Elektronik Elemanlar

11. ve 12. Hafta – MOSFET

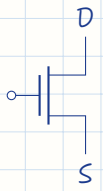
Orijinal not: elektronik-elemanlar-11-ve-12.hafta.pdf

UYARI Bu belge, el yazısı ders notlarından Claude (Anthropic) yardımıyla dijitale aktarılmıştır. Yardımcı kaynak olarak hazırlanmıştır; hata veya eksik içerebilir. Lütfen orijinal notları ve ders kaynaklarını esas alın.

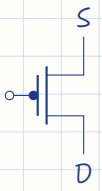
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orj. s. 1

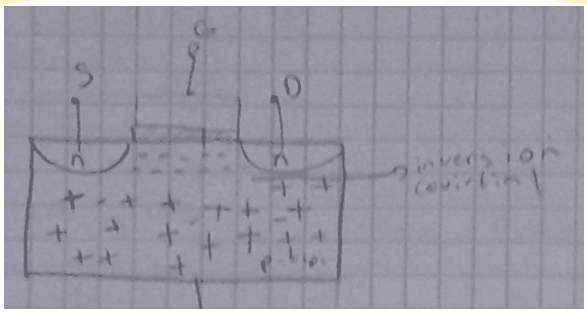
11. hafta



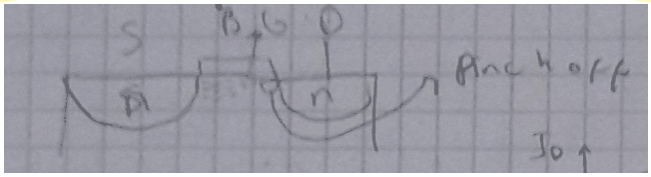
Nmos



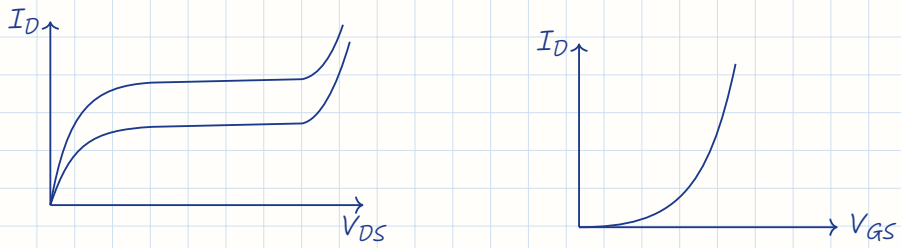
Pmos — V_{Tp} negatif



orijinal çizim, s. 1



orijinal çizim, s. 1



(Sol kenarda yuvarlak içine alınmış iki kısa not: ? okunamadı, ? okunamadı.)

orj. s. 2

Triode

$$I_D = k'_n \frac{W}{L}\left[\overbrace{(V_{GS}-V_{TH})}^{V_{ov}} V_{DS} - \frac{1}{2}V_{DS}^2\right] \qquad V_{DS} \le V_{GS}-V_{TH}$$

$$= \frac{1}{2}k'_n \frac{W}{L}\left(2(V_{GS}-V_{TH})V_{DS} - V_{DS}^2\right)$$

Sat

$$I_D = \frac{1}{2}k'_n \frac{W}{L}(V_{GS}-V_{TH})^2 \qquad V_{DS} \ge V_{GS}-V_{TH}$$

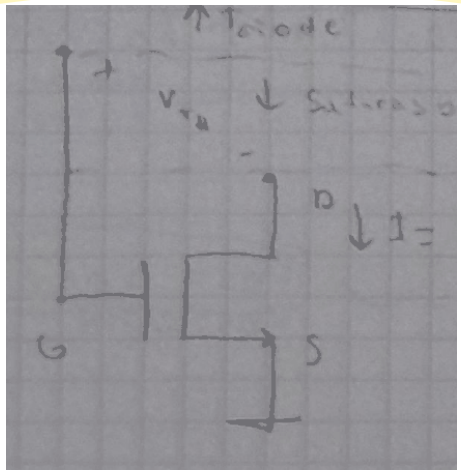
Deep triode

$$r = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})}$$

(İki koşul kutusu çizgilerle aşağıdaki "At the edge of saturation" ifadesine bağlanmış.)

At the edge of saturation

$$V_{DS} = V_{GS} - V_{TH}$$
$$V_D - V_S = V_G - V_S - V_{TH}$$
$$V_{TH} = V_G - V_D$$
$$V_{TH} = V_{GD}$$



orijinal çizim, s. 2

orj. s. 3



Diode connected transistor

Örnek 2

0,18 µm process

$L = 0{,}18\,\mu m$, $W = 2\,\mu m$, $C_{ox} = 8{,}6\ fF/\mu m^2$, $\mu_n = 450\ cm^2/Vs$, $V_{Tn} = 0{,}5\ V$

a) V_{GS} =? V_{DS} =? at the edge of saturation. $I_D = 100\ \mu A$

Çözüm:

$$k'_n = \mu_n C_{ox} = 450 \cdot 10^{-4} \cdot 8{,}6 \cdot 10^{-15} \cdot 10^{12}\ A/V^2$$
$$= 387\ \mu A/V^2$$
$$k_n = k'_n \left(\frac{W}{L}\right) = 387 \left(\frac{2}{0{,}18}\right) = 4{,}3\ mA/V^2$$
$$I_D = \frac{1}{2} k_n (V_{ov})^2$$
$$100 = \frac{1}{2}(4{,}3) \cdot 10^3 \cdot (V_{ov})^2$$
$$V_{ov} = 0{,}22\ V \longrightarrow V_{DS} = V_{GS} - V_{TH} = 0{,}22$$
$$\downarrow \quad V_{GS} = V_{TH} + V_{ov} = 0{,}5 + 0{,}22 = 0{,}72$$

b) V_{GS} is kept constant → V_{DS} =? when $I_D = 50\ \mu A$ (azaldı, grafiğe bak)

Çözüm: Triode bölgesi:

$$I_D = k_n \left[V_{ov} V_{DS} - \frac{1}{2} V_{DS}^2\right]$$
$$50 = 4{,}3 \cdot 10^3 \left[0{,}22\, V_{DS} - \frac{1}{2} V_{DS}^2\right] \longrightarrow \boxed{V_{DS} = 0{,}06\ V} \rightarrow \text{bunu alırız}$$

$V_{DS} = \boxed{?\,0{,}39}\ V \rightarrow$ sat'ta

$$V_{DS} = 0{,}06\ V$$

orj. s. 4

c) MOSFET → as a linear amplifier → (sat)

↑

$\{ V_{DS} = 0{,}3\ V$

The change in i_D resulting from V_{GS} → 0,7 V $\begin{cases} \nearrow +0{,}01\ V \Rightarrow i_D ? \\ \searrow -0{,}01\ V \Rightarrow i_D ? \end{cases}$ (← small signal)

Çözüm: $V_{GS} = 0{,}7\ V$, $V_{ov} = 0{,}2\ V$ ($V_{TH} = 0{,}5\ V$)

$V_{DS} = 0{,}3\ V$

$$I_D = \frac{1}{2} k_n (V_{ov})^2$$
$$= \frac{1}{2} 4300 \cdot 0{,}04$$
$$= 86\ \mu A$$

$V_{GS} = 0{,}71\ V \Rightarrow V_{ov} = 0{,}21\ V$

$V_{DS} = 0{,}3\ V \Rightarrow \quad i_D = \frac{1}{2} \cdot 4300\,(0{,}21)^2 = 94{,}8\ \mu A$

$V_{GS} = 0{,}69\ V$, $V_{ov} = 0{,}19\ V$

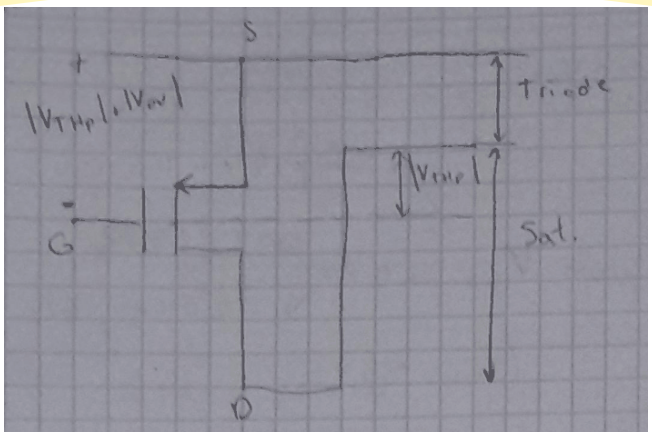
$$i_D = \frac{1}{2} \cdot 4300 \cdot (0{,}19)^2 = 77{,}6\ \mu A$$

$\Delta V_{GS} = 0{,}01\ V \rightarrow \Delta i_D = 8{,}8\ \mu A$

$\Delta V_{GS} = -0{,}01\ V \rightarrow \Delta i_D = -8{,}4\ \mu A$

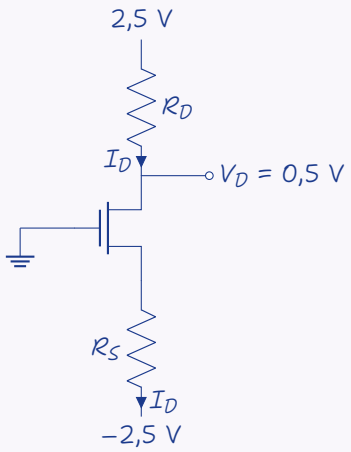
orj. s. 5

Örnek



orijinal çizim, s. 5

Örnek 5.3



$I_D = 0{,}4$ mA, $V_{TH} = 0{,}7$ V,
$\mu_n C_{ox} = 100\ \mu A/V^2$
$L = 1\ \mu m$, $W = 32\ \mu m$
$(\lambda = 0)$

Çözüm: $I_D = \frac{1}{2}\mu_n C_o$

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{2{,}5 - 0{,}5}{0{,}4} = 5\ k\Omega$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{ov}^2$$

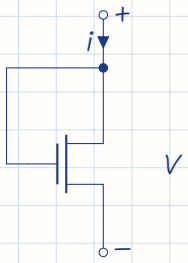
$$400 = \frac{1}{2}\cdot 100 \cdot \frac{32}{1}V_{ov}^2 \Rightarrow \boxed{V_{ov} = 0{,}5\ V}$$

$$\boxed{V_{GS} = 0{,}7 + 0{,}5 = 1{,}2\ V}$$

$$R_S = \frac{-1{,}2 - (-2{,}5)}{0{,}4} = 3{,}25\ k\Omega$$

orj. s. 6

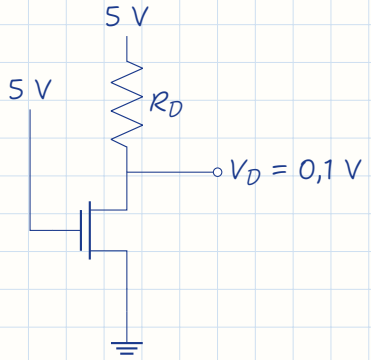
ex: 5.4



→ Daima aynı bölgede

$$i = \frac{1}{2}k_n(V - V_{TH})^2$$

ex: 5.5



$V_{TH} = 1$ V, $k_n'\left(\frac{W}{L}\right) = 1$ mA/V^2

→ Effective resistance → $\frac{V_{DS}}{I_{DS}}$ =?

$$I_D = k_n' \frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

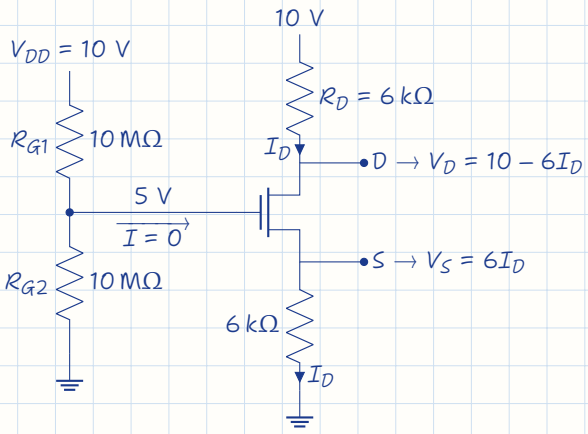
$$I_D = 1 \cdot \left[(5-1)(0{,}1) - \frac{1}{2}(0{,}1)^2\right]$$

$$= 0{,}395 \text{ mA}$$

? V_{GD} > Deep triode

$$R_{DS} = \frac{V_{DS}}{I_D} = \frac{0{,}1}{0{,}395} = 253\ \Omega \quad / \quad R_{DS} = \frac{1}{k_n V_{ov}} \Rightarrow \frac{1}{1 \cdot (5-1)} = 250\ \Omega$$

ex: 5.6



$V_{TH} = 1$ V, $k_n'(W/L) = 1$ mA/V^2, $(\lambda = 0)$

Determine all voltages and currents

$$V_G = V_{DD}\frac{R_{G2}}{R_{G2} + R_{G1}} = 10\,\frac{10}{10+10} = 5 \text{ V}$$

→ Biasing

$I_D = 0{,}5$ mA

$V_S = 0{,}5 \cdot 6 = 3$ V

$V_{GS} = 5 - 3 = 2$ V $(\rightarrow > V_{TH}$ ✓)

$V_D = 10 - 6 \cdot 0{,}5 = 7$ V

← Varsayım 1: sat

$$I_D = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_{TH})^2$$

$$I_D = \frac{1}{2} \cdot 1 \cdot (5 - 6I_D - 1)^2$$

$$18I_D^2 - 25I_D + 8 = 0$$

$I_D = 0{,}89$ (üstü çizili) , $\boxed{I_D = 0{,}5}$

↑ Bunu seçince V_{GS} negatif olur

orj. s. ?

12. hafta

Kenar notları: "? BJT / Mosfet", "Appendix ? K"

Comparison of the Mosfet and the BJT

Typical values of CMOS device parameters

	0,8 µm		0,5 µm		0,25 µm		0,18 µm		0,13 µm		65 nm
Parameter	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS	NMOS
t_{ox}	15	15	9	9	6	6	4	4	2,7	2,7	1,4
C_{ox}	2,3	2,3	3,8	3,8	5,8	5,8	8,6	8,6	12,8	12,8	25
μ	550	250	500	180	460	160	450	100	400	100	216
μC_{ox}	127	58	190	68	267	93	387	86	511	128	540
V_{THO}	0,7	−0,7	0,7	−0,8	0,5	−0,6	0,5	−0,5	0,4	−0,4	0,35
V_{DD}	5	5	3,3	3,3	2,5	2,5	1,8	1,8	1,3	1,3	1,0
$\lvert V'_A \rvert$	25	20	20	10	5	6	5	6	5	6	3
C_{ov}	0,2	0,2	0,4	0,4	0,3	0,3	0,37	0,33	0,36	0,33	0,33

(65 nm sütununun PMOS kısmı sayfa kenarında kalmış, görünmüyor.)

µ satırından ok: → NMOS'ta hep daha büyüktür çünkü taşıyıcı olarak ?kul...

Table 6.2 – BJT

	High voltage		Low voltage	
Parameter	npn	lateral pnp	npn	lateral pnp
A_E (μm^2)	500	?900	2	2
I_S (A)	5×10^{-15}	$2 \cdot 10^{-15}$	$6 \cdot 10^{-18}$	$6 \cdot 10^{-18}$
β_O	200	50	100	50
V_A (V)	130	50	35	30
τ_F	0,35 ns	30 ns	10 ps	650 ps

orj. s. 8 Sol üst köşe: "?Page 6.3"

Örnek 6.1

a) NMOS → $\frac{W}{L} = 10$, 0,18 µm process

V_{ov}, V_{GS} =? → $I_D = 100\ \mu A$, $(\lambda = 0)$

b) Table 6.2 → npn → low voltage process – $I_C = 100\ \mu A$

Çözüm:

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)V_{ov}^2$$

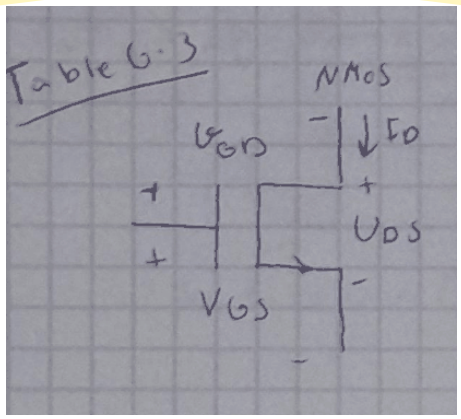
$$100\ \mu A = \frac{1}{2}\cdot 387 \cdot 10 \cdot V_{ov}^2 \Rightarrow 0{,}23\ V = V_{ov}$$

$$V_{GS} = V_{TH} + V_{ov} = 0{,}5 + 0{,}23 = 0{,}73\ V$$

b) $I_C = 100\ \mu A$ $\quad I_C = I_S e^{V_{BE}/V_T} \rightarrow I_S = 6 \cdot 10^{-18}$

$$\hookrightarrow V_{BE} = 0{,}025 \ln \frac{100 \cdot 10^{-6}}{6 \cdot 10^{-18}} = 0{,}76\ V$$

Table 6.3



orijinal çizim, s. 8

Active reg. ① $V_{GS} \geq V_{TH}$, $V_{TH} \approx 0{,}3\ V - 0{,}5\ V$

$V_{GS} = V_{TH} + V_{ov}$

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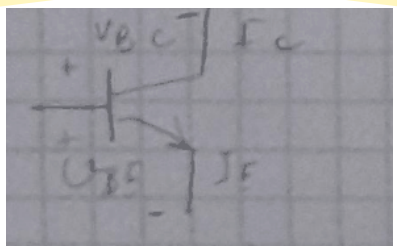
② Pinch off

$V_{GD} < V_{TH}$

$V_{DS} > V_{ov}$, $V_{ov} \approx 0{,}1\ V \longleftrightarrow 0{,}3\ V$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2\left(1 + \frac{V_{DS}}{V_A}\right)$$

$I_G = 0$



orijinal çizim, s. 8

$V_{BE} \geq V_{BE\,on}$, $V_{BE\,on} \approx 0{,}5$, Forward bias (EBJ)

Reverse bias

$V_{BC} < V_{BC\,on}$, $V_{BC\,on} \approx 0{,}4\ V$

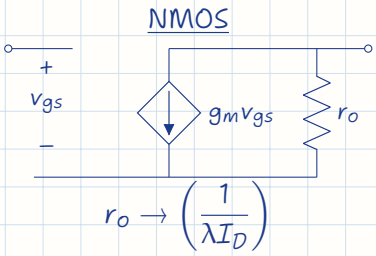
$V_{CE} \geq 0{,}3\ V$

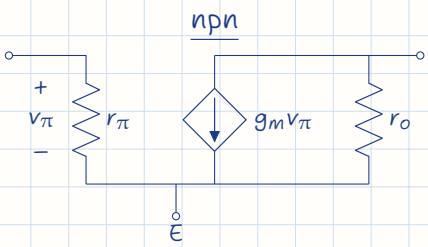
$$I_C = I_S e^{V_{BE}/V_T}\left(1 + \frac{V_{CE}}{V_A}\right)$$

$$I_B = \frac{I_C}{\beta}$$

orj. s. 9 Üstte silik kurşun kalem notu: ?Learn chapter ... circuits

Small signal





geçiş iletkenliği $g_m = \dfrac{I_D}{V_{ov}/2}$

(Transconductance)

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{ov}$$

$$g_m = \sqrt{2\,\mu_n C_{ox} \frac{W}{L} I_D}$$

$g_m = I_C / V_T$

$r_o = V_A / I_C$

$r_\pi = \beta / g_m$

Örnek 6.2

0,25 µm process → g_m, r_o, A_o → intrinsic gain → $A_o = g_m \cdot r_o$, R_{in}?

npn → 100 µA, L = 0,4 µm, W = 4 µm



Çözüm:

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 \rightarrow$$

$$100 = \frac{1}{2} \cdot 267 \cdot \frac{4}{0{,}4} \cdot V_{ov}^2$$

MOSFET → V_{ov} = 0,27 V

$$g_m = \sqrt{2\,(\mu_n C_{ox}) \left(\frac{W}{L}\right) I_D} = 0{,}73 \text{ mA/V}$$

$$R_{in} = \infty, \qquad r_o = \frac{V_A L}{I_D} = 20 \text{ k}\Omega$$

$$A_o = g_m r_o = (0{,}73)(20) = 14{,}6 \text{ V/V}$$

$$g_m = \frac{I_C}{V_T} = \frac{0{,}1}{0{,}025} = 4 \text{ mA/V}$$

$$R_{in} = r_\pi = \frac{\beta}{g_m} = \frac{100}{40}^{*} = 25 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{35}{0{,}1} = 350 \text{ k}\Omega$$

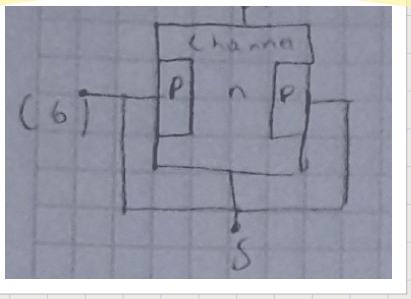
$$A_o = g_m r_o = 4 \cdot 350 = 1400 \text{ V/V}$$

* Claude notu: muhtemelen $\frac{100}{4}$ olmalı (g_m = 4 mA/V ile r_π = 25 kΩ).

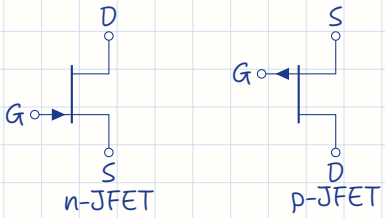
orj. s. 10

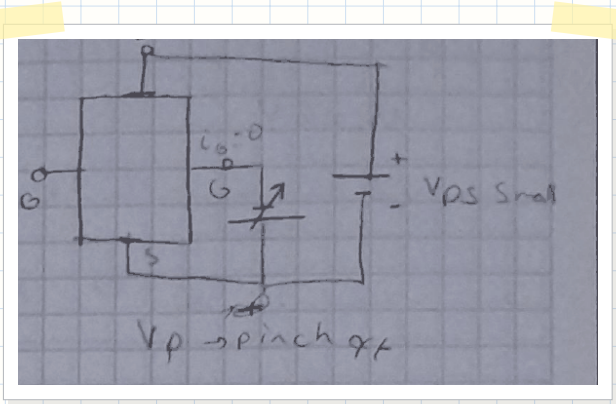
Sol üst köşede silik not: ? okunamadı

JFET → Junction field effect transistor



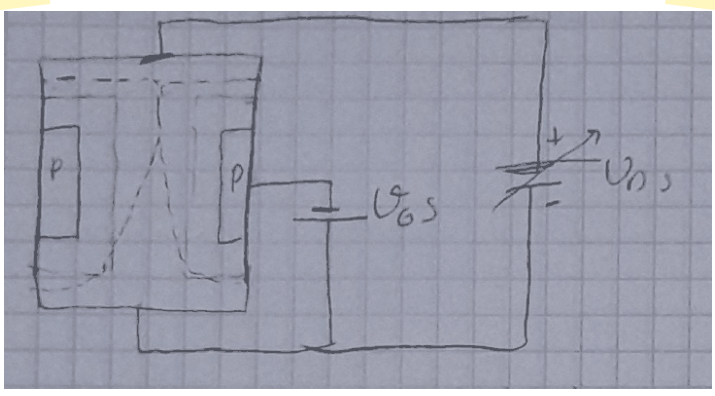
orijinal çizim, s. 10





orijinal çizim, s. 10

$V_P \rightarrow$ pinch off
Cut off $V_{GS} \leq V_P$, $i_D = 0$



orijinal çizim, s. 10

Saturation (pinch off) $V_P \le V_{GS} < 0$

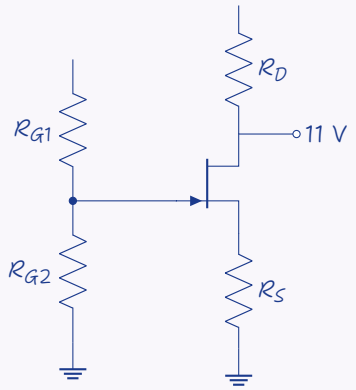
$$V_{DS} \ge V_{GS} - V_P$$

$$i_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 (1 + \lambda V_{DS})$$

Triode $V_P \le V_{GS} \le 0, \quad V_{DS} \le V_{GS} - V_P$

$$i_D = I_{DSS}\left[2\left(1 - \frac{V_{GS}}{V_P}\right)\left(\frac{V_{DS}}{-V_P}\right) - \left(\frac{V_{DS}}{V_P}\right)^2\right]$$

Örnek (PS 4.7)



$V_P = -3$ V, $I_{DSS} = 9$ mA, $\lambda = 0$
$V_G = 5$ V, $I_D = 4$ mA, $V_D = 11$ V
Design for 0,05 mA

Çözüm:

$$15 \cdot \frac{R_{G2}}{R_{G1} + R_{G2}} = 5\ \text{V} \Rightarrow \begin{matrix} R_{G1} = x \\ R_{G2} = 2x \end{matrix} \quad *$$

* Claude notu: muhtemelen $R_{G1} = 2x$, $R_{G2} = x$ olmalı (aşağıdaki sonuç değerleriyle uyumlu).

$$\frac{15}{3x} = 0{,}05\ \text{mA} \Longrightarrow x = 100\ \text{k}\Omega \qquad \begin{matrix} R_{G1} = 200\ \text{k}\Omega \\ R_{G2} = 100\ \text{k}\Omega \end{matrix}$$

$$R_D = \frac{15 - 11}{4\ \text{mA}} = 1\ \text{k}\Omega$$

$$V_{DS} \ge V_{GS} - V_P \Rightarrow V_D > V_G + 3$$

$$\downarrow$$

$$11 > 5 + 3 \rightarrow 11 > 8$$

$\rightarrow$ (pinch-off)

orj. s. 11

Çözüm:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$\sqrt{\frac{4}{9}} = \left(1 - \frac{V_{GS}}{V_P}\right) \Rightarrow \frac{2}{3} = 1 + \frac{V_{GS}}{3}$$

$$V_{GS} = 1^*$$

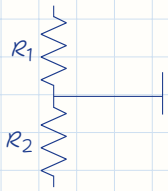
* Claude notu: muhtemelen $V_{GS} = -1$ V olmalı ($V_S = 5 - (-1) = 6$ V ile uyumlu).

$V_S = 6$ V

$$R_S = \frac{6}{4\text{m}} = 1{,}5\ \text{k}\Omega$$

$i_G = 0$ her zaman

ELM 231 Proje: Son teslim 28.11.2022



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