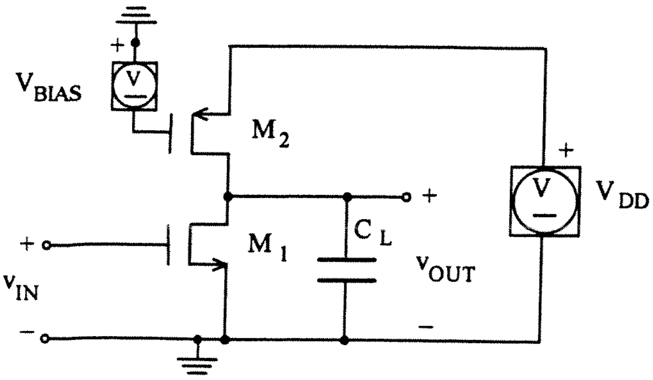
PROPERTIES BASIC AMPLIFIERS

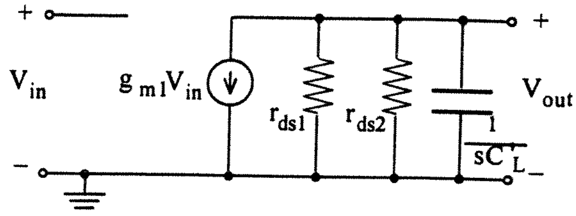
	COMMON SOURCE (CS)	COMMON DRAIN (CD)	COMMON GATE (CG)	CMOS INVERTER (CI)
Voltage-gain	high (inv.)	low (<1) (non-inv.)	high (non- inv.)	high (inv.)
Output resistance	high	low	high	high
Input resistance	high	high	low	high
Application areas	inp.stage OP	outp.stage OP	low-resistance inp.stage (signal from transmission line	uncommon sensitive hard to design

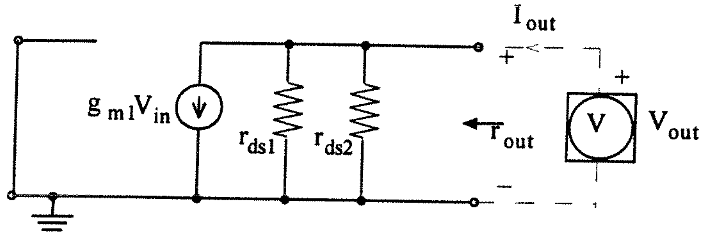
	CS	CD	CG	CI
A_o	$-\frac{g_{m1}}{g_{out}}$	$\frac{g_m}{g_{out}} \approx 1$	$\frac{g_{m1}+g_{b1}}{g_{out}} \approx \frac{g_{m1}}{g_{out}}$	$-\frac{g_{m1}+g_{m2}}{g_{out}}$
p_1	$-\frac{g_{out}}{C_L'}$	$-\frac{g_{out}}{C_L'}$	$-\frac{g_{out}}{C_L'}$	$-\frac{g_{out}}{C_L'}$
ω_u	$\frac{g_{m1}}{C_L'}$	$\frac{g_{m1}}{C_L'}$	$\approx \frac{g_{m1}}{C_L'}$	$\frac{g_{m1}+g_{m2}}{C_L'}$
g_{out}	$g_{ds1}+g_{ds2}$	$g_{m1}+g_{b1}+g_{ds1}+g_{ds2}$	$g_{ds1}+g_{ds2}$	$g_{ds1}+g_{ds2}$
g_{in}	0	0	$g_{m1}.\frac{1}{1+\frac{g_{ds1}}{g_{ds2}}}$	0

COMMON SOURCE AMPLIFIER

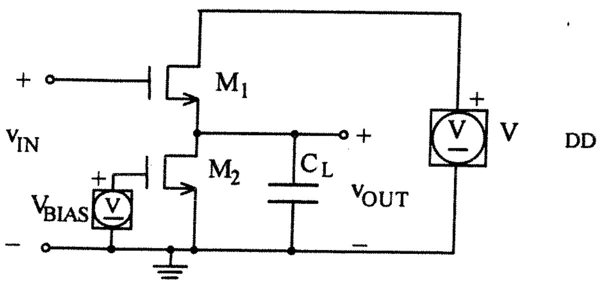


SMALL-SIGNAL EQUIVALENT CIRCUIT (SSEC)

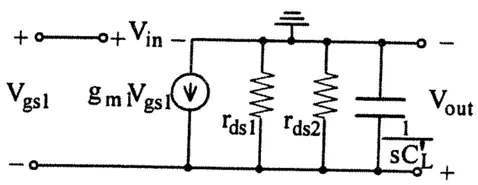


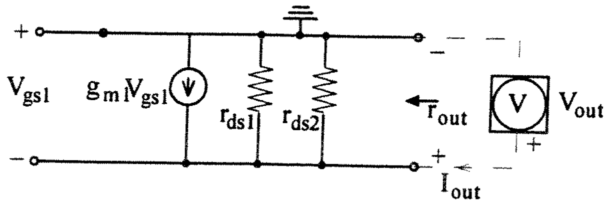


COMMON DRAIN AMPLIFIER

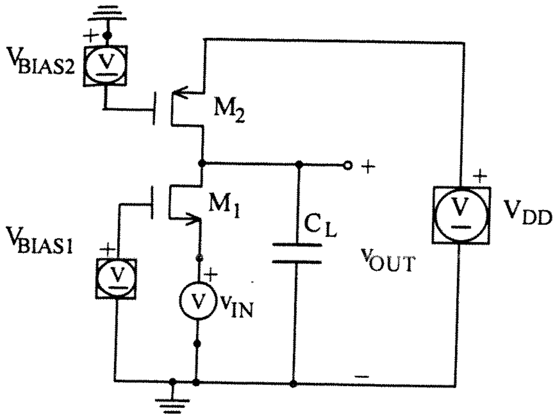


SMALL-SIGNAL EQUIVALENT CIRCUIT (SSEC)

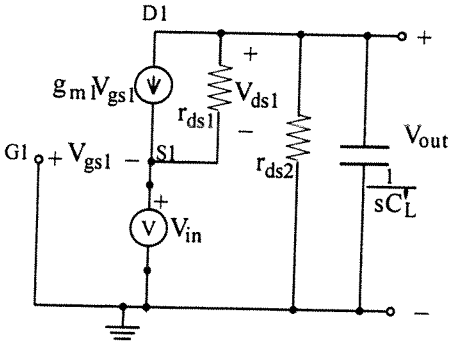


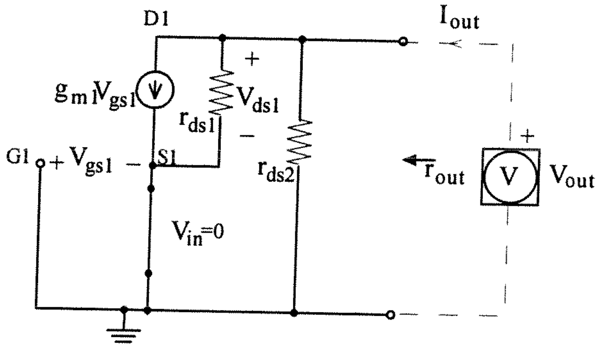


COMMON GATE AMPLIFIER

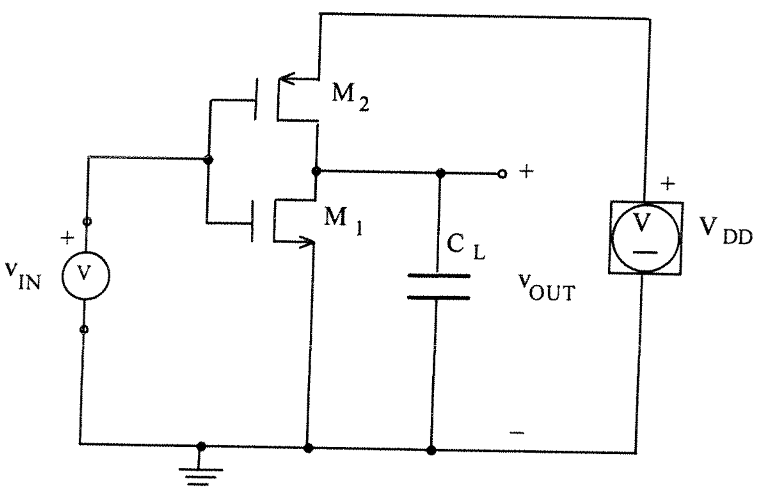


SMALL-SIGNAL EQUIVALENT CIRCUIT (SSEC)

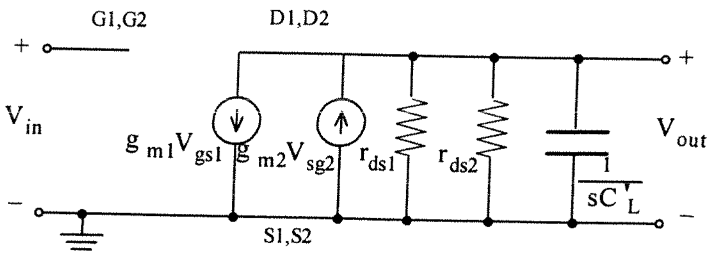




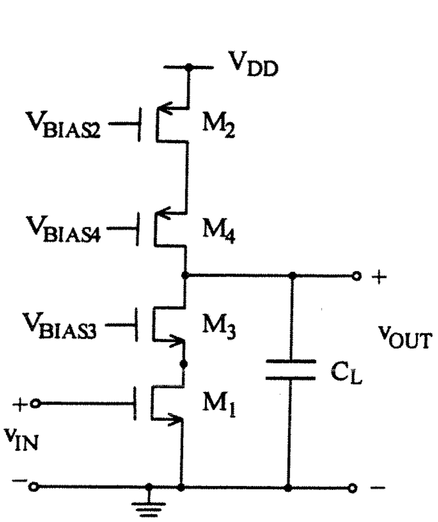
CMOS-INVERTER



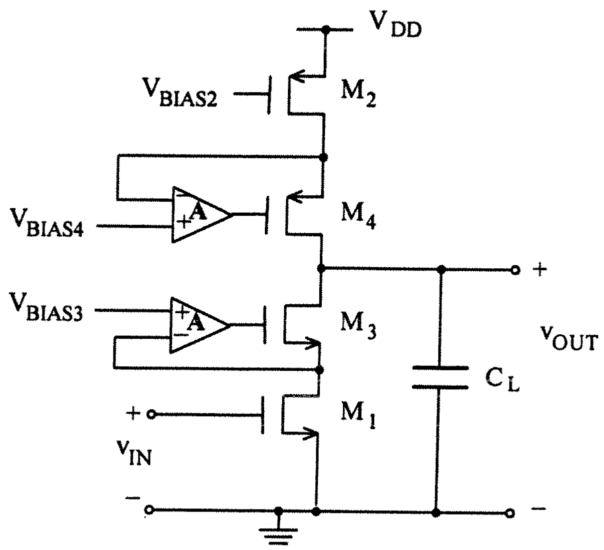
SMALL-SIGNAL EQUIVALENT CIRCUIT (SSEC)



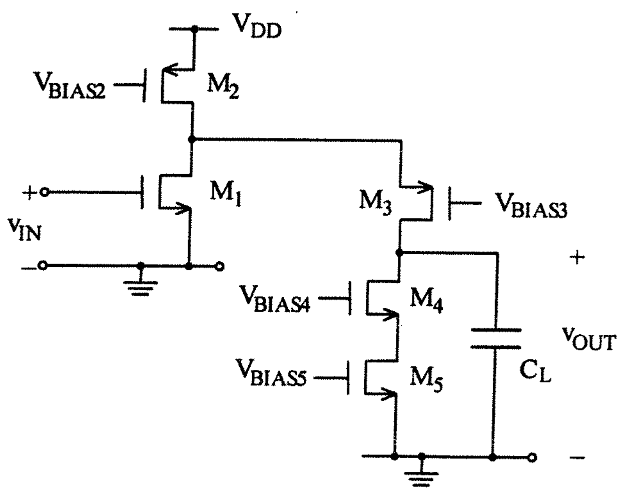
COMMON SOURCE AMPLIFIER WITH CASCODE



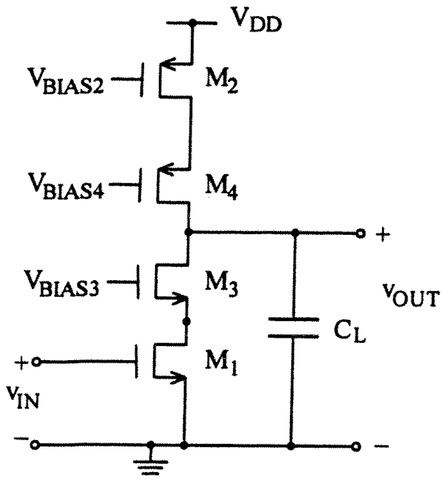
COMMON SOURCE AMPLIFIER WITH CASCODE. EXTRA BIAS



COMMON SOURCE AMPLIFIER WITH FOLDED CASCODE

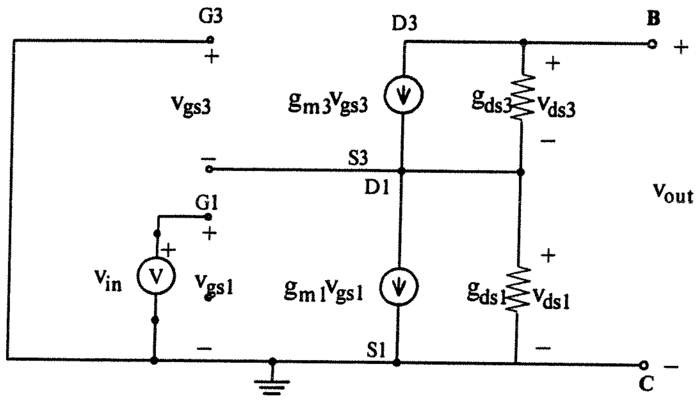


COMMON SOURCE AMPLIFIER
37 WITH CASCODE



SSEC

NMOS-part



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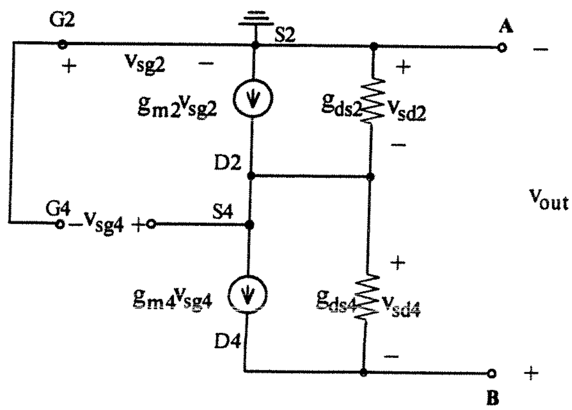
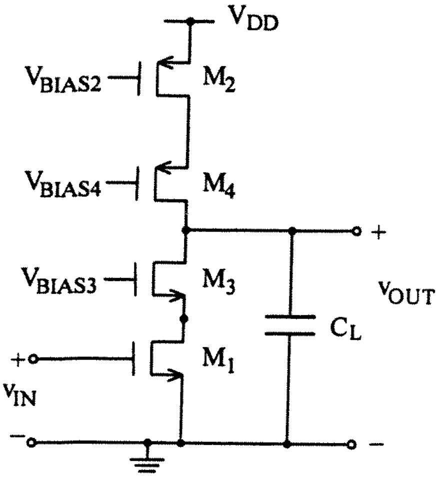
PMOS-part



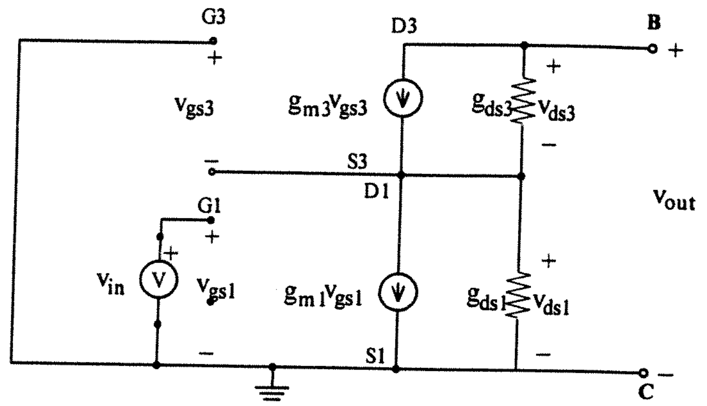
COMMON SOURCE AMPLIFIER

WITH CASCODE



SSEC

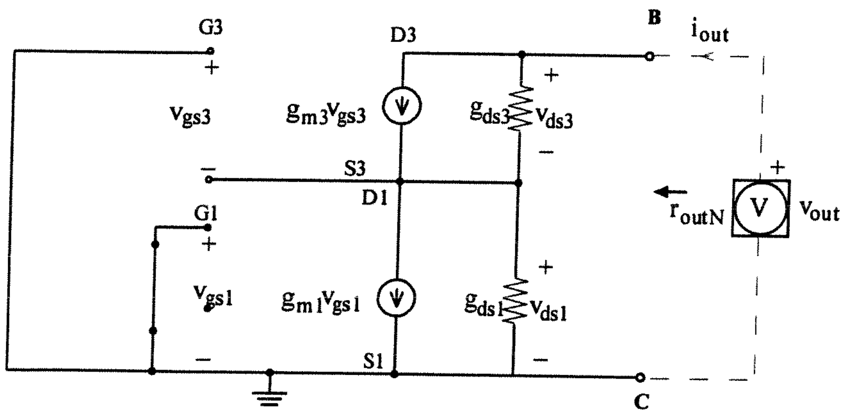
NMOS-part



Dertermine r_{out}

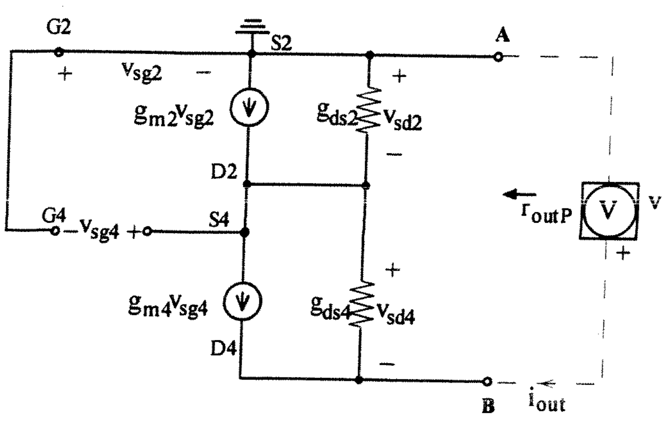
SSEC

NMOS-part



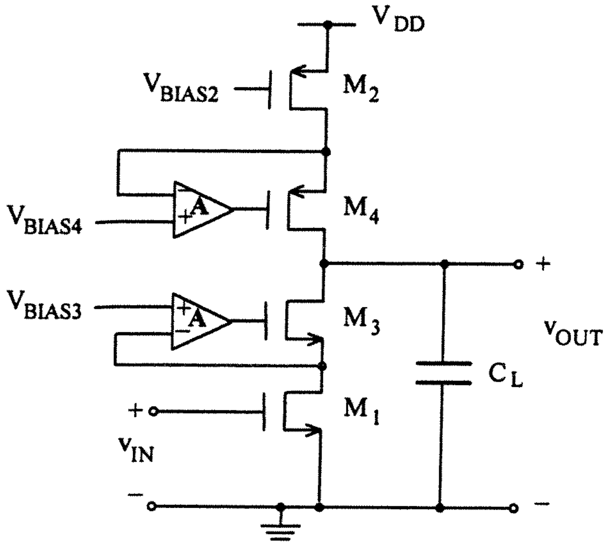
SSEC

PMOS-part



COMMON SOURCE AMPLIFIER
WITH CASCODE. EXTRA BIAS

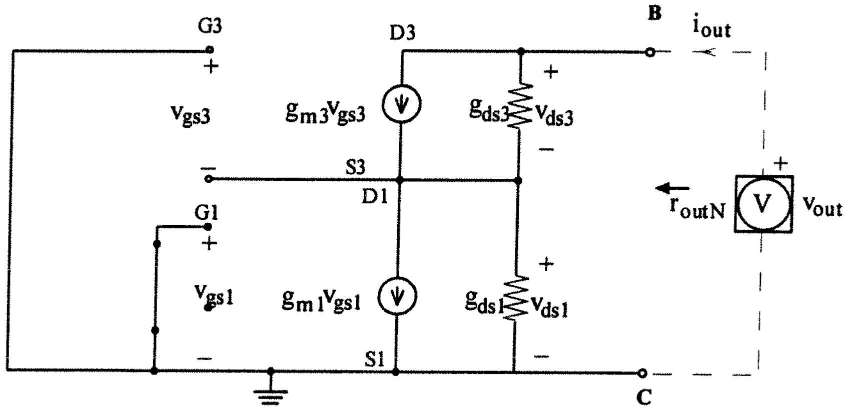
39



Determine r_{out}

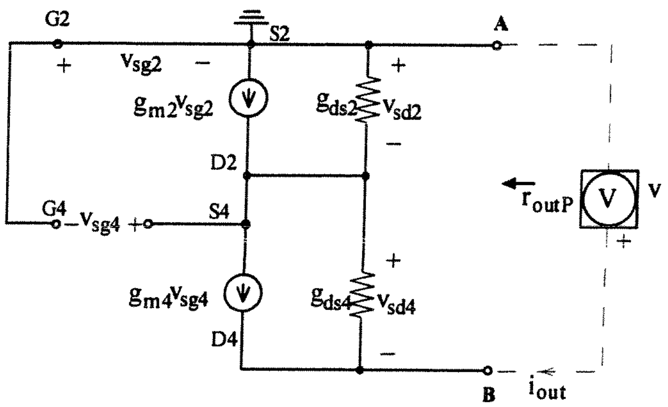
SSEC

NMOS-part

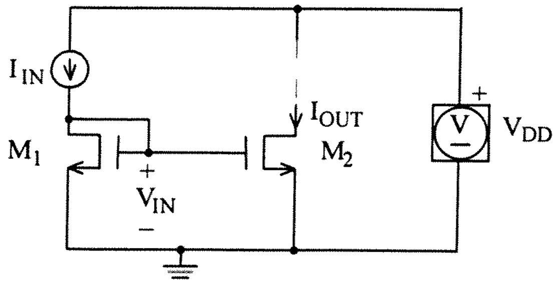


SSEC

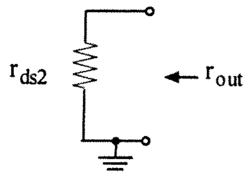
PMOS-part



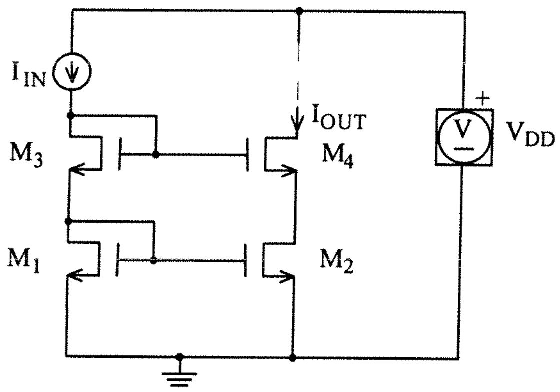
CURRENT MIRROR



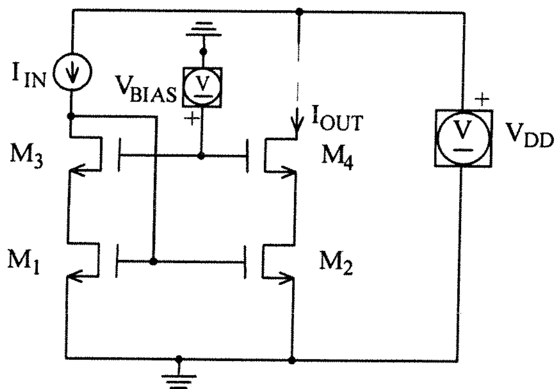
SMALL SIGNAL EQUIVALENT CIRCUIT (SSEC)



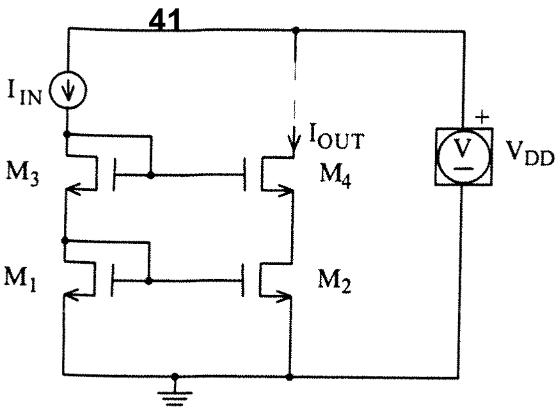
CASCODE CURRENT MIRROR



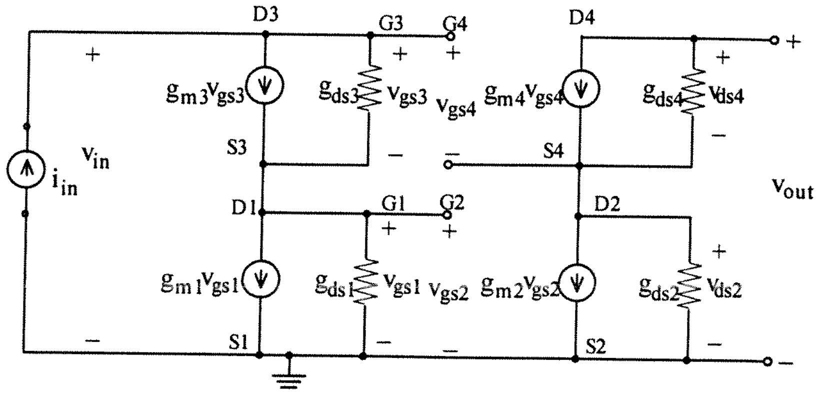
WIDE-SWING CURRENT MIRROR



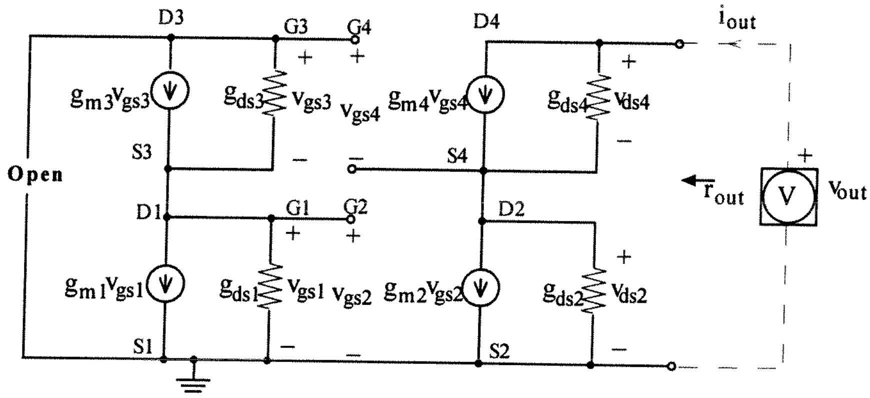
CASCODE CURRENT MIRROR

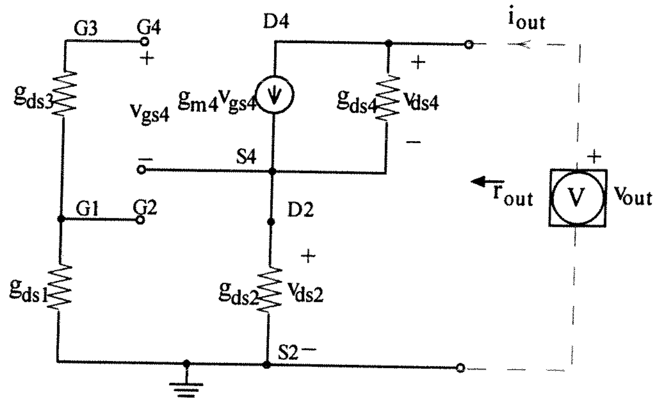


SSEC

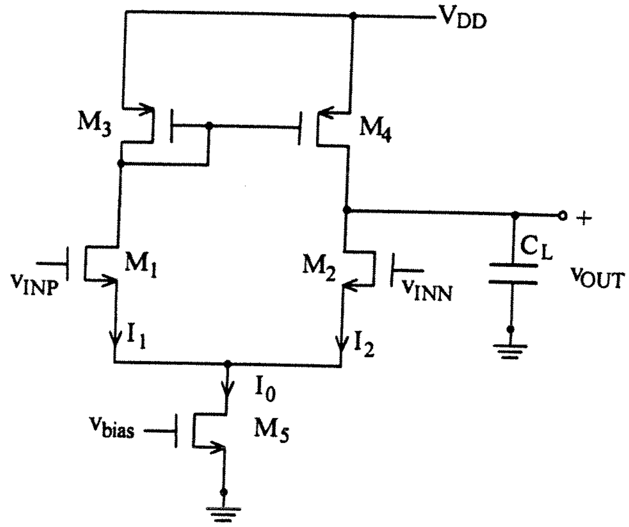


Determine r_{out}





DIFFERENTIAL GAINSTAGE **(Large signal analysis)**



Assumptions: 1) All transistors saturated
2) $V_{INP} = V_{INN} = V_{IN}$ (COMMON MODE)

CMR (Common Mode Range) = $[V_{IN\min}, V_{IN\max}]$

OR (Output Range) = $[V_{OUT\min}, V_{OUT\max}]$

$$V_{IN\min} = V_{DS5} + V_{GS1} = V_{eff5} + V_{eff1} + V_{t1} = \sqrt{\frac{I_0}{\alpha_5}} + \sqrt{\frac{I_0/2}{\alpha_1}} + V_{t1}$$

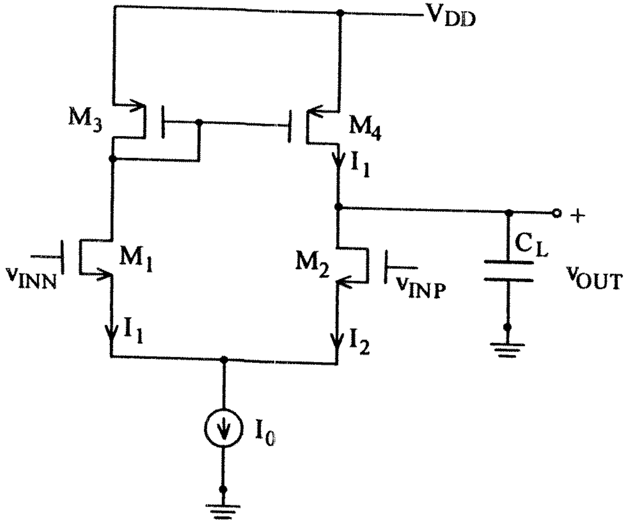
$$V_{IN\max} = V_{DD} - V_{SG3} - V_{DS1} + V_{GS1} = V_{DD} - V_{eff3} - V_{t3} - V_{eff1} + V_{eff1} + V_{t1} =$$

$$= V_{DD} - \sqrt{\frac{I_0/2}{\alpha_3}} - V_{t3} + V_{t1}$$

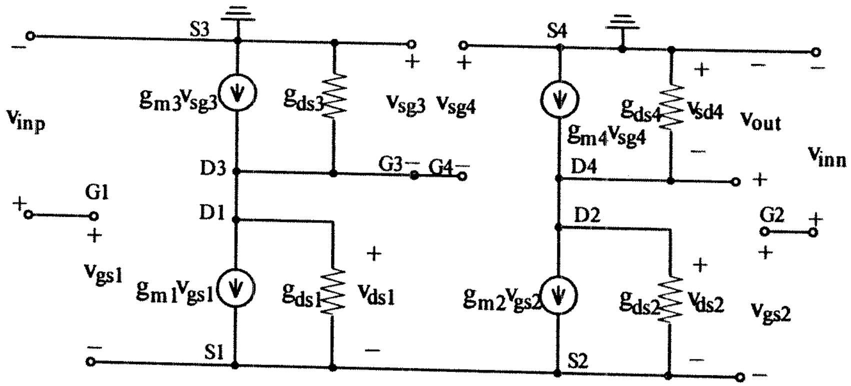
$$V_{OUT\min} = V_{DS5} + V_{DS2} = V_{eff5} + V_{eff1} = \sqrt{\frac{I_0}{\alpha_5}} + \sqrt{\frac{I_0/2}{\alpha_2}}$$

$$V_{OUT\max} = V_{DD} - V_{SD4} = V_{DD} - V_{eff4} = V_{DD} - \sqrt{\frac{I_0/2}{\alpha_4}}$$

DIFFERENTIAL GAINSTAGE



SSEC



Determine $\frac{v_{out}}{v_{inp} - v_{inn}}$ **for differential gain stage.**

1) Introduce variables v_x **(at node x, i.e. node D1,D3) and** v_y **(at node y, i.e. node S1,S2).**

2) Express $v_{gs1}, v_{gs2}, v_{sg3}$ $(=v_{sd3}), v_{sg4}, v_{ds1}, v_{ds2}, v_{sd4}$ **in** $v_{inp}, v_{inn}, v_x, v_y$ **and** v_{out}.

$v_{gs1} = v_{g1} - v_{s1} = v_{inp} - v_y$ $\qquad v_{ds1} = v_x - v_y$

$v_{gs2} = v_{g2} - v_{s2} = v_{inn} - v_y$ $\qquad v_{ds2} = v_{out} - v_y$

$v_{sg3} = -v_x$ $\qquad v_{sd3} = v_{sg3} = -v_x$

$v_{sg4} = v_{sg3} = -v_x$ $\qquad v_{sd4} = -v_{out}$

3) Nodal analysis on node x, node out and gnd.

Node x: $g_{m3}(-v_x) - g_{ds3}v_x - g_{m1}(v_{inp} - v_y) - g_{ds1}(v_x - v_y) = 0$ (1)

Node out: $g_{m4}(-v_x) - g_{ds4}v_{out} - g_{m2}(v_{inn} - v_y) - g_{ds2}(v_{out} - v_y) = 0$ (2)

gnd.: $-g_{m3}(-v_x) + g_{ds3}v_x - g_{m4}(-v_x) + g_{ds4}v_{out} = 0$ (3)

$$(3) \Rightarrow v_x = \frac{-g_{ds4}v_{out}}{g_{m3} + g_{m4} + g_{ds3}} \quad (4)$$

$$(1),(2) \Rightarrow \begin{array}{l} v_x(g_{m3} - g_{m4} + g_{ds3}) - g_{ds4}v_{out} + g_{m1}v_{inp} - g_{m2}v_{inn} - v_y(g_{m1} - g_{m2}) \\ + g_{ds1}v_x - g_{ds2}v_{out} - v_y(g_{ds1} - g_{ds2}) = 0 \end{array} \quad (5)$$

4) Assume $g_{ds1} = g_{ds2}$, $g_{ds3} = g_{ds4}$, $g_{m1} = g_{m2}$ **and** $g_{m3} = g_{m4}$

$$(5) \Rightarrow v_x g_{ds4} - g_{ds4}v_{out} + g_{m1}(v_{inp} - v_{inn}) + g_{ds2}(v_x - v_{out}) = 0 \quad (6)$$

$$(4),(6) \Rightarrow g_{m1}(v_{inp} - v_{inn}) = v_{out}(g_{ds2} + \frac{g_{ds2}g_{ds4}}{g_{m3} + g_{m4} + g_{ds3}} + g_{ds4} + \frac{g_{ds4}^2}{g_{m3} + g_{m4} + g_{ds3}}) \quad (7)$$

But $g_{ds3} = g_{ds4}$ and $g_{m3} = g_{m4}$ which gives:

$$(7) \Rightarrow g_{m1}(v_{inp} - v_{inn}) = v_{out}(g_{ds2} + \frac{g_{ds2}g_{ds4}}{2g_{m4} + g_{ds4}} + g_{ds4} + \frac{g_{ds4}^2}{2g_{m4} + g_{ds4}}) \quad (8)$$

$$(8) \Rightarrow g_{m1}(v_{inp} - v_{inn}) = v_{out}g_{ds2}(1 + \frac{g_{ds4}}{2g_{m4} + g_{ds4}}) + v_{out}g_{ds4}(1 + \frac{g_{ds4}}{2g_{m4} + g_{ds4}}) \quad (9)$$

$$(9) \Rightarrow g_{m1}(v_{inp} - v_{inn}) = v_{out}(1 + \frac{g_{ds4}}{2g_{m4} + g_{ds4}})(g_{ds2} + g_{ds4}) \quad (10)$$

$$(10) \Rightarrow g_{m1}(v_{inp} - v_{inn}) = v_{out}(\frac{2g_{m4} + 2g_{ds4}}{2g_{m4} + g_{ds4}})(g_{ds2} + g_{ds4}) \quad (11)$$

$$(11) \Rightarrow \frac{v_{out}}{v_{inp} - v_{inn}} = \frac{g_{m1}(2g_{m4} + g_{ds4})}{2(g_{ds2} + g_{ds4})(g_{m4} + g_{ds4})} \approx \frac{g_{m1}}{g_{ds2} + g_{ds4}}$$

PERFORMANCE MEASURES FOR DIFFERENTIAL GAIN STAGE

LARGE SIGNAL ANALYSIS:

- Common Mode Range, $CMR = [V_{inmin}, V_{inmax}]$
- Output range, $OR = [V_{outmin}, V_{outmax}]$
- Slew Rate, $SR = max\left\{\frac{dv_{out}}{dt}\right\}$

SMALL SIGNAL ANALYSIS:

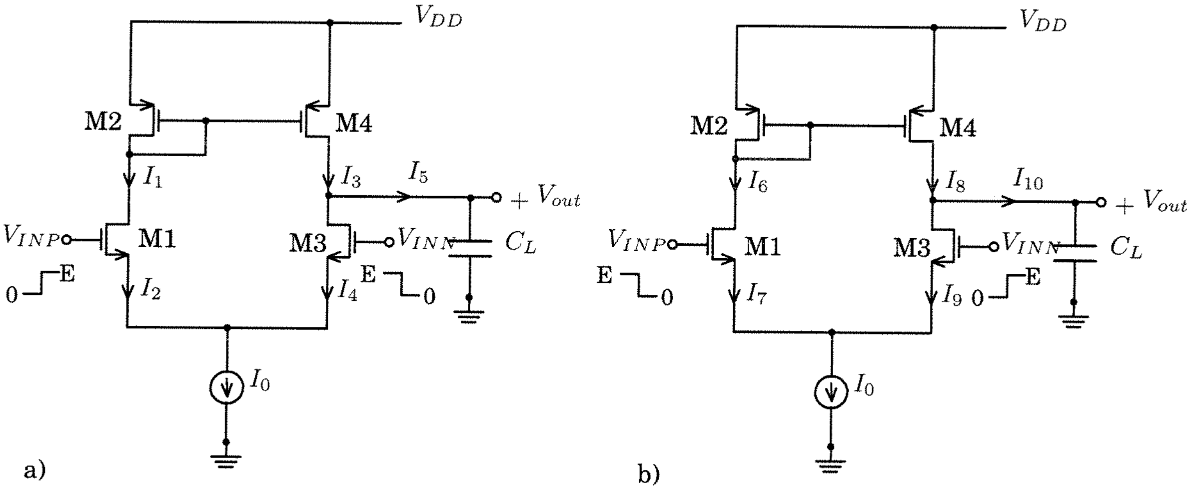
- Common Mode Rejection Ratio, $CMRR = 20 \cdot {}^{10}\log\frac{A_d}{A_{cm}}$
- Power Supply Rejection Ratio +, $PSRR_+ = 20 \cdot {}^{10}\log\frac{A_d}{A_{Vdd \rightarrow V_{out}}}$
- Power Supply Rejection Ratio -, $PSRR_- = 20 \cdot {}^{10}\log\frac{A_d}{A_{gnd \rightarrow V_{out}}}$

- A_d=Amplification for differential input signals
- A_{cm}=Amplification for common-mode input signals
- $A_{Vdd \rightarrow V_{out}}$=Amplification for variations in $+V_{dd}$ from V_{dd} to V_{out}
- $A_{gnd \rightarrow V_{out}}$=Amplification for variations in ground from ground to V_{out}

To determine $A_{Vdd \rightarrow V_{out}}$ set the AC-input signal to zero and introduce an AC-source at $V_{dd}+$. $A_{gnd \rightarrow V_{out}}$ determins in the same way by setting the AC-input signal to zero and introduce an AC-source at $V_{dd}-$ (ground).

DETERMINATION OF SLEW-RATE

To determine Slew-Rate (SR) for the differential gain-stage below, apply a square-pulse on V_{INP} and an inverted square-pulse on V_{INN}. Figure a) gives phase 1, when V_{INP} grows instantaneously from 0 to E and V_{INN} at the same time instantaneously goes from E to 0. Figure b) shows phase II that starts with V_{INP} instantaneously decreasing from E to 0 and V_{INN} instantaneously increasing from 0 to E.
E is larger than V_{tn} ($E > V_{tn}$). Transistors M1 and M3 are identical as well as M2 and M4.



Phase I:

- $V_{INP} = +E, V_{INN} = 0 \Rightarrow$ M1 conducts and M3 blocks.
- M3 blocks $\Rightarrow I_4 = 0$
  M1 conducts $\Rightarrow I_1 = I_2 = I_0$
- M2 and M4 is a current mirror and as M2 and M4 are identical $I_3 = I_1 = I_0$
- M3 blocks ($I_4 = 0$) $\Rightarrow I_5 = I_3 = I_0$

Phase II:

- $V_{INP} = 0, V_{INN} = +E \Rightarrow$ M1 blocks and M3 conducts.
- M1 blocks $\Rightarrow I_6 = I_7 = 0$
- M2 and M4 is a current mirror $\Rightarrow I_8 = I_6 = 0$
- M3 conducts $\Rightarrow I_9 = I_0$
- $I_8 = 0$ and $I_9 = I_0 \Rightarrow I_{10} = -I_9 = -I_0$

$$\text{Definition: Slew-Rate (SR)} = \max \frac{dv_{out}(t)}{dt}$$

For capacitor C_L:

$$i_{CL}(t) = C_L \frac{dv_{CL}(t)}{dt} = C_L \frac{dv_{out}(t)}{dt} \Rightarrow \frac{dv_{out}}{dt} = \frac{i_{CL}(t)}{C_L}$$

Thus, maximum value of $\frac{dv_{out}(t)}{dt}$ obtains for maximum value of $i_{CL}(t)$, which has been shown above to be I_0.

$$\textbf{I.e. } \text{Slew-Rate} = \frac{I_0}{C_L}$$

NOISE

Look at a signal voltage $v(t)$ that interferes from a noise voltage v_n, which means that $v_{tot}(t) = v(t) + v_n(t)$. The power of the signal denotes P_{signal} and the power of the noise P_{noise}.

Following performance measures is defined:

- Signal Noise Ratio, $SNR = 10 \cdot ^{10}\log \frac{P_{signal}}{P_{noise}}$
- Dynamic Range, $DR = 20 \cdot ^{10}\log \frac{|v_{in,max}(t)|}{|v_{in,min}(t)|}$

- If $|v_{in}(t)| > |v_{in,max}(t)|$ you get distorsion.
- If $|v_{in}(t)| < |v_{in,min}(t)|$ the signal gets drowned in the noise.

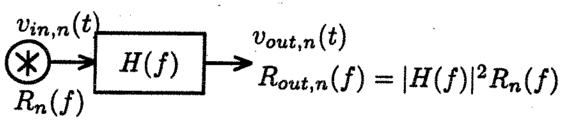
- Noise power, P_{noise}, defines as $P_{noise} = \frac{1}{T}\int_0^T v_n^2(t)dt$
- Also, if $V_n(f)$ is the Fourier transform of $v_n(t)$, $P_{noise} = \int_{-\infty}^{\infty} V_n^2(f)df$
- $V_n^2(f)$ is the *spectral density* $R_n(f)$ and $R_n(f)$ is the Fourier transform of the *autocorrelation function* $r_n(t)$. I.e. $V_n^2(f) = R_n(f) = \mathcal{F}\{r_n(t)\}$

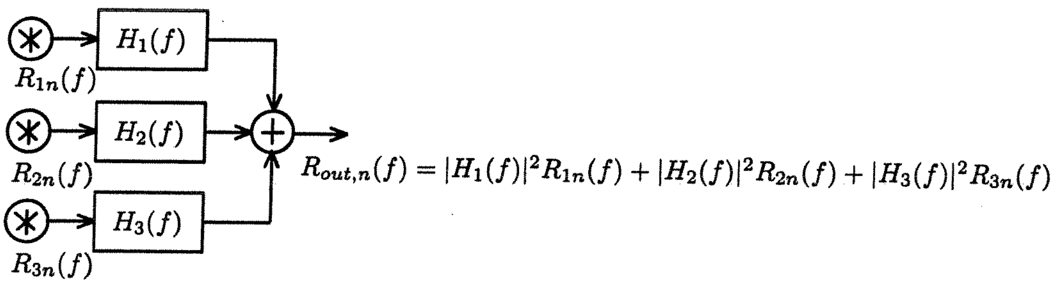
If the input signal to a linear system, with transfer function $H(f)$, has a noise component with spectal density $R_n(f)$ the output signal will get a noise component with spectral density $R_{out,n}(f)$ and

$$R_{out,n}(f) = |H(f)|^2 R_n(f)$$

If we have say three systems, $H_1(f)$, $H_2(f)$ and $H_3(f)$ with noise, $R_{1n}(f)$, $R_{2n}(f)$ and $R_{3n}(f)$ respectivly, on their inputs and the noise sources are *uncorrelated*, and if the output signals from the systems are added the spectal density of the output signal will be:

$$R_{out,n}(f) = |H_1(f)|^2 R_{1n}(f) + |H_2(f)|^2 R_{2n}(f) + |H_3(f)|^2 R_{3n}(f)$$





Noise bandwidth concept

Regard a one-pole system with transfer function

$$H(s) = \frac{A_0}{1 + \frac{s}{p_1}} \Rightarrow |H(f)| = \frac{|A_0|}{\sqrt{1 + \left(\frac{2\pi f}{p_1}\right)^2}}$$

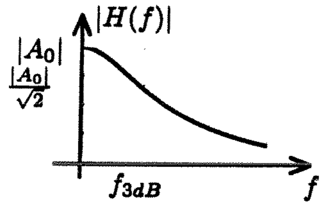
This equation gives the 3dB cut-off frequency: $f_{3dB} = \frac{|p_1|}{2\pi}$.

If you feed the system with *white noise*, that is noise with constant (independent of f) spectral density $R_i(f) = R_i$, the noise power on the output will be

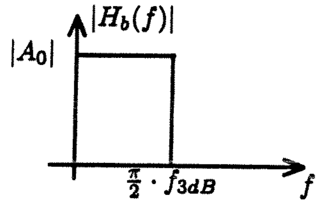
$$P_{out,noise} = \int_0^\infty |H(f)|^2 R_i df = R_i \int_0^\infty \frac{|A_0|^2}{1+\left(\frac{2\pi f}{p_1}\right)^2} = R_i \cdot \frac{|A_0|^2|p_1|}{2\pi}\left[\arctan\frac{2\pi f}{|p_1|}\right]_0^\infty$$

$$= R_i \cdot \frac{|A_0|^2|p_1|}{2\pi}\cdot\frac{\pi}{2} = R_i|A_0|^2\cdot\frac{\pi}{2}\cdot\frac{|p_1|}{2\pi} = R_i|A_0|^2\cdot\frac{\pi}{2}\cdot f_{3dB}$$

If you have a ***brick-wall filter*** with $|H_b(f)| = |A_0|$ and bandwidth $\frac{\pi}{2}\cdot f_{3dB}$ you get the same power $P_{out,noise}$. Therefore $\frac{\pi}{2}\cdot f_{3dB}$ is said to be the **noise-bandwidth** of this one-pole system.



$R_{out}(f) = R_i|H(f)|^2$



$R_{out}(f) = R_i|H_b(f)|^2$

Noise in CMOS-circuits

Noise in CMOS-circuits is *inherent* noise, not *interference* noise.
There are three different types of inherent noise.

1) Thermal noise - due to thermal excitation of charge carriers. Thermal noise is white noise.

2) Flicker noise - due to traps in the semiconductor that hold carriers, which normally gives the DC-current, for some while and than release them. (DC-current doesn't float smooth.) $R_n(f) \sim \frac{1}{f}$ (moore accurate $R_n(f) \sim \frac{1}{f^\alpha}$ where $0.8 < \alpha < 1.3$).

3) Shot noise - DC-current is a result of individual carriers, which yields a current that actually is pulsed and not smooth.

Noise models CMOS: (Regard the saturated region)

Flicker noise (spektral density $V_g^2(f) = \frac{K}{WLC_{ox}f}$) and thermal noise (spectral density $I_d^2(f) = 4kT\frac{2}{3}g_m$) dominates in CMOS-circuits.

As $i_d(t) \approx g_m v_{gs}(t)$ then $I_d(f) \approx g_m V_{gs}(f)$ and the thermal noise with spectral density $I_d^2(f) = 4kT\frac{2}{3}g_m$ can be transformed to an equivalent noise voltage on the input with the spectral density $V_{gs}^2(f) = 4kT\frac{2}{3}\frac{1}{g_m}$. $V_{gs}^2(f)$ and $V_g^2(f)$ are uncorrelated and can thus be added.