

Microelectronic Circuit Design

Fourth Edition - Part I

Solutions to Exercises

CHAPTER 1

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

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

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

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

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

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

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

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$$A_v = -\frac{R_2}{R_1} \quad | \quad -5 = -\frac{R_2}{10k\Omega} \rightarrow R_2 = 50 \text{ k}\Omega$$

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

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

(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_1 , $V_o = 6(0.5V) = 3V$,

and $v_o = 3.00 \sin(2000\pi t)$ volts.

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

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

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

$$P^{max} = \frac{(1.1 \times 15)^2}{0.95 \times 54k\Omega} = 5.31 \text{ mW} \quad P^{min} = \frac{(0.9 \times 15)^2}{1.05 \times 54k\Omega} = 3.21 \text{ mW}$$

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

CHAPTER 2

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$$n_i = \sqrt{\left(2.31 \times 10^{30} \text{ K}^{-3} \text{ cm}^{-6}\right) (300 \text{ K})^3 \exp\left[\frac{-0.66 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/K})(300 \text{ K})}\right]} = 2.27 \times 10^{13} / \text{cm}^3$$

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$$n_i = \sqrt{\left(1.08 \times 10^{31} \text{ K}^{-3} \text{ cm}^{-6}\right) (50 \text{ K})^3 \exp\left[\frac{-1.12 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/K})(50 \text{ K})}\right]} = 4.34 \times 10^{-39} / \text{cm}^3$$

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

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

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

$$E = \frac{V}{L} = \frac{1}{2 \times 10^{-4}} \frac{\text{V}}{\text{cm}} = 5.00 \times 10^3 \frac{\text{V}}{\text{cm}}$$

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(a) From Fig. 2.5: The drift velocity for Ge saturates at $6 \times 10^6 \text{ cm/sec}$.

At low fields the slope is constant. Choose $E = 100 \text{ V/cm}$

$$\mu_n = \frac{v_n}{E} = \frac{4.3 \times 10^5 \text{ cm/s}}{100 \text{ V/cm}} = 4300 \frac{\text{cm}^2}{\text{s}} \quad \mu_p = \frac{v_p}{E} = \frac{2.1 \times 10^5 \text{ cm/s}}{100 \text{ V/cm}} = 2100 \frac{\text{cm}^2}{\text{s}}$$

(b) The velocity peaks at $2 \times 10^7 \text{ cm/sec}$

$$\mu_n = \frac{v_n}{E} = \frac{8.5 \times 10^5 \text{ cm/s}}{100 \text{ V/cm}} = 8500 \frac{\text{cm}^2}{\text{s}}$$

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$$n_i^2 = 1.08 \times 10^{31} (400)^3 \exp \left[\frac{-1.12}{8.62 \times 10^{-5} (400)} \right] = 5.40 \times 10^{24} / \text{cm}^6 \quad | \quad n_i = 2.32 \times 10^{12} / \text{cm}^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} \left[(2.32 \times 10^{12})(1350) + (2.32 \times 10^{12})(500) \right]} = 1450 \, \Omega - \text{cm}$$

$$n_i^2 = 1.08 \times 10^{31} (50)^3 \exp \left[\frac{-1.12}{8.62 \times 10^{-5} (50)} \right] = 1.88 \times 10^{-77} / \text{cm}^6 \quad | \quad n_i = 4.34 \times 10^{-39} / \text{cm}^3$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} \left[(4.34 \times 10^{-39})(6500) + (4.34 \times 10^{-39})(2000) \right]} = 1.69 \times 10^{53} \, \Omega - \text{cm}$$

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$$n_i^2 = 1.08 \times 10^{31} (400)^3 \exp \left[\frac{-1.12}{8.62 \times 10^{-5} (400)} \right] = 5.40 \times 10^{24} / \text{cm}^6$$

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

Antimony (Sb) is a Column - V element, so it is a donor impurity. $n = N_D = 2 \times 10^{16} \frac{\text{electrons}}{\text{cm}^3}$

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

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Reading from the graph for $N_T = 10^{16} / \text{cm}^3$, 1230 $\text{cm}^2 / \text{V-s}$ and 405 $\text{cm}^2 / \text{V-s}$.

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

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$$\sigma = 1000 = 1.60 \times 10^{-19} \mu_n n \rightarrow u_n n = 6.25 \times 10^{21} / \text{cm}^3 = (6.25 \times 10^{19})(100) \quad | \quad \rho = \frac{1}{\sigma} = 0.001 \, \Omega - \text{cm}$$

$$(a) \quad N_D = 2 \times 10^{16} / \text{cm}^3 \quad | \quad N_A = 0 / \text{cm}^3 \quad | \quad N_T = 2 \times 10^{16} / \text{cm}^3 \quad |$$

$$\mu_n = 92 + \frac{1270}{1 + \left(\frac{2 \times 10^{16}}{1.3 \times 10^{17}} \right)^{0.91}} = 1170 \, \text{cm}^2 / \text{V} - \text{s} \quad | \quad \mu_p = 48 + \frac{447}{1 + \left(\frac{2 \times 10^{16}}{6.3 \times 10^{16}} \right)^{0.76}} = 363 \, \text{cm}^2 / \text{V} - \text{s}$$

$$(b) \quad N_T = N_D + N_A = 2 \times 10^{16} / \text{cm}^3 + 3 \times 10^{16} / \text{cm}^3 = 5 \times 10^{16} / \text{cm}^3$$

$$\mu_n = 92 + \frac{1270}{1 + \left(\frac{5 \times 10^{16}}{1.3 \times 10^{17}} \right)^{0.91}} = 990 \, \text{cm}^2 / \text{V} - \text{s} \quad | \quad \mu_p = 48 + \frac{447}{1 + \left(\frac{5 \times 10^{16}}{6.3 \times 10^{16}} \right)^{0.76}} = 291 \, \text{cm}^2 / \text{V} - \text{s}$$

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

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

$$N_T = \frac{4 \times 10^{18}}{\text{cm}^3} \quad \text{and mobilities from Fig. 2.8: } \mu_n = 150 \, \text{cm}^2 / \text{V} - \text{s} \quad | \quad \mu_p = 70 \, \text{cm}^2 / \text{V} - \text{s}$$

$$\rho \cong \frac{1}{q \mu_p p} = \frac{1}{1.60 \times 10^{-19} (4 \times 10^{18})(70)} = 0.022 \, \Omega - \text{cm}$$

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

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

$$N_T = \frac{7 \times 10^{19}}{\text{cm}^3} \quad \text{and mobilities from Fig. 2.8: } \mu_n = 100 \, \text{cm}^2 / \text{V} - \text{s} \quad | \quad \mu_p = 50 \, \text{cm}^2 / \text{V} - \text{s}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{1.60 \times 10^{-19} (7 \times 10^{19})(50)} = 1.79 \, \text{m}\Omega - \text{cm}$$

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$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (50)}{1.602 \times 10^{-19}} = 4.31 \text{ mV} \quad | \quad V_T = \frac{1.38 \times 10^{-23} (300)}{1.602 \times 10^{-19}} = 25.8 \text{ mV}$$

$$V_T = \frac{1.38 \times 10^{-23} (400)}{1.602 \times 10^{-19}} = 34.5 \text{ mV}$$

$$D_n = \frac{kT}{q} \mu_n = 25.8 \text{ mV} \left(1362 \frac{\text{cm}^2}{\text{V-s}} \right) = 35.1 \frac{\text{cm}^2}{\text{s}} \quad | \quad D_p = \frac{kT}{q} \mu_p = 25.8 \text{ mV} \left(495 \frac{\text{cm}^2}{\text{V-s}} \right) = 12.8 \frac{\text{cm}^2}{\text{s}}$$

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

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

CHAPTER 3

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

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

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$$E_{\max} = \frac{1}{\epsilon_s} \int_{-x_p}^0 -qN_A dx = \frac{qN_A x_p}{\epsilon_s} \quad E_{\max} = -\frac{1}{\epsilon_s} \int_0^{x_n} qN_D dx = \frac{qN_D x_n}{\epsilon_s} \quad \text{For the values in Ex.3.2:}$$

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

$$E_{\max} = \frac{2(1.05V)}{2.63 \times 10^{-6} \text{ cm}} = 798 \frac{\text{kV}}{\text{cm}}$$

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

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$$n \frac{kT}{q} = 1 \frac{1.381 \times 10^{-23} (300)}{1.602 \times 10^{-19}} = 0.0259 \quad | \quad T = \frac{300}{1.03} = 291 \text{ K}$$

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$$i_D = 40 \times 10^{-15} \text{ A} \left[\exp \left(\frac{0.55}{0.025} \right) - 1 \right] = 143 \text{ } \mu\text{A} \quad i_D = 40 \times 10^{-15} \text{ A} \left[\exp \left(\frac{0.70}{0.025} \right) - 1 \right] = 57.9 \text{ mA}$$

$$V_D = (0.025V) \ln \left(1 + \frac{6 \times 10^{-3} \text{ A}}{40 \times 10^{-15} \text{ A}} \right) = 0.643 \text{ V}$$

$$i_D = 5 \times 10^{-15} \text{ A} \left[\exp \left(\frac{-0.04}{0.025} \right) - 1 \right] = -3.99 \text{ fA} \quad | \quad i_D = 5 \times 10^{-15} \text{ A} \left[\exp \left(\frac{-2.0}{0.025} \right) - 1 \right] = -5.00 \text{ fA}$$

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$$(a) \quad V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.025V \ln\left(1 + \frac{40 \times 10^{-6} A}{2 \times 10^{-15} A}\right) = 0.593 V$$

$$V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.025V \ln\left(1 + \frac{400 \times 10^{-6} A}{2 \times 10^{-15} A}\right) = 0.651 V \quad \Delta V_{BE} = 57.6 \text{ mV}$$

$$(b) \quad V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.0258V \ln\left(1 + \frac{40 \times 10^{-6} A}{2 \times 10^{-15} A}\right) = 0.612 V$$

$$V_{BE} = V_T \ln\left(1 + \frac{I_D}{I_S}\right) = 0.0258V \ln\left(1 + \frac{400 \times 10^{-6} A}{2 \times 10^{-15} A}\right) = 0.671 V \quad \Delta V_{BE} = 59.4 \text{ mV}$$

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

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

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

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

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

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

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

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

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

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

The intersection of the two curves occurs at the Q-pt : (0.88 mA, 0.6 V)

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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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fzero(@(id) (10-10000*id-0.025*log(1+id/1e-13), 5e-4)

ans = 9.4258e-004

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fzero(@(id) (10-10000*(1e-14)*(exp(40*vd)-1)-vd), 0.5)

ans = 0.6316

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

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

$$I_{D1} = \frac{1.87 - 0.6 - (-20V)}{10k\Omega} = 2.13 \text{ mA} \quad | \quad I_{D2} = \frac{1.87 - 0.6 - (-10V)}{10k\Omega} = 1.13 \text{ mA} \quad | \quad V_{D3} = -(1.87 - 0.6) = -1.27 \text{ V}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

CHAPTER 4

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$$K'_n = \mu_n \frac{\epsilon_{ox}}{T_{ox}} = 500 \frac{cm^2}{V-s} \frac{3.9(8.854 \times 10^{-14} F/cm)}{25 \times 10^{-7} cm} = 69.1 \times 10^{-6} \frac{C}{V^2-s} = 69.1 \frac{\mu A}{V^2}$$

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

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

For $V_{GS} = 0V$ 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 $V_{DS} = 0.1V \rightarrow$ Triode region operation

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

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

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

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

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$$R_{on} = \frac{1}{K'_n \frac{W}{L} (V_{GS} - V_{TN})} = \frac{1}{250 \frac{\mu A}{V^2} (2 - 1)} = 4.00 k\Omega \quad | \quad R_{on} = \frac{1}{250 \frac{\mu A}{V^2} (4 - 1)} = 1.00 k\Omega$$

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

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

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

$$K_n = K'_n \frac{W}{L} \rightarrow \frac{W}{L} = \frac{1 \text{ mA}}{40 \mu\text{A}} = \frac{25}{1} \quad W = 25L = 8.75 \mu\text{m}$$

Assuming saturation region operation,

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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$$C_{GC} = \left(200 \frac{\mu F}{m^2} \right) (5 \times 10^{-6} m) (0.5 \times 10^{-6} m) = 0.500 fF$$

$$\text{Triode region : } C_{GD} = C_{GS} = \frac{C_{GC}}{2} + C_{GSO} W = 0.25 fF + \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.75 fF$$

$$\text{Saturation region : } C_{GS} = \frac{2}{3} C_{GC} + C_{GSO} W = 0.333 fF + \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.83 fF$$

$$C_{GD} = C_{GSO} W = \left(300 \frac{pF}{m} \right) (5 \times 10^{-6} m) = 1.50 fF$$

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

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

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

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

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

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

$$(a) f_T = \frac{1}{2\pi} \frac{500 cm^2/V-s}{(10^{-4} cm)^2} (1V) = 7.96 GHz \quad | \quad (b) f_T = \frac{1}{2\pi} \frac{500 cm^2/V-s}{(0.25 \times 10^{-4} cm)^2} (1V) = 127 GHz$$

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

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- (a) From the graph for $V_{GS} = 0.25 \text{ V}$, $I_D \cong 10^{-18} \text{ A}$ |
 (b) From the graph for $V_{GS} = V_{TN} - 0.5 \text{ V}$, $I_D \cong 3 \times 10^{-15} \text{ A}$
 (c) $I = (10^9 \text{ transistors})(3 \times 10^{-15} \text{ A/transistors}) = 3 \text{ } \mu\text{A}$

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Active area = $10\Lambda(12\Lambda) = 120\Lambda^2 = 120(0.125\mu\text{m})^2 = 1.88 \mu\text{m}^2$
 $L = 2\Lambda = 0.250 \mu\text{m}$ | $W = 10\Lambda = 1.25 \mu\text{m}$
 Gate area = $2\Lambda(10\Lambda) = 20\Lambda^2 = 20(0.125\mu\text{m})^2 = 0.313 \mu\text{m}^2$
 Transistor area = $(10\Lambda + 2\Lambda + 2\Lambda)(12\Lambda + 2\Lambda + 2\Lambda) = 224\Lambda^2 = 224(0.125\mu\text{m})^2 = 3.50 \mu\text{m}^2$
 $N = \frac{(10^4 \mu\text{m})^2}{3.50\mu\text{m}^2} = 28.6 \times 10^6 \text{ transistors}$

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Assume saturation region operation and $\lambda = 0$. Then I_D is independent of V_{DS} , and $I_D = 50 \mu\text{A}$.
 $V_{DS} = V_{DD} - I_D R_D = 10 - 50k\Omega(50\mu\text{A}) = 7.50 \text{ V}$. $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct.
 Q - Point = $(50.0 \mu\text{A}, 7.50 \text{ V})$

$V_{EQ} = \frac{270k\Omega}{270k\Omega + 750k\Omega} 10\text{V} = 2.647 \text{ V}$ | $R_{EQ} = 270k\Omega || 750k\Omega$ | Assume saturation region.
 $I_D = \frac{25 \times 10^{-6} \text{ A}}{2} \frac{A}{V^2} (2.647 - 1)^2 V^2 = 33.9 \mu\text{A}$ | $V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(33.9\mu\text{A}) = 6.61 \text{ V}$.
 $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct. Q - Point = $(33.9 \mu\text{A}, 6.61 \text{ V})$

V_{GS} does not change: $V_{GS} = 3.00 \text{ V}$ | $I_D = \frac{30 \times 10^{-6} \text{ A}}{2} \frac{A}{V^2} (3 - 1)^2 V^2 = 60.0 \mu\text{A}$
 $V_{DS} = V_{DD} - I_D R_D = 10 - 100k\Omega(60.0\mu\text{A}) = 4.00 \text{ V}$. $V_{DS} \geq V_{GS} - V_{TN}$, so our assumption was correct.
 Q - Point = $(60.0 \mu\text{A}, 4.00 \text{ V})$

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$$V_{GS} \text{ does not change: } V_{GS} = 3.00 \text{ V} \quad | \quad I_D = \frac{25 \times 10^{-6} \text{ A}}{2} \frac{1}{V^2} (3 - 1.5)^2 V^2 = 28.1 \mu\text{A}$$

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

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

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

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

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

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

Page 185 Upper group

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

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

Assume saturation region operation.

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

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

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

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

$$\text{Assume saturation region operation. } I_D = \frac{1}{2(25\mu A)(62k\Omega)^2} \left(\sqrt{1 + 2(25\mu A)(62k\Omega)(4 - 1)} - 1 \right)^2 = 36.8 \mu A$$

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

Page 185 Lower group

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

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

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

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

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

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

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

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

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

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

Spreadsheet iteration yields $I_D = 83.2 \mu A$.

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

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

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

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Assume saturation region operation.

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

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

Saturation region is correct. | Q-Point : (25.4 μA , -6.52 V)

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

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

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

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

(c) $V_{DS} = 0.5 V$, $V_{GS} - V_P = -2 - (-3.5) = +1.5 V$. 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 $V_{DS} \geq V_{GS} - V_P = +1.5 V$

(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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\text{Assuming pinchoff, } V_{GS} = -I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P} \right)^2 = -(5 \times 10^{-3}) (2 \times 10^3) \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 + 12.5V_{GS} + 25 = 0$$

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

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

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

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

$$V_{GS} = V_G - V_S = -I_G R_G - I_{DSS} R_S \left(1 - \frac{V_{GS}}{V_P} \right)^2 = -0.00680 - (5 \times 10^{-3}) (10^3) \left(1 + \frac{V_{GS}}{5} \right)^2 \rightarrow V_{GS}^2 - 15V_{GS} + 25 = 0$$

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.

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

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

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

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

CHAPTER 5

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$V_{BE} \ll 0, V_{BC} \ll 0 : I_C = \frac{I_S}{\beta_R} = 3 \times 10^{-16} A = 0.300 fA$$

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

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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.)

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

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

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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 : $I_B = 100 \mu A$ | $I_E = (\beta_F + 1)I_B = 5.10 \text{ mA}$ | $I_C = \beta_F I_B = 5.00 \text{ mA}$
 $V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025V \ln\left(\frac{5.00 \text{ mA}}{10^{-16} \text{ A}} + 1\right) = 0.789 \text{ V}$ | Checking: $V_{BC} = -5 + 0.789 = -4.21$

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

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(a) Resistor R is changed.

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

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

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

The nearest 5% value is 82 k Ω .

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

$$I_E = \frac{\beta_F + 1}{\beta_F} I_C = \frac{51}{50} I_C = 1.02 I_C \quad V_{BE} = V_T \ln\left(\frac{I_C}{I_S} + 1\right) = 0.025 \ln(2 \times 10^{15} I_C + 1)$$

$$V_{BE} + 8200 \left[1.02(5 \times 10^{-16}) \exp\left(\frac{V_{BE}}{0.025}\right) - 1 \right] = 9 \rightarrow V_{BE} = 0.7079 \text{ V} \text{ using a calculator solver}$$

$$\text{or spreadsheet. } I_C = 5 \times 10^{-16} \exp\left(\frac{0.7079}{0.025}\right) = 992 \mu A \quad | \quad V_{CE} = 9 - 4300I_C - (-0.708) = 5.44 \text{ V}$$

$$I_{SD} = \frac{I_{SBJT}}{\alpha_F} = \frac{2 \times 10^{-14} \text{ A}}{0.95} = 21.0 \text{ fA}$$

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Resistor R is changed :

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

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

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

$$V_{BCSAT} = (0.025V) \ln \left[\frac{0.1mA - \frac{1mA}{50}}{10^{-15} A \left(\frac{1}{0.5} \right) \left(\frac{1}{50} + 1 - 0.5 \right)} \right] = 0.627 \text{ mV} \quad | \quad V_{CESAT} = V_{BESAT} - V_{BCSAT} = 67.7 \text{ mV}$$

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

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

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

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

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

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

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

$$C_D = 4.00 \text{ mS} (25 \text{ ps}) = 0.100 \text{ pF} \quad | \quad C_D = 40.0 \text{ mS} (25 \text{ ps}) = 1.00 \text{ pF}$$

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$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (300)}{1.60 \times 10^{-19}} = 25.9 \text{ mV} \quad | \quad IS = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{350 \mu A}{\exp\left(\frac{0.68}{0.0259}\right)} = 1.39 \text{ fA}$$

$$BF = 80 \quad | \quad VAF = 70 \text{ V}$$

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

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

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

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

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

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

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

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

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

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

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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.

$$120 k\Omega \rightarrow 1.2 M\Omega \quad 82 k\Omega \rightarrow 820 k\Omega \quad 6.8 k\Omega \rightarrow 68 k\Omega$$

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

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

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

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

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

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VBE (V)	IC (A)	VBE (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