PN Junction Diode

The symbol of diode is shown in **fig. 4**. The terminal connected to p-layer is called anode (A) and the terminal connected to n-layer is called cathode (K)

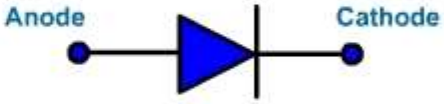


Fig.4

Reverse Bias:

If positive terminal of dc source is connected to cathode and negative terminal is connected to anode, the diode is called reverse biased as shown in **fig. 5**.

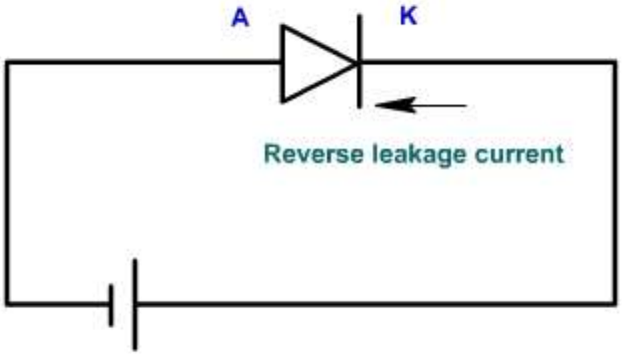


Fig.5

When the diode is reverse biased then the depletion region width increases, majority carriers move away from the junction and there is no flow of current due to majority carriers but there are thermally produced electron hole pair also. If these electrons and holes are generated in the vicinity of junction then there is a flow of current. The negative voltage applied to the diode will tend to attract the holes thus generated and repel the electrons. At the same time, the positive voltage will attract the electrons towards the battery and repel the holes. This will cause current to flow in the circuit. This current is usually very small (interms of micro amp to nano amp). Since this current is due to minority carriers and these number of minority carriers are fixed at a given temperature therefore, the current is almost constant known as reverse saturation current I_{CO}.

In actual diode, the current is not almost constant but increases slightly with voltage. This is due to surface leakage current. The surface of diode follows ohmic law (V=IR). The resistance under reverse bias condition is very high 100k to mega ohms. When the reverse voltage is increased, then at certain voltage, then breakdown to diode takes place and it conducts heavily. This is due to avalanche or zener breakdown. The characteristic of the diode is shown in **fig. 6**.

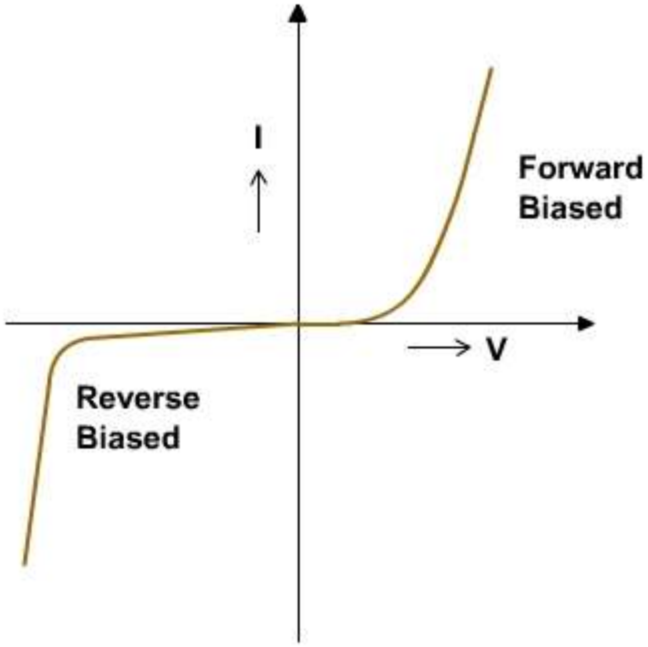


Fig.6

Forward bias:

When the diode is forward bias, then majority carriers are pushed towards junction, when they collide and recombination takes place. Number of majority carriers are fixed in semiconductor. Therefore as each electron is eliminated at the junction, a new electron must be introduced, this comes from battery. At the same time, one hole must be created in p-layer. This is formed by extracting one electron from p-layer. Therefore, there is a flow of carriers and thus flow of current.

Space charge capacitance C_T of diode:

Reverse bias causes majority carriers to move away from the junction, thereby creating more ions. Hence the thickness of depletion region increases. This region behaves as the dielectric material used for making capacitors. The p-type and n-type conducting on each side of dielectric act as the plate. The incremental capacitance C_T is defined by

$$C_T = \left|\frac{dQ}{dV}\right|$$

Since $i = \frac{dQ}{dt}$

Therefore, $i = C_T \frac{dV}{dt}$ **(E-1)**

where, dQ is the increase in charge caused by a change dV in voltage. C_T is not constant, it depends upon applied voltage, there fore it is defined as dQ / dV.

When p-n junction is forward biased, then also a capacitance is defined called *diffusion capacitance* C_D (rate of change of injected charge with voltage) to take into account the time delay in moving the charges across the junction by the diffusion process. It is considered as a fictitious element that allow us to predict time delay.

If the amount of charge to be moved across the junction is increased, the time delay is greater, it follows that diffusion capacitance varies directly with the magnitude of forward current.

$$C_D = \frac{dQ}{dV} = \frac{I\tau}{dV}$$ **(E-2)**

Relationship between Diode Current and Diode Voltage

An exponential relationship exists between the carrier density and applied potential of diode junction as given in equation E-3. This exponential relationship of the current i_D and the voltage $v_D$holds over a range of at least seven orders of magnitudes of current - that is a factor of 10^7.

$$i_D = I_0\left[\exp\left(\frac{qv_D}{nkT}\right) - 1\right] = I_0\left[e^{\left(\frac{qv_D}{nkT}\right)} - 1\right]$$ **(E-3)**

Where,

i_D= Current through the diode (dependent variable in this expression)
v_D= Potential difference across the diode terminals (independent variable in this expression)
I_O= Reverse saturation current (of the order of 10^{-15} A for small signal diodes, but I_O is a strong function of temperature)
q = Electron charge: 1.60×10^{-19} joules/volt
k = Boltzmann's constant: $1.38 \times l0^{-23}$ joules /° K
T = Absolute temperature in degrees Kelvin (°K = 273 + temperature in °C)
n = Empirical scaling constant between 0.5 and 2, sometimes referred to as the Exponential Ideality Factor

The empirical constant, n, is a number that can vary according to the voltage and current levels. It depends on electron drift, diffusion, and carrier recombination in the depletion region. Among the quantities affecting the value of n are the diode manufacture, levels of doping and purity of materials. If n=1, the value of k T/ q is 26 mV at 25°C. When n=2, k T/ q becomes 52 mV.

For germanium diodes, n is usually considered to be close to 1. For silicon diodes, n is in the range of 1.3 to 1.6. n is assumed 1 for all junctions all throughout unless otherwise noted.

Equation **(E-3)** can be simplified by defining V_T =k T/q, yielding

$$i_D = I_O\left[e\,xp\left(\frac{v_D}{nV_T}\right) - 1\right] = I_O\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right]$$ **(E-4)**

At room temperature (25°C) with forward-bias voltage only the first term in the parentheses is dominant and the current is approximately given by

$$i_D = I_O\, e^{\frac{v_D}{nV_T}}$$ **(E-5)**

The current-voltage (I-V) characteristic of the diode, as defined by (E-3) is illustrated in **fig. 1**. The curve in the figure consists of two exponential curves. However, the exponent values are such that for voltages and currents experienced in practical circuits, the curve sections are close to being straight lines. For voltages less than V_{ON}, the curve is approximated by a straight line of slope close to zero. Since the slope is the conductance (i.e., i / v), the conductance is very small in this region, and the equivalent resistance is very high. For voltages above V_{ON}, the curve is approximated by a straight line with a very large slope. The conductance is therefore very large, and the diode has a very small equivalent resistance.

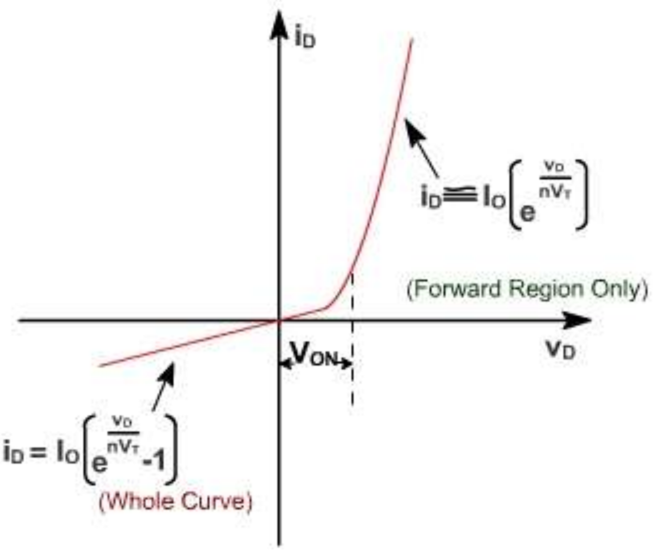


Fig.1 - Diode Voltage relationship

The slope of the curves of **fig.1** changes as the current and voltage change since the I-V characteristic follows the exponential relationship of relationship of equation (E-4). Differentiate the equation (E-4) to find the slope at any arbitrary value of $v_D$or i_D,

$$\frac{di_D}{dv_D} = \frac{I_O}{nV_T}\exp\left(\frac{v_D}{nV_T}\right) = \frac{I_O}{nV_T}e^{\frac{v_D}{nV_T}} \qquad \textbf{(E-6)}$$

This slope is the equivalent conductance of the diode at the specified values of v_D or i_D.

We can approximate the slope as a linear function of the diode current. To eliminate the exponential function, we substitute equation (E-4) into the exponential of equation (E-7) to obtain

$$\exp\left(\frac{v_D}{nV_T}\right) = \frac{i_D}{I_O} + 1 = \left(\frac{di_D}{dv_D}\right)\left(\frac{nV_T}{i_O}\right) \qquad \textbf{(E-7)}$$

A realistic assumption is that I_O<< i_D equation (E-7) then yields,

$$\frac{di_D}{dv_D} = \frac{i_D + I_O}{nV_T} \approx \frac{i_D}{nV_T} \qquad \textbf{(E-8)}$$

The approximation applies if the diode is forward biased. The dynamic resistance is the reciprocal of this expression.

$$r_d = \frac{nV_T}{i_D + I_O} \approx \frac{nV_T}{i_D} \qquad \textbf{(E-9)}$$

Although r_d is a function of i_d, we can approximate it as a constant if the variation of i_D is small. This corresponds to approximating the exponential function as a straight line within a specific operating range.

Normally, the term R_f to denote diode forward resistance. R_f is composed of r_d and the contact resistance. The contact resistance is a relatively small resistance composed of the resistance of the actual connection to the diode and the resistance of the semiconductor prior to the junction. The reverse-bias resistance is extremely large and is often approximated as infinity.

Temperature Effects:

Temperature plays an important role in determining the characteristic of diodes. As temperature increases, the turn-on voltage, v_{ON}, decreases. Alternatively, a decrease in temperature results in an increase in v_{ON}. This is illustrated in **fig. 2,** where V_{ON} varies linearly with temperature which is evidenced by the evenly spaced curves for increasing temperature in 25 °C increments.

The temperature relationship is described by equation

$$V_{ON}(T_{New}) - V_{ON}(T_{room}) = k_T(T_{New} - T_{room}) \qquad \textbf{(E-10)}$$

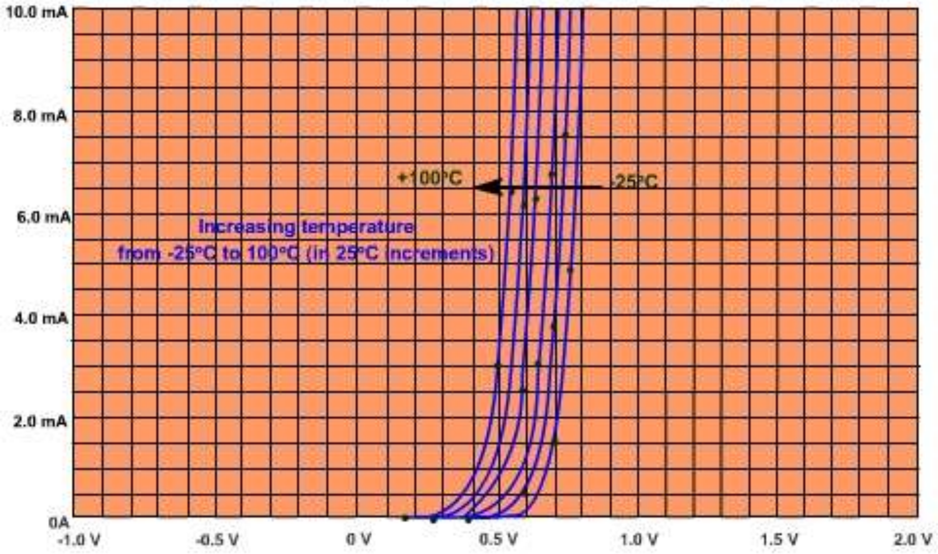


Fig. 2 - Dependence of iD on temperature versus vD for real diode (kT = -2.0 mV /°C)

where,

T_{room}= room temperature, or 25°C.
T_{New}= new temperature of diode in °C.
$V_{ON}(T_{room})$ = diode voltage at room temperature.
$V_{ON}(T_{New})$ = diode voltage at new temperature.
k_T = temperature coefficient in V/°C.

Although k_T varies with changing operating parameters, standard engineering practice permits approximation as a constant. Values of k_T for the various types of diodes at room temperature are given as follows:

k_T= -2.5 mV/°C for germanium diodes
k_T = -2.0 mV/°C for silicon diodes

The reverse saturation current, I_O also depends on temperature. At room temperature, it increases approximately 16% per °C for silicon and 10% per °C for germanium diodes. In other words, $I_O$approximately doubles for every 5 °C increase in temperature for silicon, and for every 7 °C for germanium. The expression for the reverse saturation current as a function of temperature can be approximated as

$$I_0(atT_2) = I_0(atT_1)\exp(k_i(T_2 - T_1)) = I_0(atT_1)e^{K_I(T_2 - T_1)} \qquad \textbf{(E-11)}$$

where K_i= 0.15/°C (for silicon) and T1 and T2 are two arbitrary temperatures.

Example - 1:

When a silicon diode is conducting at a temperature of 25°C, a 0.7 V drop exists across its terminals. What is the voltage, V_{ON}, across the diode at 100°C?

Solution:

The temperature relationship is described by

$V_{ON}\,(T_{New}) - V_{ON}(T_{room}) = K_T\,(T_{New} - T_{room})$

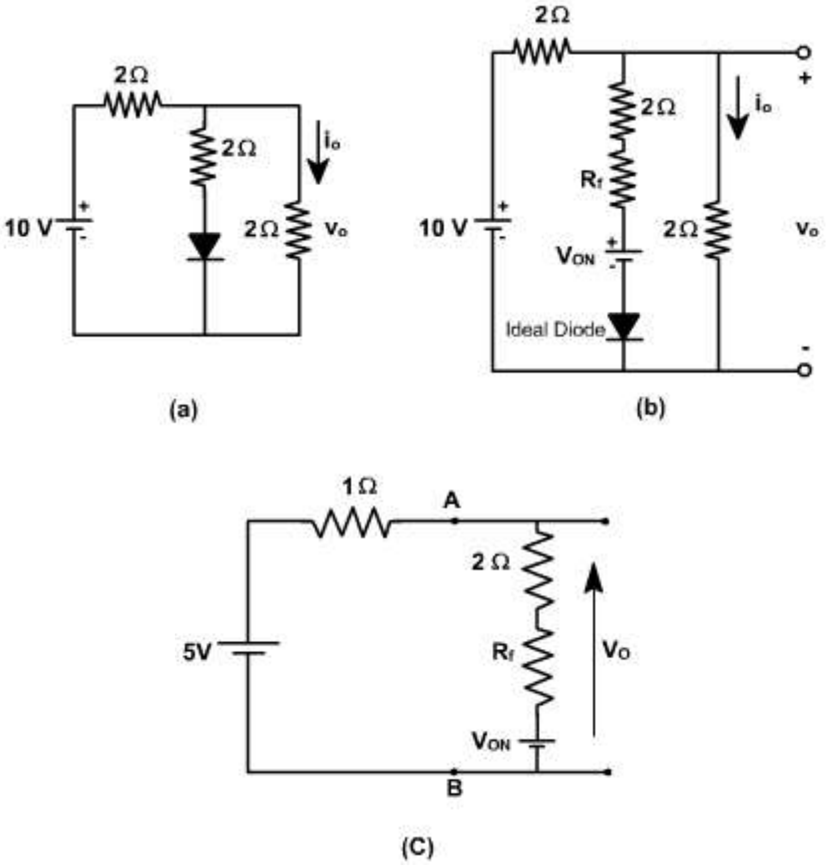
or, $V_{ON}\,(T_{New}\,) = V_{ON}\,(T_{room}) + K_T\,(T_{new} - T_{room})$

Given $V_{ON}\,(T_{room}) = 0{,}7$ V, T_{room}= 25° C, T_{New}= 100° C

Therefore, $V_{ON}\,(T_{New}\,) = 0.7 + (-2 \times 10^{-3}\,)\,(100\text{-}75) = 0.55$ V

Example - 2:

Find the output current for the circuit shown in **fig.1(a)**.



(a)

(b)

(C)

Fig.1- Circuit for Example 2

Solutions:

Since the problem contains only a dc source, we use the diode equivalent circuit, as shown in **fig. 1(b)**. Once we determine the state of the ideal diode in this model (i.e., either open circuit or short circuit), the problem becomes one of simple dc circuit analysis.

It is reasonable to assume that the diode is forward biased. This is true since the only external source is 10 V, which clearly exceeds the turn-on voltage of the diode, even taking the voltage division into account. The equivalent circuit then becomes that of **fig. 1(b)**. with the diode replaced by a short circuit.

The Thevenin's equivalent of the circuit between A and B is given by **fig. 1(c)**.

The output voltage is given by

$$v_o = \left(\frac{5 - V_{ON}}{3 + R_f}\right)(2 + R_f) + V_{ON}$$

or,

$$v_o = \frac{10 + V_{ON} + 5R_f}{3 + R_f}$$

If V_{ON}= 0.7V, and R_f= 0.2 W , then

V_o = 3.66V

Example - 3

The circuit of fig. 2, has a source voltage of $V_s = 1.1 + 0.1 \sin 1000t$. Find the current, i_D. Assume that

nV_T = 40 mV

V_{ON} = 0.7 V

Solution:

We use KVL for dc equation to yield

$V_s = V_{ON} + I_D R_L$

$$I_D = \frac{V_S - V_{ON}}{R_L} = 4 \quad mA$$

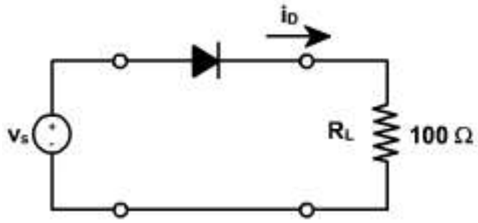


Fig.2

This sets the dc operating point of the diode. We need to determine the dynamic resistance so we can establish the resistance of the forward-biased junction for the ac signal.

$$r_D = \frac{nV_T}{I_D} = 10\ \Omega$$

Assuming that the contact resistance is negligible $R_f = r_D$ Now we can replace the forward-biased diode with a 10 W resistor. Again using KVL, we have,

$v_s = R_f\, i_d + R_L\, i_d$

$$i_d = \frac{v_S}{R_f + R_L} = 0.91 \sin 1000\,t \quad mA$$

The diode current is given by

I = 4 + 0.91 sin 1000 t mA

Since i_D is always positive, the diode is always forward-biased, and the solution is complete.