

2.626/2.627 Fall 2011 – Fundamentals of Photovoltaics

Quiz #1 – Due 9:30am Session #10

Quiz Instructions

- The undergraduate version of this quiz (2.627) consists of four (4) multipart questions for a point total of 80.
- The graduate version of this quiz (2.626) consists of five (5) multipart questions for a point total of 100.
- This is a take-home examination. The quiz will be handed out on Friday October 7th, and is due completed at 9:30am on Session 10.
- This is an individual effort. Each student is expected to hand in her/his own exam. You are not allowed to discuss the quiz with each other.
- All resources (written, verbal, and otherwise) are at your disposal. (The only exception is that you are not to talk, discuss, or otherwise share information pertaining to this quiz with other people.)
- Quizzes may be submitted online.
- Quizzes arriving within 24 hours after 9:30am on 10/13, either in person or online, will incur a 25% late penalty. Quizzes arriving 24 hours after 9:30am 10/13 will not be accepted, barring extraordinary circumstances.

1. Class Project [15 pts]

Peruse the list of 2011 class projects online 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. Better Estimates for PV Output [25 pt.]

In this course, we often use the following “peak hours” formula to calculate the daily energy output from a PV array, given the solar insolation:

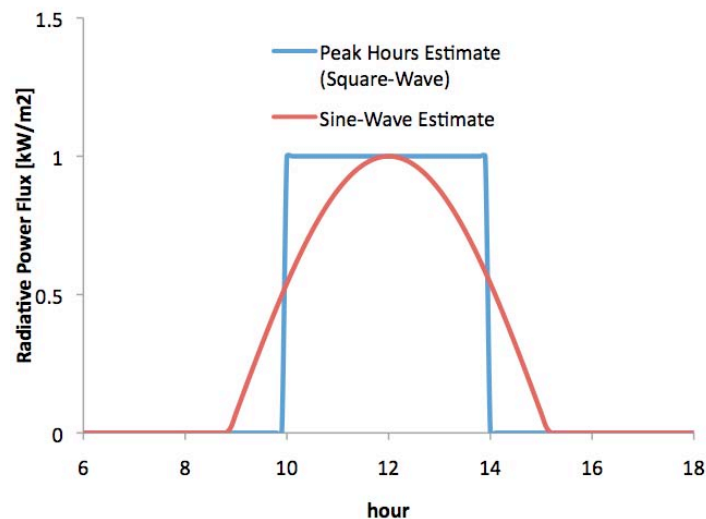
$$\text{Daily Energy Output} = \frac{P_{\text{rated}} \times S}{\Phi_{AM1.5G}}$$

P_{rated} = Rated Peak Power of PV Panel

$$S = \text{Insolation} \left[\frac{\text{kWh}}{\text{m}^2 - \text{day}} \right]$$

$$\Phi_{AM1.5G} = \text{Radiative Power Flux at peak sun} \left[\frac{\text{W}}{\text{m}^2} \right]$$

This formula is equivalent to saying that a panel will receive $S/\Phi_{AM1.5G}$ peak hours of sun per day. In other words, if Boston receives 4 kWh/m²/day, our formula will assume that our panels will see 4 hours of sun that has an intensity of 1kW/m². However, this overestimates the amount of power output from our PV array because the efficiency of a solar cell decreases at lower illumination levels. Therefore, we should really account for these lower efficiencies to get a better estimate for the power output. One possibility is to model the radiative power flux as a sine wave instead of a square wave:



To obtain our more accurate power output estimate, we need to estimate how the efficiency scales with illumination intensity. Recall that our efficiency scales with the product of the J_{sc} and V_{oc} (we'll assume that FF doesn't change with illumination intensity.)

- a) If we assume that our J_{sc} is equal to our illumination current, how does J_{sc} scale with our radiative power flux, Φ . In other words, is our $J_{sc}(\Phi)$ function linear, quadratic, exponential, logarithmic, etc? Please explain your reasoning. [7 pt.]

- b) Now that we have an estimate for J_{sc} , we can use our equation for V_{oc} to estimate how it scales with Φ :

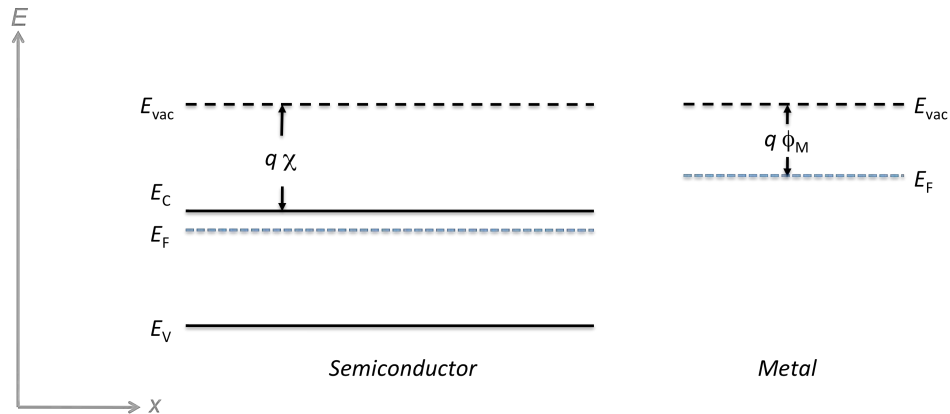
$$V_{oc} \propto \ln\left(\frac{J_{sc}(\Phi)}{J_{sc}(\Phi_{AM1.5G})} + 1\right)$$

Using your answer from part (a), please write out an expression for how V_{oc} scales with Φ . [7 pt.]

- c) Given your answer in (a) and (b) above, write out a formula for how efficiency scales with Φ . Your answer should also include some normalization factor, $\Phi_{AM1.5G}$, that denotes the peak sun radiation flux (as shown in part (b).) Again we are assuming that FF remains constant. [3 pt.]
- d) Now that we have an estimate for how the efficiency scales with the sun's radiative power flux, estimate the fractional decrease in daily energy output if we assume a sine wave function for Φ as opposed to a square wave. To get full credit, please indicate the following:
- i. The equations you used to estimate both your "peak hours" and "sine-wave" solar radiation flux as a function of time. Your "sine wave function" should have a peak radiative power flux equal to one sun illumination. (Hint: if you integrate the two curves for Φ , you should get the same insolation for both! Please take care in creating your equations!) Your solution should be valid for any value of insolation. [4 pt.]
 - ii. The equation used to estimate the ratio of daily energy output from a PV panel that sees a "sine wave" temporal profile vs. a "peak hour" (or square wave) temporal profile for Φ . [4 pt.]

3. Metal Contact / Semiconductor Energy Band Diagram [20 pts]

This question asks you to draw an energy band diagram for a metal contact / semiconductor junction. Consider the metal and semiconductor below, separated by an imaginary barrier, with vacuum energy (E_{vac}), conduction band energy (E_C), valence band energy (E_V), Fermi energy (E_F), electron affinity (χ), and work function (Φ_M) defined:



- To draw a metal contact/semiconductor energy band diagram, first line up the vacuum levels on each side of the “imaginary barrier” between the two materials, as shown above. Notice how the Fermi levels don’t line up. (*No action required*)
- Shift the semiconductor’s energy band diagram up or down until the Fermi energy matches that of the metal (make sure all horizontal lines move together – E_V , E_C , E_F , E_{vac}). Plot this configuration on an energy band diagram, labeling all variables as shown on the figure above. [5 pts]
- Once the imaginary barrier is removed, free carriers will move across the junction until equilibrium is established (diffusion and drift currents). The build-up of charge at the interface within the semiconductor will cause a field to form, which will cause the potential energy of free carriers to change within the semiconductor as one nears the junction. As a function of “x” across the semiconductor-metal junction, plot: (i) the charge distribution; (ii) the resulting electric field; (iii) the potential energy of free carriers; and (iv) the electron energy. Label axes. (Hint: You may wish to follow the general approach outlined in Lecture 5, slides 19 onward.) Congratulations, you’ve now sketched the energy band diagram of the contact! [5 pts]
- This ideal case assumes zero density of interface states. If interface states exist between the metal and the semiconductor, describe qualitatively in a sentence how you would expect the energy band diagram to change? [5 pts]
- Will this junction have a linear (ohmic) or exponential (Schottky) current-voltage response? [5 pts]

4. Recombination in Solar Cell Materials [20 pts]

You work at the PVClass solar company, a crystalline silicon solar cell company that buys wafers from other companies and then processes them into solar cells in-house, selling finished cells to customers. Your company makes cells with n-type emitters and p-type bases. You have recently been making major improvements to your solar cell fabrication process in an attempt to cut costs and stay alive in this competitive solar market. Your two most recent changes have been: (1) increasing the deposition rate of your silicon nitride (SiN_x) antireflection coating (ARC), and (2) switching your silicon wafer supplier, which can provide wafers at a much lower cost. Unfortunately, one of these changes to the cell fab line has decreased your short-circuit current dramatically. Your boss claims that this is due to increased SRH recombination due to iron contamination found in the new wafers, while you claim changing the SiN_x deposition rate has greatly increased surface recombination. Let's try to figure out who is right.

- a. You decide to measure the minority carrier lifetime of two wafers of different thicknesses. Both wafers have SiN_x ARC deposited on both sides. You get the following lifetime results:

| Thickness (μm) | Measured Lifetime, τ_{bulk} (μs) |
|--------------------------------|---|
| 180 | 12.5 |
| 500 | 22.4 |

You make the assumption that the lifetime is only limited by two major factors: recombination due to iron contaminants and surface recombination. Given this assumption, please calculate: (1) the surface recombination velocity and (2) the bulk minority carrier lifetime limited by iron (τ_{SRH}). You may assume that the diffusivity of electrons is $36 \text{ cm}^2/\text{sec}$. (Hint: See lecture 8 notes, slide 43, to learn more about decoupling bulk and surface lifetime effects.) [10 pts.]

- b. Using the τ_{SRH} you found in (a), estimate the iron concentration in the silicon. You may assume that all iron atoms are interstitials (Fe_i .) You also recall from the PV class you took in grad school that the capture cross section for Fe_i in silicon is $4 \times 10^{-14} \text{ cm}^2$ for electrons, and that the thermal velocity for electrons in silicon is calculated by $v_{th} = \sqrt{kT/m_e^*}$, where m_e^* is the effective mass of an electron in silicon. You may assume that the lifetime measurements were performed in the low-injection regime. [10 pts]

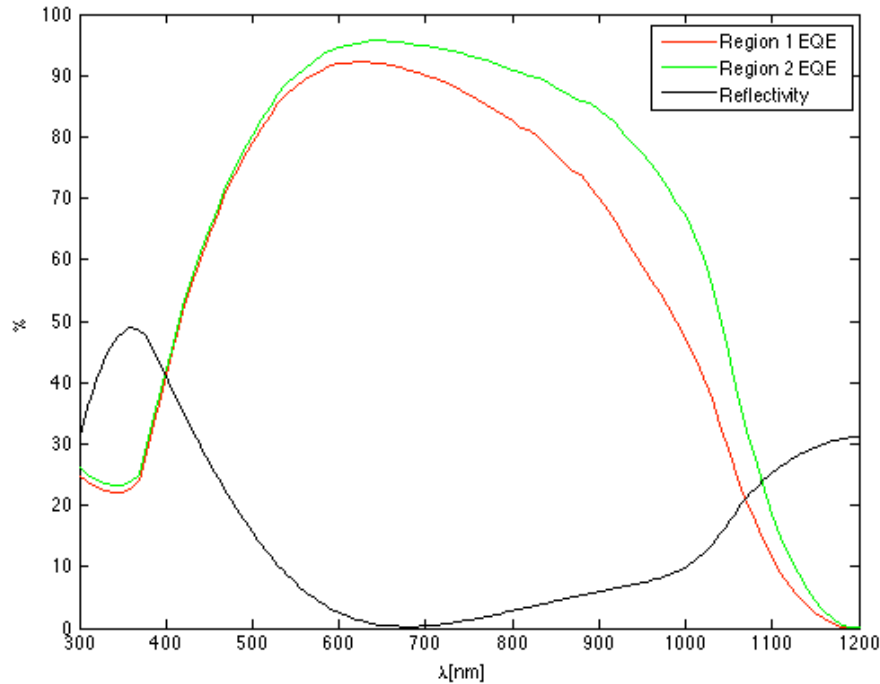
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5. Measuring Diffusion Length [20 pt.]

In Problem Set 3, we learned how to calculate EQE/IQE for a particular wavelength of light knowing the bulk diffusion length. Again, this formula is only valid for wavelengths that have an absorption depth, $1/\alpha$, that is much shorter than the device thickness and much longer than the emitter depth, such that the diffusion lengths of photogenerated carriers are not unduly affected by the front or back surface fields.

$$IQE = \left(1 + \frac{1}{\alpha L_{diff}} \right)^{-1}$$

Below are two EQE curves taken from different locations on the same multicrystalline solar cell, as well as the reflectivity of front surface (which is coated with an ARC). Region 1 is full of many small grains (and grain boundaries, *i.e.*, crystal defects), and Region 2 is in the middle of a large grain on the cell (largely devoid of defects). Notice the EQE of Region 1 (the defect-rich region) is generally lower than Region 2 (the defect-free region).



- a) The values for EQE for both regions and the reflectivity are posted online. Please use the posted data to plot IQE over the full wavelength range. [3 pt.]
- b) On the graph you calculated in part (a), please identify the three characteristic regions of the IQE data: [8 pt.]

- i. Wavelength range governed by front surface effects
 - ii. Wavelength range governed by bulk recombination
 - iii. Wavelength range governed by back-surface effects and non-absorption.
- c) With some careful manipulation of the equation shown above, we obtain the following formula:

$$IQE^{-1} = 1 + \alpha^{-1} L_{diff}^{-1}$$

From this formula, we see that if we plot IQE^{-1} against α^{-1} , then the slope of that curve is equal to the inverse of the diffusion length. Note that the values for α can be found online and are assumed to be that of crystalline silicon.

- i. Plot IQE^{-1} vs. α^{-1} for both Region 1 and Region 2. Please only plot the range of wavelengths where the IQE response is governed by bulk recombination. [3 pt.]
 - ii. From these plots, estimate the diffusion length and report their values in microns. [3 pt.]
- d) Given the information about the two regions, what recombination mechanism is most likely responsible for the difference in diffusion lengths? [3 pt.]

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