Electronics for Physicists

Analog Electronics

Chapter 7; Lecture 13

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06.02.2024

KIT, Winter 2023/24

Karlsruhe Institute of Technology

Institute for Data Processing and Electronics

Chapter 7

Field Effect Transistors

- MOSFET Basics
- Excursion: CMOS Technology
- CMOS Circuits

Overview

1. Basics
2. Circuits with R, C, L with Alternating Current
3. Diodes
4. Operational Amplifiers
5. Transistors - Basics
6. 2-Transistor Circuits
7. **Field Effect Transistors**
8. Additional Topics
   - Filters
   - Voltage Regulators
   - Noise

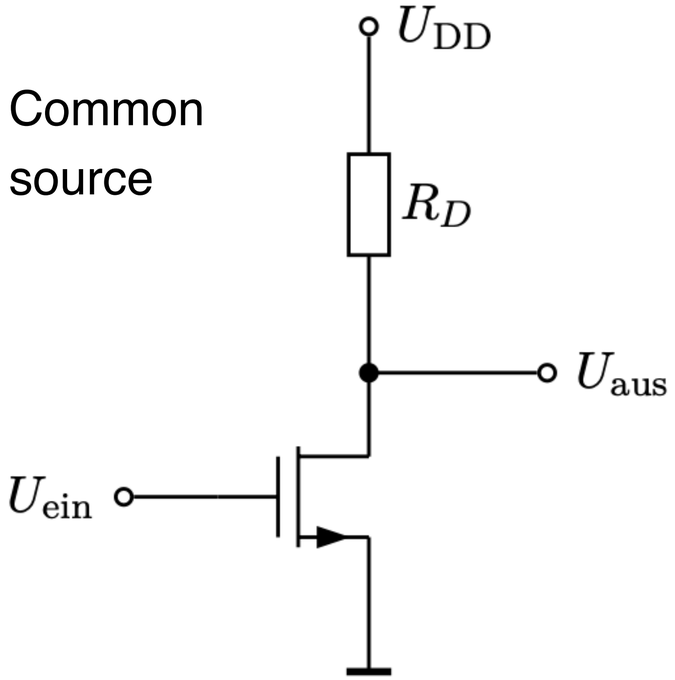
CMOS Circuits - Cont'd

In: Chapter 7: Field Effect Transistors

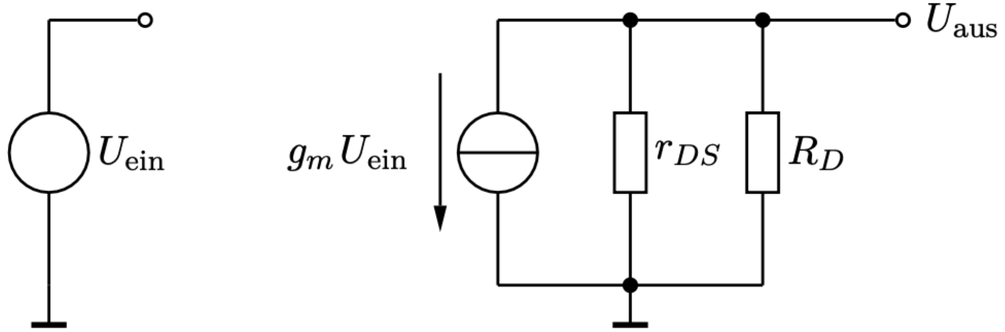
Common Source Amplifier

The Equivalent to the Common Emitter

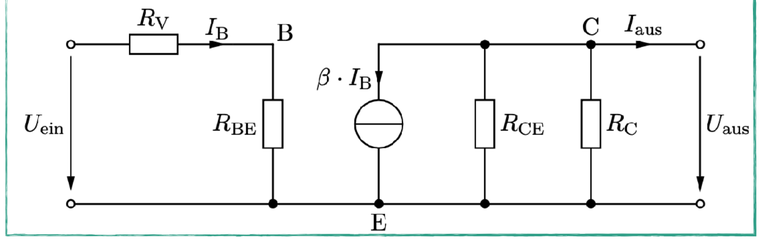
Common source



- Small signal replacement circuit:



Reminder: BJT common emitter



Amplification:

$$V_U = \frac{dU_{aus}}{dU_{ein}} = -\frac{(r_{DS} \parallel R_D)\, g_m\, dU_{ein}}{dU_{ein}} = -(r_{DS} \parallel R_D)\, g_m \approx -g_m R_D$$

($R_D \ll r_{DS}$)

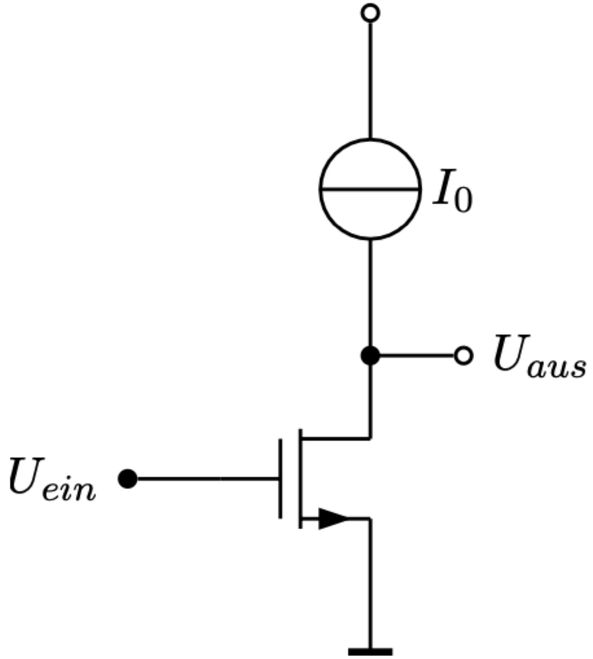
Impedances:

$$R_{ein} = \frac{dU_{ein}}{dI_{ein}} \approx \infty \qquad R_{aus} = \frac{dU_{aus}}{dI_{aus}} = R_D \parallel r_{DS} \approx R_D$$

Common Source Amplifier

Idealized Extension

- Replacing R_D with a current source:



Amplification depends R_D: Large internal resistance = large amplification

Technical aspect: large resistors need lots of space in CMOS technology

Amplification here: $V_U = -g_m\,(r_{DS} \parallel R_i) \approx -g_m\,r_{DS} = -\dfrac{g_m}{g_{DS}}$ ($R_i >> r_{DS}$)

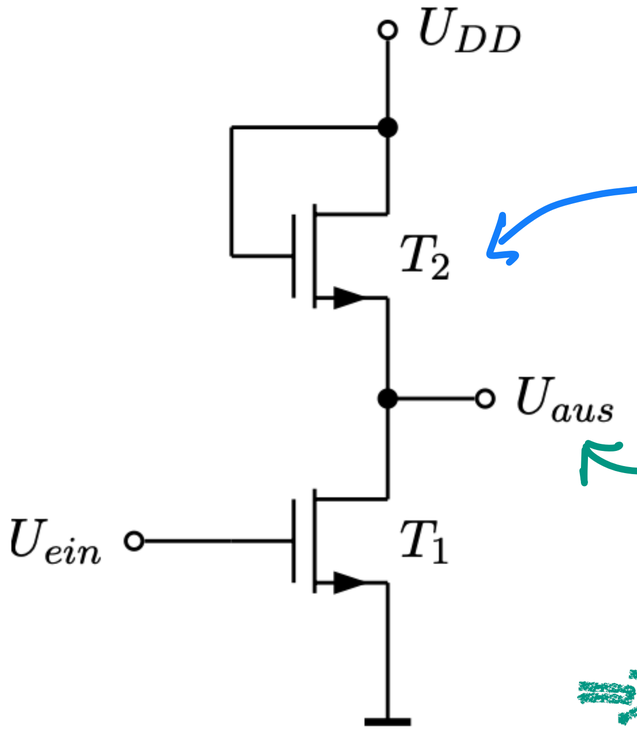
Numerical example:

I_{DS} = 100µA; $\lambda \approx 0.1\ V^{-1}$ => $g_{DS} \approx \lambda\, I_{DS}$ = 10 µS

Für $g_m \approx 100$ µS : $V_U \approx 10$

Common Source Amplifier

Concrete Implementation: FET Diode as Current Source



- In this configuration:

$r_{DS,2} = \frac{1}{g_{m,2}}$ (see S. 17)

$\Rightarrow$ amplification!

$V_u = -g_{m,1} r_{DS,2} = -\frac{g_{m,1}}{g_{m,2}}$

$\Rightarrow V_u = -\sqrt{\frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2}}$

$\Rightarrow T_1$ geometrically very large. High amplification impossible!

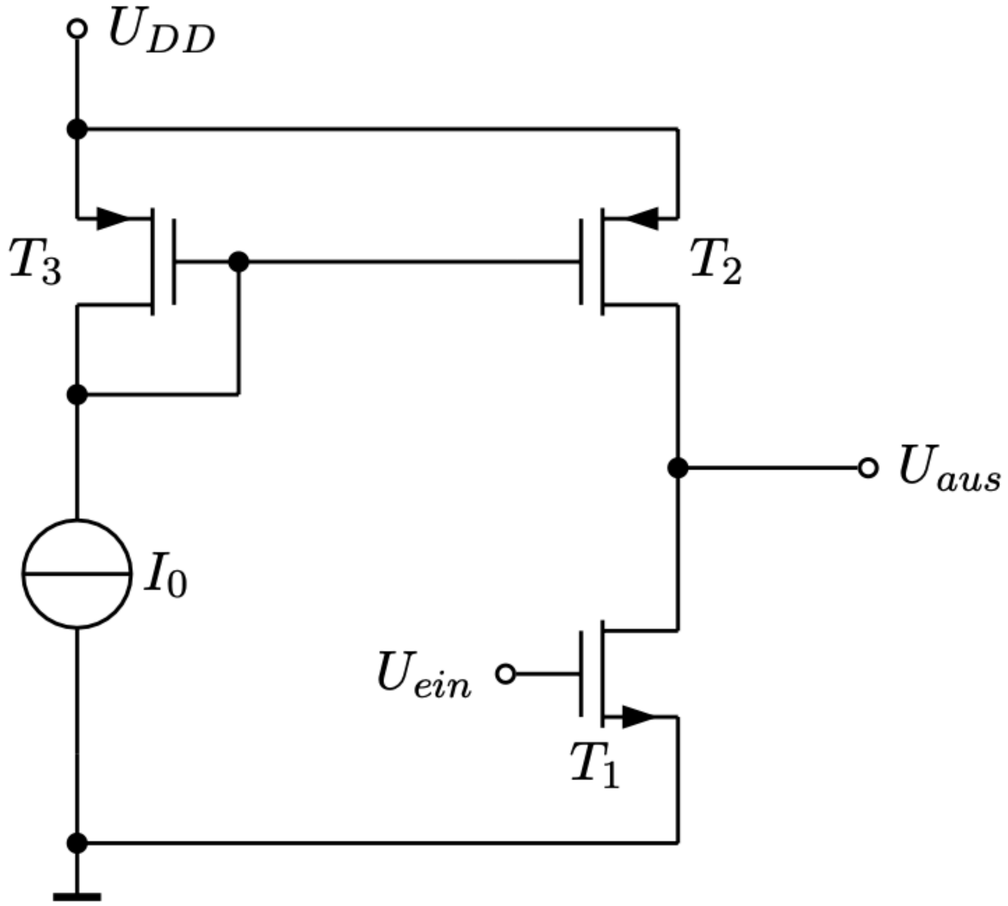
In the saturation region:

$g_m = \sqrt{2 \beta I_{DS}}$

$\beta = \mu C_{ox} \frac{W}{L}$

Common Source Amplifier

More “Bang”: Current Mirror as Current Source



In contrast to FET diode: Feedback and current into amplifier separated, with that:
Differential source-drain resistance not determined by amplification, but by R_{DS}.

Amplification:

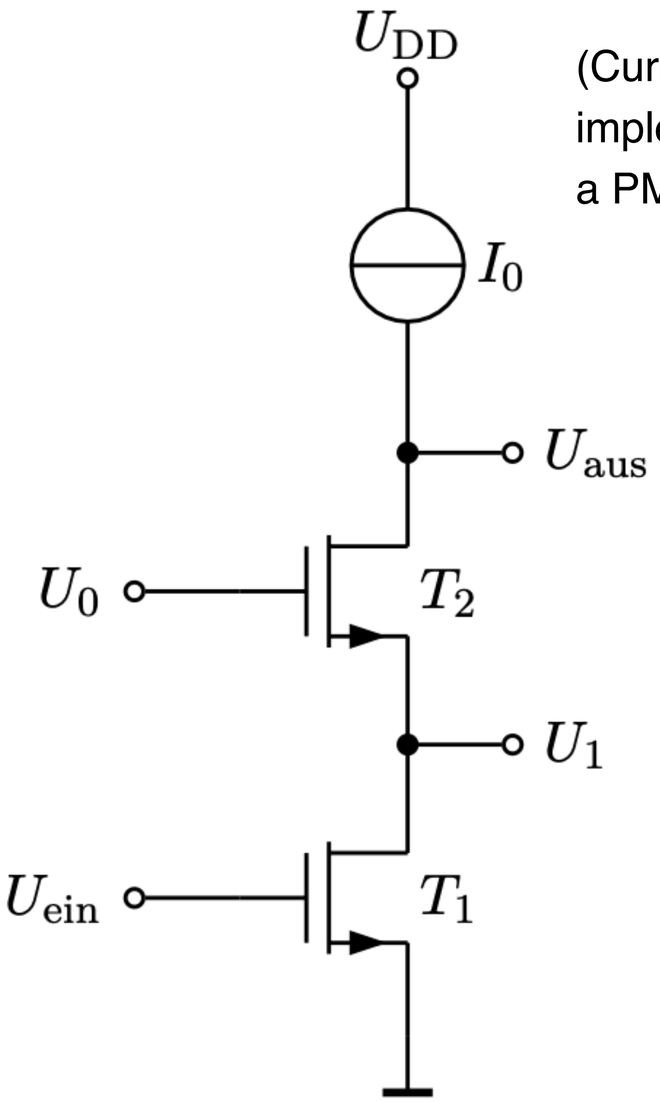
$$V_U = -\, g_{m_1} \left(r_{DS_1} \parallel r_{DS_2} \right)$$ here: $r_{DS2} >> 1/g_{m2}$

Accurate for small currents I_{DS}, since $r_{DS} = 1/g_{DS}$; $g_{DS} \approx \lambda\, I_{DS}$

Numerical example:
$g_m \approx 100\ \mu S$; $I_{DS} \sim 10\ \mu A$
mit $\lambda \approx 0.1\ V^{-1}$ => $g_{DS} \approx \lambda\, I_{DS} = 1\ \mu S$ => $r_{DS} = 1\ M\Omega$
=> $V_U = -\,50$

Cascode

The Path to larger Amplification



(Current source I_0 in concrete implementations for example a PMOS current mirror)

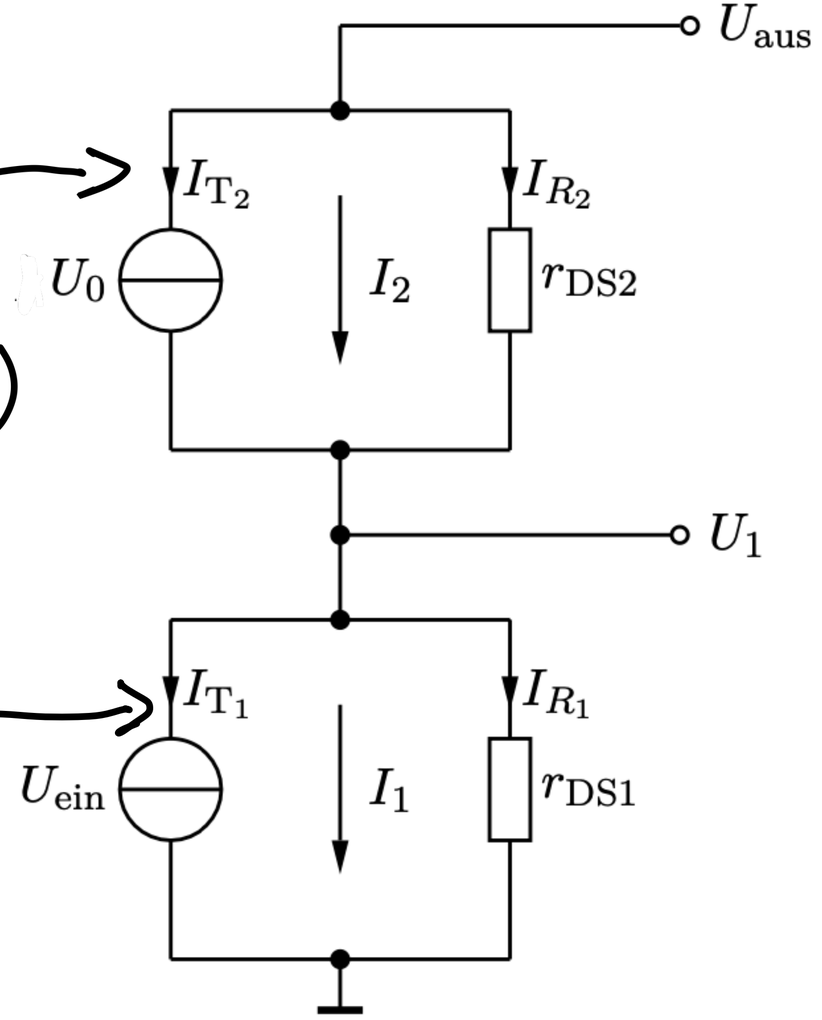
with:

$$g_m = \frac{dI_{DS}}{dU_{GS}}$$

$I_{T2} = g_{m2}(U_0 - U_1)$

$I_{T1} = g_{m1} U_{ein}$

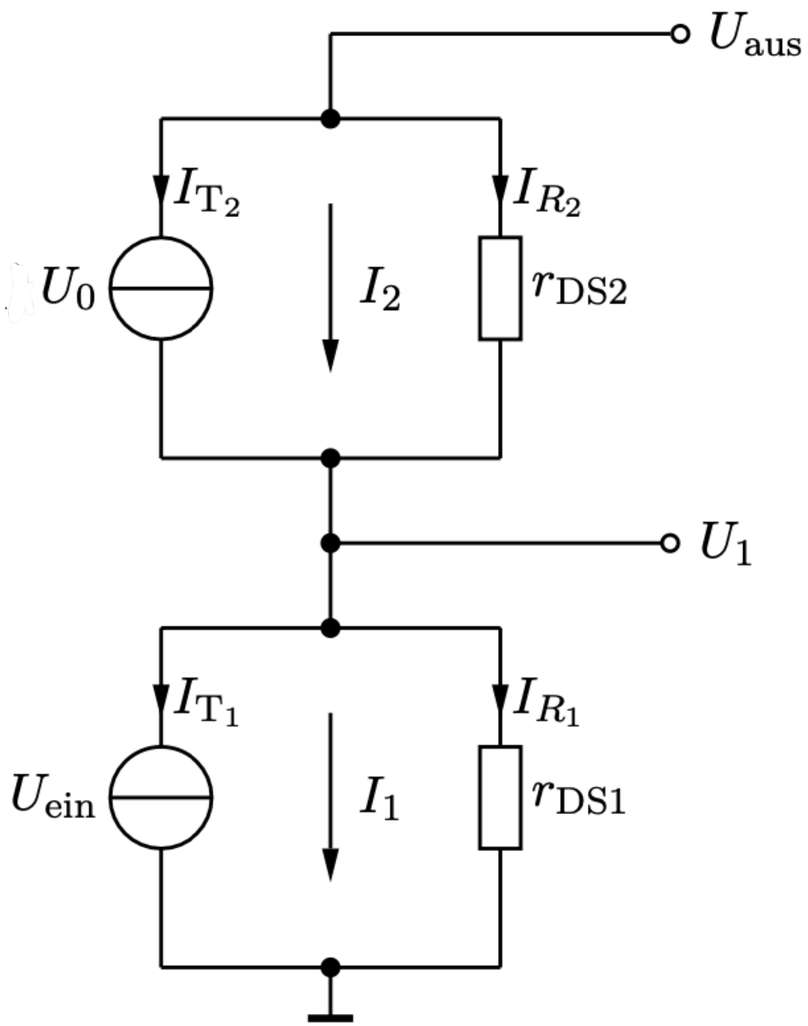
Small signal replacement circuit



Cascode

The Path to larger Amplification

- How it works:



Current source I_0 (not shown in small signal replacement circuit) defines the current in the circuit. With that:

$$dI_1 = g_{m1}\, dU_{ein} + \frac{dU_1}{r_{DS1}} = 0$$

$$\Rightarrow dU_1 = -g_{m1}\, dU_{ein} \cdot r_{DS1}$$

$$dI_2 = g_{m2}(dU_0 - dU_1) + \frac{dU_{aus} - dU_1}{r_{DS2}} = 0$$

($dU_0 = 0$ (ext. voltage))

$$\Rightarrow dU_{aus} = dU_1 (g_{m2} r_{DS2} + 1)$$

$$\Rightarrow dU_{aus} = -g_{m1}\, dU_{ein} \cdot r_{DS1} \cdot (g_{m2} r_{DS2} + 1)$$

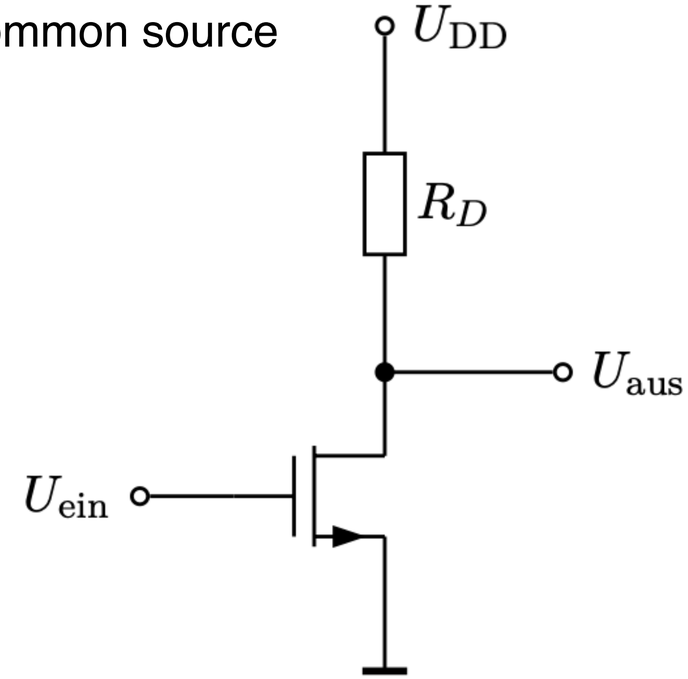
Amplification: $$V_U = \frac{dU_{\text{aus}}}{dU_{\text{ein}}} \approx -g_{\text{m}1}\, r_{\text{DS}1}\, g_{\text{m}2}\, r_{\text{DS}_2}$$

Excursion: CMOS Technology & Transistor Parameters

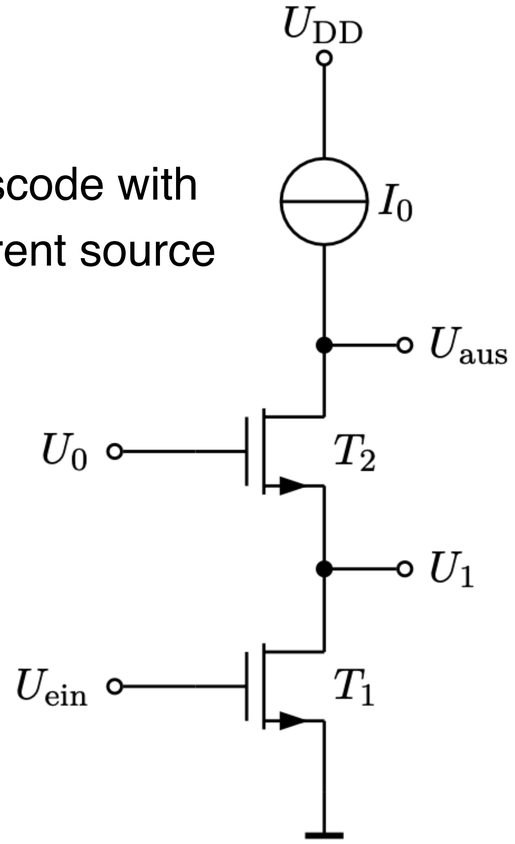
Consequences for analog Design

- Reminder: Simple amplifier:

NMOS common source amplifier



Cascode with current source



Central parameters:

g_m : transconductance

r_{DS} : differential resistance of transistor

Amplification:

$$V_U = \frac{dU_{ein}}{dU_{aus}} \qquad V_U \approx -g_m R_D \qquad V_U \approx -g_{m1} r_{DS1}\, g_{m2} r_{DS2}$$

Excursion: CMOS Technology & Transistor Parameters

Consequences for analog Design

Karlsruhe Institute of Technology

- Relevant parameters for analog behavior (for example amplification): g_m, r_{DS} (= $1/g_{DS}$)

Table 1.3 IBM digital CMOS technology characterization, from [26]

Node	nm	250	180	130	90	65
L	nm	180	130	92	63	43
t_{ox}	nm	6.2	4.45	3.12	2.2	1.8
V_{DD}	V	2.5	1.8	1.5	1.2	1
V_{th}	V	0.44	0.43	0.34	0.36	0.24
g_m (peak)	μS/μm	335	500	720	1060	1400
g_{ds}	μS/μm	22	40	65	100	230
g_m/g_{ds}	–	15.2	12.5	11.1	10.6	6.1
f_T	GHz	35	53	94	140	210

relative to width W

$= g_m \cdot r_{DS}$ → amplification for cascode etc.

from:
Oliveira, Goes: "Parametric Analog Signal Amplification Applied to Nanoscale CMOS Technologies", Springer, DOI 10.1007/978-1-4614-1671-5

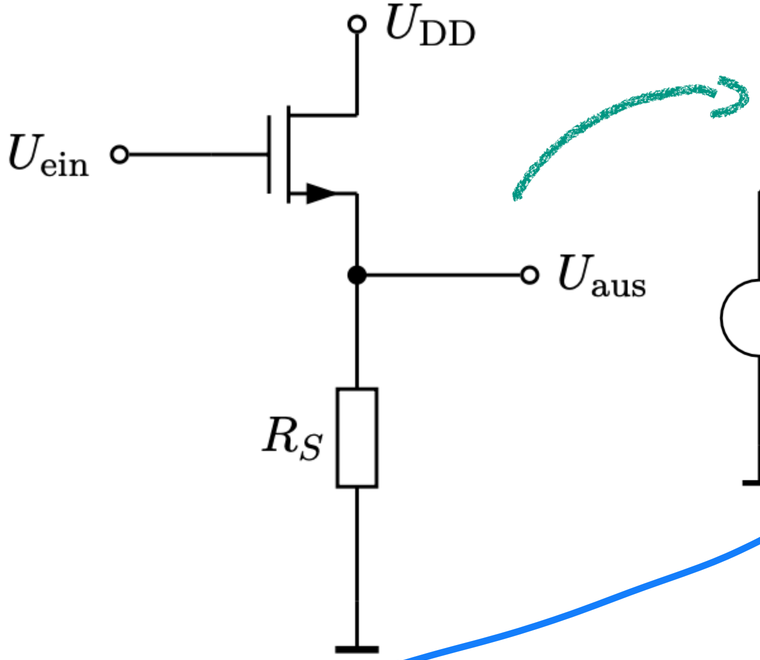
g_m, r_{DS} (and with that the amplification) degrades for smaller transistors.

(Re-)optimization, or even specific redesign of a circuit for a new technology required!

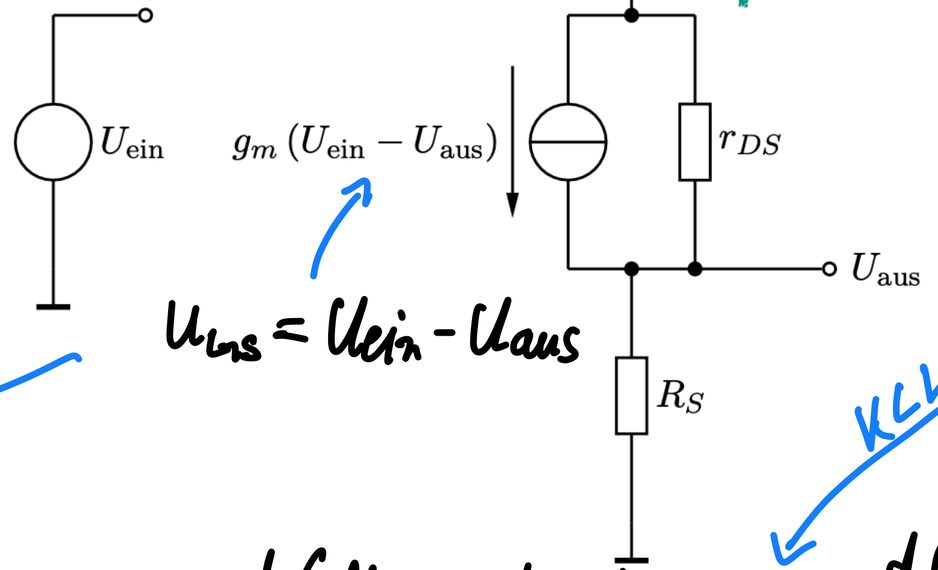
In a short conclusion, technology scaling tends to achieve a higher g_{ds} in saturation which degrades the gain but, at the same time, due to limited voltage range, the g_{ds} in linear region tends to be lower, degrading the ON resistance of the switch.

Source Follower / Common Drain

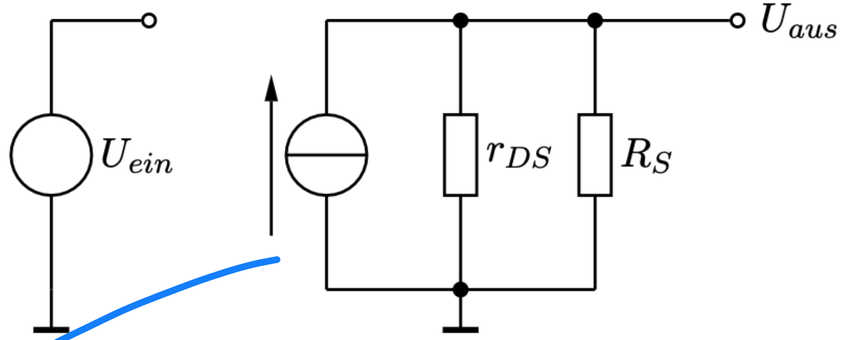
The FET Equivalent of the common Collector



Small signal replacement circuit



simplified:



$U_{GS} = U_{ein} - U_{aus}$

KCL

$I_{DS} = g_m\, dU_{GS} = g_m\, d(U_{ein} - U_{aus}) = \frac{dU_{aus}}{R_S \| r_{DS}} = \frac{dU_{aus}}{R_S'}$ $(R_S' = R_S \| r_{DS})$

$dU_{aus}\,(1 + g_m R_S') = dU_{ein}\, g_m R_S'$

$$V_u = \frac{dU_{aus}}{dU_{ein}} = \frac{g_m R_S'}{1 + g_m R_S'} < 1$$

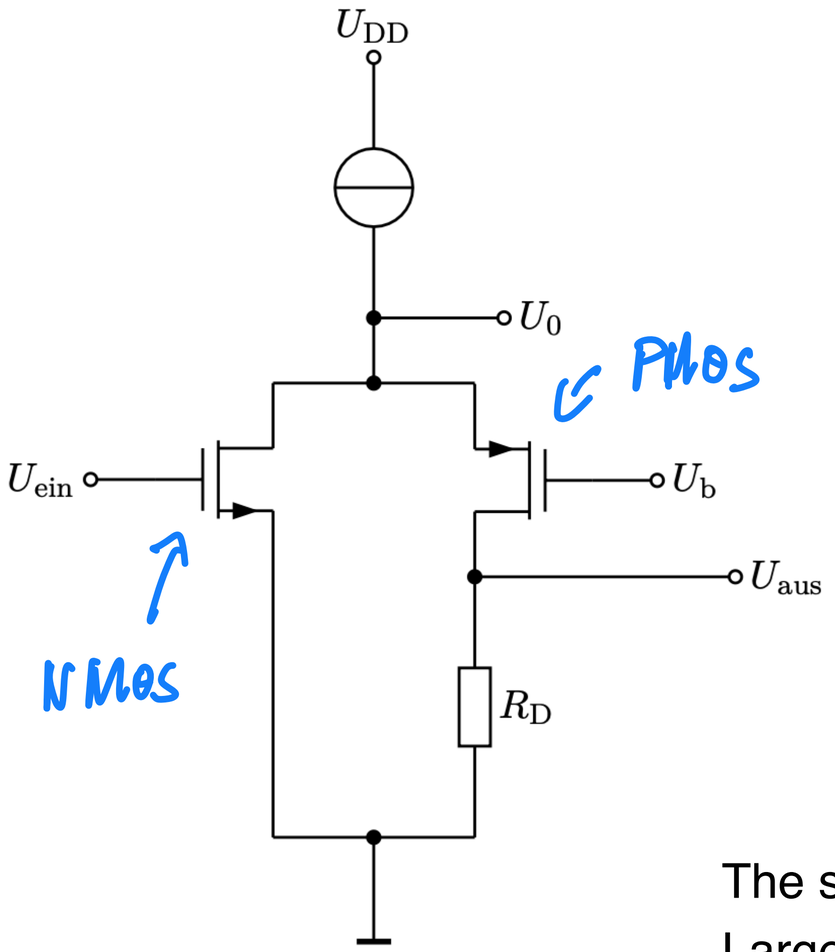
In addition: $R_{ein} \to \infty$

$R_{aus} = \frac{dU_{aus}}{dI_{aus}} = \frac{1}{g_m} \| R_S'$

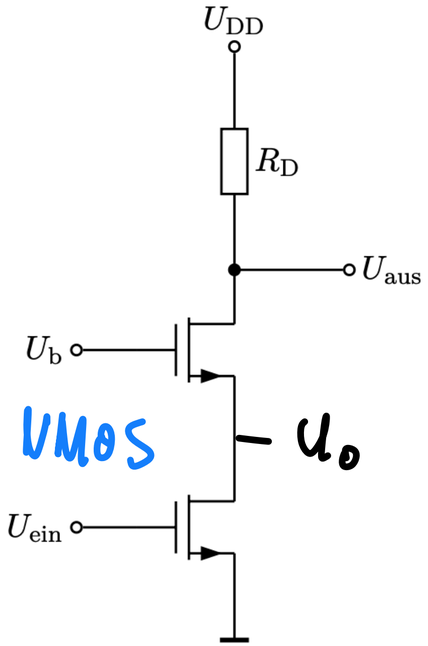
FYI: Folded Cascode

A Variation of the "regular" Cascode

- An alternative implementation of the cascode: Current split across two branches (similar to differential amplifier)



compare to: "regular" cascode

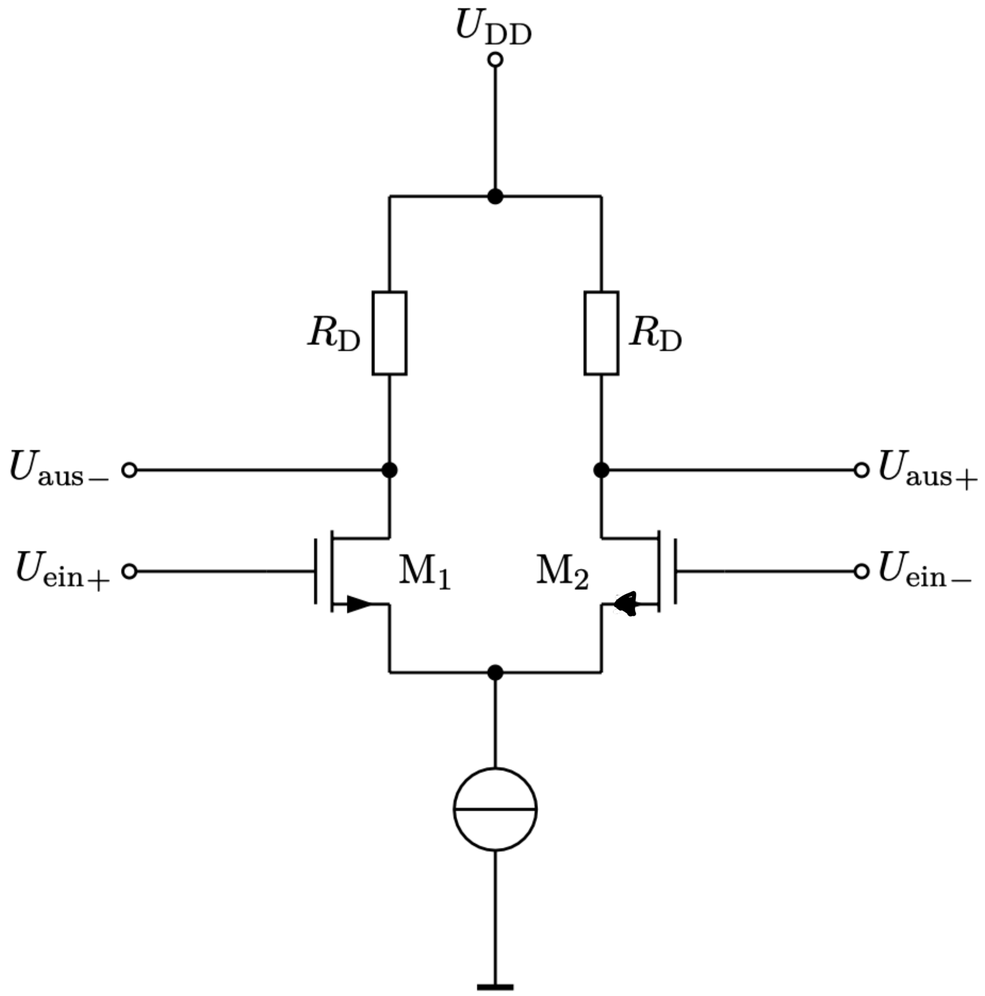


The strength of this circuit:

Larger dynamic range in output voltage!

FYI: Differential Amplifier

CMOS Implementation



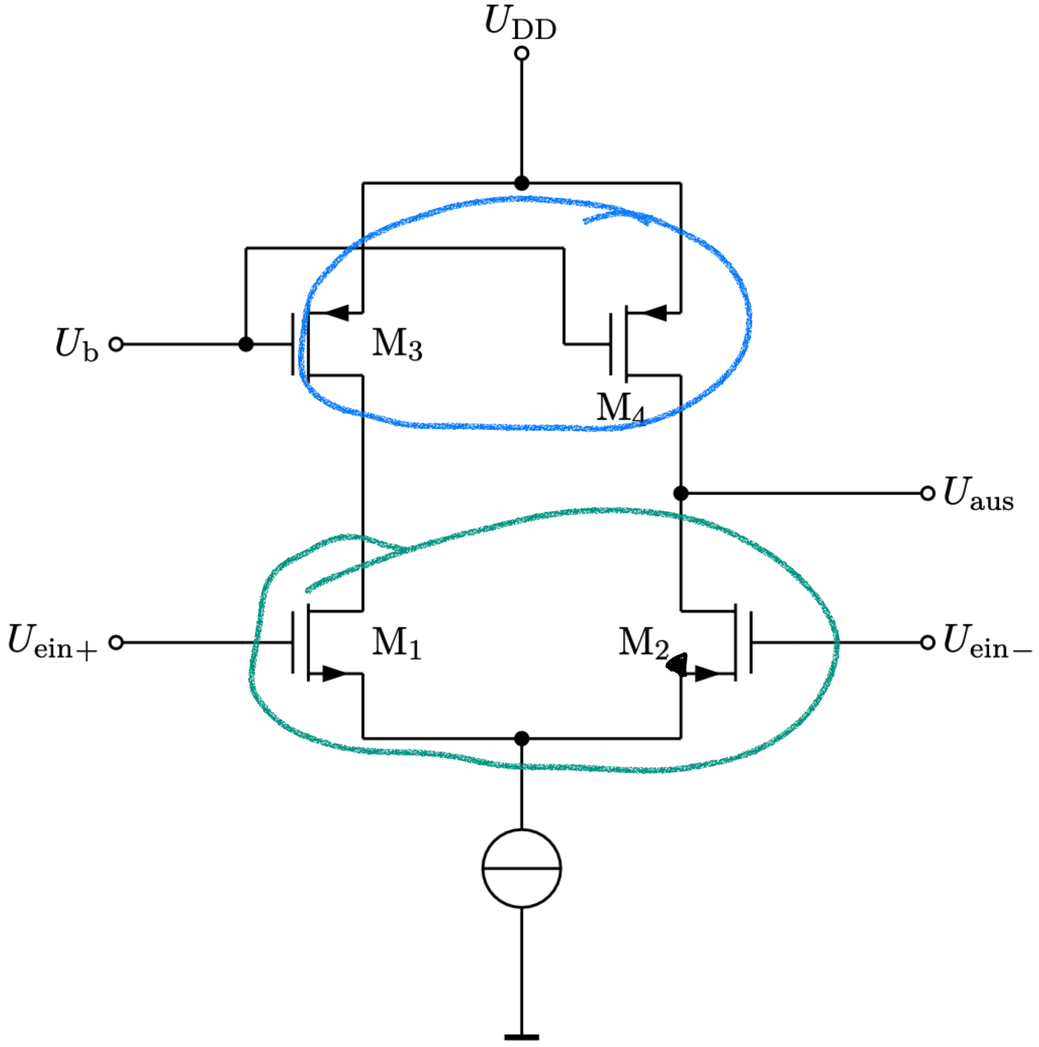
- The basic implementation

$$V_U = \frac{\mathrm{d}U_{\mathrm{aus}}}{\mathrm{d}U_{\mathrm{ein}}} = \frac{\mathrm{d}U_{\mathrm{aus}+} - \mathrm{d}U_{\mathrm{aus}-}}{\mathrm{d}U_{\mathrm{ein}+} - \mathrm{d}U_{\mathrm{ein}-}} = -g_{\mathrm{m}}\, R_D$$

… and a range of further improvements, the same as for the BJT

FYI: Differential Amplifier

CMOS Implementation



- One extension: “active load” instead of ohmic resistors:
  Enables high impedance and consequently high amplification without large voltage drop: Larger dynamic range of the amplifier.

Assumption: opposing transistors identical, resulting in:

$$g_{m1} = g_{m2} \Rightarrow g_{m12}$$

$$r_{DS1} = r_{DS2} \Rightarrow r_{DS12}$$

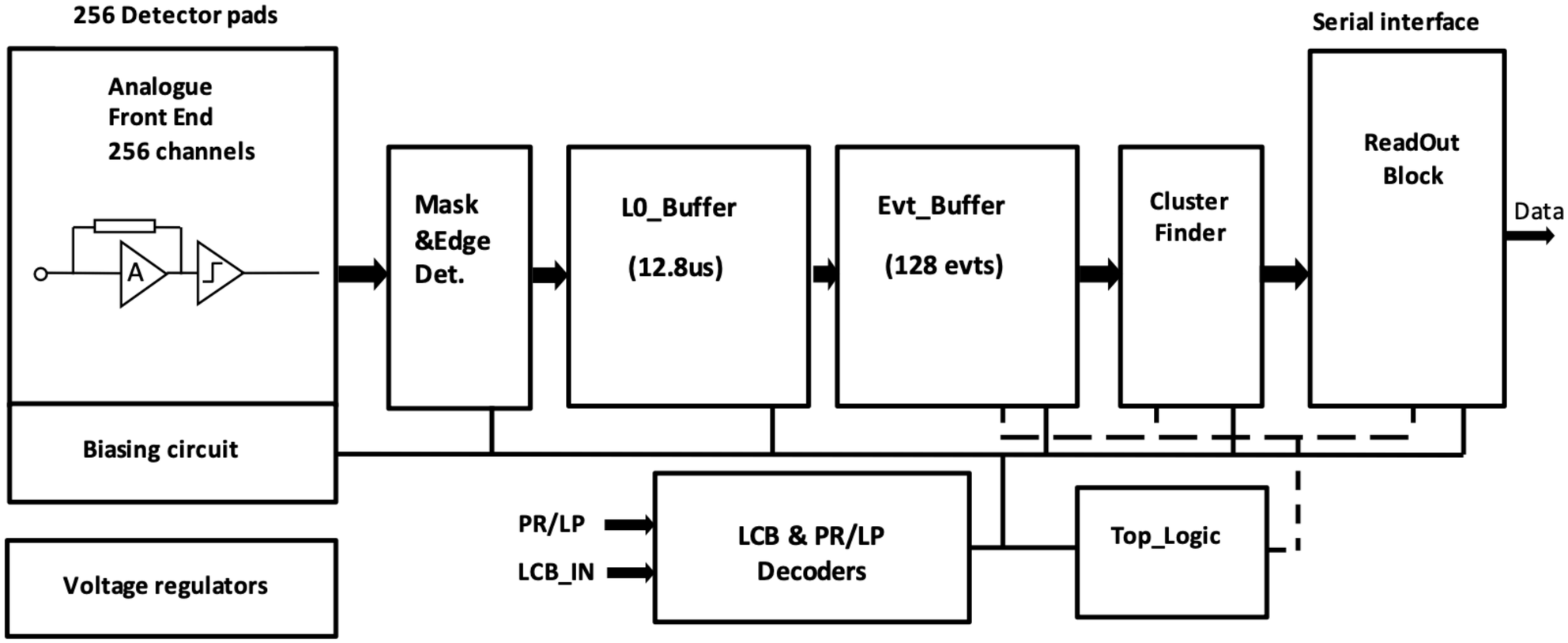
$$r_{DS3} = r_{DS4} \Rightarrow r_{DS34}$$

$$V_u = -g_{m12}\,(r_{DS12} \,/\!/\, r_{DS34})$$

As an Example: A real Circuit

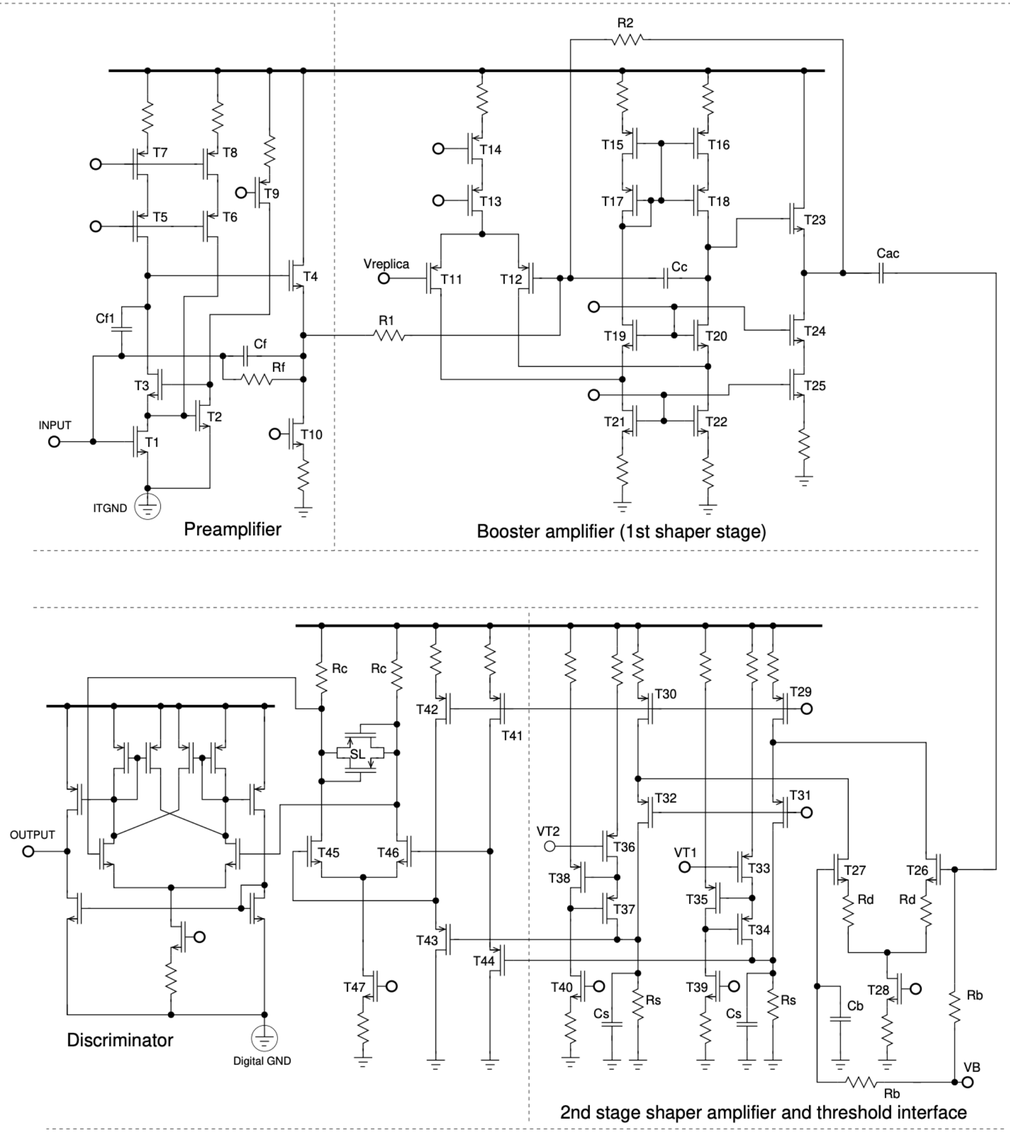
ATLAS Phase II Silicon Strip Detector (ITk Strips): Front-end ASIC ABCStar

- A complex ASIC with analog and digital parts



As an Example: A real Circuit

ATLAS Phase II Silicon Strip Detector (ITk Strips): Front-end ASIC ABCStar



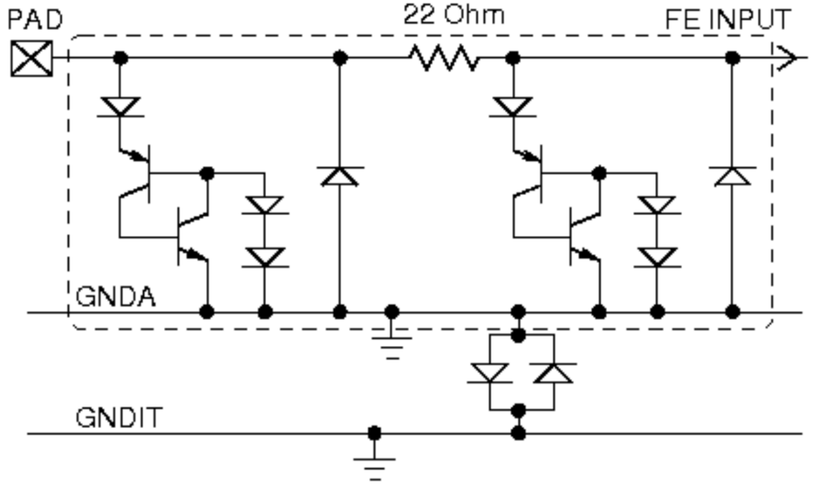
The analog front-end: 256 copies in the chip

Finally: Binary readout (strip hit or not)

But: Thresholds etc. require an analog processing of the signals.

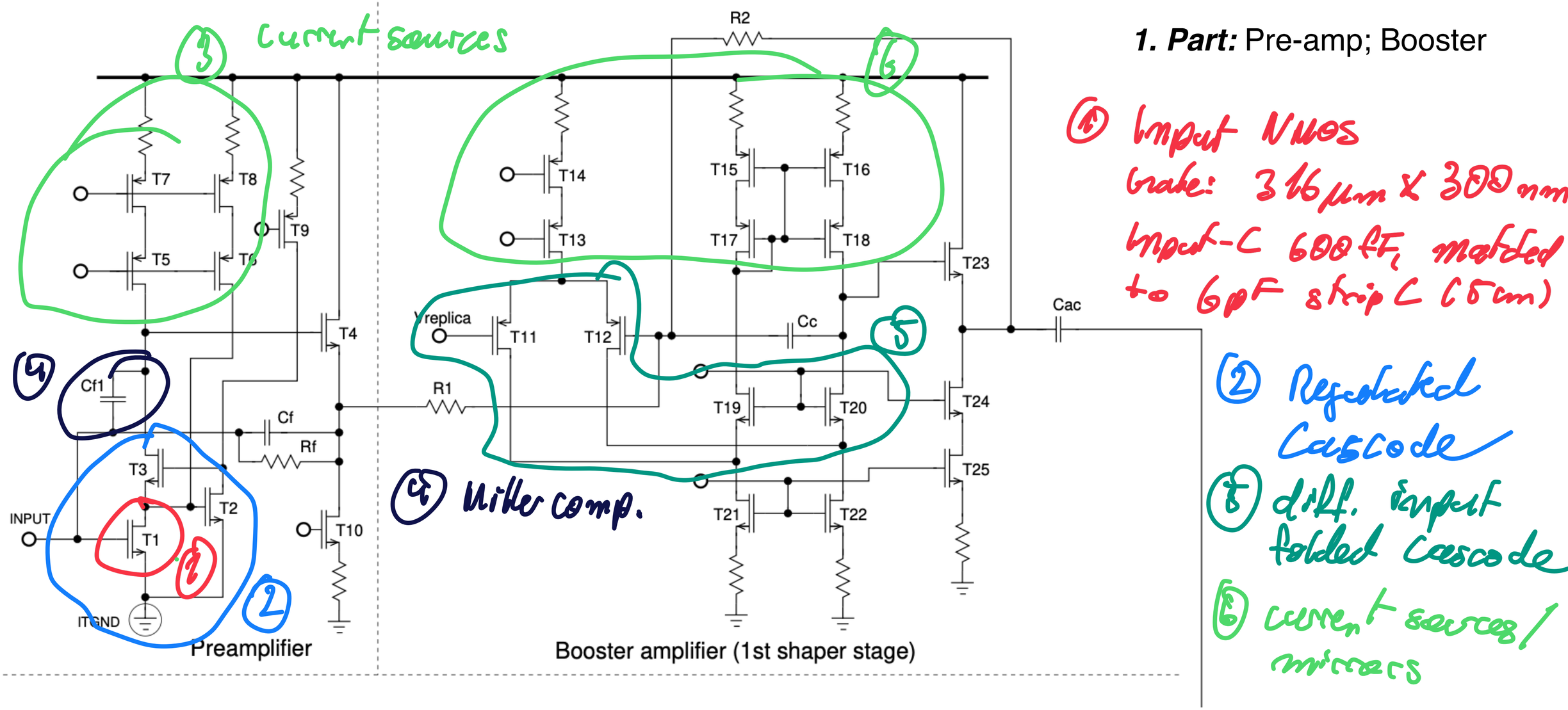
4-step circuit as analog front-end

In addition: protection circuit on input



As an Example: A real Circuit

ATLAS Phase II Silicon Strip Detector (ITk Strips): Front-end ASIC ABCStar



1. Part: Pre-amp; Booster

① Input NMOS
Gate: 316 µm x 300 nm
Input-C 600 fF, matched to 6pF strip C (5cm)

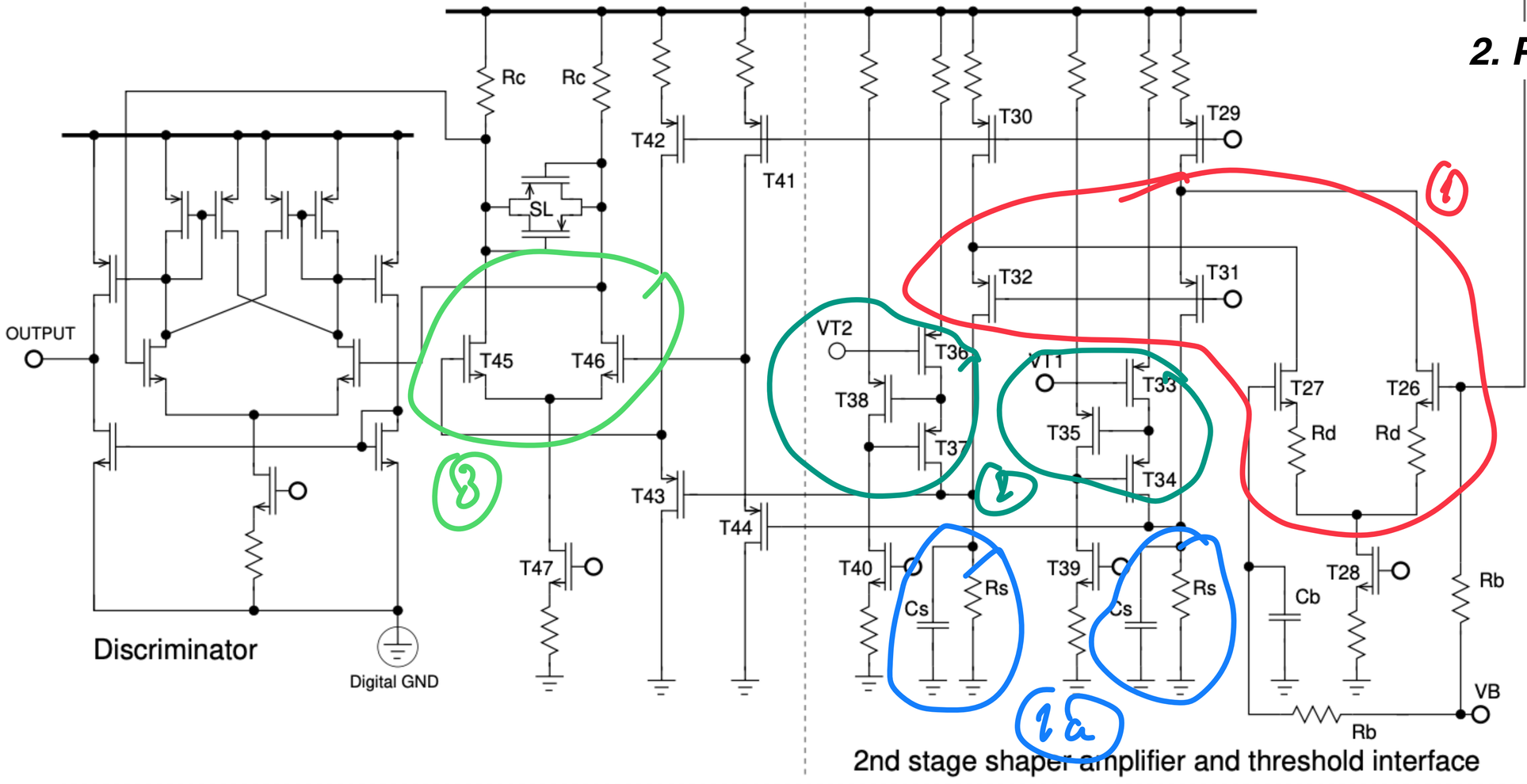
② Regulated Cascode

③ diff. input folded cascode

④ current sources / mirrors

As an Example: A real Circuit

ATLAS Phase II Silicon Strip Detector (ITk Strips): Front-end ASIC ABCStar



2. Part: Shaper, Discriminator

(1) Diff. folded cascode

(1a) integration of signal

(2) high-impedance current sources VT_1, VT_2 input to set threshold, ch-by-ch. corrections

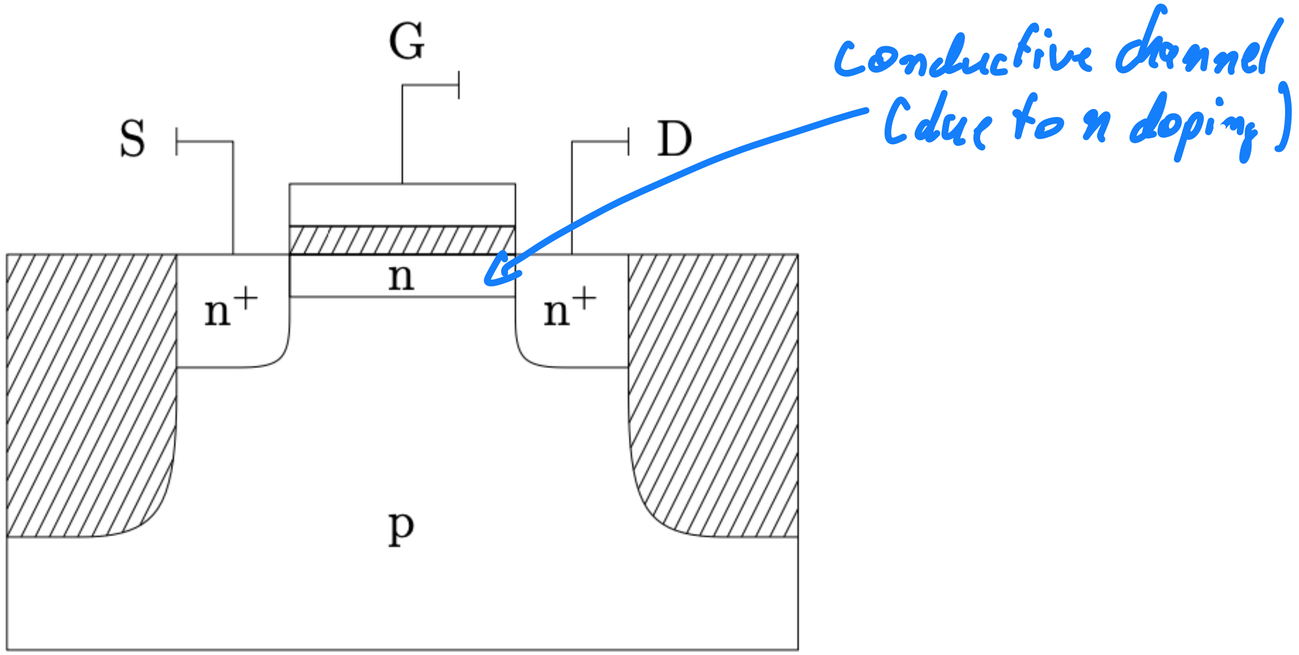
(3) differential amplifier: input to discriminator

Other Transistor Types

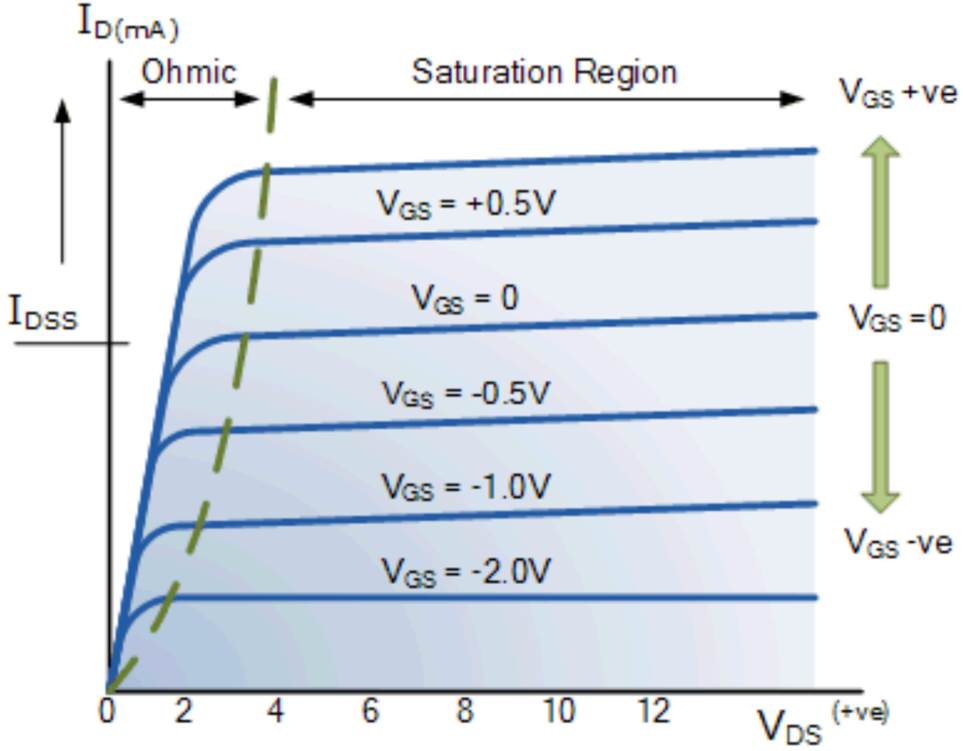
In: Chapter 7: Field Effect Transistors

Depletion-mode MOSFETs

Selbstleitende MOSFETs



- Two types of MOSFETs:
  - Enhancement-mode (Anreicherungs-Modus)
    The most common variant - considered up to now
  - Depletion-mode (Verarmungs-Modus)

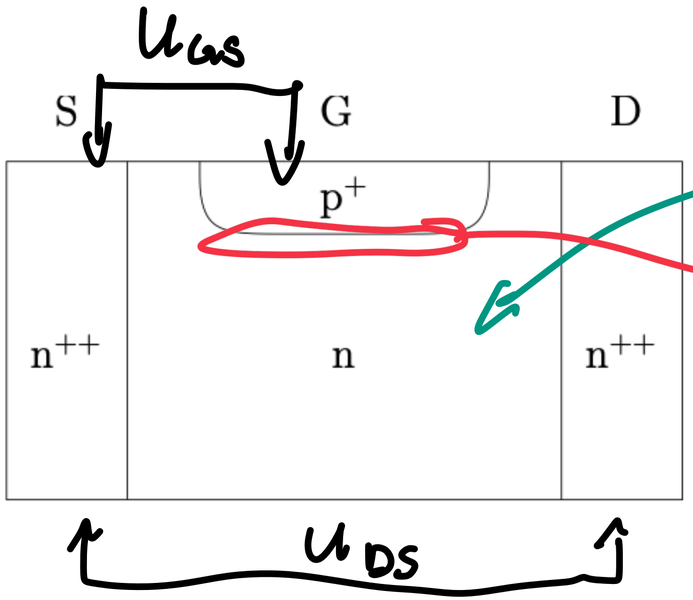


from Electonics Tutorials

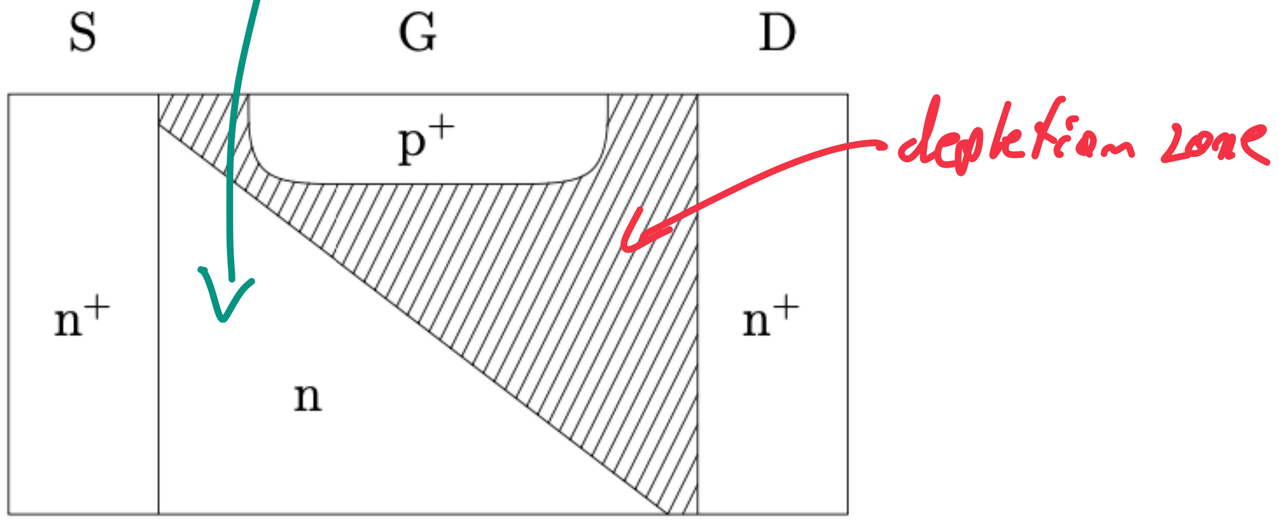
- Conductive for $U_{GS} = 0$: negative threshold voltage
  - Non-conductive only for significantly negative U_{GS}

JFET: Junction FET

Sperrschicht-FET

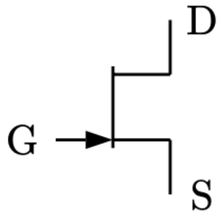


- n-conductive channel between source and drain at $U_{GS} = 0$
- Negative U_{GS} pinches off the channel: Reduction of I_{GS}
- $U_{GS} \leq 0$, $U_{DS} > 0$, results in reverse-bias on pn-junction: (Almost) no current from G to D

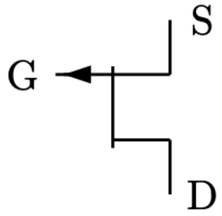


As two types:

n-channel

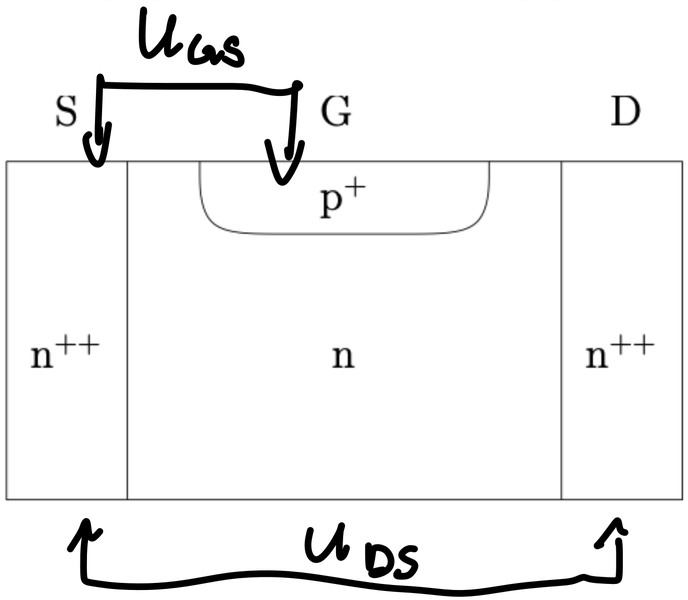


p-channel

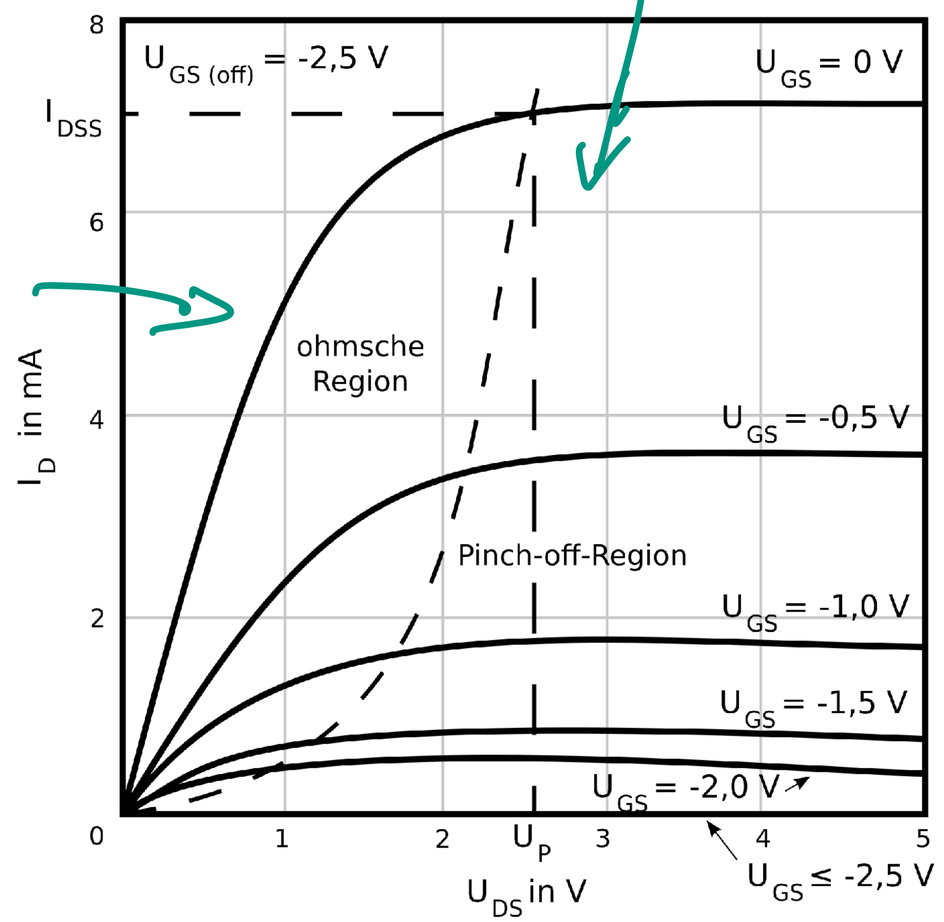


JFET: Junction FET

Sperrschicht-FET



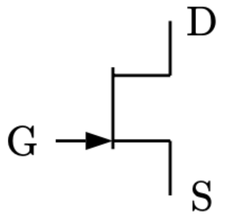
- Typical IV curve:



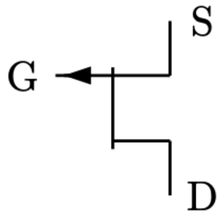
Typisches Ausgangskennlinienfeld eines n-Kanal-JFET

As two types:

n-channel



p-channel



Next Lectures:

- Analog 14 - Chapter 08 - Thursday, February 8, 2024
- Analog 15 - Chapter 08 - Tuesday, February 13, 2024

Time Plan for Next Lectures

A few Changes coming up!

Calender Week	Tuesday	Thursday
45	07.11. **Analog**	09.11. **Digital**
46	14.11. **Analog**	16.11. **Digital**
47	21.11. **Digital**	23.11. **Analog**
48	28.11. **Digital**	30.11. **Digital**
49	05.12. **Digital**	07.12. **Analog**
50	12.12. **Digital**	14.12. **Analog**
51	19.12. **Analog**	21.12. **Digital**
2	09.01. **Analog**	11.01. **Digital**
3	16.01. **Digital**	18.01. **Digital**
4	23.01. **Analog**	25.01. **Digital**
5	30.01. **Analog**	01.02. **Digital**
6	06.02. **Analog**	08.02. **Analog**
7	13.02. **Analog**	15.02. **None**

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KIT, Winter 2023/24

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