EE 566 - SOLID STATE DEVICES

SPRING 2004

ASSIGNMENT 6: SOLUTIONS

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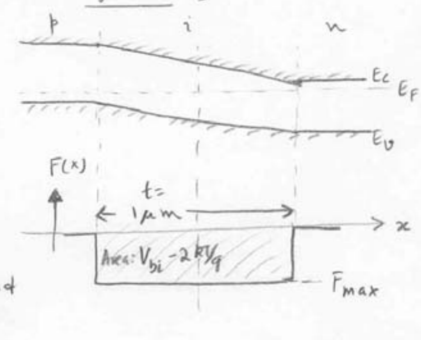
## PROBLEM 1

At $V_f = 0$,

ⓐ




Ignored spikes @ depletion edges & Δs at sides.

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.86\,V$$

$$F_{max} * t = V_{bi} - 2\frac{kT}{q}$$

With applied bias $V_f$, area decreases ⇒

$$F_{max} \approx \frac{\left(V_{bi} - 2\frac{kT}{q}\right) - V_f}{t} = \boxed{8*10^3 - 10^4 V_f\ (V/cm)}$$

Avg. electric field @ $V_f$ forward bias

ⓑ $$J_{rec} = q\int dx\,|R-G| = \frac{\pi}{2}\left(\frac{q n_i}{\tau_0}\right)\left(\frac{kT}{qF_{max}}\right)\exp\left(\frac{qV_f}{2kT}\right)$$ ← Done in class.

$\tau_p = \tau_n \approx \tau_0$

$$\boxed{J_{rec}(V_f) = \left(\frac{8.7}{8*10^3 - 10^4 V_f}\right)\exp\left(\frac{qV_f}{2kT}\right)\ \frac{\mu A}{cm^2}}$$

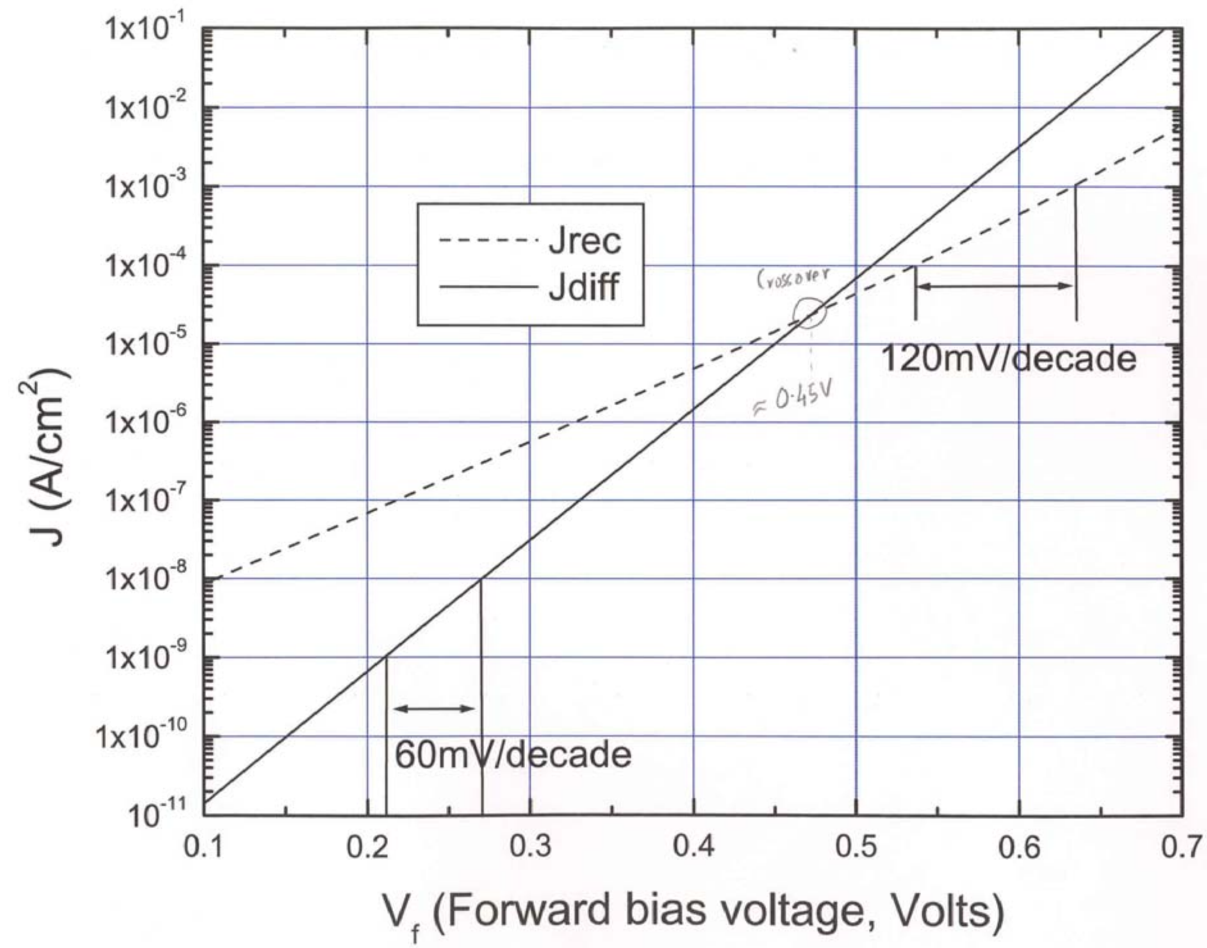
ⓒ $$J_{diff} = q\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)\left(e^{\frac{qV_f}{kT}} - 1\right)$$

$$\boxed{J_{diff}(V_f) = 3*10^{-13}\exp\left(\frac{qV_f}{kT}\right)\ A/cm^2}$$

ⓓ See plot in next page.

Important - remember!! $\begin{cases} \log_{10}(J_{diff}) \text{ has slope } \frac{kT}{q}\ln 10 = 60\,mV/\text{decade}. \\ \log_{10}(J_{rec}) \text{ has slope } 2*\frac{kT}{q}\ln 10 = 120\,mV/\text{decade} \end{cases}$

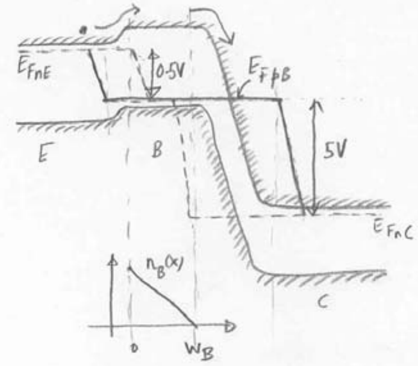
$J_{diff}$, $J_{rec}$ cross @ $V_f \approx 0.45\,V$.



Jrec
Jdiff
Crossover
≈ 0.45V
120mV/decade
60mV/decade
1x10^-1
1x10^-2
1x10^-3
1x10^-4
1x10^-5
1x10^-6
1x10^-7
1x10^-8
1x10^-9
1x10^-10
10^-11
0.1
0.2
0.3
0.4
0.5
0.6
0.7
J (A/cm^2)
V_f (Forward bias voltage, Volts)

## PROBLEM 2

a)




$W_B = 0.5\,\mu m$

$L_n$ (Minority carrier diff. length in the base)

$= \sqrt{D_n \tau_n} = \sqrt{\left(\mu_n \cdot \frac{kT}{q}\right) \cdot \tau_n}$

$\approx 44\,\mu m$

$W_B << L_n \Rightarrow$ exponentials can be approximated by straight line (linear approximation).

$$n_B(x) = n_{po} \exp\left(\frac{qV_{BE}}{kT}\right)\left(1 - \frac{x}{W_B}\right)$$

$$= N_c \exp\left(-\frac{E_C - E_{Fn}(x)}{kT}\right) \quad E_c \text{ is flat!}$$

$$\therefore \quad E_{F_n}(x) = \underbrace{E_C + kT \ln\left(\frac{n_{po}}{N_C} \exp\left(\frac{qV_{BE}}{kT}\right)\right)}_{\text{Constant, } E_{F_n}(0)} + kT \ln\left(1 - \frac{x}{W_B}\right)$$

$$E_{F_n}(x) = E_{F_n}(0) + kT \ln\left(1 - \frac{x}{W_B}\right).$$

Close to emitter, $x << W_B$, $\ln(1+x) \approx x$

$$\Rightarrow \quad \boxed{E_{F_n}(x) \simeq E_{F_n}(0) - kT \cdot \frac{x}{W_B}}$$

QFL is a LINEAR function near the emitter!!

b)

$$\boxed{GN_B = \int_0^{W_B} dx\, N_{A_B}(x) = 5 * 10^{12}/cm^2}$$

In the emitter, $L_p = \sqrt{D_p \tau_p} \approx 25\,\mu m >> W_E = 2\,\mu m$.

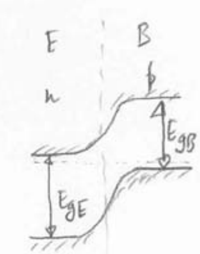
$\Rightarrow$ SHORT EMITTER.

$$\boxed{GN_E = \int_0^{W_E} dx\, N_{DE}(x) = 2 * 10^{15}/cm^2}$$

Prob. 2 contd...

(4)

(c) Neglecting bandgap narrowing in emitter,




Heavy doping
⇓
Band Gap Narrowing
$\boxed{\Delta E_g = 71\text{ meV}}$

$$\gamma_E = \frac{1}{1 + \frac{D_{pE}}{D_{nB}}\frac{GN_B}{GN_E}\frac{n_{iE}^2}{n_{iB}^2}} = \boxed{0.99925} \qquad \frac{n_{iE}^2}{n_{iB}^2} = 1$$

$$\alpha_T = 1 - \frac{W_B^2}{2L_n^2} = \boxed{0.999936}$$

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{\gamma_E \alpha_T}{1-\gamma_E\alpha_T} \approx \boxed{1228}$$

Including bandgap narrowing in emitter, ($\Delta E_g = 71$ meV)

$$\gamma_E = \frac{1}{1 + \frac{D_{pE}}{D_{nB}}\frac{GN_B}{GN_E}\exp(-\frac{\Delta E_g}{kT})} = \boxed{0.9885}$$

$\alpha_T$ remains the same.

$\beta_F \approx \boxed{86}$ ← Heavily lowered!!

(d) After including bandgap Narrowing ...

$$|J_C| = \frac{q D_n n_{iB}^2}{GN_B}\exp\left(\frac{qV_{BE}}{kT}\right) = 12.5\text{ mA/cm}^2$$

$$|J_{pE}| = \frac{q D_p n_{iE}^2}{GN_E}\exp\left(\frac{qV_{BE}}{kT}\right) = 0.15\text{ mA/cm}^2$$

$$|J_{rec}^B| = \frac{q n_{iB}^2 W_B}{2\tau_n N_A}\exp\left(\frac{qV_{BE}}{kT}\right) = 0.0008\text{ mA/cm}^2$$

$|J_B| = |J_{pE}| + |J_{rec}^B| = 0.1448\text{ mA/cm}^2$ ;

$\left|\frac{J_C}{J_B}\right| \approx 86 = \beta_F$ (verified)!

$\left|\frac{J_{pE}}{J_B}\right| \approx 99.4$, $\left|\frac{J_{rec}^B}{J_B}\right| \approx 0.6$ } > 99% of base current contributes to reverse-injection of holes into emitter!!