2.626 / 2.627: Fundamentals of Photovoltaics
Problem Set #3
Prof. Tonio Buonassisi

Please note: Excel spreadsheets or Matlab code 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 Excel or Matlab, 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: Calculate basic performance parameters (20 pts.)

In this question, we'll have you calculate many of the performance parameters of a solar cell given both the dark and illuminated I-V curves. Assume the illumination is done under AM1.5G illumination. The I-V curves are provided in a separate spreadsheet. The measured cell is similar to the one we investigated in class and has an area of 3 cm^2.

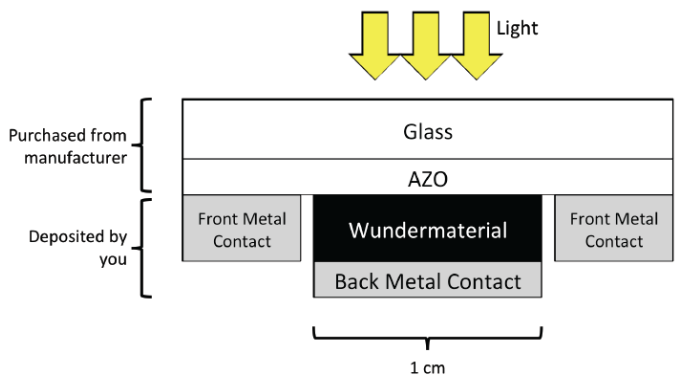
a. (11 pts) Plot the following on a *single* chart with two different y-axes (one for current density [mA/cm^2], the other for output power [mW/cm^2]):
    i. illuminated J-V curve
    ii. dark J-V curve
    iii. power output of illuminated device as a function of voltage

b. (3 pts.) On the plot created in (a), please label the following:
    i. open-circuit voltage (V_{oc})
    ii. short-circuit current density (J_{sc})
    iii. maximum power point.

c. (6 pts.) For the cell, please calculate parameters listed below. For each calculation show the formula used.
    i. Open-circuit voltage
    ii. Short-ciruit voltage
    iii. Voltage at maximum power point
    iv. Current at maximum power point
    v. Fill factor
    vi. Efficiency

Question #2: Effect of series resistance (30 pts.)

The "engineering goal" of your thesis is to make a laboratory-scale solar cell with a new absorber material, "Wundermaterial." You just spent three years optimizing the carrier mobility and lifetime in Wundermaterial by carefully tailoring deposition conditions. You're ecstatic that your advisor is satisfied with your results and supports your efforts to make a solar cell device. After using PC1D to calculate energy band diagrams for various Wundermaterial/buffer-layer heterojunctions, you opt to use aluminum-doped zinc oxide (ZnO:Al, or AZO for short) as your buffer layer, since this material combination has large V_{oc} potential. Since you can purchase AZO-coated glass (AZO layer thickness = 300 nm), you opt to use a superstrate configuration shown below, wherein light enters the device from the top (through the glass):



Your devices have an area of 1×1 cm^2, since that's a convenient size for your deposition system.

You are disappointed when your first solar cell IV curves look like straight lines, *i.e.*, Ohmic resistors. Recalling Liebig's Law of the Minimum, you set about trying to identify the root cause of the low efficiency, which you think might be high series resistance.

a. (10 pts.) You measure the resistivity of the bare AZO layer on glass using a four-point-probe tool, and find that it has a resistivity of 5×10^{-3} Ω-cm. Calculate the <u>sheet resistance</u> of this 300 nm thick AZO layer. (NB: units of sheet resistance are typically given in terms of "Ohms per square," *i.e.*, Ω/☐.)

b. (10 pts.) From your PC1D simulation (a 1-D simulation tool for solar cells,) you determine that your solar cell should operate at 35 mA/cm^2 and 0.62 V at the maximum power point. Calculate the fraction of power lost due to emitter sheet resistance. Hint: See Slides 76–81 of Lecture 6.

c. (10 pts.) You call your AZO manufacturer and ask for lower resistivity AZO or thicker layers. They are out of stock of the good stuff, and your conference presentation is fast approaching. What parameter can you change, to reduce the power loss associated with sheet resistance to below 4% of output power?

Question #3: Diffusion length and Device Performance (30 pts.)
For this problem, we will try to understand the effect of lifetime on device performance, mainly IQE and EQE.

a. (5 pts.) Let's assume we're illuminating our solar cell with monochromatic light. Given the photon flux incident on the surface is some value J_{photon} (in units of photons per area per second,) and the reflectivity is R, and the absorption coefficient α, please come up with an expression for the generation rate, G(x), of free carriers as a function of position, x. Assume that each absorbed photon generates one free carrier. Please express G(x) as a function of x, R, $J_{photon,}$ and α.

b. (5 pts.) If a carrier is generated at a position x, what is the probability of the carrier reaching the junction? We'll call this value the collection probability. Recall that the distance a carrier can travel is often characterized by some representative diffusion length, L_{diff}. Please report the collection probability, CP(x), as a function of x and L_{diff}. Hint: see Martin Green's Ch.8!

c. (5 pts.) From the results of both (a) and (b), please write an equation that relates the probability that a photon that is incident on the device surface generates a carrier that diffuses to the junction. This value is known as the EQE, or external quantum efficiency. For this problem, please make the following assumption:
    - $1/\alpha \ll$ cell thickness
    - junction depth from surface $\ll 1/\alpha$

d. (1 pt.) Given your answer in part (c), write out an equation for IQE, or internal quantum efficiency.

e. (5 pts.) The solution in part (c) is only valid for certain wavelengths and values of α. For what wavelength range are the assumption in part (c) valid for a crystalline silicon device that has a 0.5 micron thick emitter and a the overall device is 200 microns thick. Please explain your reasoning. Recall that optical properties of silicon are posted on PVCDROM.

f. (9 pts.) Impurities in silicon can greatly decrease the lifetime of photon-excited carriers. Let's explore just how bad one contaminant, iron, can have on our device. The plot given below shows the lifetime of free carriers in silicon as a function of different iron contaminants. For this problem you may assume the base is p-type and the diffusivity at room temperature of free electrons (minority carriers) is 36 cm^2/sec. The diffusion length is calculated by the following: $L_{diff} = sqrt(D*\tau)$, where τ is the lifetime of the carriers. Please answer the following:

- What lifetime will bring the IQE (not EQE!) below 90%?
- What concentration of iron interstitial atoms to reduce the lifetime so that the IQE (not EQE!) of 900nm light drops to 90%? Please note that the black markers on the plot below represent the iron interstitial concentration, which is reported in atoms/cm^3.
- If a solar cell uses silicon that is 200 μm thick, what amount of iron (in grams) does this translate to for a 1m×1m panel? Does this number surprise you?

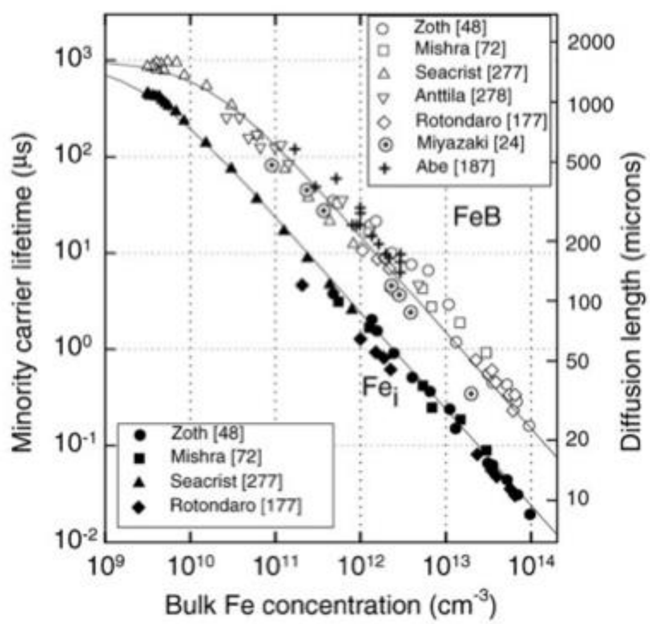


Fig. 5. The dependence of the lifetime limited by iron in the form of interstitial iron or FeB pairs on the iron contamination level. *Solid lines* are simulations according to (6) and (8), assuming $\tau_s = 1$ ms

A. A. Istratov, H. Hieslmair, and E.R. Weber, *Appl. Phys. A*, **70**, 489 (2000)

Question #4: Class project (15 pts.)

Peruse the list of class projects we posted after Lecture 7, and pick three that capture your interest. Write a short paragraph for each, describing why your background and interests are ideally matched to that project. Class instructors will use this information to form project teams, so be sure to pick wisely!

2.627 / 2.626 Fundamentals of Photovoltaics
Fall 2013