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

.modelo 40eps12 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

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

- 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

\[
\frac{Q_p}{\tau_p} = I_p
\]

\[
\Delta p(0) \propto e^v
\]

- 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 $\tau_n$ (how long a particle survives on average)
- We define a diffusion length of electrons in p type Si:

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

![Diagram showing excess minority carrier concentration and recombination in short and long bases](image)

- When $W << L_n$, almost nothing recombines in base
- When $W >> L_n$, almost all recombines in base
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:

![Diagram of NPN Transistor]

- Emitter (n-type)
- Base (p-type)
- Collector (n-type)
- EBJ (Emitter-Base Junction)
- CBJ (Collector-Base Junction)
Regions of Operation for NPN Transistor

- 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 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

- Active: the EBJ is forward biased and the CBJ is reverse biased

NPN Transistor

PNP Transistor
Electrons are injected from the emitter and diffuse to the collector.

Most of the electrons will reach the collector --- depends on $W$ and $\tau_F$.

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

\[
i_c = I_s e^{\frac{v_{be}}{V_T}}
\]

- \( I_s \) 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, $\beta$, 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:

\[ i_e = i_c + i_b \]

\[ i_b = \frac{i_c}{\beta} \]

\[ i_e = \frac{\beta + 1}{\beta} i_c \]

\[ \alpha = \frac{\beta}{\beta + 1} \quad \beta = \frac{\alpha}{1 - \alpha} \]
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

\[ i_c = I_s e^{v_{be}/V_T} \]

\[ i_c = \alpha i_e \]

• Or, using a linear current-controlled current sources and diodes
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 $i_C$

\[ i_b \rightarrow B \rightarrow i_c = \alpha i_e \]

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

- A common emitter configuration is sometimes more useful

\[ i_b = \frac{i_c}{\beta} = \frac{I_s}{\beta} e^{v_{be}/V_T} \rightarrow B \rightarrow i_c = I_s e^{v_{be}/V_T} = \beta i_b \]
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

\[ i_e = \frac{I_s}{\alpha} \frac{v_{eb}}{V_T} \]

- The common emitter configuration is

\[ i_b = \frac{I_s}{\beta} \frac{v_{eb}}{V_T} \]
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.