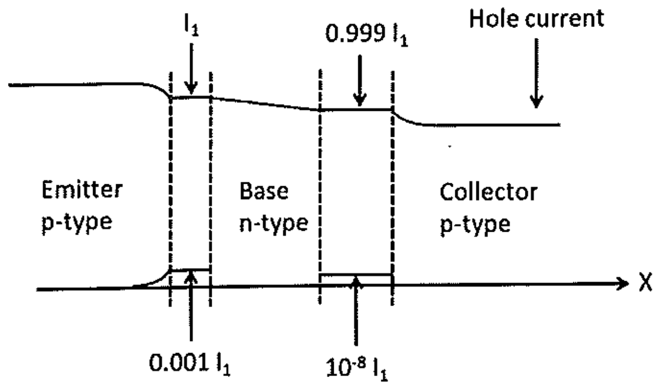
EE 121B Principles of Semiconductor Device Design, Midterm Exam

Name: ____________________

Student ID: ________________

(1) The electron and hole currents for a pnp BJT are plotted in Fig. 1. [21 points]



$I_{EP} = I_1$, $I_{EN} = 0.001 I_1$
$I_{CP} = 0.999 I_1$, $I_{CN} = 10^{-8} I_1$

Fig. 1: Electron and hole current inside a pnp transistor

Determine:

a) Transistor operation mode (active or inverted)? Explain. Active operation

since $I_{CP} < I_{EP} < I_E$ or $I_E > I_{CP} > I_C$

b) Base transport factor (*B*)

$$B = \frac{I_C}{I_{EP}} = \frac{I_{CP} + I_{CN}}{I_{EP}} \simeq \frac{I_{CP}}{I_{EP}} = \frac{0.999 I_1}{I_1} = 0.999$$

c) Emitter injection efficiency (γ)

$$\gamma = \frac{I_{EP}}{I_{EP} + I_{EN}} = \frac{I_1}{I_1 + 0.001 I_1} = \frac{1}{1.001} = 0.999$$

d) Current transfer ratio (α)

$$\alpha = B\gamma = 0.999 \times 0.999 = 0.998$$

e) Base-to-emitter current gain (β)

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.998}{1-0.998} = 499$$

f) I_E, I_C, and I_B in terms of I_1

$$I_E = I_{Ep} + I_{EN} = I_1 + 0.001 I_1 = 1.001 I_1$$

$$I_C = I_{Cp} + I_{CN} = 0.999 I_1 + 10^{-8} I_1 \simeq 0.999 I_1$$

$$I_B = I_E - I_C = 2\times10^{-3} I_1$$

g) I_{CB0} and I_{CE0}

$$I_{CB0} \simeq I_{CN} = 10^{-8} I_1$$

$$I_{CE0} = (1+\beta) I_{CB0} = 500\times10^{-8} I_1 = 5\times10^{-6} I_1$$

h) Is there any recombination-generation current inside the depletion regions? Explain.

No, since hole and electron current are constant inside the depletion regions.

(2) A npn BJT transistor is illustrated in Fig. 2. The transistor regions are assumed to be uniformly doped with $N_{DE} >> N_{AB} > N_{DC}$. Also, neglect any electric field inside the neutral regions. [36 points]

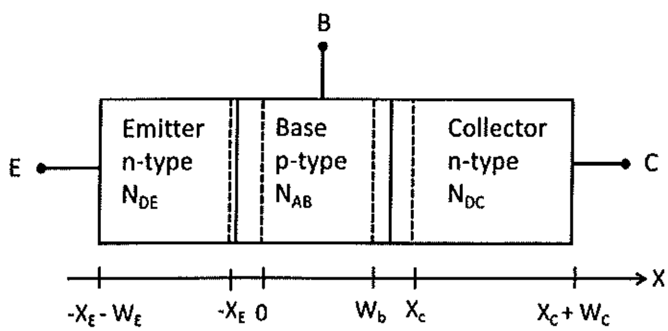


Fig. 2: Schematic of a npn transistor

a) Sketch energy band diagram under equilibrium versus position (x). Make sure to label E_c, E_v, and E_F. Which n-type region has smaller (E_C-E_F) value? Explain.

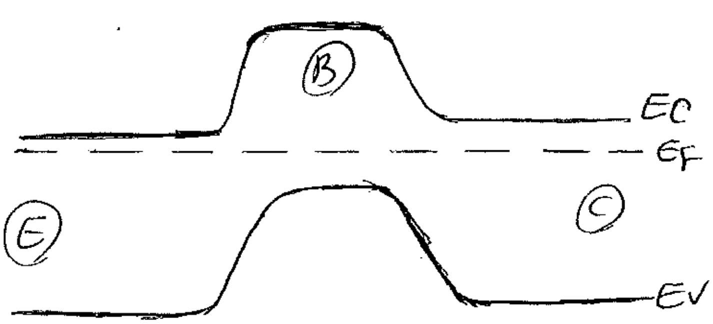
$$|E_C - E_F|_E < |E_C - E_F|_C$$

since $N_{DE} >> N_{DC}$

$$n_0 = n_i e^{(E_F - E_i)/kT}$$

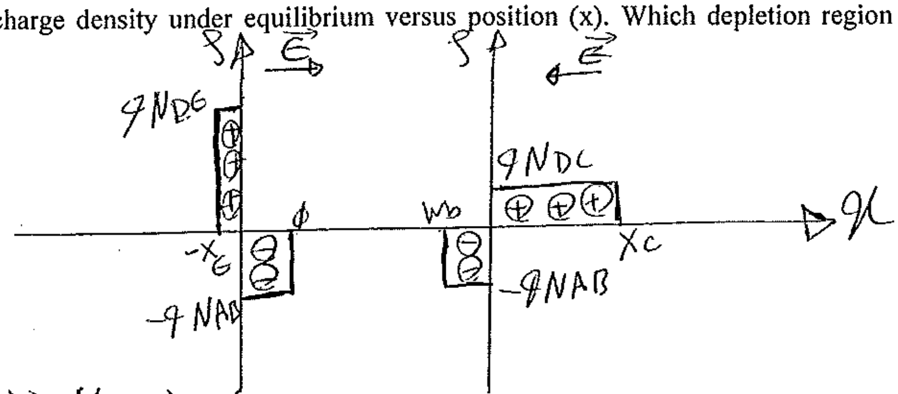
in Emitter $n_0 = N_{DE}$

and in Collector $n_0 = N_{DC}$



since $N_{DE} >> N_{DC} \Rightarrow \left.\frac{(E_F - E_i)}{kT}\right|_E >> \left.\frac{(E_F - E_i)}{kT}\right|_C \Rightarrow |E_C - E_F|_E < |E_C - E_F|_C$

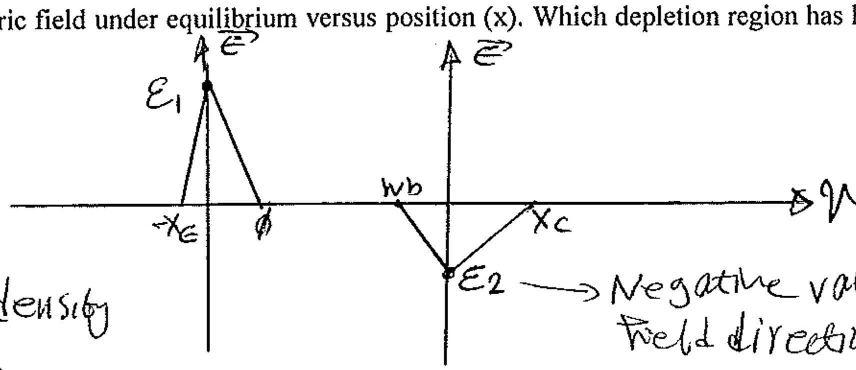
b) Sketch charge density under equilibrium versus position (x). Which depletion region will have wider width? Explain.



since $N_{DE} \gg N_{AB} > N_{DC}$ ⇒ $W_E \ll W_B$ (BE junction) and $W_B < W_C$ (BC junction)

$x_{p_0} N_a = x_{n_0} N_d$ ⇒ Depletion width is shorter on the higher doping value.

c) Sketch electric field under equilibrium versus position (x). Which depletion region has higher maximum electric field? Explain.

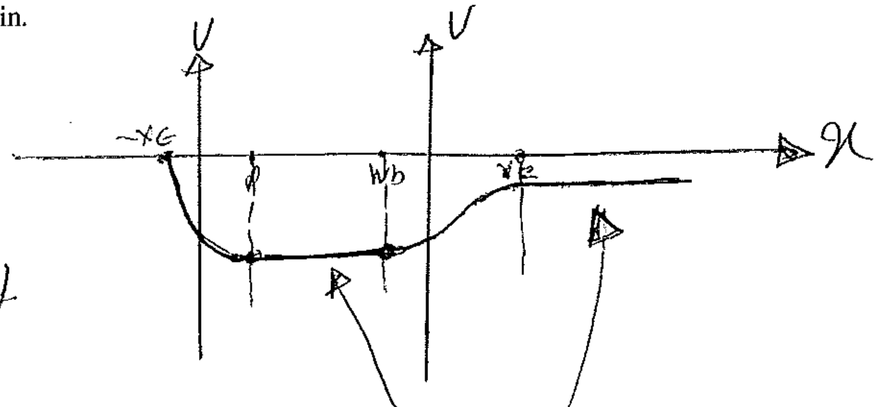


$|\mathcal{E}_1| > |\mathcal{E}_2|$

since we have higher charge density in BE region compared to BC region

$\mathcal{E}_2$ → Negative value since electric field direction is in ← −x direction

d) Sketch electrostatic potential under equilibrium versus position (x). Which depletion region has larger built-in potential? Explain.



$\vec{\mathcal{E}} = -\frac{dV(x)}{dx}$

is constant

if $\vec{\mathcal{E}} = 0$ ⇒ $V(x)$ is constant

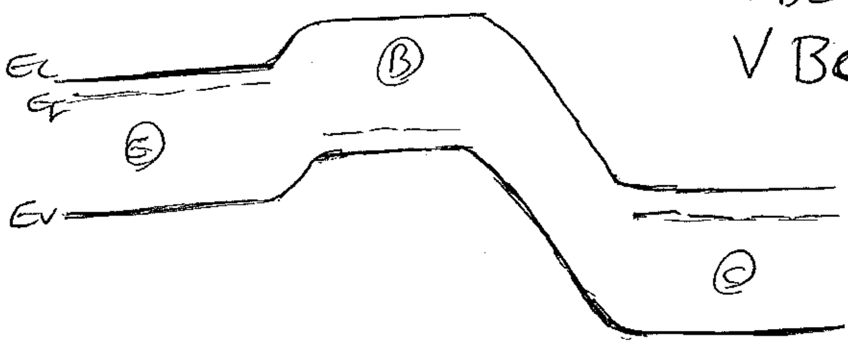
$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$ since BE junction has much higher doping level than B.C, then $V_{0(BE)} > V_0(BC)$

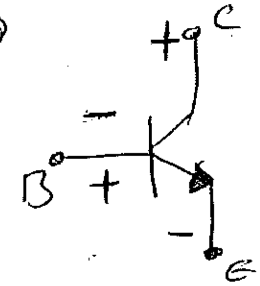
e) Sketch energy band diagram versus position (x) under active normal, inverted, saturation and cutoff modes. Determine polarity of V_{BE} and V_{BC} for each mode. Make sure to label E_c, E_v, and E_F.

Normal Active Mode:

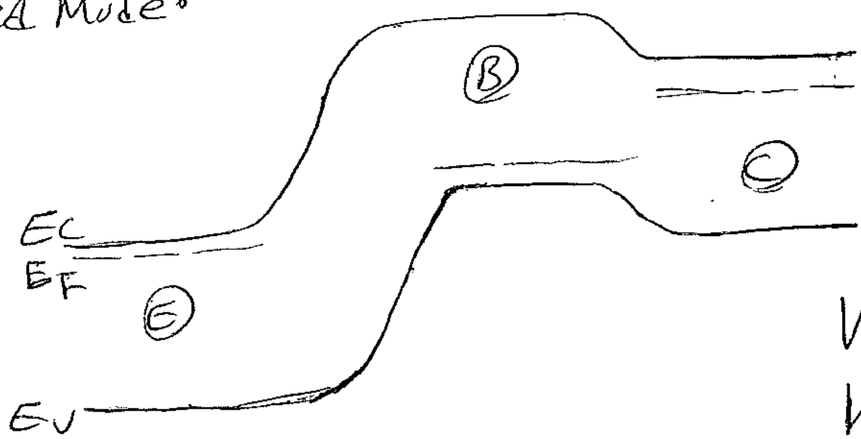
$V_{BE} > 0$

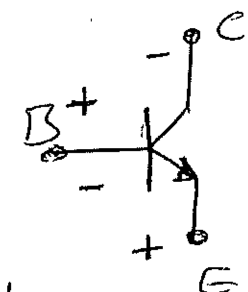
$V_{BC} < 0$





Inverted Mode:

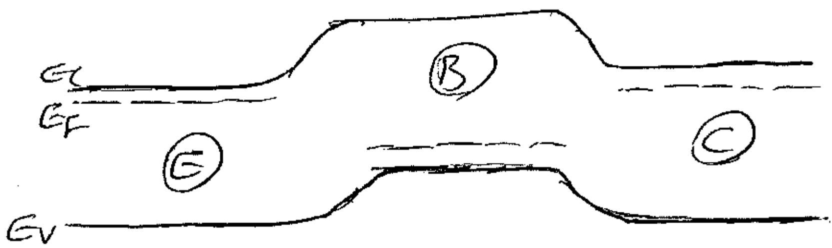


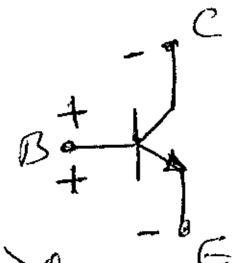


$V_{BE} < 0$

$V_{BC} > 0$

Saturation Mode:

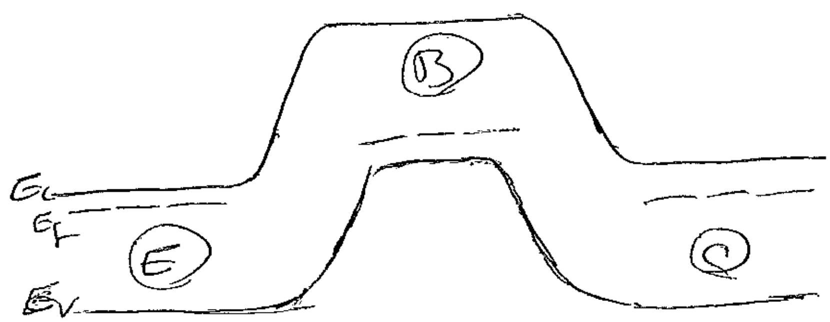


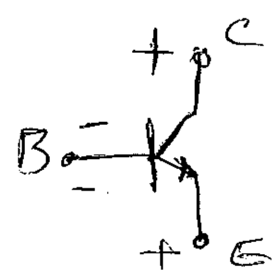


$V_{BE} > 0$

$V_{BC} > 0$

Cutoff Mode:

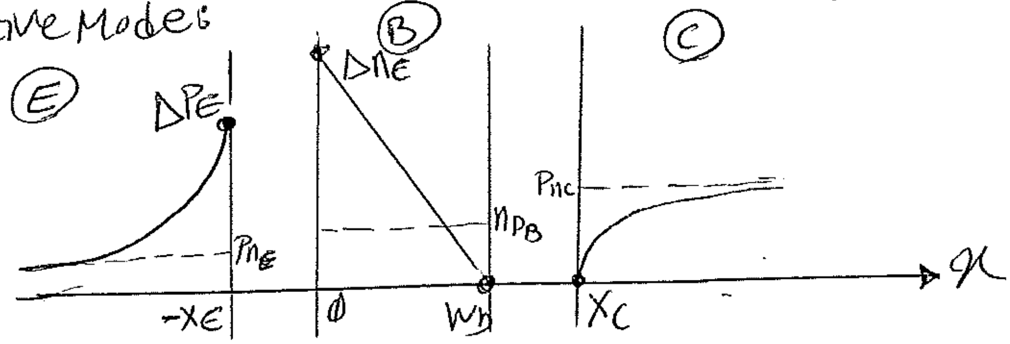




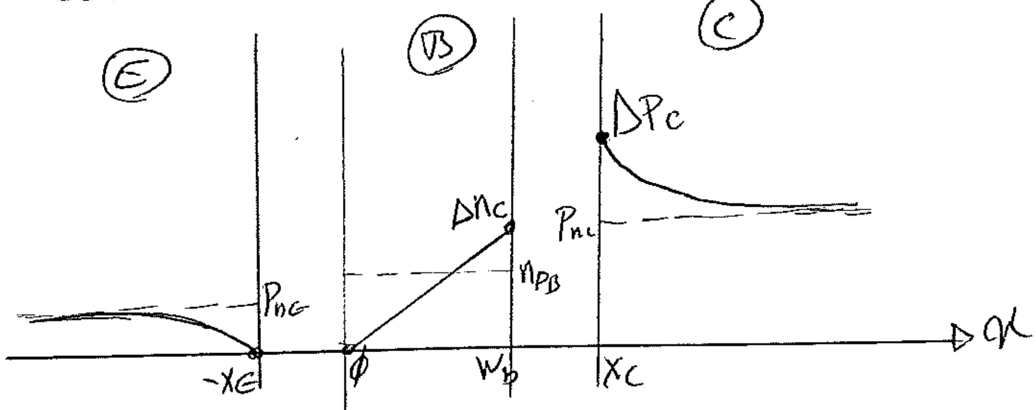
f) Sketch the minority carrier concentration versus position (x) inside the emitter, base and collector neutral regions under active normal, inverted, saturation and cutoff modes. Assume W_E & W_C >> L_p and W_b << L_n.

n^+pn^-

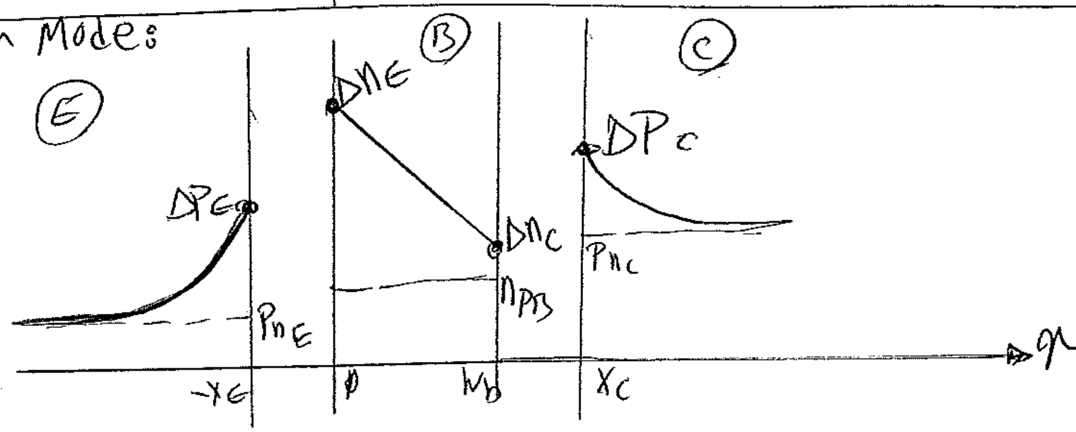
Normal Active Mode:



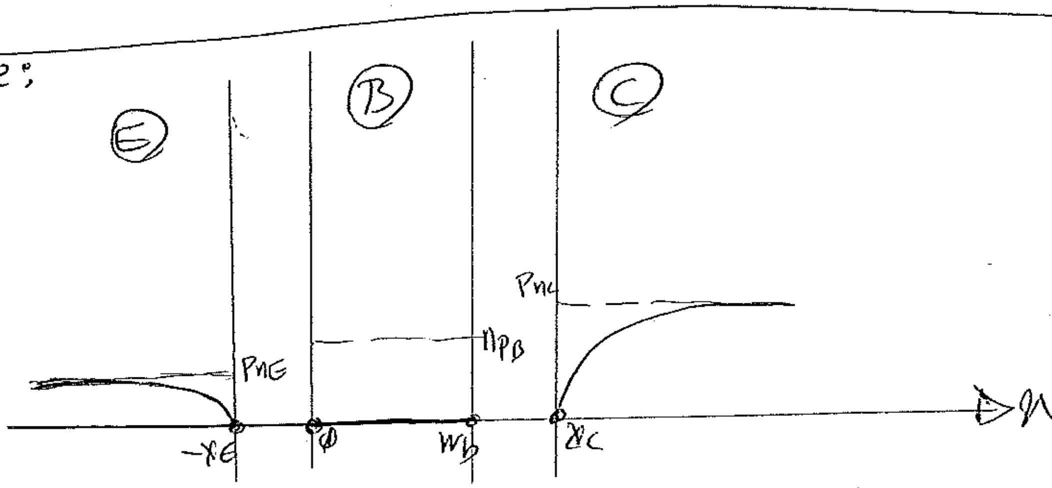
Inverted Mode:



Saturation Mode:



Cutoff Mode:



(3) Two identical npn BJT transistors made from a semiconductor material are displayed in Fig. 3 except the emitter and collector doping are interchanged. Assume $\mu_n=\mu_p$ and $\tau_n=\tau_p$. [13 points]

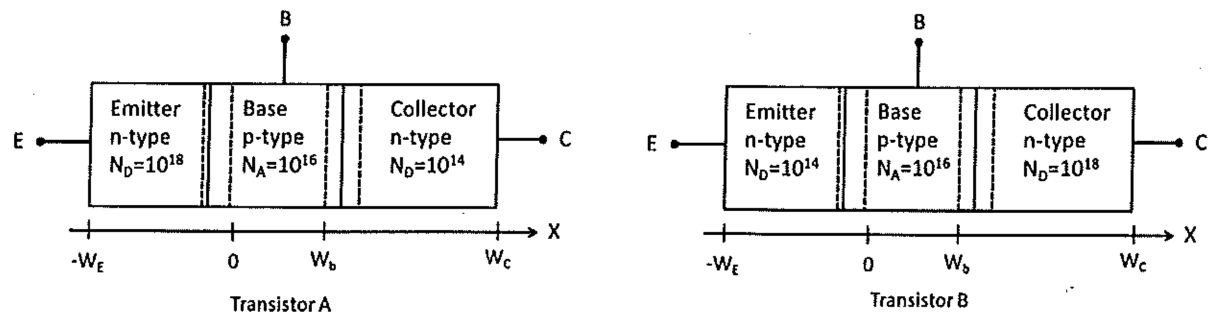


Fig. 3: Schematic of two npn transistors

a) Which transistor has higher emitter current (I_E) and emitter efficiency (γ)? Explain. $\gamma = \frac{I_{EN}}{I_{EP}+I_{EN}}$ (nPn)

Since transistor A has much higher doping in emitter compared to Base $\Rightarrow I_{Ep} \ll I_{EN}$ in transistor A

In transistor B, $N_{DE} \ll N_{AE} \Rightarrow I_{Ep} \gg I_{EN}$ in transistor B $\Rightarrow \gamma_A \gg \gamma_B$

since both transistor have similar base doping $\Rightarrow I_{EN}$ is the same but $I_{Ep}(B) > I_{Ep}(B)$ $\Rightarrow I_E(B) > I_E(A$

b) Which transistor is sensitive more to base width modulation under active mode biasing? Explain.

Transistor B is more sensetive to base width modulation since $N_{AB} \ll N_{DC}$ for transistor B $\Rightarrow$ Most depletion region will be inside the base for transistor B while in transistor A most depletion region will be in collector instead of base region. Hence transistor A looks more close to ideal transistor or less sensetive to base width mod.

c) Which transistor has the larger avalanche breakdown for C-B junction (V_{CBO})? Explain.

It can be shown that V_{CBO} is roughly inversly proportional to the doping on the lightly-doped side of the pn junction.

or think about the reverse biase BC as a capacitor.

$\Rightarrow \vec{E} \propto \left|\frac{V}{W}\right|$ (electric field; depletion width)

Now at breakdown $V \simeq V_{Br}$ and $\vec{E} = E_{cr} \simeq 10^7$ V/cm

$\Rightarrow V_{Br} \simeq E_{cr} \times W \Rightarrow$ transistor A has much lower lightly doped $\Rightarrow W_A \gg W_B \Rightarrow V_{Br}(A) \gg V_{Br}(B)$

(4) A simple pnp transistor is shown in Fig. 4. In this transistor, we leave the base contact open (I_B=0); hence, the magnitude of collector and emitter current are equal (I_E=I_C). Assume base emitter junction is forward biased and base collector junction is reverse biased such that $\exp(V_{CB}/kT) \approx 0$. Consider uniform light with the rate of (G_0) shining only on the neutral base region with low-level injection. Generation-recombination inside both depletion regions can be ignored. [30 points]

since $W_b \ll L_B$ ⇒ no recombination in base region $\frac{\delta p(n)}{\tau_B} \approx 0$ in base.

$\left|\frac{W_C}{L_C}\right| \Rightarrow \infty$ $\left|\frac{W_E}{L_E}\right| \Rightarrow \infty$ or W_C and W_E are too long and go to ∞.

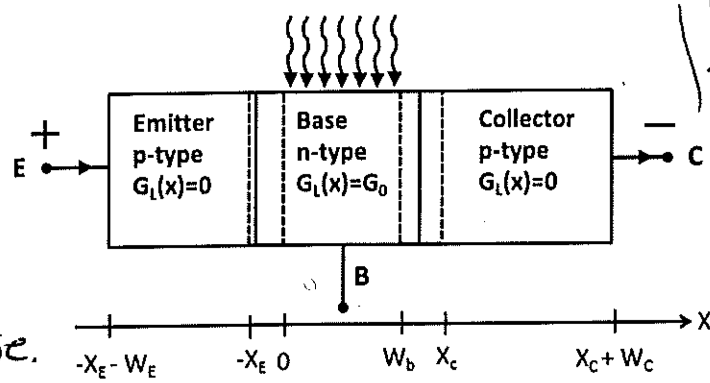
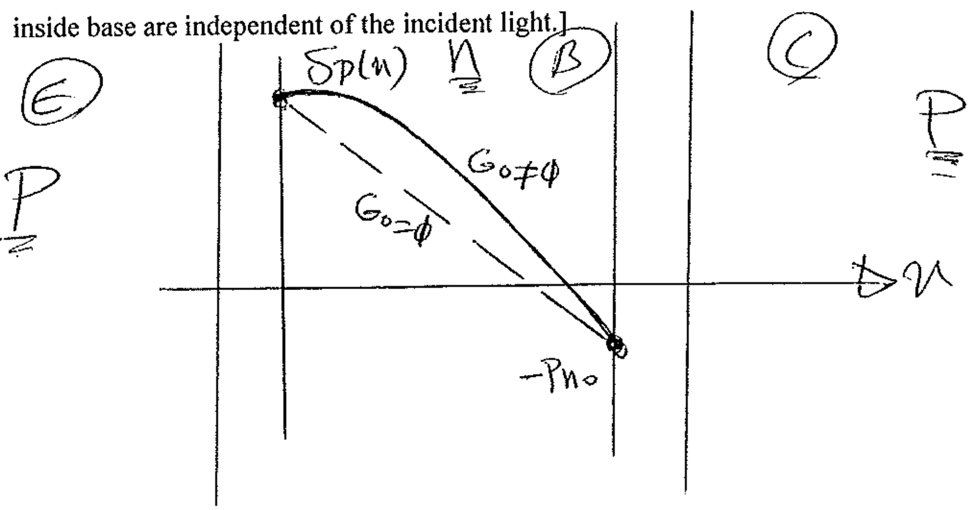


Fig. 4: Schematic of a pnp phototransistor

	Emitter	Base	Collector
Doping (cm^{-3})	N_E	N_B	N_C
Minority carrier life time	τ_E	τ_B	τ_C
Minority carrier mobility	D_E	D_B	D_C
Diffusion length	$L_E \ll W_E$	$L_B \gg W_b$	$L_C \ll W_C$

a) Sketch the minority carrier concentration inside the base neutral region for both no light (G_0=0) and with light (G_0) cases in the same graph. [Hint: Assume the boundary condition values at the edge of the depletion region inside base are independent of the incident light.]



b) Solve the minority carrier diffusion equation in steady-state inside emitter, base and collector with appropriate boundary conditions at the edge of space-charge regions and show that the minority carrier currents at the edge of the space-charge regions are:

$$I_n(-X_E) = I_{E0}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) \quad \& \quad I_p(0) = I_{B0}\left(e^{\frac{qV_{EB}}{kT}}\right) - \frac{I_L}{2}$$

$$I_p(W_b) = I_{B0}\left(e^{\frac{qV_{EB}}{kT}}\right) + \frac{I_L}{2} \quad \& \quad I_n(X_C) = I_{C0}$$

Find I_{E0}, I_{B0}, I_{C0}, and I_L in terms of G_0, ni^2, q, A and the given device parameters.

Minority carrier diffusion equations in steady-state:

$D_n\, \partial^2\delta n(x)/\partial x^2 - \delta n(x)/\tau_n + G_L(x) = 0$ & $D_p\, \partial^2\delta p(x)/\partial x^2 - \delta p(x)/\tau_p + G_L(x) = 0$

Emitter: $D_E \frac{d^2 \delta n(x)}{dx^2} = \frac{\delta n(x)}{\tau_E}$ since $G_L = \phi$

$\Rightarrow \delta n_E(x) = C_1 e^{-x/L_E} + C_2 e^{+x/L_E}$ $L_E = \sqrt{D_E \tau_E}$

we know that $\delta n_E(x = \underbrace{-X_E - W_E}_{\to -\infty}) = \phi \Rightarrow C_1$ must be zero

$\Rightarrow \delta n_E(x) = C_2 e^{+x/L_E}$ for $-X_E - W_E < x < -X_E$

B.C. at $x = -X_E \Rightarrow \delta n_E(x = -X_E) = \Delta P_E$

$\Rightarrow \boxed{\delta n_E(x) = \Delta P_E\, e^{\frac{(x + X_E)}{L_E}}}$ $\Delta n_E = n_{P_E}\left(e^{\frac{qV_{EB}}{kT}} - 1\right)$

$\Rightarrow I_n(x = -X_E) = A q D_E \frac{d\,\delta n_E(x)}{dx} = \frac{q D_E}{L_E} \Delta n_E \times A \Rightarrow$

$I_n(x = -X_E) = \frac{qAD_E}{L_E} n_{P_E}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) = I_{E0}\left(e^{\frac{qV_{EB}}{kT}} - 1\right)$

$\Rightarrow \boxed{I_{E0} = \frac{qAD_E}{L_E} n_{P_E}}$

Collector: $G_L(x) = 0 \Rightarrow \frac{d^2 \delta n_C(x)}{dx^2} = \frac{\delta n_C(x)}{L_C^2}$ $L_C = \sqrt{D_C \tau_C}$

$\Rightarrow \delta n_C(x) = C_1 e^{-x/L_C} + C_2 e^{x/L_C}$

B.C. $\delta n_C(x = X_C + W_C) = 0$ ($X_C + W_C \to \infty$) $\Rightarrow C_2$ must be zero $\Rightarrow$

$\delta n_C(x) = C_1 e^{-x/L_C}$ also $\delta n_C(x = X_C) = \Delta n_C = n_{pC}(e^{qV_{CB}/kT} - 1)$ ($e^{qV_{CB}/kT} \to 0$)

or $\delta n_C(x = X_C) \cong -n_{pC} \Rightarrow$ $\boxed{\delta n_C(x) = -n_{pC} e^{\frac{X_C - x}{L_C}}}$

$\Rightarrow I_n(x = X_C) = qAD_C \frac{d\,\delta n_C(x)}{dx} \Rightarrow I_n(x = X_C) = \frac{qAD_C}{L_C} n_{pC} = I_{C0}$

$\Rightarrow \boxed{I_{C0} = \frac{qAD_C}{L_C} n_{pC}}$

Base: $G_L(x) = G_0$ but $\frac{\delta p_B(x)}{\tau_B} = 0 \Rightarrow D_B \frac{d^2 \delta p_B(x)}{dx^2} = -G_0$

$\Rightarrow \delta p_B(x) = -\frac{G_0}{2D_B} x^2 + C_3 x + C_4$

Boundary conditions: $\delta p(x = 0) = \Delta P_E = P_n(e^{qV_{EB}/kT} - 1)$

$\delta p(x = W_b) = \Delta P_C = P_n(e^{qV_{CB}/kT} - 1) = -P_n$

$\Rightarrow C_4 = P_n(e^{qV_{EB}/kT} - 1)$ and $C_3 = \frac{G_0 W_b}{2D_B} - \frac{P_n}{W_b} e^{qV_{EB}/kT}$

$\Rightarrow I_p(x = 0) = -qAD_B \frac{d\,\delta p(x)}{dx}\Big|_{x=0} = -qAD_B C_3 \Rightarrow$

$I_p(x = 0) = \frac{qAD_B P_n}{W_b} e^{qV_{EB}/kT} - \frac{qAG_0 W_b}{2} \Rightarrow$ $\boxed{I_{B0} = \frac{qAD_B P_n}{W_b}}$ $\boxed{I_L = qAG_0 W_b}$

$I_p(x = W_b) = -qAD_B \frac{d\,\delta p(x)}{dx}\Big|_{x=W_b} \Rightarrow I_p(x = W_b) = -qAD_B\left[-\frac{G_0 W_b}{D_B} + C_3\right]$

$\Rightarrow I_p(x = W_b) = \frac{qAD_B}{W_b} P_n e^{qV_{EB}/kT} + \frac{qAG_0 W_b}{2}$

c) Express the transistor current (I_E or I_C) in terms of I_{E0}, I_{B0}, I_{C0}, and I_L only [$I = f(I_{E0}, I_{B0}, I_{C0}, I_L)$]. Plot the current versus V_{EC} at different optical generation rate (G_0) values (output characteristics) neglect any non-ideality such as base narrowing.

$I_E = I_C$

$I_E = I_{Ep} + I_{En} = I_p(0) + I_n(-x_E)$

$I_C = I_{Cp} + I_{Cn} = I_n(x_C) + I_p(W_b)$

$\Rightarrow I_E = I_{E0}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + I_{B0}\, e^{\left(\frac{qV_{EB}}{kT}\right)} - \frac{I_L}{2}$

$I_C = I_{B0}\, e^{\frac{qV_{EB}}{kT}} + \frac{I_L}{2} + I_{e0}$

Since $I_E = I_e \Rightarrow I_{E0}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + I_{B0}\, e^{\frac{qV_{EB}}{kT}} - \frac{I_L}{2}$

$= I_{B0}\, e^{\frac{qV_{EB}}{kT}} + \frac{I_L}{2} + I_{C0}$

$\Rightarrow \boxed{e^{\frac{qV_{EB}}{kT}} = 1 + \frac{I_L + I_{C0}}{I_{E0}}} \Rightarrow$

$$\boxed{I_E = I_C = I_{B0}\left(1 + \frac{I_L + I_{C0}}{I_{E0}}\right) + \frac{I_L}{2} + I_{C0}}$$ ✓

$I_L = qAG_0W_b$