# Electronics Engineering

# Analog Circuits

Comprehensive Theory

*with* **Solved Examples** and **Practice Questions**

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# Contents

## Analog Circuits

## Chapter 10



## Chapter 11



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# Analog Circuits

## Introduction to Analog Circuits

After studying the basic electronic devices and their characteristics, now we shall deal with more complex analog circuits, of which amplifiers is a very significant category. We shall start our analysis with applications of diode, a very fundamental component, in various circuit configurations such as clipper, clamper, regulator etc. Further, we shall proceed to applications of BJT and FET, particularly as an amplifier.

The other complex analog circuits, including circuits that form operational amplifiers, are also part of this book. These circuits are composed of fundamental configurations, such as differential amplifier, constant-current source, active load, and output stage, all of which have been discussed in detail.

The major emphasis throughout the book is on developing the reader's understanding for analyzing and designing various fundamental circuits, which are always an integral part of various competitive examinations. Throughout the book, a very sequential and comprehensive approach has been used, so that a beginner can also utilize the book in very efficient manner.

# Prelude to Analog Circuits

## Electronics

Electronics is defined as the science of motion of charges in a gas, vacuum, or semiconductor. Note that the charge motion in a metal is excluded from this definition.

This definition was used early in the $20^{th}$ century to separate the field of electrical engineering, which dealt with motors, generators, and wire communications, from the new field of electronic engineering, which at that time dealt with the vacuum tubes.

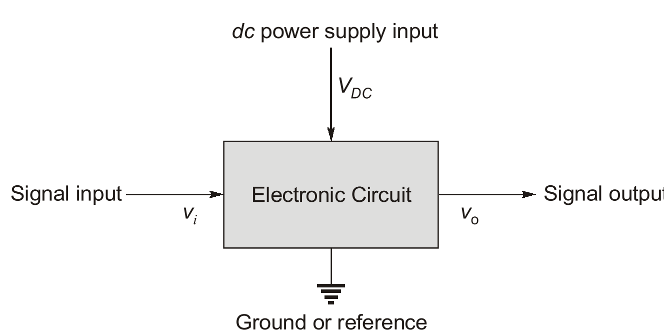
## Microelectronics

Microelectronics refers to the integrated-circuit (IC) technology that is capable of producing circuits which contain millions of components in a small piece of silicon (known as a silicon chip) whose area is on the order of 100 $mm^2$.

## Electronic Circuits

A circuit which consists of at least one electronic device (e.g. amplifier, rectifier, oscillator etc.) is known as an electronic circuit.

In most of the electronic circuits there are two inputs. One input is from power supply which provides dc voltages and currents to establish proper biasing for transistors. The second input is a signal that can be amplified by the circuit. Although the output signal can be larger than the input signal but the output power can never exceed the dc input power. Therefore, the magnitude of dc power supply is one limitation to the output signal response.



## Discrete and Integrated Circuits

Discrete electronic circuits contain discrete components, such as resistors, capacitors and transistors whereas an integrated circuit consists of a single crystal chip of silicon containing both active and passive elements and their interconnections. Such circuits are produced by the same processes used to fabricate individual transistors and diodes.

## Analog and Digital Signals

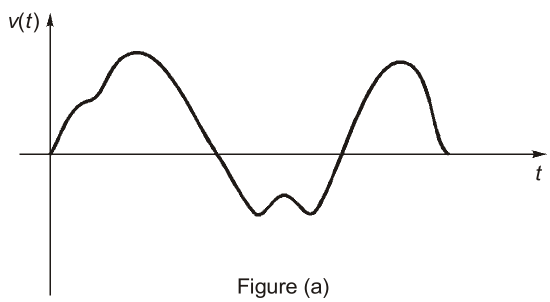


Figure (a)

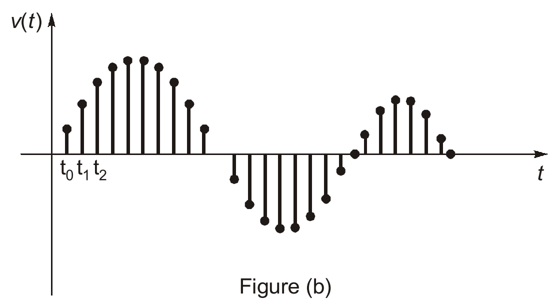


Figure (b)

The voltage signal shown graphically in Fig. (a) is called an ***analog signal***. The name derives from the fact that such a signal is analogous to the physical signal that it represents. The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity. Electronic circuits that process such signals are known as ***analog circuits***.

An alternative form of signal representation is that of a sequence of numbers shown in Fig. (b), each number representing the signal magnitude at an instant of time. The resulting signal is called a ***discrete signal***. When discrete signal is quantized in magnitude it becomes a ***digital signal***. Electronic circuits that process digital signals are called ***digital circuits***.

### Advantages of Analog Circuits

- Majority of signals in the "real world" are analog; so these signals can be directly processed in analog circuits whereas digital processing requires analog to digital and digital to analog conversion.
- Analog circuits can be designed to operate even at higher power levels.

### Advantages of Digital Circuits

- In digital circuits effect of noise is less.
- Digital circuits are easier to design.
- Digital circuits can be programmed.
- Digital data can be stored.

CHAPTER 1

# Diode Circuits

## 1.1 Introduction

The simplest and most fundamental non-linear circuit element is a diode. Just like a resistor, the diode has two terminals; but unlike the resistor which has a linear (straight-line) relationship between the current flowing through it and the voltage appearing across it, the diode has non-linear i-v characteristics. The analysis of non-linear electronic circuits is not as straight-forward as the analysis of linear electric circuits. However, there are electronic functions that can be implemented only by non-linear circuits. Examples include the generation of dc voltages from sinusoidal voltages and the implementation of logic functions.

## 1.2 Diode Circuits : DC Analysis and Models

Mathematical relationships, or ***models***, that describes the current-voltage characteristics of electrical elements allow us to analyze and design circuits without having to fabricate and test them in the laboratory. An example is Ohm's law, which describes the properties of a resistor. In this section, we will develop the dc analysis and modelling techniques of diode circuits.

To begin to understand diode circuits, consider an ***ideal diode***. It is a two terminal device having the circuit symbol of Fig. 1.1 (a) and the i-v characteristics shown in Fig.1.1 (b).

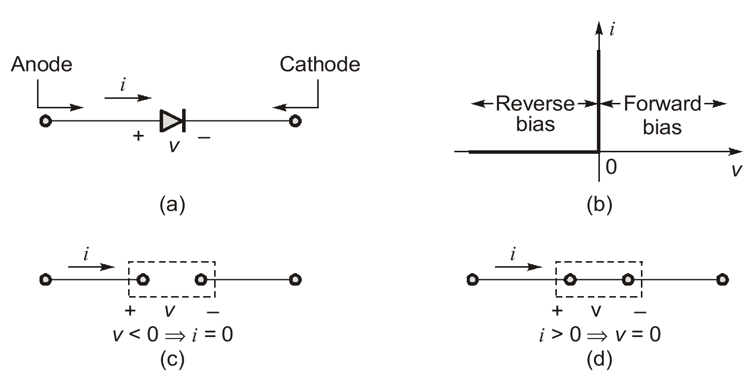



***Figure-1.1:*** *Ideal diode and its characteristics*

The terminal characteristics of the ideal diode can be interpreted to follows:

- If a negative voltage is applied to the diode, no current flows and the diode behaves as an ***open circuit*** [as shown in Fig. 1.1 (c)]. Diodes operated in this mode are said to be ***reverse biased***.
- On the other hand, if a positive current is applied to the ideal diode, zero voltage drop appears across the diode. In other words the ideal diode behaves as a ***short circuit*** in the forward direction [as shown in Fig. 1.1 (d)]. Diodes operated in this mode are said to be ***forward biased***

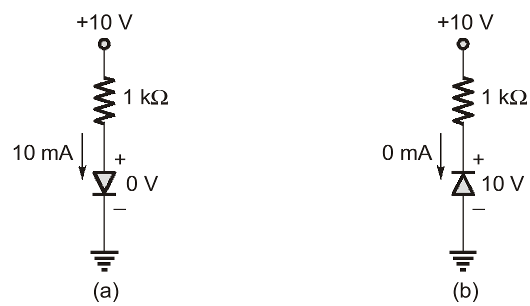



***Figure-1.2 :*** *The two modes of operation of ideal diodes and the use of external circuit to limit (a) the forward current and (b) the reverse voltage*

From the above description it should be noted that the external circuit must be designed to limit the forward current through a conducting diode, and the reverse voltage across a cut-off diode to predetermined values. Fig. (1.2) shows two diode circuits that illustrate this point. In the circuit of Fig. 1.2 (a) the diode is obviously conducting. Thus its voltage drop will be zero, and the current through it will be determined by the +10 V supply and the 1 kΩ resistor as 10 mA. The diode in the circuit of 1.2 (b) is obviously cut-off, and thus its current will be zero which in turn means that the entire 10 V supply will appear as reverse bias across the diode.

### 1.2.1 Load-Line Analysis

The circuit of Fig. (1.3) is the simplest of diode configurations. Solving the circuit of Fig. (1.3) is all about finding the current and voltage levels that will satisfy both the characteristics of the diode and the chosen network parameters at the same time.

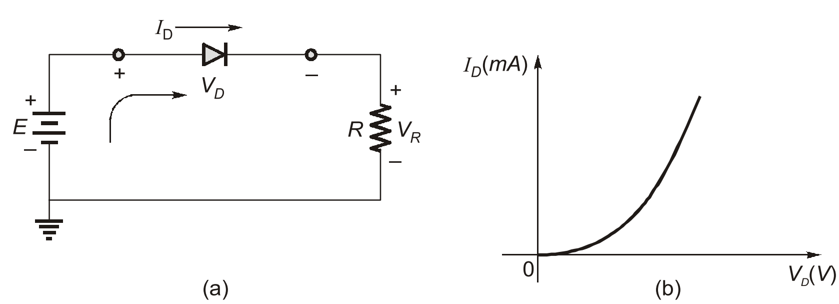



***Figure-1.3 :*** *Series diode configuration (a) Circuit (b) Characteristics*

In Fig. (1.4) the diode characteristics are placed on the same set of axis as a straight line defined by the parameters of the network. The straight line is called a ***load line*** because the intersection of the vertical axis is defined by the applied load *R*. The analysis to follow is therefore called ***load-line analysis***. The intersection of the two curves will define the solution for the network and define the current and the voltage levels for the network.

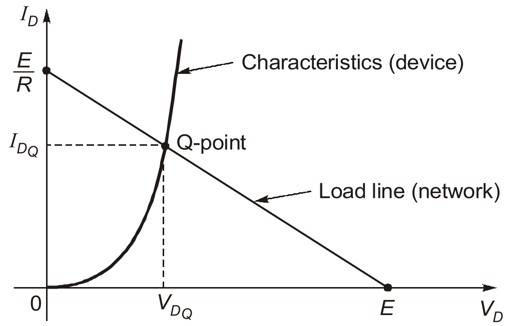



***Figure-1.4:** Drawing the load line and finding the point of operation*

- The intersection of the load line on the characteristics of Fig. (1.4) can be determined by applying Kirchhoff's voltage law in the clockwise direction, which results in

$$E - V_D - V_R = 0$$

or $$E = V_D + I_D R \qquad \text{...(1.1)}$$

- The two variables of the equation (1.1), $V_D$ and $I_D$, are the same as the diode axis variables of Fig. (1.4). This similarity permits plotting equation (1.1) on the same characteristics of Fig. (1.4).
- Set, $V_D = 0$ V in equation (1.1)

$$E = 0\text{ V} + I_D R$$

$$\therefore \quad I_D = \left.\frac{E}{R}\right|_{V_D = 0\text{ V}} \qquad \text{...(1.2)}$$

Equation (1.2) gives the magnitude of $I_D$ on the vertical axis.

- Set, $I_D = 0$ A in equation (1.1)

$$E = V_D + (0\text{ A})\,R$$

$$\Rightarrow \quad E = V_D$$

$$\therefore \quad V_D = E|_{I_D = 0\text{ A}} \qquad \text{...(1.3)}$$

Equation (1.3) gives the magnitude of $V_D$ on the horizontal axis.

- A straight line drawn between the two points will define the load line as depicted in Fig. (1.4). Change the level of $R$ (the load) and the intersection on the vertical axis will change. The result will be change in the slope of the load line and different point of intersection between the load line and the device characteristics.
- We now have a load line defined by the network and a characteristic curve defined by the device. The point of intersection between the two is the point of operation for this circuit.
- By simply drawing a line down to the horizontal axis, we can determine the diode voltage $V_{D_Q}$, whereas a horizontal line from the point of intersection to the vertical axis will provide the level of $I_{D_Q}$. The point of operation is usually called the ***quiescent point*** (abbreviated "***Q-point***") to reflect its "still, unmoving" qualities as defined by a dc network.
- The solution obtained at the intersection of the two curves is the same as would be obtained by a simultaneous mathematical solution of

$$I_D = \frac{E}{R} - \frac{V_D}{R} \qquad \text{[Derived from equation 1.1]}$$

and $$I_D = I_0\left(e^{V_D/\eta V_T} - 1\right) \qquad \text{[Diode equation]}$$

### 1.2.2 Series Diode Configuration

The approximate models will now be used to investigate a number of series diode configurations with dc inputs. This will establish a foundation in diode analysis that will carry over into the sections and chapters to follow. The procedure described can, in fact, be applied to networks with any number of diodes in variety of configurations.

- For each configuration the state of each diode must first be determined. Which diodes are "*on*" and which are "*off*"? Once determined, the appropriate equivalent can be substituted and the remaining parameters of the network determined.
- For the conduction region the only difference between the silicon diode and the ideal diode is the vertical shift in the characteristics, which is accounted for in the equivalent model by a dc supply of 0.7 V opposing the direction of forward current through the device. For voltages less than 0.7 V for a silicon diode and 0 V for the ideal diode the resistance is so high compared to the other elements of the network that its equivalent is the open circuit.
- ***In general, a diode is in the "on" state if the current established by the applied sources is such that its direction matches that of the arrow in the diode symbol, and $V_D \geq 0$ V for ideal diode, $V_D \geq 0.3$ V for germanium diode, $V_D \geq 0.7$ V for silicon diode, and $V_D \geq 1.2$ V for gallium arsenide diode.***

The series circuit of Fig. (1.5) will be used to demonstrate the approach described in the above paragraphs.

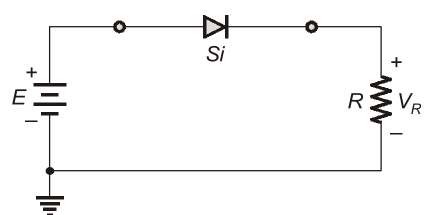



***Figure-1.5 :*** *Series diode configuration*

The state of the diode is first determined by mentally replacing the diode with a resistive element as shown in Fig. 1.6 (a). The resulting direction of $I$ is a match with the arrow in the diode symbol, and since $E > V_\gamma$ (cut-in voltage of diode), the diode is in the "on" state. The network is redrawn as shown in Fig. 1.6 (b) with the appropriate equivalent model for the forward biased silicon diode.

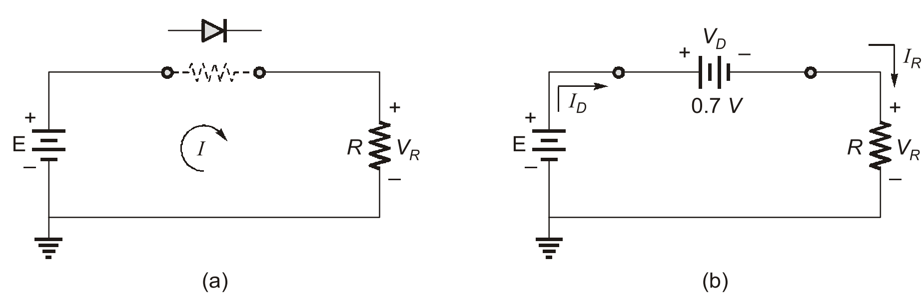



***Figure-1.6 :*** *Series diode circuit analysis in forward bias*

Following are the resulting voltage and current levels:

$$V_D = V_\gamma$$
$$V_R = E - V_\gamma$$
$$I_D = I_R = \frac{V_R}{R} \qquad ...(1.4)$$

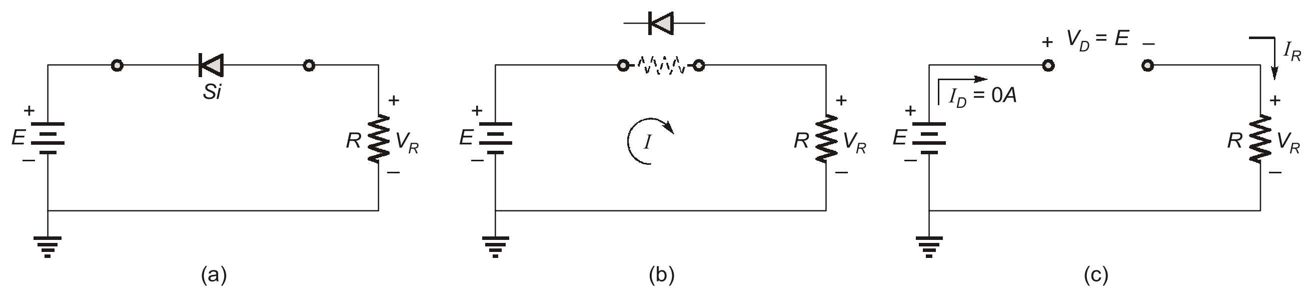



***Figure-1.7:*** *Series diode circuit analysis in reverse bias*

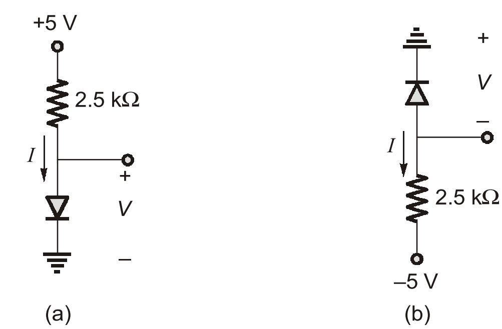
In Fig. 1.7 (a) the diode of Fig. (1.5) has been reversed. Mentally replacing the diode with a resistive element as shown in Fig. 1.7 (b) will reveal that the resulting current direction does not match the arrow in the diode symbol. The diode is in the "off" state, resulting in the equivalent circuit of Fig. 1.7 (c). Due to the open circuit, the diode current is 0 A and the voltage across the resistor R is the following:

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

The fact that $V_R = 0$ V will establish $E$ volts across the open circuit defined by Kirchhoff's voltage law. Always keep in mind that under any circumstances dc, ac instantaneous values, pulses, and so on—***Kirchhoff's voltage law must be satisfied!***

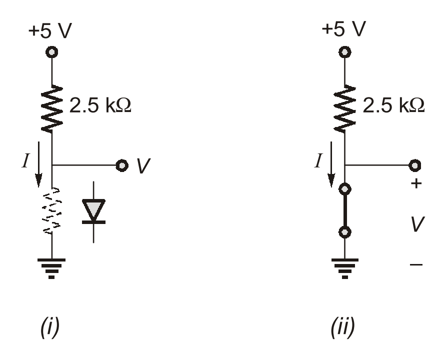
***Example*-1.1** [Single Branch Diode Circuits]

Assuming the diodes to be ideal, find the values of $I$ and $V$ in the circuits shown below:




***Solution*:**

In Fig. (a) replacing the diode with a resistive element as shown below in ***Fig. (i)***:




The resulting direction of $I$ is a match with the arrow in the diode symbol, the diode is in the "on" state. Now the network can be redrawn as shown in ***Fig. (ii)***.

The resulting voltage and current levels are the following:

$$V = 0\text{ V} \qquad \text{[as diode is ideal so } V_\gamma = 0\text{ V]}$$

and

$$I = \frac{5-0}{2.5\,k} = 2\text{ mA}$$

In Fig. (b) replacing the diode with a resistive element as shown below in ***Fig. (iii)***:

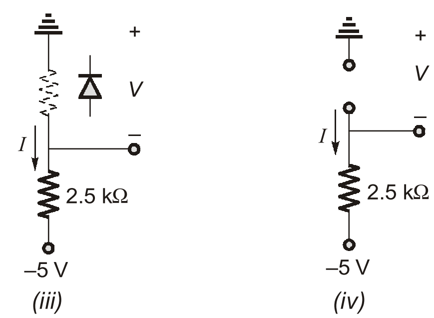



Fig. (iii) reveals that the resulting direction of current $I$ does not match the arrow in the diode symbol. The diode is in the "off" state resulting in the equivalent circuit as shown in ***Fig. (iv)***:

Resulting current and voltage can be calculated as below:

$$I = 0\text{ A} \qquad \text{[Since diode is open circuit]}$$

Now applying KVL in the circuit

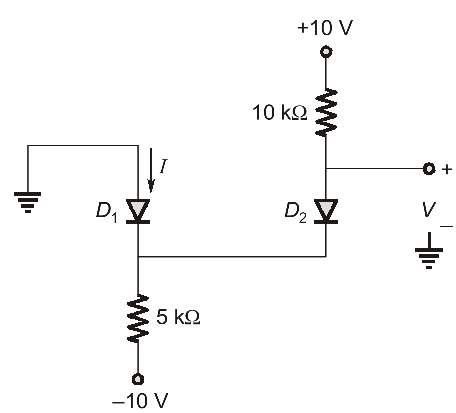
$$V + 2.5\,I - 5 = 0$$

$$\Rightarrow \quad V + 2.5 \times 0 - 5 = 0$$

$$\Rightarrow \quad V = 5\text{ V}$$

***Example*-1.2** [Multiple Branch Diode Circuit]

Assuming diodes to be ideal, find the values of $I$ and $V$ in the following circuit:

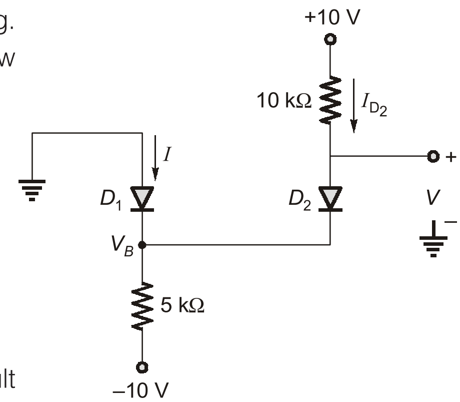



***Solution:***

**NOTE**

In such type of circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such cases, we make a plausible assumption, proceed with the analysis, and check whether we end up with a consistent solution.

For this circuit, we shall assume that both diodes are conducting. It follow that $V_B = 0$ and $V = 0$. The current through $D_2$ can now be determined from




$$I_{D_2} = \frac{10-0}{10\text{k}} = 1\text{mA}$$

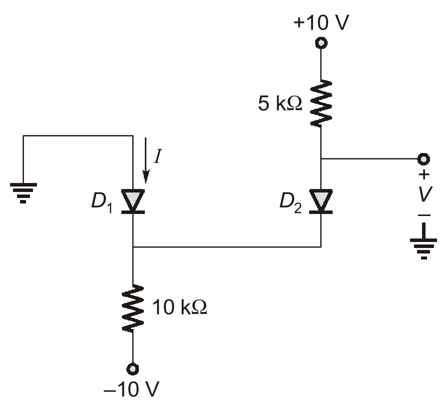
Writing a node equation at B,

$$I + 1 \text{ mA} = \frac{0-(-10)}{5\text{ k}}$$

$$\Rightarrow \quad I = +1 \text{ mA}$$

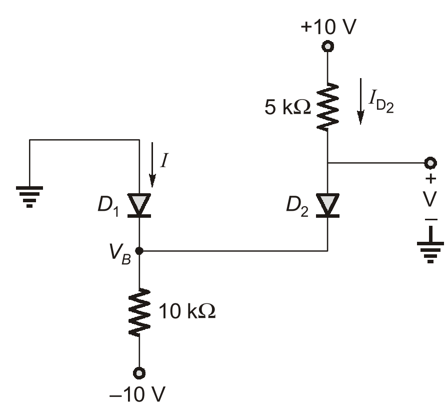
Thus $D_1$ is conducting as originally assumed and the final result is $I$ = **1 mA** and $V$ = **0 V**.

**Example-1.3** Assuming diodes to be ideal, find the values of $I$ and $V$ in the following circuit:




***Solution:***

If we assume that both diodes are conducting then $V_B$ = 0 V and $V$ = 0 V. The current in $D_2$ is obtained from




$$I_{D_2} = \frac{10-0}{5\text{k}} = 2 \text{ mA}$$

The node equation at $B$ is $$I + 2 \text{ mA} = \frac{0-(-10)}{10\text{ k}}$$

$$\Rightarrow \quad I = -1 \text{ mA}$$

$I = -1$ mA, is not possible as $I$ does not match with arrow direction of the diode $D_1$ so our original assumption is not correct. We start again, assuming that $D_1$ is off and $D_2$ is on. The current $I_{D_2}$ is given by

$$I_{D_2} = \frac{10-(-10)}{10\text{ k}+5\text{ k}} = 1.33 \text{ mA}$$

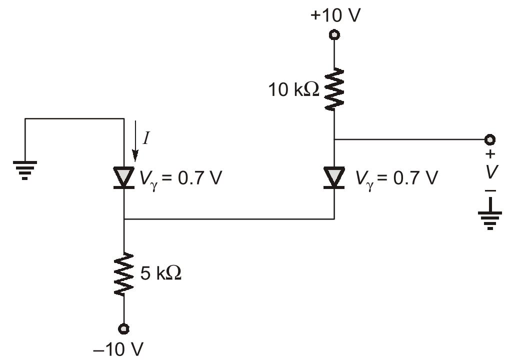
and the voltage at node $B$ is

$$V_B = -10 + 10\text{ k} \times 1.33 \text{ mA} = +3.3 \text{ V}$$

Thus $D_1$ is reverse biased as assumed, and the final result is $I$ = **0 A** and $V$ = **3.3 V**.

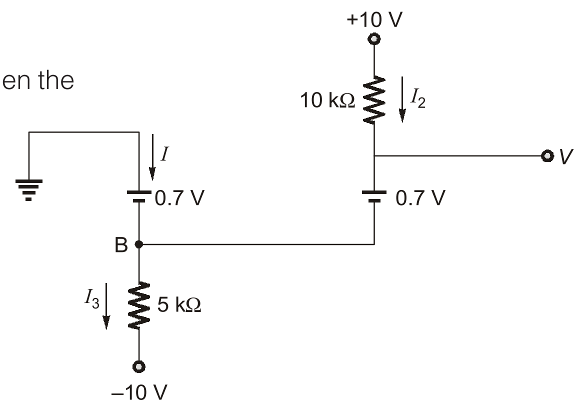
**Example-1.4** [Practical diode circuit]

Find $I$ and $V$ for the circuit shown below:




**Solution:**

We shall assume that $D_1$ and $D_2$ are forward bias then the equivalent circuit can be redrawn as shown below:




So, voltage at node $B$ is

$$V_B = -0.7 \text{ V}$$

and

$$V = 0.7 + V_B$$
$$= 0.7 - 0.7 = 0 \text{ V}$$

Hence, $I_2$ can be calculated as

$$I_2 = \frac{10-0}{10\text{ k}} = 1\text{ mA}$$

Now applying KCL at node $B$

$$I_3 = \frac{0.7-(-10)}{5\text{ k}\Omega} = 1.86\text{ mA}$$

$$I = I_3 - I_2 = 1.86 \text{ mA} - 1 \text{ mA}$$

$$\Rightarrow \quad I = 0.86 \text{ mA}$$

Thus $D_1$ is conducting as originally assumed and the final result is $I$ = 0.86 mA and $V$ = 0 V.

## 1.3 Diode Logic Gates

Diodes together with resistors can be used to implement digital logic functions. Fig. (1.8) shows two diode logic gates.

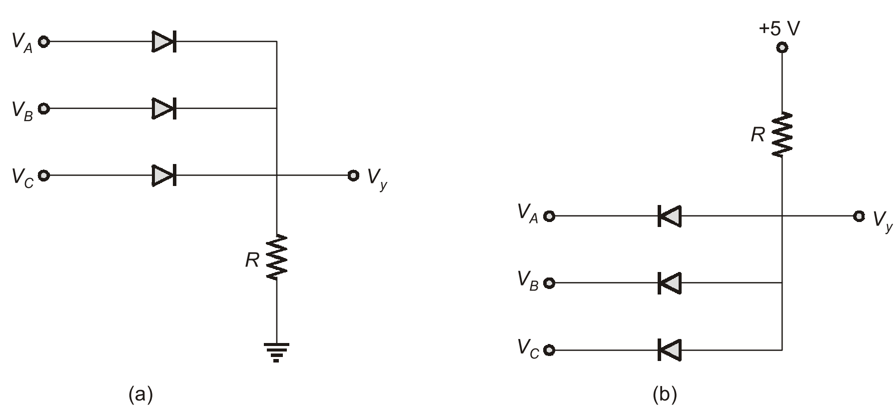
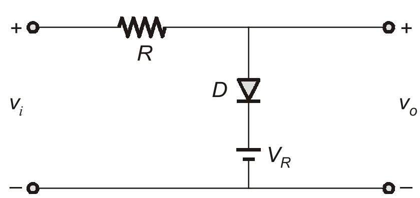



***Figure-1.8:*** *Diode logic gates (a) OR gate (b) AND gate*

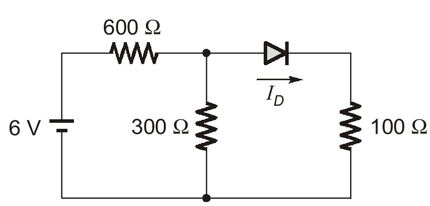
## Student's Assignments 1

**Q.1** In the circuit shown below the input $v_i$ has positive and negative swings and $v_o$ is the output then




(a) $v_o = 0$ for negative $v_i$
(b) $v_o = V_R$ for positive $v_i$
(c) $v_o = V_R$ for $v_i > V_R$
(d) $v_o = V_R$ for all $v_i$

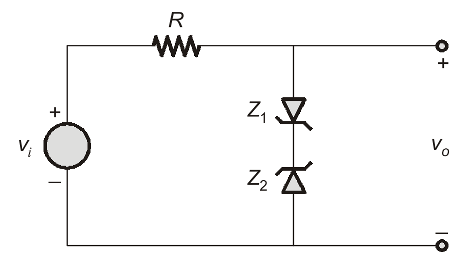
**Q.2** In the *Si* diode circuit shown below, a diode current of 6.7 mA is flowing.




Assuming diode is ideal one. Its forward resistance and cut-in voltage are

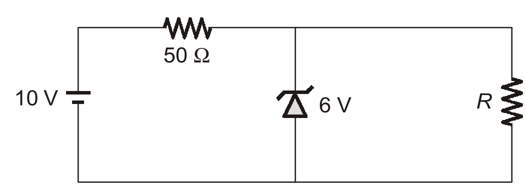
(a) 2 Ω, 0.7 V (b) 0 Ω, 0.7 V
(c) 0 Ω, 0 V (d) 4 Ω, 0 V

**Q.3** In the circuit shown below the Zener voltage $V_{Z_1} = V_{Z_2} = 5$ volts, $V_\gamma = 0.6$ V, $v_o$ is the output then



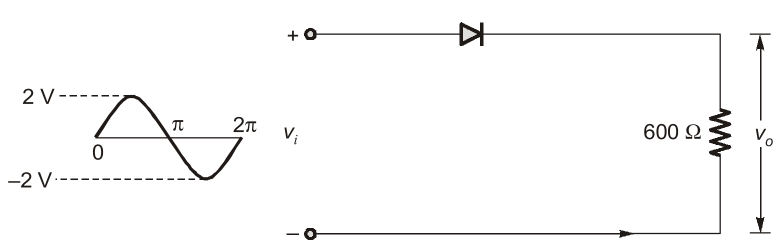

(a) For $|v_i| \le 5.6$ volts, $v_o = v_i$
(b) For $|v_i| \le 10$ volts, $v_o = v_i$
(c) For $|v_i| > 5.6$ volts, $v_o = v_i$
(d) $v_o = 5.6$ volts for all $v_i$

**Q.4** The 6 V Zener diode shown in figure has zero Zener resistance and a knee current of 5 mA. The minimum value of $R$ so that the voltage across it does not fall below 6 V is

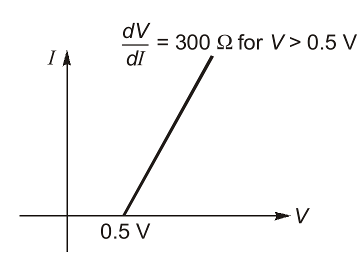



(a) 1200 Ω (b) 80 Ω
(c) 50 Ω (d) 10 Ω

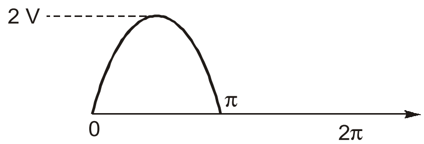
**Q.5** Consider the circuit shown in Figure (I). If the diode used here has the V-I characteristic as in Figure (II), then the output waveform $v_o$ is

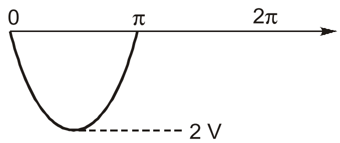


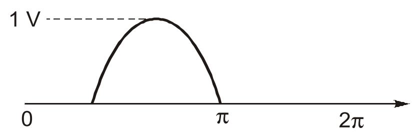

(I)

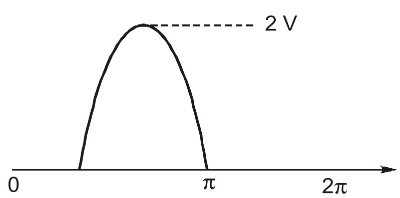



(II)

(a) 


(b) 

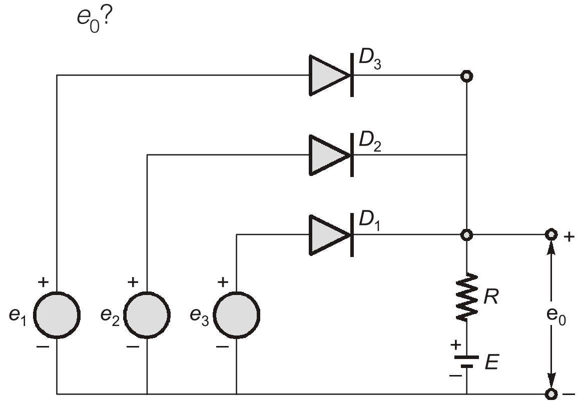

(c) 


(d) 


**Q.6** A diode is very useful for rectifier circuits due to its

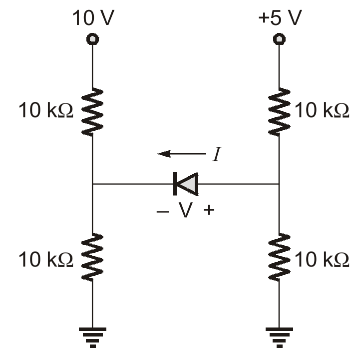
(a) ability to conduct current only in one direction
(b) ability to given current in both direction
(c) zero resistance in both direction
(d) none of these

**Q.7** In the circuit shown below, if $e_1 = 2$ V, $e_2 = 5$ V, $e_3 = 1$ V and $E = 2$ V, then which one of the diodes will be conducting and what will be the $e_0$?



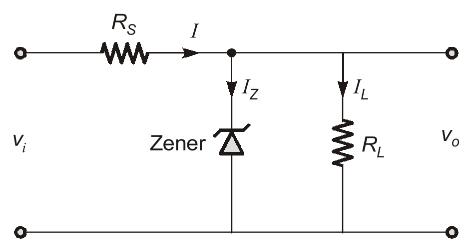

(a) $D_3$ : 1 V (b) $D_1$ : 2 V
(c) $D_2$ : 5 V (d) $D_1$ : 5 V

**Q.8** Assuming diode in the circuit is ideal one. Find the current and voltage shown in the figure.




(a) 0 mA, 2 V (b) 0 mA, –2.5 V
(c) 1 mA, 2 V (d) 1 mA, 2.5 V

**Q.9** Consider the following statements regarding the circuit given in the figure, where the output voltage is constant:




1. $v_i >$ the voltage at which the Zener breaks down.
2. $I_L <$ the difference between $I$ and $I_Z$, the current at which the Zener breaks down.
3. $R_S <$ the Zener nominal resistance.

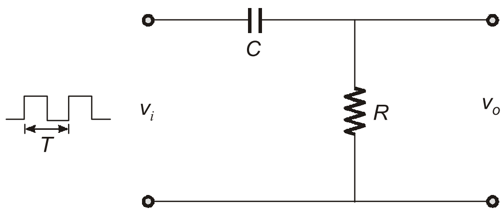
Of these statements:

(a) 1, 2 and 3 are correct
(b) 1 and 2 are correct
(c) 2 and 3 are correct
(d) 1 and 3 are correct

**Q.10** The ideal characteristics of a voltage stabilizer is

(a) constant output voltage with low internal resistance
(b) constant output current with low internal resistance
(c) constant output voltage with high internal resistance
(d) constant internal resistance with variable output voltage

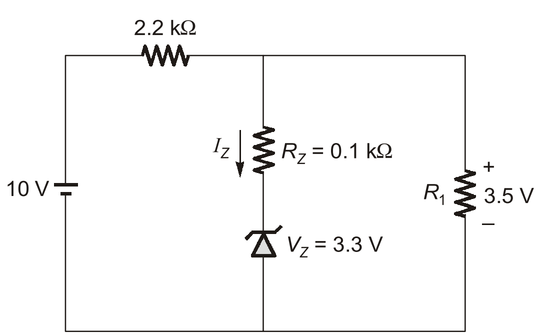
**Q.11** For the circuit given below, consider the following statements:




1. The output $v_o$ will consist of a positive and a negative spike $RC << T/2$.
2. The output $v_o$ will be similar to $v_i$ if $RC >> T/2$.
3. The output pulse will have a higher rise time if $RC$ is made progressively smaller than $T$.

Of these statements:
(a) 1, 2 and 3 are correct
(b) 1 and 2 are correct
(c) 2 and 3 are correct
(d) 1 and 3 are correct

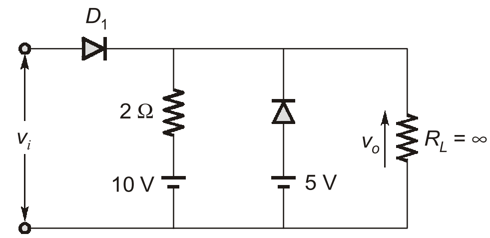
**Q.12** The current through the Zener diode in figure is



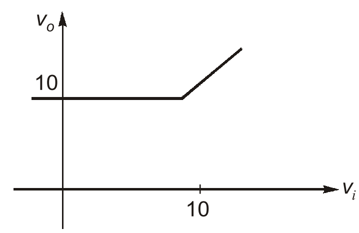

(a) 33 mA (b) 3.3 mA
(c) 2 mA (d) 0 mA

**Q.13** A forward biased Zener diode behaves as a
(a) tunnel diode
(b) Schottky diode
(c) no diode properties
(d) ordinary diode

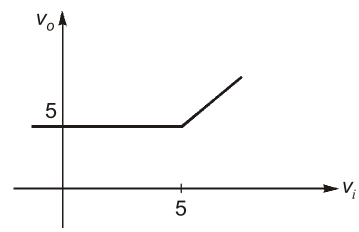
**Q.14** Assuming that diodes $D_1$ and $D_2$ of the circuit shown in figure to be ideal, the transfer characteristics of the circuit will be



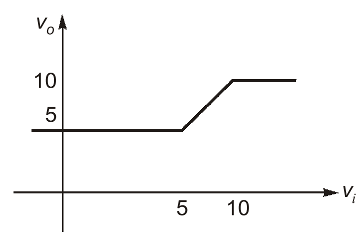

(a)



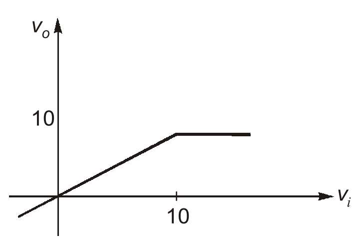

(b)



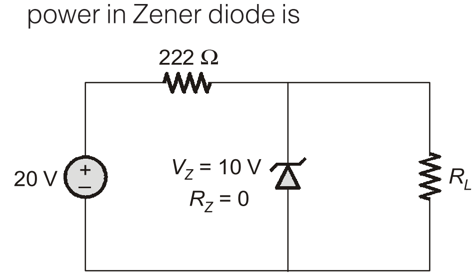

(c)




(d)




**Q.15** In the voltage regulator circuit shown below the power rating of Zener diode is 400 mW. The value of $R_L$ that will establish maximum power in Zener diode is




(a) 5 kΩ (b) 2 kΩ
(c) 10 kΩ (d) 8 kΩ

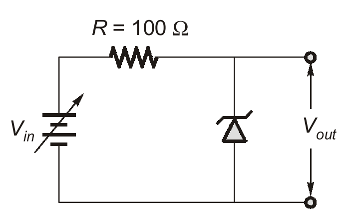
## Student's Assignments 1 Answer Key

| | | | |
|---|---|---|---|
| **1.** (c) | **2.** (c) | **3.** (a) | **4.** (b) |
| **5.** (c) | **6.** (a) | **7.** (c) | **8.** (b) |
| **9.** (b) | **10.** (a) | **11.** (b) | **12.** (c) |
| **13.** (d) | **14.** (a) | **15.** (b) | |

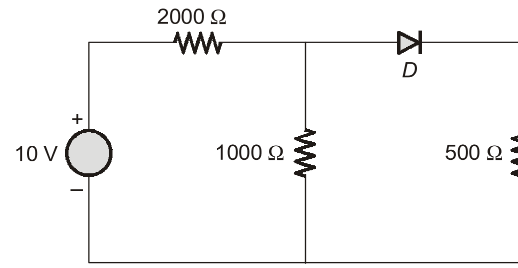
## Student's Assignments 2

**Q.1** A light-emitting diode (LED) has a greater forward voltage drop than that of common signal diode. A typical LED can be modeled as a constant forward voltage drop $v_D$ = 1.6 V. Its luminous intensity $I_v$ varies directly with forward current and is described by $I_v = 40 i_D$ millicandela (mcd).
A series circuit consists of a LED, a current-limiting resistor R, and a 5-V DC source $V_s$. Find the value of $R$ such that the luminous intensity is 1 mcd.

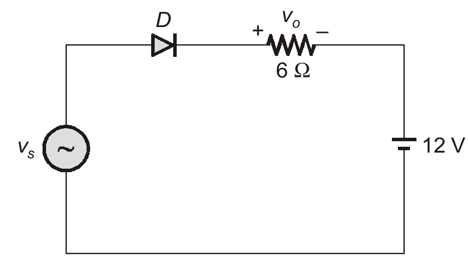
**Q.2** Determine the maximum and the minimum input voltages that can be regulated by the Zener diode of circuit shown in figure. Take $V_b$ = 5.1 V, at $I_z$ = 4.9 mA, $I_{zk}$ = 1 mA, $R_z$ = 7 Ω at $I_z$ power dissipation = 1 Watt.



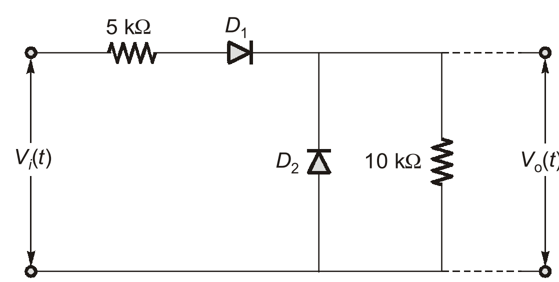

**Q.3** In the circuit shown below, the diode has a forward resistance $R_f$ = 15 Ω and a cut-in voltage $V_\gamma$ = 0.5 V. Determine the current in the diode.




**Q.4** Figure shown below is a battery charging circuit. If $v_s$ = 120 sin$\omega t$, calculate (*i*) the conduction angle of diode $D$, (*ii*) and the average value of $v_0$.




**Q.5** Sketch the waveform of the output in the circuit for one cycle for an input of 6 sin 100$\pi t$. The diode has a cut-in voltage of 0.5 V.




## Student's Assignments 2 Answer Key

**1.** 136 Ω **2.** 4.86 V, 25.7 V

**3.** 2.39 mA **4.** **(i)** 168.52° **(ii)** 44.37 V

**5.**