Columbia University
Department of Electrical Engineering
Solid State Devices and Materials
ELEN E3106/4106
Homework #2

Due: Friday, September 19th by 5pm
Goal: Practice applying the energy band model and find carrier concentrations in equilibrium.
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.
Points: 110 for 3106; 130 for 4106

- **Problem 1 (30 pts)**
  Bands, dopants, and carrier concentrations.
  (a) Chromium atoms in a silicon lattice are acceptors, with an energy 0.13 eV away from the intrinsic Fermi level. Draw this energy level in the energy band diagram. Label the energy difference.
  (b) In an otherwise intrinsic silicon piece, what effect will the chromium have on the carrier concentrations? Qualitative explanation.
  (c) Calculate the approximate donor binding energy for GaAs ($\epsilon_r = 13.2,\ m_n^* = 0.067m_0$) and choose the correct answer.
  (1)$2.6\ meV$ (2)$3.9\ meV$ (3)$5.2\ meV$ (4)$10.4\ meV$
  (d) A Si sample is doped with $10^{17}\ cm^{-3}$ boron atoms. What is the electron concentration n_0 at 300 K? Choose the correct answer. Recall the value of $n_i = 1.5 \times 10^{10}\ cm^{-3}$ for Si at 300 K.
  (1)$1.5 \times 10^{10}\ cm^{-3}$ (2)$1 \times 10^{17}\ cm^{-3}$ (3)$2.25 \times 10^{3}\ cm^{-3}$ (4)$4.44 \times 10^{13} cm^{-3}$
  (e) What is the resistivity of (d)? Choose the correct answer. Given that $\mu_p = 450\ cm^2/V{\cdot}s$ in Si.
  (1)$0.138\ \Omega - cm$ (2)$7.2\ (\Omega - cm)^{-1}$ (3)$0.138\ \Omega - m$ (4)$7.2\ (\Omega - m)^{-1}$
  (f) For a silicon sample maintained at T = 300 K the Fermi level is located 0.325 eV above the intrinsic Fermi level. What are the electron and hole concentrations? Is the silicon n-type or p-type?

- **Problem 2 (4106 students only) (20 pts)**
  Plotting the Fermi energy.
  (a) Plot three versions of the Fermi distribution function versus energy in eV for Si with the Fermi level at mid-gap at room temperature, -30 °C, and +90 °C (3 plots total using Eq. 3. 10). Label the axes and include a legend. Note that m_n^*=1.1m$_0$ and m_p^*=0.56m$_0$. These are the density of states effective masses in Si, not to be confused with the conductivity effective masses we described in class.

(b) On the same graph, but on a second axis, plot the density of states as we have been approximating them for both the conduction and the valence band.
(c) Calculate the concentration of holes and electrons in each of these three cases.
(d) What is n_i^2 for each temperature?

- **Problem 3 (30 pts)**

Consider a Ge crystal at room temperature doped with $7 \times 10^{16}\ cm^{-3}$ As atoms.
(a) Find the equilibrium electron concentration. Choose the correct answer.
(1)$2 \times 10^{13}\ cm^{-3}$ (2)$5.71 \times 10^{9}\ cm^{-3}$ (3)$7 \times 10^{16}\ cm^{-3}$
(b) Find the equilibrium hole concentration. Choose the correct answer.
(1)$2 \times 10^{13}\ cm^{-3}$ (2)$5.71 \times 10^{9}\ cm^{-3}$ (3)$7 \times 10^{16}\ cm^{-3}$
(c) Find the position of the Fermi level w.r.t intrinsic energy level (Ei).
(d) Find the position of the Fermi level w.r.t the conduction energy band (Ec).
(e) Draw the energy band diagram also.

- **Problem 4 (22 pts)**

A new semiconductor has $N_c = 10^{19}\ cm^{-3}$, $N_v = 5 \times 10^{18}\ cm^{-3}$, and $Eg = 2$ eV. If it is doped with 10^{17} donors (fully ionized), calculate the following at 627 °C:
(a) Electron carrier concentration. Choose the correct answer.
(1)$1 \times 10^{19}\ cm^{-3}$ (2)$1 \times 10^{17}\ cm^{-3}$ (3)$3.16 \times 10^{9}\ cm^{-3}$ (4)$1.77 \times 10^{13} cm^{-3}$
(b) Hole carrier concentration. Choose the correct answer.
(1)$1 \times 10^{19}\ cm^{-3}$ (2)$1 \times 10^{17}\ cm^{-3}$ (3)$3.16 \times 10^{9}\ cm^{-3}$ (4)$1.77 \times 10^{13} cm^{-3}$
(c) Intrinsic carrier concentration. Choose the correct answer.
(1)$1 \times 10^{19}\ cm^{-3}$ (2)$1 \times 10^{17}\ cm^{-3}$ (3)$3.16 \times 10^{9}\ cm^{-3}$ (4)$1.77 \times 10^{13} cm^{-3}$
(d) Sketch the simplified band diagram, showing the position of E_F.

- **Problem 5 (28 pts)**

Review questions.
(a) What does the bandgap energy physically represent?
(b) Explain physically why the bandgap of a semiconductor decreases with temperature.
(c) What does the Fermi level represent?
(d) What is an intrinsic semiconductor? What is the denotation for hole density in an intrinsic semiconductor (e.g. what symbol do we use)?
(e) What is the difference between a doped semiconductor and an extrinsic semiconductor?
(f) Explain why the mobility in a semiconductor depends on the doping density.
(g) Explain the process of EHP generation using either the energy band model or broken bond model.