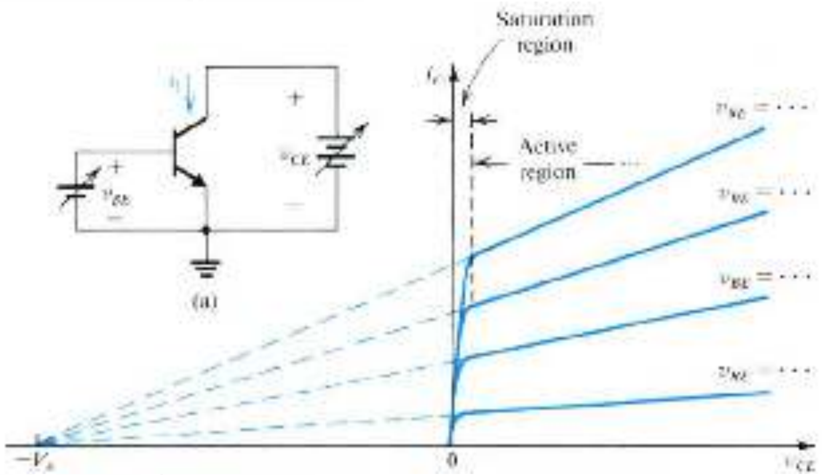
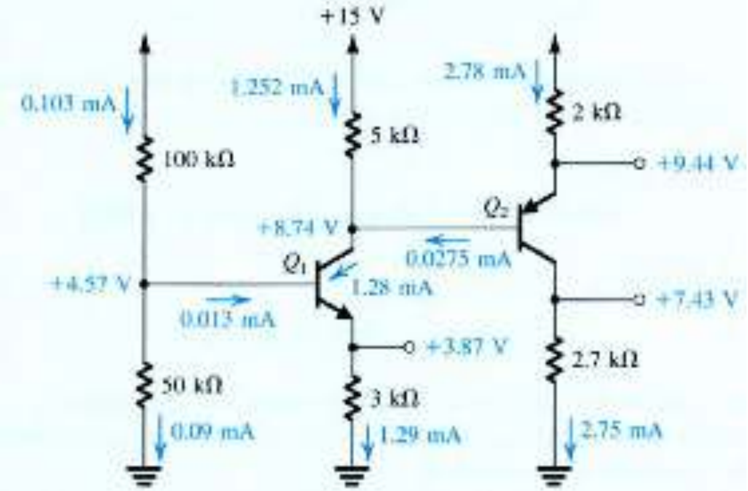
Electronics-I Course Layout

- Electronics (active devices; diodes and transistors)

1. **Analysis** (for a given circuit, find V, I, P, Z, etc.)





2. **Design** (from a specification design: amplifier, logic gate, driver, voltage regulator, etc.)

Semiconductor Materials

- Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

$$\text{Resistance } R = \rho \frac{l}{A} \ [\Omega]$$

- Conductivity $\sigma = 1/\rho$

Sigma

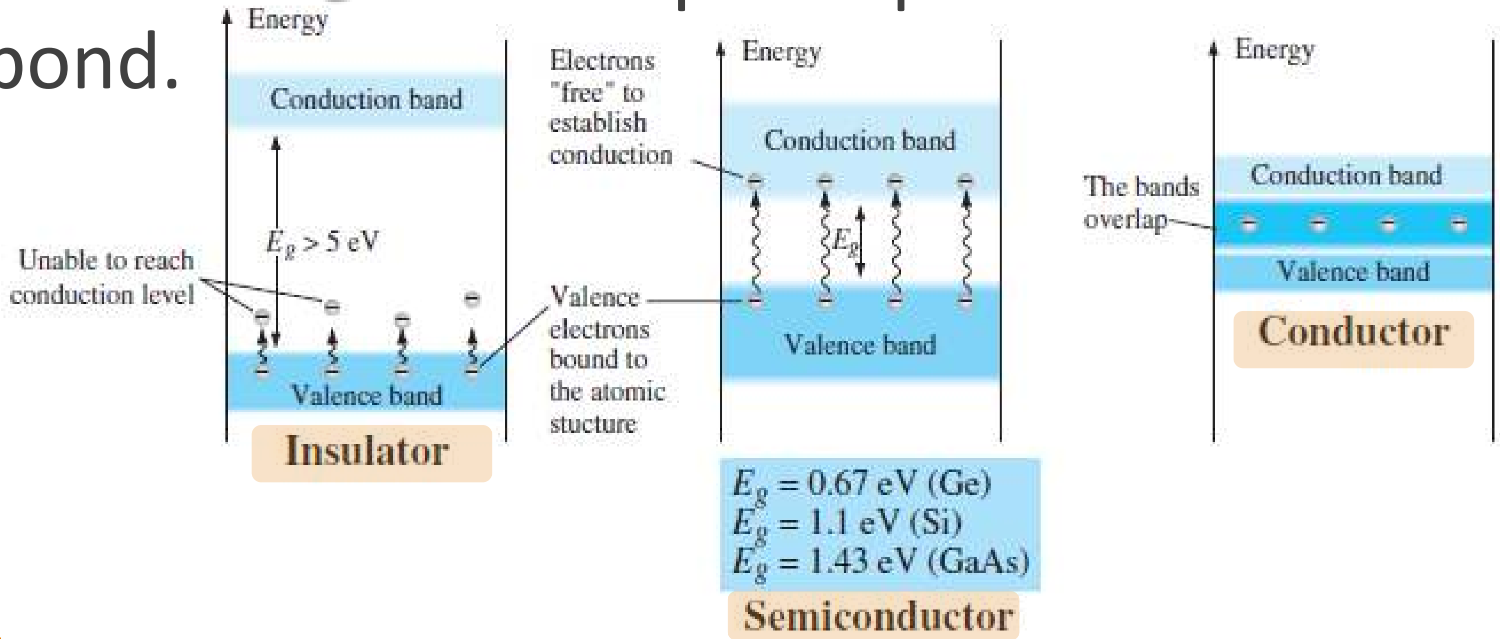
Rho

Material	Resistivity ρ [Ω·m] @ 20 °C
Silver (Ag)	1.59×10^{-8}
Copper (Cu)	1.68×10^{-8}
Gallium Arsenide (GaAs)	5×10^{-7} to 10×10^{-3}
Germanium (Ge)	4.6×10^{-1}
Silicon (Si)	6.40×10^{2}
Wood (oven dried)	$1\times10^{14} \rightarrow 1\times10^{16}$
Teflon	$10\times10^{22} \rightarrow 10\times10^{24}$

Semiconductor Materials (cont’d)

- Ge, Si, and GaAs are the three semiconductors used most frequently in the construction of electronic devices.
- Valence electron is an *e* that can participate in the formation of a chemical bond.

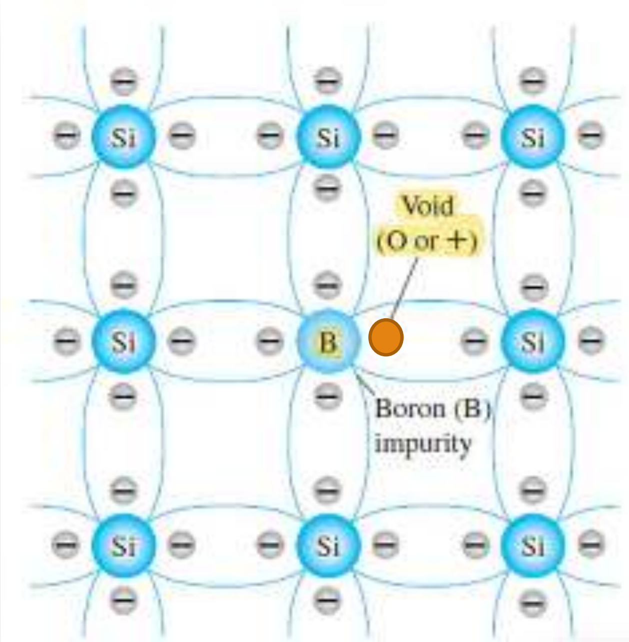
$1\text{eV}=1.6\times10^{-19}$ Joule



Semiconductor Materials (cont’d)

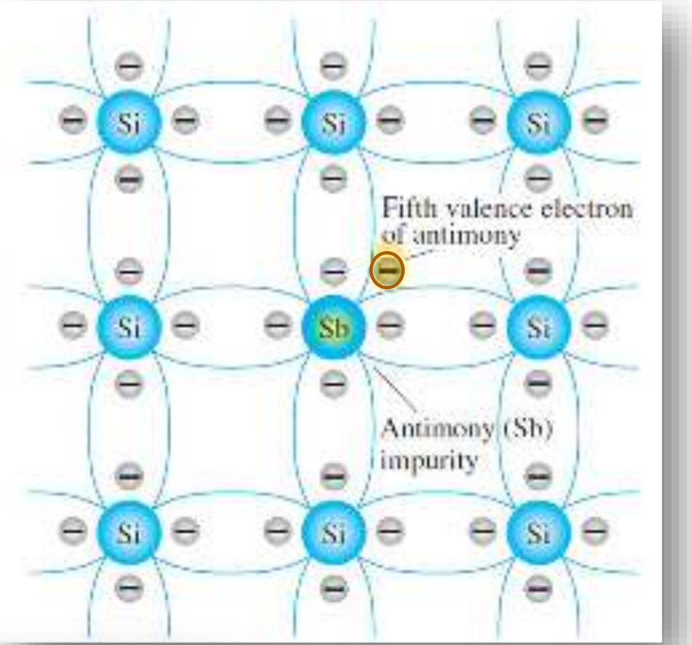
- Si is used most frequently as the base material in the construction of solid-state electronic devices.
- The characteristics of a semiconductor material can be altered significantly by adding specific impurity atoms to the relatively pure semiconductor material.
- Boron (**B**), having 3 valence electrons, and Antimony (**Sb**), having 5 valence electrons are the doping impurities used with Si.

Semiconductor Materials (cont’d)

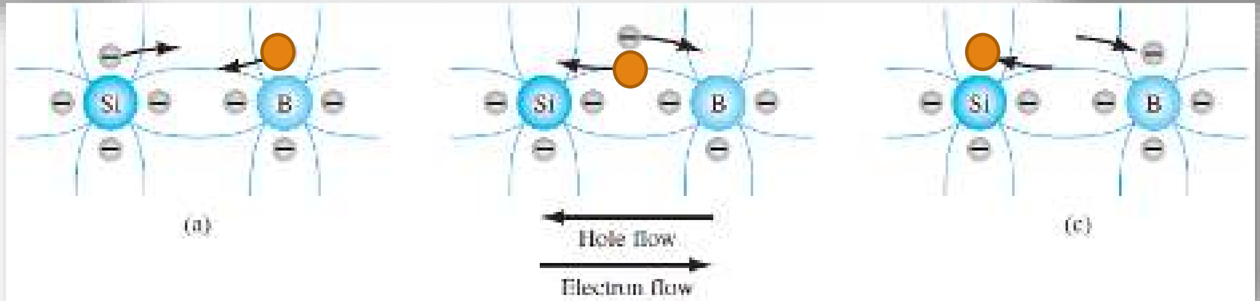


p -Type Material

n -Type Material

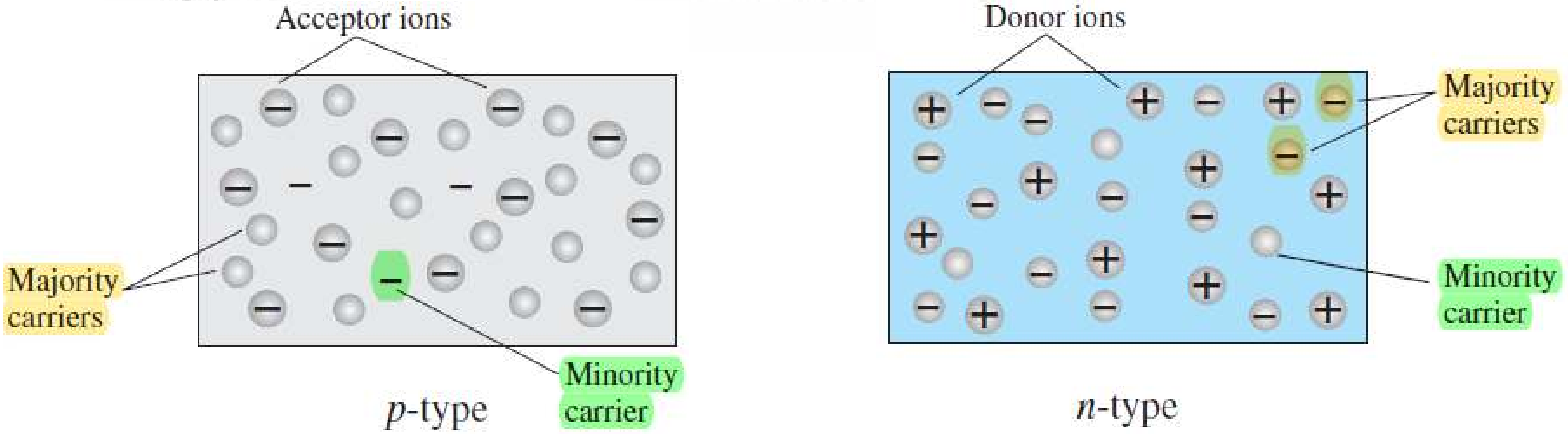


Electron vs. conventional flow



Semiconductor Materials (cont'd)

- The n-type and p-type materials represent the basic building blocks of semiconductor devices.
- In an p-type material, the hole is the majority carrier, while in n-type material, the electron is the majority carrier.



Outline

1. pn-junction and the semiconductor Diode
2. Diode Characteristic Graph (IV-Curve)
3. Temperature Effects
4. Diode Resistance Types
5. Examples
6. Reading Assignment

pn-junction and the semiconductor Diode

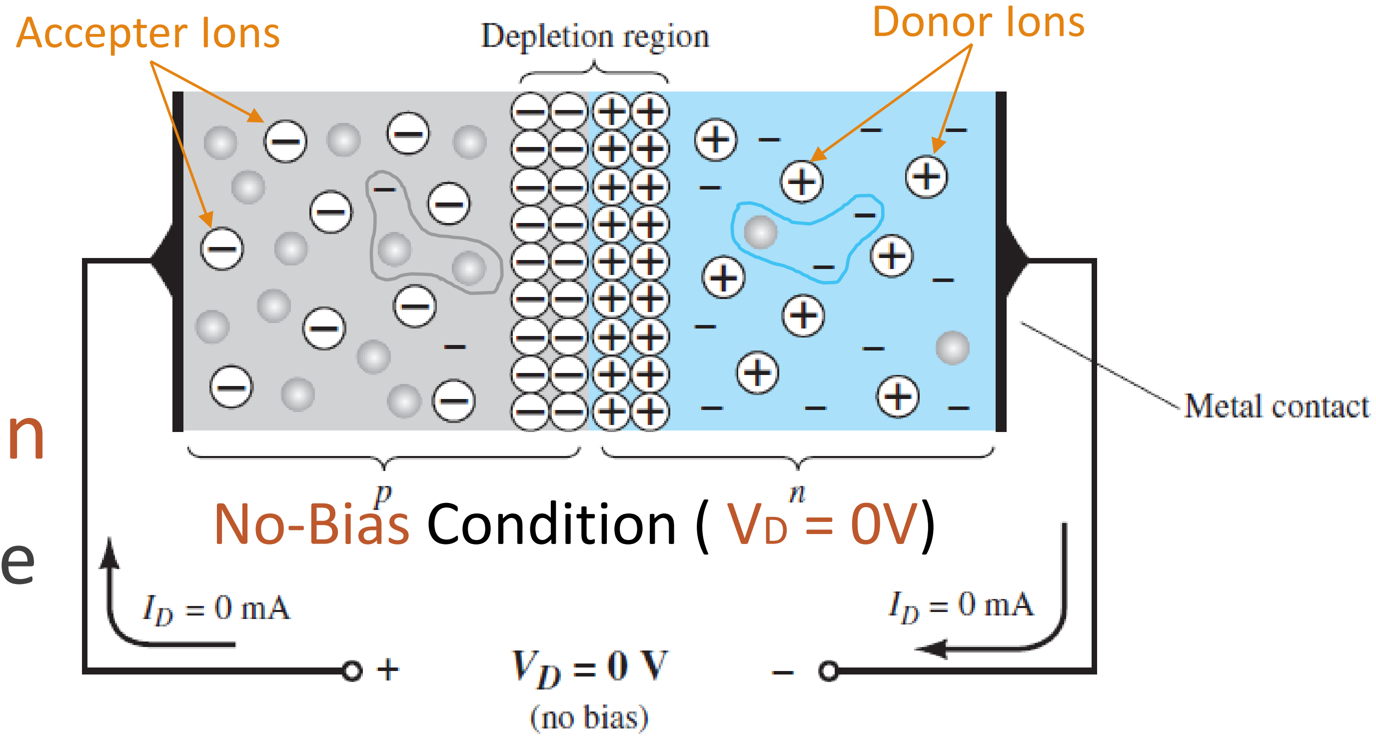
- Joining p-type material with a majority carrier of holes to n-type with a majority carrier of electrons forms the semiconductor diode.
- Depletion region:

lack of free carriers in

the region near the junction

- the net flow of charge in one

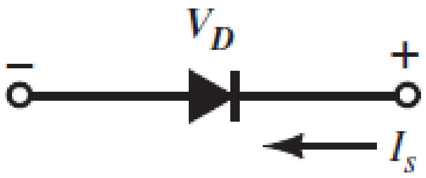
direction is zero for $V_D = 0V$.

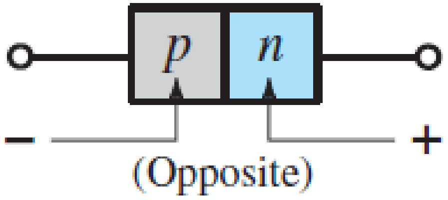


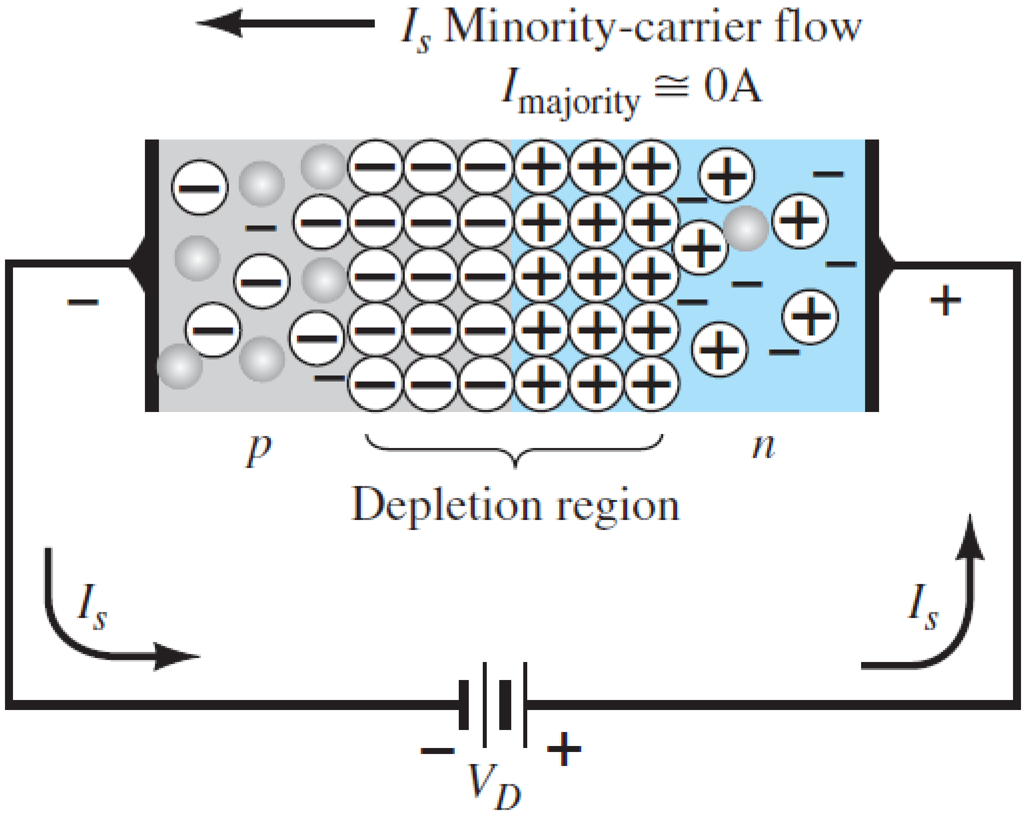
No-Bias Condition ($V_D = 0V$)

pn-junction and the semiconductor Diode (cont'd)

Reverse-Bias; OFF-Condition ($V_D < 0V$)

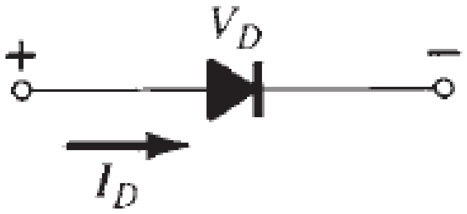


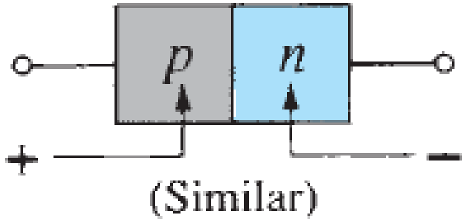


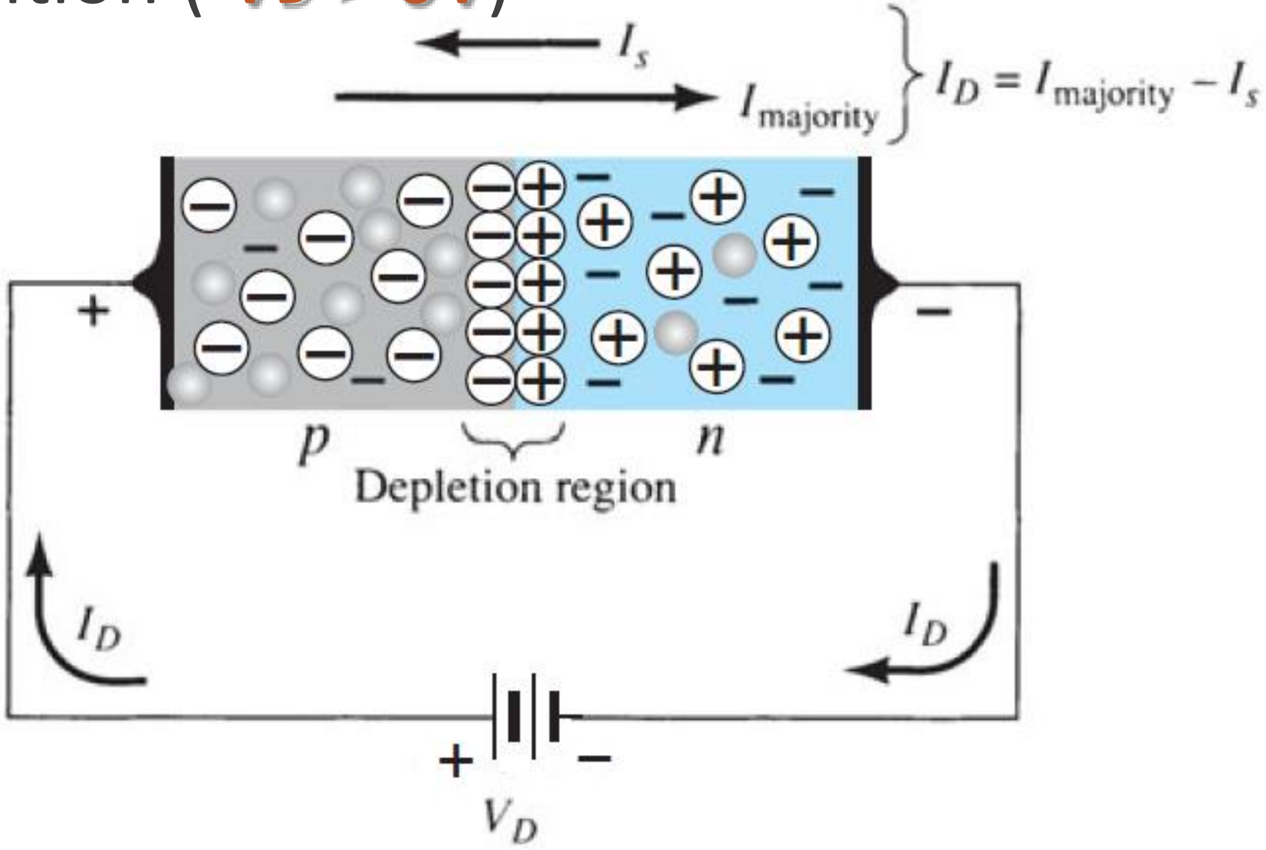


pn-junction and the semiconductor Diode (cont’d)

Forward-Bias; ON-Condition ($V_D > 0V$)





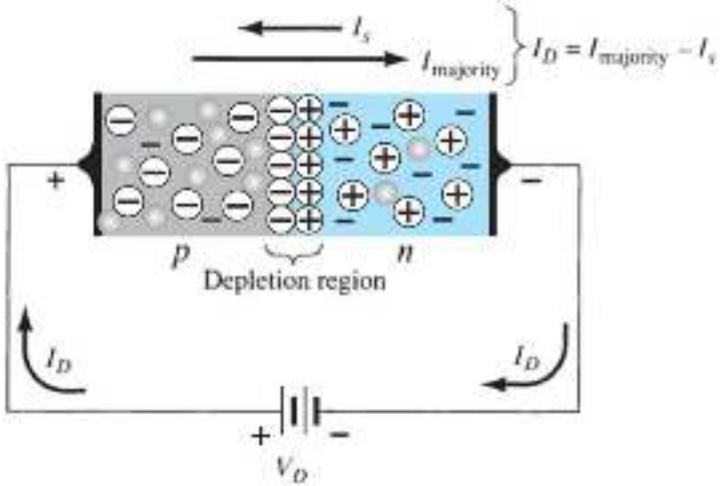


Diode Characteristic Graph (IV-Curve)

- The general characteristics of a semiconductor diode can be defined by Shockley's equation for the forward- and reverse-bias regions:

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

(A)



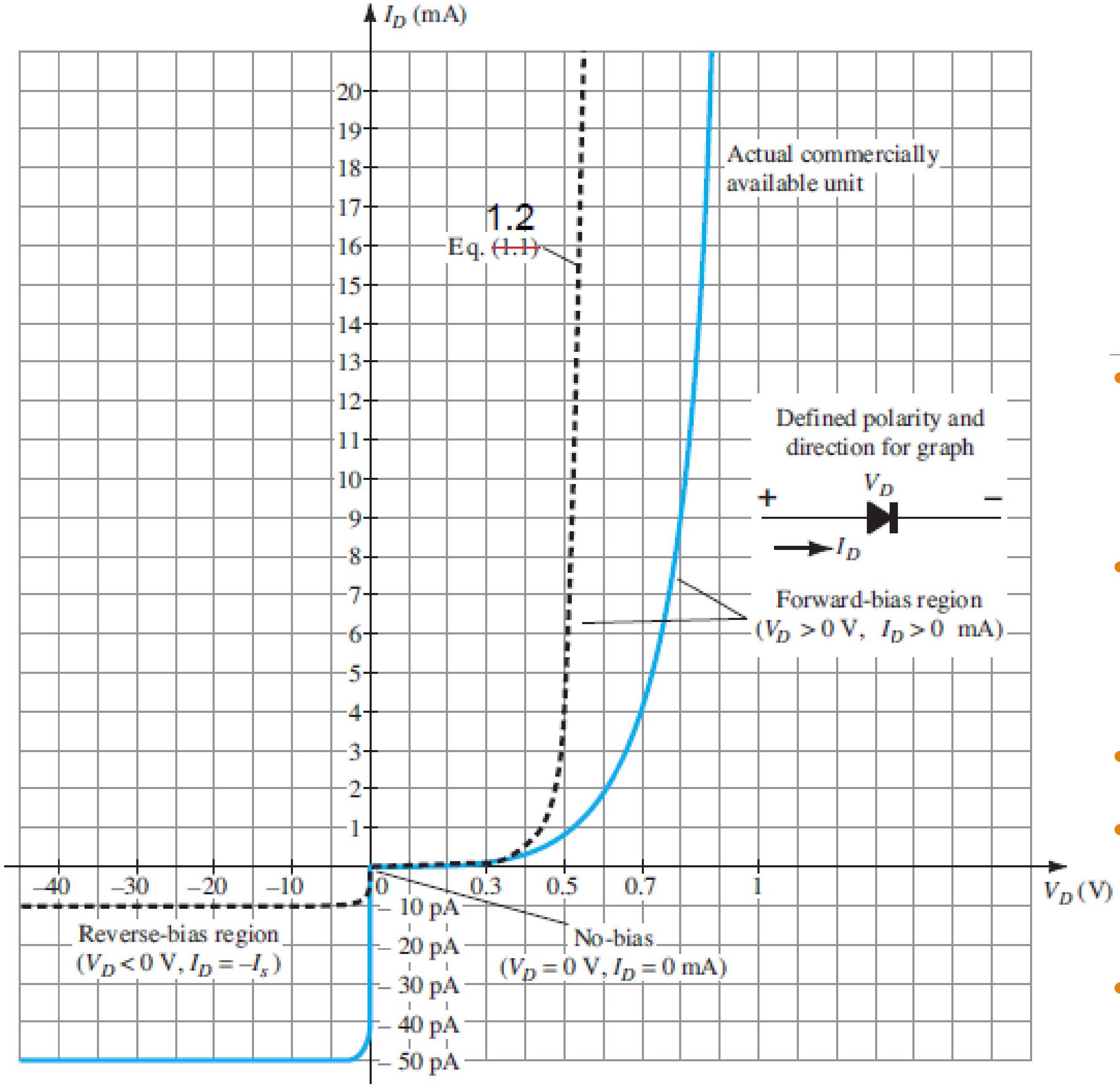
Where:

I_s is the reverse saturation current.

V_D is the forward-bias voltage across the diode.

n is an ideality factor; it has a range between 1 and 2. (a measure of how closely the diode follows the ideal diode equation)

V_T is called the thermal voltage.



Remarks: $I_D = I_s e^{V_D/nV_T} - I_s$

- As the value of V_D increases, the curve becomes almost vertical.

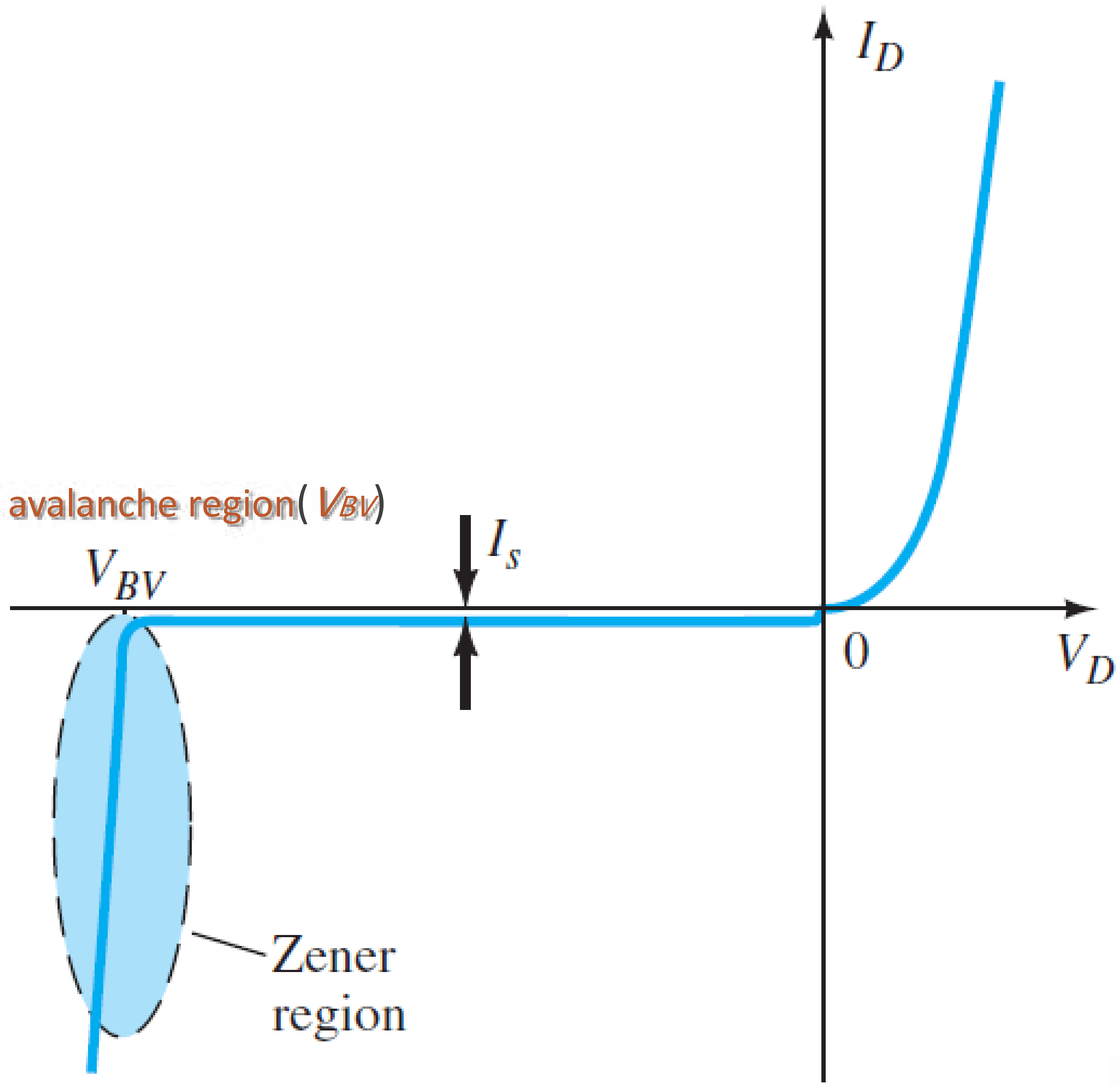
$$I_D \cong I_s e^{V_D/nV_T} \qquad (V_D \text{ positive})$$

- For negative values of VD, the exponential term drops very quickly below the level of I_D.

$$I_D \cong -I_s \qquad (V_D \text{ negative})$$

- At VD=0 V, $I_D = I_s(e^0 - 1) = I_s(1 - 1) = 0$
- Commercially available silicon diodes deviate from the ideal Diode (internal "body" resistance, external "contact" resistance of a diode.)
- The actual I_s of a commercially available diode will normally be measurably larger than that in Shockley's equation.

avalanche region(V_{BV})



Diode Characteristic Graph (IV-Curve) (cont'd)

- Applying negative voltage with the reverse polarity will result in a sharp change in the characteristics called breakdown potential (V_{BV})
- The avalanche region can be brought closer to the vertical axis by increasing the doping levels in the p- and n-type materials.
- Decreasing V_{BV} to a very low level, such as -5V, another mechanism called Zener breakdown will contribute to the sharp change in the characteristic.
- The maximum reverse bias that can be applied before entering the breakdown region is called the peak inverse voltage (**PIV** rating) or the peak reverse voltage (**PRV** rating).

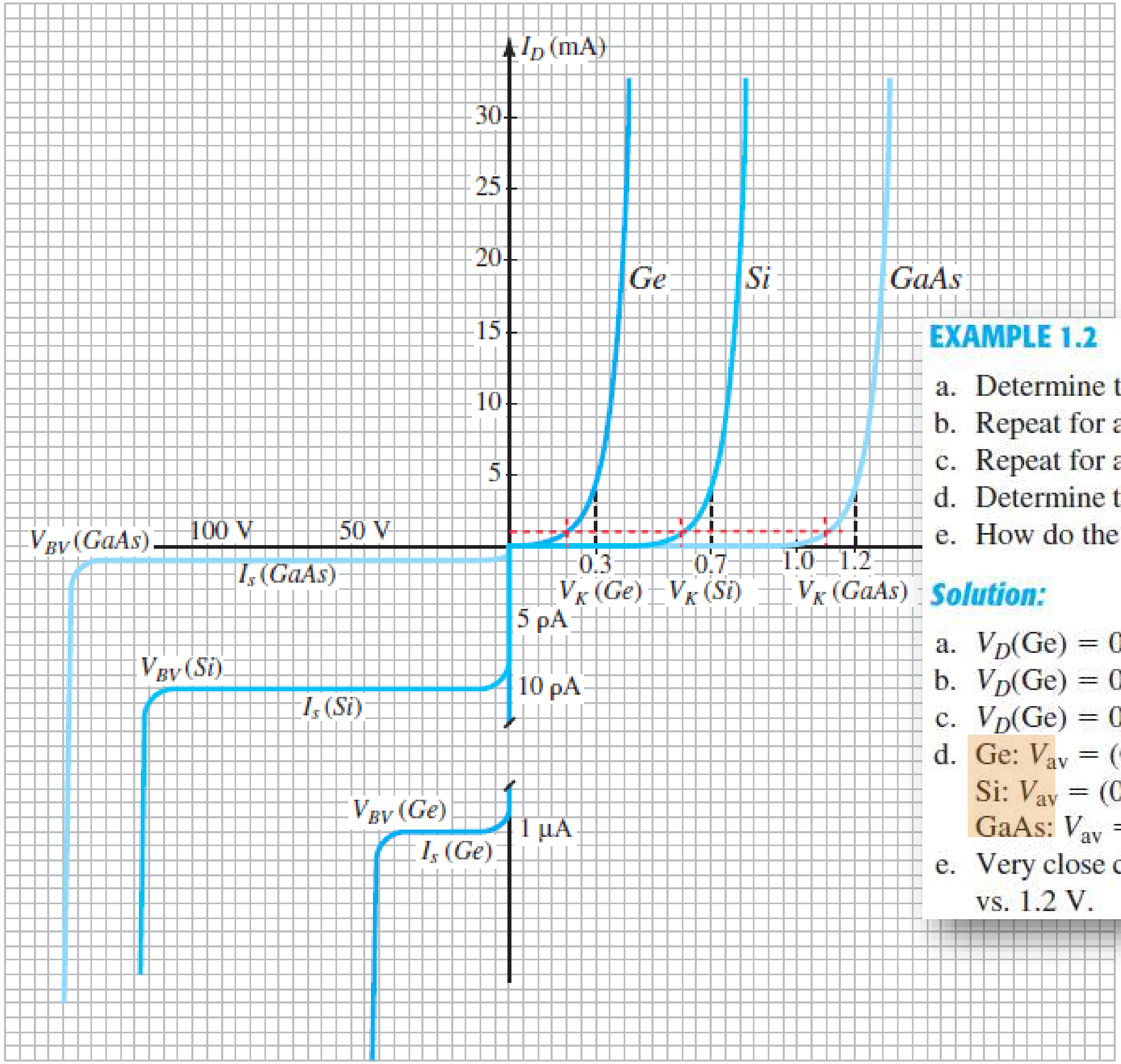


TABLE 1.3

Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

EXAMPLE 1.2

a. Determine the voltage across each diode at a current of 1 mA.
b. Repeat for a current of 4 mA.
c. Repeat for a current of 30 mA.
d. Determine the average value of the diode voltage for the range of currents listed above.
e. How do the average values compare to the knee voltages listed in Table 1.3?

Solution:

a. V_D(Ge) = 0.2 V, V_D(Si) = 0.6 V, V_D (GaAs) = 1.1 V
b. V_D(Ge) = 0.3 V, V_D(Si) = 0.7 V, V_D (GaAs) = 1.2 V
c. V_D(Ge) = 0.42 V, V_D(Si) = 0.82 V, V_D (GaAs) = 1.33 V
d. Ge: V_{av} = (0.2 V + 0.3 V + 0.42 V)/3 = 0.307 V
Si: V_{av} = (0.6 V + 0.7 V + 0.82 V)/3 = 0.707 V
GaAs: V_{av} = (1.1 V + 1.2 V + 1.33 V)/3 = 1.21 V
e. Very close correspondence. Ge: 0.307 V vs. 0.3, V, Si: 0.707 V vs. 0.7 V, GaAs: 1.21 V vs. 1.2 V.

Diode Resistance types

Diode resistance is variable due to the nonlinear shape of the characteristic curve.

1. DC (Static) Resistance

$$R_D = \frac{V_D}{I_D}$$

2. AC (Dynamic) Resistance

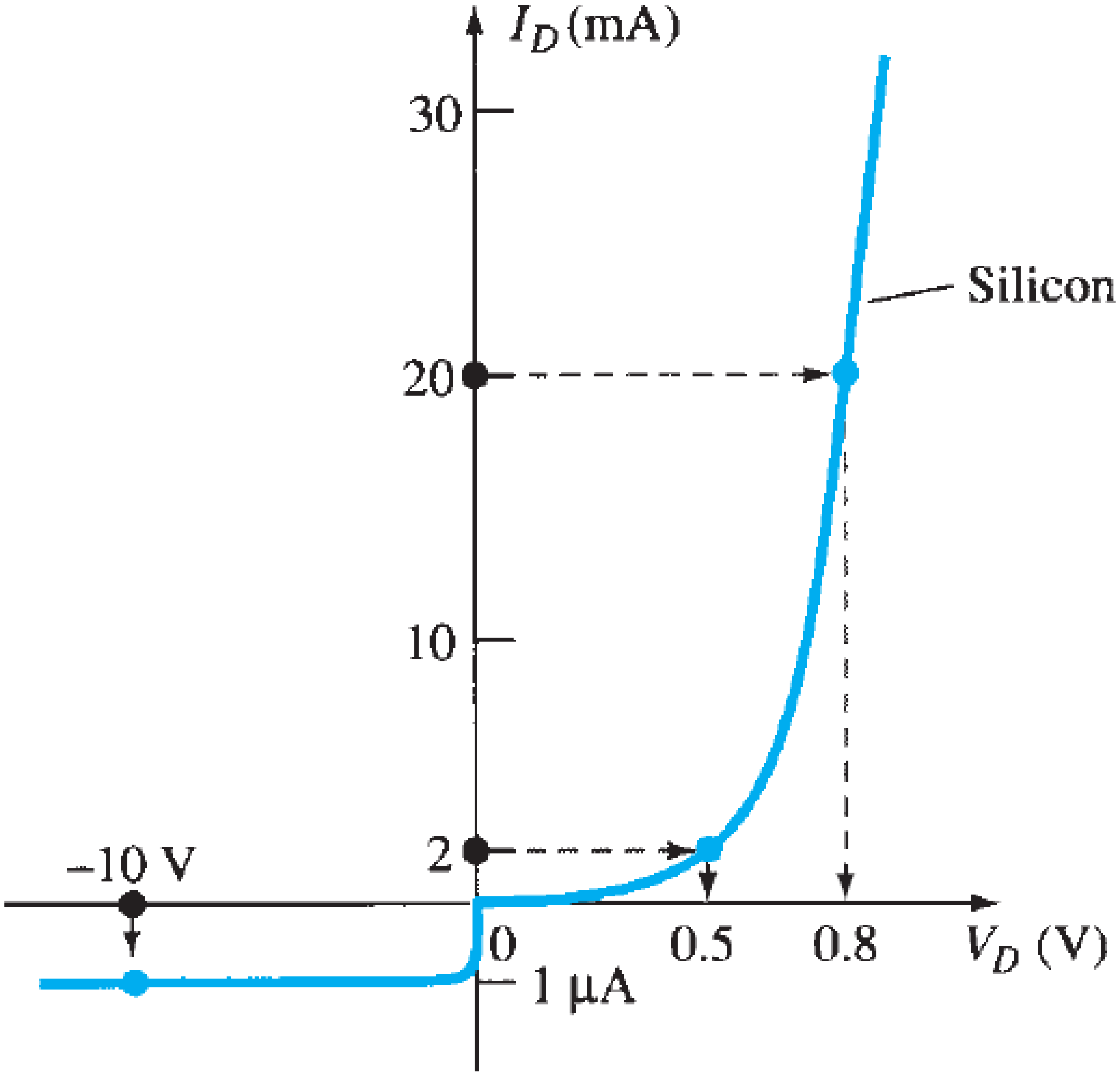
$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

$$r_d = \frac{26\ \text{mV}}{I_D}$$

3. Average AC Resistance

$$r_{\text{av}} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}}$$

Examples



EXAMPLE 1.3 Determine the dc resistance levels for the diode

a. $I_D = 2$ mA (low level)
b. $I_D = 20$ mA (high level)
c. $V_D = -10$ V (reverse-biased)

Solution:

a. At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

b. At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = \mathbf{40\ \Omega}$$

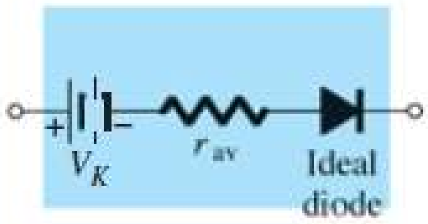
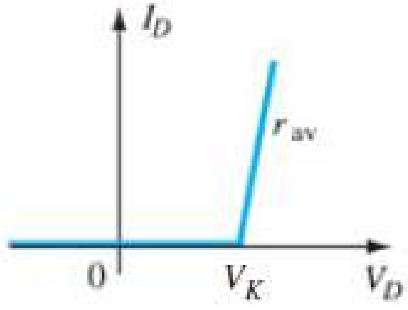
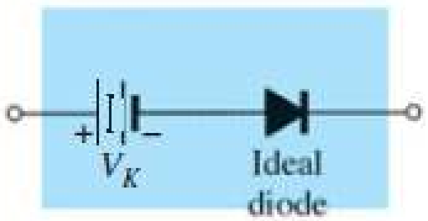
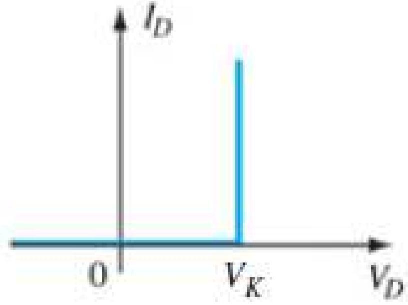
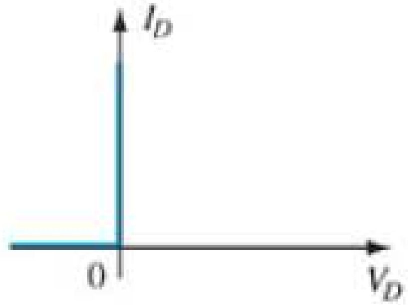
c. At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

The higher the current through a diode, the lower the dc resistance level

Outline

1. Diode Equivalent Circuits
2. Diode Load Line Analysis (aka graphical solution)
3. Series Diode Configurations
4. Parallel and Series-Parallel Configurations
5. Tutorial
6. Reading Assignment

Type	Conditions	Model	Characteristics
Piecewise-linear model			
Simplified model	$R_{\text{network}} \gg r_{\text{av}}$		
Ideal device	$R_{\text{network}} \gg r_{\text{av}}$ $E_{\text{network}} \gg V_K$		

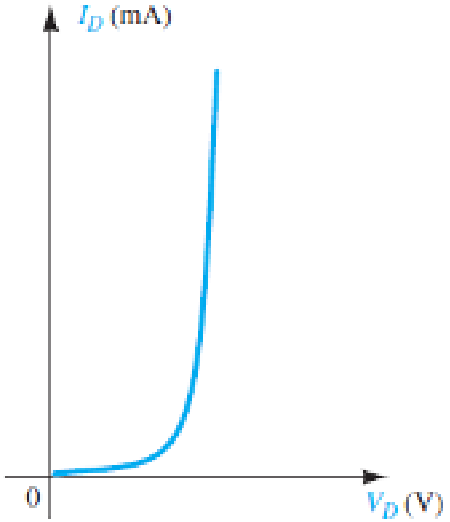


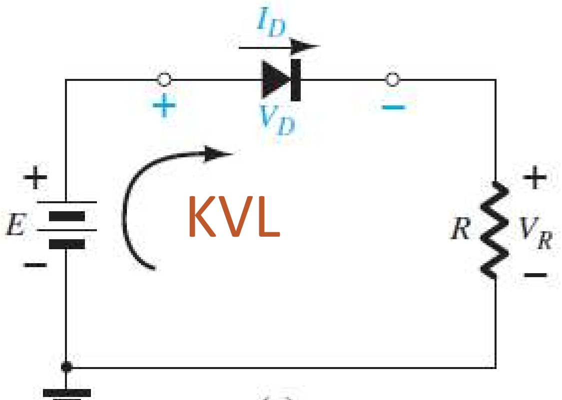
TABLE 1.3
Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

$$r_{\text{av}} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}}$$

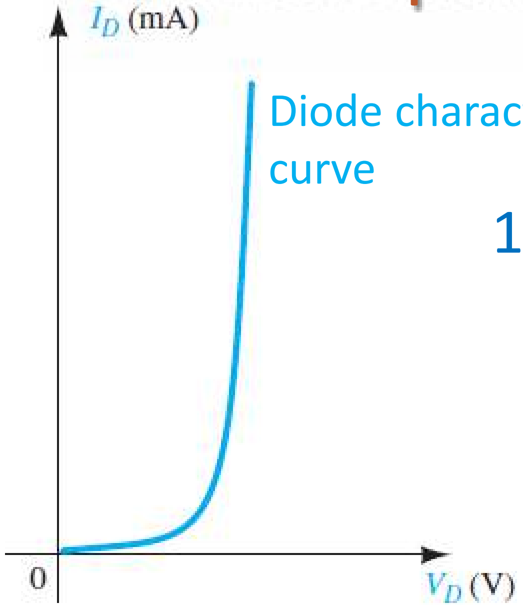
Diode Load Line Analysis (graphical solution)

- Load line analysis is used to find the **current** and **voltage** levels of the diode that will **satisfy both** the **characteristics** of the diode and the **network parameters** simultaneously.



KVL

(a)



Diode characteristic curve

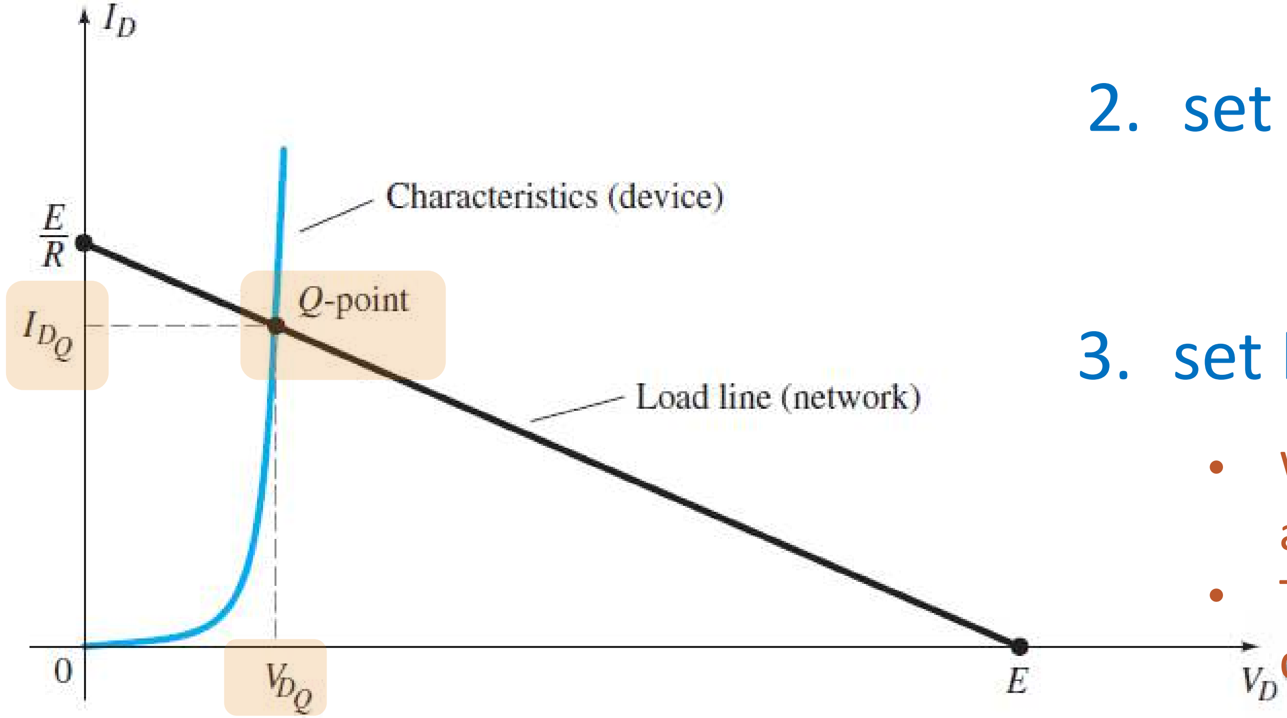
(b)

1. Apply Kirchhoff's voltage law in the clockwise direction:

$$\boxed{E = V_D + I_D R}$$

Diode Load Line Analysis (cont'd)

- The diode characteristics are placed on the same set of axes as a straight line defined by the parameters of the network.



2. set VD = 0V, $$I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}}$$
3. set ID = 0A, $$V_D = E\big|_{I_D = 0\text{ A}}$$

- We now have a load line defined by the network and a characteristic curve defined by the device.
- The point of operation (intersection) is called the quiescent point (***Q -point***)

Diode Load Line Analysis (cont’d)

- The solution obtained at the intersection of the two curves is the same as would be obtained by a simultaneous mathematical solution of:

$$I_D = \frac{E}{R} - \frac{V_D}{R}$$ and $$I_D = I_s(e^{V_D/nV_T} - 1)$$

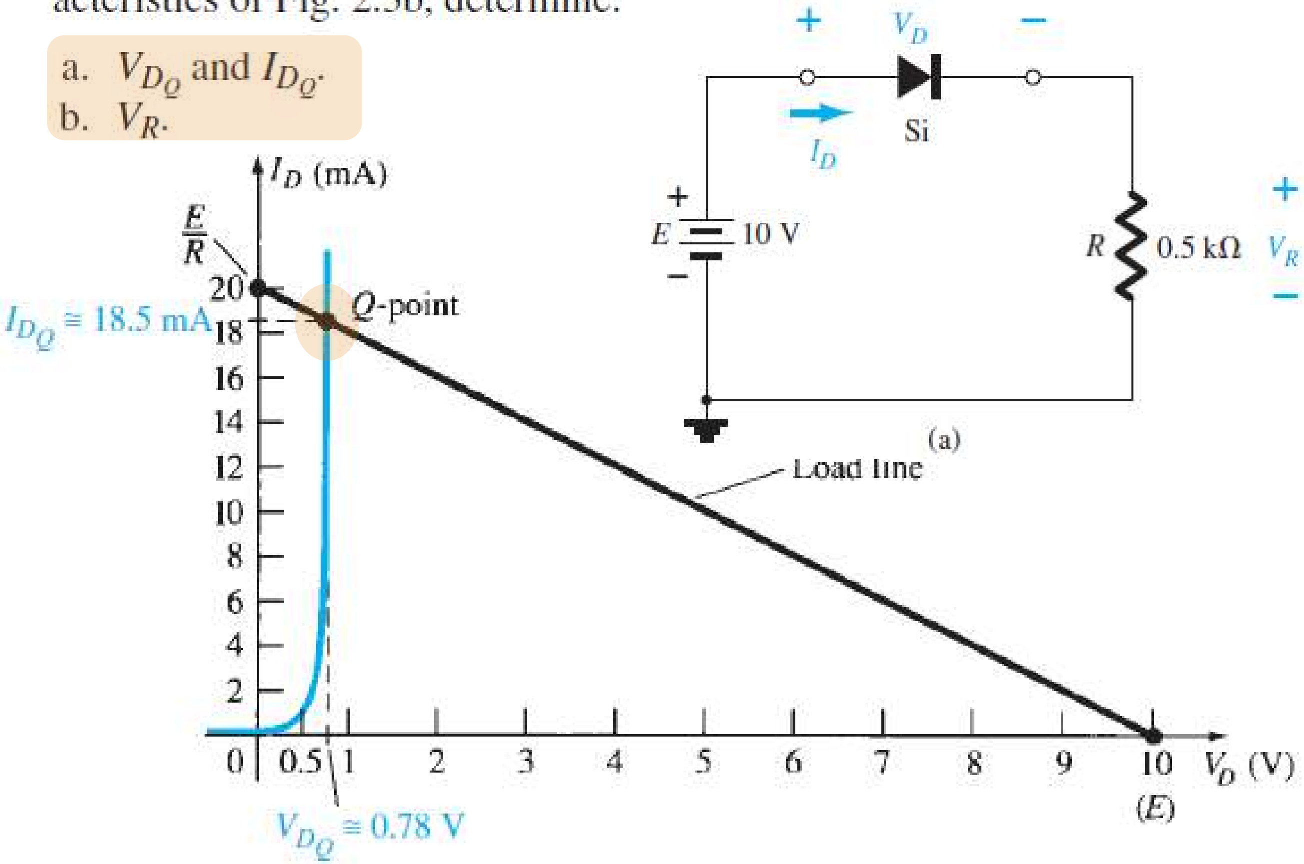
- The curve for a diode has nonlinear characteristics. Therefore, the mathematics involved would require using nonlinear techniques.

https://www.youtube.com/watch?v=kp3Bq6ATbUA

Diode Load Line Analysis (cont’d)

EXAMPLE 2.1 For the series diode configuration of Fig. 2.3a, employing the diode characteristics of Fig. 2.3b, determine:

a. V_{D_Q} and I_{D_Q}.
b. V_R.



Solution:

a. $$I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}} = \frac{10\text{ V}}{0.5\text{ k}\Omega} = 20\text{ mA}$$

$$V_D = E\big|_{I_D = 0\text{ A}} = 10\text{ V}$$

the Q -point is:

$$V_{D_Q} \cong \mathbf{0.78\ V}$$

$$I_{D_Q} \cong \mathbf{18.5\ mA}$$

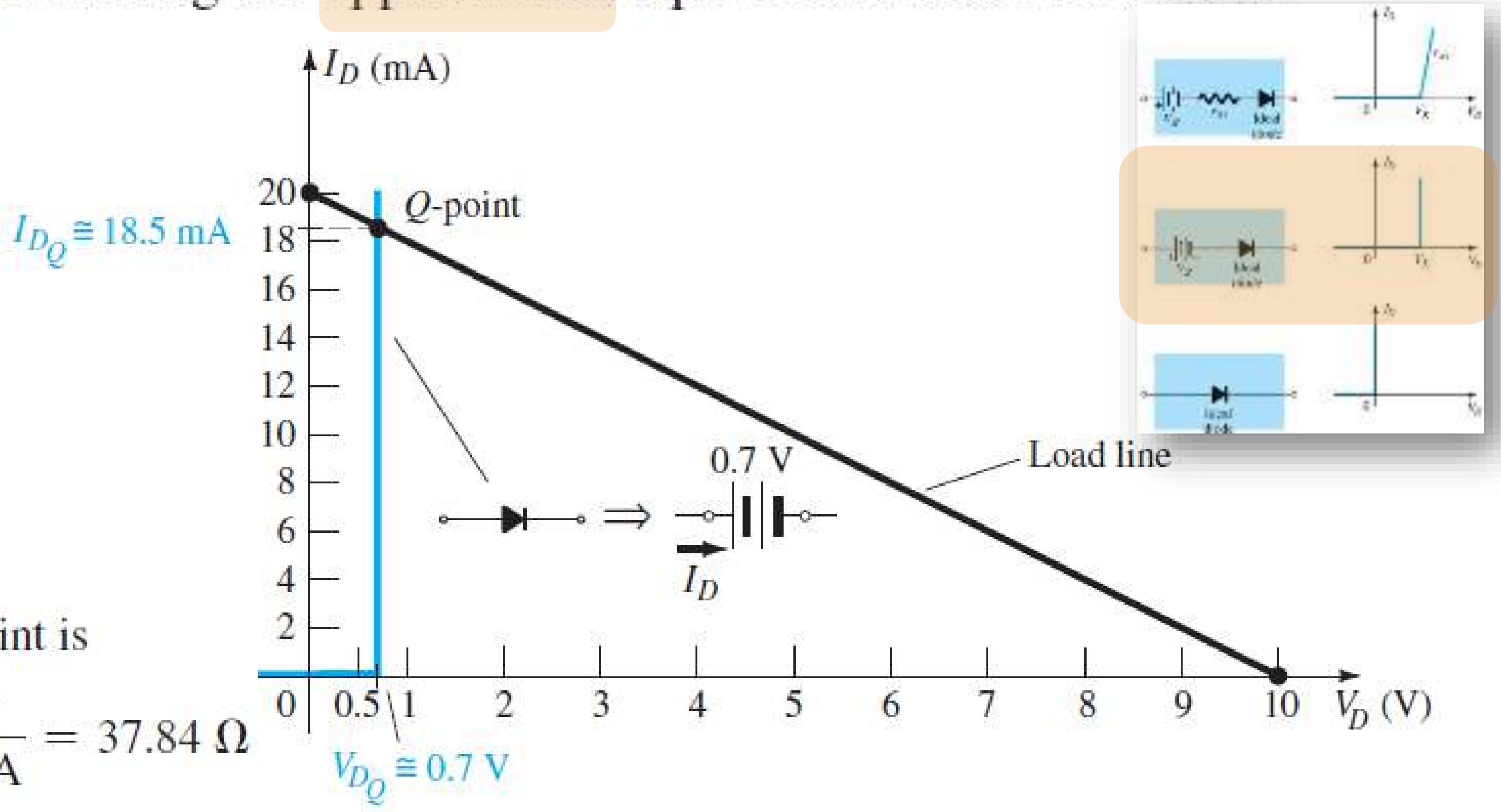
b. $V_R = E - V_D = 10\text{ V} - 0.78\text{ V} = \mathbf{9.22\ V}$

Diode Load Line Analysis (cont'd)

EXAMPLE 2.2 Repeat Example 2.1 using the approximate equivalent model for the silicon semiconductor diode.

Solution:

$$V_{D_Q} = \mathbf{0.7\ V}$$
$$I_{D_Q} = \mathbf{18.5\ mA}$$



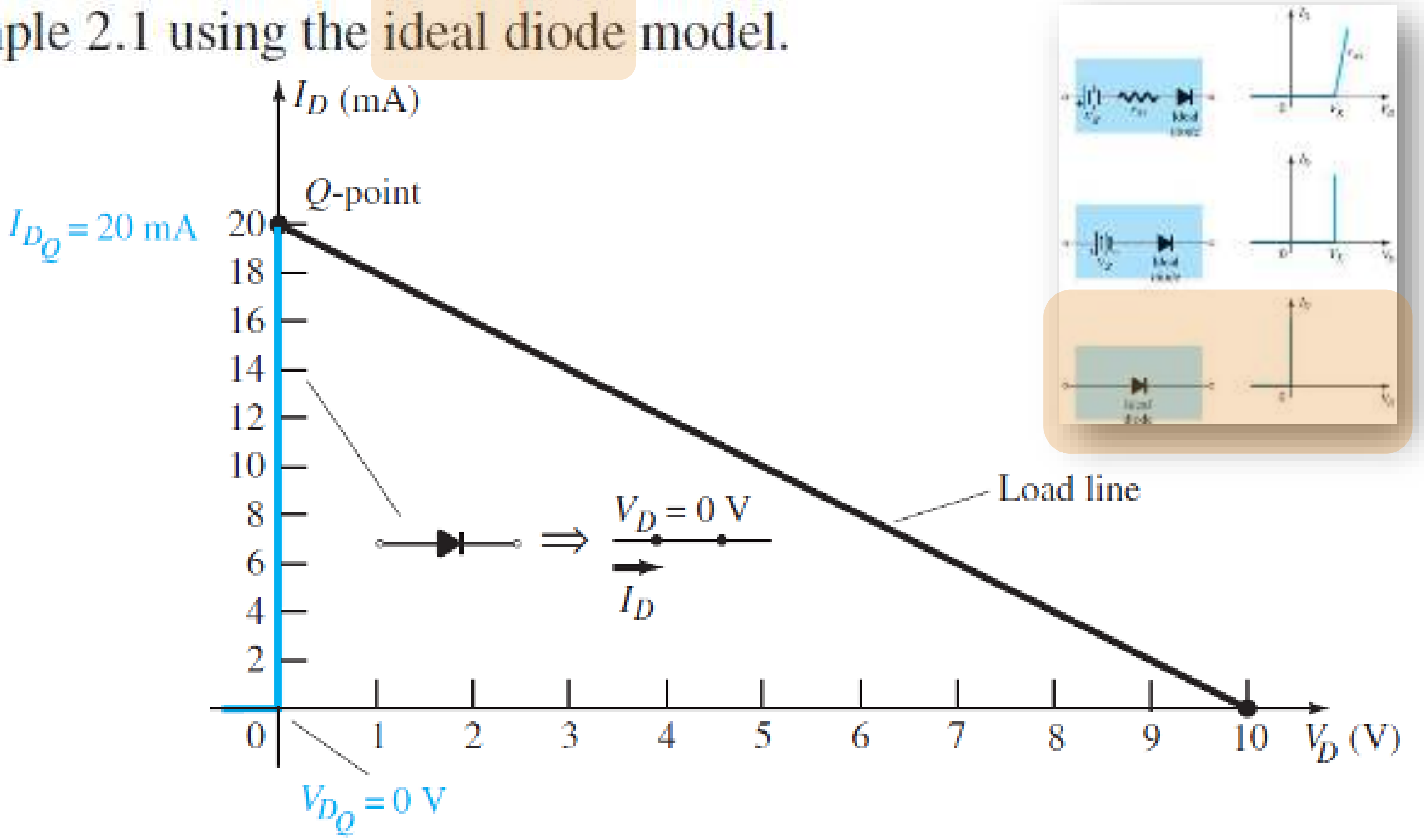
Note:

For this situation the dc resistance of the Q-point is

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0.7\ V}{18.5\ mA} = 37.84\ \Omega$$

Diode Load Line Analysis (cont’d)

EXAMPLE 2.3 Repeat Example 2.1 using the ideal diode model.



Solution:

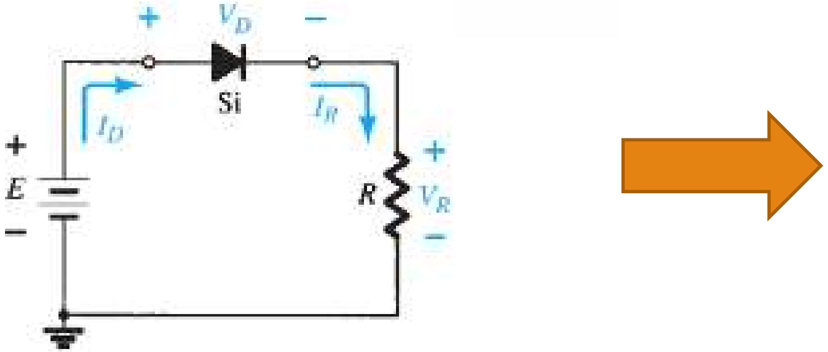
$$V_{D_Q} = 0\text{ V}$$
$$I_{D_Q} = 20\text{ mA}$$

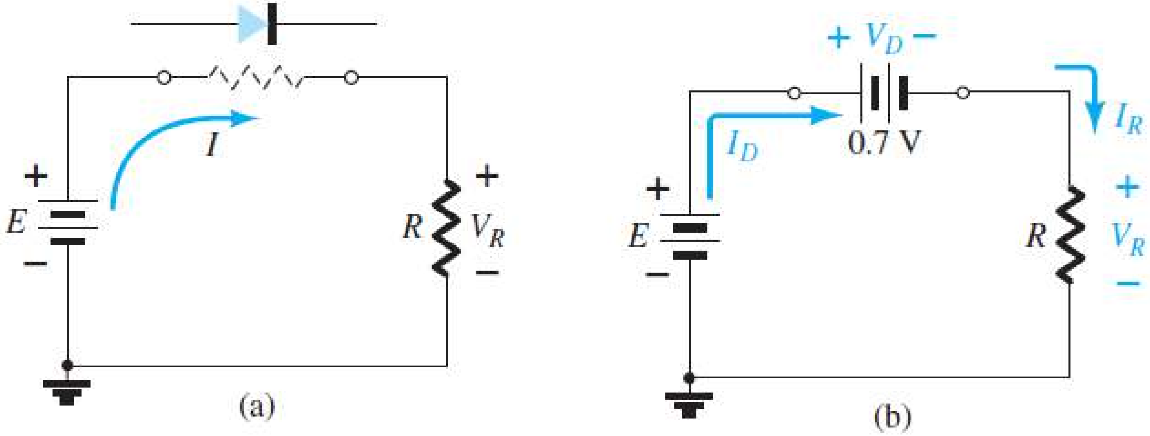
Note:

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0\text{ V}}{20\text{ mA}} = 0\ \Omega$$

Series Diode Configurations

- The state of the diode is first determined by **mentally replacing** the diode with a **resistive** element.
- If the resulting direction of (***I***) matches the **arrow** in the diode symbol, and **E>VK**, the diode is in the "**on**" state.
- The network is then **redrawn** with the appropriate **equivalent model for the forward-biased** silicon diode.



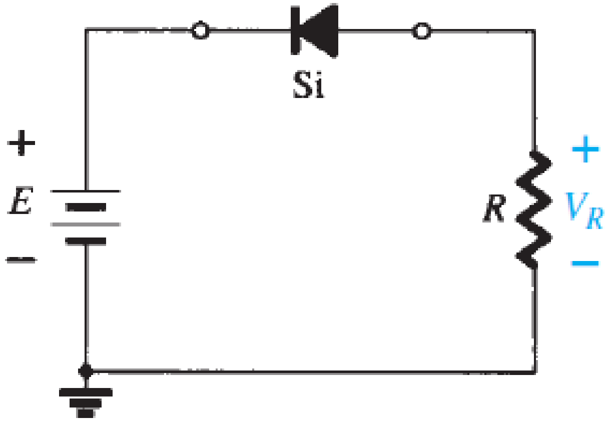


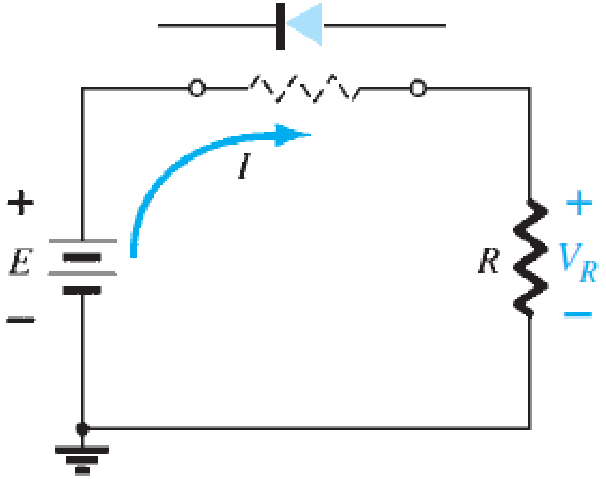
Series Diode Configurations (cont’d)

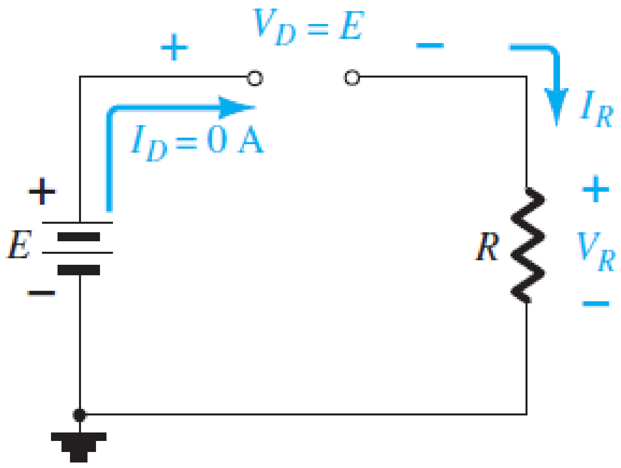
$$\boxed{V_R = E - V_K}$$

$$\boxed{I_D = I_R = \frac{V_R}{R}}$$

- If the resulting direction of ***I*** is **opposite** to the **arrow** in the diode symbol, the diode is in the “**off**” state, and $V_R = I_R R = I_D R = (0A)R = 0\,V$



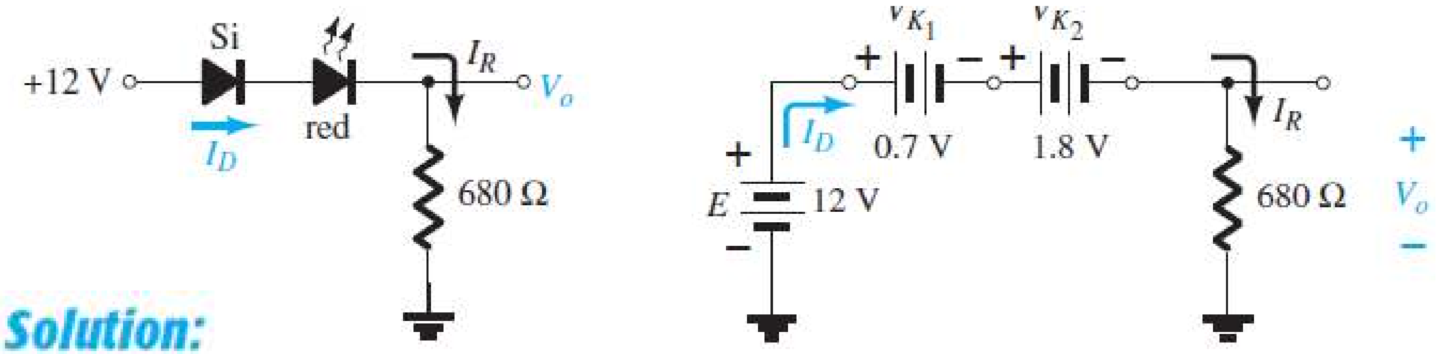




https://www.youtube.com/watch?v=28qk4jNjKqI

Series Diode Configurations (cont’d)

EXAMPLE 2.7 Determine V_o and I_D for the series circuit



Solution:

E=12V > 2.5V (0.7V+1.8V)

$$V_o = E - V_{K_1} - V_{K_2} = 12\text{ V} - 2.5\text{ V} = \mathbf{9.5\text{ V}}$$

$$I_D = I_R = \frac{V_R}{R} = \frac{V_o}{R} = \frac{9.5\text{ V}}{680\ \Omega} = \mathbf{13.97\text{ mA}}$$

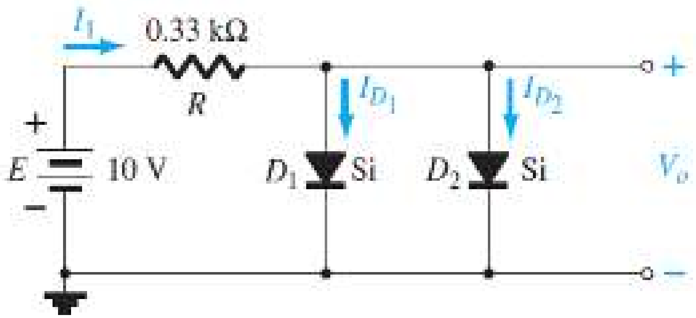
TABLE 1.9
Light-Emitting Diodes

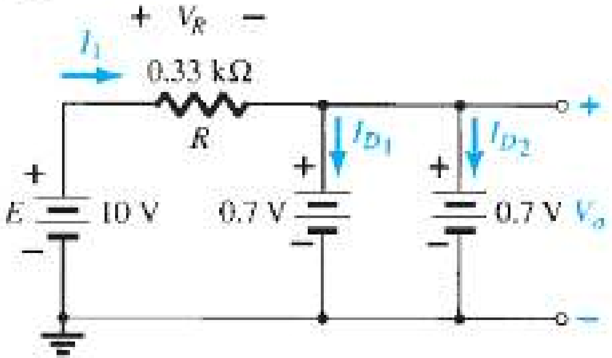
Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

AlInGaP: Aluminum gallium indium phosphide
GaAsP: Gallium Arsenide Phosphide

Parallel and Series-Parallel Configurations

EXAMPLE 2.10 Determine V_o, I_1, I_{D_1}, and I_{D_2} for the parallel diode configuration





$$V_o = \mathbf{0.7\ V}$$

Since the resulting current direction matches that of the arrow in each diode symbol and the *applied voltage is greater than 0.7 V,* both diodes are in the “on” state.

The reason for placing diodes in parallel is to increase the current rating of the diodes.

Solution: The current is

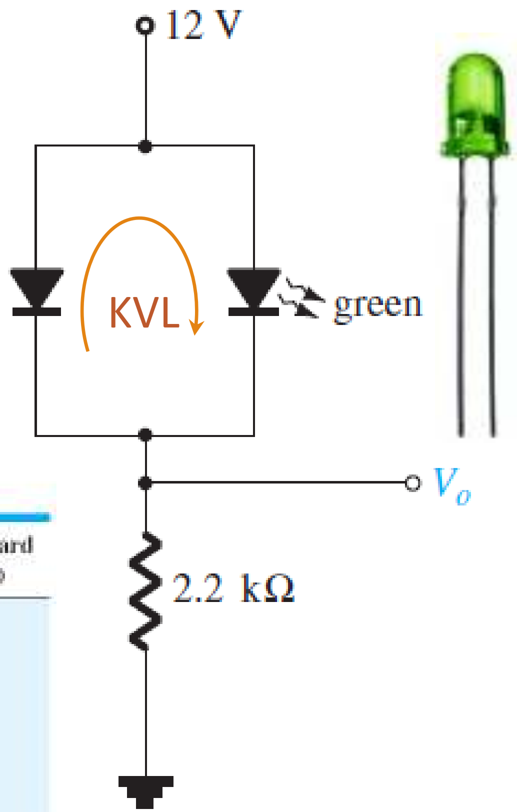
$$I_1 = \frac{V_R}{R} = \frac{E - V_D}{R} = \frac{10\ \text{V} - 0.7\ \text{V}}{0.33\ \text{k}\Omega} = \mathbf{28.18\ mA}$$

Assuming diodes of similar characteristics, we have

$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = \frac{28.18\ \text{mA}}{2} = \mathbf{14.09\ mA}$$

Parallel and Series-Parallel Configurations (cont'd)

EXAMPLE 2.12 Determine the voltage V_o for the network



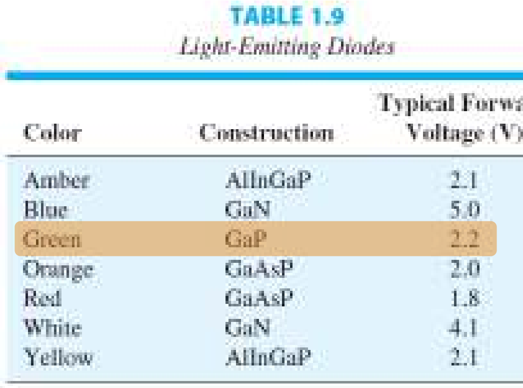


TABLE 1.9

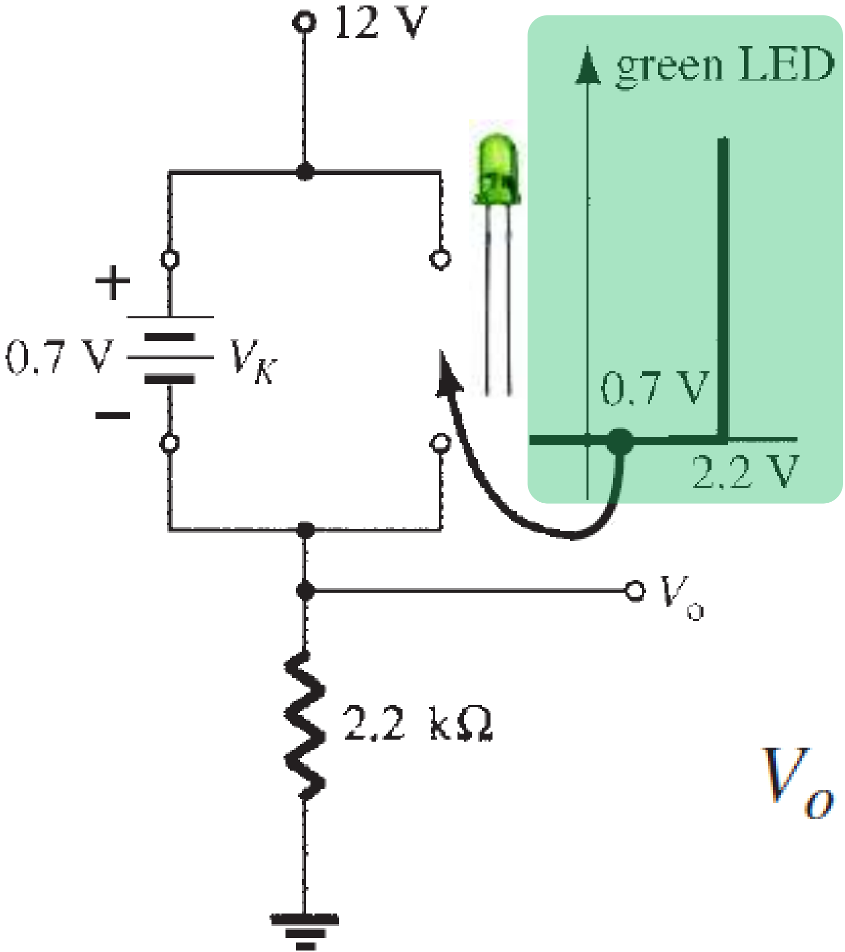
Light-Emitting Diodes

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

- Note: If both diodes were ON, there would be **more than one voltage** across the parallel diodes, **violating** one of the basic rules of network analysis:

The voltage must be the same across parallel elements.

Parallel and Series-Parallel Configurations (cont’d)



- The result is that the voltage across the green LED **will never rise above 0.7 V** and will remain in the equivalent **open-circuit state**.

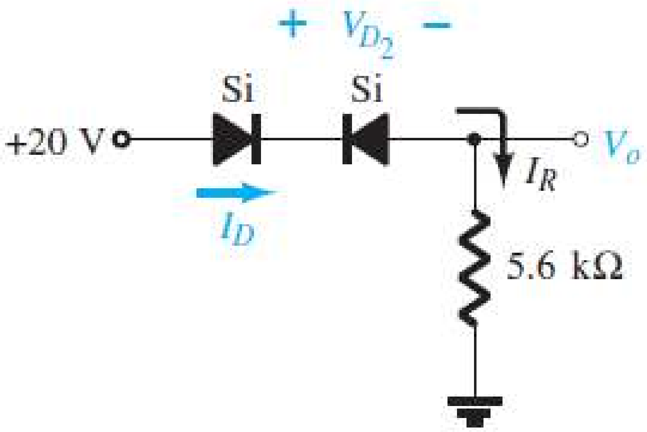
$$V_o = 12\text{ V} - 0.7\text{ V} = \mathbf{11.3\ V}$$

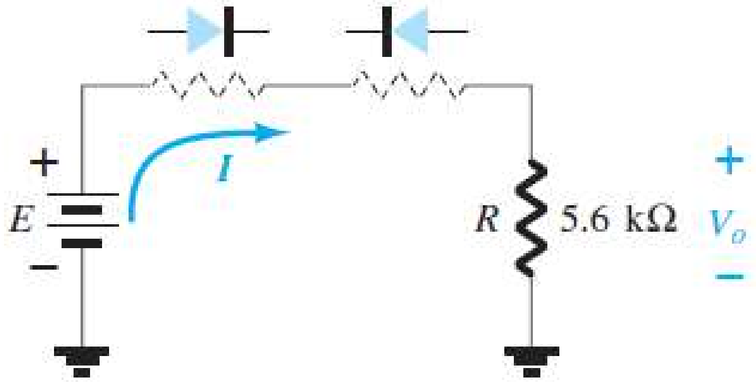
Tutorial

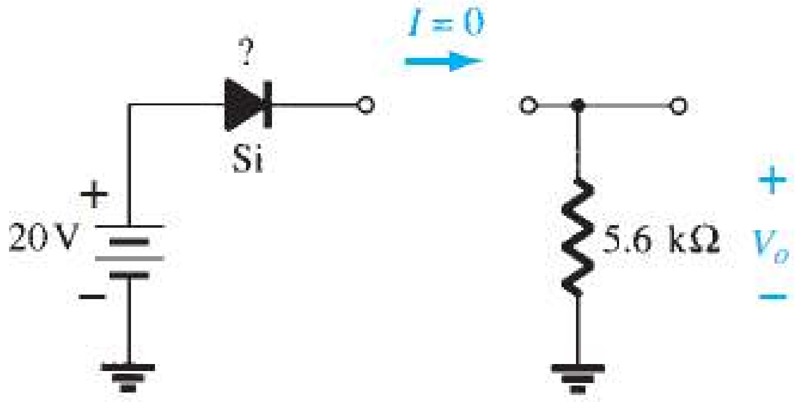
EXAMPLE 2.8 Determine I_D, V_{D_2}, and V_o for the circuit

Solution:

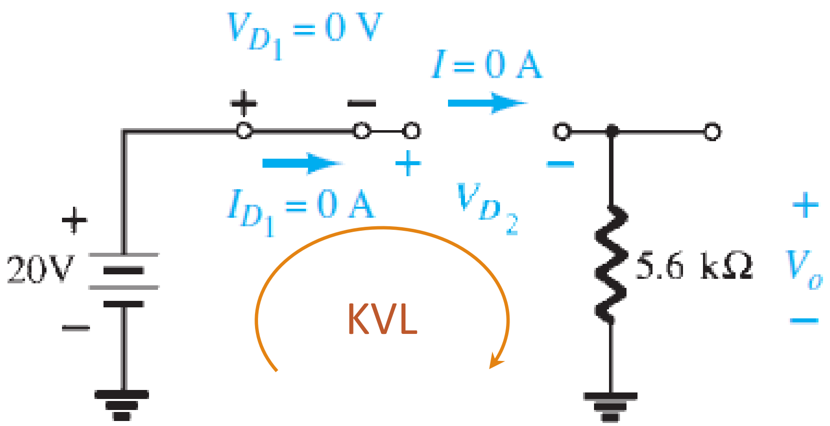
The combination of a short circuit in series with an open circuit always results in an open circuit and *$I_D = 0A$*.







Tutorial (Example 2.8 cont’d)



recall for the actual practical diode that when *ID=0A*, *VD=0V* (and vice versa)

$$V_o = I_R R = I_D R = (0\text{ A})R = \mathbf{0\ V}$$

$$V_{D_2} = V_{\text{open circuit}} = E = \mathbf{20\ V}$$

Applying Kirchhoff’s voltage law in a clockwise direction gives

$$E - V_{D_1} - V_{D_2} - V_o = 0$$

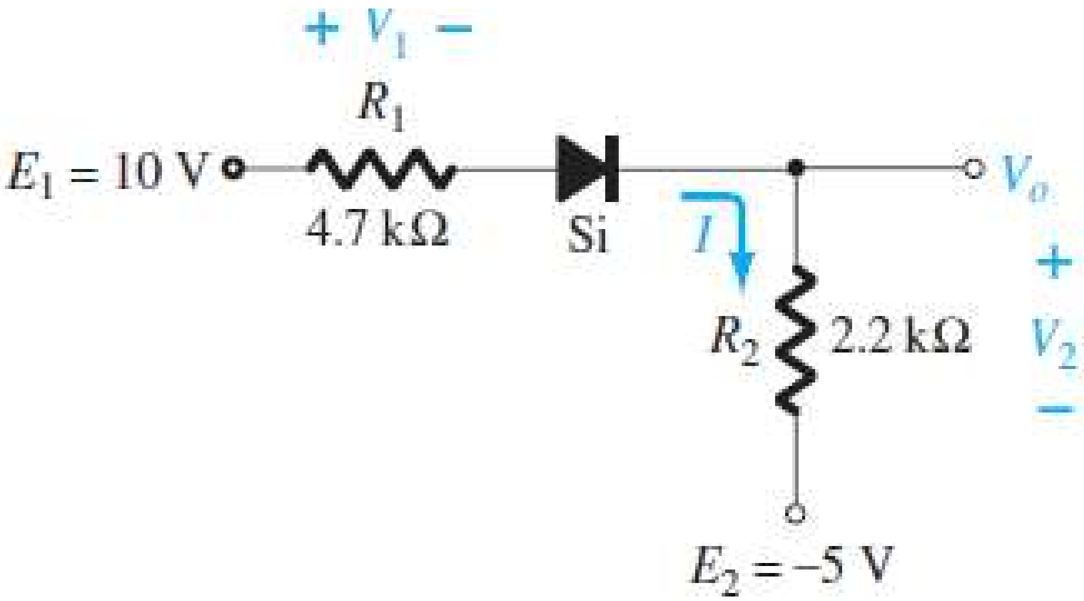
$$V_{D_2} = E - V_{D_1} - V_o = 20\text{ V} - 0 - 0$$

$$= \mathbf{20\ V}$$

$$V_o = \mathbf{0\ V}$$

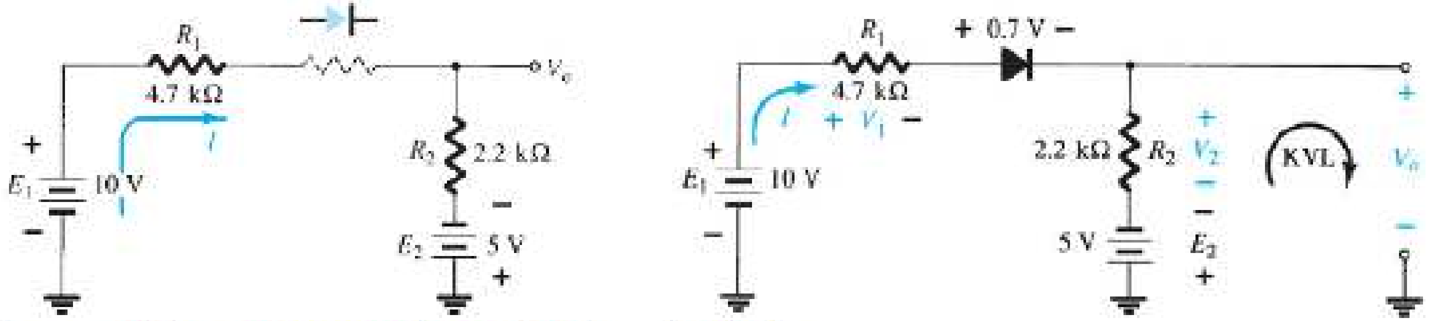
Tutorial

EXAMPLE 2.9 Determine I, V_1, V_2, and V_o for the series dc configuration



Tutorial (Example 2.9 cont'd)

Solution:



The resulting current through the circuit is

$$I = \frac{E_1 + E_2 - V_D}{R_1 + R_2} = \frac{10\text{ V} + 5\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega + 2.2\text{ k}\Omega} = \frac{14.3\text{ V}}{6.9\text{ k}\Omega}$$

$$\cong \mathbf{2.07\ mA}$$

and the voltages are

$$V_1 = IR_1 = (2.07\text{ mA})(4.7\text{ k}\Omega) = \mathbf{9.73\ V}$$

$$V_2 = IR_2 = (2.07\text{ mA})(2.2\text{ k}\Omega) = \mathbf{4.55\ V}$$

Applying Kirchhoff's voltage law to the output section in the clockwise direction results in

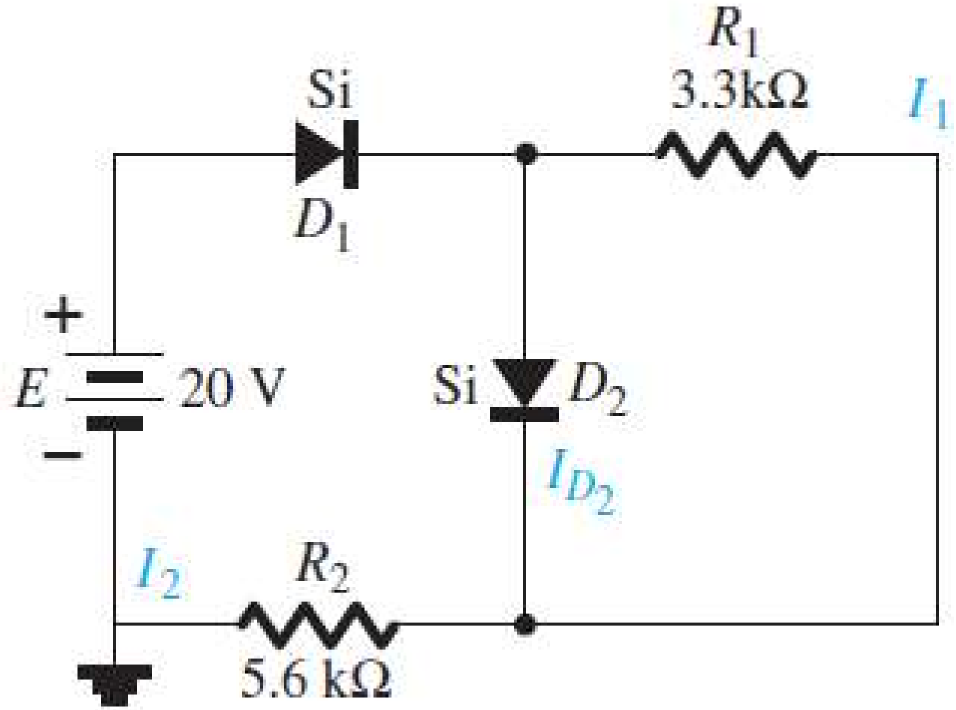
$$-E_2 + V_2 - V_o = 0$$

and

$$V_o = V_2 - E_2 = 4.55\text{ V} - 5\text{ V} = \mathbf{-0.45\ V}$$

Tutorial

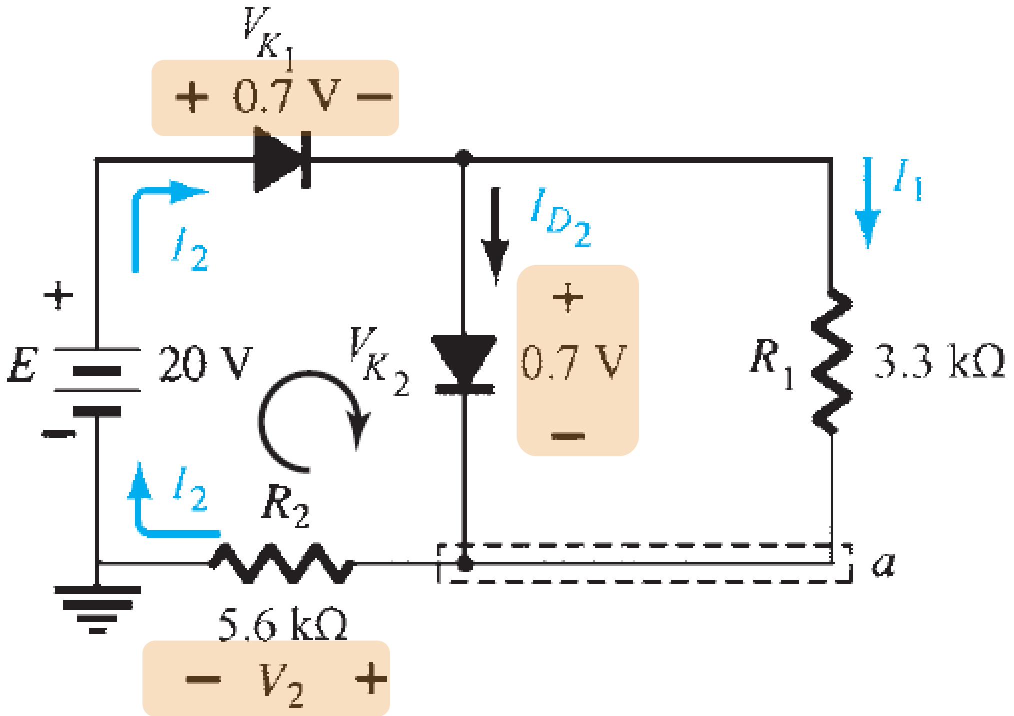
EXAMPLE 2.13 Determine the currents I_1, I_2, and I_{D_2} for the network



Tutorial (Example 2.13 cont'd)

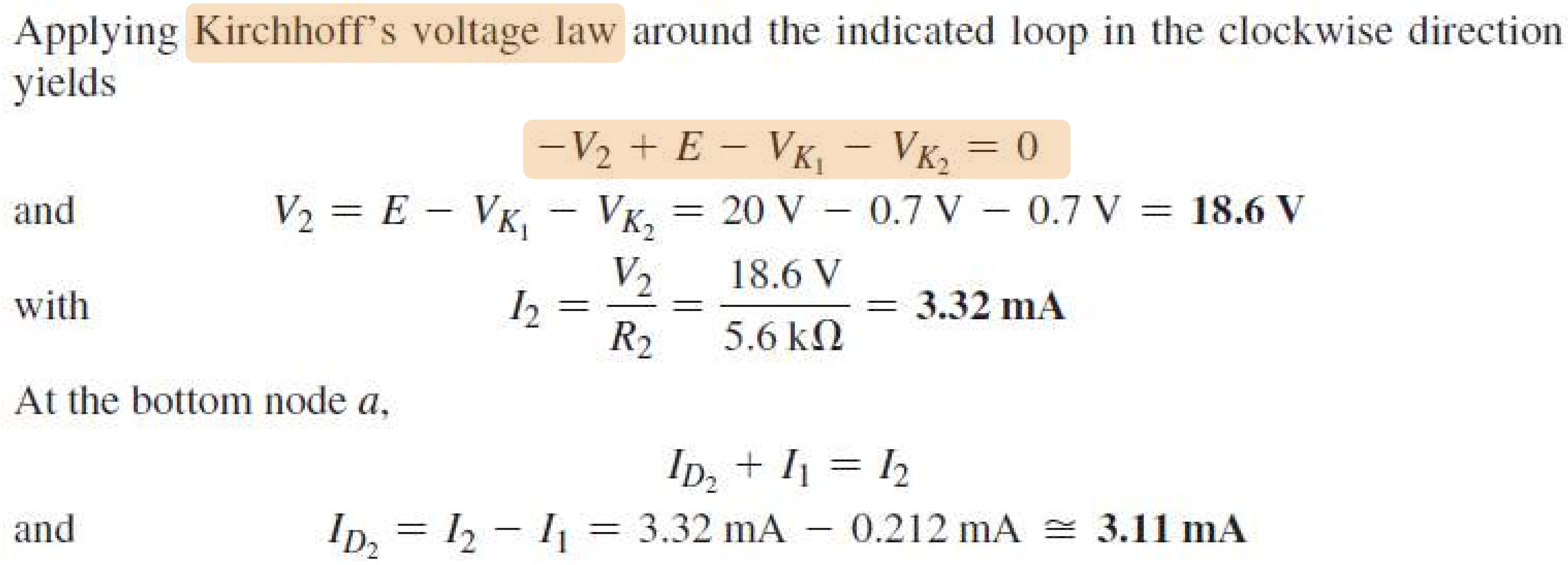
Solution:

The applied voltage is such as to turn both diodes on, as indicated by the resulting current directions in the network.



$$I_1 = \frac{V_{K_2}}{R_1} = \frac{0.7\text{ V}}{3.3\text{ k}\Omega} = \mathbf{0.212\text{ mA}}$$

Tutorial (Example 2.13 cont'd)



Applying Kirchhoff's voltage law around the indicated loop in the clockwise direction yields

$$-V_2 + E - V_{K_1} - V_{K_2} = 0$$

and $$V_2 = E - V_{K_1} - V_{K_2} = 20\text{ V} - 0.7\text{ V} - 0.7\text{ V} = \mathbf{18.6\text{ V}}$$

with $$I_2 = \frac{V_2}{R_2} = \frac{18.6\text{ V}}{5.6\text{ k}\Omega} = \mathbf{3.32\text{ mA}}$$

At the bottom node a,

$$I_{D_2} + I_1 = I_2$$

and $$I_{D_2} = I_2 - I_1 = 3.32\text{ mA} - 0.212\text{ mA} \cong \mathbf{3.11\text{ mA}}$$