Laboratory 4
Photoelectric Energy Conversion

Objective:

The objective of this lab is to gain a better understanding of the electronic properties of semiconductors by measuring the electrical characteristics of a simple p-n junction solar cell. From the measurements, you will learn how light is converted to electricity in a photovoltaic device.

Preparation

Read

- Sok-Sec6, Solar Cell, (on Compass 2G site) (Kasap reference below)
- Solar Cell PDF (on Compass 2G Site)

Equipment and samples

- Small area photovoltaic module (solar cell) with mask
- White light LED lamp
- DC power supply (2)
- Bread board
- Decade (variable) resistor box
- Voltmeter
- Newport monochromator
- Thor Labs DET100A Silicon Photodiode
- 2.2 Ω and 100 kΩ resistors
- Validyne system

Laboratory Safety - Photoelectric Energy Conversion

Required PPE

- Long Pants
- Closed toe shoes
- Safety Glasses

Introduction:

Conversion of solar energy into electricity is a clean, sustainable way to meet the growing energy requirements of the world. The simplest, most common device for such a photoelectric conversion is a p-n junction solar cell, made by placing a p-type semiconductor against an n-type semiconductor. The basic concept for a semiconductor solar cell or photovoltaic device is that the atoms in a semiconductor exposed to the sunlight will absorb photons from the solar radiation and subsequently generate charge carriers, which then move through the semiconductor to the electrical contacts as electric current. Many semiconductors can be used for this purpose, but the most common is Si. Si has become the dominant solar cell material because it has an intermediate bandgap energy of 1.12 eV, which allows a significant portion of the solar spectrum to be used for photoelectron conversion, enjoys the support of a well-established semiconductor industrial infrastructure, and is the least expensive to produce.

Conventional crystalline Si solar cells are generally made from wafers of Si crystal a few hundred micrometers in thickness, sliced from lightly p-type doped crystalline ingots. The top surface layer of the wafer is doped into n-type by diffusing n-type dopants (often phosphorous) across the surface, creating the p-n junction. Both the top and bottom surfaces of the wafer are then coated with metallization layers which serve as the electric contacts to the cell. Additional layers such as antireflective coating may be added to enhance the light absorption.

In this lab, you will study the electrical characteristics of a Si solar cell. In the first part of the lab, you will determine the I-V curves of the solar cell under forward and reverse biases. In the second part, you will investigate what will happen when light is directed onto the solar cell.

Laboratory Procedure:

I-V Characteristics of Solar Cell

Connect the p-n junction solar cell with a 2.2 Ω resistor, R, a power supply, P, and the Validyne system that will measure two voltages, V, as shown in Figure 1 below, through the terminals on the bread board. When the light is switched off, you can measure the current, I, from the reading of voltage 1, V1, by the equation I = V1/R and the voltage across the solar cell, V2, to obtain the I-V curve of the solar cell in the dark under the forward bias. After completing the measurements for forward bias in the dark, switch the leads at the power supply to reverse polarity and repeat the measurements for reverse bias. Wrap the black shielding cloth around the solar cell to block out all ambient light.

Vary the applied current and voltage by turning the knobs on the power supply. When the light indicating that the supply is current-controlled is on, only vary current and not voltage. When the light indicating that the supply is voltage-controlled is on, only vary voltage and not current. ***Make sure not to exceed a current of 0.8 A in forward bias to avoid burning the resistor. Do not exceed 1 V in reverse***

bias to avoid breaking down the solar cell. For the LED lamp, the power supply should be set to a voltage of 12 V and a current of less than 0.3 A.

Switch on the power supply connected to the LED lamp and complete the same measurements for the solar cell in the light. The black shielding cloth should be relocated to cover the entire box, blocking out all ambient light but allowing light from the LED to hit the solar cell.

Compare the I-V curve with the diode equation to estimate the ideality factor, η. Due to series and shunt (parallel) resistance (Figure 2), the curve will not perfectly fit an exponential model over the entire voltage domain. Carefully consider which region of your data to fit – it may be helpful to use a semi-log scale. For a high-efficiency device, the dark current is given by the diode equation with an ideality factor that is not too much larger than 1. Compare the dark current of this device with the diode equation and find the ideality factor. Find the series resistance by using a linear line of best fit in the region of high forward bias, and find the parallel or "shunt" resistance by using a linear line of best fit in the region of high reverse bias. Comment on the values of the ideality factor, and series and parallel resistance you obtain.

Include a plot of the I-V curves for both dark and light conditions in your report. You may need to zoom in on a particular area of the curves to show the difference between them.

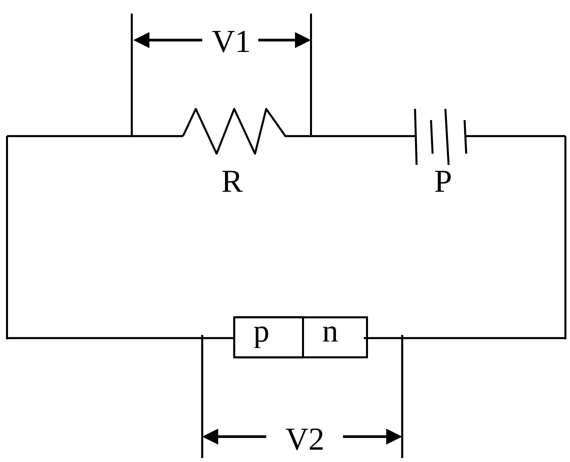

Figure 1: the circuit diagram used to measure the solar cell in operation.

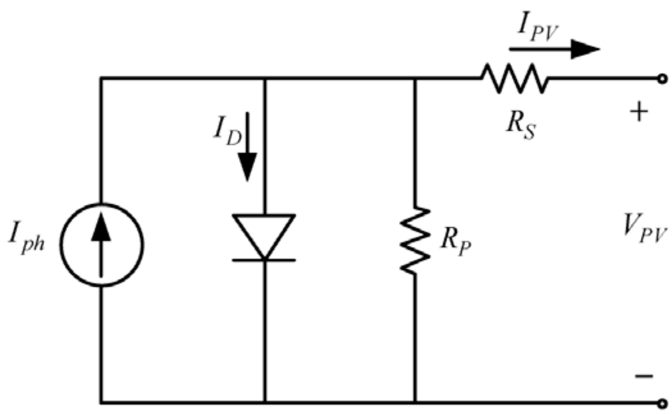

Figure 2: the equivalent circuit for a real p-n junction.

Photovoltaic Energy Conversion

Replace the power supply with a decade resistor, illuminate the solar cell with the white-light LED lamp, and measure the I-V characteristics under illumination. Vary the resistance from 0.1 Ω up to 1 MΩ. Be sure to include this data in the I-V curve construction.

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.).

Find the maximum power under illumination and the fill factor for the solar cell.

Diode Equation

$$I = -I_{\mathrm{ph}} + I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

Where I_{ph} is the photocurrent, I_0 is the reverse saturation current, e is the charge of an electron, V is the voltage, k is Boltzmann's constant, T is the absolute temperature and η is the ideality factor (typically 1-2).

Fill Factor

$$\mathrm{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}$$

Where I_m is the maximum output current, V_m is the maximum output voltage, I_{sc} is the short circuit voltage, and V_{oc} is the open circuit voltage. $I_{sc}V_{oc}$ represents the desirable goal for power delivery, but all solar cells fall short of 100% fill factor. Create a plot of power vs voltage in order to determine the maximum power point, and use this value to determine the fill factor for our solar cell. How does this compare to published or expected values for a silicon solar cell?

Input Power

Next determine the photoelectron conversion efficiency of the solar cell, $\Sigma = P_{max}/P_{in}$, by measuring the power input, P_{in}, from the LED lamp. The power coming from the LED lamp is measured by a photodiode, which provides the power received, P, according to the expression: $P = I_{pd}/R(\lambda)$, where I_{pd} is the photocurrent in the photodiode, and $R(\lambda)$, the responsivity of the photodiode at a given wavelength, λ, of the incoming light. The photodiode current, I_{pd}, is measured by placing a resistor with known resistance (approximately 100 kΩ, but be sure to measure your exact resistance using the provided multimeter) in series with the photodiode and measuring the voltage across the resistor. Make sure to subtract the "dark current" measured when the photodiode is on but the light is off from each light current measurement so that there is no net current detected at wavelengths where the white light source doesn't emit. Remember to turn off the photodiode when not in use.

Since the LED lamp covers a wide range of wavelength from 400 nm to 800 nm, an average responsivity, R_{avg}, is used to replace $R(\lambda)$ in the calculation of the power P above, namely $P = I_{pd}/R_{avg}$. R_{avg} is obtained from the following equation:

$$R_{avg} = \frac{I_1 + I_2 + I_3 + \ldots}{P_1 + P_2 + P_3 + \ldots} = \frac{\sum_{\lambda_J = 400nm}^{800nm} I_J}{\sum_{\lambda_J = 400nm}^{800nm} P_J}$$

by measuring the photodiode current, I_j, at wavelength, λj, varying from 400 nm to 800 nm (selected using the monochromator) in increments of 10 nm, and by calculating the power, P_j, at the same wavelength from $P_j = I_j/R_j$, where R_j is the intrinsic responsivity of the photodiode provided by the manufacturer (included on Compass). The power so obtained comes only from an area equal to the size of the photodiode window, which is much smaller than the area of the entire solar cell panel; therefore, a mask has been placed over the solar cell, to give a comparable area for analysis. Remove the monochromator and record the voltage across the resistor for the photodetector under illumination.

Include a plot of power vs wavelength to show how the detector response varies as a function of the wavelength of the light. Calculate the input power from the LED lamp, and use that to determine the efficiency of our solar cell. How does this efficiency compare to published values for silicon solar cells?

References:

1. S. M. Sze, Semiconductor Devices: Physics and Technology, Bell Telephone Laboratories, Inc., 1985.
2. S. O. Kasap, Principles of Electronic Materials and Devices, McGraw-Hill, 2002.