Chapter ONE

Diodes and their applications

If one side of a piece of silicon dope with a trivalent impurity and the other side with a pentavalent impurity, a $(p-n)$ junction will formed between the resulting p-type and n-type portions and a basic diode will created. A diode is a device that conducts current in only one direction. In this chapter we demonstrate the characteristics of the $(p-n)$ junction region. The volt-ampere characteristics of the $(p-n)$ junction is studied. The capacitance across the junction is calculated.

1.1 Introduction

Several common physical configurations of diodes are illustrated in Figure 1.1. The anode and cathode are indicated on a diode in several ways, depending on the type of package. The cathode is usually marked by a band, a tab, or some other feature. On those packages where one lead is connected to the case, the case is the cathode.

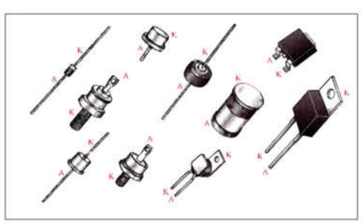


Figure 1.1: Typical diode packages with terminal identification.

Summary of diode biasing:

Forward bias:

- Bias voltage connections: positive to (p) region: negative to (n) region.
- The bias voltage must be greater than the barrier potential.
- Majority carriers flow toward the (pn) junction.
- Majority carriers provide the forward Current.
- The depletion region narrows.

Reverse bias:

- Bias voltage connections: positive to (n) region; negative to (p) region.
- The bias voltage must be less than the breakdown voltage.
- Majority carriers flow away from the (pn) junction during short transition time.
- Minority carriers provide the extremely small reverse current.
- There is no majority carrier current after transition time.
- The depletion region widens.

1.2 The diode model

There are three models of the diode:

1.2.1 The ideal model

The ideal model of a diode is a simple switch. When the diode is forward biased, it acts like closed (on) switch, as shown in figure 1.2a. When the diode is reversed biased. It acts like an open (off) switch, as shown figure 1.2b. The barrier potential, the forward dynamic resistance, and the reverse current are all neglected.

In figure 1.2c, the ideal $V-I$ characteristic curve graphically depicts the ideal diode operation.

In the ideal diode model: $V_F = 0$, $I_R = 0$ and $V_R = V_{bias}$.

1.2.2 The practical model

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 with the positive side toward

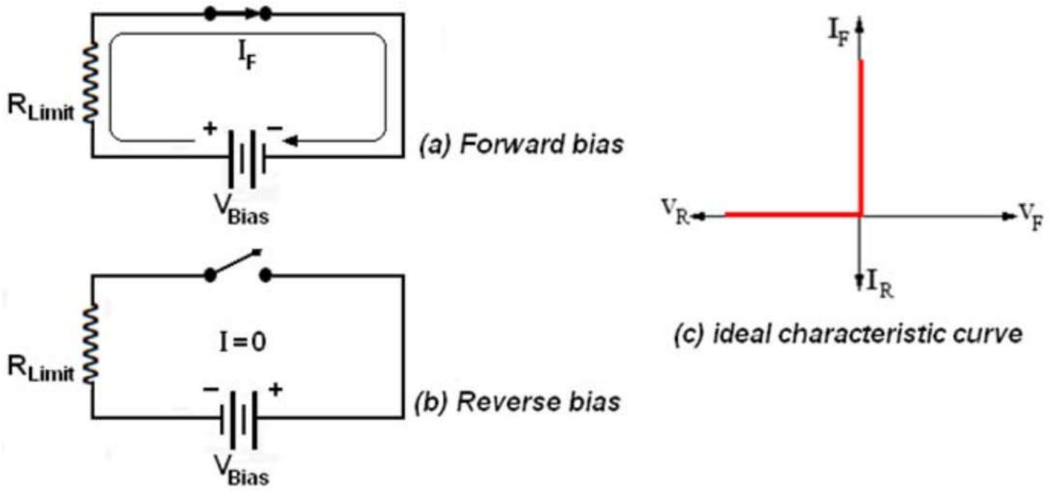


Figure 1.2: The ideal model of the diode (a) forward bias, (b) reverse bias and (c) ideal characteristic curve.

the anode, as indicated in figure3a. This equivalent voltage source represents the fixed voltage drop (V_F) produced across the forward biased ($p-n$) junction of the diode and is not an active source of voltage. This voltage (V_F) consists of the barrier potential voltage (V_o) plus the small voltage drop across dynamic resistance of the diode (r_d), as indicated by the portion of the curve to the right of the origin. The curve slopes because the voltage drops due to dynamic (r_d) as the current increases.

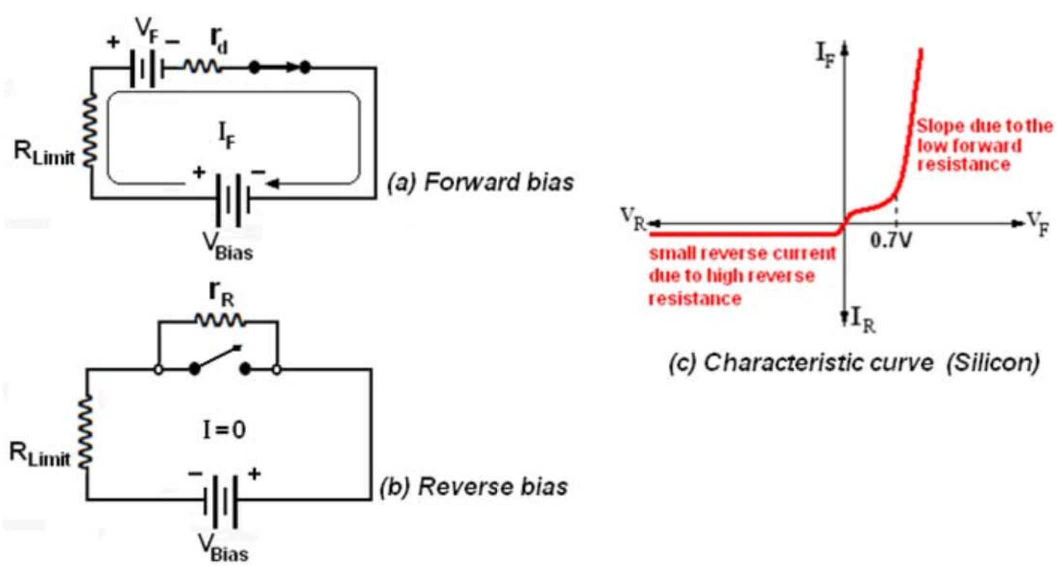


Figure 1.3: The complete model of the diode (a) forward bias, (b) reverse bias and (c) ideal characteristic curve (silicon).

1.2.3 The complete model

For the complete model of a silicon diode, the following formulas apply:

$$V_F = V_o + I_F \times r_d$$

$$I_F = \frac{(V_{Bias} - V_o)}{(R_{Limit} + r_d)}$$

The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin.

Solved problem

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

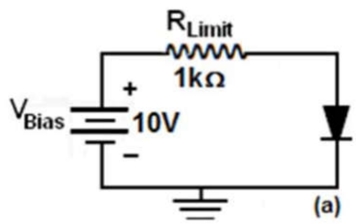


Figure 1.4:

b) Determine the reverse voltage and reverse current for the diode in figure (b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume I_R=1μA.

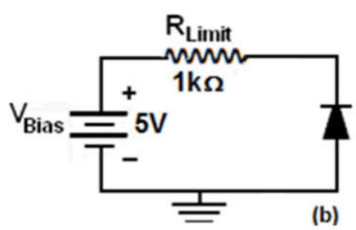


Figure 1.5:

Solution:

a) Ideal model:

$$V_F = 0\,volt$$

$$I_F = \frac{V_{bias}}{R_{Limit}} = \frac{10}{1 \times 10^3} = 10\,mA$$

$$V_{R_{limit}} = I_F \times R_{Limit} = 10\,mA \times 1k\Omega = 10\,volt$$

Practical model:

$$V_F = 0.7\,volt$$

$$I_F = \frac{V_{bias} - V_F}{R_{Limit} + r_d} = \frac{10 - 0.7}{1 \times 10^3 + 10} = 9.21\, mA$$

$$V_d = 0.7 + I_F \times r_d = 0.7 + 9.21mA \times 10 = 792mV$$

$$V_{R_{limit}} = I_F \times R_{Limit} = 9.21\, mA \times 1k\Omega = 9.21\, volt$$

If we neglected r_d then;

$$I_F = \frac{V_{bias} - V_F}{R_{Limit}} = \frac{10 - 0.7}{1 \times 10^3} = 9.3\, mA$$

$$V_{R_{limit}} = I_F \times R_{Limit} = 9.3\, mA \times 1k\Omega = 9.3\, volt$$

$b)$ Ideal model:

$$I_R = 0\, A$$

$$V_R = V Bias = 5\, V$$

$$V_{R_{limit}} = 0\, volt$$

Practical model

$$I_R = 1\, \mu A$$

$$V_{R(limit)} = I_R \times R_(Limit) = 1\mu A \times 1k\Omega = 1mV$$

$$V_R = V_(Bias) - V_{R_(limit)=5V-1mV=4.999\, volt}$$

Chapter One

Lecture 2 Diode DC Load Line, Dynamic Resistance, and Temperature Effects

1 Introduction

Understanding diode behavior is crucial for electronics design.

- DC Load Line: Graphical tool to find operating points
- Dynamic Resistance: Small-signal AC resistance

Real-world relevance: A solar charger circuit failing due to temperature-induced Q-point shifts!

2 Diode DC Load Line Analysis

2.1 Deriving the Load Line

- Circuit: Diode + resistor R + DC source V_{source}
- KVL equation:

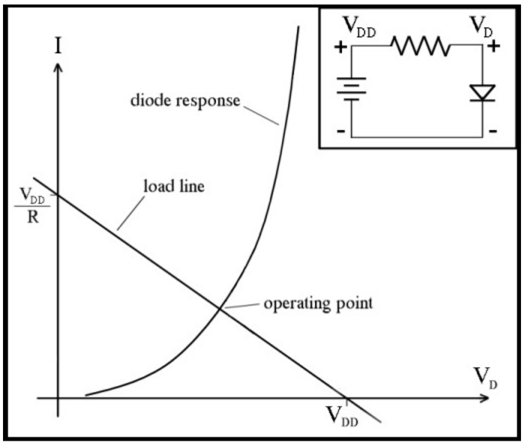
$$V_{\text{source}} = V_{\text{diode}} + I \cdot R$$

Rearranged as:

$$I = \frac{V_{\text{source}} - V_{\text{diode}}}{R} \quad \text{(Load line equation)}$$

2.2 Graphical Interpretation

- **Voltage intercept**: $V_{\text{diode}} = V_{\text{source}}$ when $I = 0$
- **Current intercept**: $I = V_{\text{source}}/R$ when $V_{\text{diode}} = 0$
- **Slope**: $-1/R$ (steeper with larger R)



2.3 Q-Point (Quiescent Point)

- Intersection of load line and diode I-V curve
- Determines steady-state (I_Q, V_Q)
- Critical for proper operation (e.g., forward bias for LEDs)

3 Dynamic Resistance

3.1 Definition and Formula

- **Dynamic Resistance (r_d)**: AC small-signal resistance in forward bias:

$$r_d = \frac{nV_T}{I_Q} \quad \text{where } V_T = \frac{kT}{q}$$

  - n: Ideality factor (1 for Si, 1-2 for GaAs)
  - V_T: Thermal voltage ($\sim$ 26 mV at 300K)
  - I_Q: Quiescent DC current from Q-point

- Derived from diode equation's slope: $r_d = \left.\frac{dV}{dI}\right|_Q$

3.2 Temperature Dependence

- **Thermal Voltage (V_T)**: Increases linearly with T:

$$V_T \propto T \quad \text{(e.g., 26mV} \to \text{34mV at 100°C)}$$

- **Quiescent Current (I_Q)**: Grows exponentially with T (due to I_S dependence)
- **Net Effect on r_d**:

$$r_d = \frac{nV_T}{I_Q} \Rightarrow r_d \downarrow \text{ as } T \uparrow$$

  - Dominated by I_Q's exponential rise
  - Critical for AC amplifiers: Gain $\propto 1/r_d$

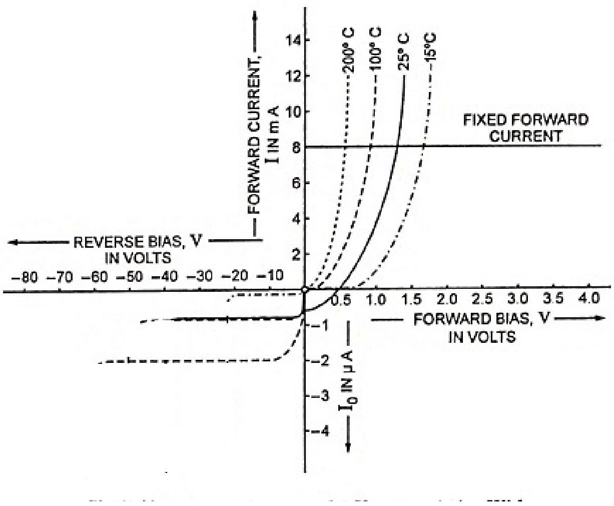
4 Temperature Effects on Diode Behavior

4.1 Forward Bias Region

- V_F decreases $\approx -2\text{mV}/°\text{C}$ (Si) **Prove that and give detail discussion**
- Diode equation:

$$I = I_S\left(e^{\frac{V}{nV_T}} - 1\right) \quad \text{where } V_T = \frac{kT}{q}$$

- V_T increases with T, I_S grows exponentially
- Net effect: I-V curve shifts **leftward**



4.2 Reverse Bias Region

- I_S doubles every 10°C (increased leakage)
  Prove that and give detail discussion

4.3 Q-Point Shift with Temperature

- Higher $T \Rightarrow V_F \downarrow \Rightarrow I_Q \uparrow$
- Risk of thermal runaway in power circuits

4.4 Temperature Impact on Dynamic Resis

- At fixed V_{source} and R:
  - $T \uparrow \Rightarrow I_Q \uparrow$ (due to I_S and V_T)
  - $r_d = \frac{nV_T}{I_Q} \downarrow$ by $\sim 50\%$ per 25°C
- **Design Tip**: Use feedback or constant-current biasing to stabilize r_d

5 Practical Implications and Solutions

5.1 Circuit Stability

- **Problems**: Q-point drift, thermal runaway, r_d variability
- **Solutions**:
  - Heatsinks
  - Temperature-compensated diodes
  - Constant-current sources for stable I_Q

5.2 Applications

- Diode thermometers (using V_F vs T)

6 Summary

- Load line slope depends on R, determines Q-point
- Temperature $\uparrow \Rightarrow V_F \downarrow$, $I_S \uparrow$
- **Dynamic Resistance**: $r_d \propto T/I_Q \Rightarrow$ decreases with T
- Always design for worst-case temperature!

Diode Capacitance: Junction and Diffusion Effects

1. Junction Capacitance (Reverse Bias)

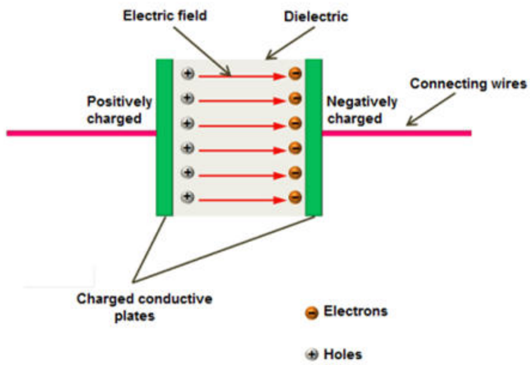
1.1 Physical Origin

- Arises from charge variation in depletion region
- Dominates under reverse bias conditions
- Mathematical expression:

$$C_j = \frac{\varepsilon_s A}{W}$$

Where:

- ε_s = Semiconductor permittivity
- A = Junction area
- W = Depletion width



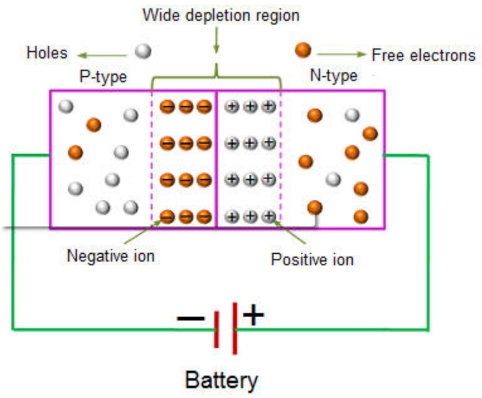
1.2 Key Equations

Depletion width for abrupt junction:

$$W = \sqrt{\frac{2\varepsilon_s(V_{bi}+V_R)}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)}$$

Built-in potential:

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_AN_D}{n_i^2}\right)$$



Simplified capacitance expression:

$$C_j = \frac{C_{j0}}{\sqrt{1+\frac{V_R}{V_{bi}}}}$$

Cjo is the depletion region capacitance without biasing voltage

1.3 Example Calculation

For silicon p$^+$n diode ($N_A = 10^{19}\,\mathrm{cm}^{-3}$, $N_D = 10^{16}\,\mathrm{cm}^{-3}$):

$$V_{bi} \approx 0.88\,\mathrm{V}$$

$$W \approx 0.94\,\mu\mathrm{m}$$

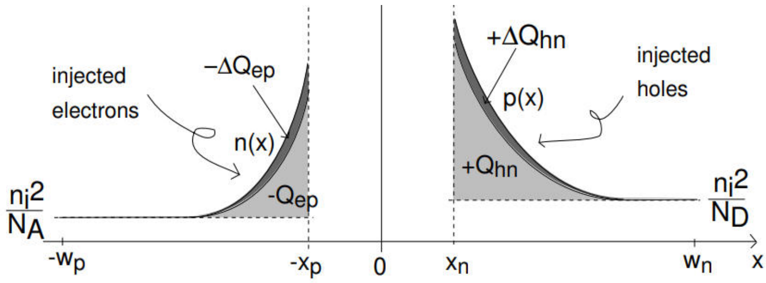
$$C_j \approx 1.1\,\mathrm{pF}$$

2. Diffusion Capacitance (Forward Bias)

2.1 Physical Origin

- Results from minority carrier storage in neutral regions
- Dominates under forward bias
- Governing equation:

$$C_d = \frac{\tau I_F}{\eta V_T}$$



Where:

  - τ = Minority carrier lifetime
  - I_F = Forward current
  - η = Emission coefficient (1-2)
  - $V_T = kT/q \approx 0.026\,\text{V}$

2.2 Key Equations

Stored charge in neutral regions:

$$Q = \tau I_S \left(e^{V_F/\eta V_T} - 1\right)$$

Total diode capacitance:

$$C_{\text{total}} = C_j + C_d$$

2.3 Example Calculation

For $\tau = 1\,\mu s$, $I_F = 10\,mA$:

$$C_d \approx 385\,\text{nF}$$

3. Comparative Analysis

Parameter	**Junction (C_j)**	**Diffusion (C_d)**
Dominant region	Reverse bias	Forward bias
Voltage dependence	$(V_{bi} + V_R)^{-1/2}$	$e^{V_F/\eta V_T}$
Typical values	pF range	nF-µF range
Temperature dep.	$\propto 1/\sqrt{T}$	$\propto T$
Applications	Varactors, tuning	Switching circuits, LEDs

4. Practical Implications

- **Junction Capacitance**:
  - Critical for RF/microwave circuits
  - Limits reverse recovery time
  - Used in voltage-controlled oscillators
- **Diffusion Capacitance**:
  - Limits diode switching speed
  - Important for power electronics

  - Dominates in LED and laser diode operation

5. Summary

- Two distinct capacitance mechanisms operate in different bias regimes
- Junction capacitance: Depletion region charge modulation
- Diffusion capacitance: Minority carrier storage effect
- Understanding both essential for high-frequency and power applications

A sinusoidal inputs:

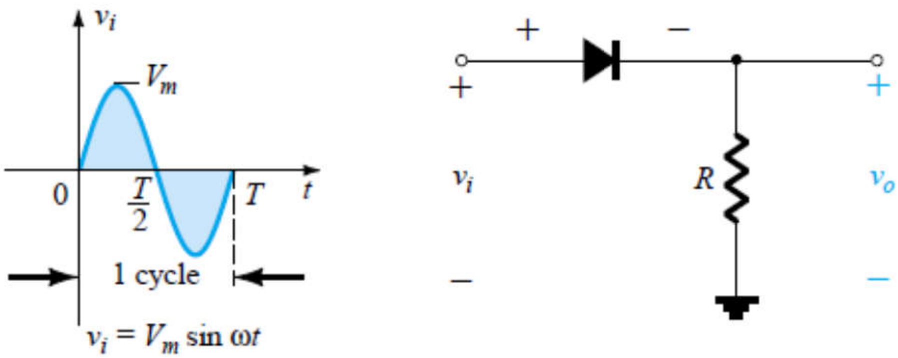


Fig.1 Half -wave rectifier.

Half wave rectifier

With an ideal diode and sinusoidal input voltage V_{in} as shown. During the time when $Vin>0$ the diode is forward biased and so the voltage across this "ideal" diode is zero. This observation is also represented by the equivalent circuit shown on Figure, which clearly indicates that the output voltage V_o is equal to the input voltage V_{in}.

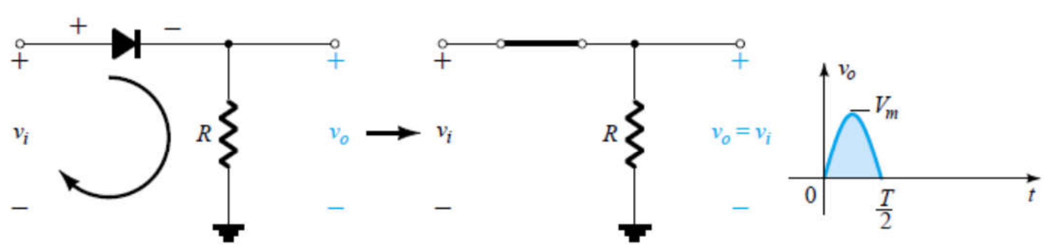


Fig. 2 Conduction region ($0 \rightarrow T/2$).

Similarly during the time when V_{in}<0, the diode is reverse biased and so the current flowing through the diode is zero, see equivalent circuit on Figure and the output voltage is zero.

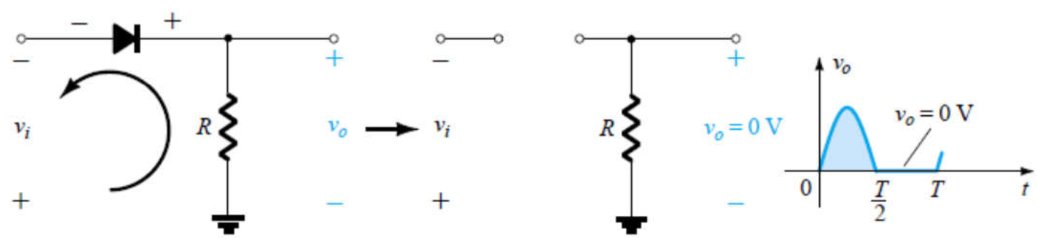


Fig . 3 . Conduction region ($T/2 \rightarrow T$).

The total response of the circuit to the input signal *Vin* is shown on Fig. 4 . Note that the presence of the diode alters the output signal in a profound way: it converts an AC (alternating current) input voltage, whose average value over time is zero, into an output voltage whose polarity does not change over time, and which has a non-zero average value. This type of voltage signal is called DC (direct current) since the direction of the current does not change over time. We have just taken the first step in the design of an AC to DC converter.

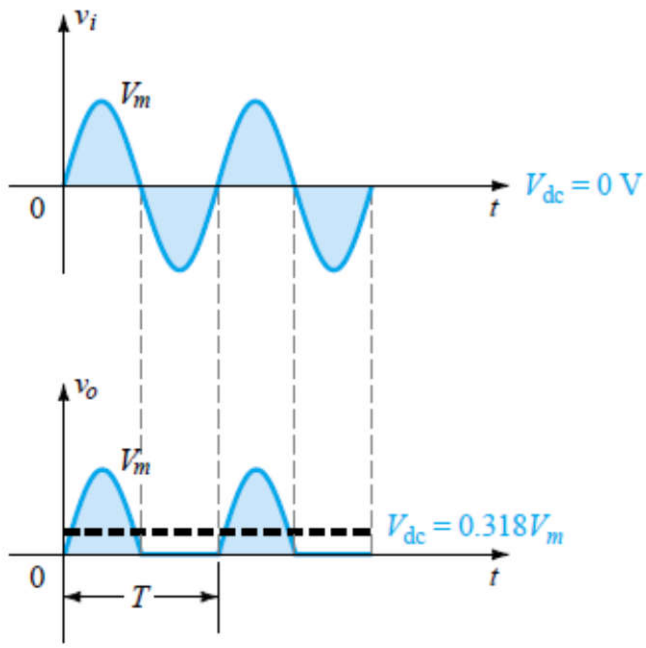


Fig. 4 Half-wave rectifier signal.

The output signal V_o is a <u>*rectified*</u> signal of the input *Vin* and the circuit that generated this signal, the circuit, is called <u>*Rectifier*</u> circuit. Furthermore, since it passes only half of the input signal it is called a <u>*Half Wave Rectifier Circuit*</u>.

A dc voltmeter is constructed to read the average values

$$V_{DC} = \frac{1}{2\pi} \int_0^{2\pi} v_o(t)\, d\tau$$

$$V_{DC} = \frac{1}{2\pi} \int_0^{\pi} V_m \sin\tau \; d\tau$$

$$V_{DC} = \frac{V_m}{2\pi} \left(-\cos\tau\right)_0^{\pi}$$

$$V_{DC} = \frac{V_m}{2\pi}(-\cos\pi + \cos 0) = \frac{V_m}{2\pi}(-(-1)+1) = \frac{V_m}{\pi}$$

$$V_{DC} = 0.318V_m$$

The effect of using silicon diode (V_T=0.7V). The applied signal must now be at least 0.7V before the diode can turn **on**. For levels of vi

- $v_o = v_{in} - V_T$ for $V_{in} > V_T$, $i_D = i_L = (v_{in} - V_T)/R_L$
- $v_o = 0$ for $V_{in} < V_T$ (Open circuit) Diode in **off** state: $i_D = i_L = 0$ and $v_o = 0$

$$V_{DC} = 0.318(V_m - V_T)$$

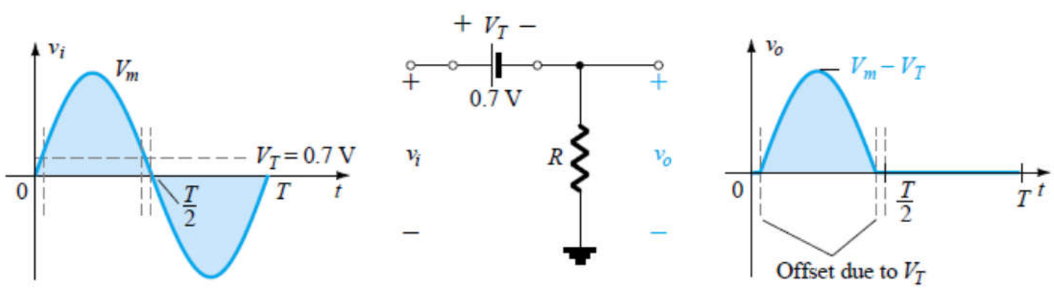


Fig.5. Effect of V_T on half wave rectified signal.

Example 1

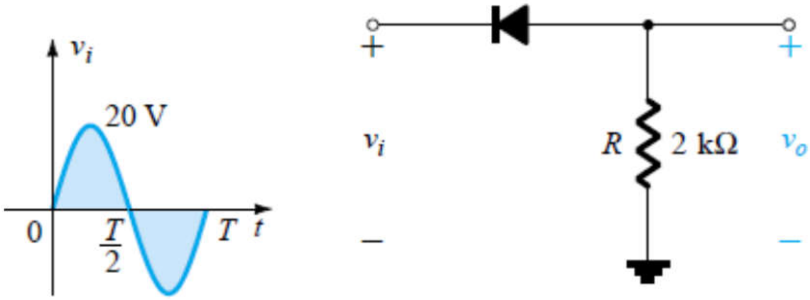


Fig.6. Example 1

a- Sketch v_o and determine V_{dc}.

b- Repeat (a) if the ideal diode is replaced by silicon diode.

c- Repeat (a)and (b) if V_{mi}=200V.

Solution

a- The diode will contact during the negative half of input.

$$V_{DC} = 0.318V_m = -0.318(20) = -6.36V$$

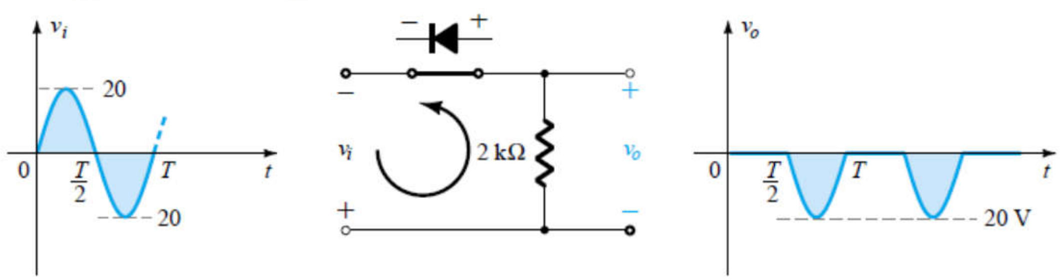


Fig.6. Resulting *vo* for the circuit of Example 1

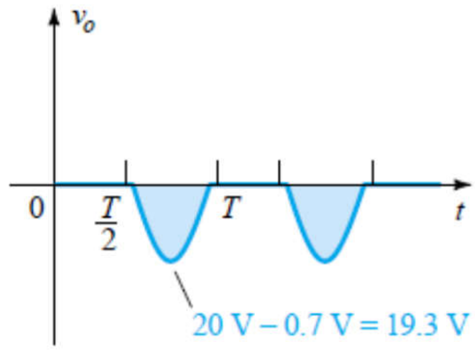


Fig.7 Effect of *VT* on output of Fig. 10.6

b- Using a silicon diode

V_{mo}=20-0.7=19.3V

$$V_{DC} = -0.318(20-0.7) = -6.14V$$

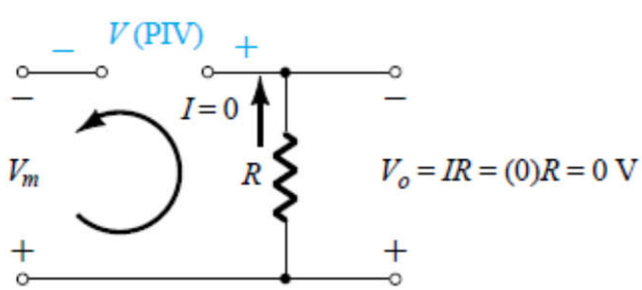
c- If the diode can stand at 200V without breakdown

$$V_{DC} = -0.318(200) = -63.6V$$

$$V_{DC} = -0.318(200-0.7) = -63.38V$$

<u>PIV</u>

The peak inverse voltage (PIV) or peak reverse voltage (PRV). The voltage rating must not be exceeded in the reverse–bias and diode enter the zener avalanche region therefore PIV>V_m .



Determining the required PIV rating for the halfwave rectifier.

Half-Wave Rectifier: RMS Voltage Derivation and Ripple Factor

1. RMS Voltage Derivation

Let the input AC voltage be:

$$v_{\text{in}}(t) = V_m \sin(\omega t)$$

For a half-wave rectifier, the output voltage is:

$$v(t) = \begin{cases} V_m \sin(\omega t), & 0 \leq t < \pi/\omega \\ 0, & \pi/\omega \leq t < 2\pi/\omega \end{cases}$$

The RMS voltage is defined as:

$$V_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T v^2(t)\, dt}$$

Substitute the waveform and period $T = \frac{2\pi}{\omega}$:

$$V_{\text{rms}} = \sqrt{\frac{1}{2\pi/\omega} \int_0^{\pi/\omega} (V_m \sin(\omega t))^2\, dt}$$

$$= V_m \sqrt{\frac{\omega}{2\pi} \int_0^{\pi/\omega} \sin^2(\omega t)\, dt}$$

Use the identity $\sin^2(\omega t) = \frac{1-\cos(2\omega t)}{2}$:

$$V_{\text{rms}} = V_m \sqrt{\frac{\omega}{2\pi} \int_0^{\pi/\omega} \frac{1-\cos(2\omega t)}{2} dt}$$

$$= V_m \sqrt{\frac{\omega}{4\pi} \int_0^{\pi/\omega} (1-\cos(2\omega t)) dt}$$

$$= V_m \sqrt{\frac{\omega}{4\pi} \left[t - \frac{\sin(2\omega t)}{2\omega} \right]_0^{\pi/\omega}}$$

$$= V_m \sqrt{\frac{\omega}{4\pi} \cdot \frac{\pi}{\omega}} = V_m \sqrt{\frac{1}{4}} = \frac{V_m}{2}$$

$$\boxed{V_{\text{rms}} = \frac{V_m}{2}}$$

2. Half-Wave Ripple Factor

The ripple factor r is defined as:

$$r = \frac{V_{\text{ripple}}}{V_{\text{dc}}}$$

For a half-wave rectifier: - $V_{\text{rms}} = \frac{V_m}{2}$ - $V_{\text{dc}} = \frac{V_m}{\pi}$
Substitute into the ripple factor equation:

$$r = \left(\frac{V_m/2}{V_m/\pi} \right)$$

$$\boxed{r = 1.21 \text{ (approximately)}}$$