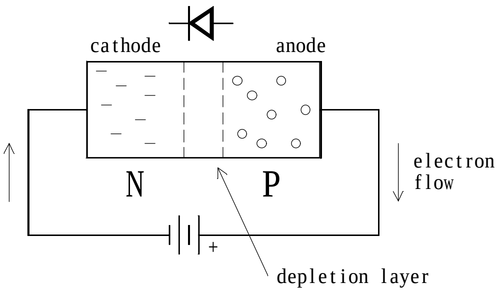
SEMICONDUCTORS

ELTE 1403

Forward biased diode:



An ideal diode acts like a closed switch when forward biased and an open switch when reverse biased. 1st approximation calculations assume an ideal diode. 2nd approximation calculations take into account the voltage drop across the diode. 3rd approximation calculations additionally take into account bulk resistance.

Voltage Drop   silicon diode .7V   germanium diode .3V

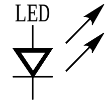
Bulk Resistance $r_B = \Delta E / \Delta I$

A *digital multimeter* won't measure the resistance on a diode due to insufficient voltage. The *diode check* function of a digital multimeter reads the knee voltage. The knee voltage is the voltage at which a forward biased diode begins to conduct.

Diode Ratings:

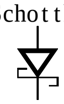
- PIV Reverse Breakdown Voltage
- I_f Forward Current Limit
- I_S Saturation Current - minority carrier current of a reverse-biased diode
- R_f Forward Resistance
- V_k Knee Voltage

LED



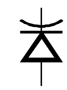
Light Emitting Diode When forward-biased, free electrons combine with holes near the junction. As they move from an area of higher energy to lower energy, they emit radiation. Assume 2V drop unless specified.

Schottky



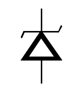
Schottky Diode has almost no charge storage, so can switch on and off much faster than an ordinary diode. Has metallic/silicon junction; low power handling; .25V offset voltage; used for high frequencies.

Varactor



Varactor is a silicon diode optimized for its variable capacitance when reversed-biased. Used for tuning frequency-dependent equipment.

Zener



Zener Diode is designed to operate in the breakdown region; used for voltage regulation.

Avalanche Effect Reverse voltage exceeds the breakdown voltage and the minority carriers are given enough energy to dislodge valence electrons from their orbits. These free electrons then dislodge others.

Zener Effect The electric field becomes strong enough across the junction of a heavily-doped reverse-biased diode to pull valence electrons from their shells. For breakdown voltages below 5V, the Zener effect dominates, above 6V the avalanche effect dominates.

Second Approximation for a Zener Diode

$$I_z = \frac{V_{in} - V_z}{R_s + R_z}$$

I_z = zener current
V_{in} = supply voltage
V_z = zener voltage
R_s = source resistance
R_z = zener resistance

Zener Resistance is the small series resistance of a zener diode when it operates in the breakdown region.

$$\Delta V_{out} = \Delta I_z R_z$$

ΔV = change in output voltage
ΔI_z = change in zener current
R_z = zener resistance

Half-Wave Rectifier: $V_{dc} = \frac{V_p}{\pi} = \frac{V_{rms}\sqrt{2}}{\pi}$

diode reverse voltage: $\text{PIV} = V_p$

diode forward current: $I_{\text{diode}} = I_{dc}$

Half-Wave Rectifier With Capacitor Filter: $\text{PIV} = 2V_p$

$V_{dc} = V_p = V_{rms}\sqrt{2}$

Full-Wave Rectifier: $V_{dc} = \frac{V_p}{\pi} = \frac{V_{rms}\sqrt{2}}{\pi}$

V_p is the voltage across the full secondary winding)

diode reverse voltage: $\text{PIV} = V_p$

diode forward current: $I_{\text{diode}} = \frac{1}{2} I_{dc}$

Full-Wave Rectifier With Capacitor Filter: $V_{dc} = \frac{1}{2}V_p = \frac{1}{2}V_{rms}\sqrt{2}$

Bridge Rectifier: $V_{dc} = \dfrac{2V_p}{\pi} = \dfrac{V_{rms}2\sqrt{2}}{\pi}$

diode reverse voltage: $\text{PIV} = V_p$

diode forward current: $I_{\text{diode}} = \frac{1}{2}I_{dc}$

Bridge Rectifier With Capacitor Filter: $V_{dc} = V_p = V_{rms}\sqrt{2}$

Further refined to include the effect of ripple voltage: $V_{dc} = V_p - \dfrac{V_{rip}}{2}$

Ripple Formula for a capacitor-input filter

$$V_{rip} = \frac{I_{dc}}{f\,C}$$

V_{rip} = peak-to-peak ripple
I_{dc} = dc peak load current
f = ripple frequency (**twice** the input frequency for a full-wave rectifier)
C = filter capacitance

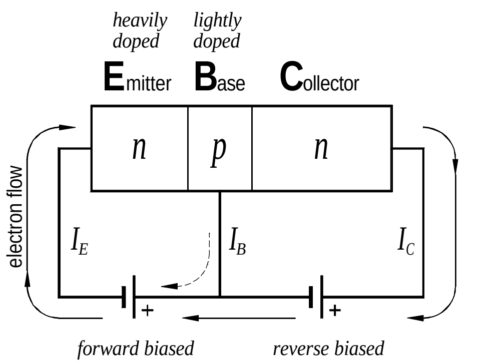
A choke is an iron-core inductor with a large value of L in Henrys. The choke has an inductive reactance in ohms of: $X_L = 2\pi f L$

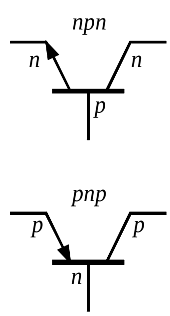
A capacitor has an inductive reactance in ohms of: $X_C = \dfrac{1}{2\pi f C}$

The resonant frequency of an inductor and capacitor (or varactor) in parallel: $f = \dfrac{1}{2\pi\sqrt{LC}}$

Clipper: Removes either the positive or negative peaks of a sine wave by shorting through a diode.
Clamper: Raises or lowers the sine wave so that it becomes mostly positive or mostly negative.
Or Gate: Output goes high when any input is high.
And Gate: Output goes high when all inputs are high

TRANSISTORS

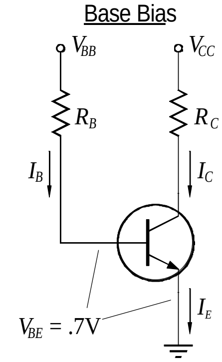




(the n is next to the arrow)

$$I_E = I_B + I_C \qquad V_{CE} = V_{CC} - I_C R_C$$

Bias: difference in potential between base and emitter.



DC Alpha: (slightly less than 1) $\alpha_{DC} = \dfrac{I_C}{I_E}$

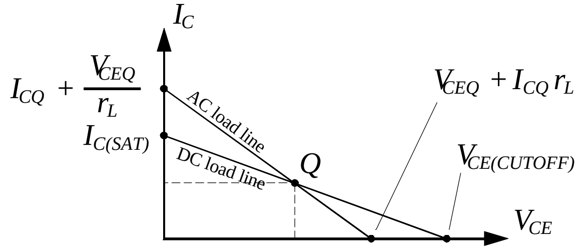
$$\alpha_{DC} = \frac{\beta_{DC}}{\beta_{DC}+1}$$

DC Beta: (usually 50 - 300) $\beta_{\text{DC}} = \dfrac{I_C}{I_B}$

h_{FE} is the same as β_{DC}, the collector to emitter current gain

The four operating regions of a transistor are **saturation**, **active**, **cutoff**, and **breakdown**.

DC and AC Load Lines, Q Point



The DC Load Line is a graph representing all possible dc operating points of the transistor for a specific load resistor. V_{CE} is the x-axis and I_{C} is the y-axis. The equation is $V_{CE} = V_{CC} - I_C R_C$. The horizontal intercept will be the supply voltage V_{CC} and the vertical intercept will be the collector current when the transistor is saturated, i.e. the collector/emitter is considered a closed switch.

The Q Point is the operating point of the transistor, usually located near the middle of the DC Load Line

AC Load Line The Q point moves along the AC load line. Steeper than the DC load line.

$$i_{c(sat)} = I_{CQ} + \frac{V_{CEQ}}{r_L}$$
$$v_{ce(cutoff)} = V_{CEQ} + I_{CQ} r_L$$

AC Compliance - maximum peak to peak AC output voltage without clipping. AC Compliance is calculated by finding the smaller of the following:

Cutoff Clipping:	Saturation Clipping:
$PP = 2I_{CQ} r_L$	$PP = 2V_{CEQ}$

When the Q point is centered on the DC load line, cutoff clipping occurs first because the AC load line is always steeper than the DC load line.

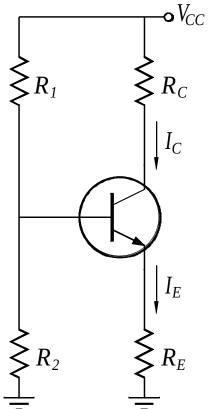
DC Compliance is the DC voltage range over which the transistor can operate; in other words V_{CC}.

Voltage Divider Bias: The *Base Bias* circuit above is usually impractical in linear circuits because the Q point is unpredictable due to variations in β_{DC}. The *Voltage Divider Bias* shown at right solves this problem. When β_{DC} is known, I_E may be calculated as:

$$I_E \cong \frac{V_B - V_{BE}}{R_E + (R_1 \| R_2)/\beta_{dc}}$$

But when $R_E >> \dfrac{R_1 \| R_2}{\beta_{dc}}$,

the equation may be reduced to: $I_E \cong \dfrac{V_B - V_{BE}}{R_E}$



1) Calculate the voltage at the base
2) The emitter voltage is .7 less than the base
3) Calculate I_E
4) $I_C \cong I_E$
5) Calculate voltage drop across R_C

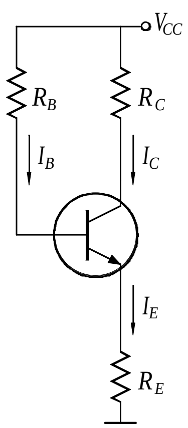
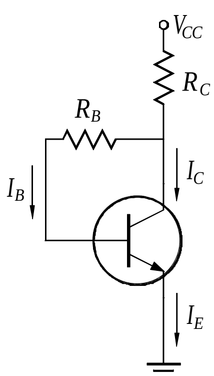
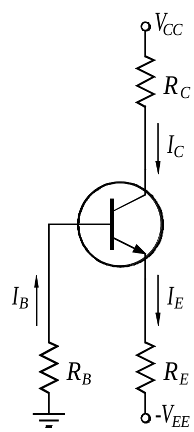
When designing the voltage divider bias amplifier, the current through the voltage divider should be at least 10 times the current through the base.

To center Q on the DC load line, V_{CE} will be ½V_{CC}, V_E will be about .1V_{CC}.

To center Q on the AC load line, use the formula:

$$I_{CQ} = \frac{V_{CC}}{R_C + R_E + r_L}$$

Other Biasing Methods

Emitter Feedback Bias	Collector Feedback Bias	Emitter Bias
		
$I_C \cong \dfrac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{dc}}$	$I_C \cong \dfrac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{dc}}$	$I_E \cong \dfrac{V_{EE} - V_{BE}}{R_E}$

AC Resistance of a Diode: where I is the dc current through the diode. To a second approximation, consider the .7V drop across the diode in calculating the value I.

$$r_{ac} = \frac{25\text{mV}}{I}$$

AC Emitter Resistance of a Transistor:

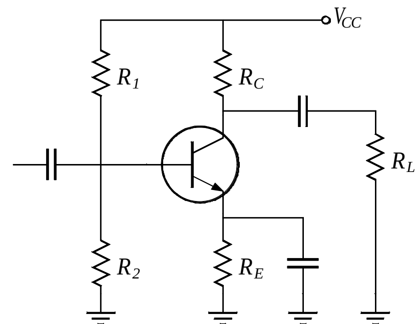
$$r'_e = \frac{25\text{mV}}{I_E}$$

AC Beta: Called β as opposed to β_{dc} (DC Beta). Referred to as h_{fe} as opposed to h_{FE} for DC Beta.

$$\beta = \frac{i_c}{i_b}$$

CE Characteristics:
Output is out of phase with input
High voltage gain is possible
May be used with a swamping resistor to stabilize the voltage gain
In a *matched load* condition, $R_L = R_C$

Common Emitter



AC Input Impedance of CE Amplifier:

$$z_{in} = R_1 \| R_2 \| \beta r'_e$$

AC Voltage Gain (CE) when the emitter is AC ground:

$$A = \frac{V_{out}}{V_{in}} = \frac{r_L}{r'_e}$$

Swamping Resistor To desensitize a CE amplifier to changes in r'_e, a resistor r_E is added between the emitter and ac ground. This stabilizes the amount of gain, but also reduces it.

$$z_{in(base)} = \beta(r_E + r'_e)$$

$$z_{in} = R_1 \| R_2 \| \beta(r_E + r'_e)$$

$$A = \frac{r_L}{r_E + r'_e}$$

Heavy Swamping The value of r_E is much larger than the value of r'_e:

$$z_{in} = R_1 \| R_2 \| \beta r_E$$

$$A = \frac{r_L}{r_E}$$

AC Input Voltage when a source resistor (a resistor in series with the input) is present.

$$v_b = \frac{v_{in} z_{in}}{R_s + z_{in}}$$

AC Load Resistance, r_L, r_c, or r_{Lac}, is the parallel combination of all AC paths from collector to ground. Remember the battery and capacitors are considered shorts.

AC Power delivered to the load (class A amplifier):
where V_L is *rms*: $P_L = \dfrac{V_L^2}{R_L}$ using peak to peak volts: $P_L = \dfrac{V_{PP}^2}{8R_L}$

Quiescent Power Dissipation of a transistor:

$$P_{DQ} = V_{CEQ} I_{CQ}$$

Efficiency of a stage: P_L is load power at AC compliance

$$\eta = \frac{P_{L(\max)}}{P_{CC}} \times 100\%$$

Total Current Drain is the voltage divider current plus the collector current:

$$I_{CC} = I_1 + I_{CQ}$$

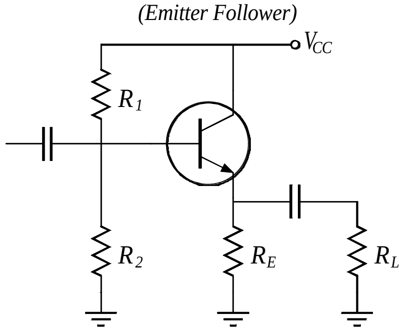
Cascaded Stages Gain: $A = A_1 A_2 A_3$

Cascaded Stages The AC load resistance of one stage is affected by the impedance of the following stage:

$$r_L = R_C \| z_{in}$$

CC Characteristics:
Voltage gain < 1
High input impedance
AC output is in phase
Low-distortion
Has power gain
Can be placed at the output of a CE amplifier to reduce output loading and thereby increase the gain.

Common Collector
(Emitter Follower)



Input Impedance (high) of a CC: $R_1 \| R_2 \| \beta(r_L + r_e')$

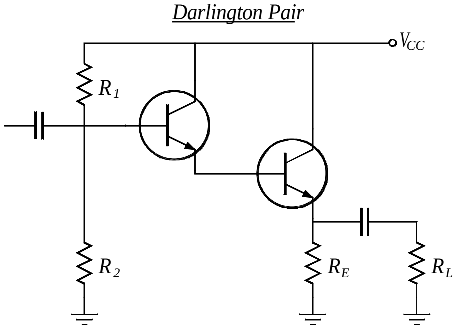
AC Voltage Gain of a CC is slightly less than 1: $A = \dfrac{r_L}{r_L + r_e'}$

AC Power Gain of a CC: $G = \beta \dfrac{r_L}{r_L + r_e'} = \beta A \cong \beta$

AC Output Power of a CC: $P_{out} = i_e^{\,2} r_L$

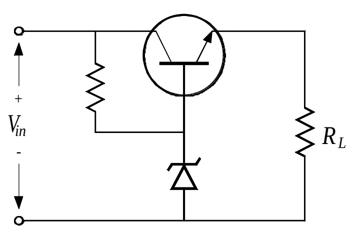
The Darlington Amplifier consists of cascaded CC's for a very large increase in input impedance.

Darlington Pair



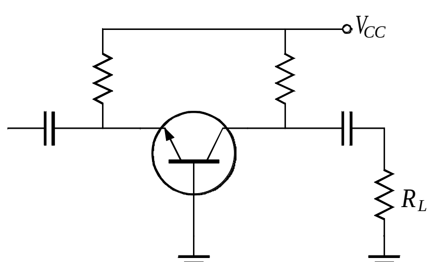
The Zener Follower is a voltage regulator circuit that offers improved load handling over the zener regulator. Voltage output is .7V less than the value of the zener diode.

Zener Follower



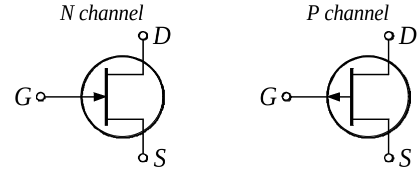
CB Characteristics:
Low input impedance
Large voltage gain
AC output in phase
Useful at high frequencies
Not as popular as CE or CC
A **differential amplifier** is a CB driven by a CE

Common Base

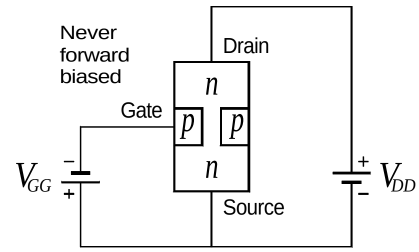


Field Effect Transistors

Junction Field Effect Transistor JFET

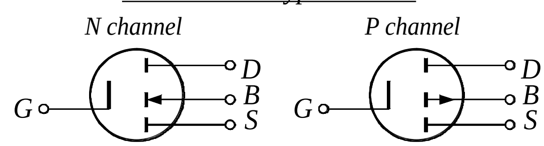


Creating a depletion region by reverse biasing the gate reduces (*pinches*) current between the drain and the source.



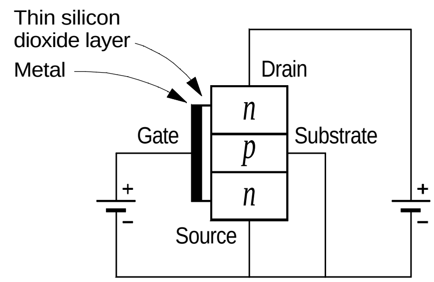
Metal Oxide Silicon Field Effect Transistors

Enhancement-type MOSFET

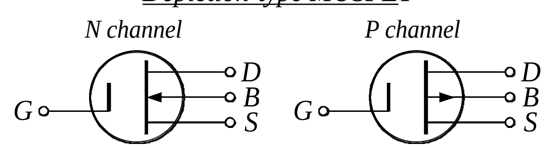


G Gate
D Drain
B Substrate*
S Source

*usually connected internally to the source



Depletion-type MOSFET



Depletion-type MOSFET

MOSFET's do not have thermal runaway.