EE566 Solid State Devices

Spring 2006
Dept of Electrical Engineering
University of Notre Dame
Instructor: Debdeep Jena (djena@nd.edu, x8835)

Assignment 4
SOLUTIONS

Problem 1

EE 566 Assignment 4 Xiu Xing

oblem 1
(4.27)

For an abrupt p^+n diode, which means $N_A \gg N_D$

Since $\frac{x_p}{x_n} = \left(\frac{N_D}{N_A}\right)$, $x_n \gg x_p$

$F_{max} = \frac{q N_D x_n}{\varepsilon_s}$, $x_n = \left\{\frac{2\varepsilon_s(V_{bi}+V_r)}{q}\left[\frac{N_A}{N_D(N_A+N_D)}\right]\right\}^{1/2} \simeq \left[\frac{2\varepsilon_s}{q N_D}(V_{bi}+V_r)\right]^{1/2}$

where V_r is the reverse-bias voltage.

Consider $V_r = V_{BD}$ (Break down voltage) $\gg V_{bi}$, $F_{max} = F_{crit}$

$$x_n \simeq \left[\frac{2\varepsilon_s}{q N_D} V_{BD}\right]^{1/2} = \frac{F_{max}\varepsilon_s}{q N_D}$$

Thus $V_{BD} = \frac{F_{crit}^2 \varepsilon_s}{2 q N_D}$, $N_D = \frac{F_{crit}^2 \varepsilon_s}{2 q V_{BD}}$

Since $\varepsilon_s(Si) = 11.8\,\varepsilon_0$, $F_{crit} = 4\times10^5\ V/cm$

We have $N_D = \frac{16\times10^{10}\ V^2/cm^2 \cdot 11.8 \times 8.85\times10^{-14}\ F/cm}{2\times1.6\times10^{-19}C \cdot 30V}$

$= 17.405\times10^{15}\ cm^{-3}$

Problem 2

Problem 2 (4.31)

In p^+-n-n^+ case, the added n-region help to increase the thickness of depletion region. Since in the left p^+-n diode, $N_A \gg N_D$ leads to $x_p \ll x_n$, and the length of n-region L should be less than the depletion region width at breakdown, we can consider when $x_n = L$, the breakdown happens.

We've got $x_n = \left[\frac{2\varepsilon_s}{qN_D} V_{BD}\right]^{1/2}$ for one-side abrupt diode.

Thus $V_{BD} = \frac{x_n^2 q N_D}{2\varepsilon_s}$ $\quad N_D = 10^{14}\ cm^{-3}$

When $x_{n1} = L_1 = 150\mu m$

$$V_{BD1} = \frac{22500 \times 10^{-8} cm^2 \times 1.6 \times 10^{-19} C \times 10^{14} cm^{-3}}{2 \times 11.8 \times 8.85 \times 10^{-14} F/cm}$$

$$= 1723.64\ V \simeq 1.724\ kV$$

When $x_{n2} = L_2 = 80\mu m$

$$V_{BD2} = \frac{V_{BD1}}{x_{n1}^2} \cdot x_{n2}^2 = 490.28\ V$$

Problem 3

Since $N_a = N_d = 10^{18}/cm^3$

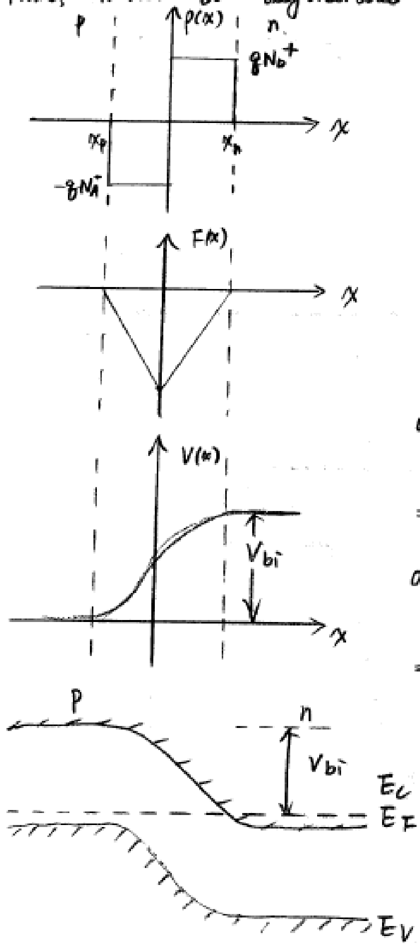
roblem 3 For GaAs, $N_c = 4.7\times10^{17}\,cm^{-3}$, $N_v = 9.0\times10^{18}\,cm^{-3}$

(a) In the Neutral region of this pn junction,

at p-side, $p \approx N_A = 10^{18}/cm^3 = N_v e^{-\frac{E_F - E_V}{kT}} \Rightarrow E_F > E_V$

at n-side, $n \simeq N_D = 10^{18}/cm^3 = N_c e^{-\frac{E_c - E_F}{kT}} \Rightarrow E_F > E_C$

Thus, n-side is degenerate semiconductor.



$N_D x_n = x_p N_A$

Since $N_D = N_A$

$x_n = x_p$

$$\frac{dF(x)}{dx} = \frac{\rho(x)}{\varepsilon_s}$$

$$F(x) = \frac{1}{\varepsilon_s}\int_{-\infty}^{x} \rho(x)\,dx$$

$$F_{max} = \frac{qN_D}{\varepsilon_s} x_n$$

at n-side,

$$n = N_D = N_c \mathcal{F}_{1/2}(\eta) \qquad \eta = \frac{E_F - E_c}{kT}$$

$$\Rightarrow E_c^n = E_F - kT\mathcal{F}_{1/2}^{-1}\left(\frac{N_D}{N_c}\right)$$

at p-side.

$$p = N_A = N_v \exp\left(\frac{E_V^p - E_F}{kT}\right) \Rightarrow E_V^p = E_F + kT\ln\frac{N_A}{N_V}$$

$$\Rightarrow qV_{bi} = E_c^p - E_c^n$$

$$= E_V^p + E_g - E_c^n$$

$$= 1.424eV + kT\ln\left(\frac{N_A}{N_V}\right) + kT\mathcal{F}_{1/2}^{-1}\left(\frac{N_D}{N_c}\right)$$

$$= 1.424 + 0.026\left(\cancel{\ln 1} - \ln 9 + \mathcal{F}_{1/2}^{-1}(2.1277)\right)$$

$$= 1.424 + 0.026\,(2.1972 + 1.49)$$

$$= 1.52\,V$$

$$x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\cdot\frac{2}{N_A}\cdot V_{bi}}$$

$$= 65.87\,nm$$

$$F_{max} = \frac{qN_D}{\varepsilon_s}\frac{W}{2} = 4.62\times10^{5}\,V/cm$$

EE566 Solid State Device

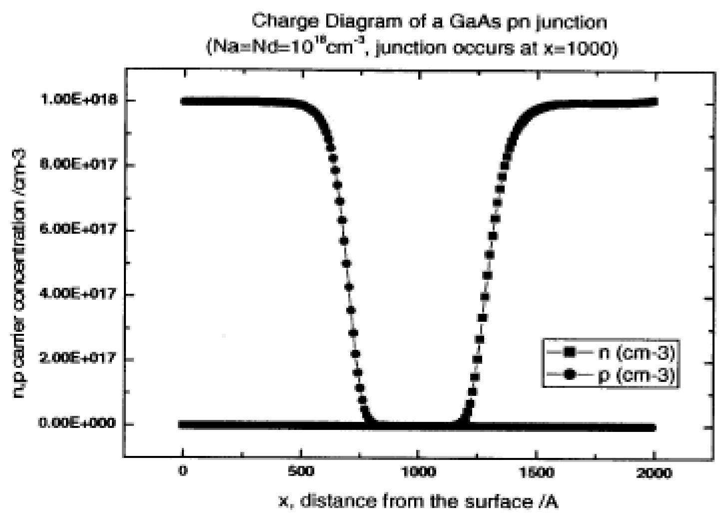
Xiu Xing

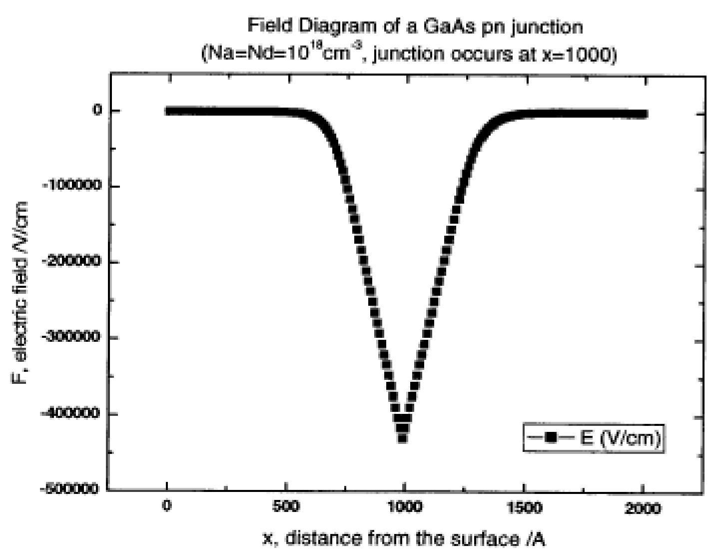
Assignment 4

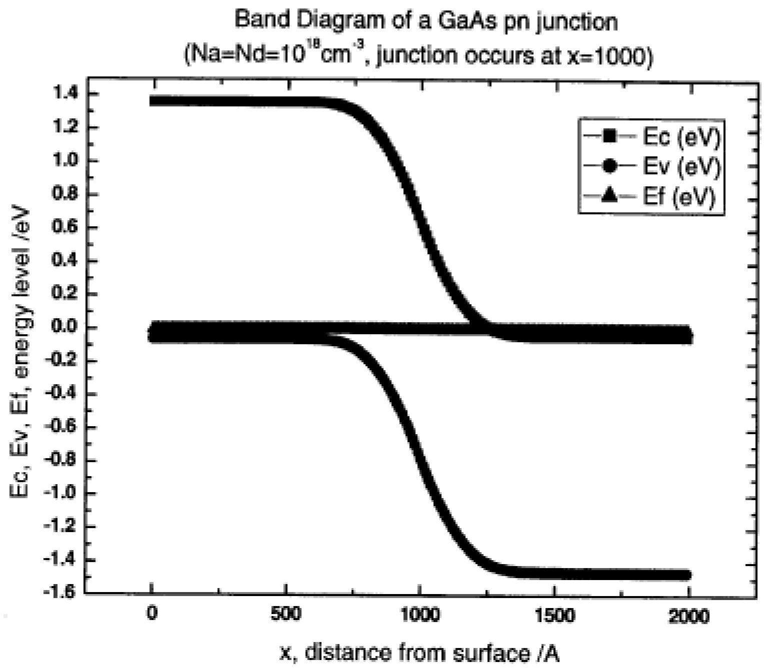
Feb.20, 2006

Problem 3

(a) It seems almost the same as calculated previously.





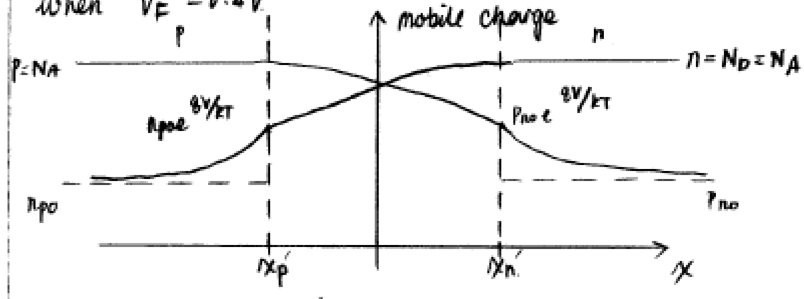


Band Diagram of a GaAs pn junction
(Na=Nd=10^18cm^-3, junction occurs at x=1000)
Ec (eV)
Ev (eV)
Ef (eV)
Ec, Ev, Ef, energy level /eV
x, distance from surface /A
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
0
500
1000
1500
2000

(b) In semiconductor is degenerate, the p-n junction may be tunneling diode under forward bias.

But it seems only n-side degenerate will not lead to this?

when $V_F = 0.4V$



where $N_A = N_D = 10^{18} cm^{-3}$

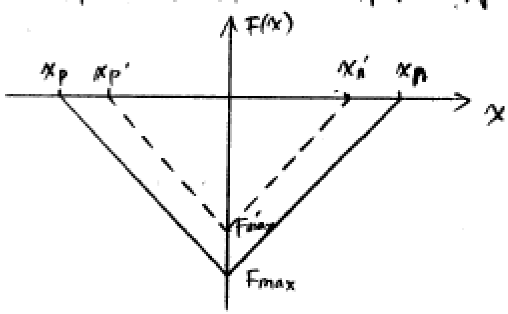
$n_{p0} = p_{n0} = \frac{n_i^2}{N_A} = \frac{(2.25\times10^6)^2}{10^{18}} = 3.06\times10^{-6} cm^{-3}$

$V = V_F = 0.4V$

$kT = 0.026 eV$

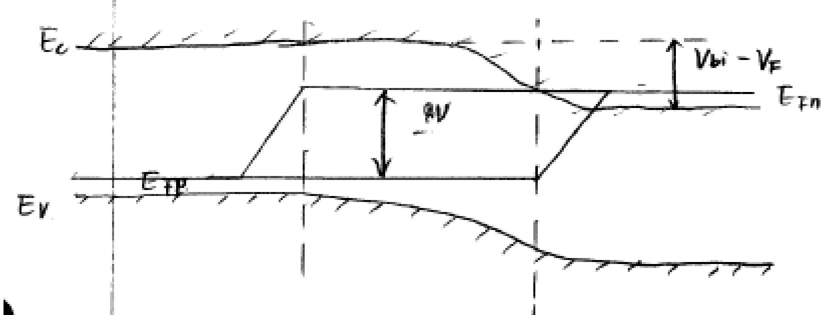
$x_p' + x_n' = \sqrt{\frac{2\varepsilon_s}{q}\cdot\frac{2}{N_A}\cdot(V_{bi}-V_F)} = 56.54 nm$

(c)



Under forward bias, depletion region will decrease and F_{max}' will decrease, too the ~~deducted~~ reduced area is $V_F = 0.4V$.

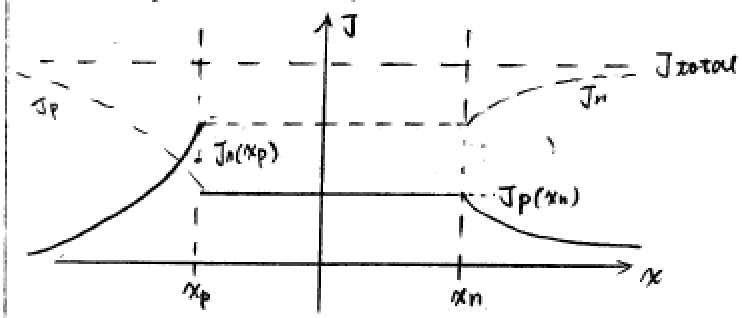
$F_{max}' = \frac{qN_D}{\varepsilon_s}\frac{W'}{2} = 3.96\times10^5 V/cm$



(d) $J_p(x) = q\frac{D_p}{L_p} p_{no}(e^{qV/kT}-1)e^{-x/L_p}$

$J_n(x) = q\frac{D_n}{L_n} n_{po}(e^{qV/kT}-1)e^{-x/L_n}$

$J_{total} = q\left(\frac{D_n}{L_n} n_{po} + \frac{D_p}{L_p} p_{no}\right)(e^{qV/kT}-1)$



$$J_n(x_p) = q\frac{D_n}{L_n} n_{po}(e^{qV/kT}-1)$$

$$= q\sqrt{\frac{D_n}{\tau_n}}\, n_{po}(e^{qV/kT}-1) = 1.6\times10^{-19}C\sqrt{\frac{100\,cm^2/s}{10\times10^{-9}s}}\cdot 5.06\times10^{-6}cm^{-3}\, 4.78\times10^{6}$$

$$= 38.7\times10^{-19+5-6+3+3}\,C\cdot cm/s\cdot cm^3$$

$$= 3.87\times10^{-13}\ A/cm^2$$

$$J_p(x_n) = q\sqrt{\frac{D_p}{\tau_n}}\, p_{no}(e^{qV/kT}-1)$$

$$= 1.6\times10^{-19}C\sqrt{\frac{20\,cm^2/s}{10\times10^{-9}s}}\times 5.06\times10^{-6}cm^{-3}\times 4.78\times10^{6}$$

$$= 38.7\times10^{-20}\times 4.472\times10^{4+3}A/cm^2 = 1.73\times10^{-13}\ A/cm^2$$

$$J_{total} = 5.6\times10^{-13}\ A/cm^2.$$

Repeat for $V_R = -5V$

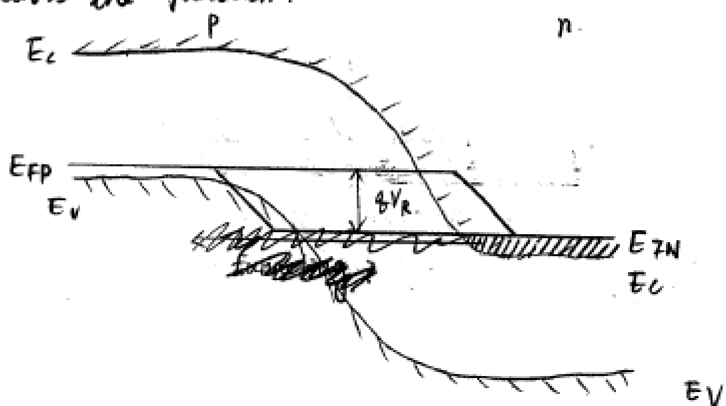
(e) $x_p'' + x_n'' = \sqrt{\frac{2\varepsilon_s}{q} \cdot \frac{2}{N_A} \cdot (V_{bi} + V_R)} \doteq 431.38\,nm$

$F''_{max} = \frac{qN_D}{\varepsilon_s} \cdot \frac{W}{2} = 3.02 \times \frac{C/cm^{-3} \cdot 10^{-8}cm}{10^{-14}F/cm} \cdot q = 3.02 \times 10^{6}\ V/cm$

$F''_{max} > F_{BD} = 400\ kV/cm$

This junction has broken down.

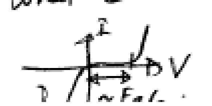
and carrier densities and electric field should be constant across the junction?



electrons will tunnel from the conduction band of n-side to the valence band of p-side? (NO)

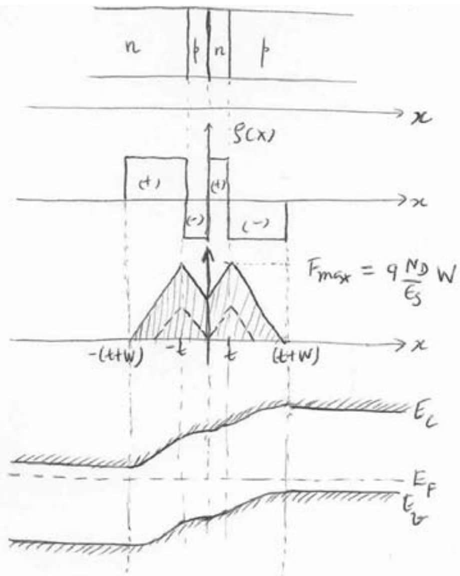
~~Sorry. I have not figured out the physical picture here. Say, when 0 bias, the junction is also "break-down", but it seems E_c^n is still above the E_V^p, so there is no tunneling?~~

Under the condition given, the zero-bias max. field @ the interface is already larger than the breakdown field of the semiconductor. Thus, the doping is too high in the n-side, and we form what can be referred to as a Backward diode'



Problem 4

(a)



$N_A = N_D = 10^{17}/cm^3.$

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = \underline{0.86 \text{ Volts.}}$$

(b) With Gummel correction,

$$V_{bi} = \text{Area under } F(x) - x \text{ curve} + 2\frac{kT}{q}.$$

$$\underbrace{V_{bi} - 2\frac{kT}{q}}_{\text{Gummel correction.}} = \text{Area under curve}$$

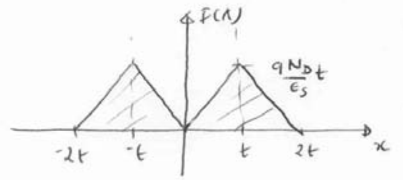
$$= \frac{q N_D W(t+W)}{\epsilon_s} - 2 * \frac{q N_D \cancel{2} t}{\cancel{2}\epsilon_s}$$

$$\therefore \quad W = \frac{1}{2}\left[\left\{t^2 + \frac{4\epsilon_s}{q N_D}\left(V_{bi} - 2\frac{kT}{q}\right)\right\}^{\frac{1}{2}} - t\right]$$

& Substituting $\begin{cases} V_{bi} = 0.86\,\text{Volts}, \quad \epsilon_s = 11.7\,\epsilon_0, \quad N_D = N_A = N_0 = 10^{17}/\text{cm}^3, \\ t = 40\,\text{nm} \end{cases}$ ②

$$\boxed{W = 52.3\,\text{nm}}$$

ⓒ Again, $F(x=0) = 0$ when the area under the $F(x)-x$ curve is



$$\underbrace{\left(V_{bi} - 2\frac{kT}{q}\right)} - V_F = 2 * \frac{1}{2} * 2t * \frac{qN_D t}{\epsilon_s}$$

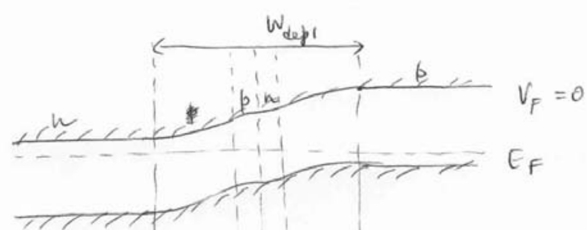
$$= \frac{2qN_D}{\epsilon_s} t^2$$

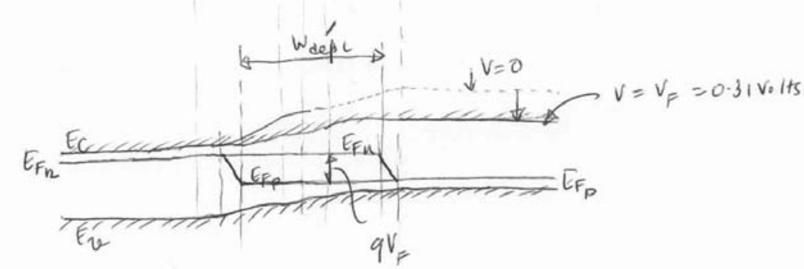
$$\approx 0.5\,V$$

$$\Rightarrow \quad \boxed{V_F \approx 0.31\,\text{Volts}}$$

It is of course forward-bias, since area under the curve (total potential) decreases.

ⓓ





e $\quad J = J_S \left(e^{qV/kT} - 1\right)$

Remains the same as a p-n junction with dopings $N_A = N_D = N_0$

Since current in an ideal diode is completely determined by the currents @ the depletion edge!

$$\therefore \quad J_S = q\left(\frac{D_n \overset{n_i^2/N_A}{n_{p0}}}{\underset{\sqrt{D_n \tau_n}}{L_n}} + \frac{D_p \overset{n_i^2/N_D}{p_{n0}}}{\underset{\sqrt{D_p \tau_p}}{L_p}} \right)$$

Plug in all #s $\Rightarrow$ $\boxed{J \approx 33 \text{ nA/cm}^2}$