SEU 3003

ELEKTRONIK

(ELECTRONICS)

Chapter 2

DIODE *PN*

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In this chapter, we will learn:

1. Diode's physical structure
2. The I-V characteristics
3. Load line and graphical analysis
4. Internal resistance
5. Diode model
6. Diode with DC power supply –
   series and parallel connection
7. Basic gates
8. Diodes applications: AC power supply –
   rectifiers with capacitor filter,
   clippers and clampers
9. Data sheets
10. Zener diode – simple voltage regulator
11. Other diodes - Photodiodes, LED's and etc

Diode's Physical Structure

- A diode is a single *pn* junction device with conductive contacts and wire leads connected to each region.

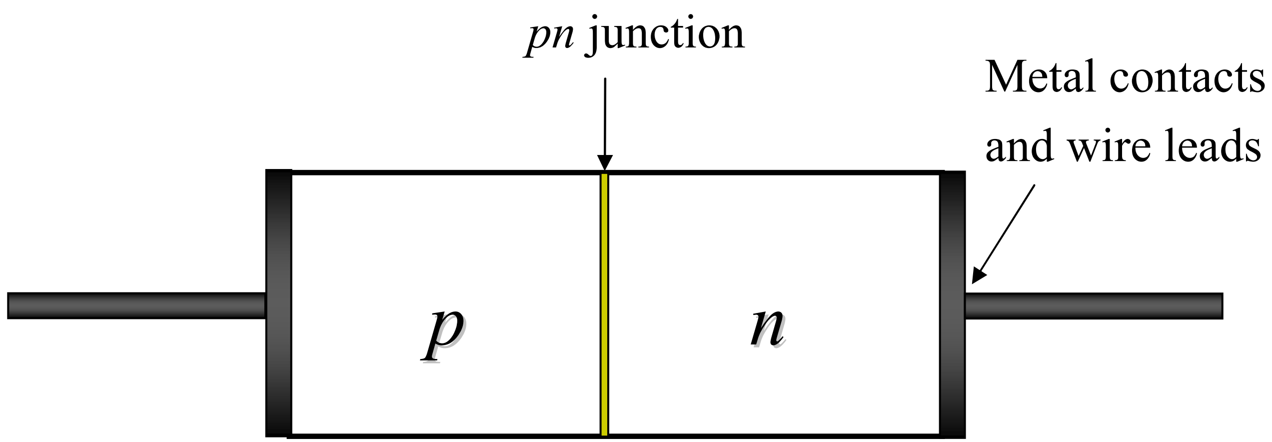


Fig.1: Basic diode structure

Diode's Physical Structure

- There are several types of diodes, but the schematic symbol for a general-purpose diode (rectifier diode) is as shown below.

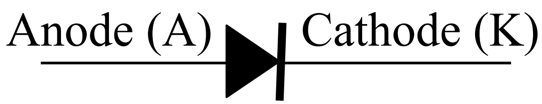


Fig.2: Schematic symbol

- The n region is called the **cathode** and p region is called the **anode**.
- The "arrow" in the symbol points in the direction of conventional current (opposite to electron flow).

Diode's Physical Structure (Forward-bias connection)

- A diode is forward-biased when a voltage source is connected as shown in figure 3.

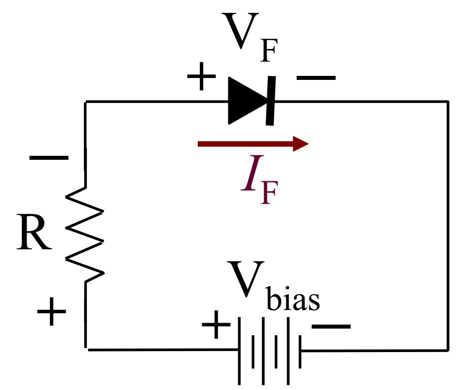


Fig.3: Forward bias

- The positive terminal of the source is connected to the anode through the current-limiting resistor.
- The negative terminal of the source is connected to the cathode.
- The forward current (I_F) is from anode to cathode as indicated.

- The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.

Diode's Physical Structure (Reverse-bias connection)

- A diode is reverse-biased when a voltage source is connected as shown in figure 4.

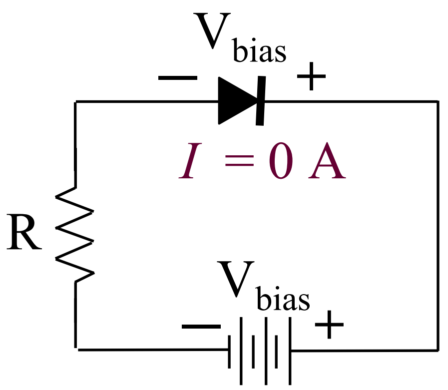


Fig.4: Reverse bias

- The negative terminal of the source is connected to the anode side of the diode and the positive terminal is connected to the cathode side.
- The reverse current is extremely small and can be considered to be zero.

- Notice that the entire bias voltage (V_{bias}) appears across the diode.

The I-V Characteristics (The ideal diode model)

- The ideal model of a diode is a simple switch.
- When the diode is forward-biased, it acts like a closed (on) switch (Fig. 5 (a)).
- When the diode is reverse-biased, it acts like an open (off) switch (Fig. 5 (b)).
- The barrier potential, the forward dynamic resistance, and the reverse current are all neglected.

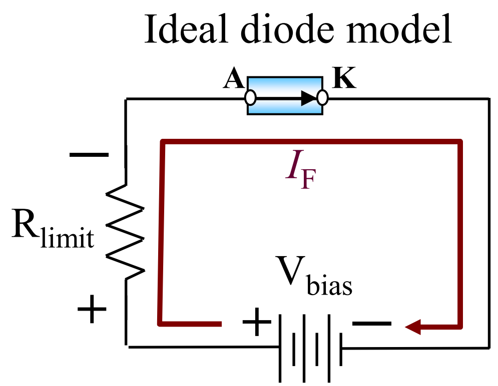


Fig.5(a): Forward bias

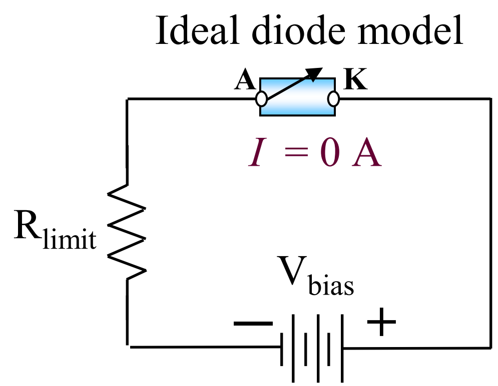


Fig.5(b): Reverse bias

Activity

- *Draw the ideal I-V characteristic curve to depicts the ideal diode operation. At x-axis, indicate V_F and V_R as positive and negative potential, respectively, and at y-axis, the I_F and I_R as positive and negative current, respectively.*

The I-V Characteristics (The ideal diode model)

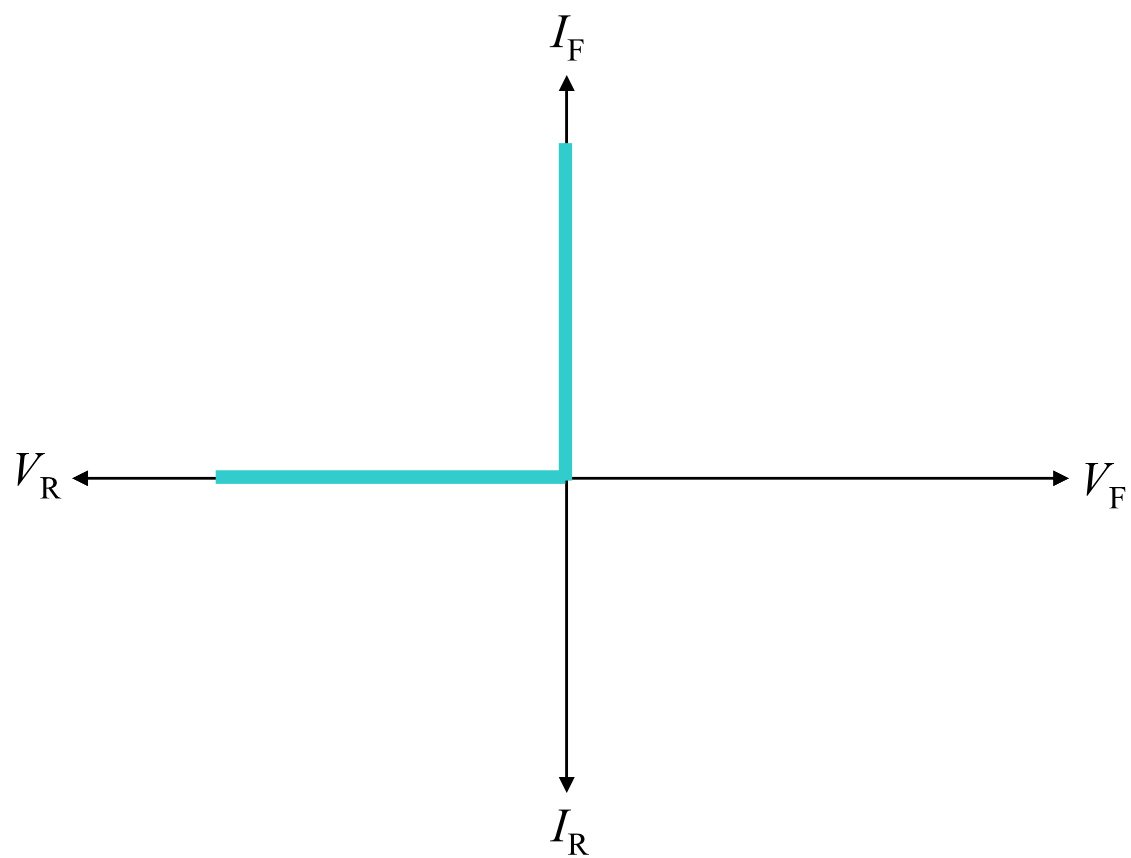


Fig.6: Ideal characteristic curve (blue)

Activity

- *Complete these equations.*

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

$$I_F = \frac{\text{V}_{\text{bias}}}{\text{R}_{\text{limit}}}$$

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

$$V_R = \text{V}_{\text{bias}}$$

The I-V Characteristics (The practical diode model)

Practical diode model

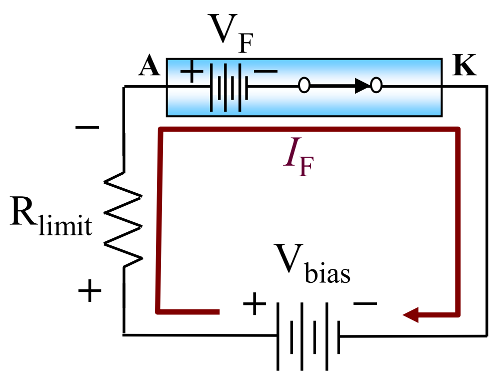


Fig.7(a): Forward bias

- The practical model adds the barrier potential to the ideal switch model.
- When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source equal to the barrier potential (0.7 V) with the positive side toward the anode.
- This equivalent voltage source represents the fixed voltage drop (V_F) produced across the forward-biased *pn* junction of the diode and is not an active source of voltage.

The I-V Characteristics (The practical diode model)

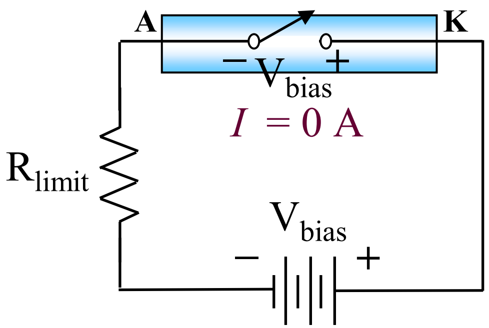


Fig.7(b): Reverse bias

- When the diode is reverse-biased, 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.

The I-V Characteristics (The practical diode model)

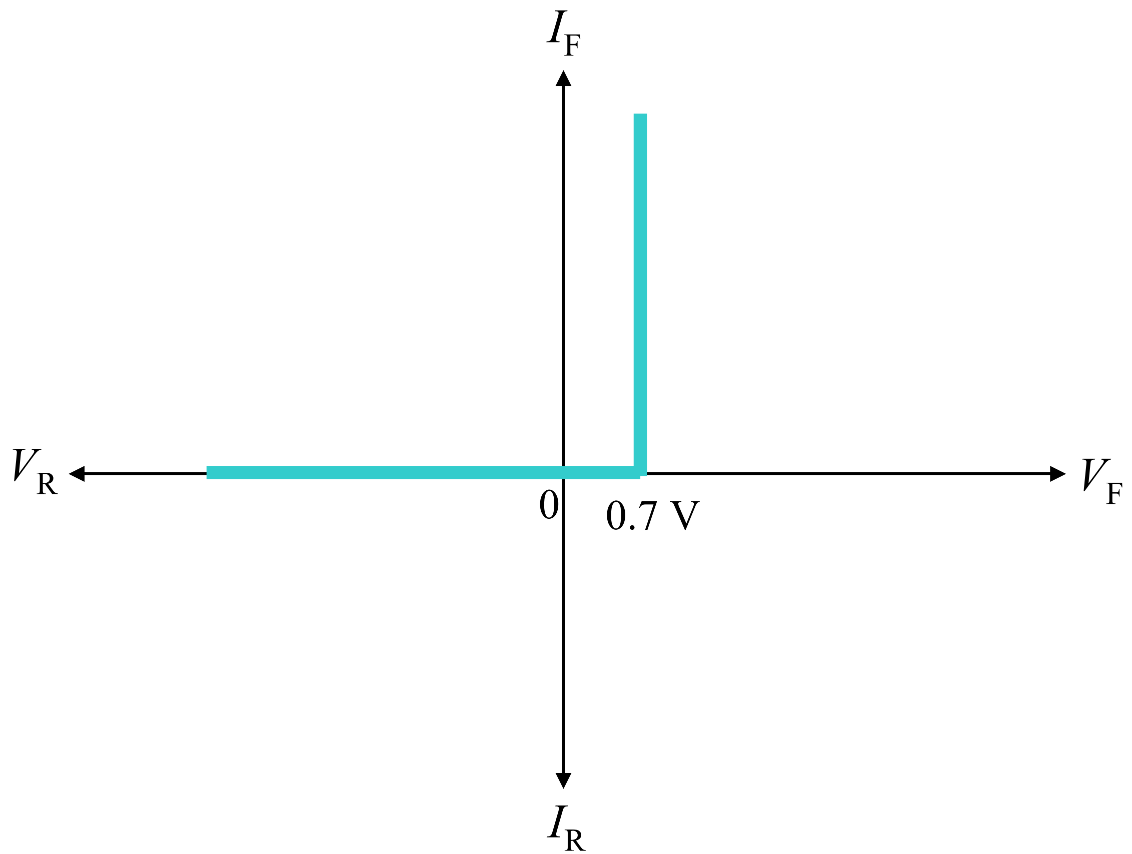


Fig.8: Characteristic curve of silicon diode (blue)

Activity

- *Using Kirchhoff's voltage law, determine:*

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

$$I_F = \frac{\mathrm{V_{bias}} - \mathrm{V_F}}{\mathrm{R_{limit}}}$$

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

$$V_R = \mathrm{V_{bias}}$$

The I-V Characteristics (The complete diode model)

Complete diode model

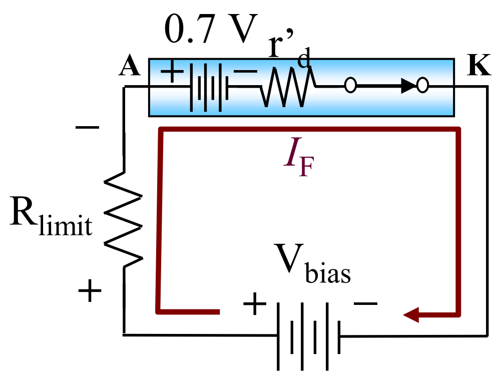
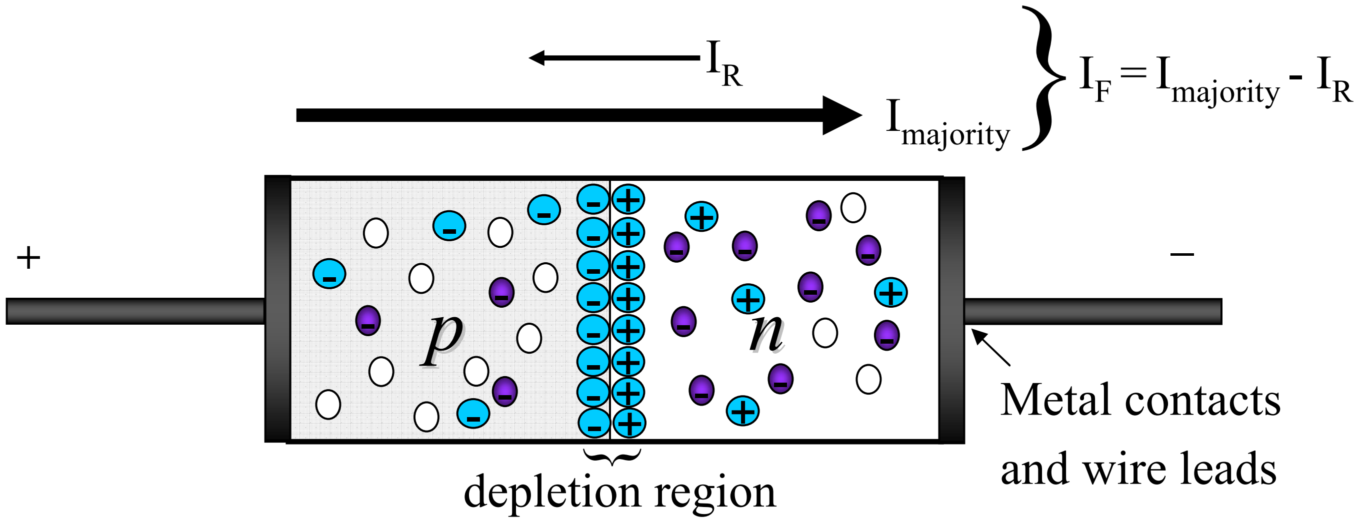


Fig.9(a): Forward bias

- The complete model of a diode consists of the barrier potential, the small forward dynamic resistance (r'_d), and the large internal reverse resistance (r'_R).
- The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.
- When the diode is forward-biased, it acts as a closed switch in series with the barrier potential voltage and the small forward dynamic resistance (r'_d).

The I-V Characteristics
(The complete diode model-forward-biased)



The I-V Characteristics (Shockley's equation)

- Using solid-state physics, general characteristics of a semiconductor diode can be defined as follows.

$$I_F = I_R\left(e^{\frac{V_F}{nV_T}} - 1\right)$$

where I_R is the reverse saturation current
V_F is the applied forward-bias voltage across the diode
n is an ideality factor, which is a function of the operating conditions and physical construction; it has a range of 1 and 2 depending a wide variety of factors

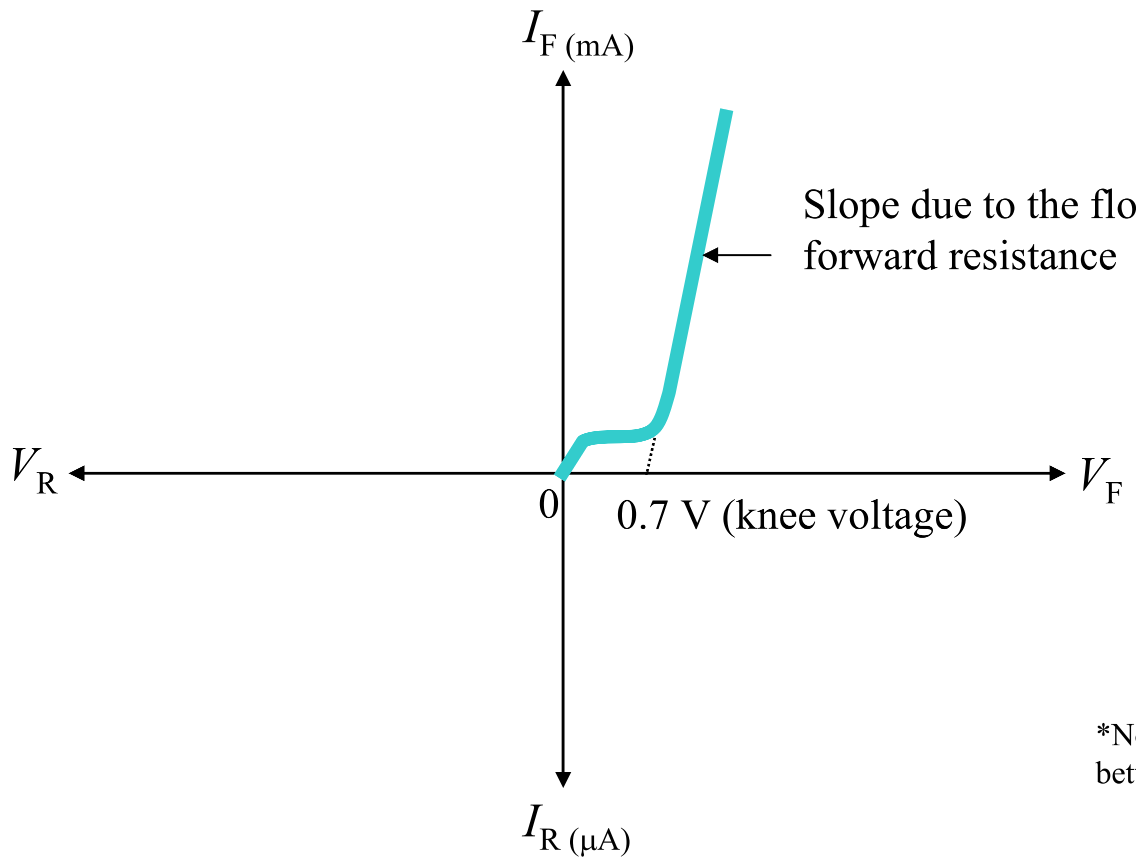
The I-V Characteristics (Thermal voltage (V_T))

- V_T is called the thermal voltage and is determined by

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

where k is Boltzmann's constant = 1.38 X 10^{-23} J/K
T is the absolute temperature in kelvins
= 273 + the temperature in °C
q is the magnitude of electronic charge = 1.6 X 10^{-19} C

The I-V Characteristics
(The complete diode model-forward biased)



*Note the difference between the I_F and I_R scales.

Fig.10: Characteristic curve of silicon diode (blue)

The I-V Characteristics (The complete diode model)

Complete diode model

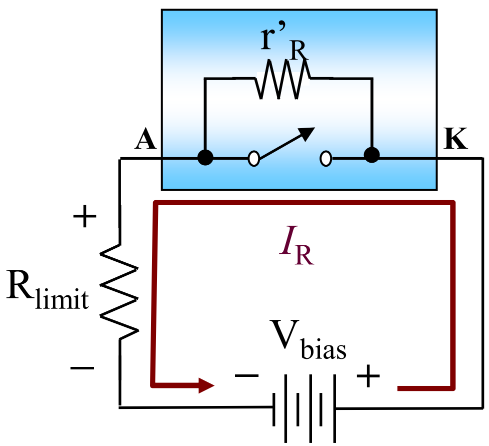
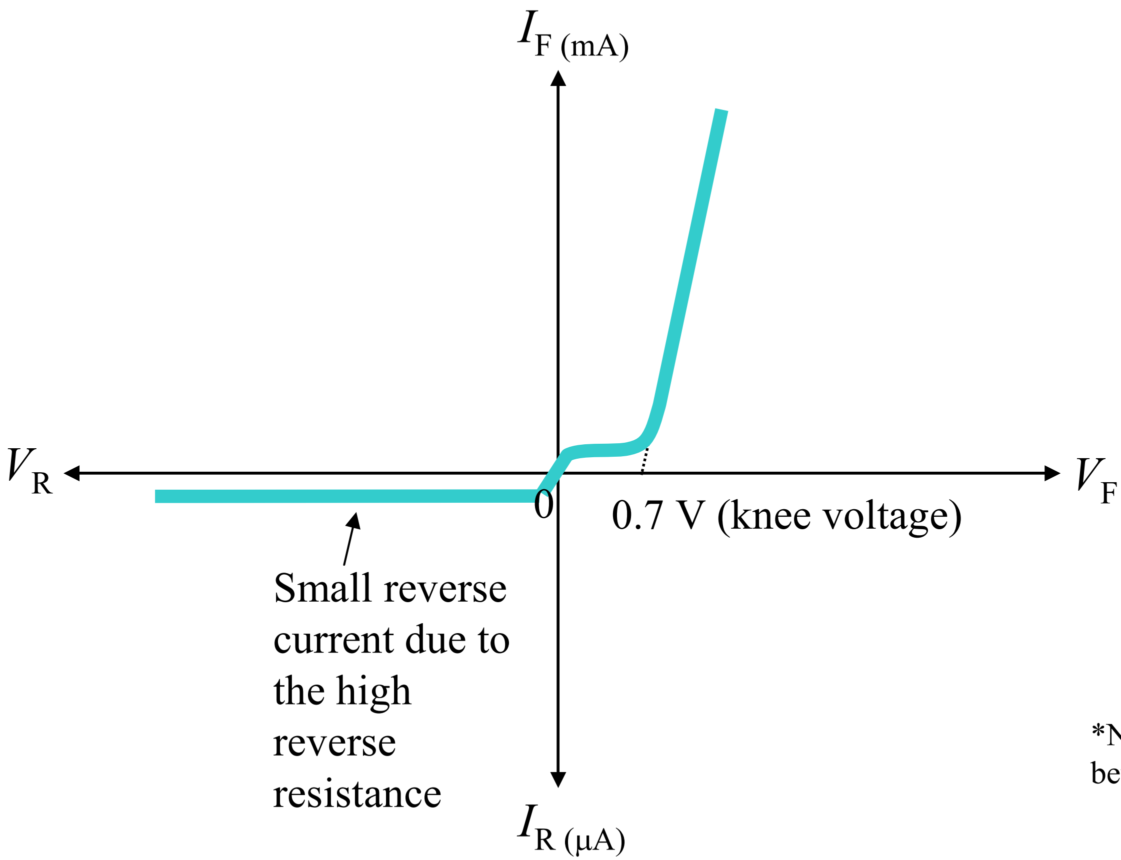


Fig.9(b): Reverse bias

- When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance (r'_R).
- The barrier potential does not affect reverse bias, so it is not a factor.

The I-V Characteristics (The complete diode model)



*Note the difference between the I_F and I_R scales.

Fig.10: Characteristic curve of silicon diode (blue)

Activity

- *Using Kirchhoff's voltage law, determine:*

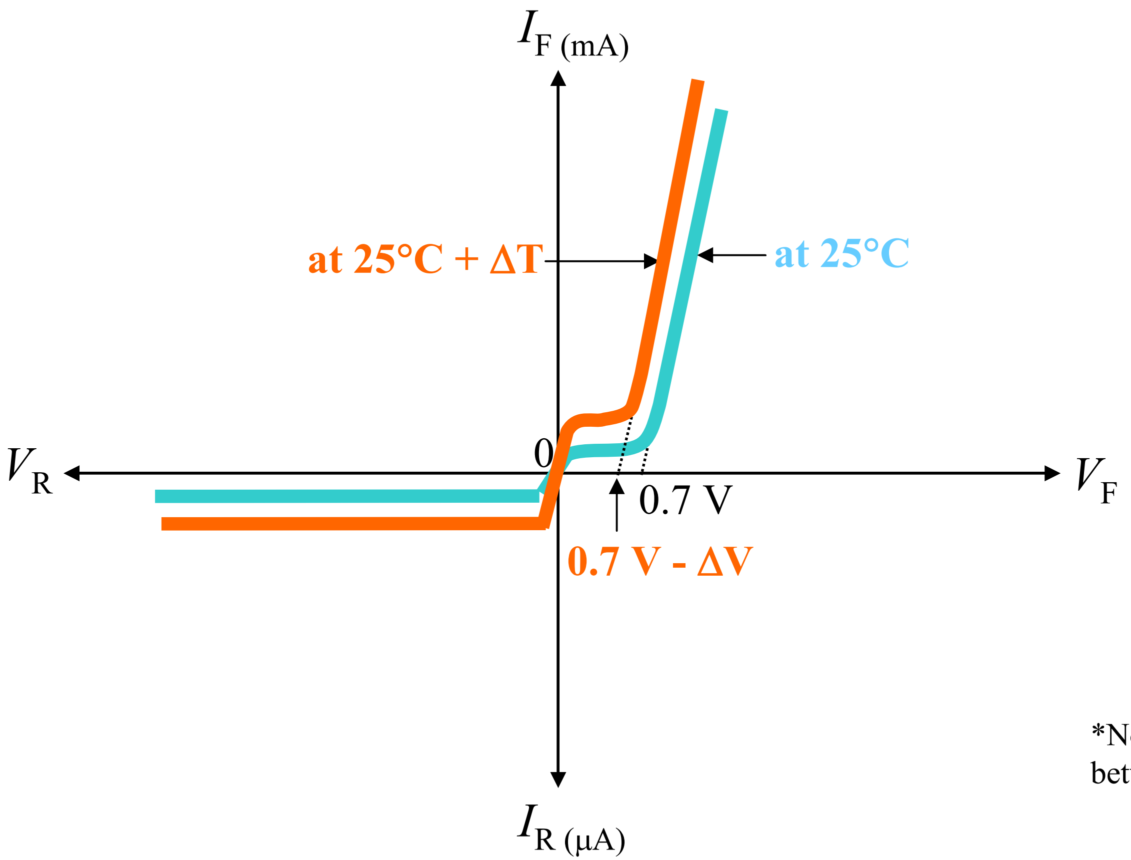
$$V_F = 0.7\ \mathrm{V} + I_F r'd$$

$$I_F = \frac{V_{bias} - 0.7\ \mathrm{V}}{R_{limit} + r'_d}$$

The I-V Characteristics (Temperature effects)

- For a forward-biased diode, as temperature is increased, the forward current increases for a given value of forward voltage.
- Also, for a given value of forward current, the forward voltage decreases.
- For a reverse-biased diode, as temperature is increased, the reverse current increases.

The I-V Characteristics (Temperature effects)

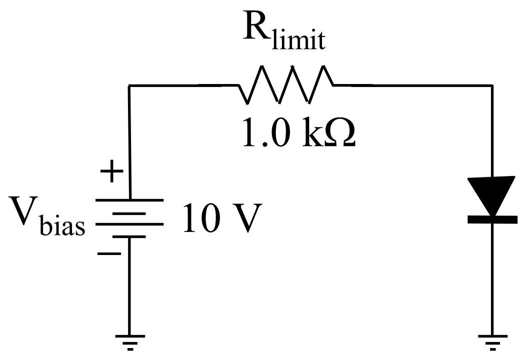


*Note the difference between the I_F and I_R scales.

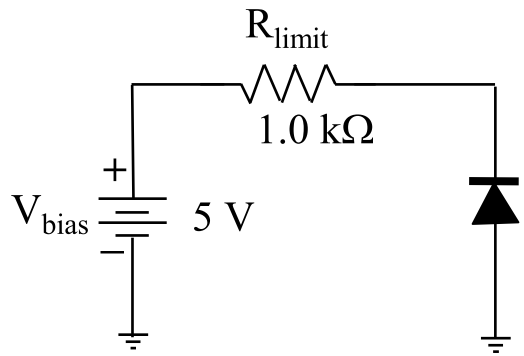
Fig.11: Temperature effect on the diode V-I characteristic.

Activity

- *Determine the forward voltage and forward current for each of the diode model. Also find the voltage across the limiting resistor in each case. Assume r'd = 10 Ω at the determined value of forward current. → Fig. (a)*
- *Determine the reverse voltage and reverse current for each diode model. Also find the voltage across the limiting resistor in each case. Assume I_R = 1 μA. → Fig. (b)*

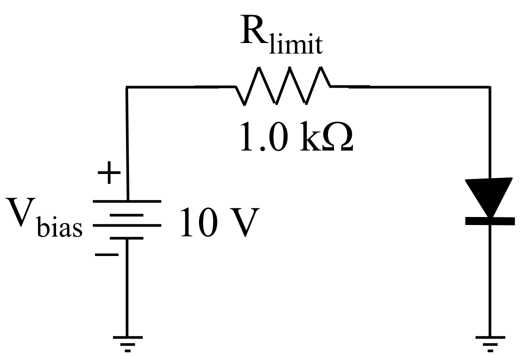


(a)



(b)

Activity (Answer)



(a)

Ideal model

$V_F = 0\ V$

$I_F = V_{bias} / R_{limit} = 10\ V / 1.0\ k\Omega = 10\ mA$

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

Practical model

$V_F = 0.7\ V$

$I_F = (V_{bias} – V_F) / R_{limit}$
$= (10\ V – 0.7\ V) / 1.0\ k\Omega = 9.3\ mA$

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

Complete model

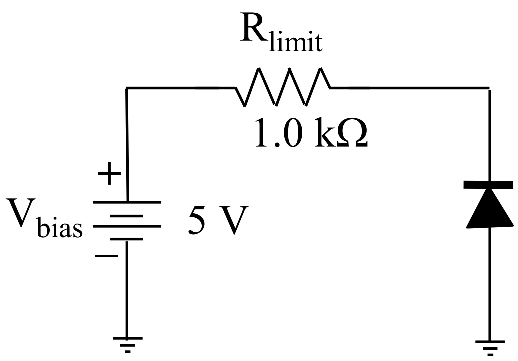
$V_F = 0.7\ V + I_F r'_d$

$I_F = (V_{bias} – V_F) / (R_{limit} + r'_d)$
$= (10\ V – 0.7\ V) / (1.0\ k\Omega + 10\ \Omega)$
$= 9.21\ mA$

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

Outline

Activity (Answer)



(b)

◈ Ideal model

$V_R = V_{bias} = 5\ V$

$I_R = 0\ A$

$V_{Rlimit} = 0\ V$

◈ Practical model

$V_R = V_{bias} = 5\ V$

$I_R = 0A$

$V_{Rlimit} = 0V$

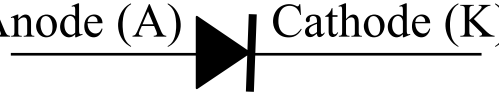
◈ Complete model

$V_F = V_{bias} - V_{Rlimit}$

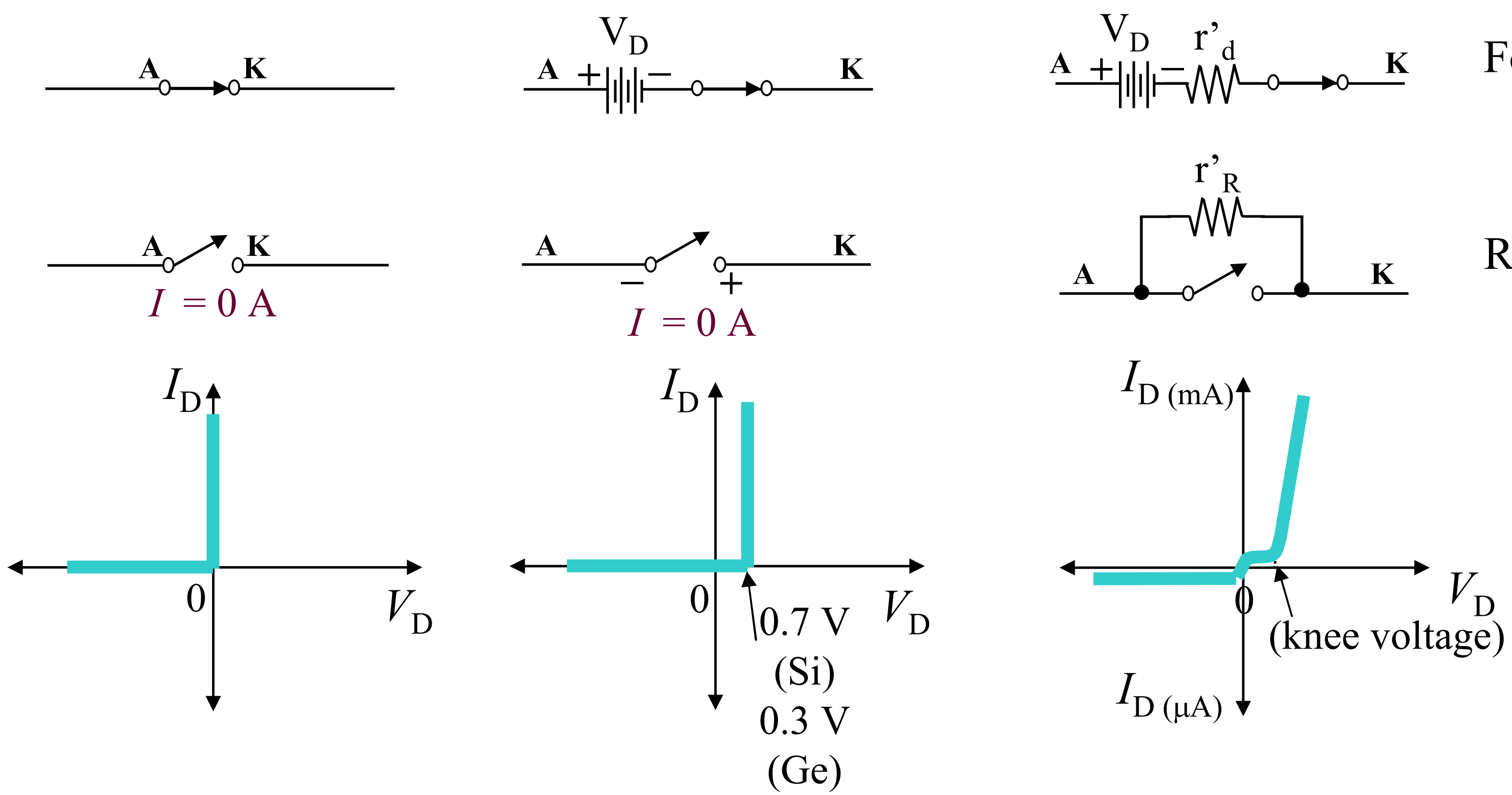
$I_R = 1\ \mu A$

$V_{Rlimit} = I_F R_{limit}$
$= (1\ \mu A)\ (1.0\ k\Omega) = 1\ mV$

In Summary



◆ Ideal model ◆ Practical model ◆ Complete model

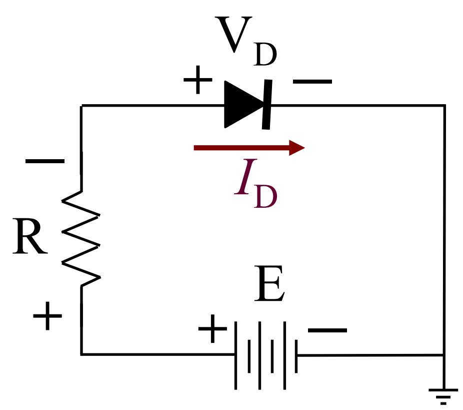


Forward-biased

Reverse-biased

Load Line and Graphical Analysis

- The circuit of Fig. 12 is the simplest of diode configuration.
- It will be used to describe the analysis of a diode circuit using its actual characteristics.



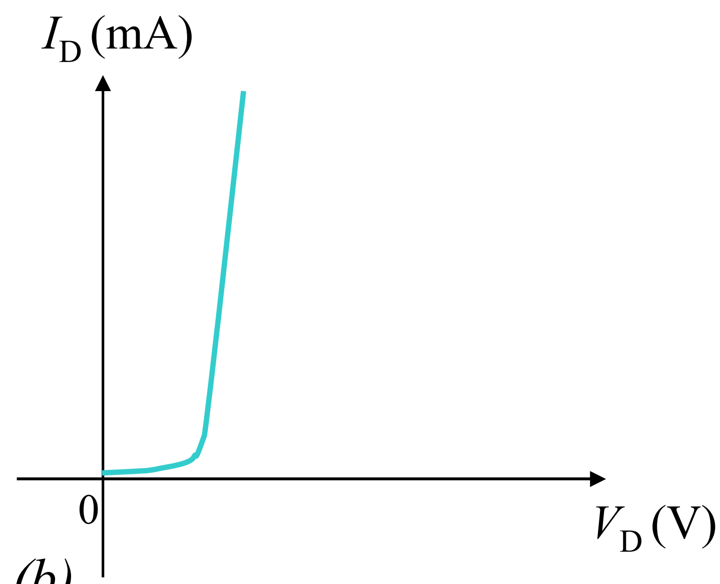
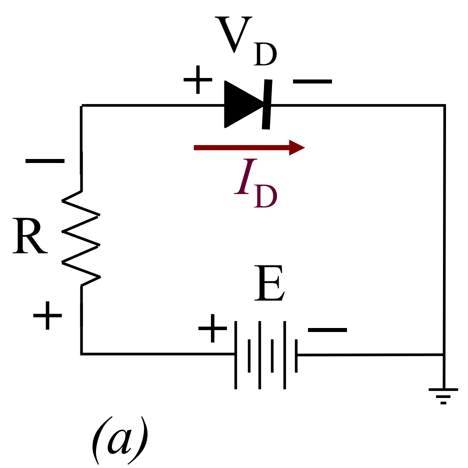


Fig.12: Series diode configuration: (a) circuit; (b) characteristics

Load Line and Graphical Analysis

- The straight line is called a load line because the intersection on the vertical axis is defined by the applied load R.
- The analysis to follow is therefore called load-line analysis.



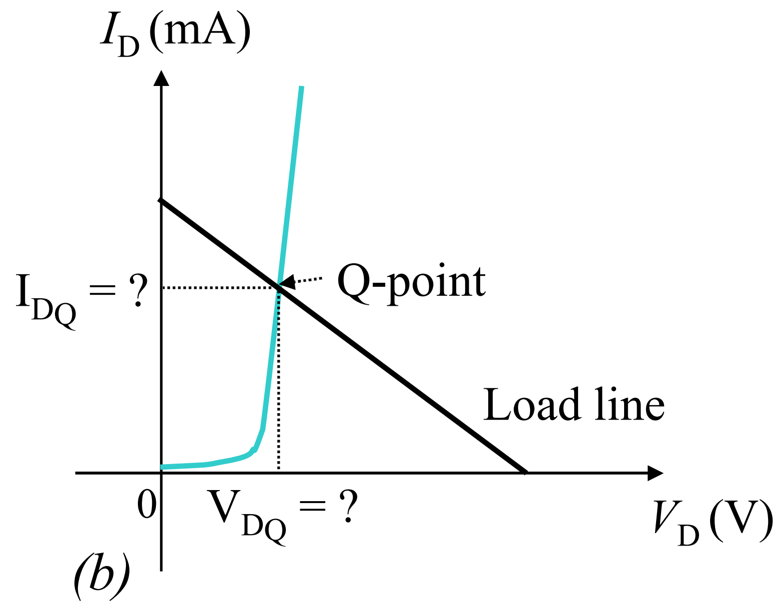
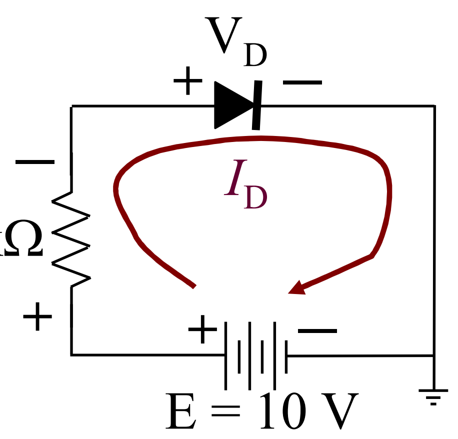


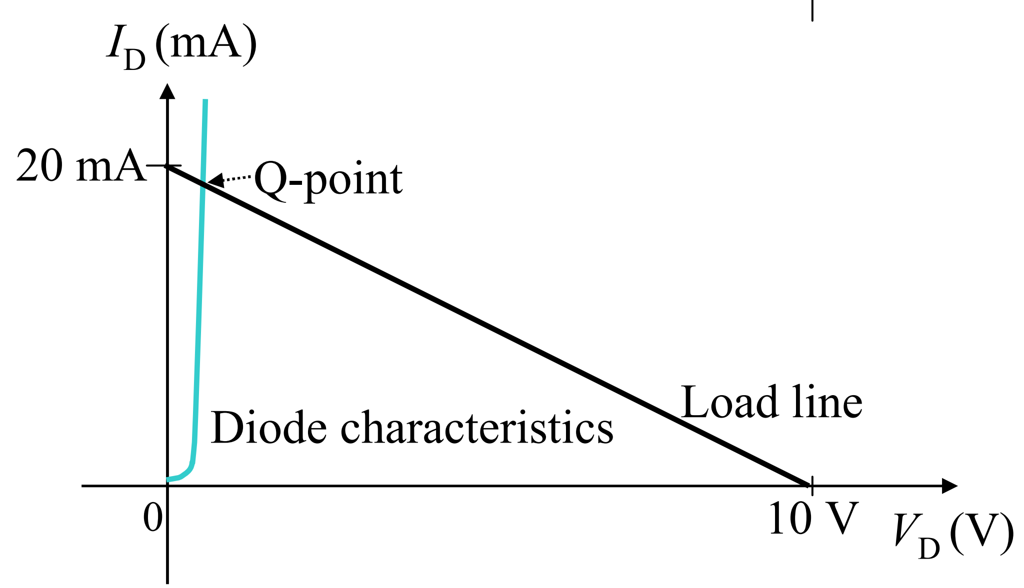
Fig.12: Series diode configuration: (a) circuit; (b) characteristics

Outline

Load Line and Graphical Analysis

◈ Example 1 (Complete model)





Applying Kirchoff's voltage law around the close loop, we have

$$E - V_R - V_D = 0$$

$$\Rightarrow V_D = E - V_R$$

$$\Rightarrow V_D = E - I_D R$$

For horizontal-axis, if $I_D = 0$ A, then

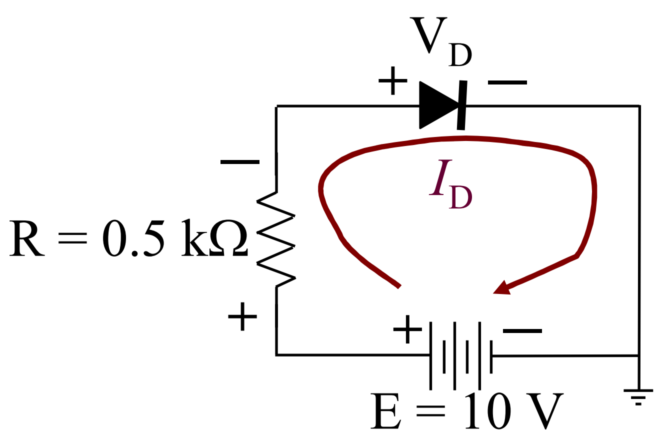
$V_D = E = 10$ V

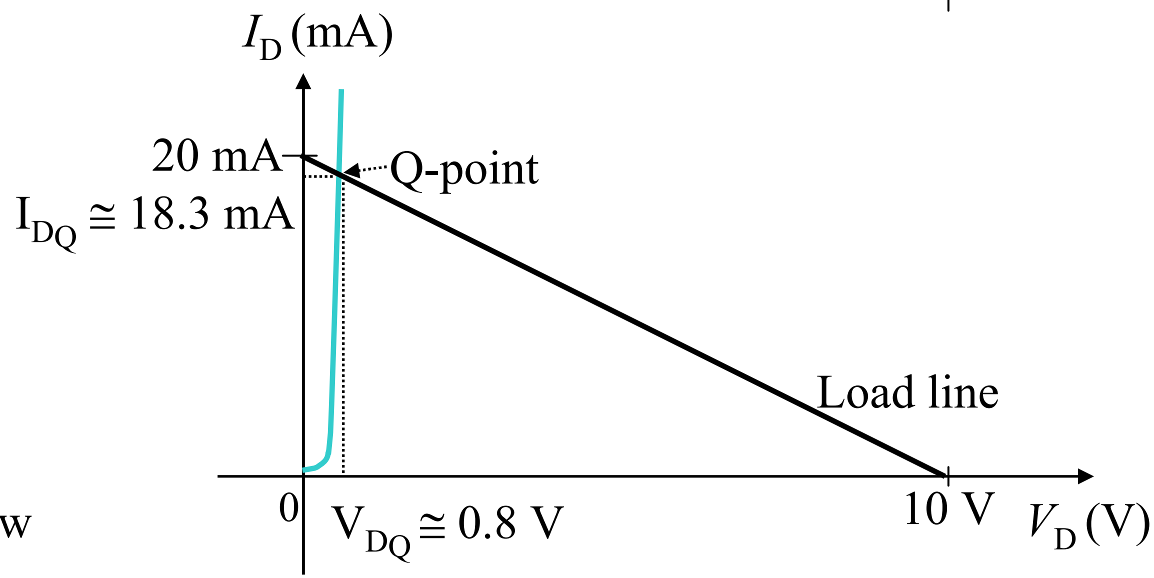
For vertical-axis, if $V_D = 0$ V, then

$I_D = E/R = 10\ V / 0.5\ k\Omega = 20$ mA

Load Line and Graphical Analysis

◈ Example 1 (Complete model)





Applying Kirchoff's voltage law around the close loop, we have

$$E - V_R - V_D = 0$$

$$\Rightarrow V_D = E - V_R$$

$$\Rightarrow V_D = E - I_D R$$

For horizontal-axis, if $I_D = 0$ A, then

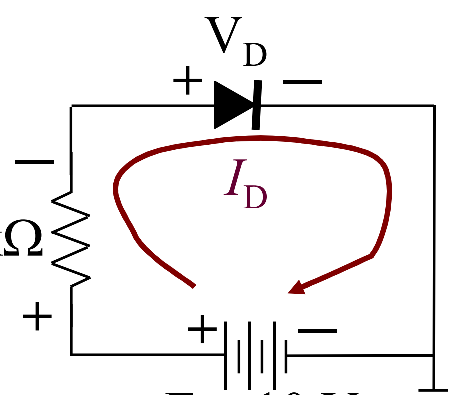
$V_D = E = 10$ V

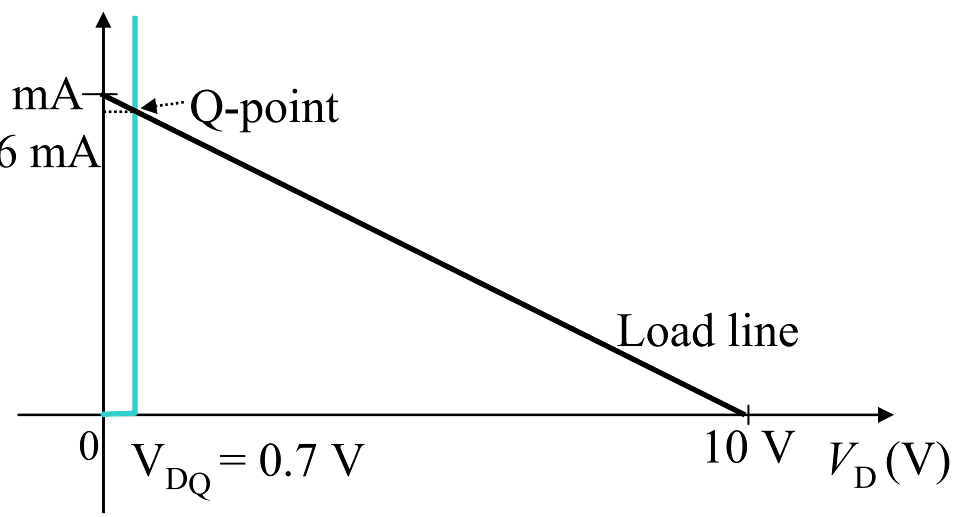
For vertical-axis, if $V_D = 0$ V, then

$I_D = E/R = 10\text{ V} / 0.5\text{ k}\Omega = 20$ mA

Load Line and Graphical Analysis

◈ Example 1 (Practical model)





Applying Kirchoff's voltage law around the close loop, we have

$$E - V_R - V_D = 0$$
$$\Rightarrow V_D = E - V_R$$
$$\Rightarrow V_D = E - I_D R$$

For horizontal-axis, if $I_D = 0$ A, then

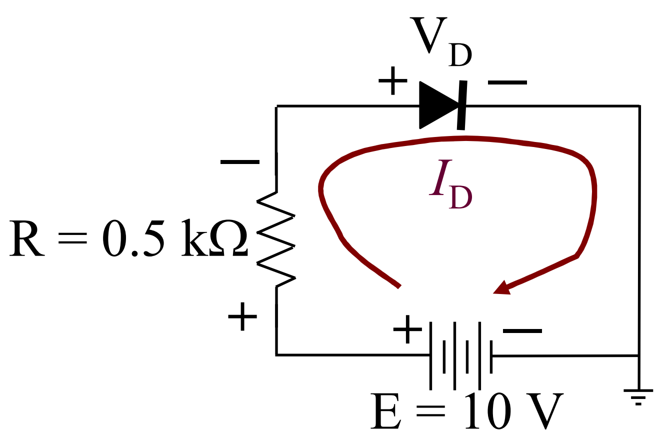
$V_D = E = 10$ V

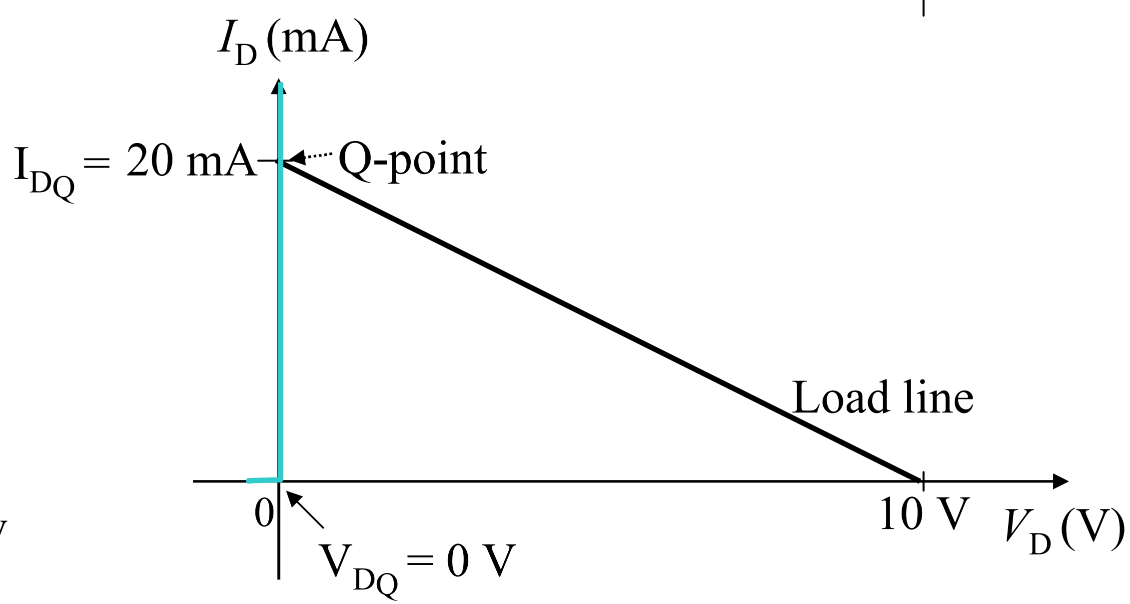
For vertical-axis, if $V_D = 0$ V, then

$I_D = E/R = 10\text{ V} / 0.5\text{ k}\Omega = 20\text{ mA}$

Load Line and Graphical Analysis

◈ Example 1 (Ideal model)





Applying Kirchoff's voltage law around the close loop, we have

$$E - V_R - V_D = 0$$

$$\Rightarrow V_D = E - V_R$$

$$\Rightarrow V_D = E - I_D R$$

For horizontal-axis, if $I_D = 0$ A, then

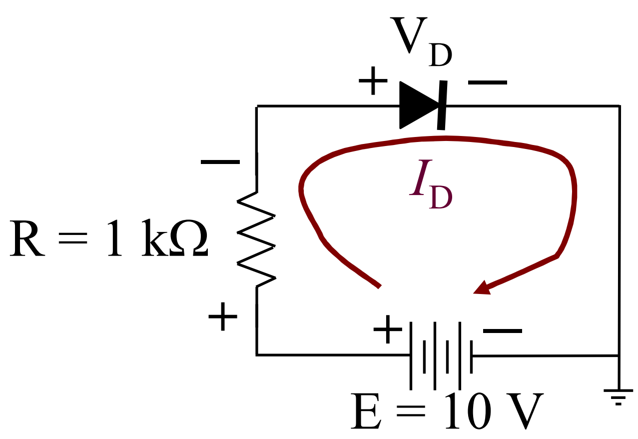
$V_D = E = 10$ V

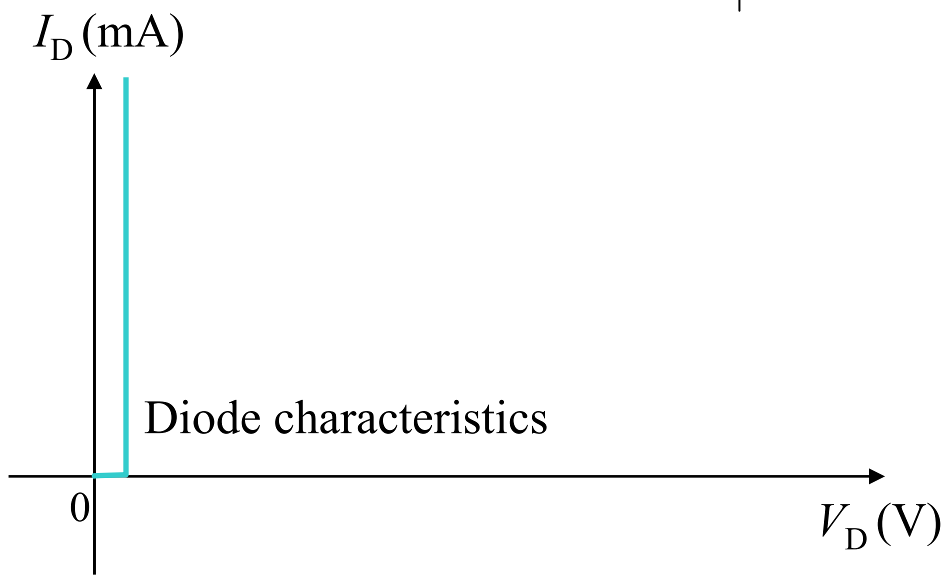
For vertical-axis, if $V_D = 0$ V, then

$I_D = E/R = 10\text{ V} / 0.5\text{ k}\Omega = 20$ mA

Activity

◆ Example 2 (Practical model)

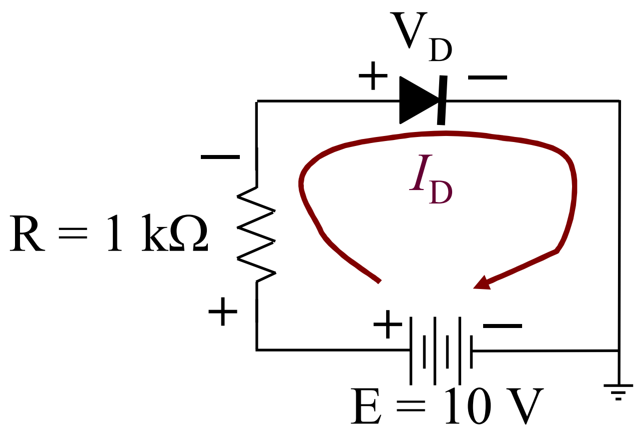


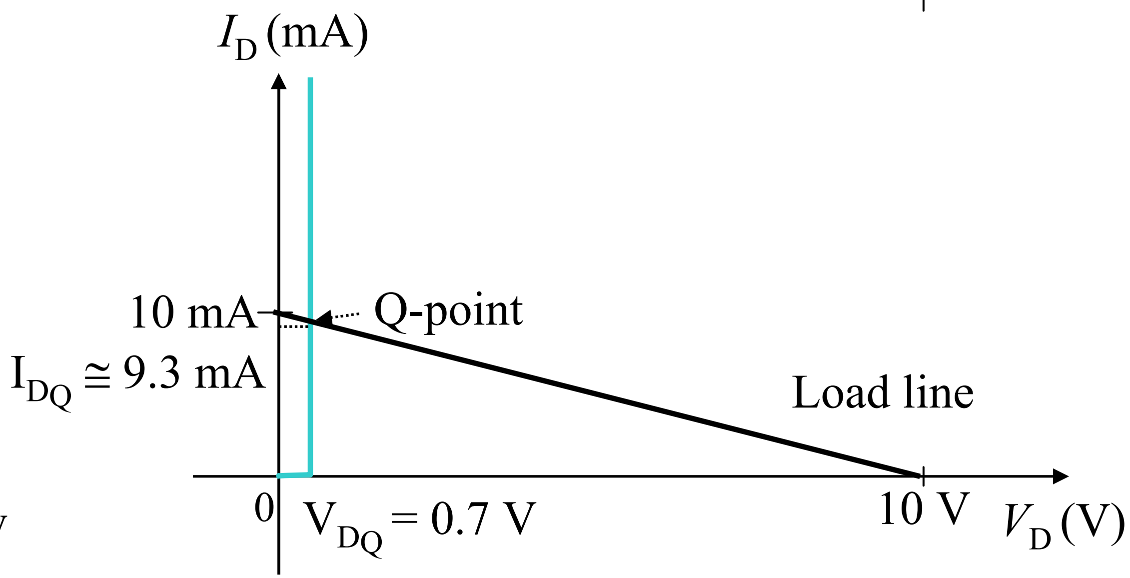


Draw the load line, identify the Q-point and determine V_{DQ} and I_{DQ}.

Activity (Answer)

- Example 2 (Practical model)





Applying Kirchoff's voltage law around the close loop, we have

$$E - V_R - V_D = 0$$
$$\Rightarrow V_D = E - V_R$$
$$\Rightarrow V_D = E - I_D R$$

For horizontal-axis, if $I_D = 0$ A, then

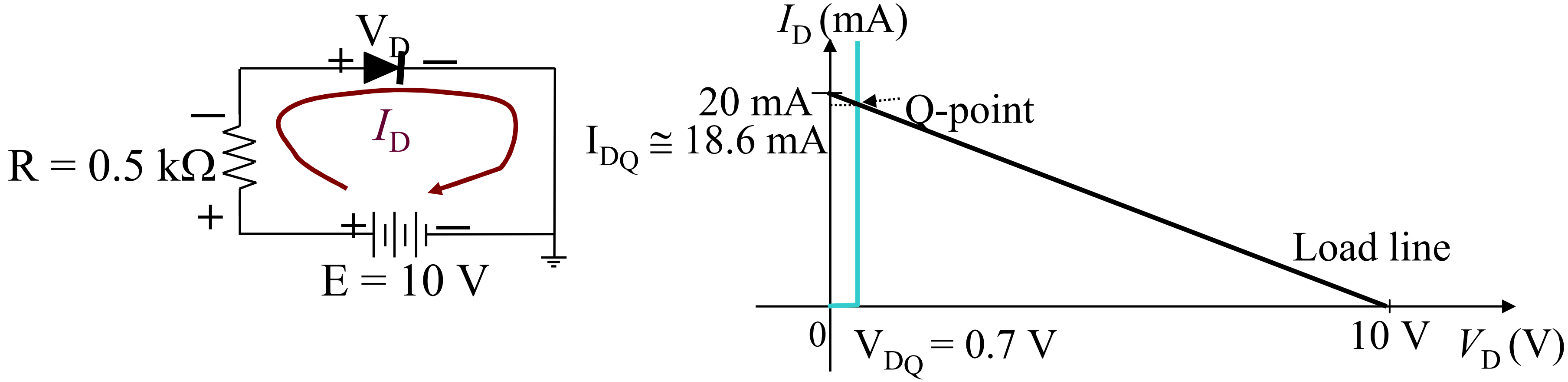
$V_D = E = 10$ V

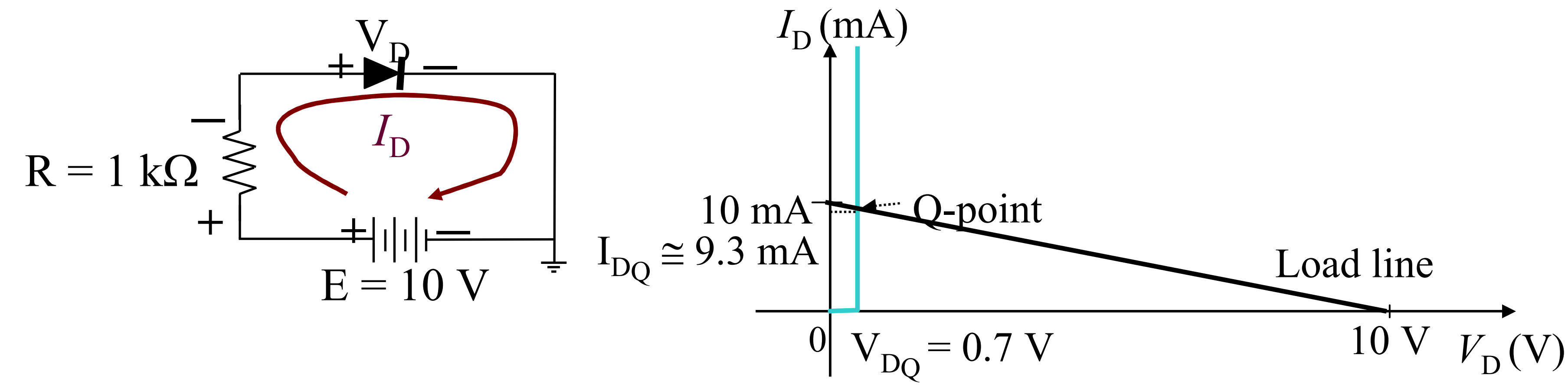
For vertical-axis, if $V_D = 0$ V, then

$I_D = E/R = 10 \text{ V} / 1 \text{ k}\Omega = 10$ mA

Load Line and Graphical Analysis

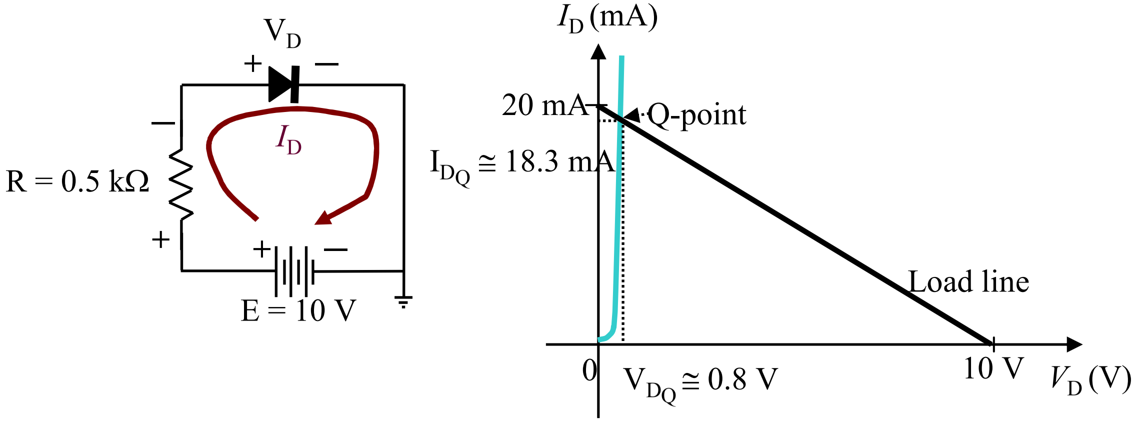
- Compare Eg. 1 and Eg. 2 (Practical model)





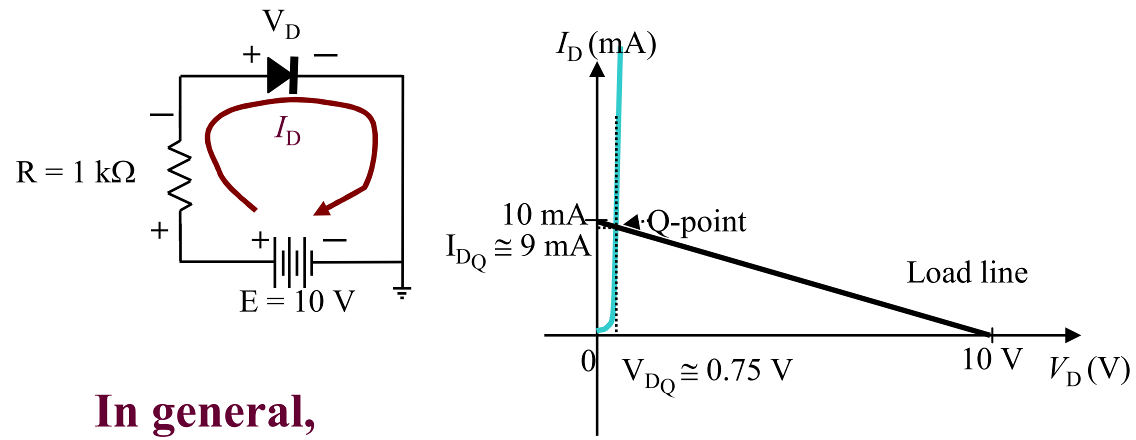
Internal resistance

- Determine the dc resistance levels for the diode of Eg. 1 and Eg. 2 (complete model).



At I_D = 18.3 mA, V_D = 0.8 V (from the curve),

$R_D = V_D / I_D \cong 44\ \Omega$



At I_D = 9 mA, V_D = 0.75 V (from the curve),

$R_D = V_D / I_D \cong 83\ \Omega$

In general,

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

Internal resistance

- As the operating point (Q-point) of a diode moves from one region to another, the resistance of the diode will also change due to nonlinear shape of the diode characteristic curve.

DC or Static Resistance

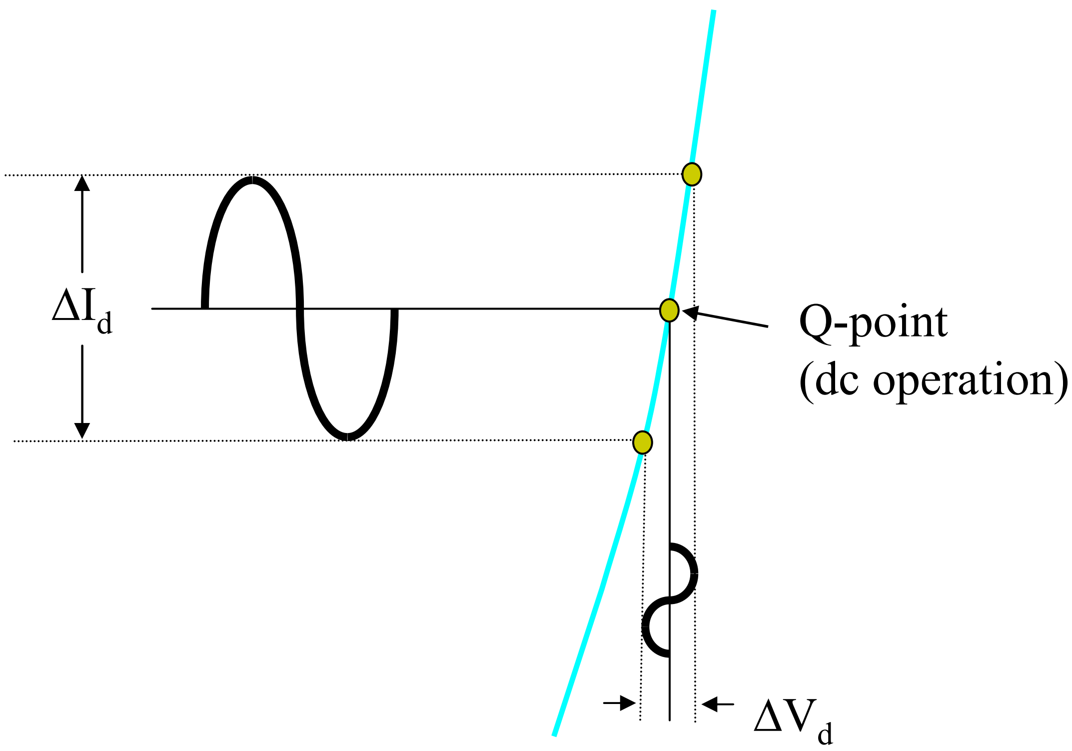
- The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time.
- Resistance of a diode, $R_D = V_D / I_D$

AC or Dynamic Resistance

- If a sinusoidal rather than a dc input is applied, the varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage.

Internal resistance

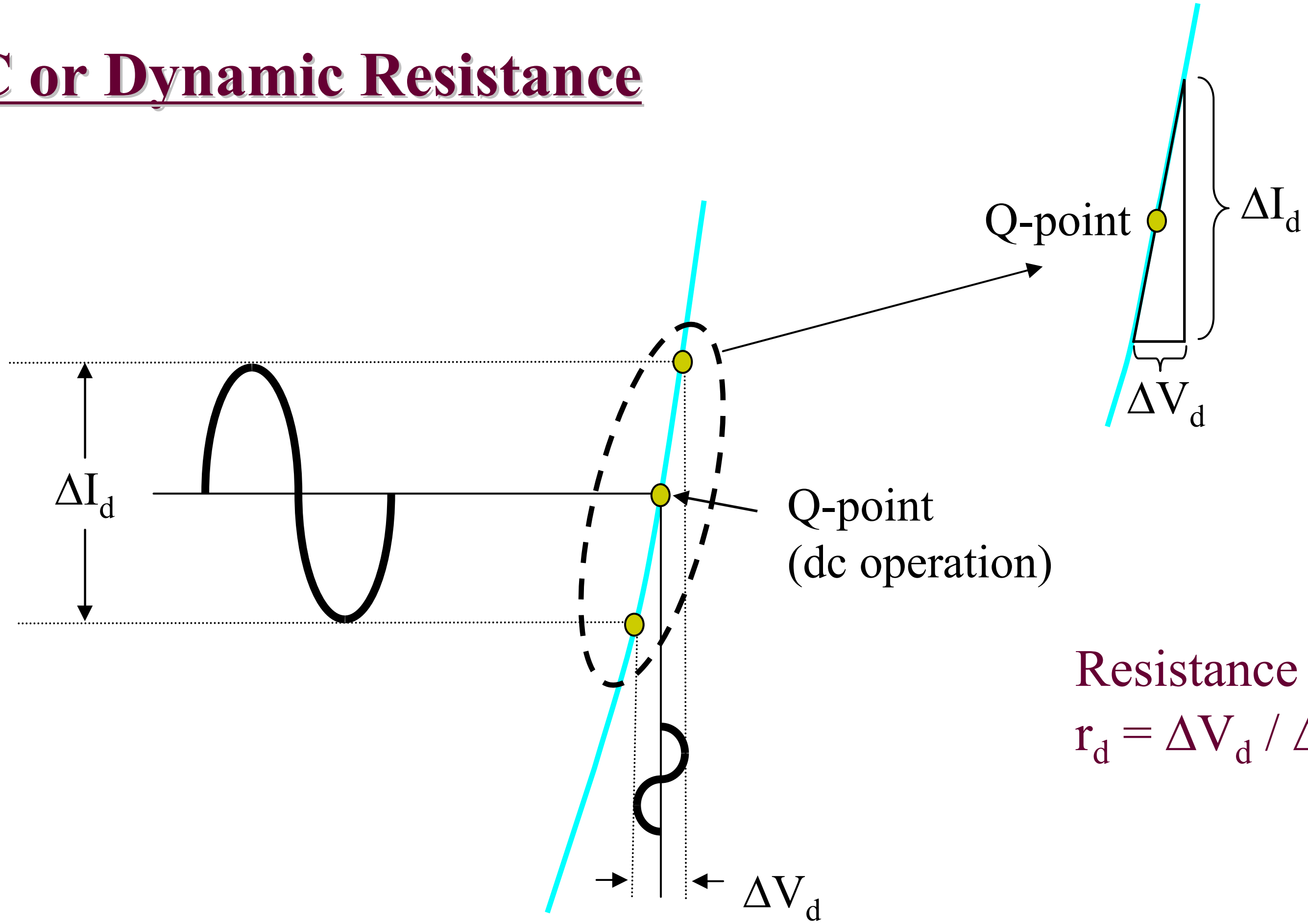
AC or Dynamic Resistance



*Note: Q stand for quiescent, which means "still or unvarying"

Internal resistance

AC or Dynamic Resistance



Resistance of a diode

$r_d = \Delta V_d / \Delta I_d$

In general,
the lower the Q-point of operation (smaller current or lower voltage), the higher is the ac resistance.

Diode with DC Power Supply

- Series Connection

Determine I_D, V_{D_2} and V_O for the series circuit of Fig. 13.

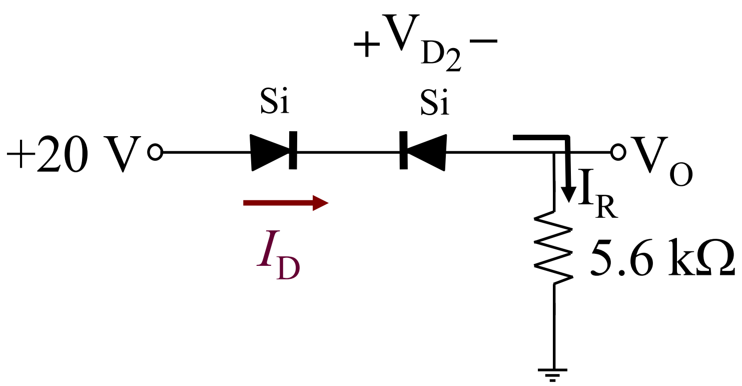


Fig.13

Diode with DC Power Supply

◆ Parallel Connection

Determine V_O, I_1, I_{D_1} and I_{D_2} for the parallel diode configuration of Fig. 14.

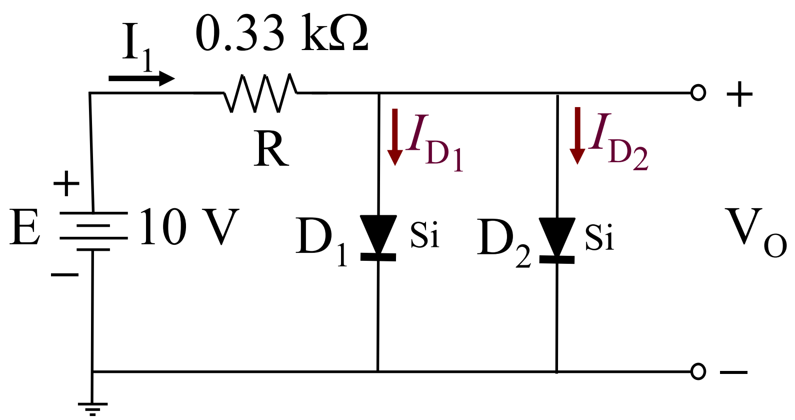


Fig.14

Diode with DC Power Supply

Series-Parallel Configuration

Determine I_1, I_2, and I_{D_2} for the network of Fig. 15.

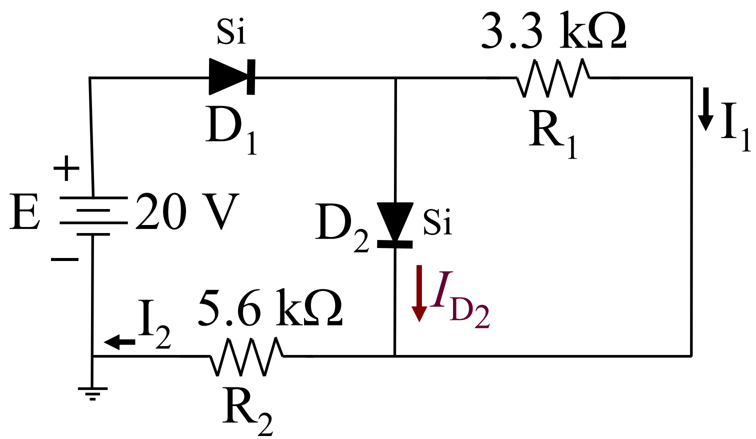


Fig.15

Basic Gates

Determine V_O for the logic gate circuit of Fig. 16. Which diode is in “ON” state? Determine the current that flows through this diode. If the diode is made of silicon, what is the new value of V_O?

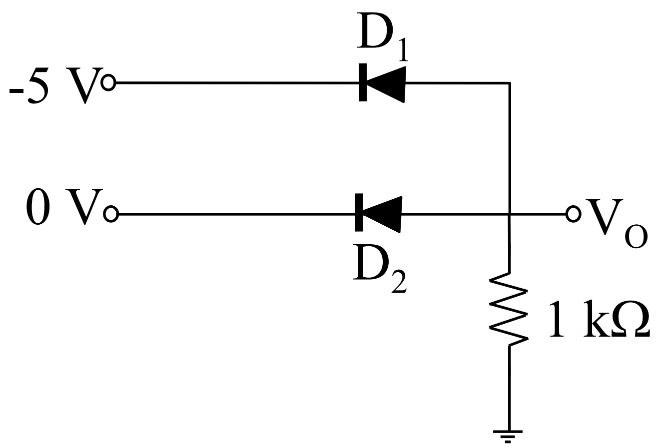


Fig.16

Activity

Determine V_O for the logic gate circuit of Fig. 17. Which diode is in "ON" state? Determine the current that flows through this diode. If the diode is made of germanium, what is the new value of V_O?

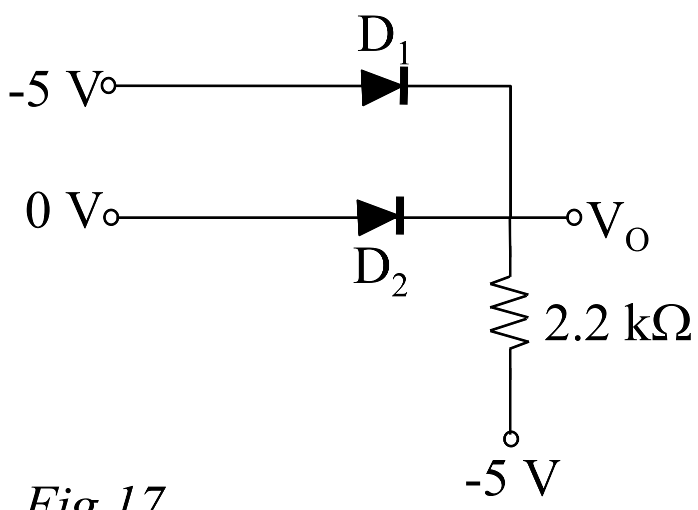


Fig.17

Activity

Complete the table, according to logic gate circuit of Fig. 18.

What is the type of this logic gate circuit?

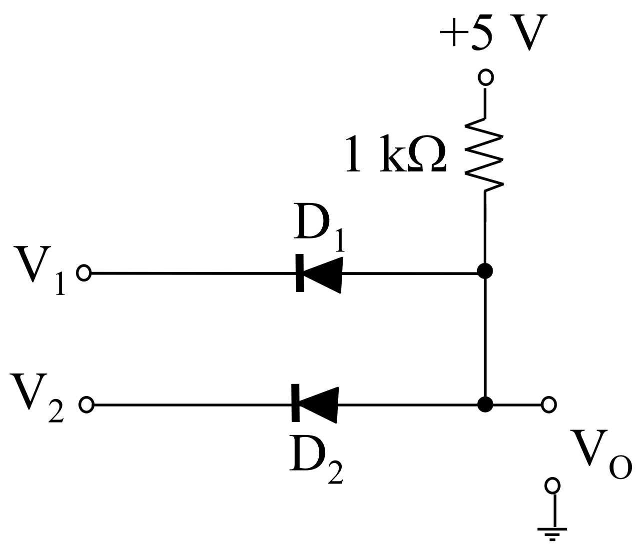


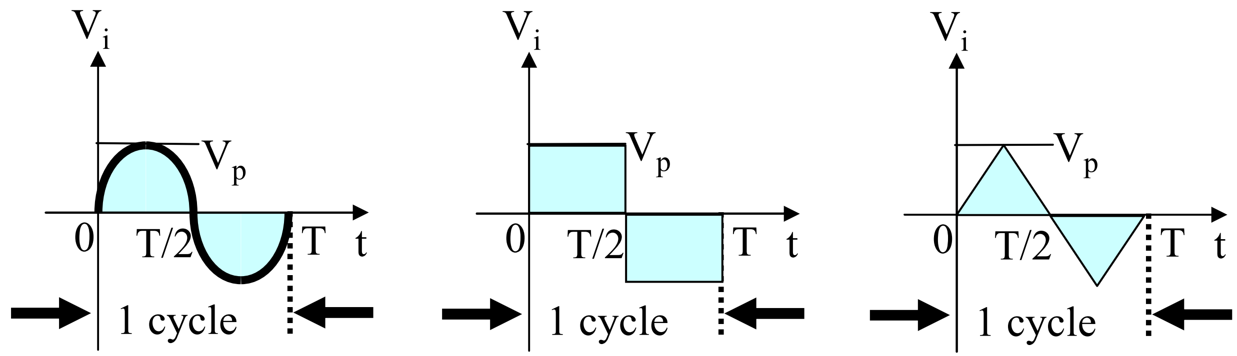
Fig.18

V_1	V_2	V_O
0 V	0 V	0 V
0 V	5 V	0 V
5 V	0 V	0 V
5 V	5 V	5 V

AND logic gate

Diode with AC Power Supply

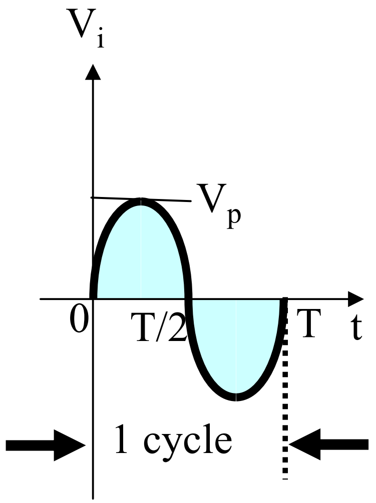
- The diode analysis will now be expanded to include time-varying functions such as the sinusoidal waveform and the square wave.



- With time-varying functions, diode can be used as:
  1. Half-wave rectifier
  2. Full-wave rectifier
  3. Clippers
  4. Clampers

Diode with AC Power Supply

RECTIFIER: Half-wave rectification



$V_i = V_p \sin \omega t$

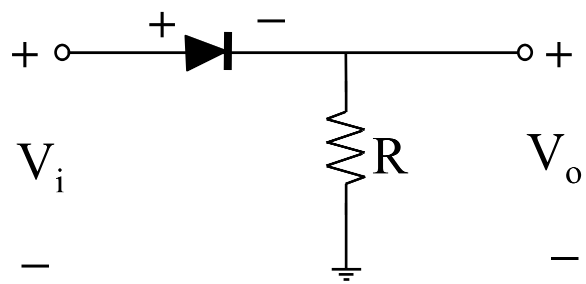
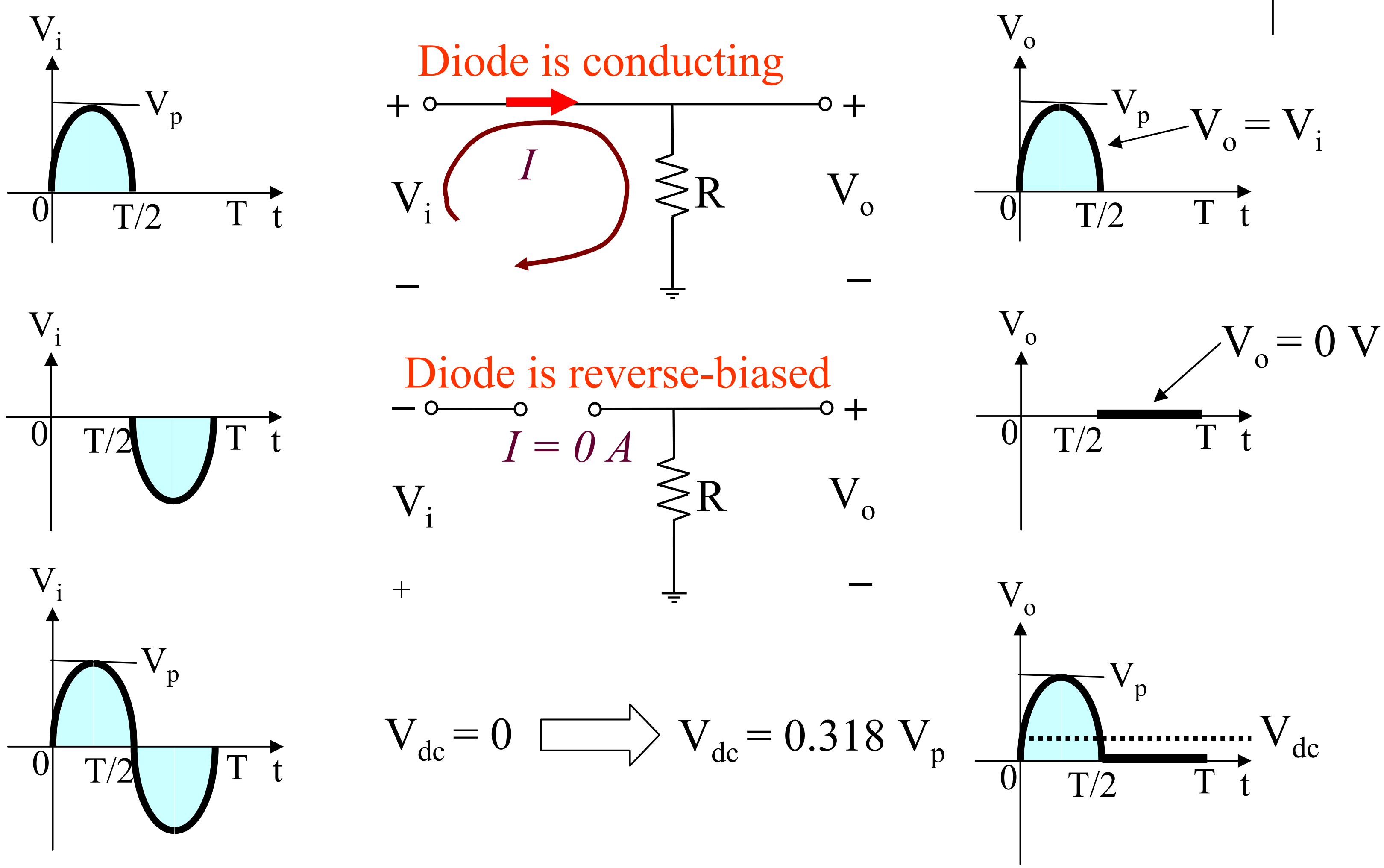


Fig.19

Diode with AC Power Supply

RECTIFIER: Half-wave rectification



$V_{dc} = 0 \Rightarrow V_{dc} = 0.318\ V_p$

Diode with AC Power Supply

RECTIFIER: Full-wave rectification

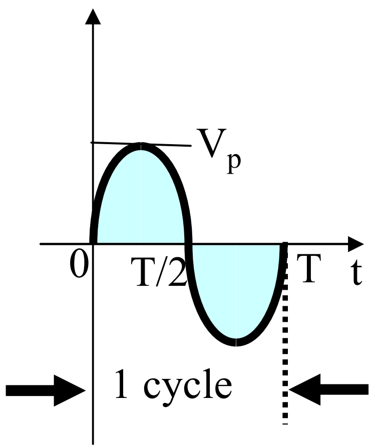
The full-wave rectifier inverts the negative portions of the sine wave so that a unipolar output signal is generated during both halves of the input sinusoid.

1. Bridge Network
2. Center-Tapped Transformer

Diode with AC Power Supply

RECTIFIER: Full-wave rectification

- Bridge Network



$V_i = V_p \sin \omega t$

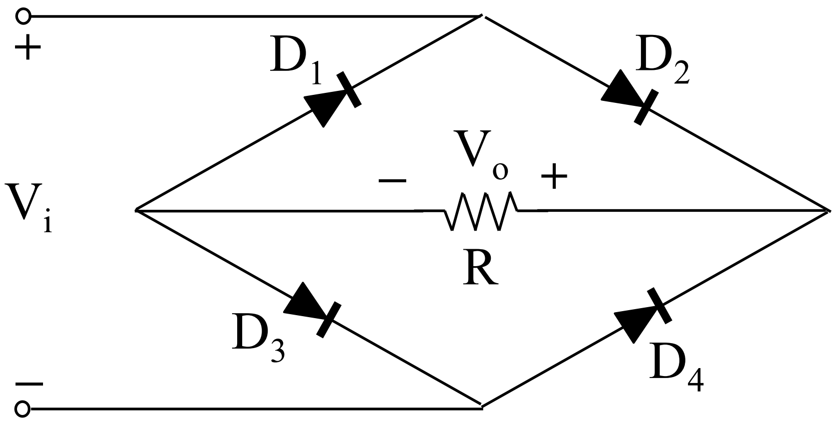
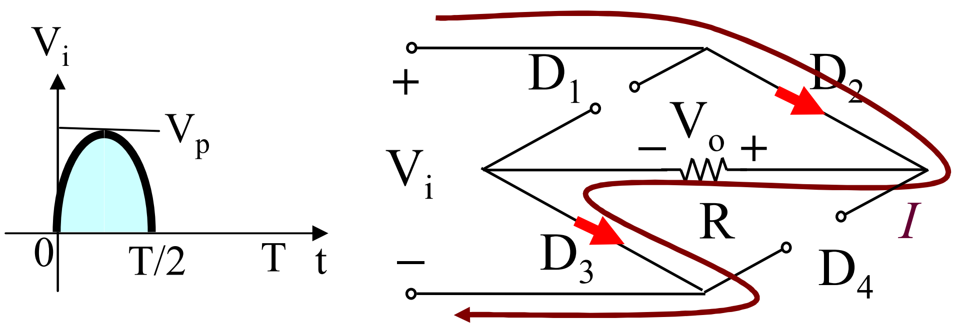


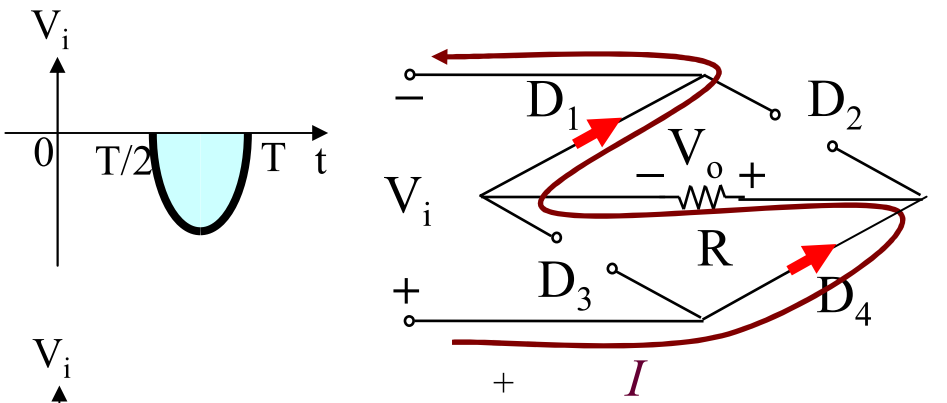
Fig.20

Diode with AC Power Supply

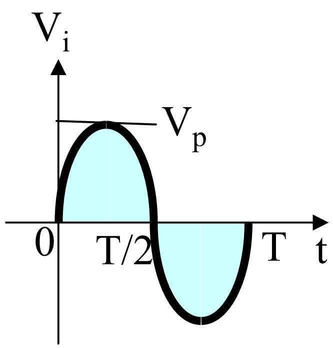
RECTIFIER: Full-wave rectification



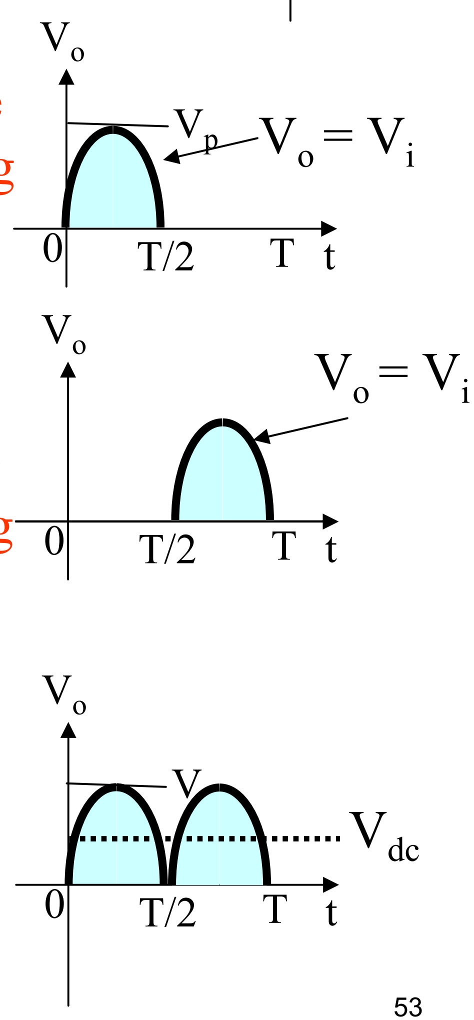
Diode D_2 and D_3 are conducting



Diode D_1 and D_4 are conducting



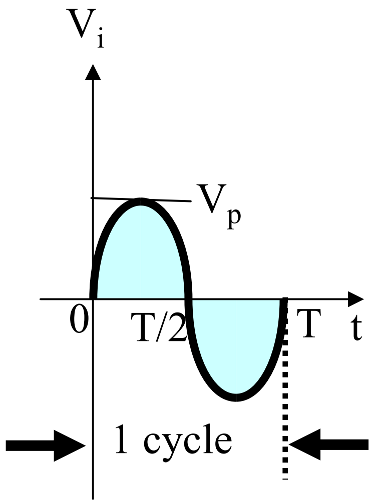
$V_{dc} = 0$ ⇨ $V_{dc} = 2\,(0.318\,V_p)$
$= 0.636\,V_p$



Diode with AC Power Supply

RECTIFIER: Full-wave rectification

- Center-Tapped Transformer



$V_i = V_p \sin \omega t$

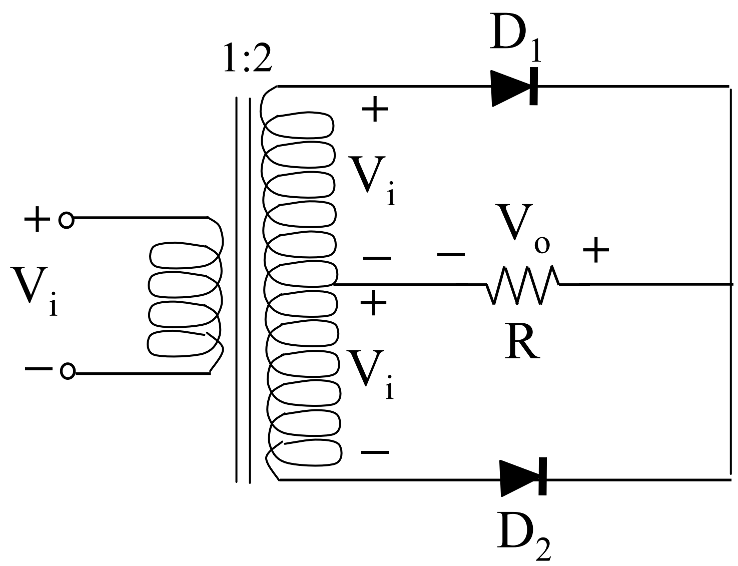
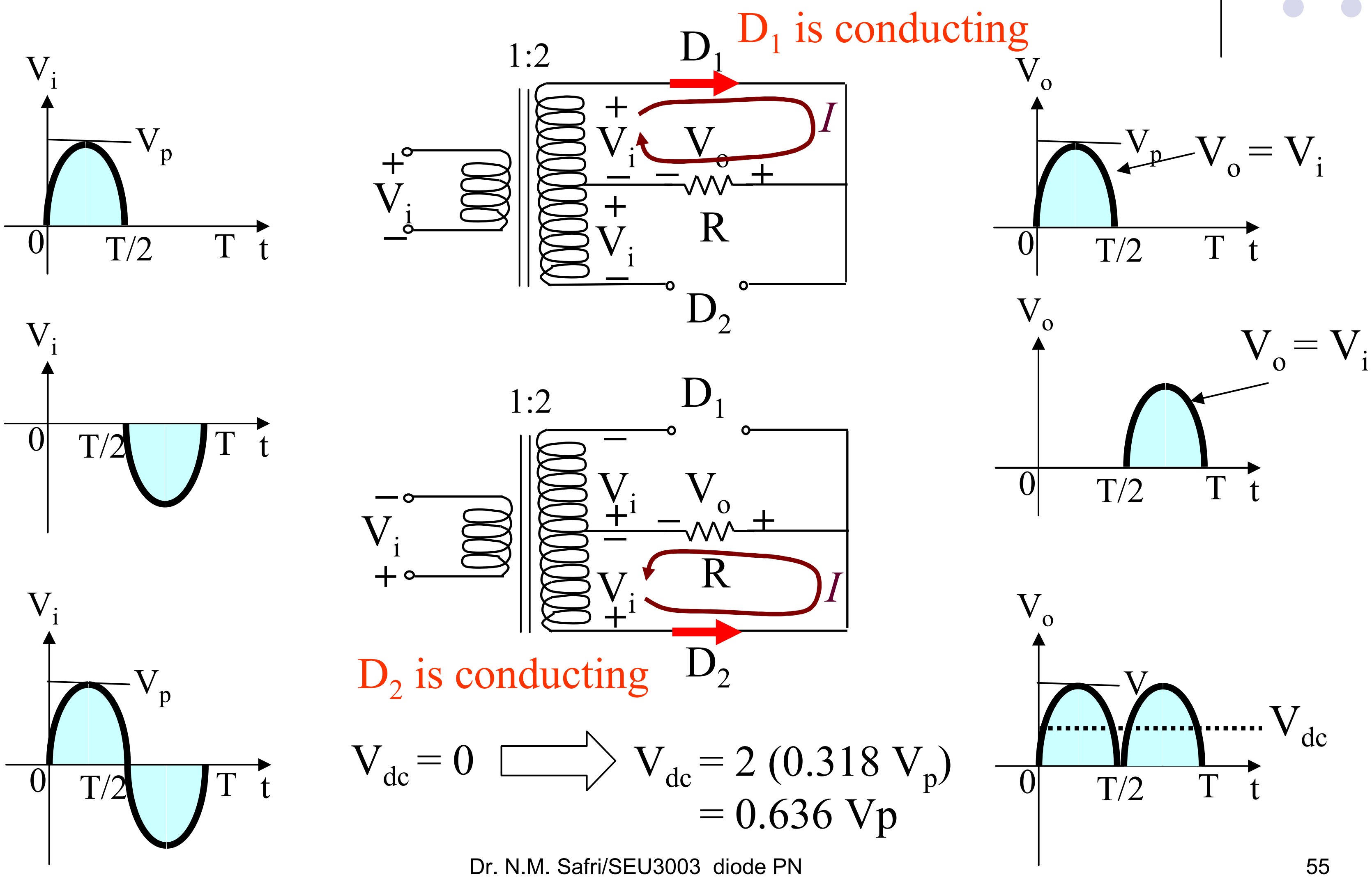


Fig.21

Diode with AC Power Supply

RECTIFIER: Full-wave rectification

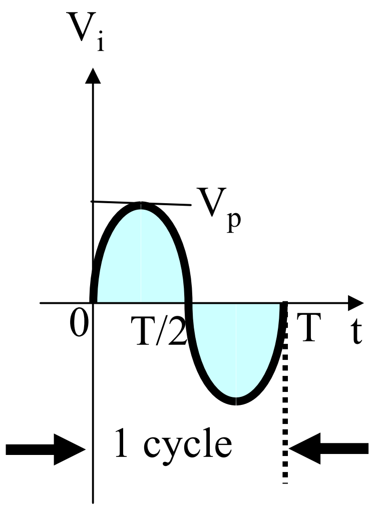


$V_{dc} = 0 \Rightarrow V_{dc} = 2\,(0.318\,V_p)$
$= 0.636\,V_p$

Diode with AC Power Supply

RECTIFIER with FILTER CAPACITANCE

If a capacitor is added in parallel with the load resistor of a half-wave rectifier to form a simple filter circuit, we can begin to transform the half-wave sinusoidal output into a dc voltage.



$V_i = V_p \sin \omega t$

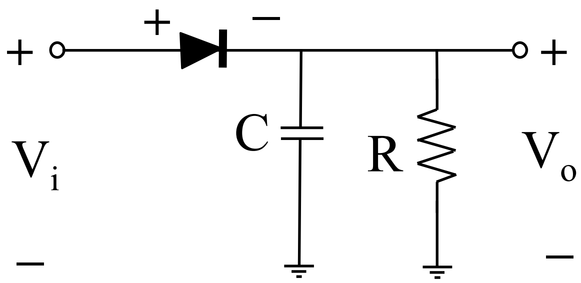
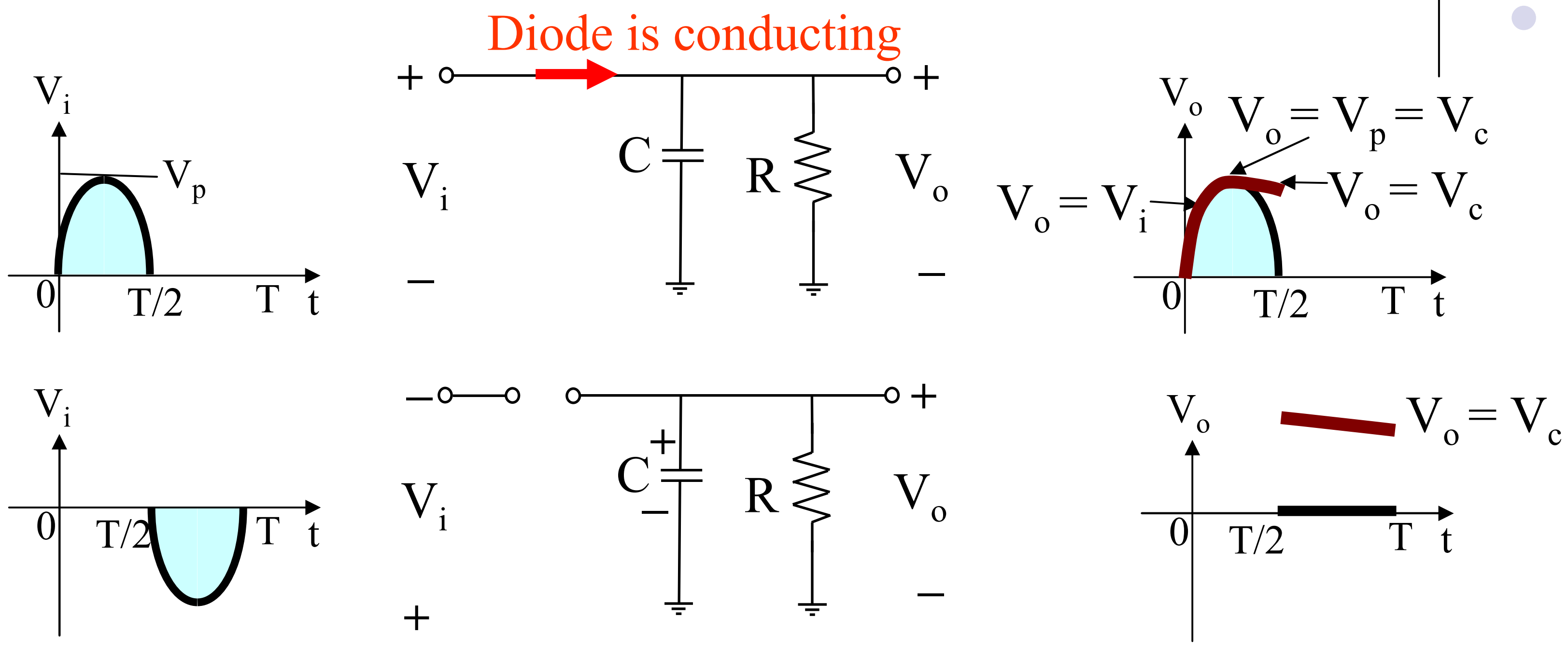
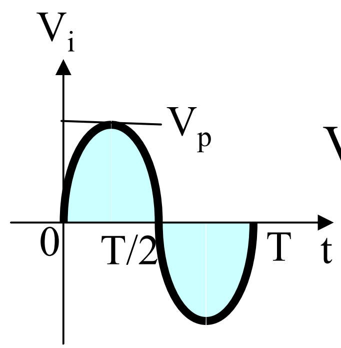


Fig.22

Diode with AC Power Supply

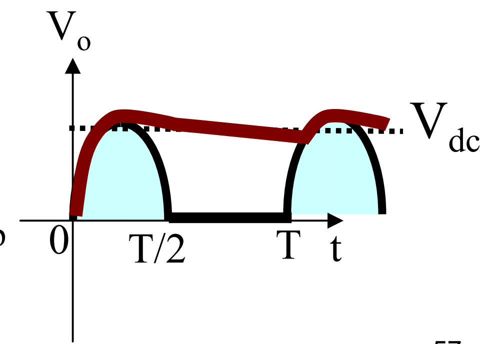
RECTIFIER with FILTER





$V_{dc} = 0$ ⇨ $V_{dc} = V_p - V_{r(p\text{-}p)}/2$

$= [1 - 1/(2fRC)]\ V_p$



Diode with AC Power Supply

CLIPPERS

- Clippers are networks that employ diodes to “clip” away a portion of an input signal without distorting the remaining part of the applied waveform.
- There are two general categories of clippers: *series* and *parallel*.
- The half-wave rectifier of Fig. 19 is an example of the simplest form of diode clipper – one resistor and a diode. Depending on the orientation of the diode, the positive and negative region of the applied signal is “clipped” off.

Tips

There is no general procedure for analyzing networks, but there are some things one can do to give the analysis some direction.

First and mort important:

1.Take careful note of where the output voltage is defined.

Next:

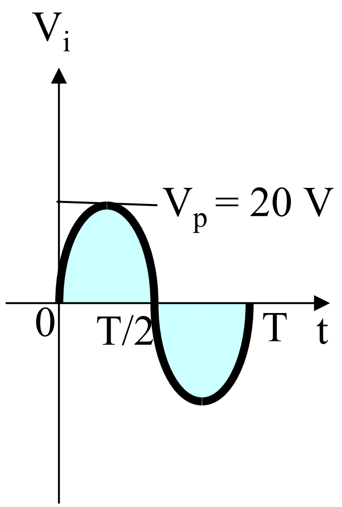
2. Try to develop an overall sense of the response by simply noting the "pressure" established by each supply and the effect it will have on the conventional current direction through the diode.

3. Determine the applied voltage (transition voltage) that will result in a change of state for the diode from the "off" to the "on" state.

4. It is often helpful to draw the output waveform directly below the applied voltage using the same scales for the horizontal axis and the vertical axis.

Activity (1)

Determine the output waveform for the sinusoidal input of Fig. 23?



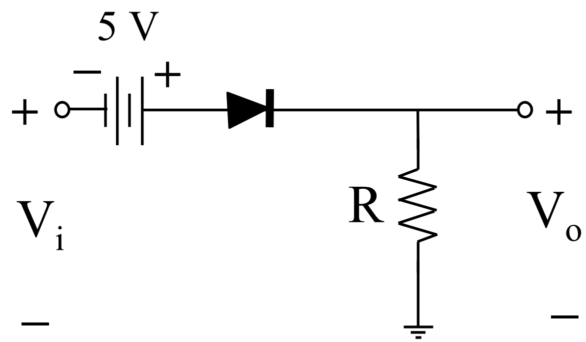
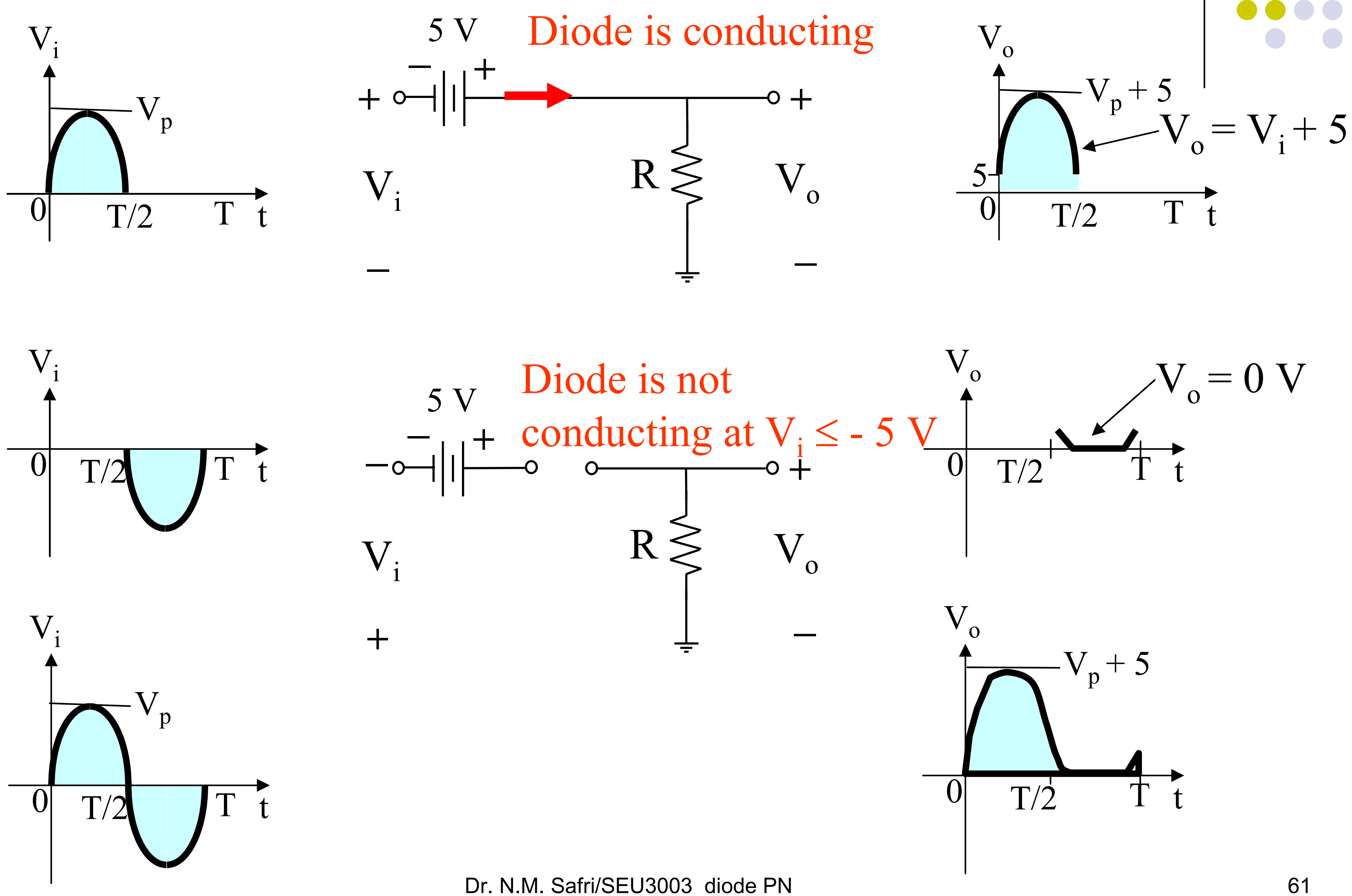


Fig.23

Answer



Vi
Vp
0
T/2
T
t
5 V
Diode is conducting
Vi
R
Vo
Vo
Vp + 5
Vo = Vi + 5
5
0
T/2
T
t
Vi
0
T/2
T
t
5 V
Diode is not
conducting at Vi ≤ - 5 V
Vi
R
Vo
Vo
Vo = 0 V
0
T/2
T
t
Vi
Vp
0
T/2
T
t
Vo
Vp + 5
0
T/2
T
t

Activity (2)

Determine the output waveform for the sinusoidal input of Fig. 24? Compare the result with the Fig. 24.

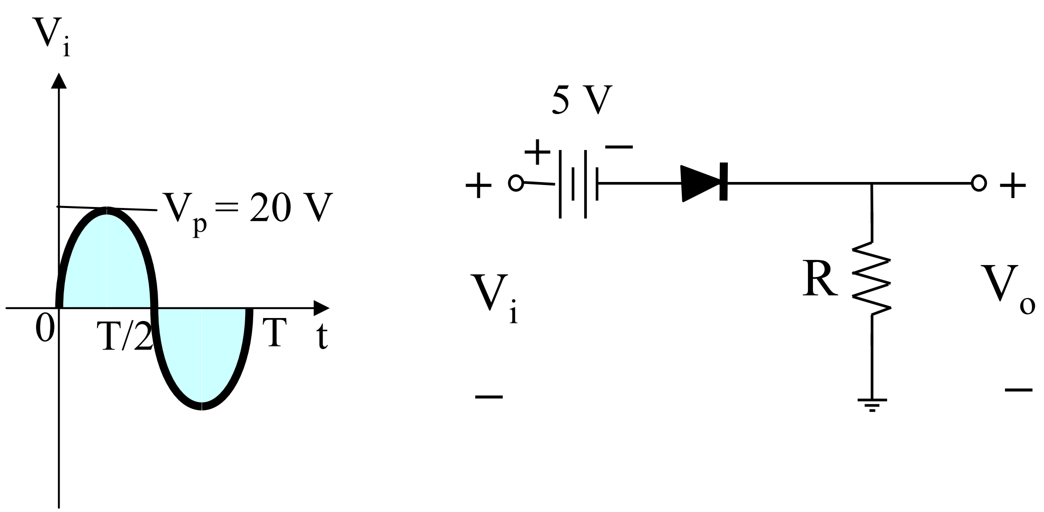
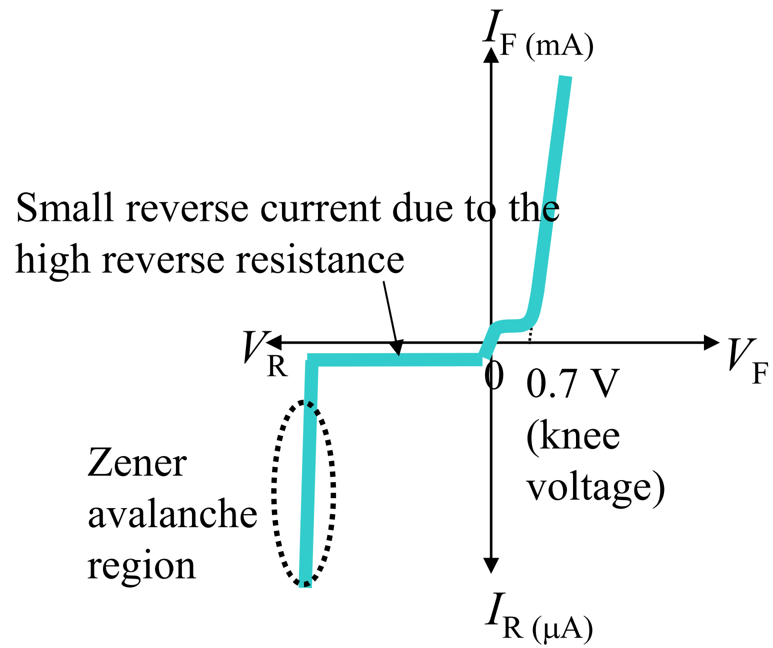


Fig.24

PIV

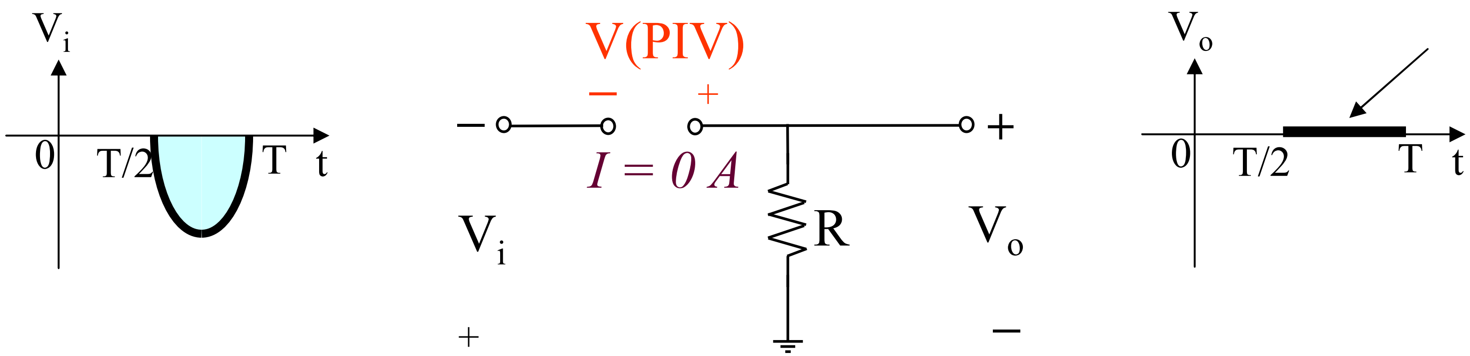
- The peak inverse voltage (PIV) rating of the diode is of primary importance in the design of rectification systems.
- It is the voltage rating that must not be exceeded in the reverse-bias region or the diode will enter the Zener avalanche region.



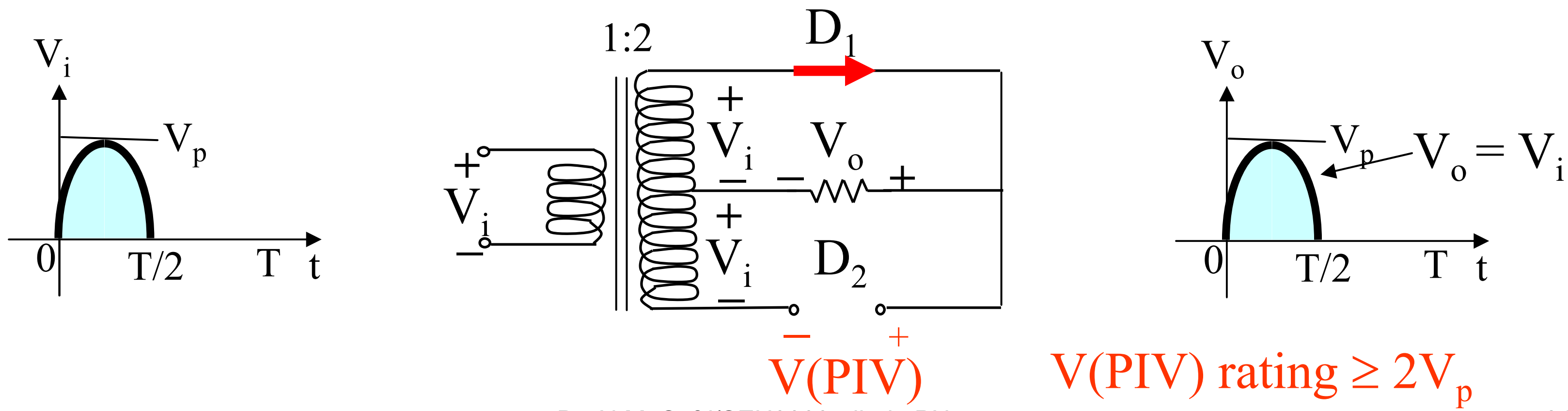
PIV

- PIV rating for half-wave rectifier

$V(PIV)$ rating $\geq V_p$



- PIV rating for full-wave rectifier



$V(PIV)$ rating $\geq 2V_p$

CLAMPERS

- A clamper is a network constructed of a diode, a resistor, and a capacitor that shifts a waveform to a different dc level without changing the appearance of the applied signal.

- Clamping networks have a capacitor connected directly from input to output with a resistive element in parallel with the output signal. The diode is also in parallel with the output signal but may not have a series dc supply as an added element.

Tips for Clamper Networks

First and mort important:

1. .Start the analysis by examining the response of the portion of the input signal that will forward bias the diode.

Next:

2. During the period that the diode is in the “on” state, assume that the capacitor will charge up instantaneously to a voltage level determined by the surrounding network.

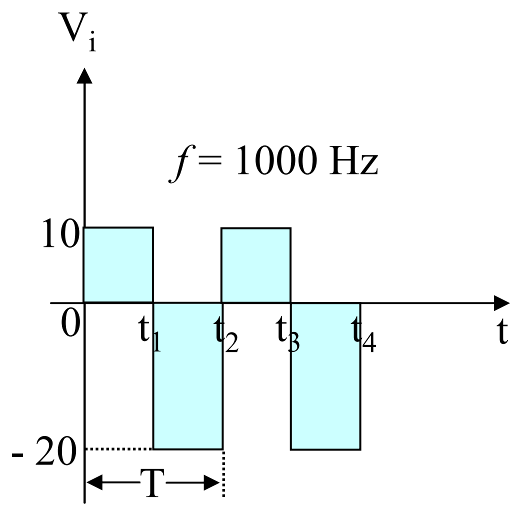
3. Assume that during the period when the diode is in the “off” state the capacitor holds on to its established voltage level.

4. Throughout the analysis, maintain a continual awareness of the location and defined polarity for V_o to ensure that the proper levels are obtained.

5. Check that the total swing of the output matches that of the input.

Activity

Determine V_o for the network of Fig. 25 for the input indicated.



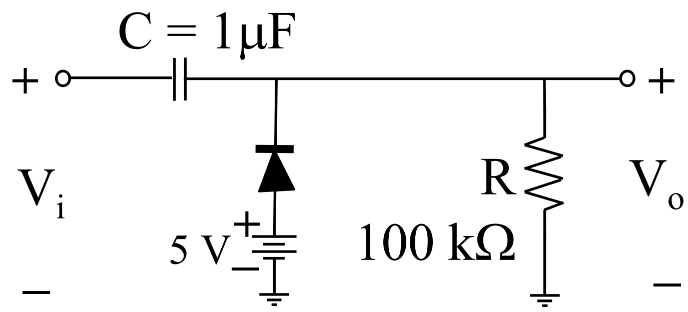


Fig.25