UNIVERSITY OF CALIFORNIA, BERKELEY
College of Engineering
Department of Electrical Engineering and Computer Sciences

MIDTERM EXAMINATION
EE 130/230A: Spring 2014
Time allotted: 60 minutes

NAME: Solution ______________ ______________

STUDENT ID#: ______________

INSTRUCTIONS:

1. **Unless otherwise stated, assume**
    a. **temperature is 300 K**
    b. **material is Si**

2. **SHOW YOUR WORK. (Make your methods clear to the grader!)**
    - Specially, while using chart, make sure that you indicate how you have got your numbers. For example, if reading off mobility, clearly write down what doping density that corresponds to.
    - Clearly write down any assumption that you have made.

- **Clearly mark (underline or box) your answers.**

3. **Specify the units on answers whenever appropriate.**

SCORE: 1 __________ **/ 20**

2 __________ **/ 20**

Total __________ **/ 40**

PHYSICAL CONSTANTS

Description	Symbol	Value
Electronic charge	q	1.6×10^{-19} C
Boltzmann's constant	k	8.62×10^{-5} eV/K
Thermal voltage at 300K	$V_T = kT/q$	0.026 V

PROPERTIES OF SILICON AT 300K

Description	Symbol	Value
Band gap energy	E_G	1.12 eV
Intrinsic carrier concentration	n_i	10^{10} cm^{-3}
Dielectric permittivity	ε_{Si}	1.0×10^{-12} F/cm

USEFUL NUMBERS

$V_T \ln(10) = 0.060$ V at T=300K

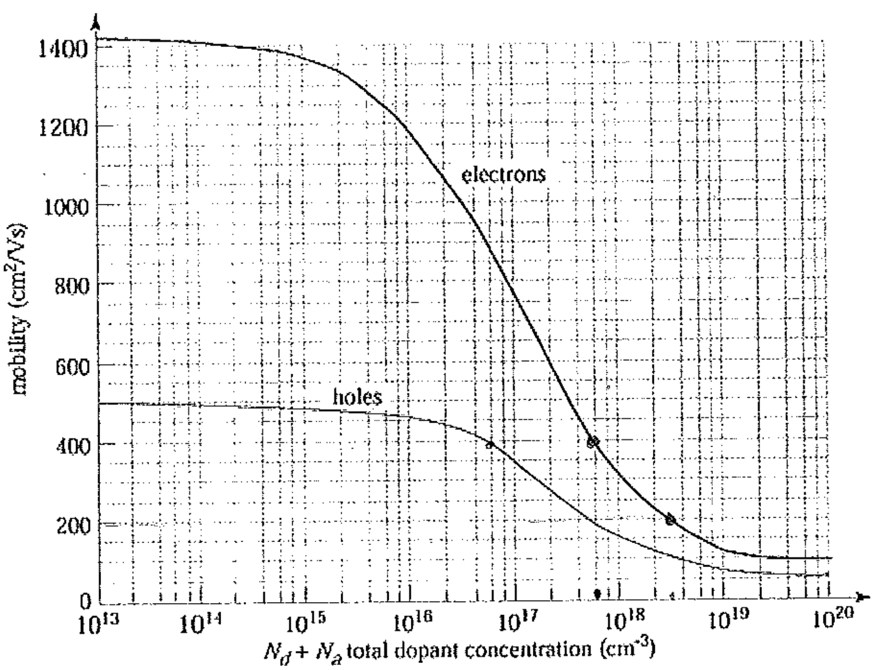
Depletion region Width:

$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\left(V_{bi}-V_{Applied}\right)}$$

Current in a PN junction:

$$I = A\left(q\frac{D_p}{L_p}p_{n0}+q\frac{D_n}{L_n}n_{p0}\right)\left(e^{qV_D/kT}-1\right)$$

Electron and Hole Mobilities in Silicon at 300K



Prob 1 [20 pts].

(a) **[4 pt]** Assume that a Si sample has been doped with Ga (which is a group III element).

(i) Will the electron density increase or decrease if one increases temperature? Why? [2pt]

(ii) Will the hole density increase or decrease if one increases temperature? Why? [2pt]

Ga → group III → acceptor

(i) $n = \frac{n_i^2}{N_{Ga}}$, increases with T due to n_i

(ii) $p = N_{Ga}$; independent except for very high T where n_i is comparable to N_{Ga}.

(b) **[6 pt]** Assume that a Si sample of length 500μm at *T=300°K* is uniformly doped with acceptors at a concentration of 2.5 x 10^{17} cm^{-3}. Following that, the semiconductor is *compensated* such that the carrier mobility comes out to be 400 cm^2/v-sec. If 5V is applied across this sample, find out the current density.

$(N_a + N_d)$ for 400 cm^2/v-sec can only be found for electrons above $2.5 \times 10^{17}/cm^3$ doping density.

$N_a + N_d = 6 \times 10^{17}/cm^3$ from the plot

$\therefore N_d = (6 - 2.5) \times 10^{17} = 3.5 \times 10^{17}/cm^3$

$\therefore n = N_d - N_a = (3.5 - 2.5) \times 10^{17} = 10^{17}/cm^3$

$J = q n \mu_n E = 1.6 \times 10^{-19} \times 10^{17} \times \frac{5}{500 \times 10^{-4}} \times 400$

$J = 6.4 \times 10^2 \ A/cm^2$

(c) **[6 pts] [20 pts]** A sample of N type Si is kept at room temperature. When an electric field with a strength of 1000 V/cm is applied to the sample, the electron velocity is measured and found to be 2 x10^5 cm/sec.

(a) [10 pts] Estimate the thermal equilibrium electron and hole densities, indicating which is the minority carrier.
(b) [10 pts] Find the position of E_F with respect to E_c and E_v.

(a) $v = \mu_n \mathcal{E} = 2\times10^5$ cm/sec

$\therefore \mu_n = \frac{2\times10^5}{1000} = 200$ cm²/V-sec

From the plot, $N_d = 3\times10^{18}$ /cm³

$\therefore$ majority $n = 3\times10^{18}$ /cm³
minority $p = \frac{10^{20}}{3\times10^{18}} = 33.33$/cm³

(b) $n = n_i e^{\frac{E_F - E_i}{kT}}$; $E_F - E_i = kT \ln \frac{3\times10^{18}}{10^{10}} = 0.5055$ eV

$E_c - E_i = E_g/2 = 1.1/2 = 0.55$ eV

$\therefore E_c - E_F = 0.55 - 0.5055 = 0.0445$ eV

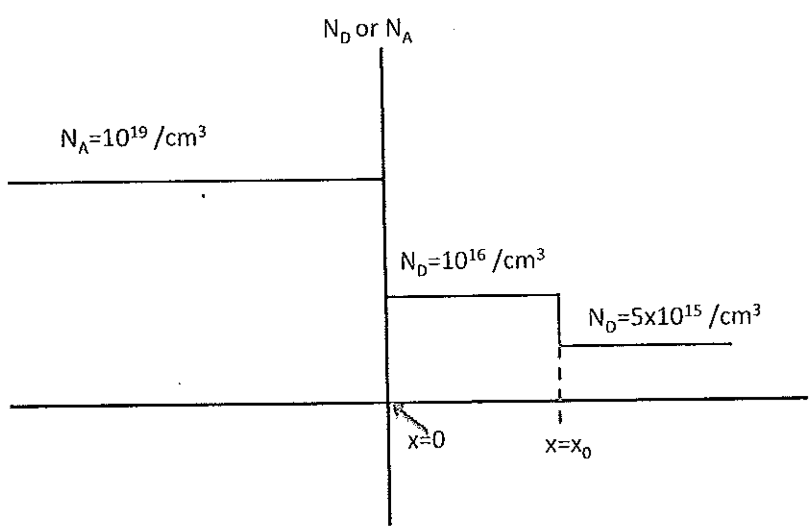
$\therefore E_F - E_v = (E_c - E_v) + (E_F - E_c) = 1.1 - 0.0445 = 1.055$ eV (d)[**4 pts**] Please indicate 'True' or 'False'

Phenomenon	True/False
Above room temperature, mobility is more dominantly affected by phonon scattering than impurity scattering	T
In Si, recombination happens mainly through band-to-band transition	F
When low level injection holds, $np=n_i^2$ also holds	F
Carrier lifetime will typically be smaller in intrinsic Si compared to doped Si	F

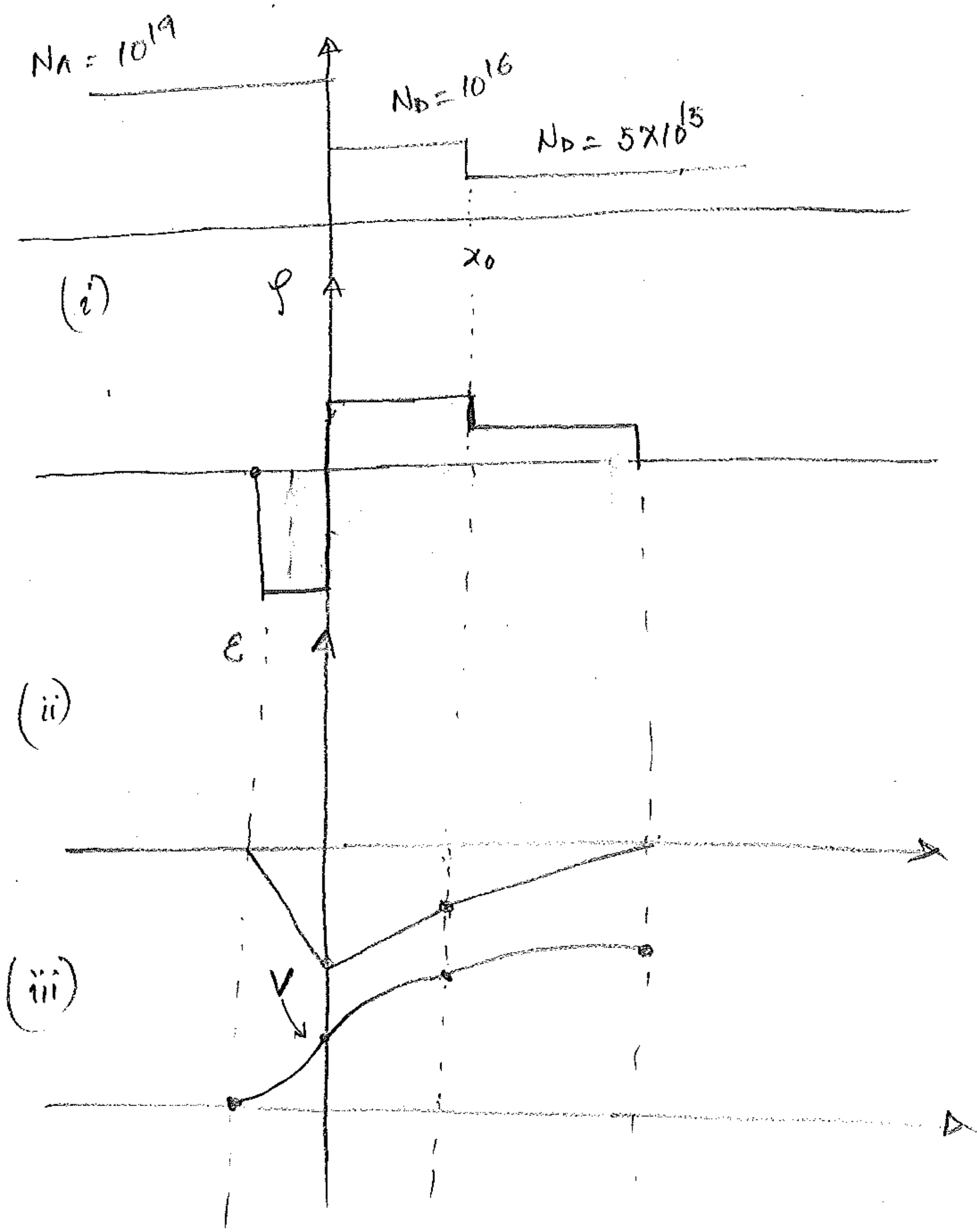
Prob 2: [20 pts] For the P-N junction diode shown below, answer the following questions. Note that the depletion width on the N-side, $x_n > x_0$. Ignore any discontinuity of electric field in the junctions. Note that the picture shown below only shows the amplitude (and not 'sign') of the doping concentrations.

While drawing the diagrams,

- please be careful to indicate ***relative quantities*** (such as the amplitude of charge densities, the curvature of potential profiles, the width of the depletion region etc)
- For each diagram you need to draw quantities at both the P and N sides
- If you are using the same diagram to answer multiple questions, please mark the answers clearly.



(i) [1 pt] Draw the charge density profile
(ii) [1 pt] Draw the Electric Field Profile
(iii) [1 pt] Draw the Potential Profile
(iv) [3 pt] Calculate the depletion region width
(v) [2 pt] Calculate the Built in potential
(vi) [2 pt] Calculate the maximum electric field
(vii) [4 pt] Draw the current density profiles for both electrons and holes [Two profiles on each side and the total current] at a forward bias of 0.3V.
(viii) [2 pt]Draw the Energy band diagram at the forward bias condition of (vi).
(ix) [2 pt] Draw the profile of quasi Fermi levels of both electrons and holes.
(x) [2 pt] Find the excess electron concentration at the edge of the depletion region at the N-side

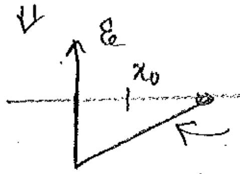


(iv) $\frac{qN_D}{2\varepsilon}x_0^2 + \frac{qN_D}{4\varepsilon}(W-x_0)^2 = V_{bi}$ [Assuming p^+N]

$\therefore \left[2x_0^2 + (W-x_0)^2\right] = \frac{2\varepsilon}{qN_D/2}V_{bi}$

Assume, $W \gg x_0$ $\quad W = \sqrt{\frac{2\varepsilon}{qN_D/2}V_{bi}}$ $\quad \therefore W \simeq \sqrt{\frac{2\varepsilon_s}{q}\frac{1}{N_D}V_{bi}} = \sqrt{\frac{2\times8.854\times10^{-14}}{1.6\times10^{-19}}\frac{11.9}{5\times10^{15}}0.87}$

$W = 4.7\times10^{-5}$ cm



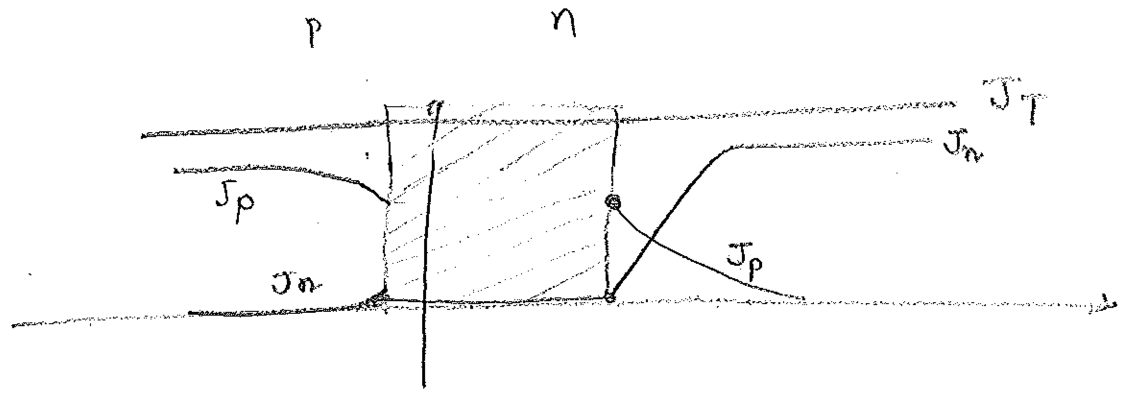
(v) $V_{bi} = KT\ln\frac{N_AN_D}{n_i^2} = KT\ln\frac{10^{19}\times10^{15}\times5}{10^{20}} = 0.8766\text{ V}$

(vi) With the same approximations as in (iv)

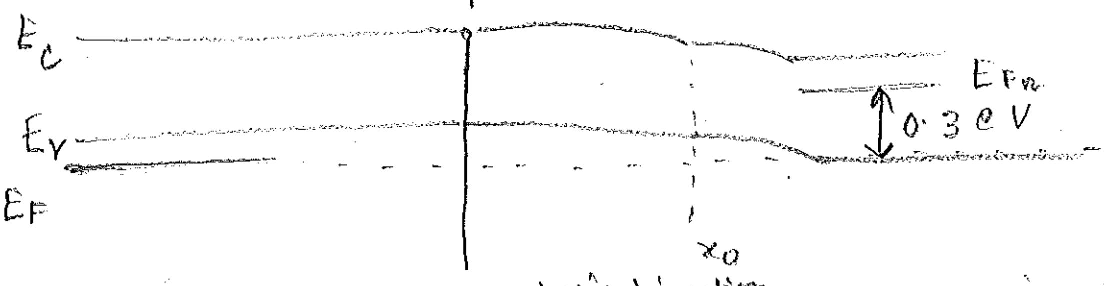
$$\mathcal{E} \approx -\frac{qN_D}{\varepsilon}(W-x)$$

$$\therefore \mathcal{E}_{max} = \frac{qN_D/2\,W}{\varepsilon} = \frac{1.6\times10^{-19}\times4.7\times10^{-5}}{11.9\times8.854\times10^{-14}}\times5\times10^{5} = 3.63\times10^{4}\text{ V/cm}$$

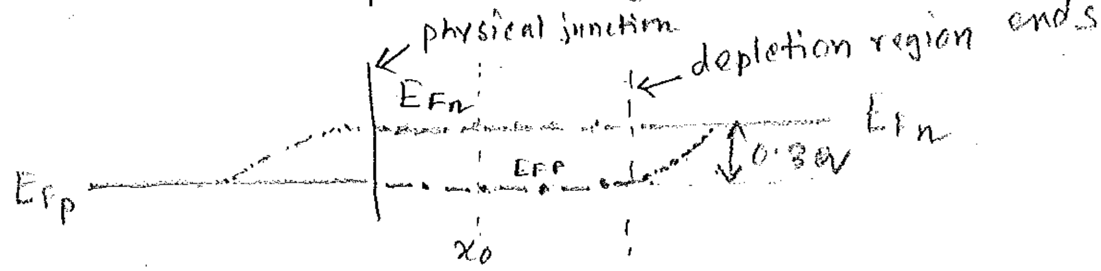
(vii)



(viii)



(ix)



(x) $\Delta p = \frac{n_i^2}{N_D}\left(e^{\frac{0.3}{0.0259}} - 1\right) = 2.145\times10^{9}/\text{cm}^3$