Name: *A. KEY*

Question 1:

An abrupt Si BJT has the following properties at 300K:

Emitter	Base	Collector
$Nd=10^{19}cm^{-4}$	$Na=10^{17}cm^{-3}$	$Nd=10^{15}cm^{-3}$
$\tau_p=.1x10^{-6}s$	$\tau_n=1x10^{-6}s$	$\tau_p=.1x10^{-6}s$
$A=10^{-4}cm^2$	$A=10^{-4}cm^2$	$A=10^{-4}cm^2$
$L_E=10x10^{-4}cm$	$L_B=10x10^{-4}cm$	$L_C=300x10^{-4}cm$

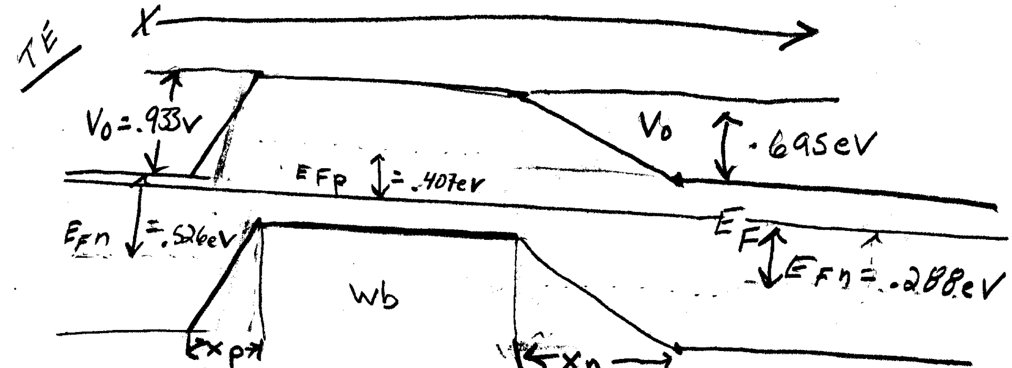
a) Draw the energy band diagram for the both junctions at TE. Show
Vo for both junctions, xn and xp for both junctions, Fermi levels, and Wb.

b) Draw the energy band diagram for the emitter base junction under .65 volts forward bias, and the CB junction under -5 volts reverse bias. Show Vo for both junctions, xn and xp for both junctions, Fermi levels, and Wb.

c) Draw the energy band diagram for the emitter base junction under -5 volts reverse bias, and the CB junction under .65 volts forward bias. Show Vo for both junctions, xn and xp for both junctions, Fermi levels, and Wb.

#1

TE



$W \simeq x_p = .11\,\mu m$

$x_n = .0011\,\mu m$

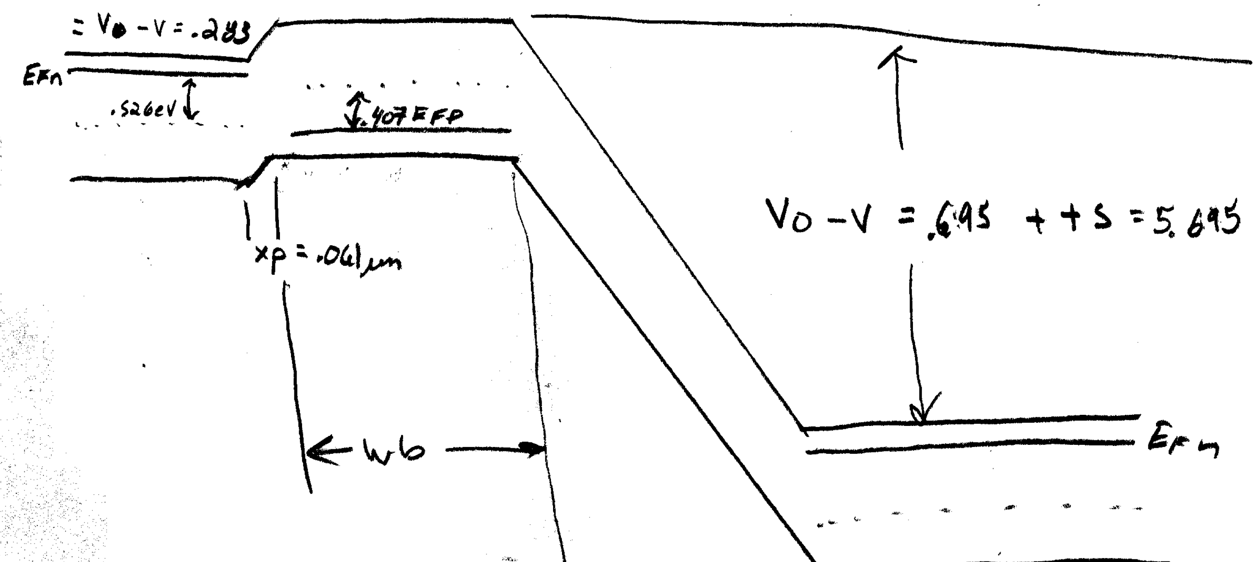
$W \simeq x_n = .95\,\mu m$

$x_p = .0095\,\mu m$

$Wb = 10\,\mu m - .11\,\mu m - .0095\,\mu m$

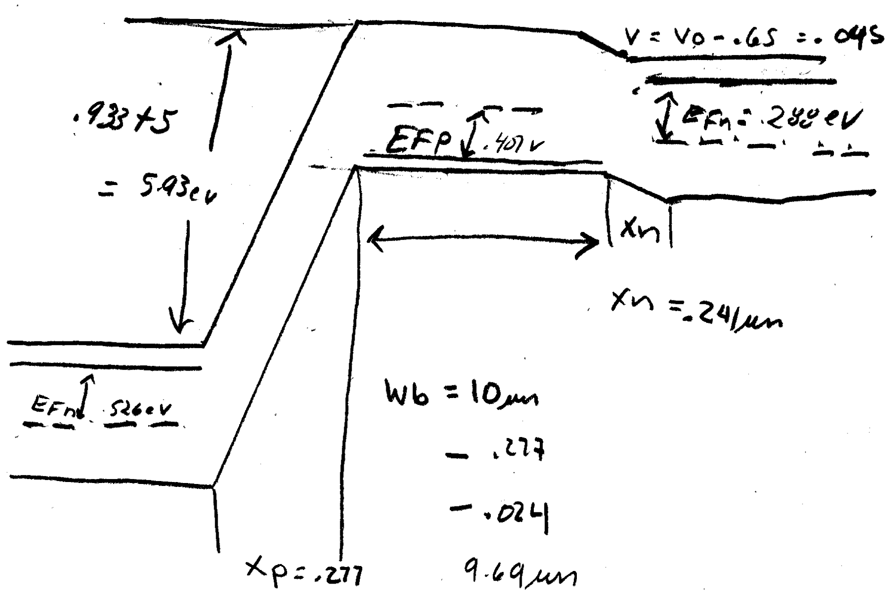
$= 9.89\,\mu m$

$V = .6S$ $\qquad$ $V = -5$



$\sim X_n = 2.72\,\mu m$

$Wb = 10\,\mu m$
$- .061\,\mu m$
$- .027\,\mu m$
$= 9.91\,\mu m$


V = Vo - .65 = .045
.933+5
= 5.93ev
EFP .407v
EFn = .288 eV
xn
xn = .241µm
EFn .526eV
Wb = 10µm
- .277
- .024
9.69µm
xp = .277

Question 2:

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a) For the BJT in question1 calculate emitter injection efficiency (γ), base transport factor (B), and common emitter current gain (β), under forward active and reverse active biasing.

$W_b = 9.91 \times 10^{-4}\ cm$ @ $V_{BE} = .65\ v$ $V_{CB} = -5\ v$

$W_b = 9.72 \times 10^{-4}\ cm$ @ $V_{BE} = -5\ v$ $V_{CB} = .65\ v$

μ_n in base $= 1000\ cm^2/v\text{-}s$ $\quad L_n = \sqrt{1000 \times .0259 \times 1 \times 10^{-6}} = 50.89 \times 10^{-4}\ cm$

μ_p in Emitter $= 100\ cm^2/v\text{-}s$ $\quad L_{PE} = \sqrt{100 \times .0259 \times .1 \times 10^{-6}} = 5.09 \times 10^{-4}\ cm$

μ_p in Collector $= 500\ cm^2/v\text{-}s$ $\quad L_{PC} = \sqrt{500 \times .0259 \times .1 \times 10^{-6}} = 11.3 \times 10^{-4}\ cm$

FA

$$B = 1 - \frac{1}{2}\frac{W_b^2}{L_n^2} = 1 - \frac{1}{2}\frac{9.91^2}{50.89^2}$$

$$= .981$$

$$\gamma = \left[1 + \frac{W_b N_a \mu_{pE}}{L_{pE} N_{d_E} \mu_{nB}}\right]^{-1}$$

$\gamma = .998$ (FF [illegible]

$\alpha = \gamma B = .979$

$$\beta = \frac{\alpha}{1-\alpha} = 46.7$$

RA

$$B = 1 - \frac{1}{2}\frac{W_b^2}{L_n^2} = 1 - \frac{1}{2}\frac{9.72^2}{50.89^2}$$

$$= .982$$

$$\gamma = \left[1 + \frac{W_b N_a \mu_{pC}}{L_{pC} N_{d_C} \mu_{nB}}\right]^{-1}$$

$\gamma = .0272$

$\alpha = \gamma B = .02231$

$\beta = .0228$ less than one!

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Question 3:

An Si BJT has the following properties at 300K:

Emitter	Base	Collector
$Nd=10^{19}cm^{-4}$	$Na=10^{17}cm^{-3}$	$Nd=10^{19}cm^{-3}$
$\tau_p=.10x10^{-6}s$	$\tau_n=1x10^{-6}s$	$\tau_p=.1x10^{-6}s$
$A=10^{-4}cm^2$	$A=10^{-4}cm^2$	$A=10^{-4}cm^2$
$L_E=10x10\text{-}^4cm$	$L_B=10x10^{-4}cm$	$L_C=300x10^{-4}cm$

a) Using an excel like program, calculate Wb for the above diode with V_{BE}=.7Volts for V_{CB}=-.5,-1,-1.5,-2,-2.5, and -10 volts.
b) Calculate β for the above conditions.
c) At what V_{CB} will Wb go to zero?
d) Which is smaller the voltage you found in part c, or the breakdown voltage of the junction?

$$W_b = L_B - x_{pE} - x_{pC}$$

V_{BC}	Wb	B	γ	β
-.5	9.81 μm	.98143	.99808	47.87
-1	9.79 μm	.98151	.99806	48.08
-1.5	9.77 μm	.98158	.99808	48.27
-2.	9.75	.98165	.99809	48.44
-2.5	9.73	.98171	.99809	48.59
-10	9.57	.98233	.99812	50.24

$$W_b = 10\times10^{-4}\,cm - .055\times10^{-4}\,cm - \left(\frac{2\times11.8\times8.85\times10^{-14}}{1.6\times10^{-19}}(V_0-V)\frac{N_d}{N_a(N_d+N_a)}\right)^{1/2}$$

$W_b = 0$

$$\left(\frac{2\times\epsilon_{Si}}{q}\,V_0-V\,\frac{N_d}{N_a(N_d+N_a)}\right)^{1/2} = L_B - x_{pE}$$

$V_0 - V$ $$V = V_0 - (L_B - x_{pE})^2\,\frac{q\,N_a(N_d+N_a)}{2\,N_d\,\epsilon_{Si}}$$

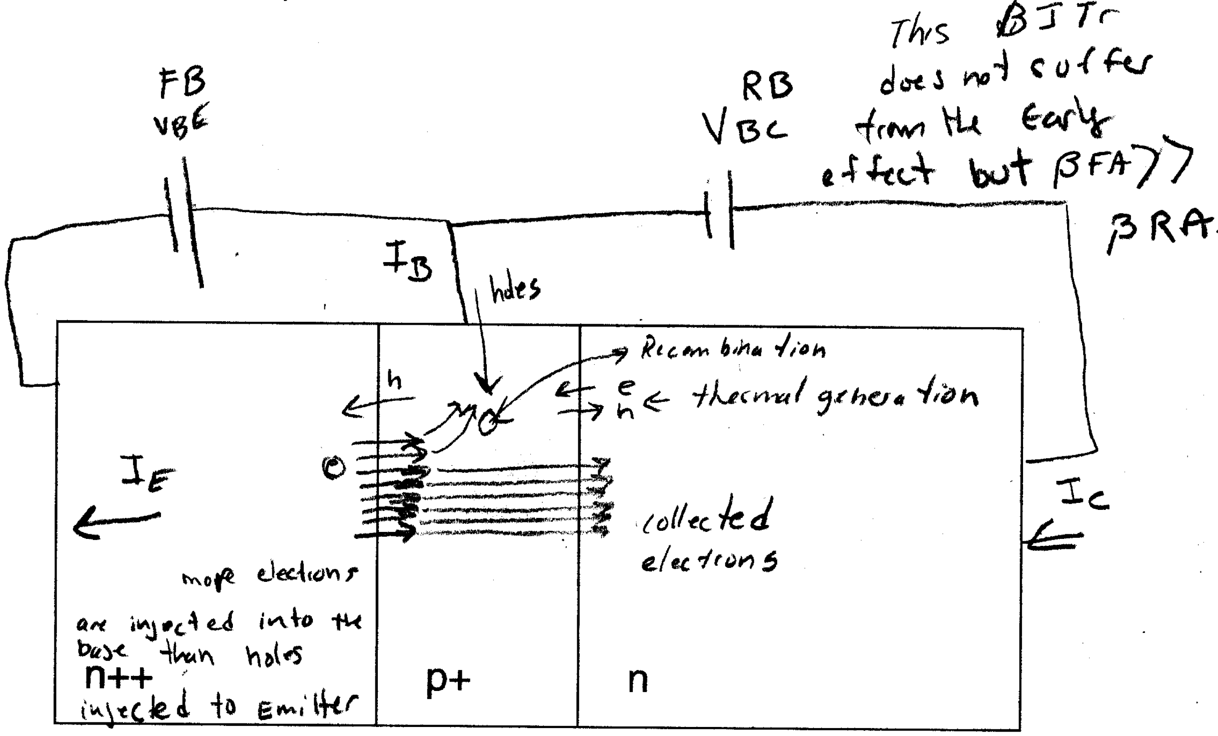
$$V = .933 - 7.622\times10^3 = 7621 \text{ Volts} \quad \beta \to \infty$$

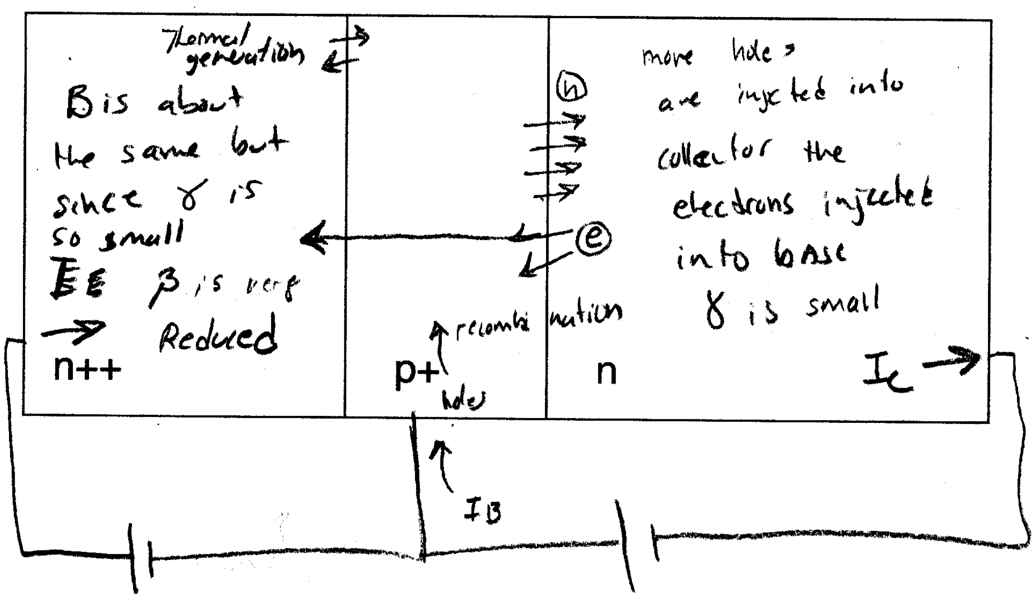
d) The CB junction breaks down at about 5 volts so β will never go ∞

Question 4:

Name: A. KEY

a) Draw and label the electron and hole currents along with terminal currents. Include direction and name of current (similar to figure 7-3 in the new edition) under forward and reverse active conditions.





Question 5:

Name: *A. KEY*

For the diode of question 1, estimate f_T. Assume that electrons travel through the depletion region at the saturation velocity.

$$f_T = \frac{1}{2\pi \tau_d} \qquad \tau_d = \tau_E + \tau_{wc} + \tau_t$$

$$\tau_E = r_e (C_e + C_c) \qquad C_e = C_{jE} + C_{sE} \qquad r_e = \frac{kT}{q I_E}$$

$$C_c = C_{jc}$$

$$I_E = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_a} + \cancel{\frac{D_p}{L_p}\frac{n_i^2}{N_D}}^{\,0}\right)\left(e^{\frac{Vq}{kT}} - 1\right)$$

L_n ← Wb!

$$I_E = 1.6\times10^{-19} \times 10^{-4}\left(\frac{.0259 \times 1000}{9.91\times10^{-4}} \frac{1.5\times10^{10^2}}{1\times10^{17}}\right) e^{\frac{.65}{.0259}} = 5.88\times10^{-16}\, e^{\frac{.65}{.0259}}$$

$$= 46\times10^{-6} \text{ Amps}$$

$$C_{SE} = \frac{q}{kT} I \tau_m = \frac{1}{.0259} \times 46\times10^{-6} \times 1\times10^{-6} = 1.8\,nF$$

$$C_{jE} = \frac{A}{2}\left[\frac{2q\epsilon}{V_0 - V} N_a\right]^{1/2} = \frac{10^{-4}}{2}\left[\frac{2\times1.6\times10^{-19} \times 11.8\times 8.85\times10^{-14} \times 1\times10^{17}}{.933 - .65}\right]^{1/2}$$

$$= 17\,pF$$

$$C_{jC} = A/2\left[\frac{2q\epsilon N_d}{V_0 - V}\right] = \frac{10^{-4}}{2}\left[\frac{2\times1.6\times10^{-19} \times 11.8 \times 8.85\times10^{-14} \times 1\times10^{15}}{(.695 + 5)}\right]^{1/2}$$

$$= .38\,pF$$

$$\tau_E = \frac{.0259}{46\times10^{-6}}\left[1.8\,nF + 17\,pF + .38\,pF\right] = 1.02\times10^{-6} \text{ seconds}$$

Note: $\tau_E \simeq \tau_n \quad 1\times10^{-6}\,s$! If we want to switch faster we have to decrease τ_n which lowers the gain.

depletion width

$$\tau_{wc} = \frac{W_{CB}}{2\langle V_{sat}\rangle} \cong \frac{x_n}{\langle v_{sat}\rangle} = \frac{2.72\times10^{-4}\,cm}{2\,10^{+7}\,\frac{cm}{s}} = 13\,ps$$

$$\tau_t = \frac{W_B^2}{2D_n} = \frac{9.91\times10^{-4^2}\,cm}{2\;1000\,cm^2/V\cdot s \times .0259\,V} = 18\,ns$$

$$\tau_d = 1.02\times10^{-6}\,s + 13\,ps + 18\,ns$$

$$\tau_d = 1.038\times10^{-6}$$

$$f_T = \frac{1}{2\pi\;1.038\times10^{-6}} = .153\,MHz$$

what if we changed τ_n to $1\times10^{-9}\,s$?

$$\tau_d \simeq 1\times10^{-9}\,s + 13\,ps + 18\,ns = 19\,ns$$

$$f_T = 8.37\,MHz$$

If we switched to a graded base $\tau_t = \frac{W_B^2}{4D_n}$

$f_T = 15.89\,MHz$

If we $\frac{1}{2}W_b$ (no graded base) $\quad \tau_t = \frac{\left(\frac{W_B}{2}\right)^2}{2\,D_n} = \frac{W_B^2}{8\,D_n} = 4.8\,ns$

$f_T = 27\,MHz \qquad \frac{W_B}{10} \rightarrow f_T \rightarrow 133\,MHz$

Question 6:

Name: A. KEY

For an npn BJT, How do you scale Wb to keep the same common emitter current gain (β) if you decrease τ_n by a factor of 10?

assume since $W_B \ll L_n$ emitter injection efficiency is not affected by changes in W_B, so that leaves us

$$B = 1 - \frac{1}{2}\frac{Wb^2}{(\sqrt{D_n \tau_n})^2}$$

$$\cancel{1} - \cancel{\frac{1}{2}}\frac{Wb_{old}^2}{\sqrt{\cancel{D_n} \tau_{n\,old}}^2} = \cancel{1} - \cancel{\frac{1}{2}}\frac{Wb_{new}^2}{\left(\sqrt{D_n \frac{\tau_{n\,old}}{10}}\right)^2}$$

$$\frac{Wb_{old}^2}{\cancel{\tau_n old}} = \frac{Wb_{new}^2}{\frac{\cancel{\tau_n old}}{10}}$$

$$Wb_{new}^2 = \frac{Wb_{old}^2}{10}$$

$$Wb_{new} = \frac{Wb_{old}}{\sqrt{10}}$$

Question 7:

Name: A. KEY

List and explain some methods of increasing the switching speed of BJTs. Include the engineering tradeoffs you have to make.

$$f_T = \frac{1}{2\pi \tau_d} \qquad f_{MAX} = \left(\frac{f_T}{8\pi R_B C_c}\right)^{1/2}$$

$$\tau_E = \frac{kT}{qI}\left(\frac{qI\tau_B}{kT} + C_e + C_c\right) \simeq \tau_n$$

If we minimize τ_n then β goes down $B = 1 - \frac{W_b^2}{2\sqrt{D_n \tau_n}}$

If we scale down W_b τ_t goes down as well

$\frac{W_b^2}{2D_n}$ and the gain can be brought back up.

however R_B increases a W_b decreases and f_{MAX} will go down.

C_c is C_{jc} and the large the V_{BC} the smaller C_{jc} is, but $\tau_{wc} = \frac{W_{CB}}{2\langle v_{sat}\rangle}$ will increase right lily

$$C_{jc} = \frac{A\epsilon_{si}}{W_{CB}}$$