Characterisation of solar cells

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Safety

You should view and understand the general lab safety and the risk assessment for this experiment before starting the experiment. There are no significant hazards associated with this experiment. But it is always good practice to turn the power supplies OFF when making changes to any circuit and ensure any electric bias applied to devices is set to zero before turning them ON/OFF.

Intended learning outcomes

By the end of this activity, you should be able to

1. Determine the Boltzmann's constant
2. Accurately determine the efficiency of solar panels
3. Identify various aspects of solar cell characterisation and optimising the power conversion efficiency
4. Explain the operation principle of diodes and solar cells.
5. Develop your scientific writing skills, specifically data collection, analysis and report writing.

You will report your results in a standard scientific paper format, emphasising robust and reliable data collection, error analysis, comparison of results with the literature, and overall data presentation. You may use MS word or LaTeX to write up your report and use Mendeley for managing your bibliography. Details about the report and assessment criteria are available on the Assessment briefs and mark schemes section on LEARN.

Pre-lab reading

Books chapters and journal articles relevant for this experiment

1. Jenny A Nelson. *Physics Of Solar Cells, The*. World Scientific Publishing Company.
   http://ebookcentral.proquest.com/lib/lboro/detail.action?docID=5227908
   Chapter 6 particularly Pg. 169 −175 covers detailed physics of pn junctions.

2. Uwe Rau. *Advanced characterization techniques for thin film solar cells*. Wiley-VCH.
   https://www.vlebooks.com/vleweb/product/openreader?id=LBORO&isbn=9783527636303
   Chapter 2− Pg. 15 −18. details fundamental IV characterisation protocols of solar cells.

3. Peter R. Michael, Danvers E. Johnston, and Wilfrido Moreno. *A conversion guide: solar irradiance and lux illuminance*. 8(4):153–166. Number: 4 Publisher: JVE International Ltd.
   https://www.jvejournals.com/article/21667
   Useful for converting measured light intensity in Lux to Irradiance (W/cm^2).

4. D. W. Kammer and M. A. Ludington. *Laboratory experiments with silicon solar cells*. 45(7):602–605.
   http://aapt.scitation.org/doi/10.1119/1.10811

5. A. Khoury, J-P. Charles, J. Charette, M. Fieux, and P. Mialhe. *Solar cells: A laboratory experiment on the temperature dependence of the open-circuit voltage*. 52(5):449–451.
   https://aapt.scitation.org/doi/abs/10.1119/1.13628

6. Michael J Morgan, Greg Jakovidis, and Ian McLeod. *An experiment to measure the I - V characteristics of a silicon solar cell*. 29(4):252–254.
   https://iopscience.iop.org/article/10.1088/0031-9120/29/4/014

Introduction

Silicon is a group IV element that has four outer electrons orbiting the core. When the outer electrons bond covalently with electrons from four neighbouring atoms, filled (valence) and empty (conduction) energy bands are formed. These bands are separated by an energy gap which is typically 1.1eV in silicon. At room temperature, the thermal fluctuation of the atoms can cause electrons to break away and become available for current conduction. If the temperature is further increased, the atomic vibration increases, freeing up more electrons. That is why the electrical conductivity of semiconductors increases with an increase in temperature.

The average energy of conduction electrons is defined by the Fermi energy, which is situated midway between the conduction and valence band [see Fig. 1(a)]. By adding impurities (dopants) of known density, this Fermi energy can be shifted closer to the bottom (top) of the conduction (valence) band, thereby providing a means of controlling the electrical conductivity. A pn-junction is formed at the interface between two differently doped regions of a single Si wafer where one region is doped with donor materials [e.g. phosphorous in Fig.1(b)] and the other with acceptor materials [e.g. Boron in Fig.1(c)].

At equilibrium, the diffusion of electrons from the n- to the p-region and holes from the p- to n-region is balanced by the built-in electric field formed by the positive (negative) space charges in the n-type (p-type) regions. This built-in electric potential, barrier typically $\sim$0.6 V for Si diodes, can be lowered (raised) by applying a forward (reverse) bias to the PN-junction. Here a forward bias refers to the situation when the positive terminal of a power supply is connected to the p-side of the semiconductor and the negative terminal to the n-type of the semiconductor.

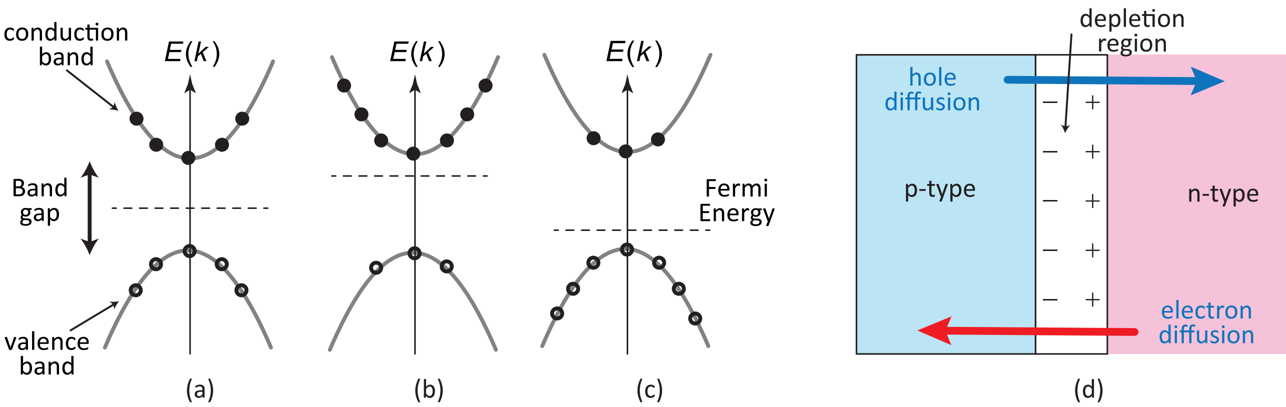

Figure 1: (a) conduction and valence band diagrams of a semiconductor whose Fermi energy is shown by the dashed line. (b,c) In n-type (p-type) semiconductor, there are more conduction electrons (holes) due to the donor (acceptor) atoms and the Fermi energy is closer to the bottom (top) of the conduction (valence) band. (d) A pn-junction forms at the interface between a p-type (blue) and n-type (red) semiconductor. The inter-diffusion of free holes and electrons and subsequent recombination results in the formation a built in electric field which stops further movement of carriers across the depletion region (white).

Diodes

When a Si diode is under forward bias, the current increases exponentially once the applied bias exceeds the threshold voltage ($\geq$ 0.6 V). On the contrary, almost negligible current flows when the diode is reverse-biased. The ideal diode equation that link the current I to an applied voltage V at a given temperature T as

$$I = I_o \left[\exp\left(\frac{qV}{k_B T} \right) - 1 \right] \tag{1}$$

Here I_0 is the reverse bias saturation current, $k_B = 1.380649 \times 10^{-23}\mathrm{J/K}$ is the Boltzmann's constant, T is the temperature of the diode and q is the electron charge.

Working principle of a solar cell

A solar cell or photovoltaic device is a light-sensing element that can generate electricity when light is absorbed by a junction formed at the interface between an n-type and p-type material. Figure 2 shows a typical band energy diagram of a PN junction and its specific photocurrent generation process for a forward-biased solar cell. When a photon of correct wavelength matching the semiconductor energy bandgap is absorbed by the solar cell, electrons are excited from the valence band to the conduction band (see 2).

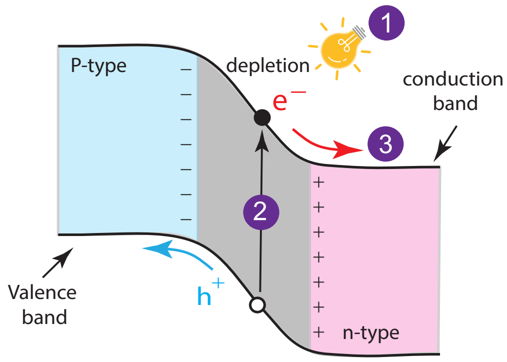

Figure 2: Working principle of a solar cell (pn-junction) with various physical processes: illumination, creation of electron-hole pair and diffusion of electron and holes.

This process forms a bound electron-hole pair which is then split into individual electron e^- and hole h^+ by the built-in electric field at the depletion region (see 3). If an external load with resistance R_L is present, this charge current flows through R_L and the internal junction resistance of the solar cell. The magnitude of the generated charge current depends on the seriesR_S and shunt resistances R_SH of the solar cell, the illumination intensity and the temperature of the solar cell.

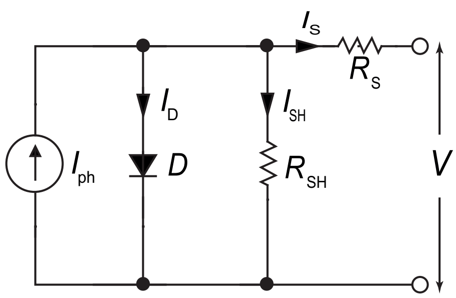

Figure 3: Equivalent circuit of a solar cell. The series R_S and shunt R_{SH} resistors represent losses within the solar cell due to electron-hole recombination or defects.

A simplified diode equivalent circuit of a solar cell, shown in Fig. 3, can accurately capture this process. It shows a parallel-connected photocurrent source I_ph, a diode D and shunt resistance R_SH in series with a series resistor R_S. The series resistance (R_S), which arises from energy barriers within the bulk or at an interface with a metal electrode, should be minimised. The shunt resistance (R_{SH}) represents parallel current conduction channels, for example, due to electron-hole recombination, and ideally should be infinite. Small shunt resistance values point to potential short-circuitry or defects within the solar cell.

Self-check: Recalling circuit analysis methods from your part A Core physics I, obtain an expression for I and V of the solar cell:

$$I = I_\mathrm{ph} - I_\mathrm{o}\left[\exp\left(q\frac{V + IR_\mathrm{S}}{nk_\mathrm{B}T}\right) - 1\right] - \frac{V + IR_\mathrm{S}}{R_\mathrm{SH}} \tag{2}$$

where $I_\mathrm{ph} = I_\mathrm{SC}$ is the short circuit current due to the photoexcited carriers and n is the ideality factor. You will need to use Kirchoff's laws along with mesh and nodal analysis.

Experiments

This main objective of this experiment is to accurately determine the efficiency $\eta = P_{\text{out}}/P_{\text{in}}$ of a solar cell where P_{in} is the input power from irradiation and P_{out} is the maximum output power. You should therefore measure both P_{in} and P_{out} accurately. The input P_{in} can be measured using a light-sensing device (e.g. LDR or lux metre), and the output P_{out} can be directly inferred from the I-V curve. To this end, you can use your Arduino kit box, Keithley 3 channel power supply and Keithley multimeter to construct a circuit that measures both voltages and current (see Fig. 4).

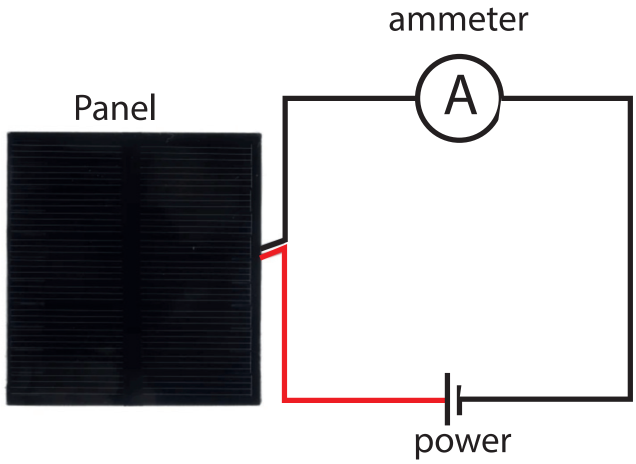

Figure 4: Current−Voltage measurement circuit. The Keithley 2110 multimeter can be used to measure current.

Equipment list:

- RS components Seed Studio 0.5W solar panel
- Arduino kit, LDR or Lux metre
- bulb (indoor)or actual sunlight (outdoors)
- Banana connectors with crocodile clips
- Keithley 2110 multimeter
- Keithley 2231A-30-3 Triple Channel DC Power Supply
- LM35 temperature sensor
- 1N4148 Signal Diode
- Software: National Instruments Multisim, OriginLab, National Instruments Labview

Note: Before starting your experiment, please consult the technical specifications of the solar panel to inform your design of the experiment and establish the range and accuracy of your measurement.

Task 1: Determination of the Boltzmann constant from (I–V) measurement of a diode

1. Construct the circuit in Fig. 4 using the *1N4148 Diode* which you have in your Arduino kit. You can use the Keithley 2231A-30-3 Triple Channel DC Power Supply and Keithley 2110 multimeter to source voltage and measure current, respectively.
2. Measure the current-voltage (I-V) characteristics of the diode staring at zero volts. Do not apply a voltage larger than 1.5 V to avoid overheating of the diode.
3. Using your data and the diode I-V curve formula Eq.(1), determine the Boltzmann constant by plotting $\ln(I)$ vs V and fitting the resulting curve to a linear function whose intercept gives the reverse saturation current $\ln(I_o)$ and its gradient is proportional to $q/k_B T$. Here $q = 1.602 \times 10^{-19} C$ is the electron charge and $T = 293$ K is temperature.

Task 2: Current-Voltage (I–V) measurement in dark

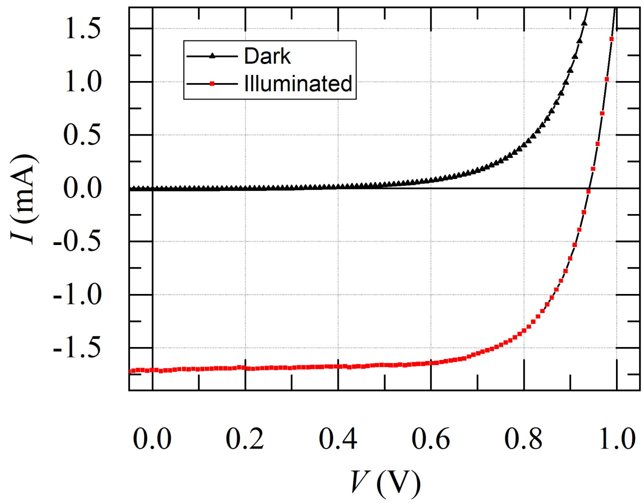

Figure 5: Example I–V curves of a solar cell under dark and light conditions. The I-V curve in the dark resembles that of a pn junction. Under Illumination (red curve), the I-V curve is shifted down by an amount equal to the short circuit photocurrent at zero voltage.

1. Design and construct the solar cell I-V measurement set-up following the circuit in Fig. 4.
2. Measure the current-voltage (I-V) characteristics of the solar cell under dark conditions. You need to ensure that no ambient light falls on the solar cell by placing it face down or covering it with any opaque material.
3. Under dark conditions, the solar cell effectively exhibits an I-V curve of a diode. By fitting this dark I-V curve to the ideal diode equation
$$I = I_0 \left(\exp(qV/nk_B T) - 1\right) \tag{3}$$
you will be able to calculate the reverse saturation I_0 and the ideality factor n of the solar cell [5]. Here k_B is the Boltzmann constant, $q = 1.602 \times 10^{-19} C$ is the electron charge, and T is the temperature of the solar cell. How does this value compare to the literature value?

Task 3: I−V measurement under light to determine the efficiency of the solar cell

Note: *Due to a limited number of lamps in the lab, plan your experiments keeping in mind that you will need to share with them with your peers.*
A solar cell efficiency report can not be complete without specifying the temperature and irradiance levels used in the experiment, as these vary geographically. In the literature, you will find reported values at 25 $^o\mathrm{C}$ and irradiance of 1 Sun = 1000 W/m^2. The sunlight spectrum resembles a black body at 5800K, but when the solar energy reaches earth, absorption in the atmosphere and scattering with chemical species modify this spectrum (see Figure 6). For this experiment, you will use a light bulb of 5000K colour temperature.

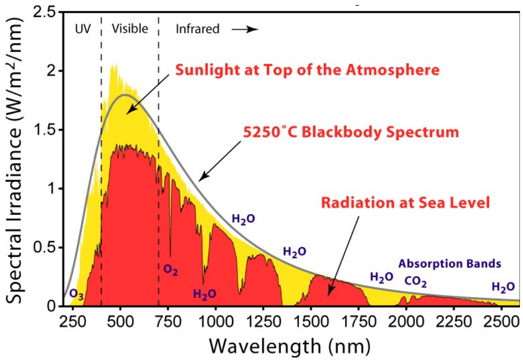

Figure 6: Full solar spectrum at sea level (red), top of the atmosphere (yellow) and black body at 5800K (black line). The area under the red curve is irradiance. Wiki Commons - Solar Spectrum. See here for more detail.

1. Switch ON the lamp and measure the I-V curve of the solar cell under light conditions. The I-V curve should be shifted vertically down by an amount equal to the short circuit current I_{SC} at V=0 (see Fig. 7). Note the open-circuit voltage V$_{OC}$ voltage where $I = 0$ and the short-circuit current I_{SC} at $V = 0$.

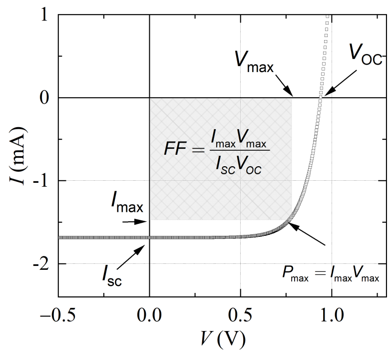

Figure 7: I-V curve under illumination showing the maximum power $P_{\max} = I_{\max}V_{\max}$, $\mathrm{I_{SC}}$, $\mathrm{V_{OC}}$ and FF of a solar cell. The shaded regions shows the maximum area (power).

2. Using a light sensor, determine the intensity of light falling on the solar cell. **Note**: Use the following approximate conversion factor, 1 lux $\simeq 8 \times 10^{-3}$ W/m^2 or equivalently 1 Sun (1000 W/m^2)$\simeq$120,000 lx, to convert intensity from the Lux meter to irradiance [4].
3. Plot the power $P = IV$ vs voltage curve and determine the maximum power $P_{\max}$ point.
4. Determine the efficiency of the solar cell using the formula

$$\eta\ [\%] = \frac{P_{\max}}{\text{Incidnet light power}} \times 100 = FF\frac{I_{\mathrm{SC}}V_{\mathrm{OC}}}{P_{\mathrm{in}}A} \times 100 = \frac{I_{\max}V_{\max}}{P_{\mathrm{in}}A} \times 100.$$

   Here A is the area of the panel, P_{in} [W/m^2] is the input power from the light source, FF is the fill factor defined in Fig. 7.

5. The gradient of the I-V curve close to I_{SC} and V_{oc} can be used to determine the solar cell series and shunt resistor values, respectively. Alternatively, you can fit your IV data to Equation 2.

Task 4: Effect of light intensity, temperature and circuit simulation

The solar panel parameters you obtained in the previous tasks are susceptible to several parameters such as *irradiance*, *wavelength* and *temperature*. Specifically, the short circuit current varies linearly with the irradiance level, and the open-circuit voltage varies logarithmically with irradiance (See. Ref. [5]). On the other hand, temperature variations affect the open circuit much more than the short circuit current. Complete the following tasks and test this hypothesis.

1. Using the Lux sensor, measure the intensity as a function of distance r from the lamp. Generally, the light intensity falls as $1/r^2$ from the source. For each intensity value, determine the efficiency of the solar panel. Observe how the solar cell efficiency (η) varies with irradiance and establish whether your measured value of the solar cell efficiency agrees with the data-sheet? If not, you need to give plausible explanations for the discrepancy.

2. Prolonged exposure of the panel to intense light at small distances (≤ 5cm) may cause overheating and lead to erroneous results. This strongly affects the open-circuit voltage, which is approximated as [5, 1]

$$V_{OC} \simeq \frac{E_g}{q} + \frac{k_B T}{q}\left(\ln \frac{I_{\mathrm{SC}}}{I_0}\right).$$

   Quantify the effect of heating by measuring the surface temperature of the solar panel. Based on your observation so far, does a solar cell perform better in Antarctica or in the Sahara desert? How does temperature of the solar cell affect I_{SC}, V_{OC} and efficiency?

3. A solar cell can be used as a light-sensing device. Based on your observations so far, how can you use the solar cell as a light-sensing device? Which parameter would you choose to do this: I_{SC} or V_{OC}?

4. Defects in solar cells are inevitable and can decrease the efficiency of the solar cell significantly. Various nanoscale analysis techniques such as electron and optical microscopy often identify atomic defects in a solar cell. Suppose you were to identify defects in the solar cell in a reasonable time considering how the photocurrent interacts with these defects and its influence on the power dissipation. Can you think of ways of imaging defects in large-area solar panels? Hint: defects cause a local increase in the temperature of the solar panel.

5. Circuit simulation software are useful for optimising the solar cell's performance. This task requires you to consider using circuit simulation tools such as LTSpice or NI-Multisim. Both LTSpice and NI-Multisim are analog circuit modelling software that you can use to model the equivalent circuit in Figure 3 with an external load resistor and explore how increasing R_{SH} and R_S influence the I-V curve. Unfortunately, TinkerCAD will not be suitable for this purpose. LTSpice is freeware that you can install on your computer. You have access to NI-Multisim on any of the university computers.

References

[1] M Auf der Maur, G Moses, JM Gordon, X Huang, Y Zhao, and EA Katz. Temperature and intensity dependence of the open-circuit voltage of ingan/gan multi-quantum well solar cells. *arXiv preprint arXiv:2104.02114*, 2021.

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