EE115 Analog Circuits

Cascode AMP, IC source follower & current mirror

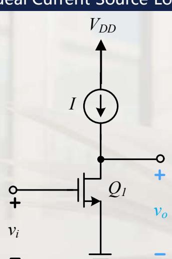
Prof. Haoyu Wang
Office: SIST Bldg. 3-530
wanghy@shanghaitech.edu.cn

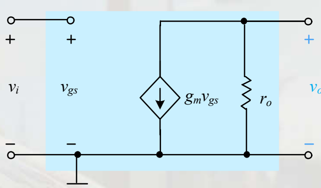
Outline

- Building blocks of IC amplifier 3
  - Cascode Amplifier
  - IC Source Follower
  - Current-Mirror Circuits with Improved Performance
- Reading: SEDTRA/SMITH book pages 539-560

Review: Basic Gain Cells w/ Ideal Current Source Load

Ideal Current Source Load





$R_{in} = \infty$

$A_{vo} = -g_m r_o$

$R_o = r_o$

- Intrinsic gain

$$g_m = \frac{I_D}{V_{OV}/2}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A' L}{I_D}$$

$$A_o = g_m r_o = \frac{V_A}{V_{OV}/2} = \frac{2V_A' L}{V_{OV}}$$

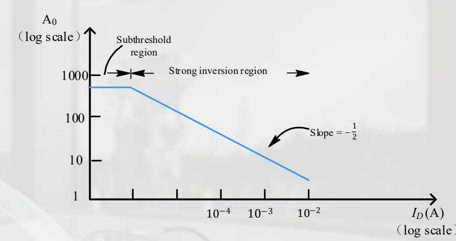
Review: Intrinsic Gain $g_m r_o$

- MOSFET

$$g_m = \sqrt{2\mu_n C_{ox}(W/L)}\sqrt{I_D}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A' L}{I_D}$$

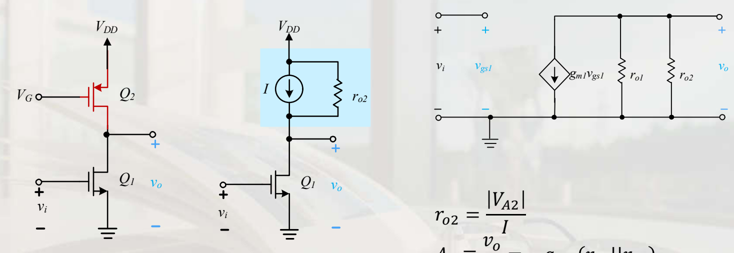
$$A_o = g_m r_o = \frac{V_A' \sqrt{2(\mu_n C_{ox})(WL)}}{\sqrt{I_D}}$$



Smaller current gives higher intrinsic gain, but paid by smaller g_m and bandwidth.

Review: Output Resistance of Current Source Load

Current source loaded/active loaded



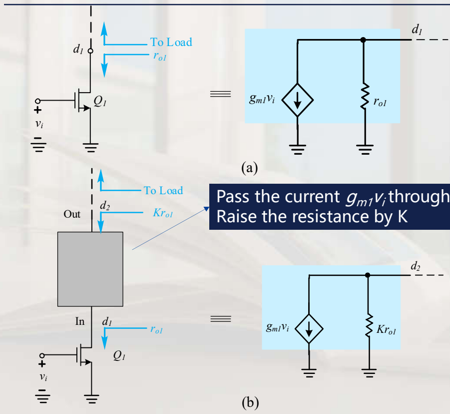
$$r_{o2} = \frac{|V_{A2}|}{I}$$

$$A_v \equiv \frac{v_o}{v_i} = -g_{m1}(r_{o1}||r_{o2})$$

$$I = \frac{1}{2}(\mu_p C_{ox})\left(\frac{W}{L}\right)_2 [V_{DD} - V_G - |V_{tp}|]^2$$

$$A_v = -\frac{1}{2} g_m r_o$$

Review: How To Increase Voltage Gain?

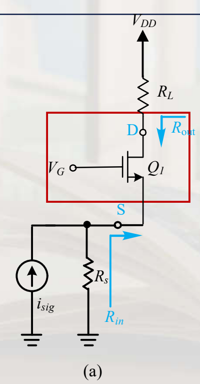


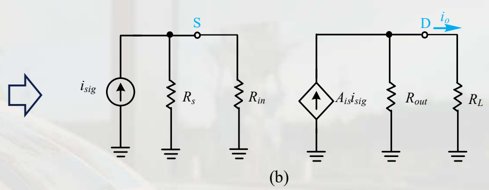
Pass the current $g_{m1}v_i$ through
Raise the resistance by K

- **Current buffer:** passes current ***but*** raises resistance level
  - Low **input resistance**
  - Unity **current gain**
  - High **output resistance**

CG, CS, CD, which circuit has the best current buffer performance?

Review: Common Gate Amplifier

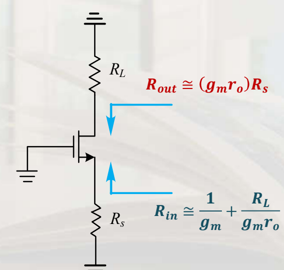


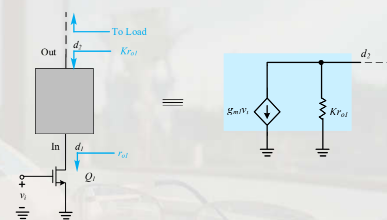


- R_{in}: input resistance
- R_o: output resistance
- A_{is}: short-circuit current gain (output grounded)

Review: Impedance Transformation of CG Amp

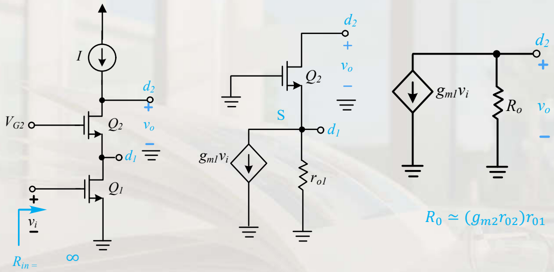
- R_S transformed to the output by multiplying by the intrinsic gain.
- R_L transformed to the input by dividing by the intrinsic gain.





CG Amplifier is an ideal current buffer load to boost voltage gain!

MOS Cascode Amplifier



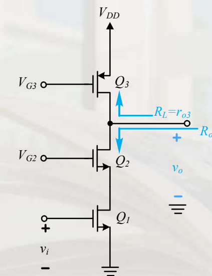
$$A_{vo} \equiv \frac{v_o}{v_i} = -g_{m1}R_o$$

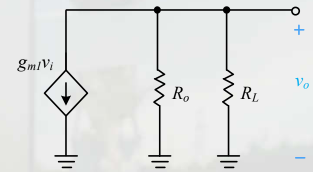
$$R_o \cong (g_{m2}r_{o2})r_{o1}$$

$$A_{vo} = -(g_{m1}r_{o1})(g_{m2}r_{o2})$$

$$A_{vo} = -(g_m r_o)^2 = -A_0^2$$

Implementation of Constant-Current Source Load





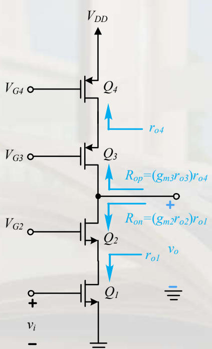
$$R_L = r_{o3}$$

$$A_v = -g_{m1}(R_o || R_L)$$

$$= -g_{m1}[(g_{m2}r_{o2} \cdot r_{o1}) || r_{o3}]$$

$$\cong -g_{m1}r_{o3}$$

Cascode Amp w/ Cascode Current-Source Load



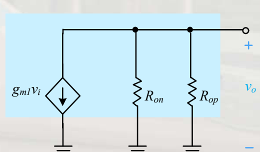
$$A_v = \frac{v_o}{v_i}$$

$$= -g_{m1}[R_{on} || R_{op}]$$

$$= -g_{m1}\{[(g_{m2}r_{o2})r_{o1}] || [(g_{m3}r_{o3})r_{o4}]\}$$

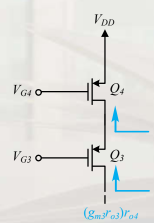
If all transistors are identical

$$A_v = -\frac{1}{2}(g_m r_o)^2 = -\frac{1}{2}A_0^2$$



Example: Cascode current source

Design the Cascode current source to provide a current of 100 μA and an output resistance of 500 kΩ. Given 0.18-μm CMOS technology, v_{DD}= 1.8 V, v_{tp}= -0.5 V, μ_pC_{ox}=90 μA/V^2, and V_A'=-5 V/μm. Use $|V_{ov}|$ = 0.3 V and determine L and W/L for each transistor, and bias voltages V_{G3}, and V_{G4}. Design to maximize the allowable signal swing at the output terminal.



$$\boxed{\begin{aligned} g_m &= \frac{I_D}{V_{OV}/2} \\ r_o &= \frac{V_A}{I_D} = \frac{V_A'L}{I_D} \\ g_m &= \sqrt{2k_n'}\sqrt{W/L}\sqrt{I_D} \\ A_o &= \frac{V_A}{V_{OV}/2} = \frac{2V_A'L}{V_{OV}} \end{aligned}}$$

Solution:

$$R_o = (g_{m3}r_{03})r_{04}$$

$$R_o = (g_m r_0)r_0$$

$$= \frac{|V_A|}{|V_{OV}|/2} \times \frac{|V_A|}{I_D}$$

$$500k\Omega = \frac{|V_A|}{0.15} \times \frac{|V_A|}{0.1mA}$$

$$|V_A| = 2.74V$$

$$L = \frac{2.74}{5} = 0.55\mu m$$

$$V_{SG4} = 0.5 + 0.3 = 0.8V$$

$$V_{G4} = 1.8 - 0.8 = 1.0V$$

$$V_{D4} = 1.8 - 0.3 = 1.5V$$

$$V_{SG3} = V_{SG4} = 0.8V$$

$$V_{G3} = 1.5 - 0.8 = +0.7V$$

$$v_{D3max} = 1.5 - 0.3 = +1.2V$$

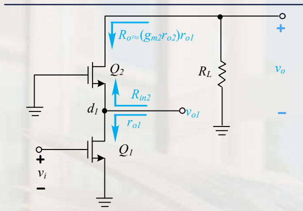
$$I_D = \frac{1}{2}(\mu_p C_{ox})\left(\frac{W}{L}\right)|V_{OV}|^2(1 + \frac{V_{SD}}{|V_A|})$$

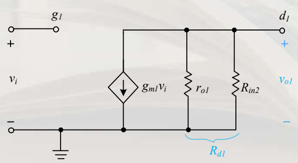
$$100 = \frac{1}{2} \times 90 \times \left(\frac{W}{L}\right) \times 0.3^2(1 + \frac{0.3}{2.74})$$

$$\frac{W}{L} = 22.3$$

Distribution of Voltage Gain in Cascode Amp

上海科技大学 ShanghaiTech University





$$A_o = -g_{m1}(R_o||R_L)$$

$$A_o = -g_{m1}(g_{m2}r_{o2}r_{o1}||R_L)$$

$$A_v = A_{v1}A_{v2} = \left(\frac{v_{o1}}{v_i}\right)\left(\frac{v_o}{v_{o1}}\right)$$

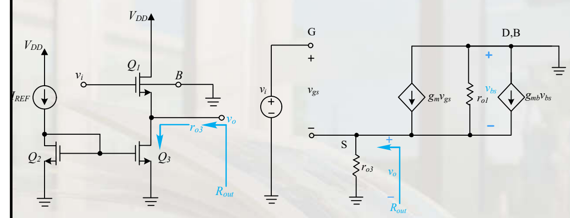
$$A_{v1} = \frac{v_{o1}}{v_i} = -g_{m1}R_{d1} = -g_{m1}(r_{o1}||R_{in2})$$

$$R_{in2} \approx \frac{R_L}{g_{m2}r_{o2}} + \frac{1}{g_{m2}}$$

Case	R_L	R_{in2}	R_{d1}	A_{V1}	A_{V2}	A_V
1	∞	∞	r_o	$-g_m r_o$	$g_m r_o$	$-(g_m r_o)^2$
2	$(g_m r_o)r_o$	r_o	$r_o/2$	$-\frac{1}{2}(g_m r_o)$	$g_m r_o$	$-\frac{1}{2}(g_m r_o)^2$
3	r_o	$\frac{2}{g_m}$	$\frac{2}{g_m}$	-2	$\frac{1}{2}(g_m r_o)$	$-(g_m r_o)$
4	$0.2r_o$	$\frac{1.2}{g_m}$	$\frac{1.2}{g_m}$	-1.2	$0.17(g_m r_o)$	$-0.2(g_m r_o)$

IC Source Follower

上海科技大学 ShanghaiTech University



$$\frac{v_o}{v_i} = \frac{R_L}{R_L + \frac{1}{g_m}}$$

$$R_L = r_{o1}||r_{o3}||\frac{1}{g_{mb}}$$

$$R_L \cong \frac{1}{g_{mb}}$$

$$\frac{v_o}{v_i} \cong \frac{g_m}{g_m + g_{mb}} = \frac{1}{1+\chi}$$

$$R_{out} = \frac{1}{g_m}||\frac{1}{g_{mb}}||r_{o1}||r_{o3}$$

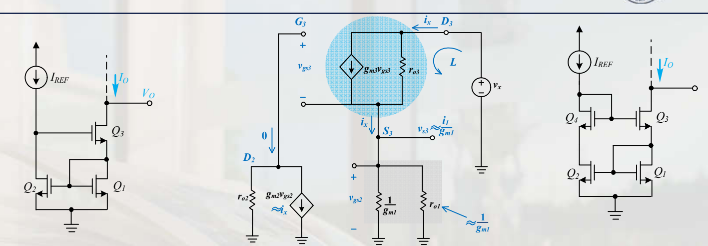
$$\cong \frac{1}{(g_m + g_{mb})} = \frac{1}{(1+\chi)g_m}$$

Body effect coefficient: $g_{mb} = \chi g_m$

PEARL 电力电子与再生能源实验室

Wilson MOS Mirror

上海科技大学 ShanghaiTech University



$$R_o \equiv \frac{v_x}{i_x}$$

$$v_{gs2} \cong i_x/g_{m1}$$

$$g_{m2}v_{gs2} = g_{m2}\frac{i_x}{g_{m1}} = i_x$$

$$v_{g3} = v_{d2} = -i_x r_{o2}$$

$$v_{gs3} = v_{g3} - v_{s3} = v_{d2} - v_{gs2} = -i_x r_{o2} - \frac{i_x}{g_{m1}} \cong -i_x r_{o2}$$

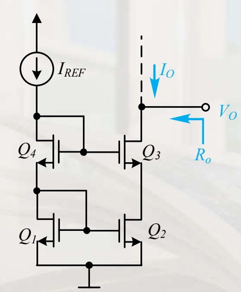
$$g_{m3}v_{gs3} = -(g_{m3}r_{o2})i_x$$

$$v_x = (i_x + g_{m3}r_{o2}i_x)r_{o3} + \frac{i_x}{g_{m1}}$$

$$R_o \equiv \frac{v_x}{i_x} = (g_{m3}r_{o3})r_{o2} + r_{o3} + \frac{1}{g_{m1}} \cong (g_{m3}r_{o3})r_{o2}$$

Cascode MOS Mirror

上海科技大学 ShanghaiTech University



$$R_o \cong g_{m3}r_{o3}r_{o2}$$

Pro: output resistance increased by $g_{m3}r_{o3}$

Con: consumes a large portion of steadily shrinking supply voltage

PEARL 电力电子与再生能源实验室