BarCharts, Inc.®

WORLD'S #1 ACADEMIC OUTLINE

Quick Study® ACADEMIC

ELECTRONICS 1 PART ONE

PART 1 of FUNDAMENTALS OF ELECTRONIC DEVICES AND BASIC ELECTRONIC CIRCUITS

CIRCUITS & SYSTEMS: BASIC DEFINITIONS

ELECTRONIC CIRCUITS

An electronic circuit is an information-bearing signal processing network formed by interconnections of passive components and/or active devices.

- **Passive Components**: Resistors, capacitors and inductors
- **Active Devices** (or energy source devices) - transistors, metal-oxide semiconductors, etc.

- **Electronic System:** An arrangement of components (passive elements and/or active devices) with a specified input signal producing a defined output signal.
- **Signal Processing**: Functionally, electronic circuits and systems *process* the input signal. Common processing includes:
  - **Amplification** (magnification)
  - **Integration**
  - **Differentiation**
  - **Filtering:** Changing the relative magnitude of different frequency components of the signal
  - **Rectification:** Selection/rejection of a particular part of the signal on polarity basis
- **Other Electronic Circuits are**:
  - **Harmonic oscillators**: produce *sinusoidal wave forms* of desired frequency; or, termed as **relaxational oscillators**, their other versions can produce nonsinusoidal wave forms such as square, impulse, triangular, etc.
  - **Digital circuits**: specific circuits which handle *pulsed wave forms*; they can perform computational operations such as addition, subtraction, multiplication, etc. in binary form.

ELECTRICAL SIGNAL

- **Electrical signal** is an information-bearing electrical entity (such as voltage or current) derived from a transducer (e.g. voice signal voltage delivered by a microphone). **Signal processing** refers to processing the electrical signal in a predetermined manner so as to enable the recovery of the information contained in it. Signal sources can be represented by (Fig.1):

- **Thevenin's equivalent circuit**: A signal source represented by a voltage generator $v_s(t)$ in series with a source (internal) resistance R_s.
- **Norton's equivalent circuit**: A signal source is depicted by a current generator with a shunt resistance R_s.

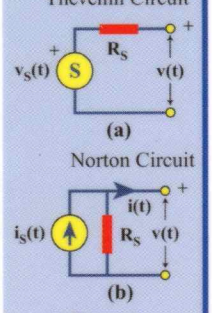

Figure 1

- Electrical signal is characterized by: **amplitude**, **frequency** and **phase** parameters. The signal is a time-varying function representing the wave-shape as a function of time. It can be **periodic** (with a definite period T, so that frequency $f = 1/T$); or, it can be **aperiodic**.

A complex waveform consists of several wave forms of different frequencies. A periodic signal with a complex envelope (of waveform) has a **discrete spectrum** of harmonic (sine/cosine) wave forms of magnitudes as decided by Fourier series expansion. An aperiodic waveform has a **continuous spectrum** of harmonic components as per Fourier integral transform.

- Examples of signal representation by Fourier series and Fourier transform: A periodic, continuous, non-sinusoidal signal can be represented by a superposition of infinite number of harmonic (sine and/or cosine) wave forms: e.g. Fourier expansion of a square wave: (see Fig.2)

$$v(t) = \frac{4A}{\pi} \sum_{m=0}^{\infty} \frac{\sin(n\omega_0 t)}{n}$$

$n = (2m+1)$, $\omega = 2\pi/t = 2\pi f =$ Fundamental angular frequency

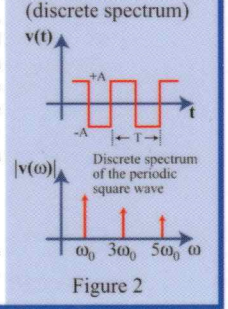

Figure 2

An aperiodic waveform representing an arbitrary time-varying signal can be depicted by Fourier transform (Fig.3):

- Fourier series and Fourier transform representations of signals enable a description of the spectral components (frequency components) constituting the signal as shown.

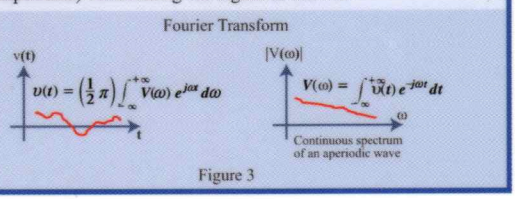

Figure 3

SIGNAL DISTORTION

Electrical signal processed by a circuit may undergo three types of distortions: amplitude distortion, frequency distortion and phase distortion.

- **Amplitude distortion**: Also known as harmonic or nonlinear distortion, this is caused by the nonlinear transfer function characteristics of the components/ devices in the circuit (Fig.4). That is, an input signal $e_i(t)$ will be delivered at the output of the circuit as:

$$e_0(t) = a_1 e_i(t) + a_2 e_i^2(t) = a_3 e_i^3(t) + \ldots,$$

where a_1, a_2, a_3, ..., etc. are the coefficients of the nonlinear transfer function. If $e_i(t)$ is a single frequency signal, the output will contain higher harmonic components due to square, cubic terms etc. As a result, the output signal wave shape (envelope) will be seen distorted (envelope distortion).

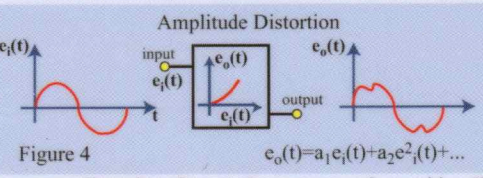

Figure 4

$e_o(t) = a_1 e_i(t) + a_2 e_i^2(t) + \ldots$

- **Frequency distortion**: Due to the presence of capacitive **(C)** and/or inductive **(L)** elements in the circuit, a complex signal (composed of a spectrum of several frequency components) will face filtering of its components, inasmuch as the reactances offered by **C** and/or **L** elements are frequency-dependent. As a result, the transfer function relating the input and the output would vary as a function of frequency.

Example, a voltage amplifier which is expected to provide a constant voltage gain (output voltage to input voltage ratio) for any frequency of the input signal may yield a varying gain *versus* frequency plot as shown (Fig.5). The drooping of **A** (gain) *versus* **f** (frequency) curve at high (HF) and low (LF) frequencies is, for example, due to low reactance of the shunt capacitance C_P and high reactance of series capacitance C_S respectively.

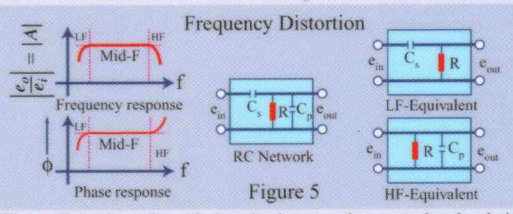

Figure 5

- **Phase distortion**: Considering the input and output signals, their relative phase angle is again decided by **C** (and/or **L**) elements present in the circuit. Hence, their phase difference is frequency-dependent. For a complex input signal (with a spectrum of frequency components), the phase angle (ϕ) of the transfer function of the circuit when plotted against frequency is typically as shown (Fig.5). Except over a midrange of frequencies, ϕ varies at low and high frequencies due to series and shunt capacitive elements of the circuit respectively (or respectively due to shunt and series inductive elements, if present).

NOISE

Noise: An undesired entity introduced into the signal in the circuit either caused by various circuit elements or electromagnetic interference coupled to the circuit from exterior sources. Noise is a random fluctuation and affects/corrupts the quality of the signal. For preserving the signal characteristics along the circuit, the noise level should be minimized (high **signal-to-noise** ratio).

CIRCUIT DEVICES

DIODES: IDEAL AND PRACTICAL VERSIONS

- A **diode** is a two terminal, unilateral device. Ideally, it conducts electricity in one direction and does not allow the current to flow in the opposite direction. Compared in Fig.6 are the current **I** - voltage **V** characteristics of a bilateral element (such as a resistor **R**) and of an ideal diode.
- A **practical diode** (such as a semiconductor diode) has a nonlinear **V-I** relationship close to being exponential in the **forward bias** with its anode kept at positive (+) potential relative to its other (cathode) terminal. In the **reverse bias** (anode being at negative potential with respect to cathode), there is a small reverse current (unlike in an ideal diode, wherein, the reverse current is equal to zero). Also, in the forward bias, invariably, there is small voltage V_γ (known as **threshold or cut-in voltage**) until which, there is no current conduction in practical diodes.

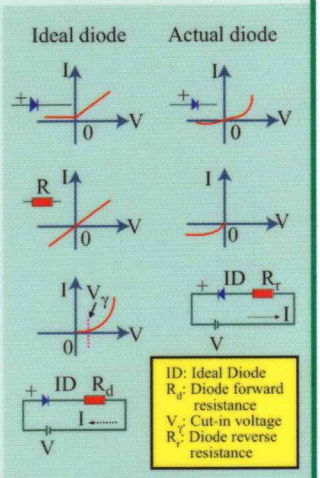

Figure 6

DIODES AS CIRCUIT ELEMENTS

- **Basic applications of diodes**:
  a) Switching element,
  b) rectifier,
  c) waveform clipper,
  d) limiter
  e) detector or demodulator.
- **Switching element**: Ideally, a diode is a short-circuit element under forward bias and behaves as an open circuit when reverse biased. Its state is set by the breakpoint at $v = 0$ and $i = 0$. For $v = 0$, $i > 0$ correspond to **on-state**. For $v < 0$, $i = 0$ correspond to **off-state** as illustrated (Fig.7).

R_{eq} = Equivalent representation of the switch
R_d = Forward resistance of the diode
R_r = Reverse resistance of the diode
FB = Forward bias
RB = Reverse bias

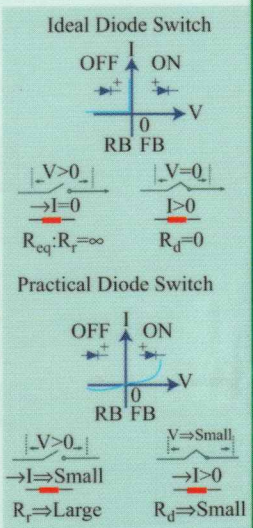

Figure 7

- **Rectifier**: A diode can be used to rectify the alternating current waveform (with bipolarity) to a one directional waveform. A simple **half-wave rectifier** is illustrated in Fig.8. The current flows through the load resistor R_L only during positive half-cycle as the diode conducts (forward biased). Hence voltage (e_o) across R_L is one-directional or rectified.

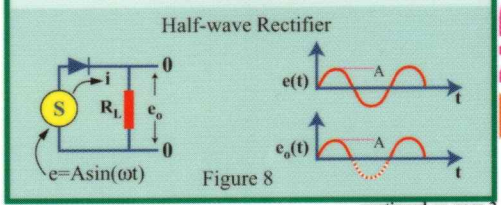

Figure 8

continued on page 2

- A **diode circuit** can be designed to clip-off the voltage above a certain value. That is, the circuit will limit voltage inputs to a maximum level. The clipper circuit and waveform clipping are as illustrated (Fig. 9).

Diode Clipping Circuit

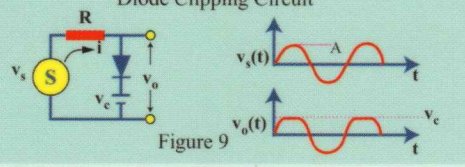

Figure 9

- A diode bilateral **limiter** is an extension of the clipping circuit (Fig.10).

Diode Bilateral Limiter

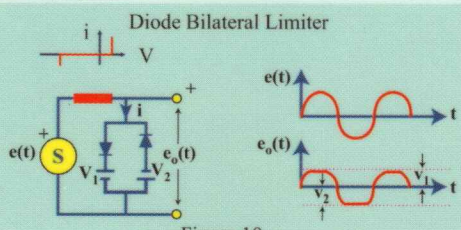

Figure 10

- **Demodulator or a detector**:This circuit is used to recover an envelope waveform (of low frequency) which modulates the amplitude of a high frequency waveform as illustrated (Fig.11). This process is called **detection** (of a signal modulated on a high frequency carrier) in radio systems.

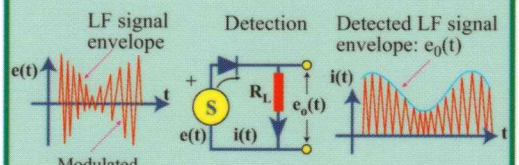

Figure 11

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SEMICONDUCTOR DIODES

DEFINITIONS

*In solid-state materials, the distribution of electrons in the outermost orbit in the atoms (termed as **valence electrons**) decide the property of the material as of being a **conductor**, an **insulator** or a **semiconductor**.*

- **Conductors**: In conductors (such as **Cu** or **Ag**), there exists a cloud of free-electrons at temperatures above absolute zero formed by weakly bound valence electrons in the outermost orbits of the atoms. When subjected to an electric field force (by applying a voltage across the material), these free-electrons will flow along the field gradient, constituting an **electric current**. With conductors, the valence band and the conduction band overlap as illustrated in (Fig.12).
- **Insulators**: In insulators (dielectrics) such as polyethylene, the valence electrons are tightly bound to the parent nuclei of the atoms and are hardly available as mobile electrons to constitute a current flow even at room temperatures. That is, there is a wide **forbidden gap energy** prevailing between the **valence** and the **conduction bands** (Fig.12).
- **Semiconductors**: With semiconducting materials (such as **Si** and **Ge**), the forbidden gap energy is small. Therefore, some free-electrons are available in the conduction band for current conduction (but not to a large extent as in conductors) at room temperature.

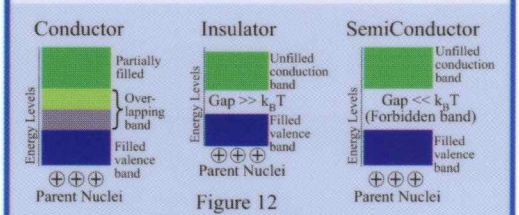


Figure 12

PN JUNCTION

A **PN junction** is constituted by placing together a P-type and an N-type semiconductor.This structure represents a simple semiconductor diode. When a PN junction is constituted, the **majority carriers**, namely electrons of the N-region and the holes of the P-region could combine at the junction forming a **depletion layer** with almost nil free carriers in the vicinity of the junction. The atoms depleted of the electrons and holes remain in this depletion region, as **ions** (Fig.14). Also PN junction formation allows the minority carriers (electrons of P-region and holes of N-region) to migrate across the junction and combine with ions in the respective regions.

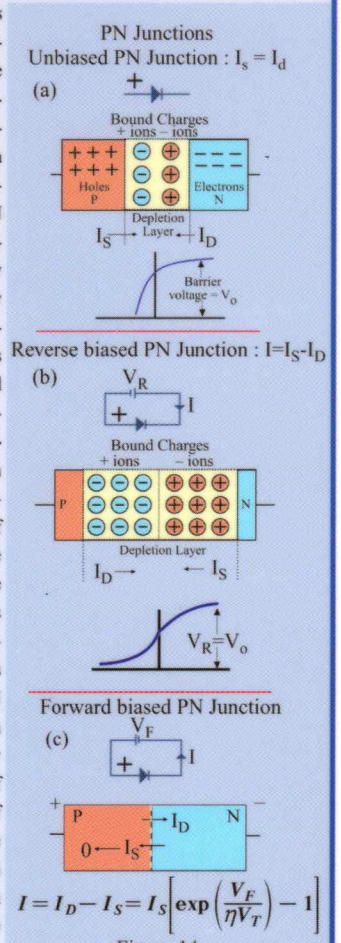


Figure 14

INTRINSIC AND EXTRINSIC SEMICONDUCTORS

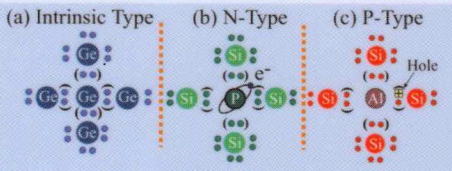


Figure 13

- The atoms of semiconducting **fourth group elements** (**Si** and **Ge**) have four valence electrons which are shared by neighboring atoms constituting a strong **covalent bonding** (see Fig.13a) which limits the current conduction to available free-electron flow (at a given **T**, temperature) as facilitated by the thermal energy induced transfer of electrons from valence band to conduction band. This corresponds to **intrinsic** (pure) state of semiconductors. (Fig. 13a).
- A semiconductor (such as Si and Ge) can also be "**doped**" with a fifth or a third group element to control its electrical conductivity. When a fifth group element (say **P**, **Sb** or **As**, with 5 valence electrons) is added, the covalent structure is completed with 4 valence electrons of P, and the available as an excess free-electron enhancing current conduction.
- **N-Type or donor impurity**:The added fifth group element in the doped semiconductor is called an N-type extrinsic semiconductor (N depicting the negative excess charge carrier introduced).
- Addition of a third group element (such as B, Ga, In) curtails a part of covalent bonding (Fig.13c) due to valency (or the available valence electrons) being only three. The vacant space or the "**hole**" created in the bonding structure is equivalent to a positive change, ready to accept an electron. Filling of a hole, by an electron, generates hole at a different site. Proliferation of the hole represents equivalently a positive charge carrier movement. Hence, a third-group element doped semiconductor is designated as a **P-type extrinsic** material, P denoting the excess positive charge carrier equivalence of the holes introduced. P-type dopants are known as **acceptors**.

JUNCTION DIODES

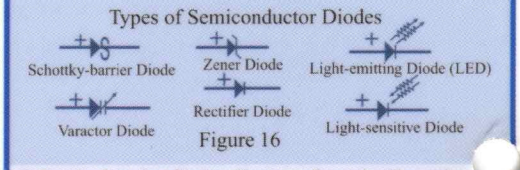


Figure 16

- **Schottky-barrier diodes**: Contact of metal with semiconductor may create a junction with properties similar to PN-junction. **e.g.**: Al or Pt may act as acceptor material when in contact with N-type silicon. Merits: No charge storage is involved facilitating fast switching, and very low forward drop = 0V cut-in threshold is obtained.
- **Photo diodes**: Reverse saturation current depends on generation of **hole-electron pairs** by the average thermal energy of the crystal. This current can be increased further by light illumination. Diodes with the provision of transmitting light flux to reach the junction are called photo diodes.
- Varactor or Varicap diodes: The junction transition capacitance C_j varies with reverse bias voltage V_R.

$$C_j = C_0\left(1 + \frac{V_R}{V_0}\right)^{-m} \qquad V_0 = \left(\frac{k_B T}{q}\right)\log_e\left(\frac{N_A N_D}{n_i^2}\right)$$

where N_A & N_D: acceptor and donor doping concentrations; n_i intrinsic carrier concentration, $V_0 \approx 0.58V$ at room temperature; $m = 1/2$ (abrupt junction), 1/3 (graded junction); $C_j = 10pF$ to 100pF for $V_R = 3V$ to 25V. Forward bias is avoided due to high shunt conductance.

BIASING A SEMICONDUCTOR DIODE

- **No applied bias**: This refers to open-circuit condition in which there is a voltage drop across the depletion region called **barrier potential** constituted by the depletion region charges. The extent of cross diffusion of majority carrier across the depletion region forming the diffusion current I_D is decided by the barrier voltage level. Apart from I_D, there is also a thermally generated **minority carrier** current (I_S). Under open circuit, no external current flows, since an equilibrium is maintained by $I_D = I_S$.
- **Under reverse bias** due to V_R applied, the minority carrier current I_S (which is independent of the barrier voltage) remains constant. But the diffusion current I_D will be reduced since V_D gets increased by $V_D + V_R$. Hence the equilibrium current is: $I_S - I_D = I_S$ (**Reverse saturation current**).

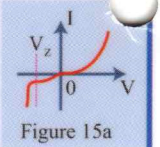


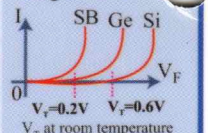
Figure 15a

The reverse voltage V_R, uncovers more ions in the depletion region and widens its width and depletion large charge concentration. Hence, the corresponding depletion layer capacitance C_j (junction capacitance) is inversely proportional to V_R, $C_j = K/V_R^n$, ($n = 1/3$ to 4 for different types of junctions fabricated).With large reverse voltage V_R, depletion layer electric field increases whose strength can rupture the covalent bonding creating electron-hole pairs. This is a regenerative process (**Zener effect**) indicated by a large increase in current at a constant reverse voltage $V_R = V_Z$ ($< 5V$). Under this breakdown, the current is limited only by an external resistor (Fig 15a).

Another mechanism of breakdown at $V_R > V_Z$ is due to acquired kinetic energy by minority carriers which can break covalent bonds by collision. This ionization process is called **avalanche breakdown** which is irreversible. Again current can be limited only by an external resistor.

- **FORWARD BIASED PN JUNCTION**: The forward bias voltage V_F effectively decreases V_D thereby facilitating $I_D > I_S$. Therefore, at steady state external current $I_D - I_S$ flows. I_D is decided by the extent of thermal energy $V_T = k_B T/q$ (k_B: Boltzmann constant, T: temperature and q: electronic charge). Corresponding to the reverse saturation current I_S, $I_D = I_S \exp(V_F/\eta V_T)$. η is a scale factor such that $1 < \eta < 2$ (1 for Ge, 2 for Si). The forward I_F *verses* V_F characteristics is therefore: $I_F = I_S[\exp(V_F/\eta V_T) - 1]$, $V_T \approx 0.026V$ for silicon at room temperature (Fig.15b).
- **CUT-IN VOLTAGE**: Semi-conductor diode has a threshold forward bias voltage below which the current is negligibly small. This threshold is called cut-in voltage. Typically, at room temperature $V_{cut\text{-}in} = V_\gamma \approx 0.2$ for Ge, ≈ 0.6 for Si and ≈ 0 for **Schottky-barrier** diodes (Fig.15b).

Figure 15b



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RECTIFIER CIRCUITS

- **High speed switching diodes**: Under forward bias, narrow depletion layer gives rise to a high transition (junction) capacitance C_j. In addition, diffusion of large minority carriers under forward bias injected across the junction causes a charge storage effect, attributing a diffusion capacitance C_D. Upon switching conditions (ON to OFF) forward-to-reverse bias changing warrants the decay of injected minority carriers. This decay rate is controlled by $(C_D + C_j)$. Only after a time t_s (storage time) in which the excess charge is removed, diode voltage drops to zero until reverse saturation is reached at t_r. The difference $(t_r - t_s)$ is called **transition time** which limits high speed switching. (In OFF to ON switching, a similar process takes place except that the time involved is negligible since stored charge is very small). PN-junction diode switching characteristics are decided by the RC time constants specified by the bias conditions.

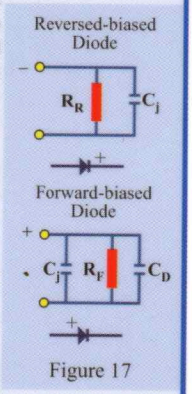


Figure 17

- **Light-emitting diodes (LED)**: When injected minority carriers in a forward-biased PN junction recombine, energy is released. In Si and Ge, it is in the form of heat. But in GaAs, it is of photon energy at red, yellow or green wavelengths depending on certain impurities added.
- **Rectifier diodes**: These are intended for ac-to-dc conversion. They are power diodes rated on the basis of **power dissipation** considerations and **reverse breakdown voltage** rating.
- **Thermal rating**: Specified by maximum allowable junction temperature (typically, 100°C for Ge and 175°C for Si devices). Power dissipation capability of diodes can be increased by using **heat sinks**.

FULL-WAVE RECTIFIER (WITH A CENTER-TAPPED TRANSFORMER)

As shown in Fig.19a, the center-tapped transformer provides two secondary voltages (with respect to the grounded center-tap) with 180° phase difference. This facilitates the diodes D_1 and D_2 to conduct alternatively over each half cycle. With a capacitor shunting the load

R_L, $R_L = \dfrac{V_{dc} + \Delta V}{2}$ where $\Delta V = \dfrac{V_s}{f \times R_L \times C}$;

f = 2x frequency applied a.c.; Ripple factor = $\dfrac{(\Delta V)_{RMS}}{V_{dc}}$;

Peak inverse voltage = 2× peak secondary voltage.

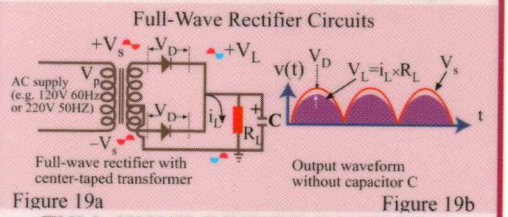


Figure 19a Figure 19b

FULL-WAVE BRIDGE RECTIFIER

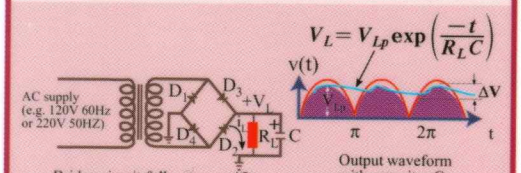


Figure 20a Figure 20b

As shown in Fig.20a, this does not need a center-tapped transformer, but requires 4 diodes. Depending on the instantaneous voltage polarities at the secondary winding ends, diode pairs (D_2, D_3) or (D_1, D_4) conduct, facilitating a full-wave rectified waveform across R_L, with the current flow directions as shown.

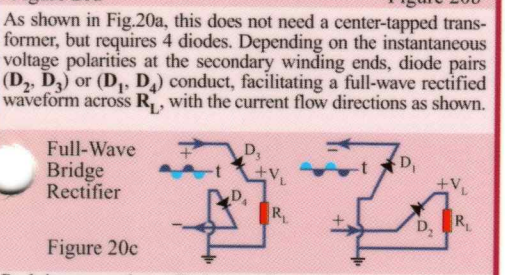


Figure 20c

Peak inverse rating = Peak secondary voltage

Ripple characteristics: Same as those of full-wave rectifier with center-tapped transformer.

HALFWAVE RECTIFIER

- In Figure 18a the transformer **TR** has a primary coil of N_P turns and a secondary coil of N_S turns wound on an iron core. The a.c. excitation at the primary is coupled to secondary via magnetic coupling mediated by the iron core.

The diode conducts during positive half-cycle of secondary voltage as decided by the forward diode characteristics. *During negative half cycle, the diode does not conduct.*

The load current $i_L = \dfrac{V_s - V_f}{R_s + R_d + R_L}$ for $V_s > V_f$; otherwise $i_L = 0$). Here $V_f = V_D$ is the forward voltage drop across the diode (≈**0.7V** for Si). R_S is the secondary winding resistance, R_d = Diode forward resistance; R_L = Load resistance.

HALFWAVE RECTIFIER WITH A CAPACITOR FILTER

- In Figure 18b the capacitor across R_L is charged to V_L (peak) during positive half-cycle and discharges through R_L during negative half-cycle with a time constant $= R_L C$. V_L is a superposition of a d.c. voltage $\approx V_L - \dfrac{\Delta V}{2}$ and a **ripple voltage** (approximately of triangular shape) of peak value $\Delta V = \dfrac{(V_s - V_f) \times T}{\tau}$, $= R_L C$ where $T = \dfrac{1}{f}$;

f = frequency; RMS value of $V = \dfrac{\Delta V}{\sqrt{3}}$.

- **RIPPLE FACTOR**

$$\frac{\triangleq V_{Ripple\ (RMS)}}{V_{DC}} \Rightarrow \frac{\left(\frac{\Delta V}{\sqrt{3}}\right)}{(V_L - 0.5\Delta V) \times 100\%}$$

Given a specific ripple factor, V is calculated at a given load voltage. Hence C is chosen such that:

$$C \geq \frac{\left(V_{dc}/R_L\right)}{(f \times \Delta V)}$$

- **PEAK-INVERSE VOLTAGE**: (of a half-wave rectifier): During negative half-cycle, the total voltage drop (reverse bias) across the diode = $V_{s(peak)} + V_{dc} \approx 2V_{s(peak)}$. Hence, the diode should be chosen such that its breakdown voltage >> $2V_{s(peak)}$.
- **DIODE DISSIPATION RATING**: Maximum diode dissipation is decided by (maximum load-current)^2 × diode forward resistance. Diode power rating should be well in excess of this dissipation level.

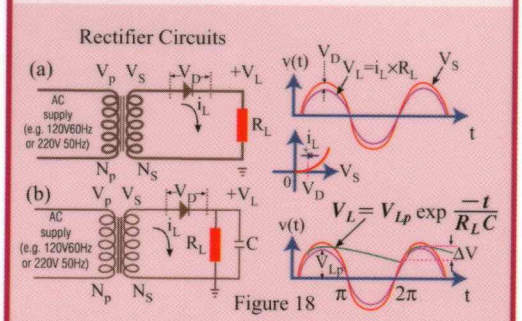


Figure 18

VOLTAGE REGULATION

A rectifier circuit delivering a load current (I_{dc}) at a d.c voltage V_{dc} across a load R_L can be represented by an equivalent circuit shown (Fig.21):

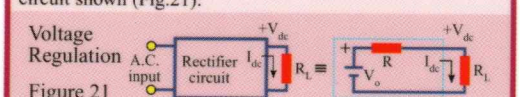


Figure 21

R is the total source resistance (constituted by forward resistance of diodes and the secondary winding resistance of the transformer). $V_{dc} = (V_0 - I_{dc} \times R_L)$. If the load resistance changes (i.e. as load current demand increase), V_{dc} drops.

$$\text{Percentage Regulation (PR)} = \frac{[V_{dc\ (no\ -\ load)} - V_{dc\ (full\ -\ load)}] \times 100}{V_{dc\ (full\ -\ load)}}\ \%$$

A regulated d.c. power supply is designed to offer a desired percentage regulation. High performance should enable drop in V_{dc} minimum from no-load to full-load conditions. (i.e. PR 0).

DIODE ENVELOPE DETECTOR

This is used in AM radio circuits to recover the low frequency audio envelope modulated on a high frequency carrier. $e(t) = V_c [1 + m \cos\ _m t] \cos\ _c t$; $_m$: Audio modulating signal frequency; $_c$: Carrier frequency, $_c >>\ _m$; and **m**: Depth of modulation.

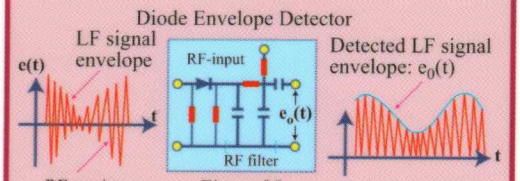


Figure 25

DIODE VOLTAGE CLAMPS

A voltage clamp shifts the associated d.c. level without changing the signal waveform, e.g. positive voltage clamp: $V_s = V_s \sin\ t$; V_f : Diode forward voltage drop. D.C. Clamping level $\triangleq V_{clamp}$. Note: $RC >> \dfrac{2\pi}{\omega}$ & $R >> R_d$ and negative clamping can be obtained by reversing the polarity of V_R and the polarity of the diode, see Fig. 24.

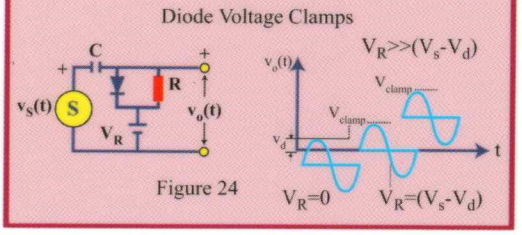


Figure 24

DIODE CLIPPING CIRCUITS

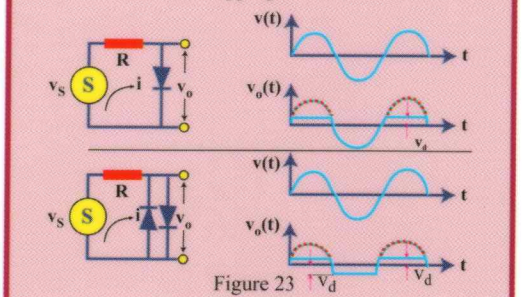


Figure 23

$$V_0 = \frac{R_d V}{R + R_d} + \frac{R V_f^*}{R + R_d} = V(R_d \quad \infty)$$

ON state: (R_d: diode forward resistance) and (V_f^*: diode projected cut-in voltage V_f)

ZENER REGULATORS

A simple regulated power supply can be constructed with a zener diode connected in shunt with the load as shown (Fig.22):

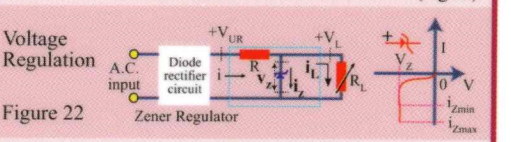


Figure 22

If V_{UR} is the unregulated voltage at the output of the diode rectifier circuit, the regulated voltage across R_L is given by:

$$V_L = \frac{R_L(R_z V_{UR} + R V_z)}{R_L(R + R_z) + R R_z}$$

where **R** is a resistor which can be designed to achieve a given % regulation in conjunction with a zener diode of breakdown voltage V_Z sustaining a safe current through it by means of R_Z limited by I_{Zmax} to I_{Zmin}. When R_L ∞;

$R = \dfrac{V_{UR} - V_{L\,max}}{I}$; and $I = I_{Lmax} + I_{Zmin} = I_{Lmin} + I_{Zmax}$.

P_z (power dissipation in the zener diode) = $V_Z I + R_Z I^2$

P_R (power dissipation in R) = $I^2 R$;

$$V_{Lmax} = R_Z I_{Zmax} + V_Z$$

$V_{Lmin} = R_Z I_{Zmin} + V_Z$; $PR = \dfrac{(V_{L\,max} - V_{L\,min}) \times 100}{V_{L\,max}}\ \%$

BIPOLAR JUNCTION TRANSISTORS (BJTs)

DEFINITIONS

Bipolar junction transistors are constituted by three semiconductor regions forming two PN junctions. The semiconductor regions are designated as **emitter**, **base** and **collector** (Fig.26). There are two types of BJTs, namely **NPN** and **PNP** transistors with the symbols as shown: The junctions are known as: Emitter-base junction (**EBJ**) and Collector-base junction (**CBJ**) see (Fig 26).

Bipolar Junction Transistors (BJTs)

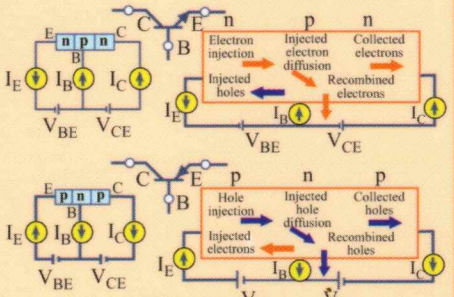


Figure 26

UNBIASED BJT

When the junctions are constituted, depletion layers are formed at the PN junctions with depletion layer potentials across each of them.

BIASED BJT

- In the active mode operation EBJ is forward-biased and CBJ is reverse-biased. These external biasings enable the depletion layer potentials at EBJ and CBJ to be decreased and increased respectively. As a result the following current-flows are realized (for example, in the NPN device): Forward bias on EBJ allows electron-injection from emitter into base and hole-injection from base to emitter. These two injections constitute the **emitter current (I_E)**. Emitted electrons in the base region (where they are minority carriers) diffuse across the base with some electrons lost through recombination and appearing as a part of **base current**. The collected electrons across the collector drift to the collector terminal. The electrons under acceleration (due to their kinetic energy) may break covalent structure to yield more carriers. That is, in the collector, there is a multiplication process prevailing. Denoting the fraction of electrons injected from the emitter as a < 1 (**emitter efficiency**), the fraction of electrons survived in the diffusion across the base (after recombination) as the **base-transport factor** (b<1) and the multiplied carrier ratio in the collector as c>>1 (**collector multiplication factor**), the net, **transistor alpha** (α= (a.b.c) <1). The emitter efficiency is decided by the doping levels in the emitter and the base. The base transport factor is dependent on base width. Referring to Fig.26, emitter current $I_E = I_C + I_B$, where

$$I_B = \underset{(I_{B_1} + I_{B_2})}{\textit{Total base current}} = I_E - I_C = \frac{I_c}{\alpha} - I_C = \frac{I_c(1-\alpha)}{\alpha}.$$

Therefore, $\frac{I_C}{I_B} = \frac{\alpha}{(1-\alpha)} \triangleq$ **transistor** β. $I_B = \frac{I_C}{\beta}$, a fraction of I_C. Since I_B is essentially decided by minority current flow across the EBJ, it is given by $I_B = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$ where $V_T = \frac{k_B T}{q}$ and I_S is the reverse saturation current across the EBJ.

EQUIVALENT CIRCUIT OF A BJT

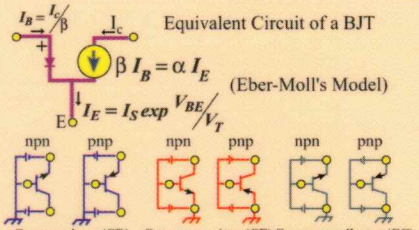


Figure 27

BJT MODES OF OPERATION

MODE	EBJ	CBJ	
Active	Forward-biased	Reverse-biased	n p n
Saturation	Forward-biased	Forward-biased	n p n
Cut-off	Reverse-biased	Reverse-biased	n p n

BJT CHARACTERISTICS

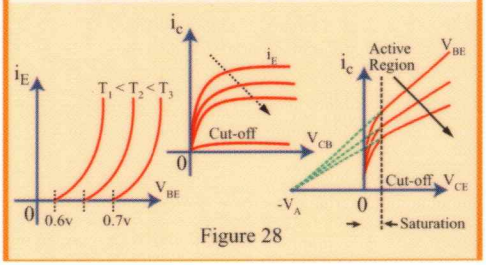


Figure 28

ANALYTICAL RELATIONS OF BJT CHARACTERISTICS

V_{BE} changes by $\approx |2\text{mV}|^0\text{C}$

$i \Rightarrow i_c, i_E, i_B$

$i_C = \alpha i_E$

$$i_C = I_s e^{\frac{V_{BE}}{V_T}} \qquad \left.\frac{\partial i_C}{\partial V_{CE}}\right|_{V_{BE} = \text{constant}} = \frac{1}{r_0}$$

$$i_E = \left(\frac{I_s}{\alpha}\right) e^{\frac{V_{BE}}{V_T}} \qquad r_0 \triangleq \text{output resistance} \approx \frac{V_A}{I_C}$$

$$i_B = \left(\frac{I_S}{\beta}\right) e^{\frac{V_{BE}}{V_T}} \qquad \left.\frac{\partial V_{BE}}{\partial i_E}\right|_{V_{CE} = \text{constant}} = r_e = \left(\frac{k_B T}{q}\right) \frac{1}{I_E}$$

SINGLE-BATTERY BIASING: CE CONFIGURATIONS

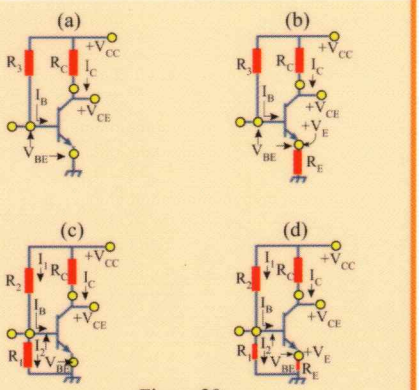


Figure 29

DETERMINATION OF BIASING RESISTOR VALUES

Figure 29(a)

$$R_3 = \frac{V_{CC} - V_{BE}}{I_B} \qquad R_C = \frac{V_{CC} - V_{CE}}{I_C} \qquad I_C = \beta I_B$$

Figure 29(b)

$$R_C = \frac{V_{CC} - V_{CE}}{I_C} \qquad R_E = \frac{V_E}{I_E} \qquad I_C = \beta I_B$$

Figure 29(c)

$$R_2 = \frac{V_{CC} - V_{BE}}{I_1} \qquad R_1 = \frac{V_{BE}}{I_2} \qquad R_C = \frac{V_{CC} - V_{CE}}{I_C} \qquad I_1 = I_2 + I_B \qquad I_B = \frac{I_C}{\beta}$$

Figure 29(d)

$$R_2 = \frac{V_{CC} - (V_E + V_{BE})}{I_1} \qquad R_1 = \frac{V_{BE} + V_E}{I_2} \qquad R_C = \frac{V_{CC} - V_{CE}}{I_C} \qquad R_E = \frac{V_E}{I_E} \qquad I_1 = I_2 + I_B \qquad I_B = \frac{I_C}{\beta}$$

OPERATING POINT (Q-POINT) DETERMINATION

Current-Bias (Fig.30)

$$V_{CC} = R_3 I_{BQ} + V_{BE} + R_E I_{EQ};$$

$$I_{EQ} = \frac{I_{CQ}}{\alpha} = \frac{I_{CQ}(1+\beta)}{\beta}; \quad I_{BQ} = \frac{I_{CQ}}{\beta};$$

$$I_{EQ} = I_{CQ} + I_{BQ}; \quad V_{CEQ} = (V_{CC} - I_{CQ} R_C)$$

$$I_{CQ} = \frac{(V_{CC} - V_{BQ})\beta}{R_3 + R_E(1+\beta)}; \quad V_{BQ} = V_{BE} + V_{EQ};$$

$$V_{EQ} = R_E \left[\frac{(1+\beta) I_{CQ}}{\beta}\right]; \quad (V_{BE} \approx 0.7\text{V})$$

Operating Point (Q-Point) Determination

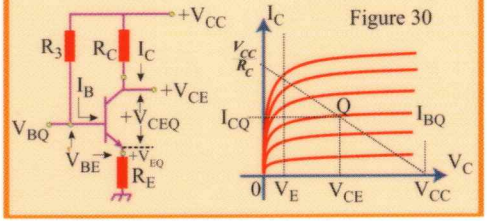


Figure 30

VOLTAGE-DIVIDER BIAS

$$R_B = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

$$R_1 = \frac{R_2 R_B}{R_2 - R_B} = \frac{R_3}{\left(1 - \left(\frac{V_{BB}}{V_{CC}}\right)\right)};$$

$$R_2 = \frac{R_1 R_B}{R_1 - R_B} = \frac{R_B V_{CC}}{V_{BB}}$$

$$V_{BE} = \text{Open Circuit Voltage} = V_{CC} \frac{R_1}{R_1 + R_2}$$

$$V_{BB} = R_B I_{BQ} + V_{BE} + R_E I_{EQ}$$

$$V_{EQ} = I_{EQ} R_E; \quad V_{BQ} = V_{BE} + V_{EQ};$$

$$V_{CQ} = V_{CC} - I_{CQ} R_C$$

$$I_{CQ} = \frac{(V_{BB} - V_{BE})\beta}{\left[R_B + R_E(1+\beta)\right]}$$

$$I_{EQ} = \frac{I_{CQ}(1+\beta)}{\beta}; \quad I_{BQ} = \frac{I_{CQ}}{\beta}$$

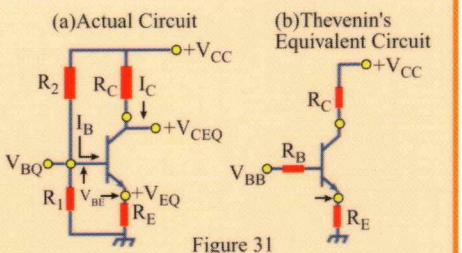
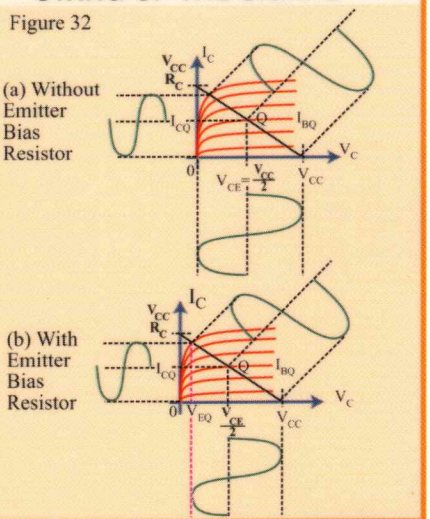


Figure 31

MAXIMUM DYNAMIC SWING OF THE SIGNAL

Figure 32



(continued on pg 5)

BIASING FOR Q-POINT STABILITY

BJT circuits are sensitive to temperature, power-supply fluctuations and variations in α (or β) from piece-to-piece. Such variations cause Q-point instability. Stabilizing methods include current-bias method, voltage-bias method and voltage divider method. Writing $I_C = \beta I_B + (1+\beta) I_{CBO}$, the second term is the leakage current component essentially due to minority carrier contribution which is sensitive to temperature.

Biasing for Q-point Stability

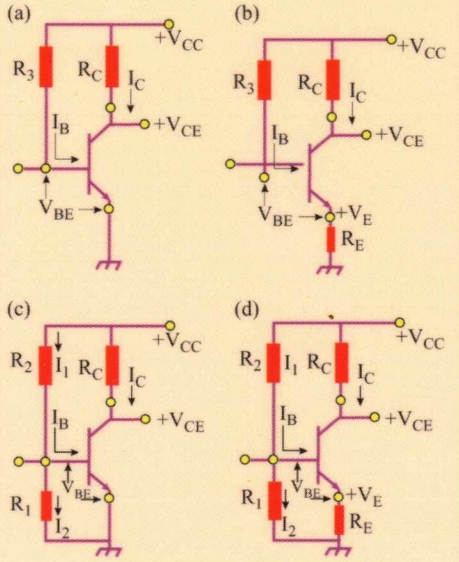


Figure 33

Stability factor: $S = \left.\frac{\Delta I_C}{\Delta I_{CO}}\right|_{V_{CE}}$

a. Single-resistor with current-biasing:
$S = (1+\beta) \Rightarrow$ Very Large (Poor Stability)

b. Current-bias with emitter resistor:

$$S = (1+\beta)\frac{1 + R_3/R_E}{1 + \beta + R_3/R_E} \to 1 ; \Rightarrow \left(\text{better stability}\right)$$

c. Voltage-biasing with collector-to-base resistor:

$$S = \frac{1+\beta}{1 + \frac{\beta R_C}{R_3 + R_C}}$$

d. Voltage-divider biasing: $S = 1 + \frac{(R_1 \| R_2)}{R_E}$

Recommended design values of S:
Small signal voltage amplifiers: S ~ 4 - 5
Large signal power amplifiers: S ~ 2

EARLY EFFECT

With the reverse-bias on CBJ, the depletion layer would extend into base (when the bias is increased), thereby reducing the effective base width (W_B). Hence, base-transport factor will increase. Thus α increases and I_C also increases with a reduction in output impedance $\frac{\partial V_{CB}}{\partial I_C}$.

The change in base width is termed as **base-width modulation** or **Early effect**. Further increase in I_C calls for excessive injection of electrons from the emitter into base. This enhancement of carriers in the base increases **base conductivity** and hence reduces emitter-efficiency (**conductivity modulation**). The result is α will decrease (Fig.36).

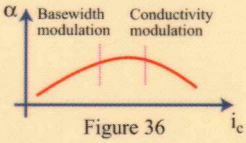


Figure 36

H-PARAMETER AND HYBRID - π PARAMETER MODELS OF BJTS

• Common emitter configuration (Fig 34):

$$v_{be} = h_{ie} i_b + h_{re} v_{ce}, \; i_c = h_{fe} i_b + h_{oe} v_{ce}$$

h_{ie} : CE Short circuit input resistance $= \left.\frac{v_{be}}{i_b}\right|_{v_{ce}=0}$

h_{re} : CE Open-circuit voltage gain $= \left.\frac{v_{be}}{v_{ce}}\right|_{i_b=0}$

h_{fe} : CE Short-circuit forward current gain $= \left.\frac{i_c}{i_b}\right|_{v_{ce}=0}$

h_{oe} : CE Open-circuit output admittance $= \left.\frac{i_c}{v_{ce}}\right|_{i_b=0}$

Common Emitter Configuration

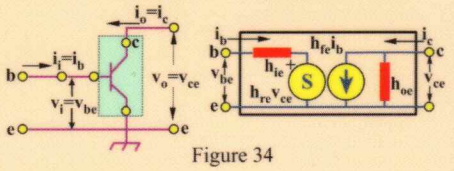


Figure 34

RELATION BETWEEN THE PARAMETERS

$g_m \triangleq$ Transfer (mutual) conductance $=$

$$\left.\frac{\partial I_C}{\partial V_{BE}}\right|_{V_{CE} = \text{cons tan t}}$$

$$I_B = I_{BEO}\left[-1 + \exp\left(\frac{V_{BE}}{\eta V_T}\right)\right], \; I_C = h_{fe} I_B$$

where $\eta = 1$ to 2; $V_T = \frac{k_B T}{q} = \left(\frac{T^\circ K}{11600}\right)$ volts

k_B: Boltzmann constant
q: Electronic charge

$$\frac{\partial I_B}{\partial V_{BE}} = \left(\frac{I_{BEO}}{\eta V_T}\right)\exp\left(\frac{V_{BE}}{\eta V_T}\right) \cong \frac{I_B}{V_T}$$

$$h_{fe} = \left.\frac{\partial I_C}{\partial I_B}\right|_{V_{CE} = \text{cons tan t}}$$

$$g_m = \left(\frac{\partial I_c}{\partial I_B}\right)\left(\frac{\partial I_B}{\partial V_{BE}}\right) = \frac{h_{fe} I_B}{\eta V_T} = \frac{I_C}{\eta V_T} \cong \frac{I_C}{0.026} \text{ S}$$

at 27°C

HYBRID - π MODEL: CE CONFIGURATION

C_p: Input Capacitance
C_o: Output Capacitance
C_μ: B-C Capacitance

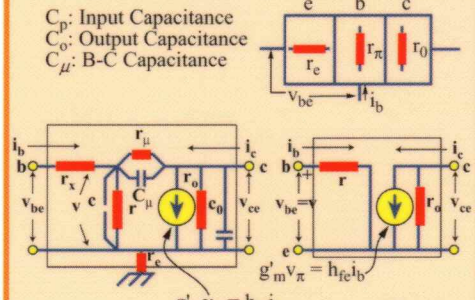


Figure 35

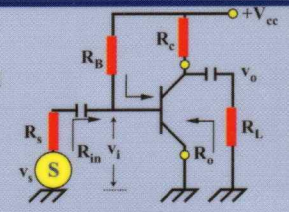
APPROXIMATE RELATION BETWEEN PARAMETERS

	CB	CE	CC(EF)
R_{in}	$\frac{h_{ie}}{h_{fe}} = h_{ib}$	h_{ie}	$h_{ie} + h_{fe} R_L$
R_0	$h_{fe} h_{oe}^{-1} = h_{ob}^{-1}$	$\frac{1}{h_{oe}} > 10k\Omega$	$\frac{h_{ie} + R_s}{h_{fe}}$
A_i	$\cong 1 = -h_{fb}$	$-h_{fe}$	h_{fe}
A_v	$\frac{R_L}{h_{ib}}$	$\frac{h_{fe} R_L}{h_{ie}}$	$\cong 1$

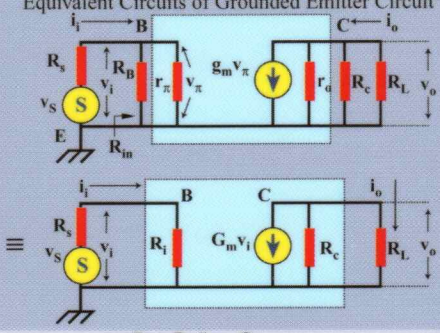
COMMON EMITTER (CE) AMPLIFIER

Figure 37

Grounded Emitter Circuit



Equivalent Circuits of Grounded Emitter Circuit



$R_{in} = R_B \| r_\pi$; $G_m = -g_m$

Gain $= G_m R_0 = -g_m (R_c \| r_o) \Rightarrow$ Voltage gain

Current gain $= \frac{i_0}{i_1} = \frac{G_m v_i}{v_i / R_i} = G_m R_i =$

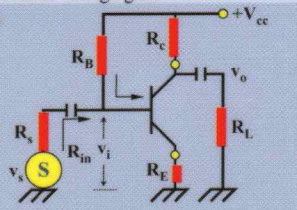
$$-g_m (R_B \| r_\pi) = \frac{-g_m r_\pi R_B}{R_B + r_\pi} = -\beta \frac{1}{1 + r_\pi / R_B}$$

$$\frac{v_0}{v_s} = \frac{v_i}{v_s} \cdot \frac{v_0}{v_i} = \left(\frac{R_{in}}{R_{in} + R_s}\right) G_m \left(R_0 \| R_L\right) \Rightarrow$$

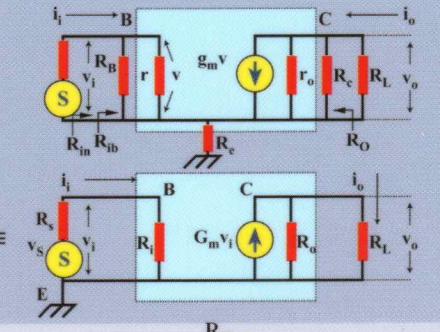
overall voltage gain

Figure 38

Common Emitter Circuit with Emitter Resistance



Equivalent Circuits of Common Emitter Circuit



$$v_b = v_\pi + v_\pi \frac{R_E}{r_\pi} + g_m v_\pi R_E =$$

$$v_\pi + \left(g_m + \frac{1}{r_\pi}\right) v_\pi R_E \therefore v_b = v_\pi \left(1 + \frac{R_E}{r_e}\right);$$

$$\frac{1}{r_e} = \left(g_m + \frac{1}{r_\pi}\right) \therefore R_{ib} = \frac{v_b}{i_b} = \frac{v_\pi \left(1 + \frac{R_E}{r_e}\right)}{\frac{v_\pi}{r_\pi}}$$

$$= r_\pi \left(1 + \frac{R_E}{r_e}\right) \approx r_\pi (1 + g_m R_E)$$

• Input resistance $= (1+\beta) \times$ Total resistance looking into the emitter circuit ÷ "Resistance reflection rule."

• $G_m = \frac{i_0}{v_i} = \frac{-g_m v_\pi}{v_i = v_b} = \frac{-g_m}{1 + \frac{R_E}{r_e}} = \frac{-g_m}{1 + g_m R_E}$

$R_{out} = R_c \| r_0 \approx R_c$

Voltage gain: $\frac{v_o}{v_s} = \frac{v_i}{v_s} \cdot \frac{v_o}{v_i} = \frac{R_{in}}{R_{in} + R_S} \cdot (-G_m)(R_o \| R_L)$

If $r_\pi (1 + g_m R_E) >> Rs$, $A_v \cong \frac{-R_C \| R_L}{r_e + R_E}$

QuickStudy

COMMON BASE (CB) AMPLIFIER

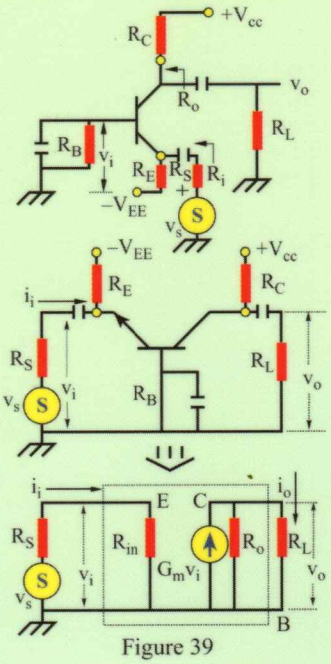


Figure 39

- $R_{in} = R_E \| r_e \approx r_e$
- $G_m = \dfrac{i_o}{v_i} = \dfrac{i_c}{v_i} = \dfrac{-\alpha i_e}{r_e}$, but $i_e = (-v_i/r_e) \therefore G_m = \dfrac{\alpha}{r_e} = g_m$
- $R_0 = R_C$ • $A_v = \dfrac{v_0}{v_i} = G_m R_0 \equiv g_m R_C$
- Overall gain: $\dfrac{v_o}{v_s} = \dfrac{R_i}{R_i + R_s} \cdot G_m (R_c \| R_L)$
- Current gain: $\dfrac{i_o}{i_i} = \dfrac{g_m v_i}{v_i / R_{in}} = g_m R_{in} = g_m r_e = \alpha$

COMMON COLLECTOR (CC) AMPLIFIER

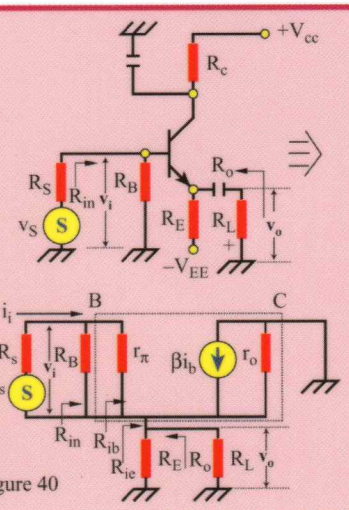


Figure 40

$R_{in} = R_b \| R_{ib}$, $R_{ib} = (1+\beta)(r_e + R_e)$; $R_e = R_E \| r_o \| R_L$

If $R_L << R_E \| r_0$, $R_{in} \approx (1+\beta)(r_e + R_L) =$

$r_e(1+\beta) + R_L(1+\beta) = r_\pi + R_L(1+\beta)$

$$\frac{v_i}{v_s} = \frac{v_b}{v_s} = \frac{R_{in}}{R_{in} + R_s}, \quad \frac{v_e}{v_i} = \frac{v_0}{v_i} = \frac{R_e}{R_e + r_e}, \; R_e = R_E \| r_0 \| R_L$$

$$A_v = \frac{v_0}{v_s} = \frac{R_{in}}{R_{in} + R_s} \cdot \left(\frac{R_e}{R_e + r_e} \right) \approx \frac{R_L}{R_L + R_o} \approx 1$$

$$A_i = \frac{i_o}{i_i} = \frac{v_o / R_L}{v_s / (R_s + R_i)} = \frac{R_{in}}{R_L}$$

$$R_{out} = R_E \| r_0 \| R_{ie} = r_e + \left(\frac{R_S}{1+\beta} \right)$$

COMPARISON OF PARAMETERS OF CB, CE, & CC AMPLIFIERS

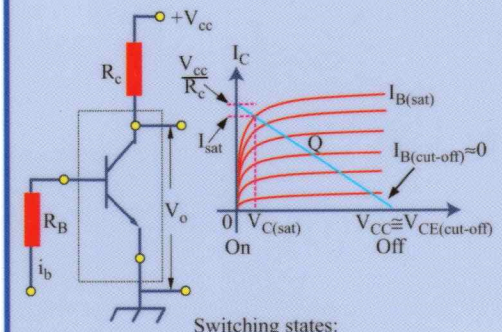
	CB	CE	CC(EF)
R_{in}	$r_e + \dfrac{r_b}{\beta_0}$	$r_b + \beta_0 r_e$	$\beta_0 (R_L + r_e)$
R_0	$r_c \to \infty$	$\dfrac{r_c}{\beta_0} \to \infty$	$r_e + \dfrac{R_s + r_b}{\beta_0}$
A_i	α_0	$-\beta_0$	β_0
A_v	$\dfrac{\alpha_0 R_L}{r_e + \dfrac{r_b}{\beta_0}}$	$-\dfrac{\alpha_0 R_L}{r_e + \dfrac{r_b}{\beta_0}}$	$\dfrac{R_L}{R_L + r_e}$

$\beta_o >> 1$; $R_L << r_e$

TRANSISTOR AS A SWITCH

Switching states (Fig. 41):

Transistor as a Switch



Switching states:

(Low voltage & High current):

$I_B = I_{B(sat)}$; $V_o = V_{CE(sat)} \cong 1$ volt

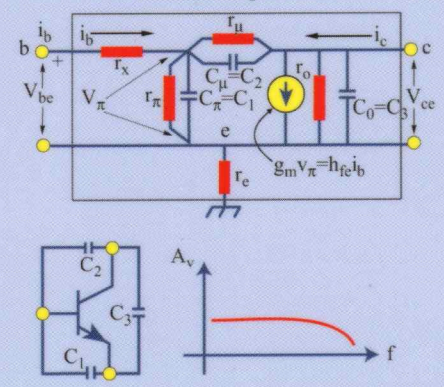
(High voltage & Low current):

$I_B \cong 0$; $V_{CE(cut-off)} \cong V_{CC}$

Figure 41

- Transistor capacitances (Fig. 42):
  - C_μ: Junction capacitance at CBJ ÷ Due to depletion layer ($\approx$10pf)
  - C_π: Diffusion capacitance at EBJ ÷ Due to storage in the base ($\approx 100 - 200$ pf)

Transistor Capacitances



Capacitance effect: High frequency gain is reduced

Figure 42

- Parasitic /stray capacitance → Due to loads and packaging
- β cut-off frequency: $f_T \triangleq \dfrac{\beta}{2\pi r_\pi (C_\mu + C_\pi)} = \beta f_\beta$

α-cut-off frequency (f_α) = $f_\beta / (1-\alpha)$

NOTICE TO STUDENT: Due to its condensed format, use this ***QuickStudy***® guide as an Electronics *guide*, **not as a replacement for assigned course work.**

DIFFERENTIAL AMPLIFIERS

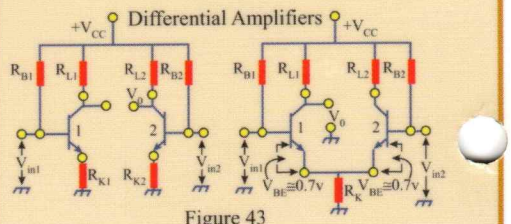


Figure 43

$$|V_{out}| = \left[V_{in1} \frac{R_{L1} \beta}{h_{ie}} - V_{in2} \frac{R_{L2} \beta}{h_{ie}} \right]$$

If $R_{L1} = R_{L2}$, $V_{out} = G(V_{in1} - V_{in2}) \Rightarrow$ Useful in amplifying differential signals from bridge circuits (Fig.44).

- Signal at $\mathbf{V_{in1}}$ drives the base current at transistor.
- This increases proportionately the collector current of transistor 1 and voltage across $\mathbf{R_{L1}}$ increases; or, the voltage output $\mathbf{V_0}$ decreases (since $\mathbf{V_0 + V_{RL1} = V_{CC}}$ = constant). $\mathbf{V_{in1}}$ and $\mathbf{V_0}$ are phase opposed. Suppose $\mathbf{V_{in1} = 0}$. Signal at $\mathbf{V_{in2}}$ drives a base current at transistor 2 and increases the collector current of 2. The emitter potential $\mathbf{V_K}$ is brute-forced at $(\mathbf{V_{B1}} - 0.7)$ volts.

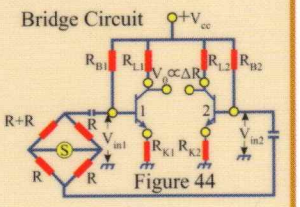


Figure 44

Therefore, increase in emitter current of transistor 2 should correspondingly reduce the emitter (and hence, the collector) current of transistor 1 so that the potential across $\mathbf{R_K}$, $\mathbf{V_K}$ remains a constant, brute-forced value. Hence a decrease in the collector current in transistor 1 should reduce the voltage drop across $\mathbf{R_{L2}}$. Or, the output voltage $\mathbf{V_0}$ should increase. That is, the input signal at transistor 2 ($\mathbf{V_{in2}}$) when increased, will cause the output voltage to increase.

V_{in1} → Inverting input signal

V_{in2} → Noninverting input signal

$V_0 \propto (V_{in2} - V_{in1})$

Basic differential amplifier enables the mathematical difference operation and can be modified to perform addition, integration, differentiation, etc. Hence, it is designated as an operational amplifier (OP-AMP). Operational amplifiers will be covered in the next guide.

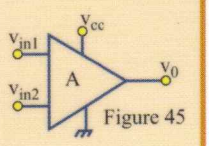


Figure 45

Part 2 of this two-part electronics series covers Operational Amplifiers, Unipolar Devices such as FET and JFET, MOSFETs, Relevant Equivalent Circuits and Frequency Response of FETs; Common-Gate Amplifiers, Common-Source Amplifiers and Common Drain Amplifiers. Look for it at your bookstore.

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