How To Increase Voltage Gain?

Open-circuit voltage gain

$$|A_0| = g_m r_{ds}$$

limited by $r_{ds}$

If we can boost up $r_{ds}$ by a factor of $K$

$$|A_0| = g_m K r_{ds}$$
Common Gate Amplifier is an Impedance Transformer

\[ R_{\text{out}} = ? \]
\[ R_{\text{in}} = ? \]

Using T-model
If we don't consider \( r_c \):
\[ i_s = 0 \] since G is grounded
\[ R_{\text{out}} = \frac{V_{\text{out}}}{I_s} = \infty \]

To find \( R_{\text{out}} \)
we have to include \( r_c \)

KVL:
\[ v_s = (i_s - g_m v_{gs}) r_o + i_s R_s \]
\[ v_{gs} = 0 - v_i = -i_s R_s \]
\[ v_s = (i_s + g_m i_s R_s) r_o + i_s R_s \]
\[ R_{\text{out}} = \frac{V_{\text{out}}}{I_s} = r_o + R_s + g_m r_o R_s \]
\[ = r_o + (1 + g_m r_o) R_s = r_o + (g_m r_o) R_s \]
Common Gate Amplifier is an Impedance Transformer

KVL: \[ v_s = (i_s + g_m v_m) r_o + i_s R_L \]
\[ v_{gs} = 0 - v_{gs} = -v_s \]
\[ (1 + g_m r_o) v_s = (r_o + R_L) i_s \]
\[ R_m = \frac{v_s}{i_s} = \frac{r_o + R_L}{1 + g_m r_o} = \frac{r_o + R_L}{g_m r_o} = \frac{1}{g_m} \]

Impedance Transformation of Common Gate Amplifier

Impedance transformation:

Look into Drain: \[ R_i \text{ amplified by } (g_m r_o) \]
Look into Source: \[ R_i \text{ reduced by } (g_m r_o) \]
Impedance Transformation of Common Base Amplifier

Similar impedance transformation in Common-Base BJT:

Look into Collector: \( R_c \parallel r_e \) amplified by \( (g_m r_e) \)

Look into Source: \( R_e \) reduced by \( (g_m r_e) \)

Note: \( R_e \) in MOS is replaced by \( R_c \parallel r_e \) in BJT

Note: for \( \beta = \infty \), these formulas reduce to those for the MOSFET

MOS Cascode Amplifier

\[ R_o = r_o + (g_m r_o) r_{ea} \]
\[ A_v = -g_m, R_o = -g_m (g_m r_o) r_{ea} \]
\[ A_i = - (g_m r_{ea}) (g_m r_o) \]

Voltage gain is much higher than single-stage common source (CS) amplifier.

The gain of cascode is almost the square of that of CS
Cascode Amplifier with Simple Active Load

\[ A_v = -g_m \left( R_o \parallel R_L \right) \]
\[ R_o \approx \left( g_m R_o \right) r_o \]
\[ R_L = r_o 3 \ll R_o \]
\[ A_v = -g_m r_o 3 \]
Similar gain as CS amplifier.
No gain boosting.

Cascode Amplifier with Cascode Current-Source Load

\[ A_v = -g_m \left( R_m \parallel R_{sp} \right) \]
\[ R_m = \left( g_m r_o \right) r_o \]
\[ R_{sp} = \left( g_m r_o \right) r_o \]
If all transistors are similar:
\[ A_v = -\frac{1}{2} \left( g_m r_o \right)^2 \]
--> High gain!
Think of Cascode as Multistage Amplifier with CS followed by CG

First stage: common source
\[ A_{v1} = -g_{m1}(r_{oi} \parallel R_{in2}) \]
\[
R_{in2} = \frac{R_L}{g_{m2}r_{o2}} + \frac{1}{g_{m2}}
\]
Second stage: common gate
\[ A_{v2} = g_{m2}r_{o2} \]
\[ A_v = A_{v1}A_{v2} \]
For ideal current source load \( R_L = \infty \)
\[ A_{vo} = (-g_{m1}r_{oi})(g_{m2}r_{o2}) \]

Folded Cascode

"Folding" the CG stage using PMOS.
\( Q_1 \) is biased with \( I_1 - I_2 \)
\( Q_2 \) is biased with \( I_2 \)
Folded cascode avoids stacking too many transistors vertically, which will be difficult for low power supply voltage \( V_{DD} \)
Useful Transistor Pairings

CC + CE
- High input resistance
- Much wider bandwidth than single CE amplifier (To be discussed later)

CD + CS
- Main benefit is wider bandwidth than single CE amplifier

CD + CE in BiCMOS technology (BJT+CMOS)
- Similar to MOS version but use BJT for higher $g_m$

Darlington Pair

Darlington pair:
- Composite BJT with $\beta = \beta_1 \beta_2$

CC+CC: high performance source follower

$$R_{in} = r_{a1} + (\beta_1 + 1) \left[ r_{a2} + (\beta_2 + 1) R_E \right]$$

CC+CC: high performance source follower with separate current bias for Q1 $\rightarrow$ high $\beta_1$