Microelectronic Circuit Design
Third Edition - Part I
Solutions to Exercises

CHAPTER 1

Page 11

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

$$1100010001_2 = 2^9 + 2^8 + 2^4 + 2^0 = 785_{10} \qquad V_O = 786(5.00mV) = 3.925\ V$$

or $\quad V_O = \left(2^{-1} + 2^{-2} + 2^{-6} + 2^{-10}\right) 5.12V = 3.912\ V$

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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 2000πt + 3 cos 1000 πt) Volts.

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$$i_{SC} = i_1 + \beta i_1 = \frac{v_s}{R_1} + \beta\frac{v_s}{R_1} = (\beta+1)\frac{v_s}{R_1} \qquad v_{OC} = \frac{(\beta+1)R_S}{(\beta+1)R_S + R_1}v_S$$

$$R_{th} = \frac{v_{OC}}{i_{SC}} = \frac{(\beta+1)R_S}{(\beta+1)R_S + R_1}\frac{R_1}{(\beta+1)} = \frac{1}{\frac{(\beta+1)}{R_1} + \frac{1}{R_S}} \rightarrow R_{th} = R_S \Big\| \frac{R_1}{(\beta+1)}$$

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

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

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

The three spectral components 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, $V_o = 10(1V) = 10V$,

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, $V_o = 6(0.5V) = 3V$,

and $v_O = 3.00\sin(2000\pi t)$ 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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$$P = \frac{V_S^2}{R_1 + R_2} \quad P^{nom} = \frac{15^2}{54k\Omega} = 4.17\ mW$$

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

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

CHAPTER 2

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

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

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

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

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$$v_p = \mu_p E = 500\,\frac{cm^2}{V-s}\left(10\,\frac{V}{cm}\right) = 5.00x10^3\,\frac{cm}{s} \qquad v_n = -\mu_n E = 1350\,\frac{cm^2}{V-s}\left(1000\,\frac{V}{cm}\right) = 1.35x10^6\,\frac{cm}{s}$$

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

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

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

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

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60x10^{-19}\left[(2.32x10^{12})(1350) + (2.32x10^{12})(500)\right]} = 1450\ \Omega - cm$$

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

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

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

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

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

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Reading from the graph for $N_T = 10^{16}/cm^3$, 1250 cm^2/V-s and 400 cm^2/V-s.
Reading from the graph for $N_T = 10^{17}/cm^3$, 800 cm^2/V-s and 230 cm^2/V-s.

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$$\sigma = 1000 = 1.60x10^{-19}\mu_n n \rightarrow u_n n = 6.25x10^{21} / cm^3 = (6.25x10^{19})(100)$$

$$(a)\ N_T = 2x10^{16} / cm^3 \qquad (b)\ N_T = 5x10^{16} / cm^3$$

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

$$\text{N}_\text{T} = \frac{4x10^{18}}{cm^3}$$ and mobilities from Fig. 2.8

$$p = N_A - N_D = 7x10^{19}\,\frac{holes}{cm^3} \qquad n = \frac{n_i^2}{p} = \frac{10^{20}}{7x10^{19}} = 1.4\,\frac{electrons}{cm^3}$$

$$\text{N}_\text{T} = \frac{7x10^{19}}{cm^3}$$ and mobilities from Fig. 2.8

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60x10^{-19}\left[(1.4)(100) + \left(7x10^{19}\right)(50)\right]} = 1.79\ \text{m}\Omega - cm$$

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

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

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

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$$D_n = \frac{kT}{q}\mu_n = 25.8mV\left(1362\,\frac{cm^2}{V-s}\right) = 35.1\,\frac{cm^2}{s} \quad D_p = \frac{kT}{q}\mu_p = 25.8mV\left(492\,\frac{cm^2}{V-s}\right) = 12.7\,\frac{cm^2}{s}$$

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

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

CHAPTER 3

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

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

$$E_{\max} = \frac{1.6x10^{-19}C\left(10^{20}/cm^3\right)\left(1.13x10^{-8}cm\right)}{11.7\left(8.854x10^{-14}F/cm\right)} = 175\frac{kV}{cm}$$

$$E_{\max} = \frac{2\left(1.05V\right)}{2.63x10^{-6}cm} = 799\frac{kV}{cm}$$

$$x_p = 0.0258\mu m\left(1+\frac{2x10^{18}}{10^{20}}\right)^{-1} = 0.0253\ \mu m \qquad x_n = 0.0258\mu m\left(1+\frac{10^{20}}{2x10^{18}}\right)^{-1} = 5.06x10^{-4}\ \mu m$$

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$$T = \frac{1.602x10^{-19}\left(25.8mV\right)}{1.03\left(1.38x10^{-23}\right)} = 291K$$

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

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

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

$$V_{BE} = V_T\ln\left(1+\frac{I_D}{I_S}\right) = 0.0258V\ln\left(1+\frac{40x10^{-6}A}{2x10^{-15}A}\right) = 0.612\ V$$

$$V_{BE} = V_T\ln\left(1+\frac{I_D}{I_S}\right) = 0.0258V\ln\left(1+\frac{400x10^{-6}A}{2x10^{-15}A}\right) = 0.671\ V \qquad \Delta V_{BE} = 59.4\ \text{m}V$$

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

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

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

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

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

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

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

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

$$I_{D1} = \frac{1.87 - 0.6 - \left(-20V\right)}{10k\Omega} = 2.13\ mA \quad I_{D2} = \frac{1.87 - 0.6 - \left(-10V\right)}{10k\Omega} = 1.13\ mA$$

$$V_{D3} = -\left(1.87 - 0.6\right) = -1.27\ V$$

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$$R_{min} = \frac{5k\Omega}{\frac{20}{5} - 1} = 1.67\ k\Omega \quad V_O = 20V\frac{1k\Omega}{5k\Omega + 1k\Omega} = 3.33\ V\ (V_Z \text{ is off}) \quad V_O = 5\ V\ (V_Z \text{ is conducting})$$

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

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

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

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

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

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

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

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

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

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

CHAPTER 4

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

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

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

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

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

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

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

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

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

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

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

Assuming saturation region operation,

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

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

$$\text{Checking}: \ g_m = \frac{2\left(1.125mA\right)}{\left(2.5-1\right)V} = 1.50\ mS$$

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

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

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

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

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

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

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

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

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

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

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

$(ii - a)$ 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

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

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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

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

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

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

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Active area $= 120\Lambda^2 = 120(0.5\mu m)^2 = 30\ \mu m^2 \quad L = 2\Lambda = 1\mu m \quad W = 10\Lambda = 5\mu m$

Gate area $= 20\Lambda^2 = 20(0.5\mu m)^2 = 5\ \mu m^2 \quad N = \dfrac{\left(10^4\mu m\right)^2}{(14\Lambda)(16\Lambda)(0.5\mu m)^2} = 1.79\ x\ 10^6$ transistors

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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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$$KP = K_n = 150U \quad LAMBDA = \lambda = 0.0133 \quad VTO = V_{TN} = 1 \quad PHI = 2\phi_F = 0.6$$
$$W = W = 1.5U \quad L = L = 0.25U$$

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(i) Assume saturation region operation and $\lambda = 0$. Then I_D is indpendent of V_{DS}, and $I_D = 50\ \mu A$.

$V_{DS} = V_{DD} - I_D R_D = 10 - 50k\Omega(50\mu A) = 7.50\ V$. $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct.

Q - Point = $(50.0\ \mu A,\ 7.50\ V)$

(ii) $V_{EQ} = \dfrac{270k\Omega}{270k\Omega + 750k\Omega}10V = 2.647\ V$ $R_{EQ} = 270k\Omega \| 750k\Omega$ Assume saturation region.

$I_D = \dfrac{25x10^{-6}}{2}\dfrac{A}{V^2}(2.647-1)^2V^2 = 33.9\ \mu A$ $V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(33.9\mu A) = 6.61\ V$.

$V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct. Q - Point = $(33.9\ \mu A,\ 6.61\ V)$

(iii) V_{GS} does not change: $V_{GS} = 3.00\ V$. $I_D = \dfrac{30x10^{-6}}{2}\dfrac{A}{V^2}(3-1)^2V^2 = 60.0\ \mu A$

$V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(60.0\mu A) = 4.00\ V$. $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct.

Q - Point = $(60.0\ \mu A,\ 4.00\ V)$

(iv) V_{GS} does not change: $V_{GS} = 3.00\ V$. $I_D = \dfrac{25x10^{-6}}{2}\dfrac{A}{V^2}(3-1.5)^2V^2 = 28.1\ \mu A$

$V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(28.1\mu A) = 7.19\ V$. $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct.

Q - Point = $(28.1\ \mu A,\ 7.19\ V)$

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$$V_{DS} = 10 - \frac{25x10^{-6}\left(10^5\right)}{2}\left(3-1\right)^2\left(1+0.01V_{DS}\right) \rightarrow V_{DS} = 10 - 5\left(1+0.01V_{DS}\right)$$

$$V_{DS} = \frac{10-5}{1.05}V = 4.76\ V \qquad I_D = \frac{25x10^{-6}}{2}\left(3-1\right)^2\left[1+0.01\left(4.76\right)\right] = 52.4\ \mu A$$

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For $I_D = 0$, $V_{DS} = 10\ V$. For $V_{DS} = 0$, $I_D = \dfrac{10V}{66.7k\Omega} = 150\mu A.$

The load line intersects the $V_{GS} = 3\text{-}V$ curve at $I_D = 50\ \mu A$, $V_{DS} = 6.7\ V$.

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$$\left(i\right)\ 4 = V_{GS} + \frac{30x10^{-6}\left(3.9x10^4\right)}{2}\left(V_{GS}-1\right)^2 \rightarrow V_{GS}^2 - 0.291V_{GS} - 5.838 = 0 \rightarrow V_{GS} = 2.566V,\ -2.275V$$

$$I_D = \frac{30x10^{-6}}{2}\left(2.566-1\right)^2 = 36.8\ \mu A \qquad \mathrm{V_{DS}} = 10 - 114k\Omega\left(36.8\mu A\right) = 5.81\ V$$

$$\text{Q-Point}:\left(36.8\ \mu A, 5.81\ V\right)$$

$$\left(ii\right)\ 4 = V_{GS} + \frac{25x10^{-6}\left(3.9x10^4\right)}{2}\left(V_{GS}-1.5\right)^2 \rightarrow V_{GS}^2 - 0.949V_{GS} - 5.955 = 0 \rightarrow V_{GS} = 2.960V,\ -2.012V$$

$$I_D = \frac{25x10^{-6}}{2}\left(2.960-1.5\right)^2 = 26.7\ \mu A \qquad \mathrm{V_{DS}} = 10 - 114k\Omega\left(26.7\mu A\right) = 6.96\ V$$

$$\text{Q-Point}:\left(26.7\ \mu A, 6.96\ V\right)$$

$$\left(ii\right)\ 4 = V_{GS} + \frac{25x10^{-6}\left(6.2x10^4\right)}{2}\left(V_{GS}-1\right)^2 \rightarrow V_{GS}^2 - 0.710V_{GS} - 4.161 = 0 \rightarrow V_{GS} = 2.426V,\ -1.716V$$

$$I_D = \frac{25x10^{-6}}{2}\left(2.426-1\right)^2 = 25.4\ \mu A \qquad \mathrm{V_{DS}} = 10 - 137k\Omega\left(25.4\mu A\right) = 6.52\ V$$

$$\text{Q-Point}:\left(25.4\ \mu A, 6.52\ V\right)$$

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(i) Assume saturation. For $I_D = 99.5\mu A,\ V_{GS} = 4V - 99.5\mu A(1.8k\Omega) = 3.821V$

$I_D = \frac{25\mu A}{2}(3.821-1)^2 = 99.5\mu A$ which agrees. $V_{DS} = 10V - 99.5\mu A(40.8k\Omega) = 5.94\ V$

Saturation region operation is correct.

$(ii)\ V_{EQ} = \frac{1.5M\Omega}{1.5M\Omega + 1M\Omega}10V = 6.00\ V \quad R_{EQ} = 1.5M\Omega \| 1M\Omega = 600k\Omega$ Assume saturation region.

$$6 = V_{GS} + \frac{25x10^{-6}(22x10^3)}{2}(V_{GS}-1)^2 \rightarrow V_{GS}^2 + 1.636V_{GS} - 20.82 = 0 \rightarrow V_{GS} = 3.818V$$

$$I_D = \frac{25x10^{-6}}{2}(3.818-1)^2 = 99.3\ \mu A \quad V_{DS} = 10 - 40k\Omega(99.3\mu A) = 6.03\ V$$

Saturation region operation is correct. Q-Point: $(99.3\ \mu A,\ 6.03\ V)$

$$(iii)\ R_1 + R_2 = \frac{10V}{2\mu A} = 5M\Omega \quad \frac{R_1}{R_1+R_2}10V = 6V \rightarrow R_1 = 5M\Omega\frac{6V}{10V} = 3\ M\Omega \rightarrow R_2 = 2\ M\Omega$$

$$R_{EQ} = 3M\Omega \| 2M\Omega = 1.2\ M\Omega$$

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$$V_{GS} = 6 - 22000I_D \quad V_{SB} = 22000I_D \quad V_{TN} = 1 + 0.75\left(\sqrt{V_{SB}+0.6} - \sqrt{0.6}\right) \quad I_D = \frac{25\mu A}{2}(V_{GS} - V_{TN})^2$$

Spreadsheet iteration yields I_D = 83.2 μA.

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Equation 4.55 becomes $6 - \left[1 + 0.75\left(\sqrt{V_{SB}+0.6} - \sqrt{0.6}\right) + 2.83\right] - V_{SB} = 0.$

$V_{SB}^2 - 6.065V_{SB} + 7.231 = 0 \rightarrow V_{SB} = 1.63V.$

$$R_S = \frac{1.63V}{10^{-4}A} = 16.3\ k\Omega \rightarrow 16\ k\Omega \quad R_D = \frac{(10-6-1.63)V}{10^{-4}A} = 23.7k\Omega \rightarrow 24\ k\Omega$$

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(i) Using Eq. (4.58) $V_{GS} = 3.3 - \frac{2x10^{-4}(10k\Omega)}{2}(V_{GS}-1)^2 \rightarrow V_{GS}^2 - V_{GS} - 2.3 = 0 \rightarrow V_{GS} = 2.097V$

$$V_{GS} = \frac{2x10^{-4}}{2}(2.097-1)^2 = 120.3\mu A \quad V_{DS} = V_{GS} \quad Q\text{-}Point: (120\ \mu A,\ 2.10\ V)$$

(ii) Since there was no voltage drop across R_G in (i), the equations and answers are identical to the first part.

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$$\frac{4-V_{DS}}{1.8x10^6} = 2.5x10^{-4}\left(4-1-\frac{V_{DS}}{2}\right)V_{DS} \rightarrow V_{DS} = 2.96\ mV \quad I_D = \frac{4-V_{DS}}{1.8x10^6} = 2.22\ \mu A$$

$$Q\text{-}Point: \left(2.22\ \mu A,\ 2.96\ mV\right) \quad \text{Checking; } I_D R_{on} = \frac{2.22\mu A}{2.5x10^{-4}\left(4-1\right)} = 2.96\ mV$$

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

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

$$\text{Q-Point}: \left(25.4\ \mu A,\ -6.52\ V\right)$$

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$$(\mathrm{i})\ \text{Circuits/cm}^2 \propto \alpha^2 = \left(\frac{1\mu m}{0.25\mu m}\right)^2 = 16$$

$$\text{Power-Delay Product } \propto \frac{1}{\alpha^3} = \frac{1}{4^3} = \frac{1}{64} \rightarrow 64 \text{ times improvement}$$

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

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

$$(iii)\ f_T = \frac{1}{2\pi}\frac{500cm^2/V-s}{\left(10^{-4}cm\right)^2}\left(1V\right) = 7.96\ GHz \quad f_T = \frac{1}{2\pi}\frac{500cm^2/V-s}{\left(0.25x10^{-4}cm\right)^2}\left(1V\right) = 127\ GHz$$

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The field in the first sentence at the top of the page should be $10^5 V/cm$.

$$\frac{V}{L} = 10^4\frac{V}{cm} \rightarrow L = \left(10^5\frac{V}{cm}\right)\left(10^{-4}cm\right) = 10\ V \quad L = \left(10^5\frac{V}{cm}\right)\left(10^{-5}cm\right) = 1\ V$$

CHAPTER 5

Page 213

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.970}{1-0.970} = 32.3 \qquad \beta_F = \frac{0.993}{1-0.993} = 142 \qquad \beta_F = \frac{0.250}{1-.250} = 0.333$$

$$\alpha_F = \frac{\beta_F}{\beta_F+1} = \frac{40}{41} = 0.976 \qquad \alpha_F = \frac{200}{201} = 0.995 \qquad \alpha_F = \frac{3}{4} = 0.750$$

Page 215

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

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

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

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

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

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

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

$$i_T = 10^{-16} A\left[\exp\left(\frac{0.750}{0.025}\right) - \exp\left(\frac{-5}{0.025}\right)\right] = 1.07\ mA$$

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

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

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

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

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

Page 225

(a) The currents do not depend upon V_{CC} as long as the collector - base junction is reverse biased. (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 226

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

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

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

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

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

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

Nearest 5% value is 82 $k\Omega$.

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

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

$$V_{BE} + 8200 \left[5.10x10^{-16} \exp\left(\frac{V_{BE}}{0.025}\right) - 1\right] = 9 \rightarrow V_{BE} = 0.7079\ V$$ using a calculator solver or spreadsheet.

$$I_C = 5x10^{-16} \exp\left(\frac{0.7079}{0.025}\right) = 992\ \mu A \qquad V_{CE} = 9 - 4300 I_C - (-0.708) = 5.44\ V$$

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

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

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

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

$$\mathrm{V_{BC}} = (0.025V)\ln\left[\frac{0.1mA - \dfrac{1mA}{50}}{10^{-15}A\left(\dfrac{1}{0.5}\right)\left(\dfrac{1}{50}+1-0.5\right)}\right] = 0.627\ mV \qquad V_{BE} - V_{BC} = 67.7mV$$

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

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

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

$$(ii)\quad f_\beta = \frac{f_T}{\beta_F} = \frac{300MHz}{125} = 2.40\ MHz$$

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

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

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$$g_m = 40\left(10^{-4}\right) = 4.00\ mS \qquad g_m = 40\left(10^{-3}\right) = 40.0\ mS$$

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

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

$$I_B = \frac{4.00 - 0.7}{120 + (75+1)16} \frac{V}{k\Omega} = 2.470\mu A \ \mid \ I_C = 75I_B = 185.3\mu A \ \mid \ I_E = 76I_B = 187.7\mu A$$

$$V_{CE} = 12 - 22000I_C - 16000I_E = 4.92V \ \mid \ Q\text{-}point: \ (185 \ \mu A, \ 4.92 \ V)$$

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$$\text{(i)} \ I_2 = \frac{I_C}{5} = \frac{50I_B}{5} = 10I_B$$

$$\text{(ii)} \ V_{EQ} = \frac{18k\Omega}{18k\Omega + 36k\Omega} 12V = 4.00V \ \mid \ R_{EQ} = 18k\Omega \| 36k\Omega = 12k\Omega$$

$$I_B = \frac{4.00 - 0.7}{12 + (500+1)16} \frac{V}{k\Omega} = 0.4111\mu A \ \mid \ I_C = 500I_B = 205.5\mu A \ \mid \ I_E = 76I_B = 206.0\mu A$$

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

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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) $V_{CE} = 0.7 \ V$ at the edge of saturation. $0.7V = 12V - \left(R_C + \frac{76}{75}16k\Omega\right)(205\mu A) \rightarrow R_C = 38.9 \ k\Omega$

$$(ii) \ V_{BESAT} = 4 - 12k\Omega(24\mu A) - 16k\Omega(184\mu A) = 0.768 \ V$$

$$V_{CESAT} = 12 - 56k\Omega(160\mu A) - 16k\Omega(184\mu A) = 0.096 \ V$$

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$$I_B = \frac{9 - 0.7}{36 + (50+1)1} \frac{V}{k\Omega} = 95.4\mu A \ \mid \ I_C = 50I_B = 4.77 \ mA \ \mid \ I_E = 76I_B = 187.7\mu A$$

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