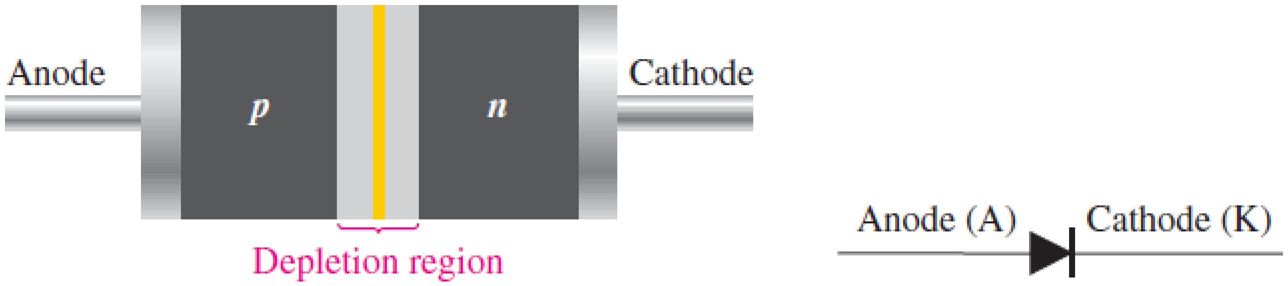


Diode

- **Frederick Guthrie** invented the diode in 1873, but did not put it into practical use.
- **Thomas Edison** independently developed it in 1880, then used it in his 1883 patent of the incandescent light bulb.
- **John Ambrose Fleming** received the first patent on the diode itself in 1904.
- In 1874, German scientist **Karl Ferdinand Braun** discovered the "unilateral conduction" across a contact between a metal and a mineral.

Diode: Symbol and Structure

- A diode is made from a small piece of semiconductor material, usually silicon, in which half is doped as a p region and half is doped as an n region with a p-n junction and depletion region in between.
- The p region is called the anode and is connected to a conductive terminal. The n region is called the cathode and is connected to a second conductive terminal.
- The basic diode structure and schematic symbol are shown in the Figure.



(a) Basic structure (b) Symbol

Diode: Concept of Diffusion and Depletion layer

- **Diffusion**: Moving of charge carriers (electrons and holes) from the region of higher concentration to the region of lower concentration.
- Before the p-n junction is formed there are equal no of electrons and holes making material neutral in terms of net charge.
- When p-n junction is formed the electrons from the n-region looses free electrons as they diffuse across the junction, this creates a layer of positive charge.
- Similarly, p-region losses holes creating a negative layer at the junction.
- These two layers of positive and negative ions form the **Depletion Region (Layer)**.

Diode: Concept of Diffusion and Depletion layer

- When depletion region reach to certain limit it stops further combining of electrons and holes (depletion region), it acts like a **barrier potential**.
- **Barrier potential** :

  The electric field in the depletion region creates an energy hill at junction that prevents free electrons from diffusing across the junction at equilibrium. (0.7 V) for silicon and (0.3 V) for germanium.

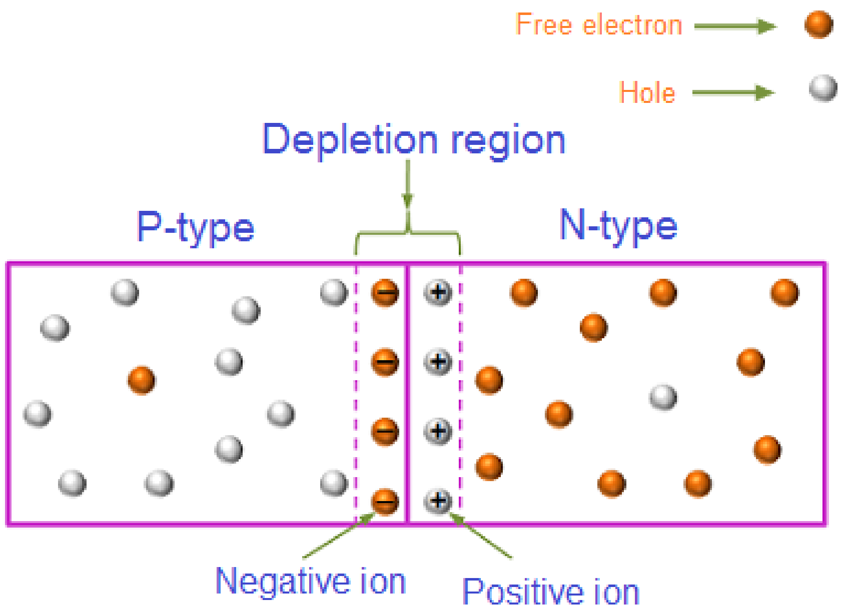


Image Credit: Physics and Radio Electronics

Diode: Forward and Reverse Biasing

- **Biasing**: Applying external of DC voltage across the terminals of electronics device to establish certain operating condition for the device.

- Diode biasing can be done in two different ways

  1) Forward biasing 2) Reverse biasing

- **Forward biasing**:

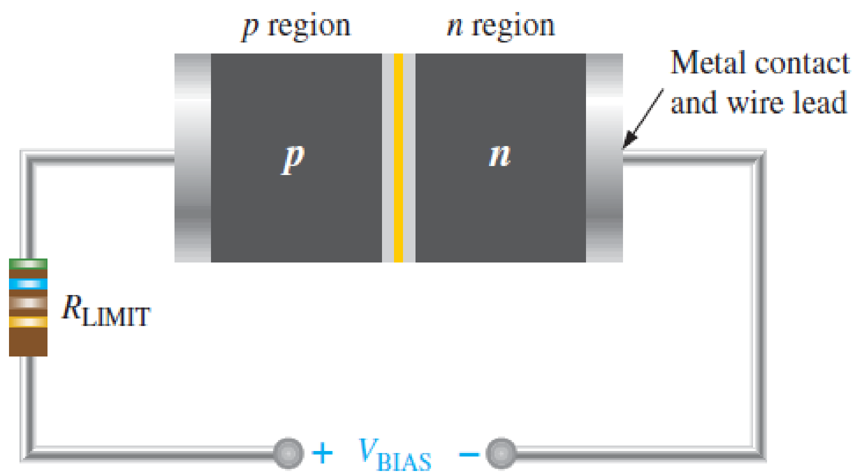
  The positive terminal of the battery is connected to the p-type material and the negative terminal of the battery is connected to the n-type material

- **Reverse biasing**:

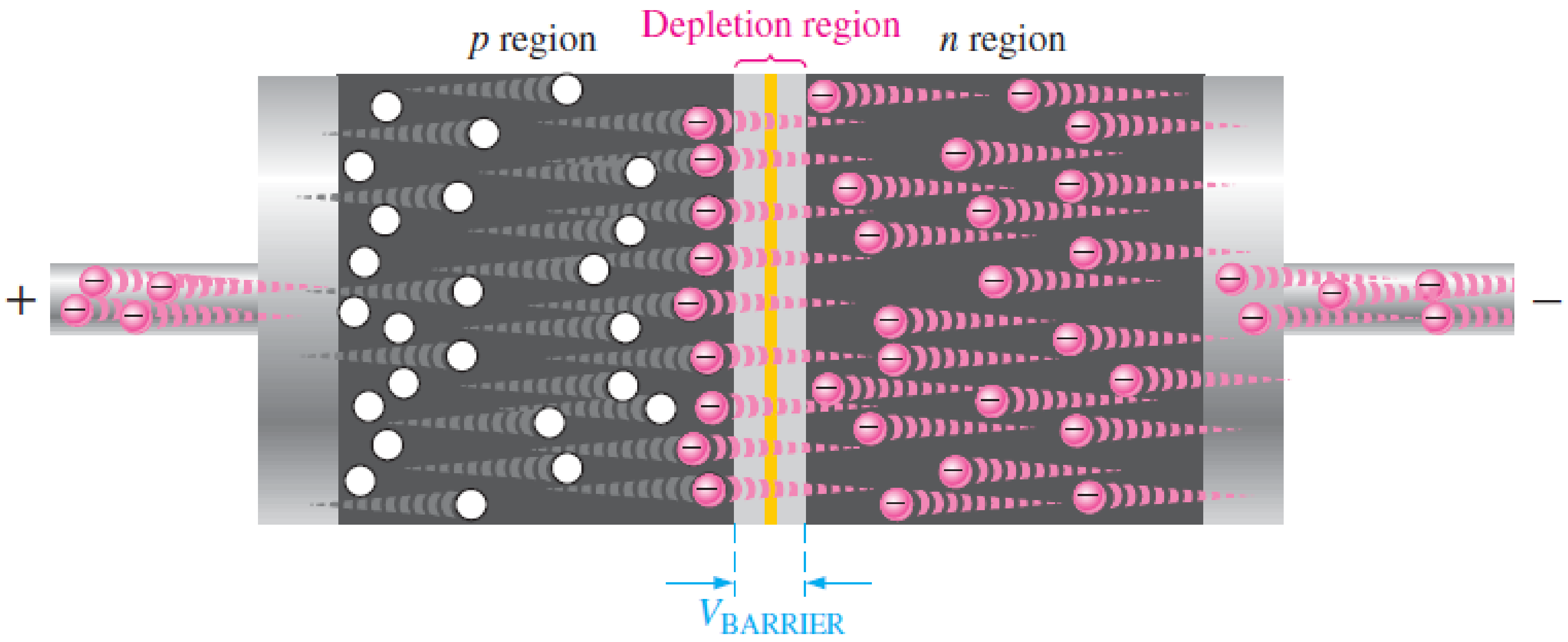
  The positive terminal of the battery is connected to n-type material and the negative terminal of the battery is connected to p-type material.

Forward Biasing

- **Forward bias** is the condition that allows current through the *pn* junction. Figure shows a dc voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias.
- This external bias voltage is designated as V_{BIAS}. The resistor limits the forward current to a value that will not damage the diode.
- Notice that the negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region.
- This is one requirement for forward bias.
- A second requirement is that the bias voltage, V_{BIAS}, must be greater than the **barrier potential**.



Forward Biasing…



Forward Biasing…

- A fundamental picture of what happens when a diode is forward-biased is shown in Figure. Because like charges repel, the negative side of the bias-voltage source "pushes" the free electrons, which are the majority carriers in the n region, toward the pn junction. This flow of free electrons is called electron current.
- The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown.
- The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region. Once in the p region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.

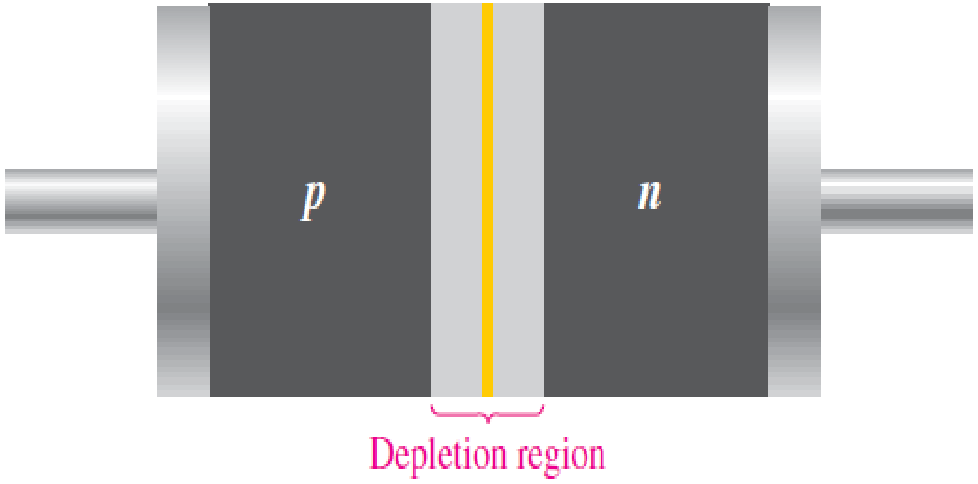
Forward Biasing…

- Now, the electrons are in the valence band in the p region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band. Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the p region. The holes in the p region provide the medium or “pathway” for these valence electrons to move through the p region.
- The valence electrons move from one hole to the next toward the left. The holes, which are the majority carriers in the p region, effectively (not actually) move to the right toward the junction, as you can see in Figure. This effective flow of holes is the hole current.

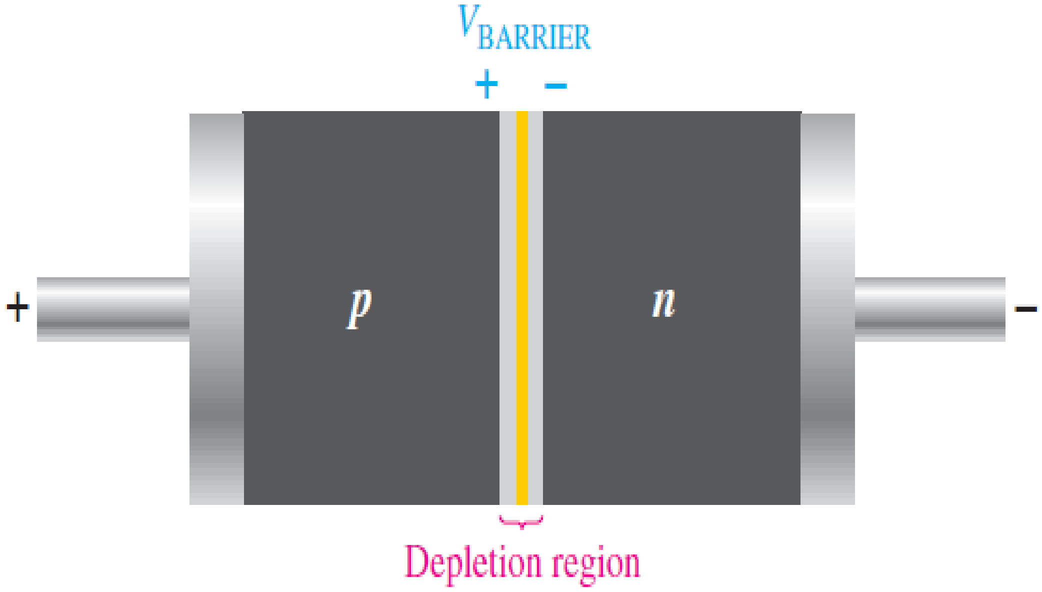
Forward Biasing…

- As the electrons flow out of the p region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave holes behind in the p region; at the same time, these electrons become conduction electrons in the metal conductor.
- Recall that the conduction band in a conductor overlaps the valence band so that it takes much less energy for an electron to be a free electron in a conductor than in a semiconductor and that metallic conductors do not have holes in their structure.
- There is a continuous availability of holes effectively moving toward the pn junction to combine with the continuous stream of electrons as they come across the junction into the p region.

Effect of Forward Bias on Depletion Region



(a) At equilibrium (no bias)



(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

Effect of Forward Bias on Depletion Region

- As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on the other side of the pn junction, the number of negative ions is reduced.
- This reduction in positive and negative ions during forward bias causes the depletion region to narrow.
- When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively "climb the energy hill" and cross the depletion region.
- The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential.
- In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region.
- This energy loss results in a voltage drop across the pn junction equal to the barrier potential (0.7 V)

Forward Biasing…

- **Effect on depletion region due to forward bias:**

  Width of depletion region decreases due to reduction in the number of positive and negative ions.

- **Effect of barrier potential during forward bias:**
  - Results in voltage drop across the p-n junction equal to barrier potential (0.7V).
  - There is a small voltage drop occurs across the p-n junction due to the internal resistance of the material called the **dynamic resistance,** is very small and can usually be neglected.

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

Forward Current in P-N Junction

- When battery voltage is applied across the junction in the forward bias, a current will flow continuously through this junction.

$$i = I_s \left[\exp\left(\frac{V}{V_T}\right) - 1 \right], \text{ where } V_T = k_B T/q\,.$$

k_B = Boltzmann's constant = 1.38×10^{-23} J/K.

q = electron charge = 1.602×10^{-19} Coul.

T = temperature in $^{\circ}K$.

$V_T \approx 25$ mV at room temperature (27 °C).

* I_s is called the "reverse saturation current."
* For a typical low-power silicon diode, I_s is of the order of 10^{-13} A (i.e., 0.1 pA).
* Although I_s is very small, it gets multiplied by a large exponential factor, giving a diode current of several mA for $V \approx 0.7$ V in a silicon diode.

$$i = I_s \left[e^{V/\eta V_T} - 1 \right]$$

$\eta = 1$

$V_T \cong 25\ mV = 0.025V$

$I_s = 10^{-13} A = 0.1\ pA$

V		i
0.1	—	5.35 pA
0.2	—	297.9 pA
0.3	—	16.27 nA
0.4	—	0.88 μA
0.5	—	4.8 μA
0.6	—	2.6 mA
0.64	—	13.2 mA
0.68	—	64.98 mA
0.70	—	144 mA
0.72	—	321 mA

Sample calculation -

1. $V = 0.1V$

$$i = I_s \left[e^{0.1/0.025} - 1 \right]$$

$$= 10^{-13} (e^4 - 1)$$

$$\boxed{\therefore i = 5.35\ pA}$$

The forward current through Si(n=2) diode is 10 mA at temperature 27ºC.The corresponding forward voltage is 0.75 Volts. What is the reverse saturation current I for each diode?

→

$I = 10\, mA$

$V = 0.75V$

$\eta = 2$

$T = 27°C = 300°K$

$V_T = \dfrac{kT}{q} = 25.88\, mV$

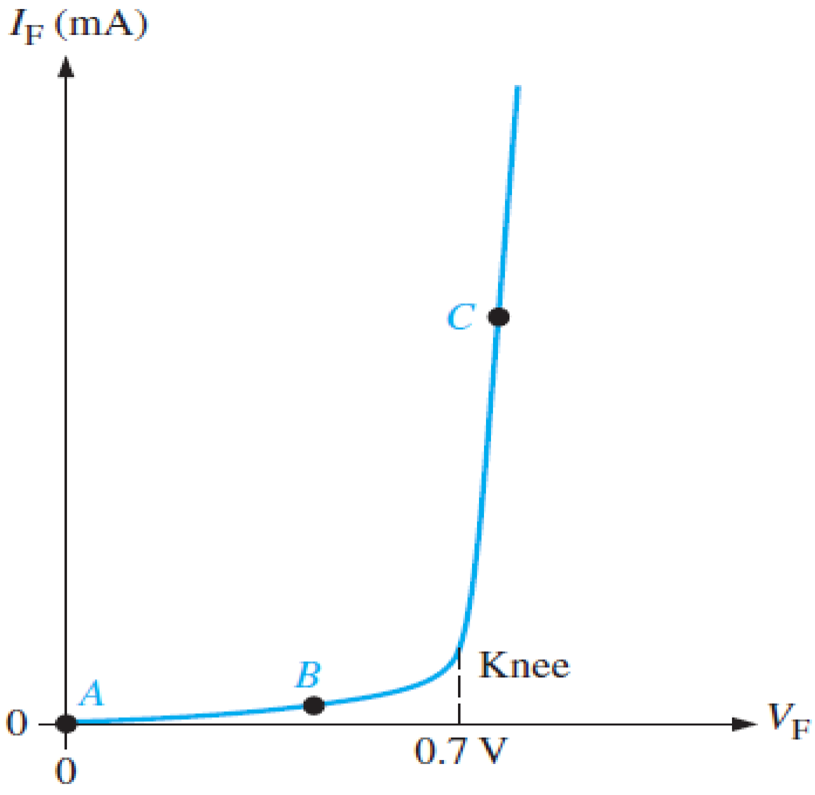
$\cong 26\, mV$

$I = I_s(e^{V/\eta V_T} - 1)$

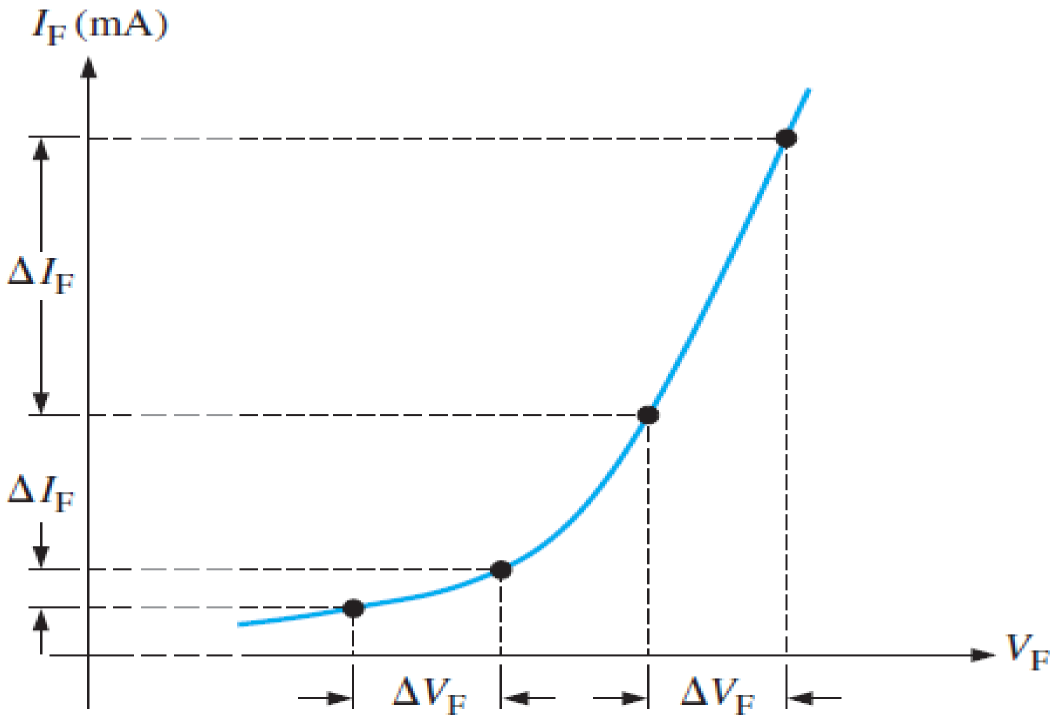
$10 \times 10^{-3} = I_s(e^{0.75/(2)(26\times10^{-3})} - 1)$

$\therefore I_s = 5.44 \times 10^{-9}\, A$

Forward Bias Characteristics

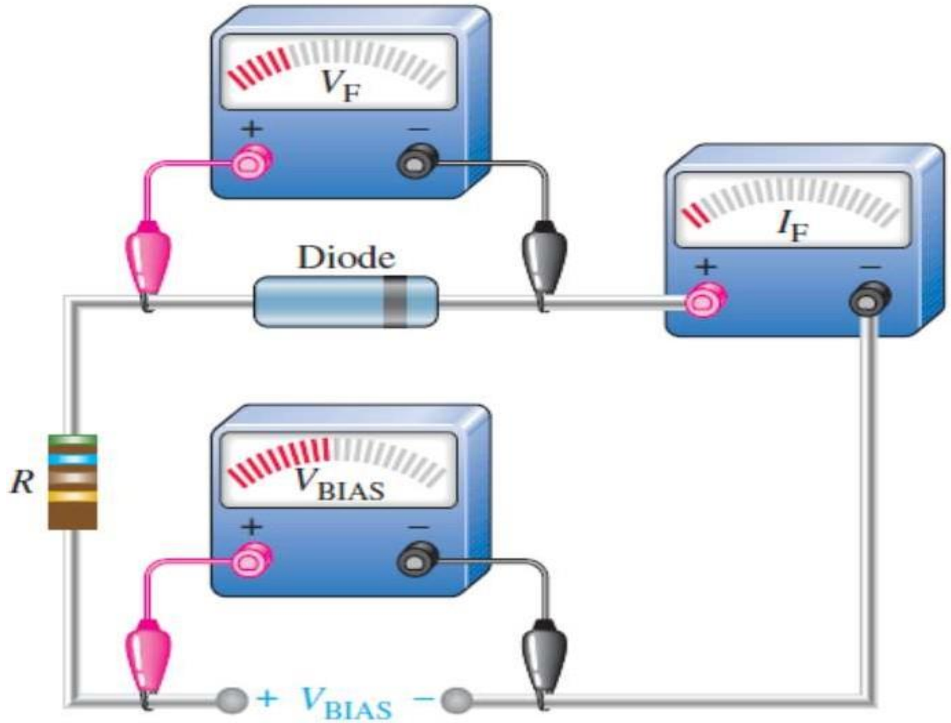


(a) *V-I* characteristic curve for forward bias.

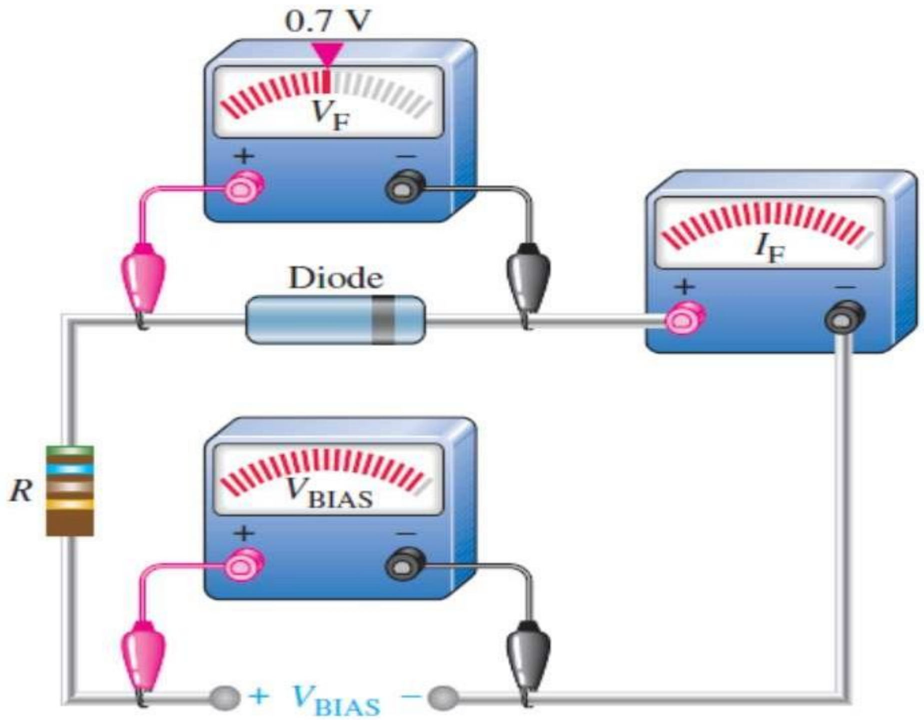


(b) Expanded view of a portion of the curve in part (a). The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F / \Delta I_F$.

Forward Bias Characteristics



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.



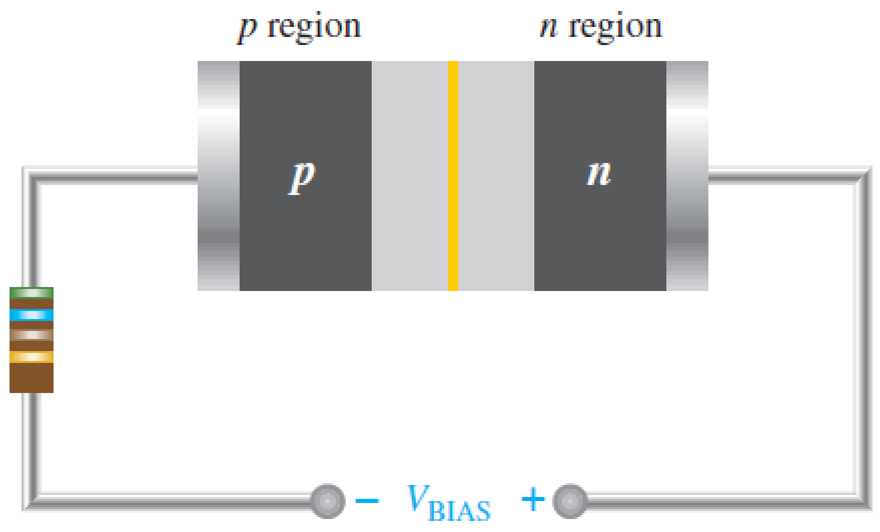
(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

Forward Bias Characteristics…

- It is a graph of V_D vs $I_{D.}$
- The forward bias voltage is very small and less the cut-in voltage (threshold voltage) therefore forward current through diode is very small.
- With Increase in forward voltage equal to threshold voltage width depletion region reduces.
- When forward voltage equal to threshold voltage, current through diode increases drastically i.e exponentially as shown in Figure.
- This current will be limited by using a resistor in series.
- Forward current is conventional current that flows from anode to cathode.
- Cut-in voltage for Silicon is 0.7 V and Germanium is 0.3 V and forward resistance in in the order of few ohms.

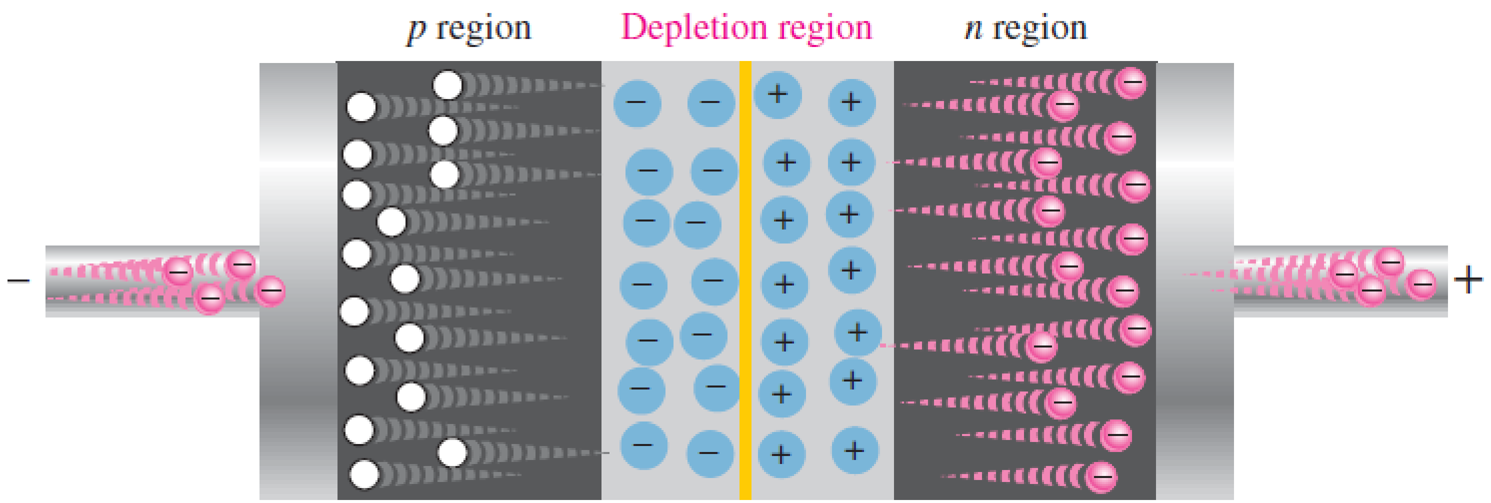
Reverse Biasing

- Reverse bias is the condition that essentially prevents current through the diode.
- The Figure shows a dc voltage source connected across a diode in the direction to produce reverse bias.
- This external bias voltage is designated as VBIAS just as it was for forward bias.
- Notice that the positive side of VBIAS is connected to the n region of the diode and the negative side is connected to the p region.
- Also note that the depletion region is shown much wider than in forward bias or equilibrium.



Reverse Biasing...

- An illustration of what happens when a diode is reverse-biased is shown in Figure.
- Because unlike charges attract, the positive side of the bias-voltage source "pulls" the free electrons, which are the majority carriers in the n region, away from the pn junction.
- As the electrons flow toward the positive side of the voltage source, additional positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.



Reverse Biasing...

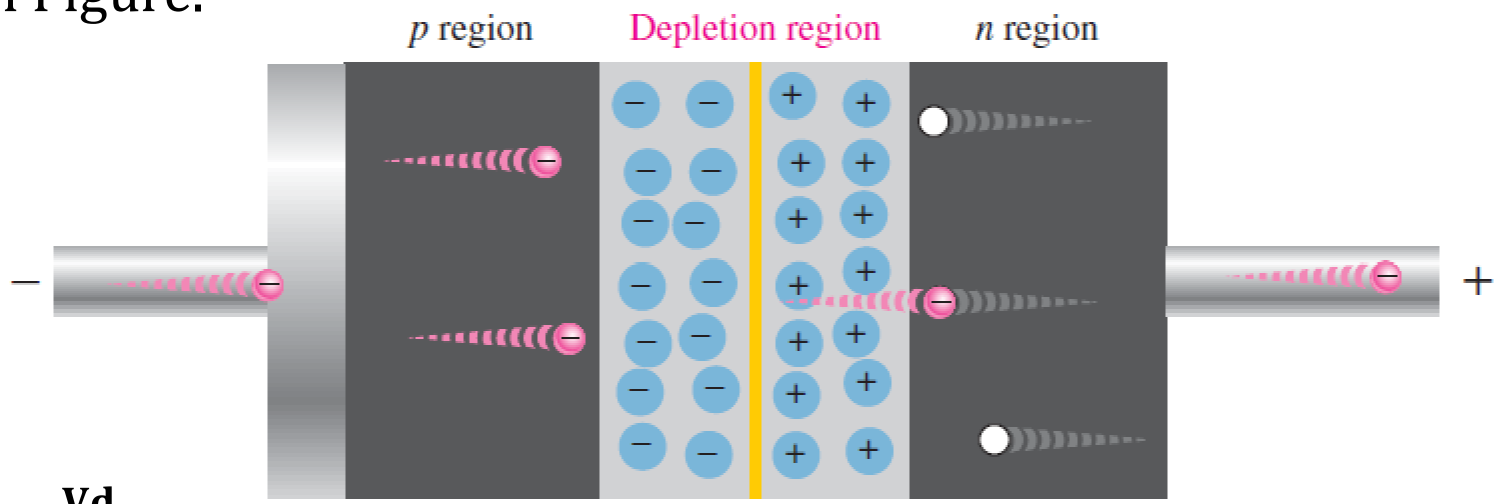
- In the p region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions. This results in a widening of the depletion region and a depletion of majority carriers.
- The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied. As the depletion region widens, the availability of majority carriers decreases.
- As more of the n and p regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, VBIAS.
- At this point, the transition current essentially ceases except for a very small reverse current that can usually be neglected.

Reverse Current

- The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the *n* and *p* regions that are produced by thermally generated electron-hole pairs.
- The small number of free minority electrons in the *p* region are “pushed” toward the *pn* junction by the negative bias voltage.
- When these electrons reach the wide depletion region, they “fall down the energy hill” and combine with the minority holes in the *n* region as valence electrons and flow toward the positive bias voltage, creating a small hole current.
- The conduction band in the *p* region is at a higher energy level than the conduction band in the *n* region. Therefore, the minority electrons easily pass through the depletion region because they require no additional energy.

Reverse Current

- Reverse current is illustrated in Figure.



Reverse biased current $\mathbf{i_o \approx I_S e^{\frac{Vd}{nVt}}}$

I_S is Saturation Current (10^{-9} to 10^{-18} A)

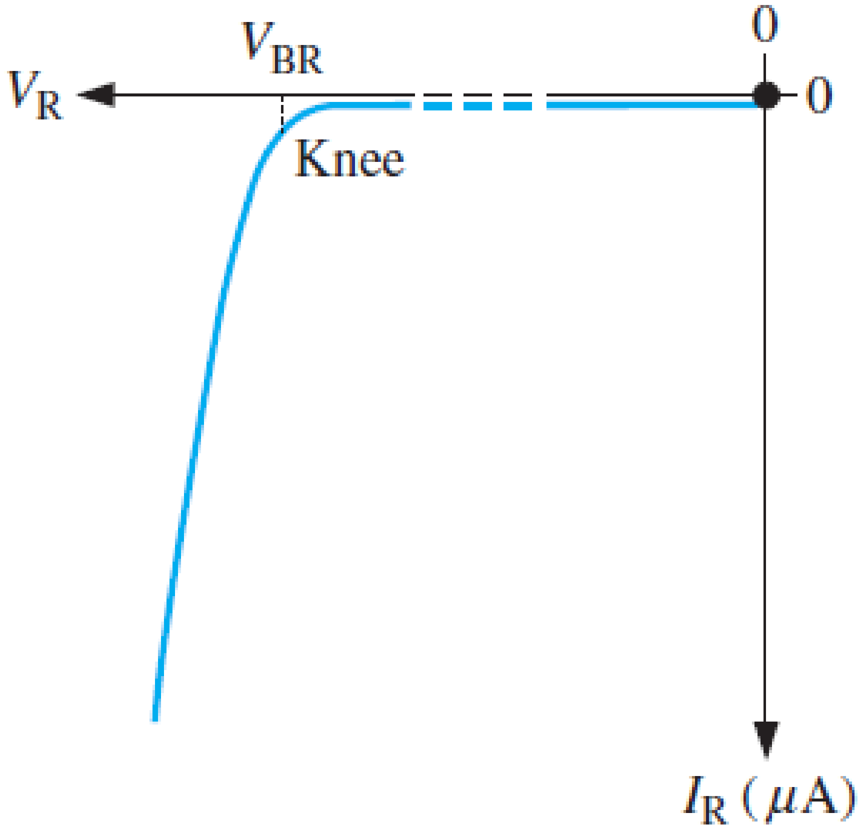
V_T is Volt-equivalent temperature (= 26 mV at room temperature)

n is Emission coefficient ($1 \leq n \leq 2$ for Si)

Reverse Breakdown

- The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the p region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band.
- The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the p region, the numbers quickly multiply. As these high-energy electrons go through the depletion region, they have enough energy to go through the n region as conduction electrons, rather than combining with holes.
- The multiplication of conduction electrons just discussed is known as the avalanche effect, and reverse current can increase dramatically if steps are not taken to limit the current.
- When the reverse current is not limited, the resulting heating will permanently damage the diode. Most diodes are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode.

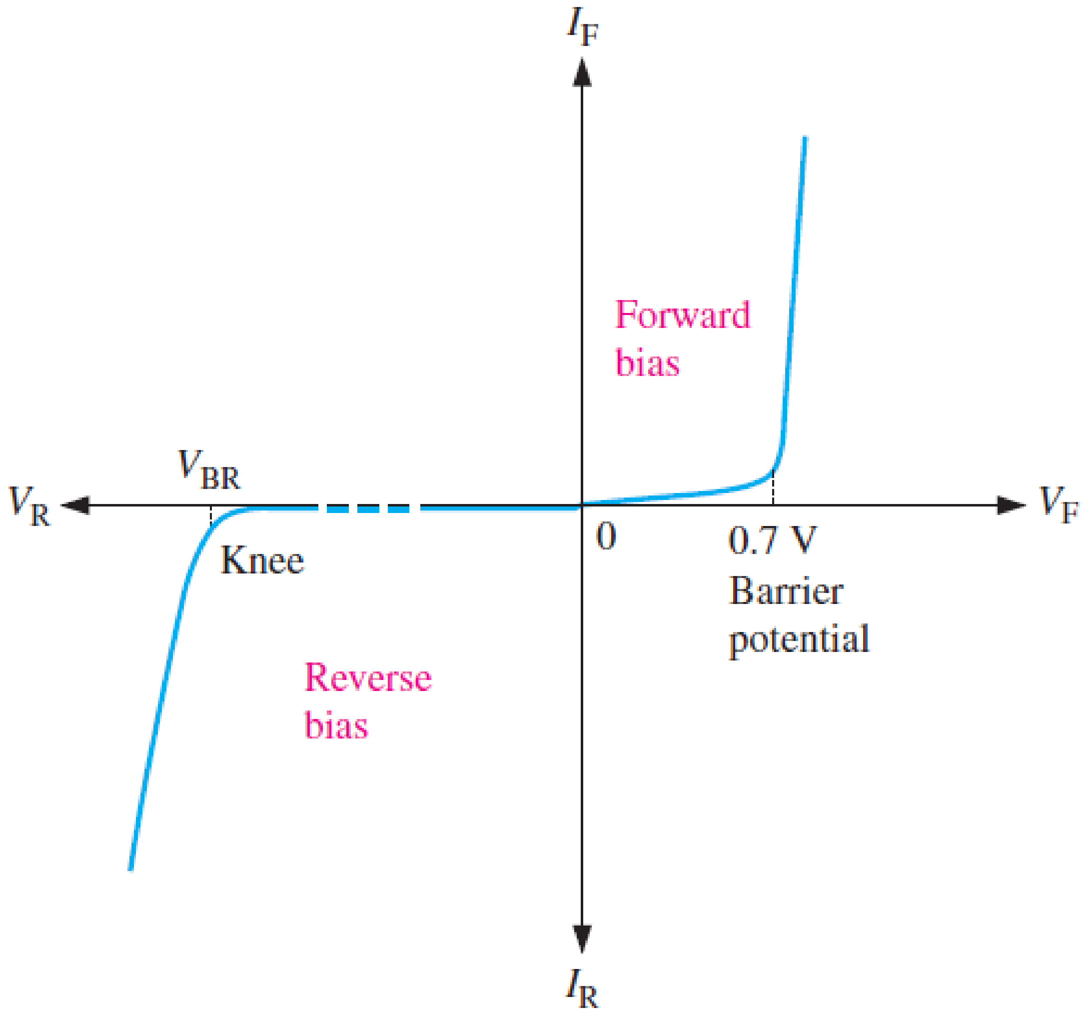
Reverse Bias Characteristics



Reverse Bias Characteristics …

- It is a graph of V_R vs I_R.
- Reverse saturation current flows due to minority carriers and hence negative.
- As the reverse voltage increase Reverse saturation current remains constant if the temperature is constant.
- As the reverse voltage reaches breakdown voltage a large current flows through the diode.
- Operation in the breakdown region is avoided because the diode may be damaged due to excessive power.
- Typically, breakdown voltage is in the range of 50 to 100 volts.
- The resistance of diode in reverse bias is very high few hundred kilo ohms.

Diode: Complete V-I Characteristics



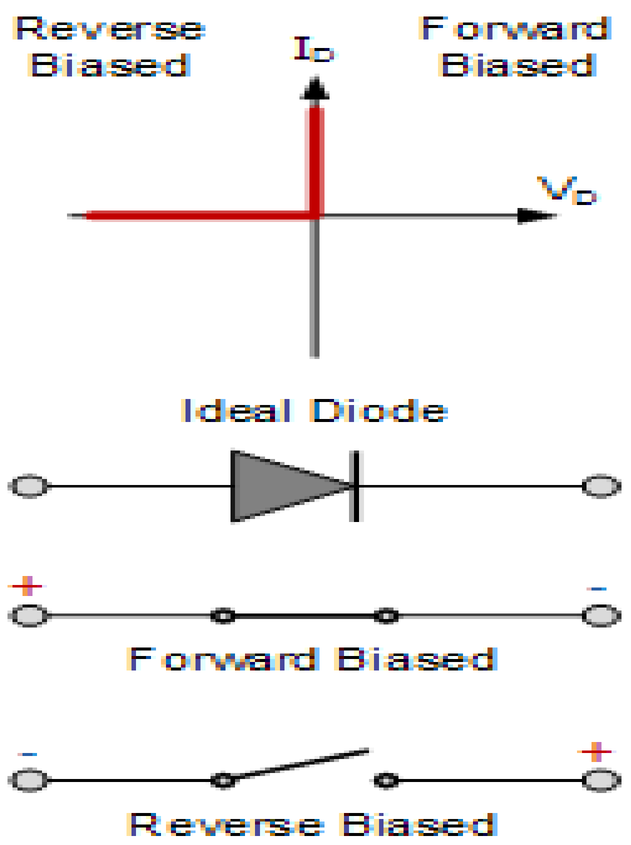
Ideal Diode

- If the diode is forward biased, then it acts as a closed switch as shown and forward resistance is 0.

$$V_F = 0\,,\; I_R = 0$$

$$V_R = V_{bias}$$

- If the diode is reverse biased diode current is zero and it acts like an open switch and applied voltage appears across the diode.

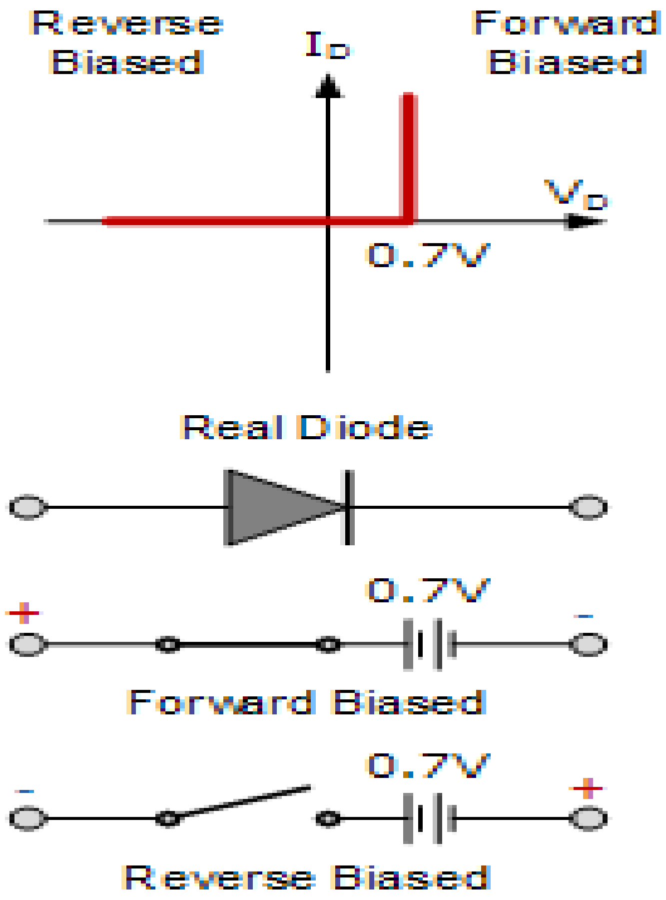


Practical Diode

- The real (practical) diode includes the barrier potential.
- If the diode is forward biased, then it acts as a closed switch with small voltage source 0.7 V.
- The barrier potential must be exceeded by the bias voltage before diode start conducting.

$$V_F = 0.7\ ,\ I_R = 0$$

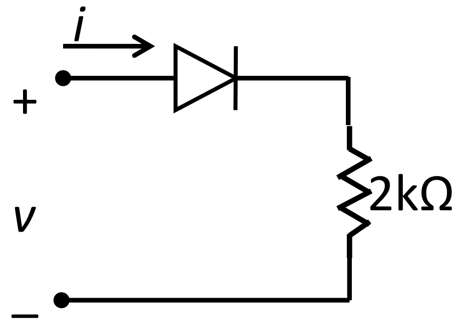
$$V_R = V_{bias}$$



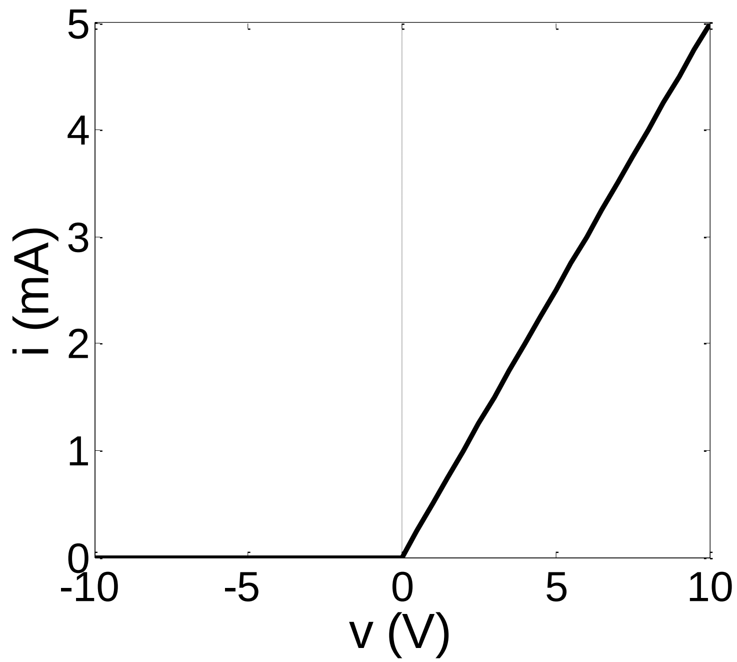
Numerical Problem1

- **Sketch *i* versus *v* to scale for each of the circuits shown below. Assume that the diodes are ideal and allow *v* to range from -10 V to +10 V.**

A)

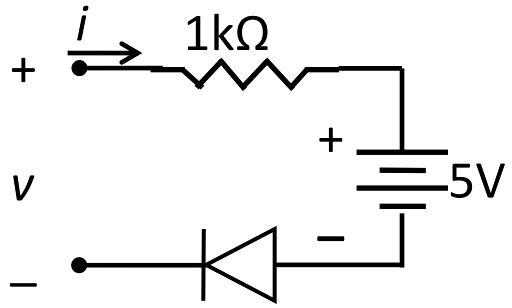


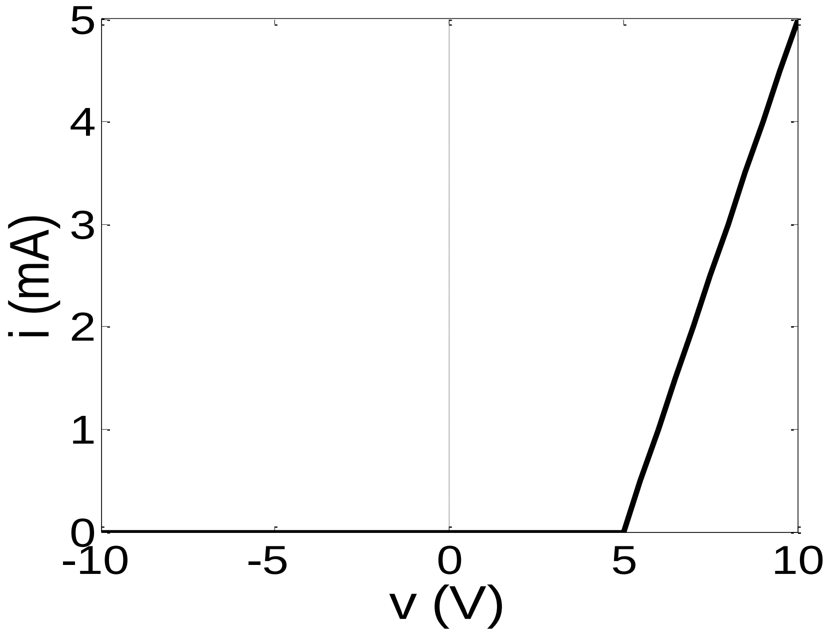
Diode is on for $v > 0$ and R=2kΩ



Numerical Problem1…

B)

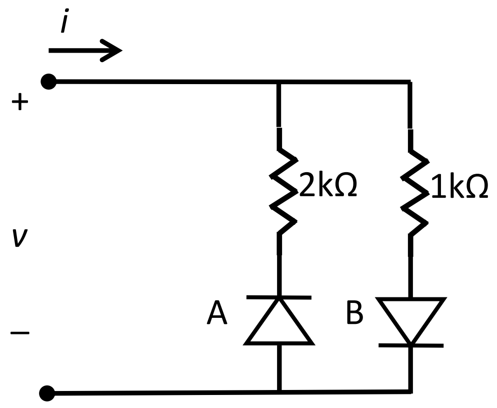


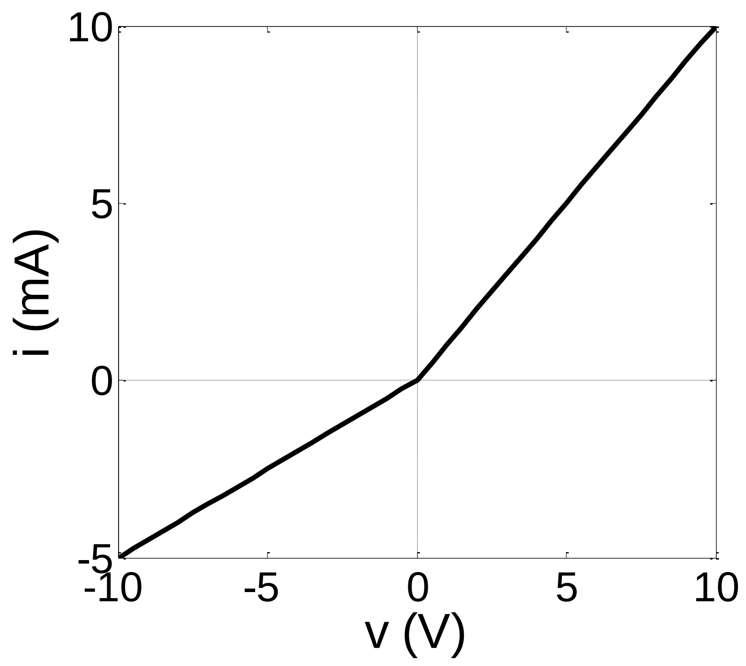


Due to the presence of the 5V supply the diode conducts only for $v > 5$, $R = 1k\Omega$

Numerical Problem1…

C)

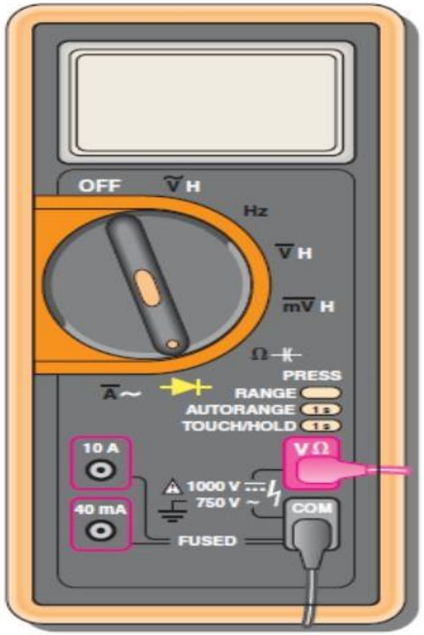


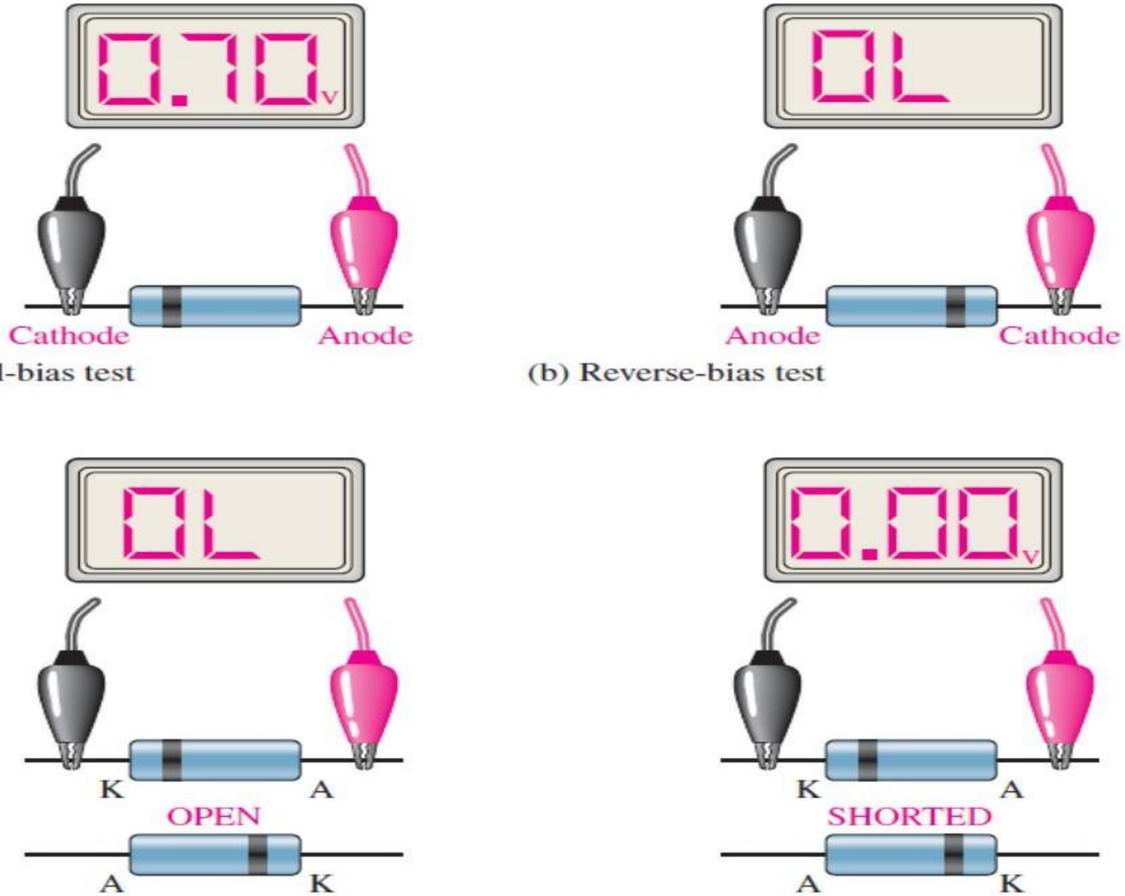


Diode B is on for $v > 0$ and R=1kΩ.

Diode A is on for $v < 0$ and R=2kΩ.

Diode Testing with DMM





(a) Forward-bias test

(b) Reverse-bias test

(c) Forward- and reverse-bias tests for an open diode give the same indication.

(d) Forward- and reverse-bias tests for a shorted diode give the same 0 V reading.

Acknowledgements

1. Electronic Devices, Thomas L. Floyd
2. Web Resources

Thank You..