Chapter 5

Exercise Solutions

E5.1

(a) $V_{TN} = 1.2\,V$, $V_{GS} = 2\,V$

$V_{DS}(sat) = V_{GS} - V_{TN} = 2 - 1.2 = 0.8\,V$

(i) $V_{DS} = 0.4 \Rightarrow$ Nonsaturation

(ii) $V_{DS} = 1 \Rightarrow$ Saturation

(iii) $V_{DS} = 5 \Rightarrow$ Saturation

(b) $V_{TN} = -1.2\,V$, $V_{GS} = 2\,V$

$V_{DS}(sat) = V_{GS} - V_{TN} = 2 - (-1.2) = 3.2\,V$

(i) $V_{DS} = 0.4 \Rightarrow$ Nonsaturation

(ii) $V_{DS} = 1 \Rightarrow$ Nonsaturation

(iii) $V_{DS} = 5 \Rightarrow$ Saturation

E5.2

(a) $K_n = \dfrac{W\mu_n C_{ox}}{2L}$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.85x10^{-14})}{450x10^{-8}} = 7.67x10^{-8}\ F/cm$$

$$K_n = \frac{(100)(500)(7.67x10^{-8})}{2(7)} \Rightarrow \underline{K_n = 0.274\ mA/V^2}$$

(b) $V_{TN} = 1.2\,V$, $V_{GS} = 2\,V$

(i) $V_{DS} = 0.4\,V \Rightarrow$ Nonsaturation

$I_D = (0.274)\left[2(2-1.2)(0.4) - (0.4)^2\right] \Rightarrow$

$\underline{I_D = 0.132\ mA}$

(ii) $V_{DS} = 1\,V \Rightarrow$ Saturation

$I_D = (0.274)(2-1.2)^2 \Rightarrow \underline{I_D = 0.175\ mA}$

(iii) $V_{DS} = 5\,V \Rightarrow$ Saturation

$I_D = (0.274)(2-1.2)^2 \Rightarrow \underline{I_D = 0.175\ mA}$

$V_{TN} = -1.2\,V$, $V_{GS} = 2\,V$

(i) $V_{DS} = 0.4\,V \Rightarrow$ Nonsaturation

$I_D = (0.274)\left[2(2+1.2)(0.4) - (0.4)^2\right] \Rightarrow$

$I_D = 0.658\ mA$

(ii) $V_{DS} = 1\,V \Rightarrow$ Nonsaturation

$I_D = (0.274)\left[2(2+1.2)(1) - (1)^2\right] \Rightarrow \underline{I_D = 1.48\ mA}$

(iii) $V_{DS} = 5\,V \Rightarrow$ Saturation

$I_D = (0.274)(2+1.2)^2 \Rightarrow \underline{I_D = 2.81\ mA}$

E5.3

$V_{TN} = 1\,V$, $V_{GS} = 3\,V$, $V_{DS} = 4.5\,V$

$V_{DS} = 4.5 > V_{DS}(sat) = V_{GS} - V_{TN} = 3 - 1 = 2\,V$

Transistor biased in the saturation region

$I_D = K_n(V_{GS} - V_{TN})^2 \Rightarrow 0.8 = K_n(3-1)^2 \Rightarrow$

$K_n = 0.2\ mA/V^2$

(a) $V_{GS} = 2\,V$, $V_{DS} = 4.5\,V$

Saturation region:

$I_D = (0.2)(2-1)^2 \Rightarrow \underline{I_D = 0.2\ mA}$

(b) $V_{GS} = 3\,V$, $V_{DS} = 1\,V$

Nonsaturation region:

$I_D = (0.2)\left[2(3-1)(1) - (1)^2\right] \Rightarrow \underline{I_D = 0.6\ mA}$

E5.4

(a) $V_{TP} = -2\,V$, $V_{SG} = 3\,V$

$V_{SD}(sat) = V_{SG} + V_{TP} = 3 - 2 = 1\,V$

(i) $V_{SD} = 0.5\,V \Rightarrow$ Nonsaturation

(ii) $V_{SD} = 2\,V \Rightarrow$ Saturation

(iii) $V_{SD} = 5\,V \Rightarrow$ Saturation

(b) $V_{TP} = 0.5\,V$, $V_{SG} = 3\,V$

$V_{SD}(sat) = V_{SG} + V_{TP} = 3 + 0.5 = 3.5\,V$

(i) $V_{SD} = 0.5\,V \Rightarrow$ Nonsaturation

(ii) $V_{SD} = 2\,V \Rightarrow$ Nonsaturation

(iii) $V_{SD} = 5\,V \Rightarrow$ Saturation

E5.5

(a) $\lambda = 0$, $V_{DS}(sat) = 2.5 - 0.8 = 1.7\,V$

For $V_{DS} = 2\,V$, $V_{DS} = 10\,V \Rightarrow$ Saturation Region

$I_D = (0.1)(2.5-0.8)^2 \Rightarrow \underline{I_D = 0.289\ mA}$

(b) $\lambda = 0.02\ V^{-1}$

$I_D = K_n(V_{GS} - V_{TN})^2(1 + \lambda V_{DS})$

For $V_{DS} = 2\,V$

$I_D = (0.1)(2.5-0.8)^2[1 + (0.02)(2)] \Rightarrow$

$\underline{I_D = 0.300\ mA}$

$V_{DS} = 10\,V$

$I_D = (0.1)\left[(2.5-0.8)^2(1 + (0.02)(10))\right] \Rightarrow$

$\underline{I_D = 0.347\ mA}$

(c) For part (a), $\lambda = 0 \Rightarrow \underline{r_o = \infty}$

For part (b), $\lambda = 0.02\ V^{-1}$,

$r_o = \left[\lambda K_n (V_{GS} - V_{TN})^2\right]^{-1} = \left[(0.02)(0.1)(2.5-0.8)^2\right]^{-1}$

or $\underline{r_o = 173\ k\Omega}$

E5.6

$$V_{TN} = V_{TNO} + \gamma\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right]$$

$2\phi_f = 0.70\,V,\quad V_{TNO} = 1\,V$

(a) $V_{SB} = 0 \Rightarrow,\ \underline{V_{TN} = 1\,V}$

(b) $V_{SB} = 1\,V$,

$V_{TN} = 1 + (0.35)\left[\sqrt{0.7+1} - \sqrt{0.7}\right] \Rightarrow \quad V_{TN} = 1.16\,V$

(c) $V_{SB} = 4\,V$,

$V_{TN} = 1 + (0.35)\left[\sqrt{0.7+4} - \sqrt{0.7}\right] \Rightarrow \ V_{TN} = 1.47\,V$

E5.7

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(10) - 5 = \left(\frac{40}{40+60}\right)(10) - 5$$

$V_G = -1\,V$

$V_S = I_D R_S - 5$

Then

$V_{GS} = V_G - V_S = -1 - (I_D R_S - 5) = 4 - I_D R_S$

Assume transistor is biased in saturation region

$$I_D = K_n(V_{GS} - V_{TN})^2 = \frac{4 - V_{GS}}{R_S}$$

$4 - V_{GS} = (0.5)(0.1)[V_{GS} - 1]^2 \Rightarrow$

$0.5V_{GS}^2 - 3.5 = 0 \Rightarrow \quad \underline{V_{GS} = 2.65\,V}$

$I_D = (0.5)(2.65 - 1)^2 \Rightarrow \quad \underline{I_D = 1.36\,mA}$

$V_{DS} = 10 - I_D(R_S + R_D) = 10 - (1.36)(1+2) \Rightarrow$

$\underline{V_{DS} = 5.92\,V}$

$V_{DS} > V_{DS}(sat)$, Yes

E5.8

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(10) - 5$$

$$= \left(\frac{200}{350}\right)(10) - 5 = 0.714\ \text{V}$$

$V_S = 5 - I_D R_S = 5 - (1.2)I_D$

So

$V_{SG} = V_S - V_G = 5 - (1.2)I_D - 0.714$

$\quad = 4.286 - (1.2)I_D$

$$I_D = \frac{4.286 - V_{SG}}{1.2}$$

$I_D = K_p(V_{SG} + V_{TP})^2$

$4.286 - V_{SG} = (1.2)(0.25) \times$

$\quad (V_{SG}^2 - 2V_{SG}(-1) + (-1)^2)$

$4.286 - V_{SG} = (0.3)V_{SG}^2 - 0.6V_{SG} + 0.3$

$0.3V_{SG}^2 + 0.4V_{SG} - 3.986 = 0$

$$V_{SG} = \frac{-0.4 \pm \sqrt{(0.4)^2 + 4(0.3)(3.986)}}{2(0.3)}$$

Must use + sign $\Rightarrow \underline{V_{SG} = 3.04\ \text{V}}$

$I_D = (0.25)(3.04 - 1)^2 \Rightarrow \underline{I_D = 1.04\ \text{mA}}$

$V_{SD} = 10 - I_D(R_S + R_D) = 10 - (1.04)(1.2 + 4)$

$\Rightarrow \underline{V_{SD} = 4.59\ \text{V}}$

$V_{SD} > V_{SD}(sat)$, Yes

E5.9

$I_D = K_n(V_{GS} - V_{TN})^2$

$0.4 = 0.25(V_{GS} - 0.8)^2 \Rightarrow V_{GS} = 2.06\ \text{V}$

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD}$$

$$2.06 = \left(\frac{R_2}{250}\right)(7.5) \Rightarrow \underline{R_2 = 68.7\ \text{k}\Omega}$$

$\underline{R_1 = 181.3\ \text{k}\Omega}$

$V_{DS} = 4 = V_{DD} - I_D R_D$

$$R_D = \frac{7.5 - 4}{0.4} \Rightarrow \underline{R_D = 8.75\ \text{k}\Omega}$$

$V_{DS} > V_{DS}(sat)$, Yes

E5.10

$$I_D = \frac{V_S - (-5)}{R_S} \text{ and } V_S = -V_{GS}$$

$$\text{So } R_S = \frac{5 - V_{GS}}{0.1}$$

$I_D = K_n(V_{GS} - V_{TN})^2$

$0.1 = (0.080)(V_{GS} - 1.2)^2 \Rightarrow V_{GS} = 2.32\ \text{V}$

$$\text{So } R_S = \frac{5 - 2.32}{0.1} \Rightarrow \underline{R_S = 26.8\ \text{k}\Omega}$$

$V_{DS} = V_D - V_S \Rightarrow V_D = V_{DS} + V_S = 4.5 - 2.32$

$V_D = 2.18$

$$R_D = \frac{5 - V_D}{I_D} = \frac{5 - 2.18}{0.1} \Rightarrow \underline{R_D = 28.2\ \text{k}\Omega}$$

$V_{DS} > V_{DS}(sat)$, Yes

E5.11

$$I_D = \frac{10 - V_{SG}}{R_S} \text{ and } \quad I_D = K_p(V_{SG} + V_{TP})^2$$

$0.12 = (0.050)(V_{SG} - 0.8)^2$

$V_{SG} = 2.35\ \text{V}$

$$R_S = \frac{10 - 2.35}{0.12} \Rightarrow \underline{R_S = 63.75\ \text{k}\Omega}$$

$V_{SD} = 8 = 20 - I_D(R_S + R_D)$

$8 = 20 - (0.12)(63.75) - (0.12)R_D$

$$R_D = \frac{20 - (0.12)(63.75) - 8}{0.12}$$

$\Rightarrow R_D = 36.25\ \text{k}\Omega$

E5.12

$$I_D = \frac{V_{DD} - V_{GS}}{R_S}, \quad I_D = K_n(V_{GS} - V_{TN})^2$$
$$10 - V_{GS} = (10)(0.2)(V_{GS}^2 - 2V_{GS}V_{TN} + V_{TN}^2)$$
$$10 - V_{GS} = 2V_{GS}^2 - 8V_{GS} + 8$$
$$2V_{GS}^2 - 7V_{GS} - 2 = 0$$
$$V_{GS} = \frac{7 \pm \sqrt{(7)^2 + 4(2)2}}{2(2)}$$

Use + sign: $\underline{V_{GS} = V_{DS} = 3.77\ \text{V}}$

$$I_D = \frac{10 - 3.77}{10} \Rightarrow \underline{I_D = 0.623\ \text{mA}}$$
$$\text{Power} = I_D V_{DS} = (0.623)(3.77)$$
$$\Rightarrow \underline{\text{Power} = 2.35\ \text{mW}}$$

E5.13

For $V_{DS} = 2.2\ V$

$$I_D = \frac{5 - 2.2}{5} \Rightarrow \underline{I_D = 0.56\ mA}$$
$$I_D = K_n(V_{GS} - V_{TN})^2$$
$$0.56 = K_n(2.2 - 1)^2$$
$$K_n = 0.389\ mA/V = \frac{W}{L} \cdot \frac{\mu_n C_{ox}}{2}$$
$$\frac{W}{L} = \frac{(389)(2)}{(40)} \Rightarrow \underline{\frac{W}{L} = 19.5}$$

E5.14

(a) The transition point is

$$V_{It} = \frac{V_{DD} - V_{TNL} + V_{TND}\left(1 + \sqrt{K_{nD}/K_{nL}}\right)}{1 + \sqrt{K_{nD}/K_{nL}}}$$
$$= \frac{5 - 1 + 1\left(1 + \sqrt{0.05/0.01}\right)}{1 + \sqrt{0.05/0.01}}$$
$$= \frac{7.236}{3.236} \Rightarrow \underline{V_{It} = 2.24\ \text{V}}$$
$$V_{Ot} = V_{It} - V_{TND} = 2.24 - 1 \Rightarrow \underline{V_{Ot} = 1.24\ V}$$

(b) We may write

$$I_D = K_{nD}(V_{GSD} - V_{TND})^2 = (0.05)(2.24 - 1)^2$$
$$\Rightarrow \underline{I_D = 76.9\ \mu A}$$

E5.15

$$V_{It} = \frac{V_{DD} - V_{TNL} + V_{TND}\left(1 + \sqrt{K_{nD}/K_{nL}}\right)}{1 + \sqrt{K_{nD}/K_{nL}}}$$
$$2.5 = \frac{5 - 1 + 1\left(1 + \sqrt{K_{nD}/K_{nL}}\right)}{1 + \sqrt{K_{nD}/K_{nL}}}$$
$$2.5 + 2.5\sqrt{K_{nD}/K_{nL}} = 5 + \sqrt{K_{nD}/K_{nL}} \Rightarrow$$
$$\sqrt{K_{nD}/K_{nL}} = \frac{5 - 2.5}{1.5} = 1.67 \Rightarrow$$
$$\underline{K_{nD}/K_{nL} = 2.78}$$

b. For $V_I = 5$, driver in nonsaturated region.

$$I_{DD} = I_{DL}$$
$$K_{nD}\left[2(V_I - V_{TND})V_O - V_O^2\right] = K_{nL}(V_{GSL} - V_{TNL})^2$$
$$\frac{K_{nD}}{K_{nL}}\left[2(V_I - V_{TND})V_O - V_O^2\right] = \left[V_{DD} - V_O - V_{TNL}\right]^2$$
$$2.78\left[2(5 - 1)V_0 - V_0^2\right] = [5 - V_0 - 1]^2$$
$$22.24V_0 - 2.78V_0^2 = (4 - V_0)^2$$
$$= 16 - 8V_0 + V_0^2$$
$$3.78V_0^2 - 30.24V_0 + 16 = 0$$
$$V_0 = \frac{30.24 \pm \sqrt{(30.24)^2 - 4(3.78)(16)}}{2(3.78)}$$
$$\Rightarrow \underline{V_0 = 0.57\ \text{V}}$$

E5.16

If the transistor is biased in the saturation region

$$I_D = K_n(V_{GS} - V_{TN})^2 = K_n(-V_{TN})^2$$
$$I_D = (0.25)(2.5)^2 \Rightarrow \underline{I_D = 1.56\ \text{mA}}$$
$$V_{DS} = V_{DD} - I_D R_S = 10 - (1.56)(4)$$
$$\Rightarrow \underline{V_{DS} = 3.76}$$
$$V_{DS} > V_{GS} - V_{TN} = -V_{TN}$$
$$3.76 > -(-2.5)$$

Yes — biased in the saturation region

$$\text{Power} = I_D V_{DS} = (1.56)(3.76)$$
$$\Rightarrow \underline{\text{Power} = 5.87\ \text{mW}}$$

E5.17

We have $V_{DS} = 1.2\ V < V_{GS} - V_{TN} = -V_{TN} = 1.8\ V$

Transistor is biased in the nonsaturation region.

$$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$$

and

$$I_D = \frac{V_{DD} - V_{DS}}{R_S} = \frac{5 - 1.2}{8} \Rightarrow$$
$$I_D = 0.475\ mA$$
$$0.475 = K_n\left[2(0 - (-1.8))(1.2) - (1.2)^2\right]$$
$$0.475 = K_n(2.88) \Rightarrow \quad K_n = 0.165\ mA/V^2$$
$$K_n = \frac{W}{L} \cdot \frac{\mu_n C_{ox}}{2}$$
$$\frac{W}{L} = \frac{(165)(2)}{35} \Rightarrow \underline{\frac{W}{L} = 9.43}$$

E5.18

(a) Transition point for the load transistor – Driver is in the saturation region.

$I_{DD} = I_{DL}$

$K_{nD}(V_{GSD} - V_{TND})^2 = K_{nL}(V_{GSL} - V_{TNL})^2$

$V_{DSL}(sat) = V_{GSL} - V_{TNL} = -V_{TNL}$

$\Rightarrow V_{DSL} = V_{DD} - V_{Ot} = 2\,V$

Then $V_{Ot} = 5 - 2 = 3\,V$, $\underline{V_{Ot} = 3\,V}$

$\sqrt{\frac{K_{nD}}{K_{nL}}}(V_{It} - 1) = (-V_{TNL})$

$\sqrt{\frac{0.08}{0.01}}(V_{It} - 1) = 2 \Rightarrow \underline{V_{It} = 1.89\,V}$

(b) For the driver:

$V_{Ot} = V_{It} - V_{TND}$

$\underline{V_{It} = 1.89\,V, \quad V_{Ot} = 0.89\,V}$

E5.19

(a) For $V_I = 5\,V$, Load in saturation and driver in nonsaturation.

$I_{DD} = I_{DL}$

$K_{nD}\left[2(V_I - V_{TND})V_O - V_O^2\right] = K_{nL}(-V_{TNL})^2$

$\frac{K_{nD}}{K_{nL}}\left[2(5-1)(0.25) - (0.25)^2\right] = 4 \Rightarrow$

$\frac{K_{nD}}{K_{nL}} = 2.06$

(b) $I_{DL} = K_{nL}(-V_{TNL})^2 \Rightarrow 0.2 = K_{nL}[-(-2)]^2$

$\underline{K_{nL} = 50\,\mu A/V^2}$ and $\underline{K_{nD} = 103\,\mu A/V^2}$

E5.20

(a) $I_{REF} = K_{n3}(V_{GS3} - V_{TN})^2 = K_{n4}(V_{GS4} - V_{TN})^2$

$V_{GS3} = 2\,V \Rightarrow V_{GS4} = 3\,V$

$(2-1)^2 = \frac{K_{n4}}{K_{n3}}(3-1)^2 \Rightarrow \underline{\frac{K_{n4}}{K_{n3}} = \frac{1}{4}}$

(b) $I_Q = K_{n2}(V_{GS2} - V_{TN})^2$

But $V_{GS2} = V_{GS3} = 2\,V$

$0.1 = K_{n2}(2-1)^2 \Rightarrow \underline{K_{n2} = 0.1\,mA/V^2}$

(c) $0.2 = K_{n3}(2-1)^2 \Rightarrow \underline{K_{n3} = 0.2\,mA/V^2}$

$0.2 = K_{n4}(3-1)^2 \Rightarrow \underline{K_{n4} = 0.05\,mA/V^2}$

E5.21

For $R_D = 10\,k\Omega, V_{DD} = 5\,V$, and $V_o = 1\,V$

$I_D = \frac{5-1}{10} = 0.4\,mA$

$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$

$I_D = 0.4 = K_n\left[2(5-1)(1) - (1)^2\right] \Rightarrow$

$\underline{K_n = 0.057\,mA/V^2}$

$P = I_D \cdot V_{DS} = (0.4)(1) \Rightarrow \underline{P = 0.4\,mW}$

E5.22

$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$

$= (0.050)\left[2(10 - 0.7)(0.35) - (0.35)^2\right]$

$I_D = 0.319$ mA

$R_D = \frac{V_{DD} - V_0}{I_D} = \frac{10 - 0.35}{0.319}$

$\Rightarrow \underline{R_D = 30.3\text{ k}\Omega}$

E5.23

(a) Transistor biased in the nonsaturation region

$I_D = \frac{5 - 1.5 - V_{DS}}{R} = 12$

$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$

$12 = 4\left[2(5 - 0.8)V_{DS} - V_{DS}^2\right]$

$4V_{DS}^2 - 33.6V_{DS} + 12 = 0 \Rightarrow \underline{V_{DS} = 0.374\,V}$

Then

$R = \frac{5 - 1.5 - 0.374}{12} \Rightarrow \underline{R = 261\,\Omega}$

E5.24

a. $V_1 = 5$ V, $V_2 = 0$, M_2 cutoff $\Rightarrow \underline{I_{D2} = 0}$

$I_D = K_n\left[2(V_I - V_{TN})V_O - V_O^2\right] = \frac{5 - V_O}{R_D}$

$(0.05)(30)\left[2(5-1)V_0 - V_0^2\right] = 5 - V_0$

$1.5V_0^2 - 13V_0 + 5 = 0$

$V_0 = \frac{13 \pm \sqrt{(13)^2 - 4(1.5)(5)}}{2(1.5)} \Rightarrow \underline{V_0 = 0.40\text{ V}}$

$I_R = I_{D1} = \frac{5 - 0.40}{30} \Rightarrow \underline{I_R = I_{D1} = 0.153\text{ mA}}$

b. $V_1 = V_2 = 5$ V

$\frac{5 - V_O}{R_D} = 2\left\{K_n\left[2(V_I - V_{TN})V_O - V_O^2\right]\right\}$

$5 - V_0 = 2(0.05)(30)\left[2(5-1)V_0 - V_0^2\right]$

$3V_0^2 - 25V_0 + 5 = 0$

$$V_0 = \frac{25 \pm \sqrt{(25)^2 - 4(3)(5)}}{2(3)} \Rightarrow \underline{V_0 = 0.205 \text{ V}}$$

$$I_R = \frac{5 - 0.205}{30} \Rightarrow \underline{I_R = 0.160 \text{ mA}}$$

$$\underline{I_{D1} = I_{D2} = 0.080 \text{ mA}}$$

E5.25

(a) $I_D = \dfrac{5-V_O}{R_D} = K_n\left[2(V_I - V_{TN})V_O - V_O^2\right]$

$$\frac{5-(0.10)}{25} = K_n\left[2(5-1)(0.10)-(0.10)^2\right] \Rightarrow$$

$$\underline{K_n = 0.248 \; mA/V^2}$$

b. $\dfrac{5 - V_0}{25} = 2(0.248)\left[2(5-1)V_0 - V_0^2\right]$

$$5 - V_0 = 12.4\left[8V_0 - V_0^2\right]$$

$$12.4V_0^2 - 100.2V_0 + 5 = 0$$

$$V_0 = \frac{100.2 \pm \sqrt{(100.2)^2 - 4(12.4)(5)}}{2(12.4)}$$

$$\Rightarrow \underline{V_0 = 0.0502 \text{ V}}$$

E5.26

$$V_{DS}(\text{sat}) = V_{GS} - V_P = -1.2 - (-4.5)$$

$$\Rightarrow \underline{V_{DS}(\text{sat}) = 3.3 \text{ V}}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 12\left(1 - \frac{(-1.2)}{(-4.5)}\right)^2$$

$$\Rightarrow \underline{I_D = 6.45 \text{ mA}}$$

E5.27

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

$$1.2 = 2\left(1 - \frac{V_{GS}}{(-2.5)}\right)^2 \Rightarrow \underline{V_{GS} = -0.564 \text{ V}}$$

E5.28

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

$$3 = I_{DSS}\left(1 - \frac{0.8}{3.8}\right)^2 \Rightarrow \underline{I_{DSS} = 4.81 \text{ mA}}$$

$$V_{SD}(\text{sat}) = V_P - V_{GS} = 3.8 - 0.8$$

$$\underline{V_{SD}(\text{sat}) = 3.0 \text{ V}}$$

E5.29

$$I_D = K\left(V_{GS} - V_{TN}\right)^2$$

a. $V_{GS} = 0.35 \Rightarrow I_D = 25(0.35 - 0.25)^2$
$\Rightarrow \underline{I_D = 0.25 \; \mu\text{A}}$

b. $V_{GS} = 0.50 \Rightarrow I_D = 25(0.50 - 0.25)^2$
$\Rightarrow \underline{I_D = 1.56 \; \mu\text{A}}$

E5.30

Assume the transistor is biased in the saturation region.

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

$$8 = 18\left(1 - \frac{V_{GS}}{(-3.5)}\right)^2 \Rightarrow \underline{V_{GS} = -1.17 \text{ V}}$$

$$\Rightarrow V_S = -V_{GS} = 1.17$$

$$V_D = 15 - (8)(0.8) = 8.6$$

$$V_{DS} = 8.6 - (1.17) = 7.43 \text{ V}$$

$$V_{DS} = 7.43 > V_{GS} - V_P = -1.17 - (-3.5)$$

$$= 2.33$$

Yes, the transistor is biased in the saturation region.

E5.31

$$I_D = 2.5 \text{ mA}$$

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

$$2.5 = 6\left(1 - \frac{V_{GS}}{(-4)}\right)^2 \Rightarrow V_{GS} = -1.42 \text{ V}$$

$$V_S = I_D R_S - 5 = (2.5)(0.25) - 5$$

$$V_S = -4.375$$

$$V_{DS} = 6 \Rightarrow V_D = 6 - 4.375 = 1.625$$

$$R_D = \frac{5 - 1625}{2.5} \Rightarrow \underline{R_D = 1.35 \text{ k}\Omega}$$

$$\frac{(20)^2}{R_1 + R_2} = 2 \Rightarrow R_1 + R_2 = 200 \text{ k}\Omega$$

$$V_G = V_{GS} + V_S = -1.42 - 4.375 = -5.795$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(20) - 10$$

$$-5.795 = \left(\frac{R_2}{200}\right)(20) - 10 \Rightarrow$$

$$\underline{R_2 = 42.05 \text{ k}\Omega} \rightarrow \underline{42 \text{ k}\Omega}$$

$$\underline{R_1 = 157.95 \text{ k}\Omega} \rightarrow \underline{158 \text{ k}\Omega}$$

E5.32

$V_S = -V_{GS}.\quad I_D = \dfrac{0 - V_S}{R_S} = \dfrac{V_{GS}}{R_S}$

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

$\dfrac{V_{GS}}{1} = 6\left(1 - \dfrac{V_{GS}}{4}\right)^2 = 6\left(1 - \dfrac{V_{GS}}{2} + \dfrac{V_{GS}^2}{16}\right)$

$0.375V_{GS}^2 - 4V_{GS} + 6 = 0$

$V_{GS} = \dfrac{4 \pm \sqrt{16 - 4(0.375)(6)}}{2(0.375)}$

$\underbrace{V_{GS} = 8.86}_{\text{impossible}}$ or $\underline{V_{GS} = 1.81 \text{ V}}$

$\underline{I_D = \dfrac{V_{GS}}{R_S} = 1.81 \text{ mA}}$

$V_D = I_D R_D - 5 = (1.81)(0.4) - 5 = -4.276$

$V_{SD} = V_S - V_D = -1.81 - (-4.276)$

$\Rightarrow \underline{V_{SD} = 2.47 \text{ V}}$

$V_{SD}(\text{sat}) = V_P - V_{GS} = 4 - 1.81 = 2.19$

So $V_{SD} > V_{SD}(\text{sat})$

E5.33

$R_{in} = R_1 \| R_2 = \dfrac{R_1 R_2}{R_1 + R_2} = 100 \text{ k}\Omega$

$I_{DQ} = 5 \text{ mA},\quad V_S = -I_{DQ}R_S = -(5)(1.2) = -6 \text{ V}$

$V_{SDQ} = 12 \text{ V} \Rightarrow V_D = V_S - V_{SDQ}$

$= -6 - 12 = -18 \text{ V}$

$R_D = \dfrac{-18 - (-20)}{5} \Rightarrow \underline{R_D = 0.4 \text{ k}\Omega}$

$I_{DQ} = I_{DSS}\left(1 - \dfrac{V_{GS}}{V_P}\right)^2 \Rightarrow 5 = 8\left(1 - \dfrac{V_{GS}}{4}\right)^2$

$V_{GS} = 0.838 \text{ V}$

$V_G = V_{GS} + V_S = 0.838 - 6 = -5.162$

$V_G = \left(\dfrac{R_2}{R_1 + R_2}\right)(-20)$

$-5.162 = \dfrac{1}{R_1}(100)(-20) \Rightarrow \underline{R_1 = 387 \text{ k}\Omega}$

$\dfrac{R_1 R_2}{R_1 + R_2} = 100 \Rightarrow (387)R_2 = 100(387) + 100R_2$

$(387 - 100)R_2 = (100)(387)$

$\Rightarrow \underline{R_2 = 135 \text{ k}\Omega}$

E5.34

$I_{DQ} = K(V_{GS} - V_{TN})^2 \Rightarrow 5 = 50(V_{GS} - 0.15)^2$

$\Rightarrow \underline{V_{GS} = 0.466 \text{ V}}$

$V_S = (0.005)(10) = 0.050 \text{ V}$

$\Rightarrow V_{GG} = V_{GS} + V_S = 0.466 + 0.050$

$\Rightarrow \underline{V_{GG} = 0.516 \text{ V}}$

$V_D = 5 - (0.005)(100) \Rightarrow V_D = 4.5 \text{ V}$

$V_{DS} = V_D - V_S = 4.5 - 0.050$

$\Rightarrow \underline{V_{DS} = 4.45 \text{ V}}$

E5.35

$I_D = K\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$

$= 100\left[2(0.7 - 0.2)(0.1) - (0.1)^2\right]$

$I_D = 9 \ \mu\text{A}$

$R_D = \dfrac{2.5 - 0.1}{0.009} \Rightarrow \underline{R_D = 267 \text{ k}\Omega}$

Chapter 5

Problem Solutions

5.1

(a) $V_{DS} = 6\,V > V_{GS} - V_{TN} = 5 - 1.5 = 3.5\,V$
Biased in the saturation region
$I_D = K_n(V_{GS} - V_{TN})^2 = (0.25)(5 - 1.5)^2 \Rightarrow$
$\underline{I_D = 3.06\,mA}$

(b) $V_{DS} = 2.5\,V < V_{DS}(sat) = 3.5\,V$
Biased in nonsaturation region
$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$
$I_D = (0.25)\left[2(5 - 1.5)(2.5) - (2.5)^2\right] \Rightarrow$
$\underline{I_D = 2.81\,mA}$

5.2

(a) $I_D = \frac{k_n'}{2} \cdot \frac{W}{L}(V_{GS} - V_{TN})^2$
$0.5 = \left(\frac{0.080}{2}\right)(5)(V_{GS} - 0.8)^2$
$\sqrt{\frac{0.5}{0.2}} + 0.8 = V_{GS} \Rightarrow \underline{V_{GS} = 2.38\,V}$
$V_{DS}(sat) = V_{GS} - V_{TN} = 2.38 - 0.8 \Rightarrow$
$\underline{V_{DS}(sat) = 1.58\,V}$

(b) $1.5 = \left(\frac{0.080}{2}\right)(5)(V_{GS} - 0.8)^2$
$\sqrt{\frac{1.5}{0.2}} + 0.8 = V_{GS} \Rightarrow \underline{V_{GS} = 3.54\,V}$
$V_{DS}(sat) = 3.54 - 0.8 \Rightarrow \underline{V_{DS}(sat) = 2.74\,V}$

5.3

a. $V_{GS} = 0$
$V_{DS}(sat) = V_{GS} - V_{TN} = 0 - (-2.5) = 2.5\,V$

i. $V_{DS} = 0.5$ V $\Rightarrow$ Biased in nonsaturation
$I_D = (1.1)[2(0 - (-2.5))(0.5) - (0.5)^2]$
$\Rightarrow \underline{I_D = 2.48 \text{ mA}}$

ii. $V_{DS} = 2.5$ V $\Rightarrow$ Biased in saturation
$I_D = (1.1)(0 - (-2.5))^2$
$\Rightarrow \underline{I_D = 6.88 \text{ mA}}$

iii. $V_{DS} = 5$ V Same as $(ii) \Rightarrow \underline{I_D = 6.88 \text{ mA}}$

b. $V_{GS} = 2$ V

$V_{DS}(sat) = 2 - (-2.5) = 4.5$ V

i. $V_{DS} = 0.5$ V $\Rightarrow$ Nonsaturation

$I_D = (1.1)[2(2 - (-2.5))(0.5) - (0.5)^2]$
$\Rightarrow \underline{I_D = 4.68 \text{ mA}}$

ii. $V_{DS} = 2.5$ V $\Rightarrow$ Nonsaturation

$I_D = (1.1)[2(2 - (-2.5))(2.5) - (2.5)^2]$
$\Rightarrow \underline{I_D = 17.9 \text{ mA}}$

iii. $V_{DS} = 5$ V $\Rightarrow$Saturation

$I_D = (1.1)(2 - (-2.5))^2$
$\Rightarrow \underline{I_D = 22.3 \text{ mA}}$

5.4

$V_{DS} > V_{GS} - V_{TN} = 0 - (-2) = 2\,V$
Biased in the saturation region
$I_D = \frac{k_n'}{2} \cdot \frac{W}{L}(V_{GS} - V_{TN})^2$
$1.5 = \left(\frac{0.080}{2}\right)\left(\frac{W}{L}\right)[0 - (-2)]^2 \Rightarrow \underline{\frac{W}{L} = 9.375}$

5.5

a. $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.85 \times 10^{-14})}{450 \times 10^{-8}}$
$\Rightarrow \frac{\epsilon_{ox}}{t_{ox}} = 7.67 \times 10^{-8} \text{ F/cm}^2$

$K_n = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L}$
$= \frac{1}{2}(650)(7.67x10^{-8})\left(\frac{64}{4}\right)$
$\underline{K_n = 0.399\,mA/V^2}$

b. $V_{GS} = V_{DS} = 3$ V $\Rightarrow$ Saturation

$I_D = K_n(V_{GS} - V_{TN})^2 = (0.399)(3 - 0.8)^2$
$\Rightarrow \underline{I_D = 1.93\,mA}$

5.6

a. $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.85 \times 10^{-14})}{600 \times 10^{-8}}$
$\Rightarrow \frac{\epsilon_{ox}}{t_{ox}} = 5.75 \times 10^{-8} \text{ F/cm}^2$

$K_n = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L}$
$= \frac{1}{2}(500)(5.75x10^{-8})\left(\frac{100}{5}\right) \Rightarrow$
$\underline{K_n = 0.288\,mA/V^2}$

b. i. $V_{GS} = 0, \quad V_{DS} = 5\text{ V}$

$V_{DS}(\text{sat}) = 0 - (-2) = 2\text{ V}$

Biased in saturation

$I_D = (0.288)(0 - (-2))^2 \Rightarrow \underline{I_D = 1.15\text{ mA}}$

ii. $V_{GS} = 2\text{ V}, \quad V_{DS} = 1\text{ V}$

$V_{DS}(\text{sat}) = 2 - (-2) = 4\text{ V}$

Nonsaturation

$I_D = (0.288)\left[2(2 - (-2))(1) - (1)^2\right]$

$\Rightarrow \underline{I_D = 2.02\text{ mA}}$

5.7

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.85 \times 10^{-14})}{400 \times 10^{-8}}$$

$$= 8.63 \times 10^{-8}\text{ F/cm}^2$$

$$K_n = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L}$$

$$= \frac{1}{2}(600)(8.63x10^{-8})\left(\frac{W}{2.5}\right)$$

$$\underline{K_n = (1.04x10^{-5})W}$$

$$I_D = K_n(V_{GS} - V_{TN})^2$$

$$1.2 \times 10^{-3} = (1.04 \times 10^{-5})W(5-1)^2$$

$$\Rightarrow \underline{W = 7.21\ \mu\text{m}}$$

5.8

Biased in the saturation region in both cases.

$$I_D = \frac{k_p'}{2} \cdot \frac{W}{L}(V_{SG} + V_{TP})^2$$

(1) $0.225 = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(3 + V_{TP})^2$

(2) $1.40 = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(4 + V_{TP})^2$

Take ratio of (2) to (1):

$$\frac{1.40}{0.225} = 6.222 = \frac{(4+V_{TP})^2}{(3+V_{TP})^2}$$

$$\sqrt{6.222} = 2.49 = \frac{4+V_{TP}}{3+V_{TP}} \Rightarrow \underline{V_{TP} = -2.33\,V}$$

Then

$$0.225 = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(3 - 2.33)^2 \Rightarrow \underline{\frac{W}{L} = 25.1}$$

5.9

$V_S = 5\text{ V}, \quad V_G = 0 \Rightarrow V_{SG} = 5\text{ V}$

$V_{TP} = -0.5\,V$

$\Rightarrow V_{SD}(sat) = V_{SG} + V_{TP} = 5 - 0.5 = 4.5\,V$

a. $V_D = 0 \Rightarrow V_{SD} = 5\text{ V}$

$\Rightarrow$ Biased in saturation

$I_D = 2(5 - 0.5)^2 \Rightarrow \underline{I_D = 40.5\text{ mA}}$

b. $V_D = 2\text{ V} \Rightarrow V_{SD} = 3\text{ V}$

$\Rightarrow$ Nonsaturation

$I_D = 2\left[2(5 - 0.5)(3) - (3)^2\right]$

$\Rightarrow \underline{I_D = 36\text{ mA}}$

c. $V_D = 4\text{ V} \Rightarrow V_{SD} = 1\text{ V}$

$\Rightarrow$ Nonsaturation

$I_D = 2\left[2(5 - 0.5)(1) - (1)^2\right]$

$\Rightarrow \underline{I_D = 16\text{ mA}}$

d. $V_D = 5\text{ V} \Rightarrow V_{SD} = 0 \Rightarrow \underline{I_D = 0}$

5.10

$V_{SD}(sat) = V_{SG} + V_{TP}$

(a) $V_{SD}(sat) = -1 + 2 \Rightarrow V_{SD}(sat) = 1\,V$

(b) $V_{SD}(sat) = 0 + 2 \Rightarrow V_{SD}(sat) = 2\,V$

(c) $V_{SD}(sat) = 1 + 2 \Rightarrow V_{SD}(sat) = 3\,V$

$$I_D = \frac{k_p'}{2} \cdot \frac{W}{L}(V_{SG} + V_{TP})^2 = \frac{k_p'}{2} \cdot \frac{W}{L} \cdot \left[V_{SD}(sat)\right]^2$$

(a) $I_D = \left(\frac{0.040}{2}\right)(6)(1)^2 \Rightarrow \underline{I_D = 0.12\,mA}$

(b) $I_D = \left(\frac{0.040}{2}\right)(6)(2)^2 \Rightarrow \underline{I_D = 0.48\,mA}$

(c) $I_D = \left(\frac{0.040}{2}\right)(6)(3)^2 \Rightarrow \underline{I_D = 1.08\,mA}$

5.11

$V_{SD}(sat) = V_{SG} + V_{TP} = 0 + 2 = 2\,V$

(a) $V_{SD} = 1\,V$, Nonsaturation

$I_D = K_p\left[2(V_{SG} + V_{TP})V_{SD} - V_{SD}^2\right]$

$I_D = (0.5)\left[2(0+2)(1) - (1)^2\right] \Rightarrow \underline{I_D = 1.5\,mA}$

(b) $V_{SD} = 2\,V$, Saturation

$I_D = K_p(V_{SG} + V_{TP})^2 = (0.5)(0+2)^2 \Rightarrow$

$\underline{I_D = 2\,mA}$

(c) $V_{SD} = 3\,V$, Saturation

Same as (b), $\underline{I_D = 2\,mA}$

5.12

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.85 \times 10^{-14})}{500 \times 10^{-8}}$$
$$= 6.90 \times 10^{-8} \text{ F/cm}^2$$

$$k_n' = (\mu_n C_{ox}) = (675)(6.90 \times 10^{-8})$$
$$\Rightarrow 46.6\ \mu\text{A/V}^2$$
$$k_p' = (\mu_p C_{ox}) = (375)(6.90 \times 10^{-8})$$
$$\Rightarrow 25.9\ \mu\text{A/V}^2$$

PMOS:

$$I_D = \frac{k_p'}{2}\left(\frac{W}{L}\right)_p (V_{SG} + V_{TP})^2$$
$$0.8 = \left(\frac{0.0259}{2}\right)\left(\frac{W}{L}\right)_p (5 - 0.6)^2$$
$$\Rightarrow \left(\frac{W}{L}\right)_p = 3.19$$
$$L = 4\ \mu\text{m} \Rightarrow \underline{W_p = 12.8\ \mu\text{m}}$$

$$K_p = \left(\frac{0.0259}{2}\right)(3.19) \Rightarrow \underline{K_p = 41.3\ \mu A/V^2 = K_n}$$

Want $K_n = K_p$

$$\frac{k_n'}{2}\left(\frac{W}{L}\right)_N = \frac{k_p'}{2}\left(\frac{W}{L}\right)_P = 41.3$$
$$\left(\frac{46.6}{2}\right)\left(\frac{W}{L}\right)_N = 41.3 \Rightarrow \left(\frac{W}{L}\right)_N = 1.77$$
$$L = 4\ \mu\text{m} \Rightarrow \underline{W_N = 7.08\ \mu\text{m}}$$

5.13

$$V_{GS} = 2 \text{ V}, \quad I_D = (0.2)(2 - 1.2)^2 = 0.128 \text{ mA}$$
$$r_0 = \frac{1}{\lambda I_D} = \frac{1}{(0.01)(0.128)} \Rightarrow \underline{r_0 = 781 \text{ k}\Omega}$$
$$V_{GS} = 4 \text{ V}, \quad I_D = (0.2)(4 - 1.2)^2 = 1.57 \text{ mA}$$

$$r_0 = \frac{1}{(0.01)(1.57)} \Rightarrow \underline{r_0 = 63.7 \text{ k}\Omega}$$
$$V_A = \frac{1}{\lambda} = \frac{1}{(0.01)} \Rightarrow \underline{V_A = 100 \text{ V}}$$

5.14

$$I_D = \left(\frac{0.080}{2}\right)(4)(3 - 0.8)^2 = (0.16)(3 - 0.8)^2 \Rightarrow$$
$$I_D = 0.774\ mA$$
$$r_o = \frac{1}{\lambda I_D} \Rightarrow \lambda = \frac{1}{r_o I_D} = \frac{1}{(200)(0.774)} \Rightarrow$$
$$\underline{\lambda(\max) = 0.00646\ V^{-1}}$$
$$V_A(\min) = \frac{1}{\lambda(\max)} = \frac{1}{0.00646} \Rightarrow \underline{V_A(\min) = 155\ V}$$

5.15

$$V_{TN} = V_{TNO} + \gamma\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right]$$
$$\Delta V_{TN} = 2 = (0.8)\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2(0.35)}\right]$$
$$2.5 + 0.837 = \sqrt{2(0.35) + V_{SB}} \Rightarrow \underline{V_{SB} = 10.4\ V}$$

5.16

$$\Delta V_{TN} = \gamma\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right]$$
$$1.2 = \gamma\left[\sqrt{2(0.37) + 10} - \sqrt{2(0.37)}\right] = \gamma(2.42)$$
Then $\gamma = 0.496\ V^{1/2}$

5.17

a. $V_G = \epsilon_{ox} t_{ox} = (6 \times 10^6)(275 \times 10^{-8})$

$\underline{V_G = 16.5 \text{ V}}$

b. $V_G = \dfrac{16.5}{3} \Rightarrow \underline{V_G = 5.5 \text{ V}}$

5.18

Want $V_G = (3)(24) = \epsilon_{ox} t_{ox} = (6 \times 10^6) t_{ox}$

$\underline{t_{ox} = 1.2 \times 10^{-5} \text{ cm} = 1200 \text{ Angstroms}}$

5.19

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} = \left(\frac{18}{18 + 32}\right)(10) = 3.6 \text{ V}$$

Assume transistor biased in saturation region

$$I_D = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S} = K_n (V_{GS} - V_{TN})^2$$
$$3.6 - V_{GS} = (0.5)(2)(V_{GS} - 0.8)^2$$
$$= V_{GS}^2 - 1.6 V_{GS} + 0.64$$

$$V_{GS}^2 - 0.6 V_{GS} - 2.96 = 0$$
$$V_{GS} = \frac{0.6 \pm \sqrt{(0.6)^2 + 4(2.96)}}{2}$$
$$\Rightarrow \underline{V_{GS} = 2.05 \text{ V}}$$

$$I_D = \frac{V_G - V_{GS}}{R_S} = \frac{3.6 - 2.05}{2} \Rightarrow \underline{I_D = 0.775 \text{ mA}}$$
$$V_{DS} = V_{DD} - I_D (R_D + R_S)$$
$$= 10 - (0.775)(4 + 2)$$
$$\Rightarrow \underline{V_{DS} = 5.35 \text{ V}}$$
$$\underline{V_{DS} > V_{DS}(\text{sat})}$$

5.20

$V_G=\left(\frac{R_2}{R_1+R_2}\right)(20)-10=\left(\frac{6}{14+6}\right)(20)-10\Rightarrow$

$V_G=-4\ V$

Assume transistor is biased in saturation region

$I_D=\frac{V_S-(-10)}{R_S}=\frac{V_G-V_{GS}+10}{R_S}=K_n(V_{GS}-V_{TN})^2$

$K_n=\left(\frac{0.060}{2}\right)(60)\Rightarrow 1.8\ mA/V^2$

$-4-V_{GS}+10=(1.8)(0.5)(V_{GS}-2)^2$

$=0.9V_{GS}^2-3.6V_{GS}+3.6$

Then $0.9V_{GS}^2-2.6V_{GS}-2.4=0$

$V_{GS}=\frac{2.6\pm\sqrt{(2.6)^2+4(0.9)(2.4)}}{2(0.9)}\Rightarrow \underline{V_{GS}=3.62\ V}$

$I_D=\frac{V_G-V_{GS}+10}{R_S}=\frac{-4-3.62+10}{0.5}\Rightarrow$

$\underline{I_D=4.76\ mA}$

$V_{DS}=20-I_D(R_D+R_S)=20-(4.76)(1.2+0.5)\Rightarrow$

$\underline{V_{DS}=11.9\ V}$

$V_{DS}=11.9\ V>V_{GS}-V_{TN}=3.62-2=1.62\ V$

5.21

$I_D=\frac{10-V_S}{R_S}=K_p(V_{SG}+V_{TP})^2$

Assume transistor biased in saturation region

$V_G=\left(\frac{R_2}{R_1+R_2}\right)(20)-10$

$=\left(\frac{22}{8+22}\right)(20)-10$

$\Rightarrow V_G=4.67\ V$

$V_S=V_G+V_{SG}$

$10-(4.67+V_{SG})=(1)(0.5)(V_{SG}-2)^2$

$5.33-V_{SG}=0.5(V_{SG}^2-4V_{SG}+4)$

$0.5V_{SG}^2-V_{SG}-3.33=0$

$V_{SG}=\frac{1\pm\sqrt{(1)^2+4(0.5)(3.33)}}{2(0.5)}$

$\Rightarrow \underline{V_{SG}=3.77\ V}$

$I_D=\frac{10-(4.67+3.77)}{0.5}\Rightarrow \underline{I_D=3.12\ mA}$

$V_{SD}=20-I_D(R_S+R_D)$

$=20-(3.12)(0.5+2)$

$\Rightarrow \underline{V_{SD}=12.2\ V}$

$\underline{V_{SD}>V_{SD}(sat)}$

5.22

$V_G=0,\ V_{SG}=V_S$

Assume saturation region

$I_D=0.4=K_p(V_{SG}+V_{TP})^2$

$0.4=(0.2)(V_S-0.8)^2$

$V_S=\sqrt{\frac{0.4}{0.2}}+0.8\Rightarrow \underline{V_S=2.21\ V}$

$V_D=I_DR_D-5=(0.4)(5)-5=-3\ V$

$V_{SD}=V_S-V_D=2.21-(-3)$

$\Rightarrow \underline{V_{SD}=5.21\ V}$

$\underline{V_{SD}>V_{SD}(sat)}$

5.23

$V_{DD}=I_{DQ}R_D+V_{DSQ}+I_{DQ}R_S$

(1) $10=I_{DQ}(5)+5+V_{GS}$ and

$I_{DQ}=\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)(V_{GS}-V_{TN})^2$

or (2) $I_{DQ}=\left(\frac{0.060}{2}\right)\left(\frac{W}{L}\right)(V_{GS}-1.2)^2$

Let $\underline{V_{GS}=2.5\ V}$

Then from (1), $10=I_{DQ}(5)+5+2.5\Rightarrow I_D=0.5\ mA$

Then from (2), $0.5=\left(\frac{0.060}{2}\right)\left(\frac{W}{L}\right)(2.5-1.2)^2\Rightarrow$

$\underline{\frac{W}{L}=9.86}$

$I_{DQ}R_S=V_{GS}\Rightarrow R_S=\frac{V_{GS}}{I_{DQ}}=\frac{2.5}{0.5}\Rightarrow \underline{R_S=5\ k\Omega}$

$I_R=\frac{10}{R_1+R_2}=(0.5)(0.05)=0.025\ mA$

Then $R_1+R_2=\frac{10}{0.025}=400\ k\Omega$

$\left(\frac{R_2}{R_1+R_2}\right)(V_{DD})=2V_{GS}\Rightarrow\left(\frac{R_2}{400}\right)(10)=2(2.5)\Rightarrow$

$\underline{R_1=R_2=200\ k\Omega}$

5.24

$V_G=\left(\frac{R_2}{R_1+R_2}\right)(10)-5$

$=\left(\frac{5.5}{14.5+5.5}\right)(10)-5=-2.25\ V$

$I_D=\frac{V_G-V_{GS}-(-5)}{R_S}=K_n(V_{GS}-V_{TN})^2$

Assume transistor biased in saturation region

$-2.25-V_{GS}+5=(0.5)(0.6)(V_{GS}-(-1))^2$

$2.75-V_{GS}=(0.3)(V_{GS}^2+2V_{GS}+1)$

$$0.3V_{GS}^2 + 1.6V_{GS} - 2.45 = 0$$

$$V_{GS} = \frac{-1.6 \pm \sqrt{(1.6)^2 + 4(0.3)(2.45)}}{2(0.3)}$$

$\Rightarrow \underline{V_{GS} = 1.24 \text{ V}}$

$$I_D = \frac{-2.25 - 1.24 + 5}{0.6} \Rightarrow \underline{I_D = 2.52 \text{ mA}}$$

$$V_{DS} = 10 - I_D(R_S + R_D)$$

$$= 10 - (2.52)(0.6 + 0.8)$$

$\Rightarrow \underline{V_{DS} = 6.47 \text{ V}}$

$\underline{V_{DS} > V_{DS}(\text{sat})}$

5.25

$$20 = I_{DQ}R_S + V_{SDQ} + I_{DQ}R_D$$

(1) $20 = V_{SG} + 10 + I_{DQ}R_D$

$$I_{DQ} = \left(\frac{k'_p}{2}\right)\left(\frac{W}{L}\right)(V_{SG} + V_{TP})^2$$

(2) $I_{DQ} = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(V_{SG} - 2)^2$

For example, let $\underline{I_{DQ} = 0.8 \text{ } mA}$ and $\underline{V_{SG} = 4 \text{ } V}$

Then $0.8 = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(4-2)^2 \Rightarrow \underline{\frac{W}{L} = 10}$

$I_{DQ}R_S = V_{SG} \Rightarrow (0.8)R_S = 4 \Rightarrow \underline{R_S = 5 \text{ } k\Omega}$

From (1) $20 = 4 + 10 + (0.8)R_D \Rightarrow \underline{R_D = 7.5 \text{ } k\Omega}$

$$I_R = \frac{20}{R_1 + R_2} = (0.8)(0.1) \Rightarrow R_1 + R_2 = 250 \text{ } k\Omega$$

$$\left(\frac{R_1}{R_1 + R_2}\right)(20) = 2V_{SG} = (2)(4)$$

$$\frac{R_1}{250}(20) = 8 \Rightarrow \underline{R_1 = 100 \text{ } k\Omega, \quad R_2 = 150 \text{ } k\Omega}$$

5.26

(a) (i) $I_Q = 50 = 500(V_{GS} - 1.2)^2 \Rightarrow \underline{V_{GS} = 1.516 \text{ } V}$

$V_{DS} = 5 - (-1.516) \Longrightarrow \underline{V_{DS} = 6.516 \text{ } V}$

(iv) $I_Q = 1 = (0.5)(V_{GS} - 1.2)^2 \Rightarrow \underline{V_{GS} = 2.61 \text{ } V}$

$V_{DS} = 5 - (-2.61) \Rightarrow \underline{V_{DS} = 7.61 \text{ } V}$

(b) (i) Same as (a) $\underline{V_{GS} = V_{DS} = 1.516 \text{ } V}$

(iv) $\underline{V_{GS} = V_{DS} = 2.61 \text{ } V}$

5.27

$$I_D = K_n(V_{GS} - V_{TN})^2$$

$$0.25 = (0.2)(V_{GS} - 0.6)^2$$

$$V_{GS} = \sqrt{\frac{0.25}{0.2}} + 0.6 \Rightarrow V_{GS} = 1.72 \text{ V}$$

$\Rightarrow \underline{V_S = -1.72 \text{ V}}$

$V_D = 9 - (0.25)(24) \Rightarrow \underline{V_D = 3 \text{ V}}$

5.28

$$I_D = \frac{5 - V_D}{R_D} \Rightarrow 0.8 = \frac{5-1}{R_D} \Rightarrow \underline{R_D = 5 \text{ k}\Omega}$$

$V_G = 0$

$$I_D = K_n(V_{GS} - V_{TN})^2 \Rightarrow 0.8 = (0.4)(V_{GS} - 1.7)^2$$

$$V_{GS} = \sqrt{\frac{0.8}{0.4}} + 1.7 \Rightarrow V_{GS} = 3.11 \text{ V}$$

$\Rightarrow V_S = -3.11 \text{ V}$

$$I_D = 0.8 = \frac{-3.11 - (-5)}{R_S} \Rightarrow \underline{R_S = 2.36 \text{ k}\Omega}$$

5.29

$$V_{DD} = V_{SD} + I_{DQ}R$$

$9 = 2.5 + (0.1)R \Rightarrow \underline{R = 65 \text{ } k\Omega}$

$$I_{DQ} = \left(\frac{k'_p}{2}\right)\left(\frac{W}{L}\right)(V_{SG} + V_{TP})^2$$

$(0.1) = \left(\frac{0.025}{2}\right)\left(\frac{W}{L}\right)(2.5 - 1.5)^2 \Rightarrow \underline{\frac{W}{L} = 8}$

Then for $\underline{L = \mu m, \quad W = 32 \text{ } \mu m}$

5.30

$$5 = I_{DQ}R_S + V_{SDQ} = I_{DQ}(2) + 2.5$$

$\underline{I_{DQ} = 1.25 \text{ } mA}$

$$I_R = \frac{10}{R_1 + R_2} = (1.25)(0.1) \Rightarrow R_1 + R_2 = 80 \text{ } k\Omega$$

$$I_{DQ} = K_p(V_{SG} + V_{TP})^2$$

$$1.25 = 0.5(V_{SG} + 1.5)^2 \Rightarrow \sqrt{\frac{1.25}{0.5}} - 1.5 = V_{SG}$$

$\underline{V_{SG} = 0.0811 \text{ } V}$

$V_G = V_S - V_{SG} = 2.5 - 0.0811 = 2.42 \text{ } V$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(10) - 5$$

$$2.42 = \left(\frac{R_2}{80}\right)(10) - 5 \Rightarrow$$

$R_2 = 59.4 \text{ } k\Omega, \quad R_1 = 20.6 \text{ } k\Omega$

5.31

$$K_p = \left(\frac{0.030}{2}\right)(20) \Rightarrow 0.30 \text{ } mA/V^2$$

$$I_D = K_p(V_{SG} + V_{TP})^2$$

$0.5 = 0.30(V_{SG} - 1.2)^2 \Rightarrow \underline{V_{SG} = 2.49 \text{ } V}$

$V_S = V_{SG} = 2.49 \text{ } V$

$$I_D = \frac{5 - V_S}{R_S} \Rightarrow R_S = \frac{5 - 2.49}{0.5} \Rightarrow \underline{R_S = 5.02 \text{ } k\Omega}$$

$$R_D = \frac{V_D - (-5)}{I_D} = \frac{5-3}{0.5} \Rightarrow \underline{R_D = 4 \text{ } k\Omega}$$

5.32

$$I_D = \frac{-V_{SD}-(-10)}{R_D} \Rightarrow 5 = \frac{-6+10}{R_D}$$

$$\Rightarrow \underline{R_D = 0.8\ \text{k}\Omega}$$

$$I_D = K_p(V_{SG}+V_{TP})^2 \Rightarrow 5 = 3(V_{SG}-1.75)^2$$

$$V_{SG} = \sqrt{\frac{5}{3}} + 1.75 = 3.04\ \text{V} \Rightarrow V_G = -3.04$$

$$V_G = \left(\frac{R_2}{R_1+R_2}\right)(10) - 5 = -3.04$$

$$R_{in} = R_1 \| R_2 = 80\ \text{k}\Omega$$

$$\frac{1}{R_1}\cdot(80)(10) = 5 - 3.04 \Rightarrow \underline{R_1 = 408\ \text{k}\Omega}$$

$$\frac{408 R_2}{408+R_2} = 80 \Rightarrow \underline{R_2 = 99.5\ \text{k}\Omega}$$

5.33

(a) $K_{n1} = \left(\frac{60}{2}\right)(4) = 120\ \mu A/V^2$

$K_{n2} = \left(\frac{60}{2}\right)(1) = 30\ \mu A/V^2$

For $v_I = 1V$, M_1 Sat. region, M_2 Non-sat region.

$I_{D2} = I_{D1}$

$$30\left[2(-V_{TNL})(5-v_O)-(5-v_O)^2\right] = 120(1-0.8)^2$$

We find $v_O^2 - 6.4v_O + 7.16 = 0 \Rightarrow \underline{v_O = 4.955\,V}$

(b) For $v_I = 3V$, M_1 Non-sat region, M_2 Sat. region. $I_{D2} = I_{D1}$

$$30[-(-1.8)]^2 = 120[2(3-0.8)v_O - v_O^2]$$

We find $4v_O^2 - 17.6v_O + 3.24 = 0 \Rightarrow \underline{v_O = 0.193\,V}$

(c) For $v_I = 5V$, biasing same as (b)

$$30[-(-1.8)]^2 = 120[2(5-0.8)v_O - v_O^2]$$

We find $4v_O^2 - 33.6v_O + 3.24 = 0 \Rightarrow \underline{v_O = 0.0976\,V}$

5.34

For $v_I = 5V$, M_1 Non-sat region, M_2 Sat. region.

$I_{D1} = I_{D2}$

$$\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_1\left[2(V_{GS1}-V_{TN1})V_{DS1}-V_{DS1}^2\right] = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_2(V_{GS2}-V_{TN2})^2$$

$$\left(\frac{W}{L}\right)_1\left[2(5-0.8)(0.15)-(0.15)^2\right] = (1)[0-(-2)]^2$$

which yields $\underline{\left(\frac{W}{L}\right)_1 = 3.23}$

5.35

a. M_1 and M_2 in saturation

$$K_{n1}(V_{GS1}-V_{TN1})^2 = K_{n2}(V_{GS2}-V_{TN2})^2$$

$$K_{n1} = K_{n2},\quad V_{TN1} = V_{TN2}$$

$$\Rightarrow \underline{V_{GS1} = V_{GS2} = 2.5\ \text{V}},\quad \underline{V_0 = 2.5\ \text{V}}$$

$$I_D = (15)(40)(2.5-0.8)^2 \Rightarrow \underline{I_D = 1.73\ \text{mA}}$$

b. $\left(\frac{W}{L}\right)_1 > \left(\frac{W}{L}\right)_2 \Rightarrow V_{GS1} < V_{GS2}$

$$40(V_{GS1}-0.8)^2 = (15)(V_{GS2}-0.8)^2$$

$$V_{GS2} = 5 - V_{GS1}$$

$$1.63(V_{GS1}-0.8) = (5 - V_{GS1} - 0.8)$$

$$2.63V_{GS1} = 5.50 \Rightarrow \underline{V_{GS1} = 2.09\ \text{V}}$$

$$\underline{V_{GS2} = 2.91\ \text{V}},\quad \underline{V_0 = V_{GS1} = 2.09\ \text{V}}$$

$$I_D = (15)(15)(2.91-0.8)^2 \Rightarrow \underline{I_D = 1.0\ \text{mA}}$$

5.36

Each transistor biased in saturation.

M_3: $V_1 = V_{GS3} = 2$ V

$$I_D = 0.5 = 0.018\left(\frac{W}{L}\right)_3(2-1)^2$$

$$\Rightarrow \underline{\left(\frac{W}{L}\right)_3 = 27.8}$$

M_2: $V_{GS2} = V_2 - V_1 = 5 - 2 = 3$ V

$$I_D = 0.5 = 0.018\left(\frac{W}{L}\right)_2(3-1)^2$$

$$\Rightarrow \underline{\left(\frac{W}{L}\right)_2 = 6.94}$$

M_1: $V_{GS1} = 10 - V_2 = 10 - 5 = 5$ V

$$I_D = 0.5 = 0.018\left(\frac{W}{L}\right)_1(5-1)^2$$

$$\Rightarrow \underline{\left(\frac{W}{L}\right)_1 = 1.74}$$

5.37

M_L in saturation

M_D in nonsaturation

$$\left(\frac{W}{L}\right)_L(V_{GSL}-V_{TNL})^2 = \left(\frac{W}{L}\right)_D\left[2(V_{GSD}-V_{TND})V_{DSD}-V_{DSD}^2\right]$$

$$(1)(5-0.1-0.8)^2 = \left(\frac{W}{L}\right)_D[2(5-0.8)(0.1)-(0.1)^2]$$

$$16.81 = \left(\frac{W}{L}\right)_D[0.83]$$

$$\underline{\left(\frac{W}{L}\right)_D = 20.3}$$

5.38

M_L in saturation

M_D in nonsaturation

$$\left(\frac{W}{L}\right)_L (V_{GSL} - V_{TNL})^2 = \left(\frac{W}{L}\right)_D \left[2(V_{GSD} - V_{TND})V_{DSD} - V_{DSD}^2\right]$$

$$(1)(1.8)^2 = \left(\frac{W}{L}\right)_D [2(5 - 0.8)(0.05) - (0.05)^2]$$

$$3.24 = \left(\frac{W}{L}\right)_D [0.4175]$$

$$\underline{\left(\frac{W}{L}\right)_D = 7.76}$$

5.39

$$I_{REF} = K_{n4}(V_{GS4} - V_{TN})^2 = K_{n3}(V_{GS3} - V_{TN})^2$$

$$V_{GS4} = 5 - V_{GS3}$$

$$\sqrt{\frac{400}{200}}(5 - V_{GS3} - 1) = (V_{GS3} - 1)$$

$$2.41V_{GS3} = 6.66 \Rightarrow \underline{V_{GS3} = 2.76\text{ V}}$$

$$\underline{V_{GS4} = 2.24\text{ V}},\ \underline{V_{GS2} = V_{GS3} = 2.76\text{ V}}$$

$$I_{REF} = K_{n3}(V_{GS3} - V_{TN})^2 = (0.2)(2.76 - 1)^2$$

$$\underline{I_{REF} = 0.620\ mA}$$

$$I_Q = K_{n2}(V_{GS2} - V_{TN})^2 = (0.1)(2.76 - 1)^2$$

$$\underline{I_Q = 0.310\ mA}$$

$$I_Q = K_{n1}(V_{GS1} - V_{TN})^2$$

$$\Rightarrow 0.310 = (0.08)(V_{GS1} - 1)^2$$

Then $V_{GS1} = \sqrt{\frac{0.310}{0.08}} + 1 \Rightarrow \underline{V_{GS1} = 2.97\ V}$

5.40

$$I_D = \frac{V_{DD} - V_0}{R_D} = \frac{5 - 0.1}{10} = 0.49\text{ mA}$$

Transistor biased in nonsaturation

$$I_D = 0.49 = (0.015)\left(\frac{W}{L}\right)[2(4.2 - 0.8)(0.1) - (0.1)^2]$$

$$0.49 = \left(\frac{W}{L}\right)[0.67] \Rightarrow \frac{W}{L} = 0.731$$

5.41

$$5 = I_D R_D + V_\gamma + V_{DS}$$

$$5 = (12)R_D + 1.6 + 0.2 \Rightarrow \underline{R_D = 267\ \Omega}$$

$$I_D = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)(V_{GS} - V_{TN})^2$$

$$12 = \left(\frac{0.040}{2}\right)\left(\frac{W}{L}\right)(5 - 0.8)^2 \Rightarrow \underline{\frac{W}{L} = 34}$$

5.42

$$5 = V_{SD} + I_D R_D + V_\gamma$$

$$5 = 0.15 + (15)R_D + 1.6 \Rightarrow \underline{R_D = 217\ \Omega}$$

$$I_D = \left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)(V_{SG} + V_{TP})^2$$

$$15 = \left(\frac{0.020}{2}\right)\left(\frac{W}{L}\right)(5 - 0.8)^2 \Rightarrow \underline{\frac{W}{L} = 85}$$

5.43

$$V_{DS}(\text{sat}) = V_{GS} - V_P$$

So $\underline{V_{DS} > V_{DS}(\text{sat}) = -V_P}$, $\underline{I_D = I_{DSS}}$

5.44

$$V_{DS}(\text{sat}) = V_{GS} - V_P = \underline{V_{GS} + 3 = V_{DS}(\text{sat})}$$

a. $V_{GS} = 0 \Rightarrow \underline{I_D = I_{DSS} = 6\text{ mA}}$

b. $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 6\left(1 - \frac{-1}{-3}\right)^2$

$\Rightarrow \underline{I_D = 2.67\text{ mA}}$

c. $I_D = 6\left(1 - \frac{-2}{-3}\right)^2 \Rightarrow \underline{I_D = 0.667\text{ mA}}$

d. $\underline{I_D = 0}$

5.45

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

$$2.8 = I_{DSS}\left(1 - \frac{1}{V_P}\right)^2$$

$$0.30 = I_{DSS}\left(1 - \frac{3}{V_P}\right)^2$$

$$\frac{2.8}{0.30} = \frac{\left(1 - \frac{1}{V_P}\right)^2}{\left(1 - \frac{3}{V_P}\right)^2} = 9.33$$

$$\frac{\left(1 - \frac{1}{V_P}\right)}{\left(1 - \frac{3}{V_P}\right)} = 3.055$$

$$1 - \frac{1}{V_P} = 3.055 - \frac{9.165}{V_P}$$

$$\frac{8.165}{V_P} = 2.055 \Rightarrow \underline{V_P = 3.97\text{ V}}$$

$$2.8 = I_{DSS}\left(1 - \frac{1}{3.97}\right)^2 = I_{DSS}(0.560)$$

$$\Rightarrow \underline{I_{DSS} = 5.0\text{ mA}}$$

5.46

$V_S = -V_{GS}, \quad V_{SD} = V_S - V_{DD}$

Want $V_{SD} \geq V_{SD}(\text{sat}) = V_P - V_{GS}$

$V_S - V_{DD} \geq V_P - V_{GS}$

$-V_{GS} - V_{DD} \geq V_P - V_{GS} \Rightarrow \underline{V_{DD} \leq -V_P}$

So $\underline{V_{DD} \leq -2.5 \text{ V}}$

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

$$2 = 6\left(1 - \frac{V_{GS}}{2.5}\right)^2 \Rightarrow V_{GS} = 1.06 \text{ V}$$

$\Rightarrow \underline{V_S = -1.06 \text{ V}}$

5.47

$$I_D = K_n(V_{GS} - V_{TN})^2$$

$$18.5 = K_n(0.35 - V_{TN})^2$$

$$86.2 = K_n(0.5 - V_{TN})^2$$

Then

$$\frac{18.5}{86.2} = 0.2146 = \frac{(0.35 - V_{TN})^2}{(0.50 - V_{TN})^2} \Rightarrow \underline{V_{TN} = 0.221 V}$$

$$18.5 = K_n(0.35 - 0.221)^2 \Rightarrow \underline{K_n = 1.11\, mA/V^2}$$

5.48

$$I_D = K(V_{GS} - V_{TN})^2$$

$$250 = K(0.75 - 0.24)^2 \Rightarrow \underline{K = 0.961\, mA/V^2}$$

5.49

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

$$10\left(1 - \frac{V_{GS}}{-5}\right)^2 = -\frac{V_{GS}}{0.2}$$

$$2\left(1 + \frac{2V_{GS}}{5} + \frac{V_{GS}^2}{25}\right) = -V_{GS}$$

$$\frac{2}{25}V_{GS}^2 + \frac{9}{5}V_{GS} + 2 = 0$$

$$2V_{GS}^2 + 45V_{GS} + 50 = 0$$

$$V_{GS} = \frac{-45 \pm \sqrt{(45)^2 - 4(2)(50)}}{2(2)}$$

$\Rightarrow \underline{V_{GS} = -1.17 \text{ V}}$

$$I_D = -\frac{V_{GS}}{R_S} = \frac{1.17}{0.2} \Rightarrow \underline{I_D = 5.85 \text{ mA}}$$

$$V_D = 20 - (5.85)(2) = 8.3 \text{ V}$$

$$V_{DS} = V_D - V_S = 8.3 - 1.17 \Rightarrow \underline{V_{DS} = 7.13 \text{ V}}$$

5.50

$$V_{DS} = V_{DD} - V_S$$

$$8 = 10 - V_S \Rightarrow V_S = 2 \text{ V} = I_D R_S = (5)R_S$$

$\Rightarrow \underline{R_S = 0.4 \text{ k}\Omega}$

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

$$5 = I_{DSS}\left(1 - \frac{-1}{V_P}\right)^2 \text{ Let } \underline{I_{DSS} = 10 \text{ mA}}$$

$$5 = 10\left(1 - \frac{-1}{V_P}\right)^2 \Rightarrow \underline{V_P = -3.41 \text{ V}}$$

$$V_G = V_{GS} + V_S = -1 + 2 = 1 \text{ V}$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \frac{1}{R_1} \cdot R_{in} \cdot V_{DD}$$

$$1 = \frac{1}{R_1}(500)(10) \Rightarrow \underline{R_1 = 5 \text{ M}\Omega}$$

$$\frac{5R_2}{5 + R_2} = 0.5 \Rightarrow \underline{R_2 = 0.556 \text{ M}\Omega}$$

5.51

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

$$5 = 8\left(1 - \frac{V_{GS}}{4}\right)^2 \Rightarrow \underline{V_{GS} = 0.838 \text{ V}}$$

$$V_{SD} = V_{DD} - I_D(R_S + R_D)$$

$$= 20 - (5)(0.5 + 2) \Rightarrow \underline{V_{SD} = 7.5 \text{ V}}$$

$$V_S = 20 - (5)(0.5) = 17.5 \text{ V}$$

$$V_G = V_S + V_{GS} = 17.5 + 0.838 = 18.3 \text{ V}$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \frac{1}{R_1} \cdot R_{in} \cdot V_{DD}$$

$$18.3 = \frac{1}{R_1}(100)(20) \Rightarrow \underline{R_1 = 109 \text{ k}\Omega}$$

$$\frac{109R_2}{109 + R_2} = 100 \Rightarrow \underline{R_2 = 1.21 \text{ M}\Omega}$$

5.52

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

$$5 = 7\left(1 - \frac{V_{GS}}{3}\right)^2 \Rightarrow \underline{V_{GS} = 0.465 \text{ V}}$$

$$V_{SD} = V_{DD} - I_D(R_S + R_D)$$

$$6 = 12 - (5)(0.3 + R_D) \Rightarrow \underline{R_D = 0.9 \text{ k}\Omega}$$

$$V_S = 12 - (5)(0.3) = 10.5 \text{ V}$$

$$V_G = V_S + V_{GS} = 10.5 + 0.465 = 10.965 \text{ V}$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD}$$

$$10.965 = \left(\frac{R_2}{100}\right)(12) \Rightarrow \underline{R_2 = 91.4 \text{ k}\Omega}$$

$\Rightarrow \underline{R_1 = 8.6 \text{ k}\Omega}$

5.53

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{60}{140 + 60}\right)(20)$$
$$\Rightarrow \underline{V_G = 6\ \text{V}}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S}$$
$$(8)(2)\left(1 - \frac{V_{GS}}{(-4)}\right)^2 = 6 - V_{GS}$$
$$16\left(1 + \frac{V_{GS}}{2} + \frac{V_{GS}^2}{16}\right) = 6 - V_{GS}$$

$$V_{GS}^2 + 9V_{GS} + 10 = 0$$
$$V_{GS} = \frac{-9 \pm \sqrt{(9)^2 - 4(10)}}{2} \Rightarrow \underline{V_{GS} = -1.30}$$
$$I_D = 8\left(1 - \frac{(-1.30)}{(-4)}\right)^2 \Rightarrow \underline{I_D = 3.65\ \text{mA}}$$

$$V_{DS} = V_{DD} - I_D(R_S + R_D)$$
$$= 20 - (3.65)(2 + 2.7)$$
$$V_{DS} = 2.85\ \text{V}$$
$$V_{DS} > V_{DS}(\text{sat}) = V_{GS} - V_P$$
$$= -1.30 - (-4)$$
$$= 2.7\ \text{V} \quad \text{(Yes)}$$

5.54

$$V_{DS} = V_{DD} - I_D(R_S + R_D)$$
$$5 = 12 - I_D(0.5 + 1) \Rightarrow \underline{I_D = 4.67\ \text{mA}}$$
$$V_S = I_D R_S = (4.67)(0.5) \Rightarrow V_S = 2.33\ \text{V}$$
$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{20}{450 + 20}\right)(12)$$
$$\Rightarrow V_G = 0.511\ \text{V}$$

$$V_{GS} = V_G - V_S = 0.511 - 2.33$$
$$\Rightarrow \underline{V_{GS} = -1.82\ \text{V}}$$
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$
$$4.67 = 10\left(1 - \frac{(-1.82)}{V_P}\right)^2 \Rightarrow \underline{V_P = -6.75\ \text{V}}$$

5.55

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2,\ V_{GS} = 0$$
$$\underline{I_D = I_{DSS} = 4\ \text{mA}}$$
$$R_D = \frac{V_{DD} - V_{DS}}{I_D} = \frac{10 - 3}{4} \Rightarrow \underline{R_D = 1.75\ \text{k}\Omega}$$

5.56

$$V_{SD} = V_{DD} - I_D R_S$$
$$10 = 20 - (1)R_S \Rightarrow \underline{R_S = 10\ \text{k}\Omega}$$
$$R_1 + R_2 = \frac{V_{DD}}{I} = \frac{20}{0.1} = 200\ \text{k}\Omega$$
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$
$$1 = 2\left(1 - \frac{V_{GS}}{2}\right)^2 \Rightarrow \underline{V_{GS} = 0.586\ \text{V}}$$

$$V_G = V_S + V_{GS} = 10 + 0.586 = 10.586$$
$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD}$$
$$10.586 = \left(\frac{R_2}{200}\right)(20) \Rightarrow \underline{R_2 = 106\ \text{k}\Omega}$$
$$\underline{R_1 = 94\ \text{k}\Omega}$$

5.57

$$V_{DS} = V_{DD} - I_D(R_S + R_D)$$
$$2 = 3 - (0.040)(10 + R_D) \Rightarrow \underline{R_D = 15\ \text{k}\Omega}$$
$$I_D = K(V_{GS} - V_{TN})^2$$
$$40 = 250(V_{GS} - 0.20)^2 \Rightarrow \underline{V_{GS} = 0.60\ \text{V}}$$

$$V_G = V_{GS} + V_S = 0.60 + (0.040)(10) = 1.0\ \text{V}$$
$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD}$$
$$1 = \left(\frac{R_2}{150}\right)(3) \Rightarrow \underline{R_2 = 50\ \text{k}\Omega}$$
$$\underline{R_1 = 100\ \text{k}\Omega}$$

5.58

For $V_O = 0.70\,V \Rightarrow$

$$V_{DS} = 0.70 > V_{DS}(sat) = V_{GS} - V_{TN}$$
$$0.75 - 0.15 = 0.6$$

Biased in the saturation region

$$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{3 - 0.7}{50} \Rightarrow \underline{I_D = 46\ \mu A}$$
$$I_D = K(V_{GS} - V_{TN})^2 \Rightarrow 46 = K(0.75 - 0.15)^2 \Rightarrow$$
$$\underline{K = 128\ \mu A/V^2}$$