EEE 434/591 – Fall 2024

Project 01

Have you ever wondered why solar cells and panels have such a low efficiency? Silicon cells barely make it into the 24% range. Is there a material that can perform much better?

It turns out that a significant part of the efficiency limitation is due to Quantum Mechanics, specifically the Photoelectric Effect. When we discussed the Photoelectric Effect for electrons in a metal, which escape into vacuum, we had to remember the following two rules:

1.) Photons get absorbed and they transfer their entire energy to the electron.
2.) The energy transferred to the electron allows it to overcome the work function barrier energy. Any additional energy will become kinetic energy of the electron.

Since these are free electrons in vacuum, they maintain their kinetic energy until they collide with an electrode or the vacuum vessel itself.

In a crystal, for example a semiconductor, the photoelectric effect works just like in a metal: The photon transfers its entire energy to an electron and raises the electron energy so that it can cross the “band gap”. The band gap replaces the metal work function in a semiconductor. The excess photon energy is then transferred to the electron and raises its kinetic energy. In a semiconductor, the electron leaves behind an electron hole, which can also pick up kinetic energy from the photon. One only must make sure that the total energy is conserved. In the crystal, however, the carriers will lose their kinetic energy very quickly (on the order of femtoseconds), much quicker than the time it takes for them to move to the external contacts. Thus, in case of a semiconductor, the kinetic energy of the electrons can be assumed to always be zero. A high-energy photon will lose most of its energy, because only the part that allows the electron to cross the band gap is being “harvested”.

Usually, you would look for a material that has the smallest work function/band gap, because it allows a larger energy range of the radiation spectrum to be harvested. However, because that band gap energy will now determine the maximum energy per photon that can be harvested, smaller band gaps are not necessarily beneficial. There is a simulation tool on Nanohub, which allows you to calculate the conversion efficiency versus band gap energy, as shown in Figure 1. https://nanohub.org/tools/pvlimits

In this project, you are supposed to find how much of the energy conversion efficiency reduction is due to the band gap energy determining the total energy harvested and not the photon energy itself. The key to answering the question is to find the number of photons per energy interval and sum them up if they are above the band gap. The harvested energy is then the product of total photons times the band gap energy.

Rather than using experimental data for the solar radiation outside of Earth’s atmosphere, we will use Planck’s Distribution to determine the number of photons per energy interval.

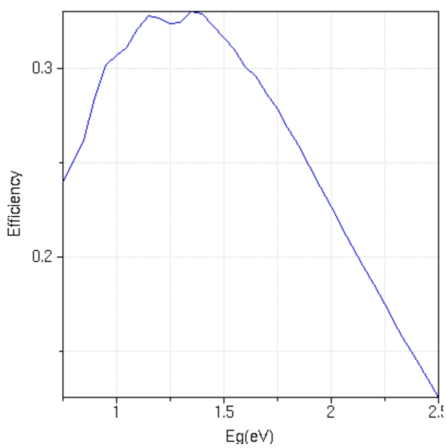

Figure 1: Photovoltaic Cell Efficiency versus Band Gap Energy as simulated on Nanohub. The efficiency peaks at 1.1 eV and 1.3 eV.

Task 1 (40 points):

Based on Planck's law for the radiance of the Sun, assuming a temperature T of 5775K, **create four plots to put in your report**, which show

1.) The spectral irradiance versus photon wavelength
2.) The spectral irradiance versus photon energy
3.) The photon flux versus photon wavelength
4.) The photon flux versus energy.

You can convert the radiance of the object to the irradiance by multiplying the radiance by the steradian angle of the Sun's disc as it is observed on Earth. That value is 6.794e-5 sr. At the end of Task 1, you should have four plots that look similar to the ones on the PV Lighthouse web site (shown in Fig. 2): https://www.pvlighthouse.com.au/cms/lectures/altermatt/solar_spectrum/intensity-or-flux

The axis labels should match the ones on PV Lighthouse, except that you should not convert the photon flux to mA, but leave it as Number of photons/s. (Not mA/(cm^2*nm), but photons/(s*m^2*nm), not mA/(cm^2*eV), but photons/(s*m^2*eV)).

I strongly recommend doing this in Python using numpy and matplotlib. An example code can be found on the following website: https://web.archive.org/web/20221105082528/https://dpotoyan.github.io/Chem324/python-intro.html#plotting-with-matplotlib

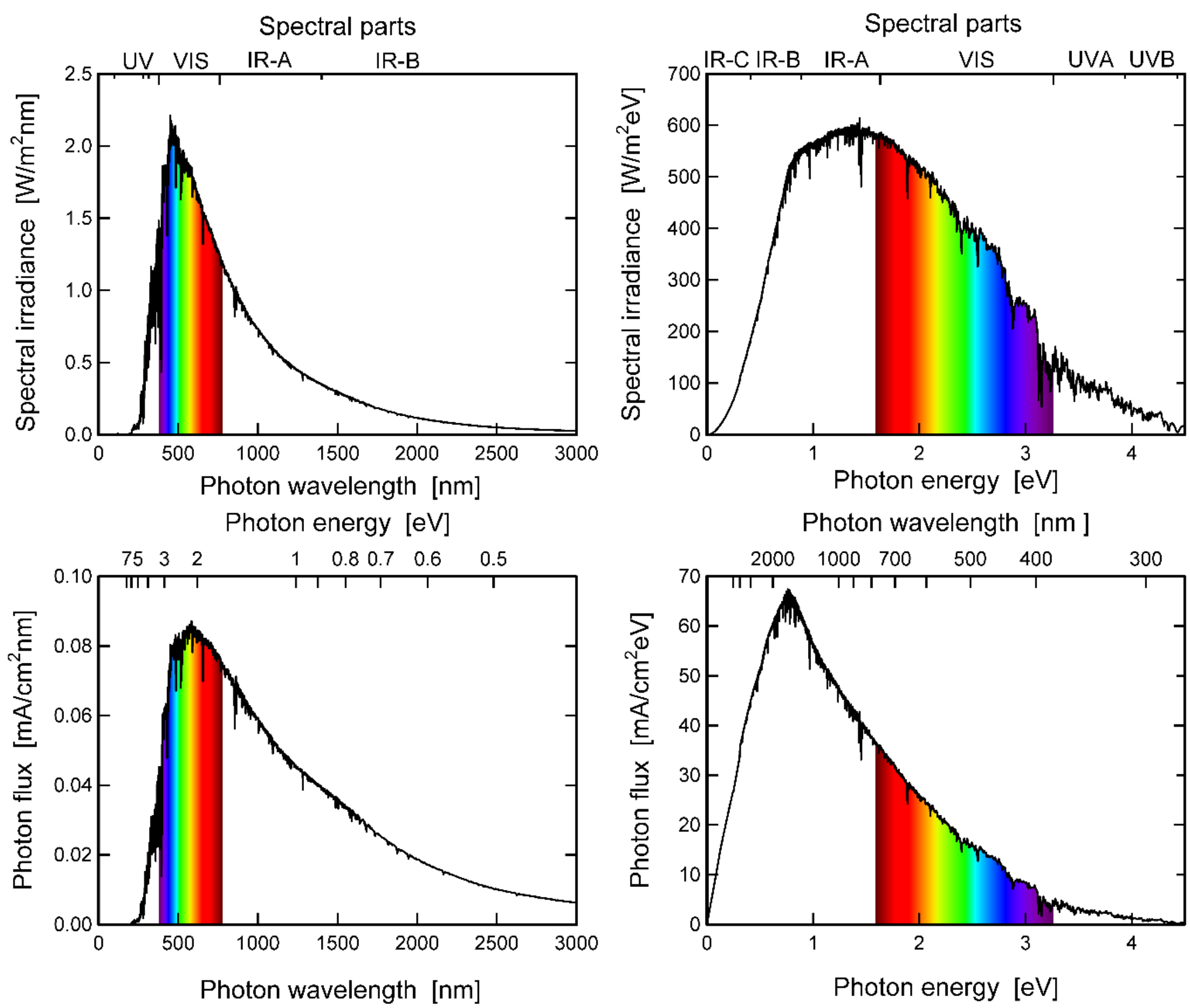

Figure 2: AM0 sun spectrum as shown on the PVLighthouse website (Copyright: Pietro P. Altermatt, on-line lectures, www.pvlighthouse.com.au).

Task 2 (40 points):

Calculate the integral of the spectral irradiance over wavelength and compare it to the integral over of the spectral irradiance photon energy (first two plots). Both integrals should be identical. They can differ slightly based on the integration limits (wavelength or energy range). Repeat the integral calculations for the plots of the photon density, multiplying the photon density for each data point with the respective photon energy. The integrals should match the values for the previous cases. This is a sanity check whether the transformations were performed properly. **List all four integral values in W/m² units in your report.**

Since we are not taking absorption in the Earth atmosphere into account, the spectrum will be close to that of AM0, which has an integral value of 1366 W/m². Since your integration limits are different, the value will be closer to 1300-1320 W/m². You should make sure that your integration limits match, because that could lead to discrepancies and might cause confusion. You can calculate the integral on a different x-axis range than the plot if you want to “zoom in” on one region of the plot, but you don’t have to. Make sure that the x-axis has points that are equidistantly spaced and have a delta of 1 between the points if you want to use the short form of the trapz function in numpy.

Task 3 (20 points):

Calculate the harvested power depending on the band gap of the absorber material. You should obtain a graph that looks like the one shown in Figure 1 but with a higher peak and less features, because you are missing things like surface recombination losses.

To get started, use the dataset of photon flux versus energy, which is Plot 4 from Task 1. Rather than integrating over all energies like in Task 2, start the integral at the band gap energy of the absorber material, for example 0.5eV. Once you calculated the integral, you should multiply this value by the band gap energy to obtain the harvested power in W/m^2.

Then, repeat the calculation, increasing the band gap energy up to 2.5eV. You can do this in a for loop or you can use the photon energy in the x array as a parameter to create an array treating the photon energy as the band gap energy. There is no preferred approach; you can use whatever method you are comfortable with.

Once you have the data set of harvested power versus band gap energy, you can divide it by the value you obtained in Task 2 to get the efficiency for every band gap energy. Finally**, plot the efficiency versus band gap energy and enter it in your report**. There should be a peak around 1.2 eV.

Bonus (10 points):

Compare the efficiency of a single junction Silicon cell (Band gap 1.1eV) with a crystalline silicon – amorphous silicon heterojunction (HIT) cell (1.1eV and 1.7eV).
https://en.wikipedia.org/wiki/Heterojunction_solar_cell

For the crystalline silicon cell, you can just pick the value for the band gap energy out of your array you calculated in Task 3 or you can perform the integration again, using a band gap energy of 1.1eV, multiplying with 1.1eV band gap energy. For the heterojunction cell, you need to stop the integration at the larger band gap value and then re-start the integration at that point, now multiplying with the larger band gap value. **List the efficiency values for the single junction Silicon cell and the Silicon Heterojunction cell in your report.**