EE 435

Lecture 6:

Current Mirrors
Signal Swing
Review from last lecture:
Performance with Common-Mode Input

Consider tail-current bias amplifier

Common-Mode Half-Circuit

\[
\begin{align*}
V_{\text{OUTC}} &= 0 \quad \text{thus } A_C = 0
\end{align*}
\]
Performance with Common-Mode Input
Consider tail-voltage bias amplifier

Review from last lecture:

This circuit has a rather large common-mode gain and will not reject common-mode signals.
Applications of Quarter-Circuit Concept to Op Amp Design

consider initially the basic single-ended amplifier

![Quarter Circuit Diagram]
Review from last lecture:

Single-stage single-input low-gain op amp

Basic Structure

Quarter Circuit

Counterpart Circuit

Practical Implementation
Review from last lecture:

Single-stage low-gain differential op amp

\[ A(s) = \frac{-g_{m1}}{2sC_L + g_{o1} + g_{o3}} \]

\[ A_o = \frac{g_{m1}}{2g_{o1} + g_{o3}} \]

\[ GB = \frac{g_{m1}}{2C_L} \]

What are the number of degrees of freedom?
(assume \( V_{DD}, C_L \) fixed)

Natural Parameters:
\[ \left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, V_{B1}, V_{B3} \right\} \]

Constraints: \( I_{D5} \approx 2I_{D3} \)

Net Degrees of Freedom: 4

Practical Parameters:
\[ \{ V_{EB1}, V_{EB3}, V_{EB5}, P \} \]
Expressions valid for both tail-current and tail-voltage op amp

Review from last lecture:
Expressions valid for both tail-current and tail-voltage op amp

So which one should be used?
• Common-mode input range large for tail current bias
• Improved rejection of common-mode signals for tail current bias
• Extra design degree of freedom for tail current bias
• Improved output signal swing for tail voltage bias (will show later)
Slew Rate

Definition: The slew rate of an amplifier is the maximum rate of change that can occur at an output node.

\[
\text{Slope} = \text{SR} + \quad \text{Slope} = \text{SR} -
\]

SR is a nonlinear large-signal characteristic.
Input is over-driven hard (some devices in amplifier usually leave normal operating region).
Magnitude of \(\text{SR}^+\) and \(\text{SR}^-\) usually same and called SR (else \(\text{SR}^+\) and \(\text{SR}^-\) must be given)

Review from last lecture:
It can be similarly shown that putting a negative step on the input steer all current to $M_2$ thus the current to the capacitor $C_L$ will be $I_T$ minus the current from $M_2$ which is still $I_T/2$. This will cause a negative ramp voltage on $V_{OUT^+}$ of value

$$SR^- = \frac{dV_{OUT^+}}{dt} = -\frac{I_T}{2C_L} = -\frac{P}{V_{DD}2C_L}$$

Since the magnitude of $SR^+$ and $SR^-$ are the same, obtain a single SR for the amplifier of value

$$SR = \frac{P}{V_{DD}2C_L}$$
Reference Op Amp

The Reference Op Amp
(CMFB not shown)

Review from last lecture:
Reference Op Amp

mixed parameters

practical parameters

The Reference Op Amp
(single-ended output)

\[ A(s) = \frac{g_{m1}}{2 \left( sC_L + g_{O1} + g_{O3} \right)} \]

\[ A_{v0} = \frac{1}{\lambda_1 + \lambda_3} \left[ \frac{1}{V_{EB1}} \right] \]

\[ GB = \frac{g_{m1}}{2C_L} \]

\[ GB = \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right] \]

\[ SR = \frac{l_1}{2C_L} \]

\[ SR = \frac{P}{2V_{DD}C_L} \]
## Amplifier Structure Summary

### Small Signal Parameter Domain

<table>
<thead>
<tr>
<th>Common Source</th>
<th>$A_{vo} = \frac{g_m}{g_o}$</th>
<th>$GB = \frac{g_m}{C_L}$</th>
</tr>
</thead>
</table>

### Practical Parameter Domain

<table>
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<tr>
<th>Common Source</th>
<th>$A_{vo} = \left(\frac{2}{\lambda}\right)\left(\frac{1}{V_{EB}}\right)$</th>
<th>$GB = \left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB}}\right)$</th>
</tr>
</thead>
</table>

### Small Signal Parameter Domain

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<tr>
<th>Reference Op Amp</th>
<th>$A_{vo} = \frac{1}{2} \frac{g_m}{g_{o1} + g_{o3}}$</th>
<th>$GB = \frac{g_m}{2C_L}$</th>
<th>$SR = \frac{g_{01}}{\lambda C_L}$</th>
</tr>
</thead>
</table>

### Practical Parameter Domain

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<tr>
<th>Reference Op Amp</th>
<th>$A_{vo} = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$</th>
<th>$GB = \left(\frac{P}{2V_{DD}C_L}\right)\cdot\left[\frac{1}{V_{EB1}}\right]$</th>
<th>$SR = \frac{P}{2V_{DD}C_L}$</th>
</tr>
</thead>
</table>

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**Review from last lecture:**
Single-stage low-gain differential op amp

Need a CMFB circuit to establish $V_{B1}$ or $V_{B2}$

CMFB amplifies difference between $V_{B1}$ and average of two signal inputs

Can apply to either $V_{B1}$ or $V_{B2}$ but not both

Often apply to only fraction of transistor
Single-stage low-gain differential op amp

Need a CMFB circuit to establish $V_{b1}$

The CMFB circuit is often quite large and requires considerable design effort!

Can the CMFB be removed?
The signal dependent current in quarter circuit is steered to output node and drives the parallel output conductances of the quarter circuit and counterpart circuit.

If the signal-dependent current could be doubled, the gain would be doubled as well!

\[
A_{VO} = \frac{-G_{M1}}{2(G_1 + G_2)}
\]

\[
BW = \frac{G_1 + G_2}{C_L}
\]

\[
GB = \frac{G_{M1}}{2C_L}
\]
Operation of Op Amp – A different perspective

Small signal differential half-circuit

If the input impedance to the counterpart circuit is infinite, connecting the bias port of the quarter circuit to $V_{0^{-}}$ instead of to $V_{BB}$ will cause the signal current in the right counterpart circuit to be equal to that in the left counterpart circuit.

This will double the signal current to $V_{0^{+}}$ and thus double the voltage gain!

This will also eliminate the need for a CMFB circuit!
Current Mirrors

If the current $I_{BB}$ is small compared to $I_{IN}$, then $I_{OUT} \approx I_{IN}$

Circuits with this property are called Current Mirrors

If multiple copies of the right circuit are placed in parallel, the current will be scaled by the number of copies

These scaled circuits are also called Current Mirrors

As long as $I_{BB} << I_{IN}$, this scaling in currents occurs even if the circuits are highly nonlinear!
Operation of Op Amp – A different perspective
Current Mirrors

• Current mirrors are really just a current amplifier
• Simple current mirror was used to eliminate CMFB and double gain in basic op amp
• Many different current mirrors exist with varying levels of performance
Basic Current Mirror

\[ I_{IN} = \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_T)^2 \]

\[ I_{OUT} = \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_T)^2 \]

\[ \frac{I_{OUT}}{I_{IN}} = \frac{W_2 L_1}{W_1 L_2} \]

At the output port, small signal equivalent is a one-port

\[ g_{out} = g_{02} \]
Basic Current Mirror

\[ I_{IN} = \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_T)^2 \]

\[ I_{OUT} = \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_T)^2 \]

\[ \frac{I_{OUT}}{I_{IN}} = \frac{W_2}{W_1} \frac{L_1}{L_2} \]

At the output port, small signal equivalent is a one-port

\[ g_{out} = g_{02} \]
Current Mirrors

- More advanced current mirrors exist
- Several of these are discussed in the text
Current Mirrors

K copies of F on right

\[ I_{\text{OUT}} = K I_{\text{IN}} \]

Replication of K copies is often simply denoted as a device sizing or scaling factor

Properties of Current Mirrors of Interest:

- Mirror Gain Accuracy
- Signal Swing at Output
- Output Impedance (ideally infinite)

More advanced current mirrors usually offer improvements in one or more of these properties
More Advanced Current Mirrors

Cascode Current Mirror

Wilson Current Mirror

Modified Wilson Current Mirror
Current Mirrors

- The concept of the current mirror was first introduced in about 1969 (not certain who introduced it)
- Many of the basic current mirror circuits were introduced within a few years after the concept first appeared
- How many current mirror circuits are there?
- Have any current mirrors been introduced recently?
- Is there still an opportunity to contribute to the current mirror field?
USPTO search on Jan 26, 2014
509 patents with “current and mirror” in title since 1976

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 509 patents.
Hits 1 through 50 out of 509

Next 50 Hits

Jump To

Refine Search TTL/(current AND mirror)

PAT. NO.
1 8,618,787 Current mirror and high-compliance single-stage amplifier
2 8,598,953 System and method for pre-charging a current mirror
3 8,598,914 Comparator circuit with current mirror
4 8,587,287 High-bandwidth linear current mirror
5 8,575,971 Current mirror and current cancellation circuit
6 8,569,674 Multiplexed photocurrent monitoring circuit comprising current mirror circuits
7 8,537,868 Laser diode write driver feedback, current mirror, and differential-pair circuitry
8 8,531,236 Current mirror arrangement and method for switching on a current
9 8,519,794 Current mirror with low headroom and linear response
10 8,511,842 Fuzzy current-based mirror waveform control
11 8,502,751 Pixel driver circuit with load-balance in current mirror circuit
12 8,471,631 Bias circuit, power amplifier, and current mirror circuit
13 8,456,227 Current mirror circuit
14 8,450,992 Wide-swing cascode current mirror
15 8,441,381 Gate leakage compensation in a current mirror
<table>
<thead>
<tr>
<th>PAT. NO.</th>
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<tbody>
<tr>
<td>8,618,787</td>
<td>Current mirror and high-compliance single-stage amplifier</td>
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<tr>
<td>8,596,943</td>
<td>System and method for pre-charging a current mirror</td>
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<tr>
<td>8,598,914</td>
<td>Comparator circuit with current mirror</td>
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<tr>
<td>8,587,287</td>
<td>High-bandwidth linear current mirror</td>
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<td>8,575,917</td>
<td>Current mirror and current cancellation circuit</td>
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<td>8,569,674</td>
<td>Multiplexed photocurrent monitoring circuit comprising current mirror circuits</td>
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<td>8,537,665</td>
<td>Laser diode write driver feedback current mirror and differential-pair circuitry</td>
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<td>Current mirror arrangement and method for switching on a current</td>
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<td>8,519,794</td>
<td>Current mirror with low headroom and linear response</td>
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<td>8,511,842</td>
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<td>8,441,281</td>
<td>Gate leakage compensation in a current mirror</td>
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<tr>
<td>8,433,329</td>
<td>Data receiving circuit with current mirror and data slicer</td>
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<tr>
<td>8,431,883</td>
<td>Photoelectric conversion device comprising a current mirror circuit connected to a field effect transistor, a buffer and a voltage detection circuit</td>
</tr>
<tr>
<td>8,405,458</td>
<td>Current mirror with low headroom and linear response</td>
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<tr>
<td>8,405,377</td>
<td>Programmable current mirror</td>
</tr>
<tr>
<td>8,400,136</td>
<td>Current mirror semiconductor device and a layout method of the same</td>
</tr>
<tr>
<td>8,384,443</td>
<td>Current mirror and current cancellation circuit</td>
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<tr>
<td>8,378,651</td>
<td>HDMI driver tail current transistors with current mirror controlled leads</td>
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<tr>
<td>8,373,391</td>
<td>Switched current mirror with good matching</td>
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<tr>
<td>8,269,478</td>
<td>Two-terminal voltage regulator with current-balancing current mirror</td>
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<tr>
<td>8,269,468</td>
<td>Charging circuit having a smooth charging transition mode including a current mirror block controlled by a charge mode transition block comprising serially connected current mirrors</td>
</tr>
<tr>
<td>8,232,903</td>
<td>Finger split and finger-shifter technique for high-precision current mirror</td>
</tr>
<tr>
<td>8,232,785</td>
<td>System and method using a current mirror to program an output voltage and current</td>
</tr>
<tr>
<td>8,195,104</td>
<td>Electronic amplification device with current mirror for integrated power amplifiers</td>
</tr>
<tr>
<td>8,188,792</td>
<td>Techniques for current mirror circuits</td>
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<tr>
<td>8,169,255</td>
<td>Offset cancellation current mirror and operating method thereof</td>
</tr>
<tr>
<td>8,154,427</td>
<td>Driver circuit, method for operating and use of a current mirror of a driver circuit</td>
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<tr>
<td>8,125,162</td>
<td>Current mirror circuit</td>
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<tr>
<td>8,121,395</td>
<td>Current mirror circuit and optical receiver circuit using the same</td>
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<tr>
<td>8,111,057</td>
<td>Cascode current mirror circuit, bandgap circuit, reference voltage circuit having the cascode current mirror circuit and the bandgap circuit, and voltage regulator</td>
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<tr>
<td>8,026,767</td>
<td>Current mirror circuit, in particular for a non-volatile memory device</td>
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<tr>
<td>7,994,861</td>
<td>System and method for pre-charging a current mirror</td>
</tr>
<tr>
<td>7,973,488</td>
<td>Constant current driver circuit with voltage compensated current sense mirror</td>
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USPTO search on Jan 22, 2012
475 patents with “current and mirror” in title since 1976

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 475 patents.
Hits 1 through 50 out of 475

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USPTO search on Jan 26, 2014

509 patents with “current and mirror” in title since 1976

34 patents with “current and mirror” in title in 2012 and 2013

- Averaged 12.4 patents/year from 1976 to 2006
- Averaged 17 patents in 2012 and 2013
USPTO search on Jan 26, 2014

509 patents with “current and mirror” in title since 1976

34 patents with “current and mirror” in title in 2012 and 2013

Number of patents/year in this area still well above the 3-decade average

Is there still an opportunity to contribute to the current mirror field?
Google Patents search on Jan 27, 2014

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**Google Advanced Patent Search**

<table>
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<tr>
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<th>Description</th>
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<td>Restrict date by</td>
<td>Restrict by filing date or issue date</td>
<td></td>
</tr>
</tbody>
</table>
Current mirror arrangement and method for switching on a current
www.google.com/patents/US8531236
Grant - Filed Nov 20, 2008 - Issued Sep 10, 2013 - Franz Lechner - Ams Ag
A current mirror arrangement comprises a switchable, adjustable current source (Q1, Q2) for providing an impression current (IP), a current mirror (SP) having an ...
Overview - Related - Discuss

Current mirror and current cancellation circuit
www.google.com/patents/US8575971
Grant - Filed Jan 18, 2013 - Issued Nov 5, 2013 - Anand Chamakura - Maxim Integrated Products, Inc.
Techniques are described to mirror currents and subtract currents accurately. In an implementation, a circuit includes a first current source coupled to a first node ...
Overview - Related - Discuss

High-bandwidth linear current mirror
www.google.com/patents/US8587287
Grant - Filed Jul 1, 2010 - Issued Nov 19, 2013 - Christian Larsen - Conexant Systems, Inc.
High linearity is essential in audio circuitry. As sampling rates for audio applications are needed, high speed and high linearity are needed in analog and mixed ...
Overview - Related - Discuss
Google Patents search on Jan 27, 2014

Hits 21-25

Current mirror with low headroom and linear response
www.google.com/patents/US8519794
Grant - Filed Feb 25, 2013 - Issued Aug 27, 2013 - Sandro Herrera - Analog Devices, Inc.
A current mirror circuit provided in an emitter follower configuration achieves linearly output over a range of input currents by operating in response to a bias ...
Overview - Related - Discuss

Bias circuit, power amplifier, and current mirror circuit
www.google.com/patents/US8471631
There is provided a bias circuit that can operate even at low voltage and control a current reflecting a change in drain voltage. A first current mirror circuit for ...
Overview - Related - Discuss

Photoelectric conversion device comprising a current mirror ...
www.google.com/patents/US8431883
Grant - Filed Jun 18, 2008 - Issued Apr 30, 2013 - Makoto Yanagisawa - Semiconductor Energy Laboratory Co., Ltd.
It is an object to provide a photoelectric conversion device which can solve the problem of leakage current or noise caused when the photoelectric conversion ...
Overview - Related - Discuss

Current mirror circuit
www.google.com/patents/US8456227
Grant - Filed Mar 14, 2011 - Issued Jun 4, 2013 - Kenichi HIRASHIKI - Kabushiki Kaisha Toshiba
In one embodiment, a current mirror circuit includes first to fourth insulated gate field effect transistors (FETs), and a bias circuit. The gate electrodes of the first ...
Overview - Related - Discuss

HDMI driver tail current transistors with current mirror ...
www.google.com/patents/US8378653
Grant - Filed Aug 17, 2009 - Issued Feb 19, 2013 - Hugh Thomas Mair - Texas Instruments Incorporated
A HDMI (High-Definition Multimedia Interface) transmitter component may be operated solely on power that is scavenged and converted from termination tail ...
Overview - Related - Discuss
Google Patents search on Jan 27, 2014

63 hits but includes some foreign patents
Comparison of Search Engines
Google Patents search on Jan 27, 2014

For most recent two-year period:

34 patents found

Google includes some foreign patents

63 patents found
Single-stage low-gain differential op amp

- Can eliminate CMFB circuit if only single-ended output is needed by connecting counterpart circuits as a current mirror.
- This will double the voltage gain and the GB as well.
- Still uses counterpart circuits but terminated in different ways.
- Although not symmetric, previous analysis results with specified modifications still nearly apply.
Single-stage low-gain differential op amp

Current-Mirror Connected Counterpart Circuit

No CMFB Circuit Needed

\[ A(s) = \frac{g_{m1}}{sC_L + g_{o1} + g_{o3}} \]

\[ A_o = \frac{g_{m1}}{g_{o1} + g_{o3}} \]

\[ GB = \frac{g_{m1}}{C_L} \quad SR = \frac{I_T}{C_L} \]

In terms of practical design space parameters

\[ A_o = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{2}{V_{EB1}} \right) \]

\[ GB = \left( \frac{P}{V_{DD}C_L} \right) \left[ \frac{1}{V_{EB1}} \right] \]

\[ SR = \frac{P}{V_{DD}C_L} \]
Signal Swing

To keep $M_1$ out of Triode Region

$L_1: \quad V_{\text{OUT}} > V_{\text{iN}} - V_{Tn}$

To keep $M_1$ out of Cutoff

$L_2: \quad V_{\text{iN}} > V_{Tn}$

To keep $M_2$ out of Triode Region

$L_3: \quad \left| V_{\text{OUT}} - V_{\text{DD}} \right| > \left| V_{\text{XX}} - V_{\text{DD}} - V_{Tp} \right|$  

$V_{\text{XX}} - V_{Tp} > V_{\text{OUT}}$
Signal Swing

\[ \mathcal{L}_1: \quad V_{\text{OUT}} > V_{\text{IN}} - V_{\text{Tn}} \]

\[ \mathcal{L}_2: \quad V_{\text{IN}} > V_{\text{Tn}} \]

\[ \mathcal{L}_3: \quad V_{\text{XX}} - V_{\text{Tp}} > V_{\text{OUT}} \]
Signal Swing

\[ V_{\text{OUT}} \]

**Region 1:** \( V_{\text{OUT}} > V_{\text{IN}} - V_{\text{Tn}} \)

**Region 2:** \( V_{\text{IN}} > V_{\text{Tn}} \)

**Region 3:** \( V_{\text{XX}} - V_{\text{Tp}} > V_{\text{OUT}} \)
Signal Swing

How do the transfer characteristics relate to the signal swing?

Observe signal swing boundaries are same as operating region changes for transfer characteristics.
Signal Swing

How do the transfer characteristics relate to the signal swing?

For this circuit, high gain and large output signal swing for small $V_{EB}$
Signal Swing of Single-Stage Op Amp

For high-gain amplifiers, $V_d$ is inherently very small so are only concerned about output signal swing vs $V_{iC}$

Generally large swings come at expense of other desirable characteristics
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed?

Wide $V_{iC}$ and $V_{OUT}$ range

Narrow $V_{iC}$ and wide $V_{OUT}$ range

Narrow $V_{OUT}$ and wide $V_{iC}$ range

Narrow $V_{iC}$ and $V_{OUT}$ range
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed?

Wide $V_{iC}$ and $V_{OUT}$ range

Expected for catalog parts and overall I/O in many applications

Narrow $V_{OUT}$ and wide $V_{iC}$ range

Acceptable when followed by high-gain stage

Narrow $V_{iC}$ and wide $V_{OUT}$ range

Acceptable when $V_{iC}$ is fixed

Narrow $V_{iC}$ and $V_{OUT}$ range

Acceptable when $V_{iC}$ fixed and followed by high-gain stage
End of Lecture 6