## THE P-N JUNCTION DIODE

We begin our introduction to semiconductor devices by examining the simplest component namely the diode. The word diode is derived from the fact that the device has two (di) electrodes (ode). It has the circuit symbol shown below.

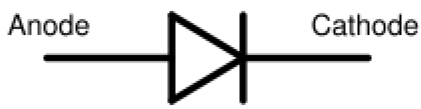



Fig. 3-1 Circuit symbol for the P-N junction diode

Diodes are a basic building block of all electronics and are used to control the direction of current flowing in circuits. The p-n junction diode is a device made from a p-n junction as shown in the figure below

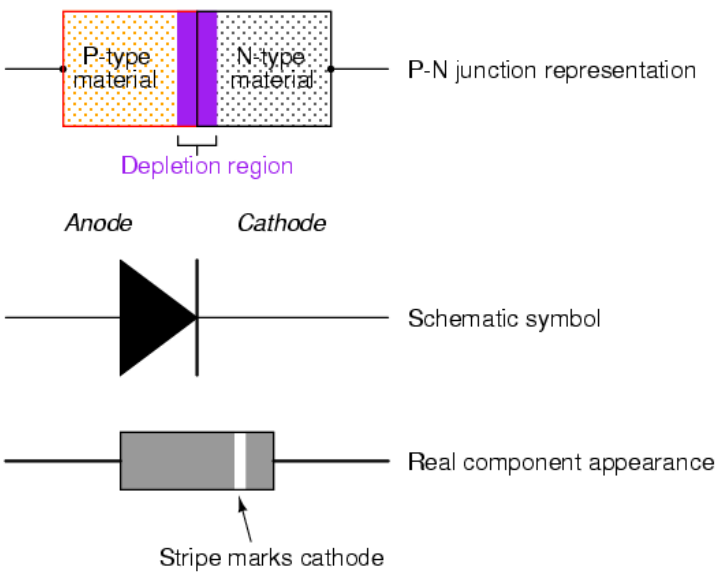



Fig. 3-2 Relationship between a p-n junction and the diode

Just like the p-n junction, a forward conducting (forward bias) diode is said to be turned on or simply on. A diode operated in this mode allows current to flow through it. If the diode is reverse biased, no current flows, that is, it blocks the flow of current and thus, behave as an open circuit. Diodes operated in this mode are said to be cut-off. Thus a diode can be described as a one-way valve for electric current.

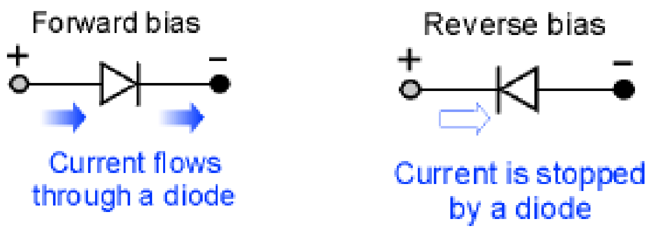
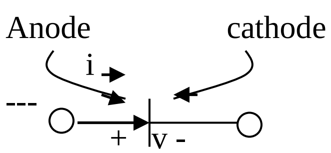


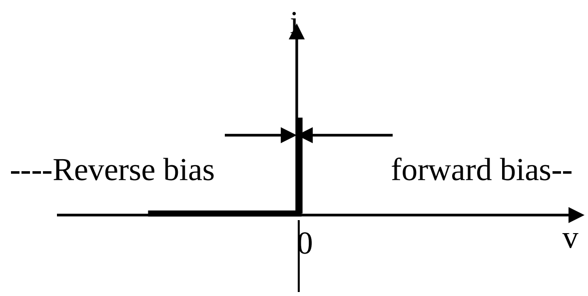

Fig. 3-3 The two modes of operation of the p-n junction diode.

**THE IDEAL DIODE**

In order to understand the essence of diode function (diode behavior), we begin with a ‘’fictitious ‘’ element, the ideal diode. The ideal diode may be considered the most fundamental non-linear element. It is a two-terminal device having the circuit symbol shown in fig. 3-4 below




(a)




(b)

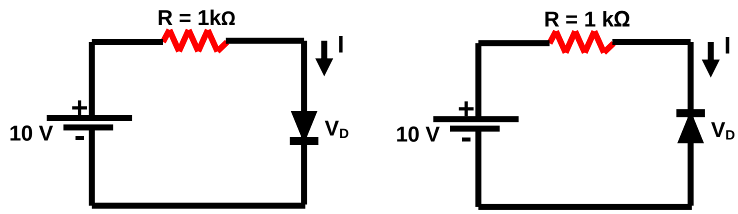
*(The positive terminal of the diode is called the anode and the negative terminal is the cathode)*

Fig 3-4

If a negative voltage is applied to the diode, no current flows and the diode behave as an open circuit. Diodes operated in this mode are said to be reverse- biased, or operated in the reverse direction. An ideal diode has zero current when operated in the reverse direction and is said to be cut-off.

If a positive current is applied to the diode, zero voltage drops appear across the diode. In other words the ideal diode behaves as a short circuit in the forward direction. It passes any current with zero voltage drop. A forward conducting diode is said to be turned on or simply on.

The following examples show two-diode circuits that illustrate this point.




(a) (b)

Fig. 3-5 The two modes of operation of the ideal diode.

(a) The diode is conducting thus its voltage drop will be zero, and the current through it will be determined by the +10V supply and the 1-KΩ resistor as 10mA

ie

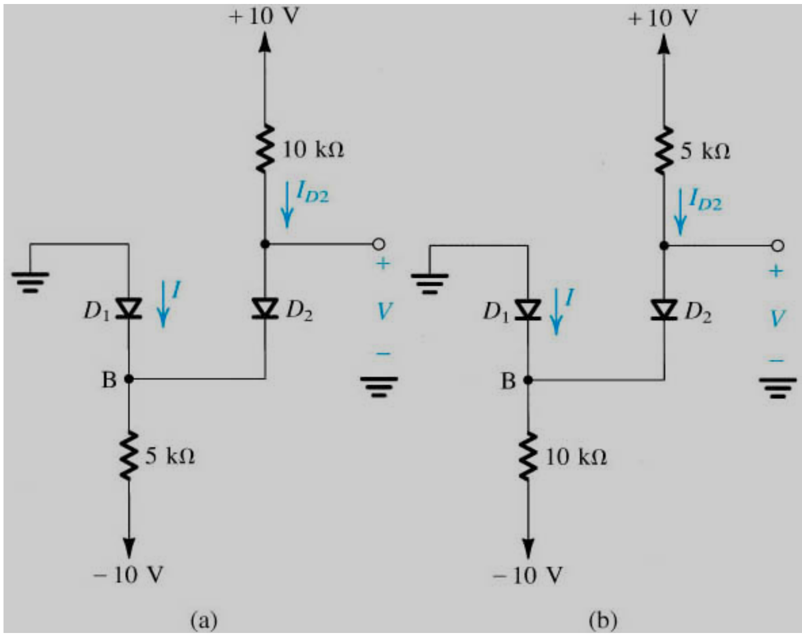
$$10 - 0 = IR$$

$$I = \frac{10}{R} = \frac{10}{1} = 10mA$$

(b) The diode would be cut off since its current will be zero, which will in turn mean that the entire 10v supply will appear as reverse bias across the diode. From the example above, it should be noted that the external circuit must be designed so as to limit the voltage across a cut off diode to predetermined values

***<u>Example 2</u>***

Assuming the diode to be ideal, find the values of I and V in the circuit below.



It is not obvious whether none, one or both diodes are conducting. Thus we make a plausible assumption, proceed with the analysis and then check whether we end up with a consistent solution. For the circuit in (a) assume both diodes are conducting. It follows that $V_B = 0$ and V = 0.

Current through $D_2$ can be determined from

$$I_{D2} = \frac{10-0}{10} = 1mA$$

Node B,

$$I + 1 = \frac{0-(-10)}{5} = 2mA$$

I =1mA

thus $D_1$ is conducting as originally assumed.
Final results I =1mA, V = 0 V

For fig.(b) assume that both diodes are conducting, then
$V_B = 0$ and V = 0

$$I_{D2} = \frac{10-0}{5} = 2mA$$

Node equation at B is;

$$I + 2 = \frac{0-(-10)}{10} = 1mA$$

Which yields I = - 1 mA
This is not possible (no reverse current). Hence original assumption is not correct.
Assume again that $D_1$ is off and $D_2$ is on.

$$I_{D2} = \frac{10-(-10)}{15} = 1.33mA$$

Voltage at node B is: $V_B$ =-10+ 10 x 1.33 = 3.3V

Thus $D_1$ is reverse biased as assumed and the final results is I =0, V = 3.3V

## **Terminal characteristics of junction diodes ''real diodes''**

The *p-n junction diode* is a device made from a p-n junction. When the device is *forward biased*, with the p-side at higher electric potential, the diode conducts current easily; but the current is very small when the diode is *reverse biased*.

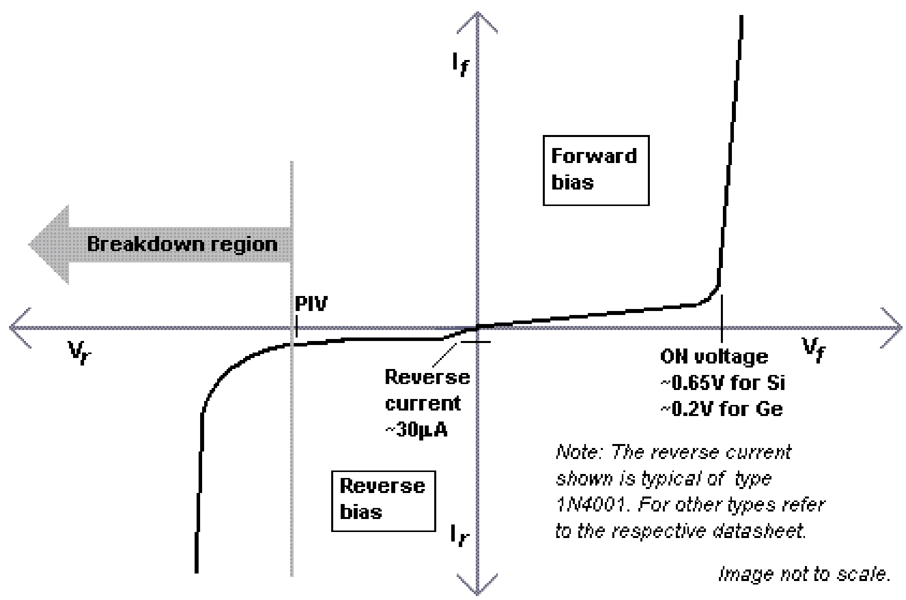



Fig. 3-6 I –V characteristics of the p-n junction diode

In a forward-biased diode the current is negligible until the voltage reaches the bias voltage, which is 0.65 V for common silicon diodes. You can think of the bias voltage as the amount of energy difference it takes to open (turn on fully) the diode. When the device is forward biased, the diode conducts current easily; but the current is very small when the diode is reverse biased.

The characteristic curve consists of three distinct regions:

1. the forward –bias region, determined by V >0
2. the reverse – bias region, determined by V<0
3. the breakdown region, determined by V< PIV

**The forward – bias region**

This region of operation is entered when the terminal voltage v is positive.
The I-v relationship is closely approximated by

$$i = I_S\left(e^{V/nV_T} - 1\right)$$

$I_s$ is constant for a given diode temperature. It is normally called the *saturation current (or scaling constant).*

The voltage $V_T$ is called the *thermal voltage* given by:

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

K – Boltzmann's constant =1.38 x $10^{23}$ $JK^{-1}$

T – is the absolute temperature of the p–n junction,

q –magnitude of electronic charge = 1.6 x $10^{-19}$C

At, room temperature the value of $V_T \approx$ 25.2mV

In the diode equation the constant ***n*** has a value between 1 and 2, depending on the material and physical structure of the diode.

For appreciable current in the forward direction, ($i \gg I_s$)

$$i = I_S\left(e^{V/nV_T}\right)$$

This relationship can be expressed alternatively in the logarithmic form

$$v = nV_T \ln\left(\frac{i}{I_S}\right)$$

let us consider the forward I –v relationship and evaluate the current $I_1$ corresponding to a diode voltage $V_1$

$$I_1 = I_S\left(e^{V_1/nV_T}\right)$$

Similarly if the voltage is $V_2$ the diode current $I_2$ will be

$$I_2 = I_S\left(e^{V_2/nV_T}\right)$$

These two equations can be combined to produce;

$$\frac{I_2}{I_1} = \frac{e^{V_2/nV_T}}{e^{V_1/nV_T}} = e^{(V_2 - V_1)/nV_T}$$

*Which can be written as:*

$$V_2 - V_1 = nV_T \ln \frac{I_2}{I_1}$$

Or in terms of base – 10 logarithms

$$V_2 - V_1 = 2.3nV_T \log_{10} \frac{I_2}{I_1}$$

This equation implies that for a decade (factor of 10) change in current, the diode voltage drop changes by $2.3nV_T$ which is approximately 60mV for n=1 and 120mV for n=2. In some situations involving diode analysis, one may be given the value for the voltage drop per decade change in current instead of the value of n.

*A glance at the i-v characteristic in the forward region reveals that the current is negligibly small for v smaller than 0.5 V. This value is usually referred to as the* ***cut-in voltage****. This is the consequence of the exponential relationship. Secondly, for a fully conducting diode, the voltage drop lies in a narrow range, approximately 0.6-0.8 V. This gives rise to a simple model for the diode, where it is assumed that a conducting diode has approximately a* ***0.7V*** *drop across it.*

***Reverse – bias region***

The reverse – bias region is entered when the diode voltage v is made negative

The equation:

$$i = I_S\left(e^{V/nV_T} - 1\right)$$

Predicts that if v is negative and a few times larger than $V_T$ (25mV) the exponential term becomes negligibly small compared to unity and the diode current becomes

$$i \approx -I_S$$

That is, current in the reverse direction is constant and equal to $I_s$. This is the reason behind the term saturation current. Reverse current is a strong function of temperature and doubles for every $10^o$ C rise in temp.

## The breakdown region

The breakdown region is entered when the magnitude of the reverse current exceeds a threshold value specific to the particular diode and called the breakdown voltage. In the breakdown region, the reverse current increases rapidly, with the associated increase in voltage drop, being very small. The fact that the diode i-v characteristic in breakdown is almost a vertical line enables it to be used in voltage regulation **(more explanation of this in the next lecture)**.

## *ANALYSIS OF DIODE CIRCUITS*

Consider the circuit shown below, consisting of a dc source V, a resistor R, and a diode. We wish to analyze this circuit to determine the current $I_D$ and voltage $V_D$.

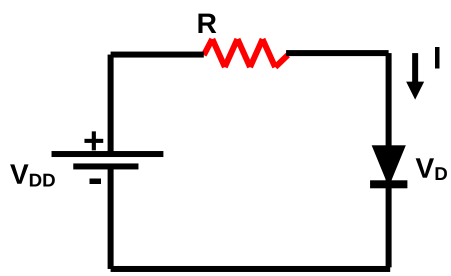



Fig. 3-7

In the diode circuit the diode is biased in the forward direction.
Assume V > 0.5 v (for silicon)
Diode current is much greater than $I_s$
Thus,

$$I_D = I_S\left(e^{V_D/nV_T}\right) - - - - - (1)$$

The other equation that governs circuit operations is obtained by writing a kirchoff loop equation:

$$V_{DD} = I_D R + V_D$$

$$I_D = \frac{(V_{DD} - V_D)}{R} - - - - (2)$$

Assuming that Is and n are known, equations 1 and 2 will have two unknown quantities $I_D$ and $V_D$. Two alternative ways for obtaining the solution are *graphical analysis* and *iterative analysis.*

**a. Graphical Analysis**

This is performed by plotting the relationships of eqn. 1 & 2 on the i-v plane. The solution can then be obtained as the co-ordinates of the point of intersection of the two graphs.

Graphical analysis aids in the visualisation of circuit operation. However, the effort involved in performing such analysis, particularly for complex circuits are too great to be justified in practice and we shall not discuss this further.

**b. ITERATIVE ANALYSIS**

Equation 1 & 2 can be solved using a simple iterative procedure as is illustrated in the ff. example.

**Example:**

Determine the current $I_D$ and the diode voltage $V_D$ for the circuit in Figure 5. With V = 5 V and R = 1 kΩ. Assume that the diode has a current of 1 mA at a voltage of 0.7 V, and that its voltage drop changes by 0.1 V for every decade change in current.

Solution:

To begin the iteration we assume that $V_D$ = 0.7 V and use Eq. 2 to determine the current.

$$I_D = \frac{(V_{DD} - V_D)}{R} = \frac{(5 - 0.7)}{1k\Omega} = 4.3mA$$

We then use the diode equation shown below to obtain a better estimate for $V_D$.

$$V_2 - V_1 = 2.3nV_T \log_{10} \frac{I_2}{I_1}$$

For our case 2.3 $nV_T$ = 0.1 V; since we have been told that the voltage drop changes by 0.1 V for every decade change in current then;

$$V_2 = V_1 + 0.1\log_{10}\frac{I_2}{I_1}$$

Substituting $V_1$ = 0.7 V, $I_1$ = 1 mA, and $I_2$ = 4.3 mA results in $V_2$ = 0.763. Thus the results of the first iteration are $I_D$ = 4.3 mA and $V_D$ = 0.763 V. the second iteration proceeds in a similar manner:

$$I_D = \frac{(V_{DD} - V_D)}{R} = \frac{(5 - 0.763)}{1k\Omega} = 4.237mA$$

$$V_2 = 0.763 + 0.1\log_{10}\frac{4.237}{4.3} = 0.762$$

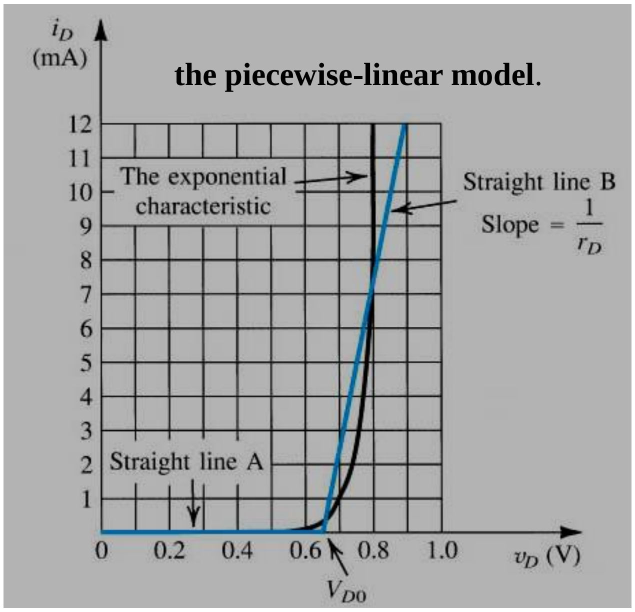
Thus, the second iteration yields $I_D$ = 4.237 mA and $V_D$ = 0.762V. Since these values are not much different from the values obtained after the first iteration, no further iterations are necessary, and the solution is $I_D$ = 4.237 mA and $V_D$ = 0.762V.

## SIMPLIFIED DIODE MODELS

The iterative analysis yields very accurate results after two or three iterations. However, there are situations which require rapid circuit analysis. For instance, a designer may want to evaluate various possibilities before deciding on a suitable circuit. To speed up the analysis process, one has to be content with less precise results and postpone accurate analysis until the final design. Two simplified models used in the analysis of diode circuits are: **The piecewise-linear model** and **constant- drop voltage model.**

### The Piecewise-Linear Model

In this model, the diode I-V characteristic in the forward direction (the exponential curve) is approximated by two straight lines, line A with zero slope and line B with a slope of $1/r_D$ as shown below.



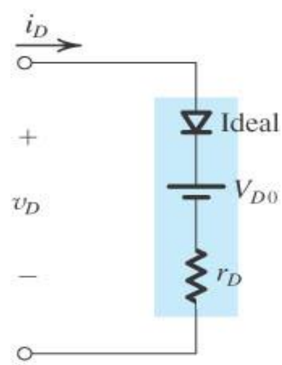

The straight-lines (or piecewise-linear) model can be described by;

$$i_D = 0, \ldots v_D \le V_{DO}$$

$$i_D = \frac{(v_D - V_{DO})}{r_D}, \ldots v_D \ge V_{DO}$$

Where $V_{DO}$ is the intercept of line B on the voltage axis and $r_D$ is the inverse of the slope of line B. For the particular example shown, $V_{DO}$ = 0.65 V and $r_D$ = 20 Ω.

The piecewise-linear model described by the equations shown above can be represented by the equivalent circuit shown below.



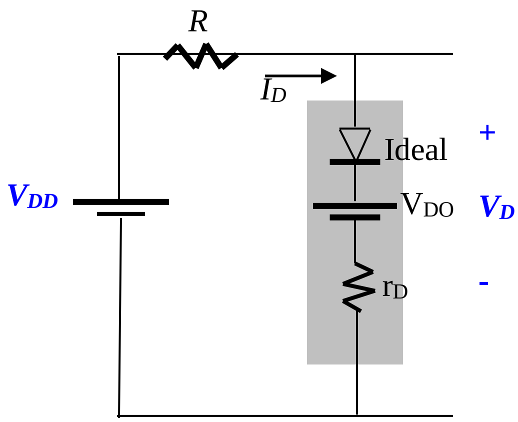

(b)

Fig 3-9 The piecewise-linear model

An ideal diode has been included in this model to constrain the current $i_D$ to flow in the forward direction only.

**Example**
Repeat the problem solved earlier with iterative analysis, utilizing the piecewise-linear model. (Take $V_{DO}$ = 0.65 V and $r_D$ = 20 Ω)

**<u>Solution</u>**
Replace the diode in fig 3-7 with the equivalent circuit model. This results in the circuit shown below.




The current $I_D$ can be obtained from the resulting circuit by writing a loop equation as shown below;

$$I_D = \frac{V_{DD} - V_{DO}}{R + r_D} = \frac{5 - 0.65}{1 + 0.02} = 4.26mA$$

The diode voltage can now be:

$$V_D = V_{DO} + I_D r_D = 0.65 + 4.26 \times 0.02 = 0.735V$$

**The Constant-Voltage-Drop Model**

An even simpler model of the diode forward characteristics can be obtained if we use a vertical straight line to approximate the fast-rising part of the exponential curve as shown below.

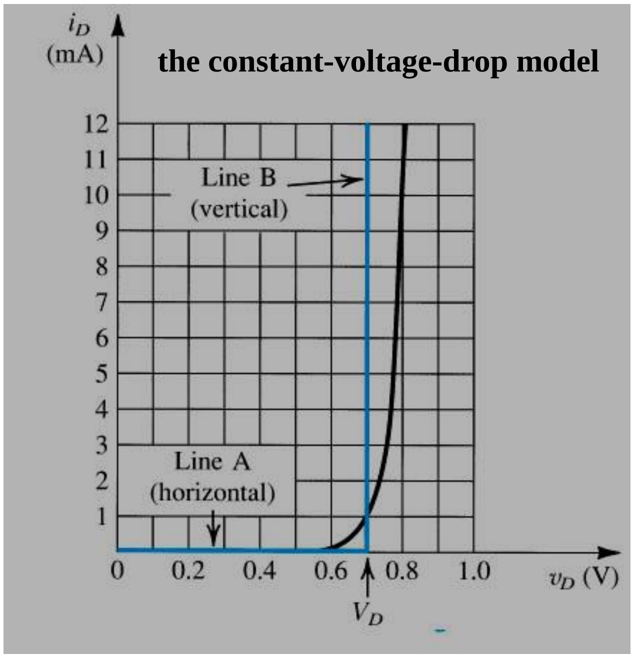
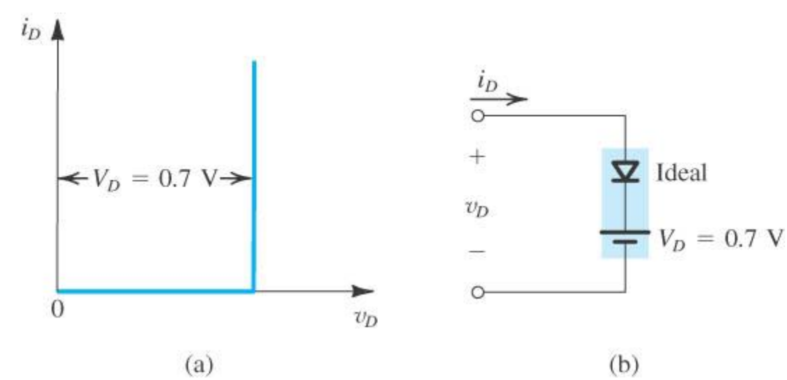



Fig 3-10 The constant drop voltage model

The resulting model simply says that a forward-conducting diode exhibits a constant voltage drop $V_D$. The value of $V_D$ is usually taken to be 0.7 V. The constant-drop-voltage model is frequently employed in the initial phases of analysis and design. It can be represented by the equivalent circuit shown below.



**Example**

Let's solve the same problem using the constant-drop-voltage model.

We obtain;

$$I_D = \frac{V_{DD} - 0.7}{R} = \frac{5 - 0.7}{1} = 4.3mA$$

**TYPES OF DIODES AND THEIR APPLICATION**

Diodes are used in many circuits. The most important applications for diodes involve their ability to pass current in one direction. Some applications exploit other important characteristics, such as the nonlinear characteristic curve. The following are types of diodes

**Rectifier diodes**

All electronic systems that use ac power (usually the mains from the wall outlet) as a power source, have an internal dc power supply that converts the ac input into the needed dc supply voltages for all of the circuits within the system. One of the most important applications of diodes is in the design of rectifier circuits. A rectifier diode forms an essential building block of the dc power supplies required to power electronic equipment The rectifier diode converts the input sinusoid to a unipolar output

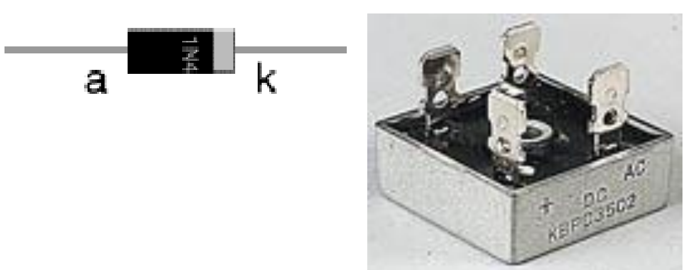



Fig. 3-11a Rectifier diodes

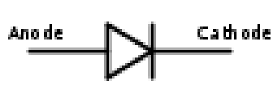



Fig. 3-11b Circuit symbol of the rectifier diode

## Signal diodes

Optimized for speed, they are used in low current and switching applications.


Fig. 3-12 Signal diode

## Zener diode

Designed to conduct in the reverse direction with a precise breakdown voltage, they are used in power supply regulation.

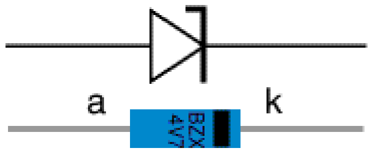



Fig. 3-13 Zener diode and its circuit symbol

## Light emitting diodes (LEDs)

Constructed from special materials that give off light when electrons and holes recombine at a forward biased p-n junction, they are useful as displays and indicators.

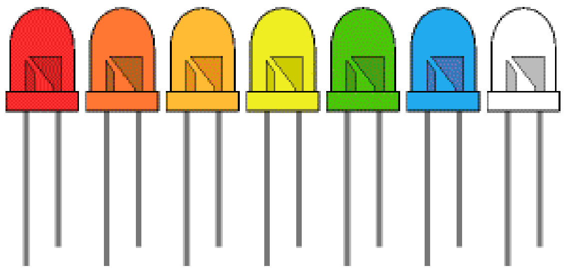


Fig. 3-14a light emitting diodes

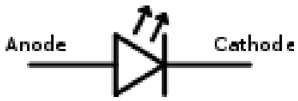


Fig. 3-14b circuit symbol of the light emitting diode

It is the most widely used light source in electronic equipment. The emission of energy may be in the form of heat, light or both. The type of material used, determines the colour and therefore the frequency of the emitted light. It replaces incandescent sources due to its longer life expectancy and lower operating power. Because of this efficiency, scientists and engineers are hard at work to develop designs that will allow LEDs to be used for many new applications, from traffic lights to atmospheric-haze detectors

## Photodiodes

Exposing a semiconductor to light can generate electron-hole pairs, which increases the number of free carriers and its conductivity. Diodes optimized to take advantage of this phenomenon are known as photodiodes.

Fig 3-15a A photodiode

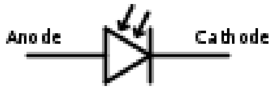



Fig 3-15b Circuit symbol of a photodiode

## Varactor diodes

Varactors are used as voltage-controlled capacitors, rather than as rectifiers. They are commonly used in parametric amplifiers, parametric oscillators and voltage-controlled oscillators as part of phase-locked loops and frequency synthesizers. For example, varactors are used in the tuners of television sets to electronically tune the receiver to different stations.

Fig 3-16 circuit symbol of a varactor

## <u>Some tips on how to test a diode</u>