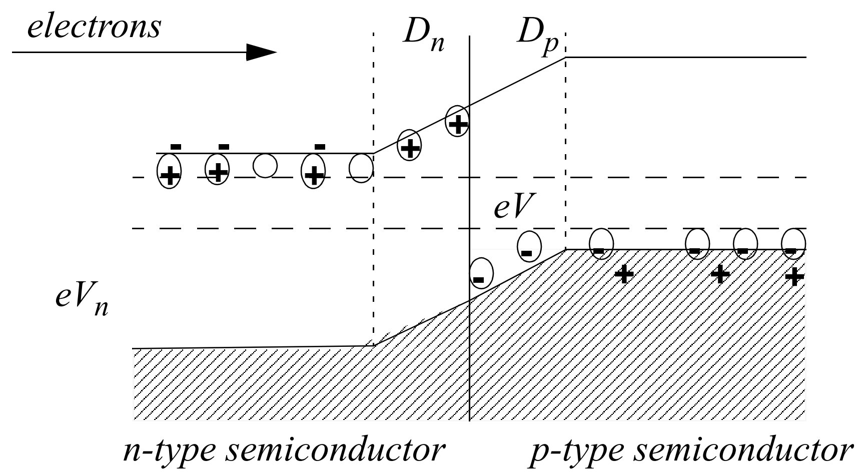
Bipolar Junction Transistors

Diffusion at a p-n Junction

- Forward-biased p-n junction



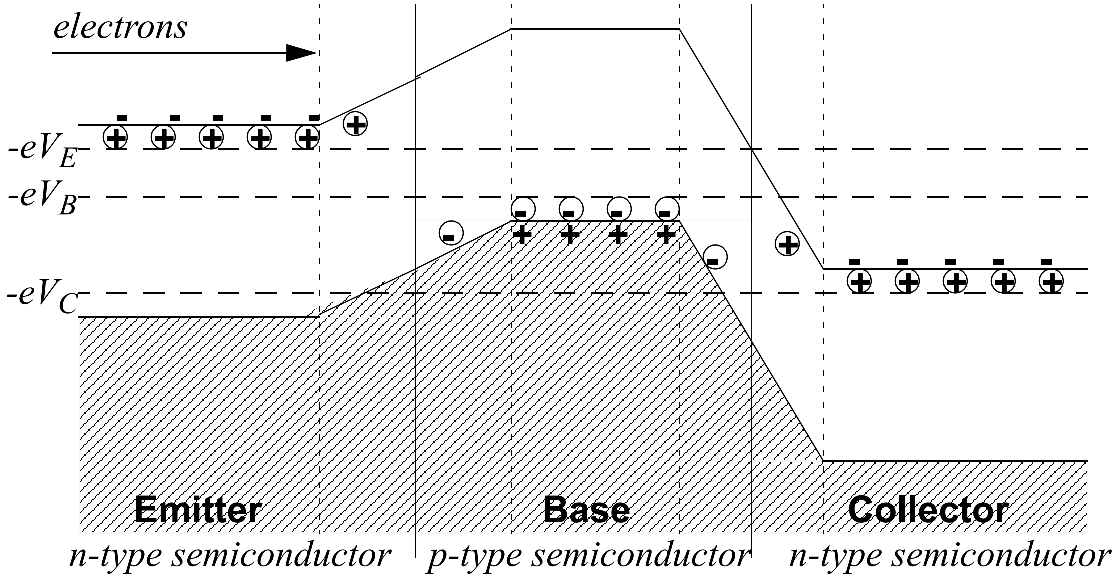
- Electrons move into p-type material and are picked up by holes.
- Mean free time in the p-type material is related to the density of holes.
- In typical doped silicon $\tau = 10^{-3}$ to 10^{-6} s to recombine, but the time between scattering is about $\tau = 10^{-12}$ s.
- The diffusion time is proportional to the diffusion length squared

$$L \propto \sqrt{\tau}$$

- The mean free path for scattering is about 0.1 μm, so the mean free path for recombination is about 100 μm.

Two p-n Junctions

- An n-p-n device has two p-n junctions



- Electrons in the n-type emitter are at the most negative potential.
  The first p-n junction is biased so electrons flow into the base.
  Some electrons will recombine in the base, others make it across the base without recombining.
- The second p-n junction is reverse-biased and has no barrier for electrons flowing from p-type to n-type material.
- Electrons that make it to the collector will immediately enter the collector to continue as current.

- A pnp transistor is very similar except that the current is due to holes.

Current Flow in a BJT

- The current in the collector is proportional to the emitter current reduced by electrons absorbed by the base.

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

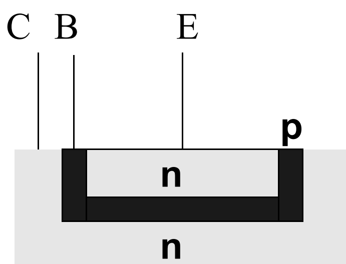
  α is the fraction of electrons able to get through the base to the collector.

  I_{co} is the reverse current due to the normal base-collector junction, but this is very small.

- An ideal junction would have $\alpha = 1$.

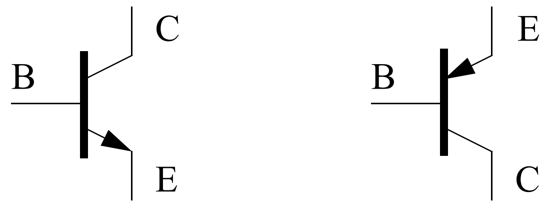
  Real transistors have $\alpha = 0.95$ to 0.99.

- α is best for thin bases or lightly doped bases.
- If the base doping is equal to the emitter doping then half the emitter current would be due to base carriers, and α could not exceed 0.5.



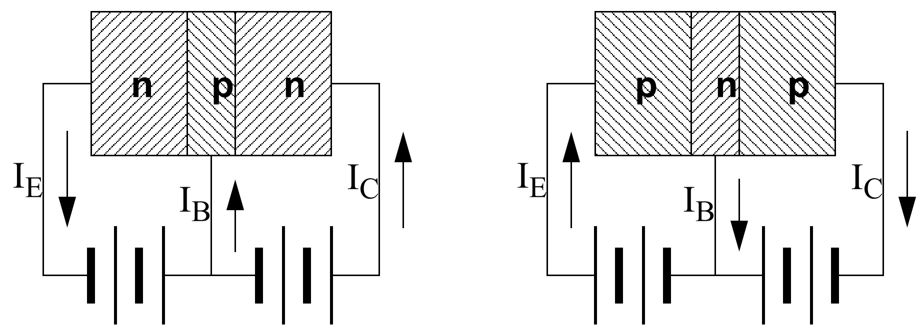
BJTs as Circuit Elements

- Schematic symbol:



npn **pnp**

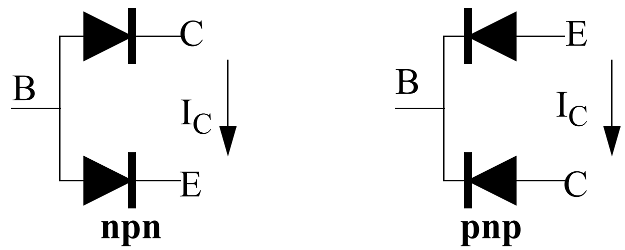
- Transistor biasing:



npn **pnp**

Diode Model

- The transistor can be viewed as two diodes



- A transistor can be checked with an ohmmeter
- Forward current I_{BE} is like a diode, exponential I with V over any orders of magnitude
- Typical currents I_C are mA at 0.6 V in Si (0.25 V in Ge)
- V_{CB} is limited by reverse breakdown like a diode: 10-20 V typically.
- Transistor limits $V_{CE\ max}$ and $P_{max} = I_C V_{CE}$

Collector Current

The collector current I_C is not like a diode!

- Use Kirchoff's law at the junction:

$$I_E = I_B + I_C$$

- Include the effect of carriers through the base:

$$I_E = I_B + \alpha I_E + I_{CO} \cong I_B + \alpha I_E$$

- The relation between base current and emitter current is:

$$I_E = \frac{1}{1-\alpha} I_B$$

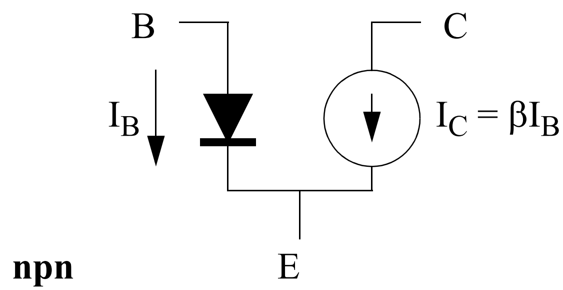
- And the relation between base current and collector current is:

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

Current Model

- A reverse bias diode looks like a current source/sink until breakdown

- Treat the C-E junction as a current source:



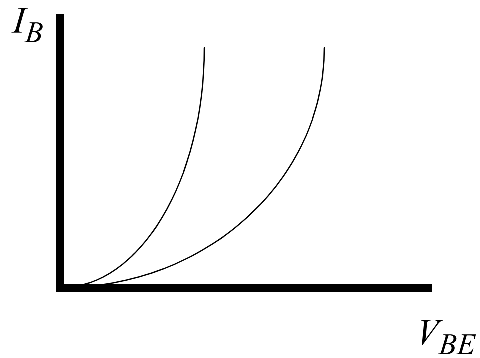
BJT Transistor Rules

1. $V_C > V_E$ **(npn),** $V_C < V_E$ **(pnp)**
2. **B-E and B-C junctions are like diodes**
3. **There are** $I_{C\,max}$, $I_{B\,max}$, **and** $V_{BE\,max}$ **like diodes**
4. $I_C = \beta I_B = h_{fe} I_B$

Voltage - Current Curves

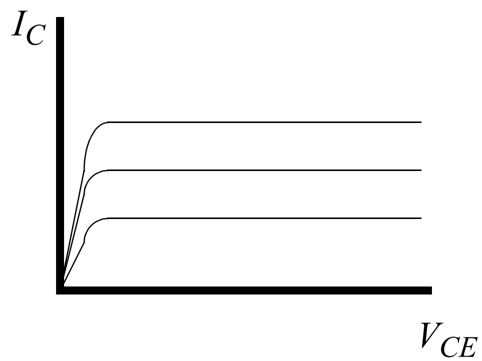
- Two graphs determine transistor properties.
- Input (V-I for base to emitter) is a typical diode graph

  Different curves depend on V_{CE} biasing



- Output (V-I for collector to emitter) looks like a current source

  Different curves depend on I_B



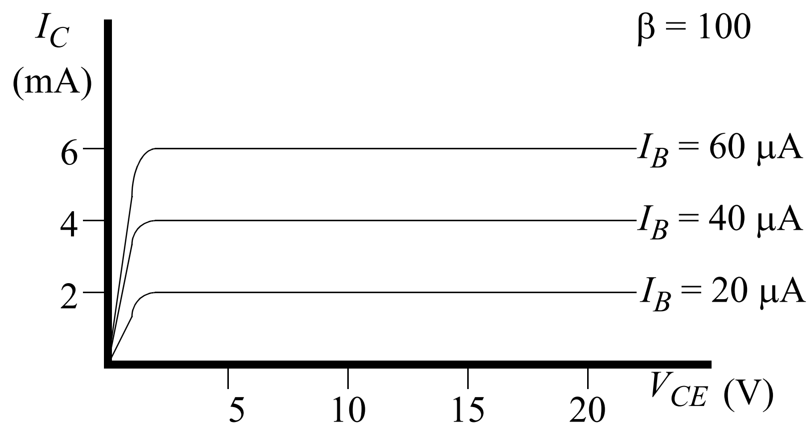
- Selecting V_{BE} and V_{CE} determines the behavior of the transistor

Beta Factor

- The relation between base current and collector current is:

$$I_C = \beta I_B$$

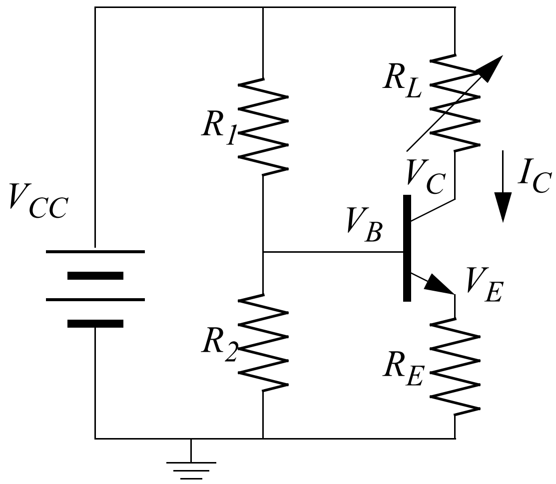
- Output transistor curves show the amplification factor β.
- Compare the ratio of I_B to I_C in the region of constant current.



In the above example, as I_B goes from 20 μA to 60 μA, I_C goes from 2 mA to 6 mA. The ratio 4 mA / 40 μA = 100 = β.

Common Emitter

- The emitter is in common to input and output.



$$V_C = V_{CC} - I_C R_L$$

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$V_E = I_E R_E \cong I_C R_E$$

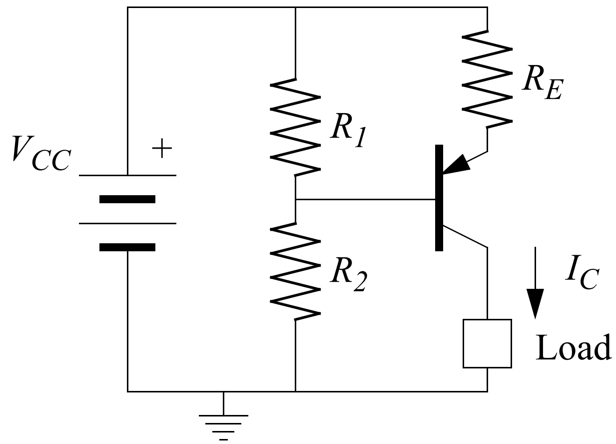
- From the transistor rules:

$$V_E = V_B - 0.6V$$

$$I_C = (V_B - 0.6V)/R_E$$

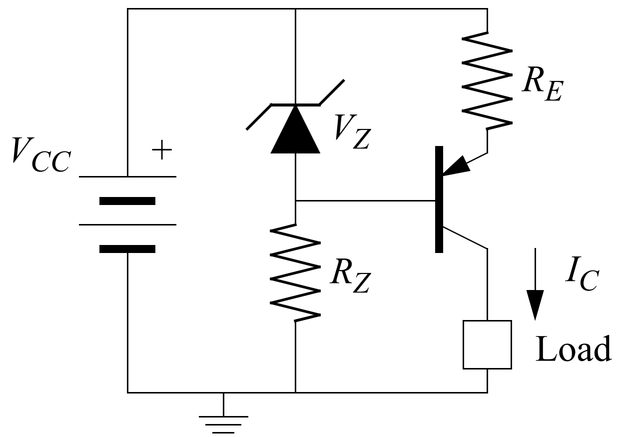
pnp Common Emitter

- A pnp-transistor is a source of current instead of a current sink.



- With the pnp the load can be directly attached to ground if the power supply is positive.

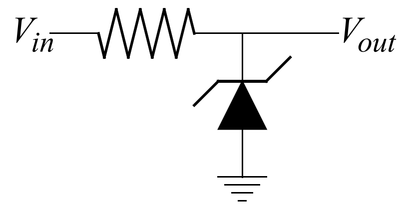
- Current sources can also be biased by diodes and zeners.



$$I_C = (V_Z - 0.6V)/R_E$$

Zener Diode Regulation

- A single zener diode and resistor will regulate voltage:



- Power consumption is based on the current through the zener:

$$P_Z = \left(\frac{V_{in} - V_{out}}{R} - I_{out}\right) V_Z$$

- Consider the following requirements:

  $V_Z = +10$ V,

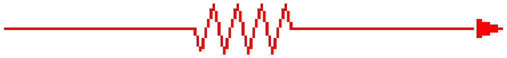
  $I_{out} < 100$ mA,

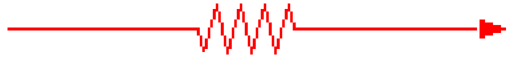
  $V_{in} = 20\text{-}25$ V.

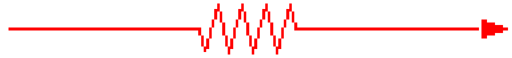
  The zener needs at least 10 mA to operate :

  $R < (20\text{-}10)$ V/110 mA $< 100\ \Omega$.

$$P = \left(\frac{25\,V-10\,V}{} - 0\,mA\right)10\,V = 3\,W$$

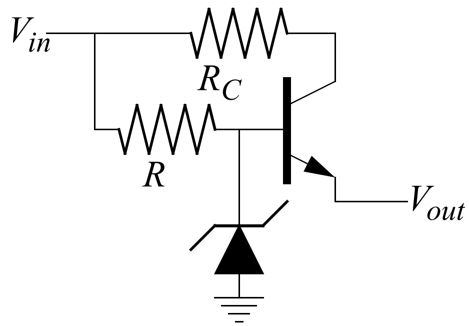






Common Collector Follower

- Combine a follower and a zener:



$$V_{out} = V_Z - 0.6V$$

- The current flows through R_C so R can be large and I_Z is small.

- As before, consider V_Z = +10.6 V, V_{in} = 20-25 V. The zener needs at least 10 mA to operate and R < (20-10) V/10 mA < 1 kΩ.
- The base current is negligible.

$$P_Z = \left(\frac{25V - 10.6V}{680\Omega} - 0mA\right)10.6V = 0.22W$$

- For the transistor, I_{out} < 100 mA.
- The maximum power dissipation in R_C or the transistor is $P = IV$ = (0.1 A)(15 V) = 1.5 W