Please review the “Exam Policies” section of the Exams page at the course web site. Please note the following two changes from policies used in the past:

1. You will be allowed to use one 8.5 × 11-inch two-sided handwritten help sheet. There are no restrictions on the material you place on the help sheets, except that no photocopied material or copied and pasted text or images are allowed. If there is a table or image from the textbook or some other source that you feel would be helpful during the exam, please notify the instructor.
2. All help sheets will be collected at the end of the exam but will be returned to you later.

The following is a list of topics that could appear in one form or another on the exam. Not all of these topics will be covered, and it is possible that an exam problem could cover a detail not specifically listed here. However, this list has been made as comprehensive as possible. You should be familiar with the topics on the previous review sheet in addition to those listed below.

Although every effort has been made to ensure that there are no errors in this review sheet, some might nevertheless appear. The textbook is the final authority in all factual matters, unless errors have been specifically identified there. You are ultimately responsible for obtaining accurate information when preparing for your exam.

**Basic CS (common source) and CE (common emitter) gain cells**
- intrinsic gain $A_o = g_m r_o$ (maximum theoretical gain w/ideal current source load and no small-signal negative feedback; there can be neg. feedback in bias ckt, though)
- for BJTs, $A_o = \frac{V_A}{V_T}$, where $V_A$ = Early voltage and $V_T$ = thermal voltage
- for MOSFETs, $A_o = \frac{V_A'}{\sqrt{2\mu C_{ox}WL}}$, where $V_A'$ = Early voltage per unit channel length
- for a realistic simple MOS or BJT current mirror acting as load, open-ckt gain is $A_{vo} = -g_m (r_{o1} r_{o2})$, where device #1 is the amplifier and device #2 is the load
- if $r_{o1} = r_{o2}$, then $A_{vo} = -\frac{1}{2} g_m r_o$

Two-port amplifier representation
- $v_{in}$ and $v_o$ are the voltages measured at the amplifier’s input and output terminals
- input port of amplifier has an equivalent input resistance $R_{in}$
- $A_y$ = voltage gain with load; $A_{vo}$ = “open-circuit” voltage gain ($R_L \rightarrow \infty$)
- output port of amplifier can be represented as a Thévenin equivalent circuit with dependent voltage source $A_{vo} v_{in}$ in series with output resistance $R_o$

Current mirrors in general
- use of MOSFETs and BJTs as active loads in amplifiers; equivalent resistance of active loads: ≈ $1/g_m$ if diode-connected; = $r_o$ if acting as current source or mirror
- significance of matching BJTs and MOSFETs
Review Topics for ELEC 351 Exam #2 (Spring 2014)

- need for diode-connected configuration
- characteristics of a “good” current source
- calculation of Norton equivalent resistance using a test source (analysis)
- calculation of Norton equivalent resistance via measured $I_O$ vs. $R_L$ data
- current steering: ability to bias multiple amplifiers from one reference branch
- one mirror can serve as the current reference for another mirror
- output current variation vs. output voltage variation (i.e., $I_O$ varies as $R_L$, and therefore the load voltage, varies)

MOSFET current mirror
- mirror only functions properly when MOSFETs are in saturation region (not in cutoff or triode regions)
- calculation of resistor value in reference circuit branch
- can make output current $I_O$ different from reference current $I_{REF}$ by using different channel widths
- simple mirror circuit
  - compliance voltage is $V_{OV} (= V_{GS} - V_t)$ of output transistor
  - output resistance is $r_o$
  - current transfer ratio: $\frac{I_O}{I_{REF}} = \frac{W_2/L_2}{W_1/L_1}$, where $Q_1$ is reference transistor, $Q_2$ is output transistor, and effect of $r_o$ is neglected
- Wilson mirror circuit
  - compliance voltage is $V_{V1} + V_{V3}$, where $Q_1$ is diode-connected transistor and $Q_3$ is output transistor (next to load)
  - output resistance is approx. $g_m r_o$, where $Q_2$ is transistor in reference leg and $Q_3$ is output transistor (next to load)

BJT current mirror
- mirror only functions properly when BJTs are in active region (not in cutoff or saturation regions)
- calculation of resistor value in reference circuit branch
- simple mirror circuit
  - compliance voltage is approx. 0.3 V ($V_{CE}\text{sat}$ of output transistor)
  - output resistance is $r_o$
  - current transfer ratio: $\frac{I_O}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta}}$, if effect of $r_o$ is neglected
- Wilson mirror circuit
  - compliance voltage is approx. 1 V ($V_{CE}\text{sat} + V_{BE}$)
  - output resistance is approx. $\beta r_o/2$
  - current transfer ratio: $\frac{I_O}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta^2}}$, if effect of $r_o$ is neglected

Differential amplifiers (“diff amps”)
- concept of differential-mode and common-mode signal voltages ($v_{id}$, $v_{od}$, and $v_{icm}$)
- $v_{id} = v_{IN1} - v_{IN2}$, $v_{od} = v_{o2} - v_{o1}$, and $v_{icm} = \frac{v_{IN1} + v_{IN2}}{2}$
- concept of a differential (or “floating”) voltage vs. a “single-ended” voltage (one side of voltage at reference node)
common-mode rejection ratio (CMRR) for differential-mode output

\[ \text{CMRR} = \frac{|A_d|}{A_{cm}} \]

expression of CMRR in dB

\[ \text{CMRR}[\text{dB}] = 20 \log \left( \frac{|A_d|}{A_{cm}} \right) \]

Differential amplifiers based on MOSFETs

- for purely differential-mode inputs, \( v_s \approx 0 \) (i.e., the node voltage at the sources of the two amplifying MOSFETs is essentially zero); there is essentially a virtual ground at the MOSFET source terminals, and the differential-mode voltage across \( R_{SS} \) is zero
- virtual ground exists at source terminals of amplifying MOSFETs (i.e., \( v_s = 0 \)) only in the purely differential mode, not in the common mode
- major advantage of diff-amp: source bypass capacitor not needed as in a common-source amplifier, even at DC
- equivalent resistance of MOSFET looking into source terminal is \( r_s = 1/g_m \)
- input common-mode range

\[ V_{CM,\text{max}} = V_{DD} - \frac{I}{2} R_D + V_i \quad \text{and} \quad V_{CM,\text{min}} = V_{SS} + V_{CS} + V_{OV} + V_t, \]

where \( V_{DD} \) and \( V_{SS} \) (neg. value) are pos./neg. power supplies; \( V_{CS} \) = compliance voltage of current mirror; \( V_{OV} \) = overvoltage \( (V_{GS} - V_i) \) of amplifying FETs; and \( R_D \) = drain resistances
- all MOSFETs must operate in the saturation region (i.e., avoid cut-off and triode)
- large-signal operation: total (bias + signal) drain currents given by

\[ i_{D1} = \frac{I}{2} + \left( \frac{I}{V_{OV}} \right) \left( \frac{v_{id}}{2} \right) \left( 1 - \frac{v_{id}}{2V_{OV}} \right)^2 \quad \text{and} \quad i_{D2} = \frac{I}{2} - \left( \frac{I}{V_{OV}} \right) \left( \frac{v_{id}}{2} \right) \left( 1 - \frac{v_{id}}{2V_{OV}} \right)^2 \]

where \( I \) = mirror current; this is valid for \(-\sqrt{2}V_{OV} \leq v_{id} \leq \sqrt{2}V_{OV}\)
- small-signal approximation (if \( v_{id} \ll 2V_{OV} \)):

\[ i_{D1} \approx I_{D1} + i_d1 \approx \frac{I}{2} + \left( \frac{I}{V_{OV}} \right) \left( \frac{v_{id}}{2} \right) \rightarrow i_{d1} \approx \frac{I}{2V_{OV}} v_{id} = \frac{1}{2} g_m v_{id} \]

voltage gain expressions:

- differential-mode or single-ended input, single-ended output

\[ A_{vol} = \frac{v_{od1}}{v_{id}} = -\frac{1}{2} g_m R_D \quad \text{and} \quad A_{vo2} = \frac{v_{o2}}{v_{id}} = +\frac{1}{2} g_m R_D, \]

where \( g_m = \frac{2I_D}{V_{OV}} = \frac{2(I/2)}{V_{OV}} = \frac{I}{V_{OV}} \) and \( v_{id} = v_{in1} - v_{in2} \);
- for greater accuracy, replace \( R_D \) with \( R_D||r_o \), where \( r_o \) is for amplifying FETs
- differential-mode input, differential-mode output

\[ A_d = \frac{v_{od}}{v_{id}} = g_m R_D \quad \text{where} \quad v_{od} = v_{o2} - v_{o1}; \]

for greater accuracy, replace \( R_D \) with \( R_D||r_o \).
- common-mode input, single-ended output

\[ A_{cm1} = \frac{v_{o1}}{v_{icm}} = A_{cm2} = \frac{v_{o2}}{v_{icm}} = -\frac{R_D}{1/g_m + 2R_{SS}} \approx \frac{R_D}{2R_{SS}}, \]

where \( R_{SS} \) = Norton equiv. resistance of current mirror

- common-mode input, differential-mode output

\[ A_{cm} = \frac{v_{od}}{v_{icm}} = 0, \text{ if MOSFETs and resistors are matched} \]

\[ A_{cm} \approx -\left( \frac{R_D}{2R_{SS}} \right) \left( \frac{\Delta R_D}{R_D} \right), \text{ if MOSFETs are matched but resistors are not matched} \]

\[ A_{cm} \approx -\left( \frac{R_D}{2R_{SS}} \right) \left( \frac{\Delta g_m}{g_m} \right), \text{ if resistors are matched but } g_m \text{ values are not matched} \]

\[ A_{cm} \approx -\left( \frac{R_D}{2R_{SS}} \right) \left( \frac{\Delta g_m}{g_m} + \frac{\Delta R_D}{R_D} \right), \text{ if neither resistors nor } g_m \text{ values are matched} \]

- CMOS diff amp with PMOS active loads

- no resistors required
- no body effect in PMOS active loads (sources can be tied to substrates)
- much higher gain than using diode-connected active loads
- \( Q_1 \) and \( Q_2 \) (amplifying MOSFETs) are matched
- \( Q_3 \) and \( Q_4 \) (current mirror active loads) are matched
- the differential-mode input, differential-mode output gain is \( A_d \approx g_m \left( \frac{r_o}{r_{o3}} \right) \),

where \( Q_1 \) is the amplifying device on one side, and \( Q_3 \) is the corresponding active load on that side

Relevant course material:

HW: #4, #5, #6
Labs: #2, #3
Textbook: Sections 7.1, 7.2.1-7.2.3, 7.4, 7.5.2-7.5.4, 8.1, 8.2
Lecture notes: (none)
Web Links: (none)
Matlab: (none)