EE 240B – Spring 2019

Advanced Analog Integrated Circuits
Lecture 4: Gain-Bandwidth Design

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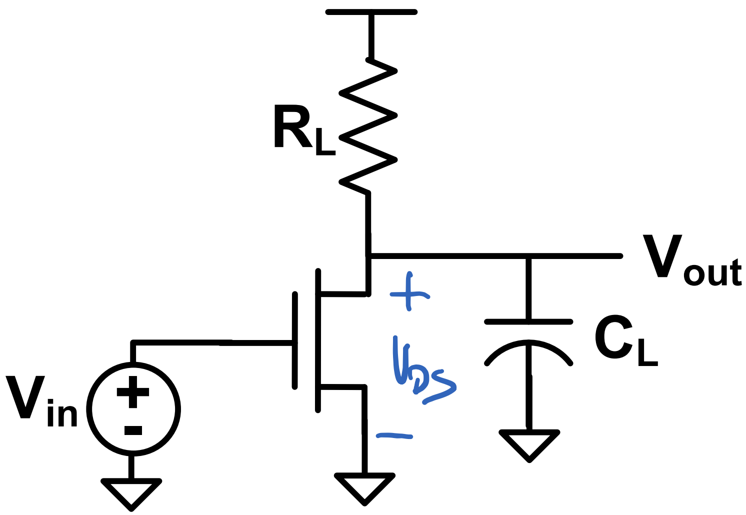
Preliminaries

- **This will be the first in a series of design methodologies we will develop**
  - To keep the discussion manageable, will generally assume that only a couple of specifications are critical a_0, ω_u
  - And that all other specs will "automatically" be met
  - In practice, can inspect specs and technology capabilities to figure out which constraints are really active, and utilize the appropriate methodology

- **Will largely ignore biasing details for now**
  - But will patch this later

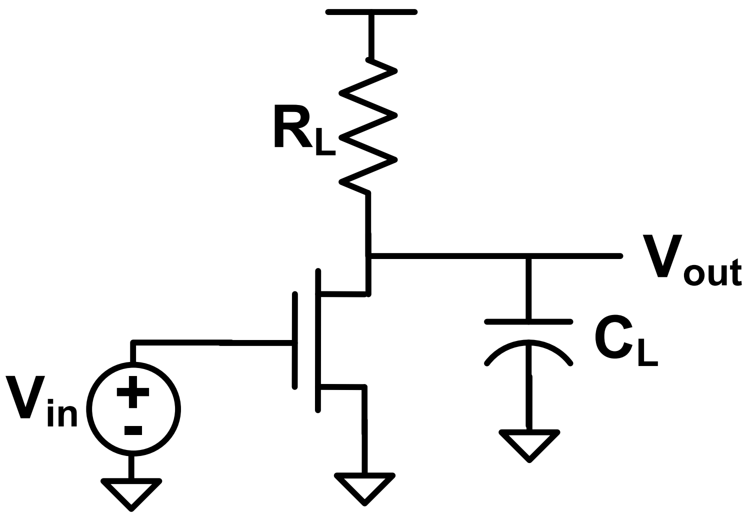
CS Amplifier Design Methodology



- **Input specifications:**
  - Minimum small signal gain A_v
  - Minimum 3dB bandwidth ω_{bw}
  - Fixed capacitive load C_L
  - Supply voltage V_{dd}
- **Goal: minimize power**
- **What are our design variables?** V_{DS}, R_L

  $W, L, V^*(V_{GS})$

Small Signal Model and Analysis



$$A_v = g_m R_L$$

$$= \frac{2I_D}{V^*} R_L$$

$$R_L = \frac{A_v V^*}{2I_D}$$

$$\omega_o = BW \cong \frac{1}{R_L C_L}$$

$$\omega_u = \omega_o \cdot A_v = \left(\frac{2I_D}{A_v V^*}\right)\frac{1}{C_L}$$

Power and g_m

- Pick V^* $\Rightarrow$ $I_D = \frac{g_m V^*}{2}$

- V_{DD} fixed

$$P = V_{DD} \cdot I_D$$

$$= \frac{g_m V_{DD} V^*}{2}$$

$$\omega_u = \frac{g_m}{C_L} = A_v \cdot \omega_o$$

$$P = \frac{A_v \omega_o (V_{DD} V^*) C_L}{2}$$

First Pass Methodology

- Pick V^*, L $\qquad L_{min}$ ---- L_{max}

  $I_D = \frac{g_m V^*}{2}$ $\qquad V^*_{min}$ --- V^*_{max}

- $\boxed{g_m = A_v \omega_0 C_L}$ $\qquad V^* \rightarrow V_{GS} \rightarrow J \rightarrow W$

- V_{GS} & W $\longrightarrow$ LUT / BAG GRAPHS

- CALC $R_L = \frac{A_v}{g_m} = \frac{1}{\omega_0 C_L}$

Side Discussion: Digital vs. Analog Power

$$P_{digital} = \alpha_{0\to 1} C_L V_{DD}^{\;2} f_{clk} \qquad P_{analog} = \tfrac{1}{2} C_L V_{DD} V^* A_v \omega_{bw}$$

$\uparrow$

- **What needs to be true for analog to be lower power than digital?**

$A_v \simeq 2$ $\qquad C_L \sim C_L$

$\omega_{BW} \cong 2\pi f_{clk}$

$\sim \alpha C_L V_{DD}^2 f_{clk} \qquad \sim C_L \underbrace{V_{DD} V^* \cdot 2\pi}\, f_{clk}$

Relate Drain Cap to Gate Cap

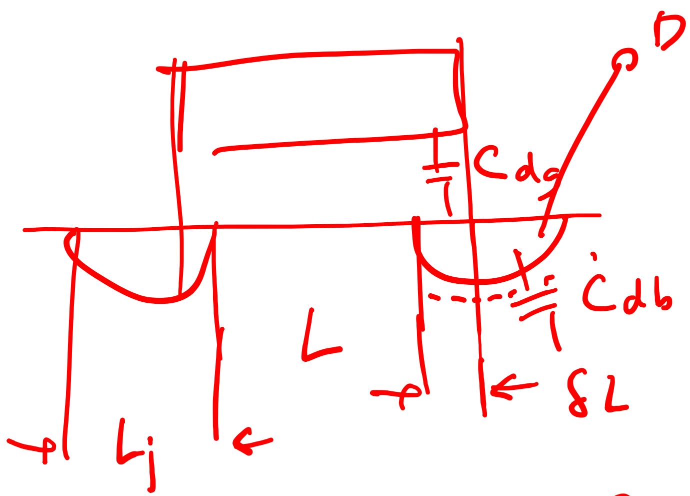
$$C_{gs} = \frac{2}{3} W \cdot L \cdot C_{ox} = \frac{2}{3} W \cdot \underset{\text{(fixed)}}{L} \cdot \frac{\varepsilon_{ox}}{t_{ox}} \propto W$$

$$C_{dd} = C_{gd} + C_{db}$$

$$= W \delta L \cdot C_{ox} + C_{db}$$

$$\propto W$$

$$C_{db} = W \cdot L_j \cdot \frac{\varepsilon_{si}}{X_{dep}}$$



$$\frac{C_{dd}}{C_{gg}} = \frac{\overset{\mu}{\left(\frac{\delta L}{L}\right)} C_{ox} + \frac{L_j}{L}\frac{\varepsilon_{si}}{X_{dep}}}{\frac{2}{3} \cdot \cancel{L} \cdot C_{ox}(1+\mu)}$$

$$\mu = \frac{\delta L}{L} = \frac{C_{gd}}{C_{gs}}$$

$$\boxed{C_{dd} = \gamma C_{gs}}$$

What about Interconnect Par.

$C_{par} \propto W \Rightarrow$ absorb into ω_t

→ Layout real device

→ simulate $\omega_t' < \omega_t$

(f_T)

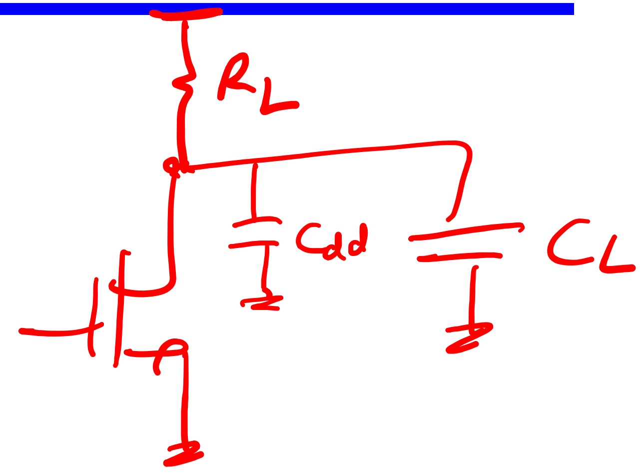
→ Use ω_T' in the design

instead

g_m vs. GBW revisited (1)

- Neglected C_{dd}

$$A_v \cdot \omega_o = \frac{g_m}{C_L + C_{dd}}$$



g_m vs. GBW revisited (2)

$$\frac{g_m}{C_{gg}} = \omega_T \qquad C_{dd} = \gamma C_{gg}$$

$$C_{dd} = \frac{\gamma g_m}{\omega_T}$$

$$\frac{g_m}{C_L + C_{dd}} = A_v \cdot \omega_o = \underbrace{\frac{g_m}{\left(C_L + \frac{\gamma g_m}{\omega_T(V^*)}\right)}}_{\text{Solve for } g_m}$$

g_m vs. GBW revisited (3)

$$g_m = A_v \omega_0 C_L + \frac{\gamma A_v \omega_0}{\omega_T} \cdot g_m$$

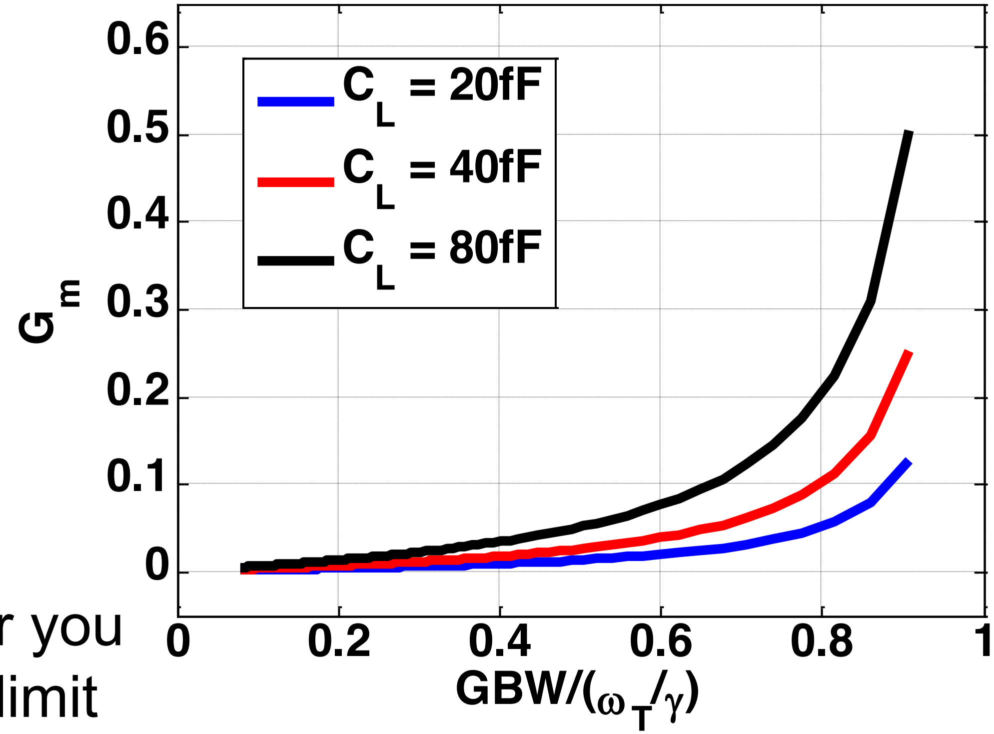
$$g_m \left(1 - \frac{\gamma A_v \omega_0}{\omega_T} \right) = A_v \omega_0 C_L$$

$$\boxed{g_m = \frac{A_v \omega_0 C_L}{1 - \frac{\gamma A_v \omega_0}{\omega_T(W^*)}}}$$

Direct Implication

$$I_D = \frac{1}{2}\left(\frac{A_V \omega_{bw} V^* C_L}{1 - A_V \omega_{bw} / (\omega_T / \gamma)}\right)$$

- **For a given V*, there is a maximum GBW you can achieve**
  - No matter how much power you spend, cannot exceed this limit (with this topology)



$A_v \omega_o = \frac{\omega_T}{\gamma} \Rightarrow$ infinite power

Methodology Take 2

(1) Pick V^*, L

(2) Compute $g_m = \dfrac{A_v \omega_0 C_L}{1 - \dfrac{\gamma A_v \omega_0}{\omega_T(V^*)}}$

(3) Find V_{GS} & W

(4) $R_L = \dfrac{1}{\omega_0 C_L}$

(5) Adjust V^*, L

min power

Methodology Take 2`

(1) pick L

$$I_D = \frac{1}{2} g_m V^* = \frac{1}{2} \frac{A_v \omega_o C_L}{1 - \frac{\gamma A_v \cdot \omega_o}{\omega_T(V^*)}} \cdot V^*$$

(2) $\min \left(\dfrac{V^*}{1 - \dfrac{\gamma A_v \omega_o}{\omega_T(V^*)}} \right) \rightarrow$ sweep V^*

(3) $V^* \rightarrow V_{GS} \longrightarrow W$

(4) Set $R_L = \dfrac{A_v}{g_m}$

What about r_o?

$$A_v = g_m (r_o || R_L)$$

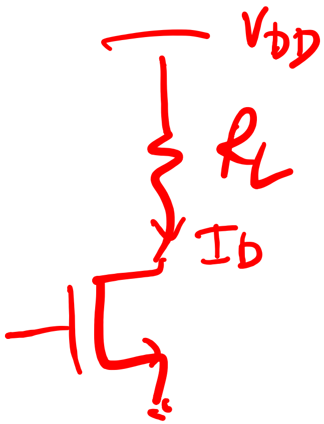
$$A_v = g_m \frac{r_o R_L}{r_o + R_L} = \frac{a_o R_L}{\frac{a_o}{g_m} + R_L}$$

$$\cancel{A_v}\left(\frac{a_o}{g_m} + R_L\right) = \frac{a_o R_L}{A_v}$$

$$R_L\left(\frac{a_o}{A_v} - 1\right) = \frac{a_o}{g_m}$$

$$R_L = \frac{a_o/g_m}{\frac{a_o}{A_v} - 1} = \frac{A_v/g_m}{1 - \frac{A_v}{\underbrace{a_o}_{V_{DS}\ \text{BIAS}}}}$$

Bias Point



$$V_{DS} = V_{DD} - I_D R_L$$

$$= V_{DD} - \frac{g_m V^*}{2} R_L$$

$$= V_{DD} - \frac{\frac{\cancel{g_m} V^*}{2} \frac{A_v}{\cancel{g_m}}}{1 - \frac{A_v}{a_o}}$$

$$V_{DS} = V_{DD} - \frac{V^* A_v}{2(1 - A_v/a_o)}$$

$$a_o = f(V_{DS})$$

pick a_o (mid rail) $\longrightarrow V_{DS} \longrightarrow a_o(V_{DS}) \longrightarrow V_{DS}'$

$\longrightarrow a_o(V_{DS}') \longrightarrow V_{DS}''$