WORLD'S #1 ACADEMIC OUTLINE

QuickStudy ACADEMIC

Electronics 1

Fundamentals of Electronic Devices & Basic Electronic Circuits

Circuits & Systems: Basic Definitions

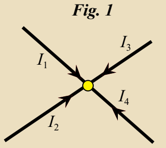
Electronic Circuits

An information- and energy-bearing signal-processing network formed by interconnections of passive components and/or active devices

- **Passive components:** Resistors, capacitors, and inductors
  - **Resistors:** Devices that consume energy from an electronic circuit
  - **Capacitors:** Devices that store energy from an electronic circuit and subsequently release the energy in the electronic circuit
  - **Inductors:** Devices that store energy from an electronic circuit via electromagnetic induction and subsequently release the energy in the electronic circuit
- **Active devices (or energy source devices):** Transistors, metal-oxide semiconductors, etc., that control the flow of electrons (i.e., current).
- **Electronic system:** An arrangement of components (passive elements and/or active devices) with a specified input signal that produces a defined output signal
- **Signal processing:** Functionally, electronic circuits and systems *process* an input signal. Common processing includes:
  - **Amplification** (magnification)
  - **Integration:** Integrating a signal over time to measure the total product of the signal
  - **Differentiation:** Rate of change of a signal with respect to time
  - **Filtering:** Changing the relative magnitude of the different frequency components of a signal
    - **Rectification:** Selection/rejection of a specific part of a signal based on polarity
    - Other electronic circuits are:
  - **Harmonic oscillators:** Produce *sinusoidal wave forms* of desired frequency; also termed as **relaxational oscillators**. Their other versions can produce nonsinusoidal wave forms (e.g., square, impulse, and triangular).
  - **Digital circuits:** Specific circuits that handle *pulsed wave forms*. They perform computational operations including addition, subtraction, and multiplication in binary form. They are immune to noise and are consistently accurate.

Resistive Circuits

Fig. 1

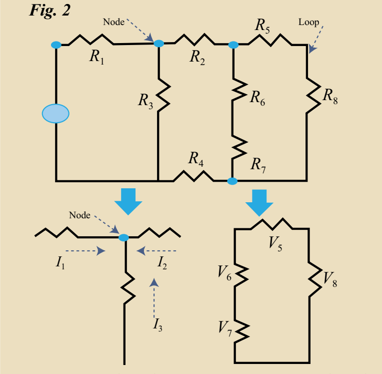


Circuits with only resistive elements can be analyzed via several methods.

- **Kirchhoff's current law (KCL):** In a closed electrical circuit or mesh, the algebraic sum of all the currents meeting at a junction is zero.
  - This implies that the total current leaving a junction is equal to the total current entering the junction. This follows the law of conservation of charge.
  - In *fig. 1*, four conductors transmit I_1, I_2, I_3, and I_4.
    - As per KCL: $I_1 + (-I_2) + (-I_3) + I_4 = 0$

      $I_1 + I_4 = I_2 + I_3$

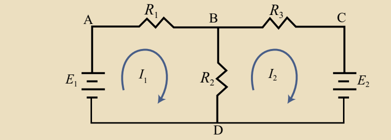
Fig. 2



$I_1 + I_2 + I_3 = 0$ (KCL) $V_5 + V_6 + V_7 + V_8 = 0$ (KVL)

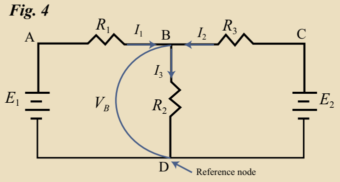
- **Kirchhoff's voltage law (KVL):** In a closed electrical circuit or mesh, the algebraic sum of all the electromotive forces (emfs) and voltage drops in resistors is equal to zero.
  - Algebraic sum of emfs + Algebraic sum of voltage drops = 0
    - This is based on the law of conservation of energy, which implies that the energy of a charge remains constant in a closed loop.

Fig. 3 Network Theorems: Analyzing Complex Circuits



- **Maxwell's loop current method:**
  - Currents in different meshes/loops are assigned continuous paths. Hence, the currents at a junction do not split into branch currents.
  - Kirchhoff's law is applied to each loop (*fig. 3*):
    - Loop 1: $-I_1R_1 - (I_1 - I_2)R_2 + E_1 = 0$
    - Loop 2: $-I_2R_3 - E_2 - (I_2 - I_1)R_2 = 0$

Fig. 4



- **Nodal analysis based on KCL and KVL:**
  - Suitable for networks with several parallel circuits with a common ground
  - Each junction in the network where three or more branches meet is considered to be a **node**.
    - One of the nodes is considered to be the **reference node**.
  - Circuits containing N nodes display N-1 node voltages (a few of the voltages are known if a voltage source is present).
  - Apply KCL at node B (*fig. 4*): $I_1 + I_3 = I_2$.
  - In the loop ABDA, voltage drop across R_1 corresponds to $E_1 - V_B$: $I_1 = \frac{E_1 - V_B}{R_1}$
  - In the loop CBDC, voltage drop across R_3 corresponds to $E_2 - V_B$: $I_3 = \frac{E_2 - V_B}{R_3}$ and $I_2 = \frac{V_B}{R_2}$
  - Use KCL at node B: $\frac{E_1 - V_B}{R_1} + \frac{E_2 - V_B}{R_3} = \frac{V_B}{R_2}$
- **Superposition method:**
  - Useful for circuits with multiple energy sources
  - Considers the individual effect of each source
  - Finally combines (superimposes) the effects
- In *fig. 5a*, consider the circuit with two voltage sources and examine the nodal voltage v_0.
- In *fig. 5b*, consider only a voltage source V_1 and short the second source. Thus, calculate the nodal voltage due to the first voltage source V_1 $(v_0)_1 = \frac{R}{2R}V_1$.
- In *fig. 5c*, short the first voltage source and only consider the second voltage source. Thus, calculate the nodal voltage $(v_0)_2 = \frac{R}{2R}V_2$.
- Use the superposition method to combine the responses due to the two voltages and obtain the resultant nodal voltage $v_0 = (v_0)_1 + (v_0)_2 = \frac{1}{2}(V_1 + V_2)$.

Time-Dependent Circuits

- Circuit responses with passive elements can be considered instantaneous and static (i.e., the response is not time dependent).
- Introduction of time-dependent passive elements (e.g., capacitors and inductors) leads to a time-dependent circuit response.
- Constitutive law governing a capacitor: $C(t) = \frac{\in A(t)}{l(t)}$
- Constitutive law governing an inductor: $L(t) = \frac{\mu N^2 A(t)}{l(t)}$
- The time-dependent response of a capacitor and an inductor allows for the function of memory and energy storage.
- Electrical energy stored in a capacitor: $W_E(t) = \frac{Cv(t)^2}{2}$
- Magnetic energy stored in a capacitor: $W_M(t) = \frac{Li(t)^2}{2}$
- A capacitor and an inductor can be used in a circuit to generate an oscillating output (i.e., an electrical signal). Consider a simple LC circuit (commonly known as a tank circuit). This results in an oscillating output.
- In the circuit shown in *fig. 6*, the capacitor is initially charged via a voltage source when the switch is in position A.
- After the capacitor is charged, the switch is changed to position B. The capacitor starts discharging, and as a result the inductor creates an electromagnetic field and stores energy discharged from the capacitor.
- When the capacitor is fully discharged, the electromagnetic field of the inductor weakens and current flows through the circuit to charge the capacitor again.
- When the capacitor is fully charged, it discharges the current in the opposite direction and creates an alternating voltage and current, which can be used as an electrical signal.

Note: This is an extremely basic method of generating an electrical signal. Several components can be added to the circuit to obtain the desired electrical signal.

Fig. 5a

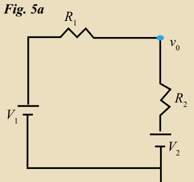


Fig. 5b

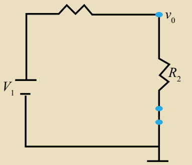


Fig. 5c

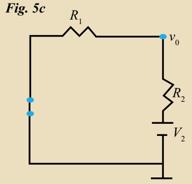
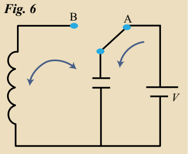


Fig. 6

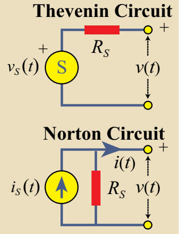


Electrical Signal

An information- and energy-bearing electrical entity (e.g., a voltage or current) that is derived from a transducer (e.g., a voice-signal voltage delivered by a microphone)

- **Signal processing:** Processing the electrical signal in a predetermined manner to recover the information or energy contained in it
- Signal sources in *fig. 7*:
  - **Thevenin's equivalent circuit:** A signal source represented by a voltage generator $v_s(t)$ in a series with a source (internal) resistance R_s.
  - **Norton's equivalent circuit:** A signal source depicted by a current generator with resistor R_s in parallel.
  - The circuits represent a collection of voltage sources, current sources, and resistors via a voltage source or a current source and a resistor.
- An electrical signal is characterized via **amplitude**, **frequency**, and **phase** parameters (*fig. 8*, p. 2).
- 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, such that frequency $f = 1/T$
  - **Aperiodic**

Fig. 7



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

Fig. 8

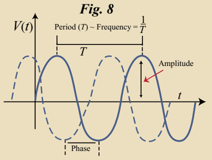
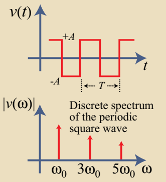


Fig. 9
Fourier Series (Discrete Spectrum)



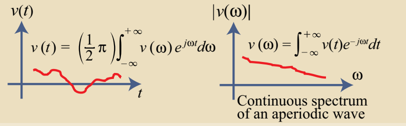
- Examples of signal representation via Fourier series and Fourier transform:
  - A periodic, continuous, nonsinusoidal signal can be represented by superpositioning an infinite number of harmonic (sine/cosine) wave forms (e.g., a Fourier expansion of a square wave) (*fig. 9*).

$$\boldsymbol{v(t)} = \frac{4A}{\pi}\sum_{m=0}^{\infty}\frac{\sin(n\omega_0 t)}{n}$$, where $\boldsymbol{n = (2m+1)}$ and

$\omega = 2\pi/t = 2\pi f$ = Fundamental angular frequency

- An aperiodic wave form that represents an arbitrary time-varying signal can be depicted via Fourier transform (*fig. 10*).

Fig. 10
Fourier Transform



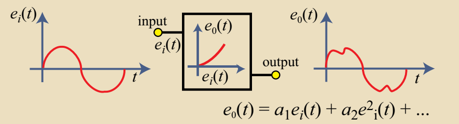
- Fourier series and Fourier transform representations of signals aid in describing the spectral components (frequency components) that constitute the signal (*fig. 10*).

Signal Distortion

An electrical signal processed by a circuit can be subject to amplitude distortion, frequency distortion, and phase distortion.

- **Amplitude distortion (harmonic or nonlinear):** Caused by the nonlinear transfer function characteristics of the components/devices in the circuit (*fig. 11*)
  - An input signal $e_i(t)$ is delivered at the output of the circuit as $e_0(t) = a_1e_i(t) + a_2e_i^2(t) = a_3e_i^3(t) + \ldots$, where $a_1, a_2, a_3, \ldots$, etc. denote the coefficients of the nonlinear transfer function.
    - If $e_i(t)$ denotes a single frequency signal, then the output contains higher harmonic components, including square and cubic terms. Hence, the output signal wave shape (envelope) appears distorted (envelope distortion).

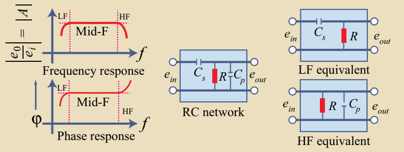
Fig. 11
Amplitude Distortion



- **Frequency distortion:** Given the presence of capacitive C and/or inductive L elements in the circuit, a complex signal (composed of a spectrum of several frequency components) is subject to the filtering of its components to the extent that the reactances exhibited by C and/or L elements are frequency dependent.
  - The transfer function that relates the input and the output varies as a function of frequency.

  EX: A voltage amplifier that is expected to provide a constant voltage gain (output voltage to input voltage ratio) for any given frequency of the input signal that can yield a varying gain *versus* frequency plot as shown in *fig. 12*. The decrease in A (gain) *versus* f (frequency) curve at high (**HF**) and low (**LF**) frequencies is due to factors such as low reactance of the shunt capacitance C_p and high reactance of series capacitance C_s, respectively.

Fig. 12
Frequency Distortion



- **Phase distortion:** Given the input and output signals, the relative phase angle is also determined via the C (and/or L) elements present in the circuit.
  - The phase difference is frequency dependent. With respect to a complex input signal with a spectrum of frequency components, the phase angle (φ) of the transfer function of the circuit when plotted relative to the frequency is typically represented as shown in *fig. 12*.
    - With the exception of over a midrange of frequencies, φ varies at low and high frequencies due to series and shunt capacitive elements of the circuit, respectively (or due to shunt and series inductive elements, respectively, if present).

Noise

An undesired entity introduced into the signal in a circuit caused either by various circuit elements or electromagnetic interference (EMI) coupled to the circuit from exterior sources

- EMI can affect the signal via electromagnetic induction, electrostatic coupling, or conduction.
- Noise is a random fluctuation that affects/corrupts the quality of the signal. It is necessary to minimize the noise level (high **signal-to-noise** ratio) to preserve signal characteristics along the circuit.

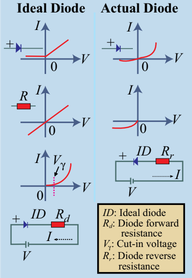
Circuit Devices

Diodes: Ideal & Practical Versions

A two-terminal, unilateral device

- Ideally, it conducts electricity in one direction and does not allow the current to flow in the opposite direction.
- *Fig. 13* shows a comparison of the current I voltage V characteristics of a bilateral element (e.g., a resistor R) and of an **ideal diode**.

Fig. 13

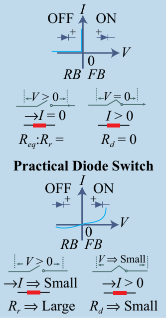


- A **practical diode** (e.g., a semiconductor diode) displays a nonlinear **V-I** relationship that is almost exponential in the **forward bias** wherein its anode is maintained at positive (+) potential relative to its other (cathode) terminal.
  - **Reverse bias:** The anode is at negative potential with respect to its cathode. A small reverse current exists in contrast to that in an ideal diode, wherein the reverse current corresponds to zero.
  - **Forward bias:** A small voltage V_γ exists (and is known as **threshold or cut-in voltage**) until the current conduction in practical diodes is absent.

Diodes as Circuit Elements

- **Basic applications of diodes:**
  - Switching element
  - Rectifier
  - Wave form clipper
  - Limiter
  - Detector or demodulator
  - Diode logic gates

Fig. 14
Ideal Diode Switch

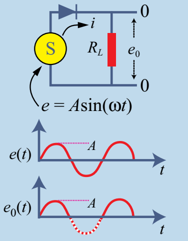


- **Switching element:** Ideally, a diode is a short-circuit element under forward bias and behaves as an open circuit when reverse biased. The state of the diode is set by the breakpoint at $\boldsymbol{v = 0}$ and $\boldsymbol{i = 0}$ (*fig. 14*).
  - With respect to $\boldsymbol{v = 0}$, $\boldsymbol{i > 0}$ corresponds to the **on-state**.
  - With respect to $\boldsymbol{v < 0}$, $\boldsymbol{i = 0}$ corresponds to the **off-state**.

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

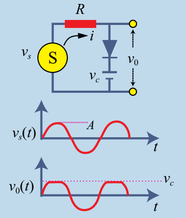
- **Rectifier:** A diode can be used to rectify the alternating current wave form (with bipolarity) to a one-directional wave form.
  - A simple **half-wave rectifier** is illustrated in *fig. 15*. The current flows through the load resistor R_L only during the positive half-cycle when the diode conducts (forward biased). Hence, voltage (e_0) across R_L is one-directional or rectified.

Fig. 15
Half-Wave Rectifier



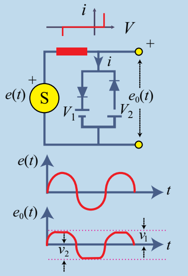
- A **diode circuit** can be designed to cut off the voltage above a certain value. Thus, the circuit limits voltage inputs to the maximum level. The clipper circuit and wave form clipping are illustrated in *fig. 16*.

Fig. 16
Diode Clipping Circuit



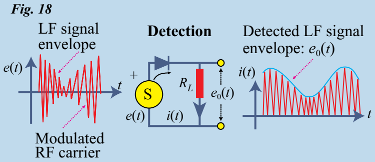
- A diode bilateral **limiter** is an extension of the clipping circuit (*fig. 17*).

Fig. 17
Diode Bilateral Limiter



- **Demodulator/detector:** This circuit is used to recover an envelope wave form of low frequency that modulates the amplitude of a high-frequency wave form (*fig. 18*).

Fig. 18



  - The process is termed as **detection** (of a signal modulated on a high-frequency carrier) in radio systems.

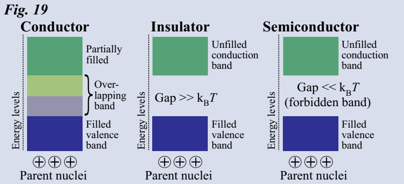
Semiconductor Diodes

Definitions

In solid-state materials, the distribution of electrons in the outermost orbit of atoms (termed as **valence electrons**) governs the property of the material as a **conductor** (e.g., **Cu** or **Ag**), an **insulator** (dielectrics including polyethylene), or a **semiconductor** (e.g., **Si** and **Ge**).

- **Conductors:** A cloud of free electrons exists at temperatures above absolute zero that is formed by weakly bound valence electrons in the outermost orbits of atoms.
  - When this is subject to an electric field force (via the application of a voltage across the material), free electrons flow along the field gradient and constitute an **electric current**. With conductors, the valence band and conduction band overlap (*fig. 19*).
- **Insulators:** Valence electrons are tightly bound to the parent nuclei of atoms and are barely available as mobile electrons to constitute a current flow even at room temperatures.
  - An **energy gap** (band gap) exists between the **valence** and **conduction bands** (*fig. 19*). The gap is significantly high in insulators, and it is not possible for valence electrons to overcome the gap despite the application of an external electric field.

Fig. 19



- **Semiconductors:** The energy gap is small, so a few free electrons can overcome the energy gap via the application of an external electric field. The electrons attain the energy level of a conduction band to facilitate current conduction at room temperature.

Intrinsic & Extrinsic Semiconductors

- The atoms of semiconducting **fourth group elements** (e.g., **Si** and **Ge**) include four valence electrons that are shared by neighboring atoms and constitute strong **covalent bonds** (*fig. 20a*).
  - This limits the current conduction to available free-electron flow (at a given T, temperature) as facilitated via the thermal energy-induced transfer of electrons from valence band to conduction band. This corresponds to an **intrinsic** (pure) state of semiconductors (*fig. 20a*).
- A semiconductor (e.g., **Si** and **Ge**) can be "**doped**" with a fifth or a third group element to control its electrical conductivity.
  - Doping implies an addition of a fifth group element (e.g., **P**, **Sb**, and **As**, with five valence electrons) or a third group element. In the case of doping with a fifth group, the covalent structure is completed with four valence electrons of **P**. Hence, the excess free electron enhances the current conduction.

Fig. 20a

Intrinsic Type

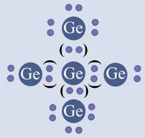


Fig. 20b

N Type

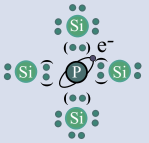
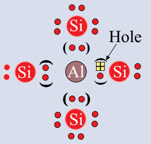


Fig. 20c

P Type



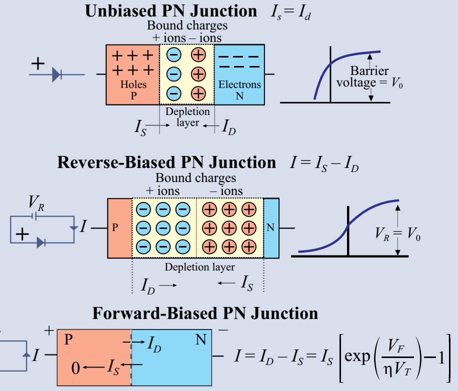
- **N-type or donor impurity:** The added fifth group element in the doped semiconductor is termed as an N-type extrinsic semiconductor (*fig. 20b*), where **N** denotes the negative excess charge carrier.
- The addition of a third group element (e.g., **B**, **Ga**, and **In**) curtails a part of covalent bonding (*fig. 20c*) because the **valency** (available valence electrons) is reduced to three.
  - The lack of electron, or the "**hole**" created in the bonding structure, is equivalent to a positive charge that is ready to accept an electron.
    - ▪Filling of a hole via an electron generates a hole at a different site.
    - ▪Proliferation of the hole represents movement of a positive charge.
  - A semiconductor doped with a third group element is designated as a **P-type extrinsic** material. Here, P denotes the excess positive charge carrier equivalence of the holes that are introduced. P-type dopants are known as **acceptors**.

PN Junction

Constituted by combining a P-type and an N-type semiconductor

- The structure represents a simple semiconductor diode.
- When a PN junction is created, the **majority carriers** (i.e., electrons of the N-region and holes of the P-region) can combine at the junction to form a **depletion layer** with almost nil free carriers in the vicinity of the junction. The atoms depleted of the electrons and holes remain in the depletion region as **ions** (*fig. 21*).
- The PN junction formation allows **minority carriers** (electrons of the P-region and holes of the N-region) to migrate across the junction and combine with ions in the respective regions.

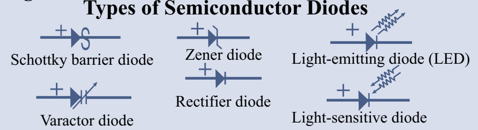
Fig. 21



Junction Diodes

Fig. 22

Types of Semiconductor Diodes



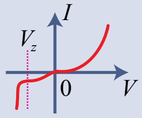
- **Schottky barrier diodes:** Contact between a metal and a semiconductor can create a junction with properties similar to a PN junction.

  EX: Al or **Pt** can act as an acceptor material when in contact with an N-type silicon. **Advantages:** Charge storage is not involved while facilitating fast switching, and an extremely low forward drop = **0 V** cut-in threshold is obtained.
- **Photo diodes:** Sensitive to light and convert light into an electrical current. They allow transmission of light flux to reach the junction.
  - A reverse saturation current depends on the generation of **hole-electron pairs** via the average thermal energy of a crystal.
  - The current can be further increased via light illumination. Diodes with the provision to transmit light flux to reach the junction are termed as photo diodes.
- **Varactor/varicap diodes:** Junction transition capacitance C_j varies with the reverse bias voltage V_R. Hence, they exhibit voltage-dependent capacitance in a reverse-biased PN junction: $C_J = C_0\left(1 + \frac{V_R}{V_0}\right)^{-n}$ and $V_0 = \left(\frac{k_B T}{q}\right)\log_e\left(\frac{N_A N_D}{n_i^2}\right)$, where:
  - N_A and N_D = Acceptor and donor doping concentrations
  - n_i = Intrinsic carrier concentration
  - $V_0 \approx$ **0.58 V** at room temperature
  - m = **1/2** (abrupt junction) or **1/3** (graded junction)
  - C_j = **10 pF** to **100 pF** for V_R = **3 V** to **25 V**
  - Forward bias is avoided due to high shunt conductance.

Biasing a Semiconductor Diode

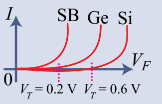
- **No applied bias:** An open-circuit condition in which a voltage drop across the depletion region termed as **barrier potential** is constituted by depletion region charges.
  - The extent of cross diffusion of the majority carrier across the depletion region forming the diffusion current I_D is determined by the barrier voltage level. In addition to I_D, a thermally generated **minority carrier** current I_S exists. Under an open circuit, external current flows are absent because an equilibrium is maintained by $I_D = I_S$.
- **Reverse bias:** V_R is applied, and thus minority carrier current I_S (independent of barrier voltage) remains constant. Diffusion current I_D is reduced because V_D increases by $V_D + V_R$.
  - The equilibrium current is $I_S - I_D = I_S$ (**reverse saturation current**). The reverse voltage V_R uncovers more ions in the depletion region and widens its width, thereby increasing the charge concentration in the depletion region.
    - ▪The corresponding depletion layer capacitance C_j (junction capacitance) is inversely proportional to $V_R \times C_J = \frac{K}{V_R^{\,N}}$, where N = **1/3** to **4** for different types of junctions that are fabricated.
  - With respect to the large reverse voltage V_R, the depletion layer electric field increases wherein strength can rupture the covalent bonding and create electron-hole pairs.
    - ▪This corresponds to a regenerative process (**zener effect**) as indicated by a large increase in current at a constant reverse voltage $V_R = V_Z$ (< **5 V**). Given the breakdown, the current is limited only by an external resistor (*fig. 23a*).

Fig. 23a



  - Another mechanism of breakdown at $V_R > V_Z$ occurs due to acquired kinetic energy by minority carriers that breaks covalent bonds via collision. This ionization process is termed as **avalanche breakdown** and is irreversible. A current can only be limited via an external resistor.
- **Forward-biased PN junction:** Forward-bias voltage V_F effectively decreases V_D and facilitates $I_D > I_S$.
  - At a steady state, external current $I_D - I_S$ flows.
    - ▪I_D is determined by the extent of thermal energy $V_T = \frac{k_B T}{q}$, where:
      - ▫ k_B = Boltzmann constant
      - ▫ T = Temperature
      - ▫ q = Electronic charge
  - The following corresponds to the reverse saturation current $I_D = I_S \exp\left(\frac{V_F}{\eta V_T}\right)$, where η denotes a scale factor such that **1 < η < 2 (1 for Ge, 2 for Si)**.
  - Forward I_F *versus* V_F characteristics are $I_F = I_S\left[\exp\left(\frac{V_F}{\eta V_T}\right) - 1\right]$, where $V_T \approx$ **0.026 V** for silicon at room temperature (*fig. 23b*).
- **Cut-in voltage:** A semiconductor diode exhibits a threshold forward-bias voltage below which the current is negligibly low. The threshold is termed as cut-in voltage. Typically, at room temperature, $V_{\text{cut-in}} = V_\gamma \approx$ **0.2** for **Ge**, ≈ **0.6** for **Si**, and ≈ **0** for **Schottky barrier** diodes (*fig. 23b*).

Fig. 23b

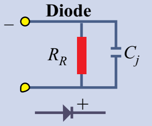


V_T at room temperature
(SB: Schottky barrier diode)

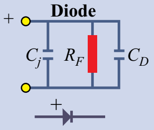
- **High-speed switching diodes:** Under forward bias, the narrow depletion layer results in a high transition (junction) capacitance C_j. Diffusion of large minority carriers under forward bias injected across the junction leads to a charge storage effect that attributed to a diffusion capacitance C_D.
  - Given ON-to-OFF switching conditions, forward-to-reverse bias changing results in the decay of injected minority carriers. The decay rate is controlled by $C_D + C_j$. After a time t_s (storage time) in which the excess charge is removed, the diode voltage decreases to zero until reverse saturation is reached at t_r. The difference $(t_r - t_s)$ is termed as **transition time**, which limits high-speed switching.
  - In OFF-to-ON switching, a similar process occurs with the exception that the time involved is negligible because stored charge is extremely low.
  - PN-junction diode switching characteristics are determined by R_C time constants specified by bias conditions.
- **Light-emitting diodes (LED):** Energy is released when injected minority carriers in a forward-biased PN junction recombine. This is in the form of heat in **Si** and **Ge**. In **GaAs**, it corresponds to photon energy at red, yellow, or green wavelengths based on the addition of certain impurities.
- **Rectifier diodes:** Intended for AC-to-DC conversion. They correspond to power diodes that are rated based on **power dissipation** considerations and **reverse breakdown voltage** rating.
- **Thermal rating:** Specified via the maximum allowable junction temperature (typically 100°C for **Ge** and 175°C for **Si** devices). The power dissipation capability of diodes can be increased by using **heat sinks**.

Fig. 24

Reverse-Biased Diode



Forward-Biased Diode



Rectifier Circuits

Mainly used to convert alternating currents into direct currents

Half-Wave Rectifier

- As shown in *fig. 25a* (p. 4), the transformer **TR** includes a primary coil of N_p turns and a secondary coil of N_s turns wound on an iron core. The AC excitation at the primary is coupled to the secondary via magnetic coupling mediated by the iron core.
- The diode conducts during the positive half cycle of secondary voltage as determined via forward diode characteristics. *The diode does not conduct during the negative half cycle.*
- The load current $i_L = \frac{V_S - V_f}{R_S + R_d + R_L}$ for $V_s > V_f$; otherwise, $i_L = 0$.
  - $V_f = V_D$ denotes the forward voltage drop across the diode (≈ **0.7 V** for **Si**).
  - R_S = Secondary winding resistance
  - R_d = Diode forward resistance
  - R_L = Load resistance

Half-Wave Rectifier with a Capacitor Filter

- In *fig. 25b* (p. 4), the capacitor across R_L is charged to $V_{L(peak)}$ during the positive half cycle and discharged through R_L during the negative half cycle with a time constant $t = R_L C$.

- V_L denotes a superposition of a DC voltage $\approx V_L - \frac{\Delta V}{2}$ and a ripple voltage (approximately of triangular shape) of peak value $\Delta V = \frac{(V_s - V_f)\times T}{\tau}$, $t = R_L C$, where:

$T = \frac{1}{f}$ f = Frequency RMS value of $V = \frac{V}{\sqrt{3}}$

- **Ripple factor** $\triangleq \frac{V_{Ripple(RMS)}}{V_{DC}} \Rightarrow \frac{\left(\frac{V}{\sqrt{3}}\right)}{(V_L - 0.5\Delta V)\times 100\%}$
  - Given a specific ripple factor, ΔV is calculated at a given load voltage. Hence, C is selected to satisfy

$$c \geq \frac{\left(\frac{V_{DC}}{R_L}\right)}{(f \times \Delta V)}$$

- **Peak-inverse voltage:** During a negative half cycle, the total voltage drop (reverse bias) across the diode = $V_{s(peak)} + V_{DC} \approx 2V_{s(peak)}$. The diode should be selected such that its breakdown voltage >> $2V_{s(peak)}$.
- **Diode dissipation rating:** Maximum diode dissipation is determined via **maximum load current**^{2} × **diode forward resistance**. The diode power rating should significantly exceed the dissipation level.

Rectifier Circuits

Fig. 25a

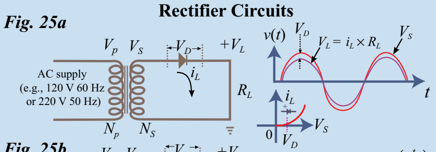
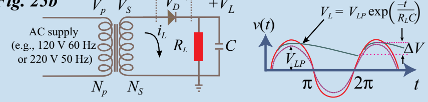


Fig. 25b

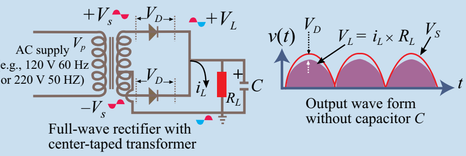


Full-Wave Rectifier with a Center-Tapped Transformer

- As shown in *fig. 26*, the center-tapped transformer provides two secondary voltages (with respect to the grounded center-tap) with a 180° phase difference.
  - This ensures that diodes D_1 and D_2 alternatively conduct over each half cycle. With a capacitor shunting the load R_L, $R_L = \frac{V_{DC} + \Delta V}{2}$, where $\Delta V = \frac{V_S}{f \times R_L \times C}$
  - **f = 2 × Frequency applied AC**
  - **Ripple factor** = $\frac{(\Delta V)_{RMS}}{V_{DC}}$
  - **Peak-inverse voltage = 2 × Peak-secondary voltage**

Fig. 26

Full-Wave Rectifier Circuits

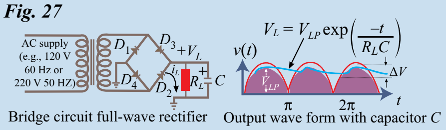


Full-wave rectifier with center-taped transformer

Output wave form without capacitor C

Full-Wave Bridge Rectifier

Fig. 27

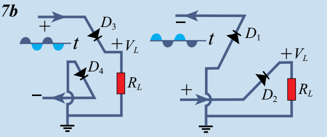


Bridge circuit full-wave rectifier

Output wave form with capacitor C

- As shown (*fig. 27*), this does not require a center-tapped transformer, although it does require four diodes. Based on the instantaneous voltage polarities at the secondary winding ends, diode pairs (D_2, D_3) or (D_1, D_4) conduct and facilitate a full-wave rectified wave form across R_L with the current flow directions as shown.

Fig. 27b

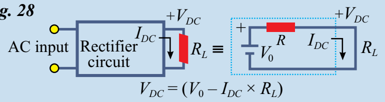


- Peak-inverse rating = Peak-secondary voltage
- **Ripple characteristics:** Identical to those of the full-wave rectifier with a center-tapped transformer

Voltage Regulation

- A rectifier circuit delivering a load current I_{DC} at a DC voltage V_{DC} across a load R_L is represented via the equivalent circuit (*fig. 28*).

Fig. 28



- R denotes the total source resistance and is constituted by the forward resistance of diodes and the secondary winding resistance of the transformer. If the load resistance changes (i.e., as load current demand increases), then V_{DC} decreases.
  - **Percentage regulation (PR) =**

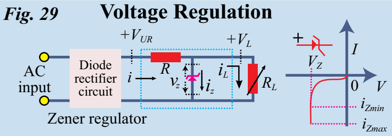
$$\frac{[V_{DC(\text{no load})} - V_{DC(\text{full load})}]\times 100}{V_{DC(\text{full load})}}\%$$

- A regulated DC power supply is designed to offer a desired percentage regulation. High performance should decrease the V_{DC} minimum from no-load to full-load conditions (i.e., $PR \to 0$).

Zener Regulators

- A simple regulated power supply is constructed with a zener diode connected in shunt with the load (*fig. 29*).

Fig. 29 Voltage Regulation



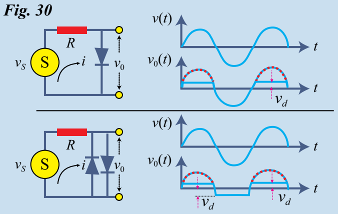
Zener regulator

- If V_{UR} denotes the unregulated voltage at the output of the diode rectifier circuit, then the regulated voltage across R_L is given as $V_L = \frac{R_L(R_z V_{UR} + RV_z)}{R_L(R + R_z) + RR_z}$, where:
  - R = Resistor that is designed to achieve a given % regulation in conjunction with a zener diode of breakdown voltage V_Z that sustains a safe current through it via R_Z limited by I_{Zmax} to I_{Zmin}.
  - When $R_L \to \infty$, $R = \frac{V_{UR} - V_{Lmax}}{I}$ and $I = I_{Lmax} + I_{Zmin} = I_{Lmin} + I_{Zmax}$.
  - P_z (power dissipation in the zener diode) = $V_z I + R_Z I^2$
  - PR (power dissipation in R) = $I^2 R$
  - $V_{Lmax} = R_Z I_{Zmax} + V_Z$
  - $V_{Lmin} = R_Z I_{Zmin} + V_Z$

$$PR = \frac{(V_{Lmax} - V_{Lmin})\times 100}{V_{Lmax}}\%$$

Diode Clipping Circuits

Fig. 30



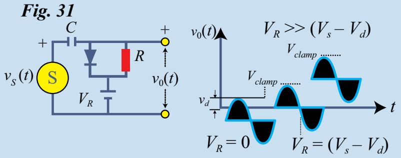
- ON state:
  - R_d = Diode forward resistance
  - V_f^* = Diode projected cut-in voltage V_f

Diode Voltage Clamps

- A voltage clamp shifts the associated DC level without changing the signal wave form (for a positive voltage clamp).
  - $V_s = V_s \sin\omega t$
  - V_f = Diode forward voltage drop
- DC clamping level ≅ V_{clamp}

Note: $RC >> \frac{2\pi}{\omega}$ & $R >> R_d$ and negative clamping is obtained by reversing the polarity of V_R and of the diode (*fig. 31*).

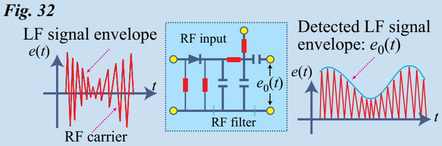
Fig. 31



Diode Envelope Detector

- Used in AM radio circuits to recover the low-frequency audio envelope modulated on a high-frequency carrier $e(t) = V_c[1 + m\cos\omega_m t]\cos\omega_c t$, where:
  - ω_m = Audio modulating signal frequency
  - ω_c = Carrier frequency, $\omega_c >> \omega_m$
  - m = Depth of modulation

Fig. 32

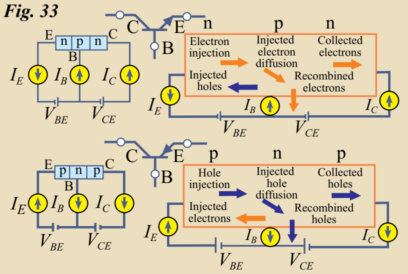


Bipolar Junction Transistors (BJTs)

Definitions

- BJTs are constituted by three semiconductor regions (**emitter**, **base**, and **collector**) forming two PN junctions.

Fig. 33



- There are two types of BJTs (**NPN** and **PNP** transistors). The symbols are shown in *fig. 33*.
- The junctions are termed as emitter-base junction (**EBJ**) and collector-base junction (**CBJ**) (*fig 33*). They are generally used as amplifiers or switches.

Unbiased BJT

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

Biased BJT

- In the active mode operation, EBJ is forward biased and CBJ is reverse biased. The external biasing decreases and increases the depletion layer potentials at EBJ and CBJ, respectively. Thus, the following current flows are realized in the NPN device:
  - Forward bias on EBJ allows electron injection from emitter into base and hole injection from the base to emitter. The injections collectively constitute the **emitter current** (I_E).
  - Emitted electrons in the base region (where they constitute minority carriers) diffuse across the base, and a few electrons are lost because they recombine and appear as a part of the **base current**. The collected electrons across the collector drift to the collector terminal. The electrons under acceleration (due to their kinetic energy) can break the covalent structure to yield additional carriers. Hence, a multiplication process prevails in the collector. Denote the:
    - ▪ Fraction of electrons injected from the emitter as **a < 1 (emitter efficiency)**
    - ▪ Fraction of electrons that survive in the diffusion across the base (after recombination) as the **base-transport factor (b < 1)**
    - ▪ Multiplied carrier ratio in the collector as **c >> 1 (collector multiplication factor)**
  - The net corresponds to **transistor alpha:**
    - ▪ $\alpha = (a.b.c) < 1$
  - The emitter efficiency is determined via the doping levels in the emitter and base. The base-transport factor depends on the base width. With reference to *fig. 33*, emitter current $I_E = I_C + I_B$, where:

Total Base Current

$$I_B = (I_{B_1} + I_{B_2}) = I_E - I_C = \frac{I_C}{\alpha} - I_C = \frac{I_C(1-\alpha)}{\alpha}$$

  - Therefore, $\frac{I_C}{I_B} = \frac{\alpha}{(1-\alpha)} \triangleq$ transistor β. Specifically,

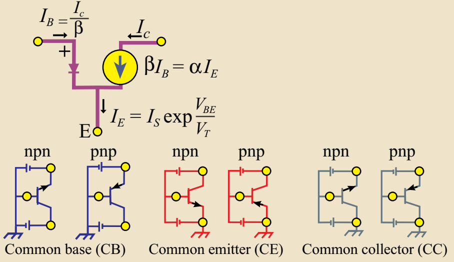
$I_B = \frac{I_C}{\beta}$ is a fraction of I_C. Given that I_B is essentially determined via minority current flow across the EBJ, it is given by $I_B = I_s \exp\left(\frac{V_{BE}}{V_T}\right)$, where $V_T = \frac{k_B T}{q}$

- I_S = Reverse saturation current across the EBJ

Equivalent Circuit of a BJT

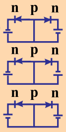
Fig. 34

Eber-Moll's Model



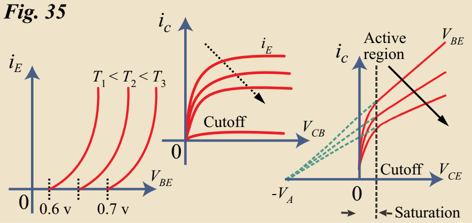
BJT Modes of Operation

MODE	EBJ	CBJ
active	forward biased	reverse biased
saturation	forward biased	forward biased
cutoff	reverse biased	reverse biased



BJT Characteristics

Fig. 35



Analytical Relations of BJT Characteristics

V_{BE} changes by ≈ |**2 mV**|/°C

$\mathbf{i} \Rightarrow i_c, i_E, i_B$

$i_C = \alpha i_E$

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

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

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

Single-Battery Biasing: CE Configurations

Fig. 36a

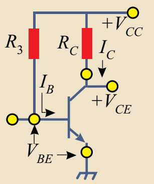


Fig. 36b

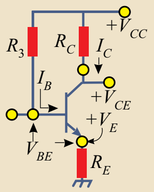


Fig. 36c

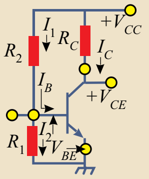
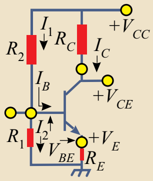


Fig. 36d



Calculation of Biasing Resistor Values

Fig. 36a

$$R_3 = \frac{V_{CC} - V_{BE}}{I_B}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$I_C = \beta I_B$$

Fig. 36b

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$R_E = \frac{V_E}{I_E}$$

$$I_C = \beta I_B$$

Fig. 36c

$$R_2 = \frac{V_{CC} - V_{BE}}{I_1}$$

$$R_1 = \frac{V_{BE}}{I_2}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$I_1 = I_2 + I_B$$

$$I_B = \frac{I_C}{\beta}$$

Fig. 36d

$$R_2 = \frac{V_{CC} - (V_E + V_{BE})}{I_1}$$

$$R_1 = \frac{V_{BE} + V_E}{I_2}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$R_E = \frac{V_E}{I_E}$$

$$I_1 = I_2 + I_B$$

$$I_B = \frac{I_C}{\beta}$$

Operating Point (Q-Point) Calculation

Current bias (*fig. 37*):

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

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

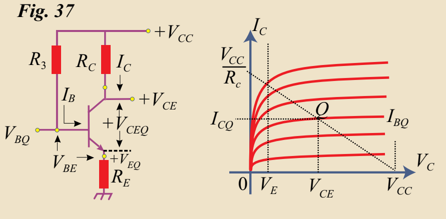
$$I_{EQ} = I_{CQ} + I_{BQ}$$

$$V_{CEQ} = (V_{CC} - I_{CQ} R_C)$$

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

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

Fig. 37



Voltage-Divider Bias

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

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

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

$$V_{BE} = \text{Open-circuit voltage} = V_{CC} = \frac{R_1}{R_1 + R_2}$$

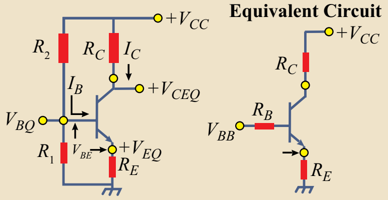
$$V_{BB} = R_B I_{BQ} + V_{BE} + R_E I_{EQ}$$

$$V_{EQ} = I_{EQ} R_E \text{ and } V_{BQ} = V_{BE} + V_{EQ}$$

$$V_{CQ} = V_{CC} - I_{CQ} R_C \text{ and } I_{CQ} = \frac{(V_{BB} - V_{BE})\beta}{[R_B + R_E(1+\beta)]}$$

$$I_{EQ} = \frac{I_{CQ}(1+\beta)}{\beta} \text{ and } I_{BQ} = \frac{I_{CQ}}{\beta}$$

Fig. 38

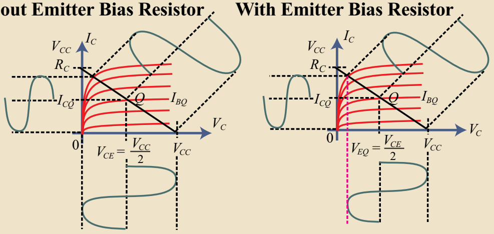


Actual Circuit

Thevenin's Equivalent Circuit

Maximum Dynamic Swing of the Signal

Fig. 39



Without Emitter Bias Resistor

With Emitter Bias Resistor

Biasing for Q-Point Stability

- BJT circuits are sensitive to temperature, power-supply fluctuations, and variations in α (or β) across various pieces. The variations cause Q-point instability.
- **Stabilizing methods:** Current-bias method, voltage-bias method, and voltage-divider method
- Given $I_C = \beta I_B + (1+\beta) I_{CBO}$, the second term corresponds to the leakage current component that is essentially due to minority carrier contribution and is sensitive to temperature.

Fig. 40a

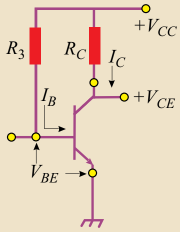


Fig. 40b

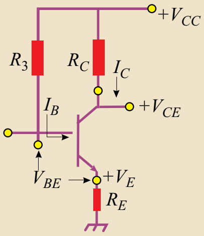


Fig. 40c

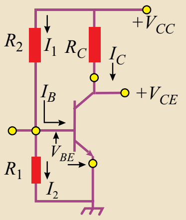
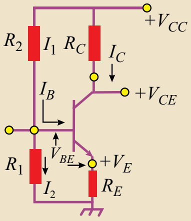


Fig. 40d



- Stability factor: $S = \left.\frac{\Delta I_C}{\Delta I_{CO}}\right|_{V_{CE}}$
- Single resistor with current biasing: $S = (1+\beta) \Rightarrow$ Very large (poor stability)
- Current bias with the emitter resistor:

$$S = (1+\beta)\frac{1 + \frac{R_3}{R_E}}{1 + \beta + \frac{R_3}{R_E}} \rightarrow 1 \Rightarrow \text{(better stability)}$$

- Voltage biasing with the collector-to-base resistor:

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

- Voltage-divider biasing: $S = 1 + \frac{(R_1 || R_2)}{R_E}$
- Recommended design values of S:
  - Small-signal voltage amplifiers: $S \sim 4 - 5$
  - Large-signal power amplifiers: $S \sim 2$

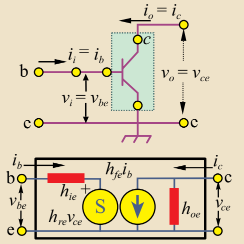
H-Parameter & Hybrid

π Parameter Models of BJTs

- Common emitter configuration (*fig. 41*):
  $v_{be} = h_{ie} i_b + h_{re} v_{ce}$ and $i_c = h_{fe} i_b + h_{oe} v_{ce}$, where:
  - 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 = $\left.\frac{i_c}{v_{ce}}\right|_{i_b=0}$

Fig. 41

Common Emitter Configuration



Relation between the Parameters

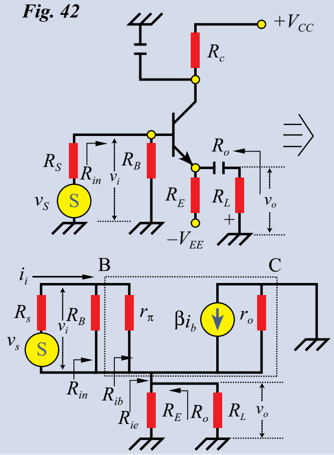
- $g_m \triangleq$ Transfer (mutual) conductance = $\left.\dfrac{\partial I_C}{\partial V_{BE}}\right|_{V_{CE}=\text{constant}}$
- $I_B = I_{BEO}\left[-1+\exp\left(\dfrac{V_{BE}}{\eta V_T}\right)\right]$ and $I_C = h_{fe} I_B$, where:
  - η = 1 to 2
- $V_T = \dfrac{k_B T}{q} = \left(\dfrac{T^\circ K}{11600}\right)$ volts, where:
  - k_B = Boltzmann constant and q = electronic charge
- $\dfrac{\partial I_B}{\partial V_{BE}} = \dfrac{I_{BEO}}{\eta V_T}\exp\left(\dfrac{V_{BE}}{\eta V_T}\right) \cong \dfrac{I_B}{V_T}$
- $h_{fe} = \left.\dfrac{\partial I_C}{\partial I_B}\right|_{V_{CE}=\text{constant}}$
- $g_m = \left(\dfrac{\partial I_C}{\partial I_B}\right)\left(\dfrac{\partial I_B}{\partial V_{BE}}\right) = \dfrac{h_{fe} I_B}{\eta V_T} = \dfrac{I_C}{\eta V_T} \cong \dfrac{I_C}{0.026} S$ at 27°C

Approximate Relation between the Parameters

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

Common Collector (CC) Amplifier

Fig. 42



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

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

$\dfrac{v_i = v_b}{v_s} = \dfrac{R_{in}}{R_{in} + R_s}$, $\dfrac{v_e = v_o}{v_i} = \dfrac{R_e}{R_e + r_e}$, and $R_e = R_E \| r_o \| R_L$

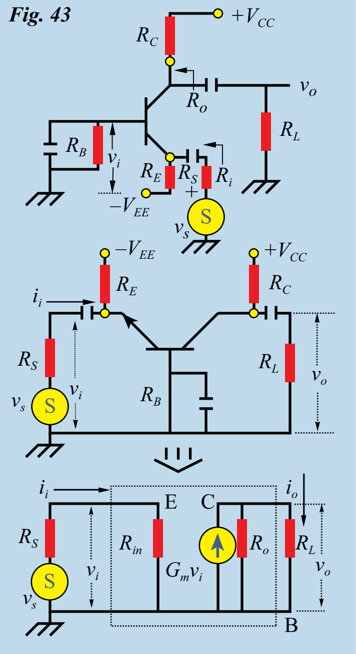
$$A_v = \frac{v_o}{v_s} = \frac{R_{in}}{R_{in}+R_s} \times \left(\frac{R_e}{R_e + r_e}\right) \approx \frac{R_L}{R_L + R_o} \approx 1$$

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

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

Common Base (CB) Amplifier

Fig. 43



$R_{in} = R_E \| r_e \approx r_e$

$G_m = \dfrac{i_o = i_c}{v_i} = \dfrac{-\alpha i_e}{r_e}$, but $i_e = \left(\dfrac{-v_i}{r_e}\right) \therefore G_m = \dfrac{\alpha}{r_e} = g_m$

$R_o = R_C$

$A_v = \dfrac{v_o}{v_i} = G_m R_0 \equiv g_m R_C$

Overall gain: $\dfrac{v_o}{v_s} = \dfrac{R_i}{R_i + R_s} \times G_m (R_c \| R_L)$

Current gain: $\dfrac{i_o}{i_i} = \dfrac{g_m v_i}{\frac{v_i}{R_{in}}} = g_m R_{in} = g_m r_e = \alpha$

Comparison of the Parameters of CB, CE & CC Amplifiers

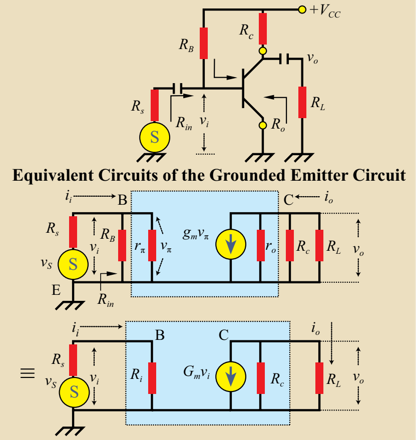
	CB	CE	CC(EF)
R_{in}	$r_e + \dfrac{r_b}{\beta_o}$	$r_b + \beta_o r_e$	$\beta_o(R_L + r_e)$
R_o	$r_e \rightarrow \infty$	$\dfrac{r_c}{\beta_o} \rightarrow \infty$	$r_e + \dfrac{R_s + r_b}{\beta_o}$
A_i	α_o	$-\beta_o$	β_o
A_v	$\dfrac{\alpha_o R_L}{r_e + \frac{r_b}{\beta_o}}$	$-\dfrac{\alpha_o R_L}{r_e + \frac{r_b}{\beta_o}}$	$\dfrac{R_L}{R_L + r_e}$
$\beta_o >> 1$ and $R_L << r_e$			

Common Emitter (CE) Amplifier

Fig. 44

Grounded Emitter Circuit

Equivalent Circuits of the Grounded Emitter Circuit



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

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

Current gain = $\dfrac{i_o}{i_1} = \dfrac{G_m v_i}{\frac{v_i}{R_i}} = G_m R_i = -g_m (R_B \| r_\pi) =$

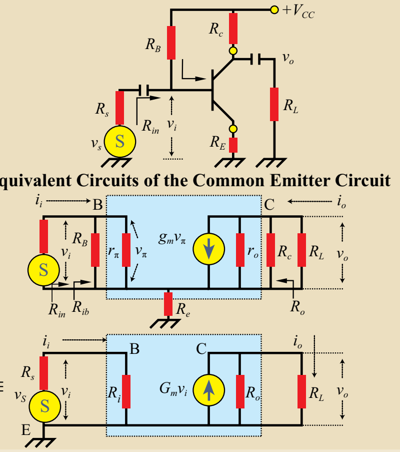
$\dfrac{-g_m r_\pi R_B}{R_B + r_\pi} = -\beta \dfrac{1}{1 + \frac{r_\pi}{R_B}}$

$\dfrac{v_o}{v_s} = \dfrac{v_i}{v_s} \times \dfrac{v_o}{v_i} = \left(\dfrac{R_{in}}{R_{in} + R_s}\right) G_m (R_o \| R_L) \Rightarrow$ Overall voltage gain

Fig. 45

Common Emitter Circuit with Emitter Resistance

Equivalent Circuits of the Common Emitter Circuit



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

$v_\pi + \left(g_m + \dfrac{1}{r_\pi}\right) v_\pi R_E \therefore v_b = v_\pi \left(1 + \dfrac{R_E}{r_E}\right)$

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

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

Input resistance = (1 + β) × Total resistance looking into the emitter circuit ÷ Resistance reflection rule

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

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

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

If $r_\pi(1 + g_m R_E) >> R_s$, $A_V \cong \dfrac{-R_C \| R_L}{r_e + R_E}$

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