EE236: Electronic Devices Lab
Lab 5: Temperature Dependence of Solar Cell I/V Characteristics

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1 Aim of the experiment

The aim was to perform the following tasks for a solar cell:

- Plot dark forward I-V at different temperatures.
- Plot lighted I-V at these temperatures.
- Observe the effect of temperature on cut-in voltage, Voc, Isc, fill factor and ideality factor.

2 Theory

The solar cell is essentially a "special" semiconductor diode with large area. The ideal semiconductor diode equation is given by

$$I = I_{01}(e^{\frac{qV_D}{kT}} - 1) \tag{1}$$

However, real materials have defects and they influence the diode current. The current voltage relationship of a real diode (solar cell in dark) is given by Eq. 2

$$I = I_{01}[e^{\frac{qV_D}{kT}} - 1] + I_{02}[e^{\frac{qV_D}{2kT}} - 1] + \frac{V - IR_s}{R_{Sh}} \tag{2}$$

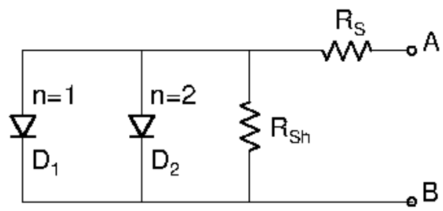

Figure 1: Equivalent circuit of solar cell under dark conditions

For a one sided junction,

$$I_{01} = q \left(\frac{D_p}{\tau_p}\right)^{\frac{1}{2}} \left(\frac{n_i^2}{N_A}\right) \tag{3}$$

and

$$I_{02} = \left(qW\sigma v_{th} N_T n_i^2\right) \tag{4}$$

where,

$$n_i^2 = N_C N_V e^{-\frac{E_g}{kT}} \tag{5}$$

D and τ are the diffusion constant and lifetime respectively, n_i the intrinsic carrier concentration, N_D the donor doping density, W the depletion width, N_C and N_V are the effective densities of states for conduction band and valence band respectively, σ as capture cross-section and v_{th} the thermal velocity.

The term involving I_{02} is caused by the presence of defects with energy near the midgap. This can be seen in Eq. 4 where I_{02} is proportional to the defect density N_T. Usually I_{02} is much larger than I_{01}. Hence, at low voltages, the term I_{02} in Eq. 2 dominates the I-V characteristic. The inverse of the slope of the curve of $\ln I$ v/s V_D is given by $\eta kT/q$. where η the ideality factor equal to 2. The magnitude of I_{02} and the range of voltage where $\eta = 2$ is a measure of defect density in the material.

As the applied voltage V increases, the term I_{01} dominates the I-V characteristic as the I_{01} term increases more steeply with voltage (ideality factor $\eta = 1$). The magnitudes of I_{01} and I_{02} is a measure of the "goodness" of the diode. The smaller the values, the better the technology and will make a better solar cell.

Under illumination there is a constant generation of free carriers that gives rise to a "reverse" current I_L. The solar cell acts as a current generator.

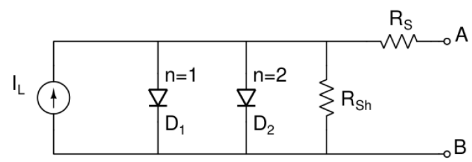

Figure 2: Equivalent circuit of a Solar Cell under illumination

Under illumination, the diode equation becomes

$$I = I_{01}[e^{\frac{qV_D}{kT}} - 1] + I_{02}[e^{\frac{qV_D}{2kT}} - 1] + \frac{V + IR_s}{R_{Sh}} - I_L \tag{6}$$

We see from Eq.6 that under illumination, the current is essentially the photo-generated current I_L bucked by the forward "dark current". The shape of the lighted I-V curve is essentially the same as the dark I-V displaced by I_L. The Fill Factor, which is the "squareness" of the lighted I-V characteristic depends on the shape of the dark I-V curve. The short circuit current is the current in the circuit by shorting leads A and B. The open circuit voltage is the voltage between A and B at zero current.

It turns out that both I_{01} and I_{02} are temperature dependent and their temperature dependence comes through n_i, which varies exponentially with temperature. This causes both, dark and lighted characteristics to depend on temperature.

In this experiment, we will measure dark and lighted characteristics and investigate how the parameters I_{SC}, V_{OC}, fill factor, cut-in voltage vary with temperature.

It is found that ideally I_{SC} increases marginally with increase of temperature (may not be obvious from these characteristics. The expected fractional increase in I_{SC} with temperature is given as [1]

$$\left[\frac{1}{I_{SC}}\right]\left[\frac{\Delta I_{SC}}{\Delta T}\right] \sim 0.0003/K \tag{7}$$

The increase is related to small reduction in the semiconductor band gap with increase of temperature such that the semiconductor absorbs more photons from the incident sun light.

In contrast with I_{SC}, the V_{OC} shows a very substantial decrease with increase in temperature. The expected fractional decrease of V_{OC} [1]

$$\left[\frac{1}{V_{OC}}\right]\left[\frac{\Delta V_{OC}}{\Delta T}\right] \sim -0.003/K \tag{8}$$

which works out to be decrease of roughly 2 mV per degree.

The cut-in voltage is defined as the voltage across the diode at a fixed forward current and it decreases as T increases. The open circuit voltage V_{oc} will also decrease. If you plot the cut-in voltage as a function of T and the V_{oc} also as a function of T on the same graph, you should expect to see a similar dependence of both quantities. The lighted I-V characteristics are intimately connected with the dark I-V characteristics.

3 Experiment

3.1 Components used

- Solar Cell with LED bank apparatus
- Temperature controller
- Resistors- 100Ω
- Potentiometer- 100Ω, 500Ω
- LM35 sensor
- Breadboard, connecting wires

3.2 Part-1: Dark forward characteristics at different temperatures

3.2.1 Circuit

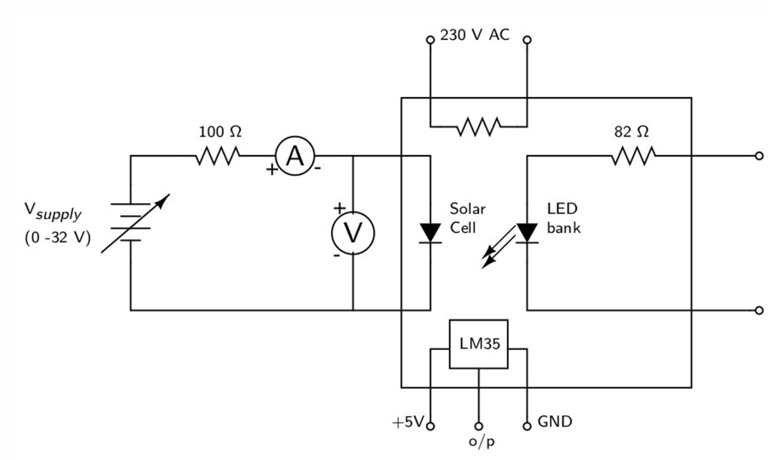

Figure 3: Dark I-V characteristics circuit

3.2.2 Readings

Voltage (V)	Current (mA)
0.000	0.00
0.091	0.05
0.180	0.15
0.253	0.40
0.307	0.81
0.346	1.37
0.372	2.03
0.392	2.75
0.400	3.12
0.407	3.51
0.413	3.90
0.425	4.70
0.438	5.94
0.449	7.18
0.463	9.32
0.473	11.48
0.482	13.67

Table 1: Solar Cell Data at 35°C

Voltage (V)	Current (mA)
0.000	0.00
0.090	0.03
0.177	0.15
0.298	0.84
0.333	1.41
0.384	3.14
0.401	4.29
0.410	5.08
0.427	7.10
0.440	9.18
0.449	11.27
0.457	13.39

Table 2: Solar Cell Data at 45°C

Voltage (V)	Current (mA)
0.000	0.00
0.089	0.04
0.209	0.31
0.288	0.93
0.321	1.52
0.344	2.18
0.368	3.28
0.384	4.44
0.392	5.25
0.408	7.28
0.420	9.36
0.429	11.45
0.436	13.57

Table 3: Solar Cell Data at 55°C

Voltage (V)	Current (mA)
0.000	0.00
0.086	0.07
0.165	0.27
0.226	0.63
0.270	1.15
0.300	1.79
0.322	2.51
0.338	3.28
0.351	4.08
0.361	4.91
0.369	5.75
0.385	7.90
0.397	10.10
0.406	12.33
0.413	14.55

Table 4: Solar Cell Data at 65°C

3.2.3 Results and Inferences

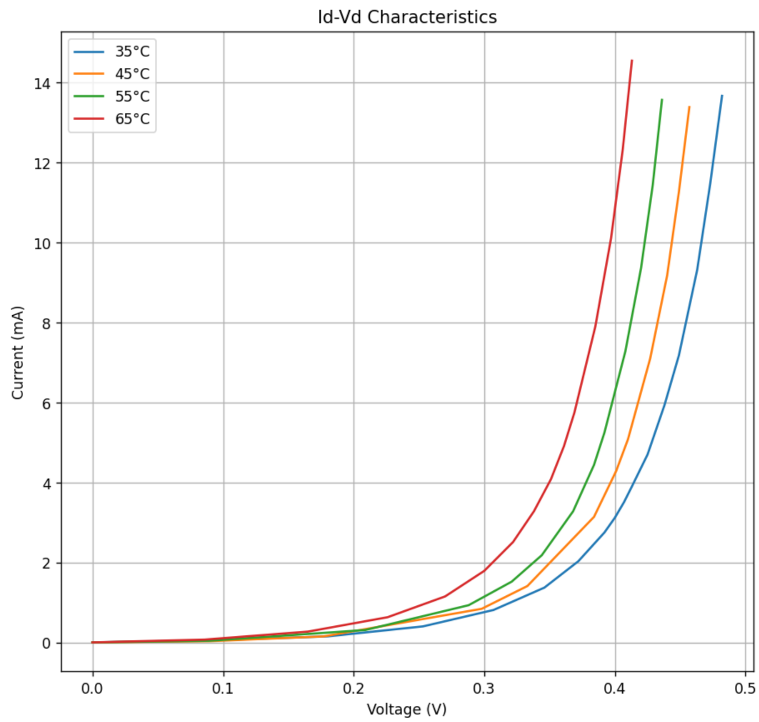

Figure 4: I-V at different temperatures

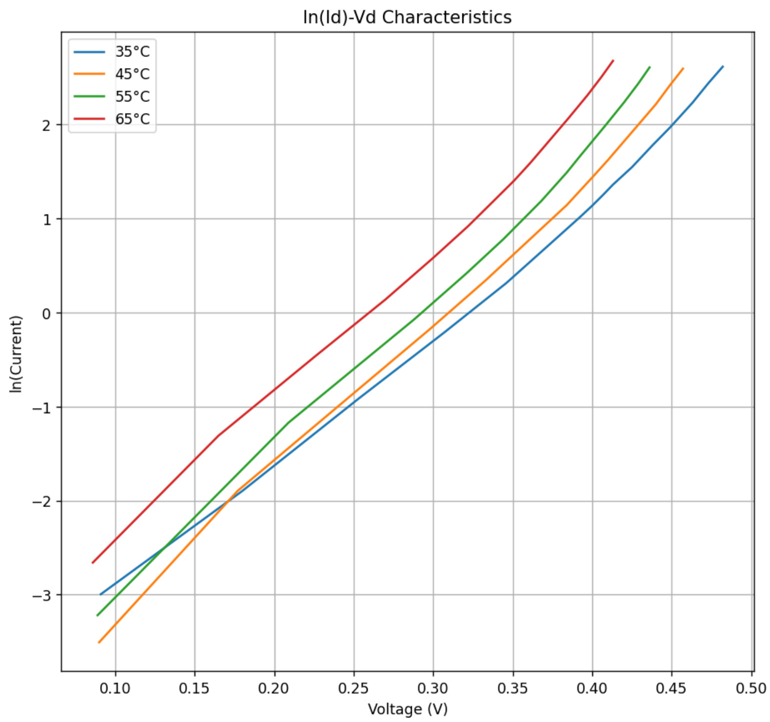

Figure 5: ln(I) vs V at different temperatures

Temp	V_d **(**$I_d = 1$**mA)**	V_d **(**$I_d = 2$**mA)**	V_d **(**$I_d = 5$**mA)**	η **(low FB)**	η **(high FB)**
35°C	0.32	0.37	0.43	2.95	2.21
45°C	0.31	0.35	0.41	2.46	1.96
55°C	0.29	0.33	0.39	2.45	1.93
65°C	0.26	0.31	0.36	2.44	2.03

Table 5: Temperature vs. Diode Voltage and Ideality Factor

3.3 Part 2 : Lighted I/V at different temperatures

3.3.1 Circuit

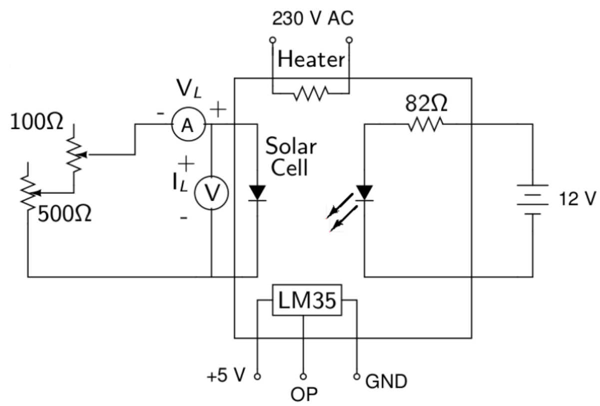

Figure 6: Lighted I-V characteristics circuit

3.3.2 Readings

Voltage (V)	Current (mA)
0.000	-11.25
0.130	-11.10
0.200	-11.00
0.300	-10.52
0.400	-8.29
0.410	-7.84
0.420	-7.10
0.430	-6.29
0.440	-5.34
0.450	-3.99
0.460	-2.47
0.465	-1.18
0.467	-0.73
0.471	0.00
Voc = 0.471 V	
Isc = 11.25 mA	

Table 6: Solar Cell Data at 35°C

Voltage (V)	Current (mA)
0.000	-11.25
0.130	-11.09
0.200	-10.95
0.300	-10.25
0.400	-6.95
0.410	-5.88
0.420	-4.80
0.430	-3.24
0.440	-1.53
0.447	0.00
Voc = 0.447 V	
Isc = 11.25 mA	

Table 7: Solar Cell Data at 45°C

Voltage (V)	Current (mA)
0.000	-11.21
0.130	-11.02
0.200	-10.77
0.300	-9.80
0.325	-9.22
0.350	-7.93
0.375	-6.5
0.400	-4.56
0.410	-2.73
0.420	-0.66
0.423	0.00
Voc = 0.423 V	
Isc = 11.21 mA	

Table 8: Solar Cell Data at 55°C

Voltage (V)	Current (mA)
0.000	-11.16
0.130	-10.93
0.200	-10.63
0.300	-9.36
0.310	-8.83
0.320	-8.31
0.340	-7.45
0.370	-4.91
0.375	-4.85
0.381	-3.24
0.386	-2.39
0.391	-1.58
0.396	-0.65
0.399	0.00
Voc = 0.399 V	
Isc = 11.16 mA	

Table 9: Solar Cell Data at 65°C

3.3.3 Results and Inferences

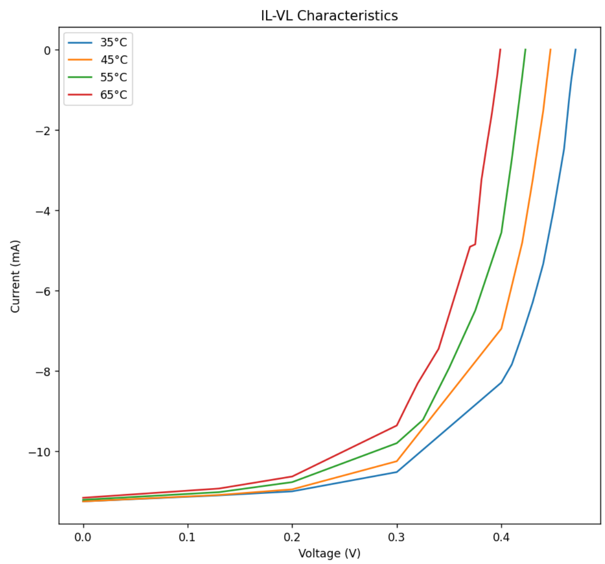

Figure 7: I-V characteristics for different temperatures

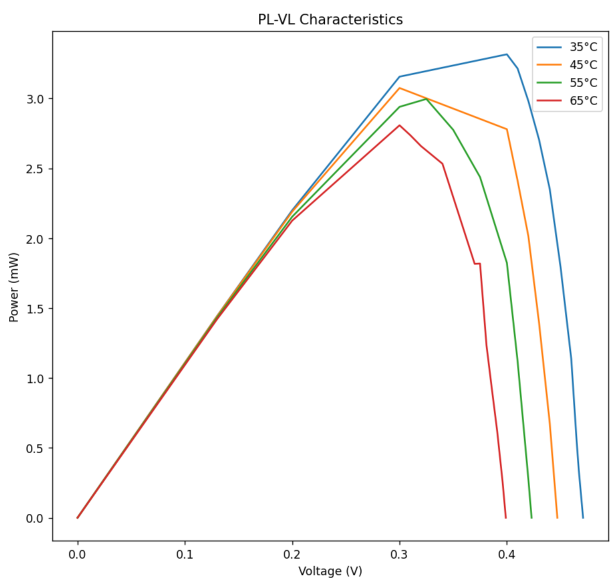

Figure 8: P-V characteristics for different temperatures

Temperature (°C)	Fill Factor
35	0.6258
45	0.6115
55	0.6319
65	0.6306

Table 10: Fill Factor Values at Different Temperatures

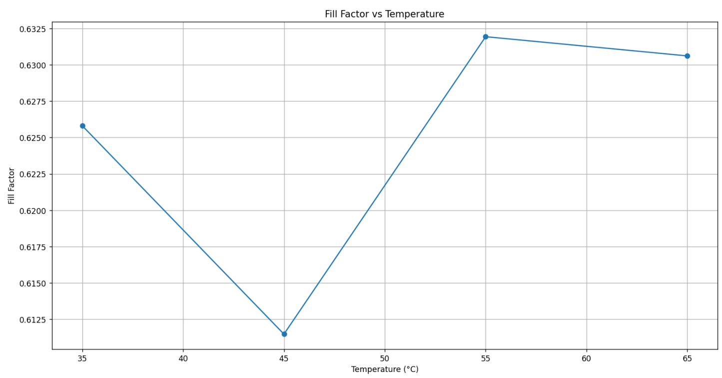

Figure 9: Fill factor vs temperature

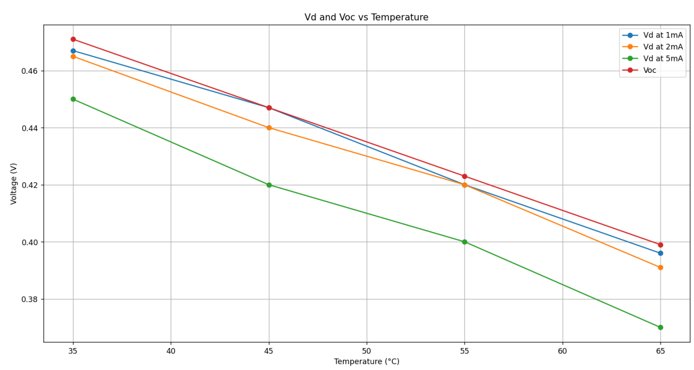

Figure 10: V_d and V_{oc} vs temperature

Comments on temperature dependence:

- V_{oc} : Decreases with increasing temperature.

- I_{sc} : Slightly decreases with increasing temperature.
- Fill Factor: Generally decreases with increasing temperature, indicating reduced efficiency at higher temperatures.

These trends are consistent with the theoretical expectations for solar cells.