Microelectronic Circuit Design
Fifth Edition - Part I
Solutions to Exercises

CHAPTER 1

Page 11

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

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

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

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

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

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

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

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

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

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$$R = 10k\Omega\left[1 + \frac{10^{-3}}{{}^oC}(-55-25)^oC\right] = 9.20\ k\Omega \qquad R = 10k\Omega\left[1 + \frac{10^{-3}}{{}^oC}(85-25)^oC\right] = 10.6\ k\Omega$$

CHAPTER 2

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

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

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

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

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

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

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

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 $2x10^7 cm/\text{sec}$

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

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

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

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

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

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

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

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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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$(a)\ N_D = 1x10^{16} / cm^3 \quad | \quad N_A = 0 / cm^3 \quad | \quad N_T = 2x10^{16} / cm^3 \quad |$

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

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

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

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

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

Page 57 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.

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

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

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

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

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

$$N_T = \frac{7x10^{19}}{cm^3} \rightarrow \mu_\text{n} = 67.5\frac{cm^2}{V-s} \mid \mu_\text{p} = 46.2\ \frac{cm^2}{V-s}$$

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

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

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

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

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

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

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

CHAPTER 3

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

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

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

$$E_{\max} = \frac{1.6x10^{-19}C\left(10^{17}/cm^3\right)\left(1.13x10^{-5}cm\right)}{11.7\left(8.854x10^{-14}F/cm\right)} = 175\frac{kV}{cm}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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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 101 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.

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

$$V_O = 20V\frac{1k\Omega}{5k\Omega + 1k\Omega} = 3.33\ V \quad (\text{V}_\text{Z} \text{ is off})$$

$$V_O = 5\ V \quad (\text{V}_\text{Z} \text{ is conducting})$$

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

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

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

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

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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

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

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 $I_D = 0$.

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

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

$V_{GS}\text{-}V_{TN} = 3\text{-}1.5 = 1.5V$ 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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$$R_{on} = \frac{1}{K_n^{'}\frac{W}{L}\left(V_{GS} - V_{TN}\right)} = \frac{1}{250\frac{\mu A}{V^2}\left(2-1\right)} = 4.00\ k\Omega \quad | \quad R_{on} = \frac{1}{250\frac{\mu A}{V^2}\left(4-1\right)} = 1.00\ k\Omega$$

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

Page 154 **V_{DS} should be 0.25 V**

$V_{GS} - V_{TN} = 2.5 - 1 = 1.5\ V$ and $V_{DS} = 0.28\ V \rightarrow$ 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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$V_{GS} - V_{TN} = 5 - 1 = 4\ V$ and $V_{DS} = 10\ V \rightarrow$ Saturation region operation

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

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

– – –

Assuming saturation region operation,

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

$$g_m = K_n(V_{GS} - V_{TN}) = 1\frac{mA}{V^2}(2.5-1)V = 1.50\ mS$$

$$\text{Checking: } g_m = \frac{2I_D}{V_{GS} - V_{TN}} \frac{2(1.125mA)}{(2.5-1)V} = 1.50\ mS$$

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

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

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

- - -

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

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

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

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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

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

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

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

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

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

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

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$$\text{Circuits/cm}^2 \propto \alpha^2 = \left(\frac{0.18\mu m}{22nm}\right)^2 = \left(\frac{0.18\mu m}{0.022\mu m}\right)^2 = \left(8.18\right)^2 = 66.9$$

$$\text{Power-Delay Product } \propto \frac{1}{\alpha^3} = \frac{1}{8.18^3} = \frac{1}{548}\text{; Rounding} \rightarrow 550 \text{ times improvement}$$

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

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

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

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

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

$$L = \left(10^5 \frac{V}{cm}\right)\left(10^{-5} cm\right) = 1\ V \quad | \quad L = \left(10^5 \frac{V}{cm}\right)\left(22x10^{-7} cm\right) = 0.22\ V$$

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

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

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

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

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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) $I = \left(10^9 \text{ transistors}\right)\left(3\text{x}10^{-15} \text{ A/transistors}\right) = 3\ \mu A$

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

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

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

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

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

Page 183 Upper group

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

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

Assume saturation region operation.

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

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

$V_{DS} = 10 - 114k\Omega(36.8\mu A) = 5.81\ V$ | 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 183 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 187 Should refer to Fig. 4.30

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

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

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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: $\left(25.4\ \mu A,\ -6.52\ V\right)$

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

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

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

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

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

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

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

– – –

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

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

(b) $V_{DS}=6\ V,\ V_{GS}-V_P=-1-\left(-4\right)=+3\ V$. 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.

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

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 2.5mA\left[1 - \frac{1V}{4V}\right]^2 = 1.41\ mA$$ | 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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BETA = $\frac{I_{DSS}}{V_P^2} = \frac{2.5mA}{(-2)^2} = 0.625\ mA$ | VTO = $V_P = -2\ V$ | LAMBDA = $\lambda = 0.025\ V^{-1}$

– – –

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

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

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

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

$V_{GS} = -\frac{0.4mA}{2}(-5)^2(1k\Omega)\left(1 - \frac{V_{GS}}{-5}\right)^2 = 5\left(1 + \frac{V_{GS}}{5}\right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0$ 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: $(1.25\ mA,\ 7.00\ V)$

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

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

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.

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

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

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

CHAPTER 5

Page 221

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

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

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$$i_C = 10^{-15} A\left[\exp\left(\frac{0.700}{0.025}\right) - \exp\left(\frac{-9.30}{0.025}\right)\right] - \frac{10^{-15} A}{0.5}\left[\exp\left(\frac{-9.30}{0.025}\right) - 1\right] = 1.45\ mA$$

$$i_E = 10^{-15} A\left[\exp\left(\frac{0.700}{0.025}\right) - \exp\left(\frac{-9.30}{0.025}\right)\right] + \frac{10^{-15} A}{100}\left[\exp\left(\frac{0.700}{0.025}\right) - 1\right] = 1.46\ mA$$

$$i_B = \frac{10^{-15} A}{100}\left[\exp\left(\frac{0.700}{0.025}\right) - 1\right] + \frac{10^{-15} A}{0.5}\left[\exp\left(\frac{-9.30}{0.025}\right) - 1\right] = 14.5\ \mu A$$

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$$i_C = 10^{-16} A\left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{0.700}{0.025}\right)\right] - \frac{10^{-16} A}{0.4}\left[\exp\left(\frac{0.700}{0.025}\right) - 1\right] = 563\ \mu A$$

$$i_E = 10^{-16} A\left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{0.700}{0.025}\right)\right] + \frac{10^{-16} A}{75}\left[\exp\left(\frac{0.750}{0.025}\right) - 1\right] = 938\ \mu A$$

$$i_B = \frac{10^{-16} A}{75}\left[\exp\left(\frac{0.750}{0.025}\right) - 1\right] + \frac{10^{-16} A}{0.4}\left[\exp\left(\frac{0.700}{0.025}\right) - 1\right] = 376\ \mu A$$

– – –

$$i_T = 10^{-15} A\left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{-2}{0.025}\right)\right] = 10.7\ mA$$

$$i_T = 10^{-16} A\left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{-4.25}{0.025}\right)\right] = 1.07\ mA$$

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

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

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

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

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

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

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

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

Page 233

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

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}+1\right) = 0.025V \ln\left(\frac{98.0\mu A}{10^{-16}A}+1\right) = 0.690\ V$$

Page 234

(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: $I_B = 100\ \mu A \ \mid \ I_E = (\beta_F + 1)I_B = 5.10\ mA \ \mid \ I_C = \beta_F I_B = 5.00\ mA$

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

– – –

Forward - active region with $V_{CB} \geq 0$ requires $V_{CC} \geq V_{BE}$ or $V_{CC} \geq 0.764\ V$

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$$(a)\ I_E = \frac{-0.7V - (-9V)}{5.6k\Omega} = 1.48\ mA$$

$$I_B = \frac{I_E}{\beta_F + 1} = \frac{I_E}{51} = 29.1\ \mu A \ \mid \ I_C = \beta_F I_B = 50 I_B = 1.45\ mA$$

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

$$(b)\ I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} 100\mu A = 102\mu A \ \mid \ R = \frac{-0.7V - (-9V)}{102\mu A} = \frac{8.3V}{102\mu A} = 81.4\ k\Omega$$

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

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

– – –

$$I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} I_C = 1.02 I_C \quad V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025 \ln\left(2x10^{15} I_C + 1\right)$$

$V_{BE} + 8200 \left[1.02\left(5x10^{-16}\right)\exp\left(\frac{V_{BE}}{0.025}\right) - 1\right] = 9 \rightarrow V_{BE} = 0.7079\ V$ using a calculator solver or spreadsheet. $I_C = 5x10^{-16} \exp\left(\frac{0.7079}{0.025}\right) = 992\ \mu A \ \mid \ V_{CE} = 9 - 4300 I_C - (-0.708) = 5.44\ V$

– – –

$$I_{SD} = \frac{I_{SBJT}}{\alpha_F} = \frac{2x10^{-14} A}{0.95} = 21.0\ fA$$

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

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

– – –

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

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

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

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$(a)\ \ D_n = \frac{kT}{q}\mu_n = 0.025V\left(500cm^2/V - s\right) = 12.5\ cm^2/s$

$(b)\ \ I_S = \frac{qAD_n n_i^2}{N_{AB}W} = \frac{1.6x10^{-19}C\left(50\mu m^2\right)\left(10^{-4}cm/\mu m\right)\left(12.5cm^2/s\right)\left(10^{20}/cm^6\right)}{\left(10^{18}/cm^3\right)\left(1\mu m\right)} = 10^{-18}A = 1\ aA$

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

– – –

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

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$$I_C = 10^{-15} A \exp\left(\frac{0.7}{0.025}\right)\left(1+\frac{10}{50}\right) = 1.74\ mA \quad | \quad \beta_F = 75\left(1+\frac{10}{50}\right) = 90.0 \quad | \quad I_B = \frac{1.74mA}{90.0} = 19.3\ \mu A$$

$$I_C = 10^{-15} A \exp\left(\frac{0.7}{0.025}\right) = 1.45\ mA \quad | \quad \beta_F = 75 \quad | \quad I_B = \frac{1.45mA}{75} = 19.3\ \mu A$$

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

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

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

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

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

– – –

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

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

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

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

– – –

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

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

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

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

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

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VBE (V)	IC (A)	V'BE (V)
0.70000	2.0155E-04	0.67156
0.67156	2.0328E-04	0.67178
0.67178	2.0327E-04	0.67178
0.67178	2.0327E-04	0.67178
