



# Lecture (02) PN-Junctions and Diodes

By:

Dr. Ahmed ElShafee

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

## Agenda

- N-type, P-type semiconductors
- N-Type Semiconductor
- P-Type Semiconductor
- PN junction
- Energy Diagrams of the *PN* Junction and Depletion Region
- Diode Operation
- **VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE**
  - Forward bias
  - **Reverse Bias**
  - ***V-I* Characteristic for Forward Bias**
  - ***V-I* Characteristic for Reverse Bias**
- **DIODE MODELS**

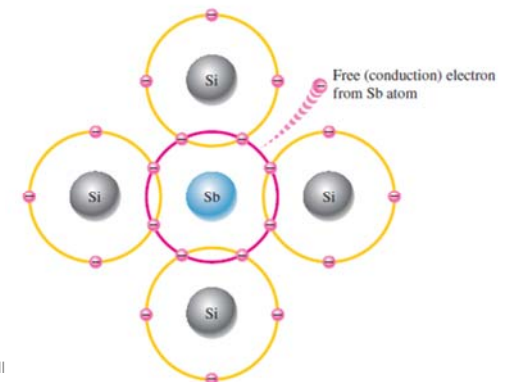
Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

## N-type, P-type semiconductors

- Semiconductors are not good conductors because of the limited number of free electrons in the conduction band and holes in the valence band
- Intrinsic silicon (or germanium) must be modified by increasing the number of free electrons or holes to increase its conductivity and make it useful in electronic devices.
- This is done by adding impurities to the intrinsic material
- Two types of extrinsic (impure) semiconductive materials, *n*-type and *p*-type, are the key building blocks for most types of electronic devices
- This process, called **doping**, increases the number of current carriers (electrons or holes).

## N-Type Semiconductor

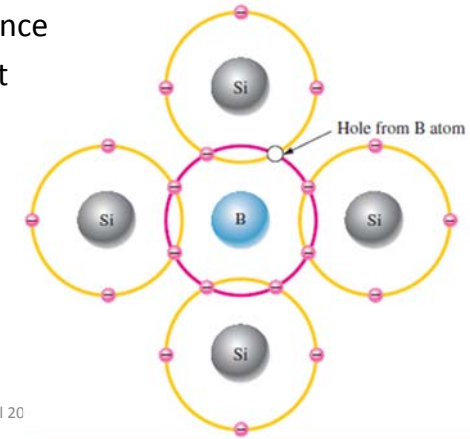
- **pentavalent** (atoms with five valence electrons) impurity atoms are added.
- Like : arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb).
- Example:
- Four of the antimony atom's valence electrons are used to form the covalent bonds with silicon atoms, leaving one extra electron.



- pentavalent atom gives up an electron, it is often called a donor atom.
- number of conduction electrons can be controlled by the number of impurity atoms added to the silicon.
- doping process does not leave a hole in the valence band
- In N-type semiconductor, the electrons are called the majority carriers.
- A few holes that are created when electron-hole pairs are thermally generated.
- Holes in an *n*-type material are called minority carriers.

## P-Type Semiconductor

- To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added, with three valence electrons
- such as boron (B), indium (In), and gallium (Ga).
- three of the boron atom's valence electrons are used in the covalent bonds; a hole results when each trivalent atom is added.
- trivalent atom can take an electron, it is often referred to as an acceptor atom.

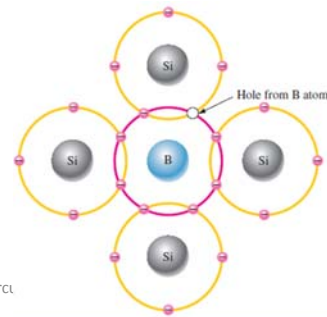


- The number of holes can be controlled by the number of trivalent impurity atoms added to the silicon.
- The holes are the majority carriers in *p*-type material.
- a few conduction-band electrons that are created when electron-hole pairs are thermally generated.
- Conduction-band electrons in *p*-type material are the minority carriers.

## PN junction

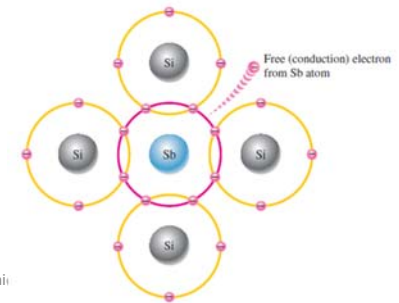
- When you take a block of silicon and dope part of it with a trivalent impurity and the other part with a pentavalent impurity, a boundary called the *pn* junction is formed between the resulting *p*-type and *n*-type portions.
- The *pn* junction is the basis for diodes, certain transistors, solar cells, and other devices,

- A *p*-type material consists of silicon atoms and trivalent impurity atoms such as boron, adding a hole when it bonds with the silicon atoms.
- However, since the number of protons and the number of electrons are equal throughout the material, there is no net charge in the material and so it is neutral



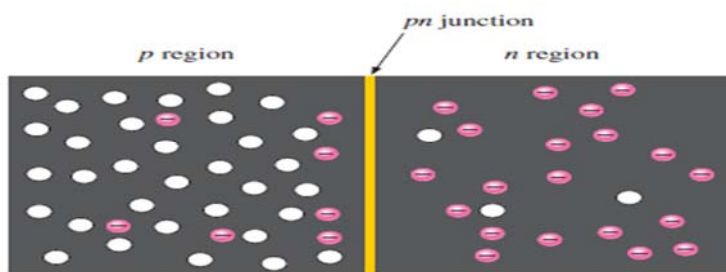
Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circ

- *n*-type silicon material consists of silicon atoms and pentavalent impurity atoms, that releases an electron when it bonds with four silicon atoms
- still an equal number of protons and electrons, no net charge in the material and so it is neutral

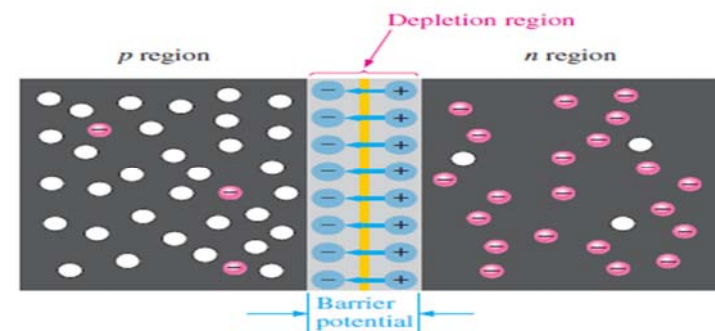


Dr. Ahmed ElShafee, ACU : Fall 2015, Electroni

- a **pn junction** forms at the boundary between the two regions and a diode is created
- The *p* region has many holes (majority carriers) and only a few thermally generated free electrons (minority carriers).
- The *n* region has many free electrons (majority carriers) and only a few thermally generated holes (minority carriers).

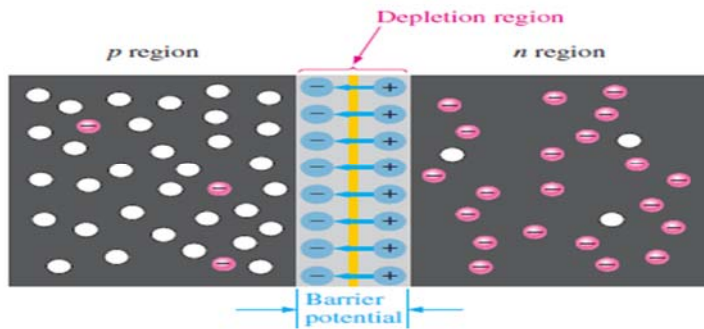


- For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region
- and a negative charge is created in the *p* region, forming a barrier potential.
- This action continues until the voltage of the barrier repels further diffusion.
- The blue arrows between the positive and negative charges in the depletion region represent the electric field.



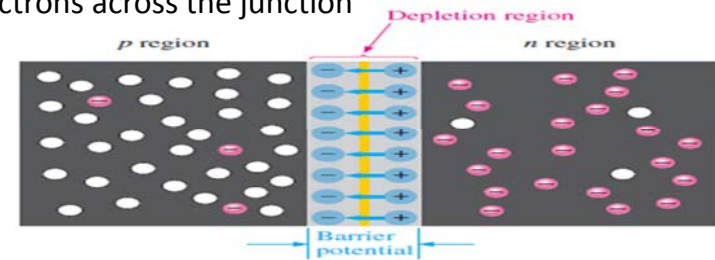
11

- When the  $pn$  junction is formed, the  $n$  region loses free electrons as they diffuse across the junction.
- This creates a layer of positive charges (pentavalent ions) near the junction.
- the  $p$  region loses holes as the electrons and holes combine.
- This creates a layer of negative charges (trivalent ions) near the junction
- Both regions presents the **depletion region**



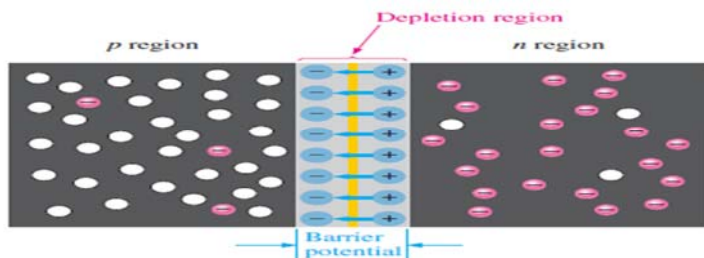
13

- term *depletion* refers, region near the  $pn$  junction is depleted of charge carriers, due to diffusion across the junction.
- depletion region is formed very quickly and is very thin compared to the  $n$  region and  $p$  region.
- After the initial surge of free electrons across the  $pn$  junction, the depletion region has expanded to a point where equilibrium is established and there is no further diffusion of electrons across the junction



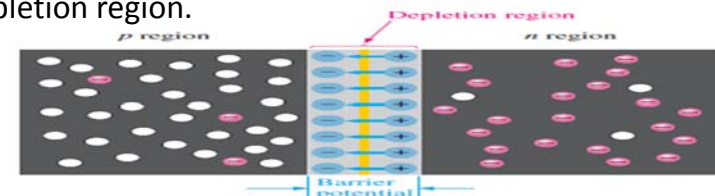
14

- Equilibrium happens as follow: A point is reached where the total negative charge in the depletion region repels any further diffusion of electrons into the  $p$  region, and the diffusion stops.
- Depletion region acts as a barrier to the further movement of electrons across the junction.



15

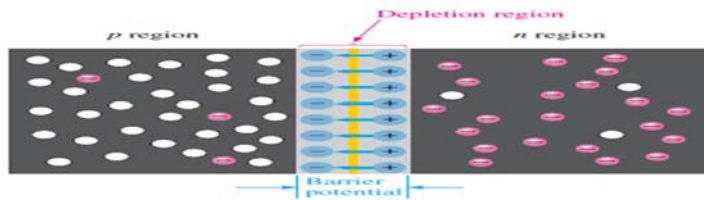
- **Barrier Potential:**
- Coulomb's law state that any positive charge and a negative charge near each other, there is a force acting on the charge
- In the depletion region positive charges and many negative charges on opposite sides of the  $pn$  junction.
- The forces between the opposite charges form an *electric field*
- xternal energy must be applied to get the
- electrons to move across the barrier of the electric field in the depletion region.



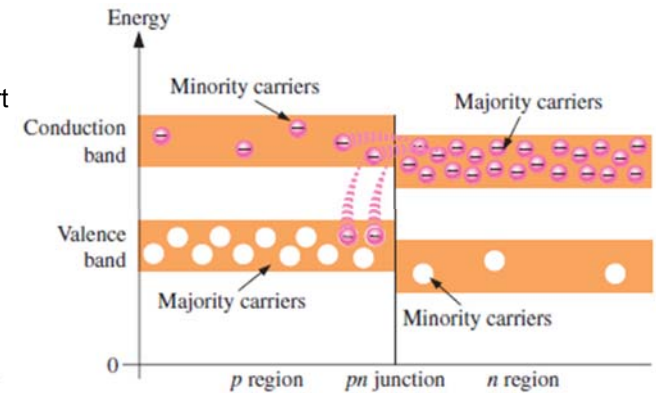
16

# Energy Diagrams of the PN Junction and Depletion Region

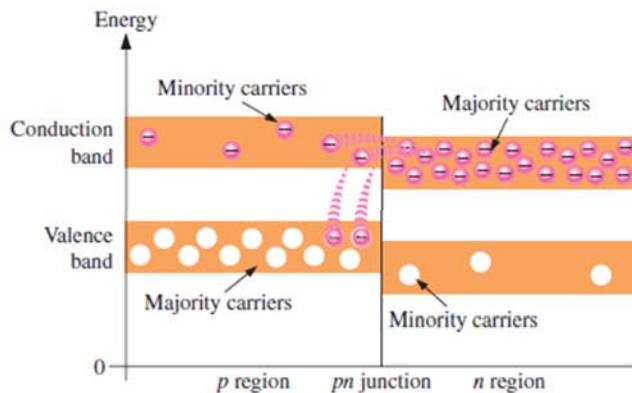
- **Barrier Potential (volts):** is The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field.
- The barrier potential of a *pn* junction depends on several factors, including the type of semiconductive material, the amount of doping, and the temperature.
- The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at



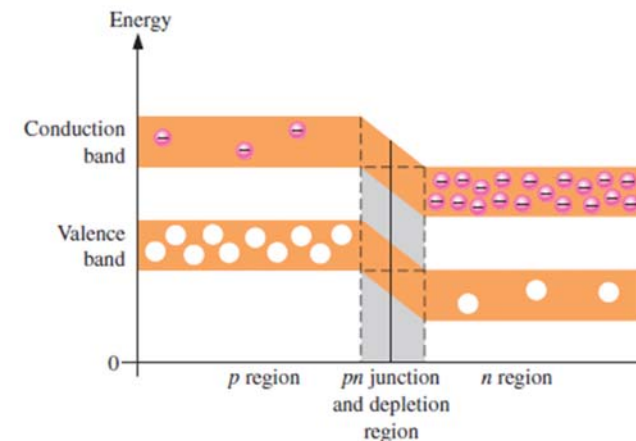
- The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material.
- *p*-type material has trivalent impurities
- *n*-type material has pentavalent impurities.
- The trivalent impurities exert lower forces on the outer-shell electrons than the pentavalent impurities.
- The lower forces in *p*-type materials mean that the electron orbits are slightly larger and hence have greater energy than the electron orbits in the *n*-type materials.



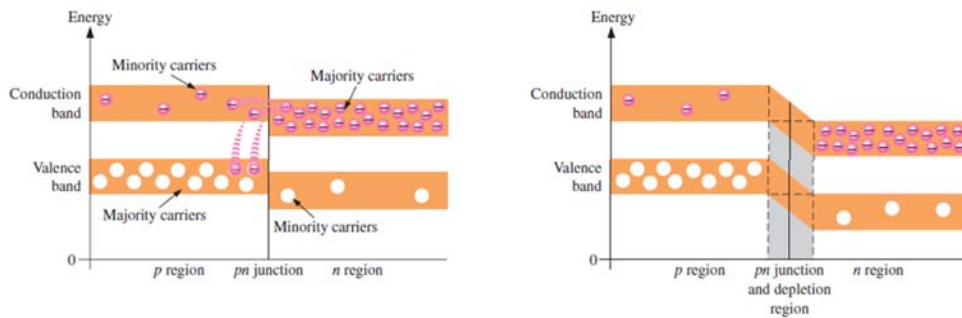
- The free electrons in the *n* region that occupy the upper part of the conduction band can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the *p*-region conduction band.
- After crossing the junction, the electrons quickly lose energy and fall into the holes in the *p*-region valence band as indicated



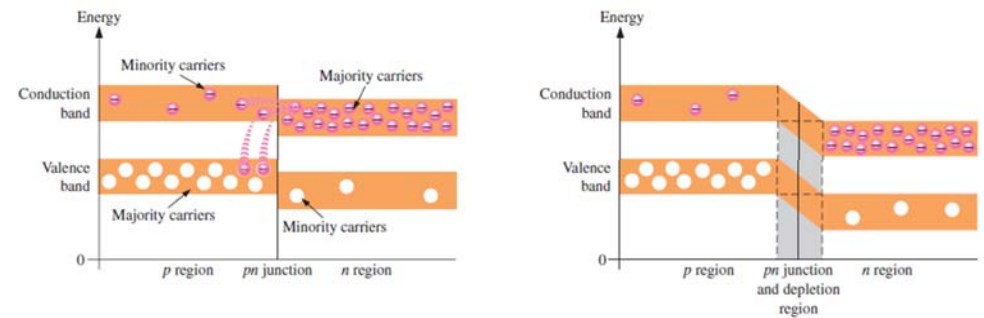
- As the diffusion continues, the depletion region begins to form and the energy level of the *n*-region conduction band decreases.
- Soon, there are no electrons left in the *n*-region conduction band with enough energy to get across the junction to the *p*-region conduction band,



- At this point, the junction is at equilibrium; and the depletion region is complete.
- There is an energy gradient across the depletion region which acts as an “energy hill” that an  $n$ -region electron must climb to get to the  $p$  region.

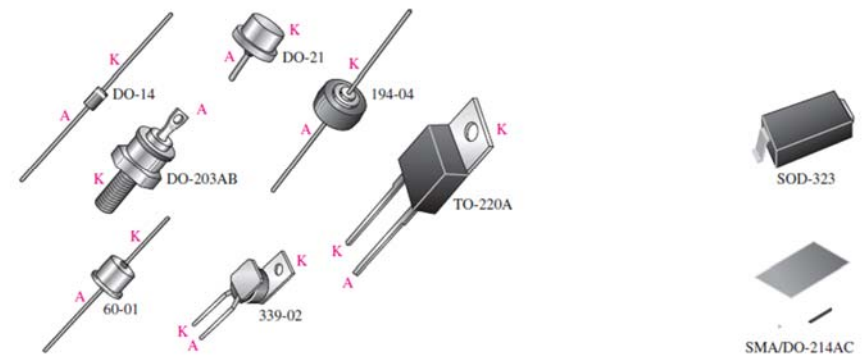
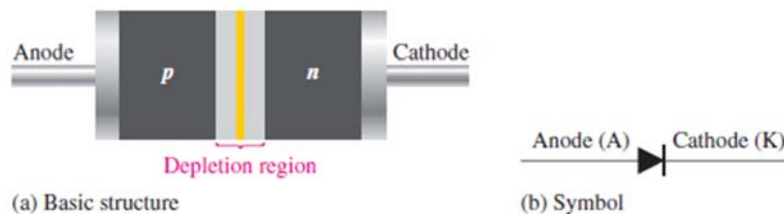


- Notice that as the energy level of the  $n$ -region conduction band has shifted downward, the energy level of the valence band has also shifted downward.
- It still takes the same amount of energy for a valence electron to become a free electron.
- In other words, the energy gap between the valence band and

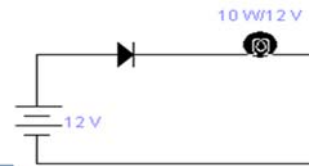


## Diode Operation

- **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  $pn$  junction and depletion region in between.
- $p$  region is called the **anode**
- $n$  region is called the **cathode**



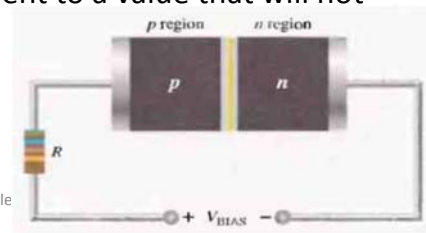
# Forward Bias



- **Forward bias** is the condition that allows current through the  $pn$  junction.

conditions:

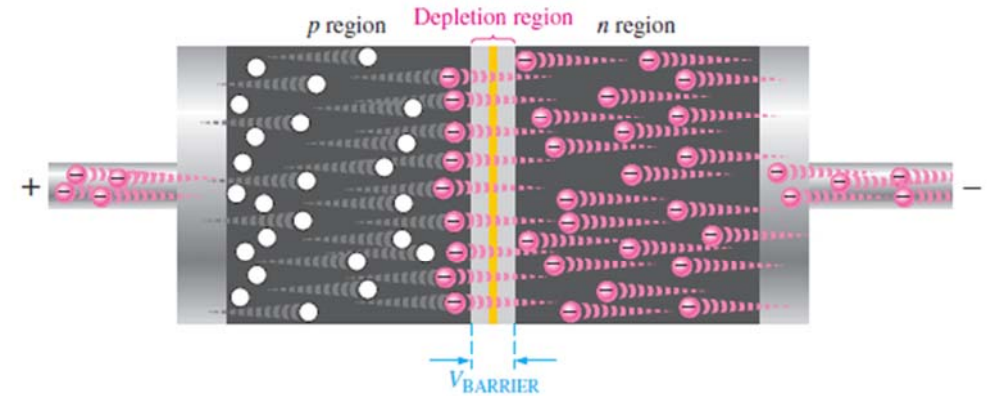
1. negative side of  $V_{BIAS}$  is connected to the  $n$  region of the diode and the positive side is connected to the  $p$  region
  2. A second requirement is that the bias voltage,  $V_{BIAS}$ , must be greater than the **barrier potential**.
- The resistor limits the forward current to a value that will not damage the diode.



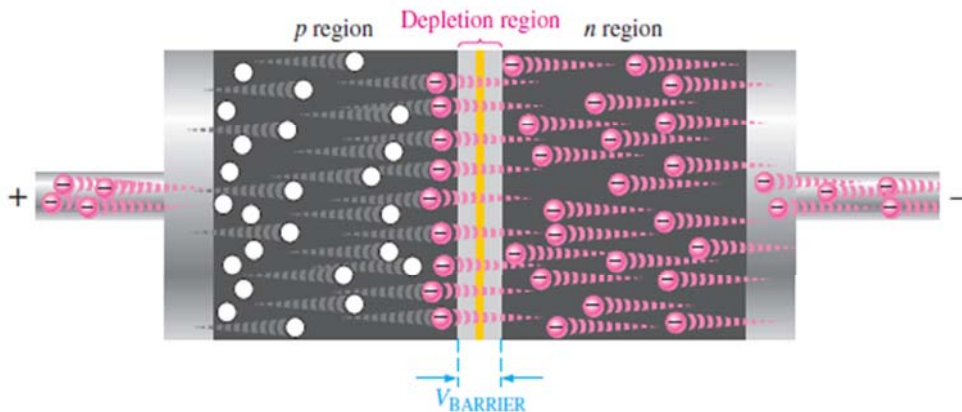
70

Dr. Ahmed ElShafee, ACU : Fall 2015, Ele

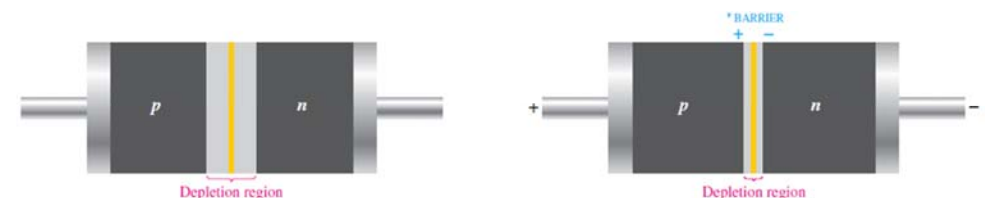
- the electrons are in the valence band in the  $p$  region
- the positive side of the bias-voltage source attracts the valence electrons toward the left end of the  $p$  region, leaving holes behind on  $p$  region.
- The valence electrons move from one hole to the next toward the left.
- $P$  region holes (majority carriers) move to the right toward the junction (attracted by depletion region), (hole current)



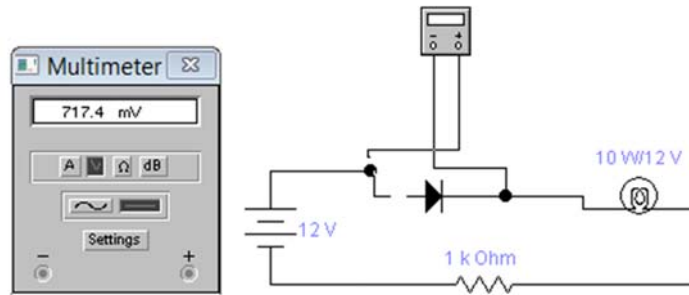
- As more electrons flow into the depletion region, the number of positive ions is reduced.
- As more holes effectively flow into the depletion region on the other side of the  $pn$  junction, the number of negative ions is reduced.
- This reduction in positive and negative ions during forward bias causes the depletion region to narrow



- As known, energy hill, is the electric field between the positive and negative ions in the depletion region, prevents free electrons from diffusing across the junction at equilibrium (*barrier potential*)
- After applying forward bias, depletion region become thin, and energy hill become smaller,



- As known barrier potential = 0.7 volt,
- Applying enough bias voltage to enable free electron to climb the potential barrier (energy hill) is 0.7 volt discounted as voltage drop over diode make depletion region disappear and enables free electrons to pass through diode.



٢٩

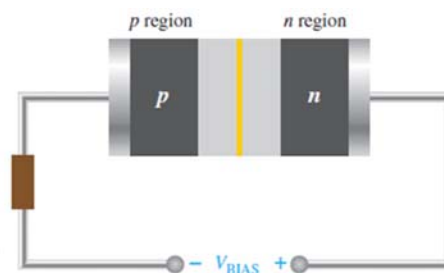
- This energy loss results in a voltage drop across the  $pn$  junction equal to the barrier potential (0.7 V)
- An additional small voltage drop occurs across the  $p$  and  $n$  regions due to the internal resistance of the material.
- For doped semi conductive material, this resistance, called the **dynamic resistance**, is very small and can usually be neglected.

٣٠

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

## Reverse Bias

- Reverse bias: positive side of  $V_{BIAS}$  is connected to the  $n$  region of the diode and the negative side is connected to the  $p$  region
- depletion region is shown much wider than in forward bias or equilibrium

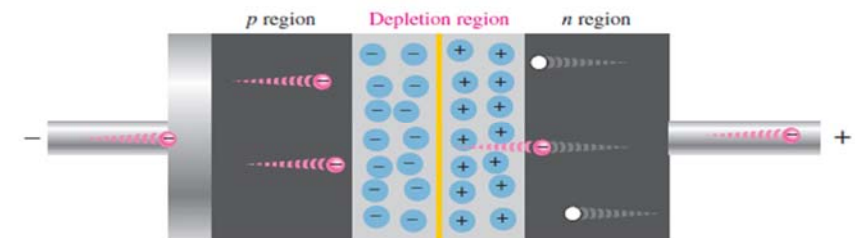


٣١

Dr. Ahmed ElShafee, ACU : Fall 20

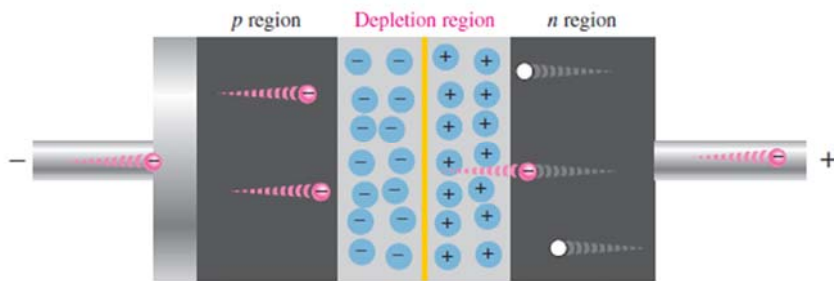
- In the  $p$  region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions.
- This results in a widening of the depletion region and a depletion of majority carriers.
- The initial flow of charge lasts for only a very short time after the reverse-bias voltage is applied.

٣٢

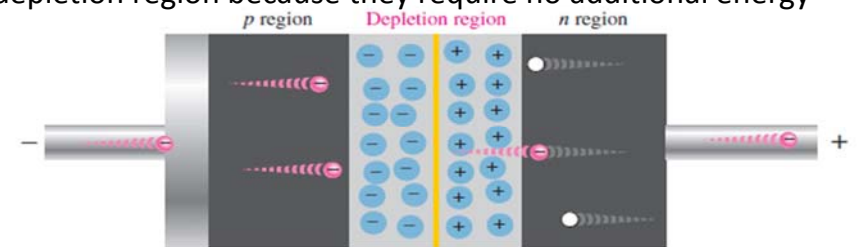




- As the depletion region widens,
  - the availability of majority carriers decreases.
  - electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage,  $V_{BIAS}$

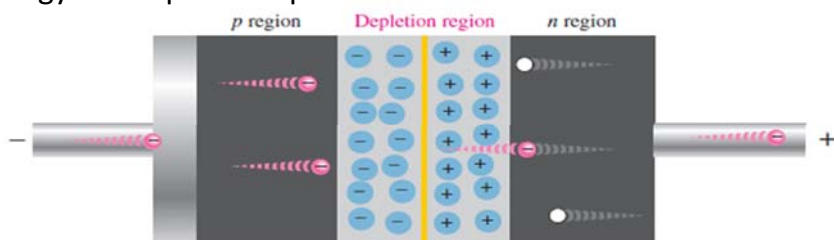


- **Reverse current:** extremely small current that exists in reverse bias, as the small number of free minority electrons in the  $p$  region are “pushed” toward the  $pn$  junction by the negative bias voltage
- When these electrons reach the wide depletion region, they “fall down the energy hill” 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

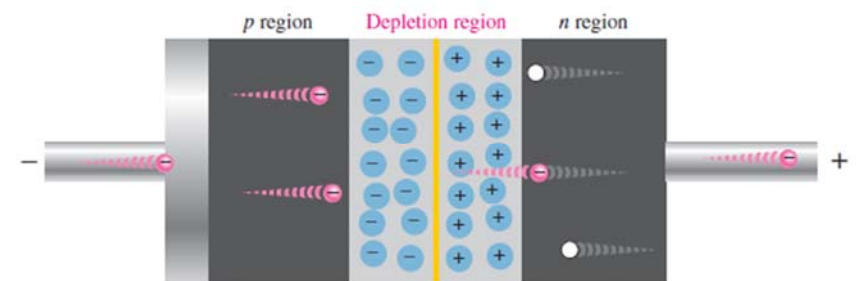


### • **Reverse Breakdown**

- if the external reverse-bias voltage is increased to a value called the *breakdown voltage*, the reverse current will increase.
- 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. (consider one electron collide with 2 electrons and so on) (**avalanche effect**)
- The newly created conduction electrons are also high in energy and repeat the process.

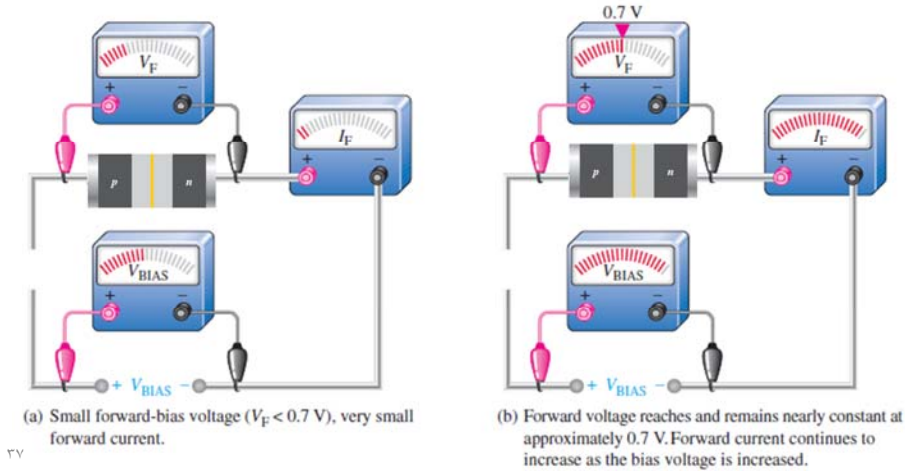


- As these high-energy electrons go through the depletion region, they have enough energy to go through the  $n$  region as conduction electrons, rather than combining with holes.
- When the reverse current is not limited, the resulting heating will permanently damage the diode.
- Most diodes are not 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.



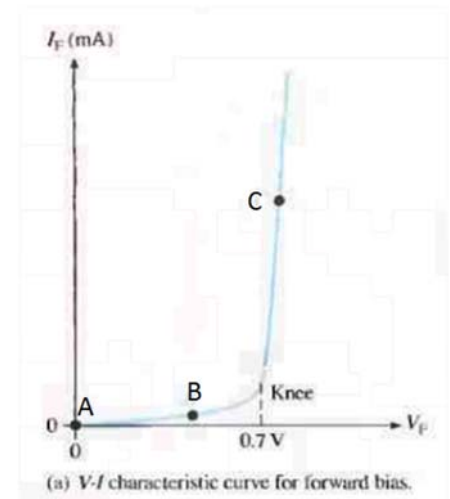
# V-I Characteristic for Forward Bias

- forward-bias voltage is applied across a diode, current flow called *forward current* and is designated  $I_F$



٣٧

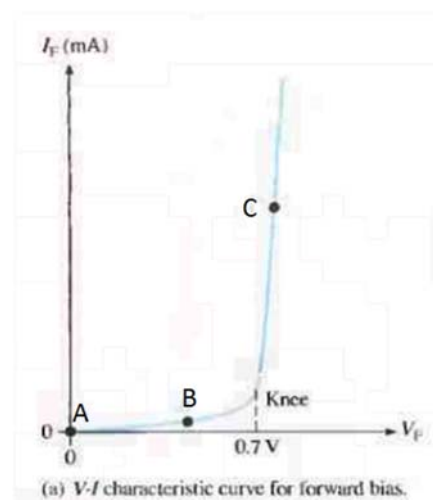
- With 0 V across the diode, there is no forward current
- increase the forward-bias voltage, the forward current *and* the voltage across the diode gradually increase,
- A portion of the forward-bias voltage is dropped across the ( ) limiting resistor
- When Forward bias reach 0.7 volt ((barrier potential), forward current begins to increase



٣٨

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

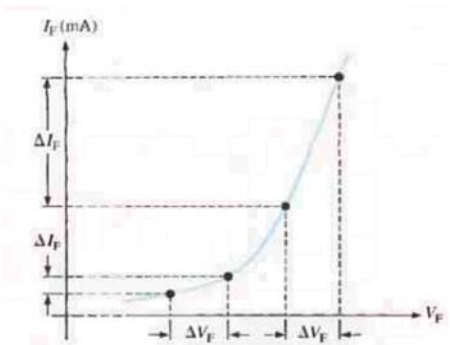
- Increasing forward bias current continues to increase very rapidly, but the voltage across the diode increases only gradually above 0.7 V (voltage drop due to diode limiting resistor)



٣٩

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

- dynamic resistance
- resistance of the forward-biased diode is not constant over the entire curve

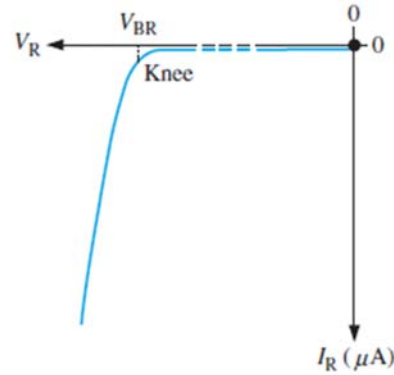


٤٠

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

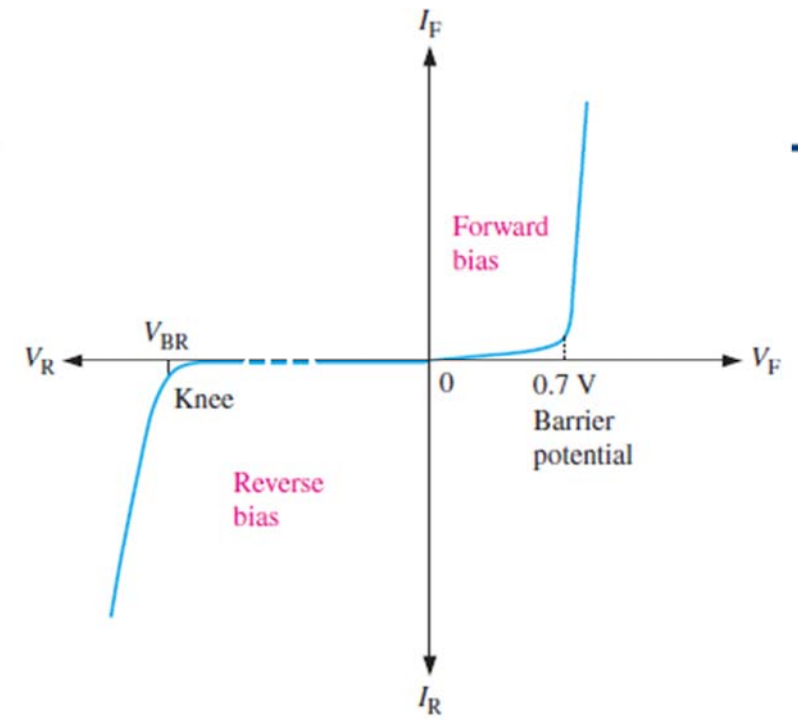
# V-I Characteristic for Reverse Bias

- 0 V across the diode, there is no reverse current
- gradually increase the reverse-bias voltage, there is a very small reverse current
- When reverse voltage across the diode ( $V_R$ ) reaches the breakdown value ( $V_{BR}$ ), the reverse current begins to increase rapidly.



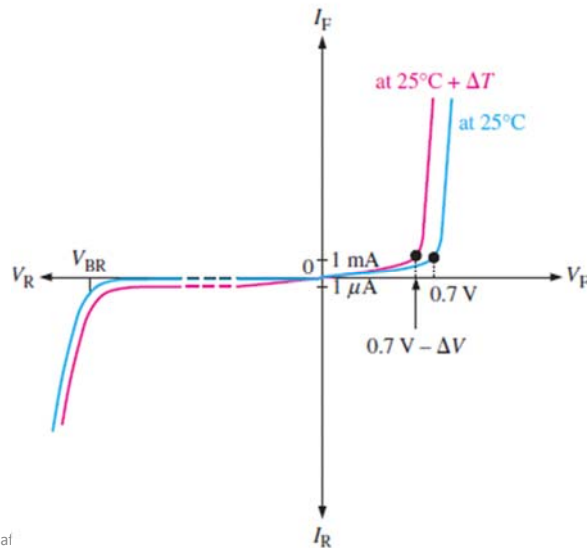
٤١

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits



٤٢

- **Temperature Effects**
- as temperature is increased, the forward current increases for a given value of forward voltage

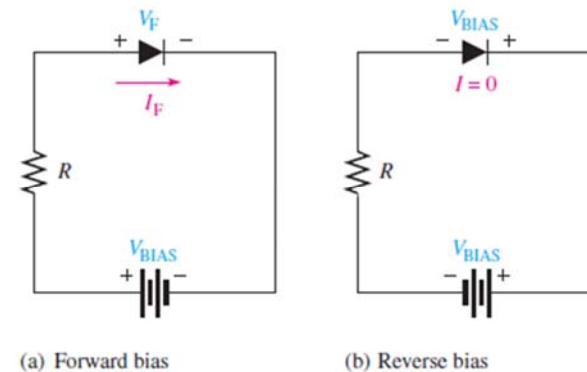


٤٣

Dr. Ahmed ElShaf

# DIODE MODELS

- **Bias Connections**

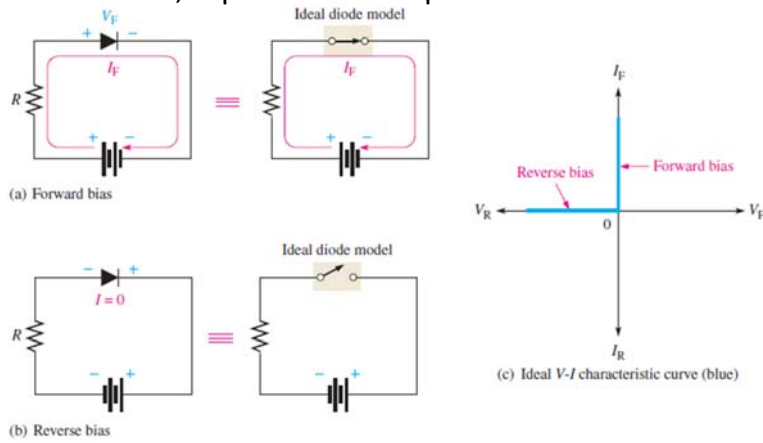


٤٤

Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits

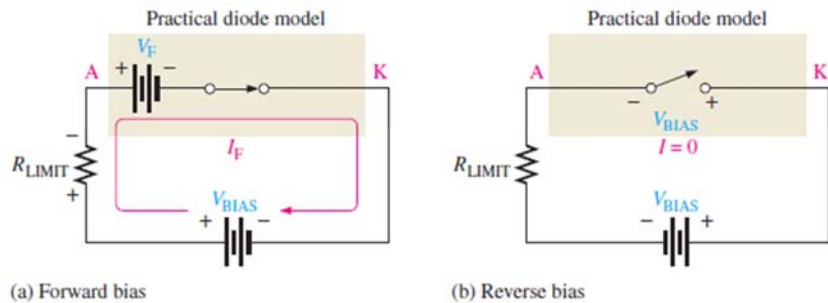
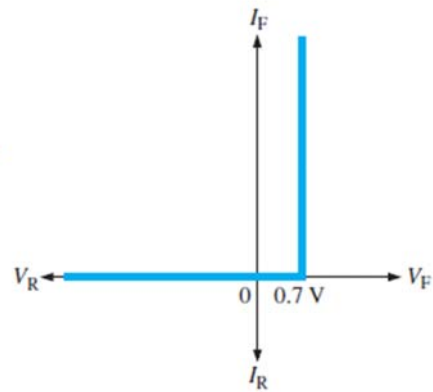
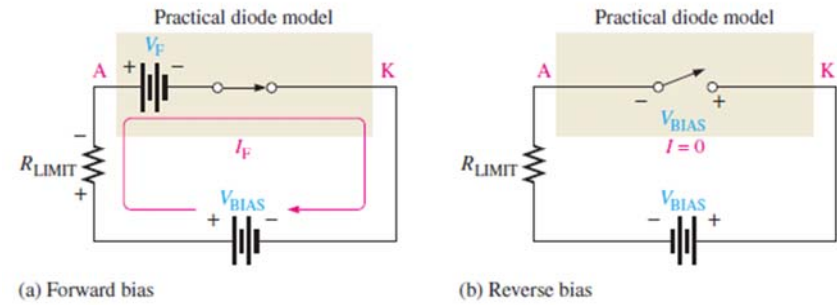
• **The Ideal Diode Model:**

- Forward biased is represented by a simple closed switch.
- reverse-biased, is presented as open switch



• **The Practical Diode Model**

- If diode is forward-biased, is equivalent to a closed switch in series with a small equivalent voltage source ( $V_F$ ) equal to the barrier potential (0.7 V)



- Applying KVL :

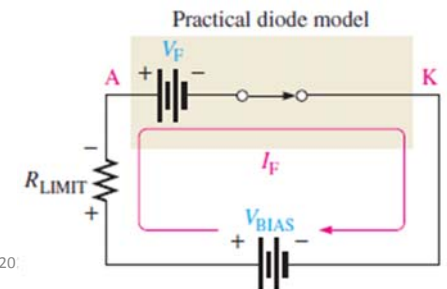
$$V_{BIAS} - V_F - V_{R_{LIMIT}} = 0$$

- Ohms law

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

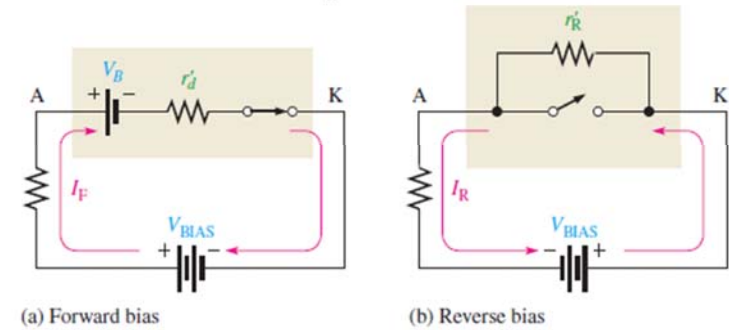
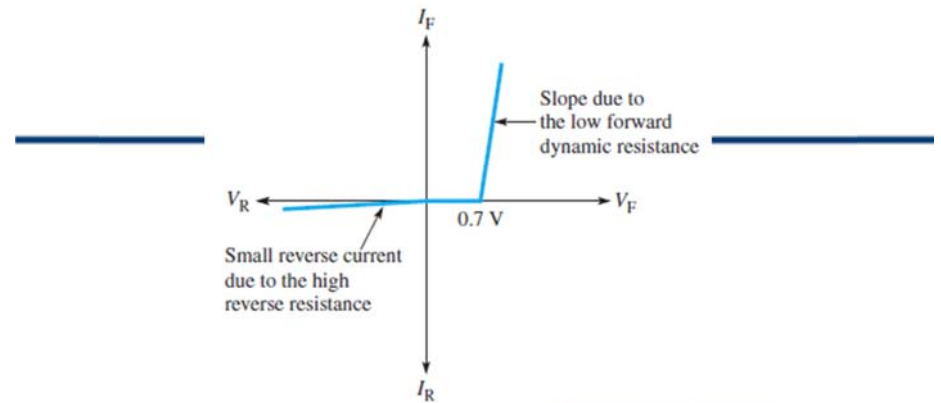
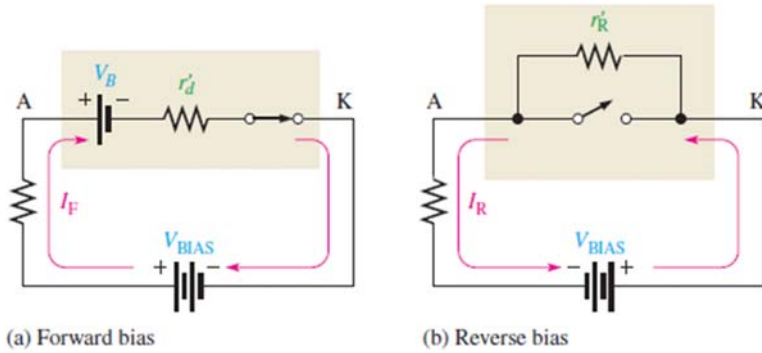
- Substituting

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$



• **The Complete Diode Model**

- Add a small forward dynamic resistance ( $r'_d$ ) and the large internal reverse resistance ( $r'_R$ ).

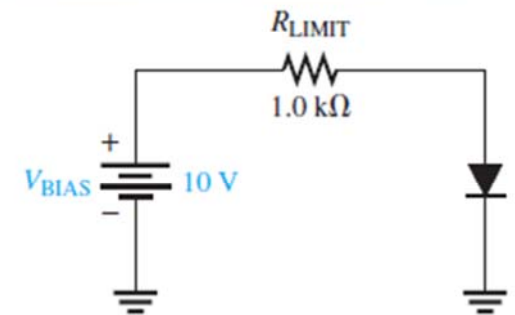
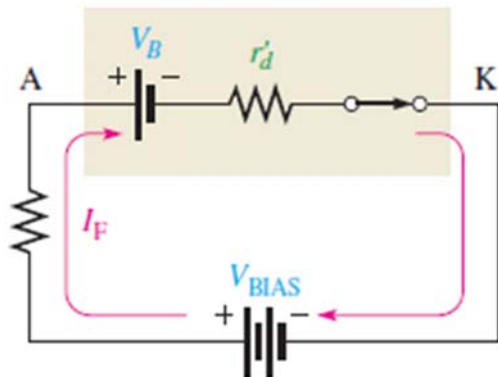


## Example 01

- (a) Determine the forward voltage and forward current for the diode in Figure 2-18(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume  $r'_d = 10 \Omega$  at the determined value of forward current.

$$V_F = 0.7 \text{ V} + I_F r'_d$$

$$I_F = \frac{V_{\text{BIAS}} - 0.7 \text{ V}}{R_{\text{LIMIT}} + r'_d}$$

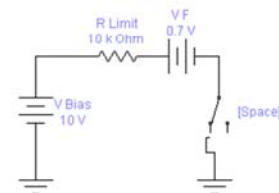
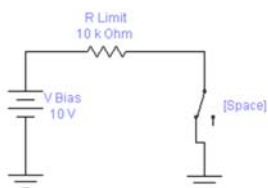
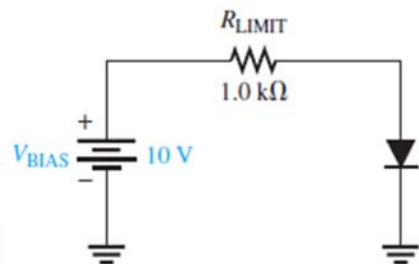


• Ideal model:

$$V_F = 0 \text{ V}$$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10 \text{ V}}{1.0 \text{ k}\Omega} = 10 \text{ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10 \text{ mA})(1.0 \text{ k}\Omega) = 10 \text{ V}$$



al

$$V_F = 0.7 \text{ V}$$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega} = \frac{9.3 \text{ V}}{1.0 \text{ k}\Omega} = 9.3 \text{ mA}$$

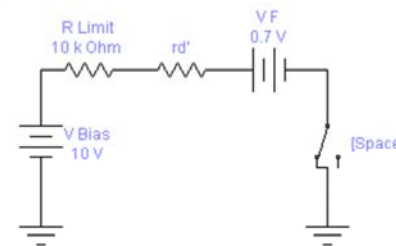
$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3 \text{ mA})(1.0 \text{ k}\Omega) = 9.3 \text{ V}$$

• Complete model

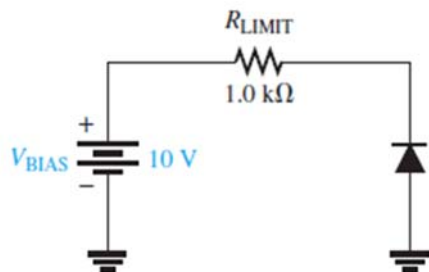
$$I_F = \frac{V_{BIAS} - 0.7 \text{ V}}{R_{LIMIT} + r'_d} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega + 10 \Omega} = \frac{9.3 \text{ V}}{1010 \Omega} = 9.21 \text{ mA}$$

$$V_F = 0.7 \text{ V} + I_F r'_d = 0.7 \text{ V} + (9.21 \text{ mA})(10 \Omega) = 792 \text{ mV}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.21 \text{ mA})(1.0 \text{ k}\Omega) = 9.21 \text{ V}$$



(b) Determine the reverse voltage and reverse current for the diode in Figure 2–18(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume  $I_R = 1 \mu\text{A}$ .

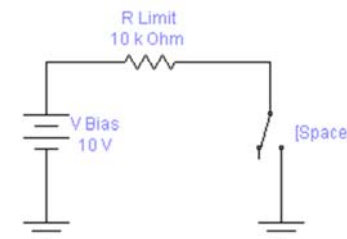


• Ideal model

$$I_R = 0 \text{ A}$$

$$V_R = V_{BIAS} = 10 \text{ V}$$

$$V_{R_{LIMIT}} = 0 \text{ V}$$



• Practical model:

$$I_R = 0 \text{ A}$$

$$V_R = V_{BIAS} = 10 \text{ V}$$

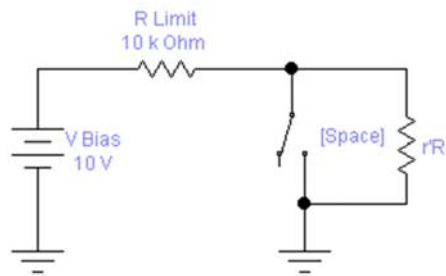
$$V_{R_{LIMIT}} = 0 \text{ V}$$

- Complete model

$$I_R = 1 \mu\text{A}$$

$$V_{R_{\text{LIMIT}}} = I_R R_{\text{LIMIT}} = (1 \mu\text{A})(1.0 \text{ k}\Omega) = 1 \text{ mV}$$

$$V_R = V_{\text{BIAS}} - V_{R_{\text{LIMIT}}} = 10 \text{ V} - 1 \text{ mV} = 9.999 \text{ V}$$



oV

15



Dr. Ahmed ElShafee, ACU : Fall 2015, Electronic Circuits