Photovoltaic energy conversion

Objective

The objective of this laboratory is for you to explore the science and engineering of the conversion of light to electricity by photovoltaic devices.

Preparation

Read Kasap sections 6.10 and 6.11; review the lecture notes.

Equipment and samples

- Small area photovoltaic modules; reverse-biased Si p-i-n photodiode.
- White light LED lamp; dc power supply; bread board; decade resistor box; voltmeter.
- Quartz halogen light source coupled to a monochromator.
- Optical chopper; lock-in amplifier.

Introduction

In MSE 307, we studied the use of thermoelectric semiconductor p-n junctions to convert a flow of heat to electrical power. In this lab, you will study how photovoltaic semiconductor p-n junctions are used to convert light to electricity. The thermodynamic limits of the Carnot efficiency are still present in a photovoltaic device but because of the large difference in temperature between the surface of the earth and the surface of the sun, the Carnot efficiency is >90%. For an ideal single-junction photovoltaic, the maximum efficiency is ≈30% because the photovoltaic energy conversion process is optimal only for photons with energies above, but not too far above, the band-gap. Various non-idealities—e.g., recombination of minority carriers at defects and surfaces, series and shunt resistance, optical reflection—reduce the efficiency of cost-effective solar cells to <20%. These non-idealities are revealed in the magnitude and shape of the I-V curve of the photovoltaic device. More detailed information can be gained by studying the conversion efficiency as a function of the wavelength of light that illuminates the device.

At noon on a clear day, the solar intensity in Central Illinois is ≈ 1000 W m^{-2}; averaging over day and night and cloud cover gives 200 W m^{-2} of average intensity. Thus, we can expect ≈ 40 W average power from a 1 m^2 photovoltaic panel constructed from high efficiency materials.

Session 1: Measure the I-V characteristics of photovoltaic devices.

- Connect a power supply, decade resistor, photovoltaic device, and volt meter to the bread-board so that you can measure the I-V characteristic in the dark.

- Illuminate the photovoltaic device with the white-light LED lamp. Omit the power supply and reconfigure the circuit so that you can measure the I-V characteristic under illumination.

- Compare the two I-V curves for the device in the dark and under illumination. For an ideal photovoltaic device, the curves are shifted from each other by a constant current. (This current is the short-circuit current I_{sc}; In an ideal device, I_{sc} is proportional to the intensity of illumination.)

- What value of the load resistor produces the maximum power under illumination? What is the fill-factor?

- For a high-efficiency device, the dark current is given by the diode equation with a non-ideality factor that is not too much larger than 1. Is it reasonable to describe the dark current of this device using the diode equation? If so, what is the non-ideality factor? Note that we are only interested in relatively large forward biases, V>>25 mV, so you can approximate the full diode equation by an approximate form,

$$I_d \approx I_0 \exp\left(\frac{eV}{\eta k_B T}\right) \quad .$$

Session 2: Measure the spectrally-resolved photocurrent of photovoltaic devices.

- The first step is to measure the spectral intensity of the output of the monochromator. The spectral intensity (power per unit wavelength) is not constant because the quartz halogen lamp emits a black-body spectrum and the reflectivity of the grating is not independent of wavelength. You will use a reverse biased p-i-n photodiode to measure the spectral intensity. The photodiode is nearly ideal in this wavelength range and, in any case, the response curve of the photodiode, i.e., the photocurrent as a function of the wavelength of light is well characterized.

- Place an optical chopper as close as possible to the output of the monochromator and place the photodiode adjacent to the chopper so that light from the monochromator illuminates uniformly illuminates the device. You may need to switch off the room lights so that you can better observe the light exiting the monochromator.

- Connect the sync output of the optical chopper to the reference input of the lockin and and connect the photodiode to the signal input of the lockin. You will want to use the settings of the lockin amplifier that provides a "virtual ground" at the input and enables the direct measurement of the short-circuit current. Measure the photocurrent as a function of the wavelength of light.

- Use your data and the response curve of the photodiode to determine the spectral intensity of the output of the monochromator.

- Now measure the spectrally resolved photocurrent of the photovoltaic device. Remove the photodiode and place a photovoltaic device adjacent to the chopper so that light from the monochromator illuminates a large fraction of the area of the device. You will probably want to use the breadboard to facilitate connecting the photovoltaic device to the lock-in. Measure the photocurrent as a function of the wavelength of light.

- Normalize the raw data by the spectral intensity of the monochromator.

- Compare your result to the behavior expected of an ideal device. For an ideal device, the photocurrent is proportional to the wavelength. In other words, for an ideal device, a plot the normalized data versus wavelength will be a straight line with a zero intercept.

- Repeat the steps above for a second photovoltaic device.