Chapter 4

Basis of analog MOS circuit

- Inverter circuit
- Differential amplifier
- Current source / Current mirror
- Complete Circuit of an Amplifier

Current Source

Application:

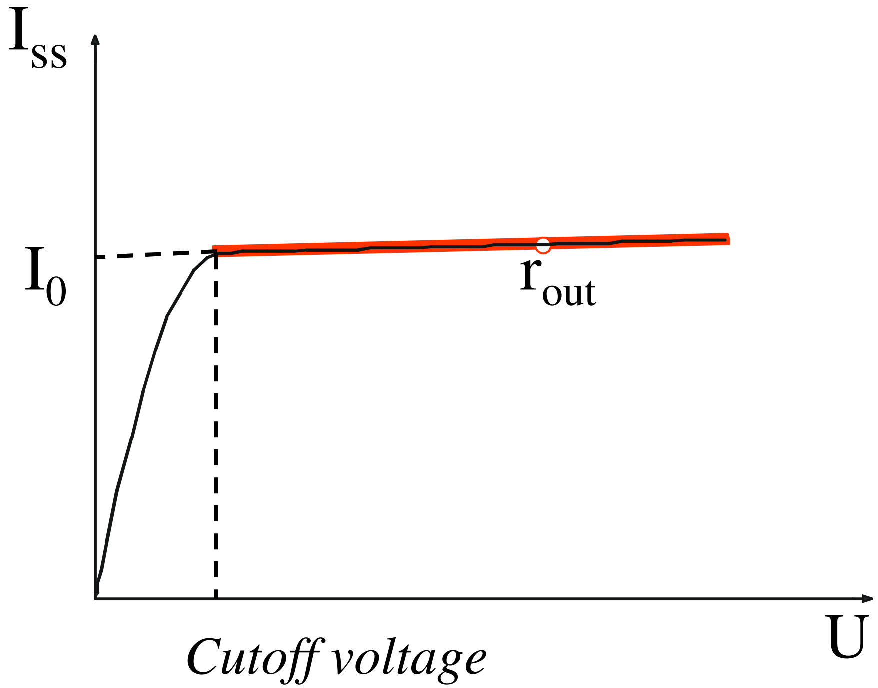
Operating point biasing,
High ohmic load for
inverter / amplifier

Key parameters:

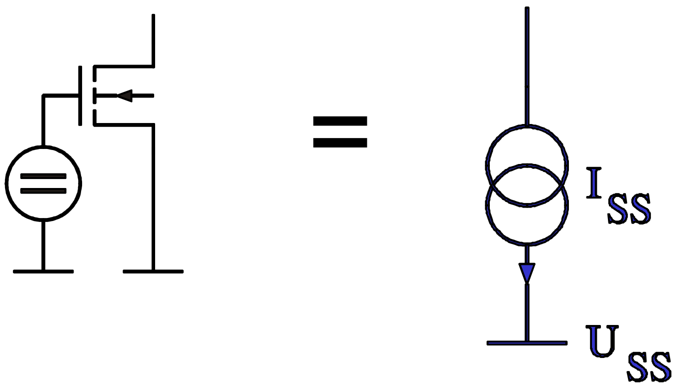
Output resistance r_{out},

Cutoff voltage

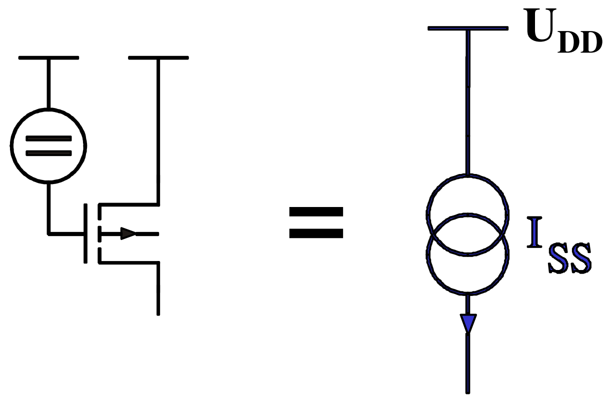
Absolute value (accuracy) I_0



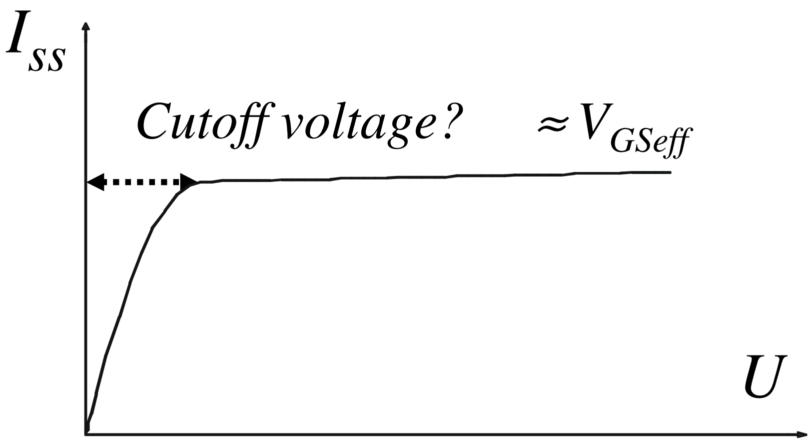
MOS-Output with fixed gate-source-voltage



Current sink



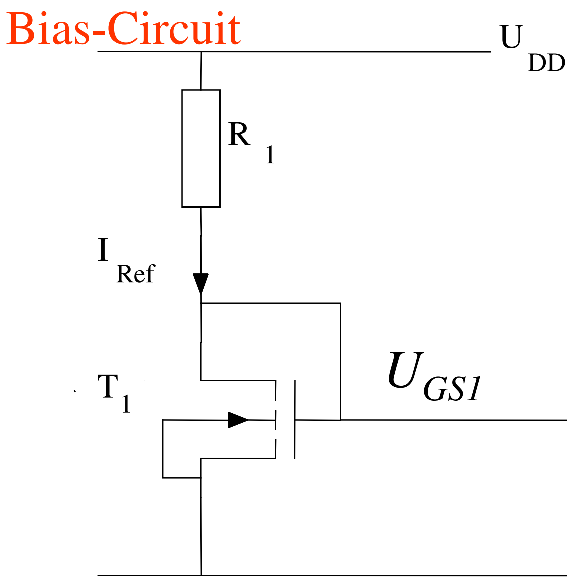
Current source



The transistor is mostly operated in the Weak Inversion / Subthreshold mode.

How to achieve a fixed gate-source-voltage?

How to achieve a fixed gate-source-voltage?



Calculation of the operation point:

$$I_{ref} \cdot R_1 + U_{GS1} = U_{DD} + |U_{SS}|$$

$$U_{GS1} = U_{DD} + |U_{SS}| - I_{ref} \cdot R_1 = U_{GSeff} + U_T$$

$$U_{GSeff} \approx 0 \Rightarrow I_{ref} = \frac{U_{DD} + |U_{SS}| - U_T}{R_1}$$

With this equation it is possible to set a reference current.

The transistor has to be dimensioned so that it operates in the subthreshold region.

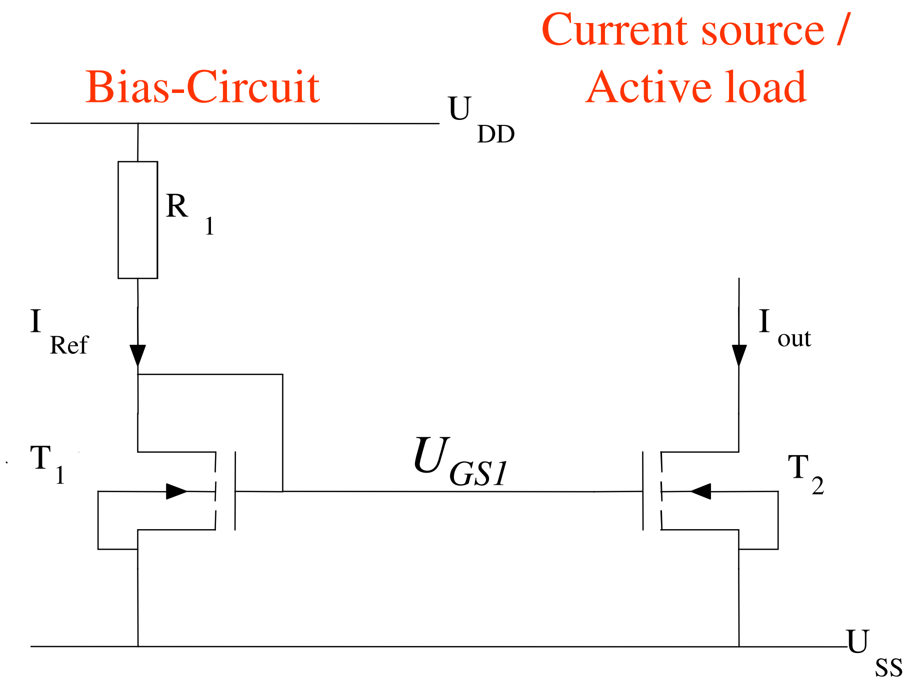
The MOS-diode delivers the accordant U_{GS1}

Current mirror:

U_{GS1} constant ?

No, but I_{ref} nearly constant

$$I_{ref} \approx \frac{U_{DD} + |U_{SS}| - U_T}{R_1}$$



$$I_{ref} = I_{D1} = \frac{\beta_0}{2} \cdot \frac{W}{L}\bigg|_1 \cdot (U_{GS1} - U_{T1})^2$$

if $T_1 = T_2$ ist $\boxed{I_{D1} = I_{D2}}$

$$I_{D2} = \frac{\beta_0}{2} \cdot \frac{W}{L}\bigg|_2 \cdot (U_{GS1} - U_{T2})^2$$

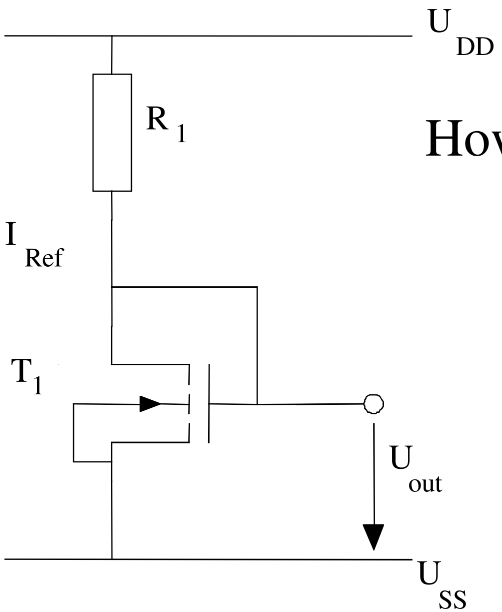
But only if $U_{DS1} \approx U_{DS2}$

Or if L very large ($\lambda \approx 0$)

$$I_{out}/I_{ref} = I_{D2}/I_{D1} = \frac{W}{L}\bigg|_2 \bigg/ \frac{W}{L}\bigg|_1$$

= *mirror ratio*

Bias-circuit with MOS diode (p-channel) as the load



How to realize a bias-circuit with MOS solely?

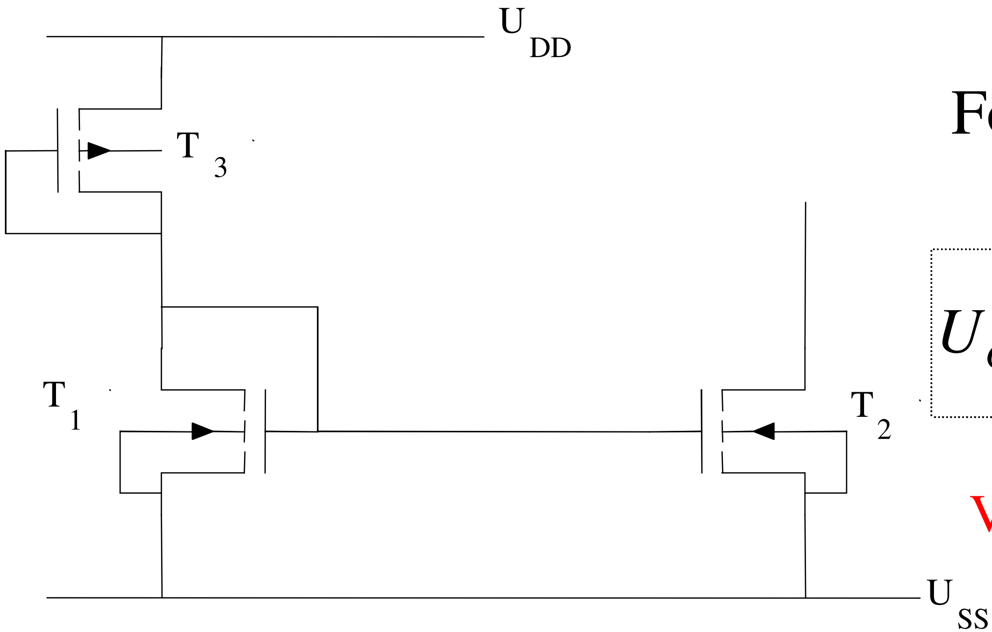
$$U_{DD} = U_{GS3} + U_{GS1}$$

$$= \underbrace{\sqrt{\frac{2 \cdot I_D}{\beta_3}}}_{U_{GSeff\,3}} + U_{T3} + \underbrace{\sqrt{\frac{2 \cdot I_D}{\beta_1}}}_{U_{GSeff\,1}} + U_{T1}$$

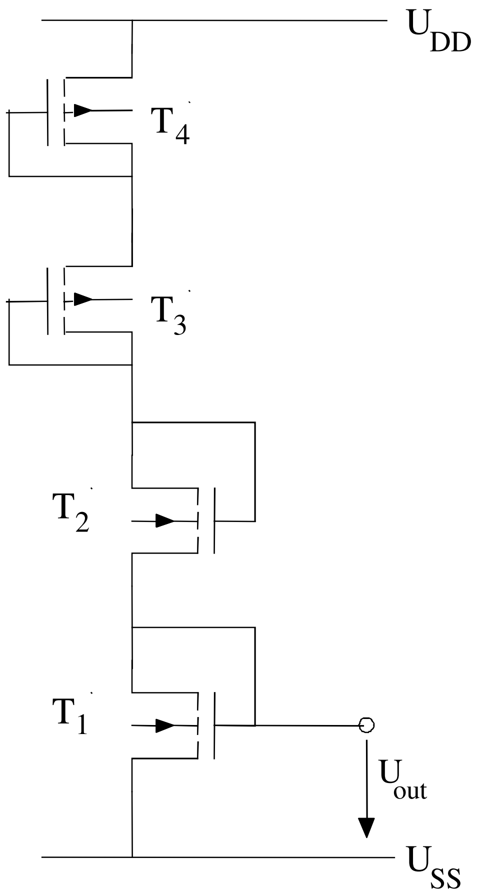
For $U_{T1} \approx |U_{T3}| \quad U_{GSeff\,1} \approx |U_{GSeff\,3}|$

$$U_{GSeff} = \frac{U_{DD} - 2 \cdot U_T}{2}\Big|_{Vdd=5V} \approx 1{,}5V$$

Very small W/L required, e.g. 5/50



Setting of current by effective gate-voltage



$$U_{GSeff} = \frac{U_{DD} - 4 \cdot U_T}{4} = \frac{5V - 4V}{4} = 0.25V$$

-> Reduction of U_{GS} to a reasonable value

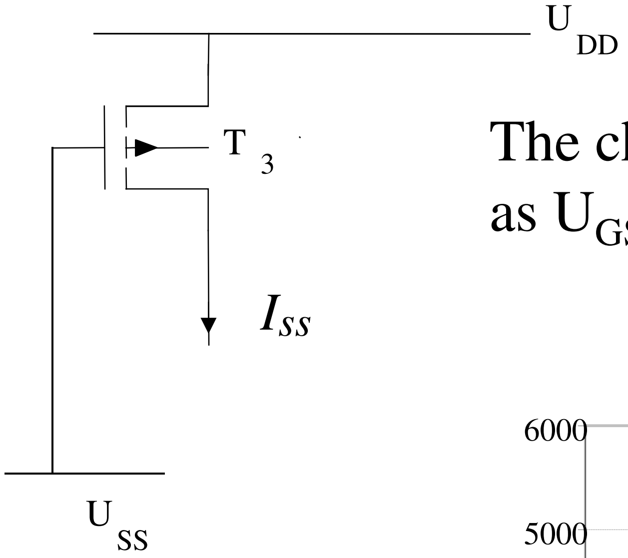
$$\text{Bias-Strom: } I_D = \beta_0 \cdot \frac{W}{L} \cdot (U_{GS1} - U_{T1})^2$$

To consider:

Bulk ?

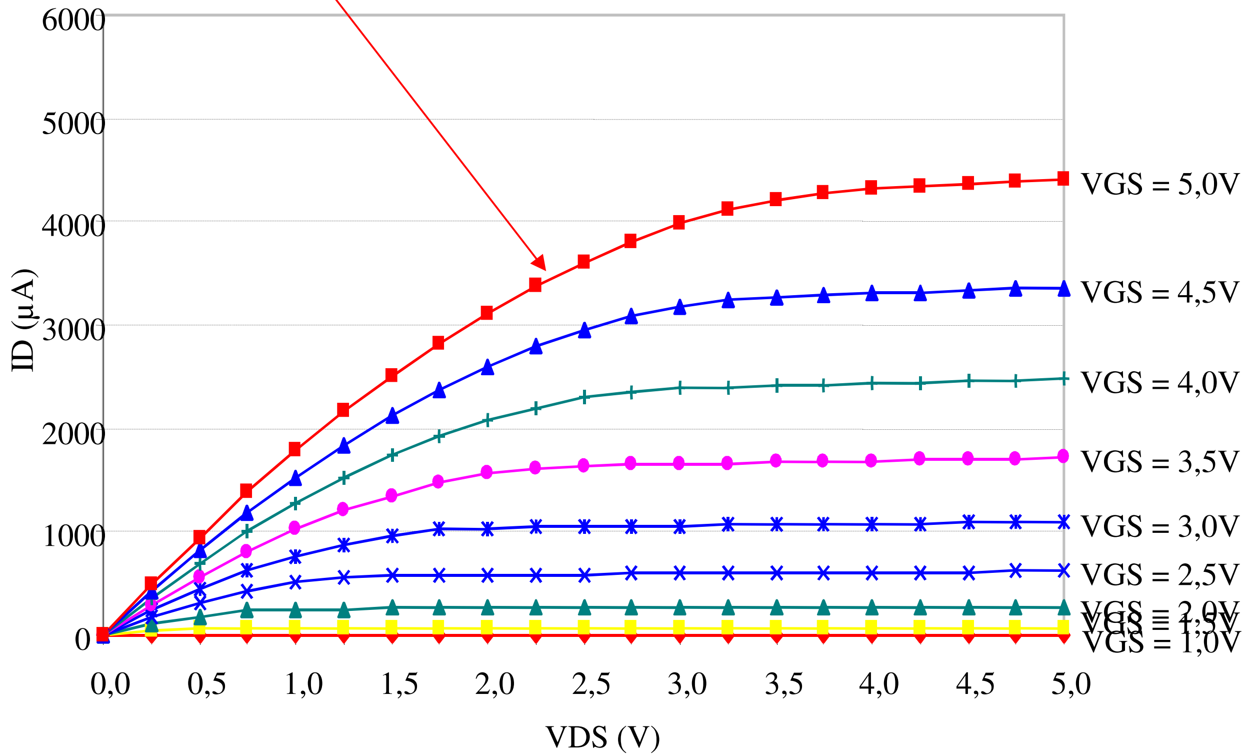
I_D sensitive to process variation

Bias-circuit with supply voltage at gate-source



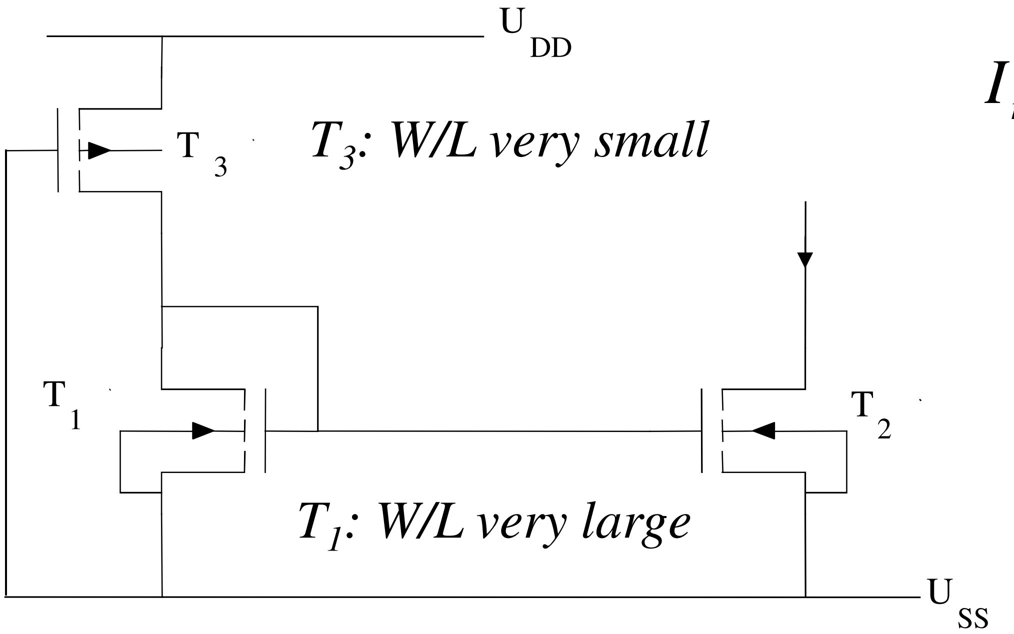
The characteristic curve is rather resistive, as U_{GSeff} is very large.

Furthermore the current is high or W/L has to be extremly low.



Reference currenr source using supply voltage for gate-source biasing

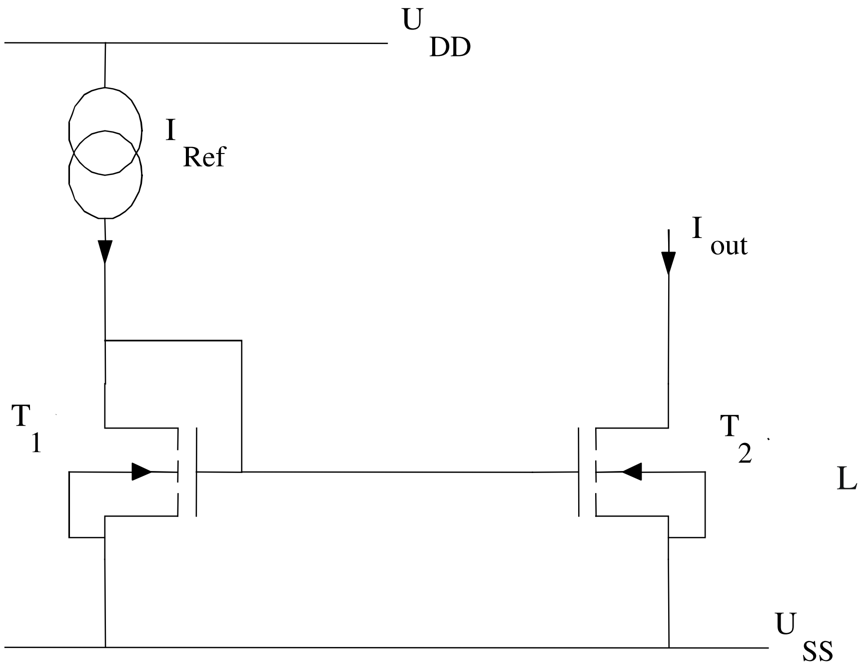
Solution: the drain-potential is kept nearly constant and is mirrored with a MOS-diode

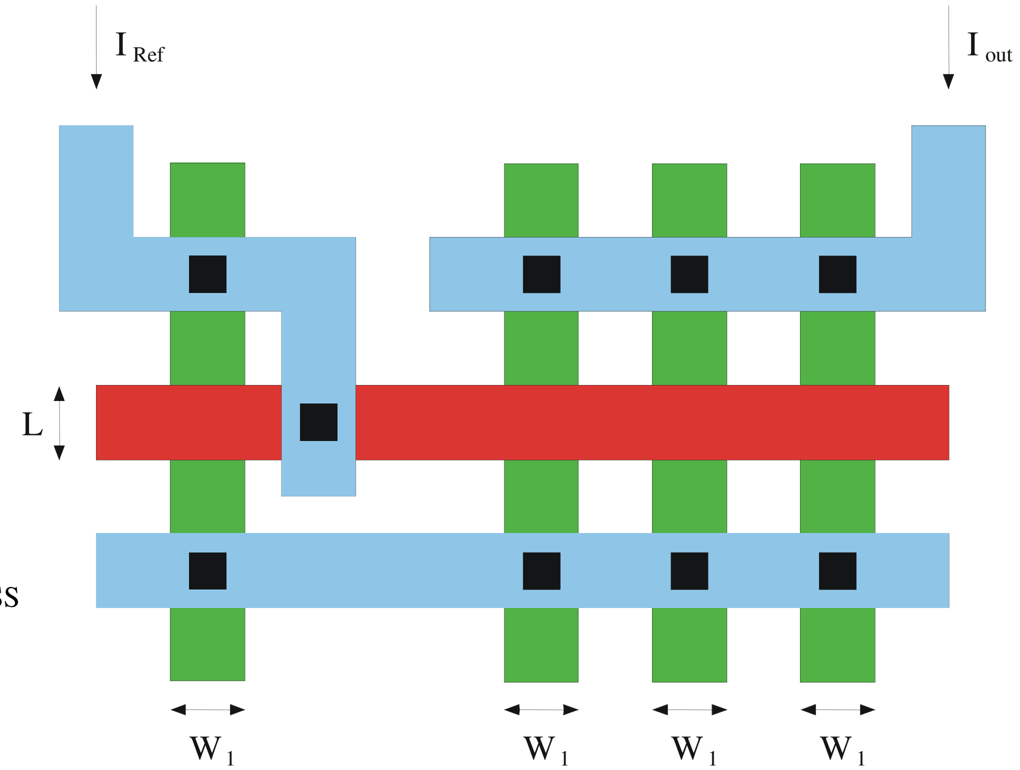


$$I_{ref} = \frac{\beta_{0P}}{2} \cdot \frac{W}{L}\bigg|_3 \cdot \left(U_{DD} - U_{T3}\right)^2$$

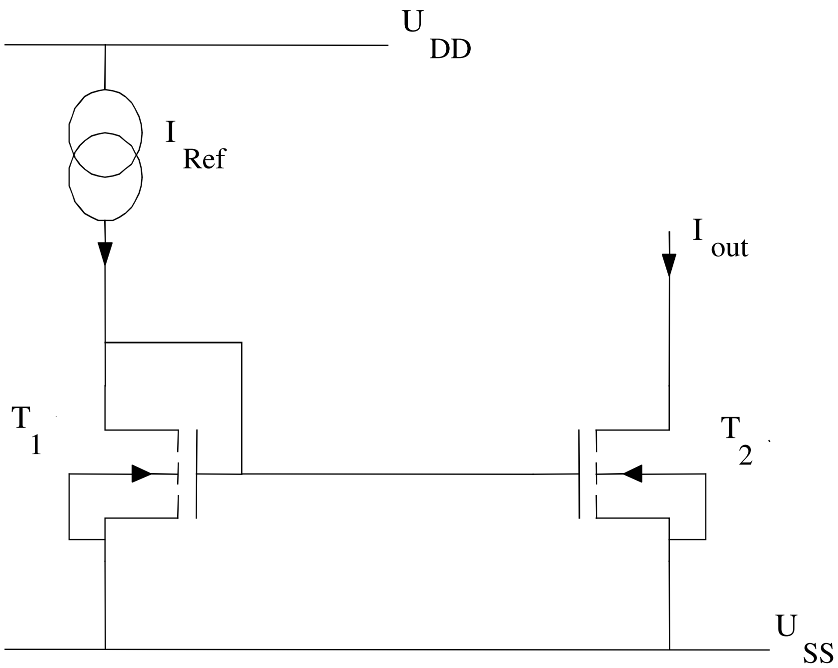
Layout for Current Mirror, e.g. $W_2 = 3*W_1$

V_T depends also on (short) channel length and (narrow) channel width.
Aim of a current mirror: constant transmission ratio.
Solution: utilization of identical cells





Consideration of channel length modulation



$$I_{Out} = \frac{\beta_0}{2} \cdot \frac{W}{L}\Big|_2 \cdot (U_{GS2} - U_{T2})^2 \cdot (1 + \lambda_2 \cdot U_{DS2})$$

$$I_{Ref} = \frac{\beta_0}{2} \cdot \frac{W}{L}\Big|_1 \cdot (U_{GS1} - U_{T1})^2 \cdot (1 + \lambda_1 \cdot U_{DS1})$$

$$\frac{I_{Out}}{I_{Ref}} = \frac{\frac{W}{L}\Big|_2 \cdot (1 + \lambda \cdot U_{DS2})}{\frac{W}{L}\Big|_1 \cdot (1 + \lambda \cdot U_{DS1})}$$

For $L_1 = L_2$ and $U_{DS1} = U_{DS2}$

$$\frac{I_{Out}}{I_{Ref}} = \frac{W_2}{W_1}$$

Deviation for the case that $U_{DS1} \neq U_{DS2}$

So far: $$\boxed{\frac{I_{Out}}{I_{Ref}} = \frac{\left.\frac{W}{L}\right|_2 \cdot \left(1+\lambda \cdot U_{DS2}\right)}{\left.\frac{W}{L}\right|_1 \cdot \left(1+\lambda \cdot U_{DS1}\right)} = \frac{W_2}{W_1}}$$ if $L_1 = L_2$ and $U_{DS1} = U_{DS2}$

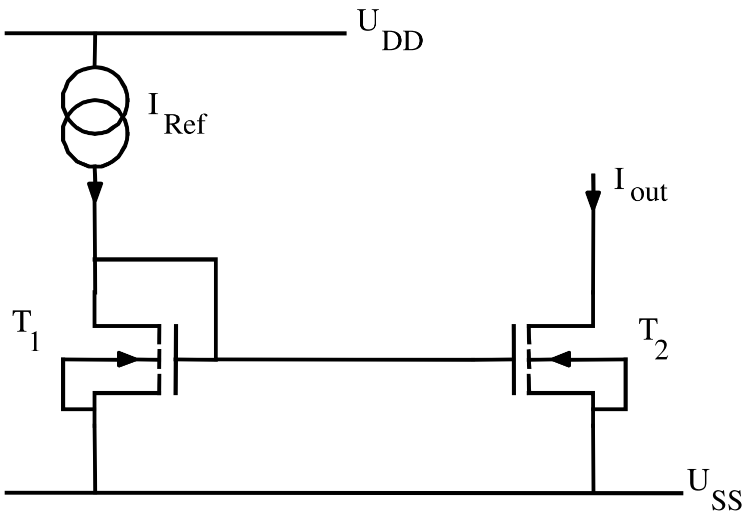
<u>Conisderation of $U_{DS1} \neq U_{DS2}$</u>

Case $\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$

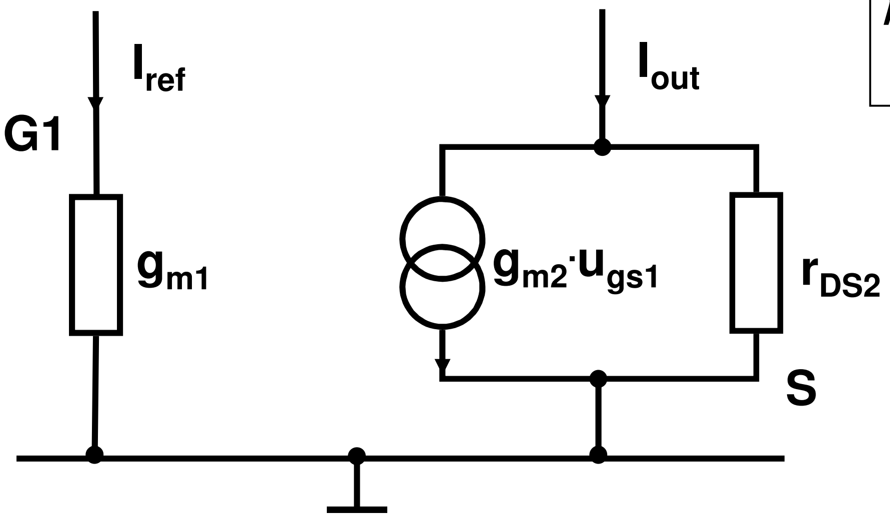
$$\frac{I_{Out}}{I_{Ref}} = \left.\frac{\left(1+\lambda \cdot U_{DS2}\right)}{\left(1+\lambda \cdot U_{DS1}\right)}\right|_{U_{DS2}=U_{DS1}+\Delta U_{DS}} = \frac{1+\lambda \cdot U_{DS1} + \lambda \cdot \Delta U_{DS}}{1+\lambda \cdot U_{DS1}}$$

$$= 1 + \frac{\lambda \cdot \Delta U_{DS}}{1+\lambda \cdot U_{DS1}} \qquad \boxed{\Rightarrow \quad L >>}$$

Small signal consideration of current mirror

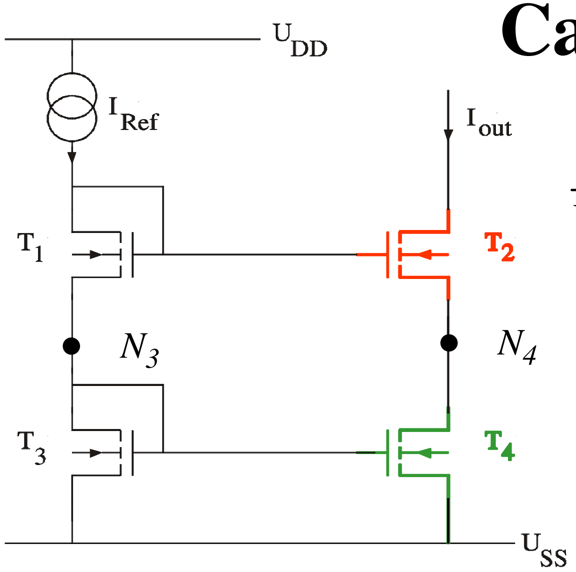


$$r_{out} = ?$$



$$r_{out} \approx r_{DS2} = \frac{1}{\lambda \cdot I_{D2}}$$

Cascoode-current source

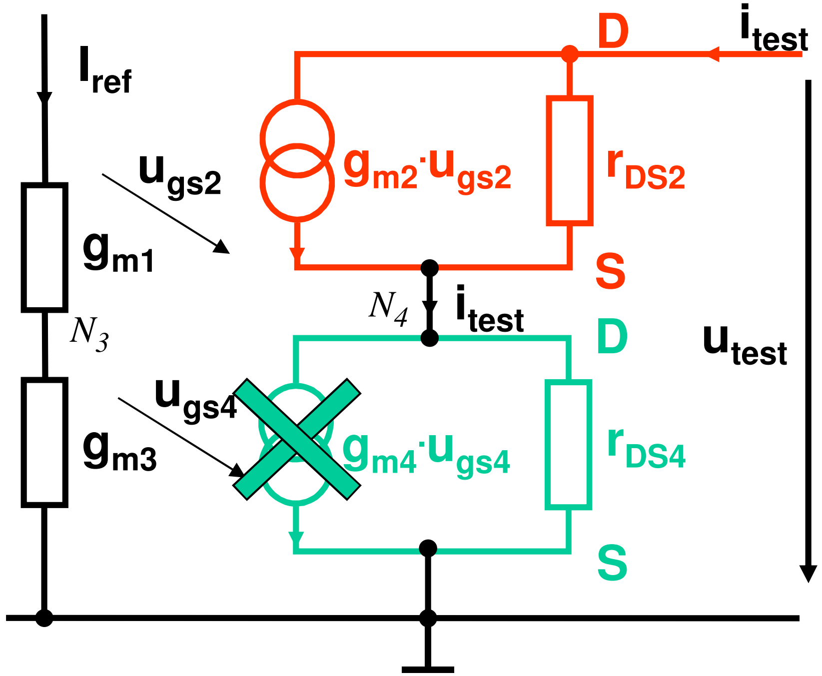


$$\frac{W/L|_1}{W/L|_2} = \frac{W/L|_3}{W/L|_4}$$

Effect of Cascode-circuit:

The drain potential of T4 (N4) is nearly equal N3 , as a small change of N4 compensates a larger change of drain current ($g_m >> g_{DS}$)

⇨ I_{out} is nearly independant of the voltage



$$r_{out} = ? \qquad = \frac{u_{out}}{i_{out}}\bigg|_{u_{in}=0} = \frac{u_{test}}{i_{test}}\bigg|_{u_{in}=0}$$

$$u_{Test} = \left(i_{Test} - g_{m2} \cdot u_{GS2}\right) r_{DS2}$$

$$+ i_{Test} \cdot r_{DS4}$$

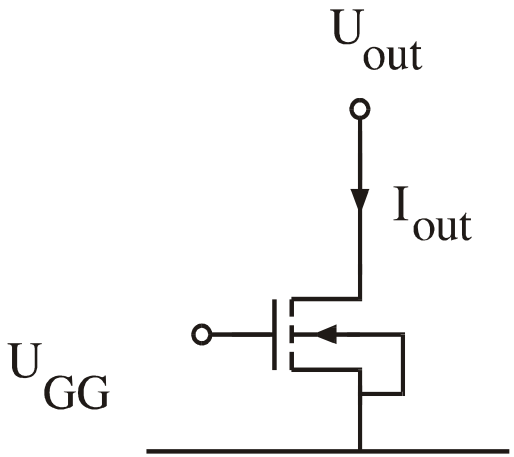
$$u_{GS2} + i_{Test} \cdot r_{DS4} = 0$$

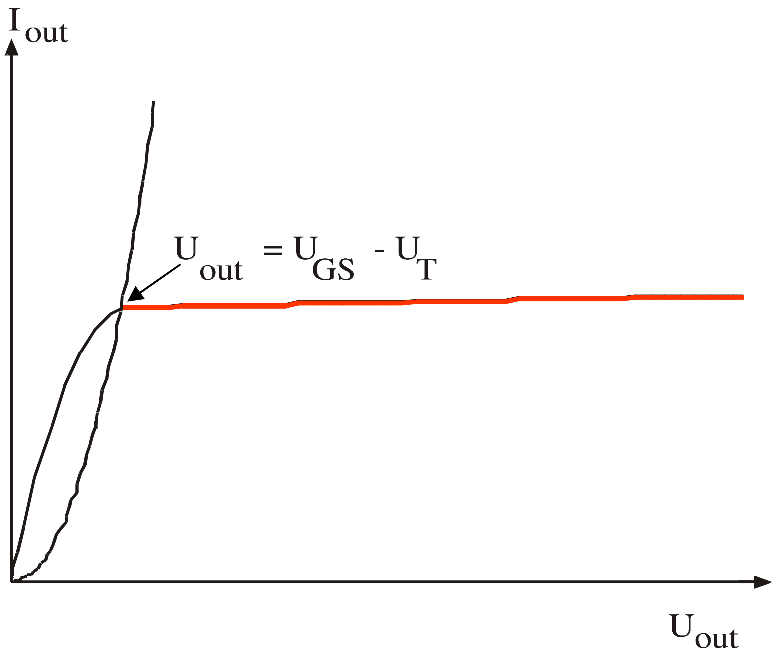
$$r_{out} = g_{m2} \cdot r_{DS4} \cdot r_{DS2} + r_{DS2} + r_{DS4}$$

$$= \underbrace{g_{m2} \cdot r_{DS2}}_{>>1} \cdot r_{DS4}$$

Operation range of current sources

a) Simple current source





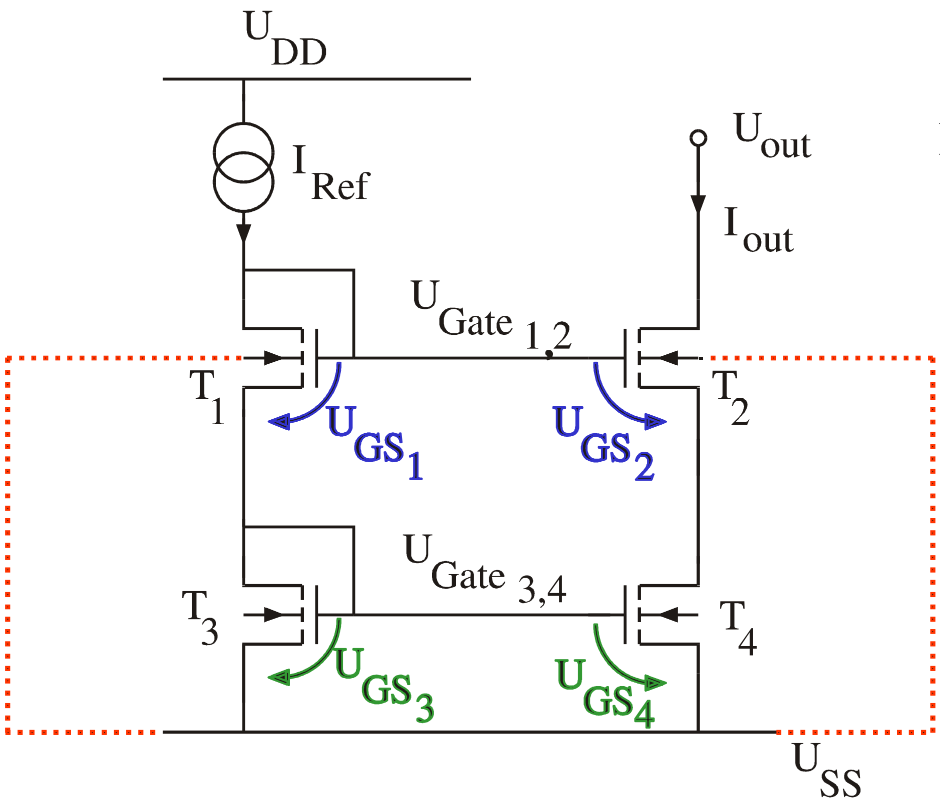
$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2 \qquad U_{DS} > U_{Dsat} \approx U_{GS} - U_T = U_{GSeff}$$

$$U_{GSeff} = \sqrt{\frac{2 \cdot I_D}{\beta}} = \sqrt{\frac{2 \cdot I_D}{\beta_0 \cdot \frac{W}{L}}}$$

$$\frac{W}{L} \uparrow \quad \Rightarrow \quad U_{GSeff} \downarrow \quad \Rightarrow$$

Large operation range

b) Cascode-current mirror/source



Due to $\frac{W/L|_1}{W/L|_2} = \frac{W/L|_3}{W/L|_4}$ and $U_{GS4} = U_{GS3}$

$$\Rightarrow U_{GS2} \approx U_{GS1}$$

Requirement: $U_{DS2} \overset{?}{>} U_{GS2} - U_{T2}$

$$\Leftrightarrow U_{D2} \overset{?}{>} U_{G2} - U_{T2}$$

Gate of T_2 is $U_{GS3} + U_{GS1}$

$$U_{G2} = U_{GS3} + U_{GS1}$$

$$U_{D2} > U_{GS3eff} + U_{T3} + U_{GS1eff} + \cancel{U_{T1}} - \cancel{U_{T2}}$$

$$U_{DS1} = U_{GS1} \quad U_{DS3} = U_{GS3}$$

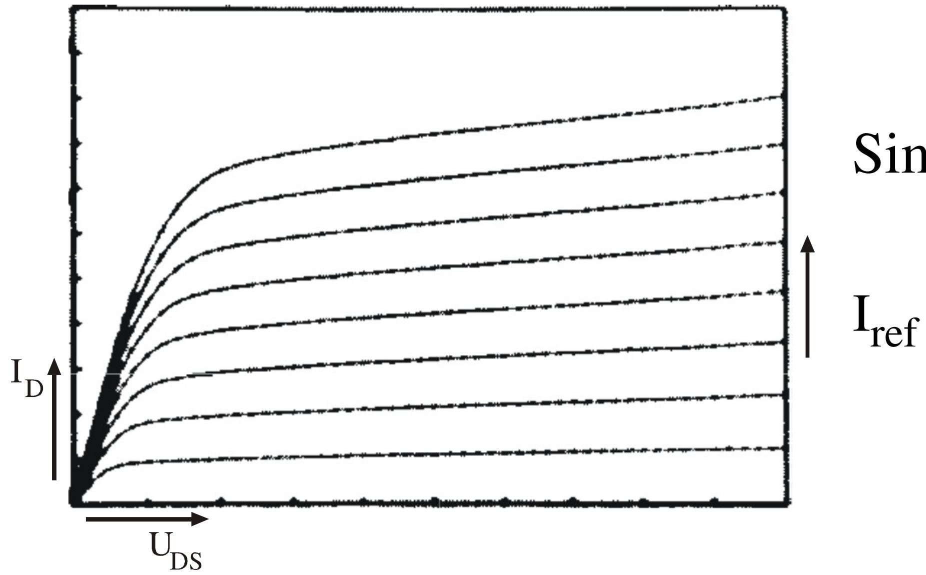
$$\Rightarrow U_{DS1,3} \overset{!}{>} U_{GS1,3} - U_{T1,3}$$

$$U_{GS3} = U_{GS3eff} + U_{T3}$$

$$U_{GS1} = U_{GS1eff} + U_{T1}$$

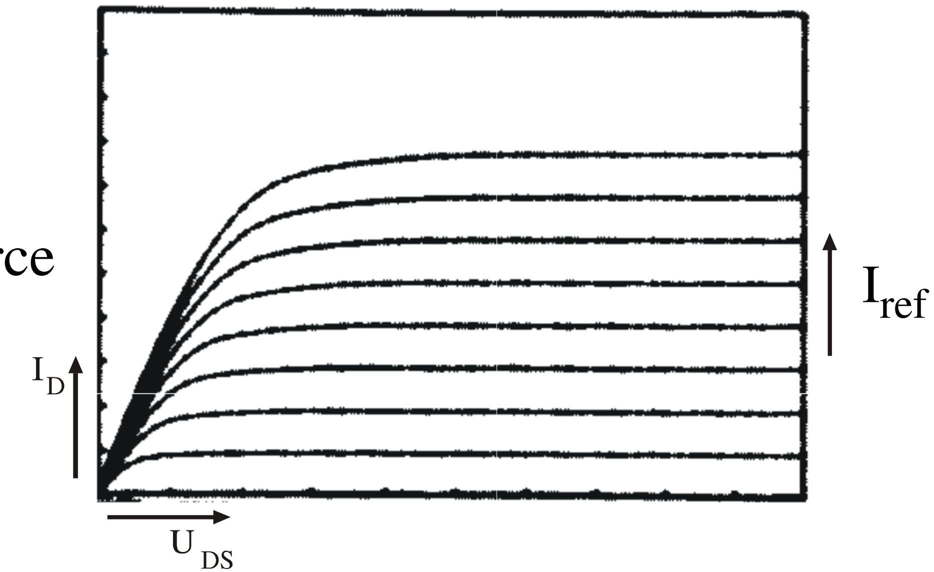
$$\boxed{U_{D2} > U_{GS3eff} + U_{T3} + U_{GS1eff}}$$

Characteristics of current curves



Simple current source

Kaskode current source



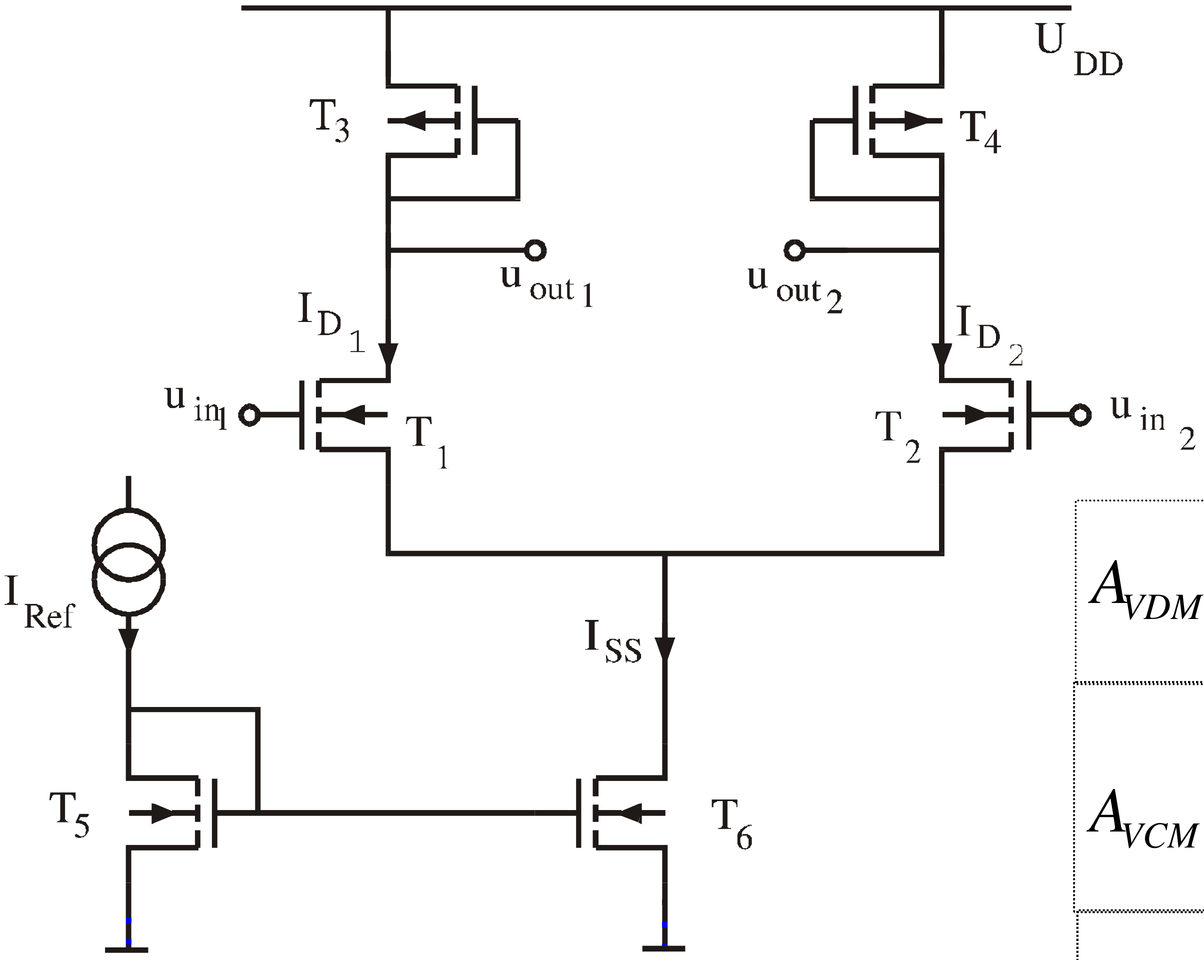
Cascode has a higher output resistance,
but a higher cutoff voltage.

Chapter 4

Basis of analog MOS circuit

- Inverter circuit
- Differential amplifier
- Current source / Current mirror
- Complete Circuit of an Amplifier

Difference amplifier stage with diode load

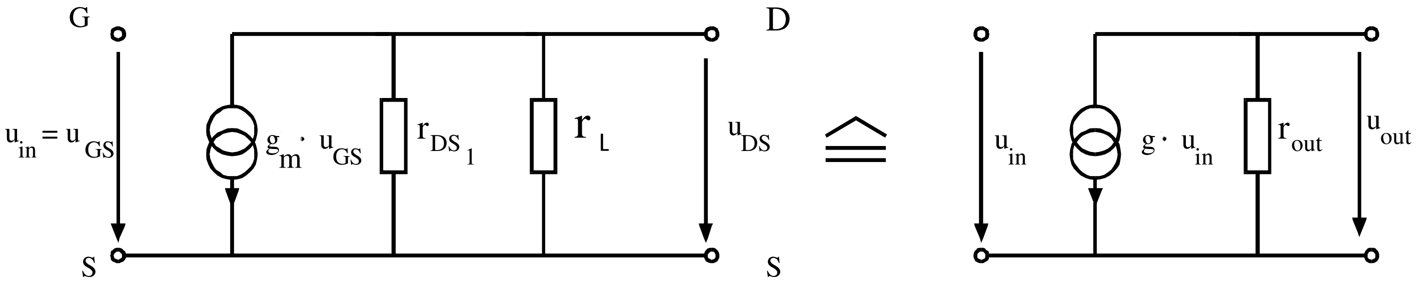


$$A_{VDM} = -g_{m1} \cdot R = -\frac{g_{m1}}{g_{m3}}$$

$$A_{VCM} = -\frac{R}{2 \cdot R_{SS}} = -\frac{1/g_{m3}}{2 \cdot r_{DS6}}$$

$$CMRR = \frac{A_{VDM}}{A_{VCM}} = 2 \cdot r_{DS6} \cdot g_{m1}$$

Set-up of an amplifier stage

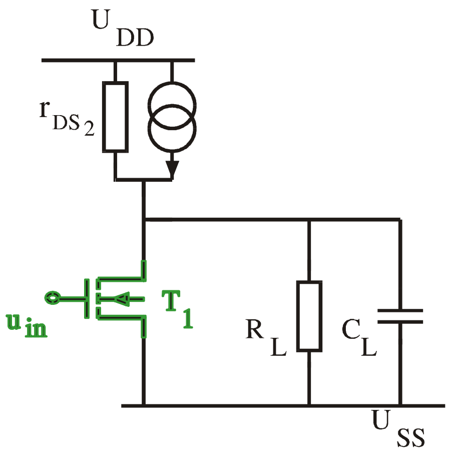


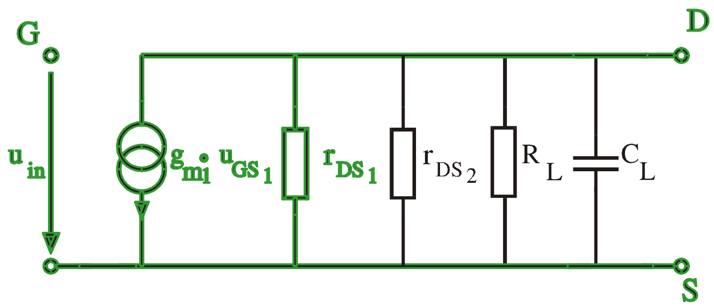
Inverter with resistive load r_L
or (active) transistor load

$$\left(r_{out} = r_{DS1} \| r_L\right)$$

$$A_V = -g_m \cdot r_{out}$$

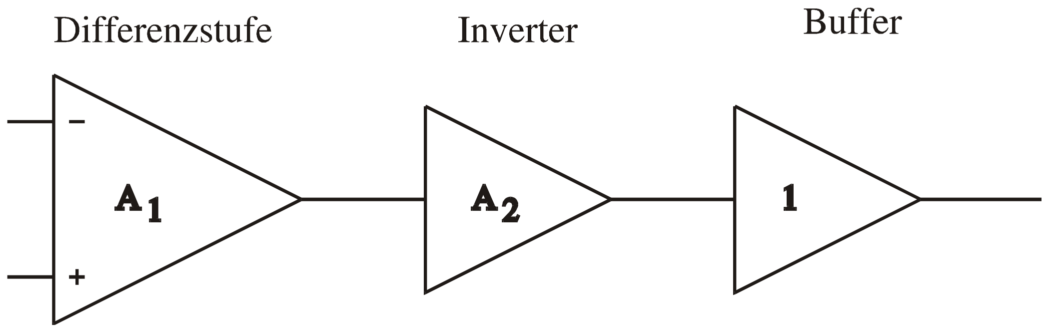
Load dependance of amplifier





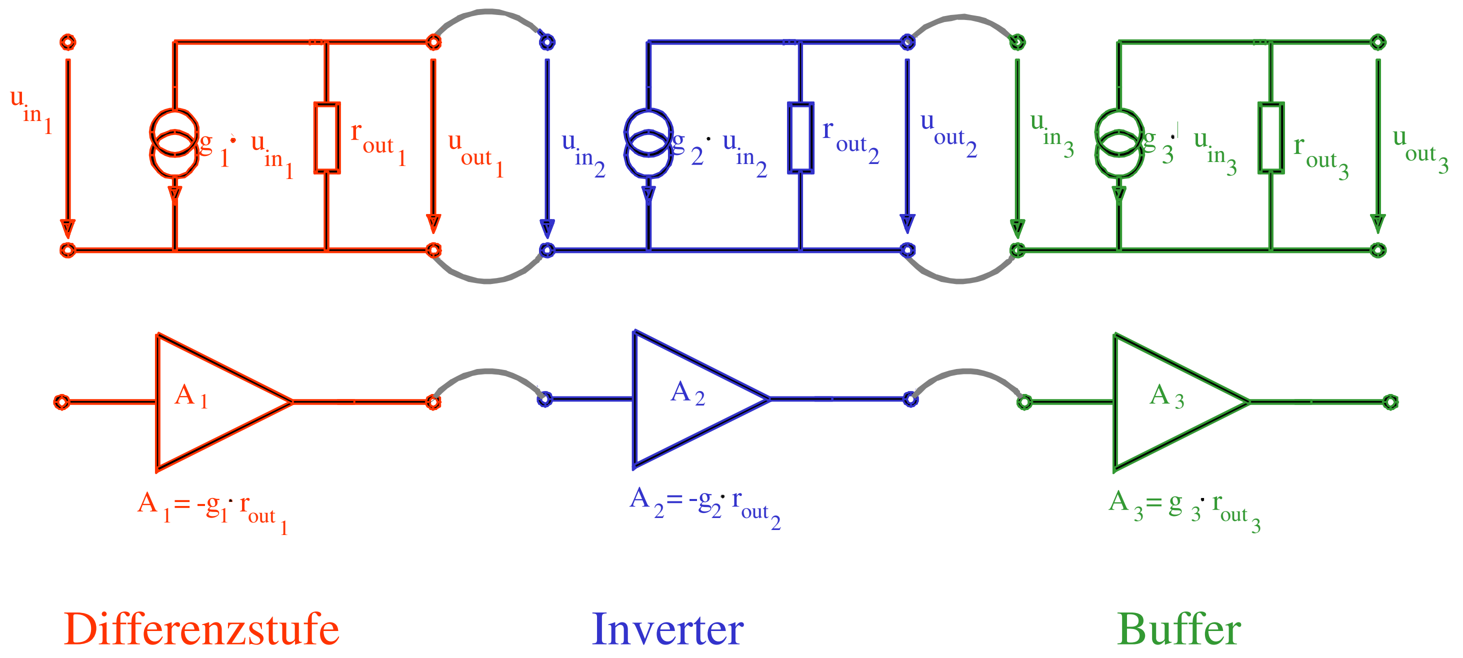
$$A_V = -g_{m1} \cdot \left(r_{DS1} \| r_{DS2} \| R_L \right) \approx -g_{m1} \cdot R_L$$

Corrective by Buffer



$$A_V = A_{V1} \cdot A_{V2} \cdot 1$$

Complete setup of an amplifier



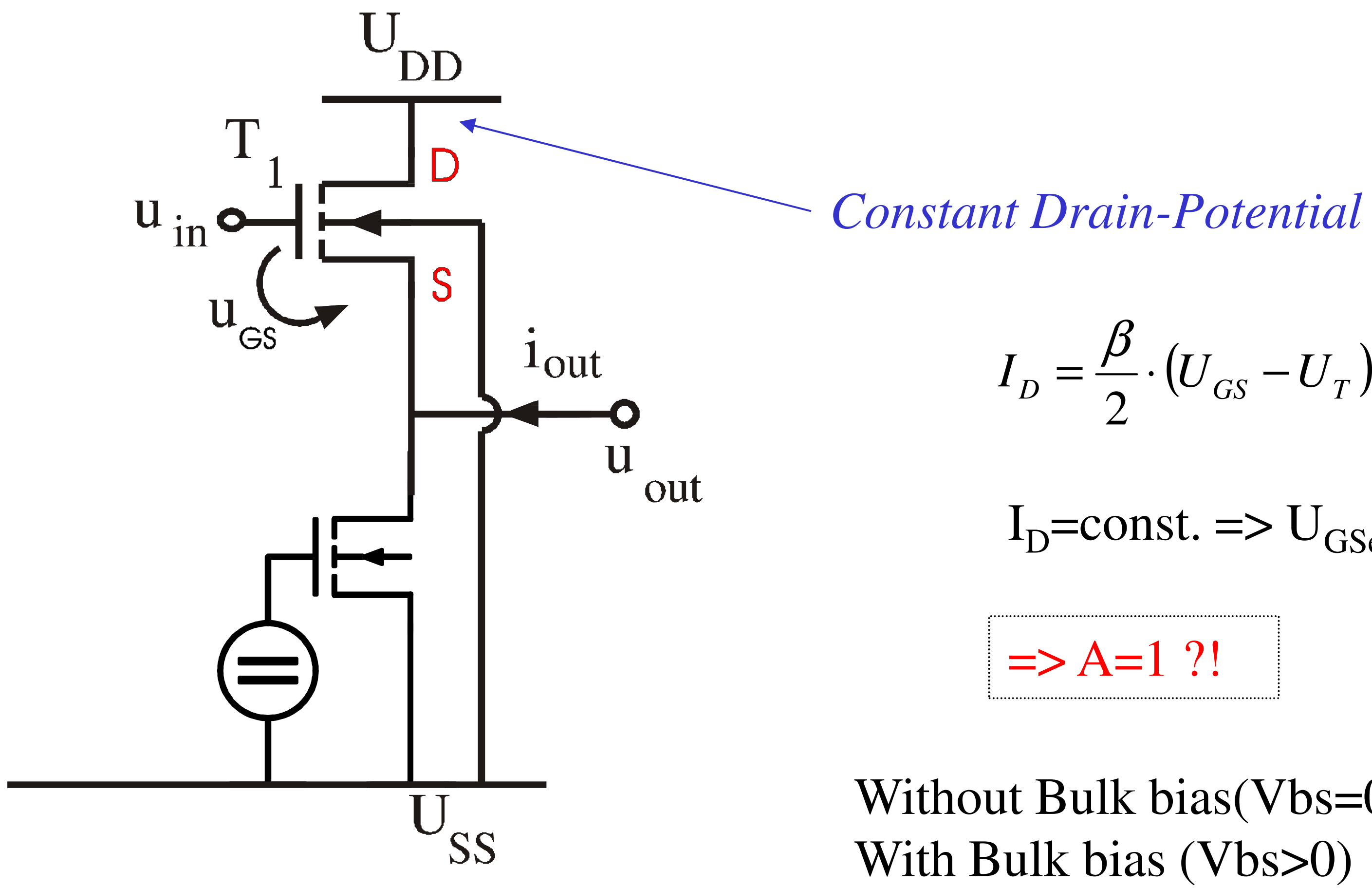
If $r_{in2} >> r_{out1} \Rightarrow$ second stage will not alter the gain of the first stage

If $r_{in3} >> r_{out2} \Rightarrow$ third stage will not alter the gain of the second stage

$$A_V = A_{V1} \cdot A_{V2} \cdot A_{V3}$$
$$= g_1 \cdot r_{out1} \cdot g_2 \cdot r_{out2} \cdot g_3 \cdot r_{out3}$$

Source follower as Buffer

A Common Drain Circuit is used



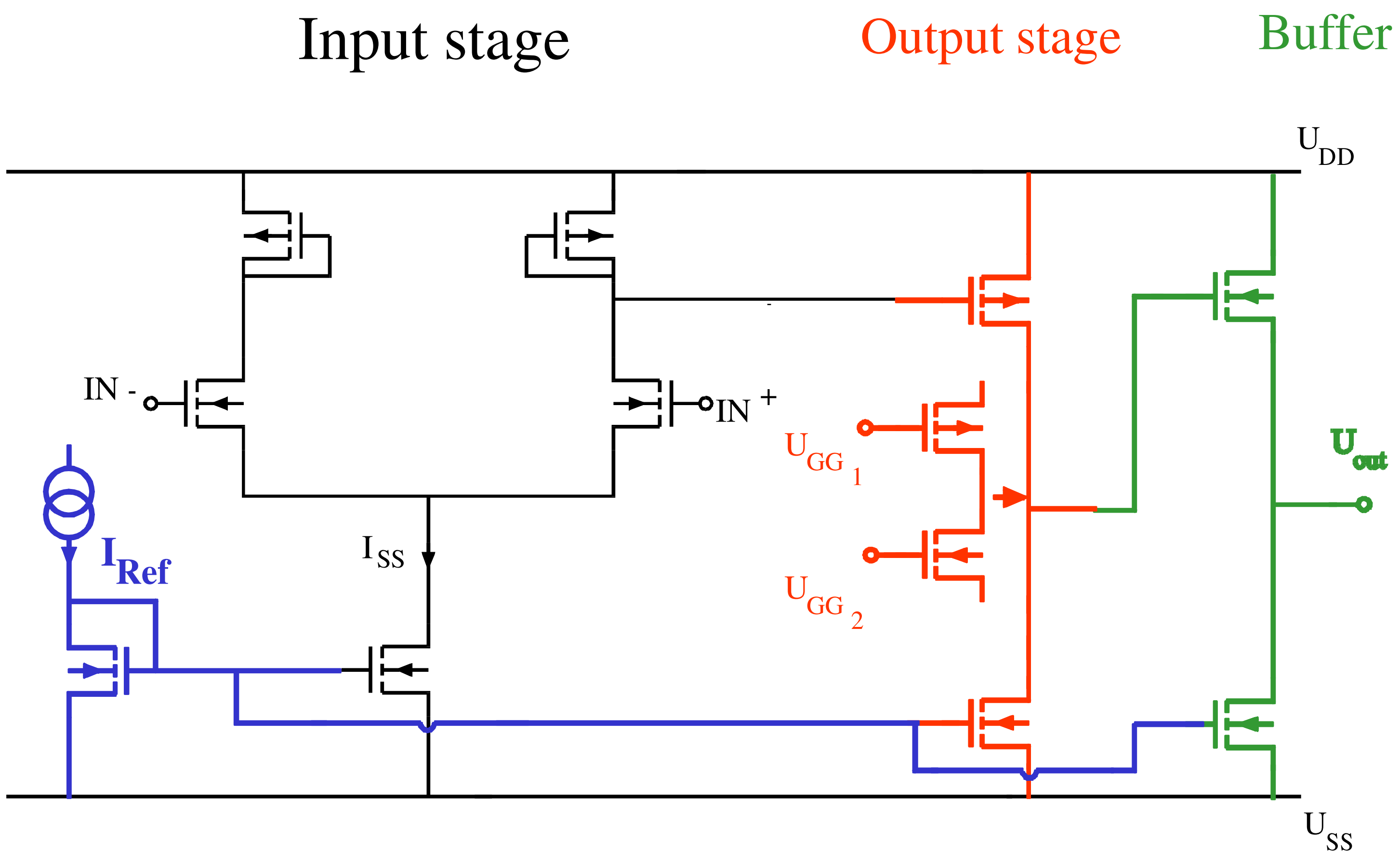
$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_T)^2$$

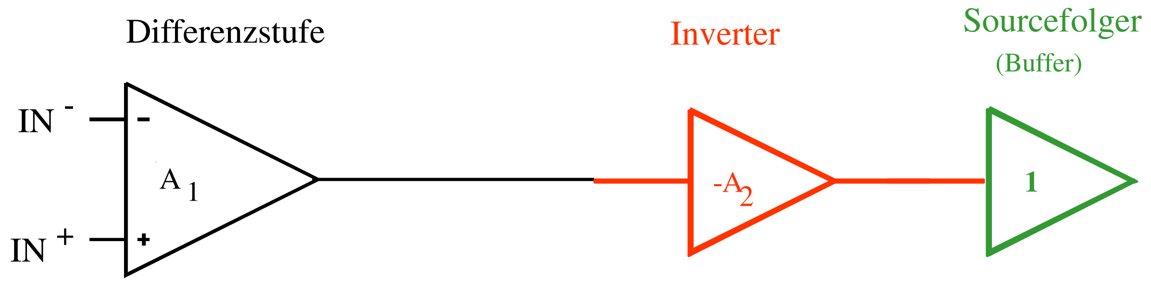
I_D=const. => U_{GSeff}=const.

=> A=1 ?!

Without Bulk bias(Vbs=0)	A≈1
With Bulk bias (Vbs>0)	A<1
With load	A<1

Multi-Stage amplifier





Most important parameters of a current source:

Output resistance r_{out},

Cutoff voltage,

Absolute value (accuracy) I_0

Task:

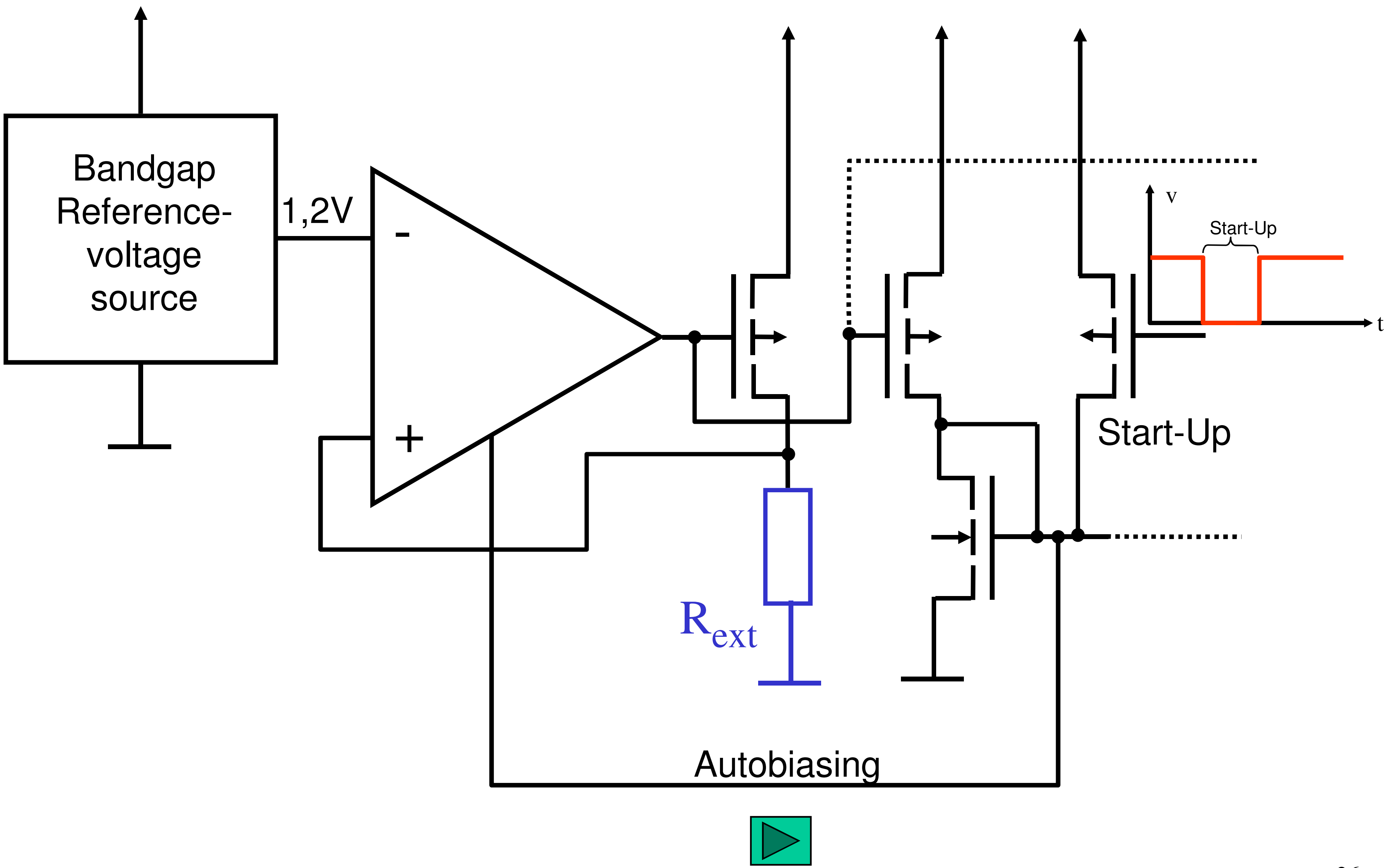
How to generate an exact reference current ?

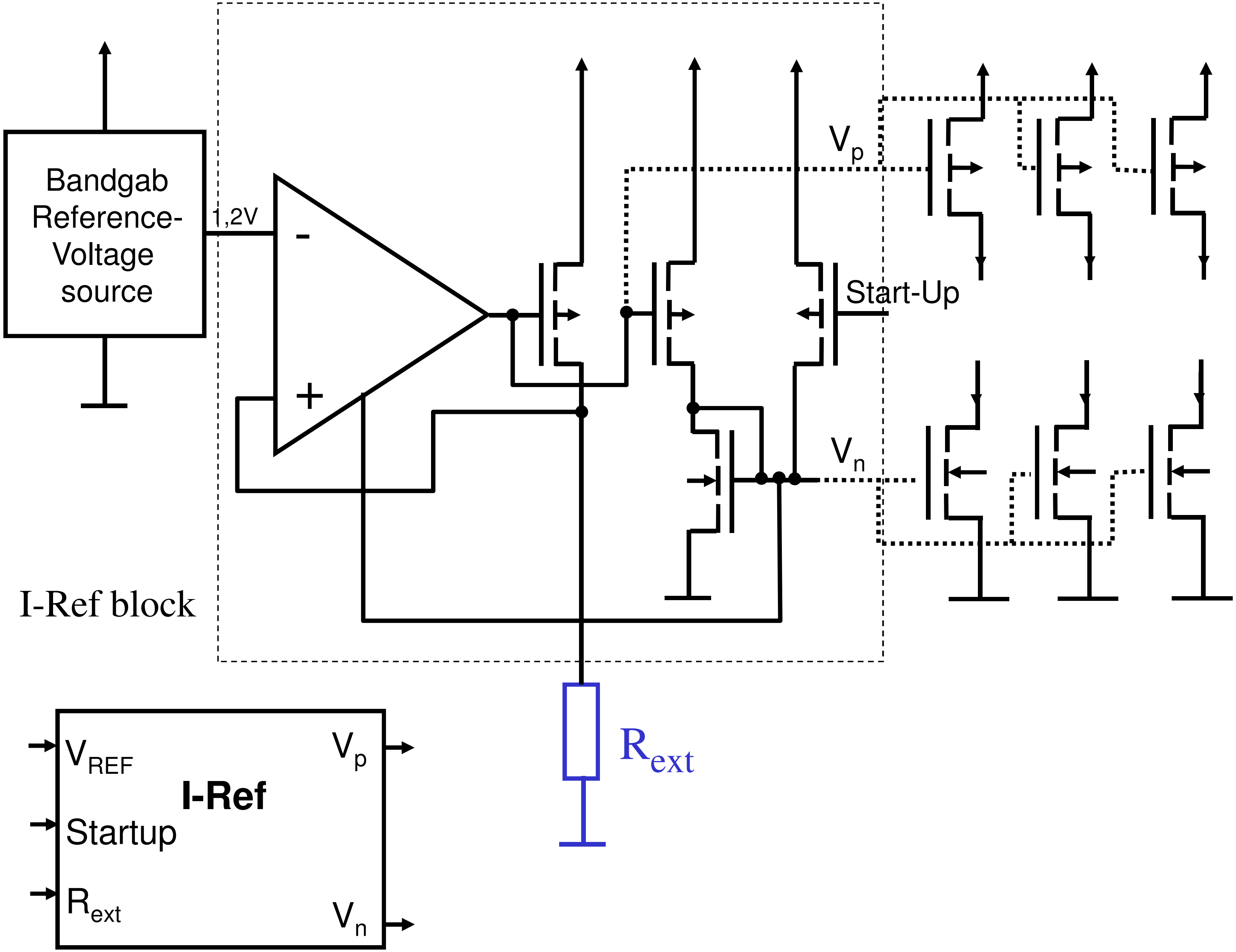
Exact reference voltage in IC: Bandgap circuit $V_{ref} = 1{,}2$ V

Iref = Vref / R, but no exact integrated resistance available

Solution: Usage of an external resistance (exact, TC=0)

Circuit to generate an exact reference current




Bandgab Reference-Voltage source
1,2V
-
+
V p
Start-Up
V n
I-Ref block
R ext
V REF
Startup
R ext
I-Ref
V p
V n