Microelectronic Circuit Design Sixth Edition - Part I Solutions to Exercises

CHAPTER 1

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Page 1

$V_{LSB} = \frac{5.12V}{2^{10} bits} = \frac{5.12V}{1024 bits} = 5.00\ mV \qquad V_{MSB} = \frac{5.12V}{2} = 2.560V$

$1100010001_2 = 2^9 + 2^8 + 2^4 + 2^0 = 785_{10} \qquad V_O = 785(5.00mV) = 3.925\ V$

or $\quad V_O = \left(2^{-1} + 2^{-2} + 2^{-6} + 2^{-10}\right)\ 5.12V = 3.925\ V$

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$V_{LSB} = \frac{5.0V}{2^8 bits} = \frac{5.00V}{256 bits} = 19.53\ mV \qquad N = \frac{1.2V}{5.00V} 256 bits = 61.44 bits$

$61 = 32 + 16 + 8 + 4 + 1 = 2^5 + 2^4 + 2^3 + 2^2 + 2^0 = 00111101_2$

$V_{LSB} = \frac{5.12V}{256 bits} = 20.0\ mV \qquad V_{LSB} = \frac{1.2V}{5.12V} 256 bits = 60\ bits$

$60 = 32 + 16 + 8 + 4 = 2^5 + 2^4 + 2^3 + 2^2 = 00111100_2$

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The dc component is $V_A = 4V$.

The signal consists of the remaining portion of v_A: $v_a = (5 \sin 2000\pi t + 3 \cos 1000\ \pi t)$ Volts.

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$v_o = -5\cos\left(2000\pi t + 25^o\right) = -\left[-5\sin\left(2000\pi t + 25^o - 90^o\right)\right] = 5\sin\left(2000\pi t - 65^o\right)$

$V_o = 5\angle -65^o \qquad V_i = 0.001\angle 0^o \qquad A_v = \frac{5\angle -65^o}{0.001\angle 0^o} = 5000\angle -65^o$

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$$A_v = -\frac{R_2}{R_1} \quad | \quad -5 = -\frac{10k\Omega}{R_1} \rightarrow R_1 = 20\ k\Omega$$

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$$v_s = \left[0.5\sin(2000\pi t) + \sin(4000\pi t) + 1.5\sin(6000\pi t)\right]$$

The three spectral component frequencies are $f_1 = 1000\ Hz \quad f_2 = 2000\ Hz \quad f_3 = 3000\ Hz$

(a) The gain of the band-pass filter is zero at both f_1 and f_3. At f_2, $V_o = 10(1V) = 10\ V$, and $v_o = 10.0\sin(4000\pi t)$ volts.

(b) The gain of the low-pass filter is zero at both f_2 and f_3. At f_2, $V_o = 5(0.5V) = 2.5\ V$, and $v_o = 2.50\sin(2000\pi t)$ volts.

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$$39\text{k}\Omega(1-0.1) \le R \le 39\text{k}\Omega(1+0.1) \quad \text{or} \quad 35.1\ \text{k}\Omega \le R \le 42.9\ k\Omega$$

$$3.6\text{k}\Omega(1-0.01) \le R \le 3.6\text{k}\Omega(1+0.01) \quad \text{or} \quad 3.56\ \text{k}\Omega \le R \le 3.64\ k\Omega$$

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$$P = \frac{V_I^2}{R_1 + R_2} \quad P^{nom} = \frac{15^2}{54k\Omega} = 4.17\ mW$$

$$P^{\max} = \frac{(1.1x15)^2}{0.95x54k\Omega} = 5.31\ mW \quad P^{\min} = \frac{(0.9x15)^2}{1.05x54k\Omega} = 3.21\ mW$$

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$$R = 10k\Omega\left[1 + \frac{2x10^{-3}}{^oC}(-55-25)\ ^oC\right] = 8.40\ k\Omega \quad R = 10k\Omega\left[1 + \frac{2x10^{-3}}{^oC}(-55-25)\ ^oC\right] = 11.2\ k\Omega$$

CHAPTER 2

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$$n_i = \sqrt{\left(2.31x10^{30}K^{-3}cm^{-6}\right)\left(300K\right)^3 \exp\left[\frac{-0.66eV}{\left(8.62x10^{-5}eV/K\right)\left(300K\right)}\right]} = 2.27x10^{13}/cm^3$$

$$n_i = \sqrt{\left(1.08x10^{31}K^{-3}cm^{-6}\right)\left(50K\right)^3 \exp\left[\frac{-1.12eV}{\left(8.62x10^{-5}eV/K\right)\left(50K\right)}\right]} = 4.34x10^{-39}/cm^3$$

$$n_i = \sqrt{\left(1.08x10^{31}K^{-3}cm^{-6}\right)\left(325K\right)^3 \exp\left[\frac{-1.12eV}{\left(8.62x10^{-5}eV/K\right)\left(325K\right)}\right]} = 4.01x10^{10}/cm^3$$

$$L^3 = \frac{cm^3}{4.34x10^{-39}}\left(10^{-2}\frac{m}{cm}\right)^3 \rightarrow L = 6.13x10^{10}m$$

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$$v_p = \mu_p E = 470\frac{cm^2}{V-s}\left(10\frac{V}{cm}\right) = 4.70x10^3\frac{cm}{s} \qquad v_n = -\mu_n E = -1420\frac{cm^2}{V-s}\left(1000\frac{V}{cm}\right) = -1.42x10^6\frac{cm}{s}$$

$$E = \frac{V}{L} = \frac{1}{2x10^{-4}}\frac{V}{cm} = 5.00x10^3\frac{V}{cm}$$

(a) From Fig. 2.5: The drift velocity for Ge saturates at $6x10^6 cm/\sec$.

At low fields the slope is constant. Choose E = 100 V/cm

$$\mu_n = \frac{v_n}{E} = \frac{4.3x10^5 cm/s}{100V/cm} = 4300\frac{cm^2}{s} \qquad \mu_p = \frac{v_p}{E} = \frac{2.1x10^5 cm/s}{100V/cm} = 2100\frac{cm^2}{s}$$

(b) The velocity peaks at $2x10^7 cm/\sec$

$$\mu_n = \frac{v_n}{E} = \frac{8.5x10^5 cm/s}{100V/cm} = 8500\frac{cm^2}{s}$$

Page 51 See Table 2.1 page 44

$$n_i^2 = 1.08x10^{31}(400)^3 \exp\left[\frac{-1.12}{8.62x10^{-5}(400)}\right] = 5.40x10^{24}/cm^6 \;\mid\; n_i = 2.32x10^{12}/cm^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60x10^{-19}\left[\left(2.32x10^{12}\right)(1420)+\left(2.32x10^{12}\right)(470)\right]} = 1420\ \Omega - cm$$

$$n_i^2 = 1.08x10^{31}(50)^3 \exp\left[\frac{-1.12}{8.62x10^{-5}(50)}\right] = 1.88x10^{-77}/cm^6 \;\mid\; n_i = 4.34x10^{-39}/cm^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60x10^{-19}\left[\left(4.34x10^{-39}\right)(6500)+\left(4.34x10^{-39}\right)(2000)\right]} = 1.69x10^{53}\ \Omega - cm$$

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$$n_i^2 = 1.08x10^{31}(400)^3 \exp\left[\frac{-1.12}{8.62x10^{-5}(400)}\right] = 5.40x10^{24}/cm^6$$

$$p = N_A - N_D = 10^{16} - 2x10^{15} = 8x10^{15}\frac{holes}{cm^3} \qquad n = \frac{n_i^2}{p} = \frac{5.40x10^{24}}{8x10^{15}} = 6.75x10^8\frac{electrons}{cm^3}$$

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Antimony (Sb) is a Column - V element, so it is a donor impurity. $n = N_D = 2x10^{16}\frac{electrons}{cm^3}$

$$p = \frac{n_i^2}{n} = \frac{10^{20}}{2x10^{16}} = 5.00x10^3\frac{holes}{cm^3} \qquad \text{n > p} \rightarrow \text{n - type silicon}$$

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$$(a)\ \ N_D = 10^{16}/cm^3 \ \mid\ N_A = 0/cm^3 \ \mid\ N_T = 10^{16}/cm^3$$

$$\mu_n = 52.2 + \frac{1365}{1+\left(\frac{1x10^{16}}{9.68x10^{16}}\right)^{0.68}} = 1180\ cm^2/V-s \;\mid\; \mu_p = 44.9 + \frac{426}{1+\left(\frac{1x10^{16}}{2.23x10^{16}}\right)^{0.72}} = 318\ cm^2/V-s$$

$N_D = 0/cm^3 \ \mid\ N_A = 3x10^{17}/cm^3 \ \mid\ N_T = 3x10^{17}/cm^3 \ \mid$

$$\mu_n = 52.2 + \frac{1365}{1+\left(\frac{3x10^{17}}{9.68x10^{16}}\right)^{0.68}} = 484\ cm^2/V-s \;\mid\; \mu_p = 44.9 + \frac{426}{1+\left(\frac{3x10^{17}}{2.23x10^{16}}\right)^{0.72}} = 102\ cm^2/V-s$$

$(b)\ N_T = N_D + N_A = 4x10^{16}/cm^3 + 6x10^{16}/cm^3 = 1x10^{17}/cm^3$

$$\mu_n = 52.2 + \frac{1365}{1+\left(\frac{1x10^{17}}{9.68x10^{16}}\right)^{0.68}} = 727\ cm^2/V-s \;\mid\; \mu_p = 44.9 + \frac{426}{1+\left(\frac{1x10^{17}}{2.23x10^{16}}\right)^{0.72}} = 153\ cm^2/V-s$$

Page 58 Use the mobilty expressions in Fig. 2.8 with a spread sheet or MATLAB

$$\sigma = 1000 = 1.60x10^{-19}\mu_n n \rightarrow u_n n = 6.25x10^{21}/cm^3 \cong (64.5)(9.68x10^{19}) \ \mid \ \rho = \frac{1}{\sigma} = 0.001\ \Omega - cm$$

$$(a)\ N_D = 2x10^{16}/cm^3 \ \mid \ N_A = 0/cm^3 \ \mid \ N_T = 2x10^{16}/cm^3 \ \mid$$

$$\mu_n = 52.2 + \frac{1365}{1+\left(\frac{2x10^{16}}{9.68x10^{16}}\right)^{0.68}} = 1070\ cm^2/V-s \ \mid \ \mu_p = 44.9 + \frac{426}{1+\left(\frac{2x10^{16}}{2.23x10^{16}}\right)^{0.72}} = 266\ cm^2/V-s$$

$$n = N_D = \frac{2x10^{16}}{cm^3} \ \mid \ p = \frac{n_i^2}{n} = \frac{10^{20}}{2x10^{16}} = \frac{5000}{cm^3} \ \mid \ \rho \cong \frac{1}{qu_n n} = \frac{1}{(1.60x10^{-19})(1070)(2x10^{16})} = 0.292\ \Omega - cm$$

$$(b)\ N_T = N_D + N_A = 2x10^{16}/cm^3 + 3x10^{16}/cm^3 = 5x10^{16}/cm^3$$

$$\mu_n = 52.2 + \frac{1365}{1+\left(\frac{5x10^{16}}{9.68x10^{16}}\right)^{0.68}} = 886\ cm^2/V-s \ \mid \ \mu_p = 44.9 + \frac{426}{1+\left(\frac{5x10^{16}}{2.23x10^{16}}\right)^{0.72}} = 198\ cm^2/V-s$$

$$p = N_A - N_D = \frac{1x10^{16}}{cm^3} \ \mid \ \text{n} = \frac{n_i^2}{p} = \frac{10^{20}}{1x10^{16}} = \frac{10000}{cm^3} \ \mid \ \rho \cong \frac{1}{qu_n n} = \frac{1}{(1.60x10^{-19})(198)(1x10^{16})} = 3.16\ \Omega - cm$$

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Boron (B) is a Column-III element, so it is an acceptor impurity.

$$p = N_A - N_D = 4x10^{18}\frac{holes}{cm^3} \ \mid \ n = \frac{n_i^2}{p} = \frac{10^{20}}{4x10^{18}} = 25\frac{electrons}{cm^3} \ \mid \ \text{p-type material}$$

$$N_T = \frac{4x10^{18}}{cm^3} \ \text{ and mobilities from expressions in Fig. 2.8:}$$

$$\mu_n = 153\ \frac{cm^2}{V-s} \ \mid \ \mu_p = 54.8\ \frac{cm^2}{V-s} \ \mid \ \rho \cong \frac{1}{q\mu_p p} = \frac{1}{1.60x10^{-19}(4x10^{18})(54.8)} = 0.0285\ \Omega - cm$$

Indium (In) is a Column-III element, so it is an acceptor impurity.

$$p = N_A - N_D = 7x10^{19}\frac{holes}{cm^3} \ \mid \ n = \frac{n_i^2}{p} = \frac{10^{20}}{7x10^{19}} = 1.43\frac{electrons}{cm^3} \ \mid \ \text{p-type material}$$

$$N_T = \frac{7x10^{19}}{cm^3} \rightarrow \mu_n = 67.5\frac{cm^2}{V-s} \ \mid \ \mu_p = 46.2\ \frac{cm^2}{V-s}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60x10^{-19}(7x10^{19})(46.2)} = 1.93\ \text{m}\Omega - cm$$

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$$V_T = \frac{kT}{q} = \frac{1.38x10^{-23}(50)}{1.602x10^{-19}} = 4.31\ mV \ \mid\ V_T = \frac{1.38x10^{-23}(77)}{1.602x10^{-19}} = 6.63\ mV$$

$$V_T = \frac{1.38x10^{-23}(300)}{1.602x10^{-19}} = 25.8\ mV \ \mid\ V_T = \frac{1.38x10^{-23}(400)}{1.602x10^{-19}} = 34.5 mV$$

$$D_n = \frac{kT}{q}\mu_n = 25.8mV(1365 + 52.2)\frac{cm^2}{V-s} = 36.6\frac{cm^2}{s}$$

$$D_p = \frac{kT}{q}\mu_p = 25.8mV(426 + 44.9)\frac{cm^2}{V-s} = 12.1\frac{cm^2}{s}$$

$$j_n = qD_n\frac{dn}{dx} = 1.60x10^{-19}C\left(20\frac{cm^2}{s}\right)\left(\frac{10^{16}}{cm^3-\mu m}\right)\left(\frac{10^4\mu m}{cm}\right) = 320\frac{A}{cm^2}$$

$$j_p = -qD_p\frac{dp}{dx} = -1.60x10^{-19}C\left(4\frac{cm^2}{s}\right)\left(\frac{10^{16}}{cm^3-\mu m}\right)\left(\frac{10^4\mu m}{cm}\right) = -64\frac{A}{cm^2}$$

CHAPTER 3

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$$\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025V \ln\left(\frac{2x10^{18}\left(10^{20}\right)}{10^{20}}\right) = 1.05\ V$$

$$w_{do} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\phi_j} = \sqrt{\frac{2(11.7)\left(8.85x10^{-14}\right)}{1.60x10^{-19}}\left(\frac{1}{2x10^{18}}+\frac{1}{10^{20}}\right)(1.05)} = 2.63x10^{-6}cm = 0.0263\ \mu m$$

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$$E_{\max} = \frac{1}{\varepsilon_s}\int_{-x_p}^{0} -qN_A dx = \frac{qN_A x_p}{\varepsilon_s} \qquad E_{\max} = -\frac{1}{\varepsilon_s}\int_{0}^{x_n} qN_D dx = \frac{qN_D x_n}{\varepsilon_s}$$ For the values in Ex.3.2 :

$$E_{max} = \frac{1.602x10^{-19}C(10^{17}/cm^3)(1.15x10^{-5}cm)}{11.7(8.854x10^{-14}F/cm)} = 178\frac{kV}{cm}$$

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$$E_{\max} = \frac{2(1.05V)}{2.63x10^{-6}cm} = 798\frac{kV}{cm}$$

$$x_p = 0.0263\mu m\left(1+\frac{2x10^{18}}{10^{20}}\right)^{-1} = 0.0258\ \mu m \qquad x_n = 0.0263\mu m\left(1+\frac{10^{20}}{2x10^{18}}\right)^{-1} = 5.16x10^{-4}\ \mu m$$

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$$n\frac{kT}{q} = 1\frac{1.381x10^{-23}(300)}{1.602x10^{-19}} = 0.0259 \quad | \quad T = \frac{300}{1.03} = 291\ K \quad |$$

$$For\ n = 1, \quad T = (1)\frac{1.602x10^{-19}(0.025)}{1.381x10^{-22}} = 290$$

Page 84 Using V_T = 25.0 mV

$$i_D = 40x10^{-15}A\left[\exp\left(\frac{0.55}{0.025}\right)-1\right] = 143\ \mu A \qquad i_D = 40x10^{-15}A\left[\exp\left(\frac{0.70}{0.025}\right)-1\right] = 57.9\ mA$$

$$V_D = (0.025V)\ln\left(1+\frac{6x10^{-3}A}{40x10^{-15}A}\right) = 0.643\ V$$

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$$i_D = 5x10^{-15}A\left[\exp\left(\frac{-0.04}{0.025}\right)-1\right] = -3.99\ fA \quad | \quad i_D = 5x10^{-15}A\left[\exp\left(\frac{-2.0}{0.025}\right)-1\right] = -5.00\ fA$$

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$$(a)\quad V_{BE}=V_T\ln\left(1+\frac{I_D}{I_S}\right)=0.025V\ln\left(1+\frac{40x10^{-6}A}{2x10^{-15}A}\right)=0.593\ V$$

$$V_{BE}=V_T\ln\left(1+\frac{I_D}{I_S}\right)=0.025V\ln\left(1+\frac{400x10^{-6}A}{2x10^{-15}A}\right)=0.651\ V \qquad \Delta V_{BE}=57.6\ \text{m}V$$

$$(b)\quad V_{BE}=V_T\ln\left(1+\frac{I_D}{I_S}\right)=0.0259V\ln\left(1+\frac{40x10^{-6}A}{2x10^{-15}A}\right)=0.614\ V$$

$$V_{BE}=V_T\ln\left(1+\frac{I_D}{I_S}\right)=0.0259V\ln\left(1+\frac{400x10^{-6}A}{2x10^{-15}A}\right)=0.674\ V \qquad \Delta V_{BE}=59.6\ \text{m}V$$

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$$\ln\left(\frac{i_D}{I_S}\right)=\ln(i_D)-\ln(I_S) \quad | \quad \text{Assume } i_D \text{ is constant, and } E_G=E_{GO}$$

$$\frac{dv_D}{dT}=\frac{k}{q}\ln\left(\frac{i_D}{I_S}\right)-\frac{kT}{q}\frac{1}{I_S}\frac{dI_S}{dT}=\frac{v_d}{T}-V_T\frac{1}{I_S}\frac{dI_S}{dT} \quad | \quad I_S=Kn_i^2=KBT^3\exp\left(-\frac{E_{GO}}{kT}\right)$$

$$\frac{dI_S}{dT}=3KBT^2\exp\left(-\frac{E_{GO}}{kT}\right)+KBT^3\exp\left(-\frac{E_{GO}}{kT}\right)\left(+\frac{E_{GO}}{kT^2}\right)$$

$$\frac{1}{I_S}\frac{dI_S}{dT}=\frac{3}{T}+\frac{E_{GO}}{kT^2}=\frac{3}{T}+\frac{qV_{GO}}{kT^2}=\frac{3}{T}+\frac{V_{GO}}{V_TT} \quad | \quad \frac{dv_D}{dT}=\frac{v_d}{T}-V_T\frac{1}{I_S}\frac{dI_S}{dT}=\frac{v_d-V_{GO}-3V_T}{T}$$

$$V_D(275K)=0.680V-1.82x10^{-3}\frac{V}{K}(300K-275K)=0.726\ V$$

$$V_D(350K)=0.680V-1.82x10^{-3}\frac{V}{K}(350K-300K)=0.589\ V$$

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$$w_d=0.113\mu m\sqrt{1+\frac{10V}{0.979V}}=0.378\ \mu m \quad | \quad E_{max}=\frac{2(V+\phi_j)}{w_d}=\frac{2(10.979V)}{0.378x10^{-4}cm}=581\frac{kV}{cm}$$

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$$I_S=10fA\sqrt{1+\frac{10V}{0.8V}}=36.7\ fA$$

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$$C_{jo} = \frac{11.7\left(8.854x10^{-14}F/cm\right)}{0.113x10^{-4}cm} = 91.7\frac{nF}{cm^2} \quad | \quad \mathrm{C_j}\left(0V\right) = 91.7\frac{nF}{cm^2}\left(10^{-2}cm\right)\left(1.25x10^{-2}cm\right) = 11.5\ pF$$

$$C_j\left(5V\right) = \frac{11.5pF}{\sqrt{1+\frac{5V}{0.979V}}} = 4.64\ pF$$

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$$C_D = \frac{10^{-5}A}{0.025V}10^{-8}s = 4.00\ pF \quad | \quad C_D = \frac{8x10^{-4}A}{0.025V}10^{-8}s = 320\ pF \quad | \quad C_D = \frac{5x10^{-2}A}{0.025V}10^{-8}s = 0.02\ \mu F$$

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Two points on the load line: $V_D = 0,\ I_D = \frac{5V}{5k\Omega} = 1\ mA;\ I_D = 0,\ V_D = 5V$

The intersection of the two curves occurs at the Q-pt: $\left(0.88\ \mathrm{mA},\ 0.6\ \mathrm{V}\right)$

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$$10 = 10^4 I_D + V_D \quad | \quad V_D = V_T\ln\left(1+\frac{I_D}{I_S}\right) \quad | \quad 10 = 10^4 I_D + 0.025\ln\left(1+\frac{I_D}{I_S}\right)$$

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```
id = fzero(@(id) (10-10000*id-0.025*log(1+id/1e-13), 5e-4)
ans = 9.4258e-004
```

Page 102 Using MATLAB:

```
vd = fzero(@(vd) (10-10000*(1e-14)*(exp(40*vd)-1)-vd), 0.5)
vd = 0.6316 V
id = (1e-14)*(exp(40*vd)-1)
id = 9.3684e-04
---
id = fzero(@(id) (10-10000*id-log(1+id/1e-13)), .001)
id = 9.4258e-04
id = fzero(@(id) (10-10000*id-log(1+id/1e-15)), .001)
id = 9.3110e-04
```

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From the answer, the diodes are on,on,off.

$$I_1 = I_{D1} + I_{D2} \qquad \frac{10V\text{-}V_B}{2.5k\Omega} = \frac{V_B - 0.6V - (-20V)}{10k\Omega} + \frac{V_B - 0.6V - (-10V)}{10k\Omega} = 0 \rightarrow V_B = 1.87\ V$$

$$I_{D1} = \frac{1.87 - 0.6 - (-20V)}{10k\Omega} = 2.13\ mA$$

$$I_{D2} = \frac{1.87 - 0.6 - (-10V)}{10k\Omega} = 1.13\ mA \mid V_{D3} = -(1.87 - 0.6) = -1.27\ V$$

$I_{D1} > 0,\ I_{D2} > 0,\ V_{D3} < 0$. These results are consistent with the assumptions.

Q-Pts: (2.13 mA, 0.60 V) (1.13 mA, 0.60 V) (0 , -1.27 V)

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$$R_{\min} = \frac{5k\Omega}{\frac{20}{5} - 1} = 1.67\ k\Omega$$

$V_O = 20V \dfrac{1k\Omega}{5k\Omega + 1k\Omega} = 3.33\ V$ (V_Z is off) | *For* $R_L \geq 1.67\ k\Omega$,

$V_O = 5\ V$ (V_Z is conducting)

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$$\frac{V_L - 20V}{1k\Omega} + \frac{V_L - 5V}{0.1k\Omega} + \frac{V_L}{5k\Omega} = 0 \rightarrow V_L = 6.25\ V \quad | \quad I_Z = \frac{6.25V - 5V}{0.1k\Omega} = 12.5mA$$

$$P_Z = 5V(12.5mA) + 100\Omega(12.5mA)^2 = 78.1\ mW$$

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Line Regulation $= \dfrac{0.1\text{k}\Omega}{0.1\text{k}\Omega + 5\text{k}\Omega} = 19.6\dfrac{mV}{V}$ Load Regulation $= 0.1\text{k}\Omega \| 5\text{k}\Omega = 98.0\ \Omega$

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$$V_{dc} = V_P - V_{on} = 6.3\sqrt{2} - 1 = 7.91\ V \quad I_{dc} = \frac{7.91V}{0.5\Omega} = 15.8\ A \quad V_r = \frac{I_{dc}}{C}T = \frac{15.8A}{0.5F}\frac{1}{60}s = 0.527\ V$$

$$\Delta T = \frac{1}{\omega}\sqrt{2\frac{V_r}{V_P}} = \frac{1}{2\pi(60)}\sqrt{2\left(\frac{0.527V}{8.91V}\right)} = 0.912\ ms \quad \theta_c = 120\pi(0.912ms)\frac{180^o}{\pi} = 19.7^o$$

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$$V_{dc} = V_P - V_{on} = 10\sqrt{2} - 1 = 13.1\ V \quad I_{dc} = \frac{13.1V}{2\Omega} = 6.57\ A \quad C = \frac{I_{dc}}{V_r}T = \frac{6.57A}{0.1F}\frac{1}{60}s = 1.10\ F$$

$$\Delta T = \frac{1}{\omega}\sqrt{2\frac{V_r}{V_P}} = \frac{1}{2\pi(60)}\sqrt{2\left(\frac{0.1V}{14.1V}\right)} = 0.316\ ms \quad \theta_c = 120\pi(0.316ms)\frac{180^o}{\pi} = 6.82^o$$

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$$\text{At 300K}: \; V_D = \frac{kT}{q}\ln\left(1+\frac{I_D}{I_S}\right) = \frac{1.38x10^{-23} J/K(300K)}{1.60x10^{-19}C}\ln\left(1+\frac{48.6A}{10^{-15}A}\right) = 0.994\ V$$

$$\text{At } 50^{o}\text{C}: \; V_D = \frac{kT}{q}\ln\left(1+\frac{I_D}{I_S}\right) = \frac{1.38x10^{-23} J/K(273K+50K)}{1.60x10^{-19}C}\ln\left(1+\frac{48.6A}{10^{-15}A}\right) = 1.07\ V$$

$$\text{Note: For } V_T = 0.025V,\ V_D = \frac{kT}{q}\ln\left(1+\frac{I_D}{I_S}\right) = 0.025V\ln\left(1+\frac{48.6A}{10^{-15}A}\right) = 0.961\ V$$

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$$V_{rms} = \frac{V_{dc}+V_{on}}{\sqrt{2}} = \frac{15+1}{\sqrt{2}} = 11.3\ V \quad | \quad C = \frac{I_{dc}}{V_r}T = \frac{2A}{0.01(15V)}\frac{1}{60}s = 0.222F = 222{,}000\ \mu F$$

$$I_{SC} = \omega C V_P = 2\pi(60Hz)(0.222F)(16V) = 1340\ A$$

$$\Delta T = \frac{1}{\omega}\sqrt{2\frac{V_r}{V_P}} = \frac{1}{2\pi(60)}\sqrt{2\frac{(0.01)(15)}{16}} = 0.363\ ms \quad | \quad I_P = I_{dc}\frac{2T}{\Delta T} = 2A\frac{2s}{60(0.363ms)} = 184\ A$$

CHAPTER 4

Page 152

$(a)\ \beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.970}{1-0.970} = 32.3 \quad | \quad \beta_F = \frac{0.993}{1-0.993} = 142 \quad | \quad \beta_F = \frac{0.250}{1-.250} = 0.333$

$(b)\ \alpha_F = \frac{\beta_F}{\beta_F+1} = \frac{40}{41} = 0.976 \quad | \quad \alpha_F = \frac{200}{201} = 0.995 \quad | \quad \alpha_F = \frac{3}{4} = 0.750$

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$$i_C = 10^{-15}A\left[exp\left(\frac{0.700}{0.0259}\right) - exp\left(\frac{-9.30}{0.0259}\right)\right] - \frac{10^{-15}A}{0.5}\left[exp\left(\frac{-9.30}{0.0259}\right) - 1\right] = 0.547\ mA$$

$$i_E = 10^{-15}A\left[exp\left(\frac{0.700}{0.0259}\right) - exp\left(\frac{-9.30}{0.0259}\right)\right] + \frac{10^{-15}A}{100}\left[exp\left(\frac{-9.30}{0.0259}\right) - 1\right] = 0.552\ mA$$

$$i_B = \frac{10^{-15}A}{100}\left[exp\left(\frac{0.700}{0.0259}\right) - exp\left(\frac{-9.30}{0.0259}\right)\right] + \frac{10^{-15}A}{0.5}\left[exp\left(\frac{-9.30}{0.0259}\right) - 1\right] = 5.47\ \mu A$$

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$$i_C = 10^{-16}A\left[exp\left(\frac{0.75}{0.0259}\right) - exp\left(\frac{0.70}{0.0259}\right)\right] - \frac{10^{-16}A}{0.4}\left[exp\left(\frac{0.70}{0.0259}\right) - 1\right] = 185\ \mu A$$

$$i_E = 10^{-16}A\left[exp\left(\frac{0.75}{0.0259}\right) - exp\left(\frac{0.70}{0.0259}\right)\right] + \frac{10^{-16}A}{75}\left[exp\left(\frac{0.75}{0.0259}\right) - 1\right] = 327\ \mu A$$

$$i_B = \frac{10^{-16}A}{75}\left[exp\left(\frac{0.75}{0.0259}\right) - 1\right] + \frac{10^{-16}A}{0.4}\left[exp\left(\frac{0.70}{0.0259}\right) - 1\right] = 142\ \mu A$$

$$i_T = 10^{-15}A\left[exp\left(\frac{0.75}{0.0259}\right) - exp\left(\frac{-2.0}{0.0259}\right)\right] = 3.77\ mA$$

$$i_T = 10^{-15}A\left[exp\left(\frac{0.75}{0.0259}\right) - exp\left(\frac{-4.25}{0.0259}\right)\right] = 3.77\ mA$$

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$$v_{CE} \geq -0.0259\ ln(0.001) = 179\ mV$$

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$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}+1\right) = 0.025V \ln\left(\frac{10^{-4}A}{10^{-16}A}+1\right) = 0.691\ V$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}+1\right) = 0.025V \ln\left(\frac{10^{-3}A}{10^{-16}A}+1\right) = 0.748\ V$$

For V_T = 0.0259 V: V_{BE} = 0.716 V, 0.775

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$$npn: V_{BE} > 0,\ V_{BC} < 0 \rightarrow \text{Forward – Active Region} \quad | \quad \text{pnp}: V_{EB} > 0,\ V_{CB} > 0 \rightarrow \text{Saturation Region}$$

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$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{0.05} = 19 \qquad \beta_R = \frac{\alpha_R}{1-\alpha_R} = \frac{0.25}{0.75} = \frac{1}{3}$$

$$V_{BE} = 0,\ V_{BC} << 0:\ I_C = I_S\left(1+\frac{1}{\beta_R}\right) = 10^{-16}A\left(1+\frac{1}{0.333}\right) = 0.400\,fA$$

$$I_E = I_S = 0.100\,fA \qquad I_B = -\frac{I_S}{\beta_R} = -\frac{10^{-16}A}{0.333} = -0.300\,fA$$

$$V_{BE} << 0,\ V_{BC} << 0: \quad I_C = \frac{I_S}{\beta_R} = 3x10^{-16}A = 0.300\,fA$$

$$I_E = \frac{I_S}{\beta_F} = \frac{10^{-16}A}{19.0} = 5.26\ aA \qquad I_B = -\frac{I_S}{\beta_F} - \frac{I_S}{\beta_R} = -\frac{10^{-16}A}{19.0} - \frac{10^{-16}A}{1/3} = -0.305\,fA$$

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(a) The currents do not depend upon V_{CC} as long as the collector - base junction is reverse biased by more than 0.1 V. (Later when Early votlage V_A is discussed, one should revisit this problem.)

(b) $I_E = 100\ \mu A \quad | \quad I_B = \dfrac{I_E}{\beta_F + 1} = \dfrac{100\mu A}{51} = 1.96\ \mu A \quad | \quad I_C = \beta_F I_B = 50 I_B = 98.0\ \mu A$

$V_{BE} = V_T \ln(1+I_C/I_S)$ = 0.0259V ln (1+98uA/0.1fA) = 0.715 V

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(a) The currents do not depend upon V_{CC} as long as the collector - base junction is reverse biased by more than 0.1 V. (Later when Early voltage V_A is discussed, one should revisit this problem.)

(b) Forward - active region : $I_B = 100\ \mu A$ | $I_E = (\beta_F + 1) I_B = 5.10\ mA$ | $I_C = \beta_F I_B = 5.00\ mA$

$V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{5.00 mA}{10^{-16} A} + 1\right) = 0.789\ V$ | Checking : $V_{BC} = -5 + 0.789 = -4.21$

Forward - active region with $V_{CB} \ge 0$ requires $V_{CC} \ge V_{BE}$ or $V_{CC} \ge 0.792$ V

For V_T = 25.9 mV, V_{BE} = 0.0259V ln(5mA/0.1fA+1) = 0.817 V and $V_{CC} \ge 0.817$ V

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$$I_E = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48\ mA \ |\ I_B = \frac{I_E}{\beta_F + 1} = \frac{I_E}{51} = 29.1\ \mu A \ |\ I_C = \beta_F I_B = 50 I_B = 1.45\ mA$$

$$V_{CE} = V_C - V_E = (9 - 4300 I_C) - (-0.7) = 3.47\ V \ |\ Q - Point = (1.45\ mA, 3.47\ V)$$

$$I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} 100\ \mu A = 102\ \mu A \ |\ R = \frac{-0.7V - (-9V)}{102\ \mu A} = 81.4\ k\Omega$$

The nearest 5% value is 82 $k\Omega$.

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$$I_E = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48\ mA \ |\ I_B = \frac{I_E}{\beta_F + 1} = \frac{I_E}{51} = 29.1\ \mu A \ |\ I_C = \beta_F I_B = 50 I_B = 1.45\ mA$$

$$I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} I_C = 102\ I_C \ |\ V_{BE} = V_T\ ln\left(\frac{I_C}{I_S} + 1\right) = 0.0259\ ln(2x10^{15}\ I_C + 1)$$

$$V_{BE} + 8200\Omega\left[1.02(5x10^{-16}A)\left[exp\left(\frac{V_{BE}}{0.0259V}\right) - 1\right]\right] = 9\ V$$

Using a calculator solver, spreadsheet, MATLAB or WolframALPHA etc., V_{BE} = 0.7333 V.

$$I_C = 5x10^{-16}\ exp\left(\frac{0.7333}{0.0259V}\right) A = 989\ \mu A \ |\ V_{CE} = 9 - 4300 I_C - (-0.7333) = 5.48\ V$$

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$$I_{SD} = \frac{I_{SBJT}}{\alpha_F} = \frac{20\text{fA}}{0.95} = 21.1\ \text{fA}$$

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$$-I_C = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48\ mA \ |\ I_B = \frac{-I_C}{\beta_R + 1} = \frac{-I_C}{2} = 0.741\ mA \ |\ -I_E = \beta_R I_B = (1) I_B = 0.741\ mA$$

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$$V_{CESAT} = (0.025V)\ln\left[\left(\frac{1}{0.5}\right)\frac{1+\dfrac{1mA}{2(40\mu A)}}{1-\dfrac{1mA}{50(40\mu A)}}\right] = 99.7\ mV$$

$$V_{BESAT} = (0.025V)\ln\left[\frac{0.1mA+(1-0.5)1mA}{10^{-15}A\left(\dfrac{1}{50}+1-0.5\right)}\right] = 0.694\ mV$$

$$V_{BCSAT} = (0.025V)\ln\left[\frac{0.1mA-\dfrac{1mA}{50}}{10^{-15}A\left(\dfrac{1}{0.5}\right)\left(\dfrac{1}{50}+1-0.5\right)}\right] = 0.627\ mV$$

Note: $V_{CESAT} = V_{BESAT} - V_{BCSAT} = 67.7mV$

For $V_T = $ 25.9 mV, scale the above results by $\frac{25.9}{25.0}$ yielding 103 mV, 0.719 V, 0.650 V.

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$$(a)\ \ D_n = \frac{kT}{q}\mu_n = 0.0259V(500cm^2/V-s) = 13.0cm^2/s$$

$$(b)\ \ I_S = \frac{qAD_n n_i^2}{N_{AB}W} = \frac{1.60x10^{-19}C(50\mu m^2)(10^{-4}cm/\mu m)(13.0cm^2/s)(10^{20}/cm^6)}{(10^{18}/cm^3)(1\mu m)} = 1.04x10^{-18}$$ rounded to 1 aA

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$$V_T = \frac{(1.38x10^{-23}J/K)(373K)}{1.60x10^{-19}C} = 32.2mV \quad | \quad C_D = \frac{I_C}{V_T}\tau_F = \frac{10A}{0.0322V}(4x10^{-9}s) = 1.24\ \mu F$$

$$f_\beta = \frac{f_T}{\beta_F} = \frac{300MHz}{125} = 2.40\ MHz$$

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$$I_C = 10^{-15}\left(exp\frac{0.7}{0.0259V}\right)\left(1+\frac{10}{50}\right)A = 0.656\ mA\ \mid\ \beta_F = 75\left(1+\frac{10}{50}\right) = 90\ \mid\ I_B = \frac{0.656mA}{90} = 7.29\ \mu A$$

$$I_C = 10^{-15}\left(exp\frac{0.7}{0.0259V}\right)A = 0.547\ mA\ \mid\ I_B = \frac{0.547mA}{75} = 7.29\ \mu A$$

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$$g_m = \frac{40}{V}\left(10^{-4}A\right) = 4.00\ mS \quad | \quad g_m = \frac{40}{V}\left(10^{-3}A\right) = 40.0\ mS$$

$$C_D = 4.00mS\left(25ps\right) = 0.100\ pF \quad | \quad C_D = 40.0mS\left(25ps\right) = 1.00\ pF$$

$$\frac{g_m}{I_D} = \frac{1}{V_T} = \frac{1}{0.02588V} = 38.6/V$$

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$$V_T = \frac{kT}{q} = \frac{1.38x10^{-23}\left(300\right)}{1.60x10^{-19}} = 25.9\ mV \quad | \ \text{IS} = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{350\mu A}{\exp\left(\frac{0.68}{0.0259}\right)} = 1.39\ fA$$

BF = 80 | VAF = 70 V

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$$V_{EQ} = \frac{18k\Omega}{18k\Omega + 36k\Omega}12V = 4.00\ V \quad | \quad R_{EQ} = 18k\Omega \| 36k\Omega = 12\ k\Omega$$

$$I_B = \frac{4.00 - 0.7}{12 + \left(75+1\right)16}\frac{V}{k\Omega} = 2.687\ \mu A \ | \ I_C = 75I_B = 202\ \mu A \ | \ I_E = 76I_B = 204\ \mu A$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.29\ V \ | \ Q\text{-}po\text{int}: \left(202\ \mu A,\ 4.29\ V\right)$$

– – –

$$V_{EQ} = \frac{180k\Omega}{180k\Omega + 360k\Omega}12V = 4.00\ V \quad | \quad R_{EQ} = 180k\Omega \| 360k\Omega = 120\ k\Omega$$

$$I_B = \frac{4.00 - 0.7}{120 + \left(75+1\right)16}\frac{V}{k\Omega} = 2.470\ \mu A \ | \ I_C = 75I_B = 185\ \mu A \ | \ I_E = 76I_B = 188\ \mu A$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.29\ V \ | \ Q\text{-}po\text{int}: \left(185\ \mu A,\ 4.93\ V\right)$$

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$$I_2 = \frac{I_C}{5} = \frac{50 I_B}{5} = 10 I_B$$

– – –

$$V_{EQ} = \frac{18k\Omega}{18k\Omega + 36k\Omega} 12V = 4.00\ V \quad | \quad R_{EQ} = 18k\Omega \| 36k\Omega = 12\ k\Omega$$

$$I_B = \frac{4.00 - 0.7}{12 + (500+1)16\ k\Omega} \frac{V}{} = 0.4111\ \mu A \ | \ I_C = 500 I_B = 205.6\ \mu A \ | \ I_E = 76 I_B = 206.0\ \mu A$$

$$V_{CE} = 12 - 22000 I_C - 16000 I_E = 4.18\ V \ | \ \text{Q-point}: (206\ \mu A,\ 4.18\ V)$$

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The voltages all remain the same, and the currents are reduced by a factor of 10. Hence all the resistors are just scaled up by a factor of 10.

120 kΩ → 1.2 MΩ 82 kΩ → 820 kΩ 6.8 kΩ → 68 kΩ

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$$I_B = \frac{9 - 0.7}{36 + (50+1)1\ k\Omega} \frac{V}{} = 95.4\ \mu A \quad | \quad I_C = 50 I_B = 4.77\ mA \quad | \quad I_E = 51 I_B = 4.87\ mA$$

$$V_{CE} = 9 - 1000(I_C + I_B) = 4.13\ V \quad | \quad \text{Q-point}: (4.77\ mA,\ 4.13\ V)$$

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IS	1.00E-15	VT	0.0259	BF	75

VBE	IC	V'BE
7.0000E-01	2.0155E-04	6.7416E-01
6.7416E-01	2.0313E-04	6.7436E-01
6.7436E-01	2.0311E-04	6.7436E-01
6.7436E-01	2.0311E-04	6.7436E-01
6.7436E-01	2.0311E-04	6.7436E-01
6.7436E-01	2.0311E-04	6.7436E-01

CHAPTER 5

Page 220

$$K_n^{'} = \mu_n \frac{\varepsilon_{ox}}{T_{ox}} = 500 \frac{cm^2}{V-s} \frac{3.9\left(8.854x10^{14} F/cm\right)}{25x10^{-7} cm} = 69.1x10^{-6} \frac{C}{V^2-s} = 69.1 \frac{\mu A}{V^2}$$

Scaling: $K_n^{'} = \frac{25x10^{-7} cm}{5x10^{-7} cm}\left(69.1 \frac{\mu A}{V^2}\right) = 345 \frac{\mu A}{V^2}$

$$K_n = K_n^{'} \frac{W}{L} = 50 \frac{\mu A}{V^2}\left(\frac{20\mu m}{1\mu m}\right) = 1000 \frac{\mu A}{V^2} \quad K_n = 50 \frac{\mu A}{V^2}\left(\frac{60\mu m}{3\mu m}\right) = 1000 \frac{\mu A}{V^2}$$

$$K_n = 50 \frac{\mu A}{V^2}\left(\frac{10\mu m}{0.25\mu m}\right) = 2000 \frac{\mu A}{V^2}$$

For $V_{GS} = 0\ V$ and $1\ V$, $V_{GS} < V_{TN}$ and the transistor is off. Therefore $I_D = 0$.

V_{GS}-V_{TN} = 2-1.5 = 0.5 V and $V_{DS} = 0.1\ V \rightarrow$ Triode region operation

$$I_D = K_n^{'} \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 25 \frac{\mu A}{V^2}\left(\frac{10\mu m}{1\mu m}\right)\left(2-1.5-\frac{0.1}{2}\right)0.1V^2 = 11.3\ \mu A$$

V_{GS}-V_{TN} = 3-1.5 = 1.5V and $V_{DS} = 0.1\ V \rightarrow$ Triode region operation

$$I_D = K_n^{'} \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 25 \frac{\mu A}{V^2}\left(\frac{10\mu m}{1\mu m}\right)\left(3-1.5-\frac{0.1}{2}\right)0.1V^2 = 36.3\ \mu A$$

$$K_n^{'} = 25 \frac{\mu A}{V^2}\left(\frac{100\mu m}{1\mu m}\right) = 250 \frac{\mu A}{V^2}$$

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$$R_{on} = \frac{1}{K_n^{'} \frac{W}{L}\left(V_{GS} - V_{TN}\right)} = \frac{1}{250 \frac{\mu A}{V^2}\left(2-1\right)} = 4.00\ k\Omega \quad | \quad R_{on} = \frac{1}{250 \frac{\mu A}{V^2}\ \ (5\text{-}1)} = 1.00\ k\Omega$$

$$V_{GS} = V_{TN} + \frac{1}{K_n R_{on}} = 1V + \frac{1}{250 \frac{\mu A}{V^2}\left(2000\Omega\right)} = 3.00\ V$$

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$V_{GS} - V_{TN} = 2.5 - 1 = 1.5\ V$ and $V_{DS} =$ 0.25 V → Triode region operation

$$I_D = K_n' \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 1000\frac{\mu A}{V^2}\left(2.5 - 1 - \frac{0.25}{2}\right)0.25V^2 = 344\ \mu A$$

$$g_m = K_n V_{DS} = 1000\frac{\mu A}{V^2}(0.25V) = 250\ \mu S$$

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$$V_{GS} - V_{TN} = 5 - 1 = 4\,V \text{ and } V_{DS} = 10\,V \rightarrow \text{ Saturation region operation}$$

$$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2 = \frac{1}{2}\frac{mA}{V^2}(5-1)^2V^2 = 8.00\,mA$$

$$K_n = K_n'\frac{W}{L} \rightarrow \frac{W}{L} = \frac{1mA}{40\mu A} = \frac{25}{1} \qquad W = 25L = 8.75\,\mu m$$

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$$(a) \quad V_{GS} - V_{TN} = 2.5 - 1 = 1.5\,V \text{ and } V_{DS} = 0.28\,V \rightarrow \text{ Linear region operation}$$

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 1\frac{mA}{V^2}\left(2.5 - 1 - \frac{0.28}{2}\right)0.28V^2 = 381\,\mu A$$

$$g_m = K_n V_{DS} = 1\frac{mA}{V^2}0.28V = 280\,\mu S$$

$$(b) \quad V_{GS} - V_{TN} = 2.5 - 1 = 1.5\,V \text{ and } V_{DS} = 4\,V \rightarrow \text{ Saturation region operation}$$

$$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2 = \frac{1}{2}\frac{mA}{V^2}(2.5-1)^2V^2 = 1.13\,mA$$

$$g_m = K_n(V_{GS} - V_{TN}) = 1\frac{mA}{V^2}(1.5) = 1.50\,mS$$

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$V_{GS} - V_{TN} = 5 - 1 = 4\ V$ and $V_{DS} = 10\ V$ → Saturation region operation

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = \frac{1}{2}\frac{mA}{V^2}(5-1)^2V^2\left[1 + 0.02(10)\right] = 9.60\ mA$$

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = \frac{1}{2}\frac{mA}{V^2}(5-1)^2V^2\left[1 + 0(10)\right] = 8.00\ mA$$

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$V_{GS} - V_{TN} = 4 - 1 = 3\ V$ and $V_{DS} = 5\ V$ → Saturation region operation

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = \frac{25}{2}\frac{\mu A}{V^2}(4-1)^2V^2\left[1 + 0.01(5)\right] = 118\ \mu A$$

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = \frac{25}{2}\frac{\mu A}{V^2}(5-1)^2V^2\left[1 + 0.01(10)\right] = 220\ \mu A$$

Digitizing the graph with a digitizer App yields $(5\,V, 204\,\mu A)$ and $(10\,V, 214\,\mu A)$

$$\lambda = \frac{1}{200\,\mu A}\frac{(214\,\mu A - 204\,\mu A)}{10\,V - 5\,V} = 0.010/V$$

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Assuming pinchoff region operation, $I_D = \frac{K_n}{2}\left(0 - V_{TN}\right)^2 = \frac{50}{2}\frac{\mu A}{V^2}\left(+2V\right)^2 = 100\ \mu A$

$$V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = 2V + \sqrt{\frac{2\left(100\ \mu A\right)}{50\mu A/V^2}} = 4.00\ V$$

– – –

Assuming pinchoff region operation, $I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2 = \frac{50}{2}\frac{\mu A}{V^2}\left[1-\left(-2V\right)\right]^2 = 225\ \mu A$

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$$V_{TN} = V_{TO} + \gamma\left(\sqrt{V_{SB} + 0.6V} - \sqrt{0.6V}\right) = 1 + 0.75\left(\sqrt{0+0.6} - \sqrt{0.6}\right) = 1\ V$$

$$V_{TN} = 1 + 0.75\left(\sqrt{1.5+0.6} - \sqrt{0.6}\right) = 1.51\ V \quad | \quad V_{TN} = 1 + 0.75\left(\sqrt{3+0.6} - \sqrt{0.6}\right) = 1.84\ V$$

- - -

(a) V_{GS} is less than the threshold voltage, so the transistor is cut off and $I_D = 0$.

(b) $V_{GS} - V_{TN} = 2 - 1 = 1\ V$ and $V_{DS} = 0.5\ V \rightarrow$ Triode region operation

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 1\frac{mA}{V^2}\left(2 - 1 - \frac{0.5}{2}\right)0.5V^2 = 375\ \mu A$$

(c) $V_{GS} - V_{TN} = 2 - 1 = 1\ V$ and $V_{DS} = 2\ V \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = 0.5\frac{mA}{V^2}\left(2-1\right)^2V^2\left[1 + 0.02\left(2\right)\right] = 520\ \mu A$$

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(a) V_{GS} is greater than the threshold voltage, so the transistor is cut off and $I_D = 0$.

(b) $\left|V_{GS}\text{-}V_{TN}\right| = \left|\text{-}2+1\right| = 1\ V$ and $\left|V_{DS}\right| = 0.5\ V \rightarrow$ Triode region operation

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS} = 0.4\frac{mA}{V^2}\left(-2 + 1 - \frac{-0.5}{2}\right)\left(-0.5\right)V^2 = 150\ \mu A$$

(c) $\left|V_{GS}\text{-}V_{TN}\right| = \left|-2+1\right| = 1\ V$ and $\left|V_{DS}\right| = 2\ V \rightarrow$ Saturation region operation

$$I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right) = \frac{0.4}{2}\frac{mA}{V^2}\left(-2+1\right)^2V^2\left[1 + 0.02\left(2\right)\right] = 208\ \mu A$$

Page 235

$(a)\ \ V_{DS} = 1.9V\ \ |\ \ V_{GS} - V_{TN} = 2.3\ V\ \ |\ \ I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS}$

$I_D = 60\mu A\left(3 - 0.7 - \frac{1.9}{2}\right)1.9 = 154\ \mu A$

(b) See Table S6.10 Fall time: $t_f = 3.7R_{on}C = 3.7\dfrac{50fF}{60x10^{-6}(3-0.7)\frac{1}{\Omega}} = 1.34\ nS$

(c) Oops! – See Sec. 5.10.7

$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{MIN}}{2}\right)V_{MIN}\ \ |\ \ V_{MIN} = min(V_{GS} - V_{TN}, V_{DS}, V_{SAT}) = 1\ V$

$I_D = 60\mu A\left(3 - 0.7 - \frac{1}{2}\right)1 = 108\ \mu A$

$V_C = V_{BL} - V_{TN}\ \ |\ \ V_C = 3 - \left[0.7 + 0.5\left(\sqrt{V_C + 0.6} - \sqrt{0.6}\right)\right] \rightarrow V_C = 1.89\ V\ \ |\ \ V_C = 3 - 0.7 = 2.3\ V$

– – –

$$n = \frac{CV}{q} = \frac{25x10^{-15}F(1.89V)}{1.60x10^{-19}C} = 2.95 \text{ x } 10^5 \text{electrons}$$

Page 237

$(a)\ \ \Delta V = \dfrac{V_C - V_{BL}}{\frac{C_{BL}}{C_C}+1} = \dfrac{1.9 - 0.95}{\frac{49C_C}{C_C}+1}V = 19.0\text{ m}V\ \ |\ \ \Delta V = \dfrac{V_C - V_{BL}}{\frac{C_{BL}}{C_C}+1} = \dfrac{0 - 0.95}{\frac{49C_C}{C_C}+1}V = -19.0\text{ m}V$

$(b)\ \ \tau = R_{on}\dfrac{C_C}{\frac{C_C}{C_{BL}}+1} = 5k\Omega\dfrac{25fF}{\frac{1}{49}+1} = 0.123\ ns$ or $\tau \cong R_{on}C_C = 5k\Omega(25fF) = 0.125\ ns$

Page 240

$(a)\ \ K_p = 40x10^{-6}\left(\frac{20}{1}\right) = 800\ \frac{\mu A}{V^2}\ \ |\ \ K_n = 100x10^{-6}\left(\frac{20}{1}\right) = 2000\ \frac{\mu A}{V^2} = 2.00\ \frac{mA}{V^2}$

$(b)\ \ V_{TN} = 0.6 + 0.5\left(\sqrt{2.5+0.6} - \sqrt{0.6}\right) = 1.09\ V$

$(c)\ \ V_{TP} = -0.6 - 0.75\left(\sqrt{2.5+0.7} - \sqrt{0.7}\right) = -1.31\ V$

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(a) For $v_I = 1\ V,\ V_{GSN} - V_{TN} = 1 - 0.6 = 0.4V$ and $V_{GSP} - V_{TP} = -1.5 + 0.6 = -0.9V$

M_N is saturated for $v_O \geq 0.4\ V$. M_P is in the triode region for $v_O \geq 1.6\ V$. $\therefore\ 1.6\ V \leq v_O \leq 2.5\ V$

(b) M_P is saturated for $v_O \leq 1.6\ V$. $\therefore\ 0.4\ V \leq v_O \leq 1.6\ V$

(c) M_N is in the triode region for $v_O \leq 0.4\ V$. M_P is saturated for $v_O \leq 1.6\ V$. $\therefore\ 0 \leq v_O \leq 0.4\ V$

– – –

$$\left(\frac{W}{L}\right)_P = \frac{K_n}{K_p}\left(\frac{W}{L}\right)_N = 2.5\left(\frac{10}{1}\right) = \frac{25}{1}$$

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Both transistors are saturated since $|V_{GS}| = |V_{DS}|$.

$$\frac{K_n}{2}\left(V_{GSN} - V_{TN}\right)^2 = \frac{K_p}{2}\left(V_{GSP} - V_{TP}\right)^2 \qquad K_n = K_p \qquad |V_{TN}| = |V_{TP}|$$

$$V_{GSN} = -V_{GSP} \rightarrow v_I = V_{DD} - v_I \rightarrow v_I = \frac{V_{DD}}{2}$$

$$\frac{10K_p}{2}\left(V_{GSN} - V_{TN}\right)^2 = \frac{K_p}{2}\left(V_{GSP} - V_{TP}\right)^2 \rightarrow \sqrt{10}\left(V_{GSN} - V_{TN}\right) = -V_{GSP} + V_{TP}$$

$$\sqrt{10}\left(v_I - 0.6\right) = 4 - v_I - 0.6 \rightarrow v_I = 1.273\ V$$

$$\frac{K_p}{2}\left(V_{GSN} - V_{TN}\right)^2 = \frac{10K_p}{2}\left(V_{GSP} - V_{TP}\right)^2 \rightarrow \left(V_{GSN} - V_{TN}\right) = \sqrt{10}\left(-V_{GSP} + V_{TP}\right)$$

$$v_I - 0.6 = \sqrt{10}\left(4 - v_I - 0.6\right) \rightarrow v_I = 2.727\ V$$

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$$C_{GC} = \left(200\frac{\mu F}{m^2}\right)\left(5x10^{-6}m\right)\left(0.5x10^{-6}m\right) = 0.500\,fF$$

$$\text{Triode region: } C_{GD} = C_{GS} = \frac{C_{GC}}{2} + C_{GSO}W = 0.25\,fF + \left(300\frac{pF}{m}\right)\left(5x10^{-6}m\right) = 1.75\,fF$$

$$\text{Saturation region: } C_{GS} = \frac{2}{3}C_{GC} + C_{GSO}W = 0.333\,fF + \left(300\frac{pF}{m}\right)\left(5x10^{-6}m\right) = 1.83\,fF$$

$$C_{GD} = C_{GSO}W = \left(300\frac{pF}{m}\right)\left(5x10^{-6}m\right) = 1.50\,fF$$

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$KP = K_n = 150U$ | $LAMBDA = \lambda = 0.0133$ | $VTO = V_{TN} = 1$ | $PHI = 2\phi_F = 0.6$

$W = W = 1.5U$ | $L = L = 0.25U$

Page 251

$$\text{Circuits/cm}^2 \propto \alpha^2 = \left(\frac{0.18\mu m}{10nm}\right)^2 = \left(\frac{0.18\mu m}{0.010\mu m}\right)^2 = (18)^2 = 324$$

$$\text{Power} - \text{Delay Product} \propto \frac{1}{\alpha^3} = \frac{1}{18^3} = \frac{1}{5832};\ \text{Rounding} \rightarrow 5830 \text{ times improvement}$$

$$i_D^* = \mu_n \frac{\varepsilon_{ox}}{T_{ox}/\alpha}\frac{W/\alpha}{L/\alpha}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right)v_{DS} = \alpha\ i_D \ \mid\ P^* = V_{DD} i_D^* = V_{DD}\left(\alpha\ i_D\right) = \alpha\ P$$

$$\frac{P^*}{A^*} = \frac{\alpha P}{(W/\alpha)(L/\alpha)} = \alpha^3 \frac{P}{A} \quad \rightarrow \quad i_D^* = \alpha\ i_D \ \mid\ P^* = \alpha\ P \ \mid\ \frac{P^*}{A^*} = \alpha^3 \frac{P}{A}$$

Page 252

$$(a)\ f_T = \frac{1}{2\pi}\frac{500cm^2/V-s}{\left(0.25x10^{-4}cm\right)^2}(1V) = 127\ GHz$$

$$(b)\ f_T = \frac{1}{2\pi}\frac{500cm^2/V-s}{(40nm)^2}(1V) = \frac{1}{2\pi}\frac{500cm^2/V-s}{\left[\left(40x10^{-9}m\right)\left(100\frac{cm}{m}\right)\right]^2}(1V) = 4.97\ THz$$

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$$\frac{V}{L} \geq 10^5\frac{V}{cm} \rightarrow V = \left(10^5\frac{V}{cm}\right)(10^{-4}cm) = 10\ V$$

$$V = \left(10^5\frac{V}{cm}\right)(10^{-5}cm) = 1\ V \quad \mid \quad L = \left(10^5\frac{V}{cm}\right)(15x10^{-7}cm) = 0.15\ V$$

$$V_{MIN} = \min\left[\left(V_{GS} - V_{TN}\right), V_{DS}, V_{SAT}\right] = \min\left[3.5, 4, 2.5\right] = 2.5\ V$$

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{MIN}}{2}\right)V_{MIN}\left(1 + \lambda V_{DS}\right) = 10^{-4}\left(4 - 0.5 - \frac{2.5}{2}\right)(2.5)\left[1 + 0.02(4)\right] = 607.5\ \mu A$$

$$V_{MIN} = \min\left[\left(V_{GS} - V_{TN}\right), V_{DS}, V_{SAT}\right] = \min\left[3.5, 4, 20\right] = 3.5\ V$$

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{MIN}}{2}\right)V_{MIN}\left(1 + \lambda V_{DS}\right) = 10^{-4}\left(3.5 - \frac{3.5}{2}\right)(3.5)\left[1 + 0.02(4)\right] = 661.5\ \mu A$$

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(a) From the graph for $V_{GS} = 0.25\ V,\ I_D \cong 10^{-18}\ A$ |

(b) From the graph for $V_{GS} = V_{TN} - 0.5\ V,\ I_D \cong 3x10^{-15}\ A$

(c) $I = (10^9 \text{ transistors})(3x10^{-15} \text{ A/transistors}) = 3\ \mu A$

From the graph in the exponential region:

$$(V_{GS}, I_D) = (0.45V, 10^{-10}A), (0.70V, 10^{-8}A) \text{ and } I_D = I_{DO} exp\left(\frac{V_{GS} - V_{TN}}{nV_T}\right)$$

$$\frac{10^{-8}}{10^{-10}} = \frac{I_{DO} exp\left(\frac{0.70 - V_{TN}}{nV_T}\right)}{I_{DO} exp\left(\frac{0.45 - V_{TN}}{nV_T}\right)} \rightarrow 100 = exp\left(\frac{0.25}{nV_T}\right) \rightarrow n = \frac{0.25}{(0.0259)ln(100)} = 2.096 \rightarrow 2.10$$

$$I_{DO} = \frac{10^{-8}}{exp\left(\frac{0.2}{0.054287}\right)} = 0.251x10^{-9}A \text{ and } I_{DO} = \frac{10^{-10}}{exp\left(\frac{-0.05}{0.054287}\right)} = 0.251x10^{-9} \mid I_{DO} = 0.251\ nA$$

Using the previous values: $nV_T = 2.086(0.02590) = 54.286\ mV \rightarrow 54.3\ mV/decade$

$I_D = I_{DO} exp\left(\frac{V_{GS} - V_{TN}}{nV_T}\right) \quad | \quad g_m = \frac{I_D}{nV_T} \quad | \quad \frac{g_m}{I_D} = \frac{1}{nV_T} = \frac{1}{0.054287} = 18.4$

$$(a)\ V_{GS} = V_{TN}: \quad \left[ln\left(1 + exp\left(\frac{0 - nV_{DS}}{2nV_T}\right)\right)\right]^2 = (0.05)\left[ln\left(1 + exp\left(\frac{0}{2nV_T}\right)\right)\right]^2$$

$$\left[ln\left(1 + exp\left(\frac{-V_{DS}}{2V_T}\right)\right)\right] = (\sqrt{0.05})ln(2) \quad | \quad 1 + exp\left(\frac{-V_{DS}}{2V_T}\right) = 1.1676$$

$$| \quad V_{DS} = -2(0.0259)ln(0.16765) \quad | \quad V_{DS} = 92.509\ mV$$

$$I_D = 100\mu A\left([ln(2)]^2 - \left[ln\left(1 + exp\left(-\frac{92.509mV}{2(25.9mV)}\right)\right)\right]^2\right) = 45.643\ \mu A$$

$$Check:\ I_D = 100\mu A(0.95)[ln(2)]^2 = 45.643\ \mu A$$

$$(b)\ V_{GS} - V_{TN} = -0.2\ V: \quad \left[ln\left(1 + exp\left(-\frac{0.2 + 1.5V_{DS}}{3V_T}\right)\right)\right]^2 = (0.05)\left[ln\left(1 + exp\left(-\frac{0.2}{3V_T}\right)\right)\right]^2$$

$$\left[ln\left(1 + exp\left(-\frac{0.2 + 1.5V_{DS}}{3V_T}\right)\right)\right] = (\sqrt{0.05})ln\left(1 + exp\left(-\frac{0.2}{3V_T}\right)\right) = 0.016427$$

$$\left(exp\left(-\frac{0.2 + 1.5V_{DS}}{3V_T}\right)\right) = -1 + exp(0.016427) = 0.016563$$

$$0.2 + 1.5V_{DS} = -3V_T ln(0.016563) \rightarrow V_{DS} = 79.077\ mV$$

$$I_D = 100\mu A(0.95)\left[ln\left(1 + exp\left(-\frac{0.2}{3V_T}\right)\right)\right]^2 = 0.51271\ \mu A$$

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(a)

$L = 2\Lambda = 0.250\ \mu m$ | $W = 10\Lambda = 1.25\ \mu m$

Active area $= 10\Lambda(12\Lambda) = 120\Lambda^2 = 120(0.125\mu m)^2 = 1.88\ \mu m^2$

Gate area $= 2\Lambda(10\Lambda) = 20\Lambda^2 = 20(0.125\mu m)^2 = 0.313\ \mu m^2$

Transistor area $= (10\Lambda + 2\Lambda + 2\Lambda)(12\Lambda + 2\Lambda + 2\Lambda) = 224\Lambda^2 = 224(0.125\mu m)^2 = 3.50\ \mu m^2$

$$N = \frac{(10^4 \mu m)^2}{3.50\mu m^2} = 28.6\ x\ 10^6 \text{ transistors}$$

(b)

$L = 2\Lambda = 40\ nm$ | $W = 10\Lambda = 200\ nm$

Active area $= 200nm(240nm) = 4.8x10^4\ nm^2 = 0.048x10^{-2}\ \mu m^2$

Gate area $= 40nm(200nm) = 8x10^3\ nm^2 = 0.008x10^{-2}\ \mu m^2$

Transistor area $= 280nm(320nm) = 8.96x10^4\ nm^2 = 8.96x10^{-2}\ \mu m^2$

$$N = \frac{(10^4 \mu m)^2}{8.96x10^{-2}\ \mu m^2} = 1.12x10^9\ transistors$$

Page 270 Upper group

$$V_{GS}^2 + V_{GS}\left(\frac{2}{K_nR_S} - 2V_{TN}\right) + V_{TN}^2 - \frac{2V_{EQ}}{K_nR_S} = 0 \quad | \quad V_{GS} = -\left(\frac{1}{K_nR_S} - V_{TN}\right) \pm \sqrt{\left(\frac{1}{K_nR_S} - V_{TN}\right)^2 - V_{TN}^2 + \frac{2V_{EQ}}{K_nR_S}}$$

$$V_{GS} = V_{TN} - \frac{1}{K_nR_S} \pm \sqrt{\left(\frac{1}{K_nR_S}\right)^2 - \frac{2V_{TN}}{K_nR_S} + V_{TN}^2 - V_{TN}^2 + \frac{2V_{EQ}}{K_nR_S}} = V_{TN} + \frac{1}{K_nR_S}\left(\sqrt{1 + 2K_nR_S\left(V_{EQ} - V_{TN}\right)} - 1\right)$$

– – –

Assume saturation region operation.

$$I_D = \frac{1}{2K_nR_S^2}\left(\sqrt{1 + 2K_nR_S\left(V_{EQ} - V_{TN}\right)} - 1\right)^2$$

$$I_D = \frac{1}{2(30\mu A)(39k\Omega)^2}\left(\sqrt{1 + 2(30\mu A)(39k\Omega)(4-1)} - 1\right)^2 = 36.8\ \mu A$$

$V_{DS} = 10 - 114k\Omega(36.8\mu A) = 5.81\ V$ | Saturation region is correct. | Q-Point: $(36.8\ \mu A,\ 5.81\ V)$

– – –

Assume saturation region operation.

$$I_D = \frac{1}{2(25\mu A)(39k\Omega)^2}\left(\sqrt{1 + 2(25\mu A)(39k\Omega)(4-1.5)} - 1\right)^2 = 26.7\ \mu A$$

$V_{DS} = 10 - 114k\Omega(26.7\mu A) = 6.96\ V$ | Saturation region is correct. | Q-Point: $(26.7\ \mu A,\ 6.96\ V)$

Assume saturation region operation.

$$I_D = \frac{1}{2(25\mu A)(62k\Omega)^2}\left(\sqrt{1 + 2(25\mu A)(62k\Omega)(4-1)} - 1\right)^2 = 25.4\ \mu A$$

$V_{DS} = 10 - 137k\Omega(25.4\mu A) = 6.52\ V$ | Saturation region is correct. | Q-Point: $(25.4\ \mu A,\ 6.52\ V)$

Page 271 Second group

$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} = \frac{1M\Omega}{1M\Omega + 1.5M\Omega} 10V = 4\ V$ | Assume saturation region operation.

$I_D = \frac{1}{2K_n R_S^2}\left(\sqrt{1 + 2K_n R_S \left(V_{EQ} - V_{TN}\right)} - 1\right)^2$

$I_D = \frac{1}{2(25\mu A)(1.8k\Omega)^2}\left(\sqrt{1 + 2(25\mu A)(1.8k\Omega)(4-1)} - 1\right)^2 = 99.5\ \mu A$

$V_{DS} = 10 - 40.8k\Omega(99.5\mu A) = 5.94\ V$ | Saturation region is correct. | Q-Point: $(99.5\ \mu A,\ 5.94\ V)$

$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} = \frac{1.5M\Omega}{1.5M\Omega + 1M\Omega} 10V = 6\ V$ | Assume saturation region operation.

$I_D = \frac{1}{2(25\mu A)(22k\Omega)^2}\left(\sqrt{1 + 2(25\mu A)(22k\Omega)(6-1)} - 1\right)^2 = 99.2\ \mu A$

$V_{DS} = 10 - 40k\Omega(99.2\mu A) = 6.03\ V$ | Saturation region is correct. | Q-Point: $(99.2\ \mu A,\ 6.03\ V)$

– – –

$I_{Bias} = \frac{V_{DD}}{R_1 + R_2} \rightarrow R_1 + R_2 = \frac{V_{DD}}{I_{Bias}} = \frac{10V}{2\mu A} = 5\ M\Omega$

$V_{EQ} = \frac{R_1}{R_1 + R_2} V_{DD} \rightarrow R_1 = (R_1 + R_2)\frac{V_{EQ}}{V_{DD}} = 5M\Omega \frac{4V}{10V} = 2\ M\Omega$

$R_2 = 5M\Omega - R_1 = 3\ M\Omega$ | $R_{EQ} = R_1 \| R_2 = 1.2\ M\Omega$

Page 274 Should refer to Fig. 5.46

$V_{GS} = 4 - 39000 I_D \quad V_{SB} = 39000 I_D \quad V_{TN} = 1 + 0.75\left(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}\right) \quad I_D = \frac{25\mu A}{2}\left(V_{GS} - V_{TN}\right)^2$

Spreadsheet iteration yields $I_D = 28.2\ \mu$A.

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$$I_G = 0 \rightarrow V_{GS} = V_{DS} = V_{DD} - I_D R_D$$

$$Eqn. 5.87: K_n R_D = (50x10^{-6})(75x10^3) = 3.75\ V$$

$$V_{FS} = \left(1 - \frac{1}{3.75} \pm \sqrt{\left(1 - \frac{1}{3.75}\right)^2 + \frac{2(10)}{3.75} - 1^2}\right) V \ = \ 2.940\ V$$

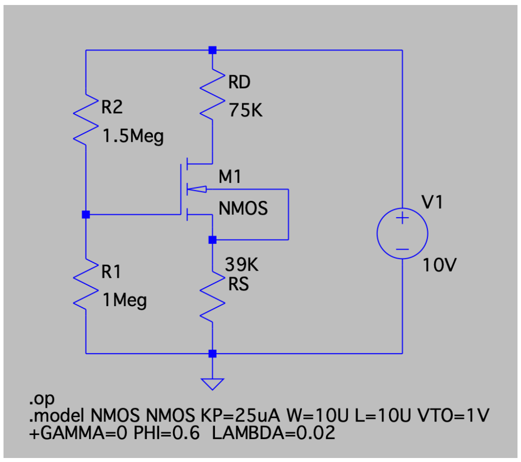
$$I_D = \frac{50\mu A}{2}(2.940 - 1)^2 = 94.13\ \mu A$$

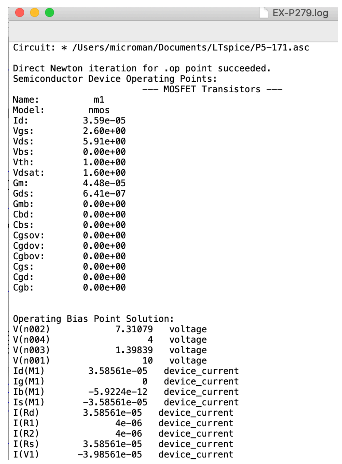
Page 279 - Use equation set on page 229
Assume saturation region operation.

$$10-6=\frac{25x10^{-6}\left(62x10^{4}\right)}{2}\left(V_{GS}+1\right)^{2}-V_{GS}\rightarrow V_{GS}^{2}+0.710V_{GS}-4.161=0\rightarrow V_{GS}=-2.426V,\ \ +1.716V$$

$$I_{D}=\frac{25x10^{-6}}{2}\left(-2.426+1\right)^{2}=25.4\ \mu A\quad|\quad V_{DS}=-\left[10-137k\Omega\left(25.4\mu A\right)\right]=-6.52\ V$$

Saturation region is correct. | Q - Point : $\left(25.4\ \mu A,\ -6.52\ V\right)$





```
EX-P279.log

Circuit: * /Users/microman/Documents/LTspice/P5-171.asc

Direct Newton iteration for .op point succeeded.
Semiconductor Device Operating Points:
                        --- MOSFET Transistors ---
Name:          m1
Model:        nmos
Id:          3.59e-05
Vgs:         2.60e+00
Vds:         5.91e+00
Vbs:         0.00e+00
Vth:         1.00e+00
Vdsat:       1.60e+00
Gm:          4.48e-05
Gds:         6.41e-07
Gmb:         0.00e+00
Cbd:         0.00e+00
Cbs:         0.00e+00
Cgsov:       0.00e+00
Cgdov:       0.00e+00
Cgbov:       0.00e+00
Cgs:         0.00e+00
Cgd:         0.00e+00
Cgb:         0.00e+00


Operating Bias Point Solution:
V(n002)             7.31079   voltage
V(n004)                   4   voltage
V(n003)             1.39839   voltage
V(n001)                  10   voltage
Id(M1)          3.58561e-05   device_current
Ig(M1)                    0   device_current
Ib(M1)          -5.9224e-12   device_current
Is(M1)         -3.58561e-05   device_current
I(Rd)          3.58561e-05   device_current
I(R1)                4e-06   device_current
I(R2)                4e-06   device_current
I(Rs)          3.58561e-05   device_current
I(V1)         -3.98561e-05   device_current
```

Page 280

$$K_R=1:\ \ V_{GSN}=\frac{2.5+\sqrt{1}(0.6)-0.6}{1+\sqrt{1}}\ =\ 1.25\ V\ \ |\ I_D=\frac{50}{2}(1.25-0.6)^2=10.6\ \mu A$$

$$K_R=5:\ \ V_{GSN}=\frac{2.5+\sqrt{5}(0.6)-0.6}{1+\sqrt{5}}\ =\ 1.00\ V\ \ |\ I_D=\frac{50}{2}(1.00-0.6)^2=4.00\ \mu A$$

$$K_R=5:\ \ V_{GSN}=\frac{2.5+\sqrt{0.2}(0.6)-0.6}{1+\sqrt{0.2}}\ =\ 1.50\ V\ \ |\ I_D=\frac{50}{2}(1.50-0.6)^2=20.3\ \mu A$$

Page 286

(a) $V_{DS} = 3\ V,\ V_{GS} - V_P = -2 - (-3.5) = +1.5\ V$. The transistor is pinched off.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 1mA\left[1 - \left(\frac{-2V}{-3.5V}\right)\right]^2 = 184\ \mu A \ \ |\ \ \text{Pinchoff requires } V_{DS} \ge V_{GS} - V_P = +1.5\ V$$

(b) $V_{DS} = 6\ V,\ V_{GS} - V_P = -1 - (-3.5) = +2.5\ V$. The transistor is pinched off.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 1mA\left[1 - \left(\frac{-1V}{-3.5V}\right)\right]^2 = 510\ \mu A \ \ |\ \ \text{Pinchoff requires } V_{DS} \ge V_{GS} - V_P = +2.5\ V$$

(c) $V_{DS} = 0.5\ V,\ V_{GS} - V_P = -2 - (-3.5) = +1.5\ V$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2}\left(V_{GS} - V_P - \frac{V_{DS}}{2}\right)V_{DS} = \frac{2(1mA)}{(-3.5)^2}\left(-2 + 3.5 - \frac{0.5}{2}\right)0.5 = 51.0\ \mu A$$

Pinchoff requires $V_{DS} \ge V_{GS} - V_P = +1.5\ V$

– – –

(a) $V_{DS} = 0.5\ V,\ V_{GS} - V_P = -2 - (-4) = +2\ V$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2}\left(V_{GS} - V_P - \frac{V_{DS}}{2}\right)V_{DS} = \frac{2(0.2mA)}{(-4)^2}\left(-2 + 4 - \frac{0.5}{2}\right)0.5 = 21.9\ \mu A$$

(b) $V_{DS} = 6\ V,\ V_{GS} - V_P = -1 - (-4) = +3\ V$. The transistor is pinched off.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 0.2mA\left[1 - \left(\frac{-1V}{-4V}\right)\right]^2 = 113\ \mu A$$

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(a) $V_{DS} = -3\ V,\ V_{GS} - V_P = 3 - 4 = -1\ V$. The transistor is pinched off.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 2.5mA\left[1 - \frac{3V}{4V}\right]^2 = 156\ \mu A \ \ |\ \ \text{Pinchoff requires } V_{DS} \le V_{GS} - V_P = -1\ V$$

(b) $V_{DS} = -6\ V,\ V_{GS} - V_P = 1 - (4) = -3\ V$. The transistor is pinched off.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 2.5mA\left[1 - \frac{1V}{4V}\right]^2 = 1.41\ mA \ \ |\ \ \text{Pinchoff requires } V_{DS} \le V_{GS} - V_P = -3\ V$$

(c) $V_{DS} = -0.5\ V,\ V_{GS} - V_P = 2 - (4) = -2\ V$. The transistor is in the triode region.

$$I_D = \frac{2I_{DSS}}{V_P^2}\left(V_{GS} - V_P - \frac{V_{DS}}{2}\right)V_{DS} = \frac{2(2.5mA)}{4^2}\left(2 - 4 - \frac{-0.5}{2}\right)(-0.5) = 273\ \mu A$$

Pinchoff requires $V_{DS} \le V_{GS} - V_P = -2\ V$

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$$\text{BETA} = \frac{I_{DSS}}{V_P^2} = \frac{2.5mA}{(-2)^2} = 0.625\ mA \quad | \quad \text{VTO} = V_P = -2\ V \quad | \quad \text{LAMBDA} = \lambda = 0.025\ V^{-1}$$

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$$\text{BETA} = \frac{I_{DSS}}{V_P^2} = \frac{5mA}{2^2} = 1.25\ mA \quad | \quad \text{VTO} = V_P = 2\ V \quad | \quad \text{LAMBDA} = \lambda = 0.02\ V^{-1}$$

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$$\text{VTO} = V_P = -5\ V \quad | \quad \text{BETA} = \frac{I_{DSS}}{V_P^2} = \frac{5mA}{(-5)^2} = 0.2\ mA \quad | \quad \text{LAMBDA} = \lambda = 0.02\ V^{-1}$$

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$$V_{GS} = V_G - V_S = -I_G R_G - I_S R_S = 0 - I_D R_S = -I_D R_S$$

$$V_{GS} = -\frac{K_n}{2}(V_{GS} - V_{TN})^2 R_S = -\frac{K_n}{2} V_{TN}^2 R_S \left(\frac{V_{GS}}{V_{TN}} - 1\right)^2 = -I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P}\right)^2 \text{ for } I_{DSS} = \frac{K_n}{2} V_{TN}^2 \text{ and } V_P = V_{TN}$$

$$V_{GS} = -\frac{0.4mA}{2}(-5)^2(1k\Omega)\left(1 - \frac{V_{GS}}{-5}\right)^2 = 5\left(1 + \frac{V_{GS}}{5}\right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0 \text{ and the rest is identical.}$$

Assuming pinchoff, $I_D = 1.91\ mA$ and $V_{DS} = 9 - 1.91mA(2k\Omega + 1k\Omega) = 3.27\ V$.

$V_{GS} - V_P = 3.09\ V$, $V_{DS} > V_{GS} - V_P$, and pinchoff is correct.

Assuming pinchoff, $V_{GS} = -I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P}\right)^2 = -(5x10^{-3})(2x10^3)\left(1 + \frac{V_{GS}}{5}\right)^2 \rightarrow V_{GS}^2 + 12.5V_{GS} + 25 = 0$

$$V_{GS} = -2.5\ V \quad | \quad I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 5mA\left(1 - \frac{-2.5}{-5}\right)^2 = 1.25\ mA$$

$V_{DS} = 12 - 1.25mA(2k\Omega + 2k\Omega) = 7.00\ V$.

$V_{GS} - V_P = -2.5 - (-5) = +2.5\ V$, $V_{DS} > V_{GS} - V_P$, and pinchoff is correct. Q-Point: $(1.25\ mA, 7.00\ V)$

(a) $V_G = -I_G R_G = -10nA(680k\Omega) = -6.80\ mV$.

$$V_{GS} = V_G - V_S = -I_G R_G - I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P}\right)^2 = -.00680 - (5x10^{-3})(10^3)\left(1 + \frac{V_{GS}}{5}\right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0$$

The value of V_G is insignificant with respect to the constant term of 25. So the answers are the same to 3 significant digits.

(b) $V_G = -I_G R_G = -1\mu A(680k\Omega) = 0.680\ V$ and now cannot be neglected.

$$V_{GS} = V_G - V_S = -I_G R_G - I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P}\right)^2 = -0.680 - (5x10^{-3})(10^3)\left(1 + \frac{V_{GS}}{5}\right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 28.4 = 0$$

$$V_{GS} = -2.226\ V \quad | \quad I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 5mA\left(1 - \frac{-2.226}{-5}\right)^2 = 1.54\ mA$$

$V_{DS} = 12 - 1.54mA(2k\Omega + 1k\Omega) = 7.38\ V$ | Q-Point: $(1.54\ mA, 7.38\ V)$
