THIẾT KẾ VI MẠCH TƯƠNG TỰ
CHƯƠNG 5: CURRENT MIRRORS

Hoàng Trang-bộ môn Kỹ Thuật Điện Tự
hoangtrang@hcmut.edu.vn

TP.Hồ Chí Minh 04/2012
Content

- Basic current mirrors
- Cascode current mirrors
- Active current mirrors
Basic current sources

\[ I_D \approx \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \]

\[ I_{Out} \approx \frac{1}{2} \mu_n C_{ox} \frac{W}{L} \left( \frac{R_2}{R_1+R_2} V_{DD} - V_{TH} \right)^2 \]

Simple Resistive Biasing For Current Source
Problems

- Output current depends on
  - Supply (Vdd)
  - Process (W/L, $V_{TH}$): $V_{TH}$ vary from wafer to wafer
  - Temperature ($R_1, R_2, \mu_n, V_{TH}$)

→ Output current is poorly defined

IS THERE A WAY OF GENERATING RELIABLE CURRENTS?
Basic Idea

Assume that $I_{\text{ref}}$ is available and precise

How do we guarantee $I_{\text{out}} = I_{\text{REF}}$?
Basic current mirror

This structure is called current mirror (For NMOS)

\[ I_{\text{REF}} \approx \frac{1}{2} \mu_n C_{\text{ox}} \left( \frac{W}{L} \right)_1 (V_{GS} - V_{TH})^2 \]

\[ I_{\text{out}} \approx \frac{1}{2} \mu_n C_{\text{ox}} \left( \frac{W}{L} \right)_2 (V_{GS} - V_{TH})^2 \]

\[ I_{\text{out}} \approx \frac{(W/L)_1}{(W/L)_2} I_{\text{REF}} \]
Basic current mirror

Current mirror for PMOS
Multiple current sources

\[ I_{OUTn} = I_{REF} \left( \frac{W}{L} \right)^n \left( \frac{W}{L} \right)_R \]
Problems

If we don’t neglect channel length modulation

\[
I_{D1} = \frac{1}{2} \mu_n C_{ox} \left( \frac{W}{L} \right)_1 (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS1})
\]

\[
I_{D2} = \frac{1}{2} \mu_n C_{ox} \left( \frac{W}{L} \right)_2 (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS2}),
\]

\[
\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \cdot \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}
\]

While \( V_{DS1} = V_{GS1} = V_{GS2} \)

but \( V_{DS2} \) may not equal \( V_{DS1} \)

**How to copy the \( I_{REF} \) in this case?**
Cascode Current Mirrors

How do we generate $V_b$ to ensure $V_x = V_y$?

→ If we chose $M_0$ and $M_3$, so that

$$\frac{(W/L)_3}{(W/L)_0} = \frac{(W/L)_2}{(W/L)_1}$$

then we have $V_{gs3} = V_{gs0}$ and $V_x = V_y$.
In (b) : the minimum allowable voltage at P is:
\[ V_{P,\text{min}} = V_N - V_{TH} = V_{GS0} + V_{GS1} - V_{TH} = (V_{gs0} - V_{TH}) + (V_{gs1} - V_{TH}) + V_{TH} \]

In (a) : \( V_b \) is chosen to allow the lowest possible value of \( V_p \) but \( I_{\text{out}} \) does not accurately keep track \( I_{\text{REF}} \) because \( V_{DS1} \) differ \( V_{DS2} \)

In (b) : \( I_{\text{out}} \) keep track \( I_{\text{REF}} \) at higher accuracy but the minimum level \( V_p \) is higher by \( V_{TH} \)
Cascode Current Mirrors (cont)

\[ V_{DD} \quad I_X \quad V_X \]

\[ M_0, M_1, M_3 \]

\[ I_{REF} \quad V_X \]

\[ \begin{align*}
M_2: & \quad \text{Tri} & \text{Sat} & \text{Sat} \\
M_3: & \quad \text{Tri} & \text{Tri} & \text{Sat}
\end{align*} \]

\[ V_A-V_{TH2}+V_{DS3} \]

\[ I_X \]

\[ V_B \]

\[ V_N-V_{GS} \]

\[ V_N-V_{TH3} \]

\[ V_X \]
Modification of cascode mirror for low voltage operation

M1 and M2 are in saturation:

M2: \( V_b - V_{TH2} \leq V_X (= V_{GS1}) \)

M1: \( = V_{GS1} - V_{TH1} \leq V_A (= V_b - V_{GS1}) \)

\[ V_{GS2} + (V_{GS1} - V_{TH1}) \leq V_b \leq V_{GS2} - V_{TH2} \]
If \( V_b = V_{GS2} + (V_{GS1} - V_{TH1}) = V_{GS4} + (V_{GS3} - V_{TH3}) \)

Then the cascode current source \( M3-M4 \) consumes minimum headroom while \( M1 \) and \( M3 \) sustain equal drain-source voltage, allowing accurate copy \( I_{REF} \).
Generate $V_b$ for cascode current mirror

M1 and M2 are in saturation:

$$V_{b,\text{min}} = V_{GS2} + (V_{GS1} - V_{TH1})$$

Select: $V_{GS5} \approx V_{GS2}$

$$V_{DS6} = V_{GS5} - R_b I_1 \approx V_{GS1} - V_{TH1}$$

M7: large $(W/L)_7$ so that $V_{GS7} \approx V_{TH7}$

$$V_{DS6} \approx V_{GS6} - V_{TH7}$$

$$V_b = V_{GS5} + V_{GS6} - V_{TH7}$$
If MS is biased at a very low current density, $I_D/(W/L)$, then $V_{GSS} \approx V_{THS} \approx V_{TH3}$, i.e., $V_N' \approx V_N - V_{TH3}$, and

$$V_B = V_{GS1} + V_{GS0} - V_{TH3} - V_{GS3} = V_{GS1} - V_{TH3}$$

implying that $M2$ is at the edge of the triode region.

In this topology, however,

$$V_{DS2} \neq V_{DS1}$$

If the body effect is considered for $M0$, $MS$ and $M3$, it is different to guarantee that $M2$ operates in saturation.
Active current mirrors

Current mirror processing a signal

\[ I_{out} = I_{in} \text{ (for } \lambda = 0) \]
Differential pair with current source load

Calculate $G_m$

Assuming $\gamma = 0$

$$G_m \approx \frac{I_{out}}{V_{in}} = \frac{g_{m1} V_{in}}{2 V_{in}} = \frac{g_{m1}}{2}$$

$$|A_v| = G_m \cdot R_{out}$$

Calculate $R_{out}$

$$R_{out} \approx (1 + g_{m2} r_{o2})(1 / g_{m1}) + r_{o2}$$

$$= 2r_{o2} + \left(1 / g_{m1}\right) \approx 2r_{o2}$$

Thus, $R_{out} = 2r_{o2} / r_{o4}$

$$|A_v| = G_{m2} \cdot \frac{2r_{o2}}{r_{o4}}$$
Differential pair with current source load (cont)

Calculate $V_p / V_{in}$

$$R_{eq} \approx \frac{1}{G_{m2}} + \frac{r_{o4}}{G_{m2} \cdot r_{o2}} = \frac{1}{G_{m2}} \left(1 + \frac{r_{o4}}{r_{o2}} \right)$$

$$\frac{V_p}{V_{in}} \approx \frac{R_{eq}}{R_{eq} + \frac{1}{G_{m1}}} \approx \frac{1 + \frac{r_{o4}}{r_{o2}}}{2 + \frac{r_{o4}}{r_{o2}}}$$

Note: if $r_{o4} \rightarrow 0$, $V_p / V_{in} \rightarrow 1/2$, and if $r_{o4} \rightarrow \infty$, $V_p / V_{in} \rightarrow 1$.

Calculate $V_{out} / V_{in}$

$$\frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_p} \cdot \frac{V_p}{V_{in}} = \frac{1 + \frac{r_{o4}}{r_{o2}}}{2 + \frac{r_{o4}}{r_{o2}}} \cdot \frac{G_{m2} \cdot r_{o2}}{1 + \frac{r_{o2}}{r_{o4}}} = \frac{G_{m2} \cdot r_{o2} \cdot r_{o4}}{2r_{o2} + r_{o4}} = \frac{G_{m2}}{2} \left[ \left(2r_{o2} \right) / r_{o4} \right]$$

Note: if $r_{o4} \rightarrow 0$, $V_{out} / V_{in} \rightarrow 1/2$, and if $r_{o4} \rightarrow \infty$, $V_{out} / V_{in} \rightarrow 1$.
Differential pair with active current mirrors

Concept of combining the drain currents of M1 and M2

M3 and M4 are identical
Differential pair with active current mirror
(large signal analysis)

Operation:
+ If $V_{in1} << V_{in2}$, M1 is off and so are M3 and M4. M2 and M5 operate in triode region, carrying zero current. Thus, $V_{out} = 0$.
+ As $V_{in1}$ approaches $V_{in2}$ for a small difference, M2 and M4 are saturated, providing a high gain.
+ As $V_{in1}$ becomes more positive than $V_{in2}$, $|I_{D1}|$, $|I_{D3}|$, and $|I_{D4}|$ increase and $I_{D2}$ decreases, eventually driving M4 into the triode region.
+ If $V_{in1} >> V_{in2}$, M2 turns off, M4 operates in deep triode region with zero current, and $V_{out} = V_{DD}$.

→ The choice of the input common-mode voltage:
For M2 to be saturated, $V_{out} \geq V_{in,CM} - V_{TH}$. Thus, to allow maximum output swings, the input CM level must be as low as possible, with $V_{in,CM} = V_{GS1,2} + V_{DS5,min}$
Asymmetric swings in a differential pair with active current mirror

Calculate $G_m$, node $P$ can be viewed as a virtual ground

\[
I_{D1} = |I_{D3}| = |I_{D4}| = \frac{g_{m1}V_{in}}{2}
\]

\[
I_{D2} = -\frac{g_{m2}V_{in}}{2}
\]

\[
I_{out} = I_{D2} + I_{D4} = -g_{m1,2}V_{in}
\]
Differential pair with active current mirror (small signal analysis) (cont)

Calculate \( R_{\text{out}} \)

\[
I_X = 2 \left( \frac{V_X}{2r_{o1,2} + \frac{1}{G_m} \cdot \frac{1}{r_{o1,2}}} \right) + \frac{V_X}{r_{o4}}
\]

where the factor 2 accounts for current copying action of M3 and M4. For \( 2r_{o1,2} >> (1/gm3) || r_{o3} \), we have \( R_{\text{out}} \approx r_{o2} || r_{o4} \)

Calculate \( A_v \)

\[
| A_v | = GmR_{\text{out}} = gm1,2 \ (r_{o2} || r_{o4})
\]
Differential pair with active current mirror (small signal analysis)(cont)

Substitution of the input differential pair by a Thevenin equivalent

Calculate $V_{eq}$ and $R_{eq}$

$$V_{eq} = g_{m1,2} \cdot r_{o1,2} \cdot V_{in}$$

$$R_{eq} = 2r_{o1,2}$$
Differential pair with active current mirror
(small signal analysis)(cont)

Calculate \( \text{Av} = \frac{V_{out}}{V_{in}} \)

The current through \( R_{eq} \) is

\[
I_{X1} = 2 \frac{V_{out} - g_{m1,2}r_{01,2}V_{in}}{2r_{01,2} + \frac{1}{g_{m3}} // r_{o3}}
\]

The fraction of this current that flows through \( 1/gm3 \) is mirrored into \( M4 \) with unity gain. That is

\[
I_{X1} + 2 \frac{V_{out} - g_{m1,2}r_{01,2}V_{in}}{2r_{01,2} + \frac{1}{g_{m3}} // r_{o3}} \cdot \frac{r_{o3}}{r_{o3} + \frac{1}{g_{m3}}} \cdot \frac{V_{out}}{r_{o4}} = 0
\]

Assuming \( 2r_{o1,2} >> (1/gm3,4)||r_{o3,4} \), we obtain

\[
\frac{V_{out}}{V_{in}} = \frac{g_{m1,2}r_{03,4}r_{01,2}}{r_{o1,2} + r_{o3,4}} = g_{m1,2}\left(\frac{r_{o1,2}}{r_{o3,4}}\right)
\]
Differential pair with active current mirror sensing a common-mode change

The CM gain is defined in terms of the single-ended output component produced by the input CM change:

\[ A_{CM} = \frac{\Delta V_{out}}{\Delta V_{in}} \]
Differential pair with active current mirror common mode properties (cont)

Simplified circuit of CM circuit

\[ A_{CM} \approx - \frac{1}{2g_{m3,4}} \frac{1}{2g_{m1,2} + R_{SS}} . \]

\[ = - \frac{1}{1+2g_{m1,2}R_{SS}} \cdot \frac{g_{m1,2}}{g_{m3,4}} \]

where we have assumed \( 1/(2g_{m3,4}) \ll r_{o3,4} \) and neglected the effect of \( r_{o1,2}/2 \).
Even with perfect symmetry, the output signal is corrupted by input CM variations, a drawback that does not exist in the fully differential circuits

**CMRR**

\[ CMRR = \left| \frac{A_{DM}}{A_{CM}} \right| = g_{m1,2} \left( \frac{r_{o1,2}}{r_{o3,4}} \right) \frac{g_{m3,4}}{g_{m1,2}} \frac{(1+2g_{m1,2}R_{SS})}{R_{SS}} = g_{m3,4} \left( 1+2g_{m1,2}R_{SS} \right) \frac{r_{o1,2}}{r_{o3,4}} \]

11 - 4 - 2012 Analog IC Design 27
END OF CHAPTER 5

CURRENT MIRROR