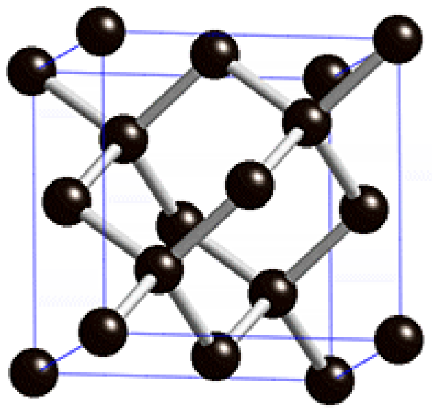
Module 2

- Semiconductor Basics
- Diodes
- BJT
- FET

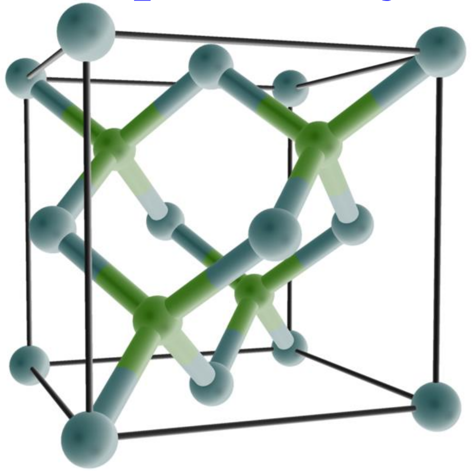
Intrinsic Semiconductors

- **Semiconductor** – a material whose conductivity lies between that of conductors (copper) and insulators (glass).
  - **Single-element** – such as Germanium (Ge) and Silicon (Si).
  - **Compound** – such as Gallium-Arsenide (GaAs).

Single-element crystal



Compound crystal



We would mostly discuss about silicon as it is the material of choice for electronic devices

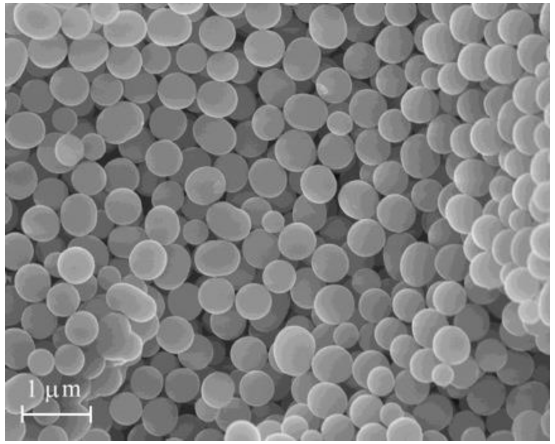
Intrinsic Semiconductors

- **What does a Semiconductor look like?**
- **Where is it used?**

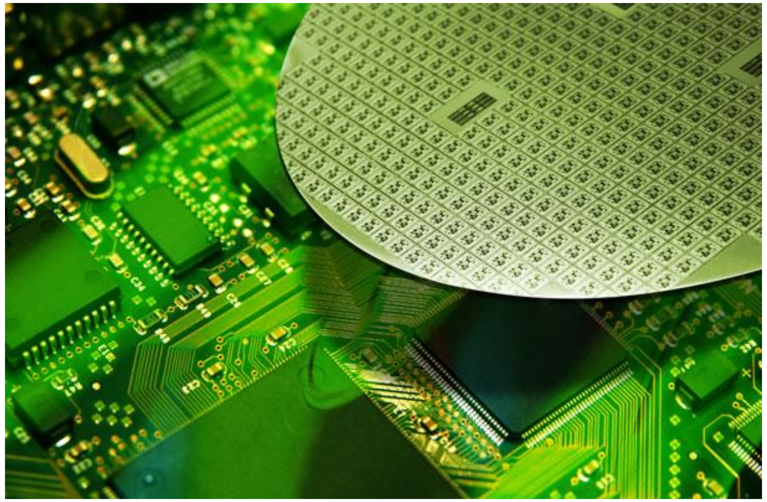
Raw Silicon

Si wafer

SiO_2 under SEM (Scanning Electron Microscope)

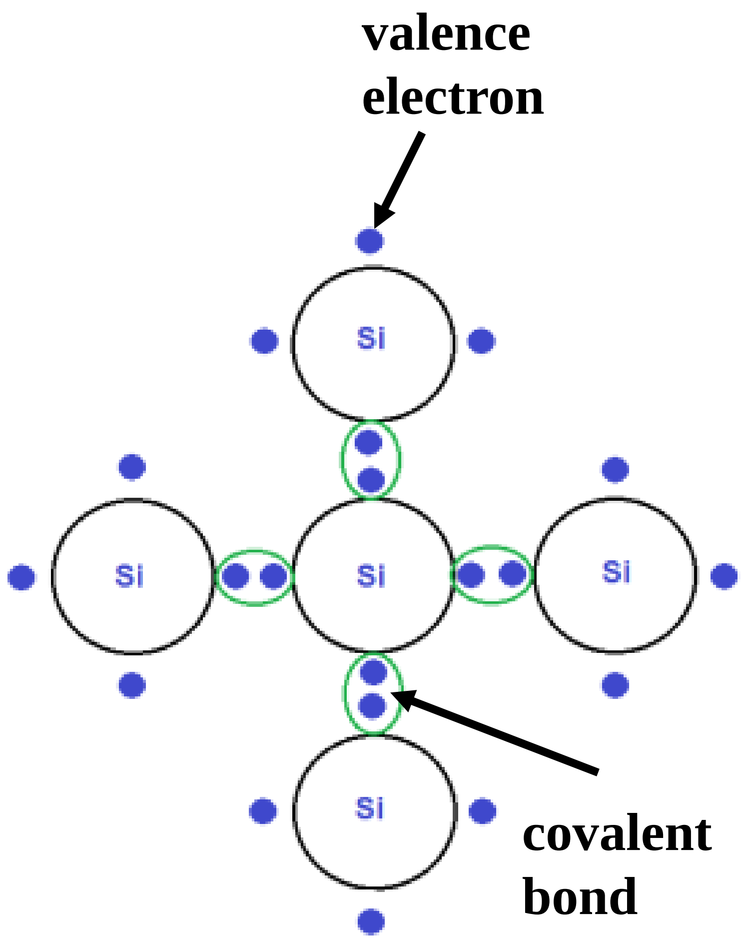


Procesed Wafer and Electronics Components



Intrinsic Semiconductors

- **Valence electron** – is an electron that participates in the formation of chemical bonds.
  - Lies in the outermost electron shell of an element
  - The number of valence electrons that an atom has determines the kinds of chemical bonds that it can form.
- **Covalent bond** – is a form of chemical bond in which two atoms share a pair of electrons
  - By sharing their outer most (valence) electrons, atoms can fill up their outer electron shell and gain stability



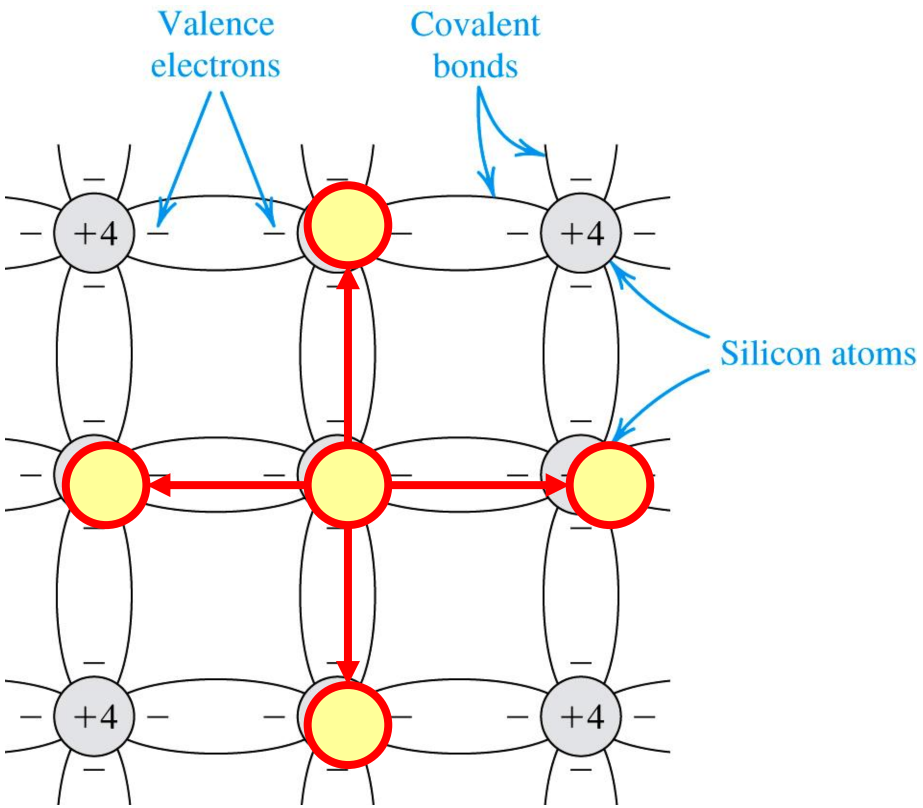
Intrinsic Semiconductors

Why use Si?

- Cheap and abundant
- Thermally stable
- SiO_2 is strong dielectric

Si atom

- Has four valence electrons (Carbon group or group IV)
- Requires four more to complete outermost shell
- Each pair of shared forms a covalent bond



Two-dimensional representation of the silicon crystal. The circles represent the inner core of silicon atoms, with +4 indicating its positive charge of +4*q*, which is neutralized by the charge of the four valence electrons. Observe how the covalent bonds are formed by sharing of the valence electrons. At 0K, all bonds are intact and no free electrons are available for current conduction.

Intrinsic Semiconductors

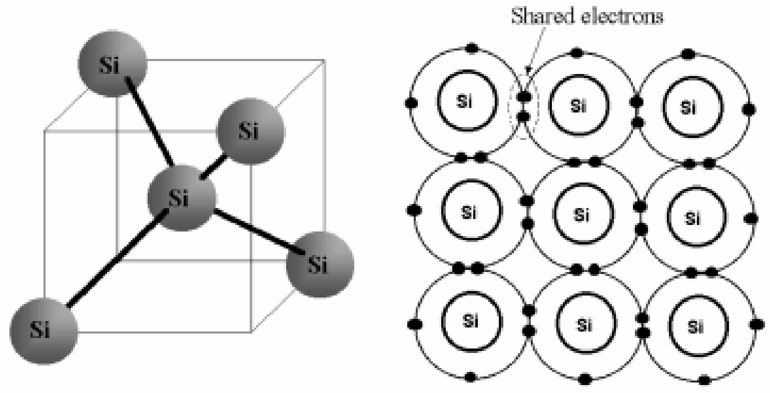
Silicon at low temp

- all covalent bonds – are intact
- no electrons – are available for conduction
- conductivity – is zero

Silicon at room temp

- some covalent bonds – break, freeing an electron and creating hole, due to thermal energy
- some electrons – will wander from their parent atoms, becoming available for conduction
- conductivity – is greater than zero

Crystal Structure of Single Crystal Silicon



The process of freeing electrons, creating holes, and filling them facilitates current flow…

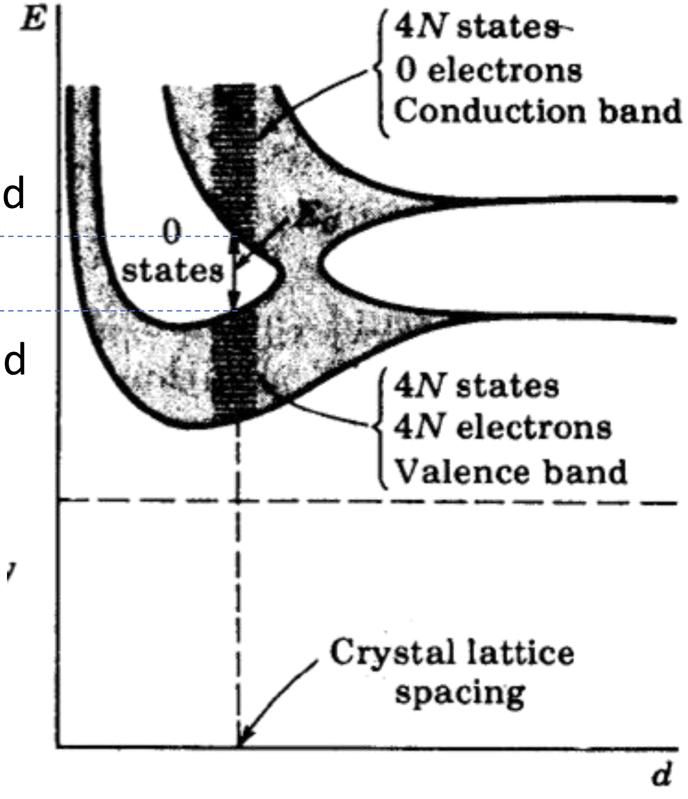
Intrinsic Semiconductors

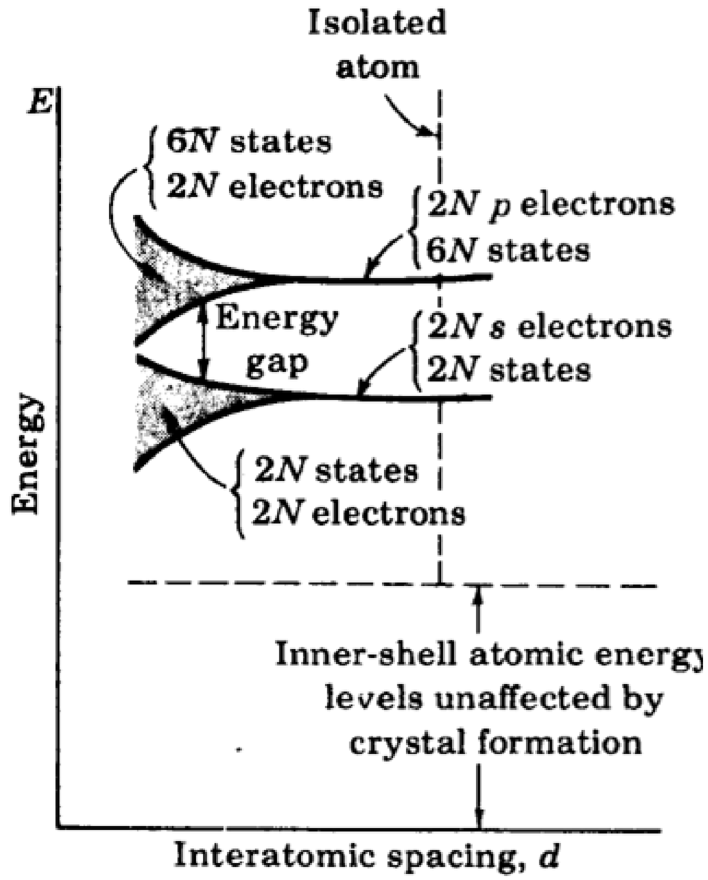
Element	Atomic number	Configuration
C	6	$1s^2 2s^2 2p^2$
Si	14	$1s^2 2s^2 2p^6 3s^2 3p^2$
Ge	32	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$
Sn	50	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^2$

Electronic Configuration

Bottom of the conduction band

Top of the valance band





Intrinsic Semiconductors

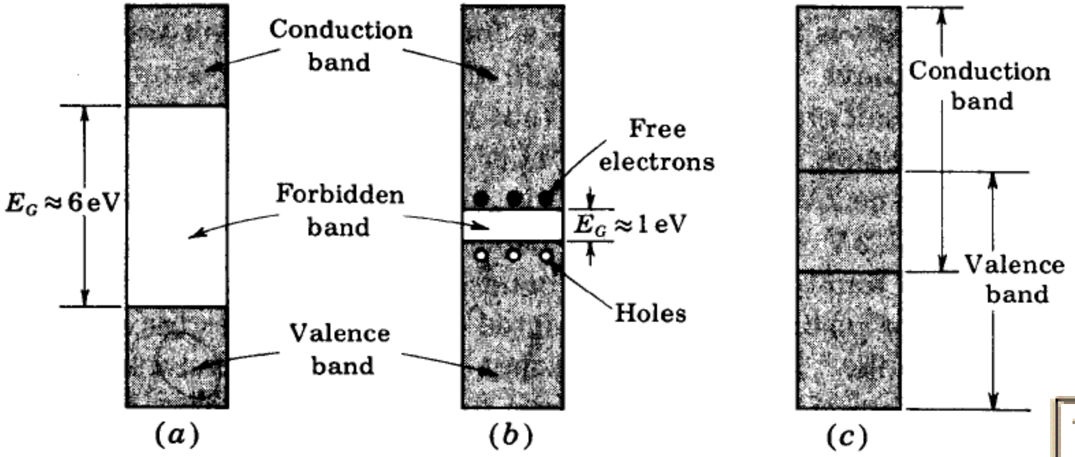
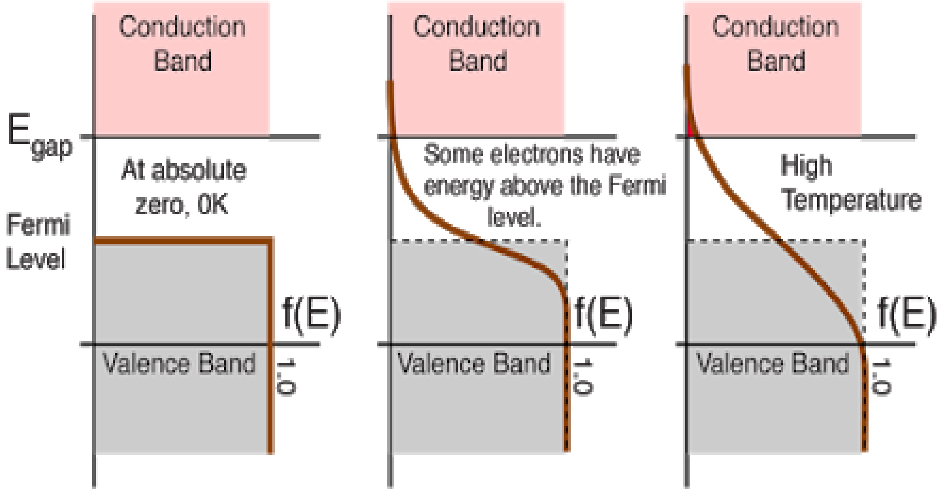


Fig. 1-4 Energy-band structure of (*a*) an insulator, (*b*) a semiconductor, and (*c*) a metal.



No electrons can be above the Fermi level at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

The probability that a particle will have energy E

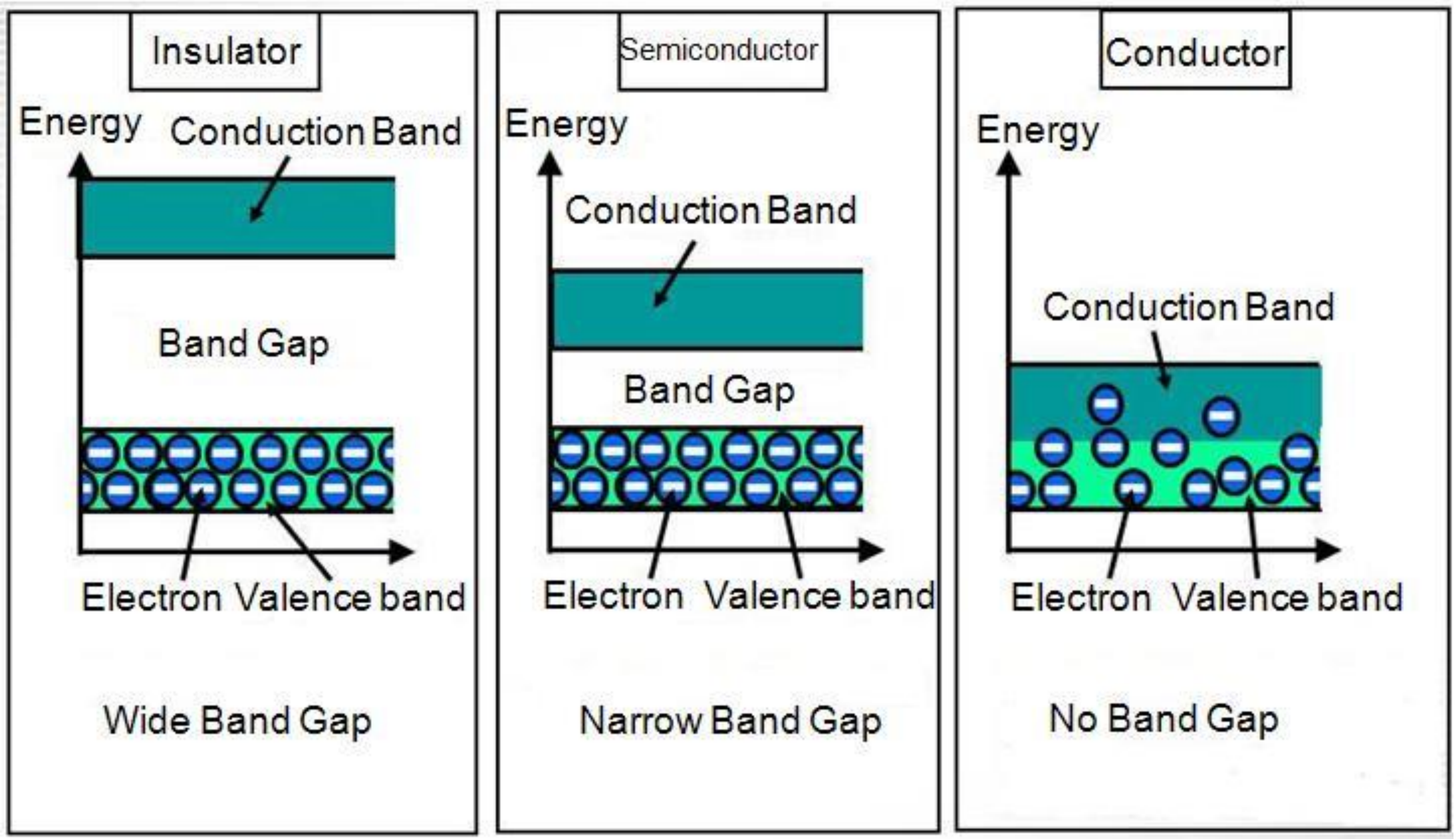
$$f(E)_{\text{Fermi-Dirac}} = \frac{1}{e^{(E - E_F)/kT} + 1}$$

See the Maxwell-Boltzmann distribution for a general discussion of the exponential term.

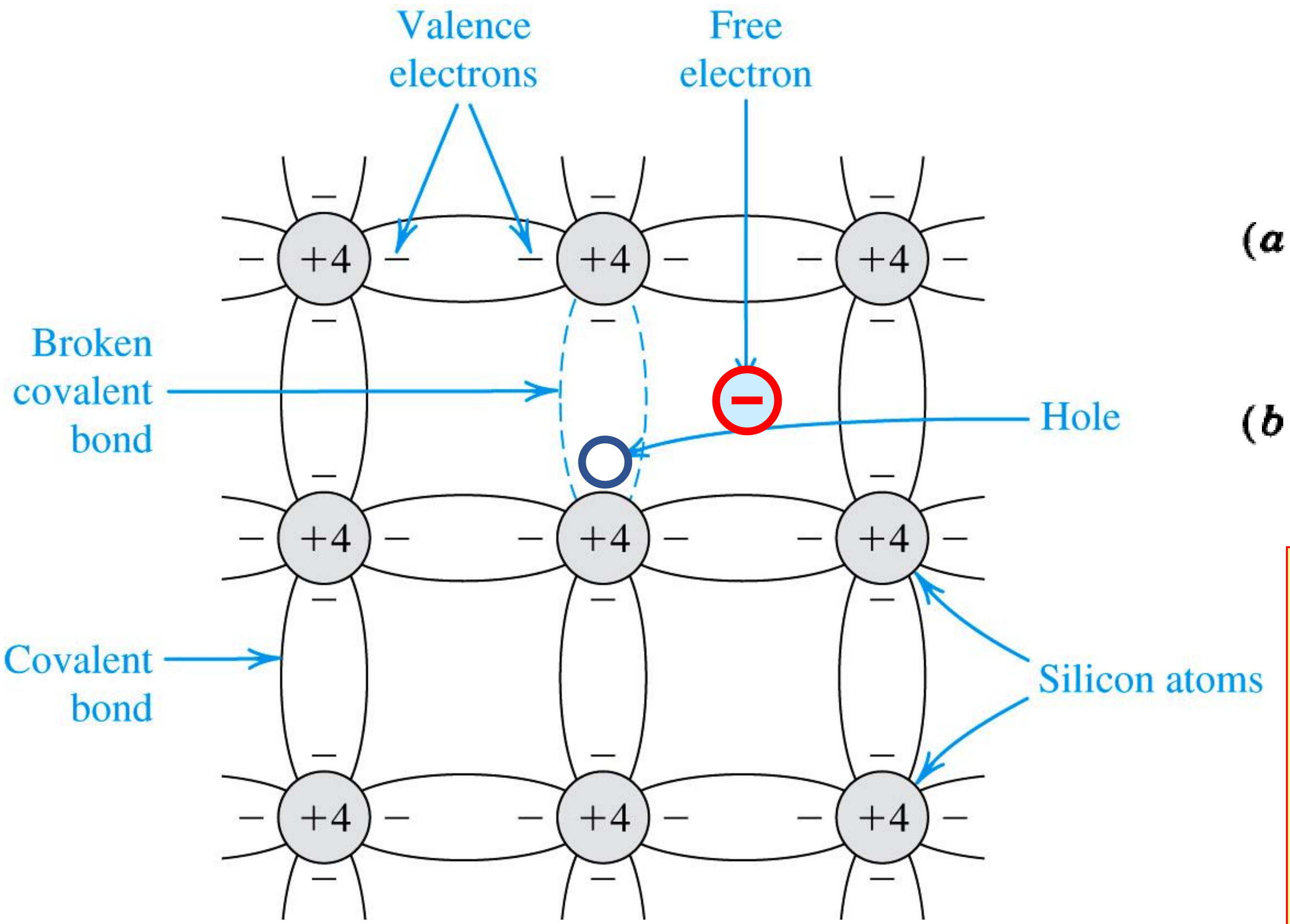
For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

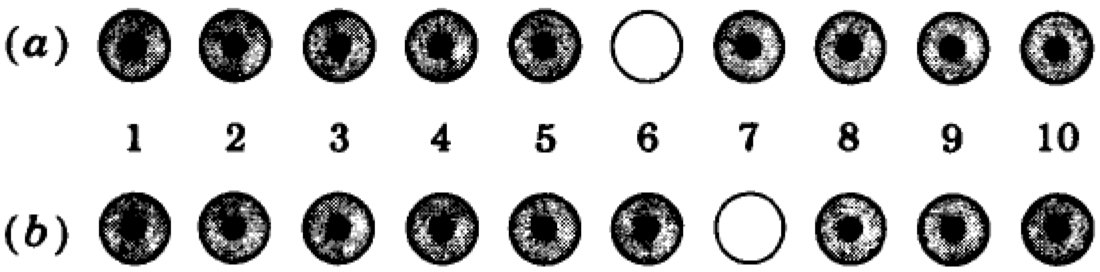
The quantum difference which arises from the fact that the particles are indistinguishable.

Insulator, Semiconductors, Conductors



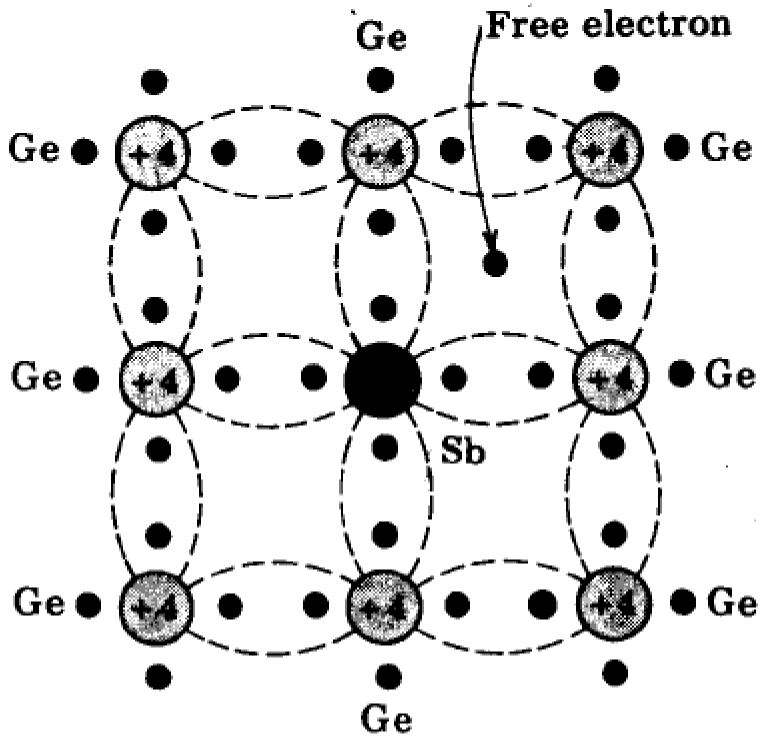
At room temperature, some of the covalent bonds are broken by thermal generation. Each broken bond gives rise to a free electron and a hole, both of which become available for current conduction.

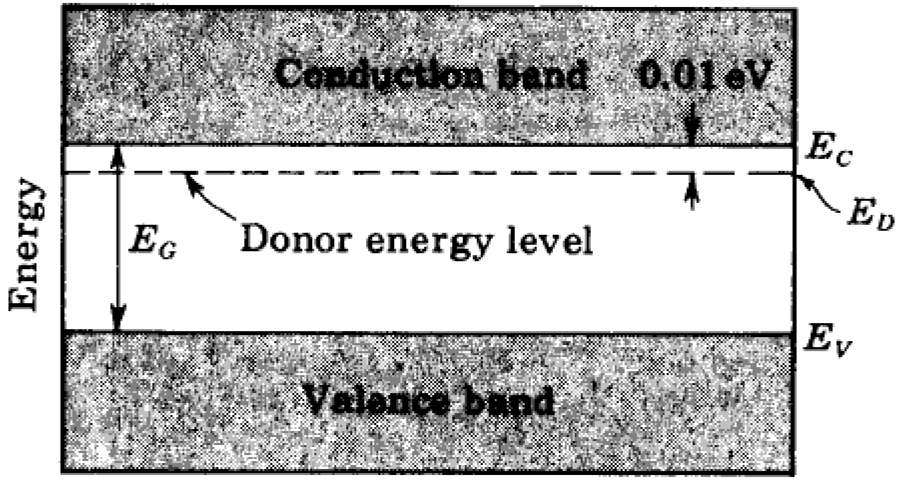




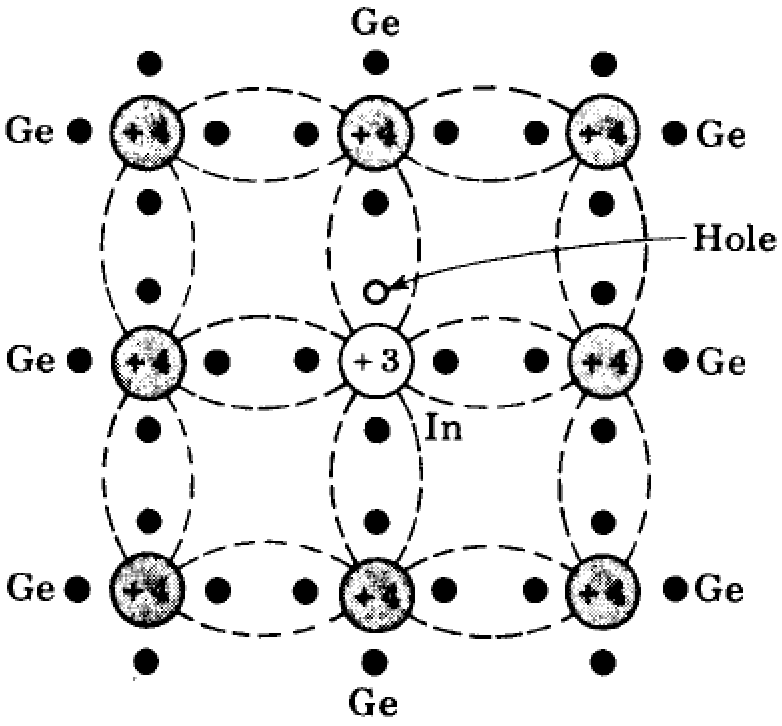
the process of freeing electrons, creating holes, and filling them facilitates current flow

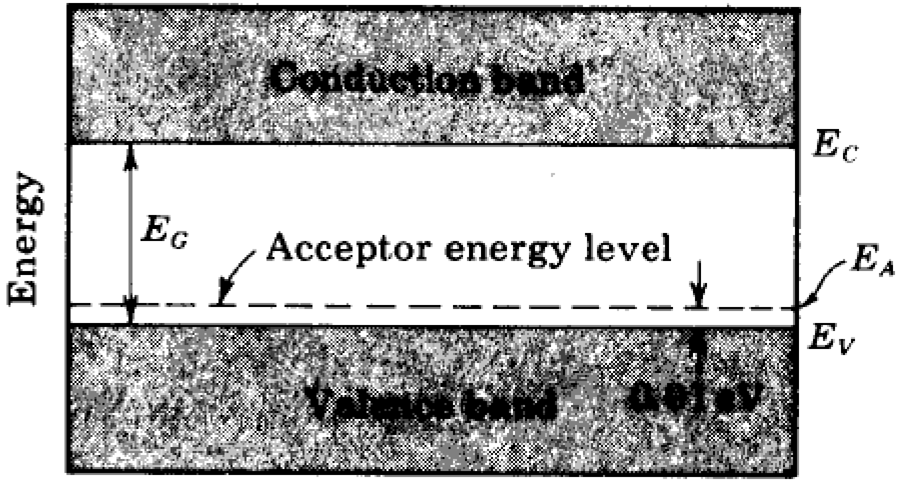
Doped/Extrinsic Semiconductors





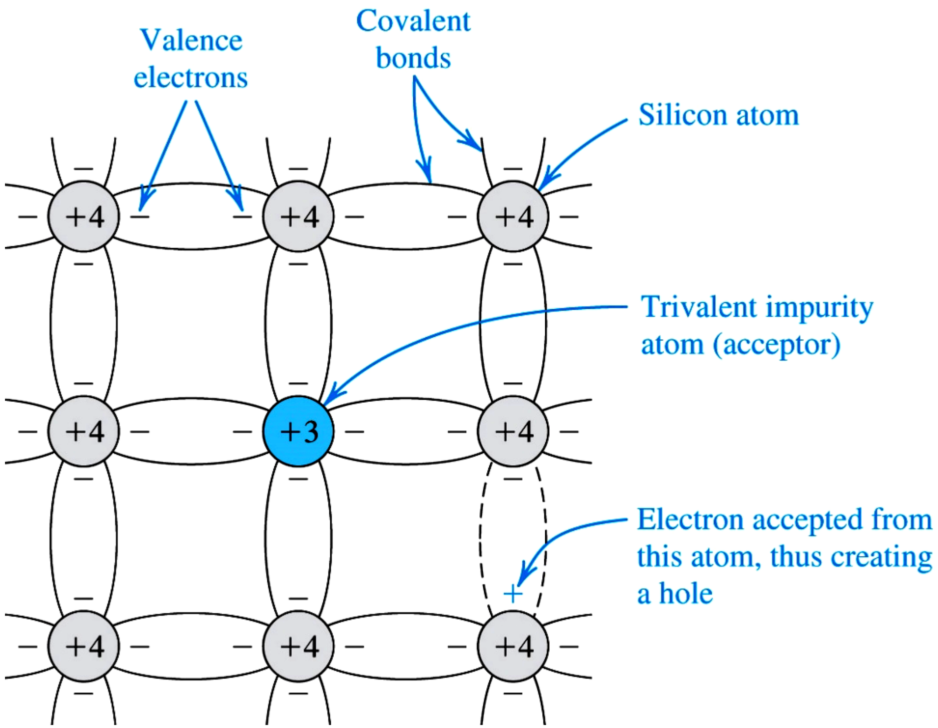
Doped/Extrinsic Semiconductors

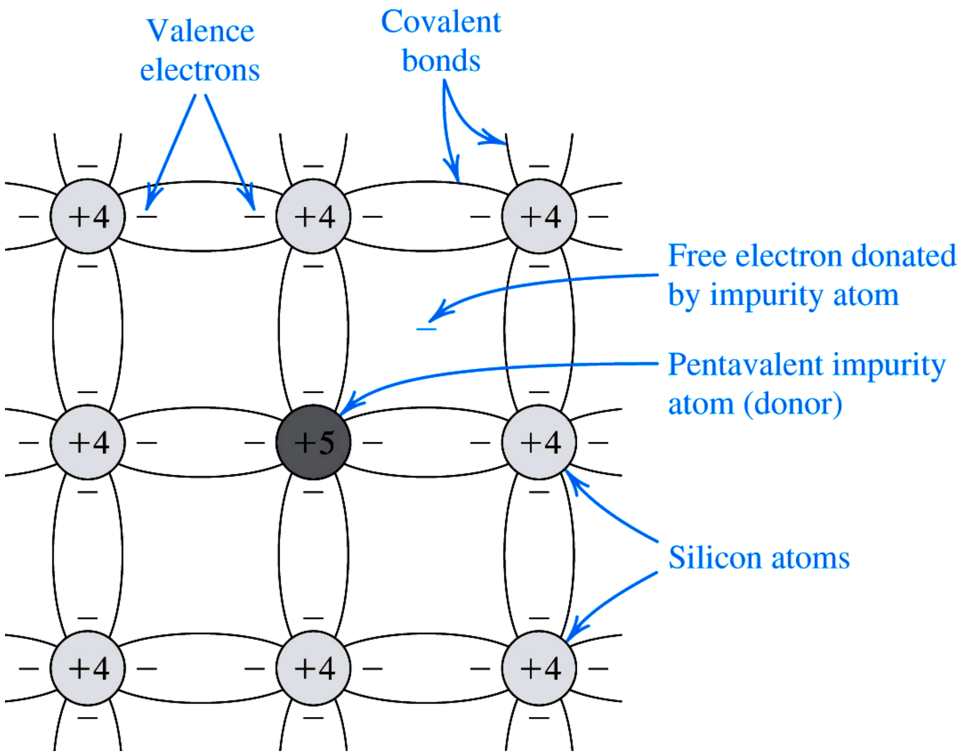




Doped/Extrinsic Semiconductors

- ***p*-type semiconductor**
  - **doped with trivalent impurity atom (e.g. Boron)**
- ***n*-type semiconductor**
  - **doped with pentavalent impurity atom (e.g. Phosphorus)**





Doped Semiconductors

- ***p*-type or *n-type* semiconductor**
  - **is electrically neutral by itself** (as standalone unit)
  - majority carriers (holes in ***p-type*** and electrons in ***n-type***) flow by replacing the **bound charges** associated with impurity atoms

Current Flow in Semiconductors

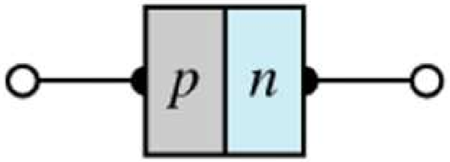
- **Summary**
  - Holes (absence of electrons, p) and free electrons (n):
  - ***p-type*** semiconductor: holes are majority carriers (p_p), free electrons (n_p) are minority carriers
  - ***n-type*** semiconductor: free electrons are majority carriers (n_n), holes are minority carriers (p_n)

- **Two distinct mechanisms for current flow (movement of charge carriers)**
  - **Drift Current (I_S)**
  - **Diffusion Current (I_D)**

p-n Junctions

One end of a silicon or germanium crystal can be doped as a *p*- type material and the other end as an *n*-type material.

The result is a *p-n* junction.

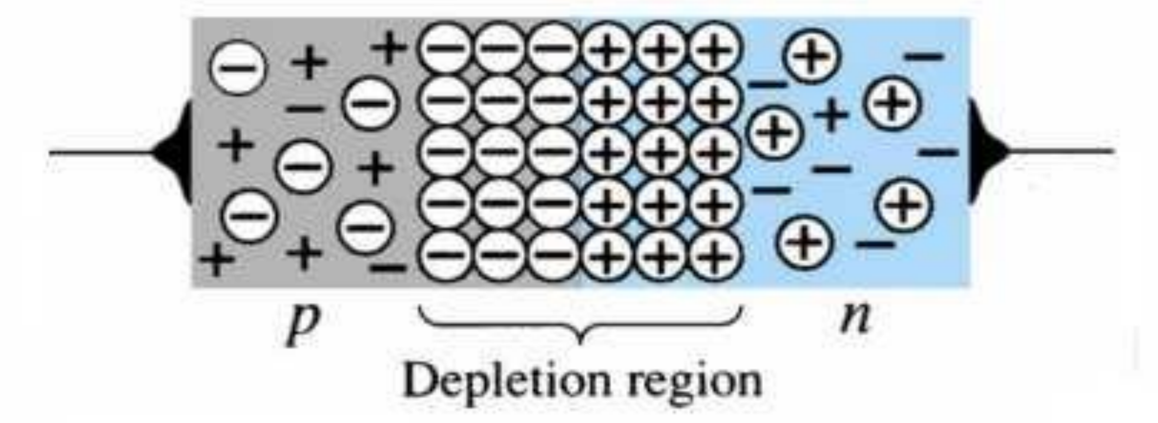


p-n Junctions

At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.

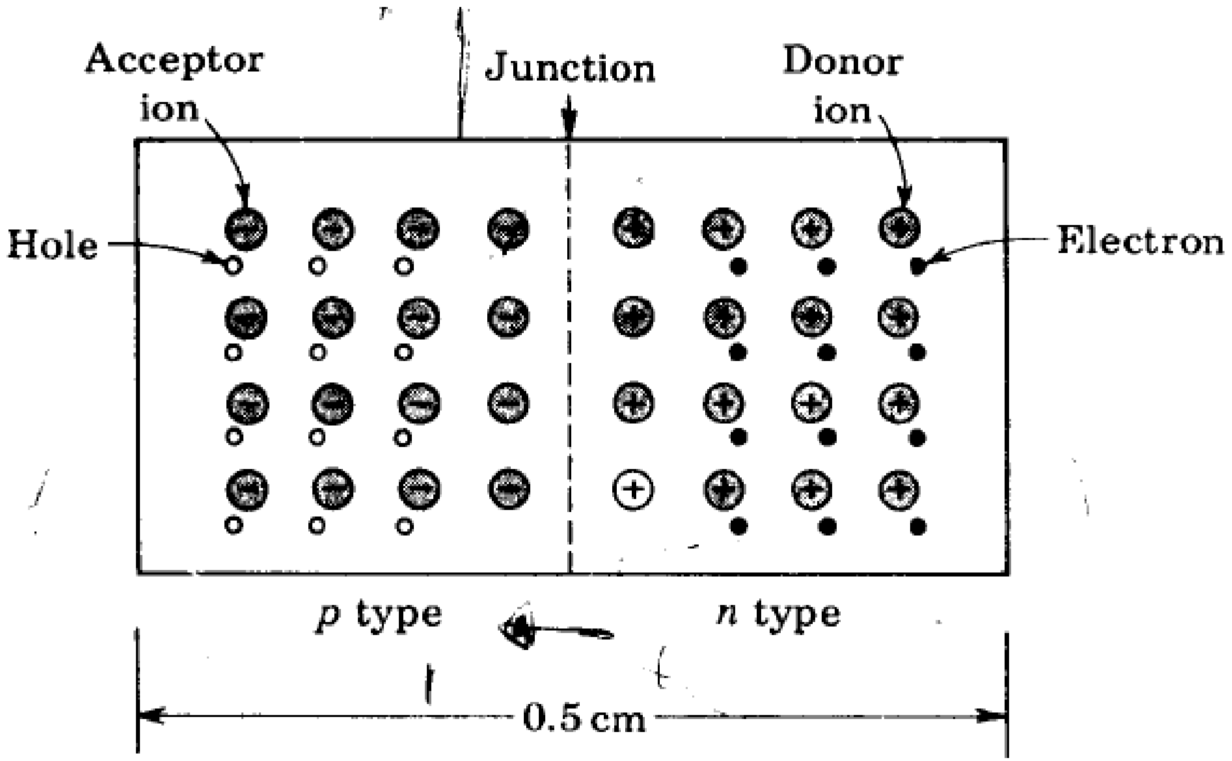
The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).

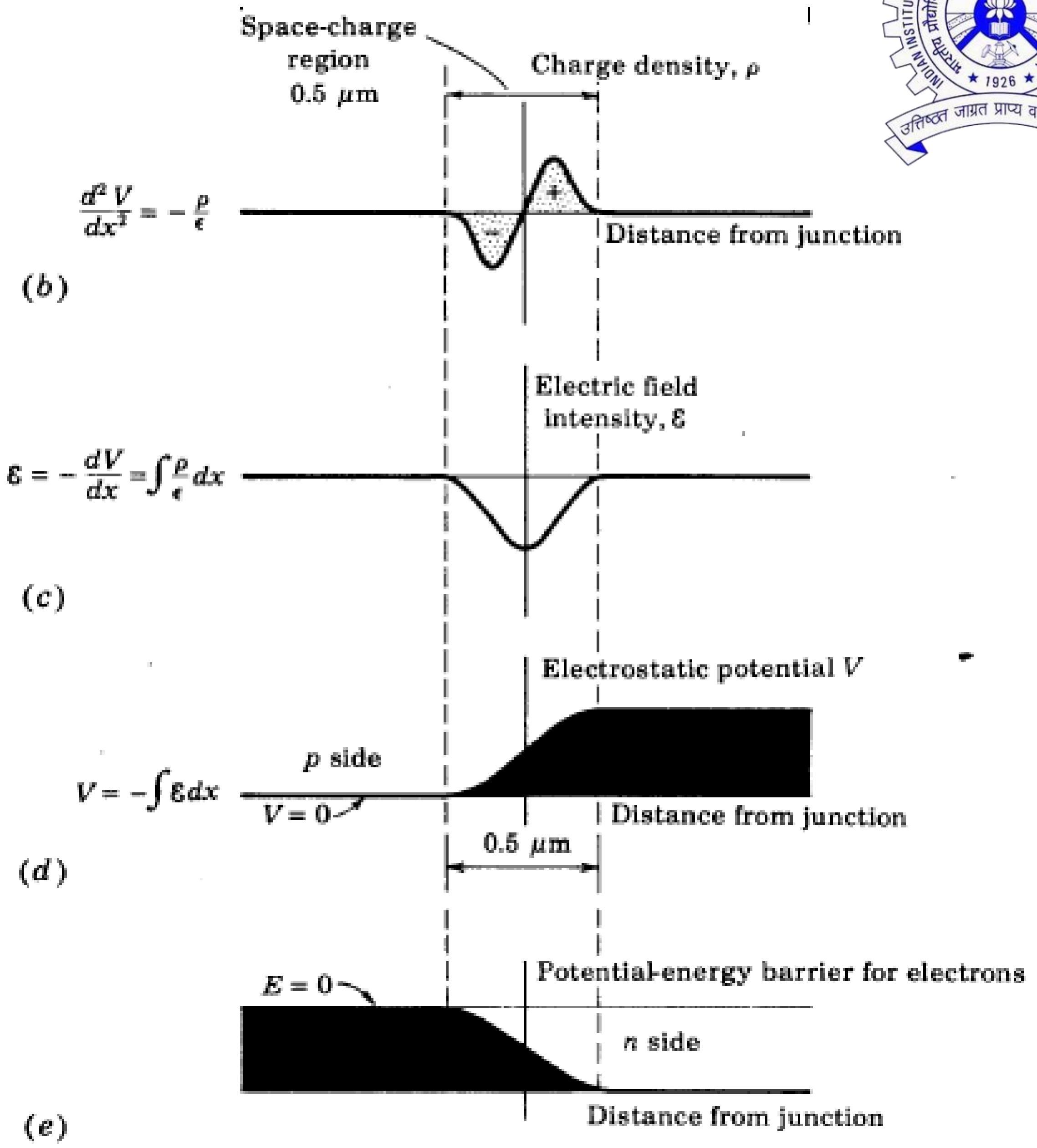
The electron migration results in a negative charge on the p-type side of the junction and a positive charge on the n-type side of the junction.



The result is the formation of a depletion region around the junction.

Junction Diode





Charge Distribution around a Junction Diode

Diode Operating Conditions

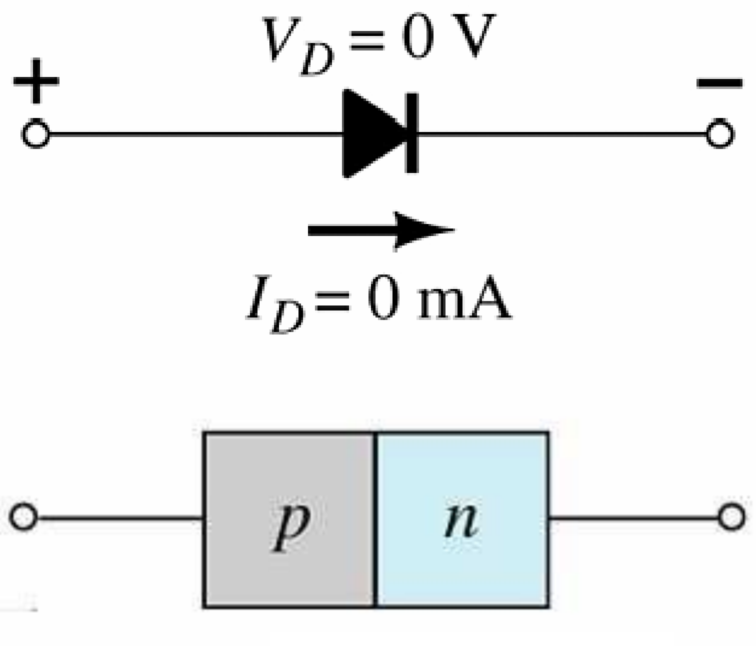
A diode has three operating conditions:

- **No bias**
- **Reverse bias**
- **Forward bias**

Diode Operating Conditions

No Bias

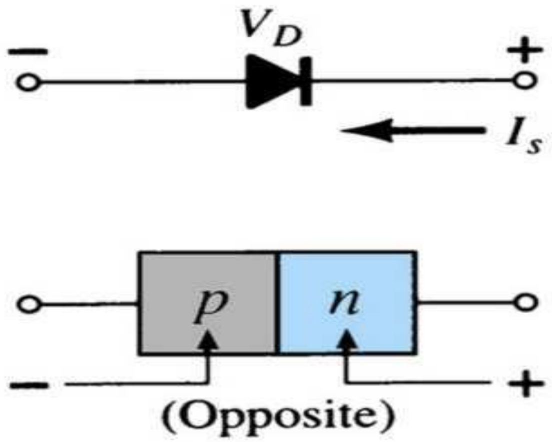
- No external voltage is applied: V_D = 0 V
- No current is flowing: I_D = 0 A
- Only a modest depletion region exists

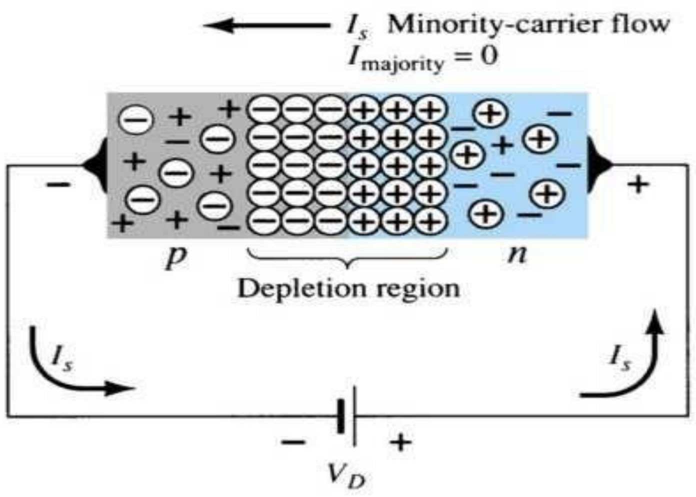


Diode Operating Conditions

Reverse Bias

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



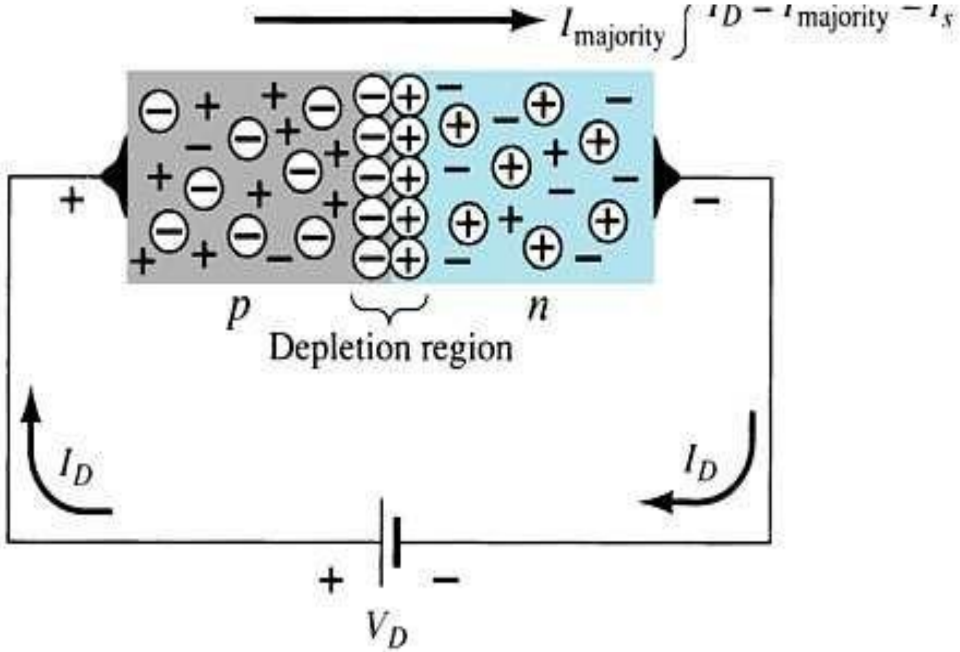


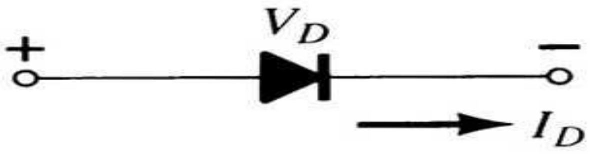
- **The reverse voltage causes the depletion region to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

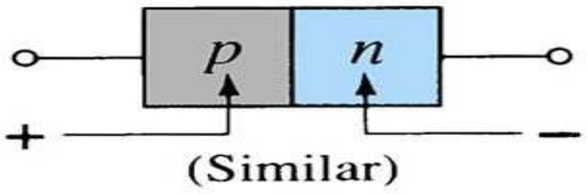
Diode Operating Conditions

Forward Bias

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



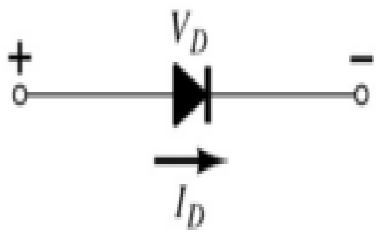




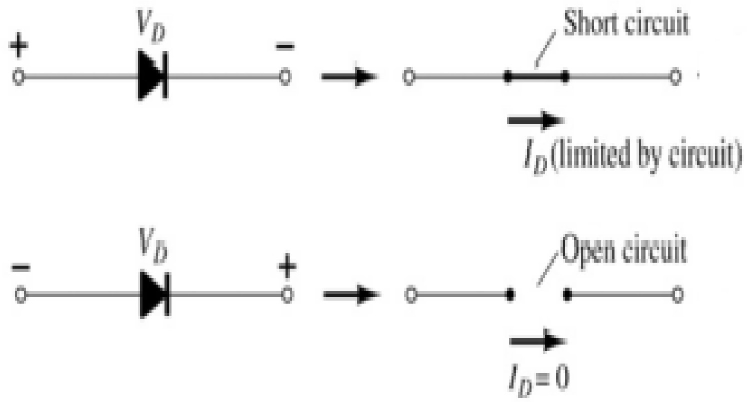
- **The forward voltage causes the depletion region to narrow.**
- **The electrons and holes are pushed toward the *p*-*n* junction.**
- **The electrons and holes have sufficient energy to cross the *p*-*n* junction.**

Diodes

The diode is a 2-terminal device.

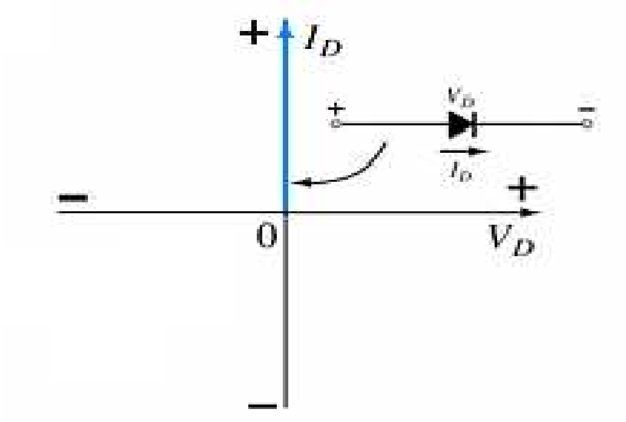


A diode ideally conducts in only one direction.



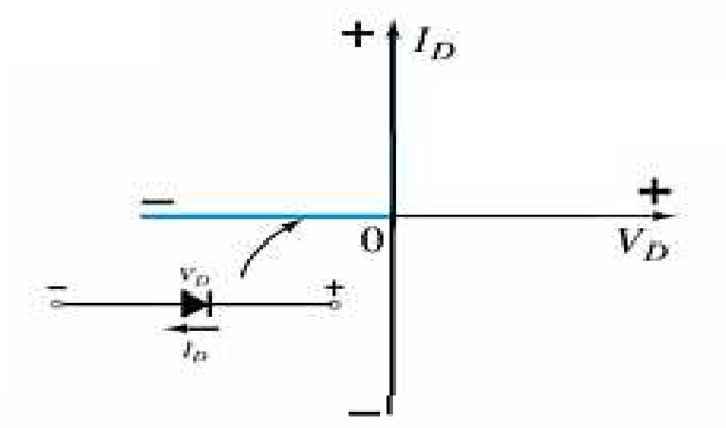
Ideal Diode Characteristics

Conduction Region



- **The voltage across the diode is 0 V**
- **The current is infinite**
- **The forward resistance is defined as $R_F = V_F / I_F$**
- **The diode acts like a short**

Non-Conduction Region



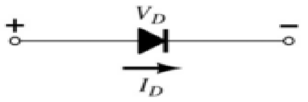
- **All of the voltage is across the diode**
- **The current is 0 A**
- **The reverse resistance is defined as $R_R = V_R / I_R$**
- **The diode acts like open**

Current flow in forward & Reverse direction

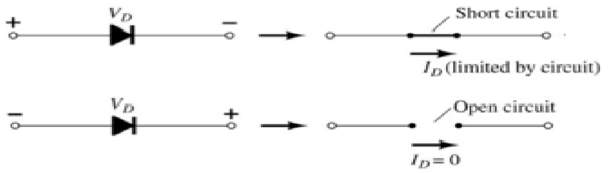
The two modes of operation of ideal diodes and the use of an external circuit to limit **(a)** the forward current and **(b)** the reverse voltage.

Ideal diodes (Switch)

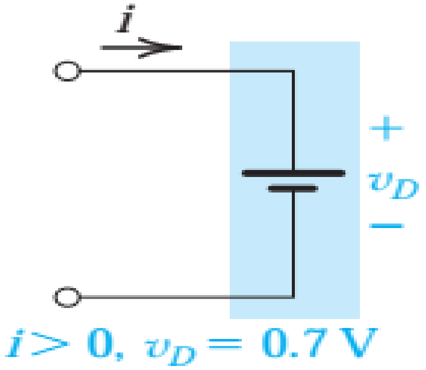
The diode is a 2-terminal device.

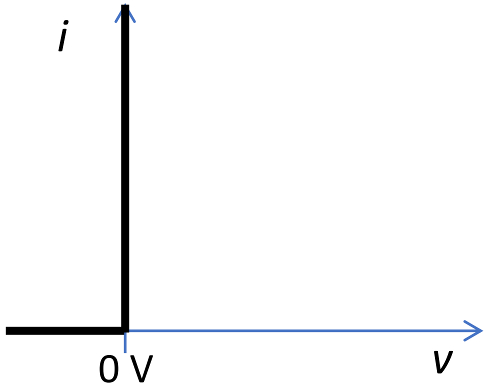


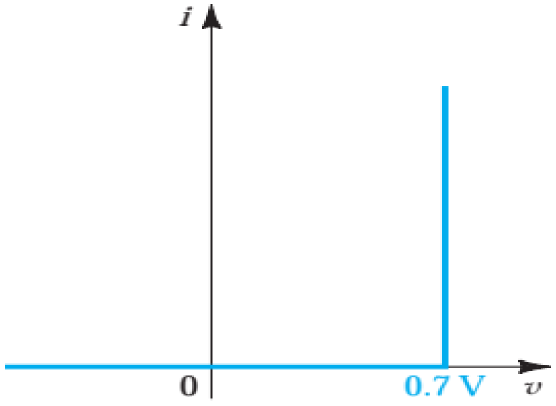
A diode ideally conducts in only one direction.

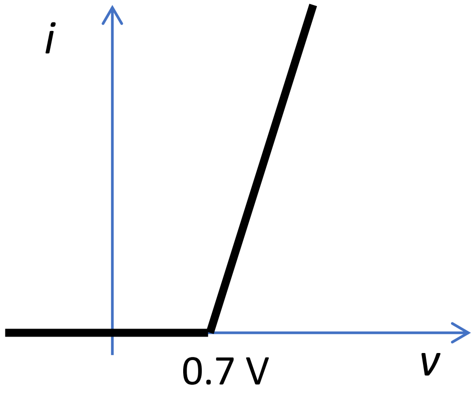


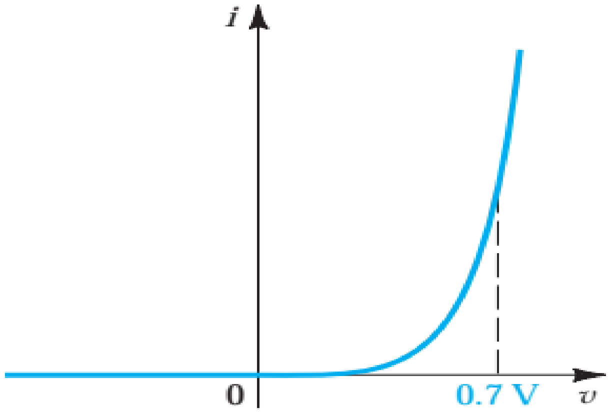
Constant voltage diode model











Actual Diode Equation

$$I_D = I_S(e^{qV_D/\eta k_B T} - 1)$$

$$= I_S(e^{V_D/\eta V_T} - 1)$$

k_B: Boltzmann's constant $= 1.38 \times 10^{-23} J/K$

T: Absolute temperature in

η: Ideality factor; We assume $\eta = 1$, In general, $1 < \eta < 2$

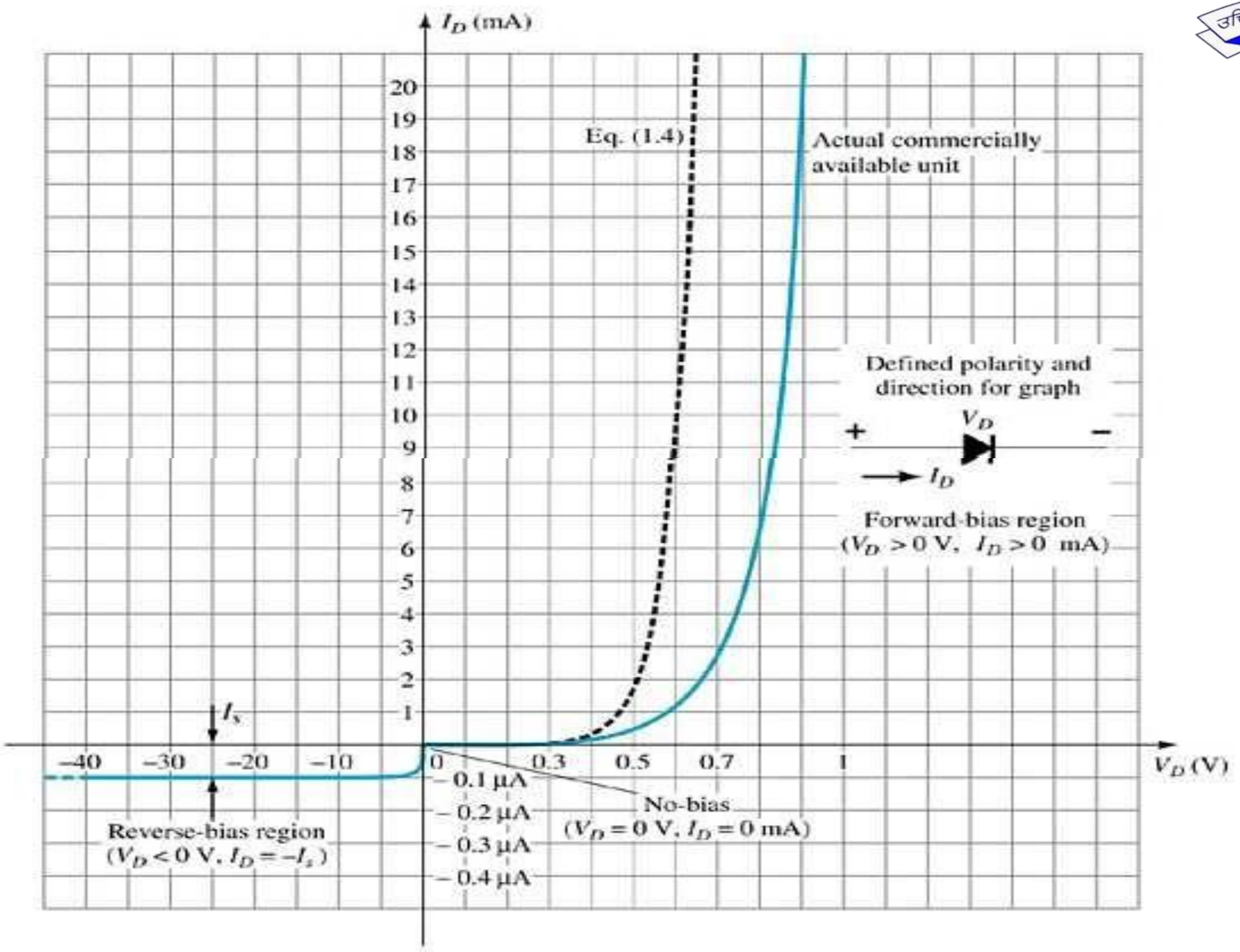
V_T : Thermal voltage; $V_T \approx 26$ mV at room temperature

Reverse saturation current:- $I_S = qA\left(\frac{D_p}{L_p}p_{n0} + \frac{D_n}{L_n}n_{p0}\right)$

Actual Diode Characteristics

Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

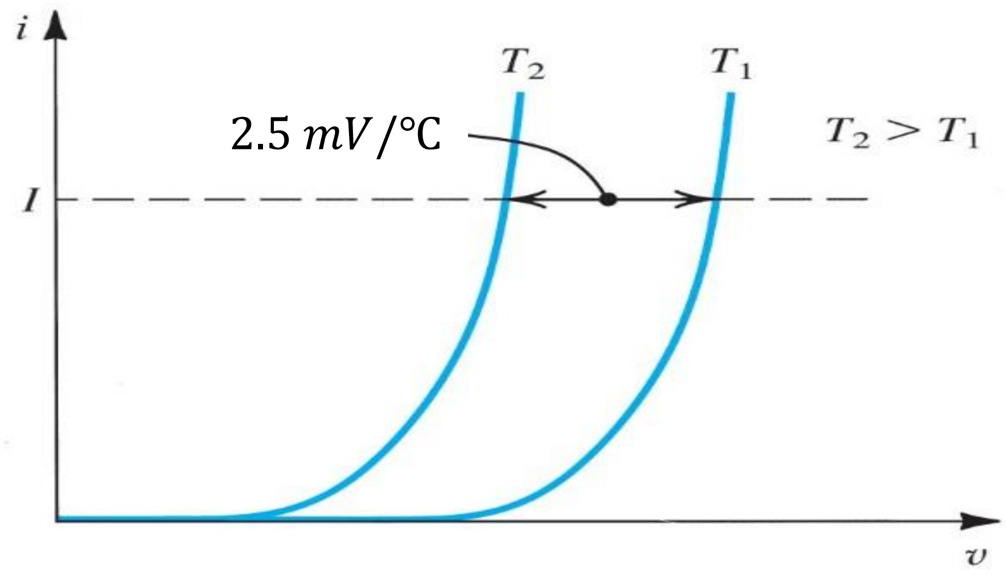


Temperature Effects

- **As temperature increases it adds energy to the diode.**
- **It reduces the required forward bias voltage for forward- bias conduction.**
- **It increases the amount of reverse current in the reverse- bias condition.**
- **It increases maximum reverse bias avalanche voltage**
- **Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.**

Temperature dependence of the diode forward characteristic

Reverse saturation current approximately doubles for every 10 °C rise in temperature.



Temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2.5 mV for every 1°C increase in temperature.

Practice problems

Find the change in the diode voltage if the current changes from 0.1 mA to 10 mA at $30°C$. Consider the value of $\eta = 1$.

Ans. 120 mV

A silicon junction diode has $v = 0.7$ V at $i = 1$ mA. Find the voltage drop at $i = 0.1$ mA and $i = 10$ mA.

Ans. 0.64 V; 0.76 V

Using the fact that a silicon diode has $I_S = 10^{-14}$ A at 25°C and that I_S increases by 15% per °C rise in temperature, find the value of I_S at 125°C.

Ans. 1.17×10^{-8} A

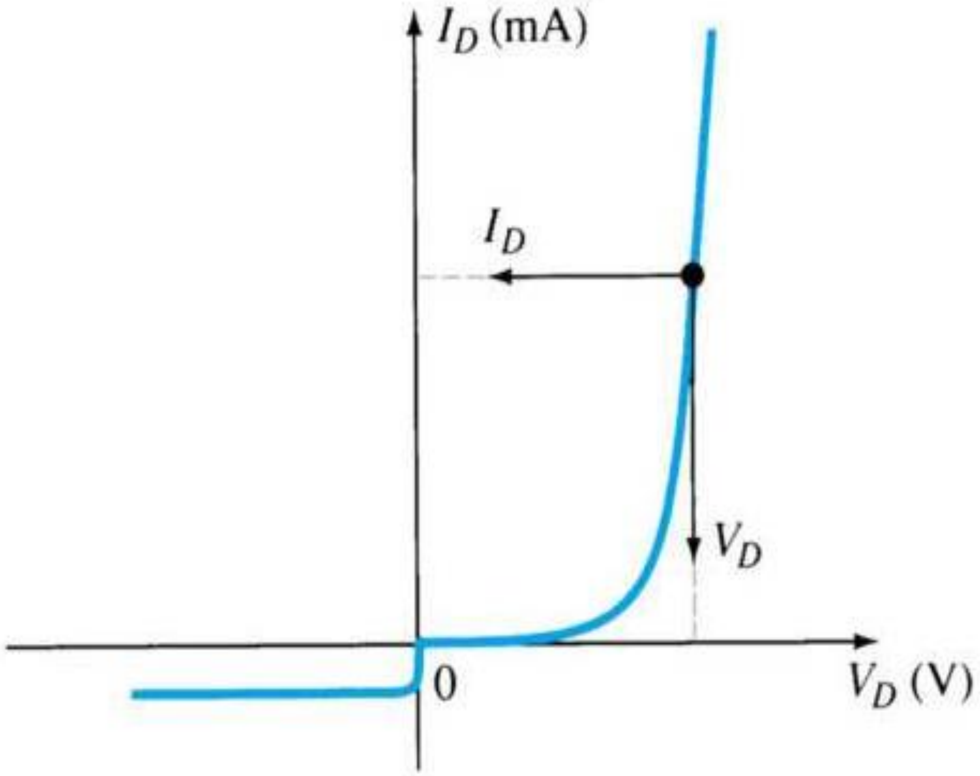
Resistance Levels

Two types of diode resistance are normally calculated:

- **DC (static) resistance**
- **AC (dynamic) resistance**

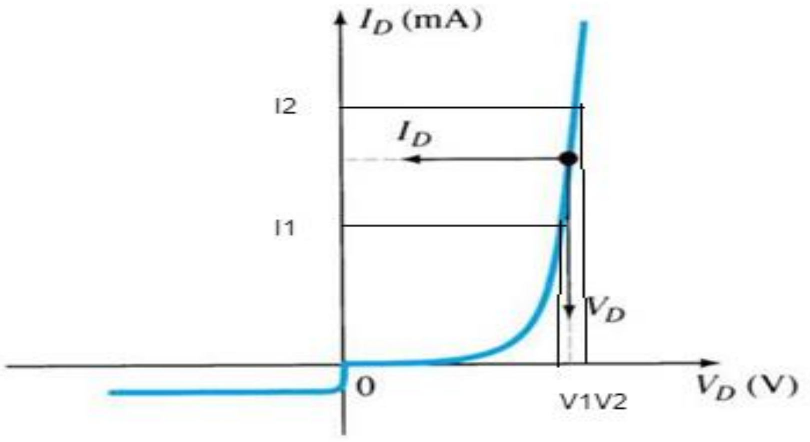
DC (Static) Resistance

For a specific applied DC voltage V_D, the diode has a specific current I_D, and a specific resistance R_D.



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

AC (Dynamic) Resistance



Static resistance of a diode is the ratio of obtained current to the voltage applied across the diode.
However ,often the static resistance is not suitable in many applications, as it varies significantly with the applied voltage. Instead, for small signal operations dynamic or incremental resistance r is
An important parameter.
The dynamic resistance is defined by dV/dI

$$r = \frac{dV}{dI} = \frac{1}{dI/dV} = \frac{\eta V_T}{I + I_0}$$

AC (Dynamic) Resistance

In the forward bias region:

$$r_d = \frac{dV_D}{dI_D} = \frac{26\ \text{mV}}{I_D}$$

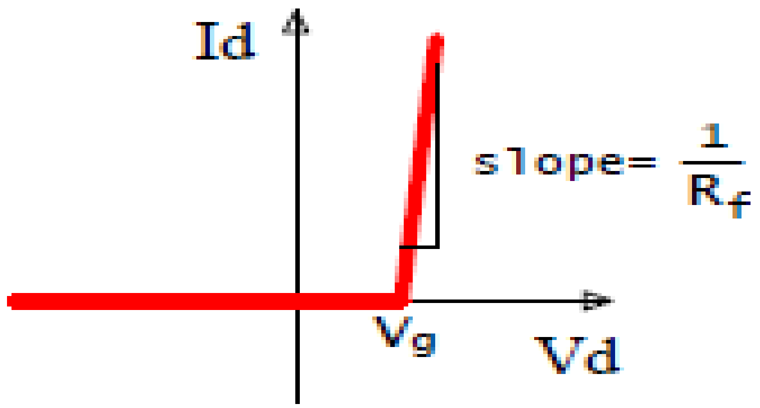
- **The forward resistance depends on the amount of current (I_D) in the diode.**

In the reverse bias region: $r_d = \infty$

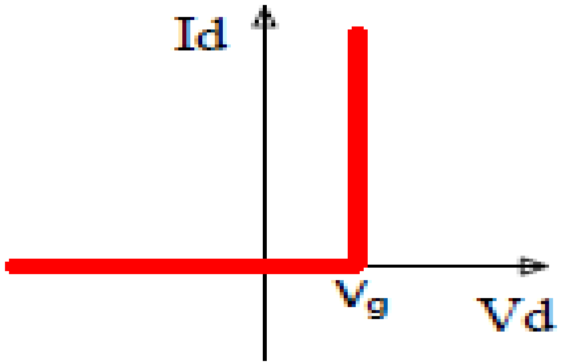
The reverse bias resistance is effectively infinite.

The diode acts like an open circuit.

Diode Models

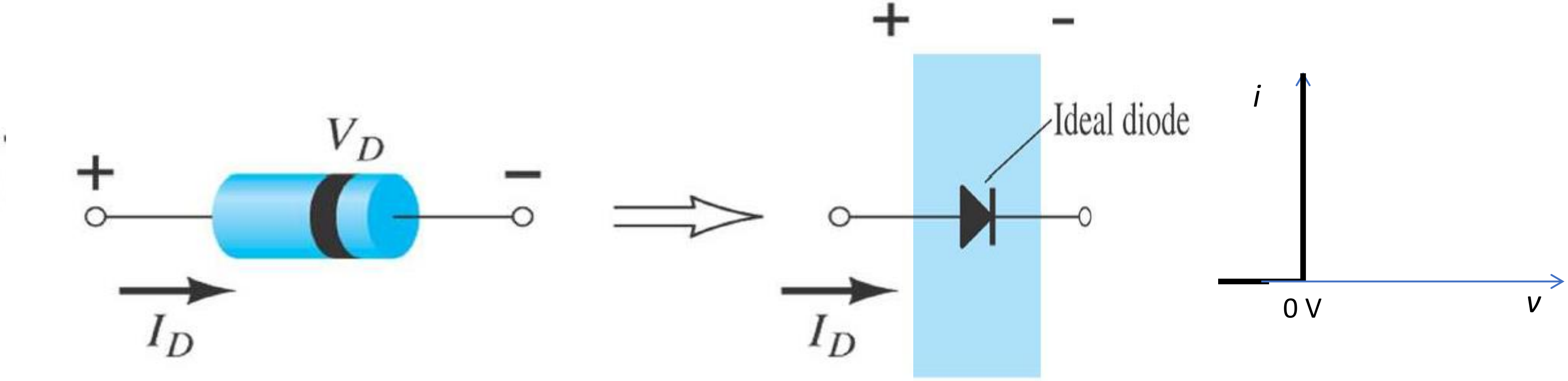


Piecewise linear approximation model of the diode



Offset diode model (0.7 Volt model)

Diode Equivalent Circuit



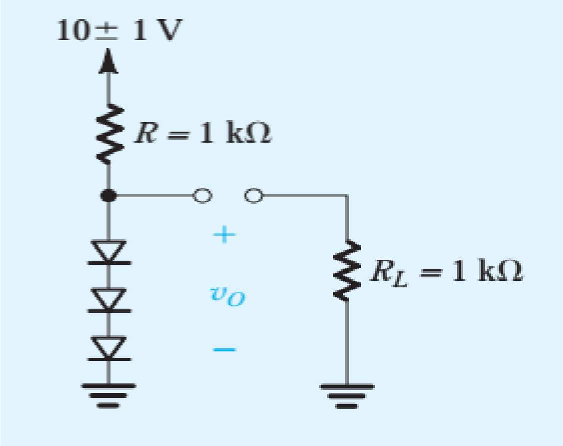
Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the *p-n* junction.
This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

- **gallium arsenide diode ≅ 1.2 V**
- **silicon diode ≅ 0.7 V**
- **germanium diode ≅ 0.3 V**

Consider the circuit shown in Fig. 4.15. A string of three diodes is used to provide a constant voltage of about 2.1 V. We want to calculate the percentage change in this regulated voltage caused by (a) a ±10% change in the power-supply voltage and (b) connection of a 1-kΩ load resistance.



With no load, the nominal value of the current in the diode string is given by

$$I = \frac{10 - 2.1}{1} = 7.9 \text{ mA}$$

Thus each diode will have an incremental resistance of

$$r_d = \frac{V_T}{I}$$

Thus,

$$r_d = \frac{25}{7.9} = 3.2\ \Omega$$

The three diodes in series will have a total incremental resistance of

$$r = 3r_d = 9.6\ \Omega$$

This resistance, along with the resistance R, forms a voltage divider whose ratio can be used to calculate the change in output voltage due to a ±10% (i.e., ±1-V) change in supply voltage. Thus the peak-to-peak change in output voltage will be

$$\Delta v_O = 2\frac{r}{r + R} = 2\frac{0.0096}{0.0096 + 1} = 19 \text{ mV peak-to-peak}$$

That is, corresponding to the ±1-V (±10%) change in supply voltage, the output voltage will change by ±9.5 mV or ±0.5%. Since this implies a change of about ±3.2 mV per diode, our use of the small-signal model is justified.

When a load resistance of 1 kΩ is connected across the diode string, it draws a current of approximately 2.1 mA. Thus the current in the diodes decreases by 2.1 mA, resulting in a decrease in voltage across the diode string given by

$$\Delta v_O = -2.1 \times r = -2.1 \times 9.6 = -20 \text{ mV}$$

Series Diode Configurations

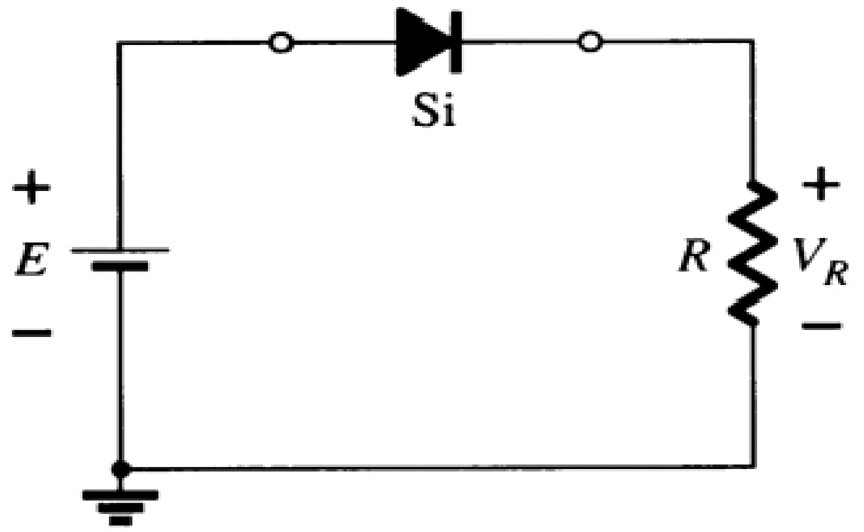
Forward Bias

Constants

- **Silicon Diode: V_D = 0.7 V**
- **Germanium Diode: V_D = 0.3 V**

Analysis (for silicon)

- $V_D = 0.7$ V (or $V_D = E$ if $E < 0.7$ V)
- $V_R = E - V_D$
- $I_D = I_R = I_T = V_R / R$



Parallel Configurations

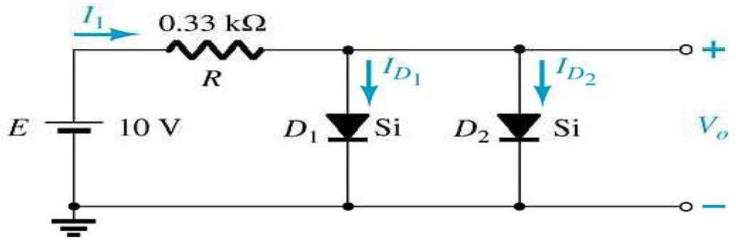
$V_D = 0.7\text{ V}$

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

$V_R = 9.3\text{ V}$

$I_R = \dfrac{E - V_D}{R} = \dfrac{10\text{ V} - .7\text{ V}}{.33\text{k}} = 28\text{ mA}$

$I_{D1} = I_{D2} = \dfrac{28\text{ mA}}{2} = 14\text{ mA}$



Breakdown mechanism

- Electrical break down of any material (say metal, conductor, semiconductor or even insulator) can occur due to two different phenomena.
- Those two phenomena are
  - **Zener breakdown**
  - **Avalanche breakdown**

Breakdown mechanism

Zener Breakdown

- When we increase the reverse voltage across the p-n junction diode, the electric field across the diode junction increases (both internal & external).
- This results in a force of attraction on the negatively charged electrons at junction. This force frees electrons from its covalent bond and moves those free electrons to conduction band.
- When the electric field increases (with applied voltage), more and more electrons are freed from its covalent bonds. This results in drifting of electrons across the junction and electron hole recombination occurs. So a net current is developed and it increases rapidly with increase in electric field.
- Zener breakdown phenomena occurs in a p-n junction diode with heavy doping & thin junction (means depletion layer width is very small).
- It is found that the Zener breakdown occurs at a field of approximately $2 \times 10^7\ V/m$. This value is reached in a typical Zener diode at voltage below 6 V.
- Zener breakdown does not result in damage of diode. Since current is only due to drifting of electrons, there is a limit to the increase in current as well.

Breakdown mechanism

Avalanche Breakdown

- Avalanche breakdown occurs in a p-n junction diode which is moderately doped and has a thick junction (means its depletion layer width is high).
- Avalanche breakdown usually occurs when we apply a high reverse voltage across the diode (obviously higher than the zener breakdown voltage, say Vz). So as we increase the applied reverse voltage, the electric field across junction will keep increasing.
- If applied reverse voltage is Va and the depletion layer width is d; then the generated electric field can be calculated as Ea =Va/d
- This generated electric field exerts a force on the electrons at junction and it frees them from covalent bonds. These free electrons will gain acceleration and it will start moving across the junction with high velocity. This results in collision with other neighboring atoms. These collisions in high velocity will generate further free electrons. These electrons will start drifting and electron-hole pair recombination occurs across the junction. This results in net current that rapidly increases.

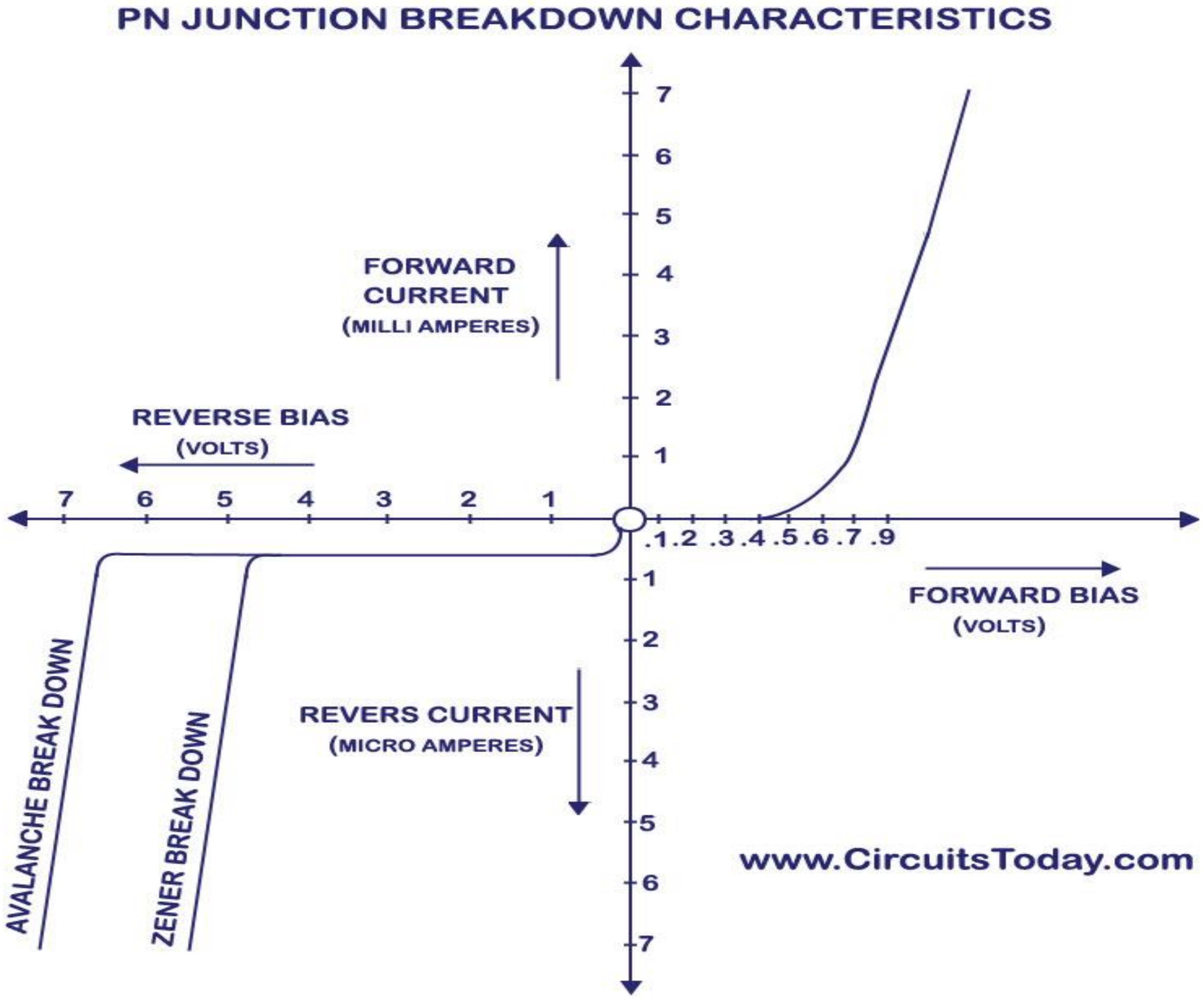
Breakdown mechanism

- So in a Zener breakdown, the electric field necessary to break electrons from covalent bond is achieved with lesser voltage than in avalanche breakdown. The reason is thin depletion layer width.
- In avalanche breakdown, the depletion layer width is higher and hence much more reverse voltage has to be applied to develop the same electric field strength (necessary enough to break electrons free)

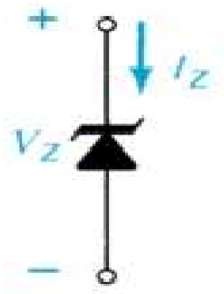
Breakdown mechanism

Zener Breakdown	Avalanche Breakdown
The process in which the electrons move across the barrier from the valence band of p-type material to the conduction band of n-type material is known as Zener breakdown.	The process of applying high voltage and increasing the free electrons or electric current in semiconductors and insulating materials is called an avalanche breakdown.
This is observed in Zener diodes having a Zener breakdown voltage V_z of 5 to 8 volts.	This is observed in Zener diode having a Zener breakdown voltage V_z greater than 8 volts.
The valence electrons are pulled into conduction due to the high electric field in the narrow depletion region.	The valence electrons are pushed to conduction due to the energy imparted by accelerated electrons, which gain their velocity due to their collision with other atoms.
The increase in temperature decreases the breakdown voltage.	The increase in temperature increases the breakdown voltage.
The VI characteristics of a Zener breakdown has a sharp curve.	The VI characteristic curve of the avalanche breakdown is not as sharp as the Zener breakdown.
It occurs in diodes that are highly doped.	It occurs in diodes that are lightly doped.

Breakdown mechanism



Zener Diode



A Zener is a diode operated in reverse bias at the Zener voltage (V_Z).

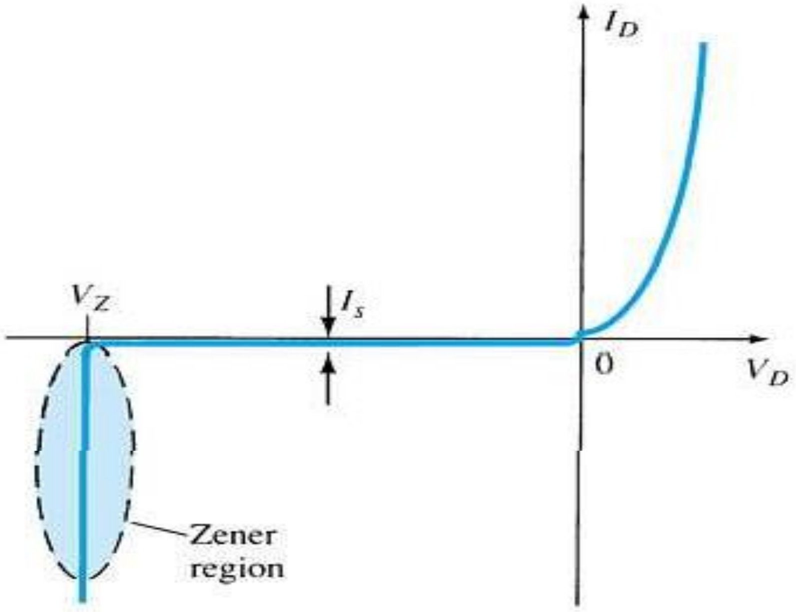
Common Zener voltages are between 1.8 V and 200 V

Zener Region

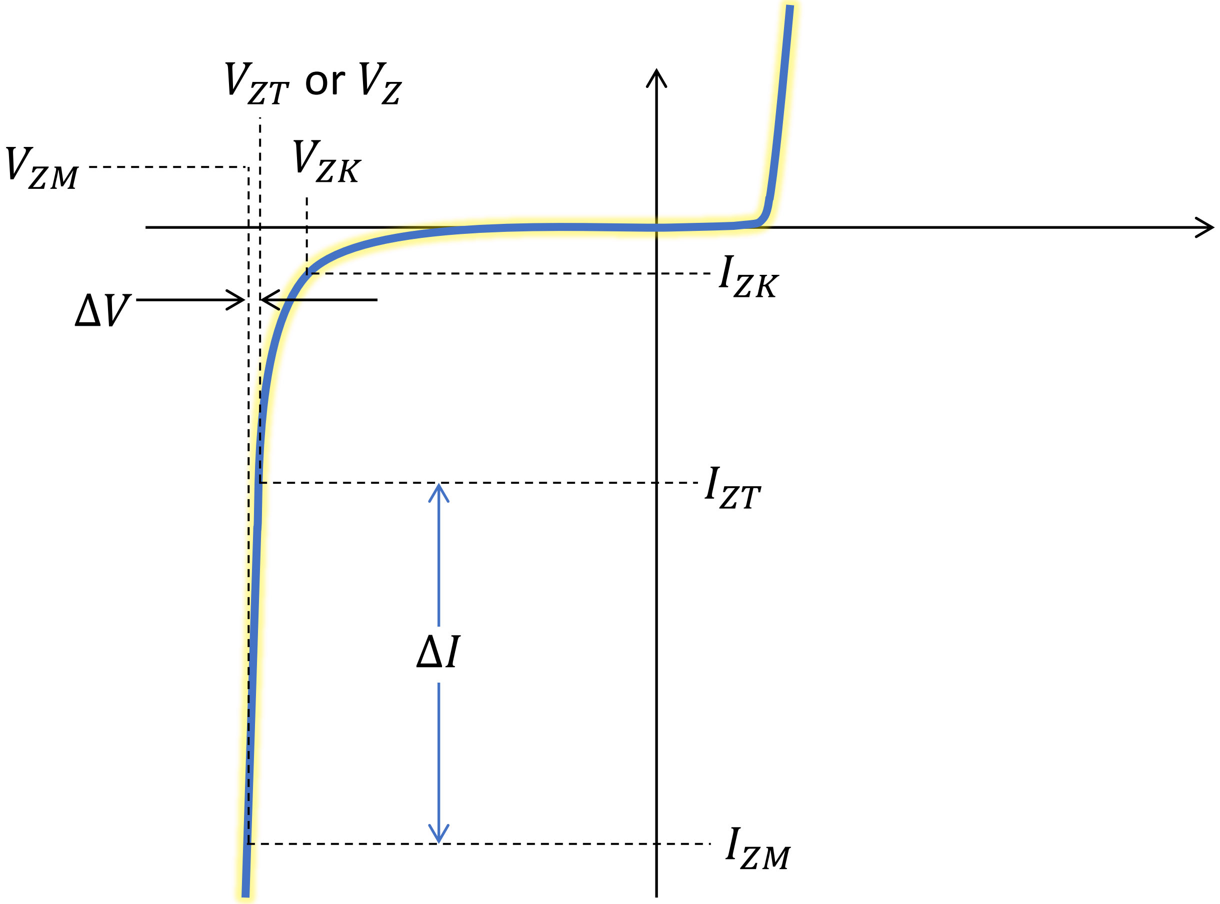
The Zener region is in the diode's reverse-bias region.

At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.

- The maximum reverse voltage that won't take a diode into the zener region is called the peak inverse voltage or peak reverse voltage.
- The voltage that causes a diode to enter the zener region of operation is called the zener voltage (V_Z).



Zener Characteristics

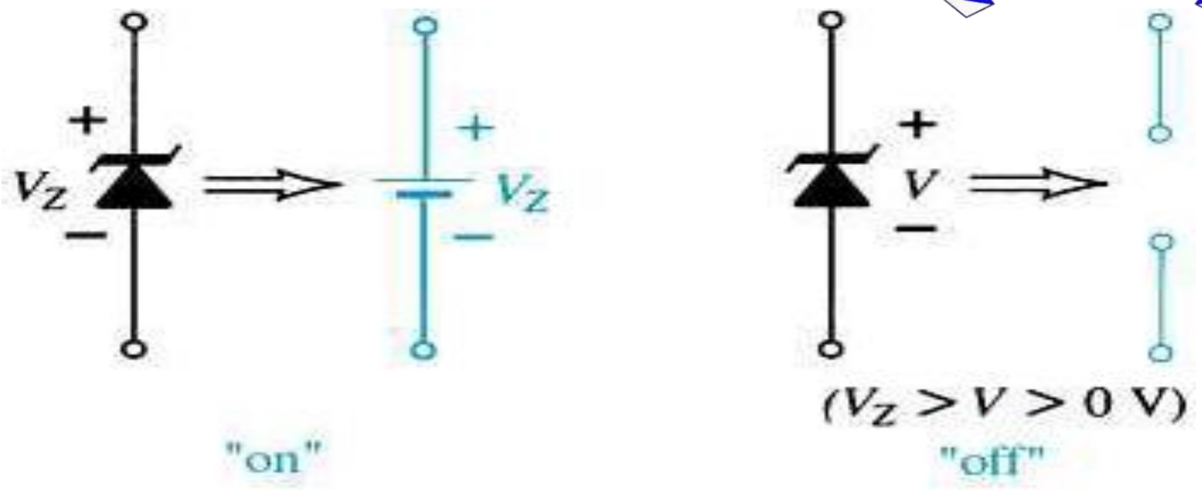


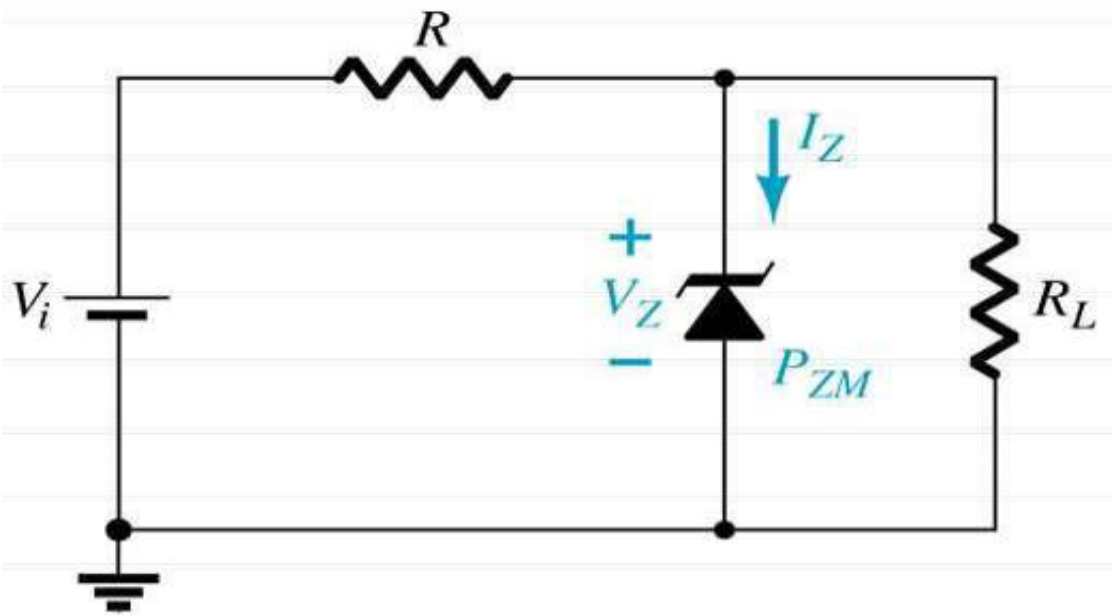
- Zener diode reverse dynamic resistance $r_Z = \frac{\Delta V}{\Delta I}$ is very less and often considered to be zero.
- Manufacturers specifies V_Z, I_{ZT}, r_Z, and the maximum power rating P_{ZM}.
- So, the maximum power rating can be calculated as – $I_{ZM} = \frac{P_{ZM}}{V_Z}$.

Zener Diodes

The Zener diode is operated in reverse bias at around the Zener Voltage (V_z).

- **When $V_i \geq V_Z$**
  - **The Zener is on**
  - **Voltage across the Zener is V_Z**
  - **Zener current: $I_Z = I_R - I_{RL}$**
  - **The Zener Power: $P_Z = V_Z I_Z$**
- **When $V_i < V_Z$**
  - **The Zener is off**
  - **The Zener acts as an open circuit**

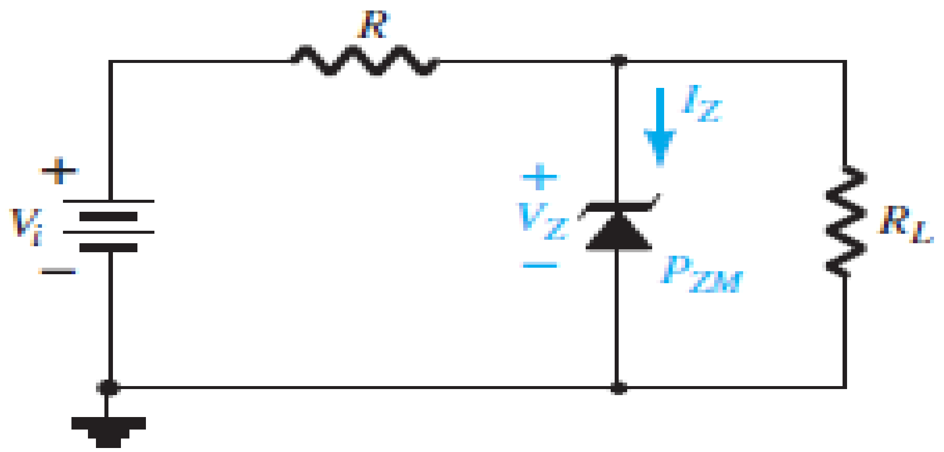




Zener Analysis

The analysis can fundamentally be broken down into two steps.

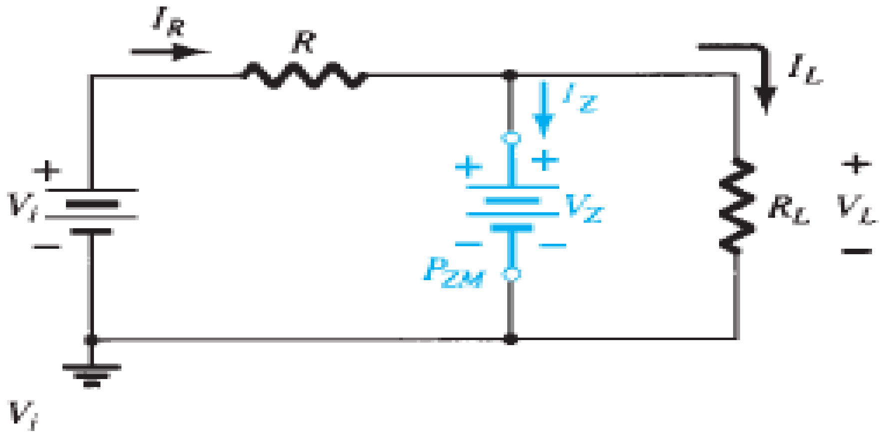
1. Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit.



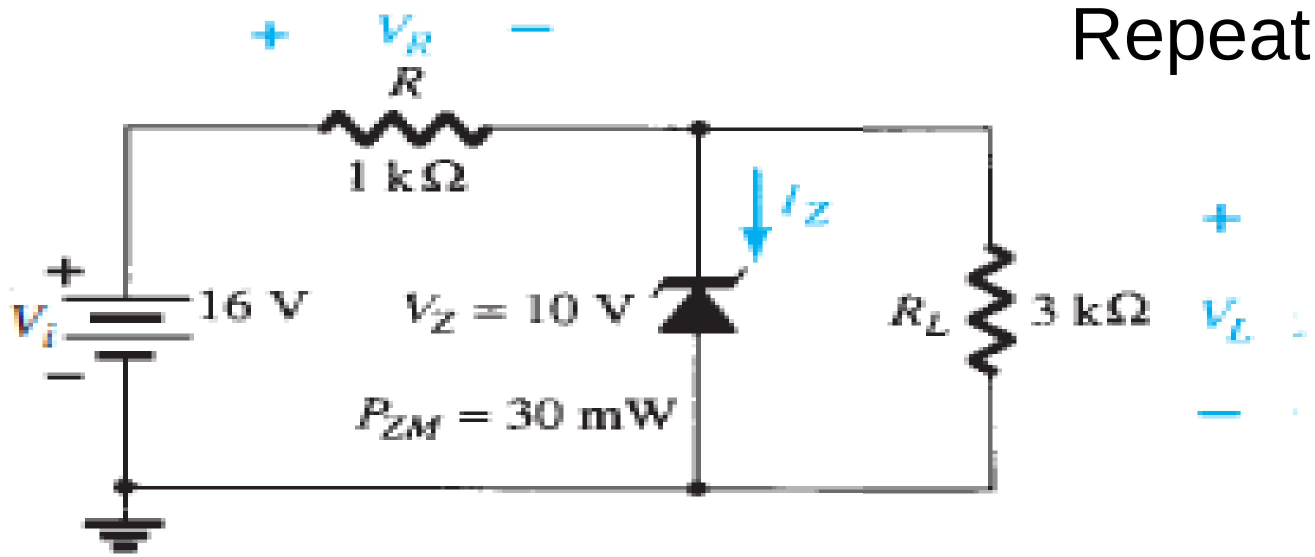
$$V = V_L = \frac{R_L V_i}{R + R_L}$$

If $V > V_Z$, the Zener diode is on

If $V < V_Z$, the diode is off

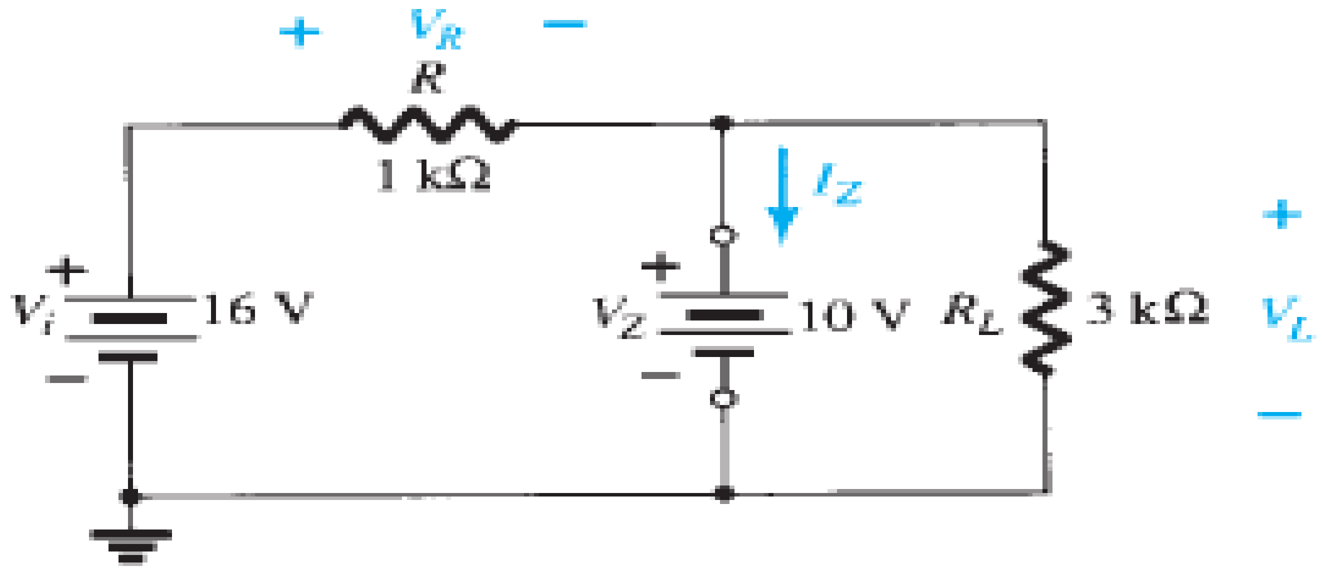


Example 2



Repeat the calculation with RL = 3 kΩ

Determine V_L, V_R, I_Z, and P_Z.

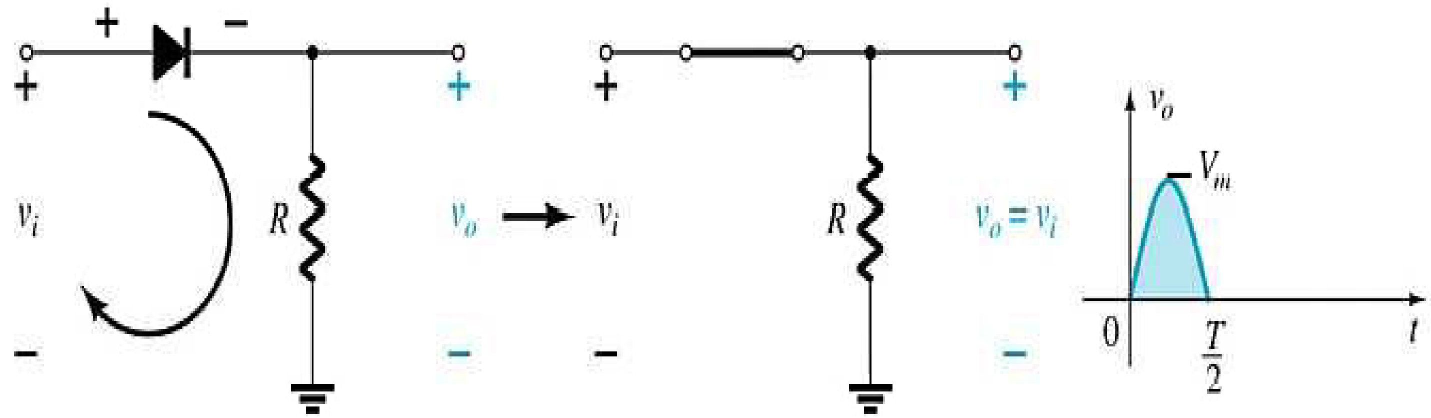


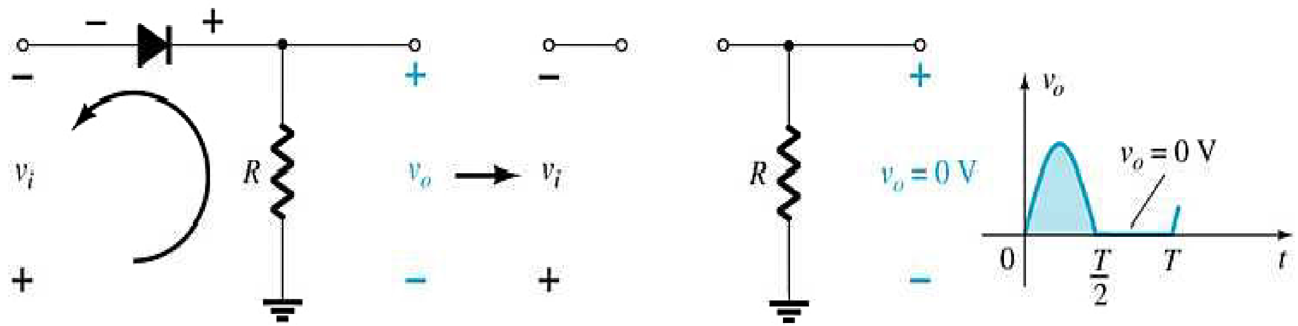
wave shaping circuit

- **Rectifier**
- **Clippers**
- **Clampers**

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.





PIV = V_m

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.

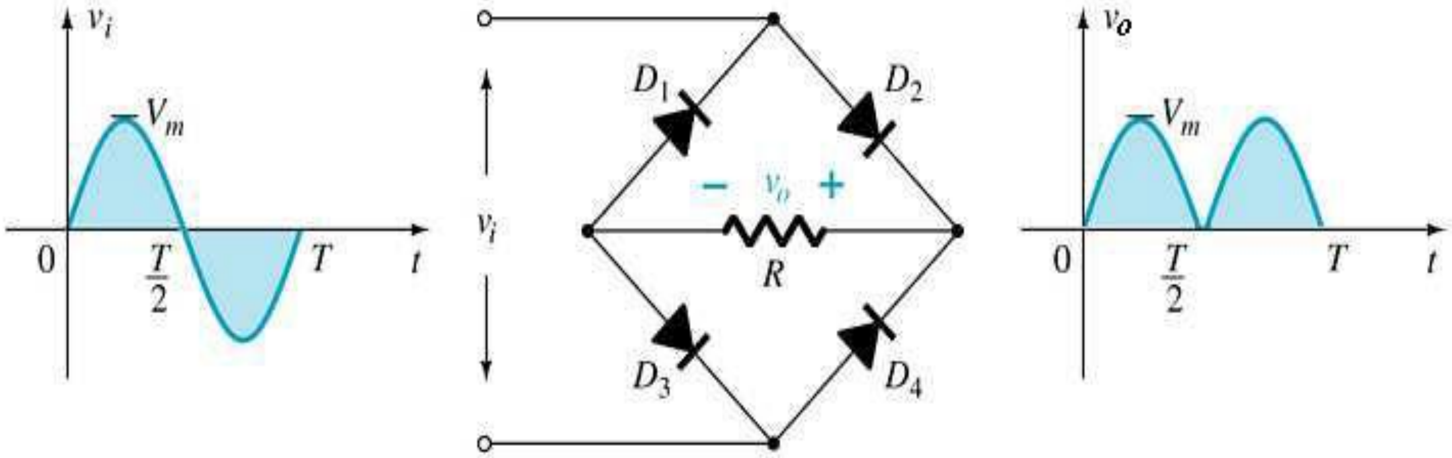
$$\textbf{PIV (or PRV)} > V_m$$

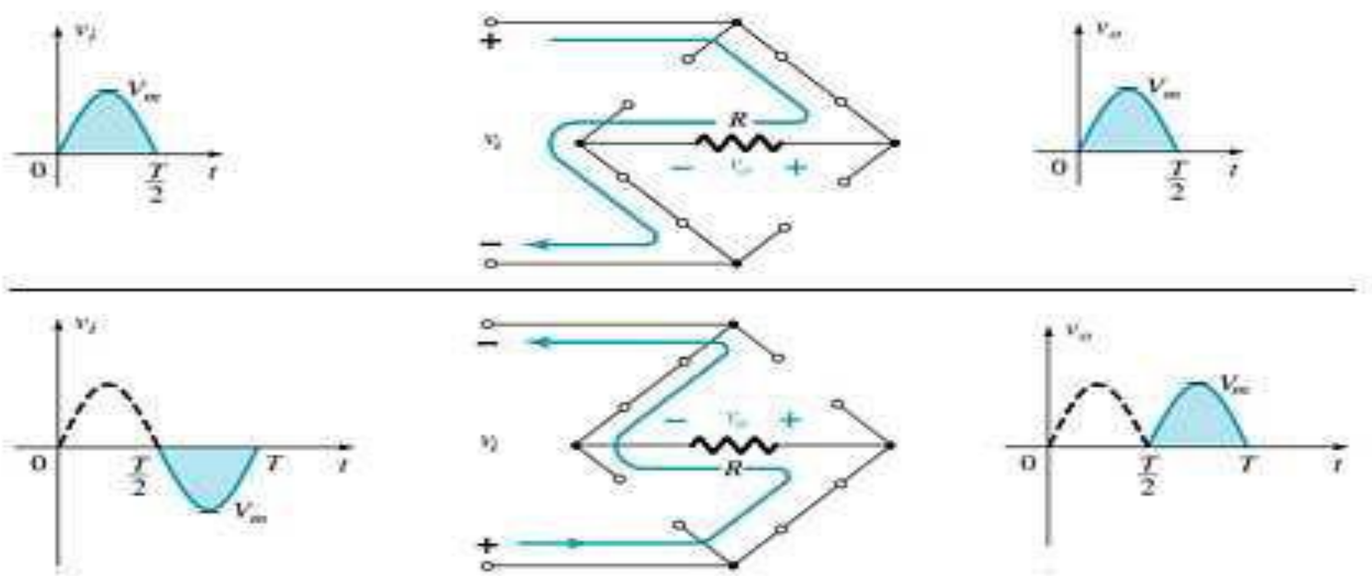
- **PIV = Peak inverse voltage**
- **PRV = Peak reverse voltage**
- V_m **= Peak AC voltage**

Full-Wave Rectification

Bridge Rectifier

- Four diodes are connected in a bridge configuration.
- $V_{DC} = 0.636V_m$





PIV = V_m

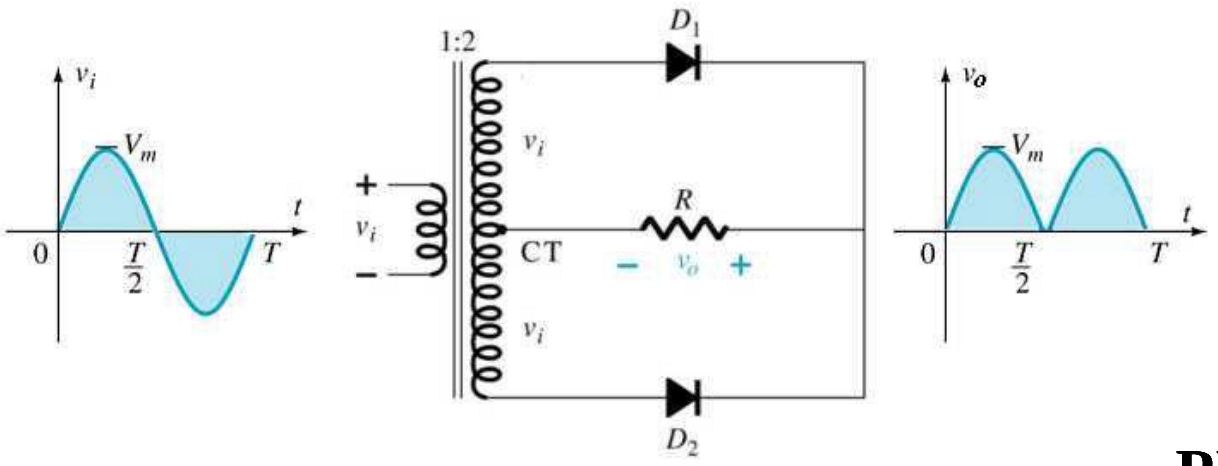
Full-Wave Rectification

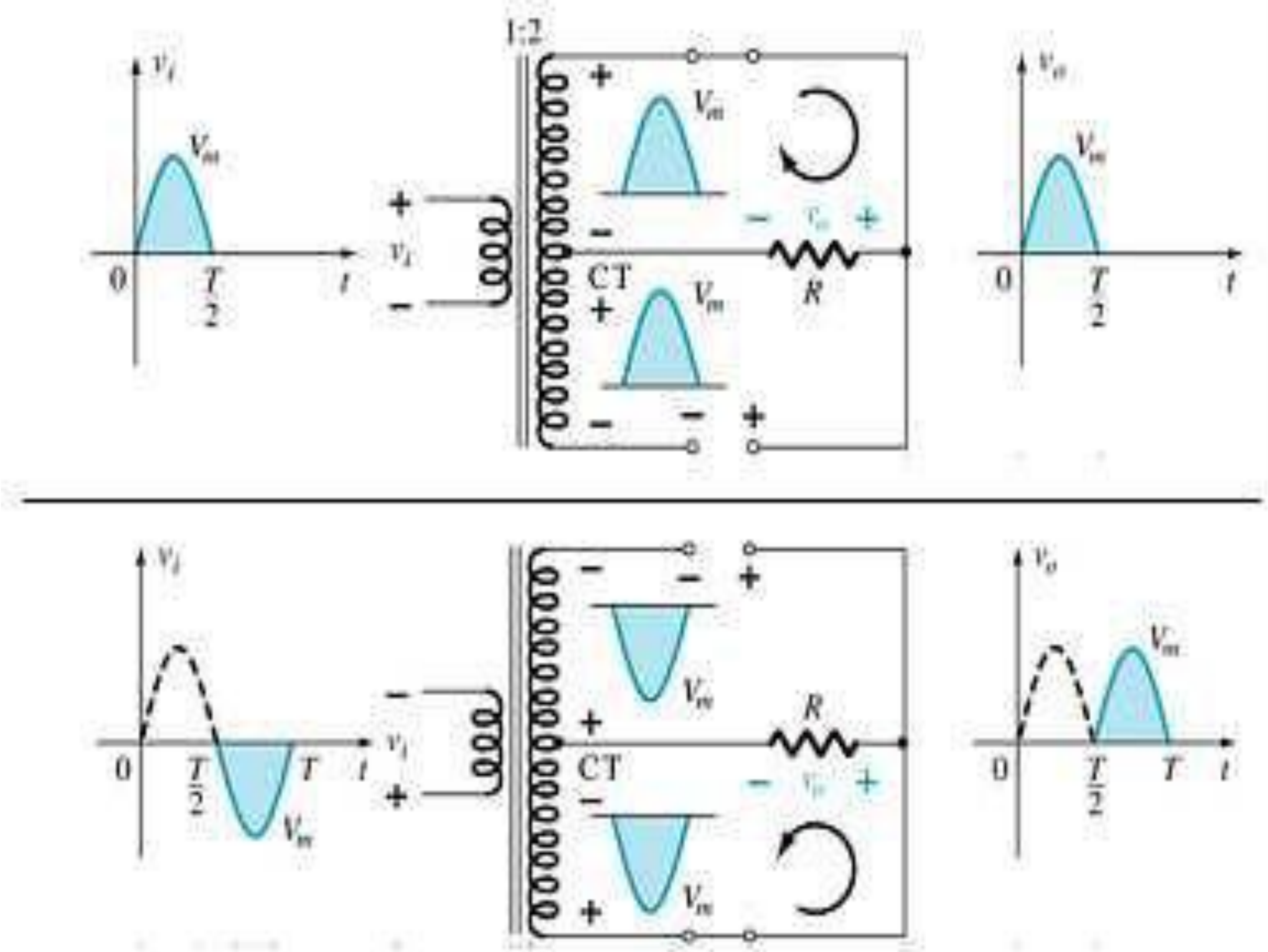
Center-Tapped Transformer Rectifier

Requires

- **Two diodes**
- **Center-tapped transformer**

$$V_{DC} = 0.636V_m$$





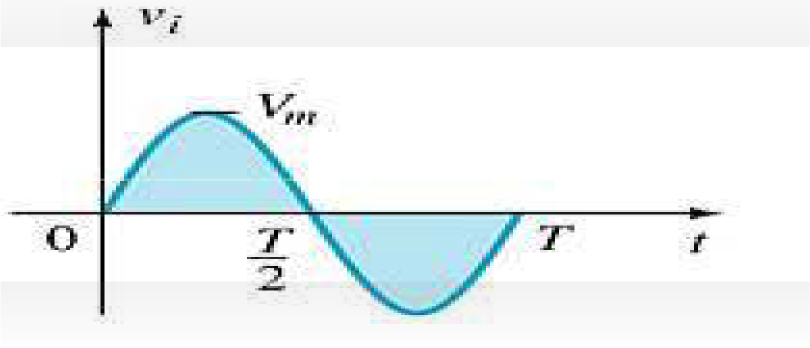
PIV = 2V$_m$

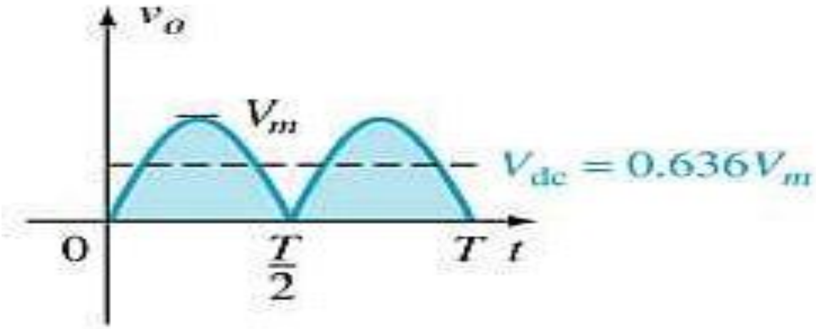
Full-Wave Rectification

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: $V_{dc} = 0.636V_m$**





Derivation of Average value for Half wave.

$$I = I_m \sin\omega t$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin\omega t \, d(\omega t)$$

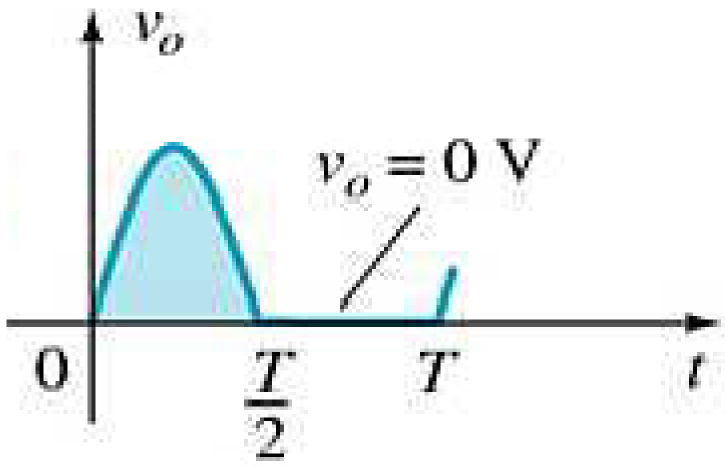
$$= \frac{1}{2\pi}\int_0^{\pi} I_m \sin\omega t \, d(\omega t)$$

$$= \frac{I_m}{2\pi}[-\cos\omega t]_0^{\pi}$$

$$= -\frac{I_m}{2\pi}[\cos\pi - \cos 0]$$

$$= -\frac{I_m}{2\pi}[-1 - 1]$$

$$I_{dc} = \frac{I_m}{\pi}$$



Derivation of RMS value for Half Wave.

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_m^2 \sin^2\omega t \, d(\omega t)}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2\omega t \, d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \sin^2\omega t \, d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{1}{2}[1 - \cos 2\omega t] \, d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\pi}}$$

$$= \sqrt{\frac{I_m^2}{4\pi}[\pi]}$$

$$= \frac{I_m}{2}$$

Derivation of Average value for Full wave

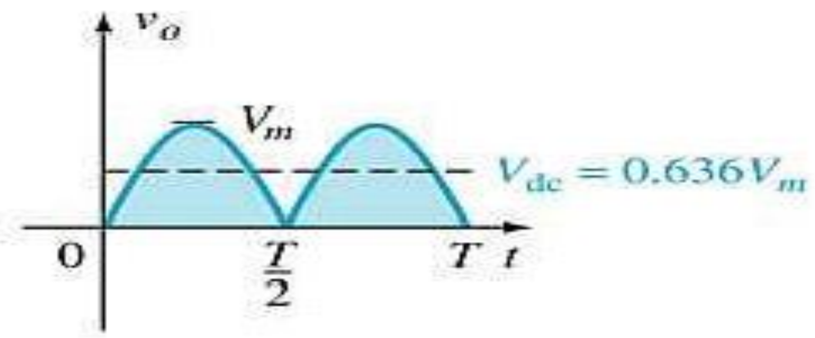
$$I_{dc} = \frac{1}{\pi}\int_{0}^{\pi} I_m \sin\omega t d\omega t$$

$$= \frac{I_m}{\pi}[-\cos\omega t]_0^{\pi}$$

$$= -\frac{I_m}{\pi}[\cos\pi - \cos 0]$$

$$=- -\frac{I_m}{\pi}[-1-1]$$

$$I_{dc} = \frac{2I_m}{\pi}$$



Derivation of RMS value for Full Wave.

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2\omega t\, d\omega t}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d\omega t}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi}[1-\cos 2\omega t]\, d\omega t}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\left[\omega t-\frac{\sin 2\omega t}{2}\right]_0^{\pi}}$$

$$= \sqrt{\frac{I_m^2}{2\pi}[\pi-0]} = I_m/\sqrt{2}$$

Efficiency of Half Wave Rectifier

- Efficiency(η) = <u>dc power delivered to load</u>

  Ac Input Power

$$\eta = \frac{I^2 dc \times R_L}{I_{rms}^2 \left(R_f + R_s + R_L\right)}$$

$$= \frac{\left(I_m/\pi\right)^2 \times R_L}{\left(I_m/2\right)^2 \times \left(R_f + R_s + R_L\right)}$$

$$\eta = \frac{4}{\pi^2} \times \frac{R_L}{\left(R_f + R_s + R_L\right)} \times 100\%$$

Rf – diode forward Resistance
Rs- Series winding Resistance
RL- Load Resistance

In best case scenario, i.e. $R_f = R_s = 0, \eta = 40.5\%$

Similarly Efficiency for Full wave Rectifier can be determined by substituting Idc and Irms Value for Full wave

Ripple Factor for Half wave Rectifier

- Ripple Factor(γ)= $\dfrac{\text{RMS value of ac component of Current}}{\text{Dc value or average value of Current}}$

$$\gamma = \frac{I_{ac}}{I_{dc}}$$

$$I_{rms} = \sqrt{I^2_{dc} + I^2_{ac}}$$

$$I_{ac} = \sqrt{I^2_{rms} - I^2_{dc}}$$

$$\gamma = \frac{\sqrt{I^2_{rms} - I^2_{dc}}}{I_{dc}}$$

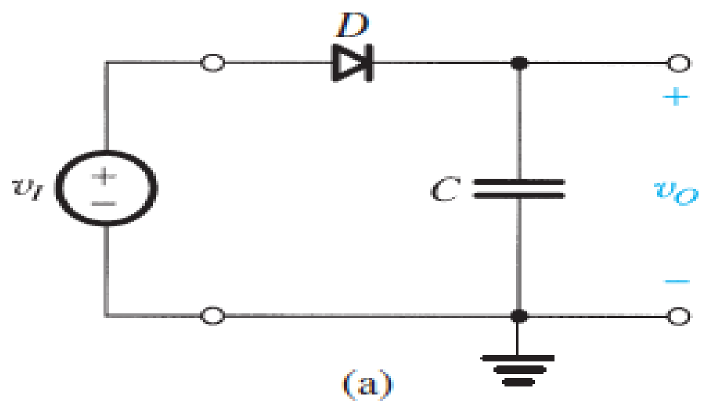
$$\gamma = \sqrt{\frac{I^2_{rms}}{I^2_{dc}} - 1}$$

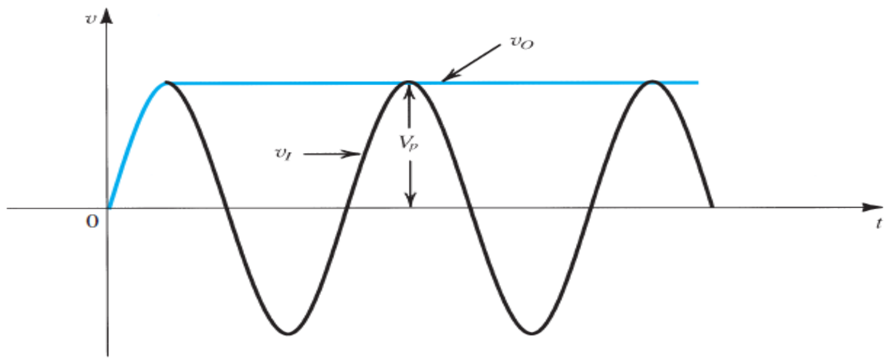
$$= \sqrt{\frac{\pi^2}{4} - 1}$$

$$= 1.21$$

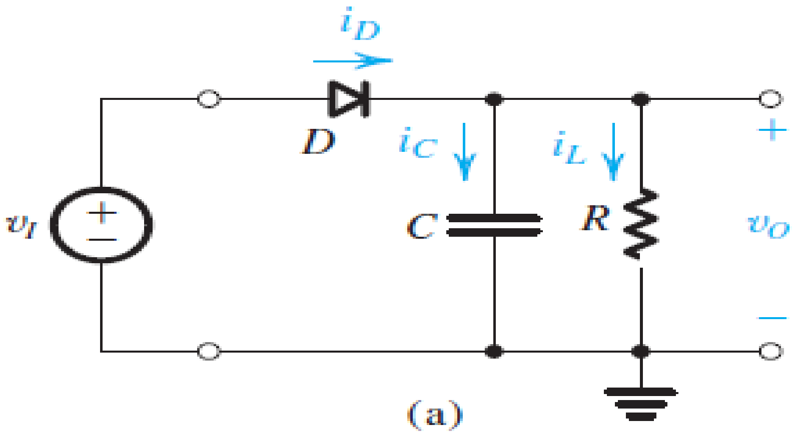
Similarly Ripple factor for full wave rectifier can be determined by substituting Irms and Idc value for full wave

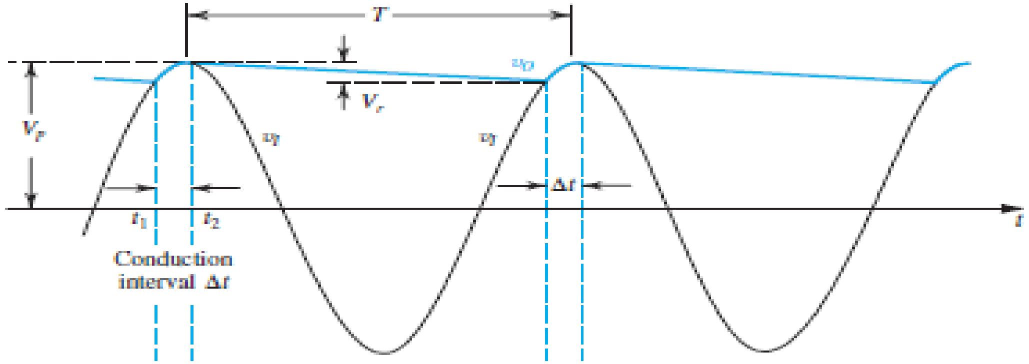
The Rectifier with a Filter Capacitor



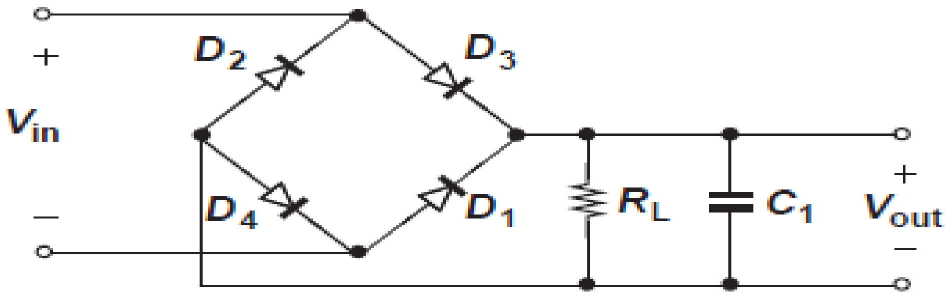


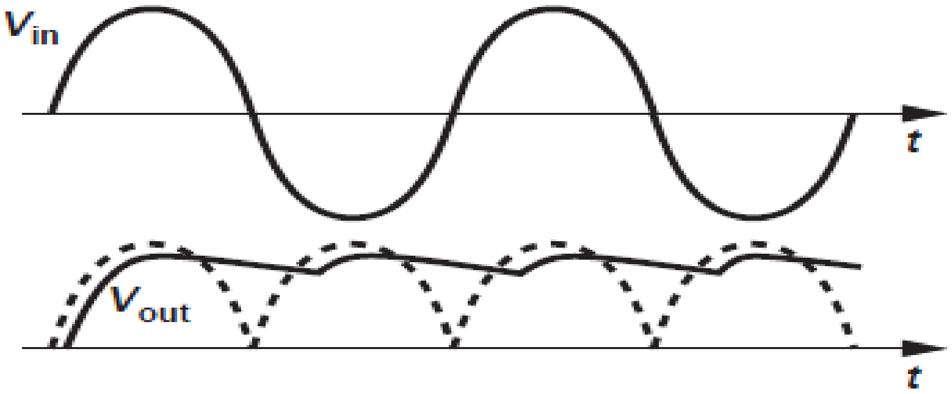
Peak rectifier or peak detector



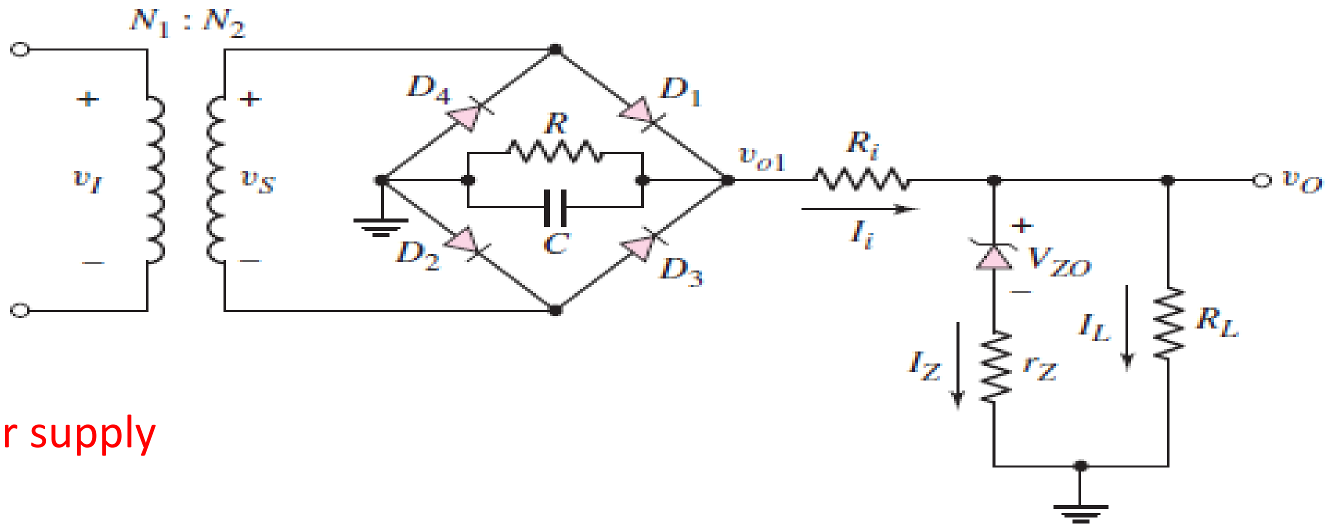


DC power supply with Filter



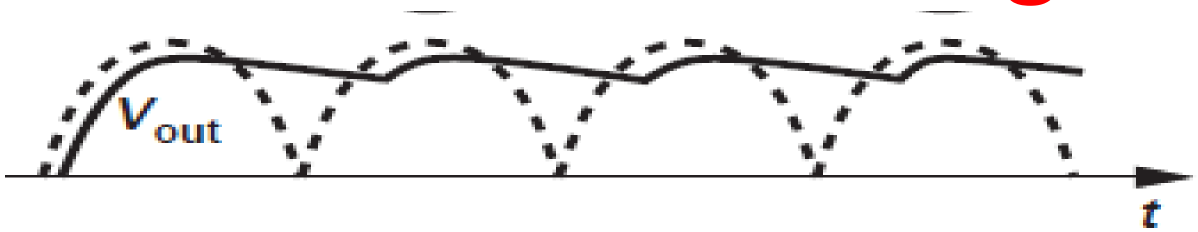


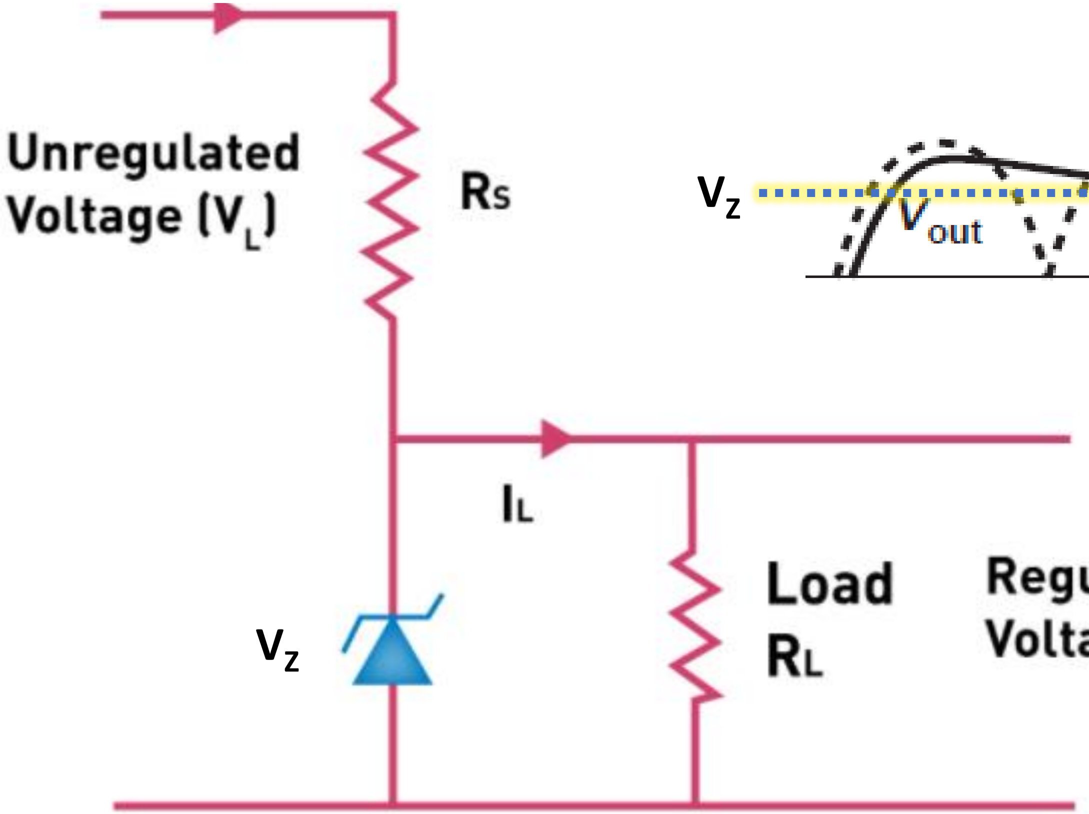
Bridge rectifier with filter

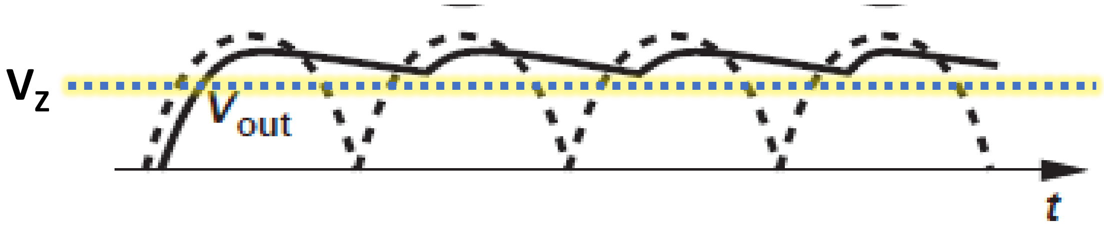


DC power supply

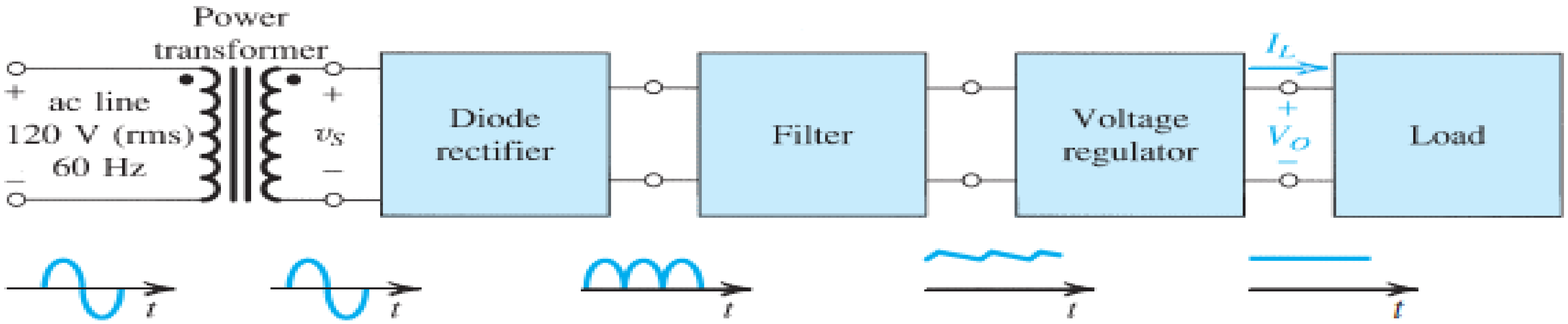
Voltage Regulation







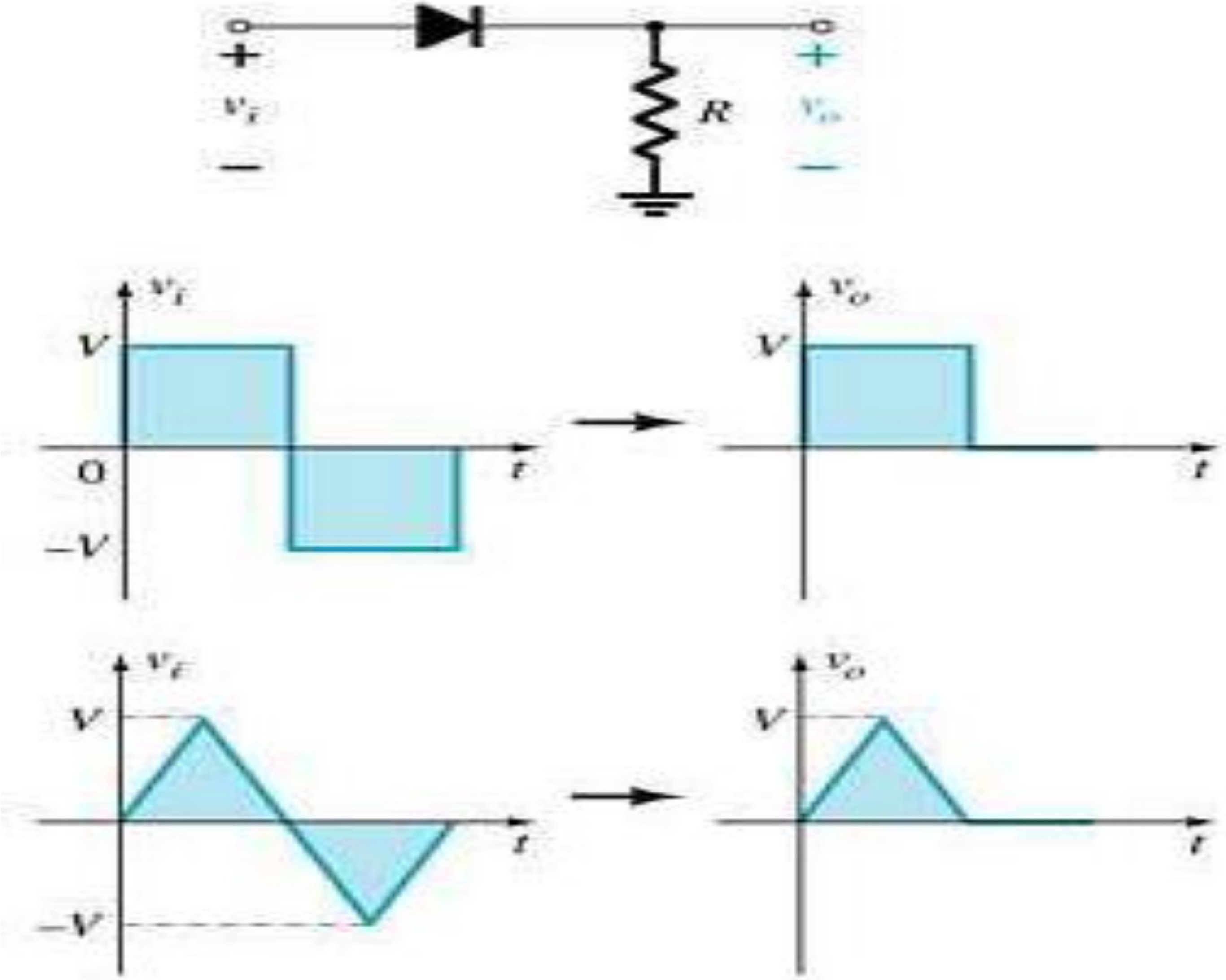
Block diagram of a dc power supply



Diode Clippers

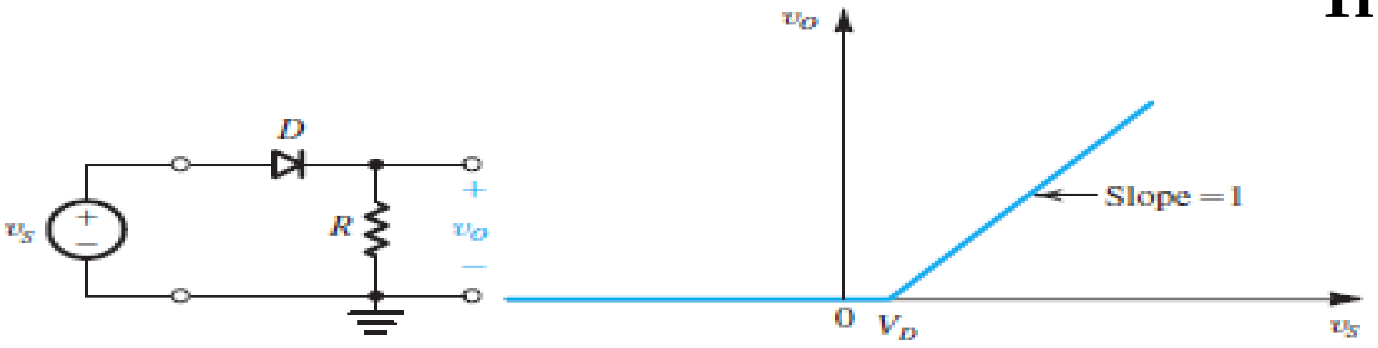
The diode in a series clipper “clips” any voltage that does not forward bias it:

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

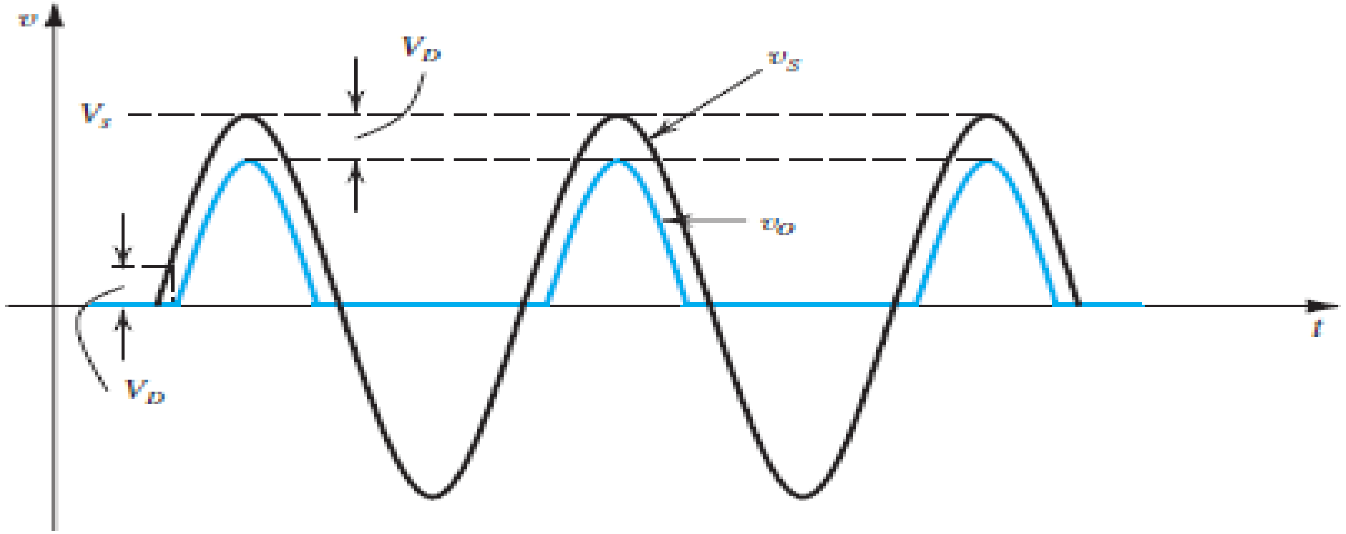


Diode Clipper with Si diode

Transfer curve

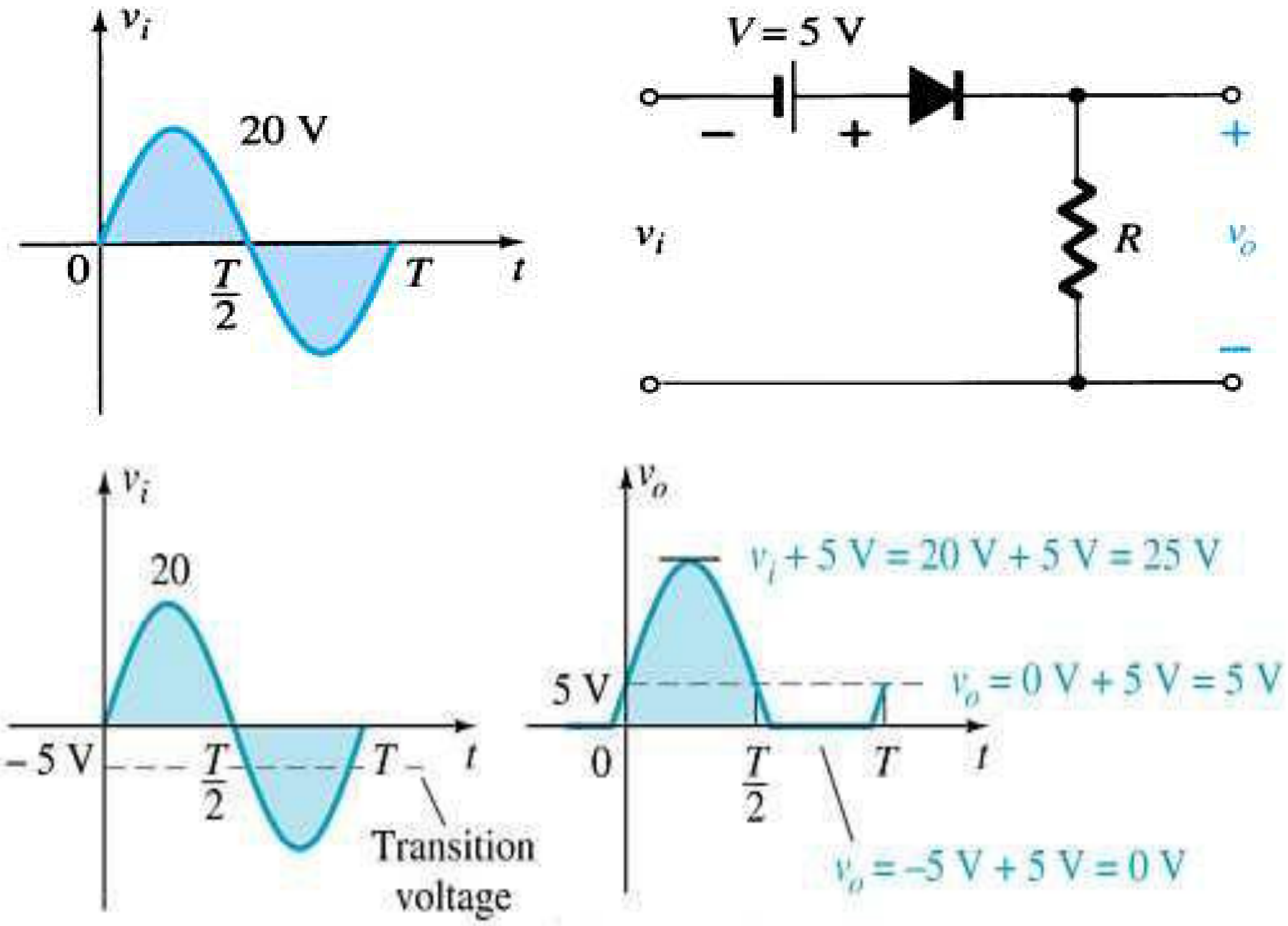


(a) (b)



Biased Clippers

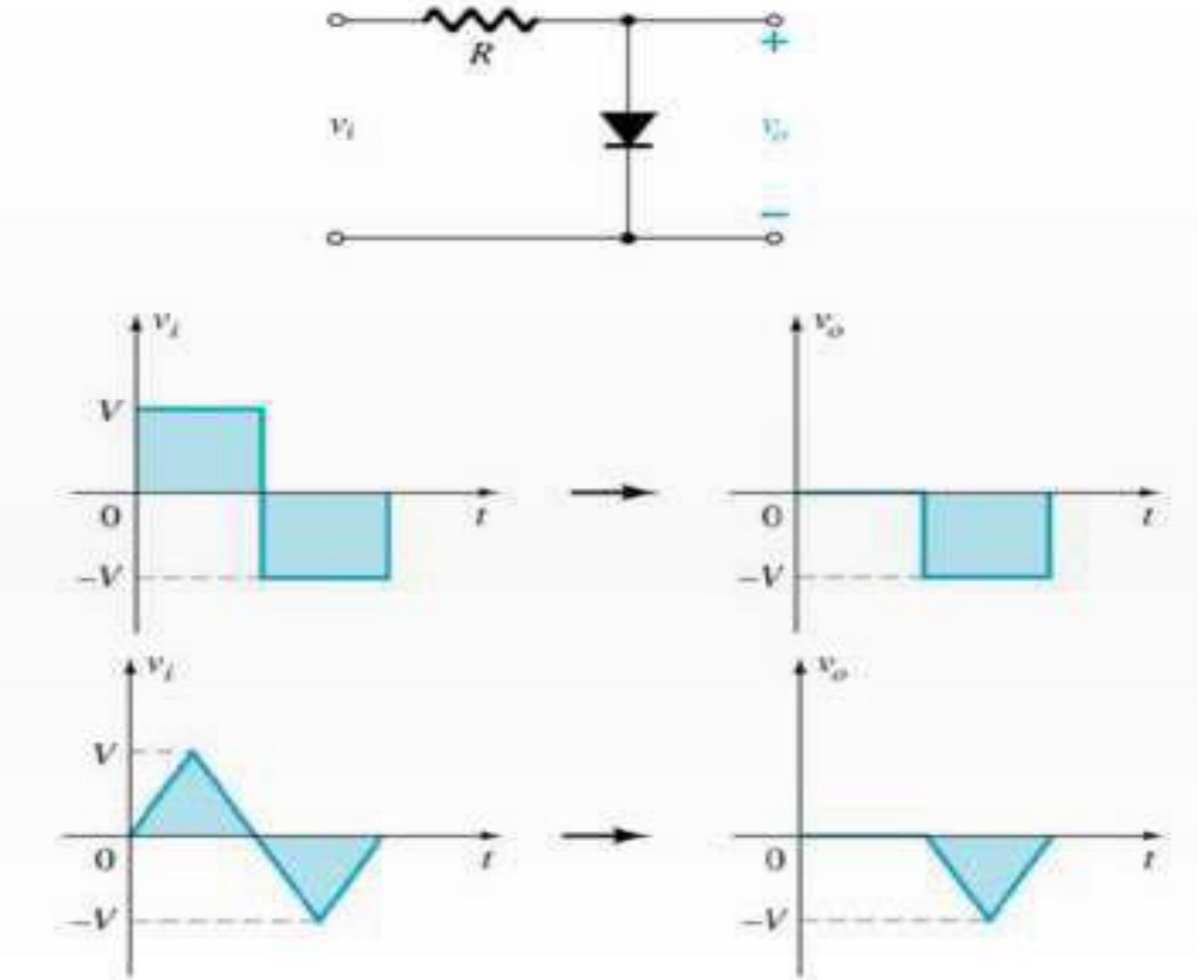
Adding a DC source in series with the clipping diode changes the effective forward bias of the diode.



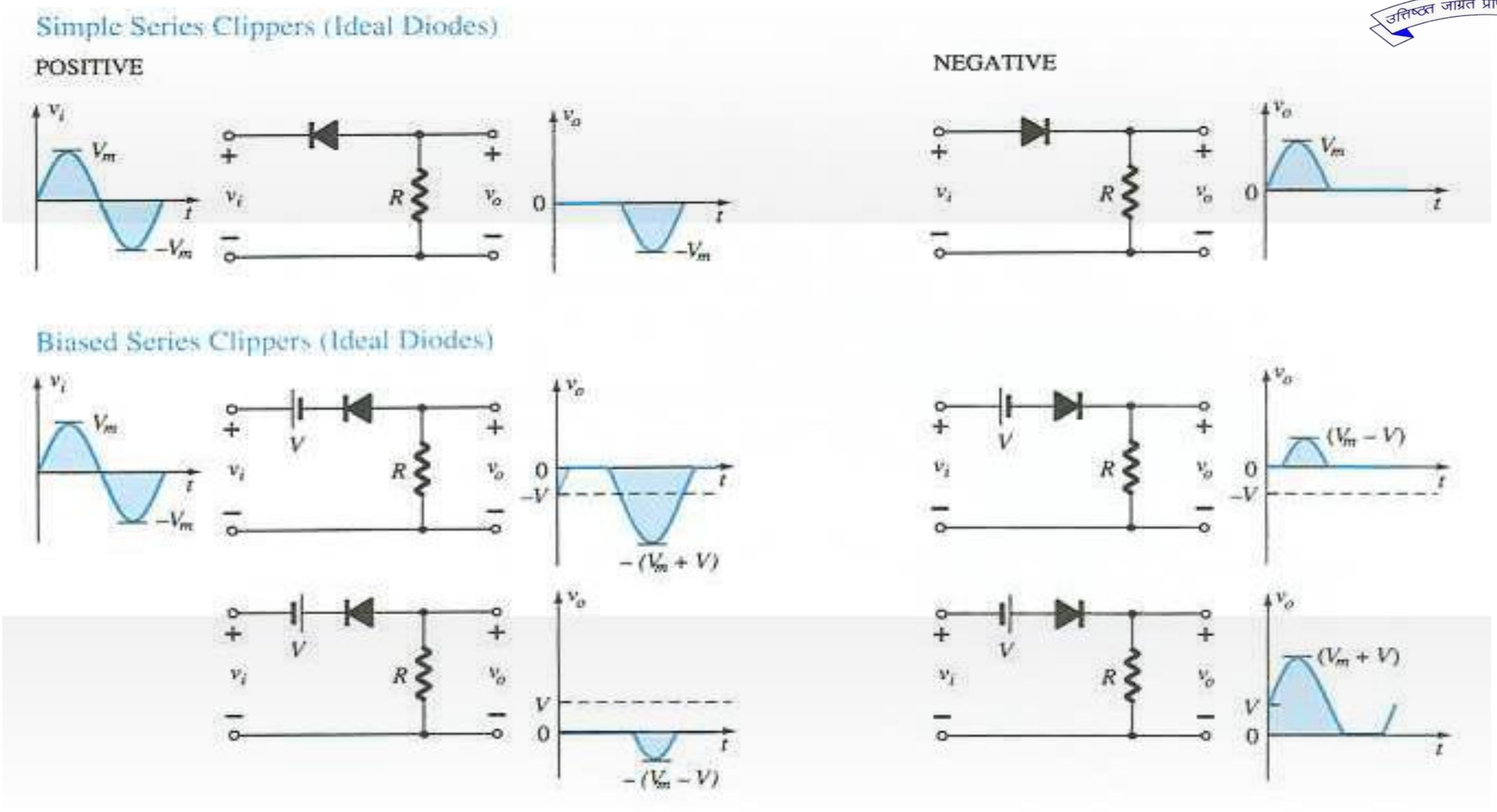
Parallel Clippers

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

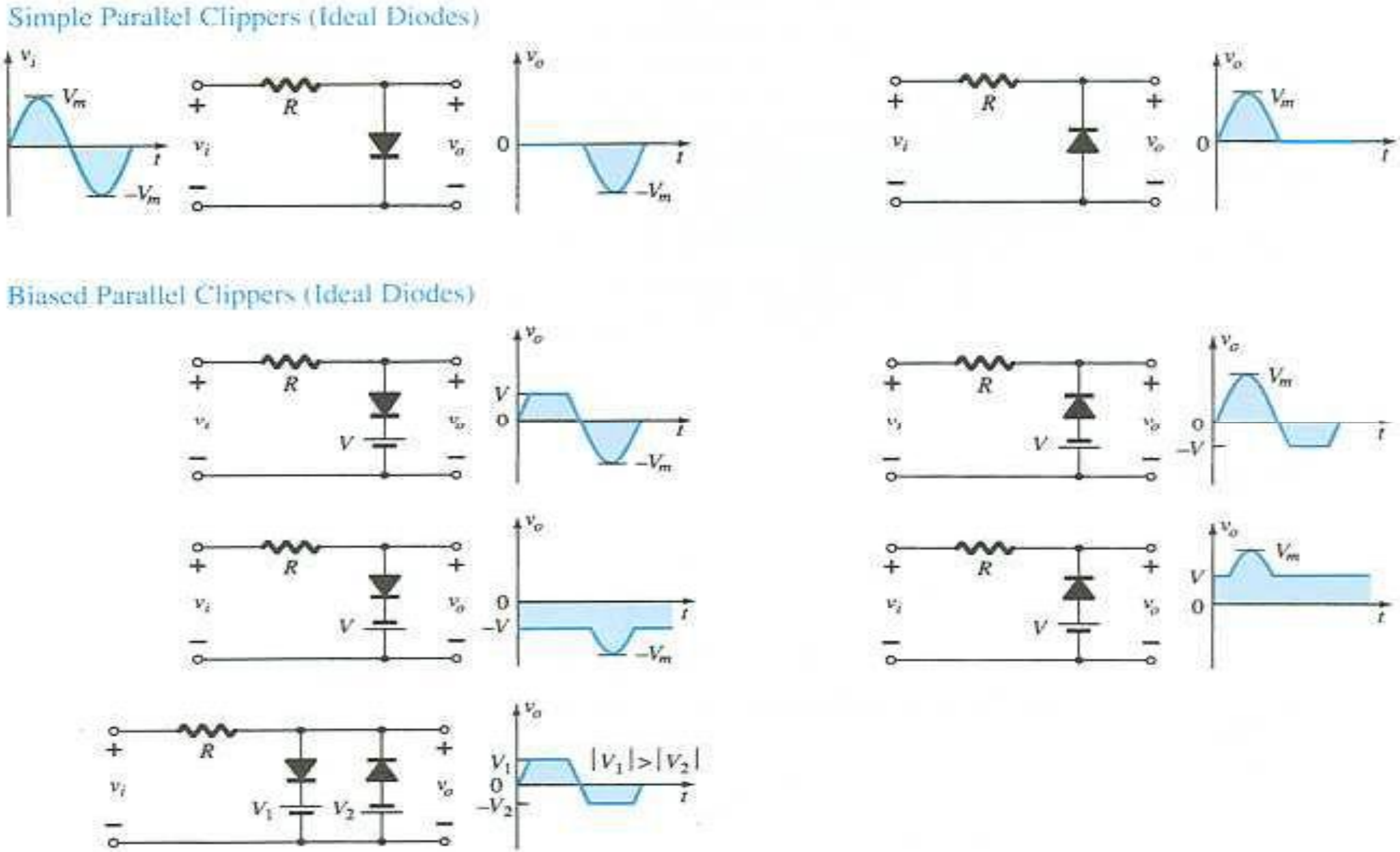
DC biasing can be added in series with the diode to change the clipping level.



Summary of Clipper Circuits



Summary of Clipper Circuits



Clampers

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

Required condition:

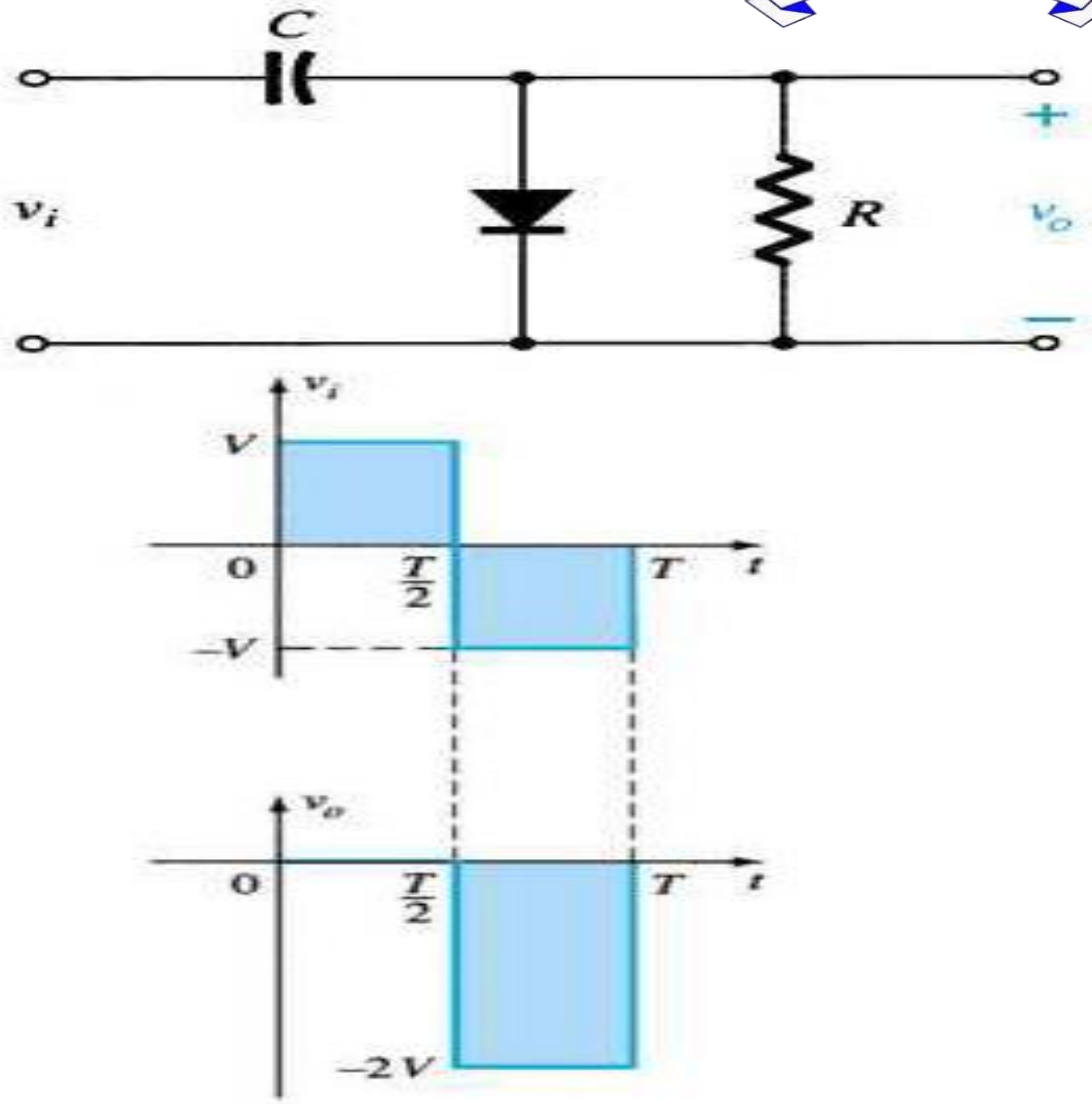
$\tau = RC \gg T$, typically $\tau > 10T$

Start the analysis by examining the response of the portion of the input signal that will forward bias the diode.

During the period that the diode is in the “on” state, the capacitor will charge up instantaneously to a voltage level determined by the surrounding network.

Assume that during the period when the diode is in the “off” state the capacitor holds on to its established voltage level.

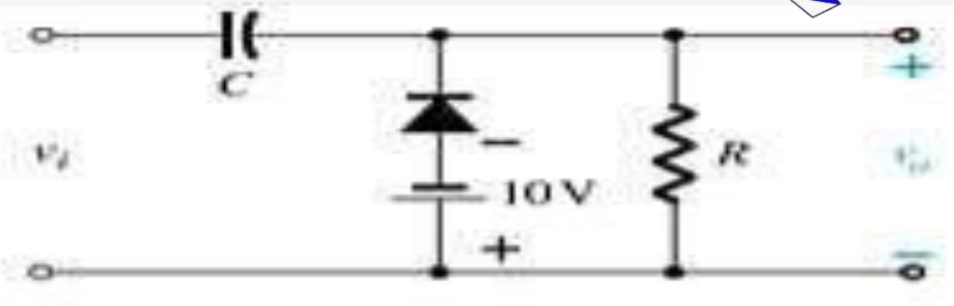
Check that the total swing of the output matches that of the input.



Biased Clamper Circuits

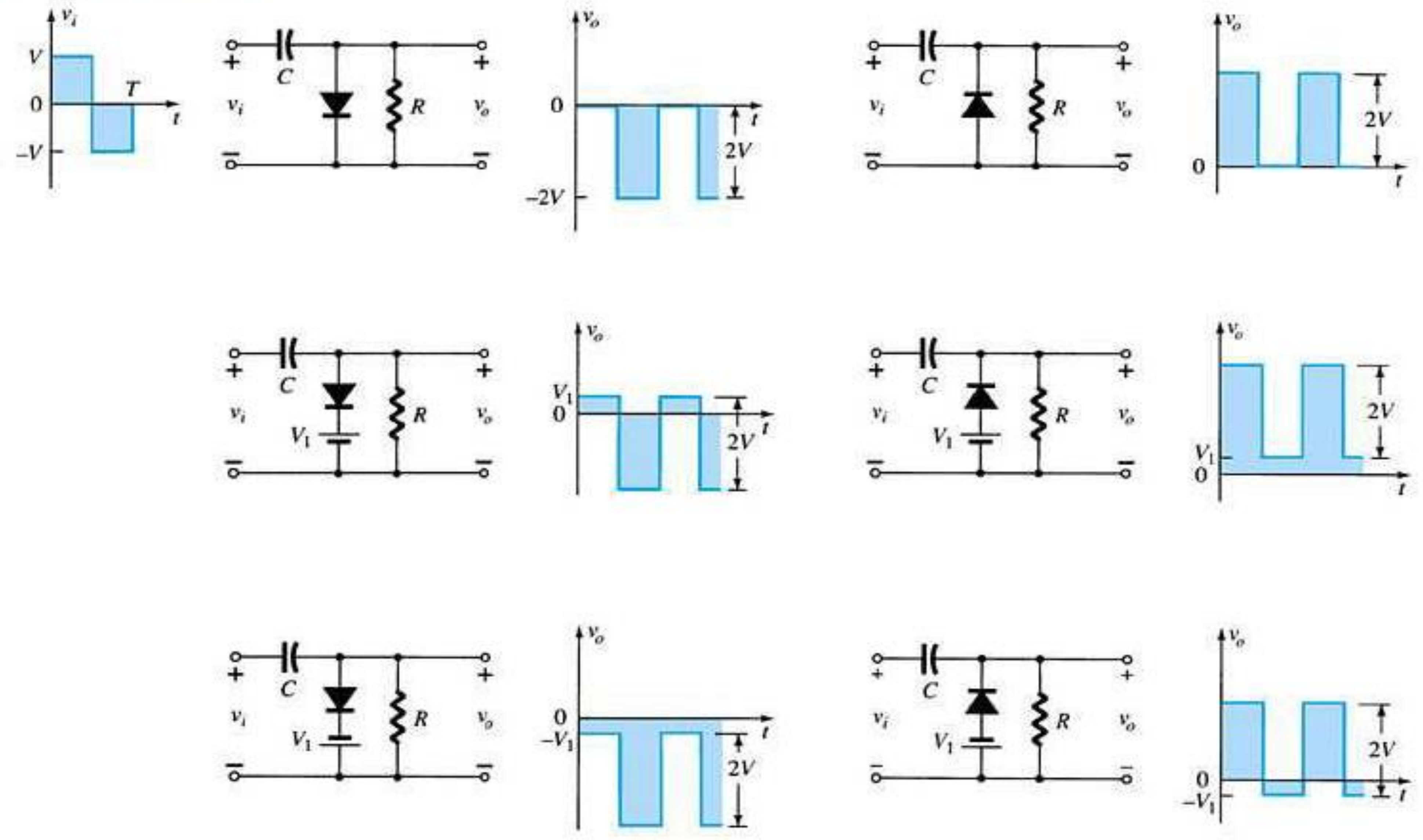
The input signal can be any type of waveform such as sine, square, and triangle waves.

The DC source lets you adjust the DC camping level.



Summary of Clamper Circuits

Clamping Networks

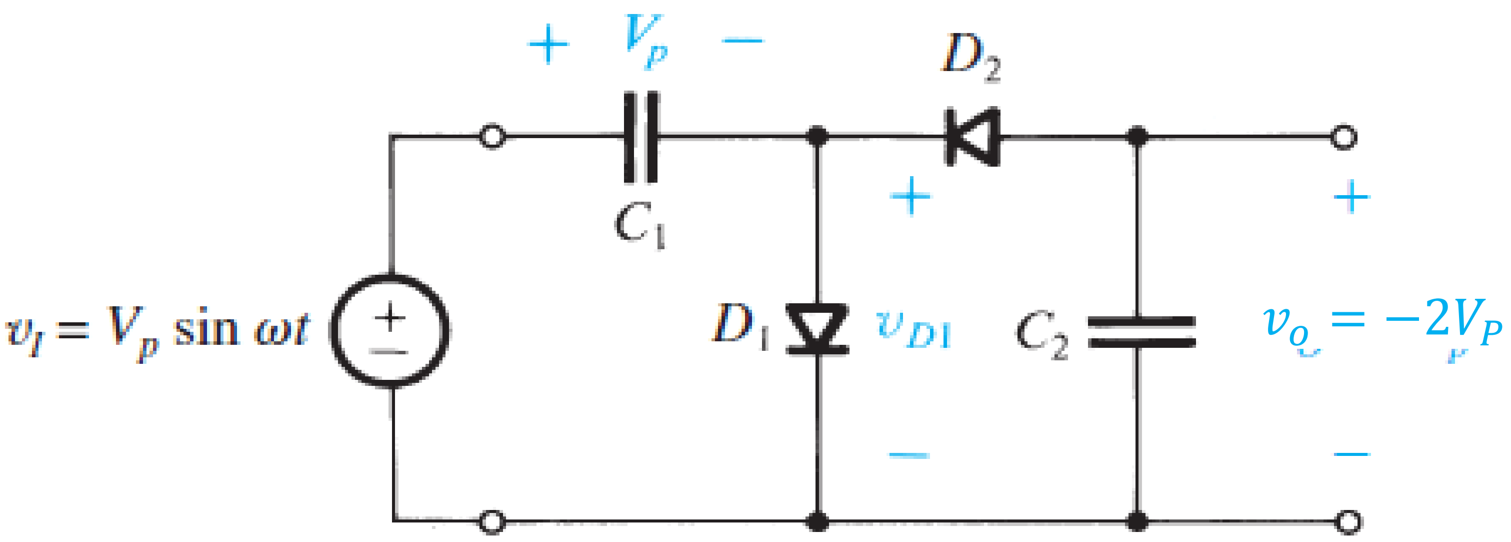


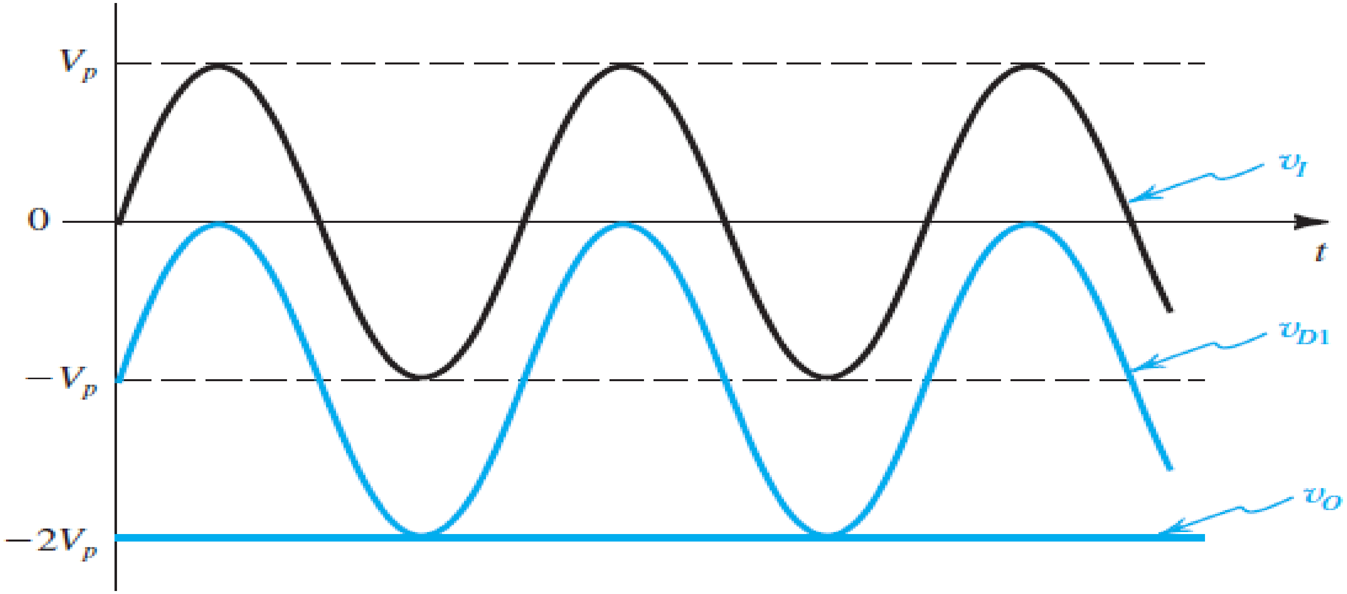
Voltage-Multiplier Circuits

Voltage multiplier circuits use a combination of diodes and capacitors to step up the output voltage of rectifier circuits.

- **Voltage Doubler**

Voltage Doubler





Practical Applications

- **Rectifier Circuits**
  - **Conversions of AC to DC for DC operated circuits**
  - **Battery Charging Circuits**

- **Simple Diode Circuits**
  - **Protective Circuits against**
  - **Overcurrent**
  - **Polarity Reversal**
  - **Currents caused by an inductive kick in a relay circuit**

- **Zener Circuits**
  - **Overvoltage Protection**
  - **Setting Reference Voltages**

Module 2

Semiconductor Devices and applications:

- Diodes √
- BJT
- FET

Bipolar Junction Transistor (BJT)

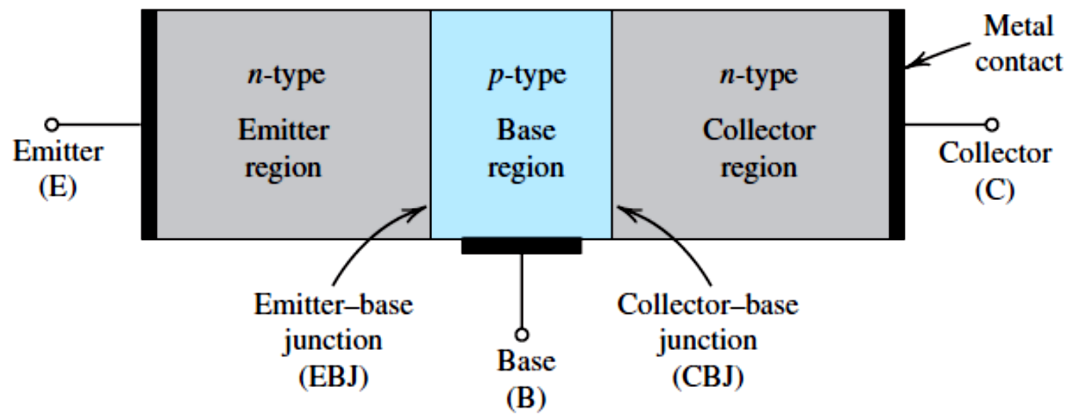
Transistor Construction

There are two types of transistors:

- *pnp*
- *npn*

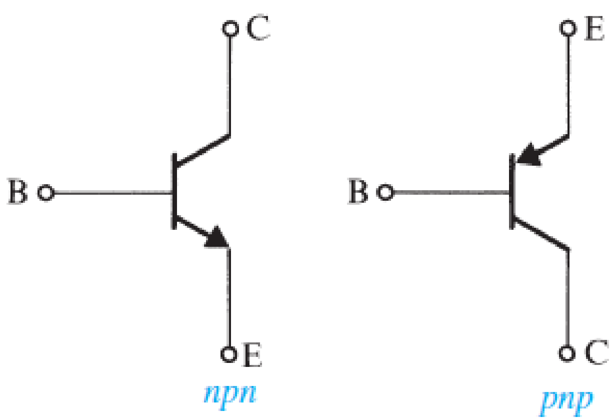
The terminals are labeled:

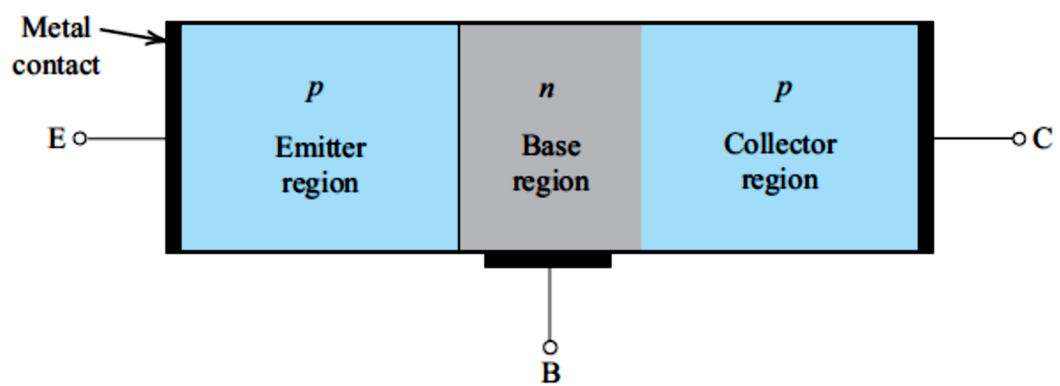
- E - Emitter
- B - Base
- C - Collector



npn

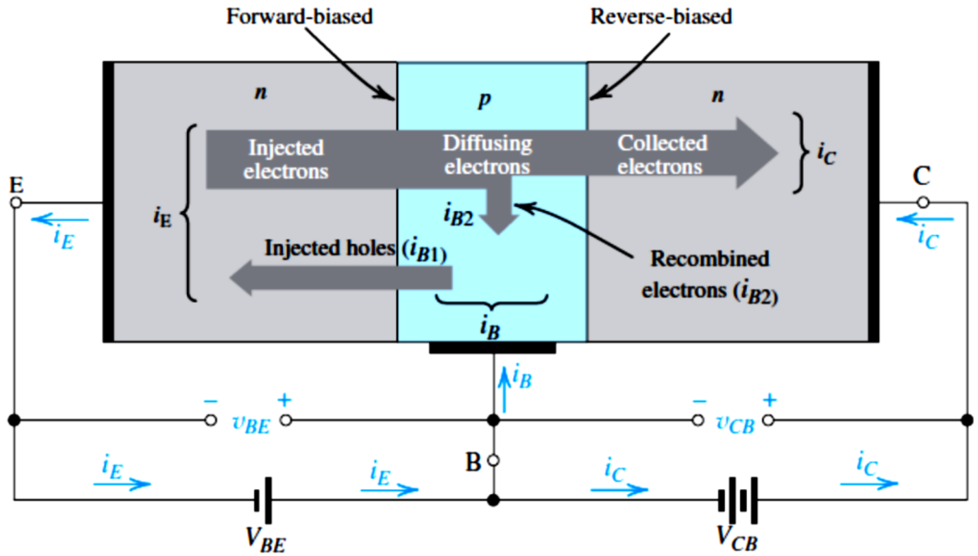
Circuit symbols:

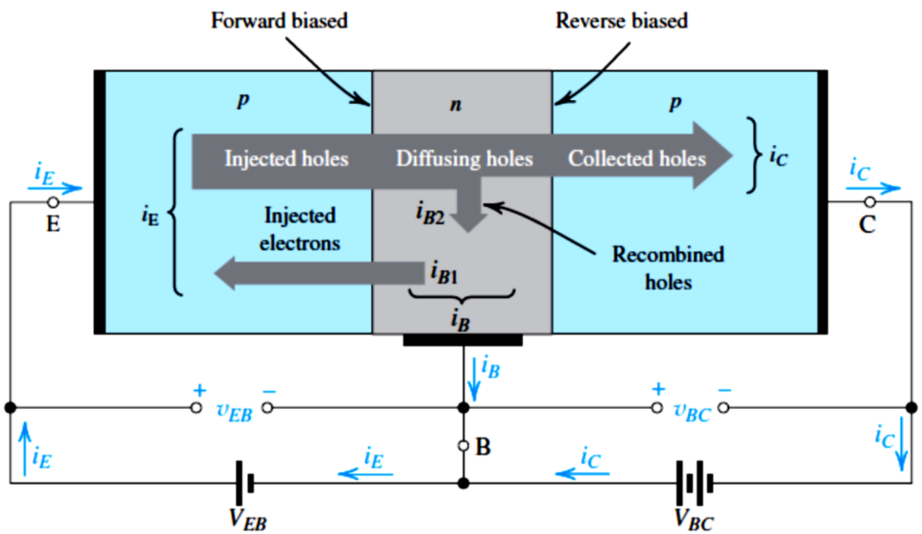




pnp

BJT Operation





- The base is much **thinner than the emitter**, and the **collector** is comparatively wider **than** both.
- The **emitter** is heavily doped so that it can inject large number of charge carriers for current conduction.
- The base passes most of the charge carriers to the collector as it is comparatively lightly doped than emitter and the collector.

Table 6.1 BJT Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

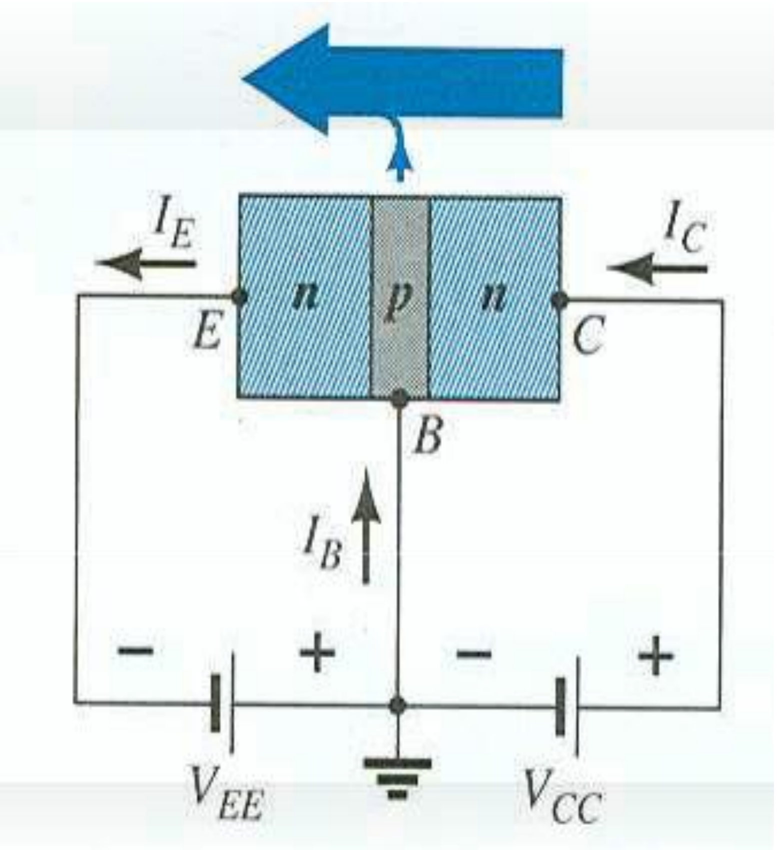
Currents in a Transistor

Emitter current is the sum of the collector and base currents:

$$I_E = I_C + I_B$$

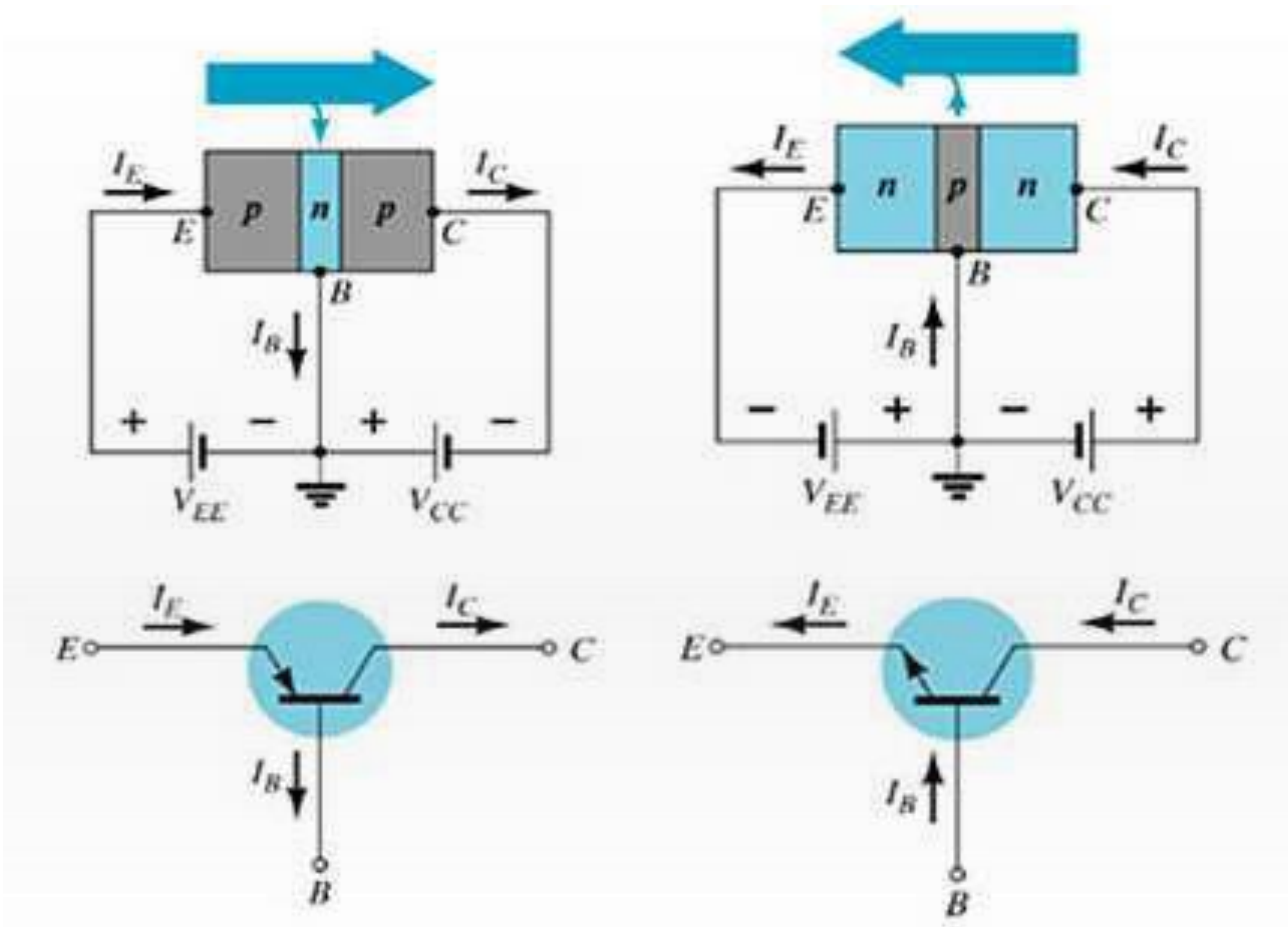
The collector current is comprised of two currents:

$$I_C = I_{C_{\text{majority}}} + I_{CO_{\text{minority}}}$$



Common-Base Configuration

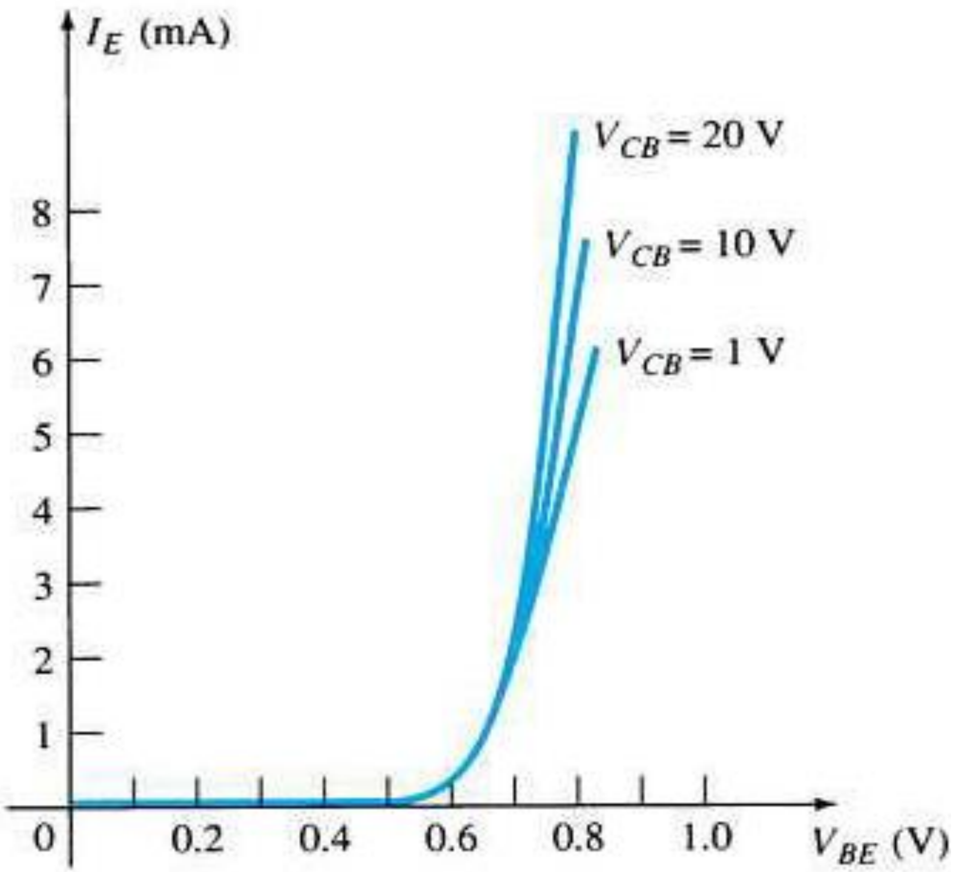
The base is common to both input (emitter–base) and output (collector–base) of the transistor.



Common-Base Amplifier

Input Characteristics

This curve shows the relationship between of input current (I_E) to input voltage (V_{BE}) for three output voltage (V_{CB}) levels.



Common-Base Amplifier

Output Characteristics

This graph demonstrates the output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E).

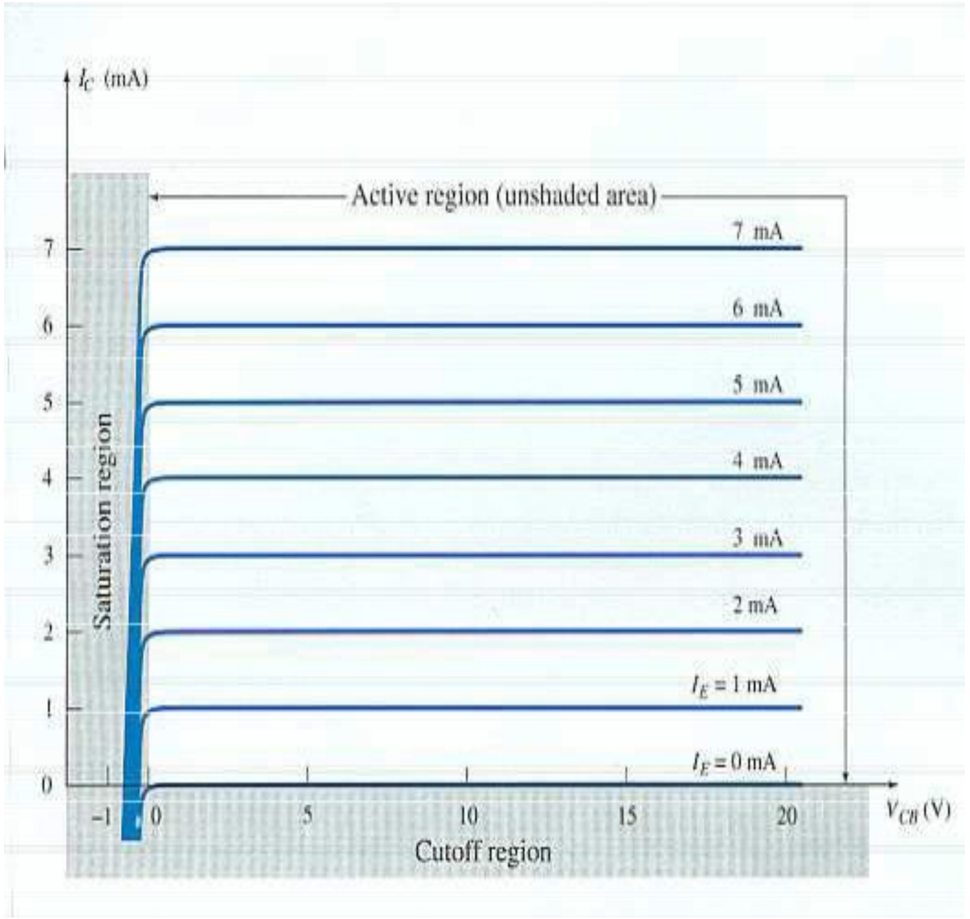


Table 6.1 BJT Modes of Operation		
Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

Operating Regions

- **Active – Main ooperating zone of the amplifier.**
- **Cutoff – The amplifier is basically off. The collector-emitter voltage is large, but current flow is minimum.**
- **Saturation – The amplifier is in full on-condition. The current flow is maximum, but collector-emitter voltage is minimum.**

Approximations

Emitter and collector currents:

$$I_C \cong I_E$$

Base-emitter voltage:

$$\mathbf{V_{BE} = 0.7\ V}$$
(for Silicon)

Alpha (α)

Alpha (α) is the ratio of I_C and I_E due to majority carriers

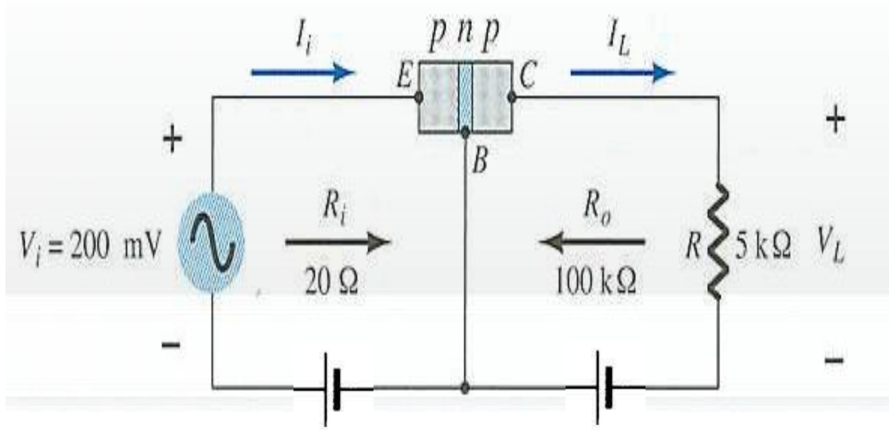
$$\alpha_{dc} = \frac{I_C}{I_E}$$

Ideally: α = 1
In reality: α is between 0.9 and 0.998

Since IC has contributions from both minority and majority carriers, we get

$$I_C = \alpha I_E + I_{CBO}$$

Transistor Amplification



Currents and Voltages:

$$I_E = I_i = \frac{V_i}{R_i} = \frac{200\text{mV}}{20} = 10\text{mA}$$

$$I_C \cong I_E$$

$$I_L \cong I_i = 10\text{ mA}$$

$$V_L = I_L R = (10\text{ ma})(5\text{ k}\quad) = 50\text{ V}$$

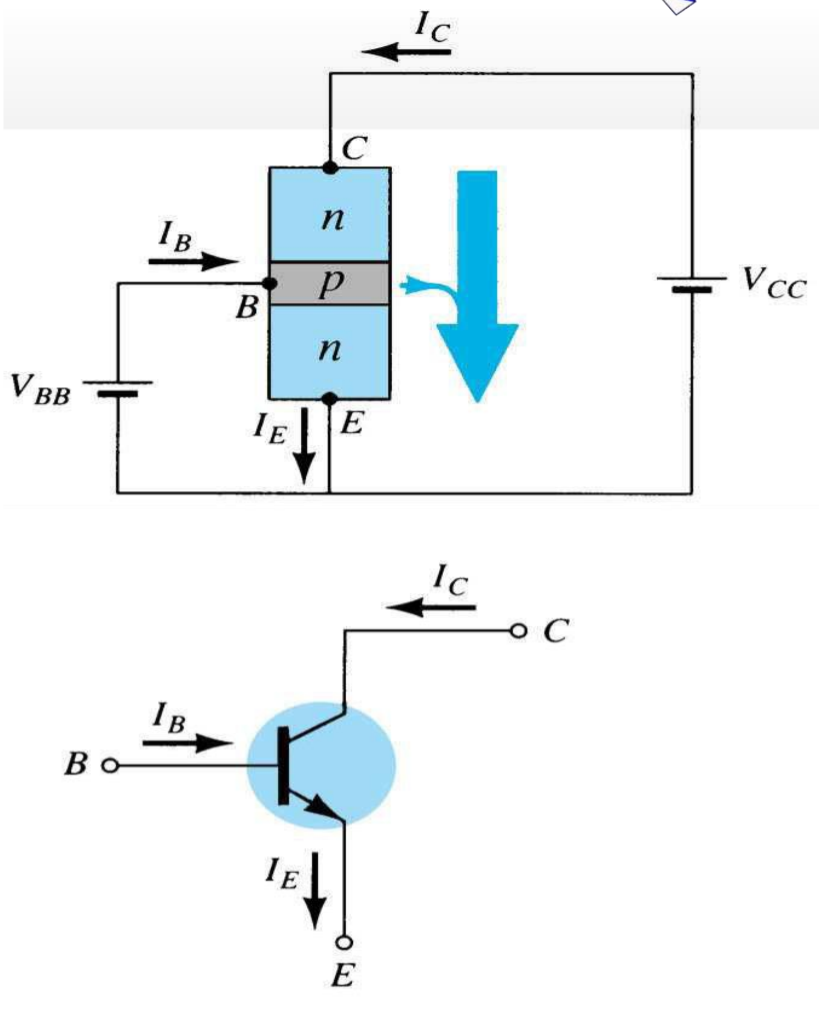
Voltage Gain:

$$A_v = \frac{V_L}{V_i} = \frac{50\text{V}}{200\text{mV}} = 250$$

Common–Emitter Configuration

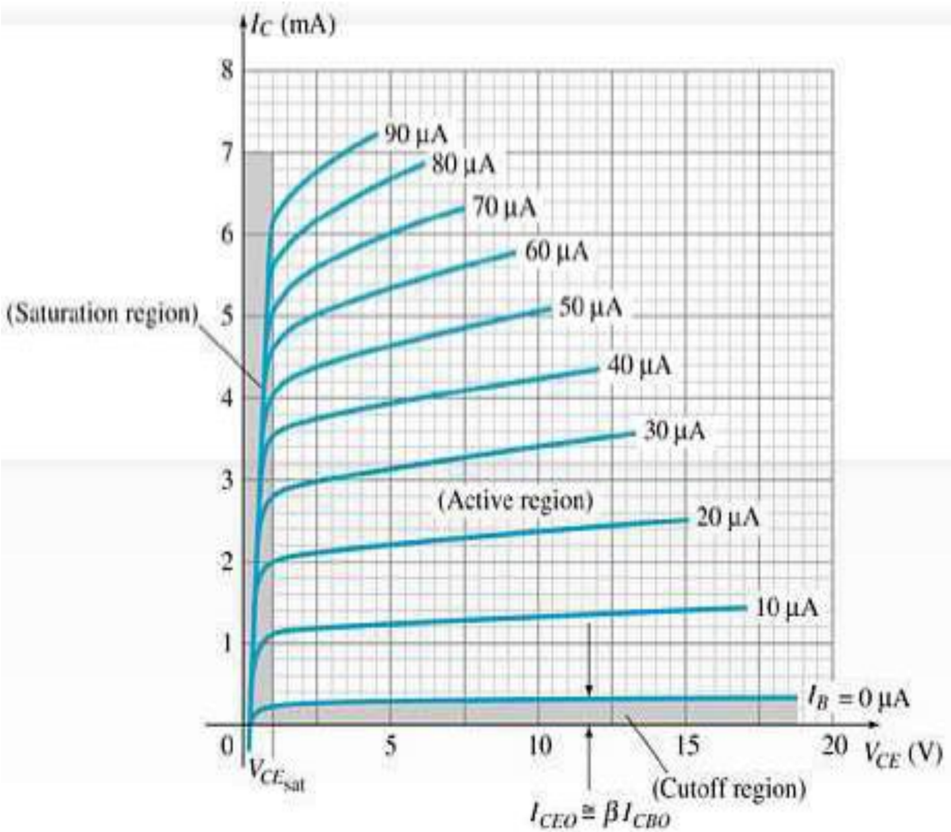
The emitter is common to both input (base-emitter) and output (collector- emitter).

The input is on the base and the output is on the collector.

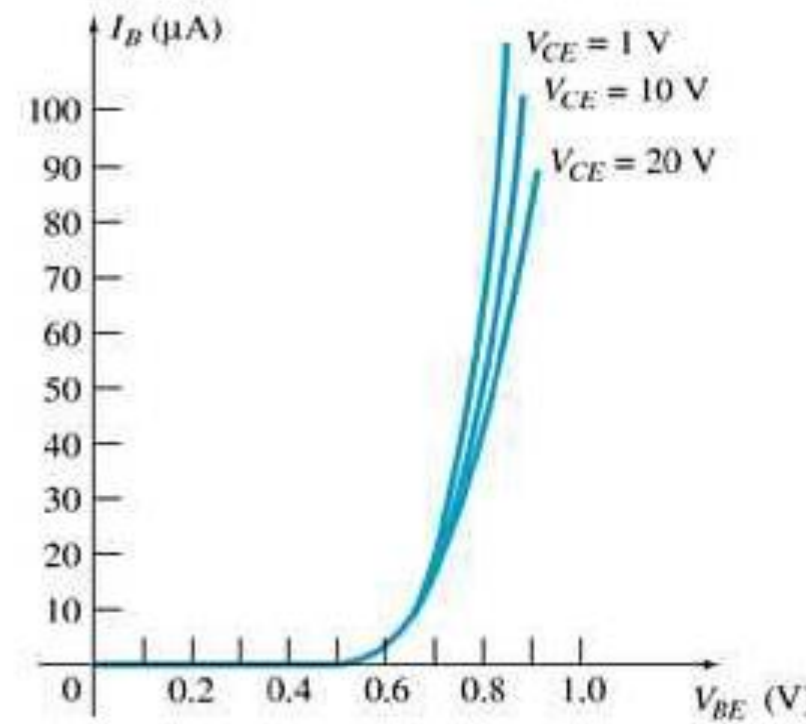


(a)

Common-Emitter Characteristics



Collector Characteristics



Base Characteristics

Common-Emitter Amplifier Currents

Ideal Currents

$$I_E = I_C + I_B \qquad I_C = \alpha\, I_E$$

Actual Currents

$$I_C = \alpha\, I_E + I_{CBO}$$

where I_{CBO} = minority collector current

From the above two equations, we get

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha} = \beta I_B + I_{CEO}$$

Where $\beta = \dfrac{\alpha}{1-\alpha} \Rightarrow \alpha = \dfrac{\beta}{\beta+1}$ $\qquad I_{CEO} = \dfrac{I_{CBO}}{1-\alpha}$

When $I_B = 0$ A the transistor is in cutoff, but there is some minority current flowing called I_{CEO}.

Beta (β)

Relationship between amplification factors β and α

$$\alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{\alpha - 1}$$

Relationship Between Currents

$$I_C = \beta I_B \qquad I_E = (\beta + 1) I_B$$

β is also known as h_{fe}.

β is the current gain in CE configuration

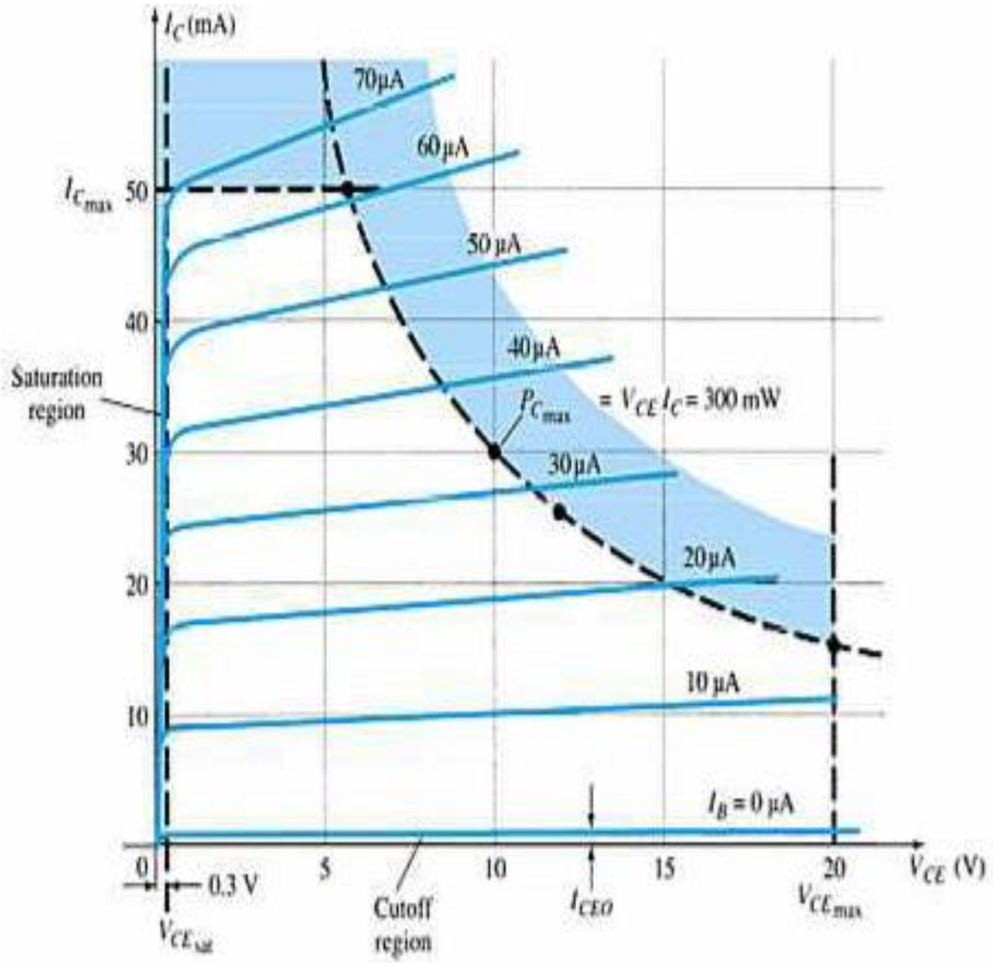
α is the current gain in CB configuration

Operating Limits for Each Configuration

V_{CE} is at maximum and I_C is at minimum ($I_{Cmax}= I_{CEO}$) in the cutoff region.

I_C is at maximum and V_{CE} is at minimum ($V_{CE\ max} = V_{CEsat} = V_{CEO}$) in the saturation region.

The transistor operates in the active region between saturation and cutoff.



Power Dissipation

Common-base:

$$P_{Cmax} = V_{CB} I_C$$

Common-emitter:

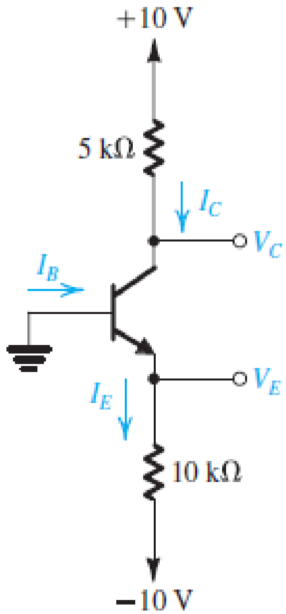
$$P_{Cmax} = V_{CE} I_C$$

Common-collector:

$$P_{Cmax} = V_{CE} I_E$$

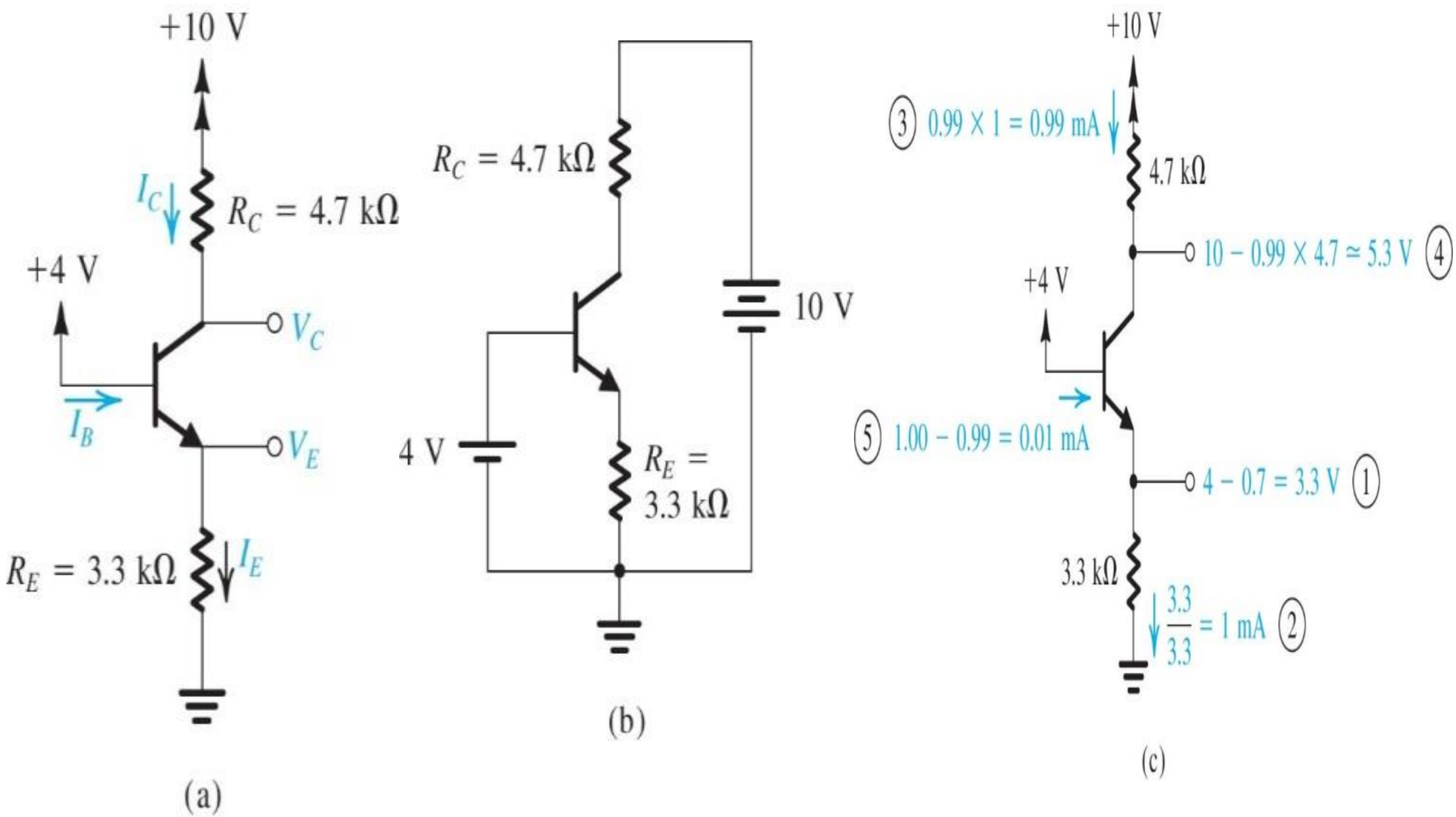
Example: Analysis of BJT circuits

Given β =50, find out find I_E, I_B, I_C, and V_C.

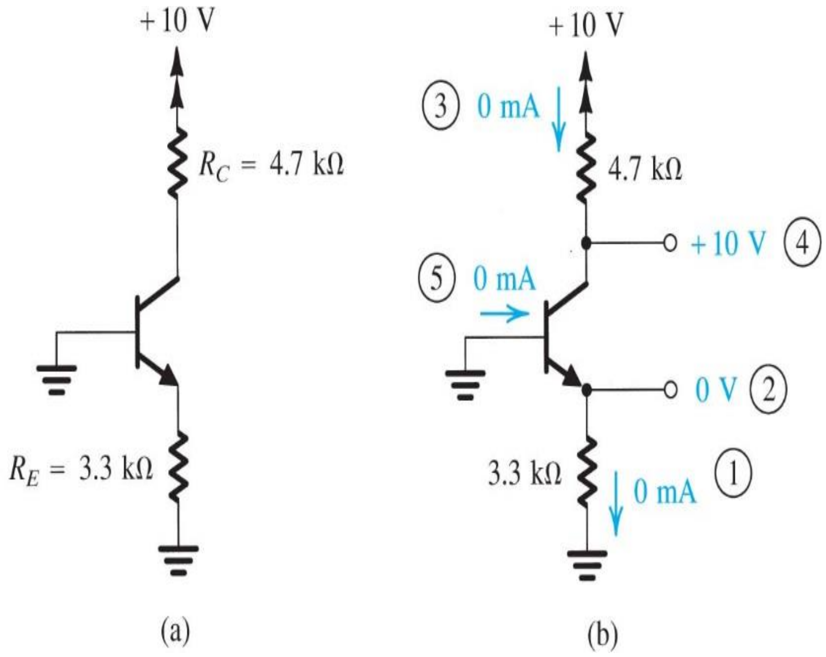


Ans. 0.93 mA; 18.2 μA; 0.91 mA; +5.45 V

Transistor Numerical

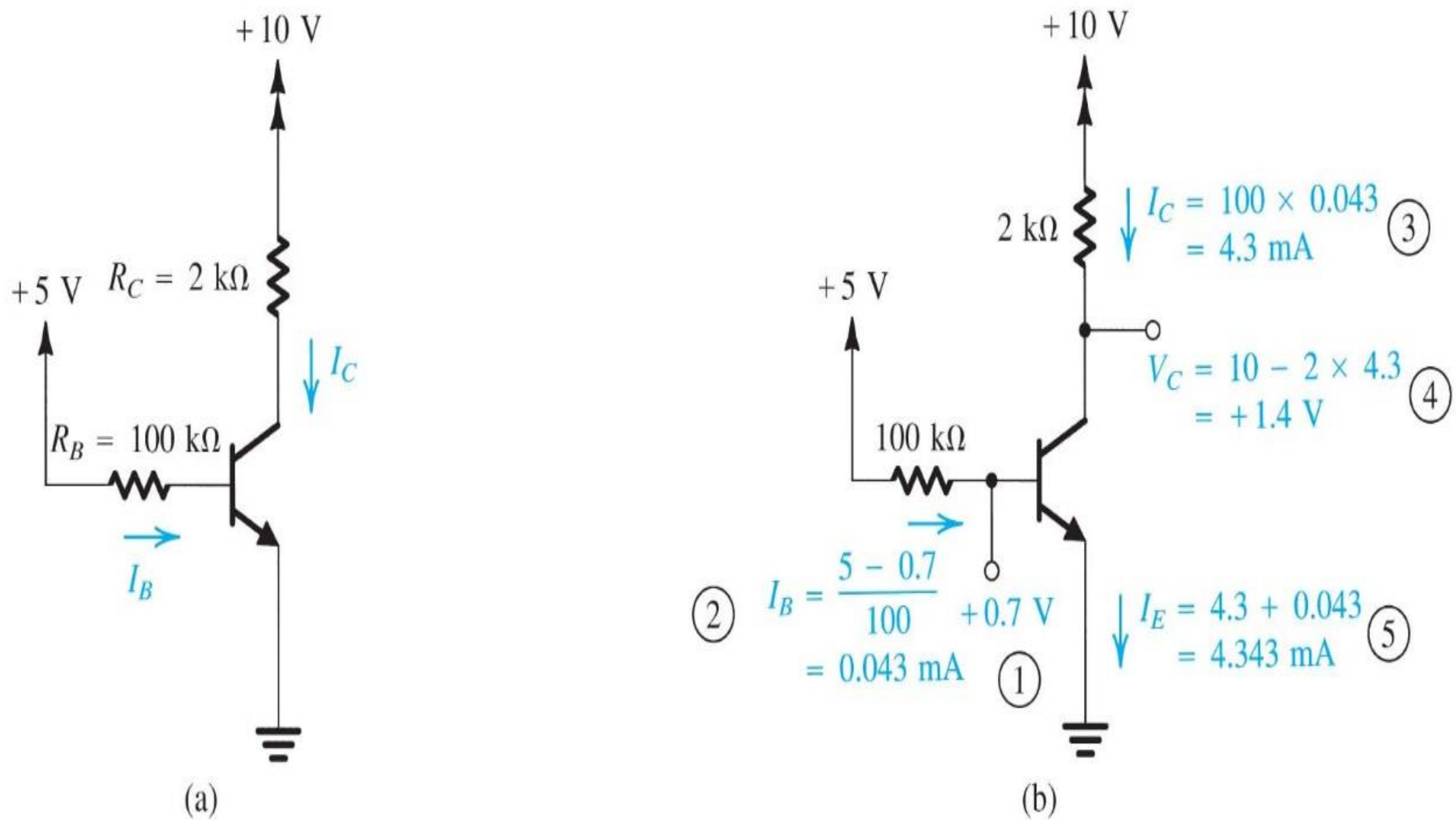


Analysis of the circuit for the aboExample 4.4: (**a**) circuit; (**b**) circuit redrawn to remind the reader of the conventions used about the dc sources; (**c**) analysis with the steps numbered.



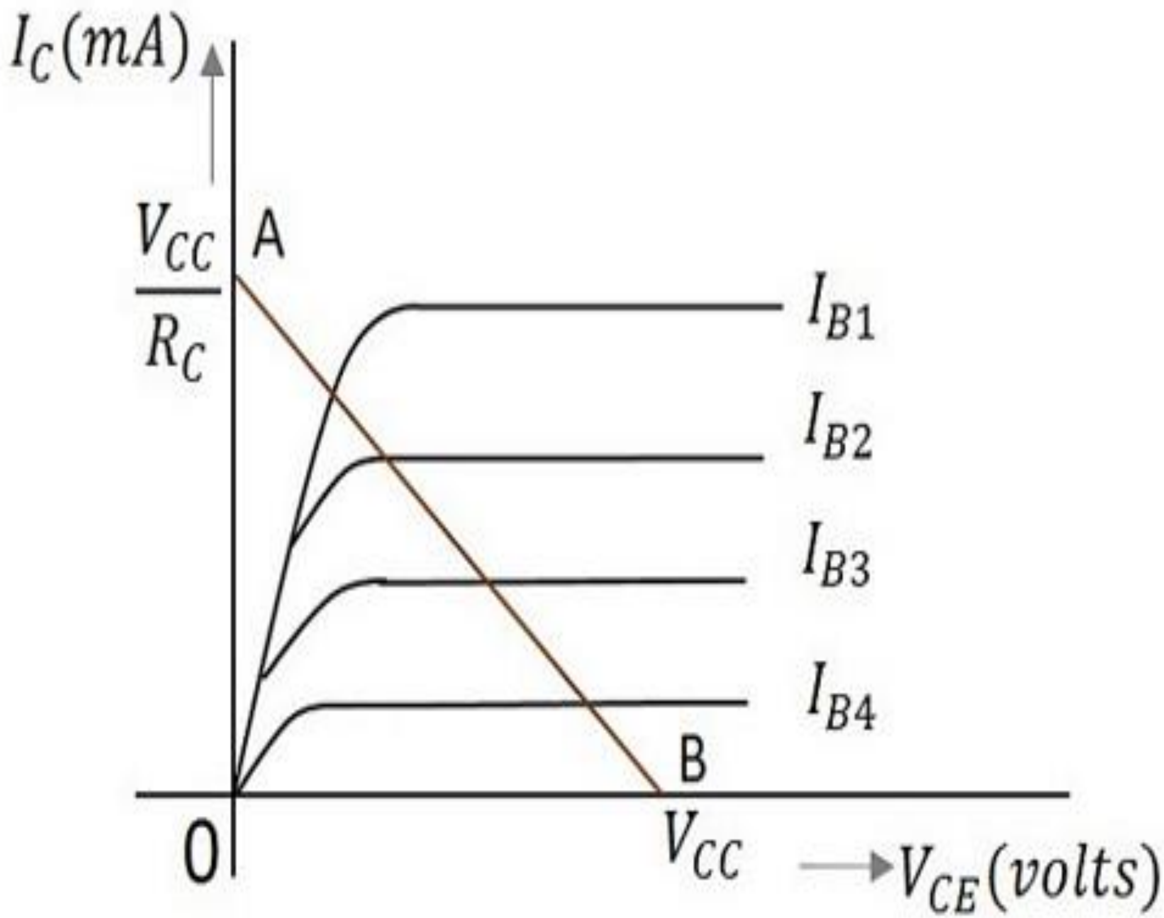
(**a**) circuit; (**b**) analysis, with the order of the analysis steps indicated by circled numbers.

Considering $\beta = 100$, calculate V_B, V_C, I_B, I_C, and I_E.



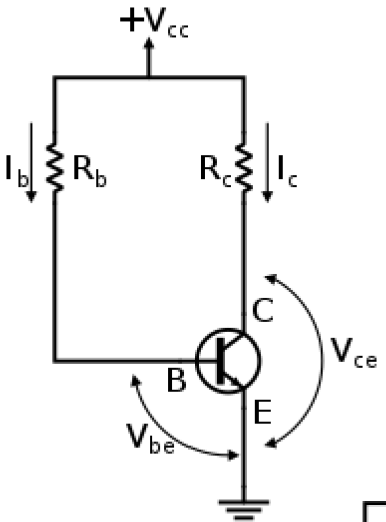
(**a**) circuit; (**b**) analysis, with the steps indicated by the circled numbers.

Load Line

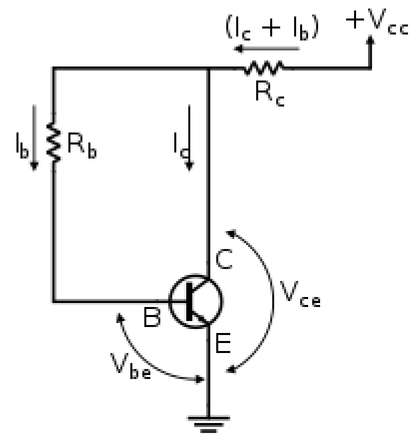


Different Types of Bias Circuits

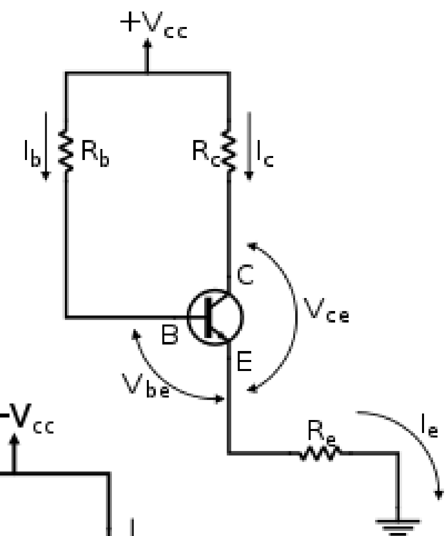
Fixed bias (base bias)



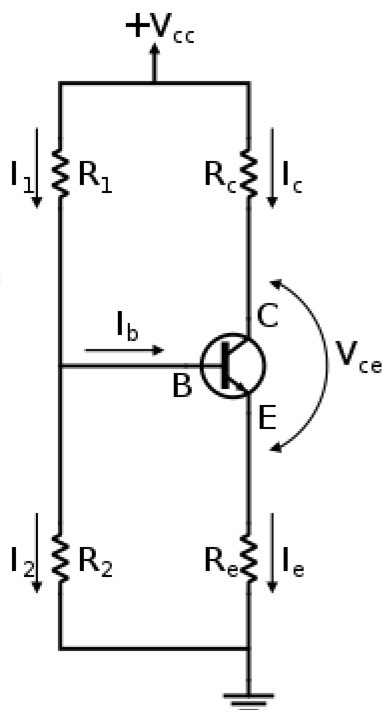
Collector feedback bias



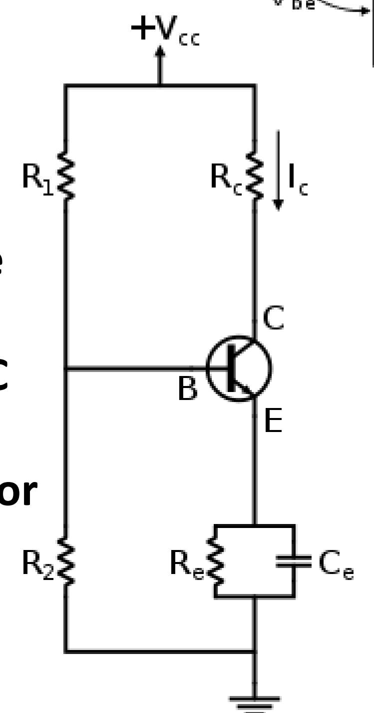
Fixed bias with emitter resistor

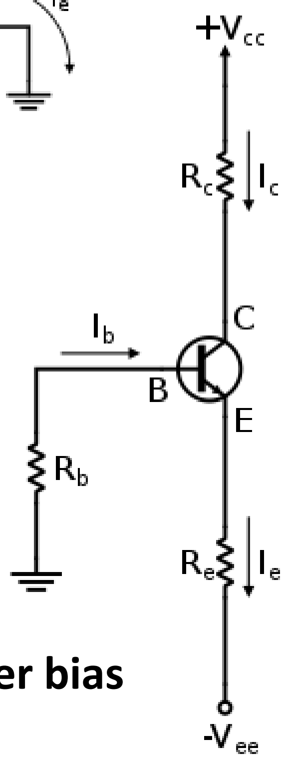


Voltage divider biasing or emitter bias



Voltage divider with AC bypass capacitor





Emitter bias

Voltage Divider bias Circuit