Lab 2. Characterization of Solar Cells

Physics Enhancement Programme
Department of Physics, Hong Kong Baptist University

1. OBJECTIVES

- To familiarize with the principles of commercial solar cells
- To characterize critical parameters
- JV curves and load line
- Energy storage with solar cell

2. INTRODUCTION

Solar energy is an indispensable component in Green Energy. A solar cell is a device which converts energy of visible light (photons) directly into electricity. Common solar cells are constructed from thin films of silicon (Si) p-n junctions. Silicon solar cells are now put into mass scale production, and the demand is worldwide and is still growing. Their applications range from powering small electronic devices (e.g. calculator) to providing the sole source of electricity to some isolated locations in HK, elsewhere in the world, and even in space.

3. BASIC THEORY

A photovoltaic cell is a device to convert solar energy into electrical energy. The energy conversion is based on the formation of a semiconductor pn junction (Fig. 1).

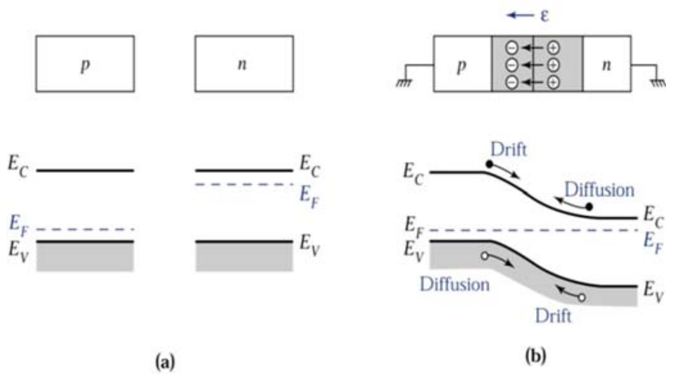


Fig. 1 – Formation of a Semiconductor pn Junction.

For solar cells made from silicon (Si), *p*-material is made by doping crystalline Si with a small concentration of group III elements (e.g. boron), whereas *n*-material is made by doping Si with group V elements (e.g. phosphorous). In the absence of light, mobile electrons and holes neutralize each other near the junction region. What are left behind? On the n-side, there are ionized, but immobile P^+ ions; on the p-side, ionized, and immobile B^- ions.

When a pn junction solar cell is exposed to the sunlight, the absorbed photons generate electron-hole pairs. Near the junction, the generated electron-hole pairs are then split apart by the built-in electric field arising from the immobile ions. The excess electrons and holes migrate to the n and p-side, respectively, giving rise to photovoltage / photocurrent.

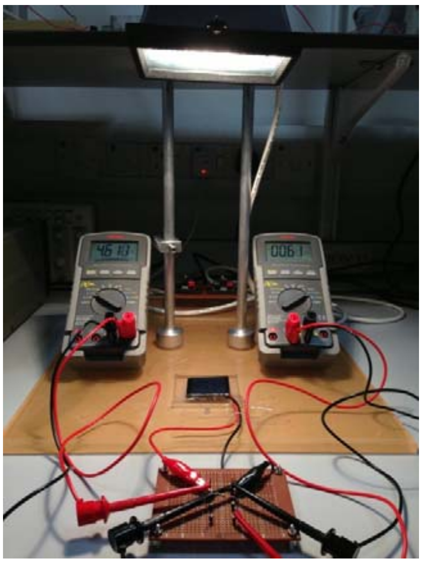
4. EXPERIMENTAL DETAILS

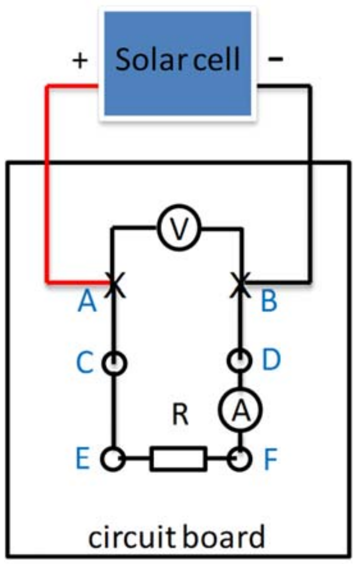
Apparatus and components:

- Solar cell (poly-Si cell)
- Tungsten lamp on a stand. The lamp will be used to imitate sunlight.
- Digital multimeters (DMM) x2. One of the DMM will be used as an ammeter to measure current, whereas the other DMM will be used as a voltmeter to measure voltage.
- Resistors
- Supercapacitor and LED

i. Measuring current (I) – voltage (V) characteristics of solar cells.

Obtain a poly Si-based solar cells from your instructor. Place it on the bottom of stand as indicated. Then slide the tungsten lamp (which imitates the sun) along the rails up and down until the lamp is about 30 cm from the cell. Wire up the solar cell in series with a DMM. The DMM should be set to measure current. Connect the positive terminal (red wire) and negative terminal (black wire) of the cell to terminal A and B on the circuit board, respectively; then connect the current input of the DMM to terminal F and the COM terminal of the DMM to the negative terminal (black wire) of the solar cell. To complete the circuit, insert different values of resistors between E and F. (See picture below)





Now insert a piece of bare wire (R = 0 Ohm). Check everything is connected properly. Then switch on the lamp and wait for about 1 minute for the lamp to warm up. Observe the current. What do you get? This current is known as the short-circuit current.

Next remove the wire and insert different values of resistors between the connectors. For each resistance value, register the current (I) and at the same time, use the second DMM as a voltmeter to measure the voltage (V) across the resistor.

Complete the table below:

R (Ω)	I (mA)	V (V)	P = VI (W)
0			
10			
…			
∞			

Some suggested values are R = 10, 51, 100, 200, 330, 1k, 1.5k, 10k, 76k, 1MΩ. You may use additional values of R if you wish. Draw a circuit diagram for your experiment. The plot I vs V, and P vs V on the same graph. Deduce from the graph: (a) The short circuit current I_{sh}, (b) the open circuit voltage V_{OC}, (c) The max power output P_{max}. What are I_m, and V_m?

ii. Use the I-V data to compute the power conversion efficiency (PCE) and compute the fill factor.

The PCE of a solar cell is a measure of its efficiency in energy conversion – in this case converting the energy of light to electricity. The PCE of a solar cell is defined by Eq.(1) below.

$$PCE = \frac{I_m V_m}{P_{in}} \qquad (1)$$

To obtain the PCE of your solar cell, you need to measure the incident light power P_{in} , typically in unit of mW/cm^2. This can be done using a commercial power meter. From a distance of about 30 cm from tungsten lamp, P_{in} is about 5.3 mW/cm^2. Use this information to deduce the PCE of your solar cell.

Another important parameter of a solar cell is the fill factor (FF). FF is defined as the ratio of I_mV_m to $I_{sh}V_{OC}$, i.e., FF = I_mV_m / $I_{sh}V_{OC}$. Using this definition for FF, we can express

$$PCE = \frac{I_m V_m}{P_{in}} = \frac{FF \cdot I_{sh} V_{oc}}{P_{in}}$$

Find the FF of your solar cell from the data from part (I). Summarize your data in the table below:

V_{OC} (V)	I_{sh} (mA)	V_m (V)	I_m (mA)	PCE (%)	FF

Question 1: Imagine you take your solar cell under the Sun at noon in HK. In summer time, the typical P_{in} is about 1000 W/m^2. What will be the expected maximum power output of your solar cell? You may assume that the PCE remains the same.

During charging, a typical cell phone consumes 1 W of electrical energy from its transformer, and the typical charging time is about 1 hour. Now imagine you have several solar cells. If your solar cells are used to replace the transformer, how many solar cells do you need to keep the charging time to within 1 hour under the summer sun in HK?

iii. Dependence of solar cell efficiency under different light illumination

With the matching load condition, determine the PCE of solar cell under different light illumination, for example, (a) tungsten lamp and (b) sunlight. Can you observe and explain the difference in the PCE?

iv. Variation of short-circuit current with distances

In Part (II), I_{SC} is measured at a distance of about 30 cm from the lamp. Now vary the distance, *d*, of the lamp from the cell and measure I_{SC}. Some suggested values are 10, 12, 15, 20, 30, 50, 80 cm etc. A good way of deciding what values to choose is to plot I_{SC} vs $1/d^2$.

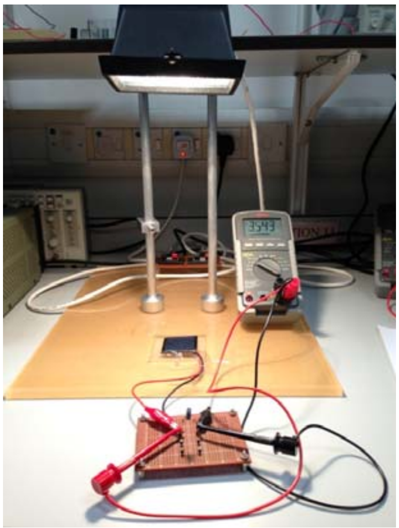
From your plot, deduce an approximation relationship (i.e. and equation) between I_{SC} and d.

Question 2: a solar cell has a short circuit current density of J_{SC} on Earth at noon. If the same cell is taken to the surface of Mars, what will be the approximate J_{SC} there?

v. Energy storage using solar cell

The optical energy captured by a solar cell can be stored, and used in a later time period. To achieve this, an energy storage element is required. In this part, we will use a supercapacitor as an energy storage element and observe the time required to charge up a supercapacitor with your solar cell.

Connect the solar cell in part (I) to terminal A (+) and B (-). Keep the lamp OFF and a distance of 30 cm away. Insert the supercap between terminal C and D. Use a DMM as a voltmeter and observe V_{AB}. Cover the solar cell with an opaque object (e.g. a black cardboard). Discharge the supercapacitor by shorting A and B with a wire. V_{AB} should go to zero.



Now switch on the lamp. Remove the shorting wire. Uncover the cardboard and observe the gradual charging of the supercapacitor with a DMM. *Write down the time T required to charge up the* supercapacitor *to a voltage of V_m*.

The approximate value of *T* can be estimated by the formula:

$$T \approx 2\ C\ (V_m)\ /\ (I_{sh}+I_m)$$

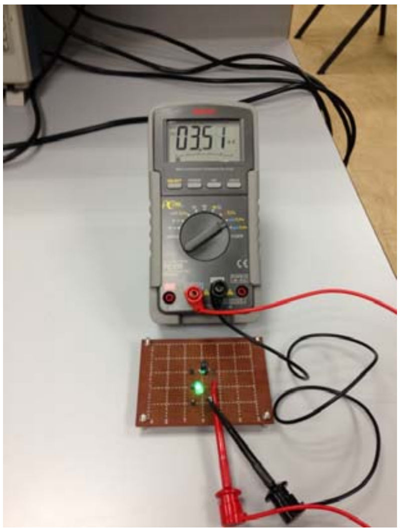
See the appendix for the derivation of this formula.

Questions:

3. Compute T using the formula above. Does the computed value agree with observed time? What is the percentage deviation? If the FF of your solar cell were 0.75, will you expect to have a better/worse agreement? Study the derivation in the appendix to justify your answer.
4. A commercial solar cell has I_{sh} = 0.5 A, I_m = 0.27 A, and V_m = 5V. How much time is needed to charge a supercapacitor (with C = 100 F) to $V = V_m$?

To see the stored energy in action, turn off the tungsten lamp, and disconnect your solar cell from the supercapacitor. *Write down the voltage and hence the energy stored in your capacitor*.

Obtain a superbright LED from your instructor. Connect the LED across the supercapacitor with the circuit board in Part (I). You should be able see the LED glowing brightly even under room lights. An LED typically operates in a voltage of about 3V and consumes a current of the order of a 2 mA. *Use these numbers to estimate how long the LED should remain bright*.



APPENDIX

Derivation of the approximate charging time of a capacitor by a solar cell.

Consider a capacitor connected directly across a solar cell under well-defined illumination conditions. The solar call is completely characterized with I_{sh}, I_m, V_{OC} and V_m. The current i(t) through a capacitor can be written as

$$\mathrm{i(t)} = \mathrm{C}\frac{\mathrm{dv}}{\mathrm{dt}}$$

$$\mathrm{dt} = \frac{C}{i}dv$$

$$\int_0^T dt = \int_0^{Vm} \frac{C}{i(t)}dv$$

In the last equation, T is the amount of time to charge up the capacitor from V = 0 (uncharged) to V_m. Exact derivation of T requires an equation that describe how i(t) varies with v, and it is not integrable by hand. Now, we make an observation. As the capacitor is charging up from V = 0 V to V_m, the solar cell outputs a current i(t) that decreases gently from I_{SC} to I_m. The average i(t) is $1/2(I_{SC} + I_m)$ and can be treated as a constant. Substituting into the equation above, we get

$$\mathrm{T} = \frac{2C}{(I_{SC} + I_m)}\int_0^{V_m} dv = \frac{2CV_m}{(I_{SC} + I_m)}$$

* In a silicon cell, i and V are related by $i(t) = I_L - I_S\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$