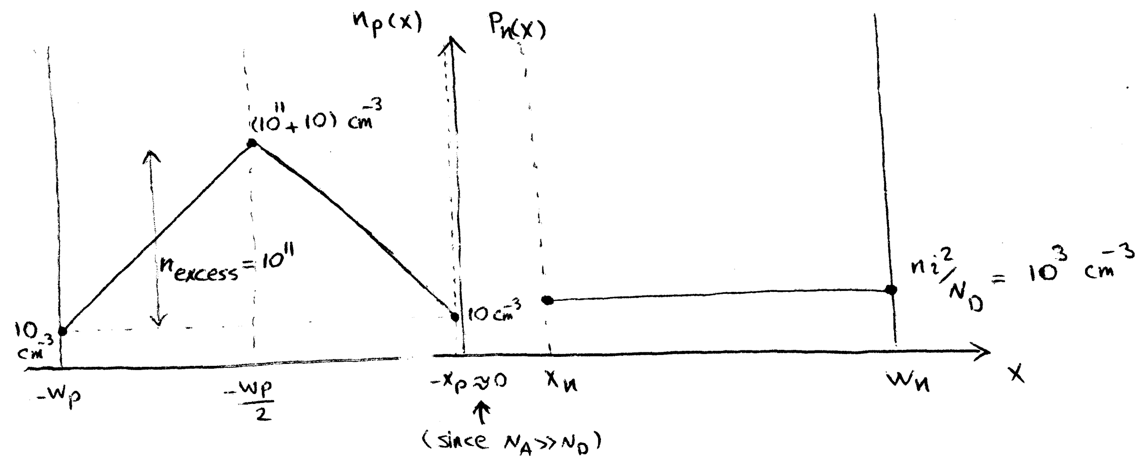
1.

a) The minority carrier concentrations at the edge of contacts and depletion region stay at the thermal equilibrium level.

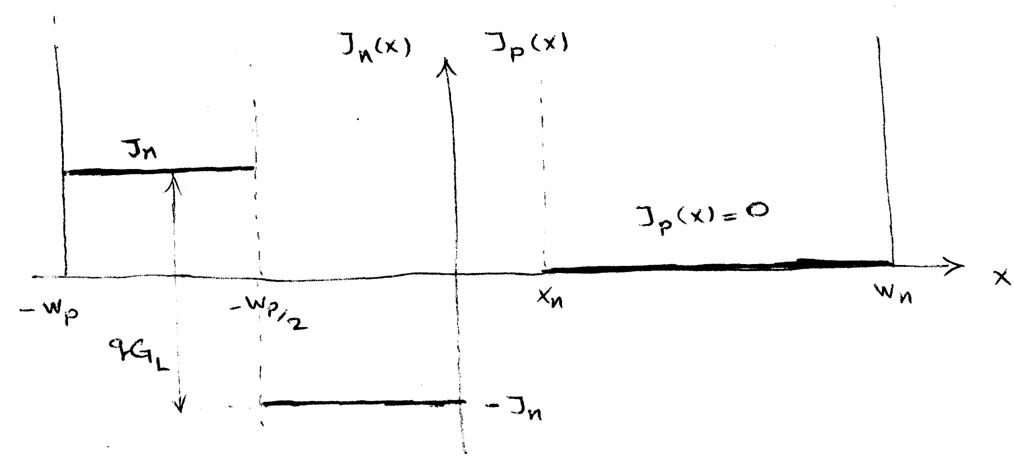
$$n_p(-W_p) = n_p(-x_p) = \frac{n_i^2}{N_A} = 10\ cm^{-3}$$

$$p_n(W_n) = p_n(x_n) = \frac{n_i^2}{N_D} = 10^3\ cm^{-3}$$

b)



c)



For a detailed solution to this problem please look at the online solutions for Tutorial #9

$$J_n = qD_n \frac{n_{excess}}{\left(\frac{W_p}{2}\right)}$$

d) $$J_D = -J_n = -\frac{2qD_n n_{excess}}{W_p}.$$

e) G_L is calculated from the discontinuity in $J_n(x)$ at $x = -\frac{W_p}{2}$: $qG_L = J_n - (-J_n) \Rightarrow G_L = \frac{2J_n}{q} = \frac{4D_n n_{excess}}{W_p}$

2.

a) $$I_C = \frac{q D_n \, n_{pBo} \, A_E}{W_B} \, e^{V_{BE}/V_{th}}$$

$$N_{aB} = 10^{17} \text{ cm}^{-3} \xrightarrow[\text{graph}]{\text{mobility-doping}} \mu_n = 780 \text{ cm}^2/\text{V.S} \Rightarrow D_n = \frac{kT}{q} \mu_n$$

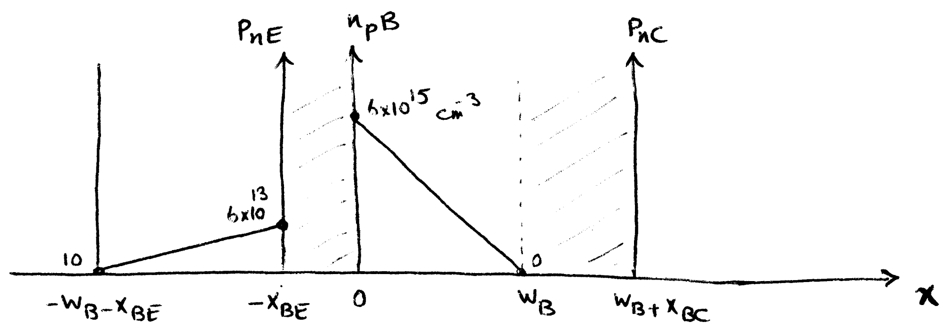
$$= 20.3 \ \frac{\text{cm}^2}{\text{s}}$$

$$V_{BE} = V_{th} \ln \left(\frac{I_C W_B}{q D_n \, n_{pBo} \, A_E} \right)$$

$$= 26\text{mV} \ln \left(\frac{50 \times 10^{-6} \text{ A} \times 0.25 \times 10^{-4} \text{ cm}}{1.6 \times 10^{-19} \text{ A.s} \times 20.3 \ \frac{\text{cm}^2}{\text{s}} \times 10^{3} \text{ cm}^{-3} \times (2.5 \times 10^{-4} \text{ cm})^2} \right)$$

$$= 0.766 \text{ V}$$

b)



$$n_{pB}(x=0) = 10^3 \text{ cm}^{-3} \, e^{V_{BE}/V_{th}} = 10^3 \text{ cm}^{-3} \, e^{0.766/0.026} = 6 \times 10^{15} \text{ cm}^{-3}$$

$$P_{nE}(x = -X_{BE}) = 10 \text{ cm}^{-3} \, e^{V_{BE}/V_{th}} = 10 \text{ cm}^{-3} \, e^{0.766/0.026} = 6 \times 10^{13} \text{ cm}^{-3}$$

c) $$I_B = \frac{q D_p \, P_{nEo} \, A_E}{W_E} \left(e^{V_{BE}/V_{th}} - 1 \right)$$

$$N_{dE} = 10^{19} \text{ cm}^{-3} \xrightarrow[\text{graph}]{\text{mobility-doping}} \mu_p = \overset{75}{\cancel{150}} \ \frac{\text{cm}^2}{\text{V.S}} \Rightarrow D_p = \frac{kT}{q} \mu_p = \overset{1.9}{\cancel{3.9}} \ \frac{\text{cm}^2}{\text{s}}$$

$$I_B = \frac{1.6 \times 10^{-19} \text{ A.s} \times \overset{1.9}{\cancel{3.9}} \ \frac{\text{cm}^2}{\text{s}} \times 10 \text{ cm}^{-3} \times (2.5 \times 10^{-4} \text{ cm})^2}{0.3 \times 10^{-4} \text{ cm}} \left(e^{0.766/0.026} - 1 \right)$$

$$= \overset{40.3}{\cancel{81}} \text{ nA}$$

d) $$g_m = \frac{I_C}{V_{th}} = \frac{50\ \mu A}{26\ mV} = 1.92 \times 10^{-3}\ S$$

$$r_\pi \simeq \frac{\beta_F}{g_m} = \frac{\dfrac{D_n N_{dE} W_E}{D_p N_{aB} W_B}}{g_m} = \frac{\dfrac{20.3 \times 10^{19} \times 0.3}{\overset{1.9}{\cancel{3.9}} \times 10^{17} \times 0.25}}{1.92 \times 10^{-3}\ S} = \overset{645}{\cancel{325}}\ k\Omega$$

$$r_o = \frac{V_{An}}{I_C} = \frac{25\ V}{50\ \mu A} = 500\ k\Omega$$

e) $$Q_{NB}(V_{BE}) = -\frac{q A_E W_B n_{pBo}}{2} e^{V_{BE}/V_{th}}$$

$$= -\frac{1.6 \times 10^{-19} \times (2.5 \times 10^{-4}\ cm)^2 \times 0.25 \times 10^{-4}\ cm \times 10^3\ cm^{-3}}{2} e^{\frac{0.766}{0.026}}$$

$$= 8 \times 10^{-16}\ A.s$$

f) $$C_b = \frac{W_B^2}{2 D_n} g_m = \frac{(0.25 \times 10^{-4}\ cm)^2}{2 \times 20.3\ \frac{cm^2}{s}} 1.92 \times 10^{-3}\ \Omega^{-1} = 29.6\ fF$$

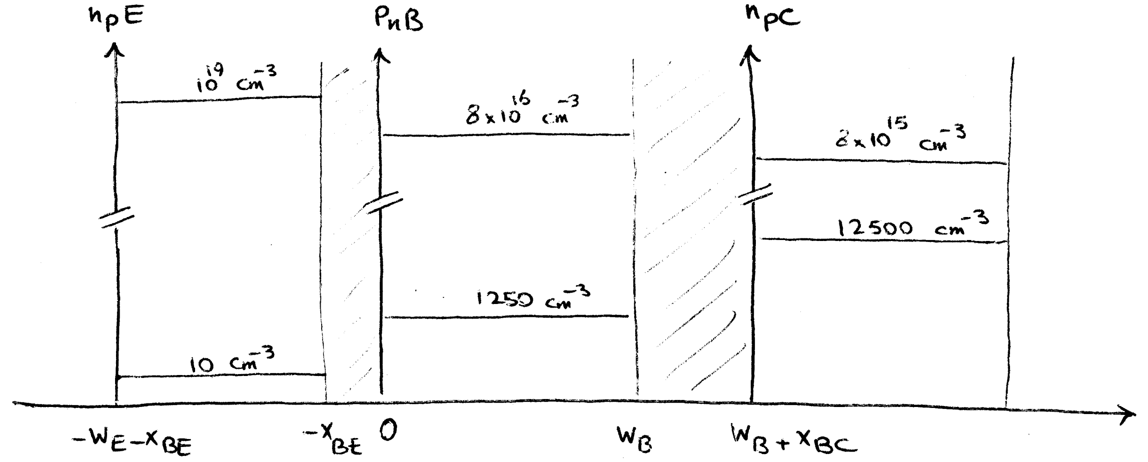
$$C_{jE} = \frac{\varepsilon_s A_E}{X_{BE}} = \frac{11.7 \times 8.85 \times 10^{-14} \times (2.5 \times 10^{-4})^2}{0.05 \times 10^{-4}} = 12.9\ fF$$

$$C_\pi = C_b + C_{jE} = 42.5\ fF$$

g) $$\frac{1}{\omega C_\pi} = r_\pi \Rightarrow \omega = \frac{1}{r_\pi C_\pi} = \frac{1}{\underset{645}{\cancel{325}} \times 10^3 \times 42.5 \times 10^{-15}} = \overset{3.6}{\cancel{7.2}} \times 10^7\ rad/s$$

3.

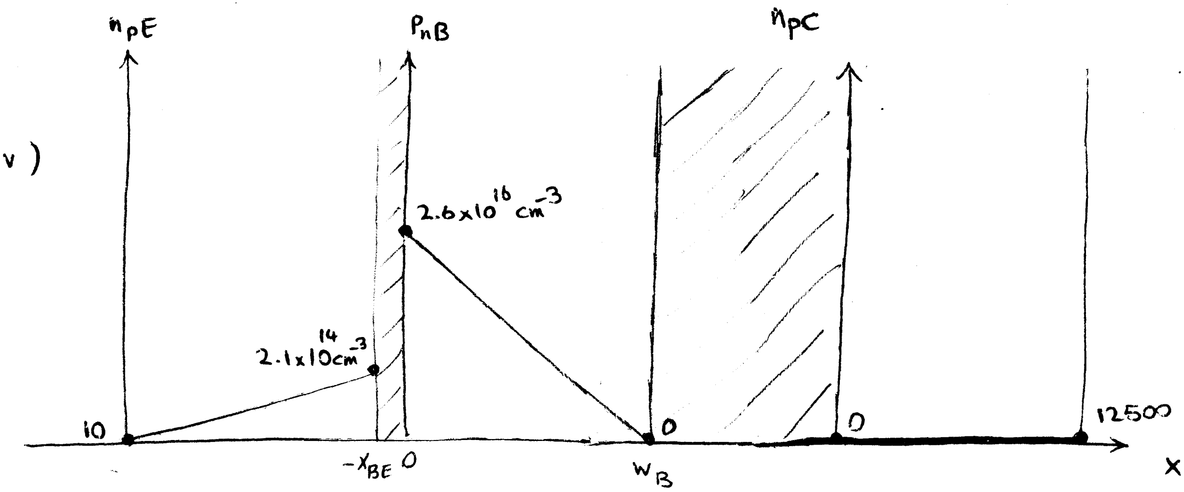
a)



b)

FAR

($V_{EC} = 2.0$ v)



$$I_C = \frac{q D_p p_{nBo} A_E}{W_B} e^{V_{EB}/V_{th}}$$

$$N_{dB} = 8\times10^{16} \text{ cm}^{-3} \Rightarrow \mu_p = 370 \ \frac{\text{cm}^2}{\text{V.s}} \Rightarrow D_p = \frac{kT}{q}\mu_p = 9.6 \ \frac{\text{cm}^2}{\text{s}}$$

$$V_{EB} = V_{th} \ln\left(\frac{I_C W_B}{q D_n p_{nBo} A_E}\right)$$

$$= 26\text{mV} \ln\left(\frac{100\,\mu\text{A} \times 250\times10^{-7} \text{ cm}}{1.6\times10^{-19} \times 9.6 \times 1250 \times (2.5\times10^{-4})^2}\right) = 0.797\text{V}$$

$$p_{nB}(x=0) = 1250 \text{ cm}^{-3} \ e^{V_{EB}/V_{th}} = 1250 \times e^{0.797/0.026} = 2.6\times10^{16} \text{ cm}^{-3}$$

$$n_{pE}(x=-x_{BE}) = 10 \ e^{V_{EB}/V_{th}} = 10 \times e^{0.797/0.026} = 2.1\times10^{14} \text{ cm}^{-3}$$

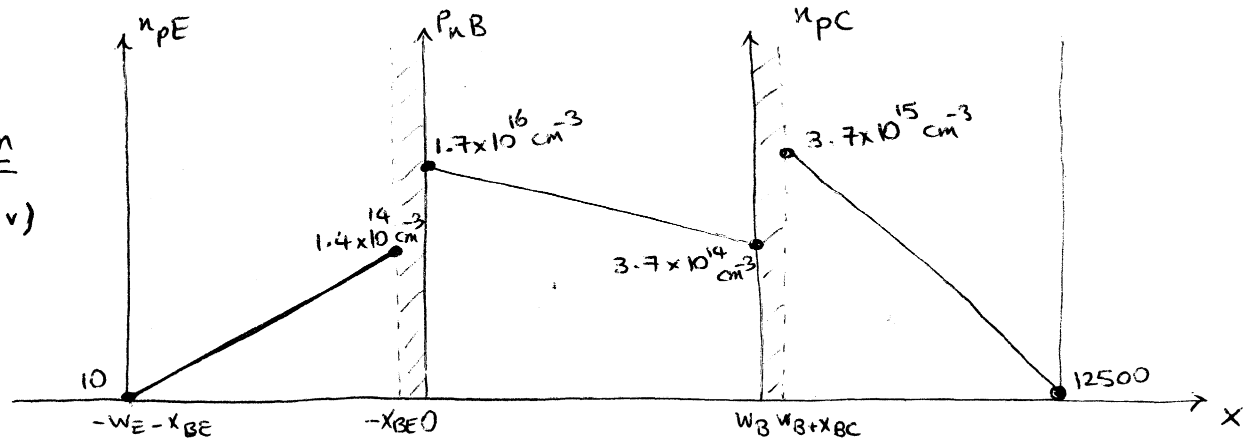
c) $$Q_{NB} = \frac{q A_E W_B P_{nBo}}{2} e^{V_{EB}/V_{th}}$$

$$= \frac{1.6\times10^{-19} \times (2.5\times10^{-4})^2 \times 250\times10^{-7} \times 1250}{2} e^{\frac{0.797}{0.026}} = 3.2\times10^{-15} \text{ A.s}$$

d)

Saturation

($V_{EC} = 0.1v$)



$$I_c = I_s\left(e^{V_{EB}/V_{th}} - e^{V_{CB}/V_{th}}\right) - \frac{I_s}{\beta_R}\left(e^{V_{CB}/V_{th}} - 1\right)$$

$$= I_s\left(e^{V_{EB}/V_{th}} - e^{(V_{CE}+V_{EB})/V_{th}}\right) - \frac{I_s}{\beta_R}\left(e^{(V_{CE}+V_{EB})/V_{th}} - 1\right)$$

$$\Rightarrow V_{EB} = V_{th} \ln\left(\frac{I_c - I_s/\beta_R}{I_s(1-e^{V_{CE}/V_{th}}) - \frac{I_s}{\beta_R} e^{V_{CE}/V_{th}}}\right)$$

$$= V_{th} \ln\left(\frac{I_c - n_{pCo}\frac{D_{nC}}{W_C} qA}{P_{nBo}\frac{D_{pB}}{W_B} qA(1-e^{V_{CE}/V_{th}}) - n_{pCo}\frac{D_{nC}}{W_C} qA\, e^{V_{CE}/V_{th}}}\right)$$

$N_{dB} = 8\times10^{+16}\ cm^{-3} \Rightarrow \mu_p = 370\ \frac{cm^2}{V.s} \Rightarrow D_{pB} = 9.6\ \frac{cm^2}{s}$

$N_{aC} = 8\times10^{15}\ cm^{-3} \Rightarrow \mu_n = 1250\ \frac{cm^2}{V.s} \Rightarrow D_{nC} = 32.5\ \frac{cm^2}{s}$

$$V_{EB} = 26\,mv \ln\left(\frac{\frac{50\times10^{-6}}{1.6\times10^{-19}\times(2.5\times10^{-4})^2} - \left(12500\times\frac{32.5}{0.75\times10^{-4}}\right)}{1250\,\frac{9.6}{250\times10^{-7}}(1-e^{-0.1/0.026}) - 12500\,\frac{32.5}{0.75\times10^{-4}}\, e^{-0.1/0.026}}\right)$$

$= 0.787$ v

$V_{CB} = V_{CE} + V_{EB} = 0.687$ v

$$p_{nB}(x=0) = p_{nBo}\, e^{V_{EB}/V_{th}} = 1250\, e^{0.787/0.026} = 1.7\times 10^{16}\ cm^{-3}$$

$$n_{pE}(x=-x_B) = n_{pEo}\, e^{V_{EB}/V_{th}} = 10\times e^{0.787/0.026} = 1.4\times 10^{14}\ cm^{-3}$$

$$p_{nB}(x=W_B) = p_{nBo}\, e^{V_{CB}/V_{th}} = 1250\, e^{0.687/0.026} = 3.7\times 10^{14}\ cm^{-3}$$

$$n_{pC}(x=W_B+x_{BC}) = n_{pCo}\, e^{V_{CB}/V_{th}} = 12500\, e^{0.687/0.026} = 3.7\times 10^{15}\ cm^{-3}$$

e) $$Q_{NB} = \frac{q A W_B}{2}\left(p_{nB}(x=0) + p_{nB}(x=W_B)\right)$$

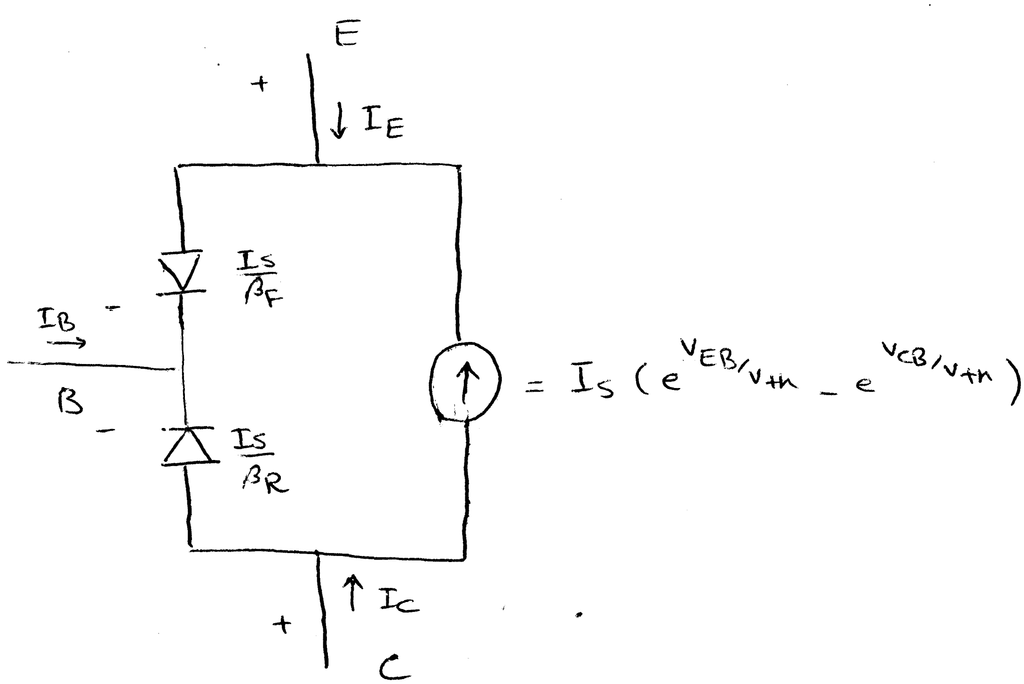
$$= \frac{1.6\times10^{-19}\times(2.5\times10^{-4})^2\times 250\times10^{-7}}{2}\left(1.7\times10^{16} + 3.7\times10^{14}\right)$$

$$= 2.2\times 10^{-15}\ A.s$$

f) $$I_C = I_S\left(e^{V_{EB}/V_{th}} - e^{V_{CB}/V_{th}}\right) - \frac{I_S}{\beta_R}\left(e^{V_{CB}/V_{th}} - 1\right)$$

$$I_B = \frac{I_S}{\beta_F}\left(e^{V_{EB}/V_{th}} - 1\right) + \frac{I_S}{\beta_R}\left(e^{V_{CB}/V_{th}} - 1\right)$$

$$I_E = -I_S\left(e^{V_{EB}/V_{th}} - e^{V_{CB}/V_{th}}\right) - \frac{I_S}{\beta_F}\left(e^{V_{EB}/V_{th}} - 1\right)$$



4.

a)

b) graphs on the next pages

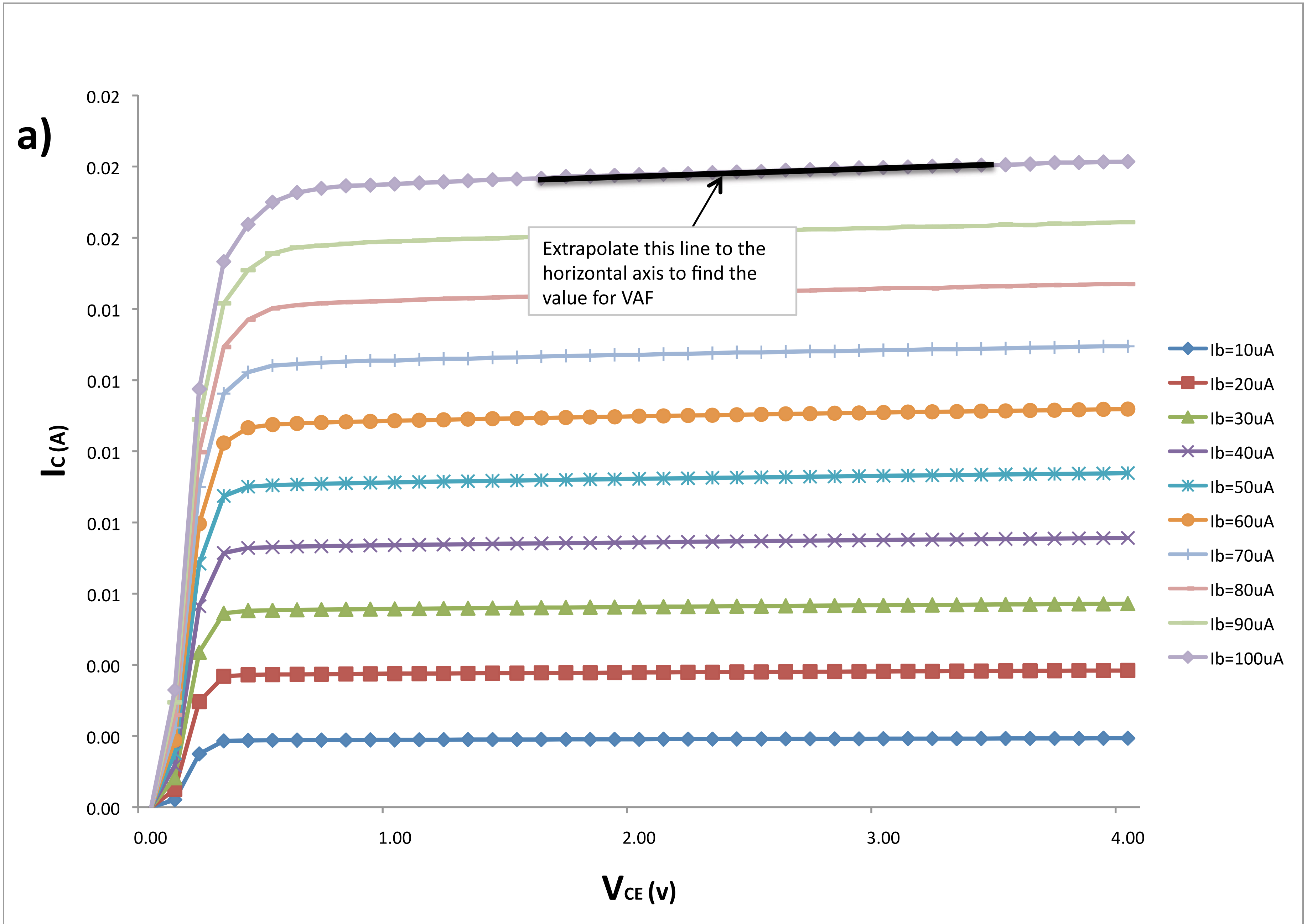
c)

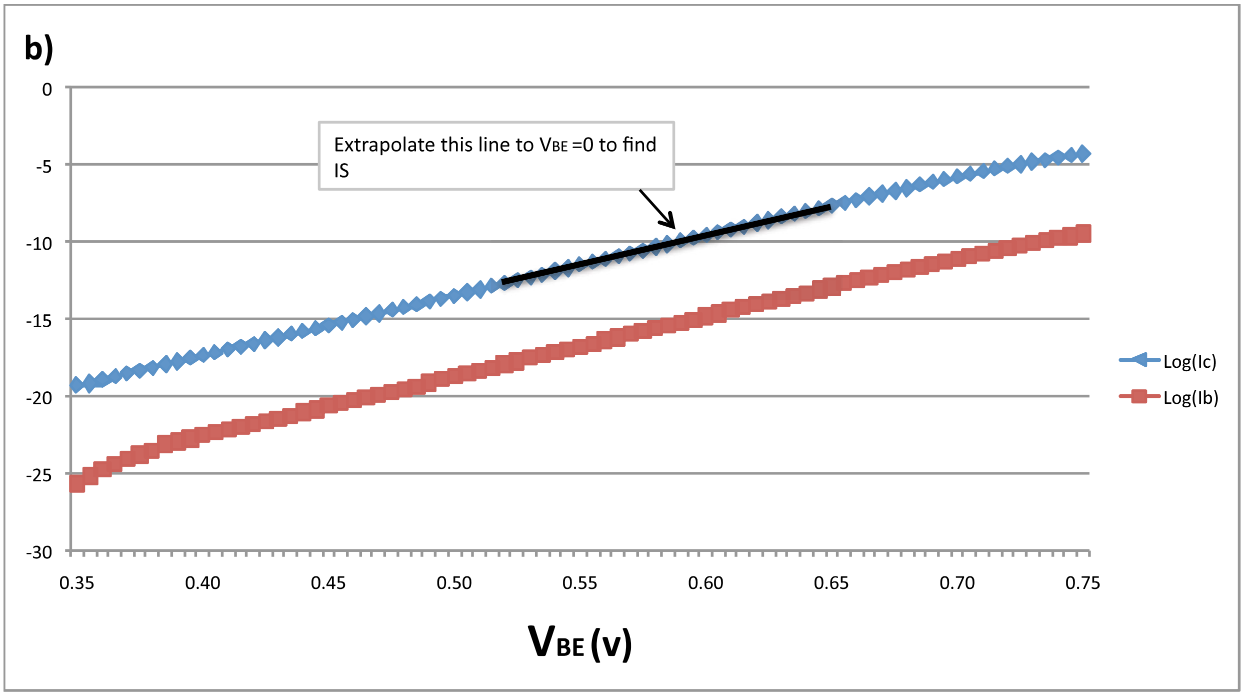
d) $I_C = I_S \, e^{V_{BE}/V_{th}}$

$\xrightarrow[\text{graph (a)}]{I_C \text{ vs. } V_{BE}} I_S = 5 \times 10^{-15} \text{ A}$

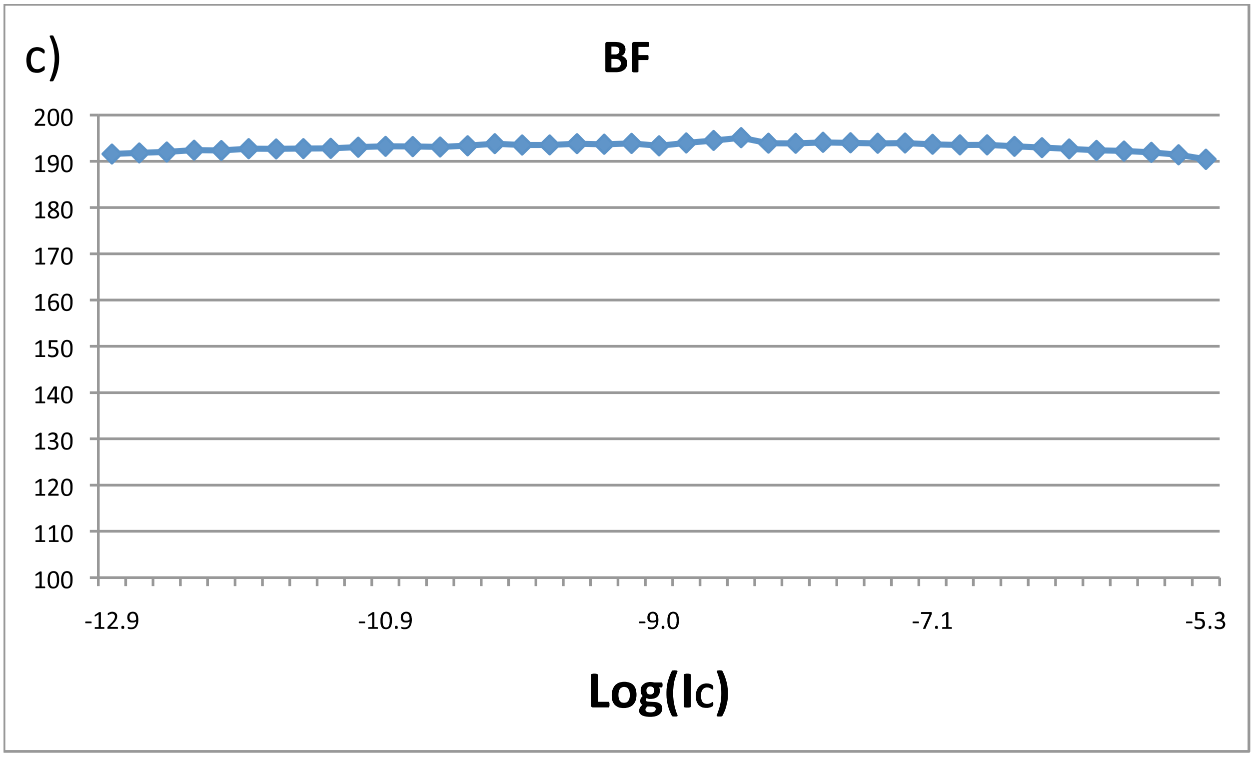
$BF = \beta_F = 1?3$ (From curren gain graph (c))

$VAF = V_{AN} = 90 \text{ V}$ (From I_C vs V_{CE} graph in part (b))


a)
0.02
0.02
0.02
0.01
0.01
0.01
0.01
0.01
0.00
0.00
0.00
Ic (A)
0.00
1.00
2.00
3.00
4.00
VCE (v)
Extrapolate this line to the horizontal axis to find the value for VAF
Ib=10uA
Ib=20uA
Ib=30uA
Ib=40uA
Ib=50uA
Ib=60uA
Ib=70uA
Ib=80uA
Ib=90uA
Ib=100uA



b)
0
-5
-10
-15
-20
-25
-30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
Extrapolate this line to VBE =0 to find IS
Log(Ic)
Log(Ib)
VBE (v)


c)
BF
200
190
180
170
160
150
140
130
120
110
100
-12.9
-10.9
-9.0
-7.1
-5.3
Log(Ic)