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Er. Ankit Goel

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Preface

The development of nation is directly proportional to requirement of engineers. India being a developing one absorbs huge number of engineers every year, and their demand in coming days can not be overlooked. This handbook is meant for all aspiring engineers who are looking for an exhaustive and precise collection of all subjects that come under Electronics discipline. It encompasses the topics of leading exams in engineering cadre i.e. GATE, IES and PSU's.

The key features of this book are

- Each topic is summarized in an exhaustive manner in the form of key points and notes.
- Every topic is taken up separately along with key points and notes.
- Focused material in entirety to prevent ambiguity in concepts.

I am thankful to Arihant Publication (India) Limited for giving me this opportunity to write such a book which covers almost 100% syllabus of GATE, IES and PSUs and thus Enlightens the path to your success.

I would like to thank Er. Akash Shukla (Project Coordinator), Aas Mohammad Malik (Cover Designer) Deepak Kumar (Inner Designer) for giving me full support during this project. My good wishes to all the readers.

Any suggestions for further improvement are most welcome.

Er. Ankit Goel

Dedicated to

My Father Shri Surendra Kumar Goel

and

My Mother Smt Munni Goel

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1

Diodes

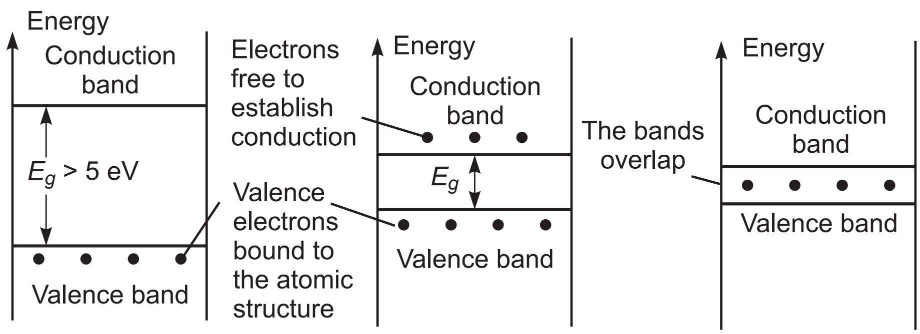
Semiconductor Physics

Semiconductor Materials

- The term **conductor** is applied to any material that will support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals.
- An **insulator** is a material that offers a very low level of conductivity under pressure from an applied voltage source.
- A **semiconductor**, therefore, is a material that has a conductivity level somewhere between the extremes of an insulator and conductor.

Band Theory

A bonding of atoms, strengthened by the sharing of electrons, is called **covalent bonding**. In the crystal, closely spaced energy levels form a band called as **energy band**. Each orbit has a separate energy band. A band of energy levels associated with valence shells is called as **valence band**. Electrons from other bands cannot be removed but electrons from valence band can be removed by supplying a little energy. The **conduction band** is generally empty. The valence band and conduction band are separated by a gap called **forbidden energy gap**.



E_g = 1.1 eV (Si) ; E_g = 0.67 eV (Ge) ; E_g = 1.41 eV (GaAs)

(a) Insulator (b) Semiconductor (c) Conductor

Key Points

- If electron from valence band is supplied with an energy more than forbidden energy gap, it gets drifted to the conduction band and is available as a free electron.
- The energy associated with electron is measured in electron volt (eV).

$$1\text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

Compound Semiconductors

Such as Gallium Arsenide (GaAs), Cadmium Sulphide (CdS), Gallium Arsenide Phosphide (GaAsP), Gallium Nitride (GaN) are constructed by two or more semiconductor materials of different atomic structures are called compound semiconductors.

Properties of Semiconductor Materials

The various materials are classified based on the width of forbidden energy gap. In metal, there is no forbidden gap and valence and conduction band are overlapped. In insulator, the forbidden gap is very large upto 7eV while in semiconductors it is upto 1eV. The silicon and germanium are widely used semiconductors. Intrinsic materials are those semiconductor that have been carefully refined to reduce the impurities to a very level-essentially as pure as can be made available through modern technology.

- The conductivity of intrinsic semiconductor is very less. The properties like conductivity can be changed by adding impurity to the intrinsic semiconductor. The process of adding impurity is called **doping**.

- A semiconductor doped with trivalent impurity atoms forms p-type material. It is called **acceptor impurity** with concentration N_A atoms per unit volume.
- A semiconductor doped with pentavalent impurity atoms forms n-type material. It is called **donor impurity** with concentration N_D atoms per unit volume.
- In p-type, holes are majority carriers and in n-type electrons are majority carriers.
- When a material is subjected to electric field, electrons move in a particular direction with steady speed called **drift speed** and current **drift current**.

Key Points

- A semiconductor material that has been subjected to the doping process is called an extrinsic material.
- Both p-type and n-type materials are called **extrinsic conductors**.
- The concentration of free electrons and holes is always equal in an intrinsic semiconductor.

$$n = p = n_i = \text{ intrinsic concentration}$$

Negative Temperature Coefficient

Those parameters decreasing with the temperature have negative temperature coefficient, *e.g.,* energy gap (E_g).

where, constant $\beta_0 = 2.2 \times 10^{-4}$ (for Ge)

$= 3.6 \times 10^{-4}$ (for Si)

$$E_g T = E_{g_0} - \beta_0 T$$

Mobility (μ), $\mu \propto T^{-m}$

Positive Temperature Coefficient

Those parameters increasing with temperature have positive temperature coefficient.

Some Important Terms

Some important terms regarding semiconductor materials are as given below

- Drift velocity $v_d = \mu E$
- Current density $J = nq\,\mu E$
- Conductivity $\sigma = nq\,\mu$
- Concentration of free electrons per unit volume $n = \dfrac{dU}{AM}$
- Semiconductor conductivity $\sigma = (n\mu_n + p\,\mu_p)\,q$
- In intrinsic semiconductor, $n = p = n_i$

Hence, conductivity $\sigma_i = n_i(\mu_n + \mu_p)q$

Intrinsic concentration $n_i = A_0 T^3 e^{-\frac{E_{G0}}{KT}}$

- In **extrinsic semiconductor**, the conductivity is given by,

For n-type, $\sigma_n = (n_n \mu_n + p_n \mu_P)\, q$

For p-type, $\sigma_p = (n_p \mu_n + p_p \mu_p)\, q$

But in n-type $p_n << n_n$

N_D = Concentration of donor impurity
N_A = Concentration of acceptor impurity
n_P = Number of electrons (concentration) in p-type
P_P = Number of holes (concentration) in p-type

and $n_n \cong N_D$ while in p-type
$n_p << p_p$ and $p_p \cong N_A$

Hence, conductivity can be calculated as,

$$\sigma_n = N_D \mu_n q \text{ and } \sigma_p = N_A \mu_p q$$

- Mass-action law $np = n_i^2$

$$\text{In } n\text{-type, } n_n p_n = n_i^2, \text{ hence } p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}$$

$$\text{In } p\text{-type, } p_p n_p = n_i^2, \text{ hence } n_p = \frac{n_i^2}{p_p} = \frac{n_i^2}{N_A}$$

Diffusion Current

Diffusion is defined as the migration of charge carriers from higher concentration to lower concentration. Due to this non-uniform concentration, there can exist a current called **diffusion current**. The diffusion current depends on concentration gradient $\frac{dp}{dx}$ or $\frac{dn}{dx}$.

Diffusion Current Density

The diffusion current density is given by,

$$\text{In } p\text{-type, } J_p = -qD_p \frac{dp}{dx}$$

$$\text{In } n\text{-type, } J_n = -qD_n \frac{dn}{dx}$$

D_p and D_n are called **diffusion constants**.

Drift Current

In open circuit, continuously graded semiconductor diffusion current exists. But net current is zero. So there exist drift current in opposite direction of diffusion current to cancel it.

Note To have drift current exists a potential internally generated. This indicates that non-uniform doping of bar, results in the induced voltage.

Einstein's Relation

In a semicondutor, this relation gives the relationship between diffusion constant, mobility and thermal voltage.

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = KT$$

$V_T = KT$ and is 26 mV at 27°C

Potential Difference and Junction Potential

The potential difference between any two points of non-uniformly doped bar depends on concentration at those two points given by

$$V_{21} = V_T \ln \frac{p_1}{p_2}, V_{21} = V_T \ln \frac{n_2}{n_1}$$

where, V_{21} = The potential difference between points 1 and 2

V_T = Thermal voltage

V_j = Junction potential

The expression for the junction potential is given by

$$V_J = V_T \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

For germanium, $V_J = 0.2$ to 0.3 V

For silicon, $V_J = 0.6$ to 0.7 V

Fermi Level

Fermi energy is defined as the energy possessed by the fastest moving electron at 0 K.

Fermi-Dirac Function

The Fermi-Dirac function of a metal or semiconductor is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

Fermi Level in *n*-type Semiconductor

$$E_C - E_F = kT \log_e \frac{N_C}{N_D}$$

where, E_c = Maximum energy of conduction band

E_V = Maximum energy of valence band

E_F = Fermi energy in eV.

$$E_C - E_F = kT \log_e \frac{N_C}{N_D}$$

Fermi Level in *p*-type Semiconductor

$$E_F = E_V + kT \log_e \frac{N_V}{N_A}$$

where, N_A = Concentration of acceptor ions

N_D = Concentration of donor ions

N_C = Material constant and can be considered as a function of temperature

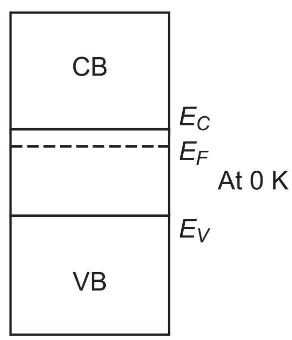
$$N_V = 2\left[\frac{2\pi - kTm_r}{h^2}\right]^{3/2}$$

$$N_C = 2\left[\frac{2\pi\, kTm_n}{h^2}\right]$$

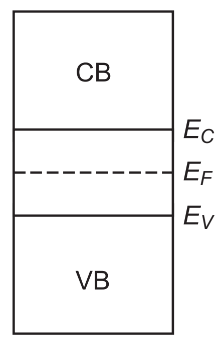
$k = 1.81 \times 10^{-23}$ J/K

m = Mass of electron

m_n = Effective mass of electron



Fermi level for *n*-type



Fermi level for *p*-type

h = Planck constant = 6.625×10^{-34} J-s

Key Points

- It *p*-type and *n*-type materials are combined chemically it results into *p*-*n* junction.
- At junction there is step change in the concentration of charge carriers.
- The region near the junction gets depleted off the free charged particles hence called as **depletion region**.
- The potential gets developed near the junction due to change in concentrations of carriers called potential barrier or cut-in voltage or junction potential or height of potential barrier. It has fixed polarity.
- The width of depletion region depends on the doping of both sides. The depletion region penetrates more on the lightly doped side.

Vacuum Diode

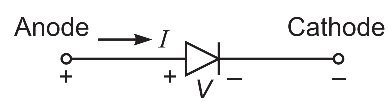
The thermionic vacuum diode has a plate and either a directly or an indirectly heated cathode. It is bulky when compared with the selenium diode or the ultra compact semiconductor diode. An ideal diode is a two terminals polarity sensitive device that has zero resistance when it is forward biased and infinite resistance when reverse biased.

A vacuum diode's characteristics follow child's three halves power law, $I = KV^{3/2}$ while current increases exponentially with voltage in a semiconductor diode.

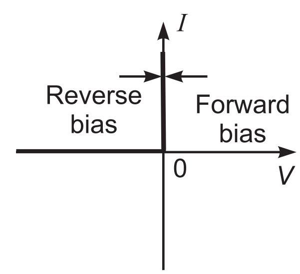
Ideal Diode

An ideal diode may be considered as most fundamental non-linear element. Silicon and germanium diodes exhibit a cut-in voltage of 0.6 V and 0.2 V respectively in their characteristic curves and thus approximate closely the ideal diode in this respect. The Peak Inverse Voltage (PIV) is the highest reverse voltage a diode can withstand before breaking down and permitting current to flow in the reverse direction.

The **static** and **dynamic resistances** of a diode may be determined from the characteristic curves and represent the DC and AC opposition to current flow offered by the diode. An equivalent circuit of a diode is a linearisation of the diode's characteristic curve and typically consists of an ideal diode in series with a battery (representing the cut-in voltage) and a resistance equal to the dynamic resistance of the diode over its linear portion.



Ideal diode symbol



***V-I* characteristic of ideal diode**

Note A diode in a series circuit with an AC voltage applied will cause half-wave rectification.

Semiconductor Diode

The two types of material *n*-type and *p*-type are chemically combined to form a *p-n* junction. A region near the junction is without any free charge particles called **depletion region**.

Note The characteristics of an ideal diode are those of a switch that can conduct current in only one direction.

Biasing of a Diode

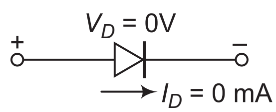
The electric field across the junction has a fixed polarity called **barrier potential** or height of the barrier. A popular semiconductor device is formed using a *p-n* junction called ***p-n* junction diode**.

No Applied Bias ($V_D = 0$V)

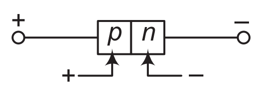
In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.

Forward Bias ($V_D > 0$V)

In forward biased condition, majority carrier carry the current, when applied voltage approaches barrier potential. The depletion region reduces as forward bias increases.



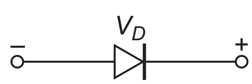
Diode in forward bias



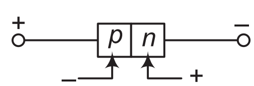
Symbol of forward bias mode

Reverse Bias ($V_D < 0$V)

On the other hand in reverse biased condition, the depletion region widens and minority carriers carry the current called **reverse saturation current** denoted as I_0.



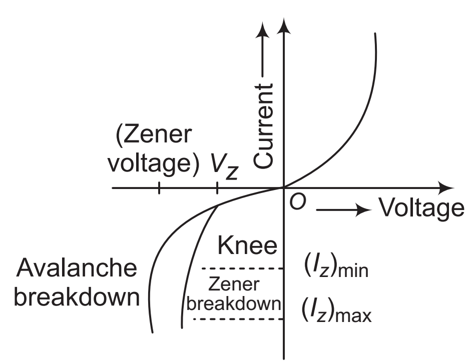
Diode in reverse bias



Symbol of reverse bias mode

Breakdown in Diode

If reverse biased voltage increases, at a particular voltage breakdown occurs due to accelerated minority charge particles. This is called **avalanche effect**. For a heavily doped diode, electric field across the depletion region is so intense to pull the electrons out of valence bands. This effect is called **zener effect**.



Breakdown *V-I* characteristics

Some Important Currents in Diode *w.r.t.* FB

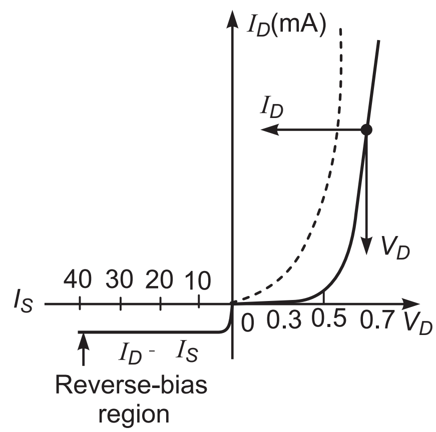
In forward biased condition, *the diode current has four components*.

I_{pp} = current due to holes in p side
I_{nn} = current due to electrons in n side
I_{pn} = current due to holes in n side
I_{np} = current due to electrons in p side

All are functions of distance from the junction. At the junction, at $x = 0$ the total current I is,

$$I = I_{pn}(0) + I_{np}(0)$$

Voltage-Current Characteristics



V-I characteristics of diode

The proportion of current due to electrons and holes varies with the distance inside the diode but sum of the currents carried by electrons and holes at any point inside the diode is always constant, equal to total forward diode current. The graph of current against voltage applied to a diode is called *V-I* characteristics.

In forward biased region, when applied voltage exceeds cut-in voltage, heavy conduction starts. Cut-in voltage is denoted as V_c and is 0.2 for Ge and 0.6 for Si diode. The reverse saturation current I_0 is almost constant in reverse biased region and is dependent on temperature.

Static and Dynamic Resistance

The static resistance is simply the ratio of DC voltage across the diode to the DC current flowing through it.

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

While the dynamic resistance is AC resistance and defined as ratio of incremental change in voltage to the corresponding change in current.

$$r = \text{dynamic resistance} = \frac{\Delta V_d}{\Delta I_d}$$

$$r = \frac{1}{\text{Slope of } V\text{-}I \text{ characteristics}}$$

The *V*- *I* characteristics is given by the equation

$$I = I_0\,(e^{V/nV_T} - 1)$$

when $\quad V > 0,\ I_l = I_0 e^{V/nT}$

when $\quad V < 0,\ I_s = -I_0$

This is called **current equation of a diode**. From this, dynamic resistance can be determined as,

$$r = \frac{1}{\text{Slope of graph}} = \frac{1}{\left\{\dfrac{dI}{dV}\right\}} = \frac{nV_T}{I_0 e^{V/nV_T}}$$

- For forward biased, V must be considered positive while for the reverse biased, V must be considered negative. This dependence of I_0 on temperature is given by

$$I_0 = KT^M e^{-V_{G0}/nV_T}$$

where, $\quad m = 2$ for Ge, 1.5 for Si

and $\quad V_{G_0} = 0.785\text{ V}$ for Ge, 1.21V for Si

- The change in voltage with respect to temperature required to keep diode current constant is given by,

$$\frac{dV}{dt} = \frac{V - (V_{G_0} + mnV_T)}{T}$$

where, $\quad n = 1$ for Ge; $n = 2$ for Si

- It is -2.10 mV/℃ for Ge and -2.3 m for Si. Practically, considered as 2.5 mV/°C for any diode. While change in I_0 will respect to temperature is given by,

$$\frac{d\ \text{In}\,(I_0)}{dT} = \frac{m}{T} + \frac{V_{G_0}}{nTV_T}$$

- It is 11% per °C for Ge while 8% per °C for Si. Practically, it is considered as after every 10°C rise in temperature, diode reverse saturation current doubles while it rises by 7% per °C rise in temperature for any diode. From this it can be written as

$$(I_0)_2 = (1.07)^{\Delta T}\,(I_0)_1$$

where, $\quad (I_0)_2 =$ Reverse saturation current at T_2

$(I_0)_1 =$ Reverse saturation current at T_1

$\Delta T = T_2 - T_1$

Transition and Diffusion Capacitance

In reverse biased condition, due to change with respect to voltage there exists a capacitive effect called as **transition capacitance** denoted as C_T.

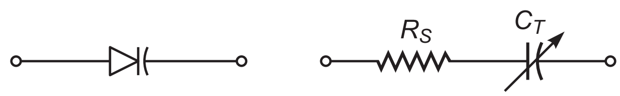
It is given by $$C_T = \frac{\varepsilon A}{W} = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

where, W = width of the carrier. W is related to barrier potential V_B by the relation, barrier potential, $V_B = \frac{1}{2}\frac{qN_A}{\varepsilon}W^2$

ε_0 and ε_r are the permittivity and relative permittivity respectively.

Hence, $$W \propto \sqrt{V_B} \text{ while } C_T \propto \frac{1}{W}$$

On the other hand, in forward biased condition also there exists a capacitive effect called as **diffusion capacitance** denoted as C_D.



(a) Circuit symbol (b) Equivalent circuit

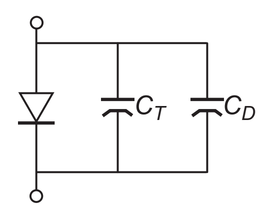
$$C_D = \frac{tI}{nV_T}$$

where, t = mean life time for holes; $C_D >> C_T$

Varactor Diode

The rate of change of stored charge with applied voltage is defined as diffusion capacitance and is denoted by C_D.

Diffusion capacitance, $$C_D = \frac{dQ}{dV}$$



Varactor diode

Note In the reverse bias region, we have the transition while in forward bias region we have difussion capacitance.

The transition capacitance effect is made purposely dominant in practice, to use the diodes in tuning circuits. Such diodes are called as **varactor diodes**.

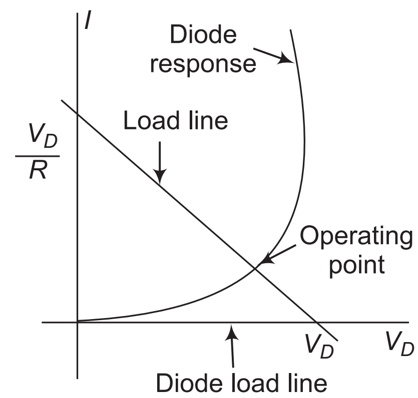
Reverse Recovery Time

The diode is used as an electronic switch in many circuits. Diode cannot be reversed instantaneously. The diode requires a time to reverses a time to reverse called as its **reverse recovery time** (t_{rr}) which is made up of storage time (t_s) and transition time (t_t).

Note In analyzing practical circuits, diode is replaced by a battery or voltage equal to cut-in voltage in series with it a forward resistance if given. This is called **equivalent mode of a diode**.

Operating Point in a Diode

The determination of current flowing in a series circuit containing a diode, resistor R_L and DC applied voltage V is made by drawing a load line on the static characteristic curve of the diode. One end of the load line is at $V_D = V$, $I = 0$, the other at $V_D = 0$, $I = \frac{V}{R_L}$. The intersection of the load line with the curve gives the ***Q*-point.**



V-I characteristics

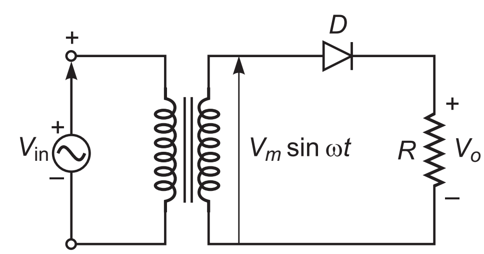
When an alternating voltage is applied to a series diode resistor circuit, a dynamic curve may be constructed to give the output current waveform for the load resistor for which the curve was drawn.

Applications of Diode

The diode can be used as a **rectifier**. A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as **rectification**.

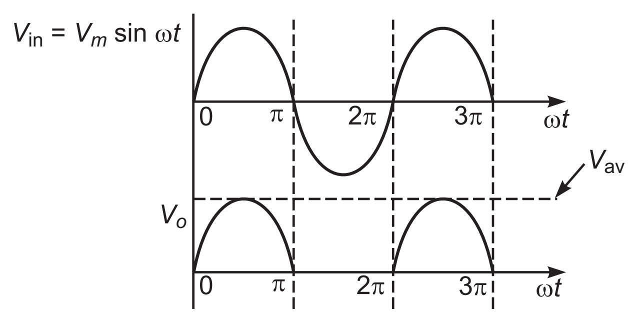
Half-Wave Rectifier

- In positive half cycle, diode D conduct and V_0 is same as V_i.
- In negative half cycle diode D does not conduct so that the voltage V_0 output is zero.



Half-wave rectifier circuit

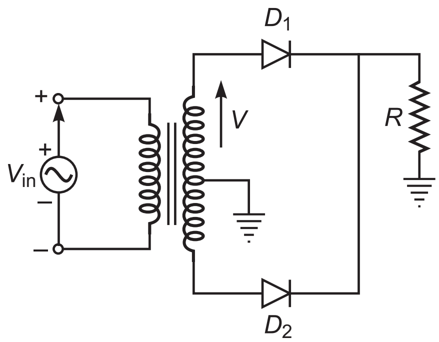
$$V_{av} = 0.318 V_m$$
$$I_{av} = V_m / \pi R$$



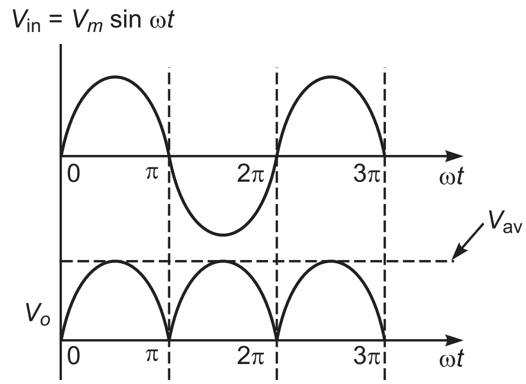
Waveform of half-wave rectifier

Full-Wave Rectifier

- In positive half cycle diode D_1 conduct but D_2 will be off and V_0 is same as V_i.
- In negative half cycle diode D_2 conduct but D_1 will be off so that the output voltage V_o is inverted of V_i (*i.e.,* half cycle)



Full wave-rectifier circuit



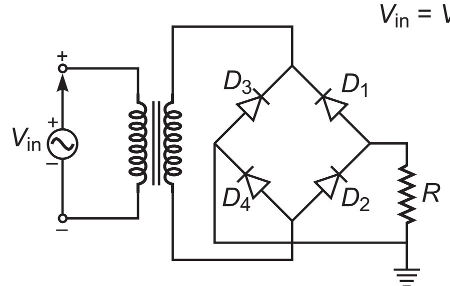
Waveform of full-wave rectifier

$$V_{av} = 2V_m / \pi \,; \quad I_{av} = \frac{2V_m}{\pi R}$$

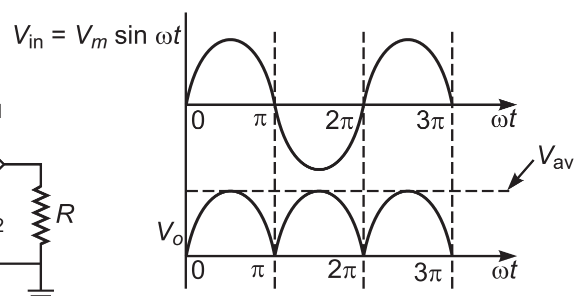
where V_m = maximum value of voltage

Bridge Rectifier

The single-phase full-wave bridge rectifier is shown in figure.



Bridge rectifier circuit



Waveform of bridge rectifier

In the positive half cycle, D_1 and D_4 are forward biased and D_2 and D_3 are reverse biased. In the negative half cycle, D_2 and D_3 are forward biased, D_1 and D_4 are reverse biased. The output voltage waveform is shown in figure, it is same as full-wave rectifier but the advantage is that PIV rating of diodes are V_m and only single secondary transformer is required.

Ripple Factor

The ripple factor is the measure of the purity of DC output of a rectifier and is defined as

$$\text{Ripple factor} = \frac{\text{rms value of the AC output voltage}}{\text{Average DC output voltage}} = \sqrt{V_o^2 + \sum_{n=1}^{\infty} V_n^2}$$

$$\text{Therefore, ripple factor} = \frac{\sqrt{V_{\text{rms}}^2 - V_o^2}}{V_o} = \sqrt{\left(\frac{V_{\text{rms}}}{V_o}\right)^2 - 1}$$

Key Points

- A half-wave rectifier is characterised by an excessive ripple, low values of ratio of rectification and transformer utilisation factor and DC saturation of the transformer core.
- The centre tapped and bridge type full-wave rectifiers improve on the half-wave characteristics but the three phase, full-wave rectifier is even better.

Basic Parameters used in Rectifying Circuits

The basic parameters used in rectifying circuits are given below

- **Ratio of rectification** $= \dfrac{\text{DC power delivered to the load}}{\text{AC input power from transformer secondary}}$

  and is a figure of merit (a measure of efficiency) to compare rectifiers.
- **Transformer utilisation factor**

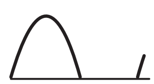
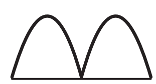
  $$= \frac{\text{DC power delivered to the load}}{\text{AC rating of transformer secondary}}$$

  and is used to determine the necessary rating of a transformer for a given DC load.

  % Voltage regulation $= \dfrac{V_{\text{no load}} - V_{\text{full load}}}{V_{\text{full load}}} \times 100\%$

  and is an indication of how the output voltage of a power supply varies with load.
- The internal resistance of a power supply, $R_{\text{int}} = \dfrac{V_{\text{NL}} - V_{\text{FL}}}{I_l}$, is due to the resistance of the diodes and transformer winding. Where V_{NL} and V_{FL} are voltage during no load and full load respectively.

Comparison of Rectifier Circuits with Resistive Load

Characteristics Parameters	Half-Wave	Full-Wave	Bridge	Three Phase Full-Wave
Secondary voltage line to line $(V_m = \sqrt{2}V)$	V	$2V$	V	V
Number of diodes	1	2	4	6
Peak inverse voltage	V_m	$2V_m$	V_m	V_m
No load DC output V_{DC}	$\frac{V_m}{\pi} = 0.318\ V_m$	$\frac{2V_m}{\pi} = 0.636\ V_m$	$\frac{2V_m}{\pi} = 0.636\ V_m$	$\frac{3V_m}{\pi} = 0.955\ V_m$
Ripple factor	1.21	0.482	0.482	0.055
Ratio of rectification	0.406	0.812	0.812	0.995
Transformer utiliation factor	0.287	0.693	0.812	0.955
DC power available from a 1 kVA Transformer watts	287	693	812	955
Ripple frequency	f	$2f$	$2f$	$6f$
Output waveform of voltage and current				

Note The reading of an AC voltmeter depends upon the type of meter and the waveform across which it is connected.

Filter Circuits for Power Supplies

Electronic filters are electronic circuits which perform signal processing functions, specifically to remove unwanted frequency components from the signal, to enhance wanted ones, or both. *Electronic filters can be classified as*

- passive or active
- analog or digital
- high-pass, low-pass, bandpass, band-reject (band-reject; notch), or all-pass.
- discrete-time (sampled) or continuous-time
- linear or non-linear
- Infinite Impulse Response (IIR type) of Finite Impulse Response (FIR type)

The ripple factor may be determined experimentally by observing the output voltage on an oscilloscope and determining the peak to peak value of the ripple voltage. This is converted to an rms value assuming it to be a sinusoid except in the case of a capacitor filter, in which the ripple will be more triangular and has an rms value of $\frac{V_{r,\,p-p}}{2\sqrt{3}}$.

Key Points

- An inductor filter has a ripple that increases with load resistance and consequently is used only with relatively high load currents.
- The ratio of this rms value to the DC average of the wave is the ripple factor.

Summary of Filter Information (Full-Wave Rectifier)

Parameters	Type of Filter				
	None	L	C	L-Section	π-Section
V_{DC}, no load	$0.636\,V_m$	$0.636\,V_m$	V_m	$V_m(N_O R_b)$	V_m
V_{DC}, load I_{DC}	$0.636\,V_m$	$0.636\,V_m$	$V_m - \frac{4170\,I_{DC}}{C}$	$0.636\,V_m$	$V_m - \frac{4170 I_{DC}}{C}$
Ripple factor r	0.48	$\frac{R_L}{1600L}$	$\frac{2410}{CR_L}$	$\frac{0.83}{LC}$	$\frac{3330}{C_1C_2LR_L}$
Peak inverse	$2\,V_m$	$2\,V_m$	$2\,V_m$	$2\,V_m$	$2\,V_m$

C is in microfarad, L in henry, R_L in ohm, V_m in volt and I_{DC} in ampere.

The ripple from a capacitor filter decreases as the load resistance increases and provides effective filtering only for light loads of 50 mA and less. The capacitor filter provides poor voltage regulation because of the increase in ripple with load current causing a decrease in average voltage.

When the ripple from a capacitor filter is known to be high, in the region of 30%, a more accurate determination of ripple may be made using

$$r = \frac{2410}{2\,CR_L} \text{ instead of } r = \frac{2410}{CR_L}.$$

A capacitor filter is characterised by the high peak current that the diodes must handle due to the capacitor recharging in a very short interval and this current increases with the value of C.

Key Points

- A diode's peak inverse voltage in a half-wave rectifier employing a capacitor filter is $2V_m$.
- L-C filter's ripple factor is independent of load provided a critical inductance, $L_C \geq \frac{R_L}{900}$ is used at all times.
- The use of a bleeder resistor or swinging choke will help to maintain good voltage regulation in an L-C filter.
- Use of an L-C filter makes the selection of filtering components very flexible and requires less capacitance than in a capacitor filter for a given amount of ripple. It also reduces the peak diode current requirement and is generally preferred for load currents in excess of 50 mA.
- Multiple L-C sections or the use of a C-L-C filter improve the filtering process and in some cases the inductor may be replaced by a resistor for light loads.

Clippers

Clipping circuits are used to select that portion of the input wave which lies above or below some reference levels.

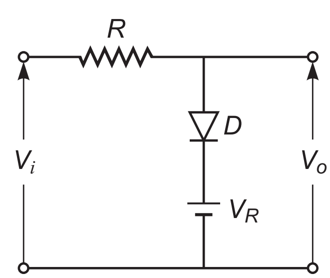
Some of the clipper circuits are discussed below.

Clipper Circuit 1

The circuit shown in figure, clips the input signal above a reference voltage (V_R).

If $V_i < V_R$, diode is reversed biased and does not conduct. Therefore, $V_o = V_i$.

If $V_i > V_R$, diode is forward biased, then $V_o = V_R$.



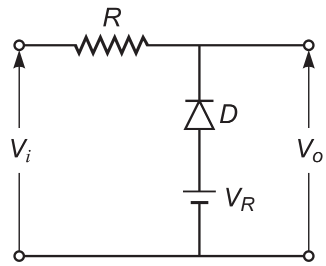
Clipper circuit 1

Clipper Circuit 2

The clipper circuit shown in figure clips the input signal below reference voltage V_R.

If $V_i > V_R$, diode is reverse biased so, $V_o = V_i$.

If $V_i < V_R$, diode is forward biased so, $V_o = V_R$.



Clipper circuit 2

Clipper Circuit 3

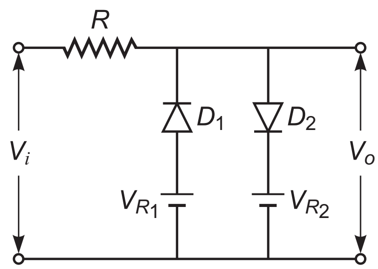
To clip the input signal between two independent levels ($V_{R_1} < V_{R_2}$), the clipper circuit is shown in figure.

The diodes D_1 and D_2 are assumed ideal diodes.

when $V_i \le V_{R_1}, V_o = V_{R_1}$

and $V_i \ge V_{R_2}, V_o = V_{R_2}$

and $V_{R_1} < V_i < V_{R_2}, V_o = V_i$



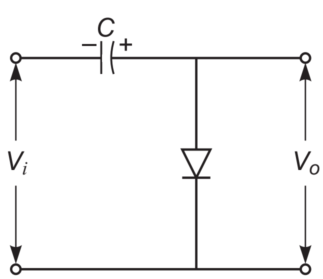
Clipper circuit 3

Clamper Circuits

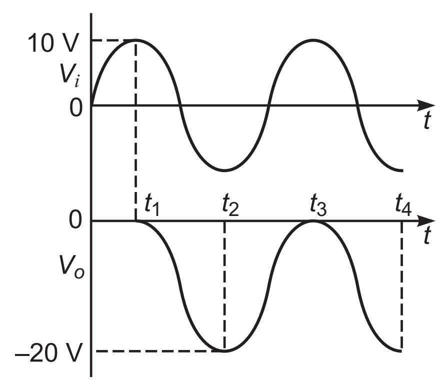
Clamping is a process of introducing a DC level into a signal. For example, if the input voltage swings from –10 V and +10 V, a positive DC clamper, which introduces +10 V in the input will produce the output that swings ideally from 0 V to +20 V. The complete waveform is lifted up by +10 V.

Negative Diode Clamper

A negative diode clamper is shown in figure below which introduces a negative DC voltage equal to peak value of input in the input signal



Negative diode clamper circuit

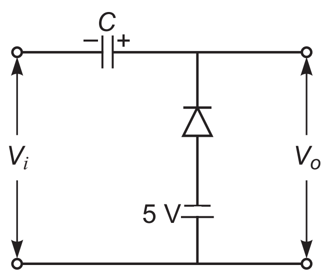


Input and output waveform of negative diode clamper

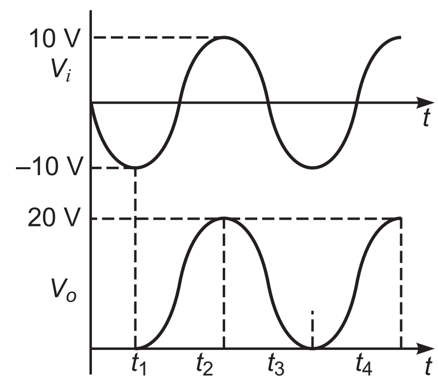
Positive Clamper

The positive clamper circuit is shown in figure, which introduces positive DC voltage equal to the peak of input signal. The operation of the circuit is same as of negative clamper.

During first negative half cycle as V_i rises from 0 to –10 V, the diode conducts. The capacitor charges during this period to 10 V, with the polarity shown.



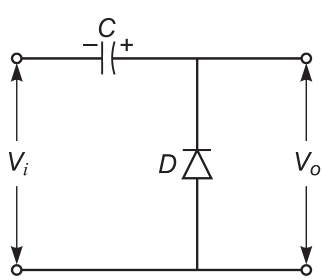
Positive clamper circuit



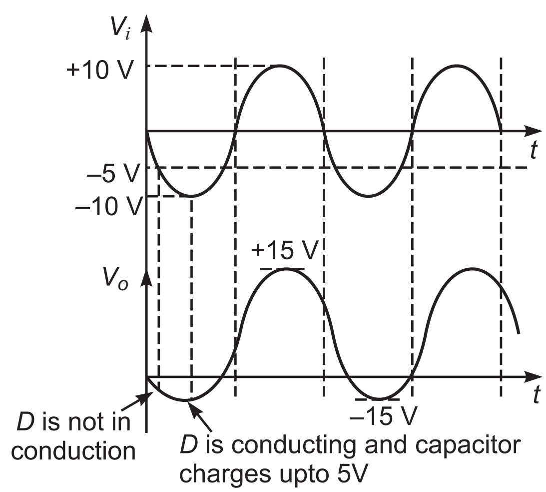
Input and output waveform of positive clamper circuit

After that V_i starts to drop which means the anode of D is negative relative to cathode, ($V_D = V_i - V_C$) thus, reverse biasing of diode and preventing the capacitor from discharging.

In the negative half cycle, when the voltage exceed from 5 V then D conducts. During input voltage variation from – 5 V to – 10 V, the capacitor charges upto 5 V with the polarity shown in figure. After that D becomes reverse biased and open circuited. Then complete AC signal is shifted upward by 5 V.



Positive clamper circuit

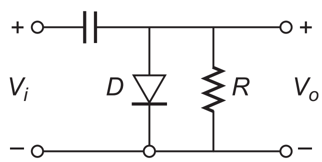


Input and output voltage waveform of positive clamper

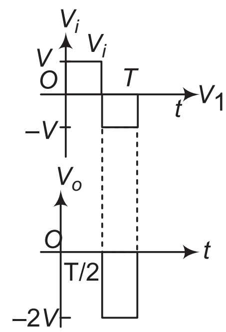
Voltage Doublers

Figure shows the circuit of voltage doubler. The circuit provides a DC voltage, which is double the peak input voltage.

A half-wave or cascade voltage doubler is a diode clamper circuit followed by a rectifier and filter, producing a DC output voltage of $-2V_m$ to $+2V_m$ depending upon diode polarities. The half-wave voltage doubler may be used to provide a high DC output voltage (typically 3kV) or to convert AC into DC in a VTVM application.

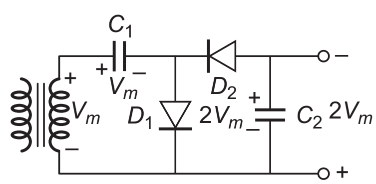


Voltage doubler circuit

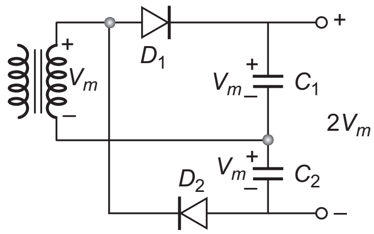


Input and output waveform of voltage doubler

A full-wave voltage doubler uses two diodes to charge two series connected capacitors to a total output voltage of $2V_m$, with a ripple frequency twice that of the input. The full-wave voltage doubler, which does not relay upon a clamping and rectifying action, can be used to provide two DC output voltages of opposite polarity with respect to ground and equal to $\pm V_m$.

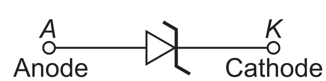


(a) **Half-wave voltage doubler**



(b) **Full-wave voltage doubler**

Zener Diode

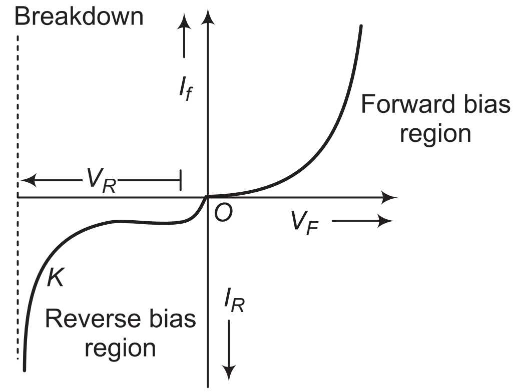


Zener diode symbol

A zener diode is a *p-n* junction operated in the reverse biased mode to take advantage of its sharply defined breakdown voltage. The zener voltage V_Z is specified at some test value of current I_{ZT}, at which the diode will exhibit some dynamic impedance $Z_T = \dfrac{\Delta V_Z}{\Delta I_Z}$ which depends upon the zener voltage of the diode and the level of zener current.

Operation

A zener diode may be used to regulate the load voltage at the value V_Z by acting as a **bypass value** to counteract line voltage or load current variations. Diodes having a breakdown voltage below about 6V rely on the true zener effect (high electric field moves electrons from bonds), while the avalanche effect is responsible for reverse current above 6 V. Zener diodes have a temperature coefficient, α_Z which generally is negative for V_Z below about 6 V but positive above 6V, and is expressed in per cent of V_Z per °C, with the change in zener voltage given by the equation.

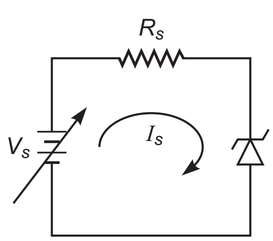


Zener diode characteristics

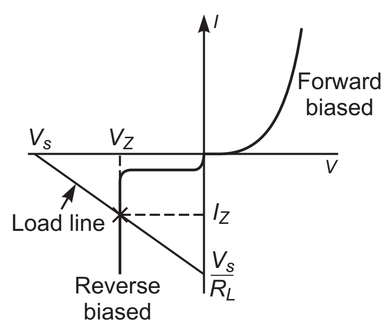
$$\Delta V_Z = V_Z \times \frac{\alpha_Z}{100} \times \Delta T$$

Zener Regulator

When zener diode is forward biased, it works as a diode and drop across it is 0.7 V. When it works in breakdown region, the voltage across it is constant (V_Z) and the current through diode is decided by the external resistance. Thus, zener diode can be used as a voltage regulator in the configuration shown in figure. The load line of the circuit is given by $V_s = I_s R_s + V_Z$.



Zener diode as regulator



V-I characteristics of zener diode

To operate the zener in breakdown region V_s should always be greater than V_Z. R_s is used to limit the current.

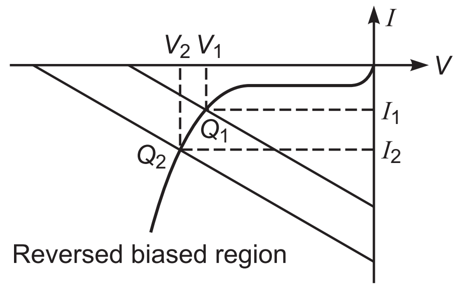
The Zener on state resistance produces more IR drop as the current increases. As the voltage varies form V_1 to V_2 the operating point shifts from Q_1 to Q_2.

The voltage at Q_1 is $V_1 = I_1 R_Z + V_Z$

and at Q_2, $V_2 = I_2 R_Z + V_Z$

Thus, change in voltage is

$V_2 - V_1 = (I_2 - I_1)R_Z;\ \Delta V_Z = \Delta I_Z R_Z$



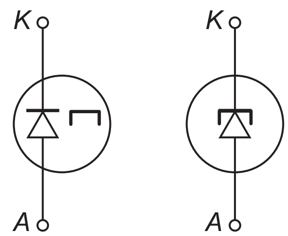
Operating point in *V-I* characteristics of zener diode

Key Points

- Reference zener diodes are available with α_Z as low as 0.0005%/°C.
- The admission of a small amount of mercury gas increases the current capability of a hot cathode gas filled tube.
- A cold cathode or glow discharge diode may be used as a DC voltage regulator in a similar manner to a zener diode.

Tunnel Diode

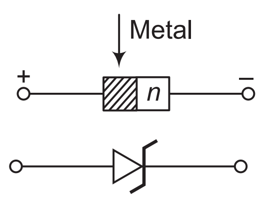
A tunnel diode's characteristics exhibit a **negative resistance region** and it may be used as an **ultra-fast switching device** or in ultra-high frequency oscillators.



Tunnel diode symbol

Schottky Diode

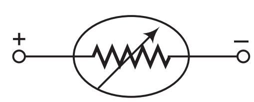
The charge storage problem of a p-n junction diode can be eliminated or minimize in a Schottky diode. This diode is also known as hot carrier diode, hot electron diode or **ESBAR diode** (epitaxial Schottky barrier). In this diode, the barrier potential is set with a contact between a metal and a semiconductor. The rectifying action depends upon the flow of electrons.



Schottky diode symbol

Thermistors

Thermistors are semiconductors which have a high negative temperature coefficient in the order of –4%/° C and may be used for temperature measurement and control. Thermistors may also be used in the self heated mode where they are sensitive to the rate of heat removal and have applications such as flow measurement devices or voltage regulators for DC or AC.



Thermistors symbol

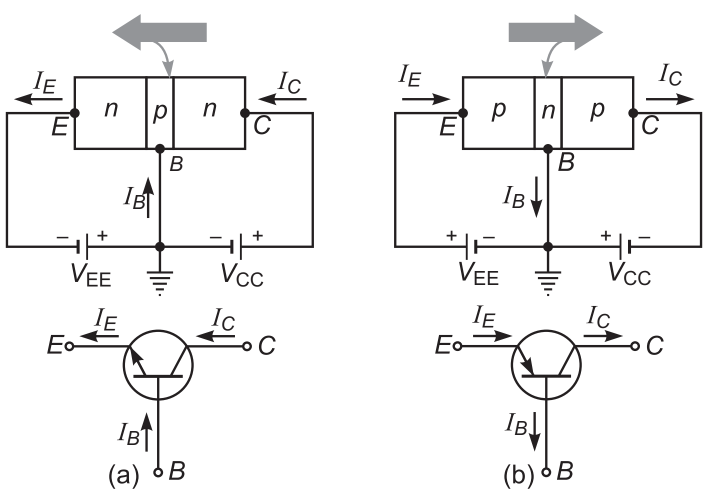
2

Transistor

A transistor is a three terminal device having terminal *i.e.,* emitter, base, collector. It is basically a semiconductor device used to amplify and switch electronic signals and electrical power.

Basic Characteristics of the Transistor

A transistor may be compared loosely with a triode in that the emitter may be thought of as a **non-heated cathode**, the collector as a plate and the base as a grid. Since, a transistor consists of either *p-n-p* or *n-p-n* slices, a very simplified model for biasing purposes comprises two diodes pointing inward or outward respectively.



Notations and symbols used with the common base configuration
(a) ***n-p-n*** **transistor** (b) ***p-n-p*** **transistor**

The transistor input characteristics is essentially that of a forward biased junction, with some dependence upon the transistor's output voltage. The collector or output characteristics for a transistor used in the CE configuration have the collector current *versus* collector voltage curves sloping upward slightly with base current as the controlling parameter.

- The CE as current gain $\beta_{AC} = h_{fe} = \dfrac{\Delta I_C}{\Delta I_B}$ (V_{CE} = constant) while $\beta_{DC} = h_{fe} = \dfrac{I_C}{I_B}$.
- In CB, AC current gain $\alpha_{AC} = h_{fb} = \dfrac{\Delta I_C}{\Delta I_E}$ (V_{CB} = constant)

  while $\alpha_{DC} = h_{fb} = \dfrac{I_C}{I_E}$ and is less than unity

$$\alpha = \frac{\beta}{1+\beta} \text{ and } \beta = \frac{\alpha}{1-\alpha}$$

In either CB or CE action, majority carriers are swept across the narrow, lightly doped base to the collector. This current is controlled by a relatively small base input current that is the result of the forward biased base emitter junction, which accounts for the amplifying action in a transistor.

Key Points

- The permissible operating area of a transistor's characteristics are defined by $I_{c,\,\text{max}}$, the maximum dissipation hyperbola and $V_{(BR)\text{CEO}}$.
- For a transistor used in the CB configuration the collector characteristics consist of practically horizontal lines of I_C *versus* V_{CB} with I_E as the controlling parameter.
- The reverse saturation current in a CB configuration = $I_{CBO} = I_{CO}$, while in a CE configuration it is $I_{CEO} = (\beta + 1)\, I_{CO}$

The Common Base Amplifier

The graphical analysis of a large signal common base amplifier involves the following steps

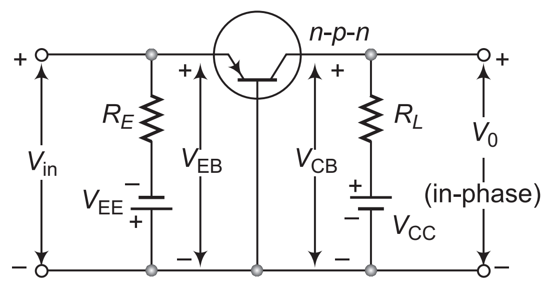
- **Draw the diagram** One end at $V_{CB} = 0$, $I_C = \dfrac{V_{CC}}{R_L}$; the other at $V_{CB} = V_{CC}$, $I_C = 0$.
- Locate the operating point Q, where $I_E = \dfrac{V_{EE}}{R_E}$

- Draw the AC load line through the Q point with a slope given by $\frac{1}{R_E}$, where $R_E = R_L \,||\, R_O$.
- Obtain the current and voltage gains by reading off the corresponding values of current and voltage from the AC load line for a given emitter current drive.

Key Points

- The current gain is less than one, but the voltage gain may be anywhere from 50 to 2000.
- For common base configuration $A_V > 1$ and $A_i < 1$, low R_{in} while high R out

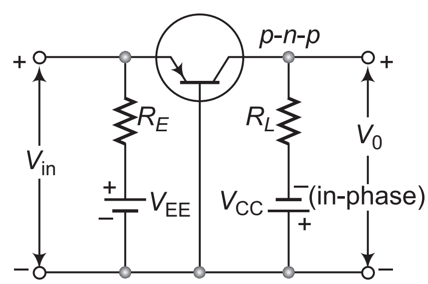
The common base amplifier is used primarily to match a very low source impedance (approximately 20 Ω) to a high load impedance (100 kΩ and up).



Common base amplifier

The AC output power may be calculated from

$$P_0 = \frac{V_{C,\,P-P} \times I_{C,\,P-P}}{8}$$



Basic *p-n-p* and *n-p-n* transistor amplifiers

The conversion or collector circuit efficiency is a measure of how successfully the active device converts DC power to AC signal power and may be close to the maximum value of 25% in a CB amplifier. The output voltage is in phase with the input voltage. Distortion of the input voltage waveform may occur due to the very low input resistance of the amplifier. Very little harmonic distortion is generated in the output of a CB amplifier except at very high values of load resistance.

Alpha (α)

In the DC mode, the levels of I_C and I_E due to the majority carriers are related by a quantity called **alpha** and *it is defined by the following equations*

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

$$I_C = \alpha\, I_E + I_{CBO};\ \text{If }\ I_E = 0\ \text{ then } I_C = I_{CBO}$$

For AC operation where point of operation moves on the characteristic curve

$$\alpha_{AC} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = \text{constant}}$$

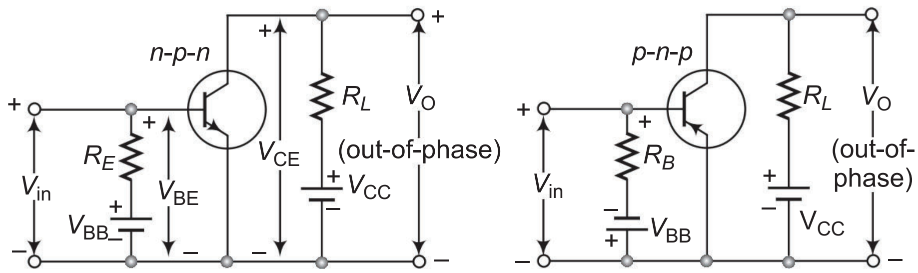
α_{AC} is called as common base short circuit amplification factor.

The Common Emitter Amplifier

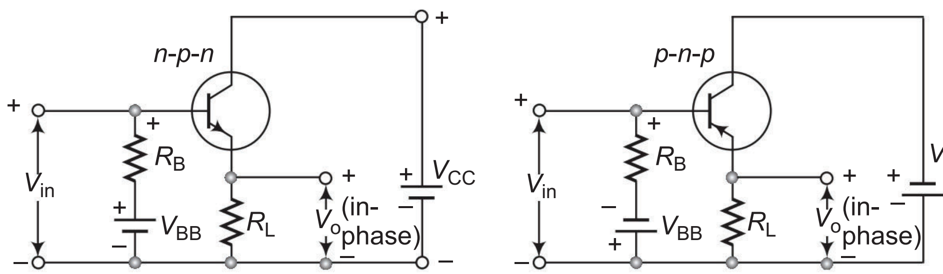
The analysis of a class *A* common emitter amplifier involves drawing the DC load line, locating the operating point at $I_B \approx \dfrac{V_{BB}}{R_B}$, drawing the AC load line through the operating point with a slope given by $\left(-\dfrac{1}{R_E}\right)$, where $R_E = R_0 \,||\, R_L$ and reading off the corresponding values of collector current and voltage from the AC load line resulting from a specified base current drive.

One of the greatest advantages of a common emitter amplifier is the ability to operate from a single supply voltage, using a resistor from V_{CC} to the base to provide bias current.

- A common emitter amplifier enjoys both a voltage and a current gain, with the result that its power gain is usually larger than in either a common base or common collector.
- The input resistance to a common emitter amplifier is in the order to 1 k Ω and is thus much higher than in a common base but lower than a common collector. Its output is inverted with respect to its input voltage.
- The maximum theoretical conversion efficiency of a class A amplifier with a direct coupled resistive load is 25%.
- If the source resistance R_S is large compared with common emitter's input resistance R_i, a condition of current drive results such that base current variation is symmetrical but base emitter voltage is not. For large signal inputs this can cause considerable distortion in the output.



Common emitter $A_V > 1$, $A_i > 1$, A_P very high, medium R_{in}, medium R_{out}



Common collector $A_V < 1$, $A_i > 1$, high R_{in} in, very low R_{out}

- Voltage drive results when, $R_S << R_i$, so that the unequal variations in base current resulting from large signal operation tend to compensate for the insensitive region of the characteristic curves at higher collector current, keeping harmonic distortion lower.
- A transistor's characteristic curve may be displayed on an oscilloscope using a manual control of base current or by using a commercial curve tracer that permits a photograph of the complete set of curves.

Note In normal amplifier operation, the transistor's base emitter junction is always forward biased but the collector base junction is reverse biased.

Beta (β)

It is defined as common emitter forward current, amplification factor.

For DC mode, beta is defined as follows

$$\beta_{DC} = \frac{I_C}{I_B} = h_{fe}$$

For practical devices β ranges from 50 to 400.

For AC situation

$$h_{fe} = \beta_{AC} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = \text{constant}}$$

Comparison between Three Transistor Configurations

S.No.	Characteristics	CB Configuration	CE Configuration	CC Configuration
1.	Input resistance	Very low (40 Ω)	Low (50 kΩ)	Very high (750 kΩ)
2.	Output resistance	Very high (1 MΩ)	High (10 kΩ)	Low (50 Ω)
3.	Current gain	Less than unity	High (100)	High (100)
4.	Voltage gain	Small (150)	High (500)	Less than unity
5.	Leakage current	Very small	Very large	Very large
6.	Applications	For high frequency applications	For audio frequency applications	For impedance matching
7.	Phase shift between input and output	0°	180°	0°

Gamma (γ)

It is defined as current gain of common collector transistor.

$$\gamma = -\frac{I_E}{I_B} = \left|\frac{I_E}{I_B}\right| = \left|\frac{I_C + I_B}{I_B}\right| = \left|1 + \frac{I_C}{I_B}\right|$$

$$\gamma = 1 + \beta$$

Typical value of γ is 50.

Relationship between α, β and γ

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

- Ascending order of α, β and γ $\quad \alpha < \beta < \gamma$
- Physical dimensions of emitter base and collector in decreasing order

  Collector < Emitter < Base

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

- Ascending order of leakage currents $I_{CO} < I_{CBO} < I_{CEO}$

Thermal Stability I : Transistor Biasing

The variation in a transistor's DC collector current with temperature in a common emitter amplifier depends upon β, I_B and I_{CO}, all of which increase with temperature.

The resulting increase in collector current and shift in operating point may cause **clipping** and **distortion** of the applied signal or it may cause **thermal run away**.

Stability Factor (S)

The stability factor S is defined as the rate of change of collector current I_C with respect to the leakage current I_{CO}, with both β and I_B held constant. This instability factor indicates how much change there is in I_C for a given change in I_{CO} and depends upon the bias circuit used.

Stability Factor for Different Configurations

- The stability factor S for a common emitter circuit using fixed bias is $(\beta + 1)$ for either a silicon or germanium transistor.
- A common base circuit has $S = 1$, which is the most stable possible.
- Stabilization methods involve, the reduction of forward bias with temperature increase, to reduce I_B and hence I_C by some means of negative feedback, in various bias circuits.
- Collector to base bias employs a resistor R_B connected from collector to base and provides bias stabilization with

$$S = \frac{(\beta + 1)}{1 + \left(\dfrac{\beta R_L}{R_L + R_B}\right)}$$

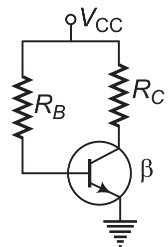
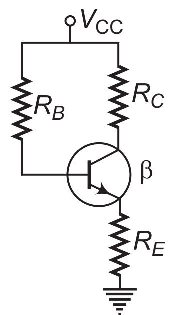
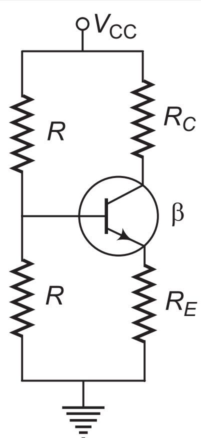
- Collector to base bias may not provide much overall increase in stability in a silicon transistor circuit, since the reduced value of R_B will allow a larger increase in I_B with temperature than with fixed bias.
- Emitter bias consists of the addition of a resistor R_E in the emitter lead, bypassed by a large capacitor C_E.

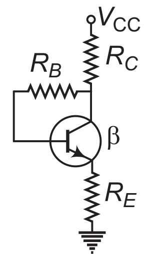
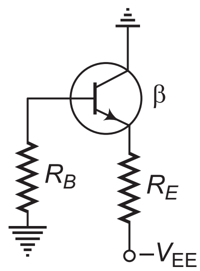
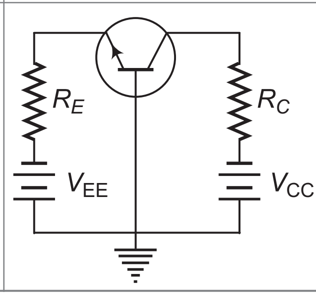
$$S = \frac{(\beta + 1)}{1 + \left(\dfrac{\beta R_E}{R_E + R_B}\right)}$$

Key Points

- Additional stability factors are S' and S'', which indicate the dependance of I_C upon I_B and β, respectively.
- In a silicon transistor, the effect of $I_B\,(S')$ is predominant over $I_{CO}\,(S)$, but the reduction of S will serve to reduce both S' and S''.
- Bias compensation involves the use of diodes or thermistors to compensate for the variations in current instead of using a negative feedback method.

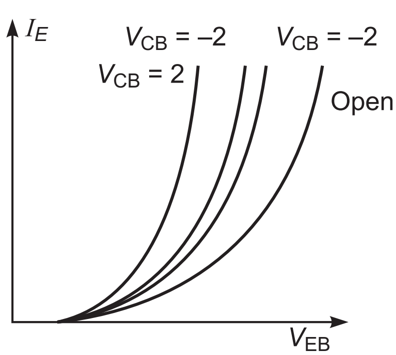
Distinguish between the Biasing Circuit

Type	Configuration	Pertinent Equations
Fixed bias		$I_B = \dfrac{V_{CC} - V_{BE}}{R_B}$ $I_C = \beta I_B$, $I_E = (\beta + 1) I_B$ $V_{CE} = V_{CC} - I_C R_C$
Emitter bias		$I_B = \dfrac{V_{CC} - V_{BE}}{R_B + (\beta + 1) R_E}$ $I_C = \beta I_B$, $I_E = (\beta + 1) I_B$ $R_i = (\beta + 1) R_E$ $V_{CE} = V_{CC} - I_C (R_C + R_E)$
Voltage divider bias		Exact $R_{Th} = R_1 \| R_2$, $E_{Th} = \dfrac{R_2 V_{CC}}{R_1 + R_2}$ $I_B = \dfrac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1) R_E}$, $I_C = \beta I_B$, $I_E = (\beta + 1) I_B$ $V_{CE} = V_{CC} - I_C (R_C + R_E)$ Approximate $\beta R_E \geq 10 R_2$ $V_B = \dfrac{R_2 V_{CC}}{R_1 + R_2}$, $V_E = V_B - V_{BE}$ $I_E = \dfrac{V_E}{R_E}$, $I_B = \dfrac{I_E}{\beta + 1}$ $V_{CE} = V_{CC} - I_C (R_C + R_E)$

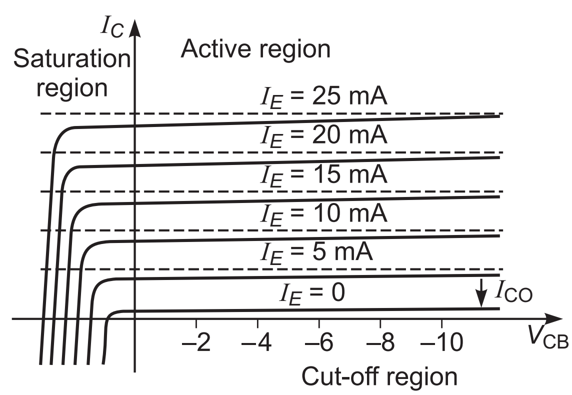
Type	Configuration	Pertinent Equations
Feedback Biasing Circuit Collector feedback		$I_B = \dfrac{V_{CC} - V_{BE}}{R_B + \beta\ (R_C + R_E)}$ $I_C = \beta\ I_B$ $I_E = (\beta + 1)\ I_B$ $V_{CE} = V_{CC} - I_C\ (R_C + R_E)$
Emitter follower		$I_B = \dfrac{V_{EE} - V_{BE}}{R_B + (\beta + 1)}$ $I_C = \beta\ I_B\ , I_E = (\beta + 1)\ I_B$ $V_{CE} = V_{EE} - I_E\ R_E$
Common base		$I_E = \dfrac{V_{EE} - V_{BE}}{R_E}$ $I_B = \dfrac{I_E}{\beta + 1}, I_C = \beta I_B$ $V_{CE} = V_{EE} + V_{CC} - I_E\ (R_C + R_E)$ $V_{CB} = V_{CC} - I_C R_C$

Input and Output Characteristics of Different Configuration

The collector current I_C is completely determined by the input current I_E and the V_{CB} voltage.

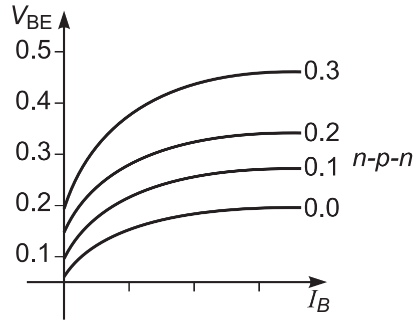


The input characteristics of Common Base (CB)configuration

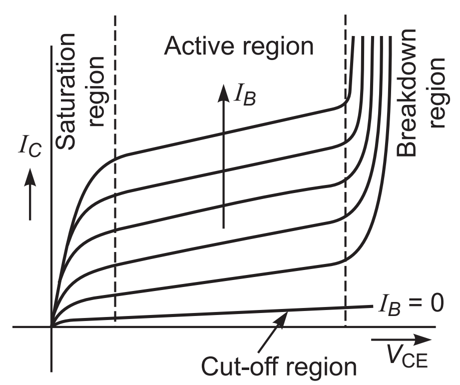


Output characteristics of Common Base (CB) configuration

The curve between I_B and V_{BE} for different values of V_{CE} are shown in figure



Input characteristics of Common Emitter (CE)



Output characteristics of Common Emitter (CE)

The output characteristics are the curve between V_{CE} and I_C for various values of I_B.

Thermal Stability II : Transistor Dissipation

The dissipation capability of a transistor at elevated ambient temperature is reduced by an amount dependent upon the case temperature and the maximum permissible junction operating temperature. This is usually determined by means of a power temperature derating chart.

If the quiescent point in a common emitter amplifier is chosen, so that $V_{CE} < \frac{V_{CC}}{2}$, the amplifier is inherently stable against thermal run away. That is, an increase in temperature will cause a reduction in transistor dissipation.

- The thermal resistance of a transistor, θ is a measure of the opposition to heat flow away from the transistor junction and is measured in °C/ W.

- The power that a transistor may safely dissipate may be determined from power dissipated at collector junctions in watt.

$$P_D = \frac{T_J - T_A}{\theta_{J-A}} \quad \text{or} \quad P_D = \frac{T_J - T_C}{\theta_{J-C}}$$

where, θ_{J-C} is the junction to case thermal resistance and T_C is the temperature of the case of the transistor.

- A heat sink is a metallic heat conducting device placed in close contact with a transistor to increase the dissipation capability of the transistor by reducing the total thermal resistance from junction to ambient θ_{J-A}. Forced air cooling may also be used.
- For transistor mounted in a heat sink, of thermal resistance $\theta_{\text{HS}-A}$, the total thermal resistance from junction to ambient is given by

$$\theta_{J-A} = \theta_{J-C} + \theta_{C-A} \,||\, (\theta_{C-\text{HS}} + \theta_{\text{HS}-A})$$
$$\theta_{J-A} \approx \theta_{J-C} + \theta_{\text{HS}-A}$$

- If the rate at which heat is released in a transistor is not to exceed the rate at which heat can be dissipated, then

$$V_{\text{CC}} - 2I_{CQ}\,(R_E + R_c)\,(S)\,(0.07\ I_{CO}) < \frac{1}{\theta_{J-A}}$$

where, I_{CQ} = No signal collector current

I_{CO} = Output collector current

Key Points

- Thermal fatigue arises from the cyclic stresses that occur in the metal interface between a transistor and the heater on which it is mounted.
- The stresses result from the repeated temperature changes that occur as equipment is turned on and off.
- The thermal cycling rating of a transistor is the number of heating and cooling cycles that a transistor may be subjected to before failure and is a function of case temperature change and power dissipation.

Hybrid Equivalent Circuit for a Transistor

Any single stage transistor amplifier, whether CB, CE or CC may be put in a standard form for small signal analysis so as to be able to identify V_g, R_g and R_L as well as the transistor's input and output terminals. The hybrid equivalent circuit for a transistor consists of a Thevenin equivalent circuit at the input and a Norton equivalent circuit at the output.

The equations relating the input and output voltages and currents in a transistors small signal equivalent circuit are given by

$$V_1 = h_i I_1 + h_r V_2; \ \ I_2 = h_f I_1 + h_0 V_2$$

where, h_i, h_r, h_f and h_0 are the h-parameters and have a second subscript of b, e or c according to the amplifier in question.

h_i = Input impedance
h_r = Reverse voltage ratio
h_f = Forward current transfer ratio
h_o = Output admittance

The h-parameters may be obtained from the transistor's characteristic curve or may be measured experimentally by using changes in current and voltage levels to stimulate AC conditions.

Typical h-parameter values for CB, CE and CC connections are shown in tables given below and are all dependent upon the collector current.

Typical *h*-parameters for A 2N3391 Silicon Transistor, Evaluated at $I_c = 1$ mA, $V_{CE} = 5$ V, $f = 1$kHz and $T_A = 25°$C

Parameter	CE	CC	CB
$h_{11} = h_i$	6,400 Ω	64,00 Ω	26.6 Ω
$h_{12} = h_r$	1.5×10^{-4}	1	0.1×10^{-4}
$h_{21} = h_f$	240	− 241	− 0.995
$h_{22} = h_o$	$6\,\mu\Omega^{-1}$	$6\,\mu\Omega^{-1}$	$0.025\,\mu\Omega^{-1}$
$1/h_0$	166 kΩ	166 kΩ	40 MΩ

Typical *h*-parameters for A 2N404 Germanium Transistor, Evaluated at $I_C = 1$ mA, $V_{CE} = 6$ V, $f = 1$ kHz, $T_A = 25°$C

Parameter	CE	CC	CB
$h_{11} = h_i$	4,000 Ω	4,000 Ω	29.4 Ω
$h_{12} = h_r$	7×10^{-4}	1	7.7×10^{-4}
$h_{21} = h_f$	135	− 136	− 0.993
$h_{22} = h_o$	$50\,\mu\Omega^{-1}$	$50\,\mu\Omega^{-1}$	$0.37\,\mu\Omega^{-1}$
$1/h_0$	20 kΩ	20 kΩ	2.7 MΩ

If the h-parameters are given for one type of amplifier connection but are required for another type, the approximate conversion formulae in may be used.

Approximate Conversion Formulae For Transistor *h*- Parameters

Parameter	CE	CB
h_{ie}	—	$\frac{h_{ib}}{1+h_{fb}}$
h_{re}	—	$\frac{h_{ib}h_{ob}}{1+h_{fb}} - h_{rb}$
h_{fe}	—	$\frac{-h_{fb}}{1+h_{fb}}$
h_{oe}	—	$\frac{h_{ob}}{1+h_{fb}}$
h_{ib}	$\frac{h_{ie}}{1+h_{fe}}$	—
h_{rb}	$\frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$	—
h_{fb}	$\frac{-h_{fe}}{1+h_{fe}}$	—
h_{ob}	$\frac{h_{oe}}{1+h_{fe}}$	—
h_{ic}	h_{ie}	$\frac{h_{ib}}{1+h_{fb}}$
h_{rc}	$1-h_{re} \approx 1$	1
h_{fc}	$-(1+h_{fe})$	$\frac{-1}{1+h_{fb}}$
h_{oc}	h_{oe}	$\frac{h_{ob}}{1+h_{fb}}$

Knowing the *h*-parameters for a transistor, the values for A_i, R_i, A_v,R_o A_{vg} and A_{ig} may be obtained using the exact equations in table by using a second subscript appropriate to the amplifier being analyzed. The value of R_g and R_L are also necessary.

Exact equations for the small signal analysis of transistor amplifiers

$$A_i = \frac{-h_f}{1 + h_0 R_L} \qquad G_0 = \frac{1}{R_0} = h_0 - \frac{h_f h_r}{h_i + R_g}$$

$$R_i = h_i + h_r A_i R_L \qquad A_{vg} = \frac{A_v R_i}{R_i + R_g}$$

$$A_v = \frac{A_i R_L}{R_i} \qquad A_{ig} = \frac{A_i R_g}{R_i + R_g}$$

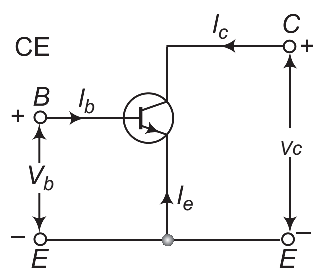
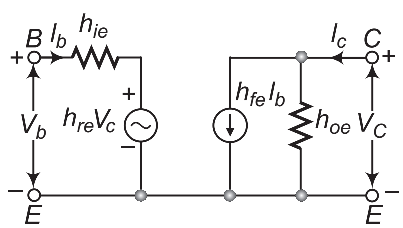
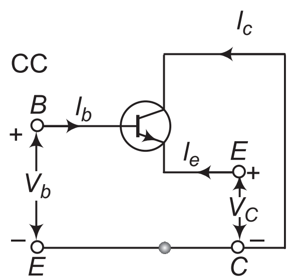
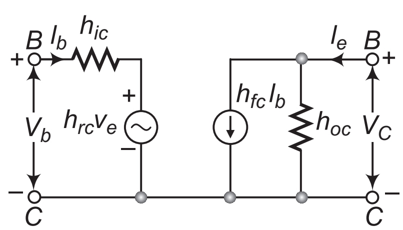
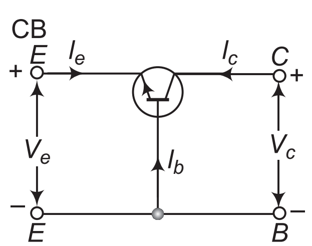
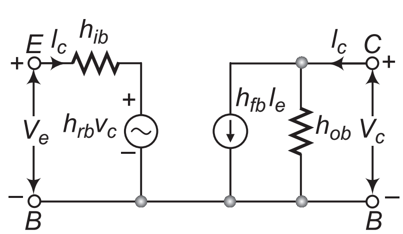
Using a transistor's *h*-parameters, it is possible to dually match R_g and R_L for the Maximum Available Power Gain (MAG) from the transistor. Equations

$$R_L = \sqrt{\frac{h_i}{\Delta h \times h_0}} \qquad \ldots\text{(i)}$$

$$R_g = \sqrt{\frac{\Delta h \times h_i}{h_0}} \qquad \ldots\text{(ii)}$$

where $\Delta h = h_i h_0 - h_0 h_f$

Circuit schematic hybrid model and *V-I*, *h*-parameter equations for the CE, CC and CB amplifier connections.

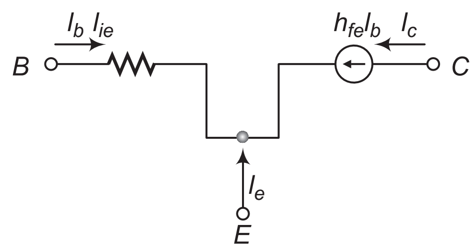
Circuit Schematic	Hybrid Model	Equations
		$V_b = h_{ie} I_b + h_{re} V_c$ $I_c = h_{fe} I_b + h_{oe} V_c$
		$V_b = h_{ic} I_b + h_{rc} V_e$ $I_e = h_{fc} I_b + h_{oc} V_e$
		$V_e = h_{ib} I_e + h_{rb} V_c$ $I_c = h_{fb} I_e + h_{ob} V_c$

A transistor amplifier's characteristics are very dependent upon the values used for R_g and R_L, but generally speaking the characteristics may be summarised as in the given ahead.

Comparison between CB, CE, CC

Quantity	CB	CE	CC
A_i	Low	High	High
A_v	High	High	Low
R_i	Low	Medium	High
R_o	High	Medium	Low

Approximate equations for A_i, R_i, A_v and R_o in terms of CE h-parameter are shown in table and are valid if, $h_{oe}R_L \leq 0.1$



Approximate hybrid equivalent circuit at low frequencies, when at low frequencies, when $h_{oe}\ R_L \leq 0.1$

Note $h_{oe} = h_{re} = 0$

Approximate equations for A_i, R_i, A_v and R_o for CB, CE or CC amplifiers, given in terms of CE h-parameters: To be used only when $h_{oe}\ R_L$ or $h_{oe}\ h_e \leq 0.1$ is given below

Characteristics Parameters	CE	CE with R_e Unbypassed	CC	CB
A_i	$-h_{fe}$	$-h_{fe}$	$1 + h_{fe}$	$\dfrac{h_{fe}}{1 + h_{fe}}$
R_i	h_{ie}	$h_{ie} + (1 + h_{fe}) R_e$	$h_{ie} + (1 + h_{fe}) R_L$	$\dfrac{h_{ie}}{1 + h_{fe}}$
A_v	$\dfrac{-h_{fe}R_L}{h_{ie}}$	$\dfrac{-h_{fe}R_L}{R_i}$	$1 - \dfrac{h_{ie}}{R_i}$	$\dfrac{h_{fe}R_L}{h_{ie}}$
R_o	∞	∞	$\dfrac{R_g + h_{ie}}{1 + h_{fe}}$	∞
R'_o	R_L	R_L	$R_O \parallel R_L$	R_L

Low Frequency Response of the Transistor Amplifier

The value of the emitter bypass capacitor in a single stage CE amplifier must be very large to provide a low value for the lower 3-dB frequency. f_1 equations for f_1 for different circuit conditions are summarized in table.

Summary of the approximate equations for mid frequency voltage gain and lower 3-dB frequency f_1. For various circuit conditions

Condition	$A_{v(MF)} = \frac{V_o}{V_s}$	$A_{v(MF)} = \frac{V_o}{V_i}$	f_1, Hz, for $\frac{V_o}{V_s}$
$R_1 \parallel R_2 >> R_i$, $R_C = 0$	$\frac{-h_{fe} R_L}{R_s + R_{i1}}$	$\frac{-h_{fe} R_L}{R_{i1}}$	$\frac{1 + h_{fe}}{2\pi C_e (R_s + R_{i1})}$
$R_1 \parallel R_2 >> R_i$, $R_C \neq 0$	$\frac{-h_{fe} R_L}{R_s + R_{i2}}$	$\frac{-h_{fe} R_L}{R_{i2}}$	$\frac{1 + h_{fe}}{2\pi C_e (R_s + R_{i2})}$
$R_1 \parallel R_2 \not> \not> R_i$, $R_C = 0$	$\frac{-h_{fe} R_L}{R_s + R_{i3}}$	$\frac{-h_{fe} R_L}{R_{i1}}$	$\frac{1 + h_{fe}}{2\pi C_e (R_s + R_{i3})}$
$R_1 \parallel R_2 \not> \not> R_i$, $R_C \neq 0$	$\frac{-h_{fe} R_L}{R_s + R_{i4}}$	$\frac{-h_{fe} R_L}{R_{i2}}$	$\frac{1 + h_{fe}}{2\pi C_e (R_s + R_{i4})}$

- The electrolyte losses in the emitter bypass capacitor affect the low frequency response somewhat, but have a significant effect on mid frequency gain.
- Low frequency response is also affected by the size of the coupling capacitors, as shown by

$$f_1 = \frac{1}{2\pi (R_S + R_i') C_C}$$

where R_i' is the effective input resistance to the amplifier.

Key Points

- The overall mid frequency voltage gain of an amplifier consisting of cascaded CE stages is the product of the gains of all of the stages. But the overall current gain must take into account the load and biasing resistors, along with the transistor input impedances.
- Analysis of cascaded stages generally proceeds from the last stage back towards the input, by determining A_i, R_i and A_v in that order.

- The overall low frequency response, $f_1(n)$ for n cascaded stages each having the same value of f_1 given by

$$f_1(n) = \frac{f_1}{\sqrt{2^{1/n} - 1}}$$

which shows that the low frequency response is poorer than for a single stage.

- The ability of an amplifier to handle a square wave signal is measured by the sag and is related to the amplifiers lower 3-dB frequency, f_1 by

$$S_{ag} = \frac{V - V_1}{V} = \frac{\pi f_1}{f} \times 100\%$$

where, f is the frequency of the square wave. To provide a low S_{ag} requires a very low value for f_1.

- Cascaded transformer coupled amplifiers designed for maximum power transfer conditions have equal current and voltage gains given by

$$A_i = A_v = \frac{N_1}{N_2} \times \frac{h_{fe}}{2}$$

If equal transistors are rused in each stage

- The lower 3-dB frequency f_1, for a transformer coupled amplifier is restricted by the transformer's primary inductance L_p , as given by

$$f_1 = \frac{R}{2\pi L_p}$$

where R is the effective resistive portion of the transistor's load and output resistance in parallel with L_p.

- In order for a transformer coupled amplifier to handle a pulse of duration t_d with less than a given amount of S_{ag}, the transformer must have a minimum primary inductance is given by

$$L_p = \frac{Rt_d}{S_{ag}}$$

High Frequency Response of the Transistor Amplifier

The hybrid-π model of a transistor at high frequencies includes the capacitive effects of the p-n junction and involves a base spreading resistance that creates a virtual base.

The transistor's high frequency parameters are given in equations below and include the transistors transconductance.

- The parameters for the approximate hybrid-π model may be obtained from the following equations. (Numerical values shown are for a 2N 2218 silicon transistor with $h_{fe} = 50$, $h_{ie} = 1\ k\Omega$, $f_T = 300$ MHz, $C_{ob} = 4$ pF, $I_e = 1.5$ mA, $T = 22°$ C.

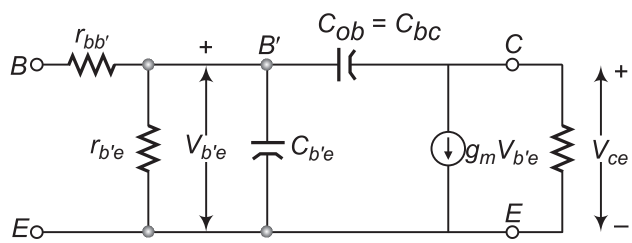
$$g_m = \frac{I_C}{V_T} = \frac{I_c\ (\text{mA})}{26} = 58\ \text{mA/V}$$

$$r_{b'e} = \frac{h_{fe}}{g_m} = 860\ \Omega$$

$$r_{bb'} = h_{ie} - r_{b'e} = 140\ \Omega$$

$$c_{b'c} = c_{ob} = 4\ \text{pF}$$

$$C_{b'e} = \frac{g_m}{22\ f_T} - C_{b'c} = 27\ \text{pF}$$



Approximate high frequency model with resistive load

$$C_{b'c} = C_{o\,b} = 4\,\text{pF}$$

$$C_{b'e} = \frac{g_n}{2\pi\, f_t} - C_{b'c} = 27\,\text{pF}$$

Note $C_{b'c}$ is usually given in the transistor manual as C_{ob} and is the CB open circuit output capacitance $C_{b'e}$ may be given by the manufacturer or it may be calculated using the equation given. f_T is the frequency at which the CE short circuit current gain drops to unity.

- The transistor's short circuit current gain varies with frequency and is characterised by the α cut-off and β cut-off frequencies, where the current gain drops by 3 dB from the value at mid frequencies in a CB and CE connection respectively.
- An important high frequency characteristics of a transistor is f_T, the gain bandwidth product and is defined to be the frequency at which a common emitter's short circuit current gain drops to unity.

- Cascaded CE stages operating at high frequency have a reduced overall bandwidth given by

$$f_{2(n)} = f_2 \sqrt{2^{1/n} - 1}$$

where, n is the number of stages and f_2 is the bandwidth of each stage.

- The ability of an amplifier to reproduce a square wave input with a low rise time, t_r, is directly proportional to the bandwidth f_2. That is

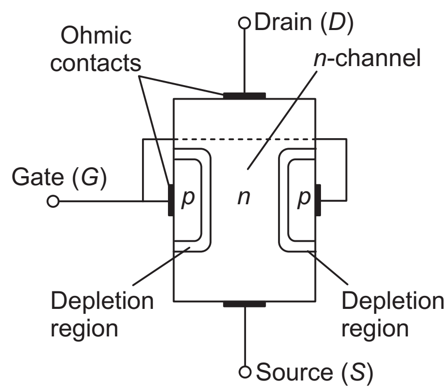
$$t_r = \frac{0.35}{f_2}$$

Key Points

- When a transistor is operated at high frequencies with a resistive load, the collector to base junction capacitance appears as an enlarged value of capacitance at the input, thus reducing voltage and current gain below the values expected at the α and β cut-off.
- The high frequency response of a transformer coupled amplifier is usually limited entirely by the transformer's leakage inductance and distributed capacitance, which creates a series resonant effect.
- Transistor noise is usually measured as a spot noise figure, NF or as the average noise figure $\overline{\text{NF}}$, with typical values between 0.5 and 5 dB depending upon the source resistance, collector current and frequency.

Field Effect Transistor Amplifiers

The Junction Field Effect Transistors (JFET) is a voltage controlled device which has a high input resistance (in the order of 100 MΩ), a high degree of isolation between input and output and a low noise figure. The main disadvantage of a JFET is its relatively low gain bandwidth product, due to the **junction capacitive effects**.



Junction Field Effect Transistor (JFET)

- Both n and p channel JFET exist, with negative and positive gate voltages respectively, controlling the drain current from the source.
- The FET got its name from the electric field that extends into the channel providing the effect of a decrease in conductivity through the transistor.
- The FET's common source characteristics may be divided into a channel ohmic region and a pinch off region.