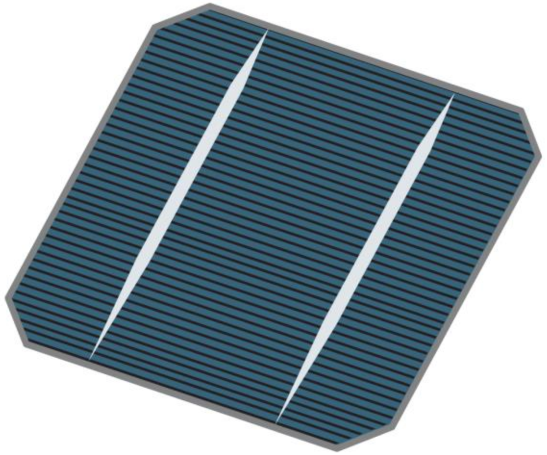
Lecture 2 – Part1
Photovoltaic (PV) Cell

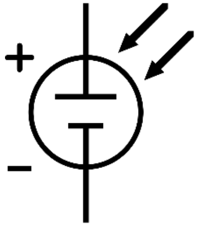
Dr. Said Emam

http://bu.edu.eg/staff/saidemam3

saidemam@feng.bu.edu.eg

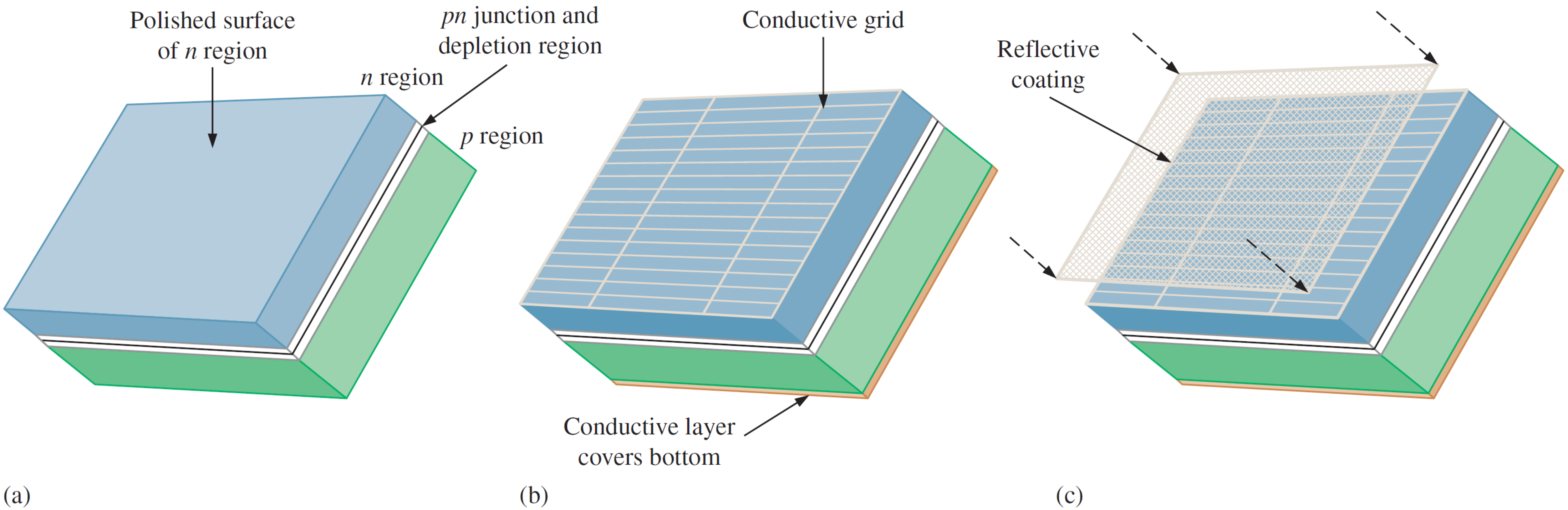
Photovoltaic (PV) Cell





- Photovoltaic (PV) cells, or solar cells, take advantage of the **photovoltaic (photoelectric) effect** by which a solar cell converts sunlight to electricity.
- Sunlight contains photons or "packets" of energy sufficient to create electron-hole pairs in the *n* and *p* regions.
- Electrons accumulate in the *n*-region and holes accumulate in the *p* region, producing a potential difference (voltage) across the cell.
- When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.

The Solar Cell Structure



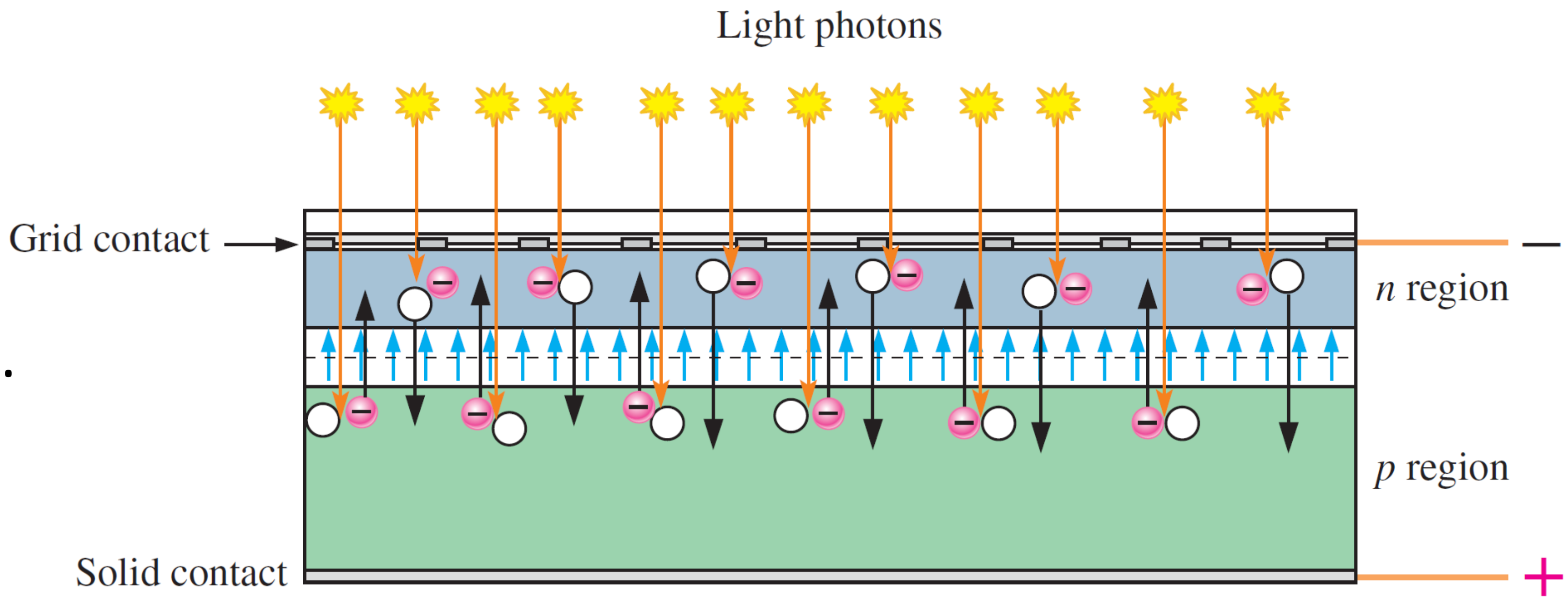
The Solar Cell Structure

- A silicon solar cell consists of a thin layer (wafer) of silicon that has been doped to create a *pn* junction.
- The silicon wafer is doped so that the *n* region is much thinner than the *p* region to permit light penetration, as shown in Figure (a).
- A grid of very thin conductive contact strips are deposited on top of the wafer by methods such as photoresist or silk-screen , as shown in Figure (b). The contact grid must maximize the surface area of the silicon wafer that be exposed to the sunlight in order to collect as much light energy as possible.
- The conductive grid across the top of the cell is necessary so that the electrons have a shorter distance to travel through the silicon when an external load is connected.
- A solid contact covering all of the bottom of the wafer is then added.
- Then an antireflective coating is placed on top the contact grid and *n* region, as shown in Figure (c). This allows the solar cell to absorb as much of the sun's energy as possible by reducing the amount of light energy reflected away from the surface of the cell.
- Finally, a glass or transparent plastic layer is attached to the top of the cell with transparent adhesive to protect it from the weather.

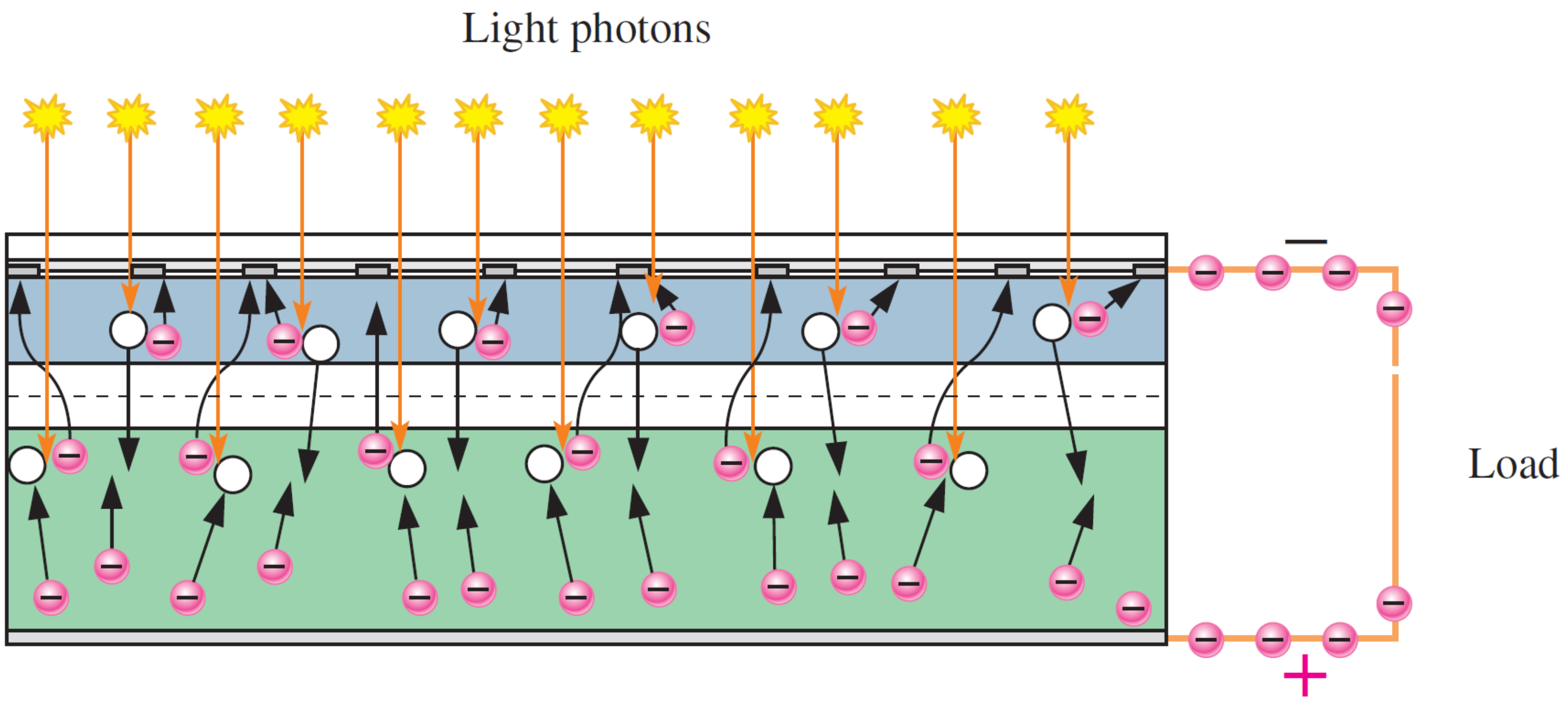
Operation of a Solar Cell

- The *n*-type layer is very thin compared to the *p* region to allow light penetration into the *p* region. The thickness of the entire cell is actually about the thickness of an eggshell.
- When a photon penetrates either the *n* region or the *p*-type region and strikes a silicon atom it creates an *electron-hole pair.*
- In the *p* region, the free electron is swept across the depletion region by the electric field into the *n* region. In the *n* region, the hole is swept across the depletion region by the electric field into the *p* region.

- Electrons accumulate in the n region, creating a negative charge;
- and holes accumulate in the p region, creating a positive charge.
- A voltage is developed between the n region and p region contacts.

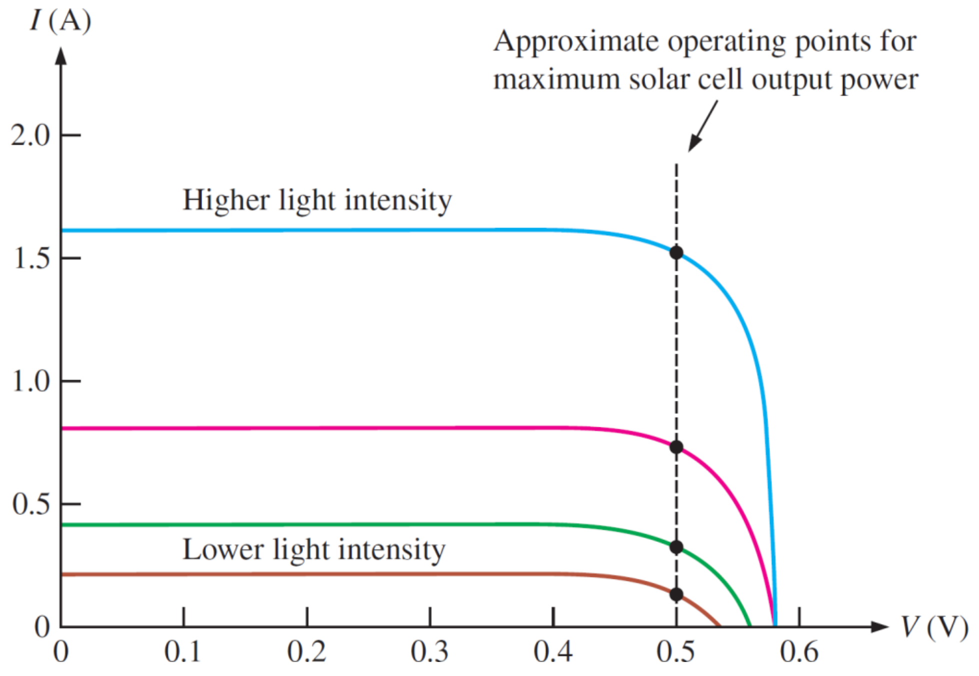


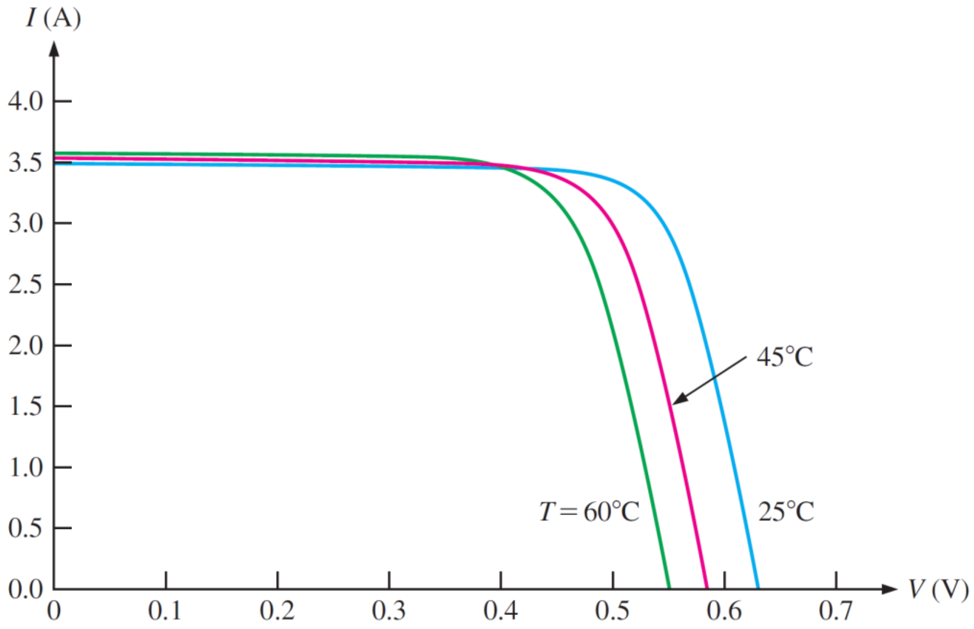
- When a load is connected to a solar cell, the free electrons flow out of the *n* region to the grid contacts on the top surface, through the negative contact, through the load and back into the positive contact on the bottom surface, and into the *p* region where they can recombine with holes.
- The sunlight energy continues to create new electron-hole pairs and the process goes on.



Solar Cell Characteristics

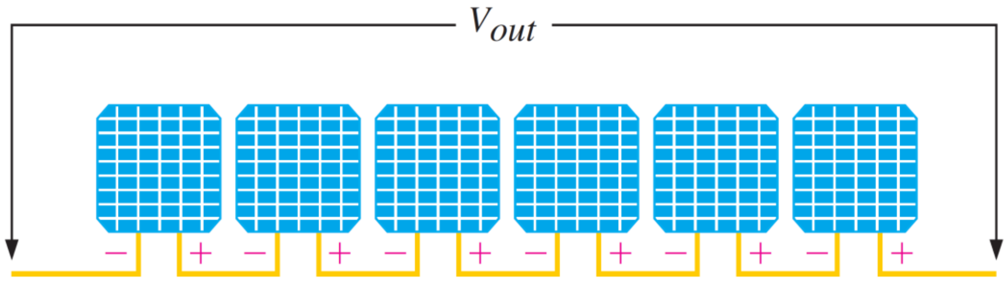
- Solar cells are typically 100 cm2 to 225 cm2 in size.
- The usable voltage from silicon solar cells is approximately 0.5 V to 0.6 V
- Higher light intensity produces more current
- The output voltage and current of a solar cell is also temperature dependent. For a constant light intensity the output voltage decreases as the temperature increases but the current is affected only by a small amount



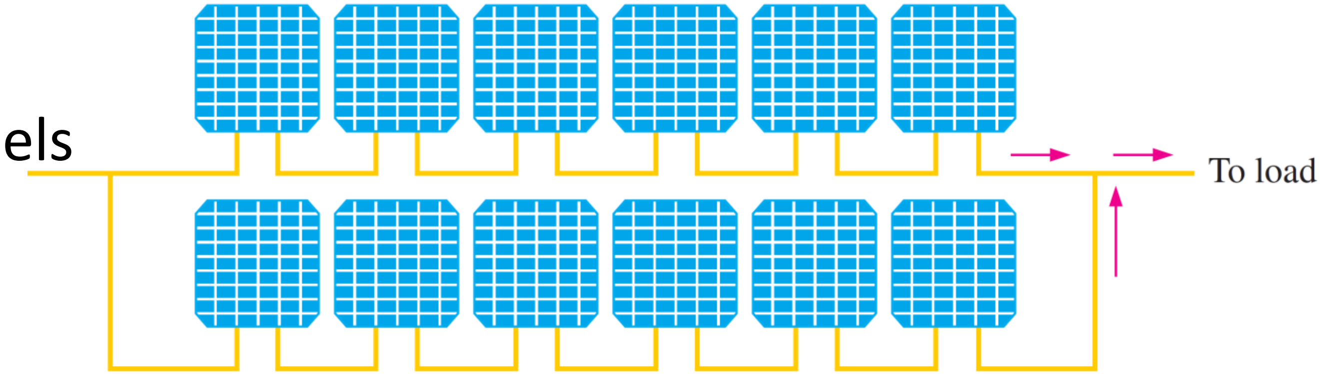


Solar Cell Panels

- A single solar cell is impractical for most applications because it can produce only about 0.5 V to 0.6 V.
- To produce higher voltages, multiple solar cells are connected in series as shown in 7(a).
- For example, the six series cells will ideally produce 6(0.5 V)= 3 V. Since they are connected in series, the six cells will produce the same current as a single cell.
- For increased current capacity, series cells are connected in parallel, as shown in part (b).
- Assuming a cell can produce 2 A, the series-parallel arrangement of twelve cells will produce 4 A at 3 V.
- Multiple cells connected to produce a specified power output are called solar panels or solar modules.



(a) Series connection increases



(b) Series-parallel connection increases current

The Solar Power System

- A basic solar power system that can supply power to ac loads generally consists of four components. These components are :
  - solar panel,
  - charge controller,
  - batteries,
  - and inverter.

Lecture 2 – part2
DIODES AND APPLICATIONS

Dr. Said Emam

http://bu.edu.eg/staff/saidemam3

saidemam@feng.bu.edu.eg

CHAPTER OUTLINE

2–1 Diode Operation
2–2 Voltage-Current (*V-I*) Characteristics of a Diode
2–3 Diode Models
2–4 Half-Wave Rectifiers
2–5 Full-Wave Rectifiers
2–6 Power Supply Filters and Regulators
2–7 Diode Limiters and Clampers
2–8 Voltage Multipliers
2–9 The Diode Datasheet
2–10 Troubleshooting

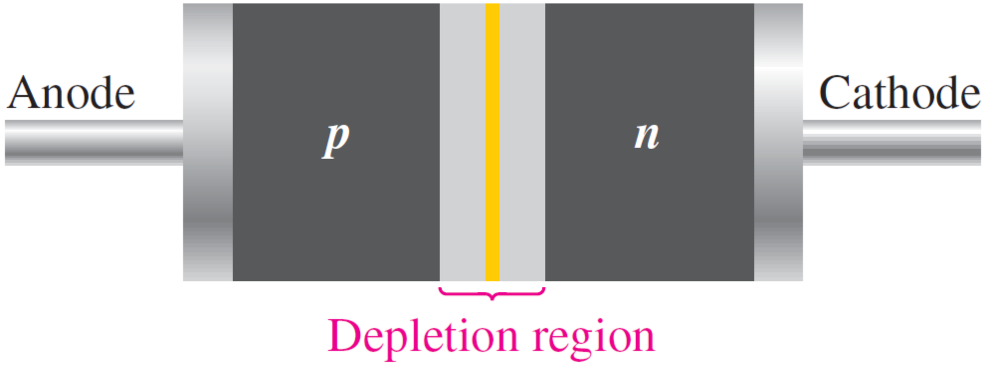
CHAPTER OBJECTIVES

- Use a diode in common applications
- Analyze the voltage-current (*V*-*I*) characteristic of a diode
- Explain how the three diode models differ
- Explain and analyze the operation of half-wave rectifiers
- Explain and analyze the operation of full-wave rectifiers
- Explain and analyze power supply filters and regulators
- Explain and analyze the operation of diode limiters and clampers
- Explain and analyze the operation of diode voltage multipliers
- Interpret and use diode datasheets
- Troubleshoot diodes and power supply circuits

KEY TERMS

- Diode
- Bias
- Forward bias
- Reverse bias
- V-I characteristic
- DC power supply
- Rectifier
- Filter
- Regulator
- Half-wave rectifier
- Peak inverse voltage (PIV)
- Full-wave rectifier
- Ripple voltage
- Line regulation
- Load regulation
- Limiter
- Clamper
- Troubleshooting

2–1 DIODE OPERATION

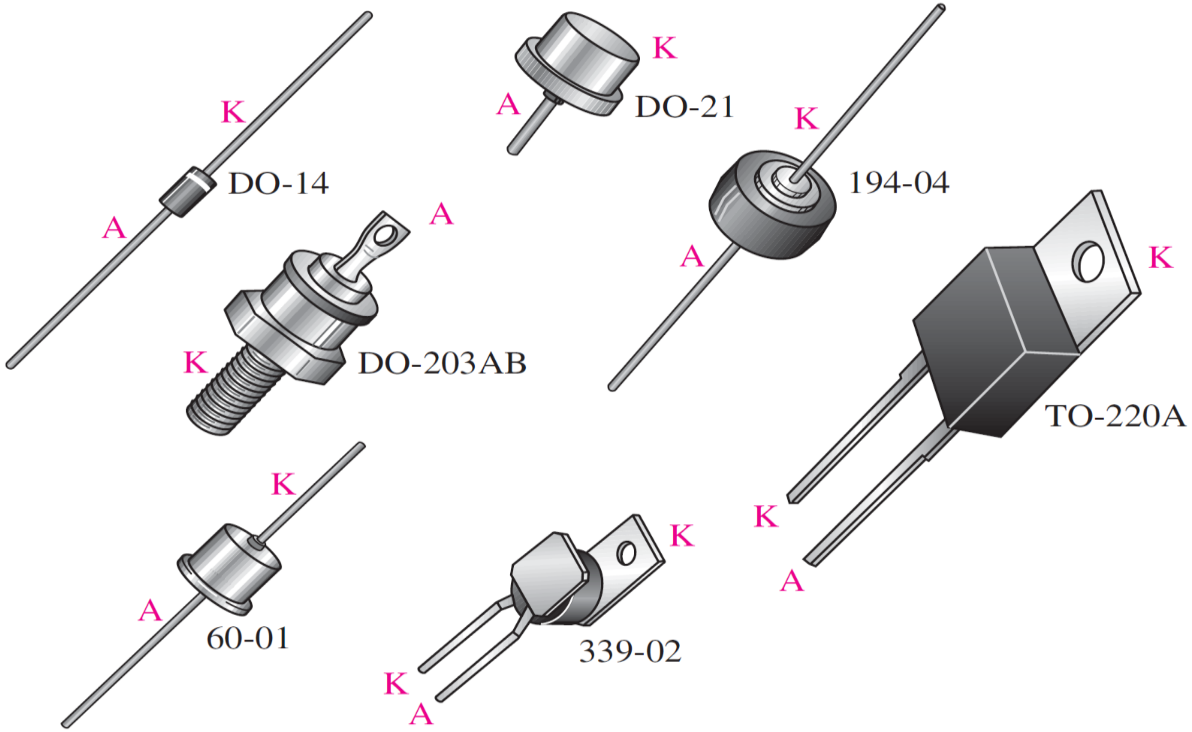


(a) Basic structure

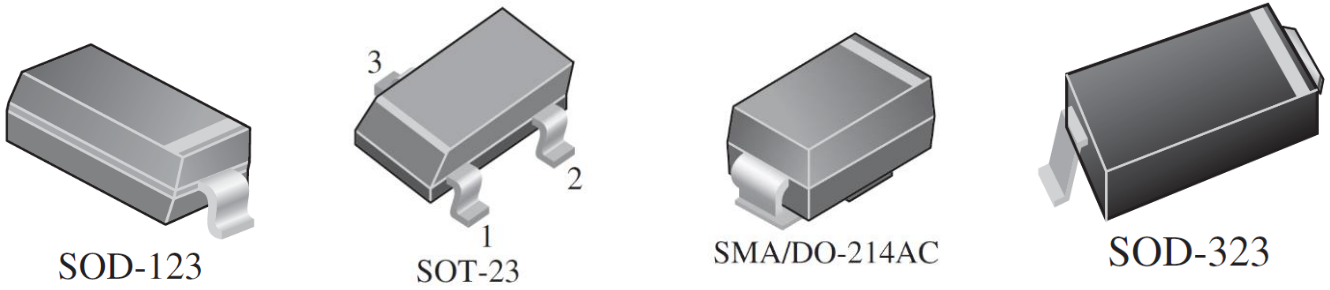
(b) Symbol

Typical Diode Packages

Through-hole mounted

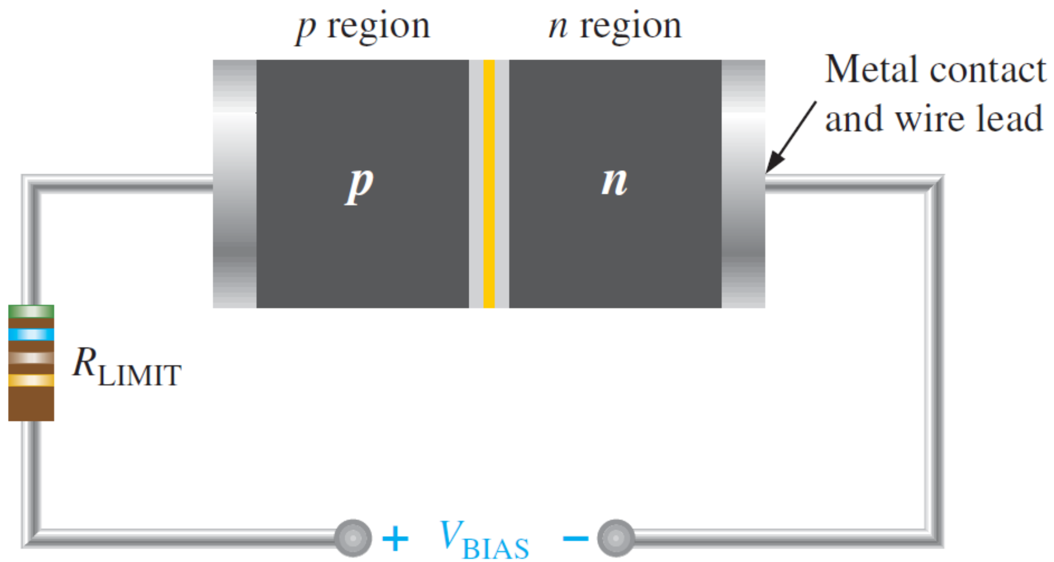


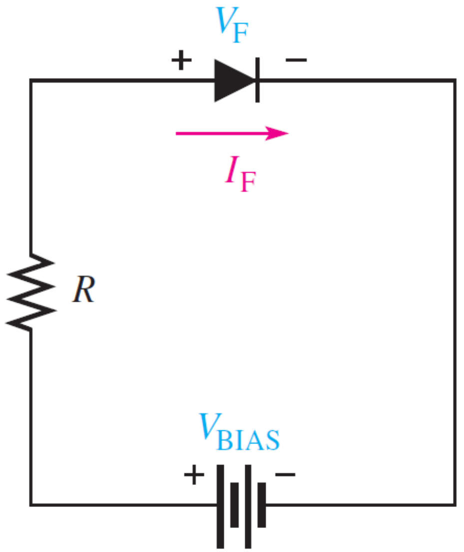
Surface-Mount Diode Packages



Forward Bias

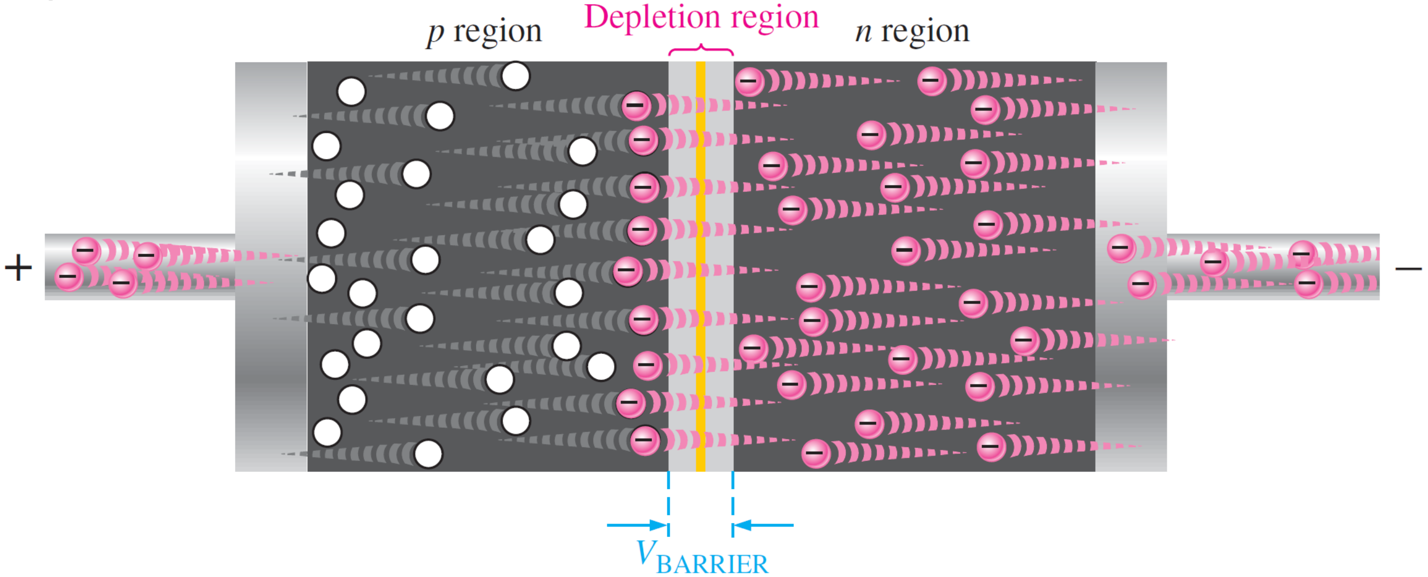
- To **bias** a diode, you apply a dc voltage across it.
- **Forward bias** is the condition that allows current through the *pn* junction.
- Notice that the negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region.
- V_{BIAS} must be greater than the **barrier potential**.
- The resistor limits the forward current to a value that will not damage the diode.





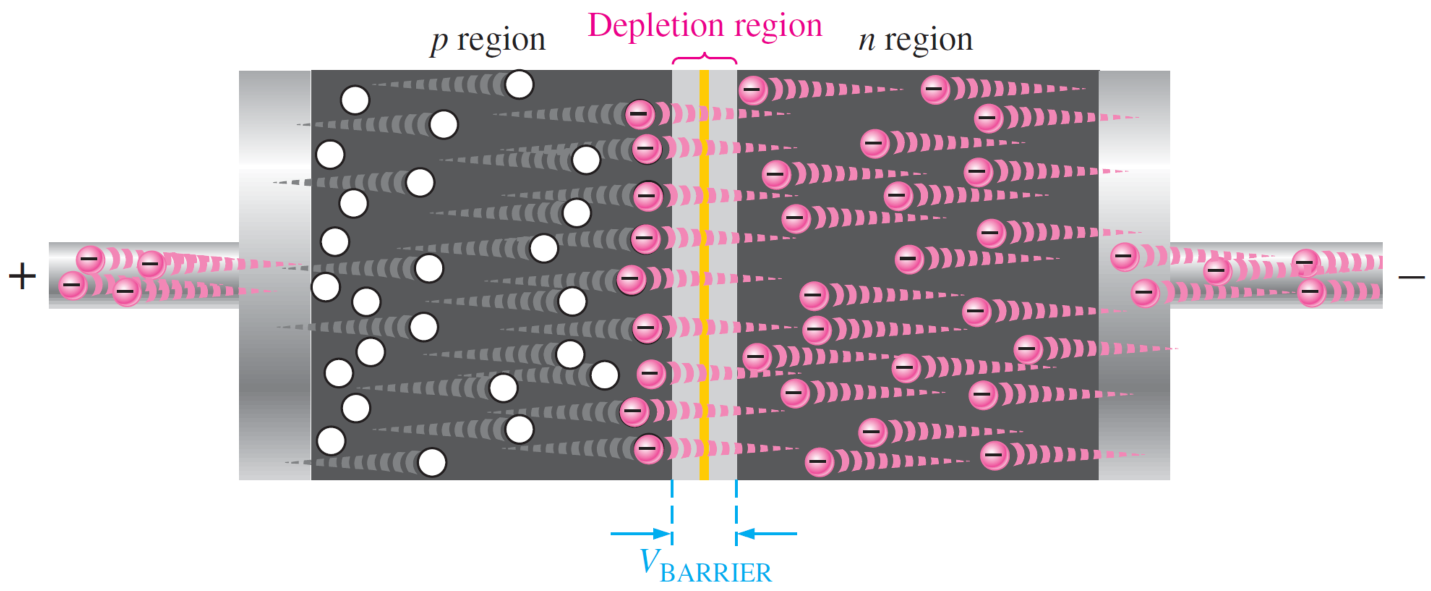
Forward Bias

- Since like charges repel, the negative side of V_{BIAS} "pushes" the free electrons toward the pn junction. ***(electron current)***
- VBIAS imparts sufficient energy to the free electrons 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.
- 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 valence electrons move from one hole to the next toward the left.
- The holes effectively (not actually) move to the right toward the junction.
- This effective flow of holes is ***the hole current.***

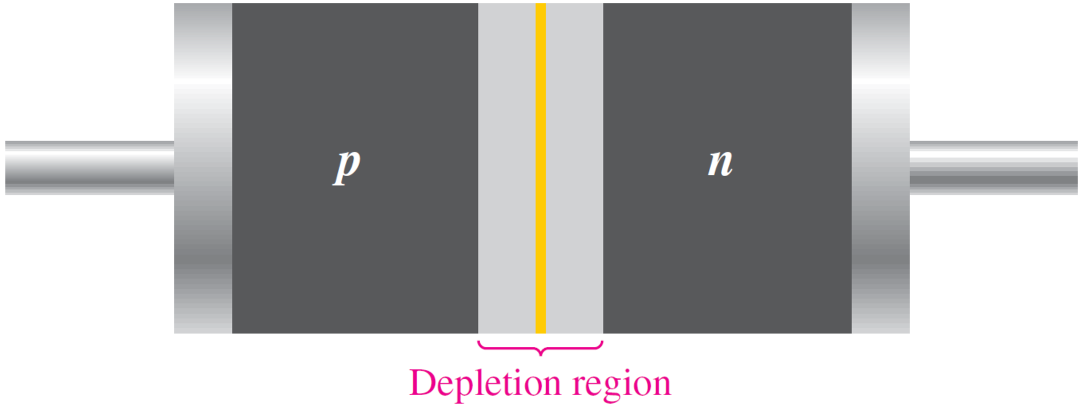


Forward Bias

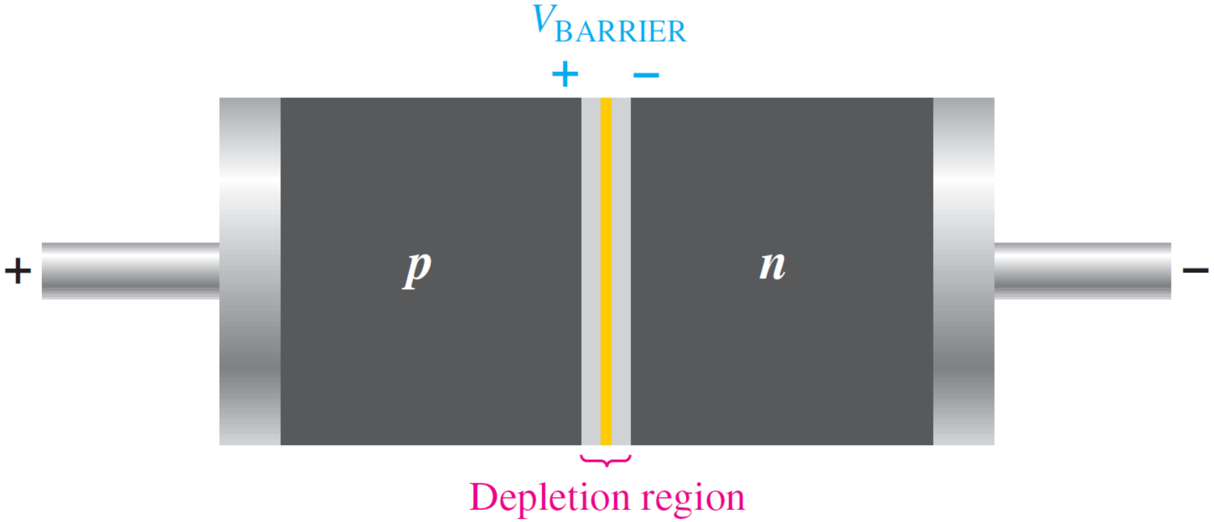
- The hole current can be seen as being created by the flow of valence electrons through the *p* region, with the holes providing the only means for these electrons to flow.
- As the electrons flow out of the *p* region to the positive side of the bias-voltage source, they leave holes behind in the *p* region; and at the same time, these electrons become conduction electrons in the metal conductor
- 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.



The Effect of Forward Bias on the Depletion Region



(a) At equilibrium (no bias)

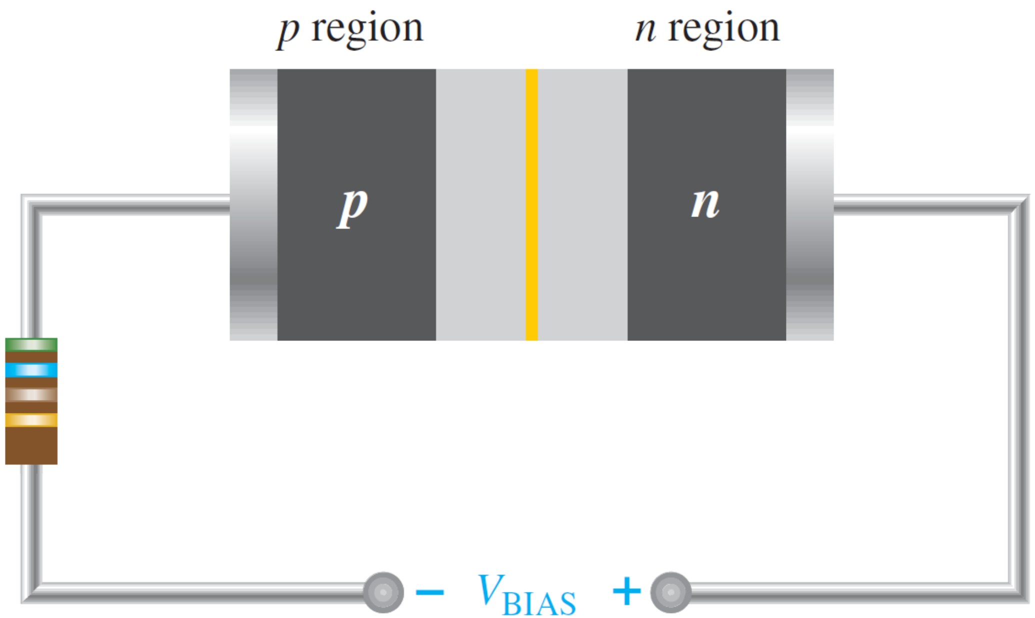


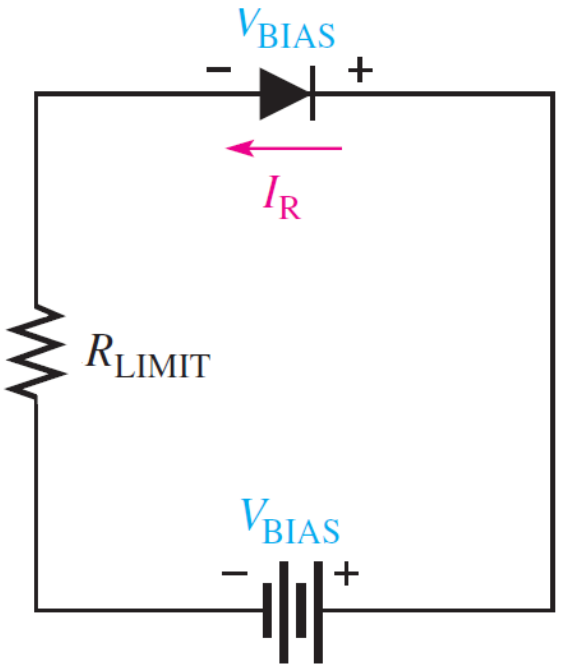
(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

- 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 indicated in Figure.

Reverse Bias

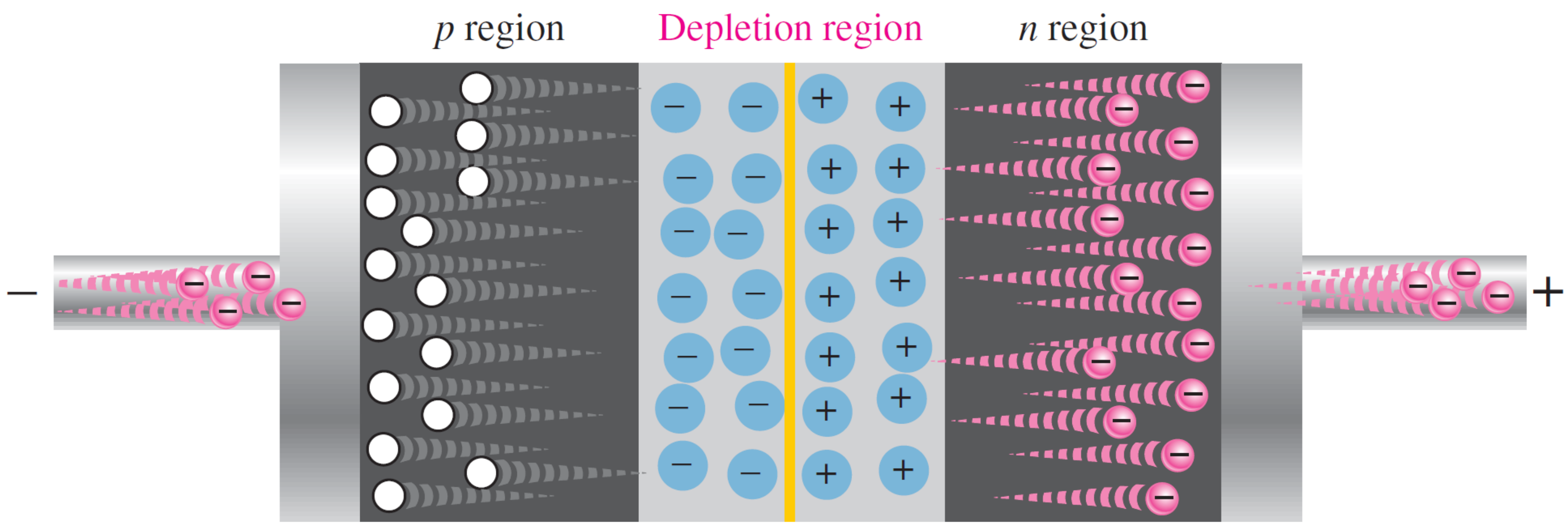
- **Reverse bias** is the condition that essentially prevents current through the diode.
- The positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region.
- Also note that the depletion region is shown much wider than in forward bias or equilibrium.





Reverse Bias

- In the n region, since unlike charges attract, the positive side of the bias-voltage source "pulls" the free electrons away from the *pn* junction → additional positive ions are created.
- 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. The flow of valence electrons can be viewed as holes being "pulled" toward the negative side.
- This results in a widening of the depletion region.

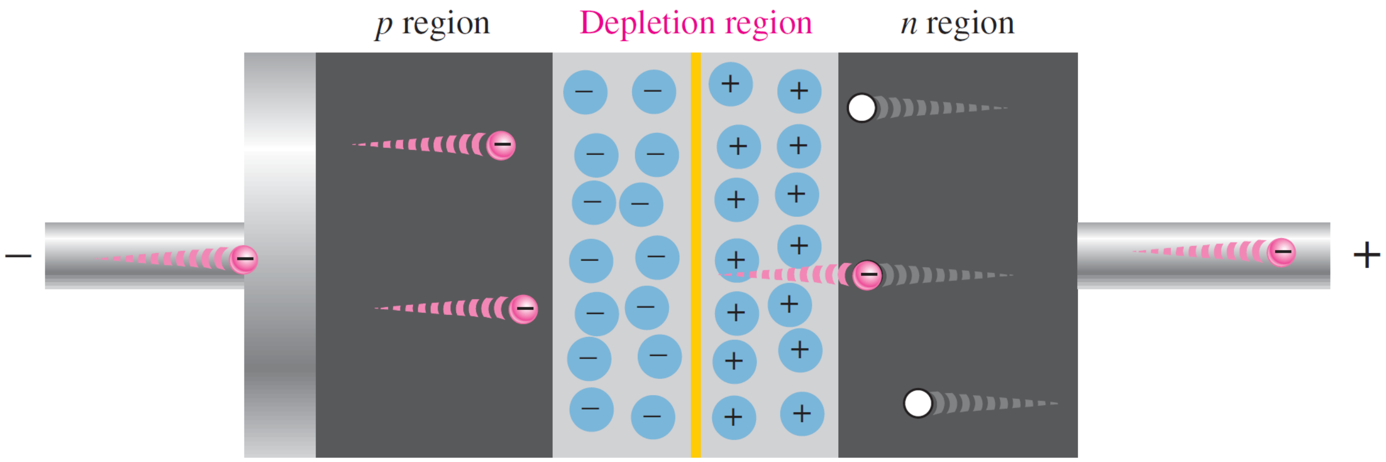


How wide does the depletion layer get in Reverse Bias?

- When the holes and electrons move away from the junction, the newly created ions increase the difference of potential across the depletion region.
- The wider the depletion region, the greater the difference of potential.
- The depletion region stops growing when its difference of potential equals the applied reverse voltage.
- When this happens, electrons and holes stop moving away from the junction.
- As the reverse voltage increases, the depletion layer gets wider.

*Reverse Current (*Minority-Carrier Current*)*

- The transition (transient) current: the flow of majority carriers at the instant of the application of the reverse bias voltage, and it lasts for a very short time.
- The reverse saturation current ($\boldsymbol{I_S}$): is the extremely small current that exists in reverse bias (after the transition current dies out), and caused by the thermally generated minority carriers in the n and p regions. (a few μA and typically in nA & pA)
- The negative terminal "pushes" the small number of free minority electrons in the p region to cross the depletion region and combine with the minority holes in the n region as valence electrons and flow toward the positive terminal.
- The term *saturation* comes from the fact that I_S reaches its maximum level quickly and does not change significantly with increases in the reverse-bias voltage.



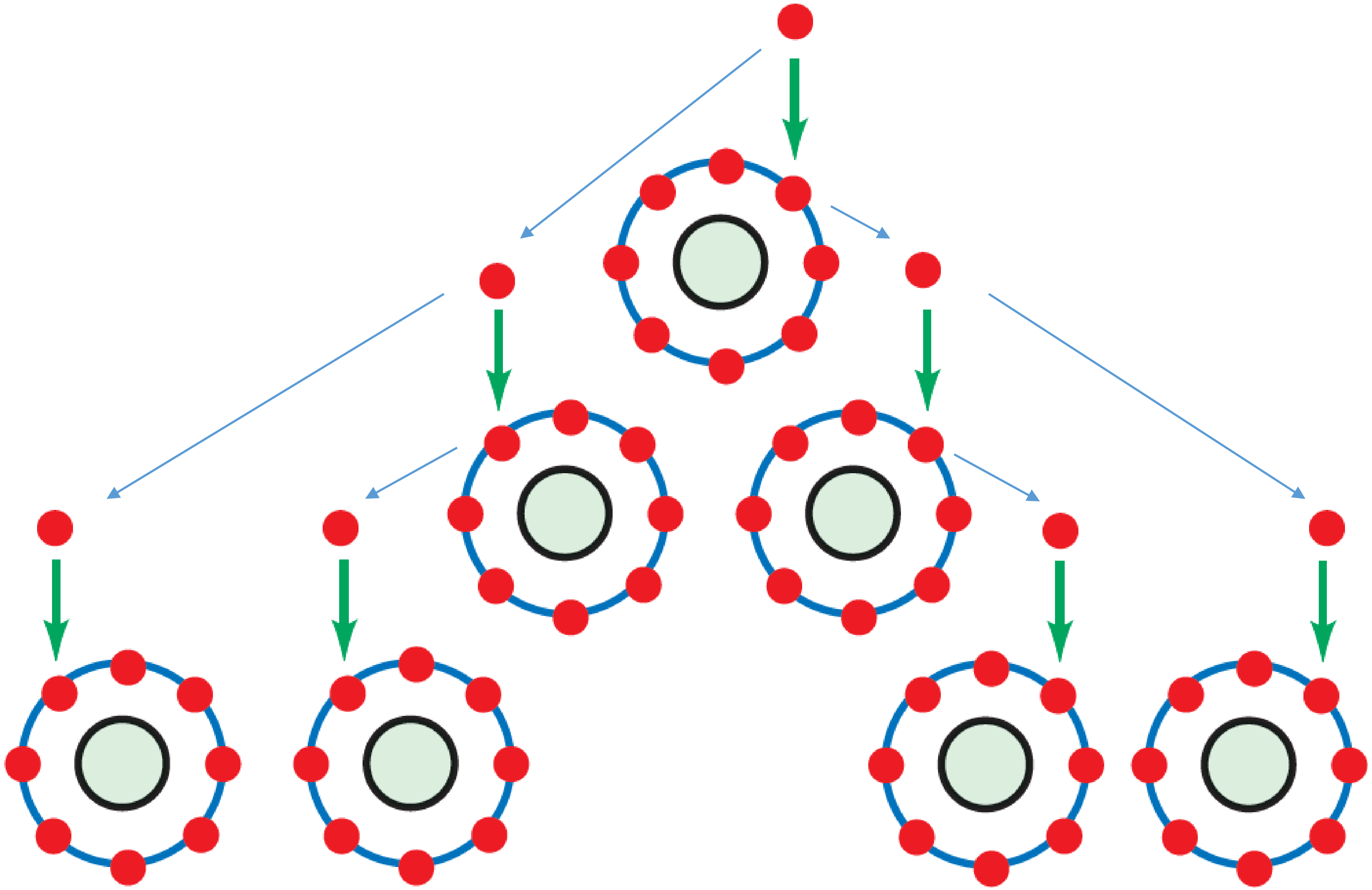
Reverse Breakdown

- Diodes have maximum voltage ratings. There is a limit to how much reverse voltage a diode can withstand before it is destroyed.
- If we continue increasing the reverse voltage, we will reach the **breakdown voltage** of the diode.
- For many diodes, breakdown voltage is at least 50 V.
- Once the breakdown voltage is reached, a large number of the minority carriers suddenly appears in the depletion layer and the diode conducts heavily.
- Where do the carriers come from? They are produced by the ***avalanche effect*** which occurs at higher reverse voltages.

Reverse Breakdown – the avalanche effect

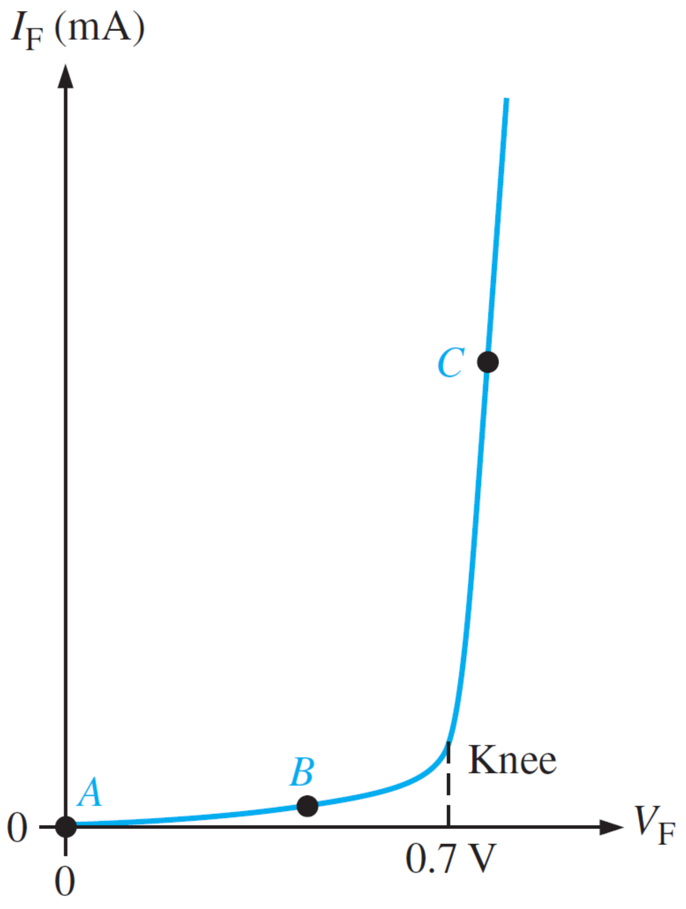
- When the reverse voltage increases, it forces the minority carriers to move more quickly.
- These minority carriers collide with the atoms of the crystal.
- When these minority carriers have enough energy, they can knock valence electrons loose, producing free electrons.
- These new minority carriers then join the existing minority carriers to collide with other atoms.
- The process is geometric because one free electron liberates one valence electron to get two free electrons. These two free electrons then free two more electrons to get four free electrons.
- The process continues until the reverse current becomes huge.

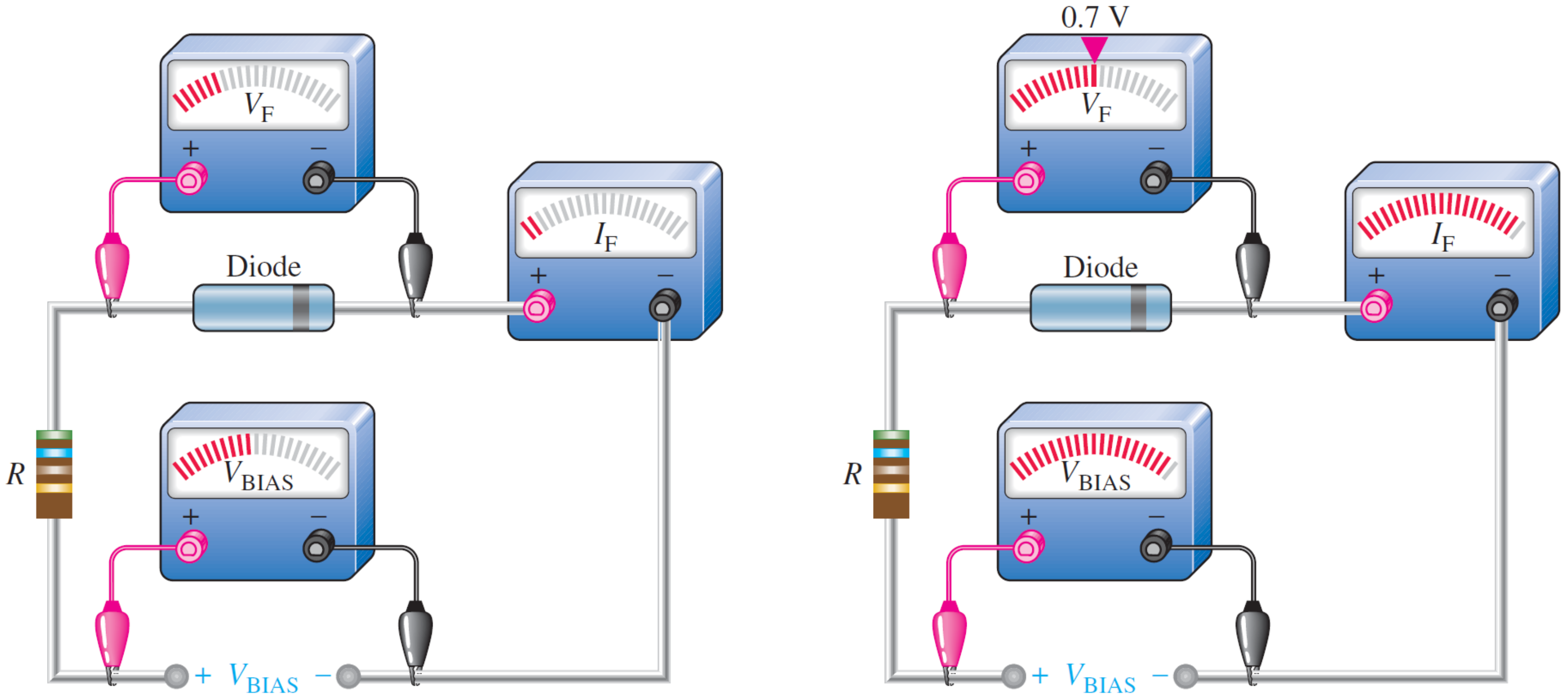
The process of ***avalanche*** is a geometric progression: 1, 2, 4, 8, . . .



2-2 $V - I$ CHARACTERISTIC OF A DIODE

$V - I$ Characteristic for Forward Bias





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

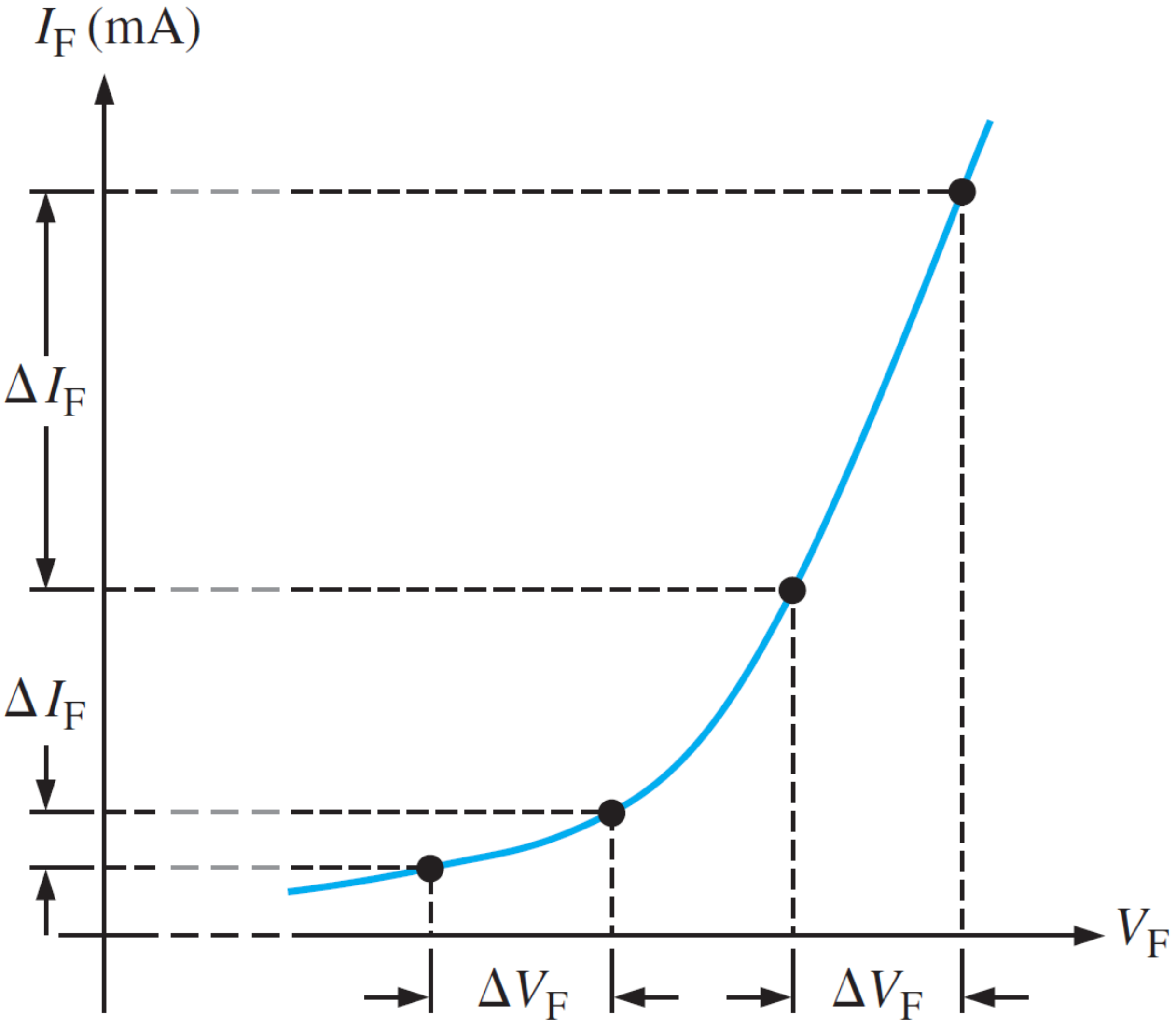
(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

▲ **FIGURE 2–9**

Forward-bias measurements show general changes in V_F and I_F as V_{BIAS} is increased.

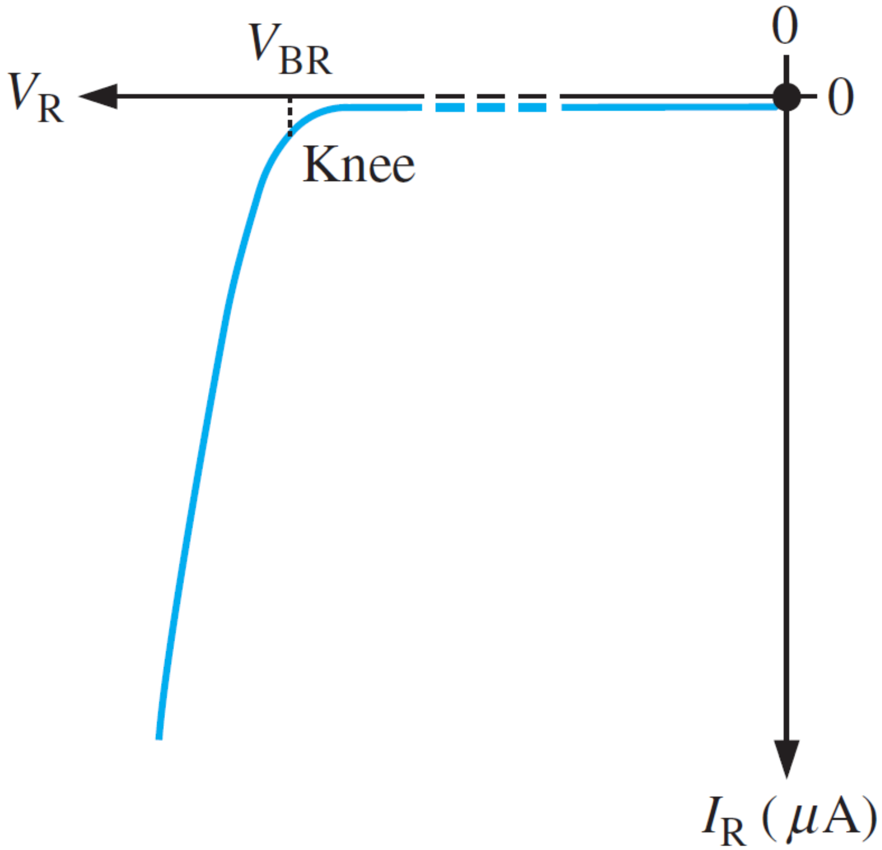
Dynamic Resistance or ac resistance (internal resistance)

- Unlike a linear resistance, the internal resistance of the forward-biased diode is not constant over the entire curve.
- The dynamic resistance $\left(r_d' = \frac{\Delta V_F}{\Delta I_F}\right)$ decreases as you move up the curve, as indicated by the decrease in the value of $\frac{\Delta V_F}{\Delta I_F}$.



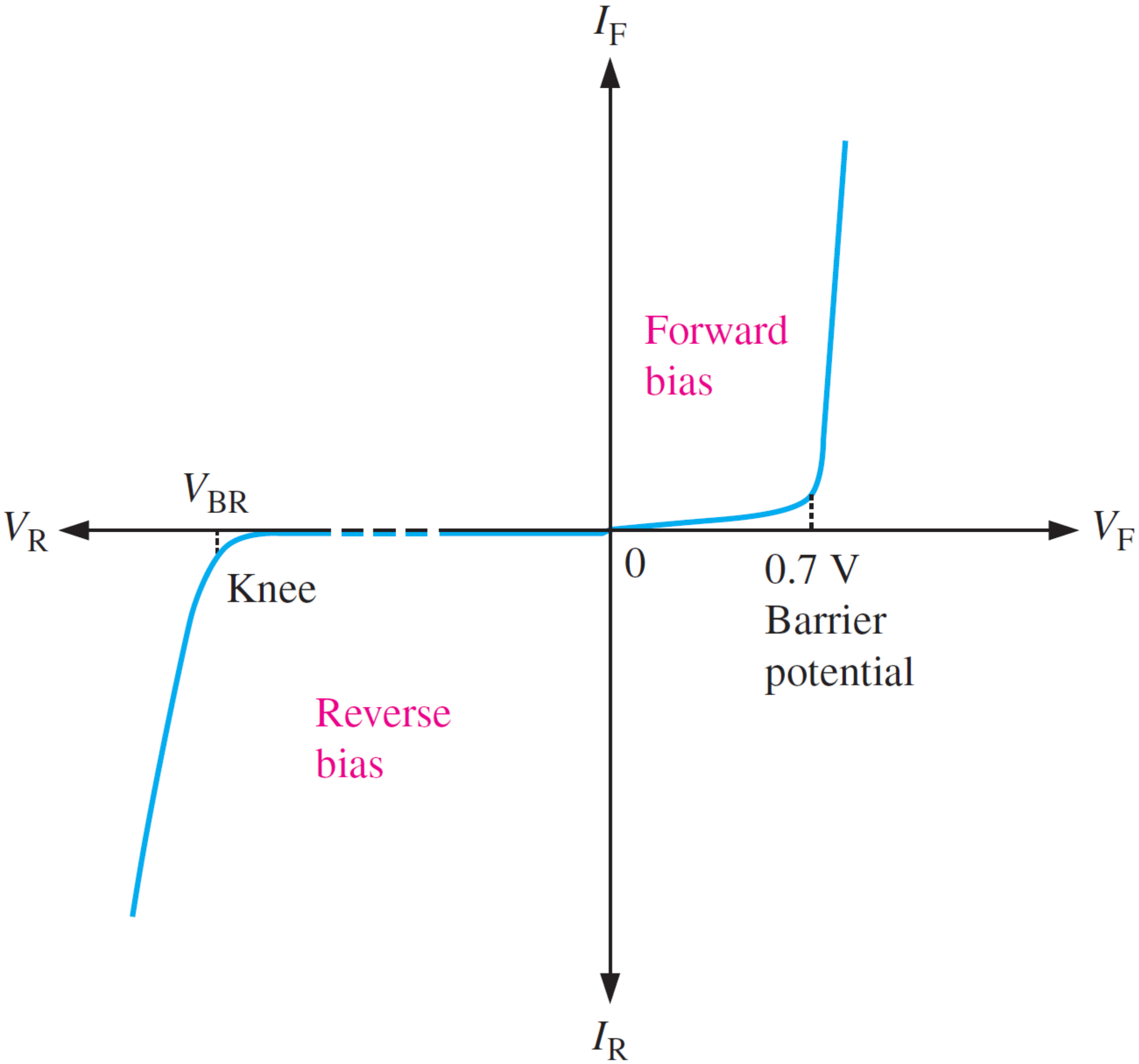
$V - I$ *Characteristic for Reverse Bias*

- As V_{BIAS} gradually increases from 0V, there is a very small reverse current and the voltage across the diode increases.
- When V_{BIAS} is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.
- As V_{BIAS} increases I_R increases very rapidly, but V_R increases very little above (V_{BR}).
- Breakdown is not a normal mode of operation for most *pn* junction devices.



- The breakdown voltage depends on the doping level, depending on the type of diode.
- A typical rectifier diode (the most widely used type) has a breakdown voltage of greater than 50 V.
- Some specialized diodes have a breakdown voltage that is only 5 V.

The Complete $V - I$ Characteristic Curve

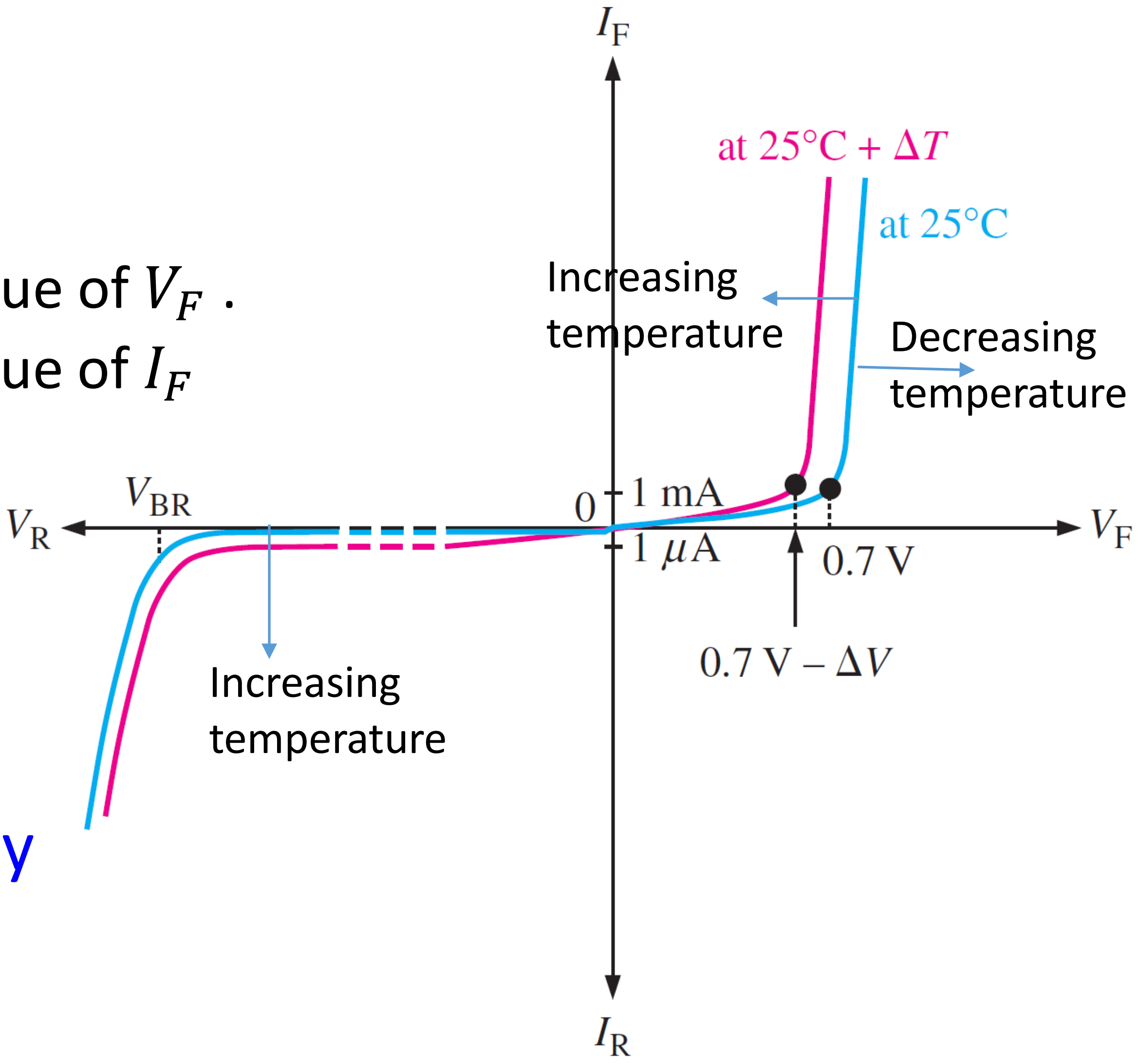


Temperature Effects

- For a forward-biased diode:
  - as T is increased, I_F increases for a given value of V_F .
  - as T is increased, V_F decreases for a given value of I_F

The barrier potential V_F decreases by 2 mV for each degree Celsius rise.

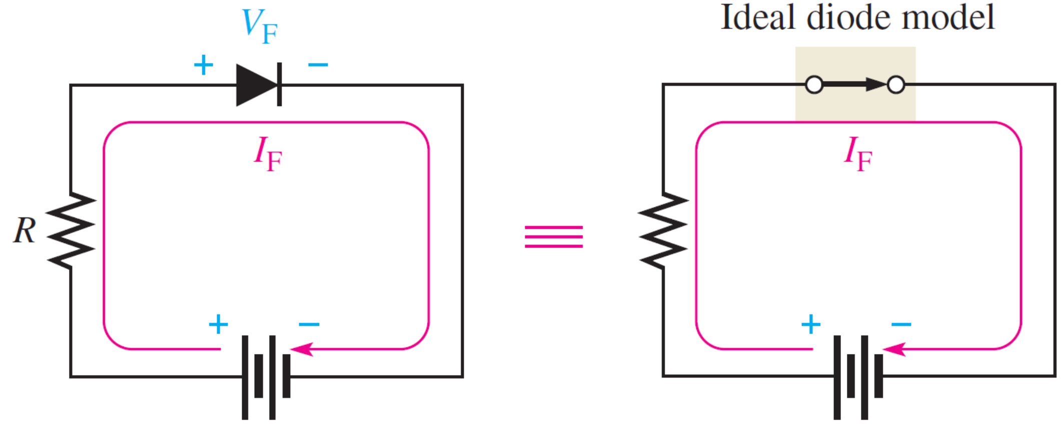
- In the reverse-bias region the reverse current of a silicon diode doubles for every 10°C rise in temperature.



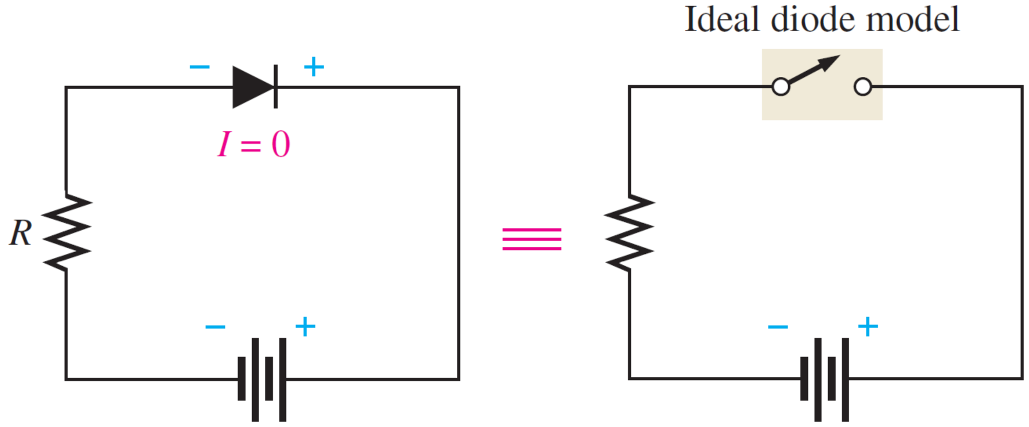
Assuming a barrier potential of 0.7 V at an ambient temperature of 25°C, what is the barrier potential of a silicon diode when the junction temperature is 100°C and At 0°C?

2–3 Diode Approximations (Diode Models)

(1)The Ideal Diode Model (the first approximation)



(a) Forward bias



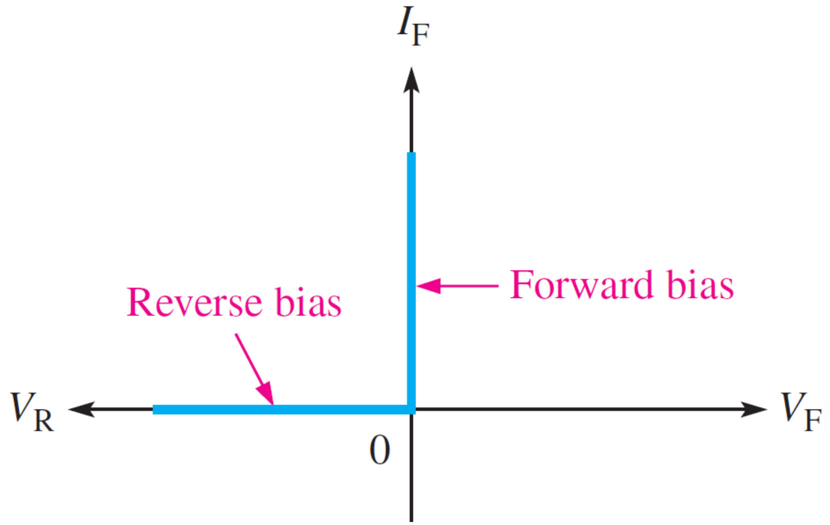
(b) Reverse bias

- When F.B.➔ diode ON (Closed switch)

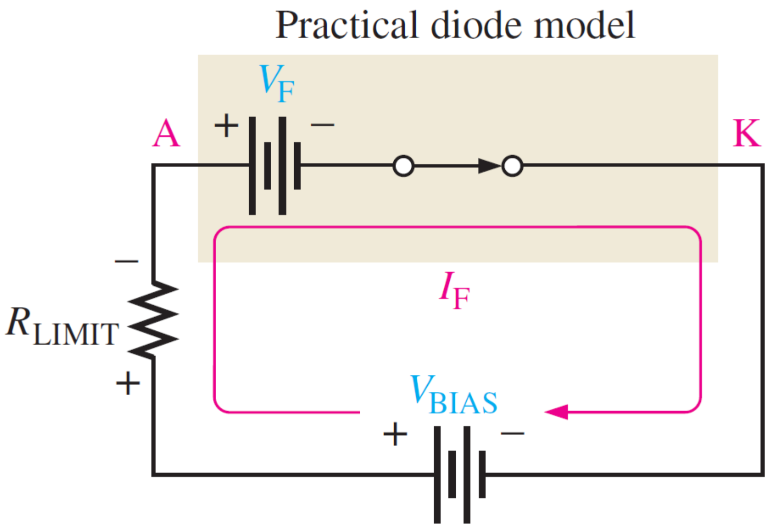
$$V_F = 0V, I_F = \frac{V_{Bias}}{R_{Limit}}$$

- When R.B.➔ diode OFF (open switch)

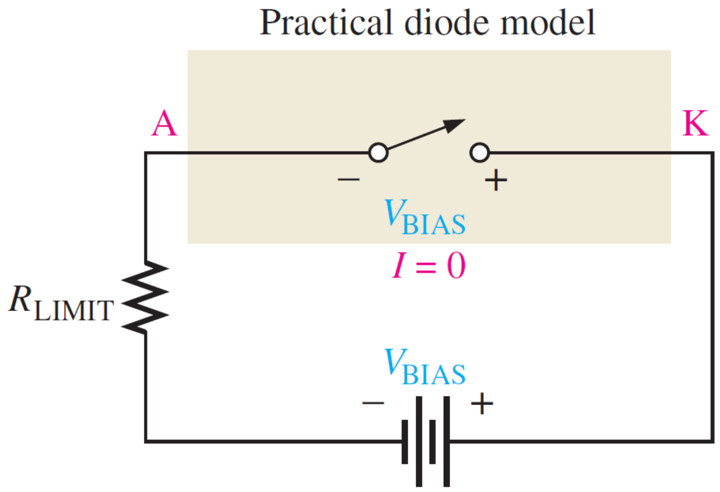
$$I_R = 0A, V_R = V_{Bias}$$



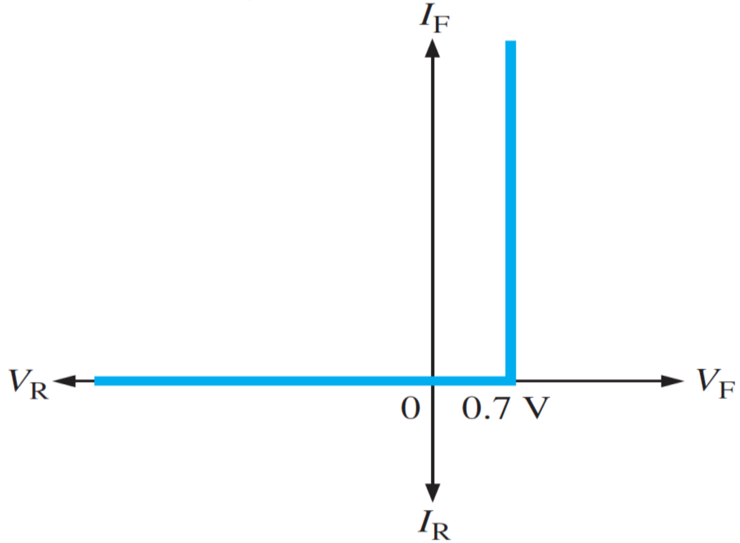
(2) The Practical Diode Model (the second approximation)



(a) Forward bias



(b) Reverse bias



(c) Characteristic curve (silicon)

- When **F.B.➔** it acts as a closed switch in series with the equivalent barrier potential voltage (V_F)

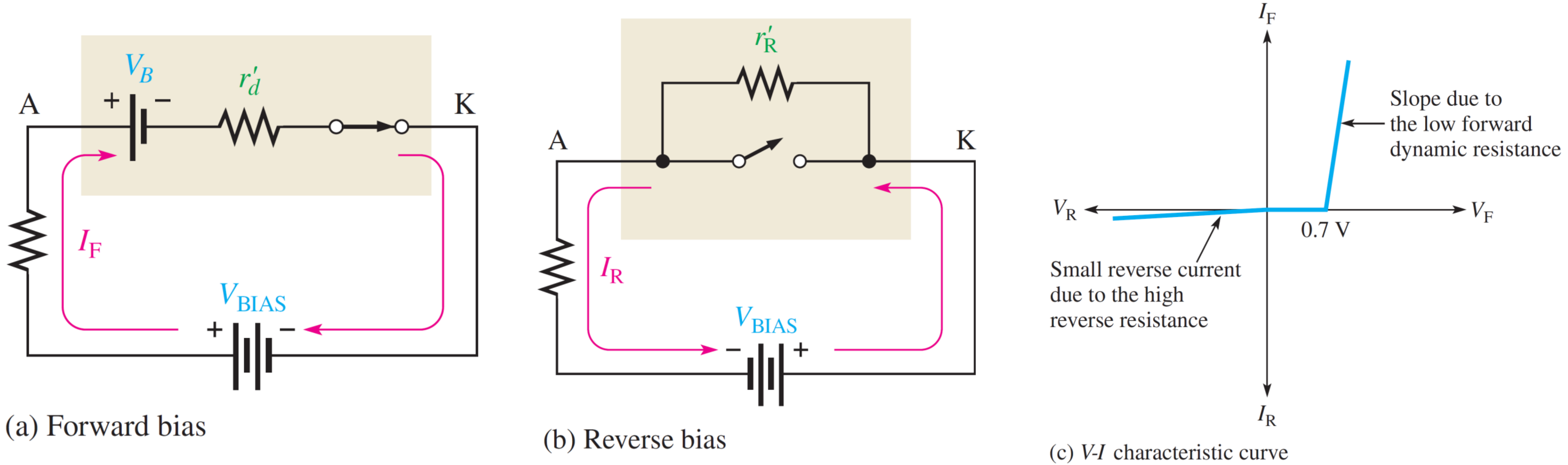
$$V_F = 0.7\ V \qquad I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

V_F is not an independent voltage source.

- When R.B.➔ it is equivalent to an open switch just as in the ideal model.
- The barrier potential does not affect reverse bias, so it is not a factor.

$$I_R = 0\text{ A} \qquad V_R = V_{BIAS}$$

(3)The Complete Diode Model (the third approximation)



(a) Forward bias

(b) Reverse bias

Slope due to the low forward dynamic resistance

Small reverse current due to the high reverse resistance

(c) V-I characteristic curve

- When **F.B.➔** it acts as a closed switch in series with the equivalent barrier potential voltage (V_B) and the small forward dynamic resistance(r'_d).

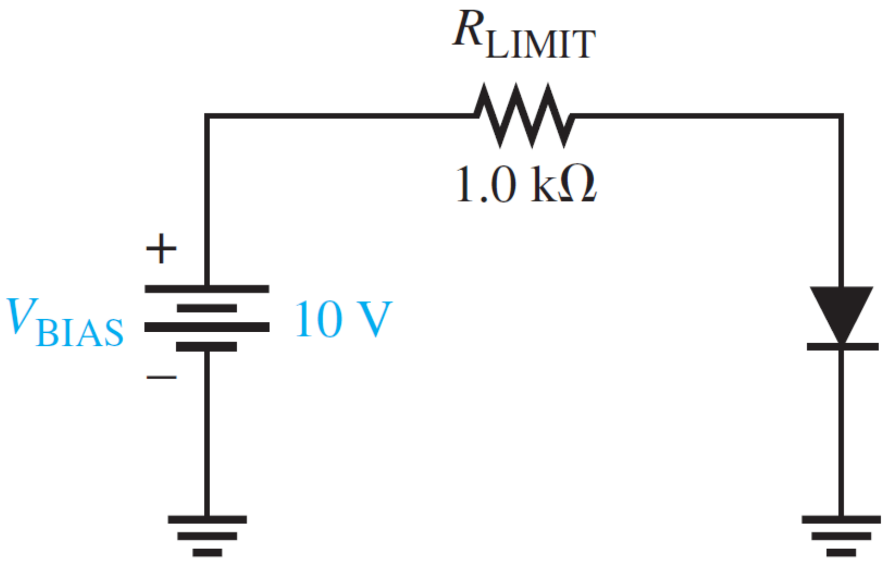
$$V_F = 0.7\text{ V} + I_F r'_d \qquad I_F = \frac{V_{BIAS} - 0.7\text{ V}}{R_{LIMIT} + r'_d}$$

- When **R.B.➔** it acts as an open switch in parallel with the large internal reverse resistance(r'_R).

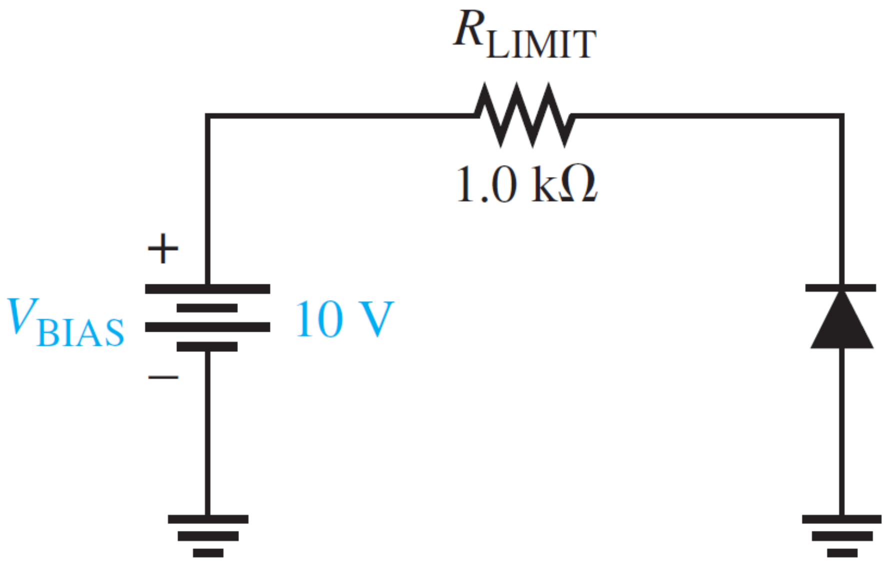
EXAMPLE 1

(a) Determine the forward voltage and forward current for the diode in Fig (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.

(b) Determine the reverse voltage and reverse current for the diode in Fig (b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\mu A$.



(a)



(b)

Solution **(a)** Ideal model:

$$V_{\text{F}} = \mathbf{0\ V}$$

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

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

Practical model:

$$V_{\text{F}} = \mathbf{0.7\ V}$$

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

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

Complete model:

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

$$V_{\text{F}} = 0.7\ V + I_{\text{F}}r'_d = 0.7\text{ V} + (9.21\text{ mA})(10\ \Omega) = \mathbf{792\ mV}$$

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

(b) Ideal model:

$$I_{\mathrm{R}} = \mathbf{0\ A}$$
$$V_{\mathrm{R}} = V_{\mathrm{BIAS}} = \mathbf{10\ V}$$
$$V_{R_{\mathrm{LIMIT}}} = \mathbf{0\ V}$$

Practical model:

$$I_{\mathrm{R}} = \mathbf{0\ A}$$
$$V_{\mathrm{R}} = V_{\mathrm{BIAS}} = \mathbf{10\ V}$$
$$V_{R_{\mathrm{LIMIT}}} = \mathbf{0\ V}$$

Complete model:

$$I_{\mathrm{R}} = \mathbf{1\ \mu A}$$
$$V_{R_{\mathrm{LIMIT}}} = I_R R_{\mathrm{LIMIT}} = (1\ \mu\mathrm{A})(1.0\ \mathrm{k\Omega}) = \mathbf{1\ mV}$$
$$V_{\mathrm{R}} = V_{\mathrm{BIAS}} - V_{R_{\mathrm{LIMIT}}} = 10\ \mathrm{V} - 1\ \mathrm{mV} = \mathbf{9.999\ V}$$

Related Problem[*] Assume that the diode in Figure 2–18(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

Example 2

A diode has a power rating of $5\ W$. If the diode voltage is $1.2\ V$ and the diode current is $1.75\ A$, what is the power dissipation? Will the diode be destroyed?

SOLUTION

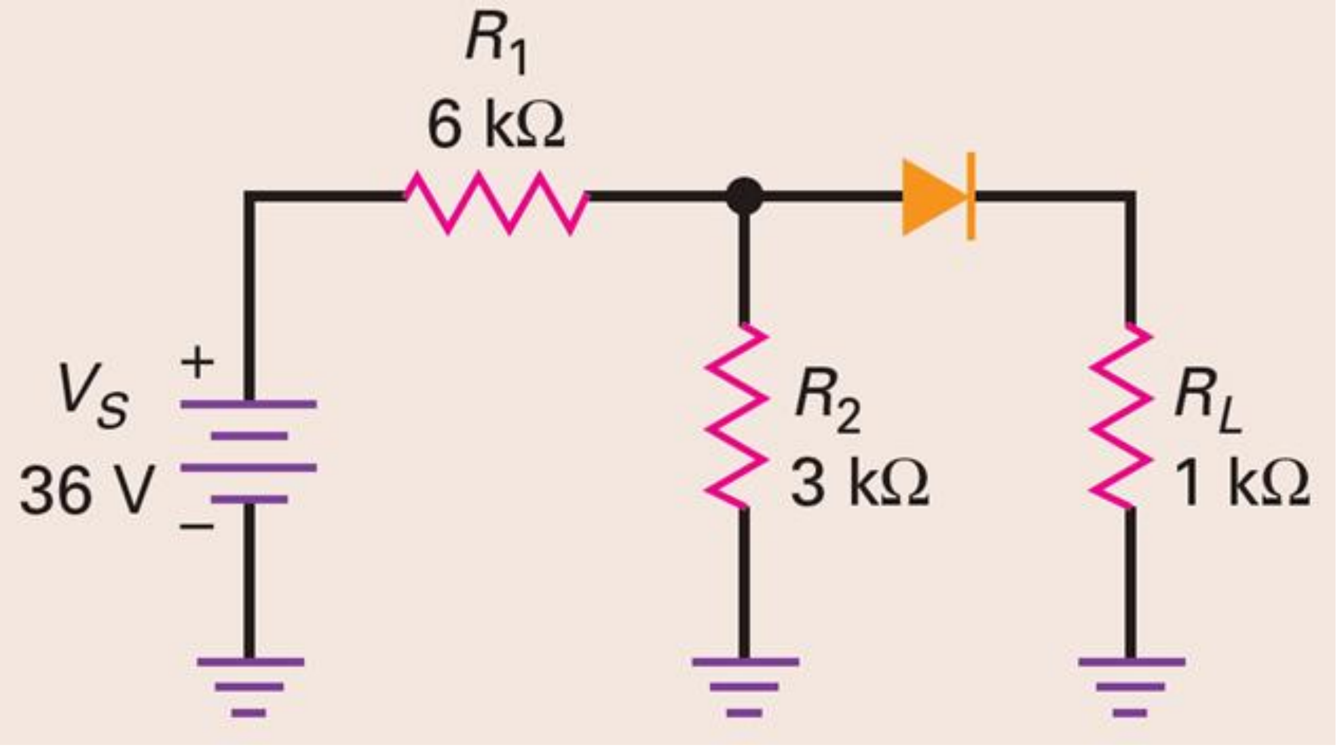
$$P_D = (1.2\ V)(1.75\ A) = 2.1\ W$$

This is less than the power rating, so the diode will not be destroyed.

The **power rating** is the maximum power the diode can safely dissipate without shortening its life or degrading its properties. $\boldsymbol{P_{max} = V_{max} I_{max}}$
where $\boldsymbol{V_{max}}$ is the voltage corresponding to $\boldsymbol{I_{max}}$.
For instance, if a diode has a maximum voltage and current of 1 V and 2 A, its power rating is 2 W.

Example 3:

Use the first and second approximations to calculate the load voltage and load current in Figure shown.



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