Analog Electronic Circuits

Chapter 1:

Semiconductor Diodes

Objectives: To become familiar with the working principles of semiconductor diode

To become familiar with the design and analysis of diode circuits

To become familiar with the diode applications, such as rectifiers, clippers and clamper

Diode:

A pure silicon crystal or germanium crystal is known as an intrinsic semiconductor. There aren't enough free electrons and holes in an intrinsic semi-conductor to produce a usable current. The electrical action of these can be modified by doping means adding impurity atoms to a crystal to increase either the number of free holes or no of free electrons.

When a crystal has been doped, it is called a extrinsic semi-conductor. They are of two types

- n-type semiconductor having free electrons as majority carriers
- p-type semiconductor having free holes as majority carriers

By themselves, these doped materials are of little use. However, if a junction is made by joining p-type semiconductor to n-type semiconductor a useful device is produced known as diode. It will allow current to flow through it only in one direction. The unidirectional properties of a diode allow current flow when forward biased and disallow current flow when reversed biased. This is called rectification process and therefore it is also called rectifier.

How is it possible that by properly joining two semiconductors each of which, by itself, will freely conduct the current in any one direction and refuses to allow conduction in other direction.

Consider first the condition of p-type and n-type germanium just prior to joining **fig. 1**. The majority and minority carriers are in constant motion.

The minority carriers are thermally produced and they exist only for short time after which they recombine and neutralize each other. In the meantime, other minority carriers have been produced and this process goes on and on.

The number of these electron hole pair that exist at any one time depends upon the temperature. The number of majority carriers is however, fixed depending on the number of impurity atoms available. While the electrons and holes are in motion but the atoms are fixed in place and do not move.

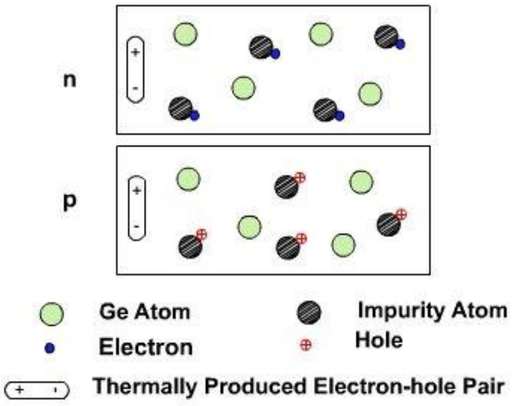
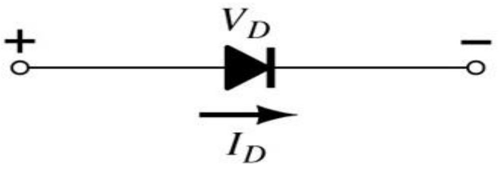


Fig.1

Diodes symbol

Simplest Semiconductor Device

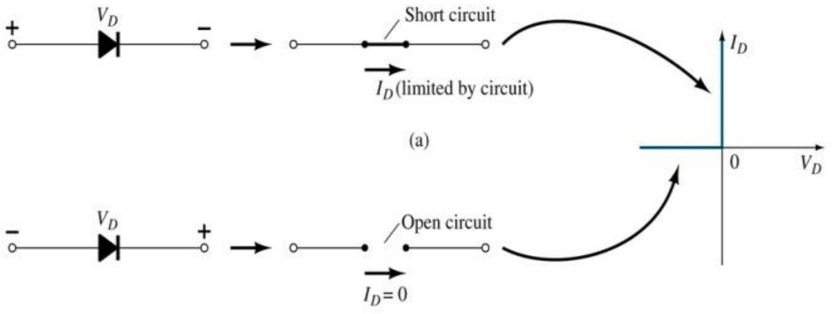


(a)

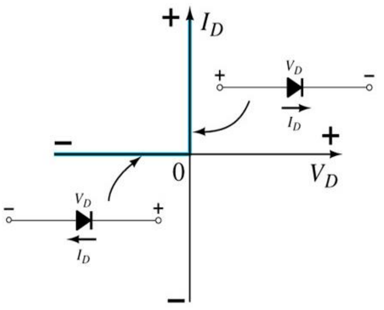
It is a 2-terminal device

Basic operation

ideally it ***conducts current in only one direction*** and acts like an ***open in the opposite direction***



Characteristics of an ideal diode: Conduction Region



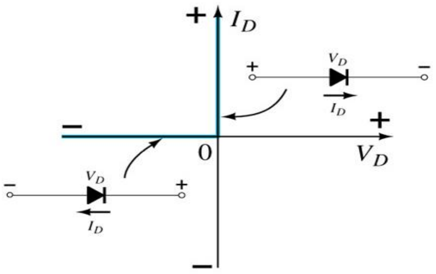
(b)

The vertical line

in the conduction region, ideally

- the voltage across the diode is 0V,
- the current is∞,
- the forward resistance (RF) is defined as RF = VF/IF,
- the diode acts like a short.

Characteristics of an ideal diode: Non-Conduction Region



(b)

The horizontal line

in the non-conduction region, ideally

- all of the voltage is across the diode,
- the current is 0A,
- the reverse resistance (RR) is defined as RR = VR/IR,
- the diode acts like open.

Semiconductor Materials

Common materials used in the development of semiconductor devices:

- Silicon (Si)
- Germanium (Ge)

Doping

The electrical characteristics of Silicon and Germanium are improved by adding materials in a process called doping.

The additional materials are in two types:

- n-type
- p-type

n-type versus p-type

n-type materials make the Silicon (or Germanium) atoms more negative.

p-type materials make the Silicon (or Germanium) atoms more positive.

Join n-type and p-type doped Silicon (or Germanium) to form a **p-n junction**.

p-n junction

When the materials are joined, the negatively charged atoms of the n-type doped side are attracted to the positively charged atoms of the p-type doped side.

The electrons in the n-type material migrate across the junction to the p-type material (electron flow). Or you could say the ‘holes’ in the p-type material migrate across the junction to the n-type material (conventional current flow).

The result is the formation of a **depletion layer** around the junction.

Operating Conditions

• No Bias • Forward Bias • Reverse Bias

No Bias Condition

As soon as, the junction is formed, the following processes are initiated **fig. 2**.

- Holes from the p-side diffuse into n-side where they recombine with free electrons.
- Free electrons from n-side diffuse into p-side where they recombine with free holes.
- The diffusion of electrons and holes is due to the fact that large no of electrons are concentrated in one area and large no of holes are concentrated in another area.
- When these electrons and holes begin to diffuse across the junction then they collide each other and negative charge in the electrons cancels the positive charge of the hole and both will lose their charges.
- The diffusion of holes and electrons is an electric current referred to as a recombination current. The recombination process decay exponentially with both time and distance from the junction. Thus most of the recombination occurs just after the junction is made and very near to junction.
- A measure of the rate of recombination is the lifetime defined as the time required for the density of carriers to decrease to 37% to the original concentration

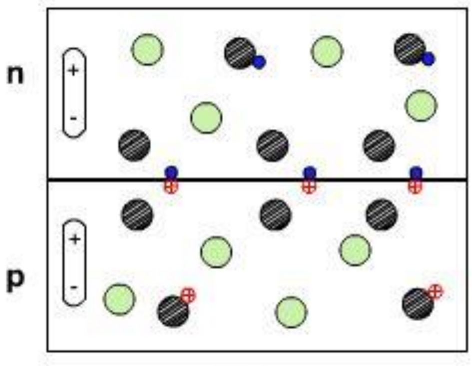


Fig.2

The impurity atoms are fixed in their individual places. The atoms itself is a part of the crystal and so cannot move. When the electrons and hole meet, their individual charge is cancelled and this leaves the originating impurity atoms with a net charge, the atom that produced the electron now lack an electronic and so becomes charged positively, whereas the atoms that produced the hole now lacks a positive charge and becomes negative.

The electrically charged atoms are called ions since they are no longer neutral. These ions produce an electric field as shown in **fig. 3**. After several collisions occur, the electric field is great enough to repel rest of the majority carriers away of the junction. For example, an electron trying to diffuse from n to p side is repelled by the negative charge of the p-side. Thus diffusion process does not continue indefinitely but continues as long as the field is developed.

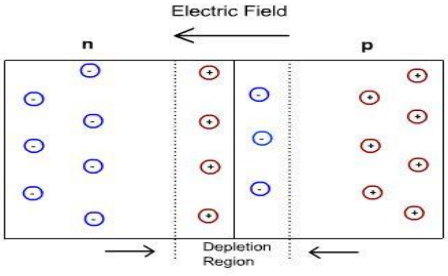
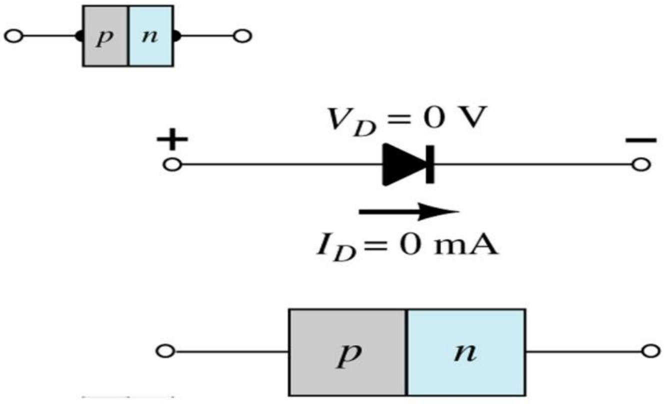


Fig.3

This region is produced immediately surrounding the junction that has no majority carriers. The majority carriers have been repelled away from the junction and junction is depleted from carriers. The junction is known as the barrier region or depletion region. The electric field represents a potential difference across the junction also called *space charge potential or barrier potential* . This potential is 0.7v for Si at 25^o Celsius and 0.3v for Ge.

The physical width of the depletion region depends on the doping level. If very heavy doping is used, the depletion region is physically thin because diffusion charge need not travel far across the junction before recombination takes place (short life time). If doping is light, then depletion is wider (long life time).

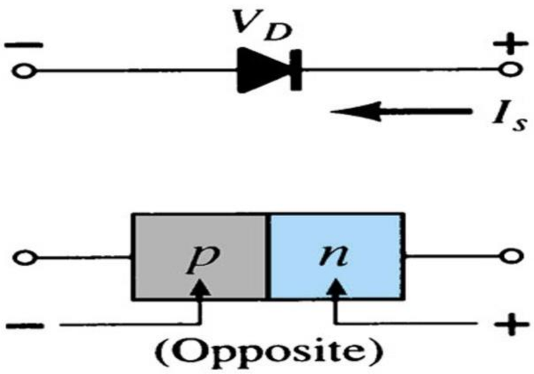
No external voltage is applied: V_D = 0V and no current is flowing I_D = 0A.

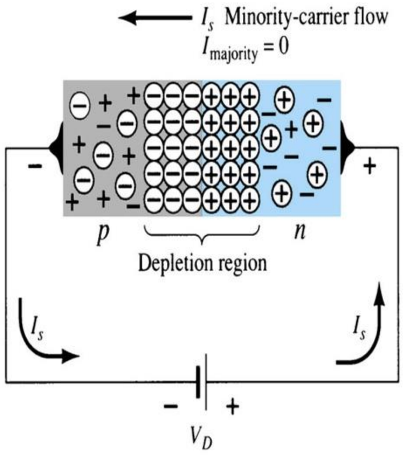


Only a modest depletion layer exists.

Reverse Bias Condition

External voltage is applied across the p-n junction in the opposite polarity of the p- and n-type materials.

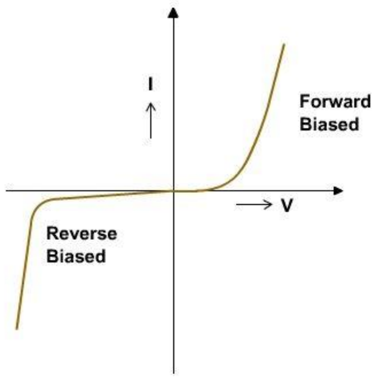




When the diode is reverse biased then the depletion region width increases, majority carriers move away from the junction and there is no flow of current due to majority carriers but there are thermally produced electron hole pair also. If these electrons and holes are generated in the vicinity of junction 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 (in terms 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}.

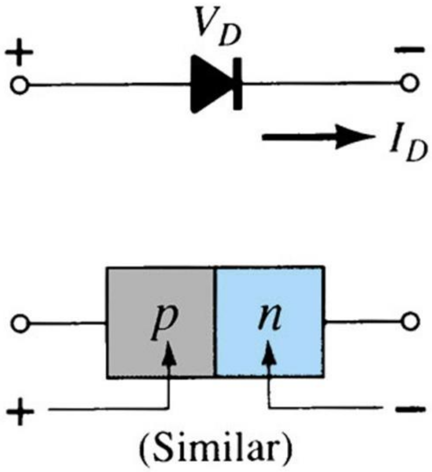
In actual diode, the current is not almost constant but increases slightly with voltage. This is due to surface leakage current. The surface of diode follows ohmic law (V=IR). The resistance under reverse bias condition is very high 100k to mega ohms. When the reverse voltage is increased, then at certain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

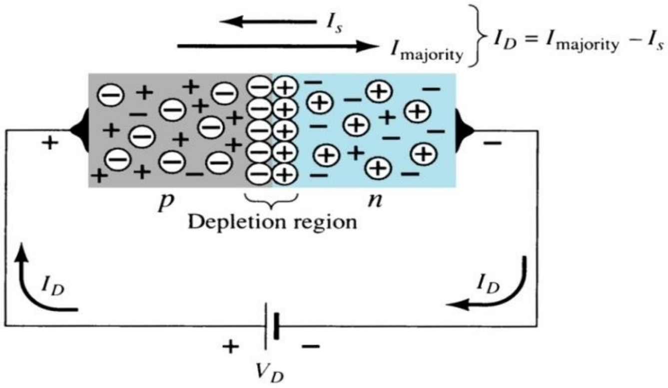
The characteristic of the diode is shown in figure.



Forward Bias Condition

External voltage is applied across the p-n junction in the same polarity of the p- and n-type materials.





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.

Diode Current Equation .

Through the use of solid-state physics the general characteristics of a semiconductor diode can be defined by the Shockley's equation, for the forward and reverse bias regions given in Equation

$$I_D = I_S\left[e^{\frac{V_D}{nV_T}} - 1\right]$$

Where I_D= Diode current

V_D= Voltage applied across the diode

I_s= reverse saturation current

n is an ideality factor which depends on the operating conditions and physical construction. n lies between 1 and 2. Unless otherwise stated we assume $n = 1$ throughout the analysis.

V_T= Thermal voltage, given by

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

Where K = Boltzmann constant = 1.38 x 10-23J / K

T = Absolute temperature in Kelvin = 273 + the temperature in °C

q = Magnitude of electronic charge = 1.6 x 10-19Coulomb

For example, at a temperature of 27° C

T = 273 + 27° C = 300 K

$V_{T=}$ $=KT/q$

= (1.38X10-^{23}) (300)/1.6x 10-19

= 26 mV

Forward Biased Condition

$$I_D = I_S\, e^{\frac{V_D}{nV_T}} - I_S$$

For positive values of V_d ,the exponential term grows very quickly and totally dominates the effect of second term. As a result

$$I_D \approx I_S\, e^{\frac{V_D}{nV_T}}$$

Observe from above Equation that, under forward biased condition, the diode current varies exponentially with the applied forward voltage *VD*.

Reverse Biased Condition

For negative values of *VD*, the exponential term in Equation forward bias drops very quickly below the

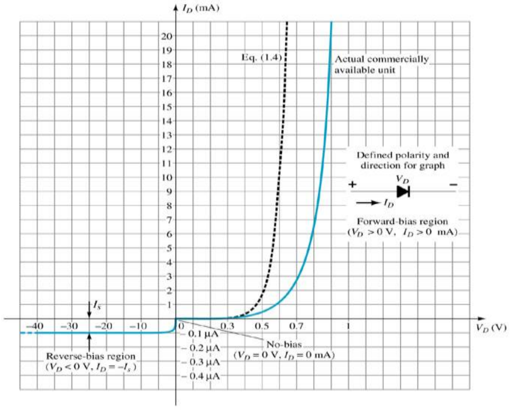
level of I_s As a result, the diode current is now given by

$$I_D = -I_S \qquad ....1.4$$

Note from Equation (1.4) that, for negative values of *VD*, the diode current is essentially constant at the level of *Is*

Actual Diode Characteristics

Note the regions for No Bias, Reverse Bias, and Forward Bias conditions.



DIODE RESISTANCE LEVELS

The forward characteristics of the diode is nonlinear since the diode current changes exponentially! with the applied forward voltage. As a result the resistance of the diode will change when the operating point moves from one region to another. Depending upon the type of the applied signal we can define the following three resistance levels of the diode.

☐ DC or static resistance

☐ AC or dynamic resistance

☐ Average ac resistance

Now let us study the definition of each of these resistance levels and the procedure to find them from the diode characteristics.

1.4.1 DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor results in a dc current. The resistance of diode to the flow of dc current is called DC or static resistance.

Let the applied dc voltage $V_{\&}$ results in a dc current J_D as shown in Fig. 1.4. The dc resistance of the diode at the operating point is given by

$$R_D = \frac{V_D}{I_D} \tag{1.6}$$

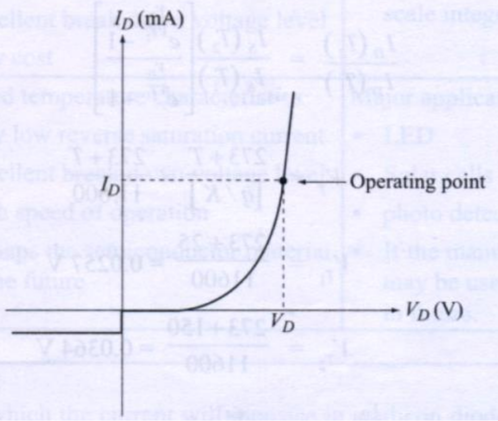


Fig. 1.4.

We can make the following observations from Fig. 1.4.

- Under reverse bias, the diode current is almost zero. Hence the dc resistance level in reverse-bias region is quite high.

- The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics.
- Higher the current through the diode, lower is the dc resistance level.

AC or Dynamic Resistance

The resistance of the diode to the flow of ac current is called the ac or dynamic resistance.

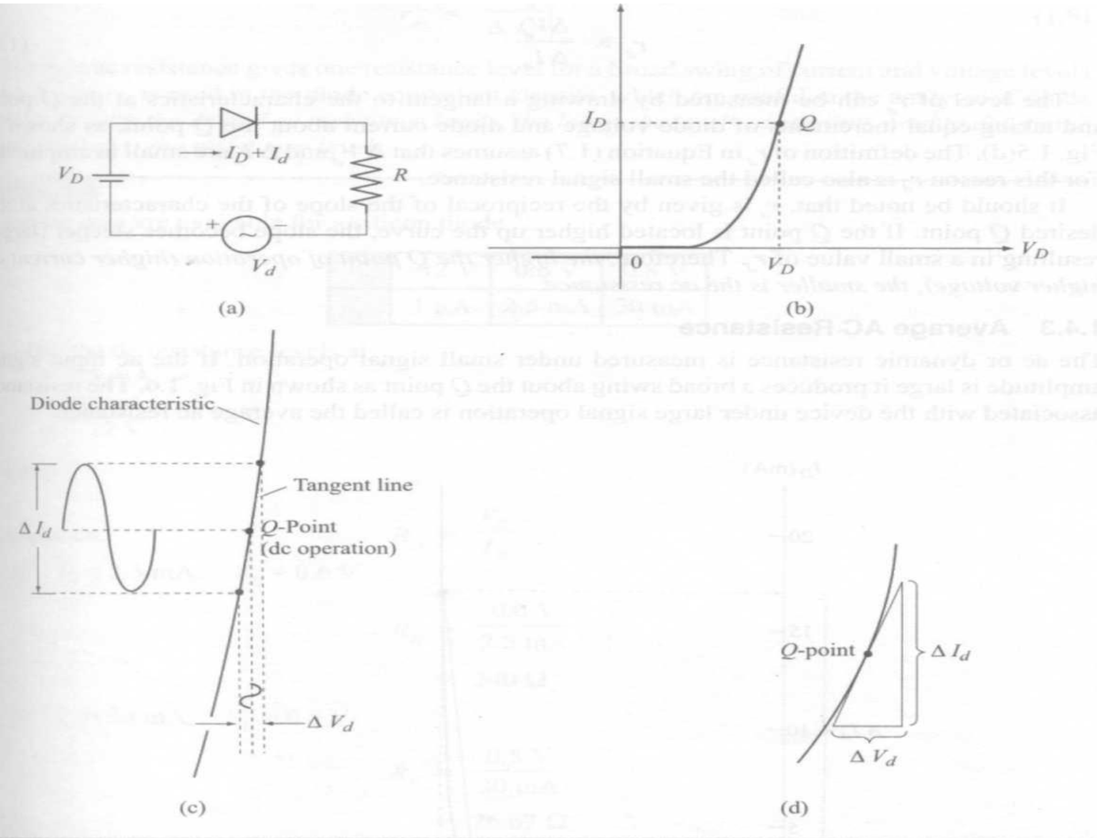


Fig. 1.5 (a) Biased diode with ac input
(b) Q point current and voltage
(c) Variation of diode current and voltage about Q point
(d) Graphical determination of ac resistance

The application of dc voltage V_D in the circuit of Fig. 1.5(a) sets up a dc current I_D resulting in an operating point Q as shown in Fig. 1.5(b). Since V_D and I_D are not changing with time, the operating point is designated as quiescent operating point or Q-point.

If a sinusoidal voltage is also applied then the diode current and voltage will also vary sinusoidally about the *Q* point as shown in Fig. 1.5(c).

$$r_d = \frac{\Delta V_d}{\Delta I_d} \tag{1.7}$$

1.4.3 Average AC Resistance

The ac or dynamic resistance is measured under small signal operation. If the ac input signal amplitude is large it produces a broad swing about the *Q* point as shown in Fig. 1.6. The resistance associated with the device under large signal operation is called the average ac resistance.

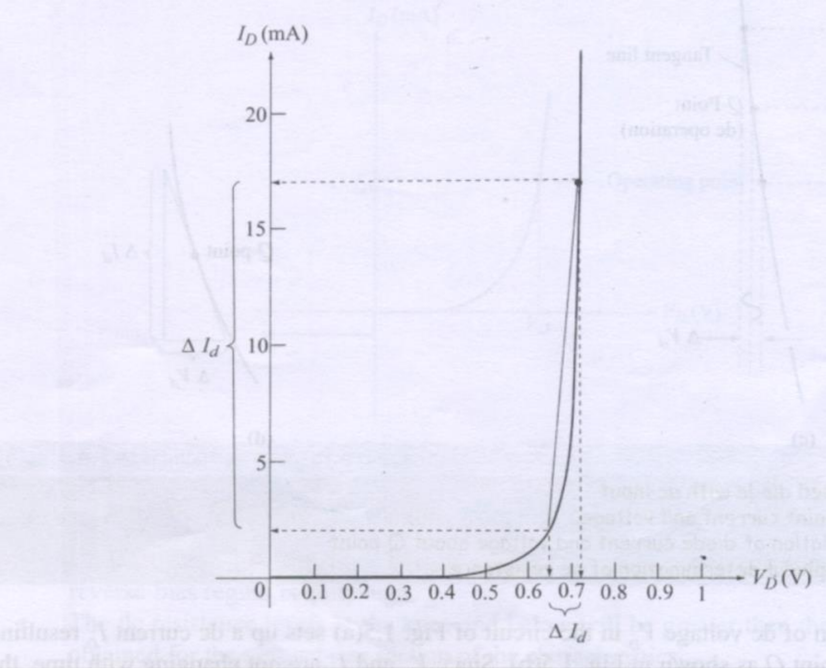
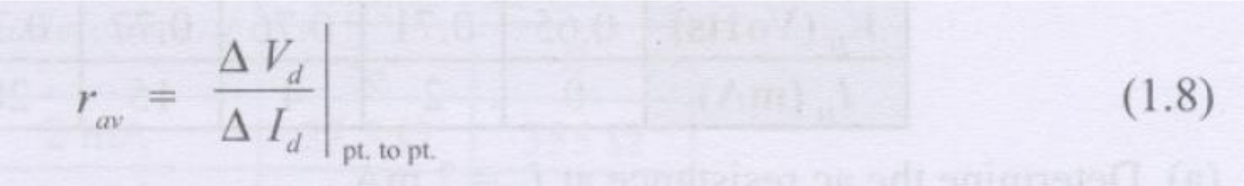


Fig. 1.6 Determining the average ac resistance between indicated limits

Average ac resistance gives one resistance level for a broad swing of current and voltage levels **in** the diode, *r* is used in the diode equivalent circuits, which are useful in the analysis of diode circuits. *As with the dc and ac resistance levels, the lower the levels of currents used to determine* r., *the higher is the resistance levels.*

The average ac resistance is the resistance determined by a straight line drawn between the two intersections established by the maximum and minimum values of input voltage as shown in fig. 1.6.



$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} \qquad (1.8)$$

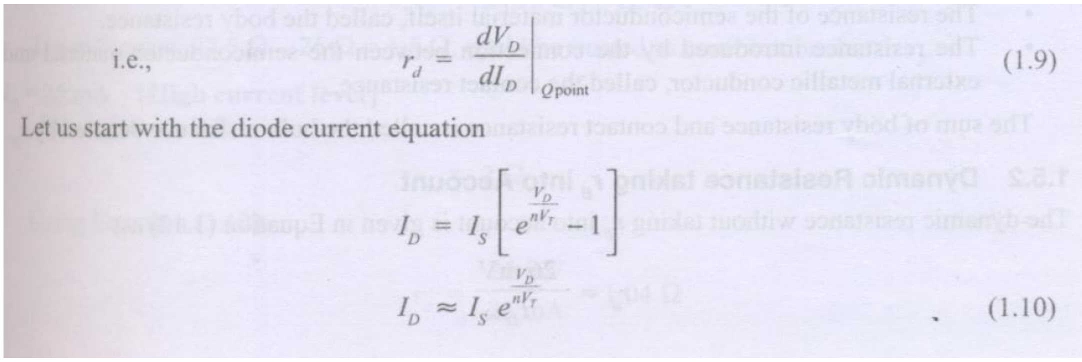
NOTE: Differences between Small Signal and Large Signal

A small signal model takes a circuit and based on an operating point (bias) and linearizes all the components. Nothing changes because the assumption is that the signal is so small that the operating point (gain, capacitance etc) doesn't change.

A large signal model on the other hand takes into account the fact that the large signal actually affects the operating point and takes into account that elements are non-linear and that circuits can be limited by power supply values. A small signal model ignores supply values.

1.5 ANALYTICAL EXPRESSION FOR DYNAMIC RESISTANCE OF DIODE

In Section 1.4.2 we have illustrated the graphical determination of dynamic resistance of diode. Graphically the dynamic resistance is equal to the reciprocal of the slope of the curve at the ***Q*** point. We can also obtain the analytical expression for dynamic resistance using the basic definition in differential calculus.



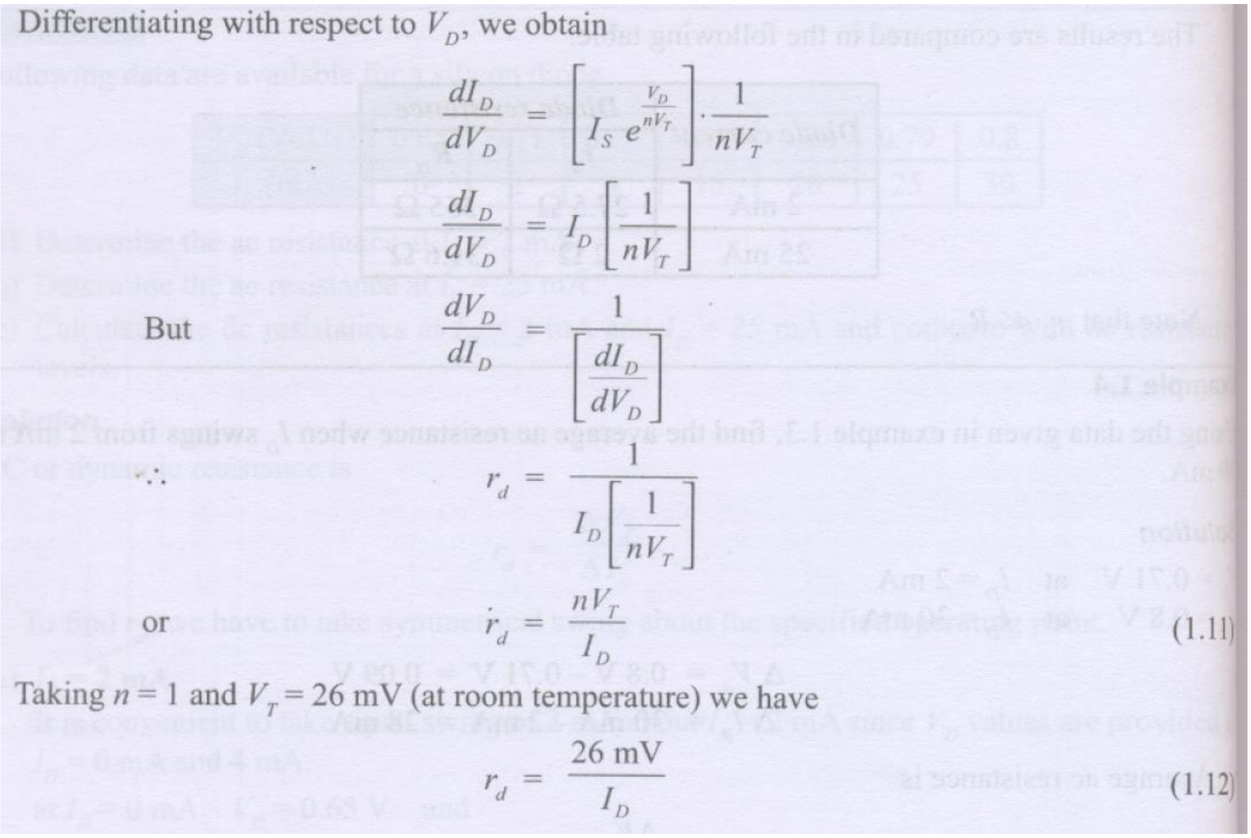
i.e.,

$$r_d = \left.\frac{dV_D}{dI_D}\right|_{Q\text{point}} \qquad (1.9)$$

Let us start with the diode current equation

$$I_D = I_S\left[e^{\frac{V_D}{nV_T}} - 1\right]$$

$$I_D \approx I_S\, e^{\frac{V_D}{nV_T}} \qquad (1.10)$$



Differentiating with respect to V_D, we obtain

$$\frac{dI_D}{dV_D} = \left[I_S \, e^{\frac{V_D}{nV_T}} \right] \cdot \frac{1}{nV_T}$$

$$\frac{dI_D}{dV_D} = I_D \left[\frac{1}{nV_T} \right]$$

But

$$\frac{dV_D}{dI_D} = \frac{1}{\left[\frac{dI_D}{dV_D} \right]}$$

$$\therefore \quad r_d = \frac{1}{I_D \left[\frac{1}{nV_T} \right]}$$

or

$$r_d = \frac{nV_T}{I_D} \qquad (1.11)$$

Taking $n = 1$ and $V_T = 26$ mV (at room temperature) we have

$$r_d = \frac{26 \text{ mV}}{I_D} \qquad (1.12)$$

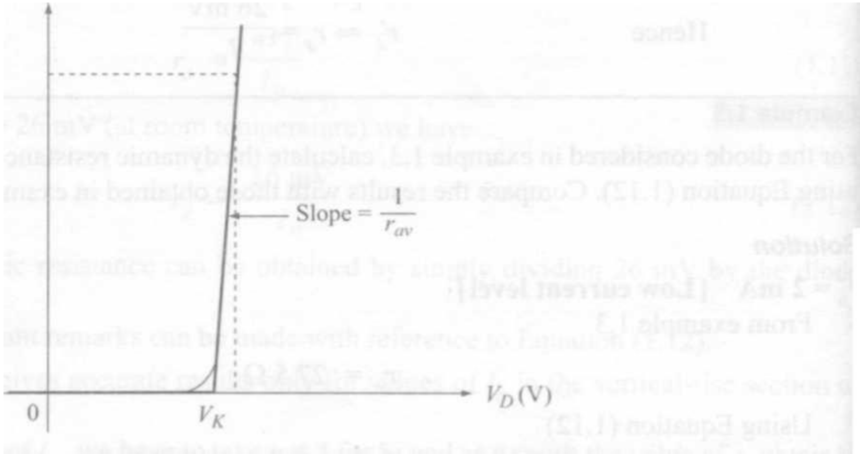
Note that, the dynamic resistance can be obtained by simply dividing 26 mV by the diode current I_D at Q point.

The following important remarks can be made with reference to Equation (1.12).

- Equation (1.12) gives accurate results only for values of I_D in the vertical-rise section of the curve.
- For lower values of I_D, we have to take $n = 2$ for Si and as a result the value of r_d obtained in Equation (1.12) must be multiplied by 2.
- For small values of I_D below the knee of the curve, Equation (1.12) becomes inappropriate.

EQUIVALENT CIRCUITS OF DIODE

The equivalent circuit of a diode is a circuit that closely approximates the diode behaviour under forward and reverse biased conditions. The diode equivalent circuit is also called the diode model. The analysis of diode circuits can be easily performed using Kirchoffs voltage law (KVL)



and Kirchotf's current law (KCL), after replacing the diodes with their equivalent circuits.

We observe the following facts from the piece-wise linear characteristics of Fig. 1.7.

For $V < V$,the diode current is zero.

- For $V_D > V_K$, the diode current increases linearly with diode voltage. The diode current is related linearly with the diode voltage by the average ac resistance r .
- The diode acts as an open circuit under reverse bias since, the reverse current through the diode is zero.

Figure 1.8 shows the piecewise linear equivalent circuit of a diode.

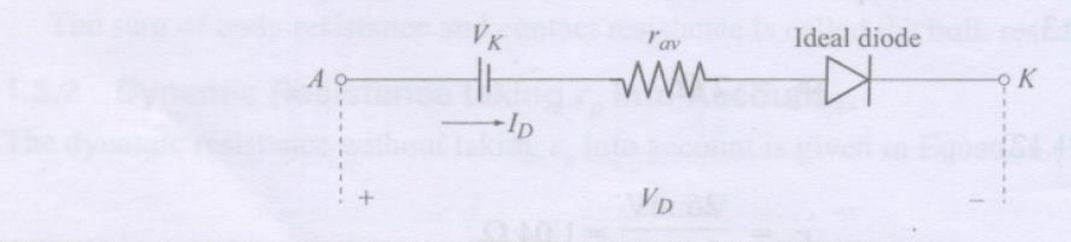


Fig. 1.8 Piecewise linear equivalent circuit of a diode

Simplified Equivalent Circuit

In most of the diode circuits external resistors will come in series with diodes during conduction. The resistance levels of these elements will be in the order of few hundred ohms to few tens of kilo-ohms. Under this condition r can be ignored owing to its sufficiently small value. If we apply the approximation, $\boldsymbol{r_m} = 0$ ***Q*** in the piecewise linear equivalent circuit of Fig. 1.8, we obtain the simplified equivalent circuit of diode shown in Fig. 1.9(b). Since r = 0, slope becomes infinite in the piecewise linear characteristics as shown in Fig. 1.9(a).

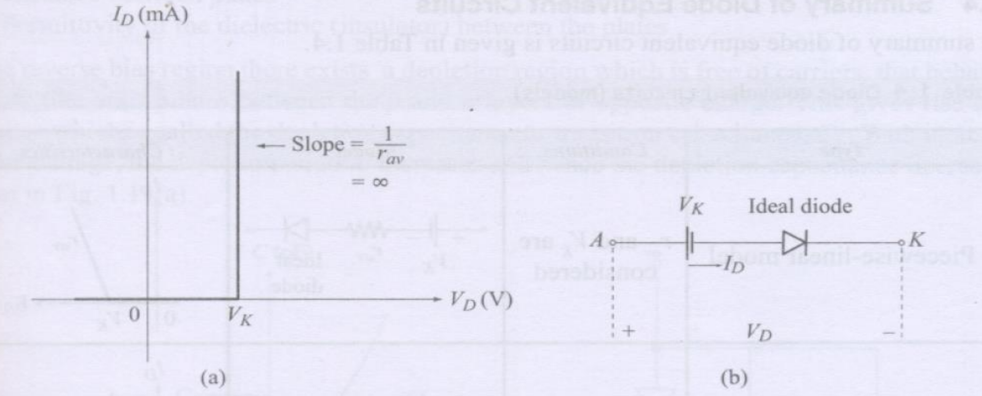


Fig. 1.9 (a) Piece wise linear characteristics with $r_{av} = 0\ \Omega$
(b) Simplified equivalent circuit of a diode

Ideal Equivalent Circuit

For Si diode, the level of V_K is 0.7 V. If the external voltage applied to the diode circuit is much greater than V_K, which is true in most of the cases, the effect of V_K can be ignored. If we apply the approximation V = 0 V to the piecewise linear characteristics and the simplified equivalent circuit of Fig. 1.9 we obtain the piecewise characteristics and the equivalent circuit of ideal diode shown in Fig. ! .10.

Ideal diode is characterised by

- Zero knee voltage (V_K= 0 V)

Zero average ac resistance (r =0Q => short circuit between anode and cathode)

- Infinite reverse resistance ***(R_r***= oo Q   open circuit between anode and cathode)

Ideal diode can be regarded as an electronic switch in the sense that, it acts as a short circuit far $V_D > 0$ *V and open circuit for* $V_D < 0$ *V.*

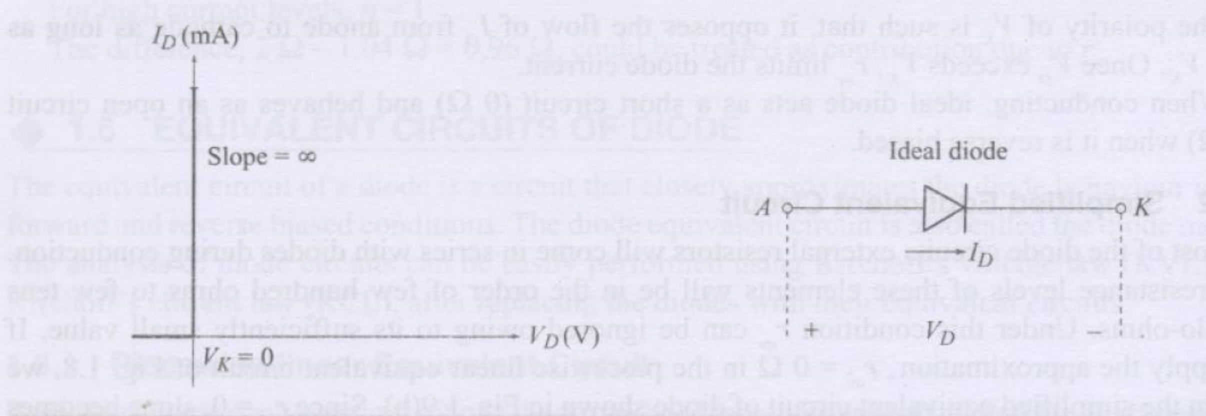


Fig. 1.10 Characteristics and equivalent circuit of ideal diode

TRANSITION AND DIFFUSION CAPACITANCE

The basic equation for the capacitance of a capacitor is given by

$$C = Q/V$$

where Q = Charge on capacitor plate

V = Applied voltage

In a diode the number of charge carriers crossing the Junction directly depends on the applied voltage, giving rise to a capacitive effect. Two capacitances exists in the diode one in the forward biased region and the other in the reverse biased region. They are

1. Transition or depletion capacitance (C_r)
2. Diffusion or storage capacitance (C_D)

Transition or Depletion Capacitance \ C_T

The basic equation for the capacitance of a parallel plate capacitor is given by

$$C = \frac{A\,\varepsilon}{d}$$

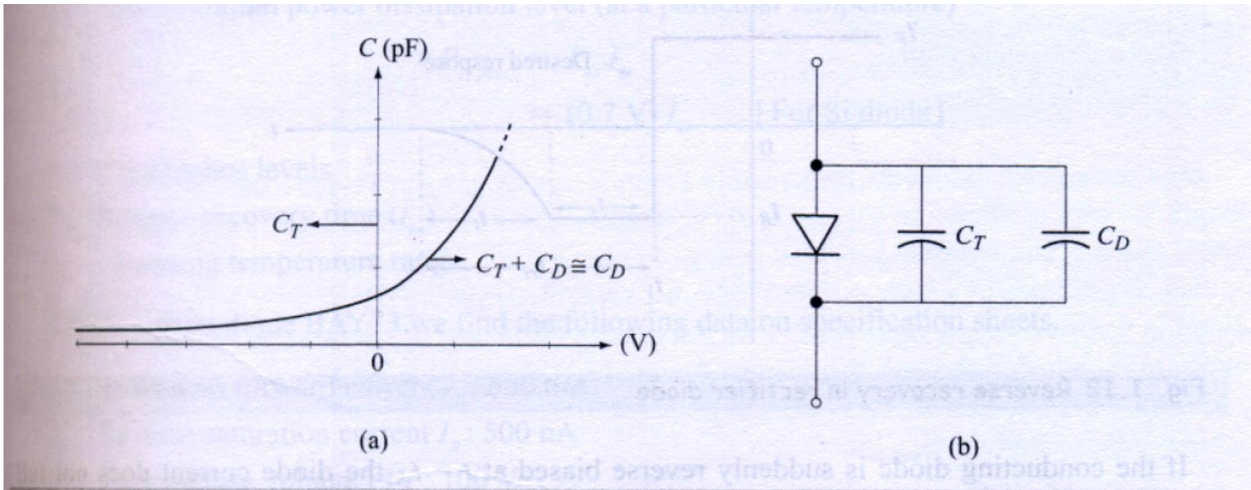
(1.16)

A = Plate area

d = Distance between plates

Permittivity of the dielectric (insulator) between the plates

In the reverse bias region there exists a depletion region which is free of carriers, that behaves essentially like an insulator between the p and n layers of opposite charge. This gives rise to a capacitance which is called the depletion capacitance or transition capacitance, C_T. With increase in reverse voltage, the depletion width d increases and hence the depletion capacitance decreases as shown in Fig. 1.11(a).



(a) (b)

Fig. 1.11 (a) Transition and diffusion capacitance versus applied bias for a Si diode
(b) Diode with its capacitances

Diffusion Capacitance or Storage Capacitance [C_D]

Under forward bias, the holes move from p side to n side and electrons from n side to p side. The electrons in p side and the holes on n side are called minority carriers. The number of excess minority carriers change with the applied bias and constitutes a voltage dependent charge storage or capacitance. Because this extra charge is caused by the diffusion of majority carriers across the junction, the capacitance is called the diffusion capacitance denoted by C_D. With increase in forward voltage, the diffusion of majority carriers will also increase giving rise to an increase in diffusion capacitance as shown in Fig. 1.11(a).

It is important to note that, depletion capacitance is dominant under reverse bias. Since the depiction width is very small under forward bias, diffusion capacitance is predominant. The effect of $\boldsymbol{C_T}$ and $\boldsymbol{C_D}$ are considered by placing them in parallel across the diode as shown in Fig. 1.11(b).

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CHARGE STORAGE AND REVERSE RECOVERY TIME

Consider a rectifier diode which is forward biased and carrying a constant forward current I_r as shown in Fig. 1.12.

Due to the application of forward bias, holes move from *p* region to *n* region and electrons move from *n* region to *p* region (it may be noted that holes in *n* region and electrons in /; region are minority carriers). Therefore when the diode is conducting, *p* region has plenty (excess) of electrons and *n* region has plenty (excess) of holes which are taking part in conduction. The excess electrons in *p* region and excess holes in « region are called stored charges and this phenomenon is called charge storage.

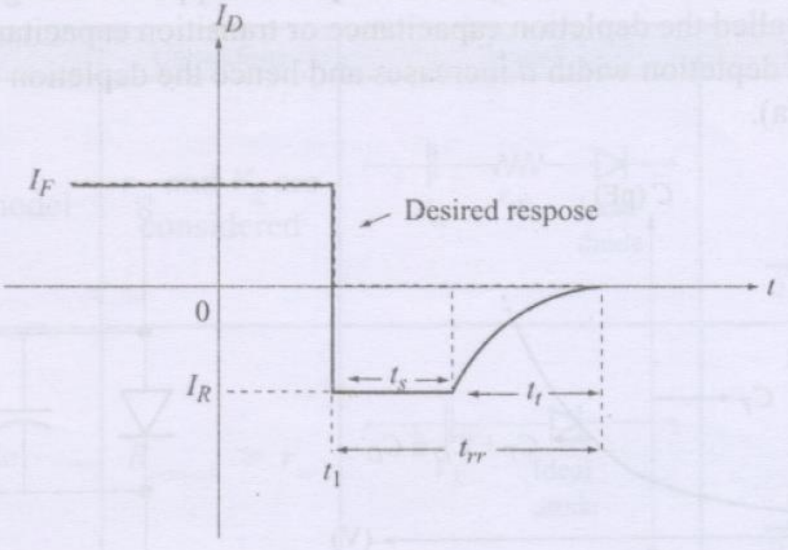


Fig. 1.12 Reverse recovery in rectifier diode

If the conducting diode is suddenly reverse biased at / = the diode current does not fall immediately from I_F to zero but it becomes zero after a time, **f** , called reverse recovery time a explained below.

1. A large number of stored charge, (minority earners) are present in each region. A certain amount of time, ***t,*** called the storage time is required for the minority carriers to return to their majority carrier state. Since excess holes in » region are moving towards *p* region and excess electrons in/j> region are moving towards n region, the current direction reverses in the diode. As a result the diode conducts a reverse current /^during the interval f.

2. Once the excess or stored charges returned to their original regions, the reverse current gradually decreases from 1_R to zero in the internal /$_;$, which is called the transition **interval.**

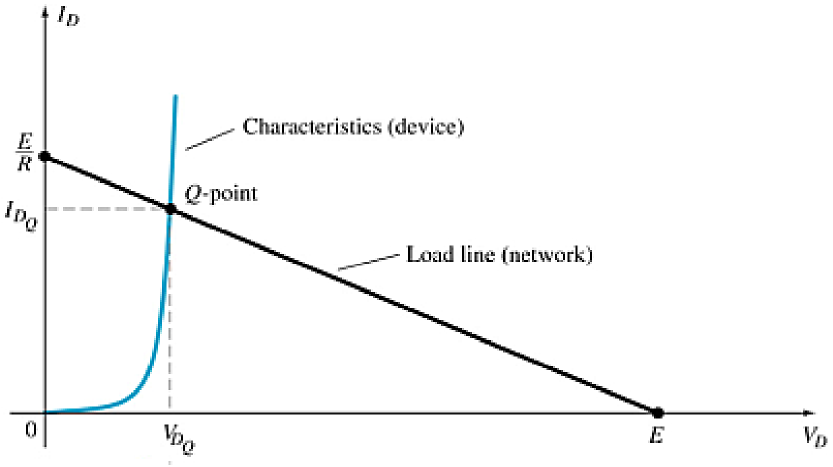
3. I he reverse recovery time ***t*** is the sum of storage time / and the transition time $\boldsymbol{t_r}$

i.e. $t_{rr} = t_s + t_t$

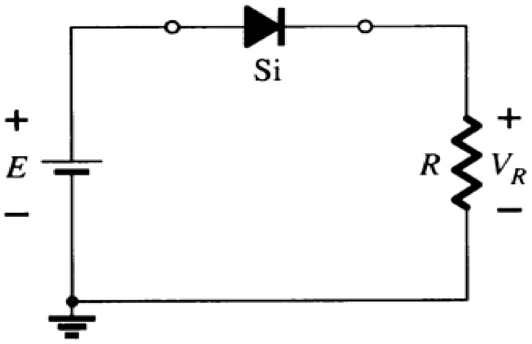
Load-Line Analysis

The load line plots all possible combinations of diode current (I_D) and voltage (V_D) for a given circuit. The maximum I_D equals E/R, and the maximum V_D equals E.

The point where the load line and the characteristic curve intersect is the Q-point, which identifies I_D and V_D for a particular diode in a given circuit.



Series Diode Configurations



Forward Bias

Constants

Silicon Diode: VD = 0.7 V

Germanium Diode: VD = 0.3 V

Analysis (for silicon)

VD = 0.7 V (or VD = E if E < 0.7 V)

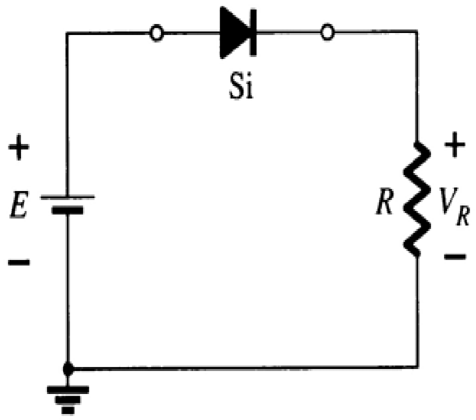
VR = E – VD

ID = IR = IT = VR / R

- **Reverse Bias**

Diodes ideally behave as open circuits Analysis

- $V_D = E$
- $V_R = 0$ V
- $I_D = 0$ A



Parallel Configurations

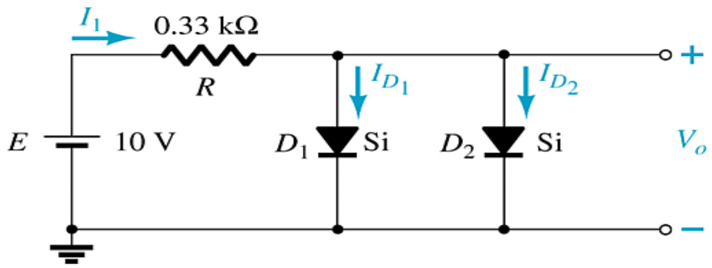
$V_D = 0.7\,V$

$V_{D1} = V_{D2} = V_O = 0.7\,V$

$V_R = 9.3\,V$

$$I_R = \frac{E - V_D}{R} = \frac{10\,V - .7\,V}{.33k\Omega} = 28\,mA$$

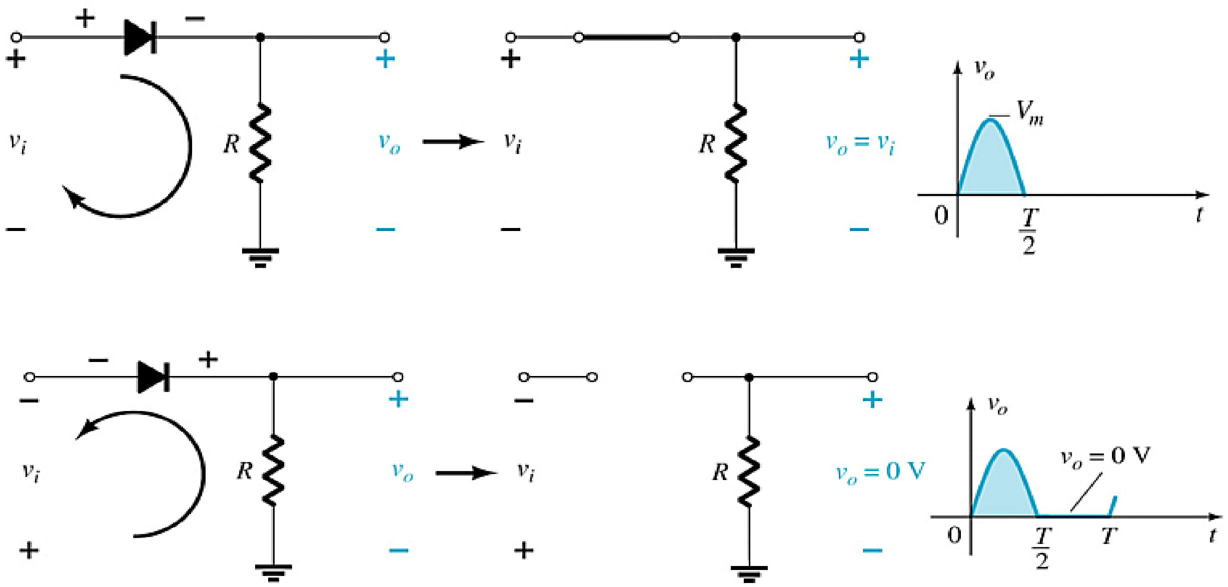
$$I_{D1} = I_{D2} = \frac{28\,mA}{2} = 14\,mA$$



Rectifiers

Half-Wave Rectification

The diode only conducts when it is forward biased, therefore only half of the AC cycle passes through the diode to the output.



The DC output voltage is 0.318V_m, where V_m = the peak AC voltage.

PIV (PRV)

Because the diode is only forward biased for one-half of the AC cycle, it is also reverse biased for one-half cycle.

It is important that the reverse breakdown voltage rating of the diode be high enough to withstand the peak, reverse-biasing AC voltage.

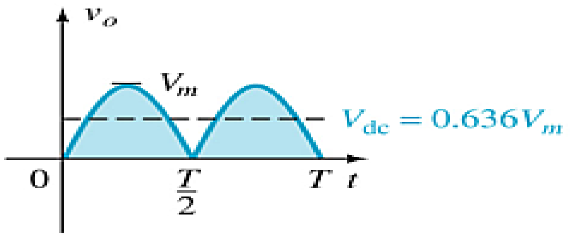
PIV (or PRV) >V_m

- PIV = Peak inverse voltage
- PRV = Peak reverse voltage

- V_m= Peak AC voltage

Full-Wave Rectification

The rectification process can be improved by using a full-wave rectifier circuit.



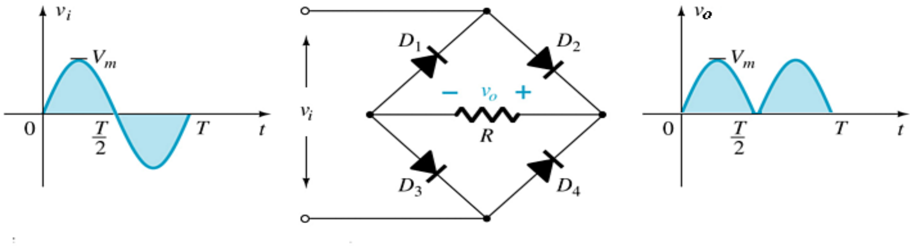
Full-wave rectification produces a greater DC output:

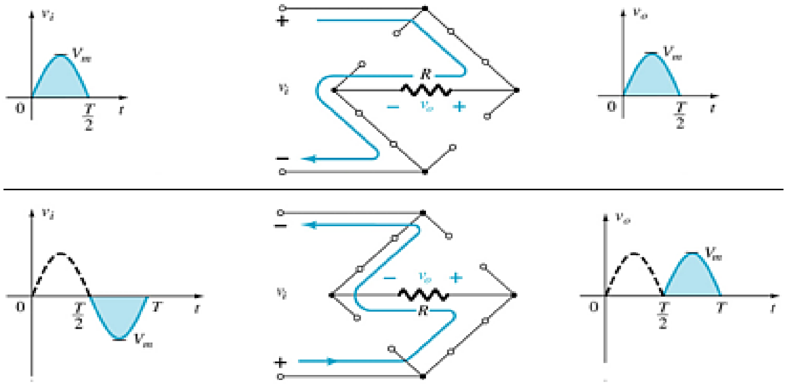
- Half-wave: $V_{dc} = 0.318V_m$
- Full-wave: $V_{dc} = 0.636V_m$

Bridge Rectifier

- Four diodes are connected in a bridge configuration

$V_{DC} = 0.636V_m$



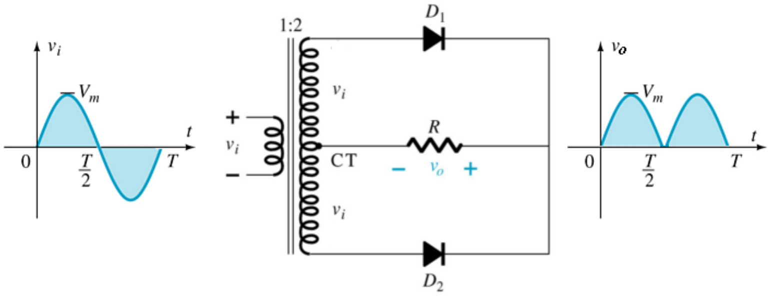


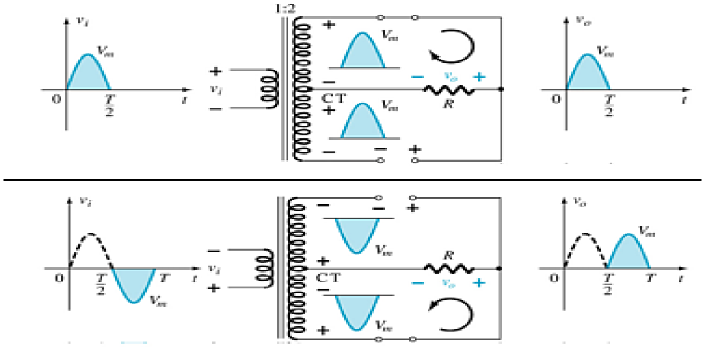
Center-Tapped Transformer Rectifier

Requires

- Two diodes
- Center-tapped transformer

$V_{DC} = 0.636V_m$





Summary of Rectifier Circuits

Rectifier	***Ideal*** V_{DC}	***Realistic*** V_{DC}
Half Wave Rectifier	$V_{DC} = 0.318V_m$	$V_{DC} = 0.318V_m - 0.7$

Bridge Rectifier	$V_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 2(0.7\ V)$
Center-Tapped Transformer Rectifier	$V_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 0.7\ V$

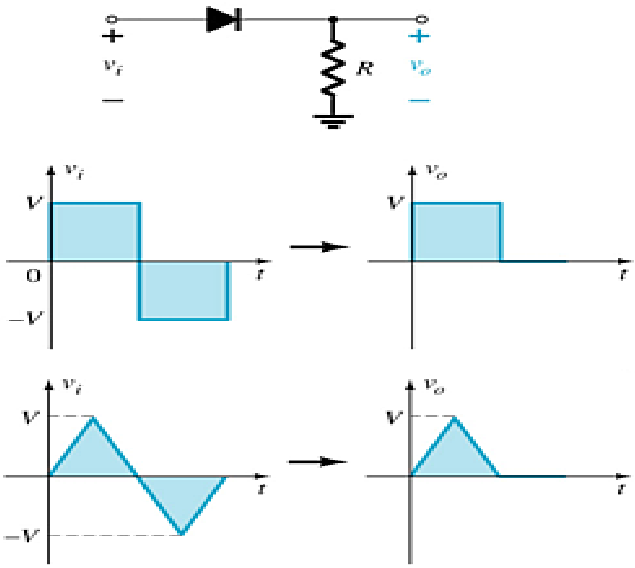
V_m= peak of the AC voltage.

In the center tapped transformer rectifier circuit, the peak AC voltage is the transformer secondary voltage to the tap.

Diode Clippers

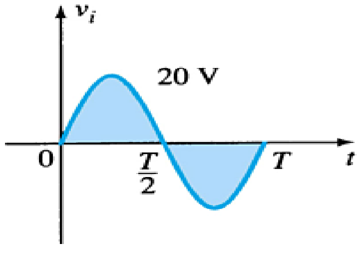
The diode in a series clipper "clips" any voltage that does not forward bias it:

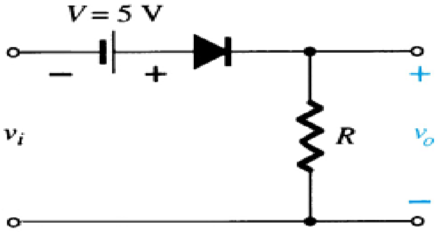
- A reverse-biasing polarity
- A forward-biasing polarity less than 0.7 V (for a silicon diode)

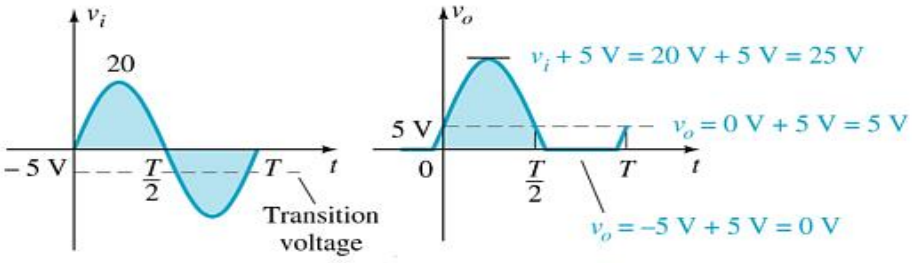


Biased Clippers

Adding a DC source in series with the clipping diode changes the effective forward bias of the diode.



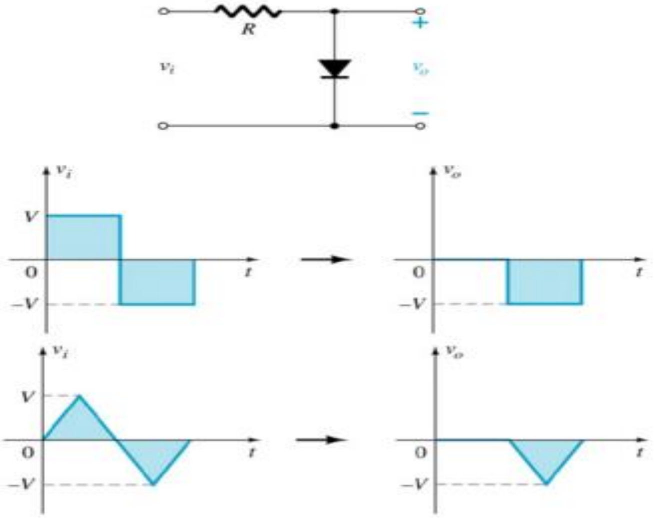




Parallel Clippers

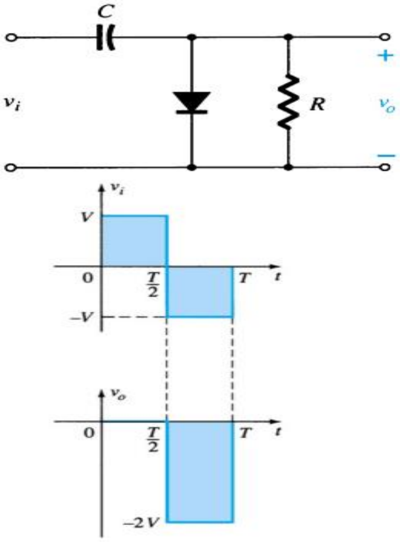
The diode in a parallel clipper circuit "clips" any voltage that forward bias it.

DC biasing can be added in series with the diode to change the clipping level.



Clampers

A diode and capacitor can be combined to “clamp” an AC signal to a specific DC level.



Biased Clamper Circuits

The input signal can be any type of waveform such as sine, square, and triangle waves.

The DC source lets you adjust the DC camping level.