Report Lab 3

Class: Optoelectronic and Photovoltaic Devices		
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Contents

1 Task 1: Room-temperature operation

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.

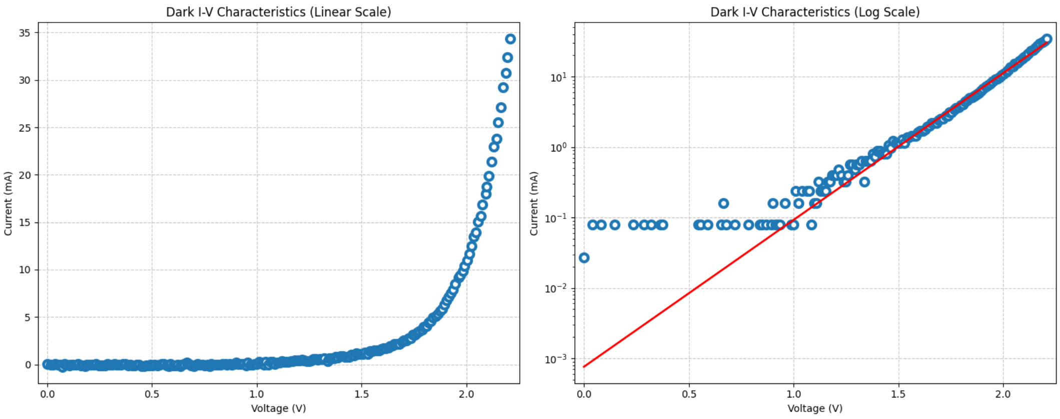


Figure 1

1.1 Task 1.1: Extract the ideality factor and the saturation current of the solar cell, by proper fitting procedure

As discussed during the lectures, the ideality factor tells us the quality of the diode. While ideal diodes exhibit $n \approx 1$, real devices generally fall within the range of 1–2. However, 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.

$$n = \frac{1}{\text{slope} \times V_T}$$

where:

$$V_T = \frac{kT}{e}$$

- V_T: Thermal voltage, calculated as $V_T = \frac{kT}{e}$
- slope: Slope of the linear fit of $\ln(I)$ vs V
- $T = 237.15 + 25 = 298.15\,\mathrm{K}$: Temperature in Kelvin

With this the values and applying the code A

The values obtained from the experiment are as follows:

- Ideality factor (n) = 7.00
- Saturation current (I_0) = 1.61×10^{-7} A
- Coefficient of determination (R^2) = 0.9988

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 R^2 value being close to 1 suggests good linear fitting selection.

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

2 Task 2: Extracting the main cell parameters

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.

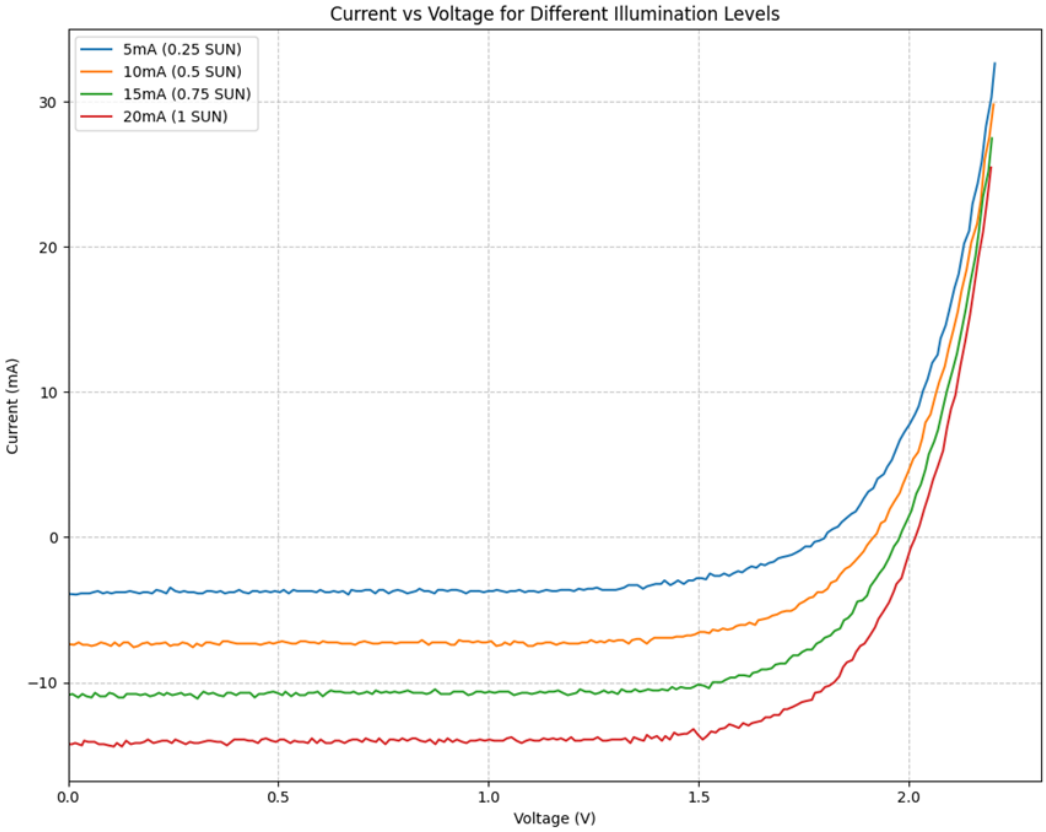


Figure 2

The above graph shows the full scale of the data. Since the area of interest is the forth quadrant, the following code A snippet was used. To focus on it resulting in the graph below

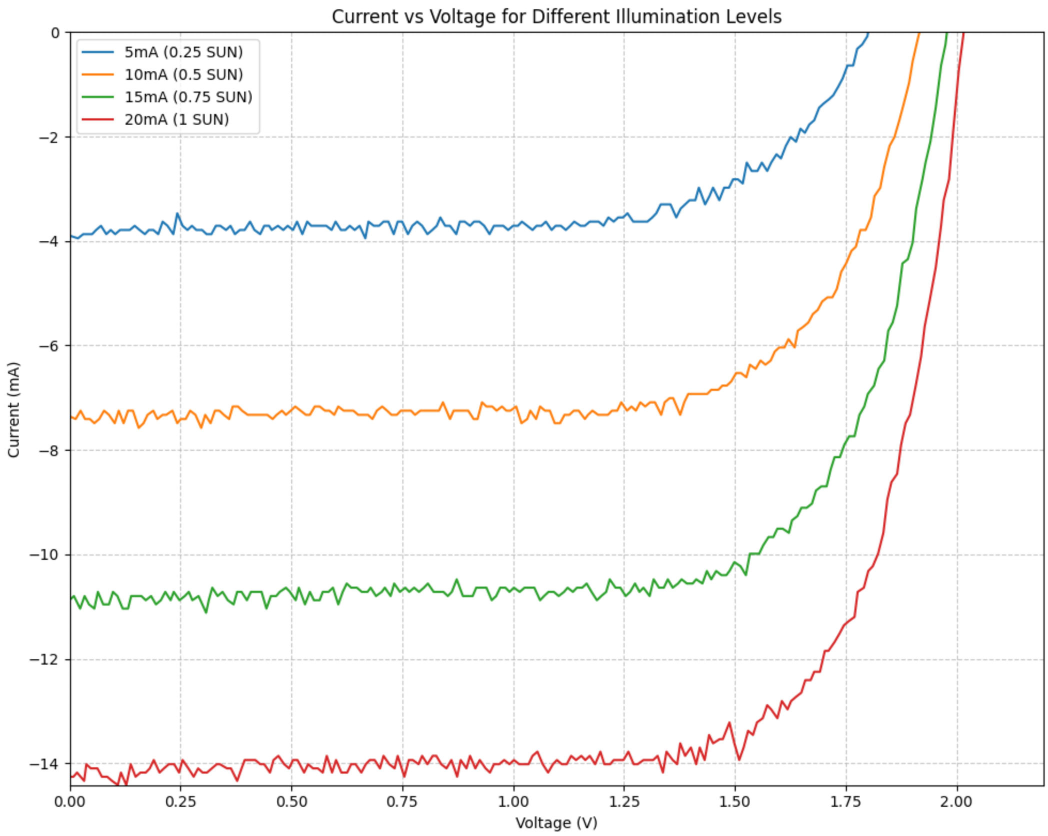


Figure 3

2.1 Task 2.1: • Extract the open circuit voltage and the short circuit current

The open-circuit voltage, V_{oc}, 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 V_{oc} and short-circuit current I_{sc}. These were identified as the voltage where current reaches zero and the current where voltage reaches zero, respectively. The resulting data showed that both I_{sc} and V_{oc} increased with illumination, as expected from theoretical principles. The results are summarized below:

Current Value	**Open-Circuit Voltage (V_{oc})**	**Short-Circuit Current (I_{sc})**
5 mA, 0.25 SUN	1.799 V	-3.897 mA
10 mA , 0.5 SUN	1.914 V	-7.357 mA
15 mA , 0.75 SUN	1.975 V	-10.88 mA
20 mA , 1 SUN	2.015 V	-14.26 mA

Table 1: Summary of extracted parameters from the I-V plot.

2.2 Task 2.2: Plot the output power as a function of the operating voltage

In this case, the power was obtained through the formula:

$$P = I \times V$$

Hence, the power is calculated 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.

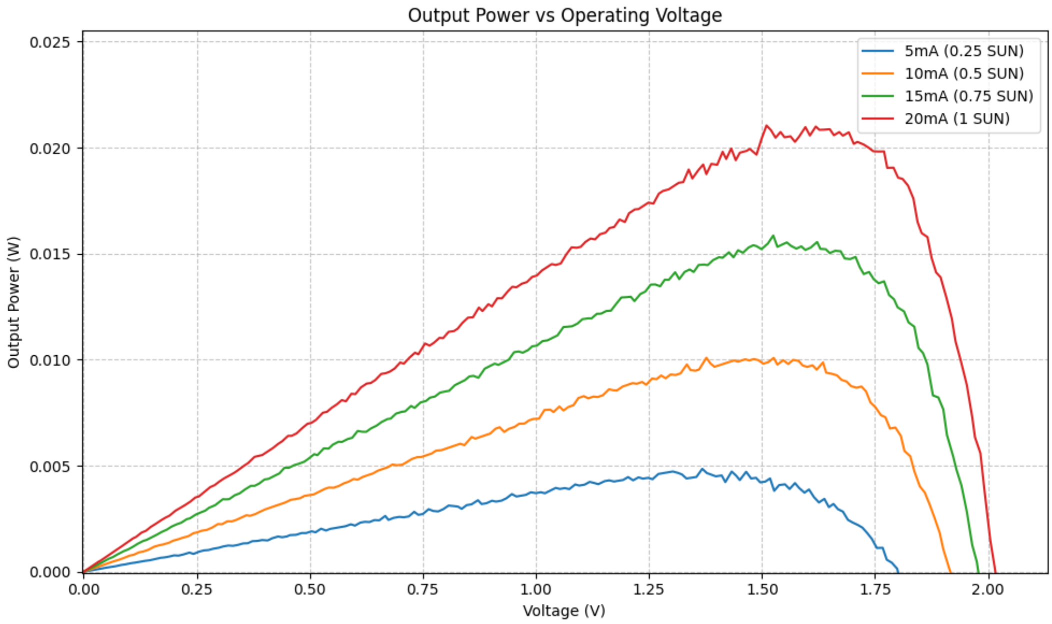


Figure 4

2.3 Task 2.3: • Extract the maximum output power and the fill factor of the solar cell and compare with state-of-the-art devices

The maximum power was obtained with the code A snippet. And it was also added to the graph for visualization purposes.

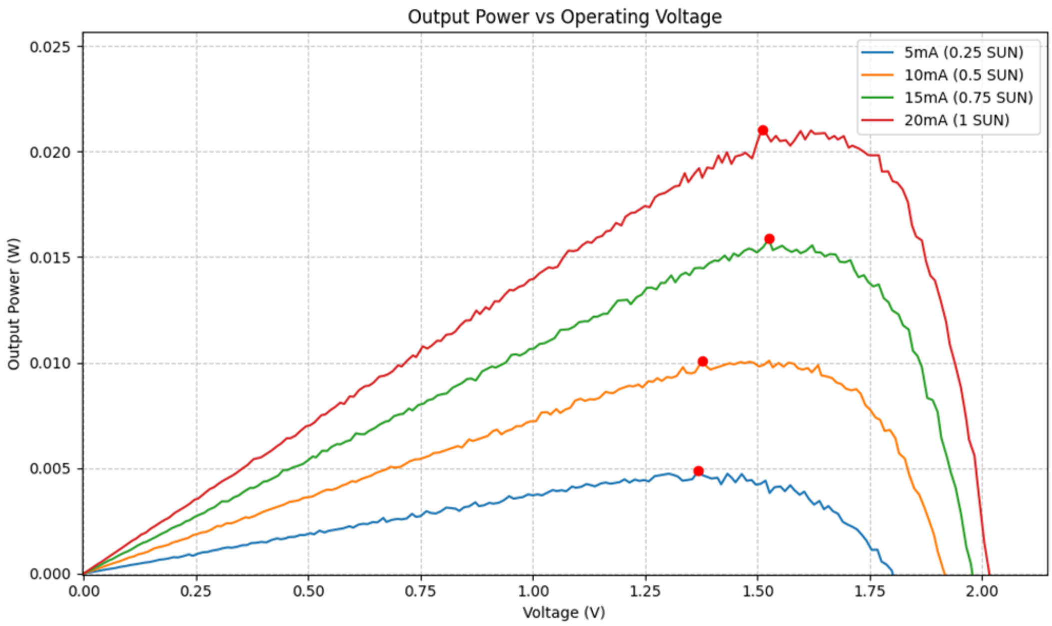


Figure 5

The fill factor, on the other hand, was calculated as the ratio of the obtained maximum power to the product of the open-circuit voltage and the short-circuit current:

$$FF = \frac{P_{\text{MP}}}{V_{\text{oc}} \times I_{\text{sc}}} \times 100$$

Resulting in the following:

Current Value	Maximum Power ($P_{\mathbf{MP}}$)	Fill Factor (%)
5 mA, 0.25 SUN	4.856 mW	69.3
10 mA, 0.5 SUN	10.093 mW	71.7
15 mA, 0.75 SUN	15.860 mW	73.8
20 mA, 1 SUN	21.049 mW	73.3

Table 2: Calculated Fill Factor and Maximum Power.

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

Solar Cell	Maximum Power (W)	Fill Factor (%)
XXR-M125 2BB-18.6	3.00	80.22
PGE2B125-165	2.94	78.30
LKS-125mm-Mono-2BB	2.73	77.70

Table 3: Characteristics of the chosen solar cells.

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 and 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 B.

3 Task 3: Extracting the main cell parameters

This task will 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).

3.1 Task3.1: Plot the variation of short circuit current as a function of illumination level

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

$$E_g(T) = E_g(T = 0K) - \frac{\alpha T^2}{T + \beta}$$

This reduction affects 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:

$$I_{\mathrm{sc}} \propto \Phi$$

and more specifically:

$$I_{\mathrm{sc}} = qG(L_n + L_p),$$

where q is the charge of an electron, G is the generation rate, and L_n and L_p are the diffusion lengths of electrons and holes, respectively.

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

$$I_{\mathrm{sc}}(T) = I_{\mathrm{sc}}(T^0)\left[1 + \alpha(T - T^0)\right],$$

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.

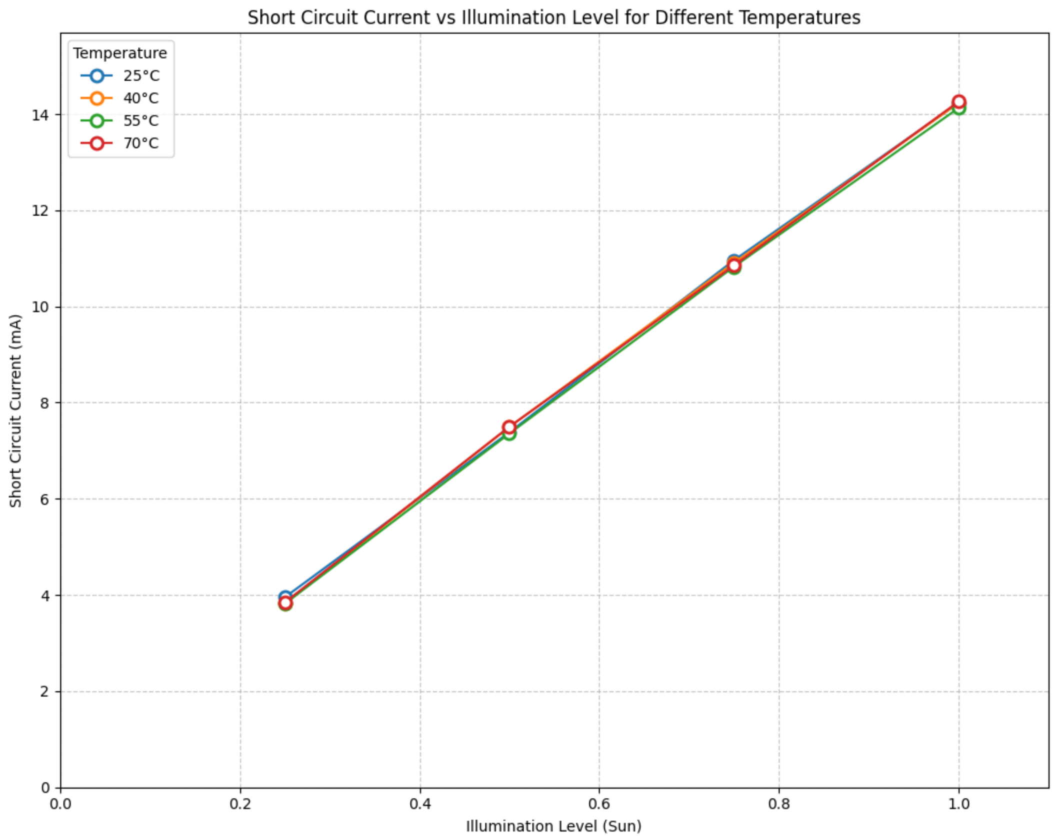


Figure 6

3.2 Task3.2: Plot the variation of open circuit voltage as a function of illumination level

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

$$V_{\mathrm{oc}} = \frac{kT}{q} \ln\left(\frac{I_{\mathrm{sc}}}{I_0}\right)$$

This logarithmic dependence explains why V_{oc} increases more rapidly at lower illumination levels and begins to saturate at higher intensities. Temperature has a significant negative impact on V_{oc}, primarily due to its effect on the dark saturation current I_0, which follows the relationship:

$$I_0 = qA\frac{Dn_i^2}{LN_D}$$

As temperature increases, I_0 increases exponentially (because n_i is very temperature-dependent), leading to a decrease in V_{oc}.

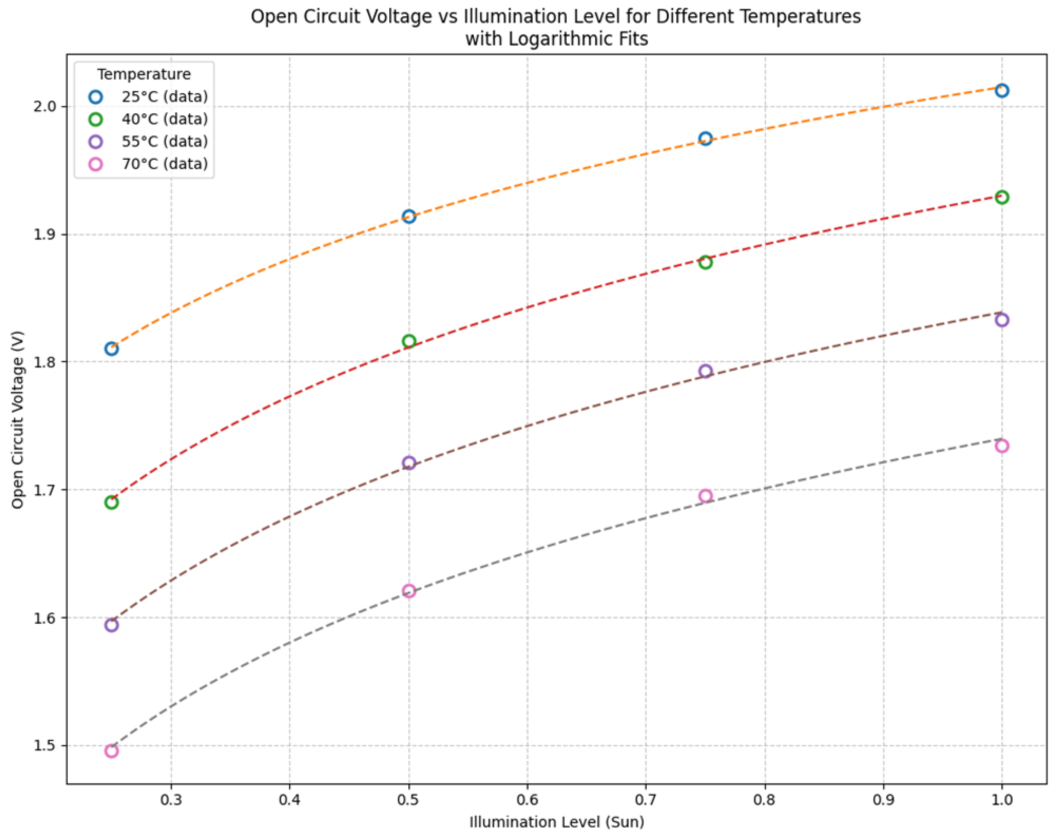


Figure 7

3.3 Task3.3: How does the fill factor change with increasing temperature

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:

$$FF = \frac{P_{\text{MP}}}{V_{\text{oc}} \times I_{\text{sc}}} \times 100$$

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

$$V_{\text{oc}} \propto \ln\left(\frac{I_{\text{sc}}}{I_0}\right)$$

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.

4 Task4: Solar cell modeling via Spice

The analysis begins by extracting the main parameters of the solar cell using the 1-diode equivalent model, which provides a detailed representation of its electrical behavior.These parameters are then used to reproduce the electrical characteristics of the solar cell through simulation using SPICE software, such as LTSpice.

The circuit below simulates the short-circuit current (I_{sc}).

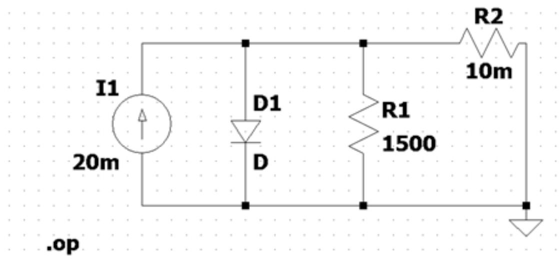


Figure 8

--- Operating Point ---

V(n001):	0.000199999	voltage
I(D1):	2.77623e-16	device_current
I(I1):	0.02	device_current
I(R1):	1.33332e-07	device_current
I(R2):	-0.0199999	device_current

Figure 9

As observed, a series resistance of 10 Ω was chosen, along with a relatively high shunt resistance of 1.5 kΩ. The current source was set to 20 mA. From the results of the simulation, the current from the current source (I_{I1}) all flows through the series resistor ($I_{\text{R2}} = -0.0199$ A, which is approximately -20 mA), which is the expected outcome.

The circuit below simulates the open-circuit voltage.

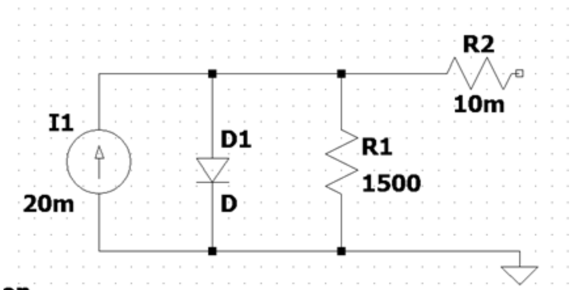


Figure 10

--- Operating Point ---

V(n001):	0.731964	voltage
V(nc_01):	0.731964	voltage
I(D1):	0.0195121	device_current
I(I1):	0.02	device_current
I(R1):	0.000487976	device_current
I(R2):	0	device_current

Figure 11

In this simulation, the resistor $R2$ receives no current, leading to an open-circuit voltage of approximately 0.73 V.

The plot below shows the IV characteristics

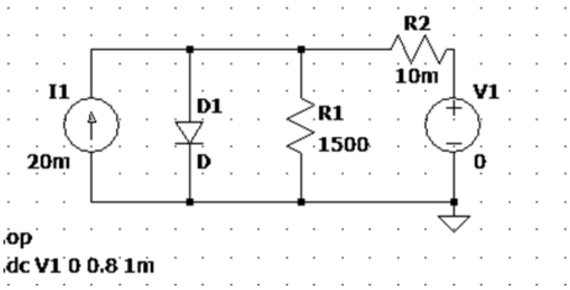


Figure 12

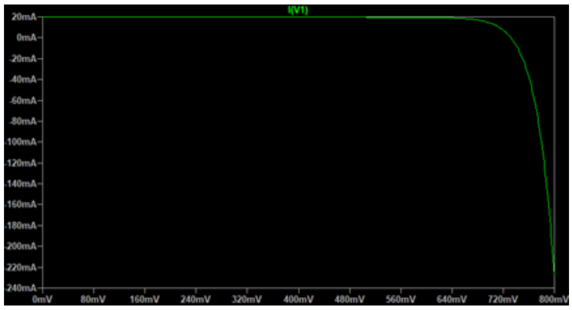


Figure 13

The plot below shows the maximum power characteristics

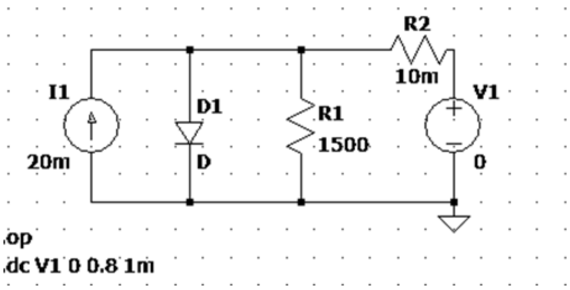


Figure 14

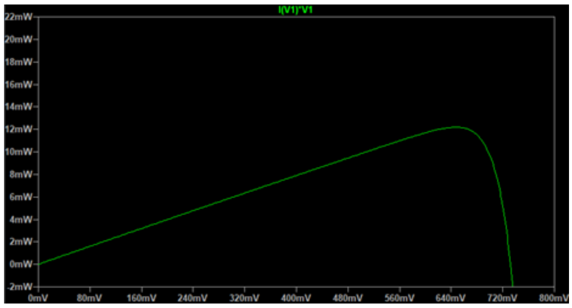


Figure 15

4.1 Task4.1: Compare the experimental data with the simulated ones

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

Table 4: Comparison of Experimental and Simulation Results

A Code

```python
# Perform linear regression
slope, intercept, r_value, p_value, std_err = stats.linregress(voltage_fit,
    ln_current)

# Calculate ideality factor and saturation current
n = 1 / (slope * VT) # Ideality factor
I0 = np.exp(intercept) # Saturation current in A
```

Code 1: python code to Perform linear regression and Calculate ideality factor and saturation current

```python
plt.xlim([0, max(voltage)])
plt.ylim([min(current), 0])
```

Code 2: python code to obtain the cell parameters

```python
max power = max(power)
```

Code 3: Python code to extract the maximum power

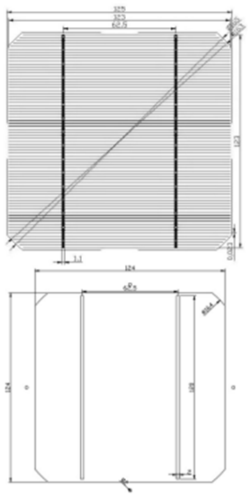
B Datasheets

Model No.	XXR-M125 2BB-19.4
Product Characteristics	
Cell Technology	Monocrystalline
Dimensions	125×125 mm
Diagonal	165 mm
Cell Thickness	180 ± 20 μm
Front Surface (-)	
No. of Busbars	2
Busbar Width	1.4 mm
Busbar Material	Aluminium
Anti Reflection Coating	Silicon nitride
Back Surface (+)	
No. of Soldering Pads	2
Soldering Pad Width	2 mm
Soldering Pad Material	Aluminium
Back Surface Field (BSF)	Aluminium
Electrical Data at STC	
Maximum Power (Pmax)	3 W
Voltage at Maximum Power Point (Vmpp)	0.51 V
Current at Maximum Power Point (Impp)	5.88 A
Open Circuit Voltage (Voc)	0.6 V
Short Circuit Current (Isc)	6.23 A
Cell Efficiency	19.4 %
Fill Factor (FF)	80.22 %
Thermal Ratings	
Temperature Coefficient of Pmax	-0.42 %/°C
Temperature Coefficient of Voc	-0.3324 %/°C
Temperature Coefficient of Isc	0.046 %/°C

Figure 16: Datasheet for Solar Cell Model XXR-M125 2BB-19.4

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

Monocrystalline solar Cells 125 x 125mm Pseudo-Square



Physical Characteristics

Dimension	125mm×125mm±0.5mm
Diameter	165mm±0.5mm
Thickness (si)	200μm±20μm
Front Side (-)	1.1±0.05mm busbars(Ag),blue anti-reflecting coating(SiNx)
Back Side (+)	2.0 mm (silver) discontinuous soldering pads

Temperature coefficients

Current(%/k)	0.043
Voltage(%/k)	-0.320
Power(%/k)	-0.420

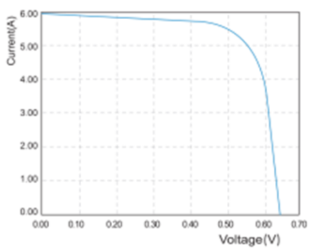
Light Intensity Dependence

Intensity(W/m2)	Voc*	Isc*	Pmpp
1000	1	1	1
900	0.9	0.99	0.89
800	0.8	0.99	0.79
500	0.5	0.96	0.48
300	0.3	0.97	0.29

Physical Characteristics

Efficiency Range (%)	Rated Power (Wp)	*Maximum Power Voltage (V)	*Maximum Power Current (A)	*Open Circuit Voltage (V)	*Short Circuit Current (A)
20.2	3.14	0.548	6.01	0.649	6.02
20.0	3.11	0.546	5.59	0.648	6.00
19.8	3.07	0.544	5.57	0.647	5.98
19.6	3.03	0.542	5.55	0.643	5.96
19.4	3.00	0.541	5.53	0.642	5.94
19.2	2.97	0.539	5.50	0.640	5.93
19.0	2.94	0.537	5.47	0.638	5.88

IV-Curve



Spectral Response

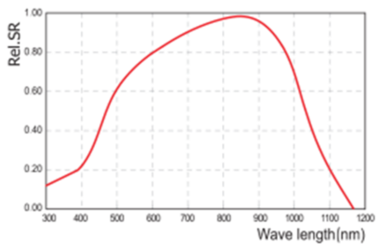


Figure 17: Datasheet for Solar Cell Model PGE2B125-165

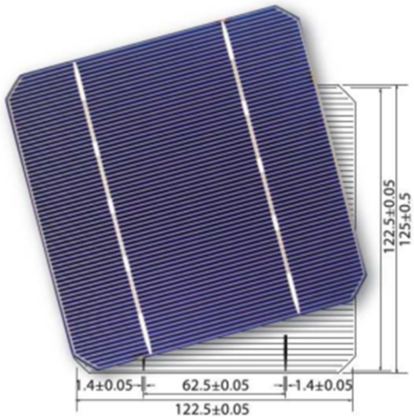
Source: https://cdn.enfsolar.com/z/pp/z2gv1s3ku0p/5fb0f3d69fa81.pdf

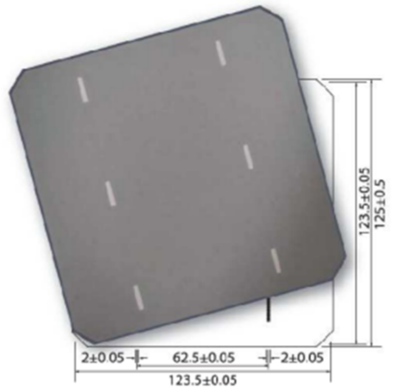
LINKING SOLAR

125S MONO SOLAR CELLS

125S

Front Pattern	Back Pattern





Mechanical Characteristics

Product	Mono-crystalline Silicon Solar Cell
Dimension	125mm×125mm, Φ165mm, tolerance±0.5mm
Thickness	200μm, tolerance±20μm
Front (cathode)	Blue silicon nitride anti-reflection coating 2×1.4mm wide discontinuous silver bus bars
Back (anode)	Aluminum back surface field 2×2mm wide discontinuous silver soldering pads

Electrical Characteristics

Efficiency (%)	Pmpp (Wp)	Vmpp (V)	Impp (A)	Voc (V)	Isc (A)	FF (%)
18.8%+	2.91	0.529	5.50	0.637	5.85	78.0
18.6%+	2.88	0.526	5.48	0.634	5.83	77.9

Figure 18: First part of datasheet for Solar Cell Model LKS-125mm-Mono-2BB

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

18.4%+	2.85	0.525	5.42	0.633	5.80	77.5
18.2%+	2.82	0.524	5.37	0.630	5.77	77.5
18.0%+	2.79	0.519	5.37	0.629	5.73	77.2
17.8%+	2.76	0.519	5.31	0.624	5.72	77.2
17.6%+	2.73	0.519	5.25	0.626	5.59	77.7

All data at STC: Irradiance 1000W/m^2, Cell temperature 25℃, AM1.5G. Pmpp ±1.5%, Efficiency ±0.2% abs.

Temperature Coefficients

TkCurrent	+0.03%/℃
TkVoltage	-0.34%/℃
TkPower	-0.44%/℃

Figure 19: second part of datasheet for Solar Cell Model LKS-125mm-Mono-2BB

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