Optoelectronic and Photovoltaic Devices course

Fifth lab – Analysis of solar cells

The aim of this set of experiments is to study the properties of solar cells as a function of the main operating parameters, including external illumination, temperature, and voltage. This goal will be achieved through the execution of a set of current-voltage measurements in different conditions. The silicon solar cell (IXOLARTM SolarBITs) is mounted on a Peltier-based temperature controller, and is placed under a LED-based light source (acting as a solar simulator), whose current can be modulated by a suitable circuit. A controlling board has been developed by the ACME team, and is directly mounted onto an Arduino Due board. The Arduino Due has two digital-to-analog converters (DACs), that are used to control the current on the LEDs, and to apply a variable voltage to the solar cell during the current-voltage measurements. Through circuits based on op-amps, the Arduino Due board can measure the voltages and current with a good resolution, in the ranges of interest. Labview is used to acquire the experimental data, i.e. the current-voltage measurements collected in different conditions.

**Room-temperature operation**

* Set the TEC temperature at 25 °C.
* Acquire the current-voltage characteristics of the solar cells in dark (i.e. in absence of external illumination)
* Plot the curve in linear and logarithmic scale

To understand the behavior of the solar cell in the absence of illumination, the first set of measurements was performed at room temperature (25°C) with no external light source (i.e., in the dark). The acquired I-V curve was plotted on both linear and logarithmic scales to analyze diode characteristics.

A graph of a function

Description automatically generated with medium confidence

* **Extract the ideality factor and the saturation current of the solar cell, by proper fitting procedure and Comment the experimental results, based on the theoretical considerations made during the lectures**

As discussed during the lectures, the ideality factor tells us the quality of the diode. While ideal diodes exhibit , and real devices generally fall within the range of 1–2, the experiment produced unusually high values. This anomaly likely results from series resistance effects or other non-idealities, such as recombination losses or fabrication defects in the solar cell.

where;

* = slope of the linear fit of

With this the values and applying the code

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Description automatically generated

The values obtained where A math equations with black text

Description automatically generated with medium confidence

As mentioned before, the ideality factor obtained experimentally greatly diverts away from what was discussed during the lectures and this can come from a few reasons, including the series resistance effect. Nonetheless, the value being close to 1 suggest good linear fitting selection.

Furthermore, the saturation current is relatively low as compared to the value of the datasheet which was present in the datasheet. This is desirable for high efficiency because the cell in this way exhibits minimal leakage current under reversed bias.

**Extracting the main cell parameters**

* **Set the illumination level to 1 Sun (maximum illumination level) and measure the current-voltage characteristics under light at 5, 10, 15, 20mA**

Under 1 Sun illumination (maximum intensity), the I-V characteristics of the solar cell were measured at four different current levels: 5 mA, 10 mA, 15 mA, and 20 mA. The data was plotted, and the area of interest (the fourth quadrant) was isolated for analysis, as it represents the power-generation region of the solar cell.

A graph of different colored lines

Description automatically generated

The above graph shows the full scale of the data.

Since the area of interest is the forth quadrant, the following code snippet was used;



To focus on it resulting in the graph below

A graph of different colored lines

Description automatically generated

* **Extract the open circuit voltage and the short circuit current**

The open circuit voltage,  is the voltage where the current is zero while the short circuit current is obtained as the current value where the voltage is zero on the above I-V plot. This gives

Key parameters extracted from the I-V plot included the open-circuit voltage and short-circuit current . These were identified as the voltage where current reaches zero and the current where voltage reaches zero, respectively. The resulting data showed that both Is increased with illumination, as expected from theoretical principles. The results are summarized below:

|  |  |  |
| --- | --- | --- |
| **CURRENT VALUE** | **OPEN-CIRCUIT VOLTAGE ()** | **SHORT-CIRCUIT CURRENT ()** |
| 5mA 0.25SUN | 1.799 V | -3.897mA |
| 10mA 0.5SUN | 1.914 V | -7.357 mA |
| 15mA 0.75SUN | 1.975 V | -10.88 mA |
| 20mA 1SUN | 2.015 V | -14.26mA |

* Plot the output power as a function of the operating voltage

In this case, the power was obtained through the formula

Hence the power is obtained and plotted versus the related voltage. This provided insight into the power characteristics of the solar cell, including the maximum power point (mpp), where the cell operates with the highest efficiency.

A graph of different colored lines

Description automatically generated

* Extract the maximum output power and the fill factor of the solar cell and compare with state-of-the-art devices (find 3 datasheets on the internet and add to the report)

The maximum power was obtained with the code snippet



And it was also added to the graph for visualization purposes

A graph of a voltage

Description automatically generated with medium confidence

The Fill factor on the other hand was gotten as the ration of the obtained maximum power to the product of the open circuit voltage and the short circuit current.

Resulting to the following ;

|  |  |  |
| --- | --- | --- |
| **CURRENT VALUE** | **Maximum power** | **Fill Factor (%)** |
| 5mA 0.25SUN | 4.856 mW | 69.3 |
| 10mA 0.5SUN | 10.093mW | 71.7 |
| 15mA 0.75SUN | 15.860 mW | 73.8 |
| 20mA 1SUN | 21.049 mW | 73.3 |

compare with state-of-the-art devices (find 3 datasheets on the internet and add to the report)

The chosen solar cells are and the data of interest are reported on the table below:

|  |  |  |
| --- | --- | --- |
| **SOLAR CELL** | **Maximum Power (W)** | **Fill Factor (%)** |
| XXR-M125 2BB-18.6 | 3 | 80.22 |
| PGE2B125-165 | 2.94 | 78.3 |
| LKS-125mm-Mono-2BB | 2.73 | 77.7 |

Comparing these figures, the solar cells used in the lab exhibit fill factors slightly below those of state-of-the-art devices, which commonly achieve values exceeding 75%. This discrepancy suggests higher resistive losses, non-ideal recombination dynamics in the lab cells, potentially attributable to material quality, junction design, or fabrication imperfections. **Find attached in the appendix the datasheets**

**Cell parameters as a function of illumination level and temperature**

* Measure the I-V curves of the solar cells at different illumination levels (0.25, 0.50, 0.75, 1.00 Sun) and different temperature levels (25, 40, 55, 70 °C)
* Plot the variation of short circuit current as a function of illumination level, fit with the expected theoretical behavior, and comment on the observed trend through the use of formulas seen during lectures

A graph with a line and a point

Description automatically generated with medium confidence

Like all semiconductor devices, solar cells are sensitive to temperature, with increases in temperature reducing the band gap of a semiconductor, following the expression;

thereby affecting most of the semiconductor material parameters. The observed linear relationship between short-circuit current and illumination level as seen on the plot fits with the theoretical behavior, following

and more specifically;

Through this the short-circuit current actually shows a slight increase with temperature, following

where α is the temperature coefficient. This increase occurs because the reduced bandgap at higher temperatures allows more photons to create electron-hole pairs, leading to increased photogeneration and thus higher short-circuit current.

* Plot the variation of open circuit voltage as a function of illumination level, fit with the expected theoretical behavior, and comment on the observed trend through the use of formulas seen during lectures

A graph of different temperature levels

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As observed on the plot, the relationship between the open-circuit voltage and illumination level follows a logarithmic behavior, as described by the equation;

This logarithmic dependence explains why increases more rapidly at lower illumination levels and begins to saturate at higher intensities. Temperature has a significant negative impact on Voc, primarily due to its effect on the dark saturation current , which follows the relationship

As temperature increases, increases exponentially (because is very temperature dependent), leading to a decrease in .

* How does the fill factor change with increasing temperature? Describe and explain briefly the observed effects

The fill factor decreases with increasing temperature, which can be explained by the fundamental physics of solar cells. This decrease occurs primarily because temperature has a stronger negative effect on open-circuit voltage as earlier explained, compared to its slight positive effect on short-circuit current . The fill factor, defined earlier as;

is particularly sensitive to changes in . As temperature increases, the bandgap of the semiconductor decreases, leading to an increase in the dark saturation current which significantly reduces according to the relationship

Additionally, higher temperatures increase carrier recombination rates and series resistance, both of which contribute to a reduction in the fill factor. This temperature-induced degradation of the fill factor is one of the main reasons why solar cell efficiency decreases at higher operating temperatures, typically showing a reduction of about 0.4-0.5% per degree Celsius for silicon solar cells.

**Solar cell modeling via Spice**

* Extract the main parameters of the solar cell (consider the 1-diode equivalent model)
* Use the previously extracted parameters to reproduce the electrical characteristics of the solar cell by Spice (you can use LTSpice, for example)

The circuit below simulates the short circuit Current , .

A diagram of a circuit

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As observed a series resistance of ohm was chosen and a relatively high shunt resistance of 1.5k. Also the current source was set to 20mA. From the results of the simulator, the current from the current source all goes to the series resistor which is what is expected.

The circuit below, simulates the open circuit voltage.

A diagram of a circuit

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From the simulation, the resistor R2, receives no current as shown and this leads to an open circuit voltage of about 0.73V.

The plot below shows the IV characteristics

A diagram of a circuit

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The plot below shows the maximum power characteristics

A diagram of a circuit

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* Compare the experimental data with the simulated ones and comment in the lab report

|  |  |  |
| --- | --- | --- |
| Results | Short Circuit Current | Open Circuit Voltage |
| Experimental | 20mA | 2.01V |
| Simulation | 20mA | 0.73V |

APPENDIX 1: XXR-M125 2BB-19.4 SOLAR CELL

A screenshot of a computer

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Source: <https://www.enfsolar.com/pv/cell-datasheet/2416>

APPENDIX 2: PGE2B125-165

A screenshot of a diagram

Description automatically generated

Source : https://cdn.enfsolar.com/z/pp/z2gv1s3ku0p/5fb0f3d69fa81.pdf

APPENDIX 3 : LKS-125mm-Mono-2BB

A screenshot of a computer

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A screenshot of a report

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Source : https://cdn.enfsolar.com/z/pp/fm4n56crp/5e1dc9fd65b87.pdf