CHAPTER 6

Single-Stage Integrated-Circuit Amplifiers

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

Hsin Chen, 2005
Outline

• Comparison between the MOS and the BJT
• From discrete circuit to integrated circuit
  - Philosophy, Biasing, …etc.
• Frequency response
• The Common-Source and Common-Emitter amplifier with active loads
• The Common-Gate and Common-Base amplifier with active load
• The Source and Emitter Follower
• The CS and CE amplifier with source degeneration
• Current mirrors with improved performance
• Cascode amplifier and transistor pairings
6-1 Comparison between the MOS and the BJT

DC characteristics

- Transconductor \((i_D - v_{GS} \text{ v.s. } i_C - v_{BE})\)

\[v_{DS} = v_{GS} - v_t\]

- c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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• Channel-length modulation \((i_D - v_{DS})\) v.s. Early effect \((i_C - v_{CE})\)
Low-frequency operation

- **Input resistance**

- **Transconductance**

  \[ g_m = \sqrt{2(\mu_n C_{ox}) \left(\frac{W}{L}\right)} I_D \]

- **Output resistance**

- **Intrinsic gain**

  \[ g_m = \frac{I_C}{V_T} \]

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c.f.: *Microelectronic Circuits, 5th ed.*, Sedra/Smith

*Hsin Chen, 2005*
High-frequency operation

- Cutoff frequency

\[ f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \]

For \( C_{gs} \gg C_{gd} \) and \( C_{gs} \approx \frac{2}{3} WLC_{ox} \)

\[ f_T \approx \frac{1.5\mu V_{OV}}{2\pi L^2} \]

\[ f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} \]

For \( C_{\pi} \gg C_{\mu} \) and \( C_{\pi} \approx C_{dc} \)

\[ f_T \approx \frac{2\mu V_T}{2\pi W^2} \]

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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Trends in IC technology

- Technology speed figure of merit v.s. Time:

![Graph showing technology speed figure of merit over time](image)

- Estimated frequency performance based on scaling

<table>
<thead>
<tr>
<th>Technology</th>
<th>( f_t )</th>
<th>( f_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35 micron</td>
<td>25GHz</td>
<td>40GHz</td>
</tr>
<tr>
<td>0.25 micron</td>
<td>40GHz</td>
<td>( \approx )60-70GHz</td>
</tr>
<tr>
<td>0.18 micron</td>
<td>60GHz</td>
<td>( \approx )90-100GHz</td>
</tr>
</tbody>
</table>

C.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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## Comparison

From analogue or digital point of view?

<table>
<thead>
<tr>
<th></th>
<th>BJT</th>
<th>MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC range of operation</td>
<td>$I_C \propto e^{V_{BE}}$</td>
<td>$2-3$ decades of $I_D \propto (V_{GS}-V_T)^2$</td>
</tr>
<tr>
<td>Small-signal output resistance ($r_o$)</td>
<td>Slightly larger</td>
<td>Smaller for short channel</td>
</tr>
<tr>
<td>Cutoff frequency ($f_T$)</td>
<td>100GHz</td>
<td>50GHz</td>
</tr>
<tr>
<td>Switch implementation</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Noise (thermal about the same)</td>
<td>Less 1/f</td>
<td>More 1/f</td>
</tr>
<tr>
<td>Capacitor implementation</td>
<td>Voltage dependent</td>
<td>Reasonably good</td>
</tr>
</tbody>
</table>

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith
6-2 From Discrete- to Integrated- circuit

Components

(The pictures are copied from http://140.114.23.141/htdocs/course/922_EE226002/Introduction.pdf, S.H. Hsu)

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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Hardware products

(The pictures are copied from http://140.114.23.141/htdocs/course/922_EE226002/Introduction.pdf, S.H. Hsu)
c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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**Design topologies**

- Active load to replace R
  \[ R = ? \]
- Current biasing
- Direct-coupled
  → Differential architecture to decouple DC signals (Ch7)

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c.f.: *Microelectronic Circuits, 5th ed.*, Sedra/Smith  
Hsin Chen, 2005
IC Biasing – current mirror (amplifier)

- \( \frac{I_o}{I_{\text{REF}}} = \)
- Minimum \( V_o = \)
- Effect of \( r_o : \)

*Note: Graph shows the relationship between \( I_o \) and \( V_o \) with a slope of \( \frac{1}{r_o} \).*
Current steering
BJT current mirror

\[ I_o / I_{REF} = \]

- Minimum \( V_o = \)

- Effect of \( r_o : \)

\[ \frac{I_O}{I_{REF}} = \frac{m}{1 + \frac{m+1}{\beta}} \]

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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6-3 Frequency response

• In analysing the frequency response of circuits, capacitors $\rightarrow 1/\omega C$ inductors $\rightarrow sL$

$$T(s) = \frac{a_ms^n + a_{m-1}s^{m-1} + \cdots + a_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_0}$$

Substituting $s=j\omega$ into $T(s)$ $\rightarrow$ The gain and phase response v.s. $\omega$

$$T(s) = a_m \frac{(s-Z_1)(s-Z_2)\cdots(s-Z_m)}{(s-P_1)(s-P_2)\cdots(s-P_n)}$$

Zeros : 
Poles : 

c.f.: *Microelectronic Circuits, 5th ed.*, Sedra/Smith

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**Bode plot**

\[ |T(s)| \quad \angle T(s) \]

- A pole: \[ T(s) = \frac{1}{s + p_0} \]
- A zero: \[ T(s) = s + z_0 \]

How about positive-valued poles/zeros?

c.f.: *Microelectronic Circuits, 5th ed.*, Sedra/Smith

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Example

\[ T(s) = \frac{10s}{(1 + s/10^2)(1 + s/10^5)} \]
Example- continued

\[ T(s) = \frac{10s}{(1 + s/10^2)(1 + s/10^5)} \]
High-frequency response

- Frequency response of a direct-coupled amplifier

\[
F_H(s) = \frac{(1 + s / z_1)(1 + s / z_2) \cdots (1 + s / z_n)}{(1 + s / p_1)(1 + s / p_2) \cdots (1 + s / p_n)}
\]

We are mostly interested in **3-dB frequency**, \( f_H \) (or \( f_{3dB} \))

c.f.: *Microelectronic Circuits, 5th ed.*, Sedra/Smith

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Methods to derive $f_H$

- If a dominant pole exists

$$F_H(s) \approx \frac{1}{1 + s / w_{p1}}$$

- If not, use the cond. $|F(w_H)| = \frac{1}{2}$ to derive

$$w_H \approx \frac{1}{\sqrt{\left(\frac{1}{w_{p1}^2} + \frac{1}{w_{p2}^2} + \cdots + \frac{1}{w_{pn}^2}\right) - \left(\frac{1}{w_{z1}^2} + \frac{1}{w_{z2}^2} + \cdots + \frac{1}{w_{zn}^2}\right)}}$$

- Open-circuit time constants

$$w_H \approx \frac{1}{\sum_i C_i R_{io}}$$

$R_{io}$: resistance seen by $C_i$ when all other Cs are open-circuit and all sources equal zeros

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith  
Hsin Chen, 2005
Example 6.6

(a) 

(b) 

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith
Single-stage IC Amplifiers

\[ I_x \]

\[ -V_x + (V_{gs} + V_x) \]

\[ g_m V_{gs} \]

\[ V_{gs} + V_x \]

\[ R_{gs} \]

\[ R_{in} \]

\[ R_{sig} \]

\[ V_{gs} \]

\[ V_{gs} \]

\[ \frac{V_{gs}}{R_{sig}} \]

\[ \frac{V_{gs}}{R_{in}} \]

\[ R_{gd} \equiv \frac{V_x}{I_x} \]

\[ R_L' \]

\[ V_{gs} + V_x \]

\[ \text{c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith} \]

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Miller’s theorem – one useful technique for analysing freq response

\[ V_2 = KV_1 \]

\[ Z_1 = Z/(1 - K), \quad Z_2 = Z/(1 - \frac{1}{K}) \]

(a) (b)

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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Example 6.7

\[ R_{\text{sig}} = 10 \, \text{k}\Omega \]

\[ V_{\text{sig}} \]

\[ Z \]

\[ 1 \]

\[ 2 \]

\[ V_i \]

\[ V_o \]
6-4 Common-Source and Common-Emitter amplifiers with active loads

Common-source amplifier

\[
R_i = \\
A_{vo} = \\
R_o =
\]

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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Common-source amplifier with active load

\[ V_{DD} \]
\[ V_{SG} \]
\[ Q_3 \]
\[ Q_2 \]
\[ v \]
\[ i \]
\[ v_o \]
\[ I_{REF} \]

(a)

\[ Q_2 \] in triode
\[ Q_2 \] in saturation
Slope = \( \frac{1}{r_{o2}} \)
\[ v_{SG} = V_{SG} \]

\[ 0 \]
\[ (V_{SG} - |V_{ds}|) V_{SG} \]
\[ |V_{OV2}| \]

(b)

\[ i_{D1} \]
\[ Q_1 \] in triode
\[ Q_1 \] in saturation
\[ v_{GS1} = V_{IB} \]
\[ v_{GS1} = V_{IA} \]

Load curve
\[ v_{OA} = V_{DD} - (V_{SG} - |V_{gs}|) = V_{DD} - |V_{OV2}| \]

(c)

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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• Large-signal characteristics

\[ V_{OA} = V_{DD} - |V_{OV2}| \]

- I: Cutoff
- II: \( Q_1 \) Saturation, \( Q_2 \) Triode
- III: \( Q_1 \) Saturation, \( Q_2 \) Saturation
- IV: \( Q_1 \) Triode, \( Q_2 \) Saturation

• Small-signal characteristics (in region III)

\[ R_{in} = \] 
\[ A_v = \] 
\[ R_{out} = \]

c.f.: Microelectronic Circuits, 5th ed., Seok Sigun
• High-frequency response

(i) Analysis by Miller’s Theorem

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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(ii) Analysis by **Open-circuit time constants**

(a) 

(b) 

(c) 

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith  
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(iii) Exact analysis
Formulas for Common-Emitter amplifier with active load

\[ V_{\text{sig}} \]

\[ R_{\text{sig}} \]

\[ B \]

\[ r_c \]

\[ B' \]

\[ C_{\mu} \]

\[ C_{\pi} \]

\[ r_\pi \]

\[ V_{\pi} \]

\[ g_m V_{\pi} \]

\[ r_o \]

\[ R_L \]

\[ C_L \]

\[ V_o \]

\[ R'_L \]

\[ (a) \]

\[ V'_{\text{sig}} \]

\[ R'_{\text{sig}} \]

\[ B' \]

\[ C_{\mu} \]

\[ C_{\pi} \]

\[ g_m V_{\pi} \]

\[ R'_L \]

\[ C_L \]

\[ V_o \]

\[ (b) \]

c.f.: Microelectronic Circuits, 5th ed., Sedra/Smith

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