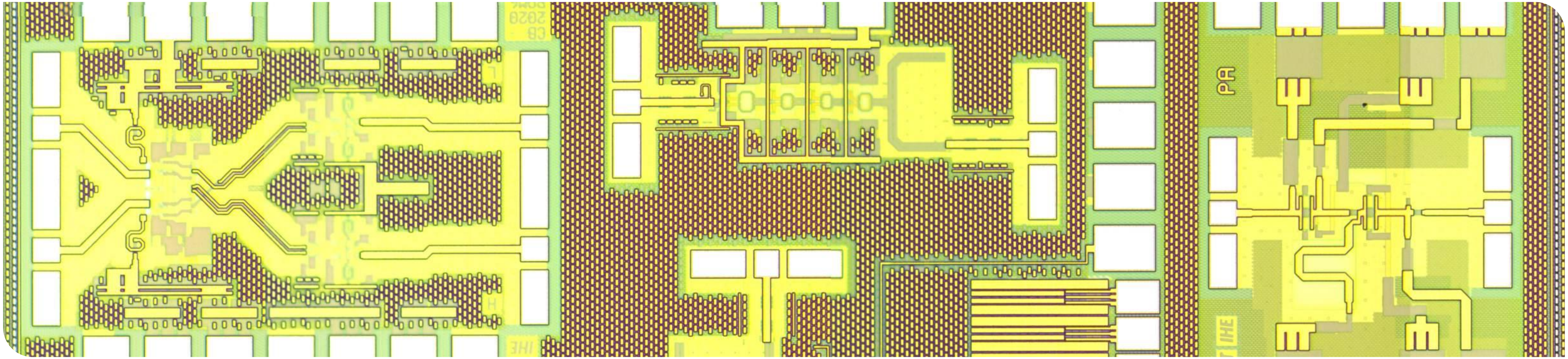
ES Übung 4 – Feldeffekttransistoren

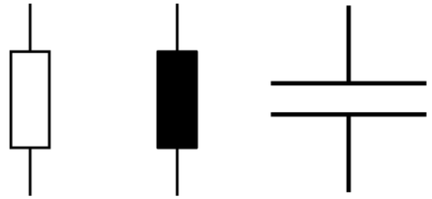
M.Sc. Matthias Möck



Was bisher geschah …

Linear

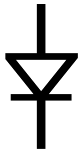
Ü1



$$i(\omega) = \frac{u(\omega)}{Z(\omega)}$$

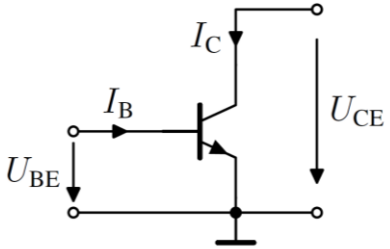
Nichtlinear

Ü2



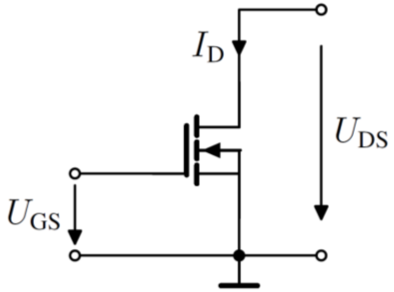
$$I_D = I_S e^{\frac{U_D}{U_T}}$$

Ü3



$$I_C = \beta I_S e^{\frac{U_{BE}}{U_T}} \left(1 + \frac{U_{CE}}{U_A}\right)$$

Ü4

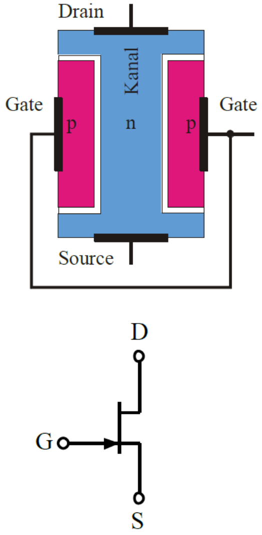


$$I_D = \frac{\beta}{2} (U_{GS} - U_{th})^2 \left(1 + \frac{U_{DS}}{U_A}\right)$$

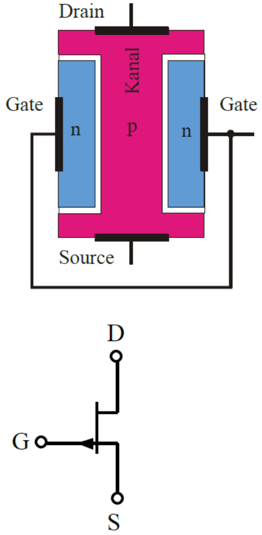
FETs – Übersicht

Sperrschicht-Feldeffekttransistor (JFET)

n-Typ



p-Typ

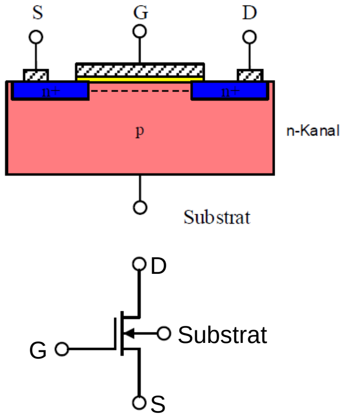


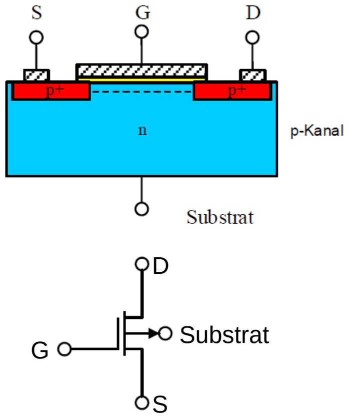
Isolierschicht-Feldeffekttransistor (MOSFET)

n-Typ

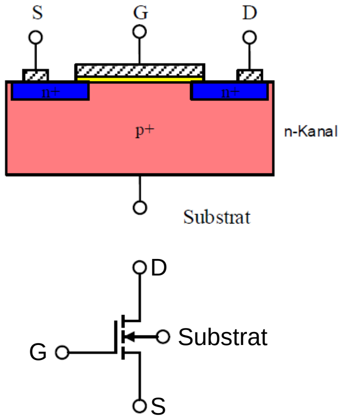
p-Typ

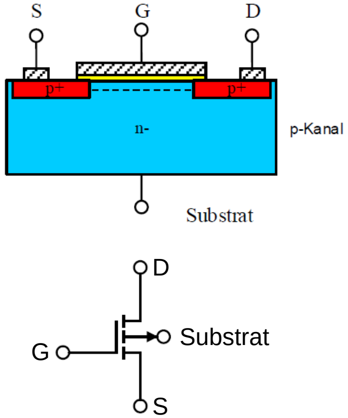
Selbstleitend (Verarmungstyp)





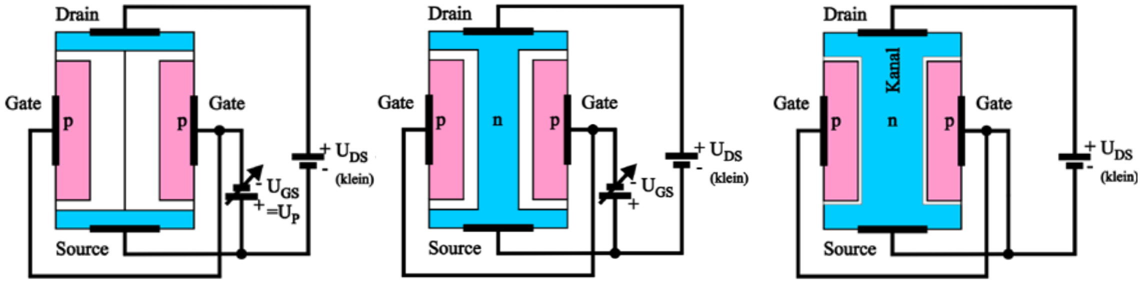
Selbstsperrend (Anreicherungstyp)





FETs – Funktionsprinzip

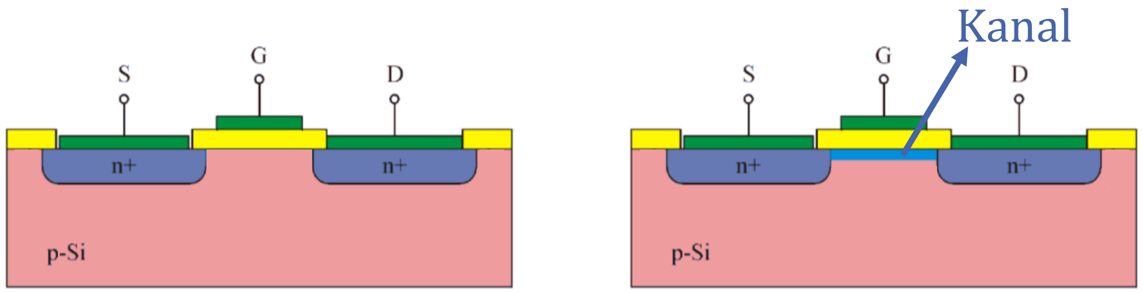
Sperrschicht-Feldeffekttransistor (JFET)



$U_{GS} = U_{th}$ | $U_{GS} < 0$ | $U_{GS} = 0$

- U_{GS} beeinflusst die Sperrschichtweite eines in Sperrrichtung betriebenen pn-Übergangs
- Gate ist nicht vom Kanal isoliert → nur negative U_{GS}, da pn-Übergang sonst in Flussrichtung

Isolierschicht-Feldeffekttransistor (MOSFET)

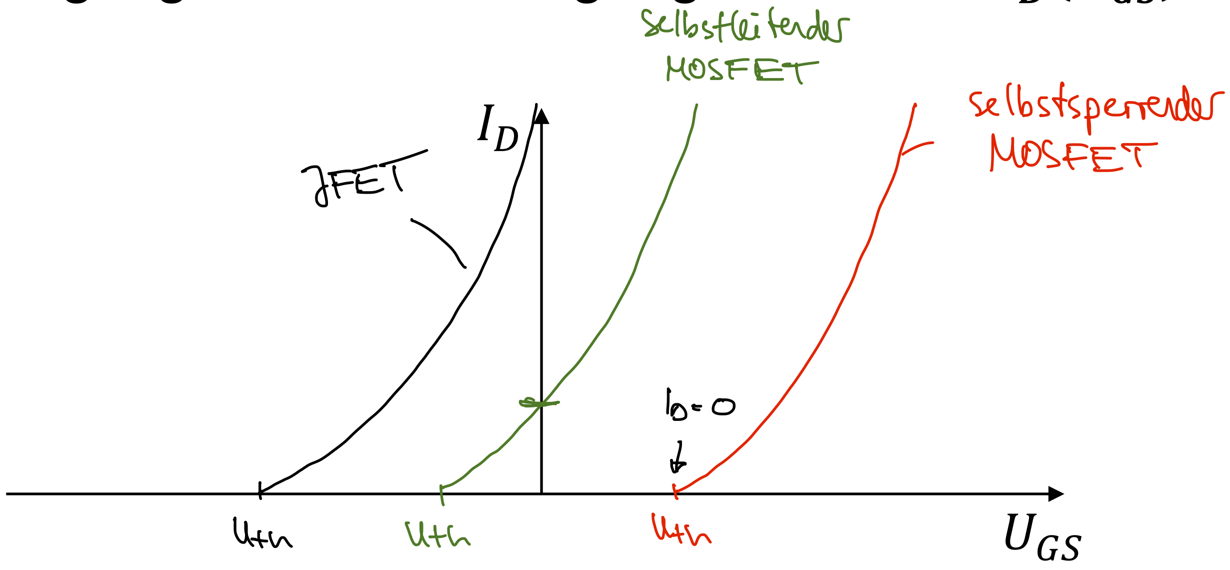


$U_{GS} \leq U_{th}$ | $U_{GS} > U_{th}$

- U_{GS} beeinflusst Ladungsträgerdichte in der unter dem Gate-Kontakt liegenden Inversionsschicht → für $U_{GS} > U_{th}$ bildet sich leitfähiger Kanal zwischen Source und Drain
- Gate ist vom Kanal isoliert → kein Gatestrom für positive und negative U_{GS}

FETs – Kennlinien

Eingangs- oder Übertragungskennlinie: $I_D(U_{GS})$



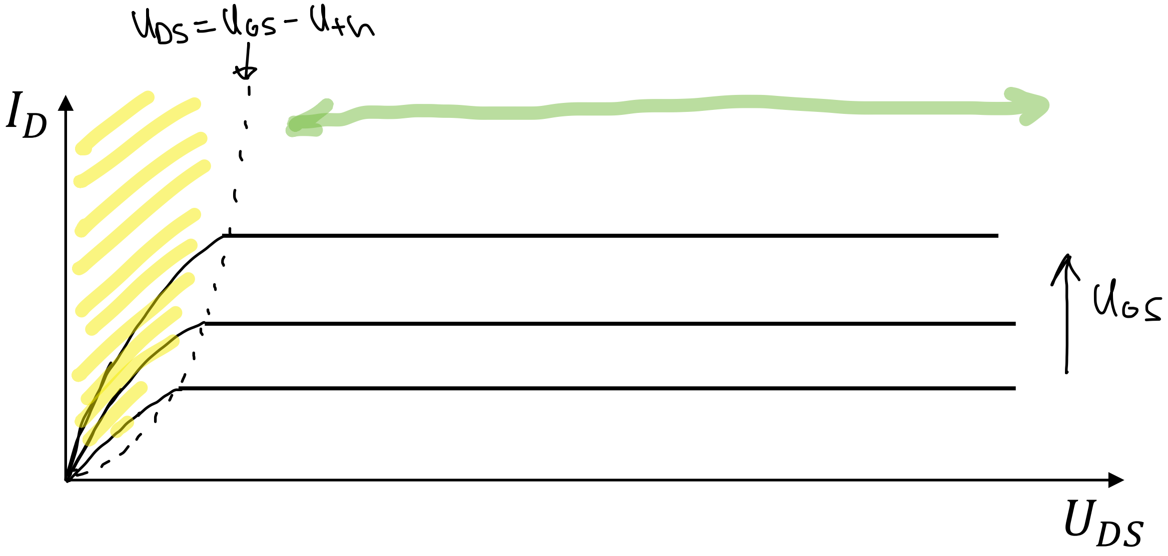
$$I_D = I_{D0} \cdot \left(1 - \frac{U_{GS}}{U_{th}}\right)^2$$

$U_{GS} = U_{th} \rightarrow I_D = 0$

$U_{GS} = 0 \rightarrow I_D = I_{D0}$

FETs – Kennlinien – ohne Early-Effekt / Kanallängenmodulation

Ausgangskennlinie: $I_D(U_{DS})$

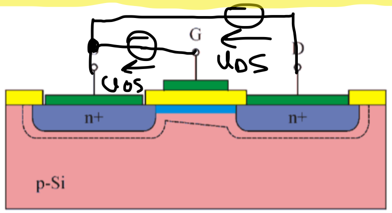


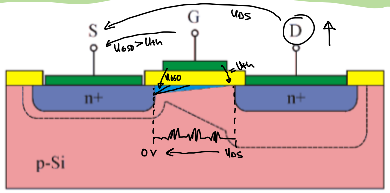
$$I_D = \begin{cases} 0 & U_{GS} \leq U_{th} \\ \beta \cdot \left[(U_{GS} - U_{th}) \cdot U_{DS} - \frac{U_{DS}^2}{2} \right] & \text{linearer Bereich} \\ \frac{\beta}{2} (U_{GS} - U_{th})^2 & \text{Sättigung} \end{cases}$$

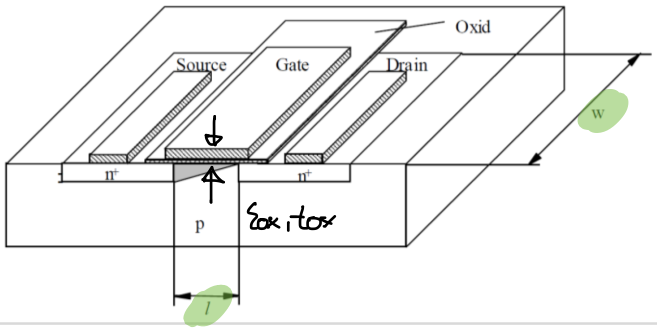
$$\beta = \mu_n \cdot C_{ox}' \cdot \frac{W}{\ell} \qquad [\beta] = \frac{A}{V^2}$$

Linearer Bereich:
$U_{DS} < U_{GS} - U_{th}$

Sättigung:
$U_{DS} \geq U_{GS} - U_{th}$

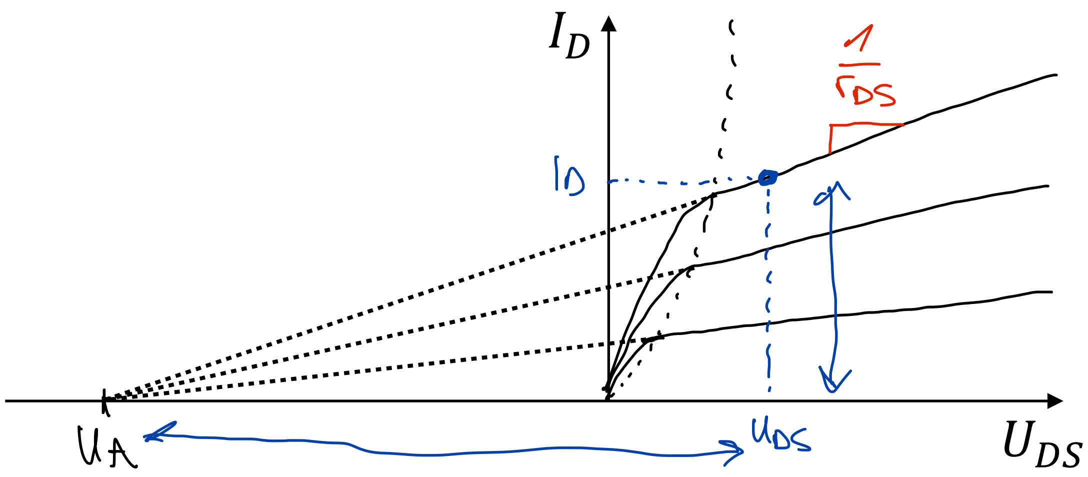






FETs – Kennlinien

Ausgangskennlinie: $I_D(U_{DS})$ - mit Kanallängenmodulation (Early-Effekt)

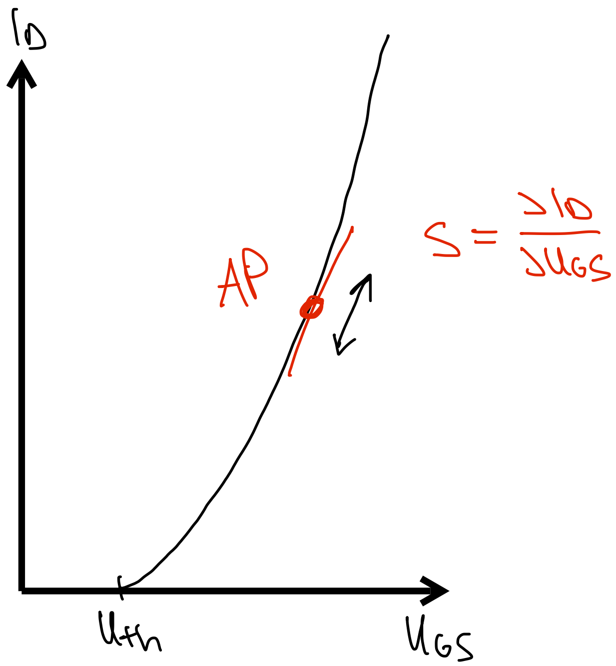


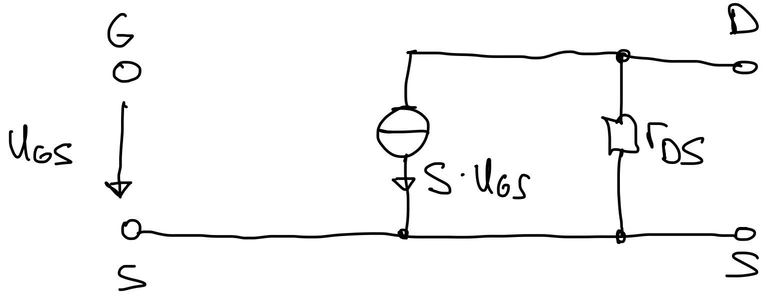
$|U_A| \sim L$

$\boxed{U_A = \frac{1}{\lambda}}$

$$I_D = \begin{cases} 0 & U_{GS} \leq U_{th} \\ \beta \cdot \left[(U_{GS} - U_{th}) \cdot U_{DS} - \frac{U_{DS}^2}{2} \right] \cdot \left(1 + \frac{U_{DS}}{|U_A|}\right) & \text{linearer Bereich} \\ \frac{\beta}{2} (U_{GS} - U_{th})^2 \cdot \left(1 + \frac{U_{DS}}{|U_A|}\right) & \text{Sättigung} \end{cases}$$

FETs – Kleinsignalersatzschaltbild





ohne KLM

$$r_{DS} = \infty$$

$$S = \frac{\partial}{\partial U_{GS}} \left[\frac{\beta}{2} (U_{GS} - U_{th})^2 \right]$$

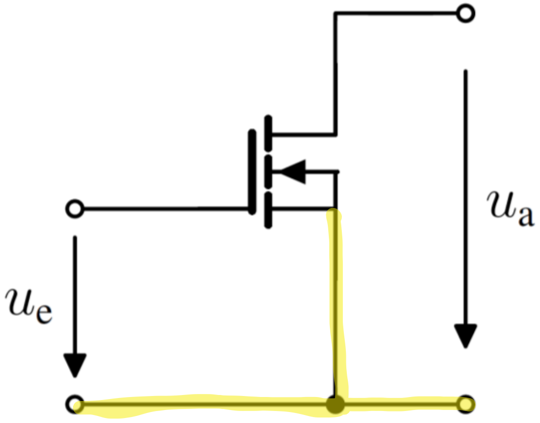
$$S = \beta \cdot (U_{GS} - U_{th})$$

allgemein / mit KLM

$$r_{DS} = \frac{|U_A| + U_{DS}}{I_D}$$

$$S = \beta \cdot (U_{GS} - U_{th}) \cdot \left(1 + \frac{U_{DS}}{|U_A|}\right)$$

FETs – Grundschaltungen

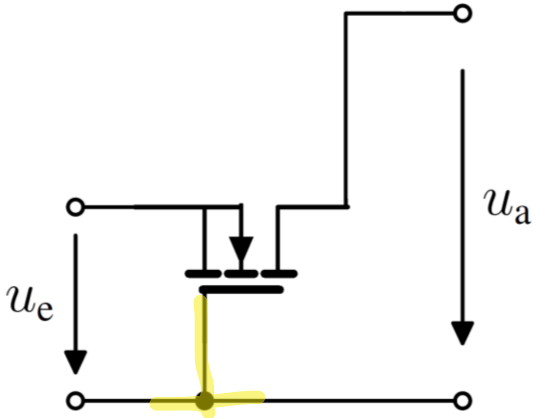


Source-Schaltung

$$r_e = \infty$$

$$r_a = R_D \parallel r_{DS}$$

$$A = -S \cdot (R_D \parallel r_{DS})$$

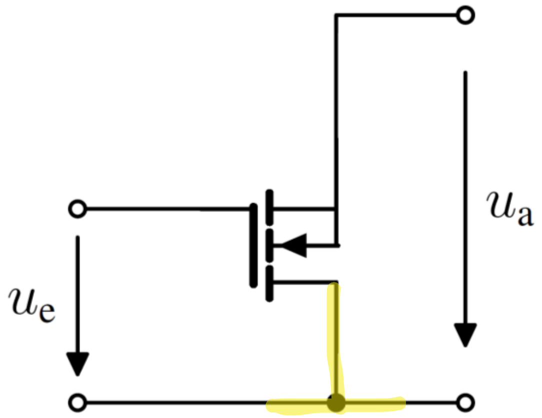


Gate-Schaltung

$$r_e = \frac{1}{S}$$

$$r_a = R_D \parallel r_{DS}$$

$$A = S \cdot (R_D \parallel r_{DS})$$



Drain-Schaltung

$$r_e = \infty$$

$$r_a = \frac{1}{S} \parallel R_S$$

$$A = \frac{S \cdot R_S}{1 + S \cdot R_S}$$

Aufgabe 1

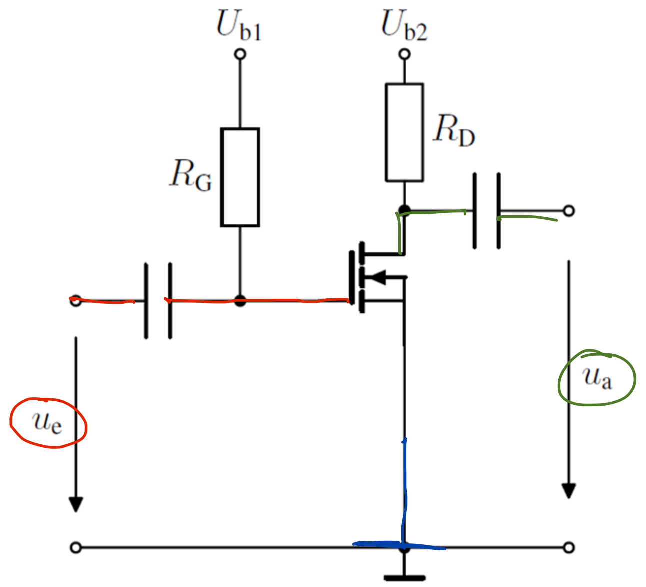
a) ges.: Transistor-Typ und Grundschaltung

↳ selbstsperrender n-MOSFET
(Anreicherungstyp)

Eingang : Gate
Ausgang : Drain

} Source-Schaltung

Gegeben:
$U_{b2} = 2\ \mathrm{V}$, $R_G = 10\ \mathrm{k\Omega}$, $R_D = 200\ \Omega$,
$\beta = 61{,}3\ \frac{\mathrm{mA}}{\mathrm{V}^2}$, $U_{GS} = 1\ \mathrm{V}$,
$U_{th} = 0{,}6\ \mathrm{V}$, $|U_A| = 50\ \mathrm{V}$



Aufgabe 1

b) ges.: Graphische Bestimmung des Arbeitspunkts

$U_{b2} = R_D \cdot I_D + U_{DS}$

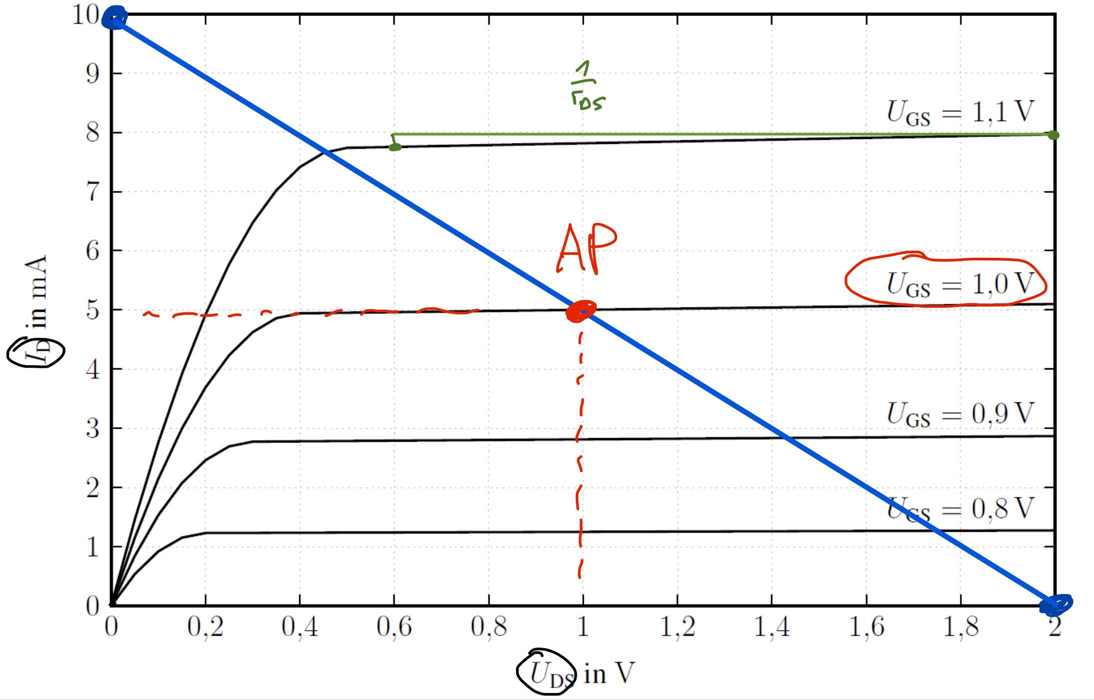
$I_D = \dfrac{U_{b2} - U_{DS}}{R_D}$

$U_{DS} = 0 \longrightarrow I_D = \dfrac{U_{b2}}{R_D} = 10\,mA$

$U_{DS} = U_{b2} \longrightarrow I_D = 0$

Gegeben:

$U_{b2} = 2\ \mathrm{V}$, $R_G = 10\ \mathrm{k\Omega}$, $R_D = 200\ \Omega$,
$\beta = 61{,}3\ \frac{\mathrm{mA}}{\mathrm{V}^2}$, $U_{GS} = 1\ \mathrm{V}$,
$U_{th} = 0{,}6\ \mathrm{V}$, $|U_A| = 50\ \mathrm{V}$

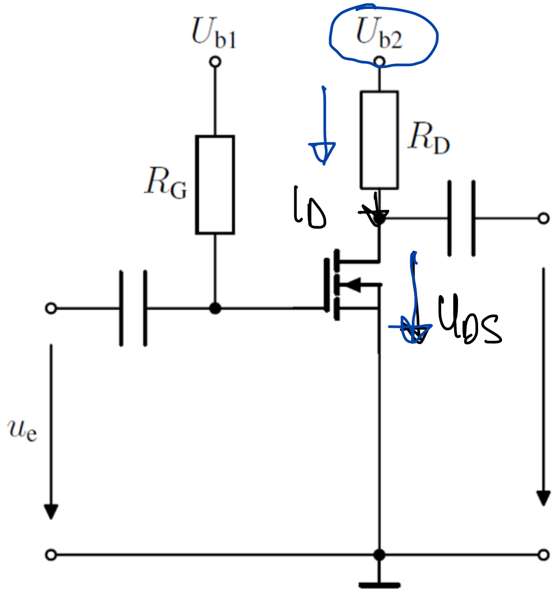


AP:

$U_{GS} = 1{,}0\ V$

$U_{DS} = 1{,}0\ V$

$I_D = 5\,mA$

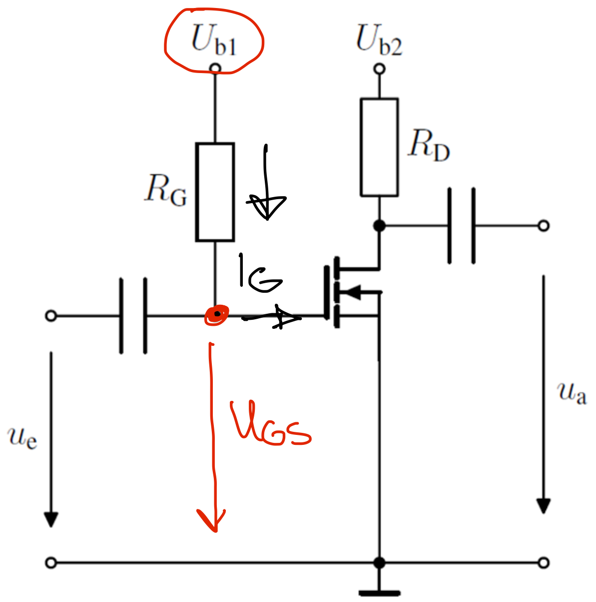


Aufgabe 1

c) ges.: Spannung U_{b1}

$$I_G = 0 \Rightarrow U_{b1} = U_{GS} = \underline{1\,V}$$

Gegeben:
$U_{b2} = 2\text{ V},\ R_G = 10\text{ k}\Omega,\ R_D = 200\ \Omega,$
$\beta = 61{,}3\ \frac{\text{mA}}{\text{V}^2},\ U_{GS} = 1\text{ V},$
$U_{th} = 0{,}6\text{ V},\ |U_A| = 50\text{ V}$



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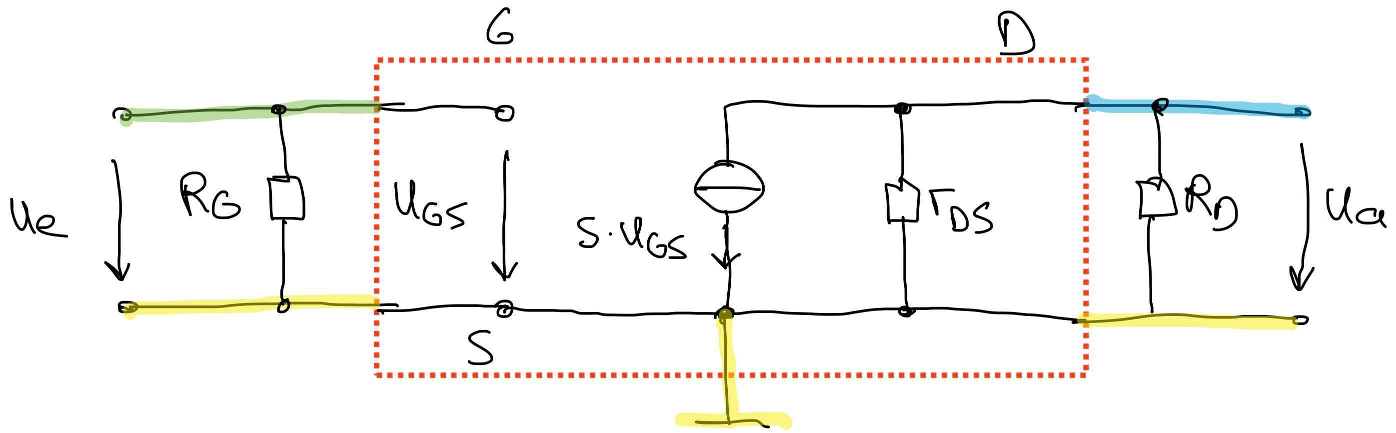
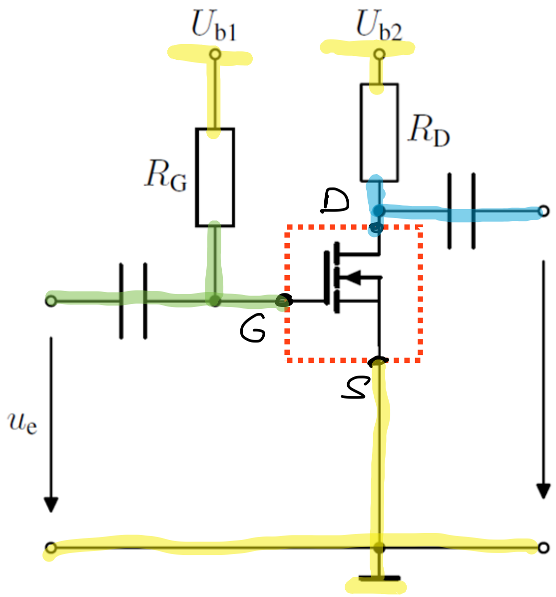
Aufgabe 1

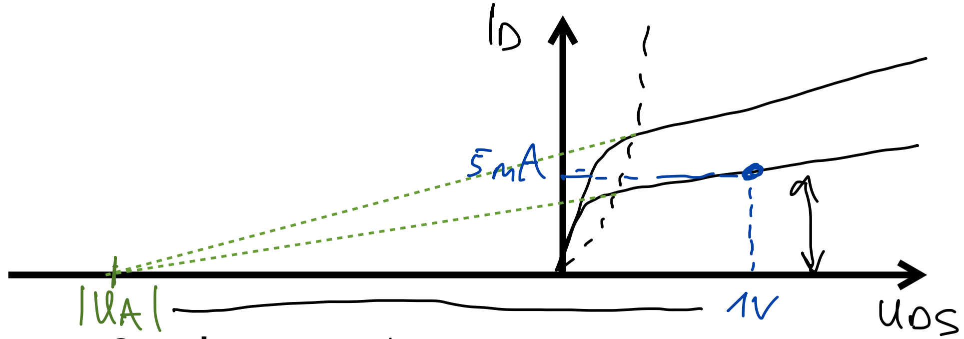
d) ges.: KS-ESB

Gegeben:
$U_{b2} = 2\text{ V},\ R_G = 10\text{ k}\Omega,\ R_D = 200\ \Omega,$
$\beta = 61{,}3\ \frac{\text{mA}}{\text{V}^2},\ U_{GS} = 1\text{ V},$
$U_{th} = 0{,}6\text{ V},\ |U_A| = 50\text{ V}$





Aufgabe 1



Gegeben:
$U_{b2} = 2\text{ V}$, $R_G = 10\text{ k}\Omega$, $R_D = 200\ \Omega$,
$\beta = 61{,}3\ \frac{\text{mA}}{\text{V}^2}$, $U_{GS} = 1\text{ V}$,
$U_{th} = 0{,}6\text{ V}$, $|U_A| = 50\text{ V}$

e) ges.: $A = \frac{u_a}{u_e}$ unbelastet & mit $R_L = 50\ \Omega$

$$\boxed{\begin{aligned}A_{ub} &= -S\cdot(R_D \| r_{DS}) \\ A_{bel} &= -S\cdot(R_D \| r_{DS} \| R_L)\end{aligned}}$$

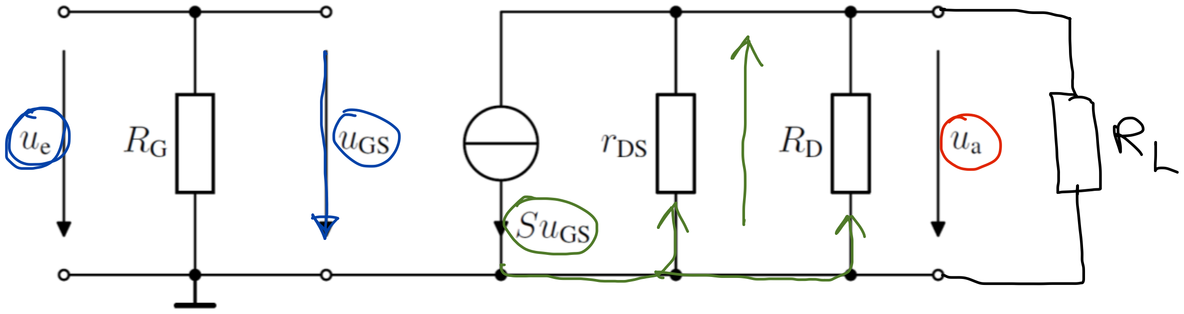
$$A_{ub} = -25\text{ mS}\cdot(200\,\Omega \| 10{,}2\text{ k}\Omega) \approx -4{,}9$$

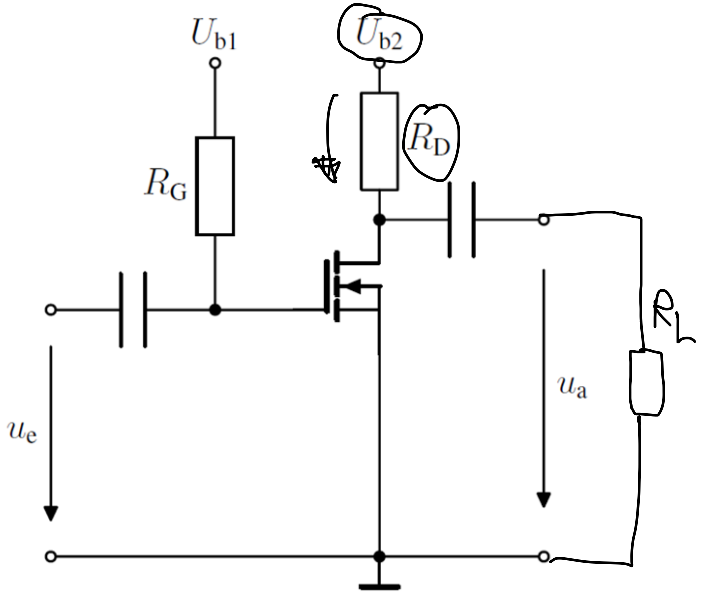
$$A_{bel} = -25\text{ mS}\cdot(200\,\Omega \| 10{,}2\text{ k}\Omega \| 50\,\Omega) \approx -1$$

mit $S = \frac{\partial I_D}{\partial U_{GS}} = \frac{\partial}{\partial U_{GS}}\left[\frac{\beta}{2}(U_{GS}-U_{th})^2\cdot\left(1+\frac{U_{DS}}{U_A}\right)\right]$

$$\boxed{S = \beta(U_{GS}-U_{th})\left(1+\frac{U_{DS}}{U_A}\right)} = 25\text{ mS}$$

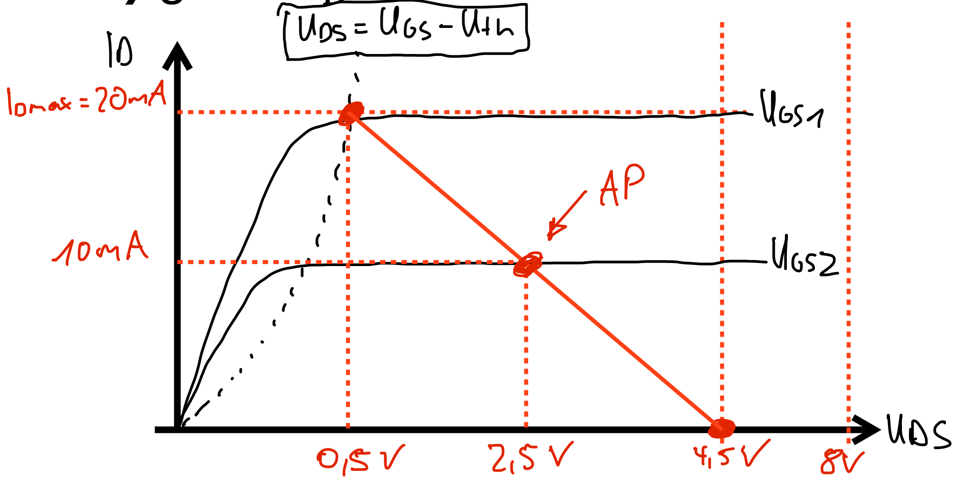
und $r_{DS} = \frac{|U_A| + U_{DS}}{I_D} = \frac{50\text{ V} + 1\text{ V}}{5\text{ mA}} \approx 10{,}2\text{ k}\Omega$





Aufgabe 2

b) ges.: R_D für maximale Aussteuerbarkeit, U_{DS}, I_D



$$I_D = \frac{\beta}{2} \cdot \underbrace{(U_{GS1} - U_{th})^2}_{} = 20\,mA$$

$$U_{DS} = U_{GS1} - U_{th} = \sqrt{\frac{2 \cdot 20mA}{160\,\frac{mA}{V^2}}} = 0{,}5\,V$$

Gegeben:
$U_b = 4{,}5\,V$, $R_S = 50\,\Omega$,
$\beta = 160\,\frac{mA}{V^2}$, $U_{th} = 0{,}5\,V$

$$U_b = R_D \cdot I_D + U_{DS} + R_S \cdot I_D \quad (*)$$

$$I_D = \frac{U_b - U_{DS}}{R_D + R_S}$$

$$U_{DS} = U_b \rightarrow I_D = 0$$

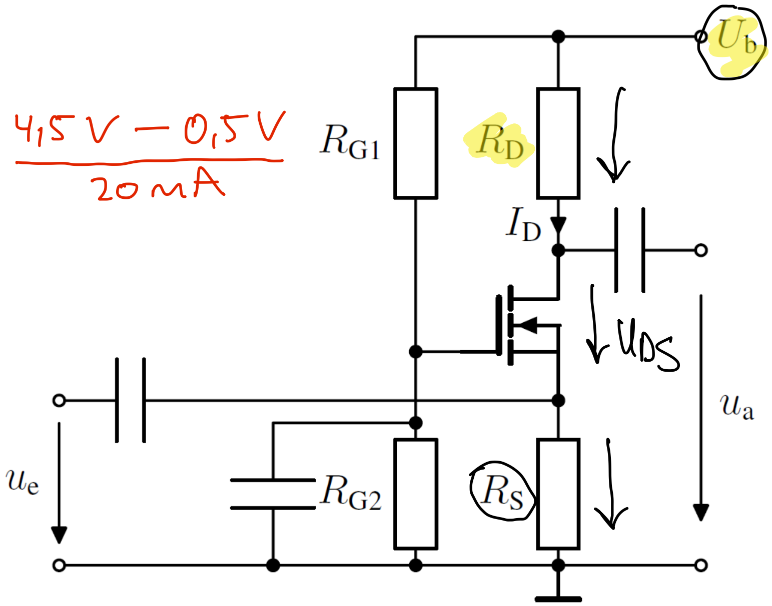
$$(*) \rightarrow R_S + R_D = \frac{U_b - U_{DS}}{I_D} = \frac{4{,}5\,V - 0{,}5\,V}{20\,mA}$$

$$R_S + R_D = 200\,\Omega$$

$$R_D = 200\,\Omega - R_S$$

$$\underline{R_D = 150\,\Omega}$$

AP: $U_{DS} = 2{,}5\,V$
$I_D = 10\,mA$



Aufgabe 2

c) ges.: U_{GS}, R_{G1}, R_{G2}

$$I_{D,AP} = \frac{\beta}{2} \cdot (U_{GS2} - U_{th})^2 = 10\,\mathrm{mA}$$

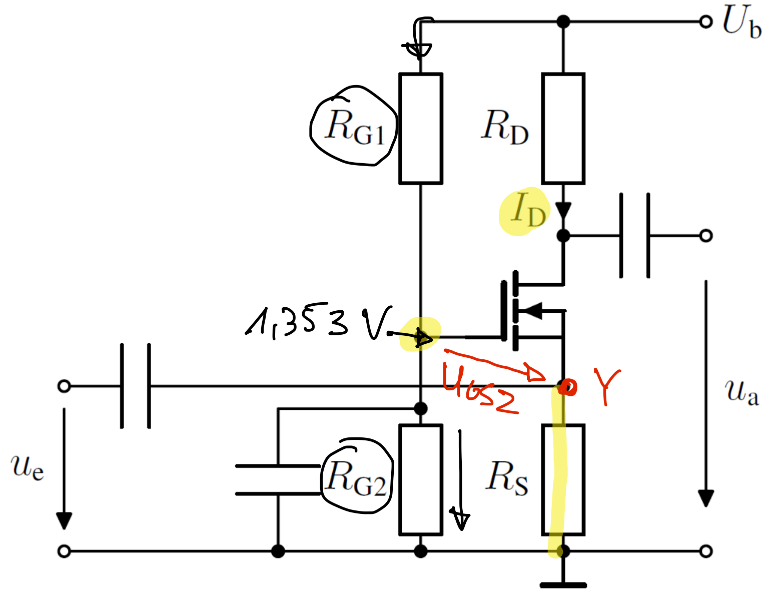
$$U_{GS2} = U_{th} + \sqrt{\frac{2 \cdot I_{D,AP}}{\beta}} = \underline{853{,}55\,\mathrm{mV}}$$

$$U_x = U_{GS2} + R_S \cdot I_D$$
$$= 853{,}55\,\mathrm{mV} + 50\,\Omega \cdot 10\,\mathrm{mA} = \underline{1{,}353\ldots\,\mathrm{V}}$$

$$U_x = \frac{R_{G2}}{R_{G1}+R_{G2}} \cdot U_b \Rightarrow R_{G2} = (R_{G1}+R_{G2}) \cdot \frac{U_x}{U_b}$$
$$= 50\,\mathrm{k\Omega} \cdot \frac{1{,}353\,\mathrm{V}}{4{,}5\,\mathrm{V}}$$
$$\approx \underline{15\,\mathrm{k\Omega}}$$

$$R_{G1} = 50\,\mathrm{k\Omega} - R_{G2} \approx \underline{35\,\mathrm{k\Omega}}$$

Gegeben:
$U_b = 4{,}5\,\mathrm{V}$, $R_S = 50\,\Omega$,
$\beta = 160\,\frac{\mathrm{mA}}{\mathrm{V}^2}$, $U_{th} = 0{,}5\,\mathrm{V}$,
$R_{G1} + R_{G2} = 50\,\mathrm{k\Omega}$



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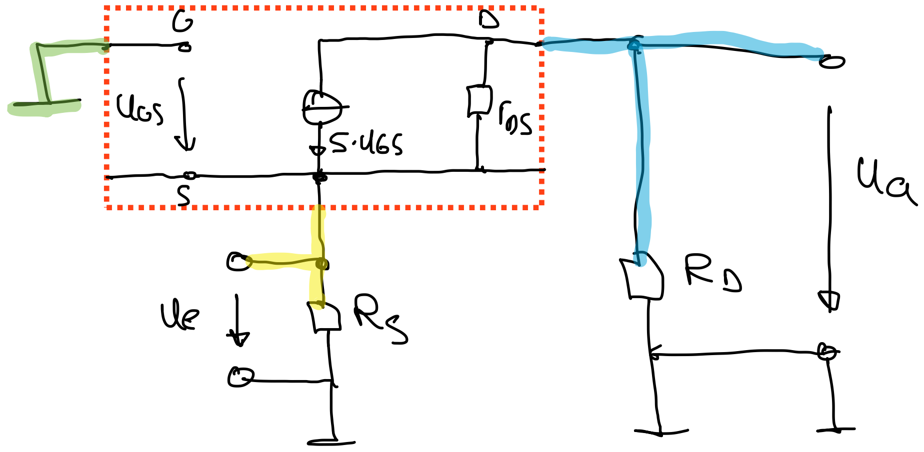
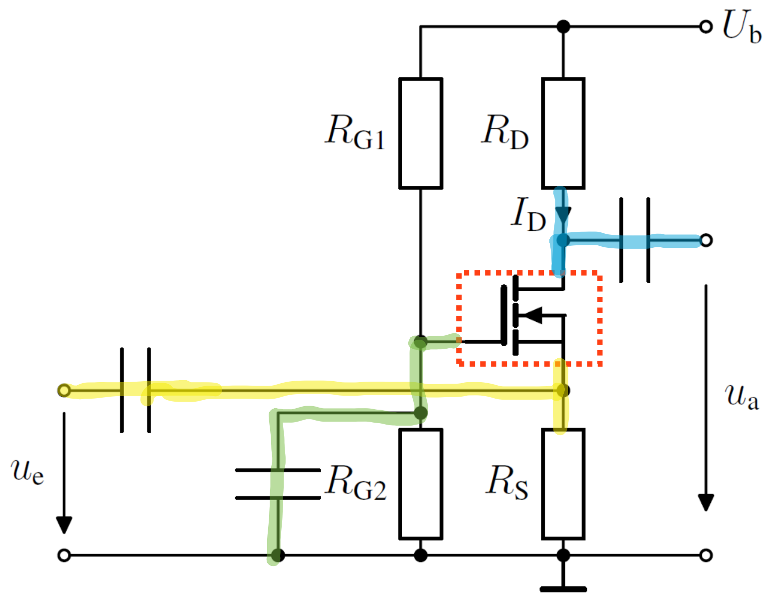
Aufgabe 2

d) ges.: KS-ESB

Gegeben:
$U_b = 4{,}5\ \text{V},\ R_S = 50\ \Omega,$
$\beta = 160\ \frac{\text{mA}}{\text{V}^2},\ U_{th} = 0{,}5\ \text{V}$

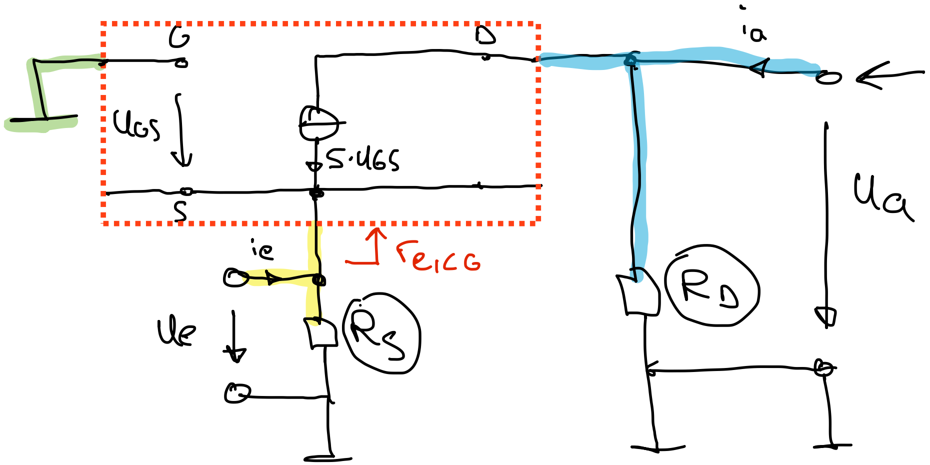




Aufgabe 2

e) ges.: KS-Eingangs- und -Ausgangswiderstand

<u>Gegeben</u>:
$U_b = 4{,}5\ \mathrm{V}$, $R_S = 50\ \Omega$,
$\beta = 160\ \frac{\mathrm{mA}}{\mathrm{V}^2}$, $U_{th} = 0{,}5\ \mathrm{V}$



$$r_e = \frac{1}{S} \parallel R_S = \frac{1}{\beta \cdot (U_{GS} - U_{th})} \parallel R_S$$

$$= 17{,}7\ \Omega \parallel 50\ \Omega$$

$$\approx \underline{13\ \Omega}$$

$$r_a = R_D = \underline{150\ \Omega}$$

Aufgabe 2

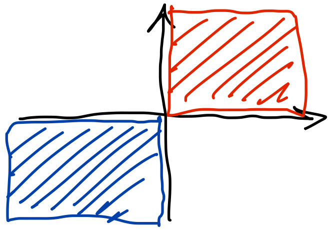
Gegeben:
$U_b = 4{,}5\ \mathrm{V}$, $R_S = 50\ \Omega$,
$\beta = 160\ \frac{\mathrm{mA}}{\mathrm{V}^2}$, $U_{th} = 0{,}5\ \mathrm{V}$

f) ges.: KS-Spannungsverstärkung A

$$A = \frac{u_a}{u_e} = S \cdot r_a = \beta \cdot (U_{GS} - U_{th}) \cdot R_D$$

$$\underline{A = 8{,}48}$$

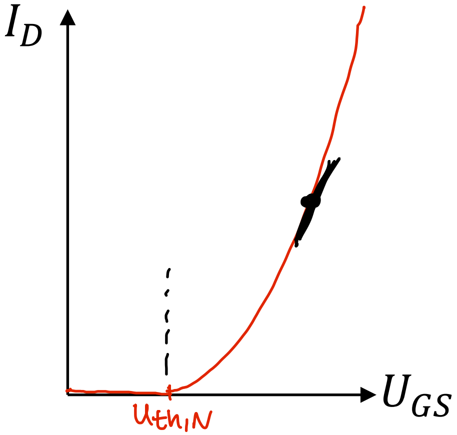
CMOS

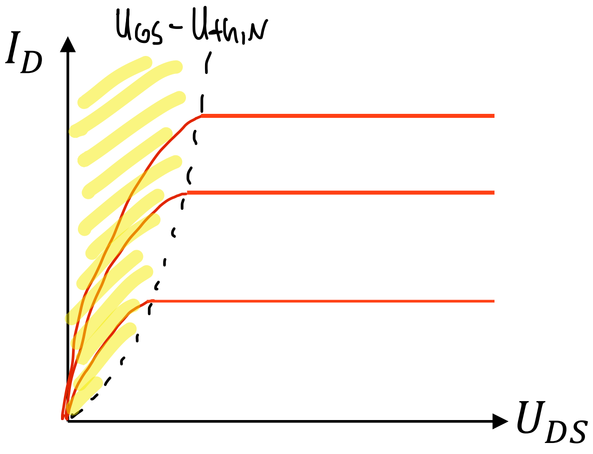


$$\boxed{I_{D,N} = -I_{D,P}}$$

wenn: $\beta_P = \beta_N$ & $|U_{th,N}| = |U_{th,P}|$

n-MOS



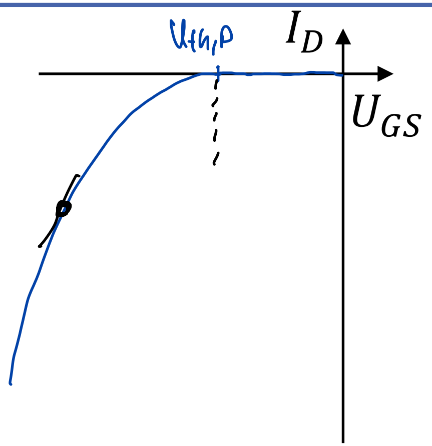


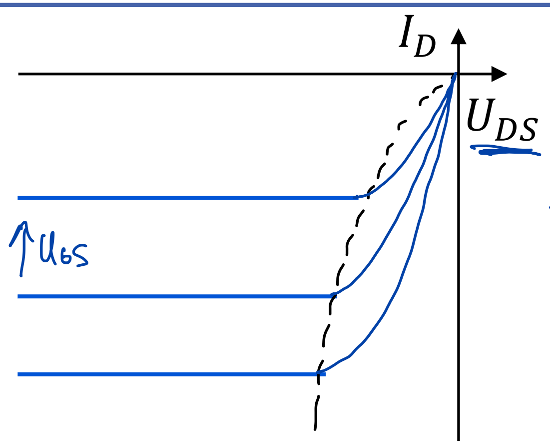
$$\boxed{U_{GS} > 0, \quad U_{DS} > 0, \quad U_{th,N} > 0}$$

$$I_{D,N} = \frac{\beta}{2}(U_{GS} - U_{th})^2 \cdot \left(1 + \frac{U_{DS}}{|U_A|}\right) \qquad \text{Sättigung}$$

$$S_N = \frac{\partial I_D}{\partial U_{GS}} = \beta (U_{GS} - U_{th})\left(1 + \frac{U_{DS}}{|U_A|}\right)$$

p-MOS





$$\boxed{U_{GS} < 0, \quad U_{DS} < 0, \quad U_{th,P} < 0}$$

$$-I_{D,P} = \frac{\beta}{2}(U_{GS} - U_{th})^2 \cdot \left(1 - \frac{\overset{<0}{U_{DS}}}{|U_A|}\right) \qquad \text{Sättigung}$$

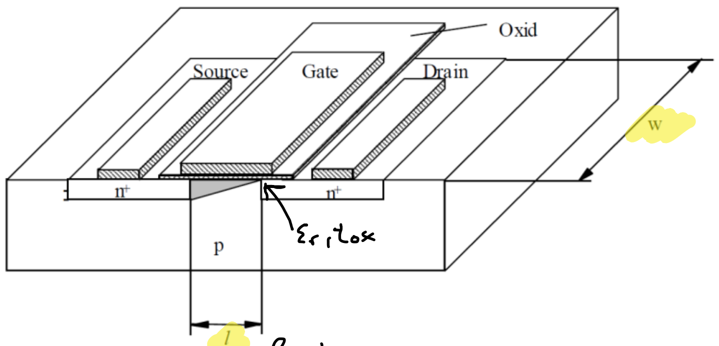
$$S_P = \frac{\partial I_D}{\partial U_{GS}} = -\beta \underbrace{(U_{GS} - U_{th})}_{<0} \underbrace{\left(1 - \frac{U_{DS}}{|U_A|}\right)}_{>0}$$

$$S_P > 0$$

Aufgabe 3

a) ges.: Gate-Breite W_P, damit $\boxed{\beta_P = \beta_N}$

Gegeben:
$U_b = \pm 1\ \mathrm{V}$, $|U_{th,N,P}| = 0{,}4\ \mathrm{V}$, $w_N = 6\ \mu\mathrm{m}$,
$l_{N,P} = 22\ \mathrm{nm}$, $C'_{ox} = 3{,}66\ \frac{\mathrm{fF}}{\mu\mathrm{m}^2}$,
$\mu_N = 1200\ \frac{\mathrm{cm}^2}{\mathrm{Vs}}$, $\mu_P = 400\ \frac{\mathrm{cm}^2}{\mathrm{Vs}}$



$$C_{ox} = \varepsilon_0 \varepsilon_r \cdot \frac{l \cdot w}{t_{ox}}$$

$$C_{ox}' = \frac{\varepsilon_0 \varepsilon_r}{t_{ox}}$$

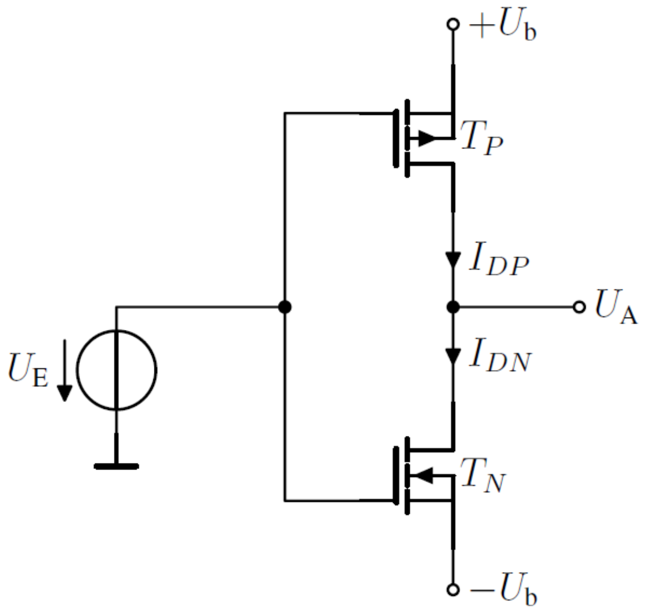
$$\beta_N = \mu_N \cdot C_{ox}' \cdot \frac{W_N}{l_N} \leftarrow$$

$$\beta_P = \mu_P \cdot C_{ox}' \cdot \frac{W_P}{l_P} \leftarrow$$

$$\mu_P \cdot C_{ox}' \cdot \frac{W_P}{l_P} \overset{!}{=} \mu_N \cdot C_{ox}' \cdot \frac{W_N}{\cancel{l_N}}$$

$$W_P = \frac{\mu_N}{\mu_P} \cdot W_N = \underline{\underline{18\ \mu\mathrm{m}}} = 3 \cdot W_N$$

$$\longrightarrow \beta_N = \beta_P = 120\ \frac{\mathrm{mA}}{\mathrm{V}^2}$$



Aufgabe 3

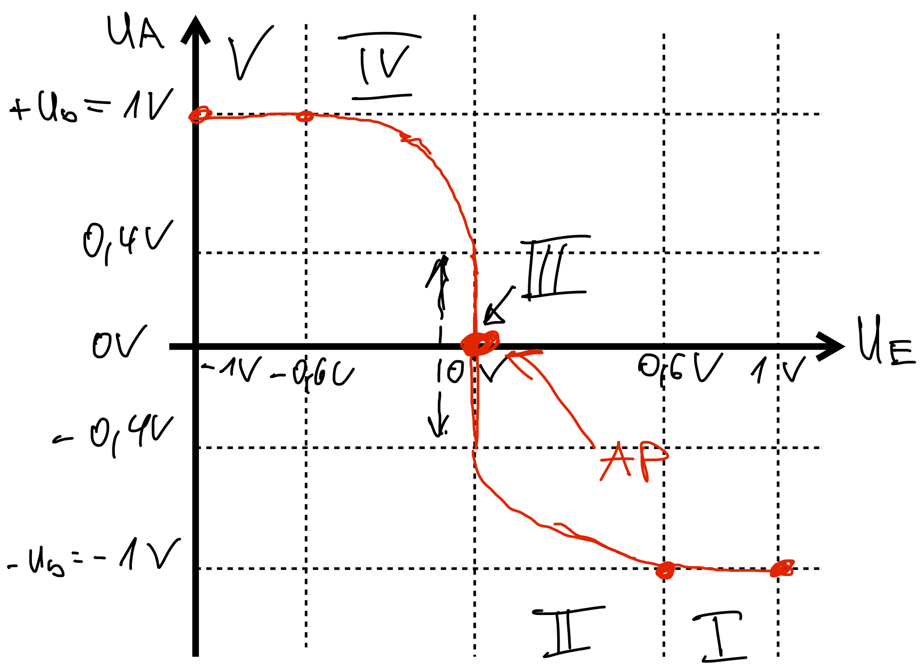
Karlsruhe Institute of Technology

Gegeben:

$U_b = \pm 1\ \mathrm{V}, |U_{th,N,P}| = 0{,}4\ \mathrm{V},$

$\beta_{N,P} = 120\ \frac{\mathrm{mA}}{\mathrm{V}^2}$

b) ges.: Übertragungskennlinie $U_A = f(U_E)$,
AP für $U_A = U_E$



I : p-MOS sperrt

II : p-MOS : Sättigung
n-MOS : linearer Bereich

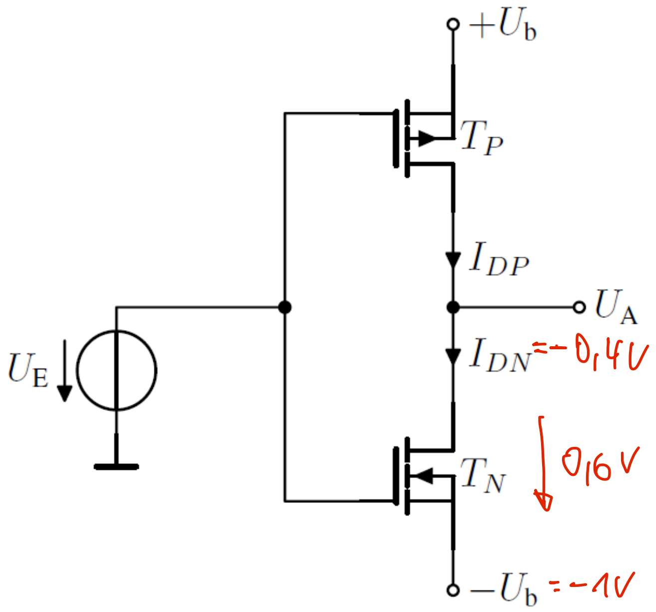
III : beide in Sättigung

IV : p-MOS : linearer Bereich
n-MOS : Sättigung

V : n-MOS sperrt

→ $U_{DS,N} > U_{GS,N} - U_{th,N}$

$1V > 1V - 0{,}4V = 0{,}6V$



Aufgabe 3

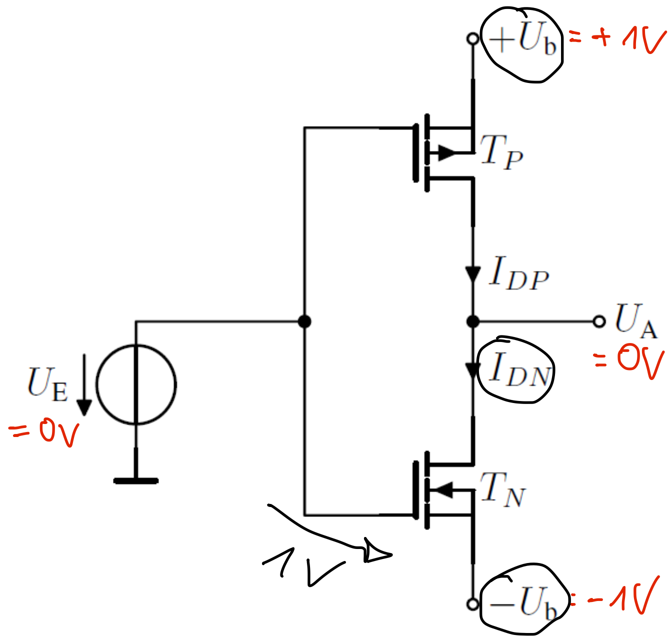
Gegeben:
$U_b = \pm 1\ \text{V},\ |U_{th,N,P}| = 0{,}4\ \text{V},$
$\beta_{N,P} = 120\ \frac{\text{mA}}{\text{V}^2}$

c) ges.: I_D & P_{DC} im Arbeitspunkt

$$I_D = \frac{\beta}{2} \cdot (U_{GS} - U_{thN})^2 = \frac{120\ \frac{mA}{V^2}}{2} \cdot (1V - 0{,}4V)^2$$

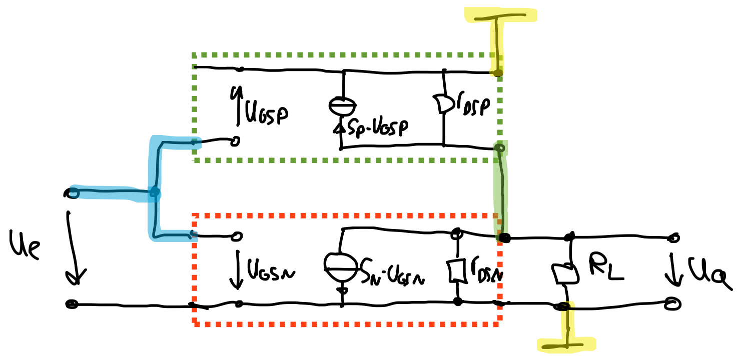
$$I_D = 21{,}6\ mA$$

$$P_{DC} = 2 \cdot U_b \cdot I_D = 2 \cdot 1V \cdot 21{,}6\,mA = \underline{43{,}2\ mW}$$



Aufgabe 3

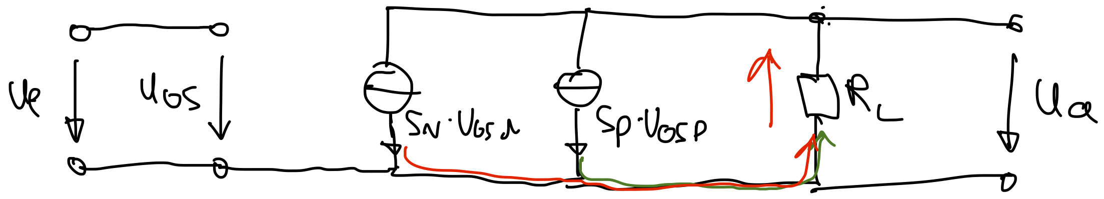
d) ges.: KS-ESB und $A = \frac{u_a}{u_e}$

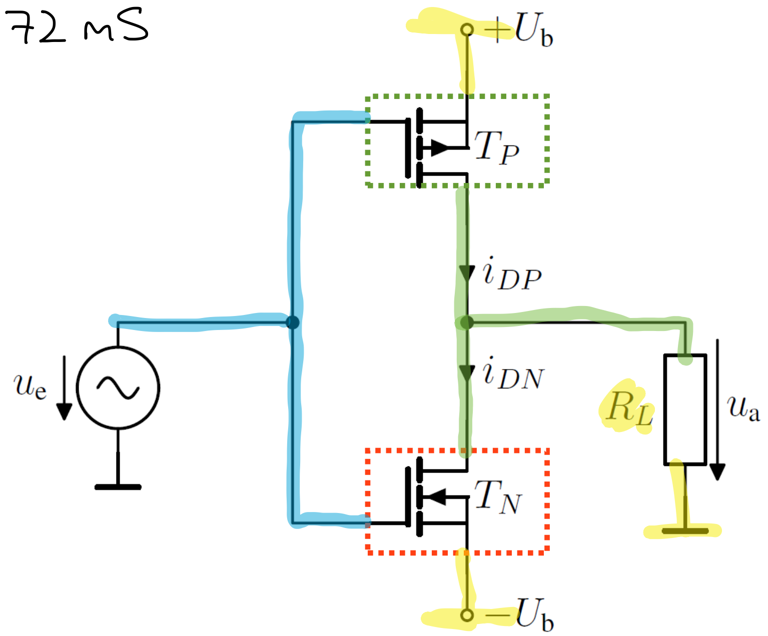


$$A = \frac{u_a}{u_e} = -(S_N + S_P) \cdot R_L$$

mit $S_N = S_P = \beta \cdot (U_{GS} - U_{th}) = 72\ \mathrm{mS}$

$$A = -144$$

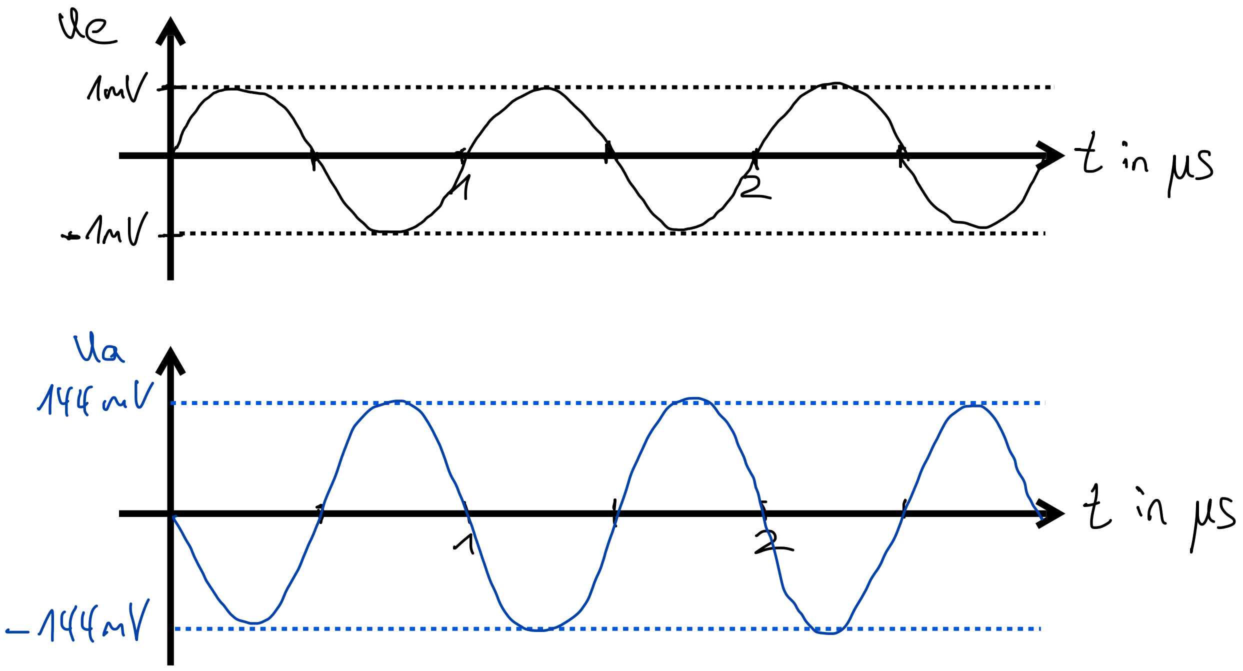




Aufgabe 3

e) ges.: $u_e(t)$ und $u_a(t)$ im Zeitbereich

$A = -144$



Gegeben:
$U_b = \pm 1\ \mathrm{V}$, $|U_{th,N,P}| = 0{,}4\ \mathrm{V}$,
$\beta_{N,P} = 120\ \frac{\mathrm{mA}}{\mathrm{V}^2}$, $R_L = 1\ \mathrm{k\Omega}$,
$\hat{u}_e = 1\ \mathrm{mV}$, $f = 1\ \mathrm{MHz}$