ASSIGNMENT 4 SOLUTIONS

PROBLEM 1 SOLUTION

(a) $V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = \boxed{1.22\ V}$

$W = \left[\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) V_{bi}\right]^{1/2} \approx \boxed{440\text{nm}}$

Since $\frac{N_A}{N_D} = 10$, $x_n = \frac{1}{1+10} * W \approx \boxed{40\text{nm}}$

$x_p = \frac{10}{1+10} * W \approx \boxed{400\text{nm}}$ $\quad x_p \sim 10\, x_n$

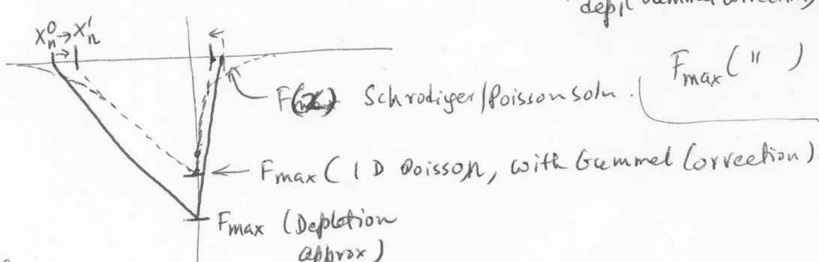
$F_{max} = \frac{2 V_{bi}}{W} \approx \boxed{55.5\ \text{kV/cm}}$

$\ll F_{breakdown} = 400$ kV/cm.

$C_{depl} = \frac{\epsilon_s}{W} \approx \boxed{26\ \text{nF/cm}^2}$

Sketches & Plots: Next pages by QIN.

(b) Plots - next pages.

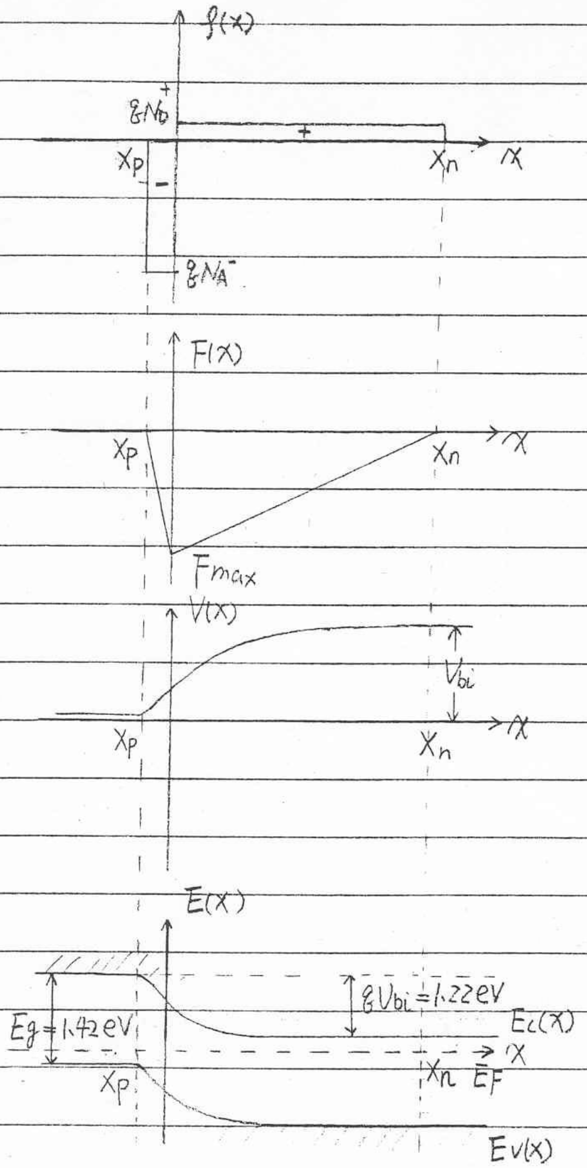


Sketch (Exaggerated)

W_{depl}(Gummel Correction) < W_{depl}(Depl. approx)

F_{max}(") < F_{max}(")

BUT: V_{bi} remains the SAME!!

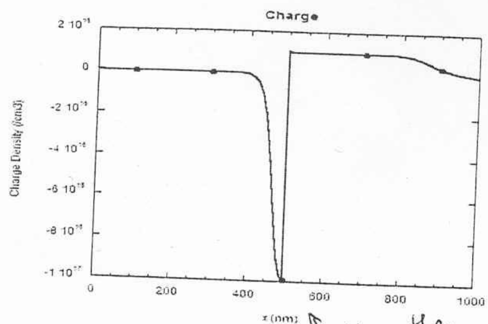


ρ(x)
qN_D^+
+
x
X_p
X_n
−
qN_A^-
F(x)
x
X_p
X_n
Fmax
V(x)
V_bi
x
X_p
X_n
E(x)
qV_bi = 1.22eV
Ec(x)
Eg = 1.42eV
x
X_p
X_n
E_F
Ev(x)

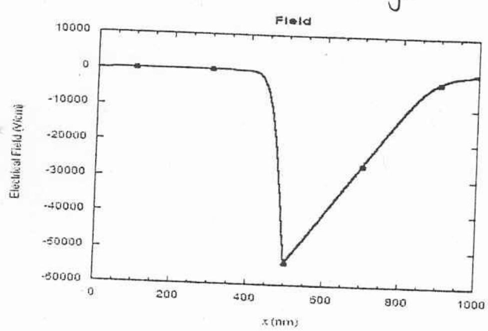
Plot - by Qin.

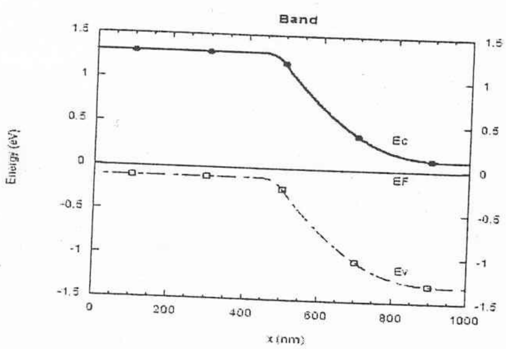
③

Plot - by Qin



Use the junction as x = 0.





PROBLEM 2 SOLUTION

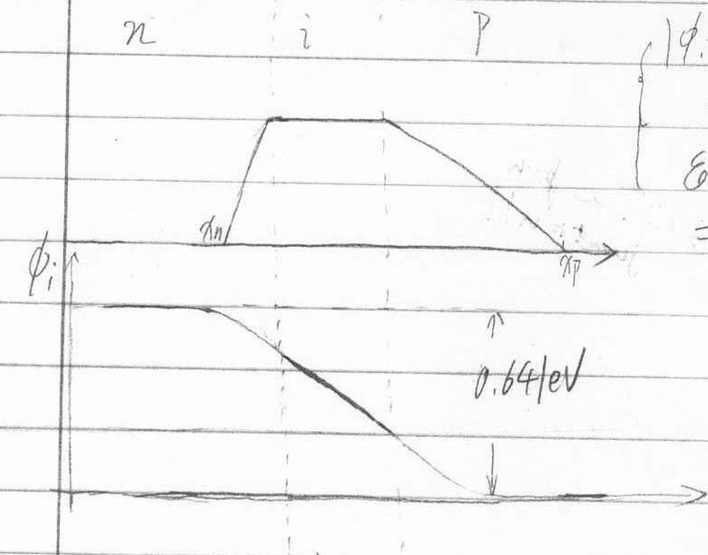
MKC 4.5 a) From the figure, we can consider the case as abrupt junction.

Consider in n-region $N_D = 1\times10^{16}$, in p-region $N_A = 0.5\times10^{15}$

$q\phi_i = kT\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$

$= 0.026 \cdot \ln\left(\frac{10^{16}\times 10^{15}}{(1.4\times10^{10})^2}\right) = 0.641eV$

$\therefore \phi_i = 0.641V$



$$\begin{cases} |\phi_i| = \frac{1}{2}x_n \cdot E_{max} + E_{max}\cdot W_i + \frac{1}{2}x_p E_{max} \\ x_n N_D = x_p \cdot N_A \\ E_{max} = \frac{qN_D x_n}{\epsilon_s} \end{cases}$$

$\Rightarrow x_n = 2.6\times10^{-6}$ cm

$x_p = 2.6\times10^{-5}$ cm

$E_{max} = 4kV/cm$

b) in p-n junction.

$\phi_i = 0.64V$

$$\begin{cases} |\phi_i| = \frac{1}{2}E_{max}(x_n + x_p) \\ N_D x_n = N_A x_p \\ E_{max} = \frac{qN_D x_n}{\epsilon_s} \end{cases} \Rightarrow E_{max} = 1.3\times10^5 V/cm$$

$\therefore E_{max_{p\text{-}n}} > E_{max_{p\text{-}i\text{-}n}}$

$\frac{qN_D}{\varepsilon_s}$.

PROBLEM 3 SOLUTION

roblem4. a) i) $E_f - E_i = kT\ln\left(\frac{N_D}{n_i}\right) = 0.026 \times \ln\left(\frac{5\times10^{15}}{1.4\times10^{10}}\right) = 0.33eV$

ii) $\rho = 10\,\Omega\cdot cm$ From fig 1.16 (use fig 1.15) we can find the value $\mu_p = 460 cm^2 V^{-1} s^{-1}$

$\rho = \frac{1}{q\mu_p p} \Rightarrow p \simeq 1.5\times10^{15} cm^{-3}$

$E_i - E_f = kT\ln\left(\frac{p}{n_i}\right) = 0.026 \times \ln\frac{1.5\times10^{15}}{1.4\times10^{10}} = 0.3eV$

b) $q\phi_B = 0.85eV$

i) $q\phi_i = q\phi_B - (E_c - E_F)$

$= q\phi_B - kT\ln\frac{N_C}{n_D} = 0.85 - 0.026\cdot\ln\frac{3.2\times10^{19}}{5\times10^{15}}$

$= 0.622eV$ $\therefore \phi_i = 0.622$ Volt

(ii) $q\phi_B = q\phi_m - q\chi = 6.125 - 4.05 = 2.075$

(For the work function of Pt, I can find different value from 5.9eV ~ 6.35eV, I choose the average number $\frac{5.9+6.35}{2} = 6.125$

The 0.85eV barrier is not consistent with idealized schottky theory. The reason is Fermi level pining, which makes the $q\phi_B$ almost independent on the kind of metal $q\phi_B \approx \frac{2}{3}E_g = 0.75$ good.

c. when complete depleted, $x_d = 2.5\,\mu m$

$$\mathcal{E}_{max} = \frac{qN_D x_d}{\epsilon_s} = \frac{1.602\times10^{-19}\cdot 5\times10^{15}\cdot 2.5\times10^{-4}}{11.7\times 8.85\times10^{-14}}$$

$$= 1.93\times10^{5}\ V/cm$$

∴ It is possible to deplete the whole n^- layer without reaching the breakdown voltage of $3\times10^5\ V/cm$.

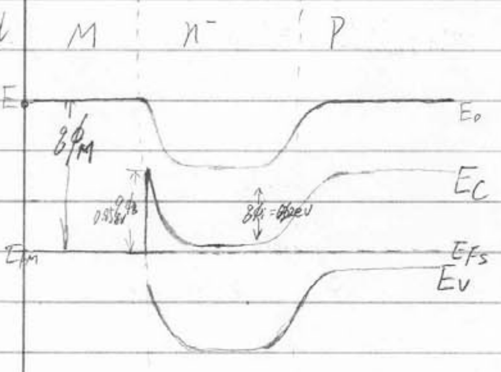
when completly depleted, $x_d = 2.5\,\mu m$

$$\frac{1}{2}\mathcal{E}_{max} x_d = \frac{qN_D x_d^2}{2\epsilon_s} = \phi_i - V_a$$

$$\Rightarrow V_a = 23.5V$$

reversed Bias.

d.

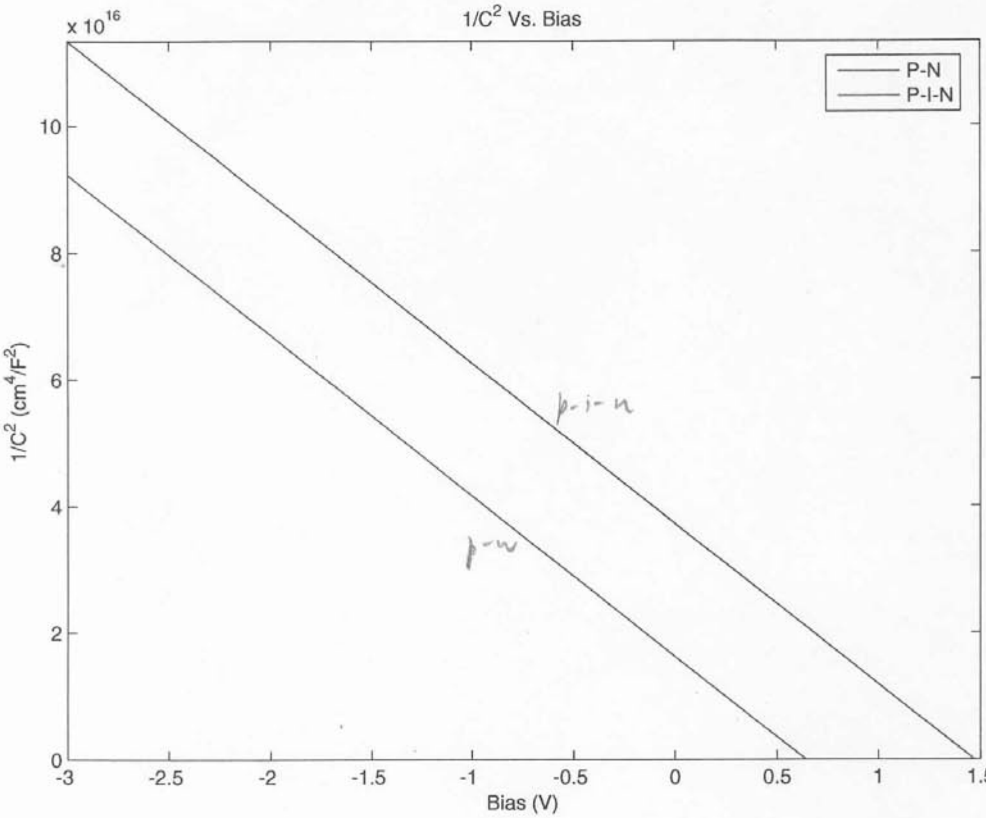


$$q\phi_i = kT\ln\left(\frac{N_D N_A}{n_i^2}\right)$$

$$= 0.026\times\ln\left(\frac{5\times10^{15}\cdot 1.5\times10^{15}}{(1.4\times10^{10})^2}\right)$$

$$= 0.629\ eV$$

2/4



1/C2 Vs. Bias
x 10^16
P-N
P-I-N
p-i-n
p-n
1/C2 (cm4/F2)
Bias (V)
0
2
4
6
8
10
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5

Fig4

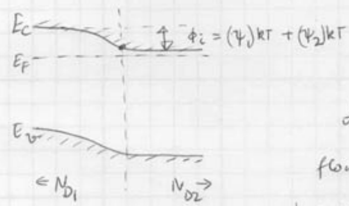
PROBLEM 4 SOLUTION

ASSIGNMENT 4 – EE 566 – Solid State Devices, Spring 2005. –(Solution).

Problem 1 –

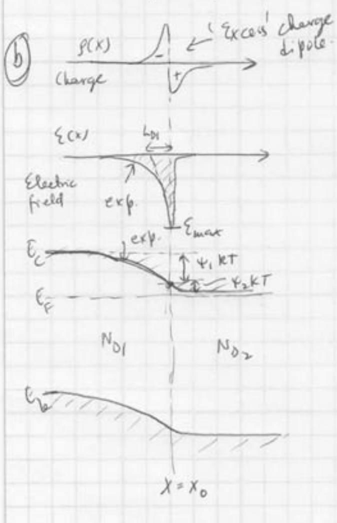
(a) Potential barrier is $\phi_i = \frac{kT}{q} \ln\left(\frac{N_{D2}}{N_{D1}}\right) = 0.12\ \text{Volt}$

$\boxed{\phi_i = 120\,\text{meV}}$



for electron flow from region $1 \rightarrow 2$, there is no barrier. However, for electron flow from $2 \rightarrow 1$, there is a potential barrier $\phi_i \simeq 120\,\text{meV}$. However, this barrier is very small, & any applied bias greater than 120 mV will make the current ohmic in both directions. So, there is rectification, but it is VERY WEAK.

(b)



(c) The exact solution to Poisson Eq^n is

$$\frac{\partial^2 \psi(x)}{\partial x^2} = \frac{q^2 N_D(x)}{\epsilon_S kT}\left[1 - e^{-\psi(x)}\right]$$

$\downarrow$ which yields for Electric field (Done in class!)

$$|\mathcal{E}(x)|^2 = \frac{2kT N_D}{\epsilon_S}\left[\psi(x) + e^{-\psi(x)} - 1\right]$$

Denoting total band bending in 'N_{D1}' region as $\psi_1 kT$ & in 'N_{D2}' region as $\psi_2 kT$, and equating the field at $x = x_0$, the interface,

$$\left\{\begin{array}{l} \frac{2kT N_{D1}}{\epsilon_S}\left[-|\psi_1| + e^{|\psi_1|} - 1\right] = \frac{2kT N_{D2}}{\epsilon_S}\left[|\psi_2| + e^{-|\psi_2|} - 1\right] \\ \text{also,} \quad |\psi_1| + |\psi_2| = \frac{\phi_i}{kT} = \frac{120\,\text{meV}}{26\,\text{meV}} \ @300\text{K}. \end{array}\right.$$

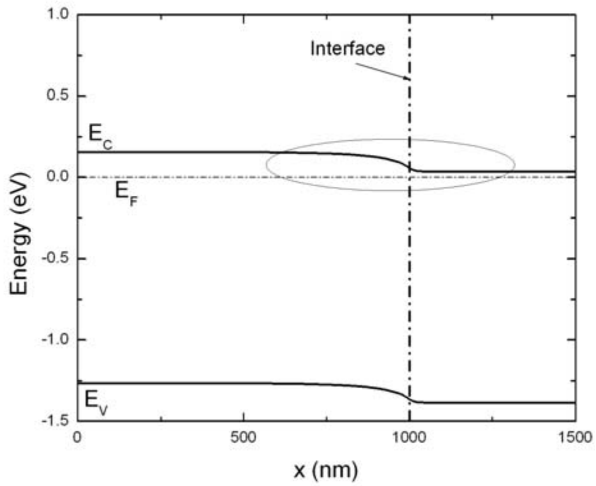
Solve simultaneously to get $\boxed{\begin{array}{l}|\psi_1| = 3.6517 \\ |\psi_2| = 0.9636\end{array}}$

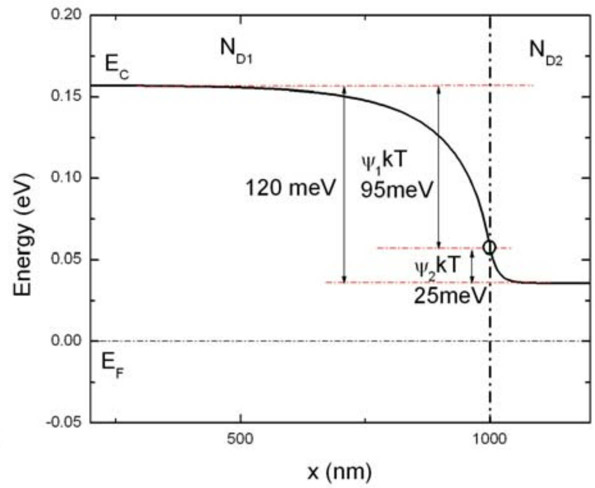
$\Rightarrow$ 95 meV drops in 'N_{D1}'

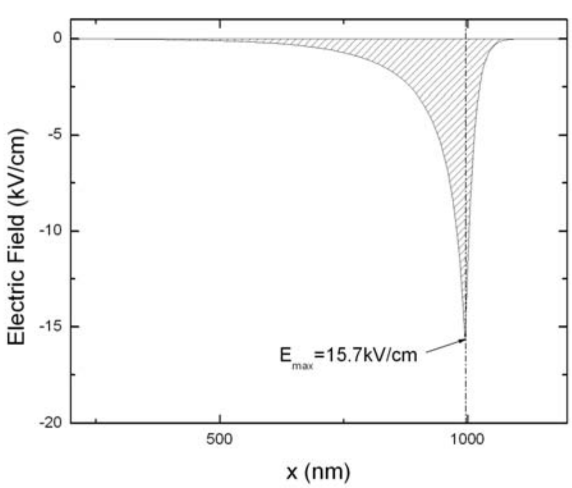
25 meV drops in 'N_{D2}', &

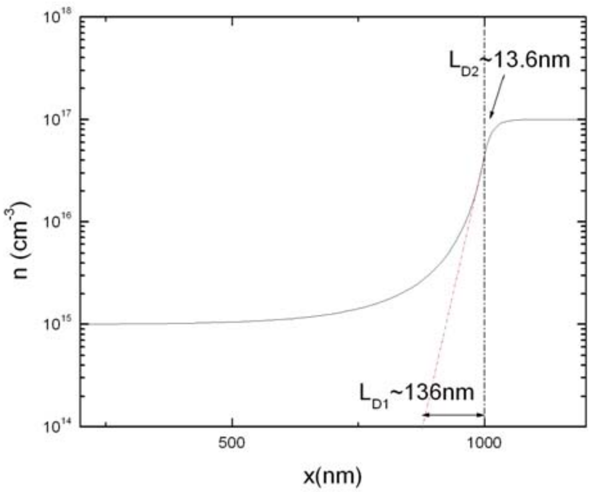
$$\mathcal{E}_{max}\,(\text{Exact}) = \left\{\frac{2kT N_{D1}}{\epsilon_S}\left(-|\psi_1| + e^{-|\psi_1|} - 1\right)\right\}^{1/2} \simeq \boxed{15.7\ \text{kV/cm}}$$

The simulated band diagrams using 1D Poisson are shown below. As can be seen, the band bending, the maximum electric field at the interface, and the Debye lengths match our exact calculations very well. This example illustrates that only for very simple structures can the Poisson equation be solved exactly. Most of the simulation for real devices is done numerically.



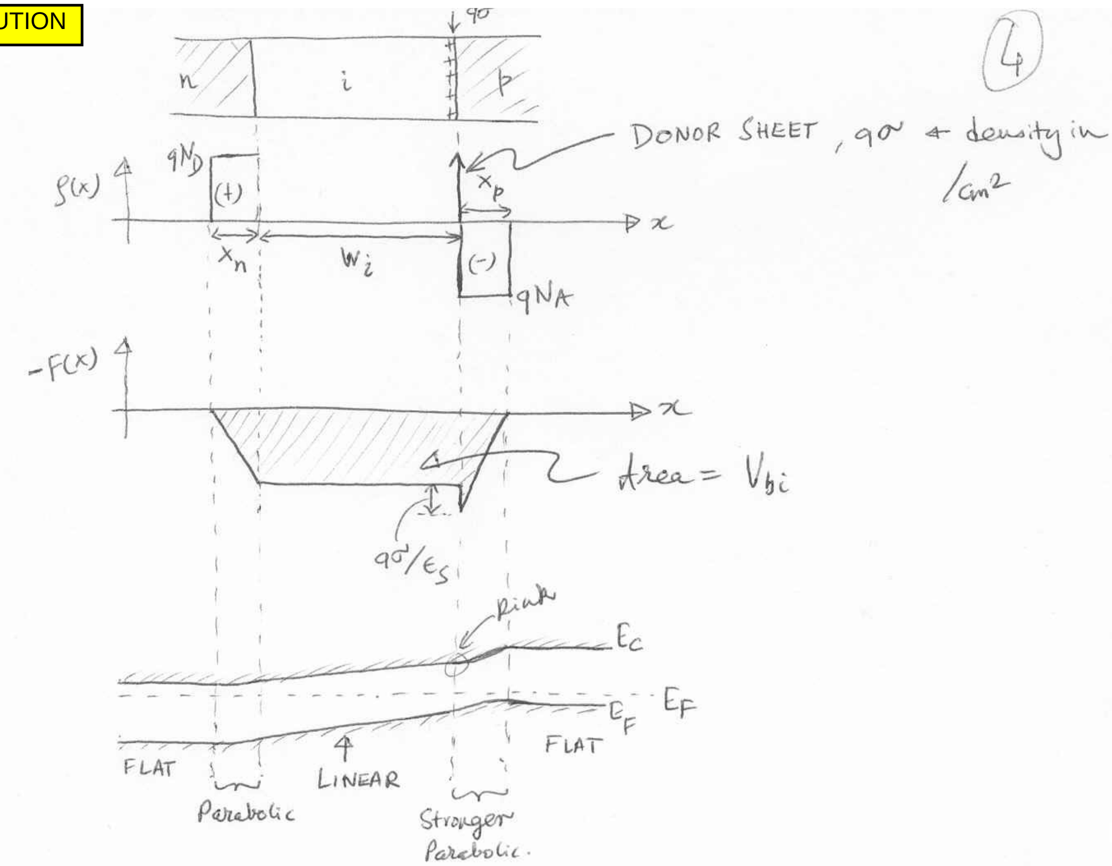






PROBLEM 5 SOLUTION

(c)



Charge Neutrality: $qN_A x_p = qN_D x_n + q\sigma$.

$$\therefore \quad x_p = x_n + \frac{\sigma}{N_A} \rightarrow V_{bi} = \frac{qN_A}{\epsilon_s}x_p^2 + \left(\frac{W_i qN_A}{\epsilon_s} - \frac{q\sigma}{\epsilon_s}\right)x_p$$

$$\text{(a)} - \left[+ \frac{1}{2}\frac{q\sigma^2}{\epsilon_s N_A} - \frac{W_i q\sigma}{\epsilon_s} \right.$$

AREA UNDER F(x) - x plot.

$$C_{p-i-n} = C_{p-n}$$

$$\text{(b)} - \frac{\epsilon_s}{x_n + x_p + W_i} = \frac{\epsilon_s}{W} \leftarrow \left(\frac{2\epsilon_s}{q}\cdot\frac{2}{N_A}\cdot V_{bi}\right)^{1/2}$$

With i-layer + Sheet doping — No i-layer.

Solve (a) & (b) together to get -

$$\boxed{W_i = (\sqrt{2}-1)\frac{\sigma}{N_A}} \Rightarrow W_i \approx (\sqrt{2}-1) * \frac{10^{11}\times 5}{10^{17}} \text{ cm}$$

$$\boxed{W_i \approx 20.7 \text{ nm}}$$