EE 330
Lecture 20

• Operating Points for Amplifier Applications
• Amplification with Transistor Circuits
• Small Signal Modelling
Simplified Multi-Region Model

Alternate equivalent model

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

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

- \( V_{BE} = 0.7V \)
- \( V_{CE} = 0.2V \)  \( I_C < \beta I_B \)  \( \text{Saturation} \)

- \( I_C = I_B = 0 \)  \( V_{BE} < 0 \)  \( V_{BC} < 0 \)  \( \text{Cutoff} \)

A small portion of the operating region is missed with this model but seldom operate in the missing region.
**Simplified Multi-Region dc Model**

**Equivalent Simplified Multi-Region Model**

\[
I_C = \beta I_B
\]

\[
V_{BE} = 0.6V
\]

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

- **Forward Active**
  - \(V_{BE} > 0.4V\)
  - \(V_{BC} < 0\)

- **Saturation**
  - \(V_{BE} = 0.7V\)
  - \(V_{CE} = 0.2V\)
  - \(I_C < \beta I_B\)

- **Cutoff**
  - \(I_C = I_B = 0\)
  - \(V_{BE} < 0\)
  - \(V_{BC} < 0\)

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

Review from Last Lecture
Sufficient regions of operation for most applications

- Forward Active
- Cutoff
- Reverse Active
- Simplified Forward Saturation
- Saturation

Review from Last Lecture
The vertical npn transistor

- Emitter area only geometric parameter that appears in basic device model
- Transistor much larger than emitter
- Multiple-emitter devices often used (TTL Logic) and don't significantly increase area
In contrast to the MOSFET where process parameters are independent of geometry, the bipolar transistor model is for a specific transistor! Area emitter factor is used to model other devices. Often multiple specific device models are given and these devices are used directly. Often designer can not arbitrarily set $A_E$ but rather must use parallel combinations of specific devices and layouts.

Review from Last Lecture

A challenge in modeling the BJT

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1 Parameters are defined in Chapters 3 and 4.
2 Some of these Gummel-Poon parameters differ considerably from those given in Table 2C.4. They have been obtained from curve fitting and should give good results with computer simulations. The parameters of Table 2C.4 should be used for hand analysis.
3 Parameters that are strongly area-dependent are based upon an npn emitter area of 390 $\mu^2$ and perimeter of 80 $\mu$, a base area of 2200 $\mu^2$ and perimeter of 200 $\mu$, and a collector area of 10,500 $\mu^2$ and perimeter of 425 $\mu$. The lateral pnp has rectangular collectors and emitters spaced 10 $\mu$ apart with areas of 230 $\mu^2$ and perimeters of 60 $\mu$. The base area of the pnp is 7400 $\mu^2$ and the base perimeter is 345 $\mu$.
4 CJS is set to zero for the lateral transistor because it is essentially nonexistent. The parasitic capacitance from base to substrate, which totals 1.0 pF for this device, must be added externally to the BJT.
A challenge in modeling the BJT

Top View of Vertical npn

Cross-Sectional View
A challenge in modeling the BJT

Review from Last Lecture

This looks consistent but …
A challenge in modeling the BJT

This looks consistent but ...

consider an individual slice

Lateral flow of base current causes a drop in base voltage across the base region

What is $V_{BEk}$?
A challenge in modeling the BJT

\[
I_C = \sum_{i=1}^{7} A_{Si} e^{V_{BE_i}/V_t} = A_E J_S e^{V_{BE}/V_t}
\]

This looks consistent but …

- Lateral flow of base current causes a drop in base voltage across the base region
- And that drop differs from one slice to the next
- So \( V_{BE} \) is not fixed across the slices
- Since current is exponentially related to \( V_{BE} \), affects can be significant
- Termed **base spreading resistance** problem
- Strongly dependent upon layout and contact placement
- No good models to include this effect
- Major reason designer does not have control of transistor layout detail in some bipolar processes
- Similar issue does not exist in MOSFET because the corresponding gate voltage does not change with position since \( I_G = 0 \)

Review from Last Lecture
Modeling of the MOSFET

Goal: Obtain a mathematical relationship between the port variables of a device.

\[
\begin{align*}
I_D &= f_1(V_{GS}, V_{DS}, V_{BS}) \\
I_G &= f_2(V_{GS}, V_{DS}, V_{BS}) \\
I_B &= f_3(V_{GS}, V_{DS}, V_{BS})
\end{align*}
\]
Throughout the small input range, the “distant” nonlinearities do not affect performance
Small-Signal Operation

- If slope is steep, output range can be much larger than input range
- The slope can be viewed as the voltage gain of the circuit
- Nonlinear circuit behaves as a linear circuit near Q-point with small-signal inputs
Small signal operation of nonlinear circuits

\[ V_{IN} = V_M \sin \omega t \]

\[ V_M \text{ is small} \]

- Small signal concepts often apply when building amplifiers
- If small signal concepts do not apply, usually the amplifier will not perform well
- Small signal operation is usually synonymous with “locally linear”
- Small signal operation is relative to an “operating point”
Operating Point of Electronic Circuits

Often interested in circuits where a small signal input is to be amplified

The electrical port variables where the small signal goes to 0 is termed the Operating Point, the Bias Point, the Quiescent Point, or simply the Q-Point

By setting the small signal to 0, it means replacing small voltage inputs with short circuits and small current inputs with open circuits

When analyzing small-signal amplifiers, it is necessary to obtain the Q-point

When designing small-signal amplifiers, establishing of the desired Q-point is termed “biasing”

• Capacitors become open circuits (and inductors short circuits) when determining Q-points

• Simplified dc models of the MOSFET (saturation region) or BJT (forward active region) are usually adequate for determining the Q-point in practical amplifier circuits

• DC voltage and current sources remain when determining Q-points

• Small-signal voltage and current sources are set to 0 when determining Q-points
Operating Point of Electronic Circuits

\[ V_{DD} = 8V \]

\[ 4K \]

\[ C_2 \]

\[ V_{SQ} = ? \]

\[ 30K \]

\[ 200K \]

\[ 60K \]

\[ V_{DD} = 8V \]

\[ 200K \]

\[ 4K \]

\[ C_2 \]

\[ V_{CQ} = ? \]

\[ 2K \]

\[ 200K \]

\[ A = 100 \mu \]

\[ V(t) = V_M \sin(\omega t + \theta) \]

\[ V_{OUT} \]

\[ R_1 \]

\[ R_2 \]

\[ M_1 \]

\[ R_3 \]

\[ R_4 \]

\[ V_{SS} \]

\[ V_{IN(t)} \]

\[ -2V \]

\[ V_{OUT(t)} \]

\[ V_{IN(t)} \]

\[ 4V \]

\[ R_1 \]
Operating Point Analysis of MOS and Bipolar Devices

Example:

Determine $V_{\text{OUTQ}}$ and $V_{\text{CQ}}$

Will formally go through the process in this example, will go into more detail about finding the operating point later.
Operating Point Analysis of MOS and Bipolar Devices

Example:
Determine $V_{OUTQ}$ and $V_{CQ}$

\[ V_{DD} = 9\text{V} \]

\[ V_{OUT} \]

\[ 50\text{K} \]

\[ 1\text{K} \]

\[ 25\text{K} \]

\[ 1\text{K} \]

\[ 4\text{K} \]

\[ \beta I_B \]

\[ I_B \]

\[ 0.6\text{V} \]

\[ \beta I_B \]
Operating Point Analysis of MOS and Bipolar Devices

Example:
Determine $V_{\text{OUTQ}}$ and $V_{\text{CQ}}$

Assume $\beta = 100$

Assume $I_B \ll I_1$ (must verify)

$V_{\text{DD}} = 9V$

Assume $I_B \ll I_1$

$V_{\text{OUTQ}} = 0V$

$V_{\text{CQ}} = 6.6V$

$V_{\text{CQ}} = 9V - I_{\text{CQ}} \cdot 1K = 9V - 2.4V = 6.6V$

$V_{\text{OUTQ}} = I_L \cdot 4K = 0V$

$V_{\text{DD}} = 9V$

$V_{\text{OUTQ}}$ and $V_{\text{CQ}}$

Diagram of circuit with labeled components and equations for calculation.

$\text{Assume } \beta = 100$

$V_{\text{CQ}} = 6.6V$

$V_{\text{OUTQ}} = 0V$
Amplification with Transistors

From Wikipedia: (approx. 2010)

Generally, an **amplifier** or simply **amp**, is any **device** that changes, usually increases, the amplitude of a **signal**. The "signal" is usually voltage or current.

From Wikipedia: (Oct. 2015)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that increases the **power** of a **signal**.

From Wikipedia: (Feb. 2017)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that increases the **power** of a **signal** (a time varying voltage or current).

What is the “power” of a signal? Does Wikipedia have such a basic concept right?
Signal and Power Levels

\[ P_{RL} < P_{VIN} \]
\[ V_{OUT} < V_{IN} \]
Signal and Power Levels

\[ P_{RL} < P_{VIN} \]

\[ V_{OUT} < V_{IN} \]
Amplification with Transistors

From Wikipedia: (Feb. 2017)

An amplifier, electronic amplifier or (informally) amp is an electronic device that increases the power of a signal (a time varying voltage or current).

- It is difficult to increase the voltage or current very much with passive RC circuits
- Voltage and current levels can be increased a lot with transformers but not practical in integrated circuits
- Power levels can not be increased with passive elements (R, L, C, and Transformers)
- Often an amplifier is defined to be a circuit that can increase power levels (be careful with Wikipedia and WWW even when some of the most basic concepts are discussed)
- Transistors can be used to increase not only signal levels but power levels to a load
- In transistor circuits, power that is delivered in the signal path is supplied by a biasing network
- Signals that are amplified are often not time varying
Amplification with Transistors

Usually the gain of an amplifier is larger than 1

\[ V_{OUT} = A_V V_{IN} \]

Often the power dissipated by \( R_L \) is larger than the power supplied by \( V_{IN} \)

An amplifier can be thought of as a dependent source that was discussed in EE 201

Input and output variables can be either V or I or mixed
Applications of Devices as Amplifiers

Typical Regions of Operation by Circuit Function

MOS

Logic Circuits

Triode and Cutoff

Linear Circuits

Saturation

Bipolar

Saturation and Cutoff

Forward Active
Consider the following MOSFET and BJT Circuits

**BJT**

- $V_{CC}$
- $R$
- $V_{OUT}$
- $Q_1$
- $V_{IN}(t)$
- $V_{EE}$

**MOSFET**

- $V_{DD}$
- $R_1$
- $V_{OUT}$
- $M_1$
- $V_{SS}$

Assume BJT operating in FA region, MOSFET operating in Saturation

Assume same quiescent output voltage and same resistor $R_1$

Note architecture is same for BJT and MOSFET circuits

One of the most widely used amplifier architectures
Consider the following MOSFET and BJT Circuits

- MOS and BJT Architectures often Identical
- Circuit are Highly Nonlinear
- Nonlinear Analysis Methods Must be used to analyze these and almost any other nonlinear circuit
Methods of Analysis of Nonlinear Circuits

KCL and KVL apply to both linear and nonlinear circuits.

Superposition, voltage divider and current divider equations, Thevenin and Norton equivalence apply only to linear circuits!

Some other analysis techniques that have been developed may apply only to linear circuits as well.
Methods of Analysis of Nonlinear Circuits

Will consider three different analysis requirements and techniques for some particularly common classes of nonlinear circuits

1. **Circuits with continuously differential devices**

   Interested in obtaining transfer characteristics of these circuits or outputs for given input signals

2. **Circuits with piecewise continuous devices**

   Interested in obtaining transfer characteristics of these circuits or outputs for a given input signals

3. **Circuits with small-signal inputs that vary around some operating point**

   Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point

Other types of nonlinearities may exist and other types of analysis may be required but we will not attempt to categorize these scenarios in this course
1. Nonlinear circuits with continuously differential devices

Analysis Strategy:

Use KVL and KCL for analysis

Represent nonlinear models for devices either mathematically or graphically

Solve the resultant set of nonlinear and linear equations for the variables of interest
2. **Circuits with piecewise continuous devices**

\[ f(x) = \begin{cases} f_1(x) & x < x_i \text{ region 1} \\ f_2(x) & x > x_i \text{ region 2} \end{cases} \]

**Analysis Strategy:**

Guess region of operation

Solve resultant circuit using the previous method

Verify region of operation is valid

Repeat the previous 3 steps as often as necessary until region of operation is verified

- It helps to guess right the first time but a wrong guess will not result in an incorrect solution because a wrong guess can not be verified
- Piecewise models generally result in a simplification of the analysis of nonlinear circuits
3. Circuits with small-signal inputs that vary around some operating point

Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point.

Analysis Strategy:

Use methods from previous class of nonlinear circuits.

More Practical Analysis Strategy:

Determine the operating point (using method 1 or 2 discussed above after all small signal independent inputs are set to 0).

Develop small signal (linear) model for all devices in the region of interest (around the operating point or “Q-point”).

Create small signal equivalent circuit by replacing all devices with small-signal equivalent.

Solve the resultant small-signal (linear) circuit.

Can use KCL, DVL, and other linear analysis tools such as superposition, voltage and current divider equations, Thevenin and Norton equivalence.

Determine boundary of region where small signal analysis is valid.
Small signal operation of nonlinear circuits

If $V_M$ is sufficiently small, then any nonlinear circuit operating at a region where there are no abrupt nonlinearities will have a nearly sinusoidal output and the variance of the magnitude of this output with $V_M$ will be nearly linear (could be viewed as “locally linear”).

This is termed the “small signal” operation of the nonlinear circuit.

When operating with “small signals”, the nonlinear circuit performs linearly with respect to these small signals thus other properties of linear networks such as superposition apply provided the sum of all superimposed signals remains sufficiently small.

Other types of “small signals”, e.g. square waves, triangular waves, or even arbitrary waveforms often are used as inputs as well but the performance of the nonlinear network also behaves linearly for these inputs.

Many useful electronic systems require the processing of these small signals.

Practical methods of analyzing and designing circuits that operate with small signal inputs are really important.
Small signal operation of nonlinear circuits

$$V_{\text{IN}} = V_M \sin \omega t$$  

$V_M$ is small

Practical methods of analyzing and designing circuits that operate with small signal inputs are really important

Two key questions:

How small must the input signals be to obtain locally-linear operation of a nonlinear circuit?

How can these locally-linear (alt small signal) circuits be analyzed and designed?
Consider the following MOSFET and BJT Circuits

One of the most widely used amplifier architectures
Small signal operation of nonlinear circuits

\[ V_{IN} = V_M \sin(\omega t) \]

\( V_M \) is small

Example of circuit that is widely used in locally-linear mode of operation

Two methods of analyzing locally-linear circuits will be considered, one of these is by far the most practical.
Small signal operation of nonlinear circuits

\[ V_{IN} = V_M \sin \omega t \]

\( V_M \) is small

Two methods of analyzing locally-linear circuits for small-signal excitations will be considered, one of these is by far the most practical

1. Analysis using nonlinear models
2. Small signal analysis using locally-linearized models
Small signal analysis using nonlinear models

By selecting appropriate value of $V_{SS}$, $M_1$ will operate in the saturation region

Assume $M_1$ operating in saturation region

$V_{IN} = V_M \sin \omega t$

$V_M$ is small

$V_{OUT} = V_{DD} - I_D R$

$I_D = \frac{\mu C_{OX} W}{2L} (V_{IN} - V_{SS} - V_T)^2$

$I_{DQ} = \frac{\mu C_{OX} W}{2L} (V_{SS} + V_T)^2$

$V_{OUT} = V_{DD} - \frac{\mu C_{OX} W}{2L} (V_{IN} - V_{SS} - V_T)^2 R$

$V_{OUT} = V_{DD} - \frac{\mu C_{OX} W}{2L} (V_M \sin \omega t - [V_{SS} + V_T]^2) R$
Small signal analysis example

\[ V_{IN} = V_M \sin \omega t \]

\( V_M \) is small

\[ V_{OUT} = V_{DD} - \frac{\mu C_{OX} W}{2L} \left( V_M \sin \omega t - [V_{SS} + V_T] \right)^2 R \]

Recall that if \( x \) is small

\[ (1 + x)^2 \approx 1 + 2x \]

\[ V_{OUT} \approx V_{DD} - \frac{\mu C_{OX} W}{2L} \left[ V_{SS} + V_T \right]^2 \left( 1 - \frac{V_M \sin \omega t}{[V_{SS} + V_T]} \right)^2 R \]

\[ V_{OUT} \approx \left\{ V_{DD} - \frac{\mu C_{OX} W}{2L} \left[ V_{SS} + V_T \right]^2 R \right\} + \left\{ \frac{\mu C_{OX} W}{2L} \left[ V_{SS} + V_T \right] R \right\} \left( \frac{2V_M \sin \omega t}{[V_{SS} + V_T]} \right) R \]
Small signal analysis example

By selecting appropriate value of $V_{SS}$, $M_1$ will operate in the saturation region

Assume $M_1$ operating in saturation region

$$V_{OUT} \approx \left\{ V_{DD} - \frac{\mu C_{ox} W}{2L} [V_{SS} + V_T]^2 R \right\} + \left\{ \frac{\mu C_{ox} W}{L} [V_{SS} + V_T] R \right\} V_M \sin \omega t$$
Small signal analysis example

Assume $M_1$ operating in saturation region

\[ V_{OUT} = V_{DD} - \frac{\mu C_{ox} W}{2L} \left[ V_{SS} + V_T \right]^2 R \]  
\[ + \frac{\mu C_{ox} W}{L} \left[ V_{SS} + V_T \right] R \]  
\[ V_M \sin \omega t \]

**Quiescent Output**

**ss Voltage Gain**

\[ A_v = \frac{\mu C_{ox} W}{L} \left[ V_{SS} + V_T \right] R \]
\[ V_{OUTQ} = \left\{ V_{DD} - \frac{\mu C_{ox} W}{2L} \left[ V_{SS} + V_T \right]^2 R \right\} \]

\[ V_{OUT} \approx V_{OUTQ} + A_v V_M \sin \omega t \]

Note the ss voltage gain is negative since $V_{SS} + V_T < 0$!
Small signal analysis example

Assume $M_1$ operating in saturation region

$$V_{OUT} \approx V_{OUTQ} + A_v V_M \sin \omega t$$

$$A_v = \frac{\mu C_{ox} W}{L} \left[ V_{ss} + V_T \right] R$$

$$V_{OUTQ} = \left\{ V_{DD} - \frac{\mu C_{ox} W}{2L} \left[ V_{ss} + V_T \right]^2 R \right\}$$

But – this expression gives little insight into how large the gain is!
And the analysis for even this very simple circuit was messy!
Small signal analysis example

\[ V_{\text{OUT}} \approx V_{\text{OUTQ}} + A_V V_M \sin \omega t \]
Small signal analysis example

\[ V_{OUT} \approx V_{OUTQ} + A_v V_M \sin \omega t \]

\[ A_v = \frac{\mu C_{ox} W}{L} [V_{ss} + V_T] R \]
Small signal analysis example

\[ V_{\text{OUT}} \approx V_{\text{OUTQ}} + A_V V_M \sin \omega t \]

\[ A_V = \frac{\mu C_{ox} W}{L} \left[ V_{ss} + V_T \right] R \]
Small signal analysis example

\[ V_{OUT} \approx V_{OUTQ} + A_V V_M \sin \omega t \]

Here \( V_{IN} = V_M \sin \omega t \)

\[ A_v = \frac{\mu C_{ox} W}{L} [V_{ss} + V_T] R \]

Serious Distortion occurs if signal is too large or Q-point non-optimal
Here “clipping” occurs for high \( V_{OUT} \)
Small signal analysis example

\[ V_{OUT} \approx V_{OUTQ} + A_v V_M \sin \omega t \]

\[ A_v = \frac{\mu C_{ox} W}{L} \left[ V_{ss} + V_T \right] R \]

V_{IN} = V_M \sin \omega t

Serious Distortion occurs if signal is too large or Q-point non-optimal

Here “clipping” occurs for low V_{OUT}
End of Lecture 20