Characteristics of Finer Feature Size Processes

Bipolar Process
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
Bipolar Junction Transistors

- Operation
- Modeling
Carriers in Doped Semiconductors

n-type

p-type
Carriers in Doped Semiconductors

Current carriers are dominantly electrons
Small number of holes are short-term carriers

Current carriers are dominantly holes
Small number of electrons are short-term carriers
Carriers in Doped Semiconductors

<table>
<thead>
<tr>
<th>Type</th>
<th>Majority Carriers</th>
<th>Minority Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-type</td>
<td>electrons</td>
<td>holes</td>
</tr>
<tr>
<td>p-type</td>
<td>holes</td>
<td>electrons</td>
</tr>
</tbody>
</table>
Carriers in MOS Transistors

Consider n-channel MOSFET

Saturation Region

Channel

Triode Region
Carriers in MOS Transistors

Consider n-channel MOSFET

Saturation Region

Carriers in electrically induced n-channel are electrons
Carriers in MOS Transistors

Consider p-channel MOSFET

Channel

Saturation Region

Triode Region
Carriers in MOS Transistors

Consider p-channel MOSFET

Saturation Region

Triode Region

Carriers in electrically induced p-channel are holes
Carriers in MOS Transistors

Carriers in channel of MOS transistors are Majority carriers
Bipolar Transistors

- Bipolar Devices Show Basic Symmetry
- Electrical Properties not Symmetric
- Designation of C and E critical

With proper doping and device sizing these form Bipolar Transistors
Bipolar Transistors

npn transistor

pnp transistor

n-channel MOSFET

p-channel MOSFET

In contrast to a MOSFET which has 4 terminals, a BJT only has 3 terminals.
Bipolar Operation

Consider npn transistor

Under **forward bias** current flow into base and out of emitter

Current flow is governed by the diode equation

Carriers in emitter are electrons (majority carriers)

When electrons pass into the base they become minority carriers

Quickly recombine with holes to create holes base region

Dominant current flow in base is holes (majority carriers)
Bipolar Operation

Consider npn transistor

Under forward BE bias and reverse BC bias current flows into base region.

Carriers in emitter are electrons (majority carriers).

When electrons pass into the base they become minority carriers.

When minority carriers are present in the base they can be attracted to collector.
Bipolar Operation
Consider npn transistor

If no force on electron is applied by collector, electron will contribute to base current.
Consider npn transistor

If no force on electron is applied by collector, electron will contribute to base current. Electron will recombine with a hole so dominant current flow in base will be by majority carriers.
Consider npn transistor

When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction.
Bipolar Operation

Consider npn transistor

When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction

Will contribute to collector current flow as majority carriers
Bipolar Operation

Consider npn transistor

So, what will happen?
Bipolar Operation

Consider npn transistor

So, what will happen?

Some will recombine with holes and contribute to base current and some will be attracted across BC junction and contribute to collector.

Size and thickness of base region and relative doping levels will play key role in percent of minority carriers injected into base contributing to collector current.
Bipolar Operation

Consider npn transistor

Under forward BE bias and reverse BC bias current flows into base region

Carriers in emitter are electrons (majority carriers)

When electrons pass into the base they become minority carriers

When minority carriers are present in the base they can be attracted to collector

Minority carriers either recombine with holes and contribute to base current or are attracted into collector region and contribute to collector current
Bipolar Operation

Consider npn transistor

Under forward BE bias and reverse BC bias current flows into base region

Efficiency at which minority carriers injected into base region and contribute to collector current is termed $\alpha$

$\alpha$ is always less than 1 but for a good transistor, it is very close to 1

For good transistors $0.99 < \alpha < 0.999$

Making the base region very thin makes $\alpha$ large
Bipolar Transistors

principle of operation of pnp and npn transistors are the same

minority carriers in base of pnp are holes

npn usually have modestly superior properties because mobility of electrons Is larger than mobility of holes
Bipolar Operation

Consider npn transistor

In contrast to MOS devices where current flow in channel is by majority carriers, current flow in the critical base region of bipolar transistors is by minority carriers.
Bipolar Operation

\[ I_C + I_B = -I_E \]
\[ I_C = -\alpha I_E \]

\[ I_C = \frac{\alpha}{1-\alpha} I_B \]

\[ \beta = \frac{\alpha}{1-\alpha} \]
\[ I_C = \beta I_B \]

\( \beta \) is typically very large
often 50<\( \beta \)<999
$I_C = \beta I_B$

$\beta$ is typically very large

Bipolar transistor can be thought of a current amplifier with a large current gain

In contrast, MOS transistor is inherently a transconductance amplifier

Current flow in base is governed by the diode equation

$$I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

Collector current thus varies exponentially with $V_{BE}$

$$I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$
$I_C = \beta I_B$

$\beta$ is typically very large

Collector current thus varies exponentially with $V_{BE}$

$$I_C = \beta I_S e^{\frac{V_{BE}}{V_t}}$$

This exponential relationship (in contrast to the square-law relationship for the MOSFET) provides a very large gain for the BJT and this property is very useful for many applications!!
following convention, pick $I_C$ and $I_B$ as dependent variables and $V_{BE}$ and $V_{CE}$ as independent variables.
Simple dc model

Summary:

\[ I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}} \]

\[ I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}} \]

\[ V_t = \frac{kT}{q} \]

This has the properties we are looking for but the variables we used in introducing these relationships are not standard.

It can be shown that \( \tilde{I}_S \) is proportional to the emitter area \( A_E \).

Define \( \tilde{I}_S = \beta^{-1} J_S A_E \) and substitute this into the above equations.
Simple dc model

\[ I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}} \]
\[ I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}} \]
\[ V_t = \frac{kT}{q} \]

\[ I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \]
\[ I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \]
\[ V_t = \frac{kT}{q} \]

\( J_S \) is termed the saturation current density

Process Parameters : \( J_S, \beta \)
Design Parameters: \( A_E \)
Environmental parameters and physical constants: \( k, T, q \)

At room temperature, \( V_t \) is around 26mV
\( J_S \) very small – around .25fA/u^2
Transfer Characteristics

\[ J_S = 0.25 \text{fA/u}^2 \]
\[ A_E = 400 \text{u}^2 \]

\( V_{BE} \) close to 0.6V for a two decade change in \( I_C \) around 1mA
Transfer Characteristics

\[ J_S = 0.25 \text{fA}/\mu^2 \]
\[ A_E = 400 \mu^2 \]

\( V_{BE} \) close to 0.6V for a four decade change in \( I_C \) around 1mA
Simple dc model

Output Characteristics

\[ I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \]
Simple dc model

Better Model of Output Characteristics

\[
I_C \quad V_{CE}
\]

\[
V_{BE} \text{ or } I_B
\]
Simple dc model

Typical Output Characteristics

Forward Active region of BJT is analogous to Saturation region of MOSFET
Saturation region of BJT is analogous to Triode region of MOSFET
Simple dc model

Typical Output Characteristics

Projections of these tangential lines all intercept the \(-V_{CE}\) axis at the same place and this is termed the Early voltage, \(V_{AF}\) (actually \(-V_{AF}\) is intercept)

Typical values of \(V_{AF}\) are in the 100V range
**Simple dc model**

Improved Model

\[
I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}
\]

\[
I_C = J_S e^{\frac{V_{BE}}{V_t}} \left(1 + \frac{V_{CE}}{V_{AF}}\right)
\]

Valid only in Forward Active Region
Simple dc model

Improved Model

\[ V_t = \frac{kT}{q} \]

\[ I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \]

\[ I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \]

Valid in all regions of operation

V_{AF} effects can be added

Not mathematically easy to work with

Note dependent variables changes

Termed Ebers-Moll model

Reduces to previous model in FA region
Simple dc model

Ebers-Moll model

\[
I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{V_{BE}/V_t} - 1 \right) + J_S A_E \left( e^{V_{BC}/V_t} - 1 \right)
\]

\[
V_t = \frac{kT}{q}
\]

\[
I_C = J_S A_E \left( e^{V_{BE}/V_t} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{V_{BC}/V_t} - 1 \right)
\]

Process Parameters: \{J_S, \alpha_F, \alpha_R\}

Design Parameters: \{A_E\}

\[
\alpha_F \text{ is the parameter } \alpha \text{ discussed earlier}
\]

\[
\alpha_R \text{ is termed the “reverse } \alpha\text{”}
\]

\[
\beta_F = \frac{\alpha_F}{1-\alpha_F} \quad \beta_R = \frac{\alpha_R}{1-\alpha_R}
\]

\[
\alpha_F = \frac{\beta_F}{1+\beta_F} \quad \alpha_R = \frac{\beta_R}{1+\beta_R}
\]

Typical values for process parameters:

\[
J_S \sim 10^{-16} A/\mu^2 \quad \beta_F \sim 100, \quad \beta_R \sim 0.4
\]
Simple dc model

Ebers-Moll model

\[
I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)
\]

\[
V_t = \frac{kT}{q}
\]

\[
I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)
\]

With typical values for process parameters in forward active region \((V_{BE} \sim 0.6V, V_{BC} \sim -3V)\), with \(V_t = 26mV\) and if \(A_E = 100\mu^2\):

\[
J_S \sim 10^{-16}A/\mu^2 \quad \beta_F \sim 100, \quad \beta_R \sim 0.4
\]

\[
I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)
\]

\[
I_C = 10^{-14} \left( 1.05 \times 10^{10} \right) - \frac{10^{-14}}{.28} \left( 7.7 \times 10^{-51} - 1 \right)
\]

Completely dominant!

Makes no sense to keep anything other than \(I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} \right)\) in forward active
Simple dc model

Ebes-Moll model

\[ I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{v_{BE}}{v_t}} - 1 \right) + J_S A_E \left( e^{\frac{v_{BC}}{v_t}} - 1 \right) \]

\[ V_t = \frac{kT}{q} \]

\[ I_C = J_S A_E \left( e^{\frac{v_{BE}}{v_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{v_{BC}}{v_t}} - 1 \right) \]

Alternate equivalent expressions for dependent variables \{I_C, I_B\} defined earlier for Ebers-Moll equations in terms of independent variables \{V_{BE}, V_{CE}\} after dropping the "-1" terms

\[ I_C = J_S A_E e^{v_{BE}/v_t} \left( 1 - \left[ \frac{1 + \beta_R}{\beta_R} \right] e^{-v_{CE}/v_t} \right) \]

\[ I_B = J_S A_E e^{v_{BE}/v_t} \left( \frac{1}{\beta_F} - \frac{1}{\beta_R} e^{-v_{CE}/v_t} \right) \]

No more useful than previous equation but in form consistent with notation introduced earlier
Simple dc model

Simplified Multi-Region Model

- Observe $V_{CE}$ around 0.2V when saturated
- $V_{BE}$ around 0.6V when saturated
- In most applications, exact $V_{CE}$ and $V_{BE}$ voltage in saturation not critical

$V_{BE} = 0.7V$

$V_{CE} = 0.2V$

Saturation
Simple dc model
Simplified Multi-Region Model

\[ I_C = J_S A_e \exp\left(\frac{v_{BE}}{v_t}\right) \left(1 - \left[\frac{1 + \beta_R}{\beta_F}\right] e^{-\frac{v_{CE}}{v_t}}\right) \left(1 + \frac{V_{CE}}{V_{AF}}\right) \]

\[ I_B = J_S A_e \exp\left(\frac{v_{BE}}{v_t}\right) \left(\frac{1}{\beta_F} - \frac{1}{\beta_R} e^{-\frac{v_{CE}}{v_t}}\right) \]

\[ V_{BE} = 0.7V \]
\[ V_{CE} = 0.2V \]

Forward Active
Saturation
Cutoff
Simple dc model

Simplified Multi-Region Model

\[ I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left(1 + \frac{V_{CE}}{V_{AF}}\right) \]

\[ I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \]

\[ V_t = \frac{kT}{q} \]

Forward Active

Saturation

Cutoff

\[ V_{BE} = 0.7V \]
\[ V_{CE} = 0.2V \]
\[ I_C = I_B = 0 \]
Simple dc model

Simplified Multi-Region Model

\[ I_C = J_S A_E \frac{V_{BE}}{V_t} \left( 1 + \frac{V_{CE}}{V_{AF}} \right) \]

\[ I_B = \frac{J_S A_E}{\beta} \frac{V_{BE}}{V_t} \]

\[ V_t = \frac{kT}{q} \]

\[ V_{BE} > 0.4V \]

Forward Active

\[ V_{BC} < 0 \]

\[ V_{BE} = 0.7V \]

Saturation

\[ V_{CE} = 0.2V \]

\[ I_C < \beta I_B \]

\[ I_C = I_B = 0 \]

Cutoff

\[ V_{BE} < 0 \]

\[ V_{BC} < 0 \]

A small portion of the operating region is missed with this model but seldom operate in the missing region.
Simple dc model

Equivalent Simplified Multi-Region Model

\[ I_C = \beta I_B \left(1 + \frac{V_{CE}}{V_{AF}}\right) \]

\[ I_B = \frac{J_S A_E}{\beta} e^{\frac{v_{BE}}{V_t}} \]

\[ V_t = \frac{kT}{q} \]

\[ V_{BE} > 0.4V \quad V_{BC} < 0 \quad \text{Forward Active} \]

\[ V_{BE} = 0.7V \quad I_C < \beta I_B \quad \text{Saturation} \]

\[ V_{CE} = 0.2V \]

\[ I_C = I_B = 0 \quad V_{BE} < 0 \quad V_{BC} < 0 \quad \text{Cutoff} \]

A small portion of the operating region is missed with this model but seldom operate in the missing region.
Adequate when it makes little difference whether $V_{BE}=0.6V$ or $V_{BE}=0.7V$
Simplified dc model

Mathematically

\[ V_{BE} = 0.6V \]
\[ I_C = \beta I_B \]

Or, if want to show slope in \( I_C - V_{CE} \) characteristics

\[ V_{BE} = 0.6V \]
\[ I_C = \beta I_B (1 + \frac{V_{CE}}{V_{AF}}) \]
Simplified dc model

Equivalent Simplified Multi-Region Model

\[ I_C = \beta I_B \quad \text{Forward Active} \]

\[ V_{BE} = 0.6V \quad V_{BC} < 0 \]

\[ V_t = \frac{kT}{q} \]

\[ V_{BE} = 0.7V \quad I_C < \beta I_B \quad \text{Saturation} \]

\[ V_{CE} = 0.2V \]

\[ I_C = I_B = 0 \quad V_{BE} < 0 \quad V_{BC} < 0 \quad \text{Cutoff} \]

A small portion of the operating region is missed with this model but seldom operate in the missing region.
End of Lecture 19