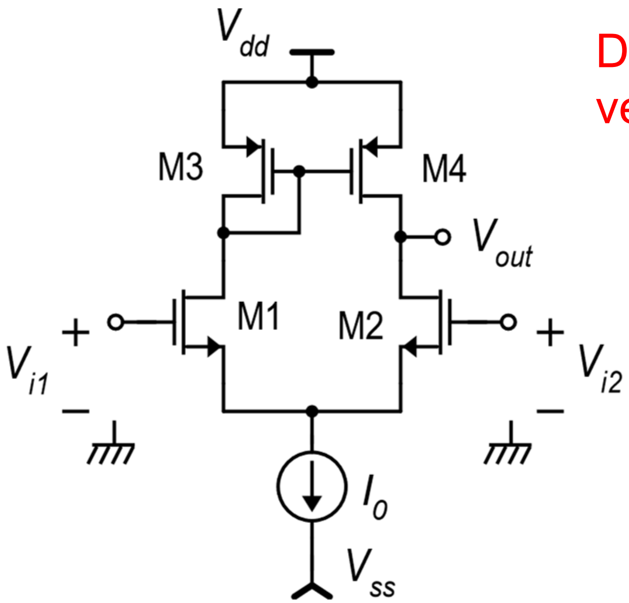
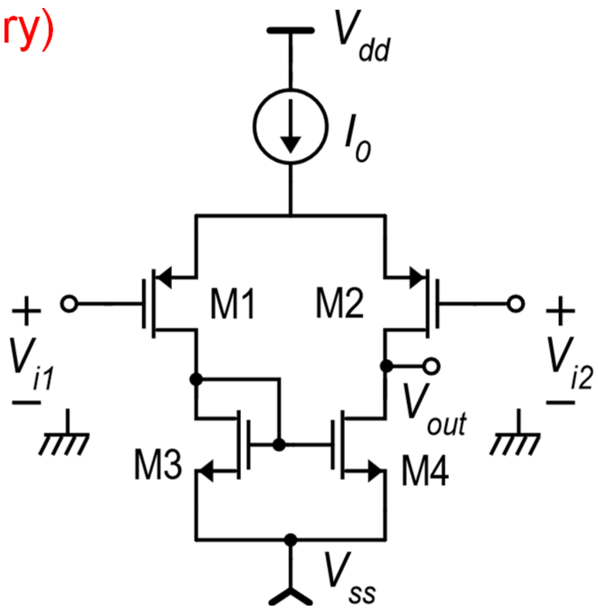
Dual versions of CMOS circuits

Simple differential amplifier with mirror load



"n" version

Dual (complementary) versions



"p" version

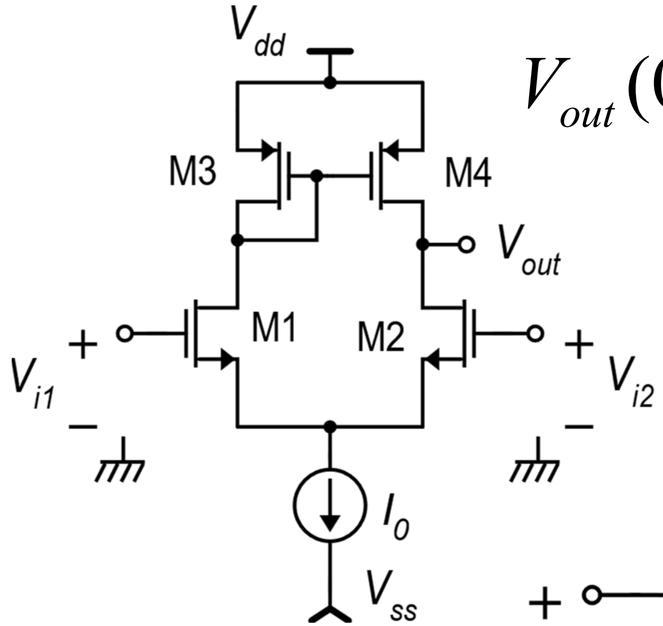
Ranges of the «p» version

$$\min(V_{out}) = V_C - V_{GS2} + V_{DSAT2}$$

$$\max(V_{out}) = V_{dd} - |V_{DSAT4}|$$

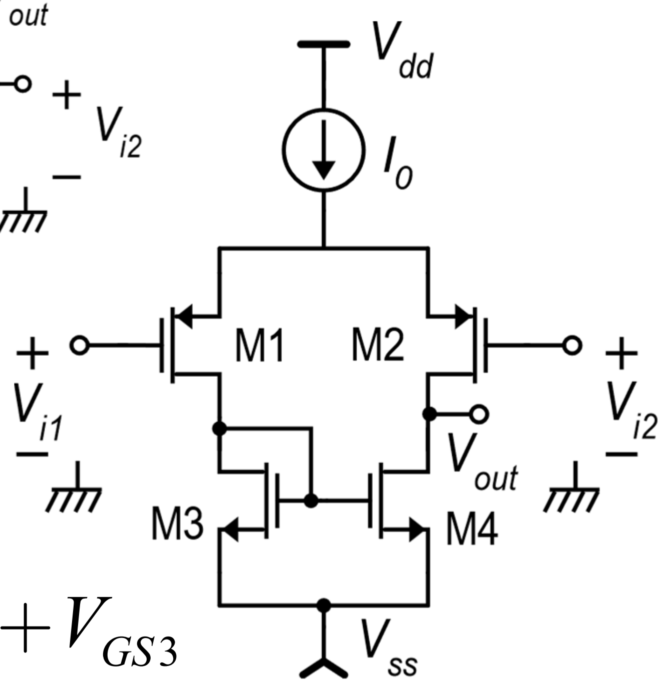
$$\min(V_C) = V_{ss} + V_{MIN-tail} + V_{GS1}$$

$$\max(V_C) = V_{dd} - |V_{GS3}| - V_{DSAT1} + V_{GS1}$$



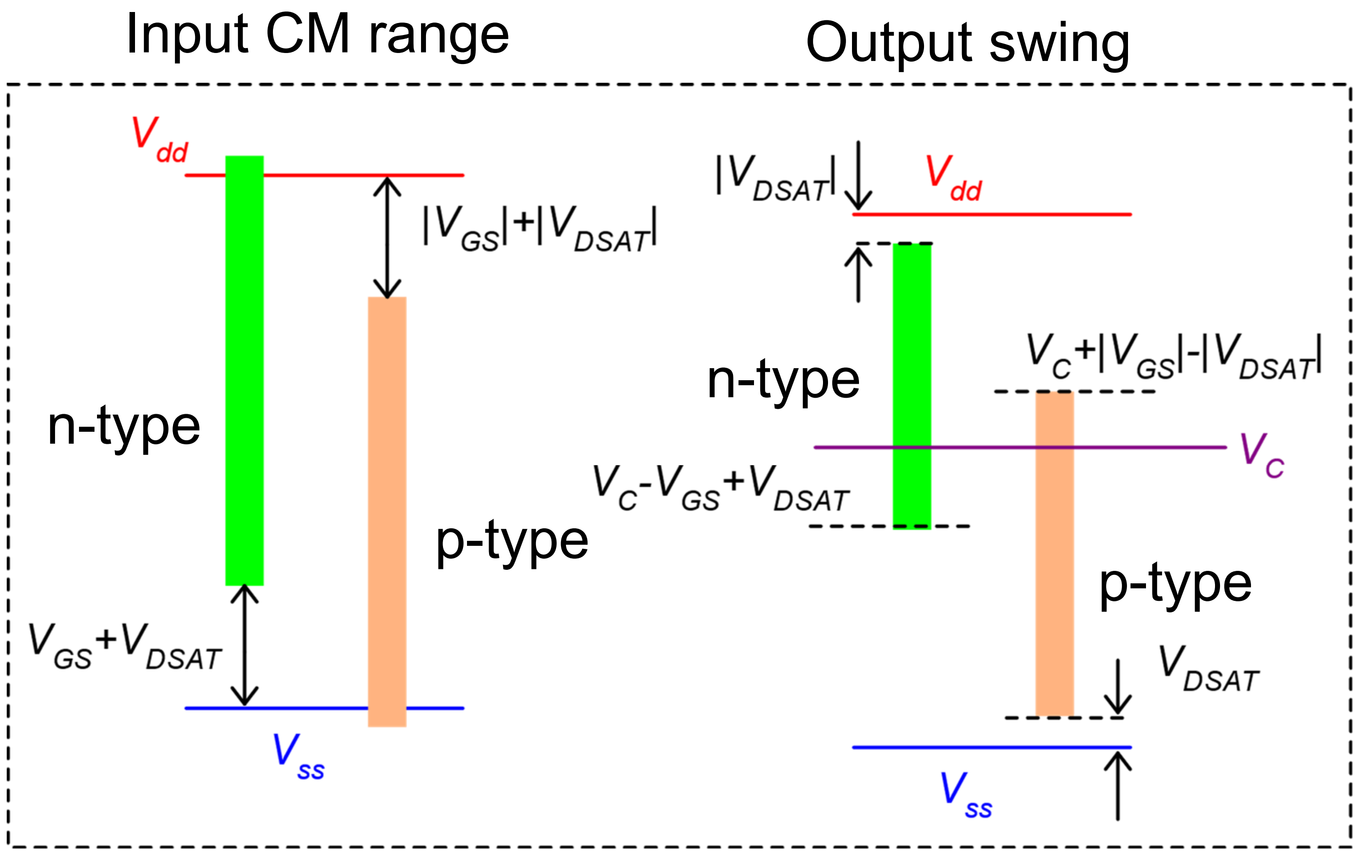
$$V_{out}(0) = V_{dd} - |V_{GS3}|$$

- $\min(V_{out}) = V_{ss} + V_{DSAT4}$
- $\max(V_{out}) = V_C + |V_{GS2}| - |V_{DSAT2}|$
- $\min(V_C) = V_{ss} + V_{GS3} + |V_{DSAT1}| - |V_{GS1}|$
- $\max(V_C) = V_{dd} - V_{MIN-tail} - |V_{GS1}|$



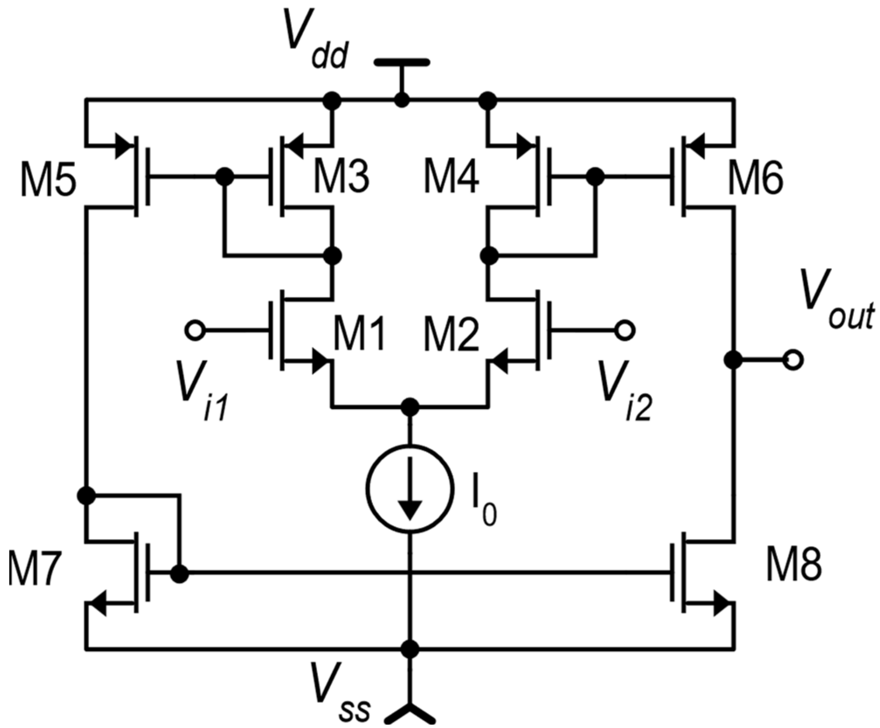
$$V_{out}(0) = V_{ss} + V_{GS3}$$

Ranges: graphical representation



Improving the output swing: the OTA

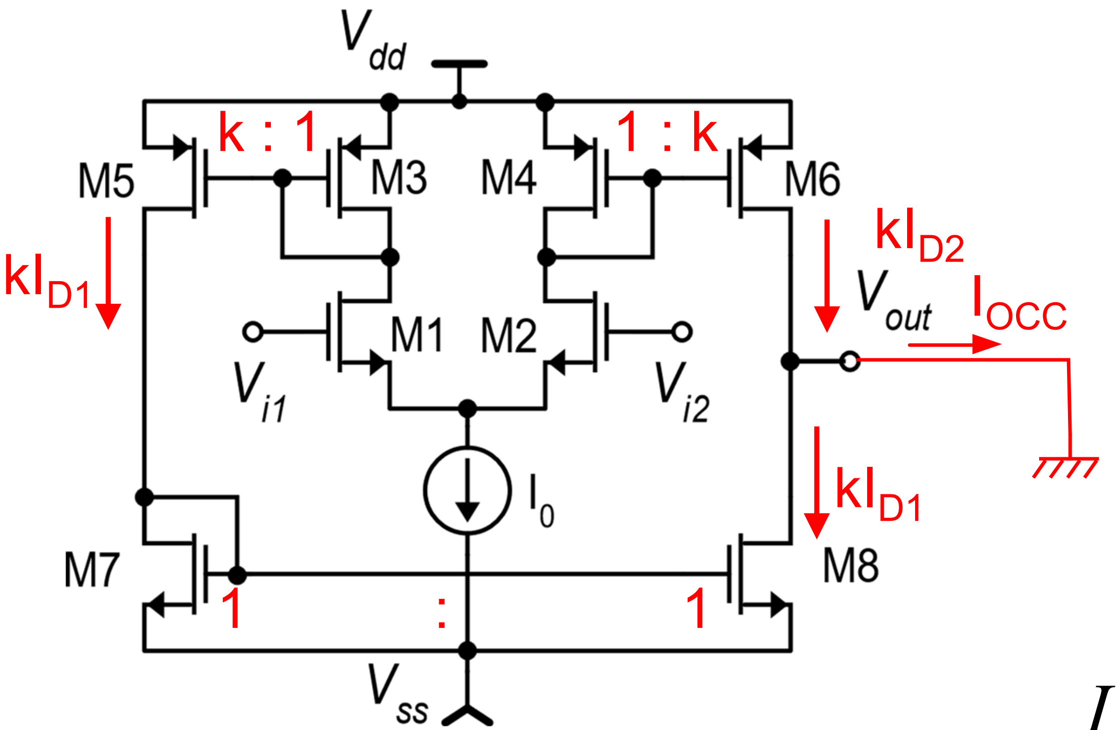
OTA: Operational Transconductance Amplifier



The term OTA generally indicates all single-stage amplifiers with high output resistance. The folded cascode amplifier is often classified as an OTA.

Historically, the term OTA has been used to indicate the topology shown in this slide

OTA: simple analysis



$$A_d = G_m R_{out}$$

$$I_{OCC} \cong k\left(I_{D2} - I_{D1}\right) \cong -k \cdot g_{m1} v_d$$

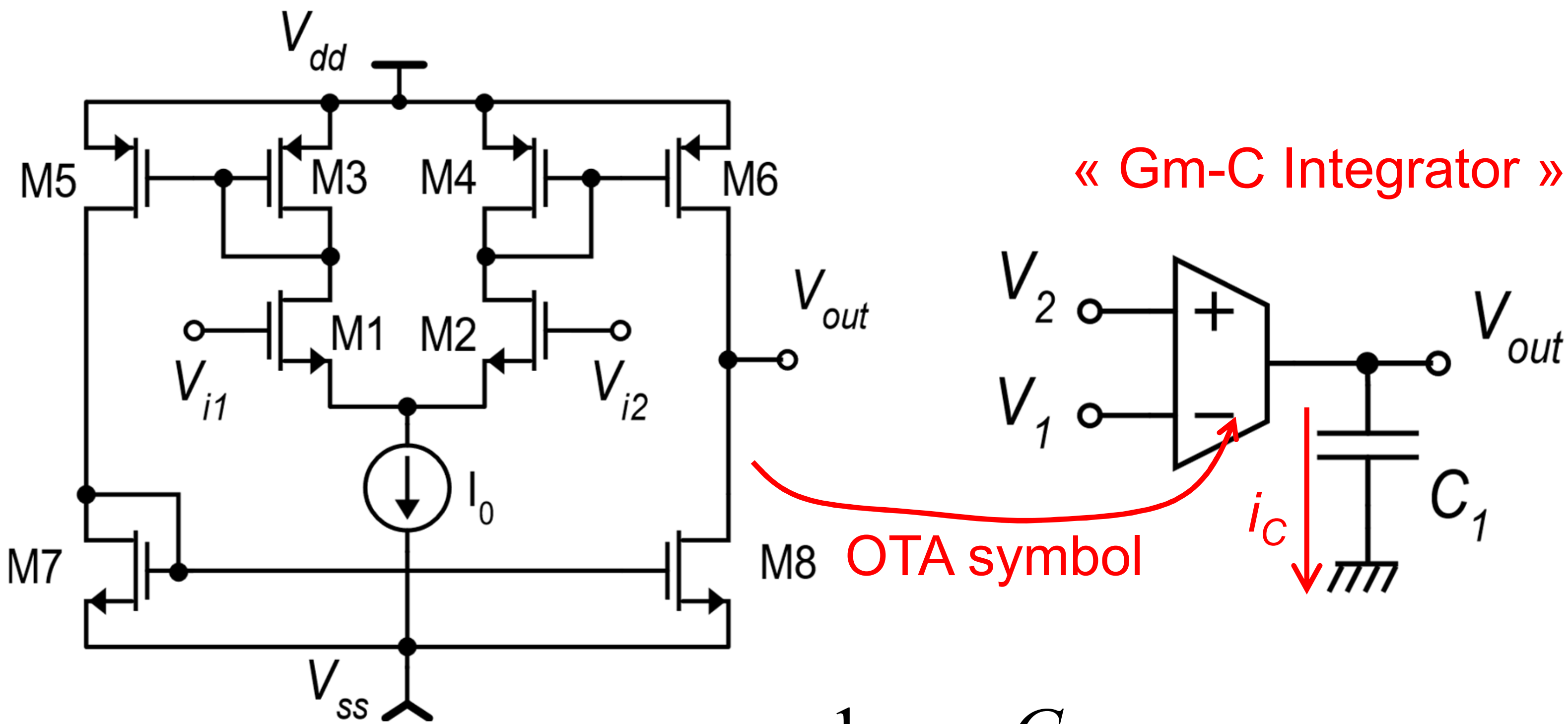
$$G_m = -k g_{m1}$$

$$R_{out} = r_{d6} // r_{d8} = \frac{1}{\lambda_6 I_{D6} + \lambda_8 I_{D8}}$$

$$I_{D6} = I_{D8} = kI_{D1}$$

$$A_d = -k \frac{I_{D1}}{V_{TE1}} \frac{1}{kI_{D1}\left(\lambda_6 + \lambda_8\right)} = \boxed{\frac{1}{V_{TE1}} \frac{1}{\left(\lambda_6 + \lambda_8\right)}}$$

Usage of the OTA as a transconductance amplifier

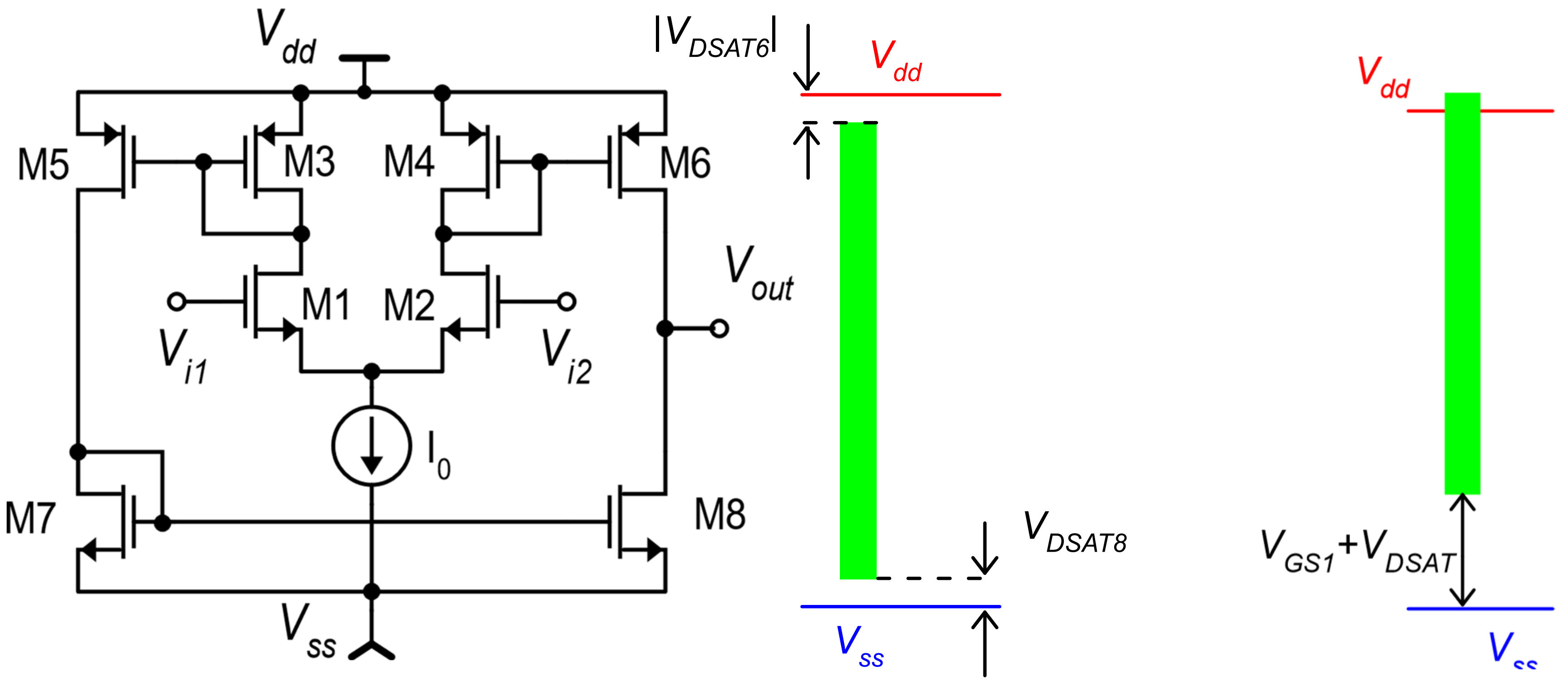


$$V_{out} = i_c \frac{1}{sC_1} = \frac{G_m}{sC_1}\left(V_2 - V_1\right)$$

Differential Integrator

The Gm-C integrator is the basis of the Gm-C analog filters

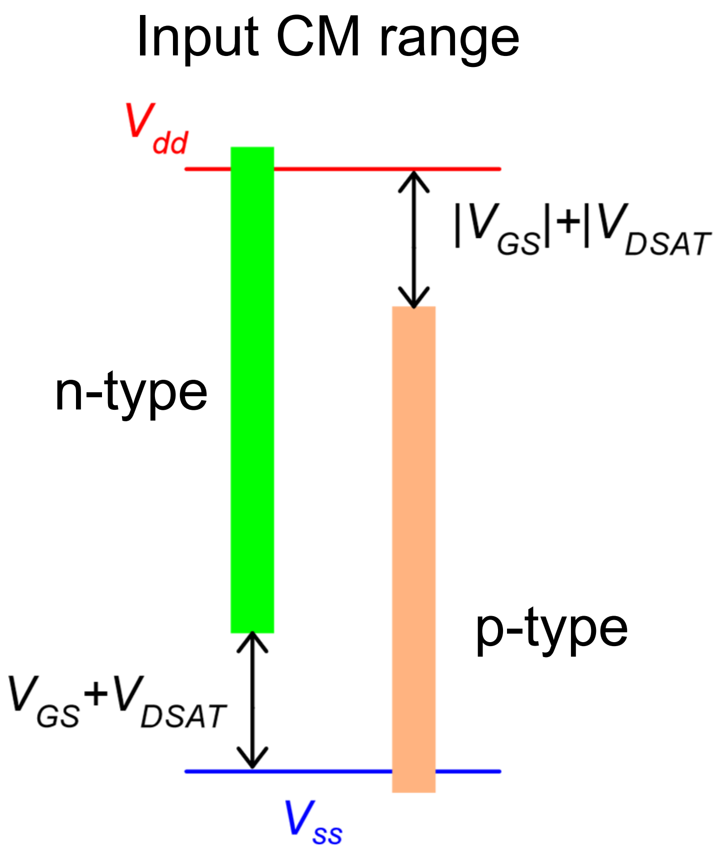
OTA output swing



Output swing

Input CM range

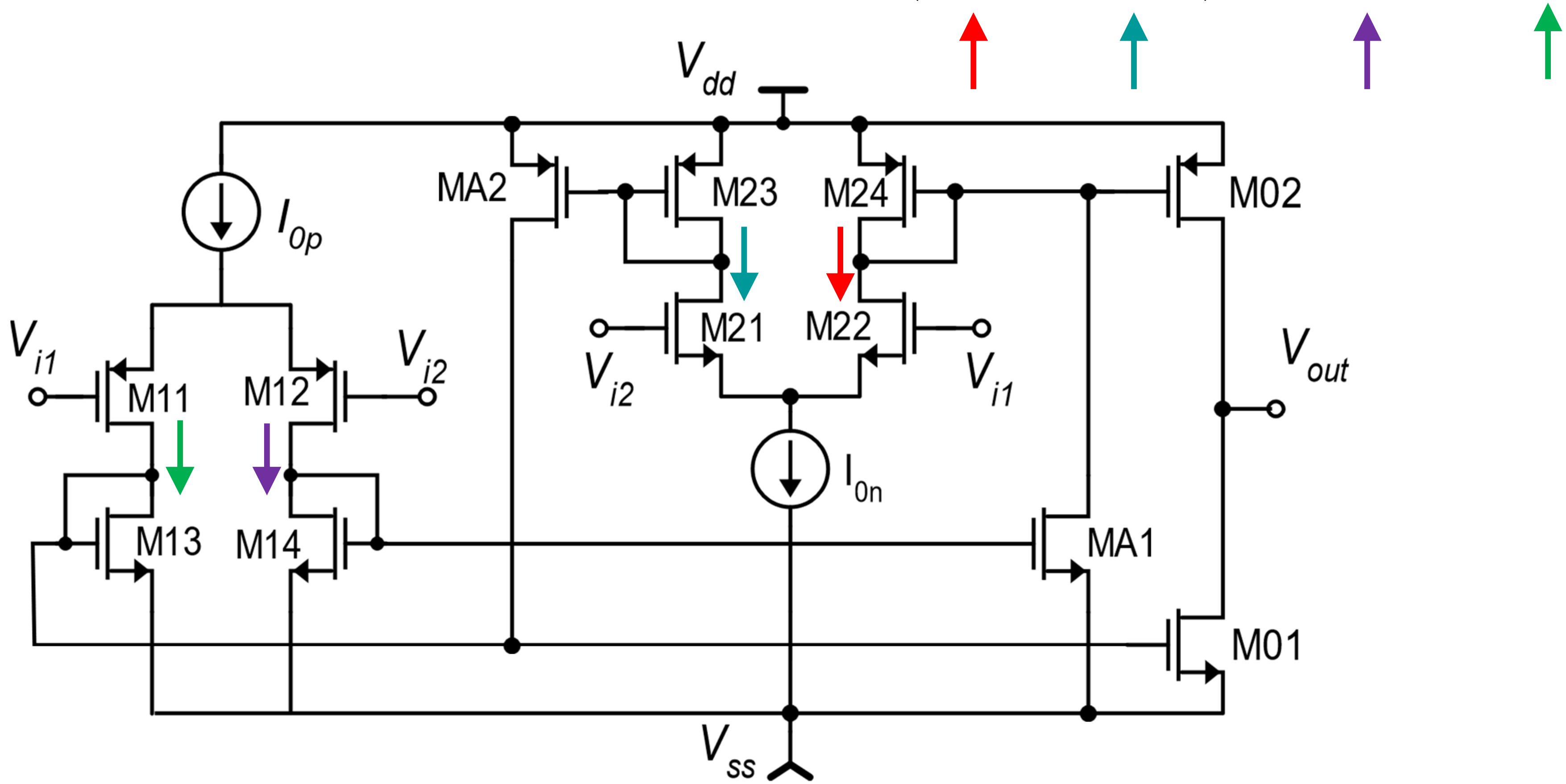
OTA with rail-to-rail input CM range



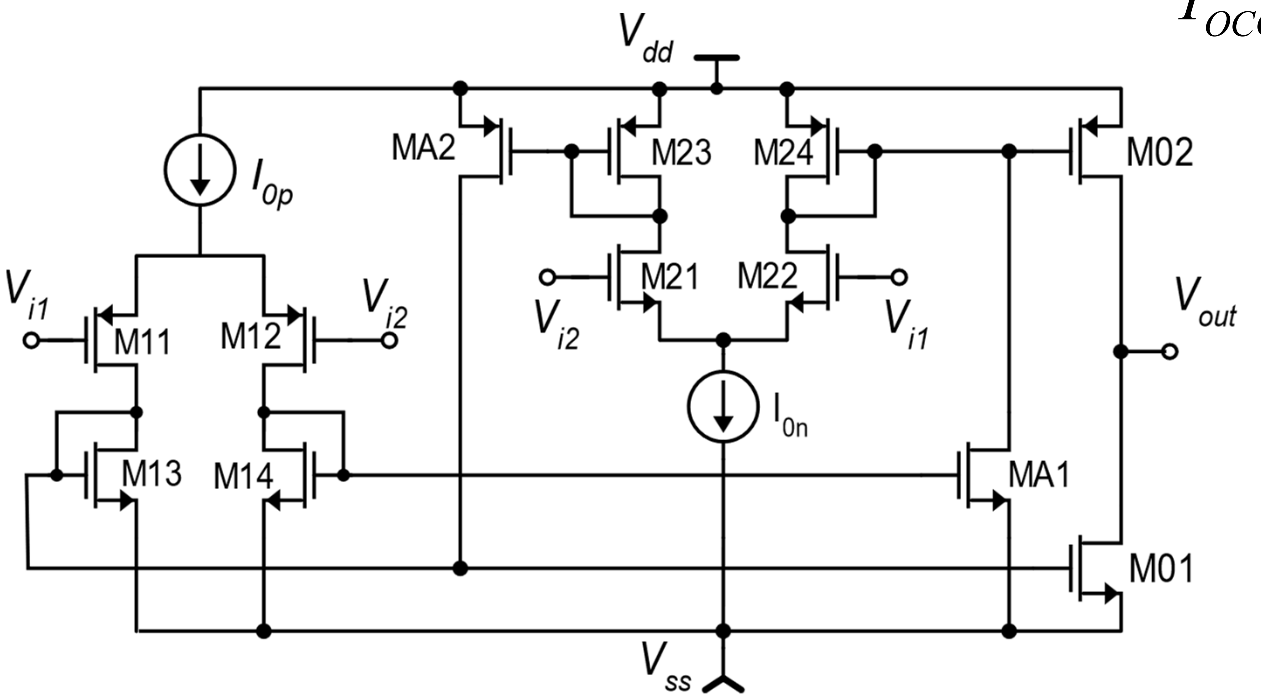
The idea is to make an n-type and p-type OTAs work together,
In this way, for any value of the input common mode range, there is at least one OTA that operates correctly

OTA with rail-to-rail input CM range

$$I_{OCC} = (I_{D22} - I_{D21}) + (I_{D12} - I_{D11})$$



OTA rail-to-rail: equivalent Gm and dc gain

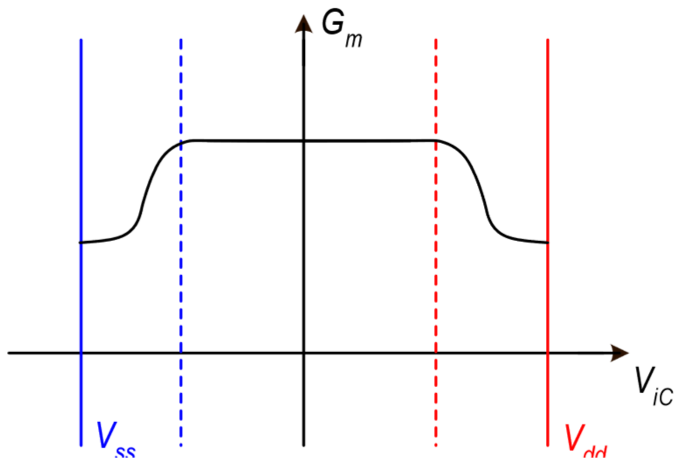


$$I_{OCC}=\left(I_{D22}-I_{D21}\right)+\left(I_{D12}-I_{D11}\right)$$

$$I_{OCC}\cong G_m v_d$$

$$I_{OCC}\cong g_{mp}v_d+g_{mn}v_d$$

$$G_m=g_{m-n}+g_{m-p}$$



$$R_{out}=r_{d01}//r_{d02}=\frac{1}{\lambda_{01}I_{D01}+\lambda_{02}I_{D02}}$$

Example of CMOS Op-Amp RRIO using a folded cascode input stage and a complementary p-n input pair

TEXAS INSTRUMENTS

OPA354, OPA2354, OPA4354

SBOS233G – MARCH 2002 – REVISED APRIL 2018 www.ti.com

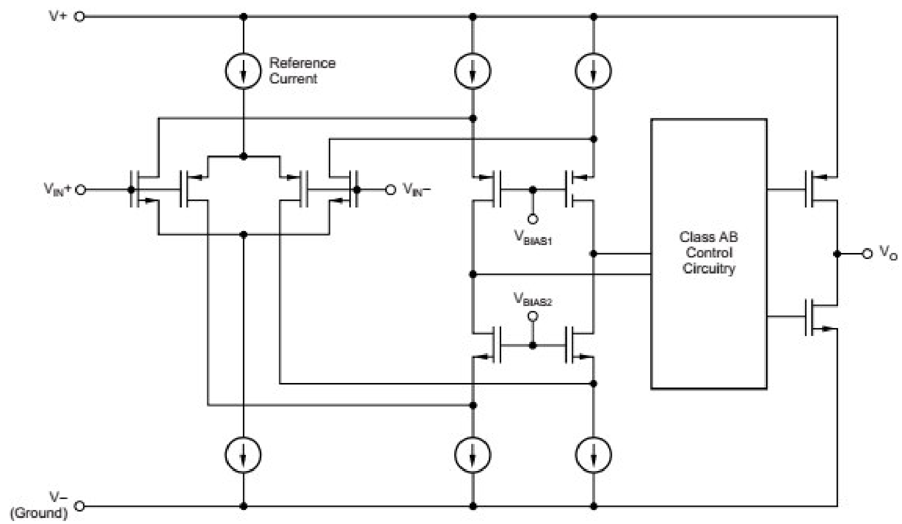
8 Detailed Description

8.1 Overview

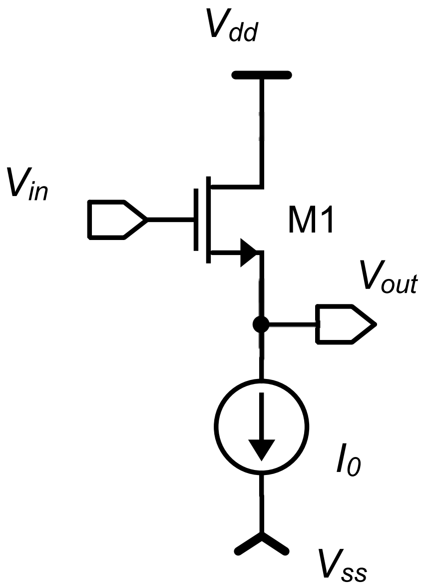
The OPAx354 is a CMOS, rail-to-rail I/O, high-speed, voltage-feedback operational amplifier designed for video, high-speed, and other applications. It is available as a single, dual, or quad op amp.

The amplifier features a 100-MHz gain bandwidth, and 150-V/μs slew rate, but the amplifier is unity-gain stable and can operate as a 1-V/V voltage follower.

8.2 Functional Block Diagram



The source follower



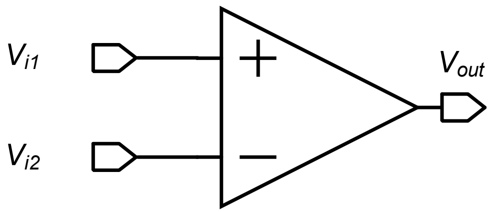
$$V_{out} = V_{in} - V_{GS}$$

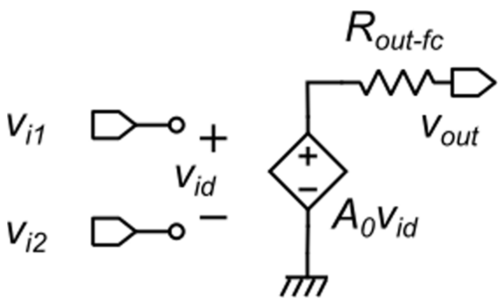
$$A \cong 1,\ R_{in} = \infty, \quad R_{out} \cong \frac{1}{g_m}$$ (small)

The source follower can be used as an output stage to be placed, for example after an high gain stage as the folded cascode.

The source follower as an output stage: advantage

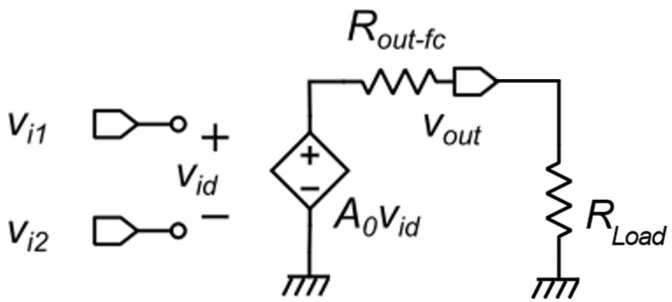
Folded cascode amplifier





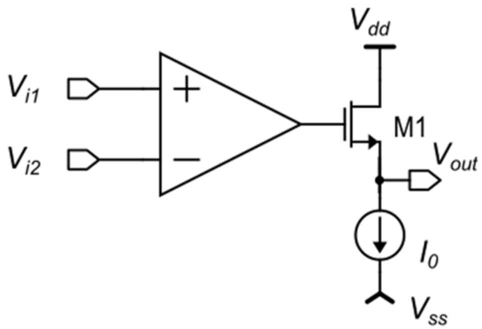
Equivalent circuit

If we have to drive a resistive load



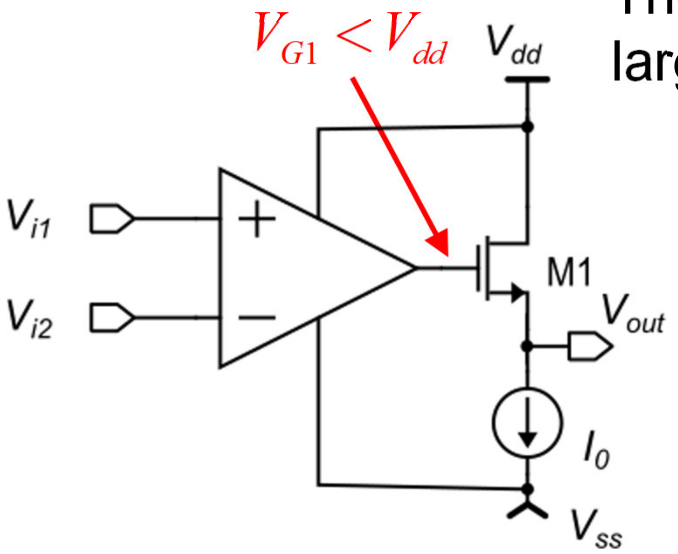
$$v_{out} = A_0 v_d \frac{R_{Load}}{R_{out} + R_{Load}}$$

For $R_{out} \gg R_{Load}$, this coefficient can be <<1 reducing the available gain



Adding a source follower at the output we have the same gain A_0 with a much lower output resistance

The source follower as an output stage: drawback



The input voltage of the source follower cannot be larger than V_{dd}

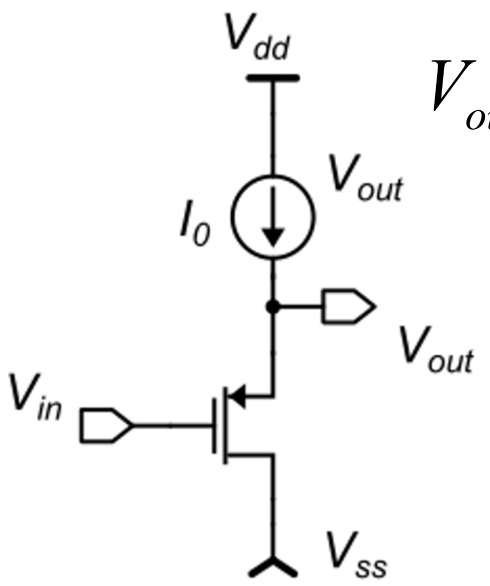
$$V_{out} = V_{G1} - V_{GS}$$

$$V_{out} < V_{dd} - V_{GS}$$

The output swing looses a VGS margin with respect to the higher power rail (V_{dd})

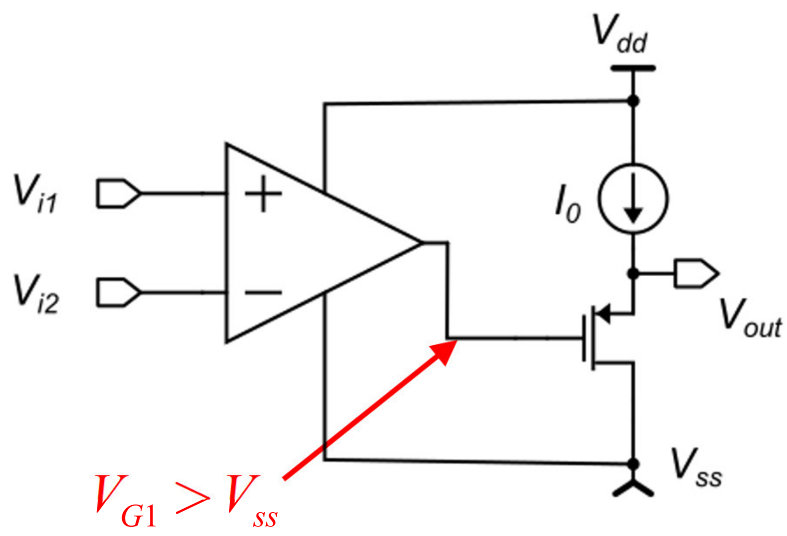
This drawback strongly limits the usage of the source follower as an output stage in modern integrated circuits. It can be used only if a rail-to-rail output swing is not required.

P-type source follower



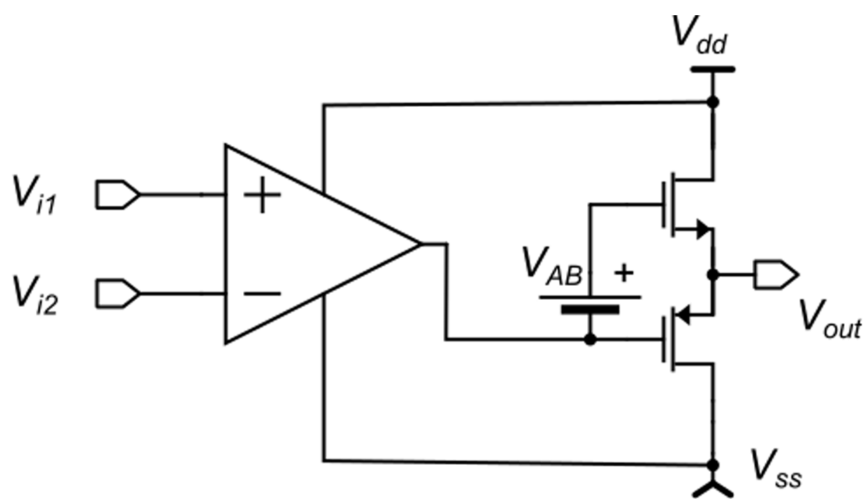
$$V_{out} = V_{in} + \left|V_{GS}\right|$$

$$V_{out} > V_{ss} + \left|V_{GS}\right|$$



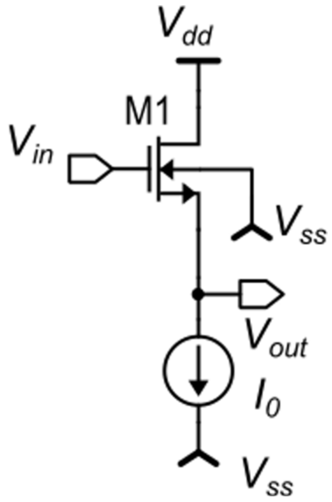
With the p-type source follower we loose a $|V_{GS}|$ margin to V_{ss}.
This is equally not compatible for rail-to-rail applications

Class AB source follower



This stage looses a VGS margin to both rails. It is used only for amplifiers that can count on high supply voltage. Not used in general purposes operational amplifiers

Source follower as voltage shifter



$$V_{out} = V_{in} - V_{GS}$$

$$V_{GS} = \left(V_{GS} - V_t\right) + V_t$$

In strong inversion:

$$\left(V_{GS} - V_t\right) = \sqrt{\frac{2I_D}{\beta}}$$

V_{out} is shifted down by V_{GS}.

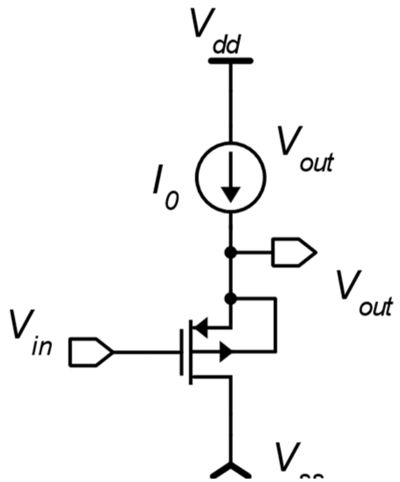
Unfortunately the voltage shift (VGS) is not constant, but depends on the output signal:

$$V_t = f\left(V_{BS}\right) = f(V_{SS} - V_{out})$$

This causes distortion for wide input signals

The problem can be solved by connecting the source to the body (tot possible in standard n-well CMOS processes)

P-type voltage shifter



$$V_{out} = V_{in} + \left| V_{GS} \right|$$

The p-type source follower acts as a positive voltage shifter.

In standard n-well CMOS processes it is possible to connect the source to the body (n-well) obtaining a constant voltage shift ($|V_{GS}|$)