Part 1: Semiconductor Diodes

1. Introduction

A diode is a two-terminal semiconductor device formed by two doped regions of silicon separated by a ***pn*** junction. In this chapter, the most common category of diode, known as ***the general-purpose diode***, is covered, as well as explaining the operation and characteristics of the diode.

The importance of the diode in electronic circuits cannot be overemphasized. Its ability to conduct current in one direction while blocking current in the other direction is essential to the operation of many types of circuits, such as, the ac rectifier circuits, diode limiters, diode clampers, and diode voltage multipliers, which are covered in the second part of this chapter.

The last part of this chapter describes the operation of a very special diode used in regulation which is the ***Zener diode***.

2. Diode description

A diode is made from a small piece of semiconductor material, in which half is doped as a **p region** and half is doped as an **n region**. The p region is called the anode **(A)** and is connected to a conductive terminal. The n region is called the cathode **(K)** and is connected to a second conductive terminal. The basic diode structure and schematic symbol are shown in **Fig.2.1**.

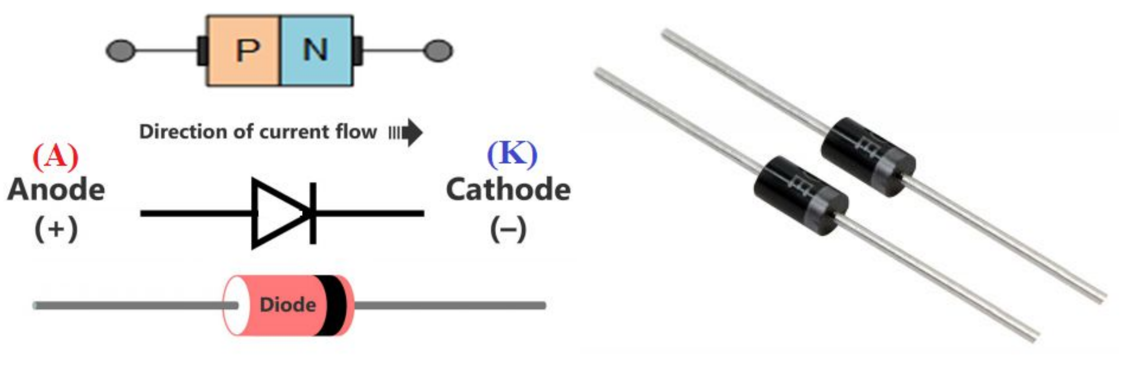


Fig.2.1: Semiconductor Diode

3. Voltage current characteristics

The forward and reverse current-voltage (IV) characteristics of a diode are generally compared on a single characteristic curve. (**see Fig.2.2**)
Forward and reverse current values are shown on the vertical axis of the graph. Forward Voltage represented to the right and Reverse Voltage to the left.
The combined Forward Voltage and Forward Current values are located in the upper right part of the graph and Reverse Voltage and Reverse Current in the lower left corner. Different scales are normally used to display forward and reverse values.

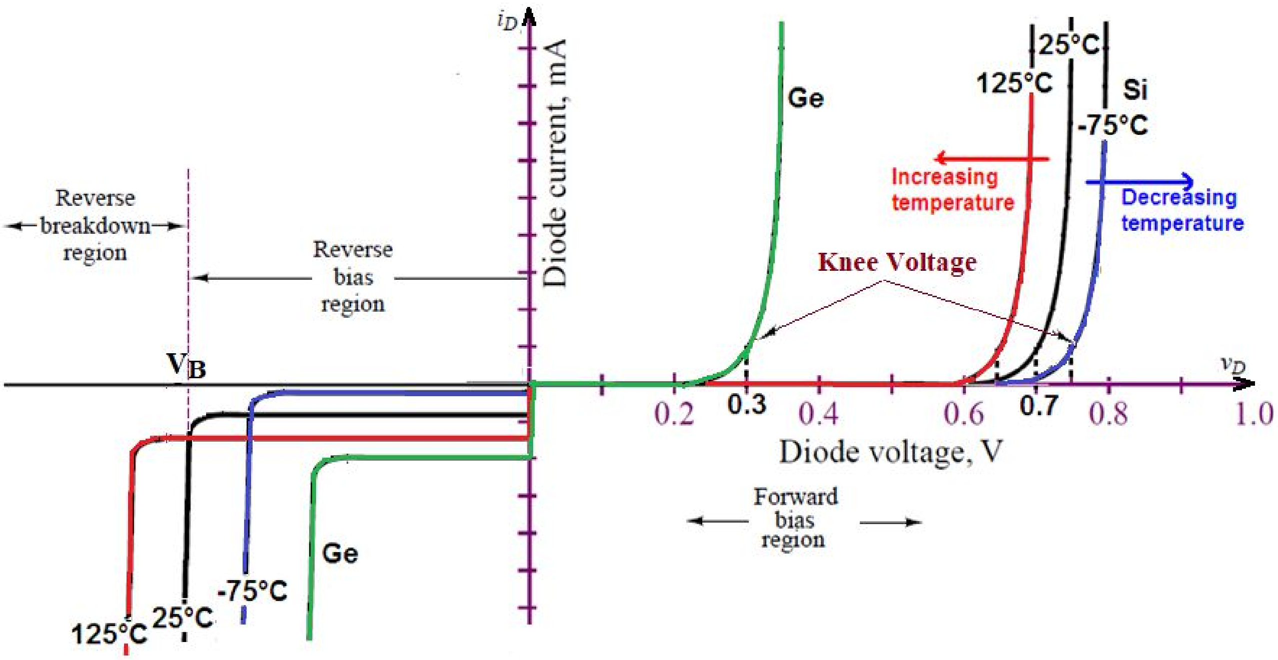


Fig.2.2: I-V Diode characteristics

Forward Characteristic

When a diode is forward biased it conducts current (I_D) in forward direction. The value of I_D is directly dependent on the amount of forward voltage, so:

- ✓ Forward Voltage is measured across the diode and Forward Current is a measure of current through the diode.
- ✓ When the forward voltage across the diode equals 0V, forward current equals 0 mA.
- ✓ When the value starts from the starting point (0) of the graph, if V_D is progressively increased in 0.1 V steps, I_D begins to rise.

- ✓ When the value of V_D is large enough to overcome the barrier potential of the P-N junction, a considerable increase in I_D occurs. The point at which this occurs is often called the **knee voltage.**
- ✓ For germanium diodes, Barrier potential is approximately 0.3 V, and for silicon, 0.7 V.
- ✓ If the value of I_D increases much beyond the knee voltage, the forward current becomes quite large. This operation causes excessive heat to develop across the junction and can destroy a diode.
- ✓ To avoid this situation, a protective resistor is connected in series with the diode. This resistor limits the forward current to its maximum rated value.

Important Notes:

- ***Temperature effects in the forward-bias region the characteristics of the silicon diode shift to the left at a rate of 2.5 mV per centigrade: $\Delta V/\Delta T=-2.5[mV/°C]$***
- ***The ideality factor for germanium diode (Ge), n= 1 and for silicon diode (Si), n= 2 for relatively low levels of diode current (at or below the knee of the curve), and n= 1 for Ge and Si for higher levels of diode current (in the rapidly increasing section of the curve).***

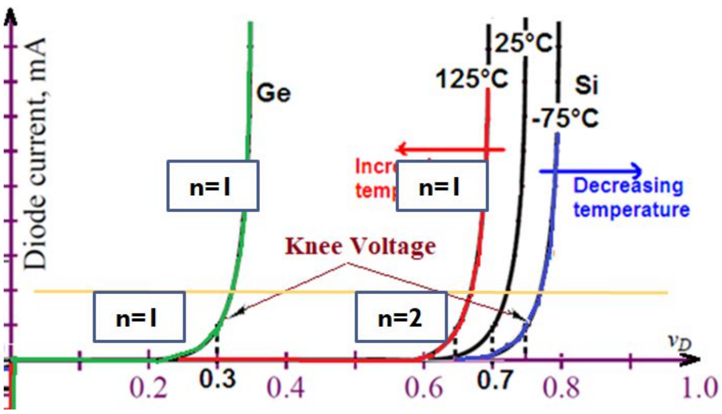


Fig. 2.3: About the ideality factor

Example:

If V (25°C)= 0.6V find the voltage at the temperature of -75°C.

$\Delta V/\Delta T= -2.5[mV/°C]$

$(V_{25}-V_{-75}) /(25-(-75)) =- 2.5mV/°C$

$(0.6-V_{-75}) /(25-(-75)) =-2.5mV/°C$

$V_{-75} =0.85V$

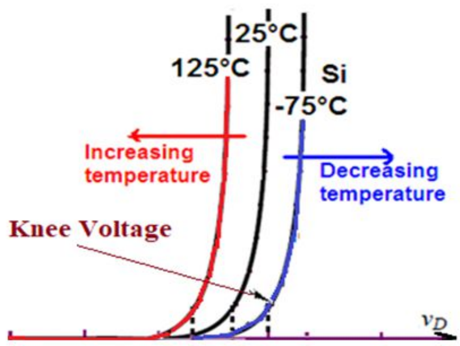


Fig.2.3.a: Temperature change

Reverse Characteristic

When a diode is reverse biased, it conducts Reverse current that is usually quite small (values expressed in microamperes). In general, the reverse current remains constant over a large part of reverse voltage. At the breakdown voltage (**V_B**) point, current increases very rapidly. The voltage across the diode remains reasonably constant at this time.

This constant-voltage characteristic leads to a number of applications of diode under reverse bias condition. The processes which are responsible for current conduction in a reverse-biased diode are called as Avalanche breakdown and Zener breakdown.

Note:

In the reverse-bias region the reverse saturation current of a silicon diode doubles for every 10°C rise in temperature.

Resistance levels of a diode

The operation point of a diode moves from one region to another ⇒the resistance of the diode will also change (because of non-linear shape of the characteristic curve)

a) DC or static resistance

The application of a DC voltage to a diode circuit will result in an operating point (**Q point**) on the characteristic curve that will not change with time.

$$\boxed{R_D = V_D / I_D}$$

Q point: Quiescent (it means unvarying)

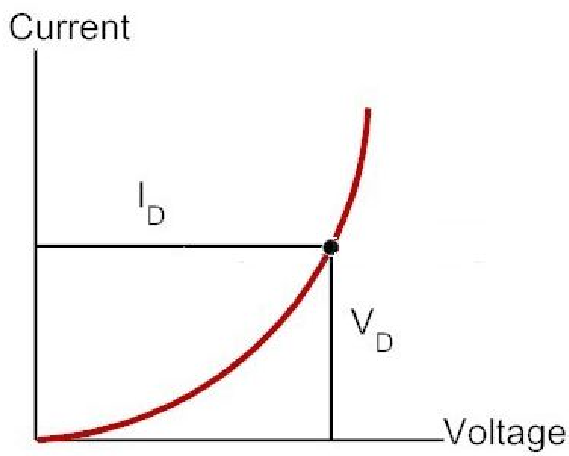


Fig.2.4.a: DC or static resistance

b) AC or dynamic resistance

The varying input will move the instantaneous operation point up and down. Using the characteristic curve and the operating point (Q which is the average or DC offset of our AC signal):

$$\boxed{r_D = \Delta V_D / \Delta Id}$$

From **Shockley**'s equation:

$\mathbf{I_D = I_s\,(e^{V_D/nVT} - 1)}$

$1/r_D = d(I_D)/d(V_D) = I_s\,((1/nVT) * e^{V_D/nVT}) \approx I_D/nVT$

$\boxed{\mathbf{r_D = nVT/\,I_D}}$

At room temperature and n=1, $r_D = (26mV)/I_D$

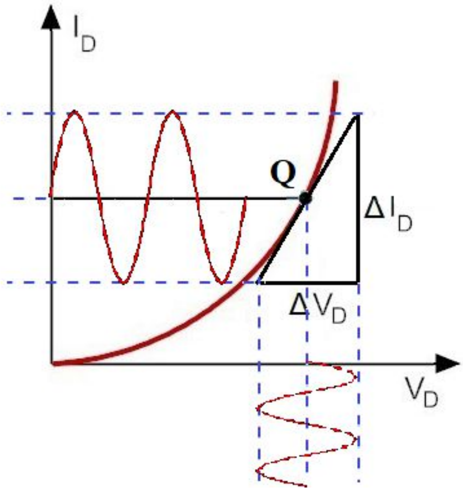


Fig.2.4.b: AC or dynamic resistance

4. Diode models(Diode approximations)

Diode approximation is a mathematical method used to approximate the nonlinear behavior of real diodes to enable calculations and circuit analysis. There are three different approximations used to analyze the diode circuits.

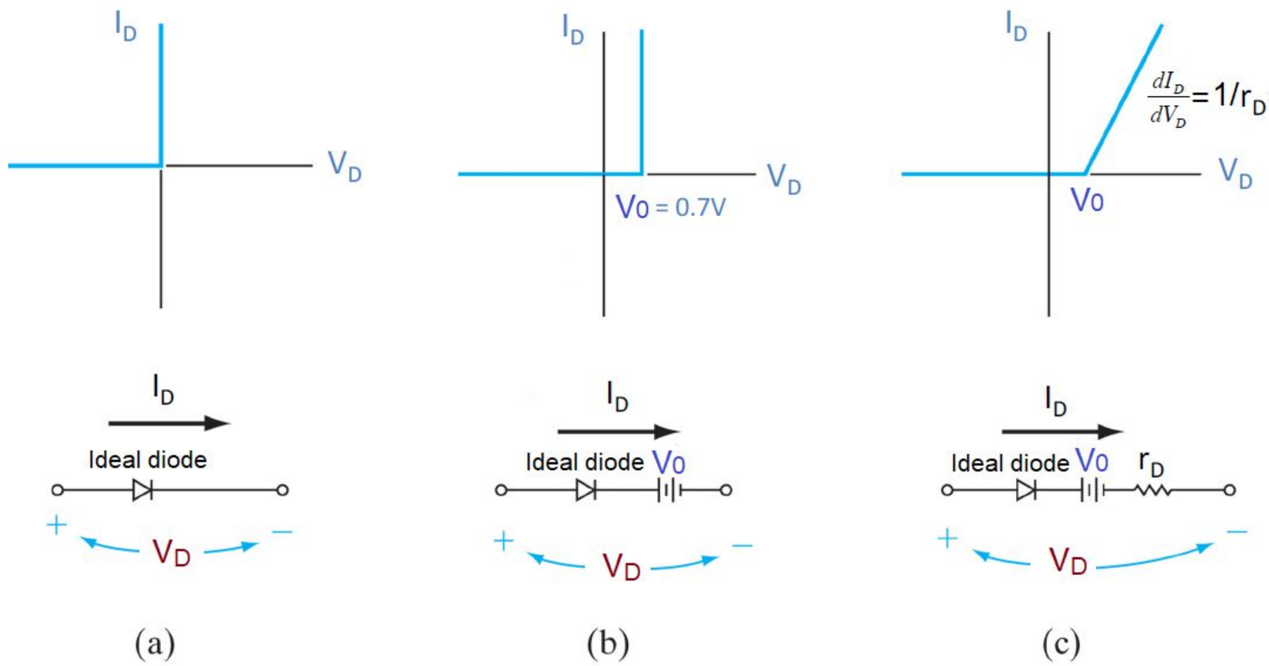


Fig.2.5: Diode approximations (characteristics and circuits)

First Diode Approximation⇒ Ideal diode model

In the first approximation method, the diode is considered as a forward-biased diode and as a closed switch with zero voltage drop. It is not apt to use in real-life circumstances but used only for general approximations where preciseness is not required. (See Fig.2.5.a and Fig.2.5.d)

Good for determining which diodes are conducting and which are cut-off in a multiple diode circuit

Good for obtaining very approximate values for diode currents, especially when the circuit voltages are much greater than V_D.

Fig.2.5.d: Ideal diode model

Second Diode Approximation⇒ Practical diode model

In the second approximation, the diode is considered as an ideal diode in series with a battery to turn on the device. (See Fig.2.5.b)

- A voltage of 0.7V or greater is necessary to turn on the forward-biased diode.
- The diode turns off if the voltage is less than 0.7V.
- A Germanium diode needs 0.3V to turn on.

Easy to use and very popular for the quick hand analysis that is essential in circuit design.

Third Diode Approximation⇒ Piecewise-linear model

The third approximation of a diode includes voltage across the diode and voltage across a resistance r_d (low), this resistance corresponds to the resistance of p and n materials. It changes based on the amount of forwarding voltage and the current flowing through the diode at any given time. (See Fig.2.5.c)

5. Diode circuit analysis

5.1. Load line analysis

The load line equation of the circuit of Fig.2.6.a:

$I_D = (Vi-V_D)/R$ …………………(1)

From **Shockley**'s equation:

$I_D = I_s\,(e^{V_D/nVT} - 1)$……………….……(2)

The solution of the system of the equations (1) and (2) is the operating point of the circuit.

The graphical solution is given by the figure 2.6.b. with Q point (quiescent point) is the operating point of the circuit.

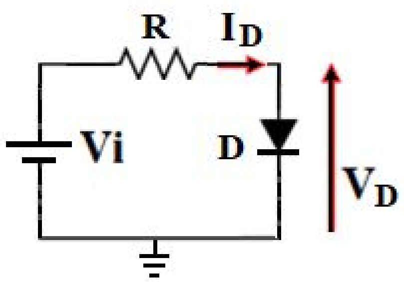


Fig.2.6.a: Diode Circuit

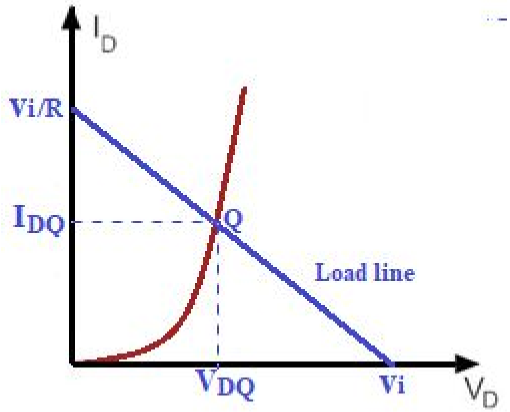


Fig.2.6.b: Load line analysis

5.2. Analysis by assumption (Example of ideal diode)

In the case of ideal diode approximation, we have to perform the following steps:

(1) Assume a bias state for each diode (Guess)

$\Rightarrow$ Forward biased diode or reverse biased diode

(2) Apply the equality conditions (Consistent with your assumptions)

Forward bias $\Rightarrow$ V_D=0 (the diode is replaced by a short circuit)

Reverse bias $\Rightarrow$ I_D=0 (the diode is replaced by an open circuit)

(3) Analyze the circuit: Determine all required circuit values.

- Determine I_D through each short circuit
- Determine V_D across each open circuit

(4) Check the results of step (3) to see if the assumptions are correct.

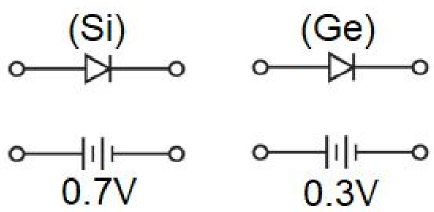
- Diode in Forward bias cannot have a negative current flowing through it.
  If I_D <0 $\Rightarrow$Wrong assumption
  If I_D >0 $\Rightarrow$Correct assumption
- Diode in Reverse bias cannot have a positive voltage across it.
  If V_D <0 $\Rightarrow$ Correct assumption
  If V_D >0 $\Rightarrow$ Wrong assumption

(5) If your assumptions are incorrect, then, change your assumptions and repeat from step (1)

Note: in the case of practical diode circuit analysis, we perform the same steps but we have to take in consideration the following notes:

In Step (2):

Forward bias for (Si) diode $\Rightarrow$ V_D=0.7V (the diode is replaced by a voltage drop of 0.7V)
Forward bias for (Ge) diode $\Rightarrow$ V_D=0.3V (the diode is replaced by a voltage drop of 0.3V)



In Step (4):

Diode in Reverse bias cannot have a positive voltage across it also:

If V_D(Si) <0.7V $\Rightarrow$ Correct assumption	If V_D(Ge) <0.3V $\Rightarrow$ Correct assumption
If V_D(Si) >0.7V $\Rightarrow$ Wrong assumption	If V_D(Ge) >0.3V $\Rightarrow$ Wrong assumption

6. General diodes specifications

1) Forward voltage drop at a specified current and temperature : is the forward-conducting junction level (~0.7 for silicon diode and 0.3 for germanium diode)

2) Maximum forward current I_{Fmax} : is the maximum amount of forward current that the diode can carry for an indefinite period. If the average current exceeds this value, the diode will overheat and, eventually, will be destroyed.

3) Reverse breakdown voltage (V_R or V_{RB}) : This is the largest amount of reverse-bias voltage the diodes' junction can withstand for an indefinite period of time. If a reverse voltage exceeds this level, the voltage will punch through the depletion layer and allow current to flow backwards through the diode, which is a destructive operation (except for the case of a Zener diode).

4) The reverse saturation current "I_S" at a specified temperature.

5) Maximum power dissipation P_{Dmax} : The diode power dissipation (P_D) is calculated by multiplying the forward voltage drop and the forward current. Exceeding the maximum power dissipation will result in thermal breakdown of the diode. So: $P_D=I_D*V_D$ should be less than P_{Dmax}

Notes:

- ***Excessive forward current and reverse breakdown voltage are the most common causes of diode failure. In both cases the diode gets very hot (the PN junction will be destroyed).***
- ***Occasional exceeding of the maximum rate of voltage or current for very short times (few milliseconds) may not overheat the junction, but repeated peaks may fatigue the junction***

7. Peak Inverse Voltage (PIV)

- ✓ The **PIV** or the peak reverse voltage (**PRV**) **varies** from one circuit to another.
- ✓ PIV is the **maximum value** of **reverse voltage** which occurs at the **peak of the input** cycle, when the diode is **reverse biased**.
- ✓ If the PIV is greater than the reverse break-down voltage (**V_{RB}**) of the used diode, the diode may be **destroyed**. Where, **V_{RB}** is the maximum voltage that a diode can **withstand** in the **reverse direction** (**V_{RB}** is given by the constructor**)**.