2.626 / 2.627: Fundamentals of Photovoltaics
Problem Set #2
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<u>**Please note**</u>: Excel, OriginLab, Matlab, or Mathematica code (or a combination of all) may be used to calculate the answers to many of the problems below, but **any submitted code or spreadsheets will not be reviewed by the grader**. If you require computer-aided software, please write-out the formulas or methodology used to calculate your answer in a clear and concise manner. **If methodology is not presented, then answers will receive no credit.** Additionally, clearly circle all final answers.

Question #1

In this problem, you will estimate efficiency limits for solar cells as a function of their band gap energy.

a. The short-circuit current density of a solar cell can be calculated from the measured external quantum efficiency $EQE(\varepsilon_\gamma)$ using the expression

$$J_{sc} = \int_{\Delta}^{\infty} C(\varepsilon_\gamma)\, I_{AMX}(\varepsilon_\gamma)\, EQE(\varepsilon_\gamma)\, d\varepsilon_\gamma$$

where $I_{AMX}(\varepsilon_\gamma)$ is the spectral irradiance incident upon the cell, ε_γ is the incident photon energy, and Δ is the band gap of the solar cell.

- Find the functional form of C in the integral given above that will make the above integral true. (Hint: unit analysis will, again, be helpful).

b. Using the functional fit for the AM0 spectral irradiance $I_{AM0}(\varepsilon_\gamma)$ found in HW1 - problem 1, plot the short-circuit current density J_{sc} from part (a) as a function of band gap energy Δ in units of $mA\, cm^{-2}$. Be careful with unit conversions! Typical band gap energies Δ may range from 0.0 – 5.0 eV. Assume an external quantum efficiency of 1.0 (that is, for every absorbed photon, an electron-hole pair is created).

- Recall: The functional fit for AM0 spectral irradiance $I_{AM0}(\varepsilon_\gamma)$ has the form

$$I_{AM0}(\varepsilon_\gamma) = A\frac{{\varepsilon_\gamma}^3}{exp(\beta\varepsilon_\gamma) - 1}$$

c. Using the information calculated in part (b) above, estimate how solar cell efficiency changes as a function of band gap energy Δ. To do so, assume that the output voltage of the device is equal to the band gap energy per fundamental unit of charge (*i.e.* $V_{output} = \frac{\Delta}{q}$).

   - Plot this estimated device efficiency vs. band gap energy Δ.

d. On the plot created in part (c), please mark the estimated maximum efficiencies of the following materials according to their band gap energy: c-Si, Ge, a-Si:H.

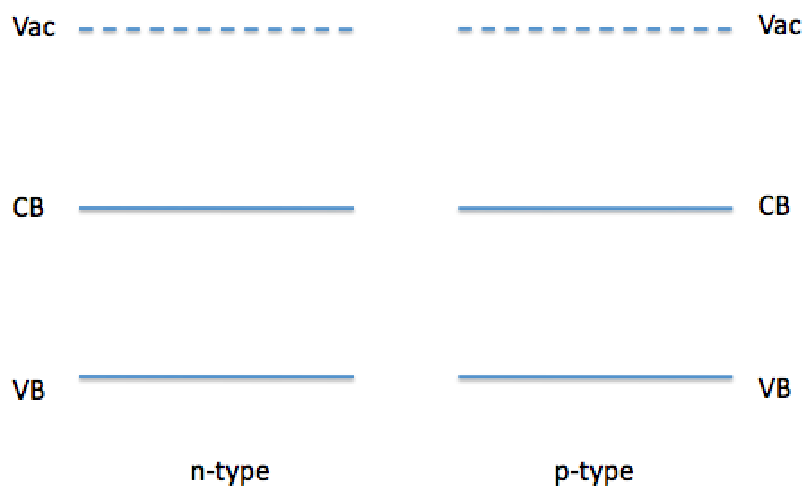
e. Grad Students Only: Repeat part (c) and part (d), numerically, using data for the AM1.5 spectral irradiance.

Question #2

In this problem, you will explore silicon doping and the diode equation by creating a PN junction using two semiconductors of different doping concentrations.

a. An n-type material has a 1e20 cm^{-3} phosphorous concentration and a p-type material has a 1e17 cm^{-3} boron concentration.

  - Estimate the chemical potential $\{\mu_N, \mu_P\}$ (known ubiquitously in solar cell physics as the "Fermi Energies") of both materials. Draw and label the chemical potentials on the diagram below with vertical spacing labeled in eV from conduction and valence bands, respectively.



b. Now combine the two materials together and draw the resulting band diagram on the graph below, assuming thermodynamic equilibrium has been reached. Label the intrinsic chemical potential μ_i, chemical potential μ (i.e. Fermi energy) valence band maximum, conduction band minimum, vacuum level energy, and width of the space-charge region.

c. Given the dopant densities in part a, calculate the built-in bias V_{BI} (*i.e.* the voltage drop across the junction).

d. What is the width of the space charge region at 0 applied voltage? How does the width change at -0.5 and +0.5 applied volts?

Question #3

In this problem, you will plot and manipulate I-V curves. You may choose your direction of current flow through a solar cell equivalent circuit. You may assume ideal solar cells, and use any equations that fit solar cell output current.

a. Plot "dark" current I-V curve {I(V) versus applied bias V} from -0.5 to 0.8 volts in units of mA. Label the saturation current density, I_0, in this plot. You will need to estimate certain parameters to do this. Indicate the equation used to produce this plot.

b. Re-plot the I-V curve in part (a), now under illuminated conditions. Use the short-circuit current value found in 1e for crystalline silicon.

c. Plot output power P(V) vs. V and determine maximum efficiency for AM1.5 irradiance conditions.

d. On the diagram below, label the direction of the net flow of current through the illuminated device.