Small Signal Diode Models

- This small signal diode model is for the mid-band frequency range
- At high frequencies, impedances due to parasitic C’s become a factor
- SPICE will model these parasitics if the values are properly entered in the device models

```
************************
* B2 Spice default format (same as Berkeley Spice 3F format)

diode 1  0 40eps12
R 2  1  1K
V 2  0 DC 0
IVm 1  0 0

.model 40eps12 D  is = 1e-15   rs = 0.00426912   n = 0.926332   tt = 1e-09   cjo = 1e-11   vj = 0.7
+ m = 0.5   eg = 0.6   xti = 0.5   kf = 0   af = 1
+ fc = 0.5   bv = 1200   ibv = 0.0001
```

Junction (Depletion) Capacitance

- Depletion capacitance in terms of SPICE3 model parameters

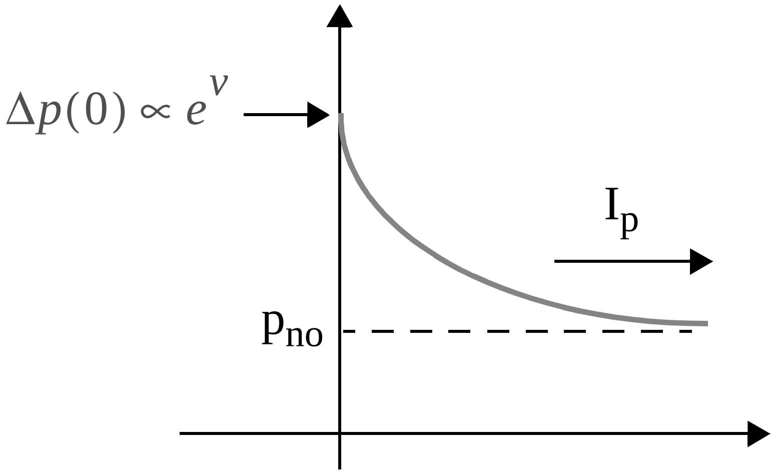
$$C_j = \frac{C_{jo}}{\left(1 - \frac{V_D}{V_j}\right)^m}$$

- This is the dominant capacitance component under reverse bias conditions
- It is also present under forward bias conditions --- since there is a depletion region
- For forward bias, this equation is not very accurate, and $2C_{jo}$ is used (why is it greater than C_{jo}?)
- But this is not the dominant component for forward bias

Forward Bias Small Signal Diode Models

- Dominant capacitance is due to stored diffusion charge
- If n-side is more lightly doped than p-side, then diffusion current is dominated by holes injected into the n-side

$$\frac{Q_p}{\tau_p} = I_p$$



- SPICE models this in terms of an average transit time, the average time a hole stays in the n region of the diode (or: an electron stays in the p region)

$$Q_p = I_p \tau_T$$

Diode Models

- The corresponding capacitance is nonlinear, but can be specified at an operating point

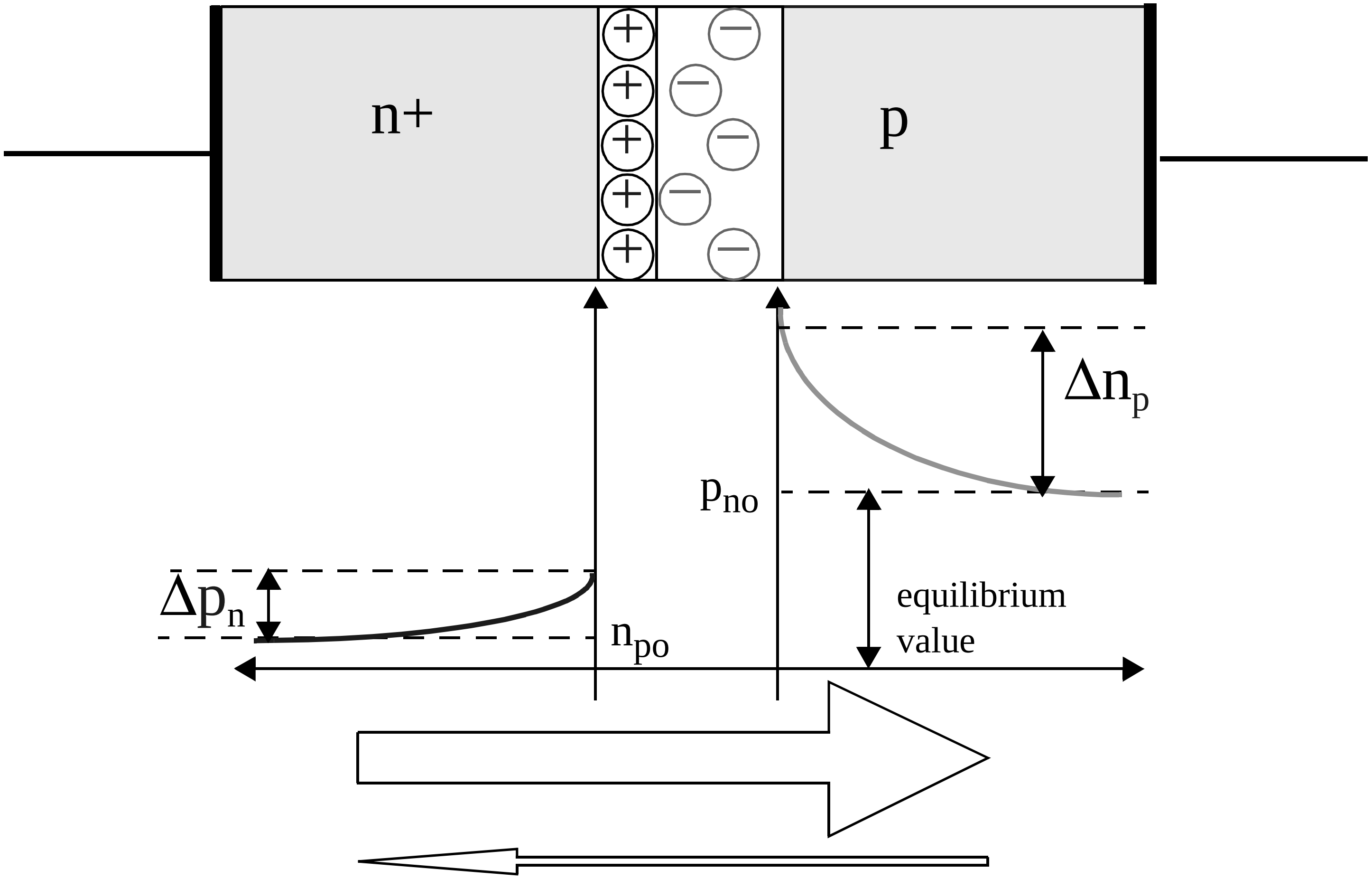
- What does the complete diode SPICE model look like?

Small Signal SPICE Diode Models

- What does the small signal diode model look like after determining the dc operating point?

Asymmetrical diode

- In the asymmetrical junction (p^+n or n^+p), the lightly doped region is sometimes called “the base”
- Usually, most of the current flowing through a p^+n or n^+p junction is due to injection of minority carriers into “base” from the highly doped region.



Short base vs long base

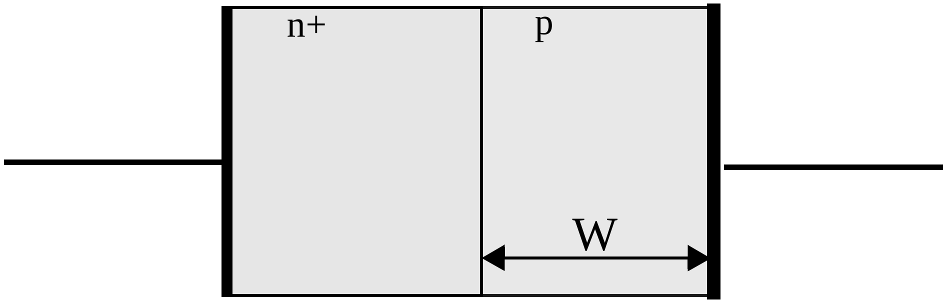
- How far, on average, a minority carrier goes in the base depends upon:

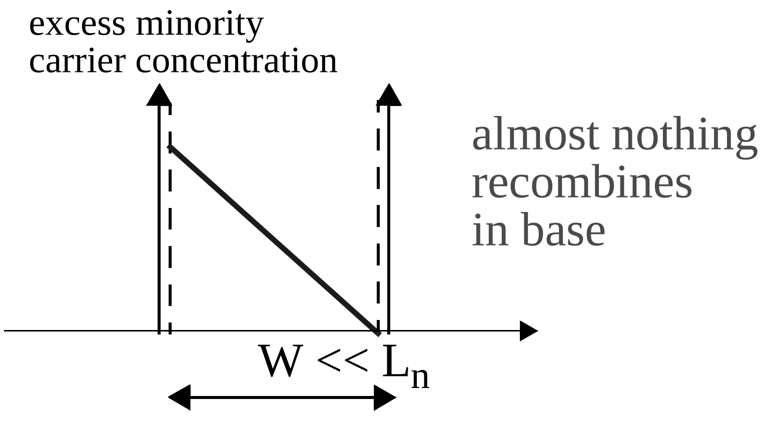
  - Diffusion constant D_n (how fast the particles flow)

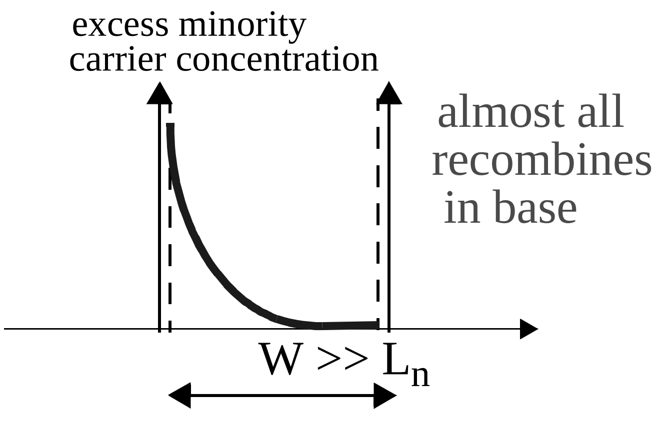
  - Minority carrier lifetime τ_n (how long a particle survives on average)

- We define a diffusion length of electrons in p type Si:

$$L_n = \sqrt{\tau_n D_n}$$

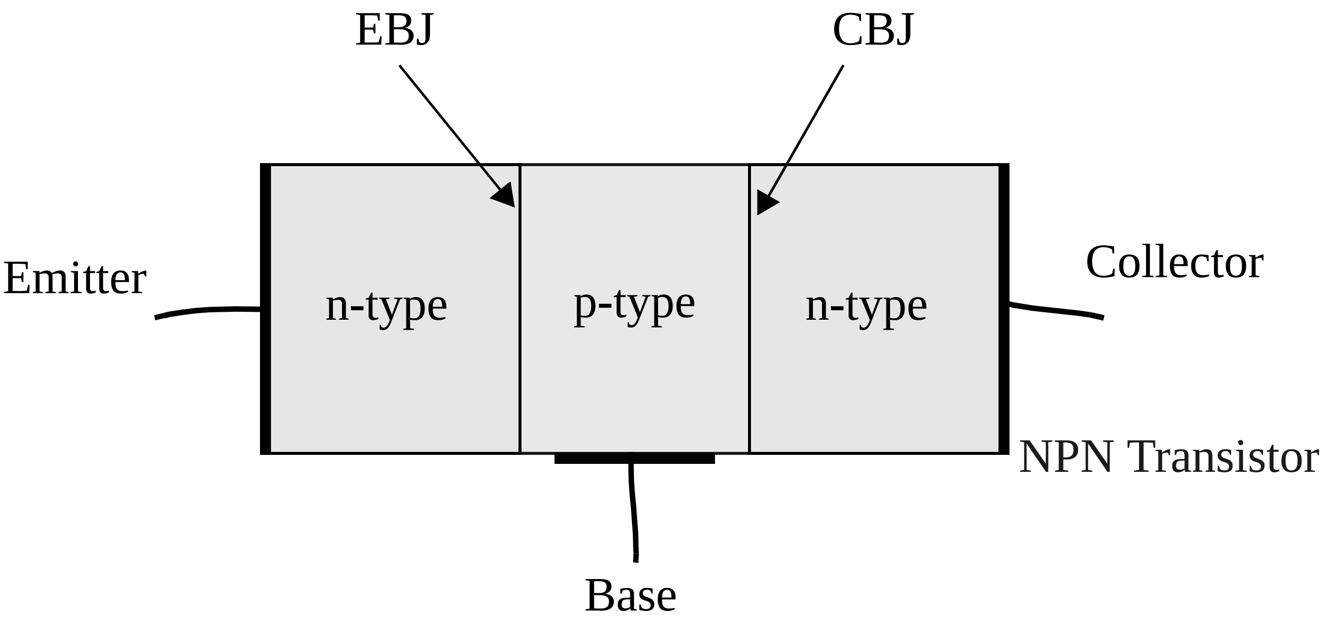






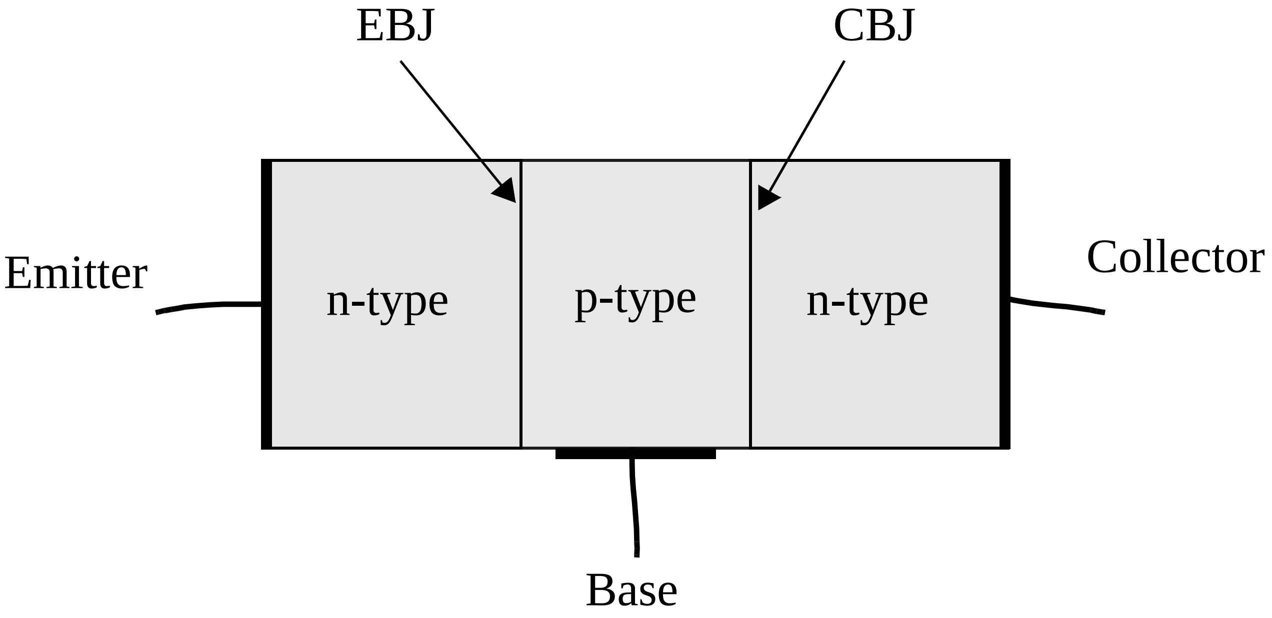
Bipolar Junction Transistors --- BJTs

- Bipolar refers to the conduction of both holes and electrons
- Two connected p-n junctions
- But unlike diodes, provides gain/amplification -- behaves like a controlled source
- Terminology:



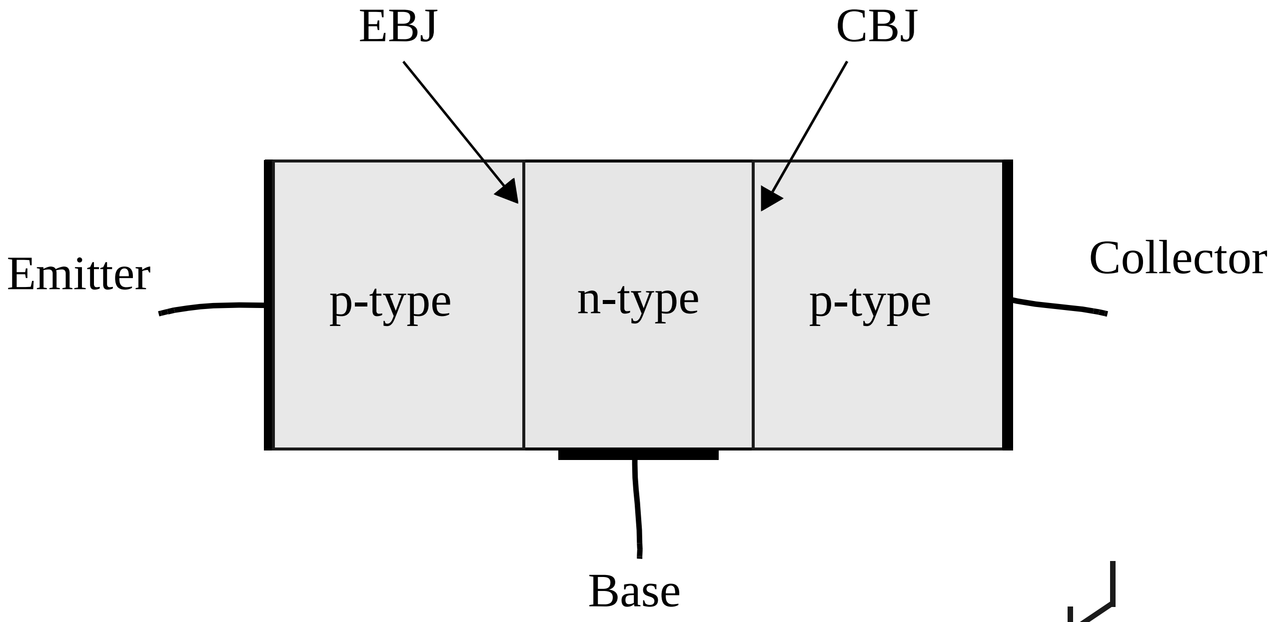
Regions of Operation for NPN Transistor

- Cut-off: both p-n junctions are reverse biased
- Saturation: both p-n junctions are forward biased
- <u>Active</u>: the EBJ is forward biased and the CBJ is reverse biased



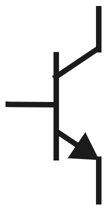
PNP Bipolar Junction Transistor

- Regions of operation are characterized in the same way
- Cut-off: both p-n junctions are reverse biased
- Saturation: both p-n junctions are forward biased
- Active: the EBJ is forward biased and the CBJ is reverse biased

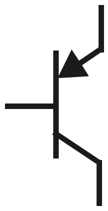


PNP and NPN Transistors in Active Region

- <u>Active</u>: the EBJ is forward biased and the CBJ is reverse biased

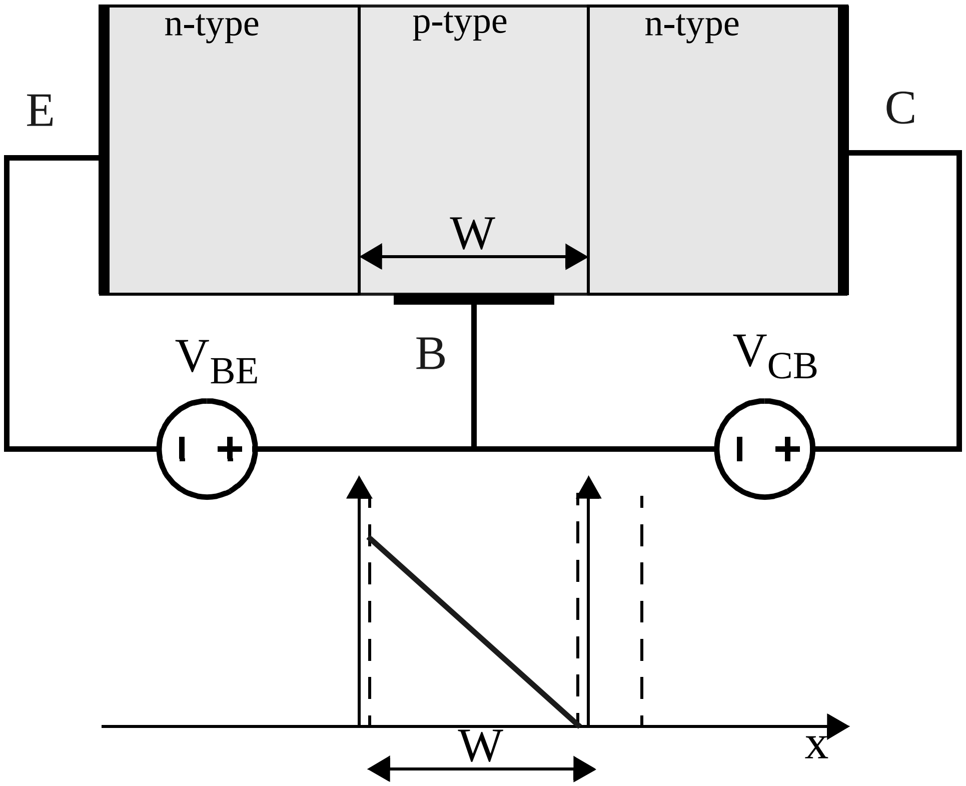


NPN Transistor



PNP Transistor

Active Region Operation



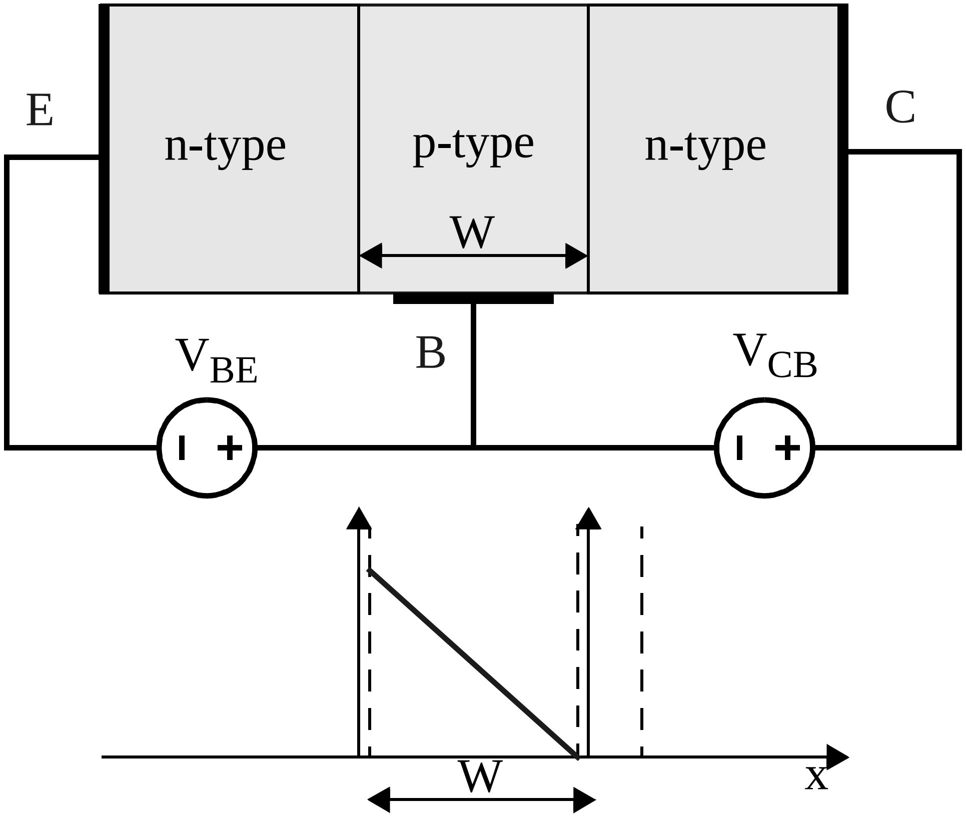
- Electrons are injected from the emitter and diffuse to the collector
- Most of the electrons will reach the collector --- depends on W and τ_F

- Excess carrier concentration at CBJ is zero since electric field collects everything

Active Region Operation

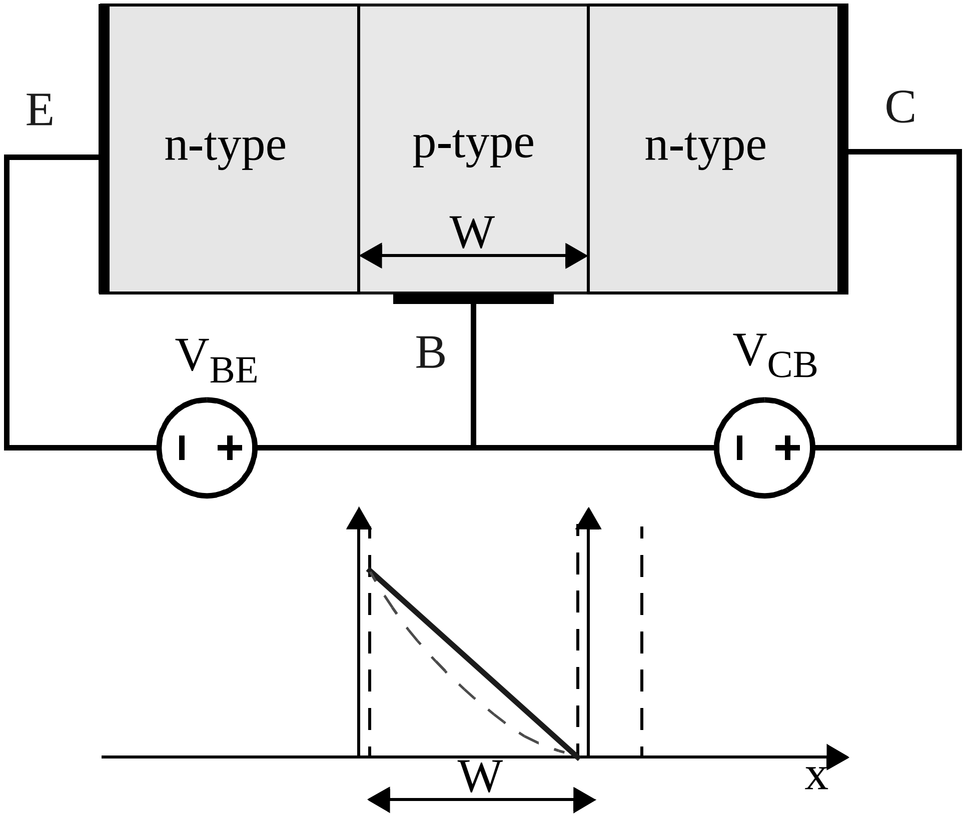
- The maximum n_p concentration at EBJ depends on the V_{BE}
- The slope of the n_p distribution determines the diffusion current from collector to emitter

$$i_c \propto \frac{dn_p}{dx}$$



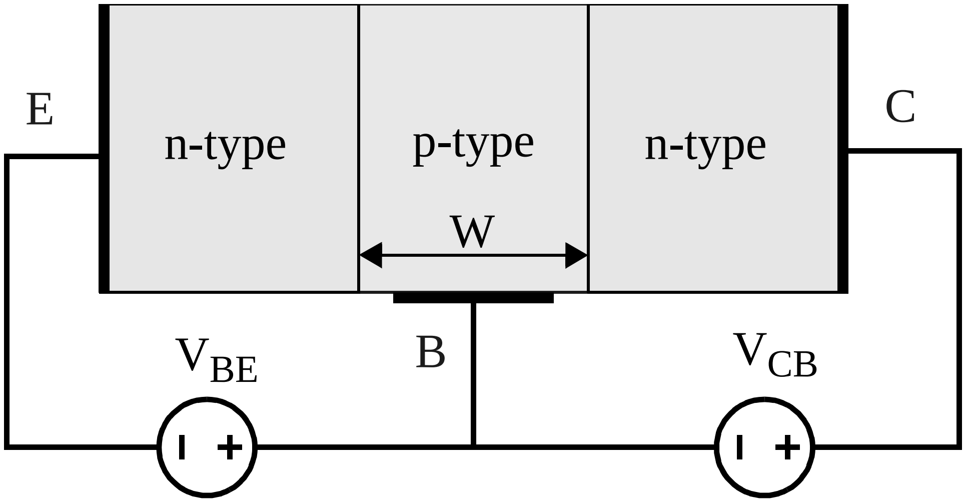
Active Region Operation

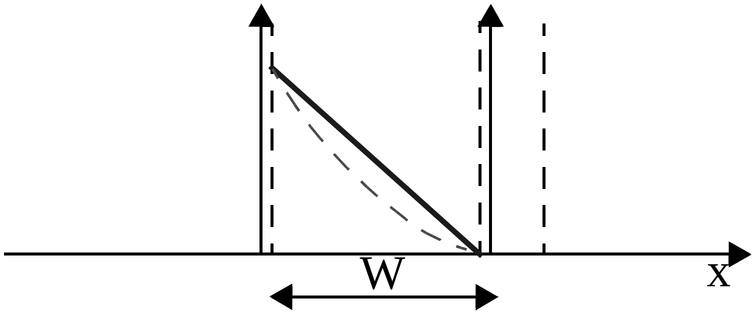
- But some of the carriers in the base recombine
- Electrons lost to recombination correspond to holes supplied to the base --- a current i_b
- The distribution is no longer linear



Active Region Operation

- Why does the distribution change in a convex, as opposed to concave manner?





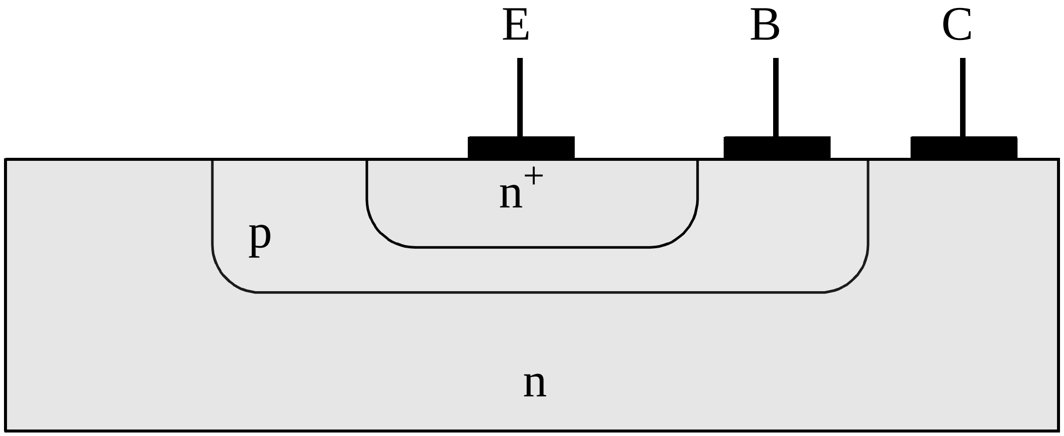
- i_c is practically independent of V_{CB}. Why?

Active Region Operation

- Assuming that there is no recombination in the base and no injection from base to emitter, the collector current, i_c is simply

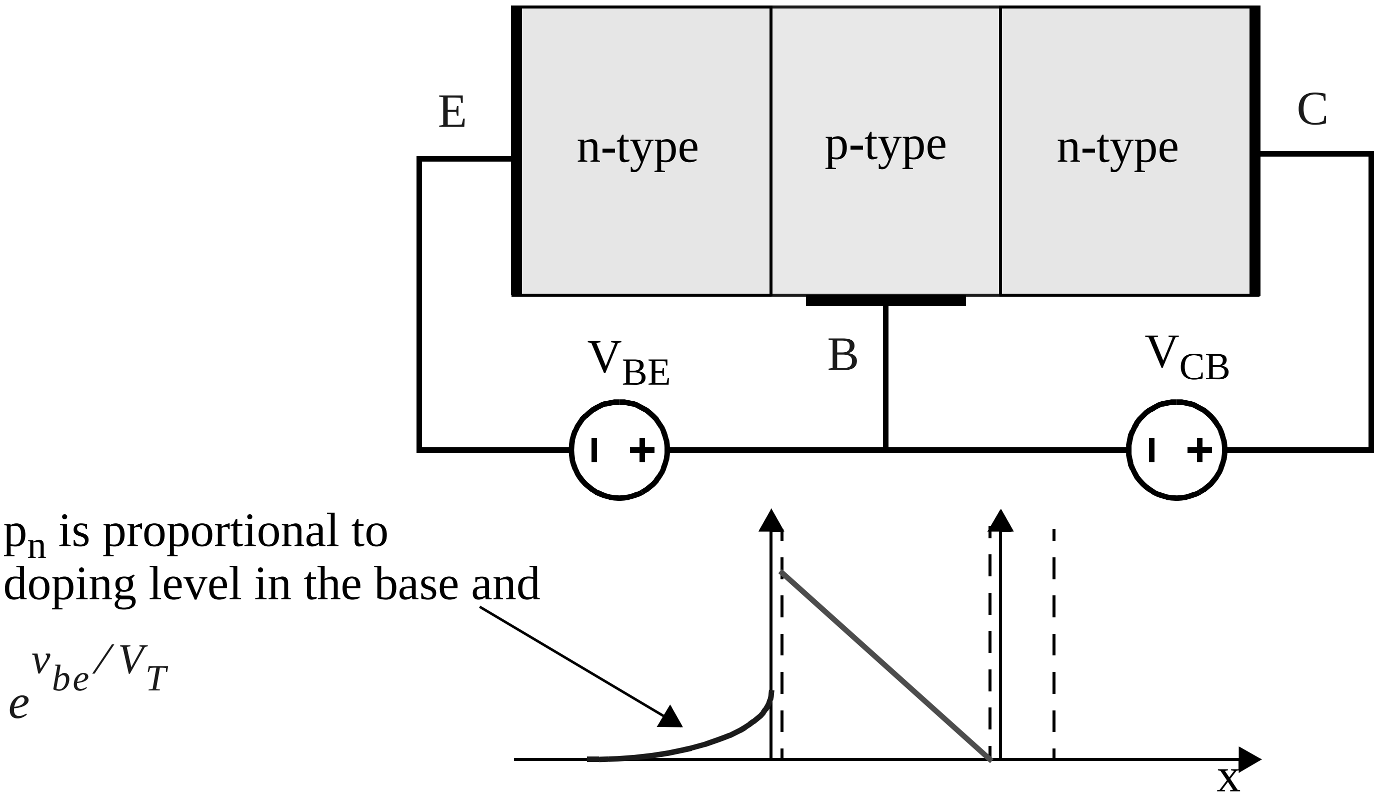
$$i_c = I_s e^{v_{be}/V_T}$$

- I_s is ~ 10^{-12} to 10^{-15}, and directly proportional to the EBJ area
- On ICs the EBJ junctions can be used to scale one transistor size (hence current) relative to another



Base Current

- i_{b1}: Component due to holes from external ckt replacing those lost via recombination in the base
- i_{b2}: dominant portion comes from holes injected from the base to emitter



p_n is proportional to doping level in the base and

e^{v_{be}/V_T}

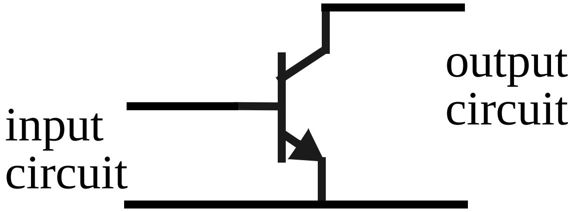
Base Current

- Recombination current, i_{b1} is also proportional to e^{v_{be}/V_T}
- Therefore, the total base current is proportional to i_c

$$i_c = I_s e^{v_{be}/V_T}$$

- The proportionality factor, β, is the common emitter current gain:

$$i_b = \frac{i_c}{\beta} = \frac{I_s}{\beta} e^{v_{be}/V_T}$$

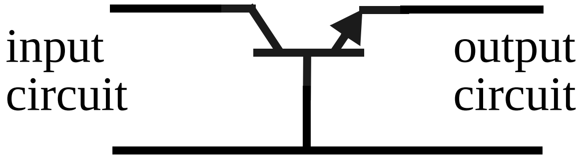


- $\beta \approx 100 - 200$, and is determined by the BE doping levels and the width of the base, W

Emitter Current

- $\alpha < 1$ is the common base gain

$$i_c = \alpha i_e$$



- By conservation of charge:

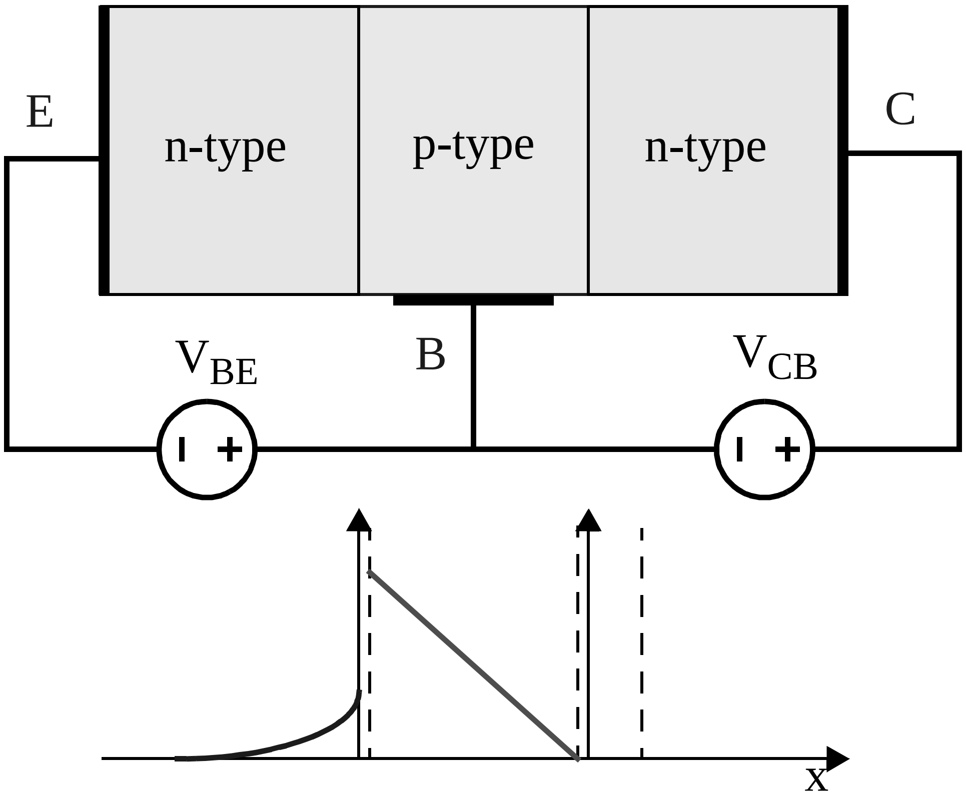
$$i_e = i_c + i_b$$

$$i_b = \frac{i_c}{\beta} \qquad i_e = \frac{\beta + 1}{\beta} i_c$$

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

Active Region: Controlled Source Behavior

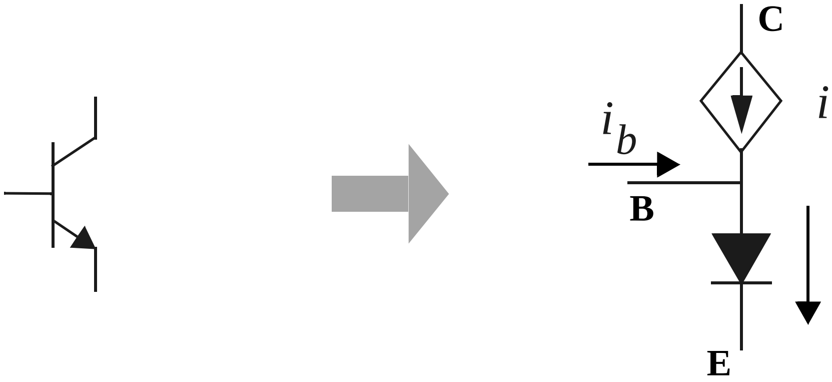
- An applied base-emitter voltage, V_{BE}, causes a collector current that is independent of the base-collector voltage (in the active region)
- Behaves like a voltage controlled current source
- Active region is used for amplification in analog design



Equivalent Circuit Models

- Please read about Eber-Moll model in Sec. 4.13 of your textbook!

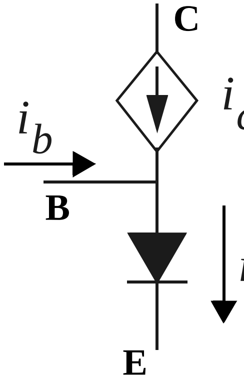
- We can model the transistor behavior in the active region using diodes and controlled sources



$$i_c = I_s e^{v_{be}/V_T}$$

$$i_e = \frac{i_c}{\alpha}$$

- Or, using a linear current-controlled current sources and diodes

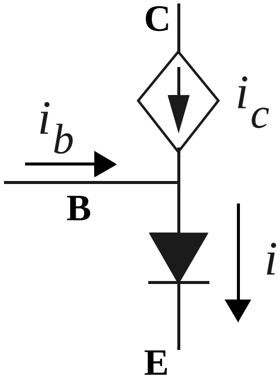


$$i_c = \alpha i_e$$

$$i_e = \frac{i_c}{\alpha} = \frac{I_s}{\alpha} e^{v_{be}/V_T}$$

Equivalent Circuit Models

- The circuit models on the previous page represent the transistor in terms of the common-base current gain --- gain from i_E to i_C

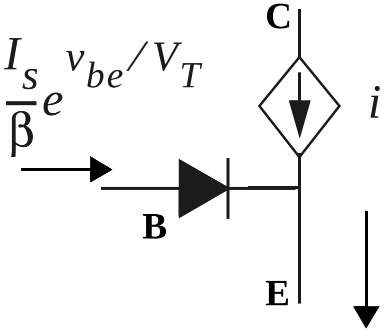


$$i_c = \alpha i_e$$

$$i_e = \frac{I_s}{\alpha} e^{v_{be}/V_T}$$

- A common emitter configuration is sometimes more useful

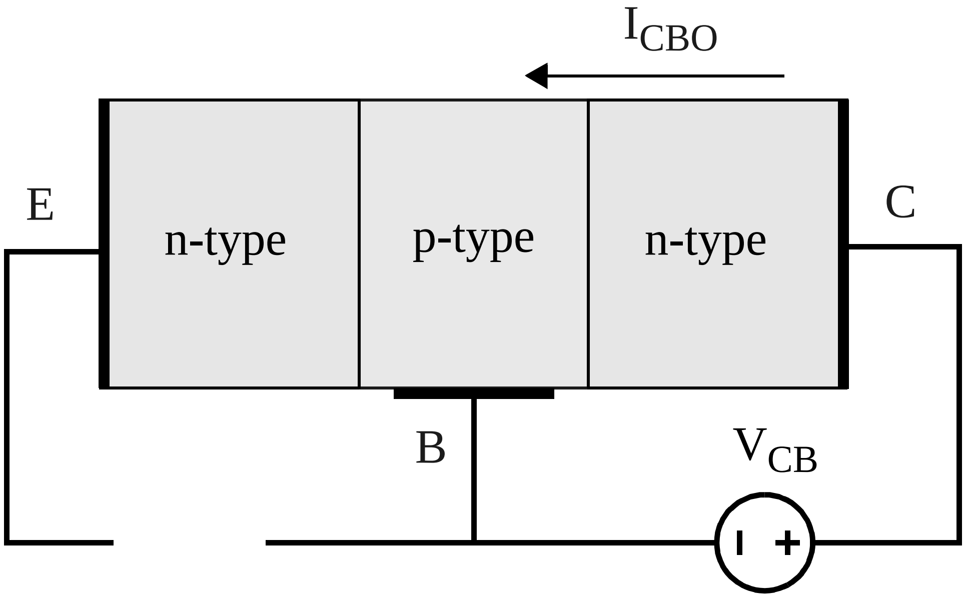
$$i_b = \frac{i_c}{\beta} = \frac{I_s}{\beta} e^{v_{be}/V_T}$$



$$i_c = I_s e^{v_{be}/V_T} = \beta i_b$$

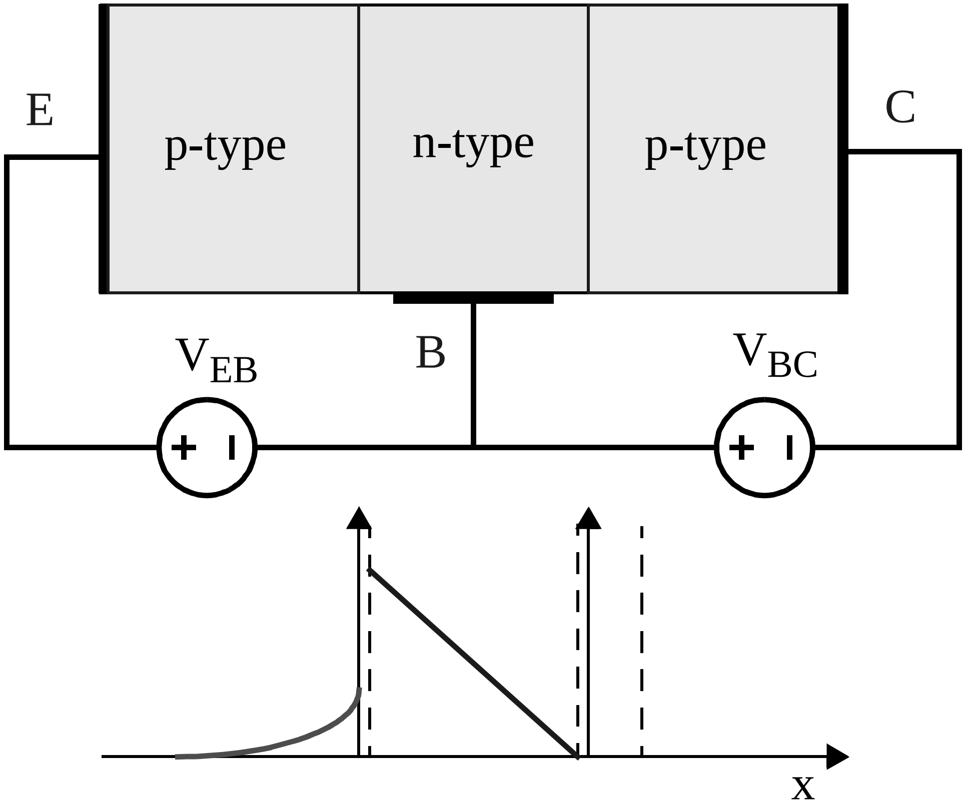
Active Region Currents

- The only current we've ignored is a negligible one, I_{CBO}, the leakage current from the collector to the base
- I_{CBO} is measured like a reverse-biased diode current with the emitter open circuited
- Like the saturation current of a diode, I_{CBO} is small and temperature dependent



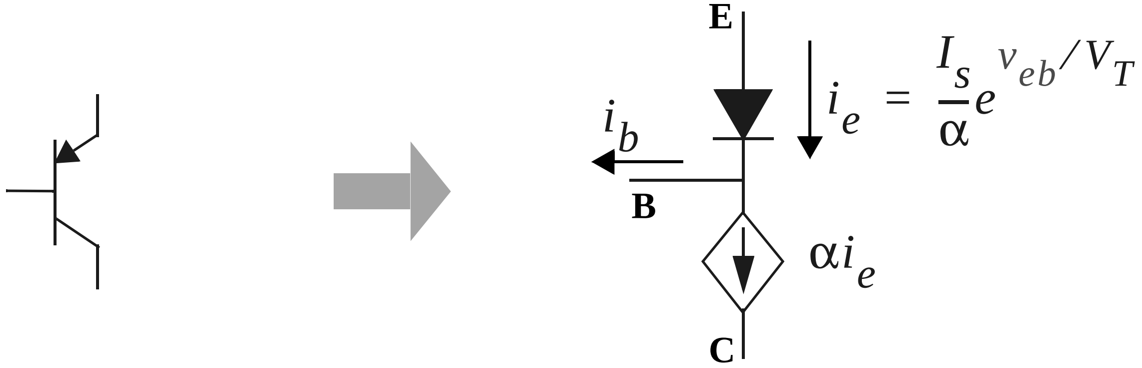
PNP: Active Region

- Operates the same way as the NPN, but the applied voltages are reversed for the active region --- EBJ is forward biased and CBJ is reverse biased



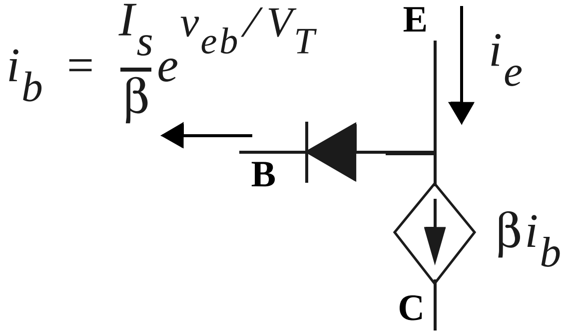
PNP Equivalent Circuit Models

- We can model the PNP in the active region using diodes and controlled sources



$$i_e = \frac{I_s}{\alpha} e^{v_{eb}/V_T}$$

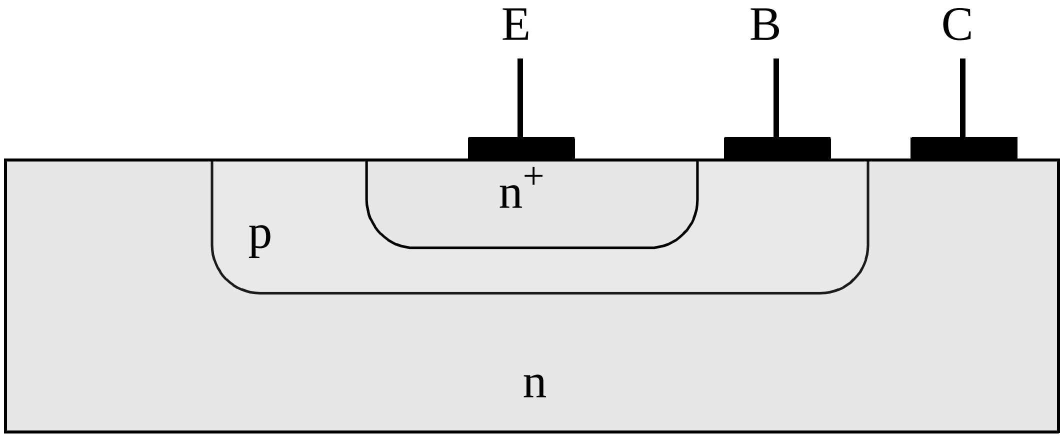
- The common emitter configuration is



$$i_b = \frac{I_s}{\beta} e^{v_{eb}/V_T}$$

Collector and Emitter

- Note that while the emitter and collector are always of the same type, they are not interchangable!
- They're doping levels are quite different



If you swap emitter and collector (EBJ reverse biased, CBJ forward) you get so-called inverse mode of operation. It is like active region, but the current transistor usually has much worse performance.