Columbia University
Department of Electrical Engineering
Solid State Devices and Materials
ELEN E3106/4106
Homework #3

Due: Friday, September 26th by 5pm
Goal: Practice 1) sketching energy band diagrams in the present of electric fields, 2) calculating excess carrier concentrations under excitation, and 3) calculating drift and diffusion currents.
Instructions: Show your work and include units in answers for full credit. For the multiple-choice questions, please clearly mark your selection. No credits will be given for answers without supporting work or explanation, even if the final value is correct. Unless stated otherwise, make the assumptions we have been taking in class (the sample is at 300 K).
Points: 110 pts for 3106. 130 pts for 4106.

- **Problem 1 (15 pts)** Energy band diagram relationship to electric field.
  Sketch, with proper labeling of energies and distances, the simplified band diagram of a semiconductor with a band gap of 2 eV which is subjected to the following electrostatic potential profile: 0 V for x = 0 to 1 μm (Region A); linearly increasing from 0 to 1.5 V between 1 μm and 4 μm (Region B); constant potential after that from x = 4 to 5 μm (Region C). Label the bandgap energy, the regions, the conduction and valence band edges, and the energy difference in eV between Regions A and C.

- **Problem 2 (14 pts)** Excess carriers and quasi-Fermi levels in nonequilibrium.
  An n-type Si sample with $N_d = 10^{14}\ cm^{-3}$ is steadily illuminated such that $g_{op} = 10^{13}\ EHP/cm^3 - \mu s$. If $\tau_n = \tau_p = 1\ \mu s$ for this excitation,
  (a) Calculate the separation in the quasi-Fermi levels, $(F_n - F_p)$, and choose the correct answer..
  (b) Draw a band diagram.

- **Problem 3 (15 pts)** Optical carrier generation and recombination effects on concentrations.
  An n-type Si sample is doped at $10^{15}\ cm^{-3}$. We shine light on it to create EHPs at $10^{19}\ cm^{-3}/s$.
  (a) What is the steady state concentration of minority carriers, if the lifetime is $150\ ns$?
  (b) How long for the hole concentration to reach a value that is 10% higher than the thermal equilibrium value?
  (c) How long does it take for the hole concentration to drop 10%, after the light is switched off?

- **Problem 4 (24 pts)** Drift and diffusion.
  A semiconductor bar of length 3 mm with intrinsic carrier concentration of $10^{10}\ cm^{-3}$ is uniformly doped with donors at a concentration of $2 \times 10^{13}\ cm^{-3}$ and acceptors at a concentration of $10^{13}\ cm^{-3}$.

(a) If $D_n = 50\ cm^2/s$ and $D_p = 20\ cm^2/s$ calculate the electron and hole drift current densities for an applied voltage of $5\ V$. In this semiconductor, electrons are in the ohmic regime for fields less than $10^5\ V/cm$, but travel with a saturation velocity of $10^8\ cm/s$ for fields above that. For holes, they are ohmic below $10^4\ V/cm$, and travel with a saturation velocity of $10^5\ cm/s$ s above that field.

(b) What carrier gradients would be required to move this much current in the same material through diffusion only?

- **Problem 5 (10 pts)** Drift and diffusion.
  A novel semiconductor sample has L = 3 μm, W = 1 μm, and a thickness of 0.2 μm. It has an intrinsic carrier concentration of $10^{12}\ cm^{-3}$. If it has an ionized donor concentration of $2 \times 10^{12}\ cm^{-3}$, calculate the electron and hole currents for an applied bias of 10 V across the length of the bar, assuming ohmic behavior for electrons, but holes are traveling at saturation velocity. Use the quadratic equation for calculating carrier concentration that we introduced during our discussions on compensated semiconductors. The electron and hole diffusion coefficients are $20\ cm^2/s$ and $5\ cm^2/s$, respectively. The electron and hole saturation velocities are $10^8\ cm/s$ and $10^7\ cm/s$, respectively, in this semiconductor.

- **Problem 6 (12 pts)** Review questions.
  (a) Do absorption coefficients of photons increase or decrease with photon energy? Why?
  (b) Why do minority carrier concentration quasi-Fermi levels change more than majority carrier quasi-Fermi levels?
  (c) What do we mean by "deep" versus "shallow" traps? Which are more harmful for semiconductor devices and why? What is an example of a deep trap in Si?

- **Problem 7 (20 pts)**

For this problem, you will need to run the simulation program, Carrier Statistics Lab – Carrier Distributions, Fermi-Dirac, which is part of the ABACUS Tool Suite on nanoHUB.org. Be sure you have an account through your Columbia credentials, then proceed with the exercises below. .

Simulate an n-type doped (Nd=1e15/cm3) (i) Si (ii) Ge and (iii) GaAs. (take Na=10/cm3) (Hint: You can simulate different temperature ranges, and you can change the axis range by clicking on the concentration y-axis to see a more realistic carrier concentration curve).

(a) Find the freeze-out temperature for (i), (ii), (iii). (T_freeze-out: N/Nd=0.99) (i.e., only 99% of the donor atoms are ionized). Include a screenshot of the plot you used to get your result.
(b) Find the temperature at which extrinsic behavior ceases to exist and intrinsic behavior occurs in (i), (ii), (iii).. Suppose extrinsic behavior is valid till N/Nd<=1.01. Include a screenshot of the plot you used to get your result.
(c) The difference between (a) and (b) is the working range for that material. Find the working range for (i), (ii), (iii). Which material (i), (ii), or (iii) has the highest working range and why?

- **Problem 8 (Required for 4106 students ONLY, 20 pts)**

A silicon crystal that has 5×10^{22} atoms/cm^3 is known to contain 10^{-4} atomic fraction of arsenic (As) as an impurity. It then receives a uniform doping of 3×10^{16} cm^{-3} phosphorus (P) and a subsequent uniform doping of 10^{18} cm^{-3} boron (B) atoms. A thermal annealing treatment then completely activates all impurities.

(a) What is the conductivity type of the silicon sample, n-type or p-type? Choose the correct answer.
(1)n-type (2)p-type

(b) What is the density of majority carriers? Show your work and choose the correct answer..
(1)4.03×10^{18} cm^{-3} (2)5.03×10^{16} cm^{-3} (3)5.03×10^{18} cm^{-3} (4)4.03×10^{16} cm^{-3}