Lecture 11: Current Source Matching & Temperature Independent Biasing

- Announcements:
  - Lab#2 online: starts this week
  - 240A HW#1A online soon

- Lecture Topics:
  - High Swing Current Sources (cont.)
  - Current Source Matching Considerations
  - Temperature Independent Biasing (quick)

- Last Time:
  - Problem: Body effect $M_4, M_6, M_2$ increases from $V_T$'s

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\[
(V_T - V_{gs4}) + (V_T - V_{gs4}) + V_{off} \leq V_{ov}
\]

BIG PROBLEM!

**Solutions:**

1. Tie the wells of $M_4, M_6, M_2$ to their sources.
   - $V_T = V_{to} + 2V_{gs4} = V_{to}$
   - But don't want to do this due to too much area consumed → cost ↑

2. Bias $M_4$ so that $V_{gs4} = V_T + 2V_{ov}$
   - $\Rightarrow V_{gs4} = V_T + 3V_{ov}$
   - \[ \left( \frac{W}{L} \right)_{M_4} = \frac{1}{3} \left( \frac{W}{L} \right)_{M_2} \]
     - safely margin!

   \[ V_{min} = 3V_{ov} \]

   Not optimum, but safe → $M_4$, stay in saturation
**EE 140: Analog Integrated Circuits**

**Lecture 11w: Current Source Matching & Temperature Independent Biasing**

**Solution:** Use an alternative bias scheme.

**Alternate Biasing Scheme for Cascode**

\[
I_{DAC} = \frac{1}{2} \mu_n C_{ox} \left( \frac{W}{L} \right) (V_{GS1} - V_{t}) (1 + \lambda V_{DS1})
\]

If \( V_{DS1} \neq V_{DS3} \)

\[
I_{O} = \frac{(1 + \lambda V_{DS1}) I_{REF}}{1 + \lambda V_{DS3}} \rightarrow I_{O} \neq I_{REF}
\]

\[
V_{DS1} = V_{DS3} \rightarrow I_{O} = I_{REF}
\]

Note: Still must worry about Body effect!

Design defensively

\[
V_{GS1} > V_{t} + 2V_{OV}
\]
Current Source Matching Considerations

In MOS, we often need matched current sources:

\[ I_{01} = I_{02} \]
\[ I_{01} = \frac{1}{2} \mu n C_{ox} \left( \frac{W}{L} \right) (V_{GS1}-V_{t})^2 \]
\[ I_{02} = \frac{1}{2} \mu n C_{ox} \left( \frac{W}{L} \right) (V_{GS2}-V_{t})^2 \]

These won't be perfectly matched if

\[ \frac{W_{L1}}{W_{L2}} \neq \frac{V_{t1}}{V_{t2}} \]

We always have this due to finite fabrication tolerances.

Need to quantify their impact — how much mismatch in \( I_{01} \) \( I_{02} \) are caused by

Define average & mismatch quantities:

\[ \text{Average} \]
\[ I_{D} = \frac{1}{2} [I_{D1} + I_{D2}] \]
\[ \Delta I_{D} = I_{D1} - I_{D2} \]
\[ \frac{W}{L} = \frac{1}{2} \left[ \frac{W_{L1}}{W_{L2}} + \frac{W_{L2}}{W_{L1}} \right] \]
\[ \Delta V_{t} = V_{t1} - V_{t2} \]
\[ V_{t} = \frac{1}{2} [V_{t1} + V_{t2}] \]

\[ \frac{\Delta I_{D}}{I_{D}} \approx \text{fractional current mismatch} \]
\[ \frac{\Delta (W/L)}{(W/L)} \approx \frac{V_{t1}}{V_{t2}} \]

Re-arranging:

\[ I_{D1} = I_{D} + \frac{\Delta I_{D}}{2} \]
\[ \frac{W_{L1}}{W_{L2}} = \frac{(W_{L2})}{(W_{L1})} - \frac{\Delta (W/L)}{2} \]

\[ \frac{V_{t1}}{V_{t2}} = \frac{V_{t} + \Delta V_{t}}{2} \]

\[ \frac{V_{t1}}{V_{t2}} = \frac{V_{t} - \Delta V_{t}}{2} \]
Plug those into the current equation:

\[ I_D = \frac{I_D^0 + \frac{\Delta I_D}{2}}{} \]

\[ = \frac{1}{2} \mu_n C_X \left( \frac{W}{L} + \frac{\Delta(V_{GS})}{2} \right) \left[ V_{GS} - V_T - \frac{\Delta(V_T)}{2} \right]^2 \]

\[ = \frac{1}{2} \mu_n C_X \left( \frac{W}{L} + \frac{\Delta(V_{GS})}{2} \right) \left[ V_{GS} - V_T + \frac{\Delta(V_T)}{4} \right] \]

\[ = \frac{1}{2} \mu_n C_X \left( \frac{W}{L} + \frac{\Delta(V_{GS})}{2} \right) \left[ V_{GS} - V_T \right] \]

\[ I_D^0 = \frac{I_D}{2} \mu_n C_X \left( \frac{W}{L} \right) \frac{V_{GS}}{2} \left( \frac{\Delta(V_{GS})}{2} \right) \]

\[ \frac{\Delta I_D}{I_D} = \frac{\Delta(V_{GS})}{(W/L)} - \frac{\Delta(V_T)}{(W/L)} \]

\[ \Delta I_D = \frac{\Delta I_D}{I_D} \times I_D \]

\[ V_{OV1} \rightarrow \minimize this component \]

\[ V_{DD} \rightarrow V_{OV1} \rightarrow \Delta I_D \uparrow \times \]

\[ \rightarrow \text{to combat } (W/L) \uparrow \rightarrow \Delta I_D \uparrow \]

\[ \text{Chip Size Trends for Future:} \]

\[ \text{1990's} \quad \text{Digital} \]

\[ \text{2010} \quad \text{OOG} \quad \text{Ctrl.} \]

\[ \text{1990's} \quad \text{Analog} \]

\[ \text{2010} \quad \text{Analog} \]

\[ \text{chip area reduces} \]

\[ \text{smaller, but must keep Vdd small} \]

\[ \text{chip area remains same!} \]
**VBE-Referenced Biasing**

\[ V_{cc} - V_{BE} = I_0 \frac{V_{BE1}}{R_2} = V_{T} \ln \left( \frac{I_{ref}}{I_{s1}} \right) \]

\[ I_{ref} = \frac{V_{T}}{R_2} \ln \left( \frac{I_{ref}}{I_{s1}} \right) \]

\[ I_{ref} = \frac{V_{T}}{R_2} \ln \left( \frac{1}{\frac{\partial I_{ref}}{\partial V_{cc}}} \right) \]

\[ \sum I_{ref} = \frac{V_{cc}}{V_{T}} \frac{\partial I_{ref}}{\partial V_{cc}} \]

\[ \frac{\partial I_{ref}}{\partial V_{cc}} = \frac{V_{cc}}{V_{T}} \frac{1}{\ln \left( \frac{1}{\frac{\partial I_{ref}}{\partial V_{cc}}} \right)} \]

**Problem:** \( I_{ref} \) still dependent on \( V_{cc} \)

\[ S_{V_{cc}} = \frac{1}{\ln(I_{ref}/I_{s1})} \left[ \frac{\partial V_{cc}}{\partial V_{cc}} \right] = \frac{1}{\ln(I_{ref}/I_{s1})} \]

If we can eliminate this '1',

then \( S_{V_{cc}} = 0 \) — need to eliminate \( I_{ref} \) dependence on \( V_{cc} \)

**Solution:**

**Graphically:**

- Use self-biasing
- Graphical representation of the circuit
- Need to bootstrap out of this point
- If must satisfy both curves, then the circuit must operate here
- \( I_{ref}(\alpha V_{cc}) \)

**npn current source**

Finishes \( R_2 \) which makes this finite.

This is pretty darn good!

\[ S_{V_{cc}} = 0 \]
Determine Temperature Dependence of the VBE Reference

Definition. Fractional Temperature Coefficient
\[ TC_f = \frac{1}{I_0} \frac{\partial I_0}{\partial T} \text{ temperature} \]
For \( I_0 = \frac{V_{BE}}{R} \):
\[ TC_f = \frac{1}{I_0} \frac{\partial I_0}{\partial T} = \frac{R}{V_{BE}} \left( \frac{1}{R} \frac{\partial V_{BE}}{\partial T} - \frac{V_{BE}}{R^2} \frac{\partial R}{\partial T} \right) \]
\[ TC_f \approx -1 \frac{\partial V_{BE}}{\partial T} + \frac{1}{R} \frac{\partial R}{\partial T} \]
Some Typical TC_f's:
- Diffused R's ~ 1000 - 1500 ppm/°C
- Poly Si R's ~ 500 ppm/°C
- V_{BE} ~ 2300 ppm/°C
\[ TC_f \sim -3200 - 1000 \approx -3300 
\]
\[ = -4200 \text{ ppm/°C} \sim 0.437 \% /°C \]
\[ 0 \rightarrow 70^°C: \sim 25\% I_0 \text{ variation} \]
\[ -55 \rightarrow 125^°C: \sim 60 - 70 \% I_0 \text{ variation} \]
Not so good!

\[ I_0 \] Referenced Bias Circa:

Based on the Wiener current source:
\[ \frac{I_0}{V_{cc}} = \frac{1}{R_1} + \frac{1}{R_2} \]
Here, \( I_{ref} \neq I_0 \)
So sensitive to \( V_{cc} \) variations
But can fix this by setting \( I_{ref} = I_0 \)
Use self-biasing:

\[ V_{cc} \]

Just use mismatches to make \( N_x \) device?
Assuming $I_{rz} = N I_{r1}$:

KVL: $I_0 R + V_{BE} - V_{BE2} = V_T \ln N$

$I_0 = \frac{V_T}{R} \ln N = \frac{kT}{q}$ (const.)

$I_{zf}$:

Two possible operating pts.

$\Rightarrow$ we start-up circuit to guarantee this one (where we have very small $S_{Vcc}$)

$\frac{kT}{2}$ Reference Temperature Dependence

$T_{Cf} = \frac{\partial I_0}{\partial T} = \frac{\partial}{\partial T} \left( \frac{q}{kT} \right) \frac{R}{V_T} \ln N$

$\therefore T_{Cf} = \frac{V_T}{kT} - \frac{\partial R}{\partial T}$

$\approx T_{Cf}^k T_{Cf}^e \sim 1500 \text{ ppm/}^\circ C$

Better than $V_{BE}$-Ref, but still not zero...

How can get $\sim$?

Bandgap Reference

Basic Idea:

$V_{BE} \rightarrow$ neg. $T_{Cf}$

$\frac{kT}{q} \rightarrow$ pos. $T_{Cf}$

Add together to cancel $\rightarrow$ get $T_{Cf} = 0$!

0th Order Picture:

Choose $k$ to get $T_{Cf} = 0$.

What should $k$ be? (0th Order Picture)

$\Rightarrow$ get ballpark estimate

→ over
Bandgap voltage obtained via a linear extrapolation to 0K. (Not the same as what one usually sees in physics)

\[ \frac{kT}{q} \]

\[ \approx 26\text{mV} \]

\[ 0.1\text{mV/}^\circ\text{C} \]

\[ 1.205\text{V} \]

\[ V_{BE} \]

\[ V_{GO} \]

\[ 300K \]

\[ OK \]

[Ok Order] 
There will actually be some curvature

So will only get this @ one temperature