EE236: Experiment 4

Temperature dependence of Solar Cell I/V Characteristics

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Contents

1 Overview of the experiment

This report contains my approach to the experiment, the circuit's design with the relevant simulation code and output plots.

1.1 Aim of the experiment

- To plot and understand I/V characteristics of solar cell at different temperatures and calculate ideality factor
- To plot and understand lighted I/V characteristics of solar cell when used as power source at different temperatures and calculate fill factor
- To understand the effect of R_s and R_{sh} on I/V characteristics of solar cell

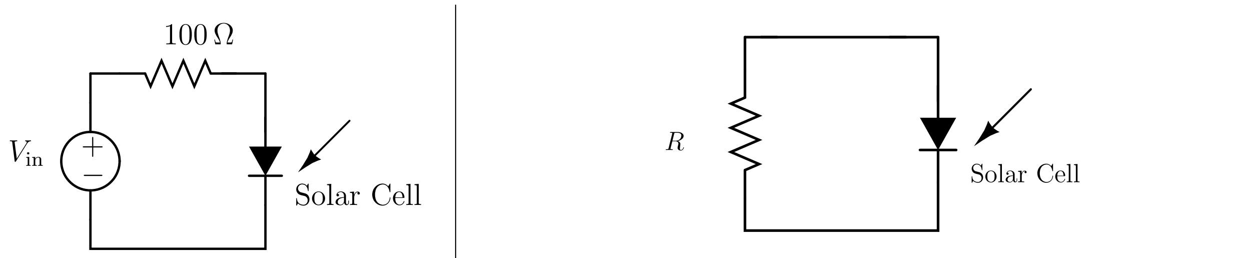
1.2 Methods

First, a comparison between parameters (V_D, η) was made by simulating the circuit at 5 different temperatures from the Dark I/V characteristics of Solar Cell.
Then, Lighted I/V and P/V characteristics of Solar Cell when using as a power source to calculate and compare fill factor, V_D, V_{OC} for the below temperatures.
Lastly, the effect of series resistance and shunt resistance was observed on Solar Cells by changing the provided solar cell model file and using that as a power source.
All parameters were calculated using python by exporting the vectors generated by NGSPICE.
The circuit was simulated at following temperatures (35°C, 45°C, 55°C, 65°C, 75°C).

2 Design

2.1 I/V Characteristics of Solar Cell

I/V characteristics circuit was taken from experiment 3 handout (Figure 1a).
Voltage was varied from -2 to $+2$.



(a) Dark I/V characteristics and η

(b) Lighted I/V characteristics when used as a power source

Figure 1: I/V characteristics and measurement of parameter of Solar Cell

Analytically,

$$I = I_0 \left(e^{\frac{q \cdot V_D}{\eta k T}} - 1 \right) - I_L \tag{1}$$

By taking natural logarithm of I and neglecting -1, we get $\log(I + I_L)/V$ characteristics

$$\ln\left(I + I_L\right) = \ln(I_0) + \frac{q \cdot V}{\eta k T} \quad \rightarrow \quad \ln(I + I_L) = \underbrace{\frac{q}{\eta k T}}_{slope} \cdot V + \underbrace{\ln(I_0)}_{y-intercept} \tag{2}$$

This graph is a straight line in some range of I, V. Also, $I_L = 0$ for Dark characteristics. We can calculate its slope to get η and y-intercept by interpolating that straight line.

$$\text{slope} = \frac{\ln I_2 - \ln I_1}{V_2 - V_1} = \frac{1}{\eta V_T} \rightarrow \eta = \frac{1}{V_T} \left(\frac{V_{D_2} - V_{D_1}}{\ln I_2 - \ln I_1} \right) \tag{3}$$

The voltage V_D at a current (I_D) was found using binary search (python's `bisect` library). Then, 2 consecutive I_D's gave 2 consecutive V_D's of the simulation with which slope is calculated using the above equation.

2.2 Lighted I/V Characteristics of Solar Cell when used as Power source

Then, the circuit for measurement of V_{OC} and I_{SC} was also taken from experiment 3 slides (Figure 1b) with $I_L = 8mA$. R was varied from 1 to 500Ω.
I_{SC} is maximum current through the cell.
V_{OC} is maximum voltage across the cell.
I_{MP}, V_{MP} and P_{MP} were taken from $P_R - V_D$ graph.

$$\text{Fill Factor} = \frac{I_{\text{MP}} \cdot V_{\text{MP}}}{I_{\text{SC}} \cdot V_{\text{OC}}}$$

2.3 Effect of R_s and R_{sh}

Again, the same circuit ((Figure 1b)) was used.
The values of R_s and R_{sh} were changed one by one and keeping the other at default value (i.e. R_s varies and $R_{sh} = 1k\Omega$, R_{sh} varies and $R_s = 10\Omega$). $I_L = 8mA$ for all cases.

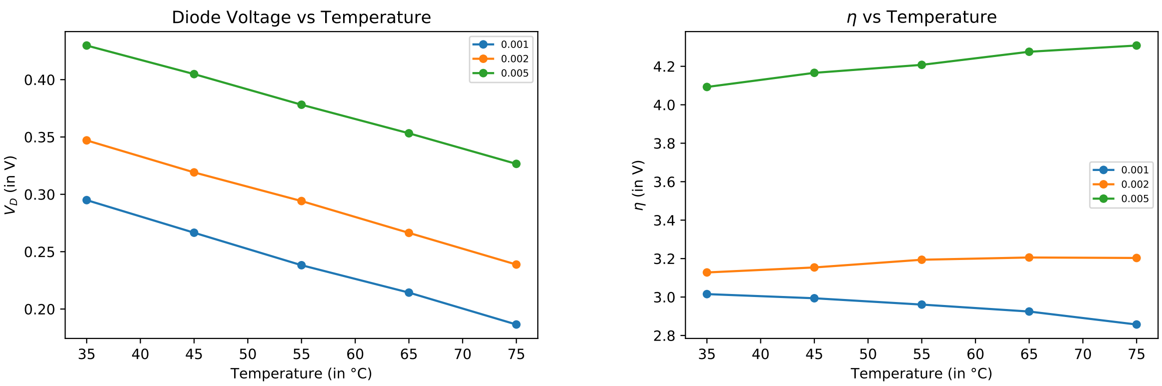
3 Simulation results

3.1 Plots

3.1.1 Dark I/V Characteristics of Solar Cell

Temperature (in °C)	V_D $(I_D = 1mA)$ (in V)	V_D $(I_D = 2mA)$ (in V)	V_D $(I_D = 5mA)$ (in V)	η $(I_D = 1mA)$	η $(I_D = 2mA)$	η $(I_D = 5mA)$
35	0.29496092	0.3470438	0.42974029	3.01526176	3.12787909	4.09260234
45	0.26653333	0.31912922	0.40482576	2.99364881	3.15392024	4.16613286
55	0.23820773	0.29415421	0.37812199	2.96076854	3.1939794	4.20767881
65	0.21432451	0.26638577	0.35322061	2.92465729	3.20568068	4.2757691
75	0.1865106	0.23878679	0.3265640	2.8571428	3.20316681	4.30818336

Table 1: V_D, η at different temperature and I_D values



(a) Diode Voltage vs Temperature (current in A) (b) η vs Temperature (current in A)

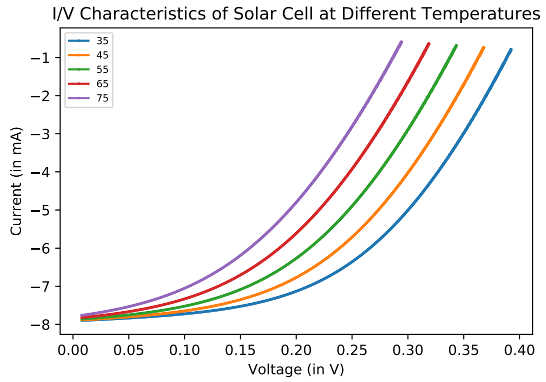
Figure 2: Temperature Dependence of Solar Cell

As visible in Figure 2, the variation of both Diode Voltage and η with Temperature is approximately linear.
The values decreases as temperature increases except when $I_D = 5mA$ (η increases).
For higher currents, diode voltage is higher and η is lower.

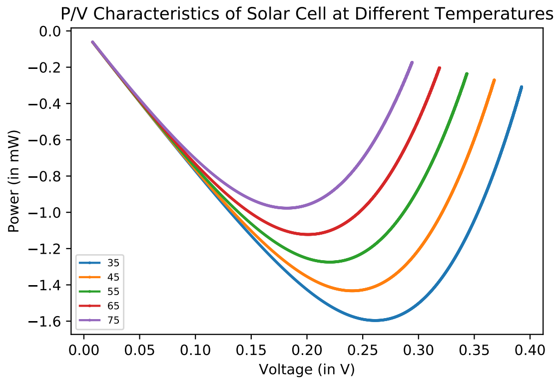
3.1.2 Lighted I/V Characteristics of Solar Cell when used as Power source

Temperature(in °C)	I_{SC} (in mA)	V_{OC} (in V)	Fill Factor
35	0.39245622	7.898107899999999	0.5150015044548059
45	0.367912146	7.8848731700000005	0.49390802180148974
55	0.343345655	7.861959720000001	0.4721343180554779
65	0.31877807399999997	7.82385279	0.44993563412103377
75	0.294242195	7.76296307	0.427657857218279

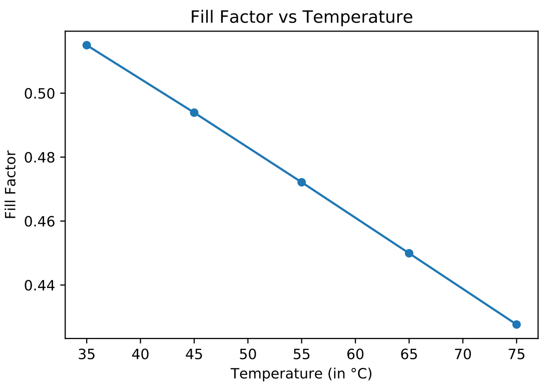
Table 2: Parameter values obtained from the characteristics



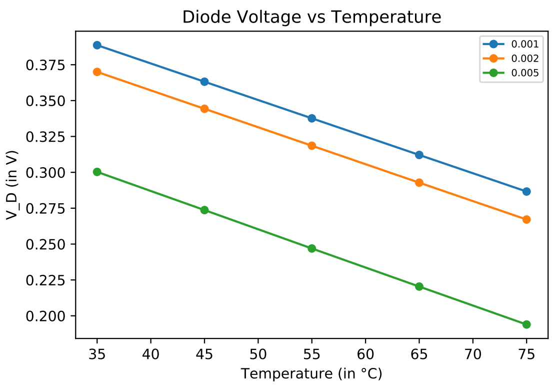
(a) I/V Characteristics (temperature in °C)



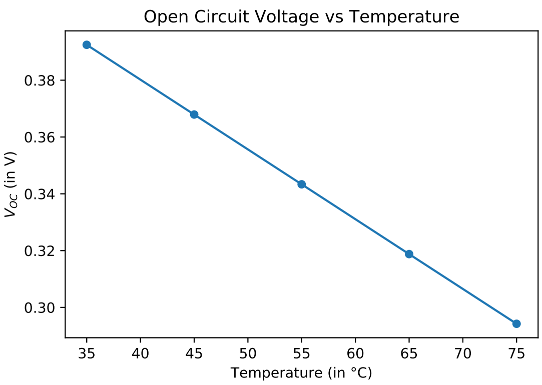
(b) P/V Characteristics (temperature in °C)



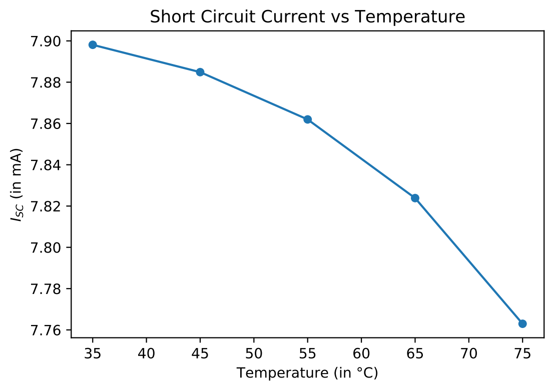
(c) Fill Factor



(d) Diode Voltage (current in A)



(e) V_{OC}

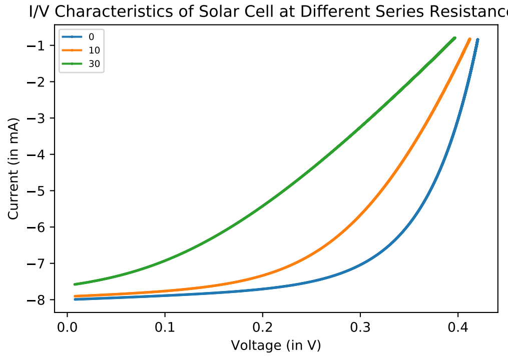


(f) I_{SC}

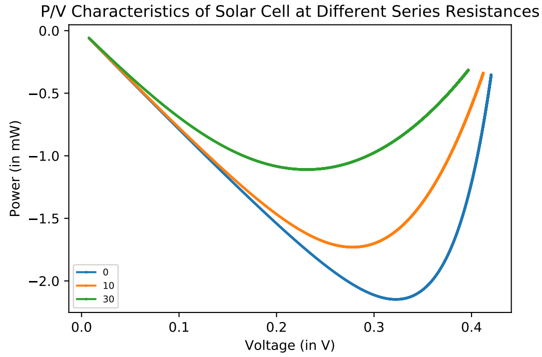
Figure 3: Temperature Dependence of Solar Cell as a Power Source

As shown in figure 3, the fill factor, open circuit voltage and V_D have linear variation whereas short circuit current has a non linear change (like a parabolic trajectory).
They all reduce with increase in temperature.

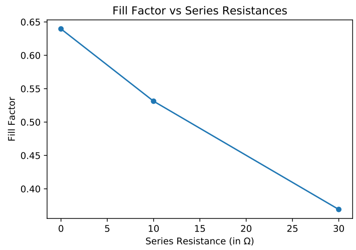
3.1.3 Effect of R_s and R_{sh}



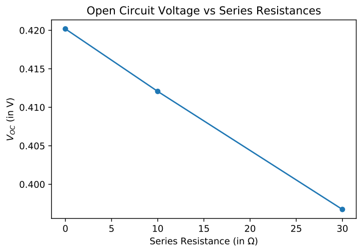
(a) I/V Characteristics (temperature in °C)



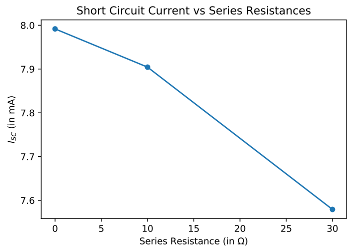
(b) P/V Characteristics (temperature in °C)



(c) Fill Factor

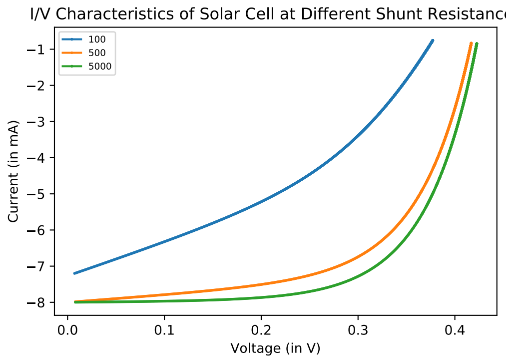


(d) V_{OC}

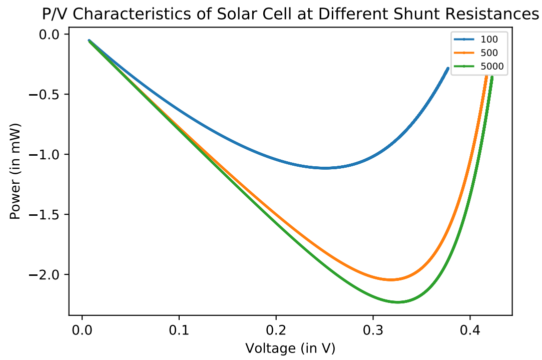


(e) I_{SC}

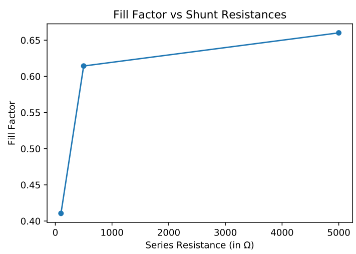
Figure 4: Effect of R_s on Solar Cell at Different Temperatures



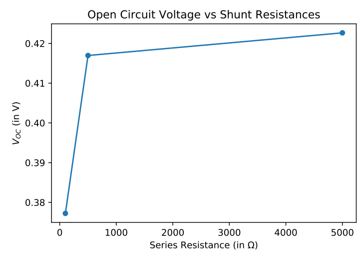
(a) I/V Characteristics (temperature in °C)



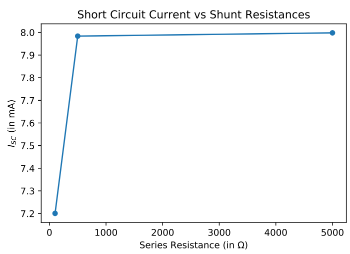
(b) P/V Characteristics (temperature in °C)



(c) Fill Factor



(d) V_{OC}



(e) I_{SC}

Figure 5: Effect of R_{sh} on Solar Cell at Different Temperatures

Figure 4 shows by using higher series resistance the I/V Characteristics becomes flatter (the bulge reduces, also evident in P/V Characteristics). Hence, cell performance degrades.
Figure 5 shows by using higher shunt resistance the I/V Characteristics becomes curvier (the bulge increases, also evident in P/V Characteristics). Hence, cell performance improves.
Fill factor, open circuit voltage and short circuit all changes (reduces) as R_s increases, but in the case of R_{sh}, all 3 increases but the rate of increase decreases, i.e. even for large changes in R_{sh}, there is very small change in the values (especially in the case of short circuit current 0.01mA when R_{sh} increases from 500 to 5K).

3.2 Code Snippets

3.2.1 Dark I/V Characteristics of Solar Cell

3.2.1.1 Temperature = 35°C

```
Param Rathour (190070049), I/V characteristics of Solar Cell
.include Solar_Cell.txt              ; Includes Solar Cell Model
R1 mid out 100
X1 out gnd solar_cell IL_val = 0     ; Solar Cell
Vin in gnd dc 0                      ; DC source Vin
Vdummy in mid 0
.dc Vin -2 2 0.01                    ; DC Analysis
.control
set temp = 35
run
let I_D = I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
plot log(abs(I_D)) vs V_D
wrdata 11.txt I_D vs V_D
.endc
.end
```

3.2.1.2 Temperature = 45°C

```
Param Rathour (190070049), I/V characteristics of Solar Cell
.include Solar_Cell.txt              ; Includes Solar Cell Model
R1 mid out 100
X1 out gnd solar_cell IL_val = 0     ; Solar Cell
Vin in gnd dc 0                      ; DC source Vin
Vdummy in mid 0
.dc Vin -2 2 0.01                    ; DC Analysis
.control
set temp = 45
run
let I_D = I(Vdummy)
let V_D = V(out)
```

```
plot I_D vs V_D
plot log(abs(I_D)) vs V_D
wrdata 12.txt I_D vs V_D
.endc
.end
```

3.2.1.3 Temperature = 55°C

```
Param Rathour (190070049), I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 mid out 100
X1 out gnd solar_cell IL_val = 0    ; Solar Cell
Vin in gnd dc 0                     ; DC source Vin
Vdummy in mid 0
.dc Vin -2 2 0.01                   ; DC Analysis
.control
set temp = 55
run
let I_D = I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
plot log(abs(I_D)) vs V_D
wrdata 13.txt I_D vs V_D
.endc
.end
```

3.2.1.4 Temperature = 65°C

```
Param Rathour (190070049), I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 mid out 100
X1 out gnd solar_cell IL_val = 0    ; Solar Cell
Vin in gnd dc 0                     ; DC source Vin
Vdummy in mid 0
.dc Vin -2 2 0.01                   ; DC Analysis
.control
set temp = 65
run
let I_D = I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
plot log(abs(I_D)) vs V_D
wrdata 14.txt I_D vs V_D
.endc
.end
```

3.2.1.5 Temperature = 75°C

```
Param Rathour (190070049), I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 mid out 100
X1 out gnd solar_cell IL_val = 0    ; Solar Cell
Vin in gnd dc 0                     ; DC source Vin
Vdummy in mid 0
.dc Vin -2 2 0.01                   ; DC Analysis
.control
set temp = 75
run
let I_D = I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
plot log(abs(I_D)) vs V_D
wrdata 15.txt I_D vs V_D
.endc
.end
```

3.2.2 Lighted I/V Characteristics of Solar Cell when used as Power source

3.2.2.1 Temperature = 35°C

```
Param Rathour (190070049), Lighted I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
X1 out gnd solar_cell IL_val = 8e-3 ; Solar Cell
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
set temp = 35
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 21.txt I_D vs V_D
.endc
.end
```

3.2.2.2 Temperature = 45°C

```
Param Rathour (190070049), Lighted I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
X1 out gnd solar_cell IL_val = 8e-3 ; Solar Cell
```

```
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
set temp = 45
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 22.txt I_D vs V_D
.endc
.end
```

3.2.2.3 Temperature = 55°C

```
Param Rathour (190070049), Lighted I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
X1 out gnd solar_cell IL_val = 8e-3 ; Solar Cell
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
set temp = 55
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 23.txt I_D vs V_D
.endc
.end
```

3.2.2.4 Temperature = 65°C

```
Param Rathour (190070049), Lighted I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
X1 out gnd solar_cell IL_val = 8e-3 ; Solar Cell
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
set temp = 65
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 24.txt I_D vs V_D
```

```
.endc
.end
```

3.2.2.5 Temperature = 75°C

```
Param Rathour (190070049), Lighted I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
X1 out gnd solar_cell IL_val = 8e-3 ; Solar Cell
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
set temp = 75
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 25.txt I_D vs V_D
.endc
.end
```

3.2.3 Effect of R_s

3.2.3.1 $R_s = 0\Omega$

```
Param Rathour (190070049), Effect of R_S on I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 0
rsh temp gnd 1e3
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3a1.txt I_D vs V_D
.endc
.end
```

3.2.3.2 $R_s = 10\Omega$

```
Param Rathour (190070049), Effect of R_S on I/V characteristics of Solar Cell
.include Solar_Cell.txt              ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 0
rsh temp gnd 1e3
Vdummy in gnd 0
.dc R1 1 500 0.1                     ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3a1.txt I_D vs V_D
.endc
.end
```

3.2.3.3 $R_s = 30\Omega$

```
Param Rathour (190070049), Effect of R_S on I/V characteristics of Solar Cell
.include Solar_Cell.txt              ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 10
rsh temp gnd 1e3
Vdummy in gnd 0
.dc R1 1 500 0.1                     ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3a2.txt I_D vs V_D
.endc
.end
```

3.2.4 Effect of R_{sh}

3.2.4.1 $R_{sh} = 100\Omega$

```
Param Rathour (190070049), Effect of R_Sh on I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 10
rsh temp gnd 100
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3b1.txt I_D vs V_D
.endc
.end
```

3.2.4.2 $R_{sh} = 500\Omega$

```
Param Rathour (190070049), Effect of R_S on I/V characteristics of Solar Cell
.include Solar_Cell.txt             ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 0
rsh temp gnd 500
Vdummy in gnd 0
.dc R1 1 500 0.1                    ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3b2.txt I_D vs V_D
.endc
```

```
.end
```

3.2.4.3 $R_{sh} = 5k\Omega$

```
Param Rathour (190070049), Effect of R_S on I/V characteristics of Solar Cell
.include Solar_Cell.txt            ; Includes Solar Cell Model
R1 in out 0
IL gnd temp dc 8e-3
d1 temp gnd diode
.model diode d (is=(1e-13) n=1)
d2 temp gnd diode2
.model diode2 d (is=(2e-6) n=2)
rs temp out 0
rsh temp gnd 5k
Vdummy in gnd 0
.dc R1 1 500 0.1                   ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_D = V(out)
plot I_D vs V_D
wrdata 3b3.txt I_D vs V_D
.endc
.end
```

3.3 Python Code for Plots

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy import stats
import math
import pandas as pd
import bisect
```

3.3.1 Dark I/V Characteristics of Solar Cell

```python
temp = [(i) for i in range(35,85,10)]
I_D = [1e-3, 2e-3, 5e-3]
V_D = np.zeros((len(temp), len(I_D)))
eta = np.zeros((len(temp), len(I_D)))
for i in range(5):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab4\\1' +  str(i+1)
    + '.txt', header = None, skipinitialspace=True, delim_whitespace=True)
    idx = [bisect.bisect_left(data[1], j) for j in I_D]
    V_D[i]=([data[0][j] for j in idx])
```

```
    slope = [(math.log(data[1][j]) - math.log(data[1][j-1]))
    /((data[0][j]) - (data[0][j-1])) for j in idx]
    eta[i] = [1/(26/1000*j) for j in slope]
    print("V_D for I_D =", str(I_D), "mA and Temperature =", temp[i], "°C" ,
    V_D[i])
    print("eta for I_D =", str(I_D), "mA and Temperature =", temp[i], "°C" ,
    eta[i])
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Temperature (in °C)')
ax1.set_ylabel('$V_D$ (in V)')
ax1.set_title('Diode Voltage vs Temperature')
for j in range(len(I_D)):
    ax1.plot(temp, V_D[:,j], '-o', markersize=5)
ax1.legend(I_D, fontsize = 'x-small')
fig2, ax2 = plt.subplots()
ax2.set_xlabel('Temperature (in °C)')
ax2.set_ylabel('$\eta$ (in V)')
ax2.set_title('$\eta$ vs Temperature')
for j in range(len(I_D)):
    ax2.plot(temp, eta[:,j], '-o', markersize=5)
ax2.legend(I_D, fontsize = 'x-small')
fig1.savefig('11.pdf')
fig2.savefig('12.pdf')
```

3.3.2 Lighted I/V Characteristics of Solar Cell when used as Power source

```
temp = [(i) for i in range(35,85,10)]
I_D = [1e-3, 2e-3, 5e-3]
V_D = np.zeros((len(temp), len(I_D)))
V_OC = []
I_SC = []
P_MAX = []
FF = []
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage (in V)')
ax1.set_ylabel('Current (in mA)')
ax1.set_title('I/V Characteristics of Solar Cell at Different Temperatures')
fig2, ax2 = plt.subplots()
ax2.set_xlabel('Voltage (in V)')
ax2.set_ylabel('Power (in mW)')
ax2.set_title('P/V Characteristics of Solar Cell at Different Temperatures')
fig3, ax3 = plt.subplots()
ax3.set_xlabel('Temperature (in °C)')
ax3.set_ylabel('Fill Factor')
ax3.set_title('Fill Factor vs Temperature')
fig4, ax4 = plt.subplots()
```

```
ax4.set_xlabel('Temperature (in °C)')
ax4.set_ylabel('V_D (in V)')
ax4.set_title('Diode Voltage vs Temperature')
fig5, ax5 = plt.subplots()
ax5.set_xlabel('Temperature (in °C)')
ax5.set_ylabel('$V_{OC}$ (in V)')
ax5.set_title('Open Circuit Voltage vs Temperature')
fig6, ax6 = plt.subplots()
ax6.set_xlabel('Temperature (in °C)')
ax6.set_ylabel('$I_{SC}$ (in mA)')
ax6.set_title('Short Circuit Current vs Temperature')
for i in range(5):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab4\\2' +  str(i+1)
    + '.txt', header = None, skipinitialspace=True, delim_whitespace=True)
    V = data[0]
    I = 1000*data[1]
    P = I*V
    V_OC.append(max(abs(V)))
    I_SC.append(max(abs(I)))
    P_MAX.append(max(abs(P)))
    FF.append(P_MAX[-1]/(V_OC[-1]*I_SC[-1]))
    idx = [bisect.bisect_left(I, -1000*j) for j in I_D]
    V_D[i]=([V[j] for j in idx])
    ax1.plot(V, I, '-o', markersize=1) #, color = colour[j]
    ax2.plot(V, P, '-o', markersize=1) #, color = colour[j]
ax1.legend(temp, fontsize = 'x-small')
ax2.legend(temp, fontsize = 'x-small')
print("V_OC for Temperature =", str(temp), "°C is" , V_OC, "in V")
print("I_SC for Temperature =", str(temp), "°C is" , I_SC, "in mA")
print("Fill Factor for Temperature =", str(temp), "°C is" , FF)
ax3.plot(temp, FF, '-o', markersize=5)
for j in range(len(I_D)):
    ax4.plot(temp, V_D[:,j], '-o', markersize=5)
ax4.legend(I_D, fontsize = 'x-small')
ax5.plot(temp, V_OC, '-o', markersize=5)
ax6.plot(temp, I_SC, '-o', markersize=5)
fig1.savefig('21.pdf')
fig2.savefig('22.pdf')
fig3.savefig('23.pdf')
fig4.savefig('24.pdf')
fig5.savefig('25.pdf')
fig6.savefig('26.pdf')
```

3.3.3 Effect of R_s

```
R_S = [0, 10, 30]
V_OC = []
I_SC = []
P_MAX = []
FF = []
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage (in V)')
ax1.set_ylabel('Current (in mA)')
ax1.set_title('I/V Characteristics of Solar Cell at Different Series
Resistances')
fig2, ax2 = plt.subplots()
ax2.set_xlabel('Voltage (in V)')
ax2.set_ylabel('Power (in mW)')
ax2.set_title('P/V Characteristics of Solar Cell at Different Series
Resistances')
fig3, ax3 = plt.subplots()
ax3.set_xlabel('Series Resistance (in Ω)')
ax3.set_ylabel('Fill Factor')
ax3.set_title('Fill Factor vs Series Resistances')
fig4, ax4 = plt.subplots()
ax4.set_xlabel('Series Resistance (in Ω)')
ax4.set_ylabel('$V_{OC}$ (in V)')
ax4.set_title('Open Circuit Voltage vs Series Resistances')
fig5, ax5 = plt.subplots()
ax5.set_xlabel('Series Resistance (in Ω)')
ax5.set_ylabel('$I_{SC}$ (in mA)')
ax5.set_title('Short Circuit Current vs Series Resistances')
for i in range(len(R_S)):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab4\\3a' +  str(i+1)
    + '.txt', header = None, skipinitialspace=True, delim_whitespace=True)
    V = data[0]
    I = 1000*data[1]
    P = I*V
    V_OC.append(max(abs(V)))
    I_SC.append(max(abs(I)))
    P_MAX.append(max(abs(P)))
    FF.append(P_MAX[-1]/(V_OC[-1]*I_SC[-1]))
    ax1.plot(V, I, '-o', markersize=1) #, color = colour[j]
    ax2.plot(V, P, '-o', markersize=1) #, color = colour[j]
ax1.legend(R_S, fontsize = 'x-small')
ax2.legend(R_S, fontsize = 'x-small')
print("V_OC for Series Resistance =", str(R_S), "Ω is" , V_OC, "in V")
print("I_SC for Series Resistance =", str(R_S), "Ω is" , I_SC, "in mA")
print("Fill Factor for Series Resistance =", str(R_S), "Ω is" , FF)
ax3.plot(R_S, FF, '-o', markersize=5)
```

```
ax4.plot(R_S, V_OC, '-o', markersize=5)
ax5.plot(R_S, I_SC, '-o', markersize=5)
fig1.savefig('3a1.pdf')
fig2.savefig('3a2.pdf')
fig3.savefig('3a3.pdf')
fig4.savefig('3a4.pdf')
fig5.savefig('3a5.pdf')
```

3.3.4 Effect of R_{sh}

```
R_Sh = [100, 500, 5000]
V_OC = []
I_SC = []
P_MAX = []
FF = []
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage (in V)')
ax1.set_ylabel('Current (in mA)')
ax1.set_title('I/V Characteristics of Solar Cell at Different Shunt
Resistances')
fig2, ax2 = plt.subplots()
ax2.set_xlabel('Voltage (in V)')
ax2.set_ylabel('Power (in mW)')
ax2.set_title('P/V Characteristics of Solar Cell at Different Shunt
Resistances')
fig3, ax3 = plt.subplots()
ax3.set_xlabel('Series Resistance (in Ω)')
ax3.set_ylabel('Fill Factor')
ax3.set_title('Fill Factor vs Shunt Resistances')
fig4, ax4 = plt.subplots()
ax4.set_xlabel('Series Resistance (in Ω)')
ax4.set_ylabel('$V_{OC}$ (in V)')
ax4.set_title('Open Circuit Voltage vs Shunt Resistances')
fig5, ax5 = plt.subplots()
ax5.set_xlabel('Series Resistance (in Ω)')
ax5.set_ylabel('$I_{SC}$ (in mA)')
ax5.set_title('Short Circuit Current vs Shunt Resistances')
for i in range(len(R_Sh)):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab4\\3b' +  str(i+1)
    2+ '.txt', header = None, skipinitialspace=True, delim_whitespace=True)
    V = data[0]
    I = 1000*data[1]
    P = I*V
    V_OC.append(max(abs(V)))
    I_SC.append(max(abs(I)))
    P_MAX.append(max(abs(P)))
```

```
    FF.append(P_MAX[-1]/(V_OC[-1]*I_SC[-1]))
    ax1.plot(V, I, '-o', markersize=1) #, color = colour[j]
    ax2.plot(V, P, '-o', markersize=1) #, color = colour[j]
ax1.legend(R_Sh, fontsize = 'x-small')
ax2.legend(R_Sh, fontsize = 'x-small')
print("V_OC for Shunt Resistance =", str(R_Sh), "Ω is" , V_OC, "in V")
print("I_SC for Shunt Resistance =", str(R_Sh), "Ω is" , I_SC, "in mA")
print("Fill Factor for Shunt Resistance =", str(R_Sh), "Ω is" , FF)
ax3.plot(R_Sh, FF, '-o', markersize=5)
ax4.plot(R_Sh, V_OC, '-o', markersize=5)
ax5.plot(R_Sh, I_SC, '-o', markersize=5)
fig1.savefig('3b1.pdf')
fig2.savefig('3b2.pdf')
fig3.savefig('3b3.pdf')
fig4.savefig('3b4.pdf')
fig5.savefig('3b5.pdf')
```

4 Experiment completion status

Completed everything in Lab successfully.

5 Questions for reflection

Please see my Design and Simulation Result sections for my comments.
Overall, the lab was good.
Thanks!