EECS170A Fall2006 Midterm Exam Solution

11/7/2006 3:30 to 4:50pm
Professor Peter Burke

Note: For all questions, no credits will be given to any answers with units.

PROBLEM ONE: (20 points)

A p-n junction is doped at $N_A = 10^{16}$ cm^{-3} and $N_D = 10^{17}$ cm^{-3}.

A) (5 points) Find the density of holes on the p-side.

Since $N_A >> n_i$, the hole concentration, $p = N_A = 10^{16}$ cm^{-3}

(Acceptable range of p is (0.9 – 1.1) x 10^{16} cm^{-3})

B) (5 points) Find the density of electrons on the p-side.

The electron concentration:

$$n = (n_i)^2 / p = (10^{10})^2 / 10^{16} = 10^4 \ \text{cm}^{-3}$$

(Acceptable range of n is (0.9 – 1.1) x 10^4 cm^{-3})

C) (5 points) Find the density of holes on the n-side.

Since $N_D >> n_i$, the electron concentration, $n = N_D = 10^{17}$ cm^{-3}

The hole concentration:

$$p = (n_i)^2 / n = (10^{10})^2 / 10^{17} = 10^3 \ \text{cm}^{-3}$$

(Acceptable range of p is (0.9 – 1.1) x 10^3 cm^{-3})

D) (5 points) Find the density of electrons on the n-side.

Since $N_D >> n_i$, the electron concentration, $n = N_D = 10^{17}$ cm^{-3}

(Acceptable range of n is (0.9 – 1.1) x 10^{17} cm^{-3})

PROBLEM TWO: (35 points)

An on-chip resistor is to be made of p-doped silicon, with dimensions 10 μm long, 1 μm wide, and 0.1 μm thick. The desired resistance is 10KΩ. What doping level should be used?

Given: Length, $L = 10\ \mu m = 10^{-5}\ m$
Width, $W = 1\ \mu m = 10^{-6}\ m$
Thickness, $H = 0.1\ \mu m = 10^{-7}\ m$
Resistance, $R = 10\ K\Omega = 10^{4}\ \Omega$

$R = \rho L / A$ *(10 pts for writing out this equation)*

$\rho = R.A / L = R.W.\ H / L$
$= (10^{4}\ \Omega) \times (10^{-6}\ m) \times (10^{-7}\ m) / (10^{-5}\ m)$
(5 pts for correctly substitute the numbers)
$= 10^{-4}\ \Omega.m$
$= 10^{-2}\ \Omega.cm$
(- 10pts for correct answer for ρ*;*
- 10pts for wrong answer due to the wrong substitution of numbers;
- 0 pts for wrong answer with correct substitution of number.)

In order to find the doping level (N_A)*, look at the graph from page 4 for p-type:*

$N_A = 10^{19}\ cm^{-3}$

(Acceptable range of N_A *is* $(0.8 – 1.0) \times 10^{19}\ cm^{-3}$*)*

(- 10pts for correct answer for N_A*;*
- 10pts for wrong N_A *but consistent with wrong* ρ *calculated above;*
- 0 pts for wrong N_A *with correct* ρ *calculated above;*
- 5 pts for correct N_A *but* N_D *was also written)*

PROBLEM THREE: (45 points)

Assume equilibrium for all of problem three.

Consider a semiconductor that is n-doped with dopant density N_D that depends on position as follows:

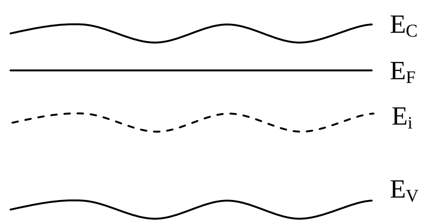
$N_D(x) = N_{D0} + \delta N_D \sin(kx)$,

Where $N_{D0} >> n_i$, and $\delta N_D << N_{D0}$

k, δN_D, and N_{D0} are constants.

Express your answers in terms of k, δN_D, and N_{D0}, and known constants and materials properties of silicon, such as n_i, E_G, KT, q, D_N, μ_n, etc...

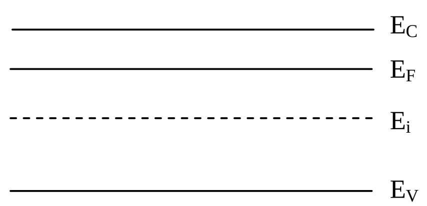
A) (10 points) Sketch the band diagram. (Qualitive.)



5 pts for constant E_F, and above E_i
4 pts for constant E_F, but below E_i or constant E_i
5 pts for correct E_C and E_V

Alternatively,

With assumption: $\delta N_D << N_{D0}$



5 pts for constant E_F, and above E_i
4 pts for constant E_F, but below E_i
5 pts for correct E_C and E_V

B) (10 points) Find the electric field everywhere.

Electric field, $\varepsilon = -dV/dx = 1/q\, dE/dx$ *(3 pts for writing this equation)*

$E_F - E_i = K_BT \ln(n/n_i)$, where K_B = Boltzman's constant

$d(E_F - E_i) / dx = -d E_i / dx = d(K_BT \ln(n/n_i)) / dx$

(3 pts for writing this equation)

$= d(K_BT \ln[(N_{D0} + \delta N_D \sin(kx)) /n_i)] / dx$

$= K_BT (ni/ N_D(x))\, d(\delta N_D \sin(kx) /n_i) / dx$

$= K_BT (ni/ N_D(x))\, (\delta N_D\, k \cos(kx) /n_i)$

$= K_{B.}T.\delta N_{D.}k\cos(kx) / N_D(x)$

$\therefore\ \varepsilon(x) = 1/q\ dE_i / dx = -\ (1/q).(K_{B.}T.\delta N_{D.}k\cos(kx) / N_D(x))$

(4 pts for correct answer of ε, no credits for ε = 0*)*

C) (10 points) Find the drift current density due to electrons everywhere.

$J_{N\,|\,drift}(x) = q.\ \mu_n.\ n.\ \varepsilon$ *(2 pts for writing this equation)*

$= -\ \mu_n.\ N_D(x).\ (K_B.\ T.\ \delta N_D.\ k.\ \cos(kx) / N_D(x))$

$= -\ \mu_n.\ K_{B.}\ T.\ \delta N_{D.}\ k.\ \cos(kx)$

(- 8 pts for correct answer of $J_{N\,|\,drift}$;

- 8pts for wrong answer of $J_{N\,|\,drift}$ due to the wrong ε from Q3c

- no credits for leaving answers as dE_i/dx, or dE_C/dx or dE_V/dx or ε)

D) (10 points) Find the diffusion current density due to electrons everywhere.

Under equilibrium,

$J_{N\,|\,diff}(x) = -\ J_{drift\,|\,n}$

$= \mu_n.\ K_{B.}\ T.\ \delta N_{D.}\ k.\ \cos(kx)$

(- 10 pts for correct $J_{N\,|\,dif;f}$

- 10 pts for wrong $J_{N\,|\,diff}$ due to the wrong $J_{N\,|\,drift}$ from Q3d)

Or alternative method:

$J_{N\,|\,diff} = qD_N\nabla n$

(2 pts for writing this equation)

$= qD_N\ d(N_{D0} + \delta N_D \sin(kx)) / dx$

(3 pts for writing this equation, need to express ∇ as d/dx, no credits for $\nabla(N_{D0} + \delta N_D \sin(kx))$)

$= qD_N\delta N_D\ k.\ \cos(kx)$

(5 pts for correct $J_{N\,|\,diff}$, no credits for $J_{N\,|\,diff}(x) = 0$)

From Eisten's relationship:

$D_N = \mu_n.\ K_{B.}\ T / q$

$\therefore\ J_{N\,|\,diff}(x) = \mu_n.\ K_{B.}\ T.\ \delta N_{D.}\ k.\ \cos(kx)$

E) (5 points) Find the total current density everywhere.

In equilibrium, the total current density, $J_{total} = 0$. *(5 pts for correct J_{total})*

Or alternative method:

$J_N = J_{N\,|\,drift} + J_{N\,|\,diff}$ *(2 pts for writing this equation)*

$= - \mu_n . K_{B.} T. \delta N_{D.} k. \cos(kx) + \mu_n . K_{B.} T. \delta N_{D.} k. \cos(kx)$

$=0$

(- 3 pts for correct J_{total};

- 3 pts for wrong J_{total} due to the wrong $J_{N \mid drift}$ from Q3e and wrong $J_{N \mid diff}$ from Q3d, but no credits for leaving answers as ∇n or $\nabla N_D(x)$)

Similarly,

$$J_P = J_{P \mid drift} + J_{P \mid diff} = 0$$

$$\therefore J_{total} = J_N + J_P = 0$$