Optical Characterisation of Single Junction Mono-crystalline Silicon Solar Cell

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Declaration

I hereby declare that the internship report titled “Optical Characterisation of Mono-crystalline Silicon Solar Cell” submitted by me had been carried out under the supervision of Mr. Mahbubul Hoq, Director, Institute of Electronics, Atomic Energy Research Establishment (AERE), Ganakbari, Dhaka and Mr. Muhammad Lutfor Rahman, Senior Lecturer, Department of Mathematics and Natural Sciences, BRAC University. It is further declared that the research work presented here is based on original work carried out by me. Any reference to work done by any other person or institution or any material obtained from other sources have been duly cited and referenced.

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Abstract

In this paper the character of a solar cell in terms of minority carrier diffusion length through surface photovoltage (SPV) technique is studied. SPV is measured with respect to wavelength where the spectral range is 400-1200 nm. A 200 μm thickness of 3″ X 3″ mono-crystalline silicon solar cell is used for the calculation purpose; through which the values of total carrier generation and recombination during illumination are found. For the range, 700-1000 nm wavelength penetration depth of the cell can be found. This helps in plotting of a curve that eventually gives us the value of carrier diffusion length which also helps in determining minority carrier lifetime of the cell, short circuit current density, optimum value of generation etc.

For further study of the cells character, an efficiency test and an external quantum efficiency test is done via pre-set instruments built for the specific purpose, which helps in further confirmation of the quality of the fabricated cell.

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CHAPTER 1: CARRIER COUNT WITH VSPV

1.1 Introduction

Solar cell consists of a p-n junction that reacts to light particles—photons hitting its surface causing a voltage to be created due to outflow of carrier. This is essentially done when electron-hole pairs are generated on the surface of the wafer due to energy transferred when a photon hits the surface. For the outmost efficiency we must ensure the generation-recombination rate to be under control, i.e. the recombination rate must not exceed the rate of generation.

Majority carriers i.e. electron for N-type material and hole for P-type material flow from the former to the latter thus producing an open circuit voltage. This happens due to the electron-hole pair recombination in the diode that causes an electron flow in the external circuit for dark current and minority electron generation-collection causes an external electron flow giving rise to current for light current [1].

The rate of recombination is the least near the junction point and with increasing distance from it the rate increases. This increasing recombination rate generally causes the current in the solar cell to suffer since the minority electron being generated is not being collected due to increased recombination.

To summarize it can be said that carrier recombination in a p-n junction causes reduction of short circuit current (I_{sc}) and open circuit voltage (V_{oc}). In order to maximize output this recombination rate must be brought under control and in order to understand this relation we are going to take a quantitative approach and find the relation [in terms of equations] between the recombination, generation of carriers with the output efficiency of the solar cell.

1.2 Quantitative derivation of carrier generation and recombination:

Continuity equation for electrons $\frac{\partial x}{\partial t} = -\nabla \cdot \left(\vec{J}_n / -q\right) + G - R$

According to semiconductor equation conservation laws derived from Gauss's law, at steady state one of Maxwell's equations is thus represented:

$\nabla . \overrightarrow{D} = \rho$

$\nabla . -\frac{\overrightarrow{J_n}}{q} = G_{op} - R$

Where $\vec{D} = k\varepsilon_0 \vec{E} = \nabla k\varepsilon_0 \vec{V}$ i.e. the electrical flux density

$\rho = q(p - n + N_D{}^{+} - N_A{}^{-})$ i.e. the volume charge density

$\vec{J}_n = nq\mu_n \vec{E} + q\vec{D}_n n\nabla$ i.e. electron charge density

$\vec{J}_p = pq\mu_p \vec{E} - q\vec{D}_p p\nabla$ i.e. the electron current density

Where J_p and J_n are the current flow equations

$R = f(n, p)$ → the rate of recombination

$G_{op} =$ Optimum generation rate

Diode current & recombination:

$\nabla \cdot (\vec{J}_n / -q) = (G_{op} - R)$

$\frac{d}{dx}(\vec{J}_n / -q) = (G_{op} - R)$

$\int_0^L dJ_n = q\int_0^L \left[R(x) - G_{op}(x)\right] dx$

$J_n(L) - J_n(0) = q\int_0^L \left[R(x) - G_{op}(x)\right] dx$

Current & Recombination-Generation:

$$J_n(L) - J_n(0) = q\int_0^L [R(x) - G_{op}(x)]dx + J_p(0) - J_p(0)$$

$$-\{J_n(0) + J_p(0)\} = J_D(V) = q\int_0^L [R(x) - G_{op}(x)]dx - J_n(L) - J_p(0)$$

$$J_D(V) = J_n(L) - J_n(0) = q(R_{TOT} - G_{TOT})$$

$$qR_{TOT} = q\int_0^L R(x)dx - J_n(L) - J_p(0)$$

$$qG_{TOT} = q\int_0^L G_{op}(x)dx$$

$$J_D(V_A) = q\{R_{TOT}(V_A) - G_{TOT}\}$$

$$R_{TOT} = \int_0^L R(x)dx - J_n(L) - J_p(0)$$

$$G_{TOT} = \int_0^L G_{op}(x)dx$$

Dark current density can be expressed as:

$$J_D^{dark}(V_A) = qR_{TOT}^{dark}(V_A)$$

Short circuit current density (light generated current) on the other hand is thus represented:

$$J_{SC} = J_D^{light}(0) = q\{R_{TOT}^{light}(0) - G_{TOT}\}$$

$$J_{SC} = qG_{TOT}(L_n + L_p)$$

For electron

$$J_{SC} = qG_{TOT}(L_n)$$

Where this L_n is the diffusion length, D is the diffusivity, and τ is the lifetime and can be expressed by:

$L_n = \sqrt{D\tau_n}$

1.3 Practical data sources:

$N_A = 10^{16}/cm^3$

$N_D = 10^{19}/cm^3$

$D = 27\ \frac{cm^2}{s}$ This is constant for silicon

Area of mono-crystalline silicon solar cell:

$A = 58.06\ cm^2$

Cell thickness, $t = 195\ \mu m$ measured by dial indicator.

Front junction depth $X_{jf} = 0.3\ \mu m$ back junction depth $X_{jb} = 0.8 \mu m$ [1].

We know that for solar cell the short circuit current density obtained [1]:

$J_D{}^{super}\ (V_A) = J_D{}^{Light}(0) + J_D{}^{dark}\ (V_A)$

$J_D{}^{Light} = q(R_{tot} - G_{tot})$

From Lundstrom's derivation we know that [1]:

$G_{max} = \int_0^{\infty} G_{op}(x)dx = 2.97\ X\ 10^{17}\ cm^{-2}s^{-1}$

From which we get:

$G_{tot} = \int_0^{2L} G_{op}(x)dx = 2.97\ X\ 10^{17}\ cm^{-2}s^{-1}$

Solving which we get the value of the initial value of generation L = 0: $C = 2.97\ X\ 10^{17}$

This helps in finding the value of optimum generation from the total generation.

Total generation is calculated by the following equation:

$J_{sc} = q\ G_{tot}\ (L_n + L_p)$

For electron $L_p = 0$.

For a certain J_{sc} we get variable value of G_{tot} for different values of L_n.

1.4 Simulation results:

For $J_{sc} = 25.16\ mA/cm^2$ and $L_n = 88\ \mu m$

$$G_{tot} = \frac{J_{sc}}{qL_n} = \frac{25.16}{1.602\ X\ 10^{-19} X\ 88} = 1.78409 \text{ X } 10^{18}\ /\text{cm}^2\text{s}$$

Table 1 Percentage of carrier generation & recombination in different regions of the cell [1].

Percentage of Carrier Generation & Recombination			
Carrier	Emitter (%)	Depletion region (%)	Base (%)
generation	0.37	0.14	0.49
recombination	0.75	0.02	0.23

Table 2 The generations for the total cell as well as different part of the cell

Generation					
L (?m)	G_{op}	G_{tot}	G 37% in emitter	G 14% in junction	G 49% in base
88	1.50509E+18	1.78409E+18	6.60114E+17	2.49773E+17	8.74205E+17

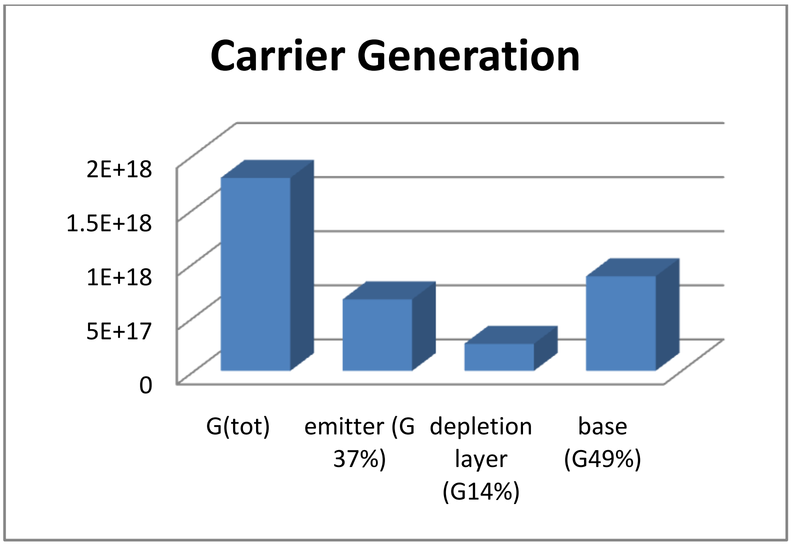

Figure 1 Representation of Table 2 in chart form.

Table 3 Carrier recombination is represented in percentage of the generated carrier in the specific areas.

Recombination				
L (?m)	R_{tot}	R 75% in emitter	R 2% in junction	R 23% in base
88	7.01148E+17	4.95085E+17	4.99545E+15	2.01E+17

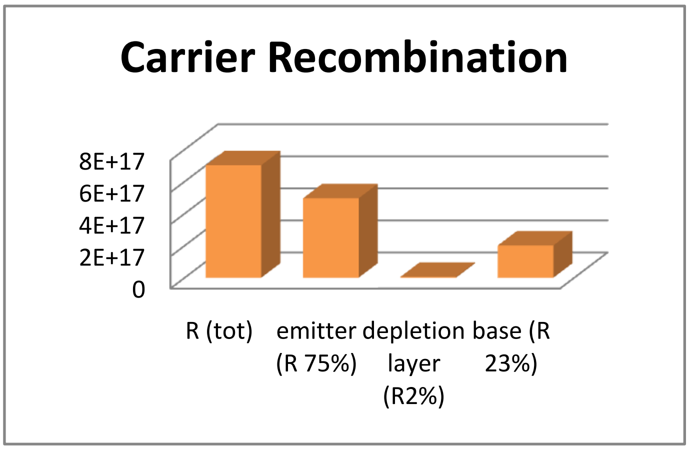

Figure 2 Representation of Table 3 in chart form.

The remaining carriers in specific areas are calculated by subtracting the recombination from the generation.

Table 4 Remaining carrier is represented after deducting the recombination from the generation of a specific area.

Remaining carrier		
Emitter	depletion layer	base
1.65E+17	2.45E+17	2.00E+17

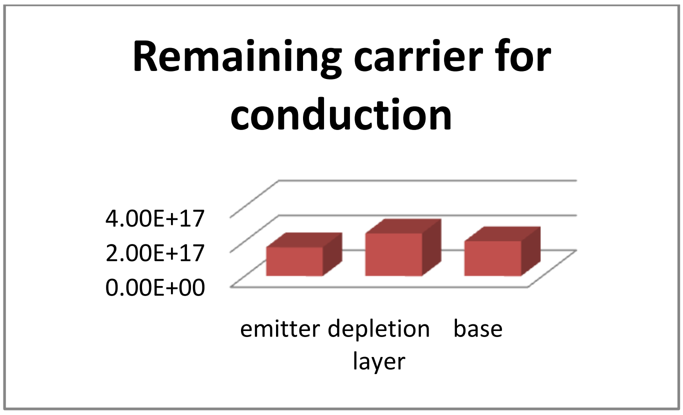

Figure 3 Representation of Table 4 in chart form

1.5 Vspv functionality:

Light induces SPV in this particular instrument used is detected as a function of wavelength. The instrument in itself is simple-digitally controlled incident light measurement system that essentially finds the minority carrier lifetime of a solar cell wafer. In our case this is silicon based cell.

The system is designed to operate at variable wavelengths ranging from 500nm to 1200nm. The figures below show the full setup that includes:

1. 150W fibre optical microscopic illuminator
2. Motorized monochromator
3. Stepper motor
4. Aurum coated wafer chunk
5. Ito/Aurum coated quartz plate
6. Light chopper
7. Vacuum pump
8. Contact probe
9. Stanford research 510 lock-in amplifier

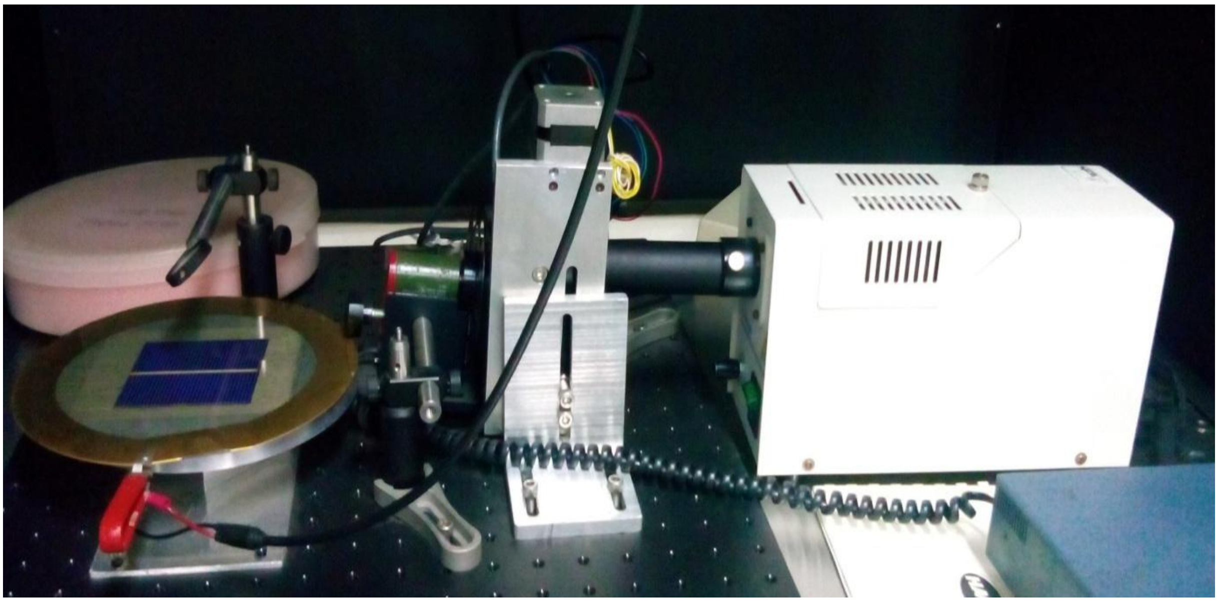

Figure 4 150W fibre optical microscopic illuminator, Motorized monochromator, Stepper motor, Aurum coated wafer chunk, Ito/Aurum coated quartz plate, Light chopper, Vacuum pump, Contact probe.

Figure 5 Stanford research 510 lock-in amplifier.

In order for this setup to work a computer must be connected to see the digital result. The block diagram below shows how these two figures are connected practically:

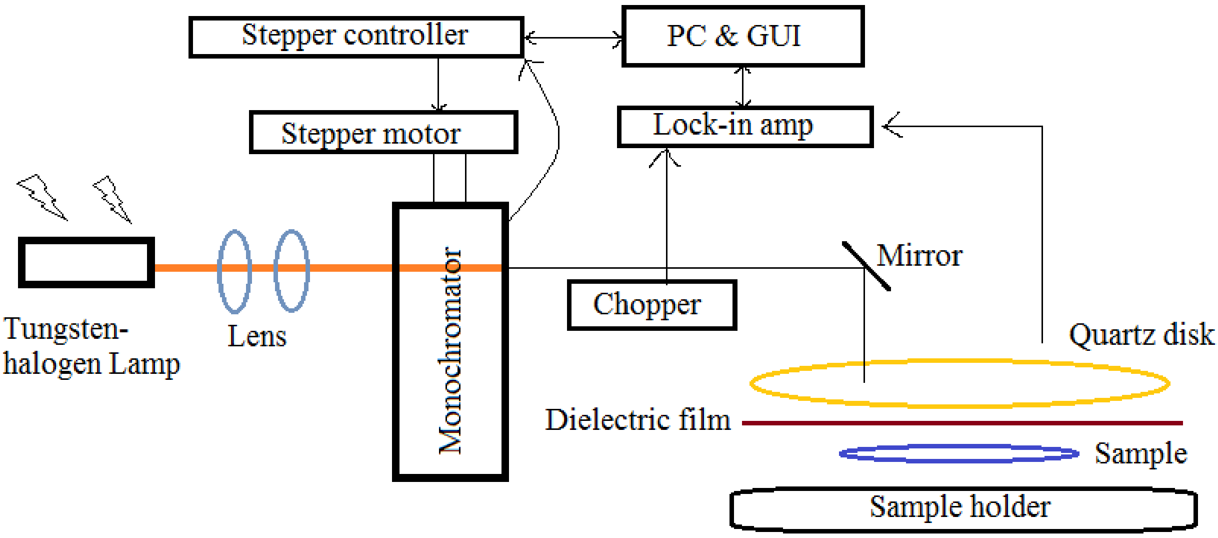

Figure 6 The block diagram of spv measurement system

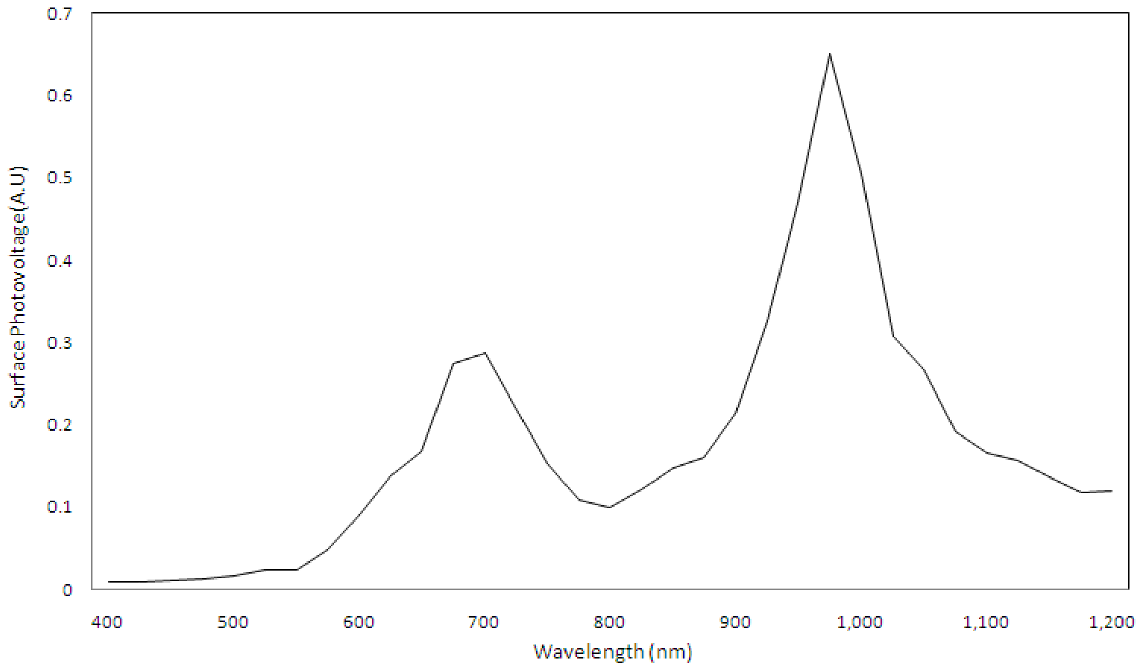

Figure 7 The form of graph displayed, where λ-SPV is plotted.

With the help of this displayed data (ideal), a reciprocal of α versus reciprocal of spv is plotted which ideally looks like:

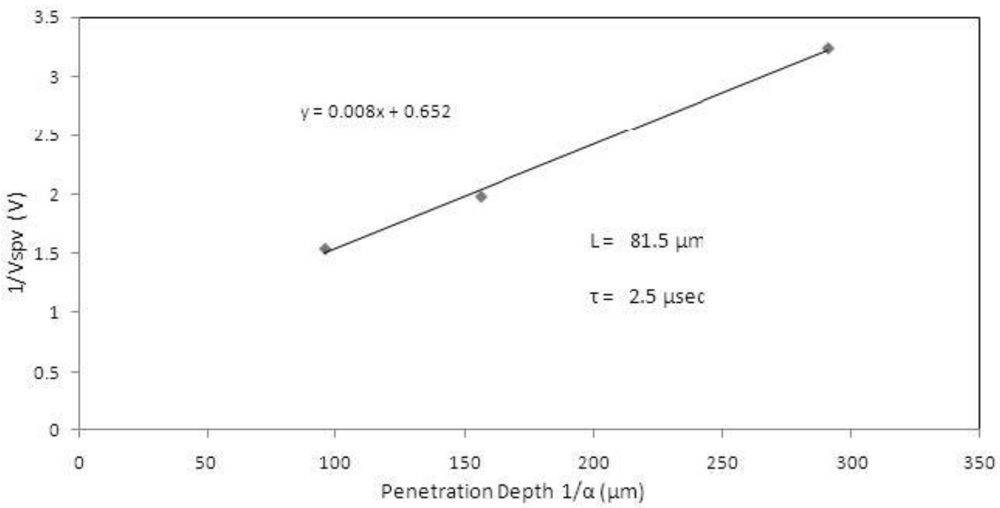

Figure 8 The ideal form of penetration depth versus 1/Vspv graph that is plotted with the help of data in fig. 7.

This graph is used to find the value of diffusion length that is found by its x-intercept.

1.6 Practical results:

Table 5 Data obtained from the SPV measurement system and corresponding data for plotting graph.

λ (nm)	Reflectance (AU)	α	Reciprocal of α [x]	Reciprocal of V(spv) [y]
700	0.14828	1.90E+03	0.000526316	6.743997842
720	0.282144	1.66E+03	0.00060241	3.544289441
740	0.497867	1.42E+03	0.000704225	2.008568553
760	0.671692	1.19E+03	0.000840336	1.488777594
780	0.846444	1.01E+03	0.000990099	1.181413065
800	0.904327	8.50E+02	0.001176471	1.105794696
820	1.071993	7.07E+02	0.001414427	0.932841912
840	0.878304	5.91E+02	0.001692047	1.138557948
860	0.606555	4.80E+02	0.002083333	1.64865511
880	0.431608	3.83E+02	0.002610966	2.316917203
900	0.246659	3.06E+02	0.003267974	4.054180062
920	0.377795	2.40E+02	0.004166667	2.646938154
940	0.253231	1.83E+02	0.005464481	3.948963595
960	0.170218	1.34E+02	0.007462687	5.874819349
980	0.203929	9.59E+01	0.010427529	4.903667453

1000	0.192707		6.40E+01	0.015625		5.189225093

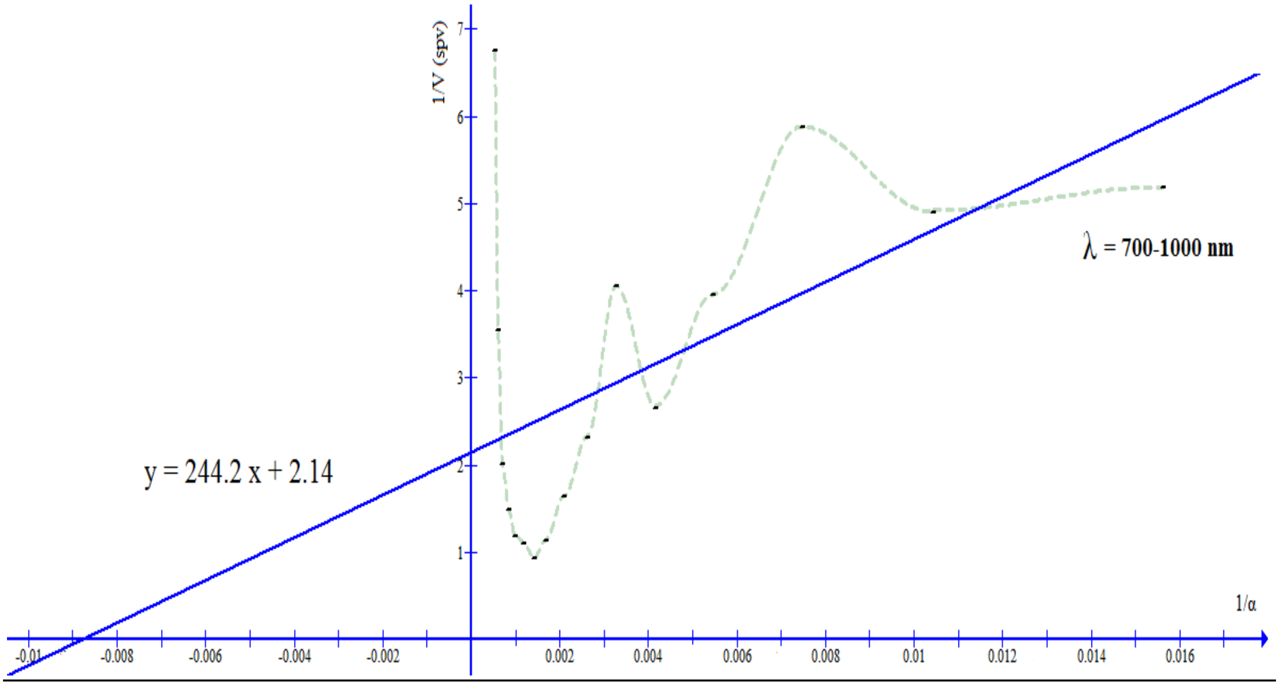

Figure 9 The corresponding graph of table.5, displaying data for reciprocal of α and reciprocal of V plotted [2].

Data shown here are collected via surface photo-voltage measurement technique under illumination of different wavelengths. This data has been used to plot a reciprocal for α versus reciprocal of V (spv) (which matches the ideal form mentioned before), by drawing an average linear curve we get the value of L = 88µm at the X–intersection, which is also the value of L that has been used previously for our carrier generation calculation and minority carrier lifetime simulation.

CHAPTER 2: EFFIECIENCY MEASUREMENT WITH SUN SIMULATOR

2.0 Introduction

Efficiency is the ratio of output to input; in case of solar cell energy conversion we call this value η. This is the percentage of solar energy to which the cell is exposed that is readily being converted to electrical energy. The value of η can be calculated by:

$$\eta = \frac{P_{at \max \ power \ \ point}}{E \ X \ A},$$

Where E is the input light energy in W/m^2, and A is the surface area of the solar cell in m^2.

Generally this I-V characteristic would fall under electrical characterisation, however since the measurement is usually taken by sun or sun-simulator i.e. optically induced; this is also an optical characterisation.

2.1 Machine functionality and specification:

The sun simulator is essentially a solar cell I-V measurement system that consists of multiple components such as the K201 solar simulator, K101 photovoltaic power metre, K401 solar simulator power supply, K202 auto controller, K901 sample mounting jig and K730 the software that measures the IV characteristics. The specifications of these models are given in tables 6, 7 and 8 [3].

Figure 10 Individual components: K201, K101 and K901 (left to right).

Table 6 Specifications of K201 [3].

Specs	Value
Class	AAA
Effective beam area	55X55 mm^2
Intensity	~1.2sun
Lamp	Xe

Table 7 Specifications for K101 [3].

Specs	Value
Power type	DC/Pulse Electrical Power Source / Meter
Operation type	- Constant Current / Voltage Operation
Voltage range	-10 ~ +10V.
Current range	30mA, 1A, 20A(User Selectable)
Sweep type	Automatic I-V Sweep
Input type	Reference Cell / Photodiode Input

Table 8 Specifications for K202 [3].

Specs	Value
Calibration	Auto intensity to 1 Sun
Ari mass filter auto control	AM 0 to AM 1.5
Optical shutter control	Auto

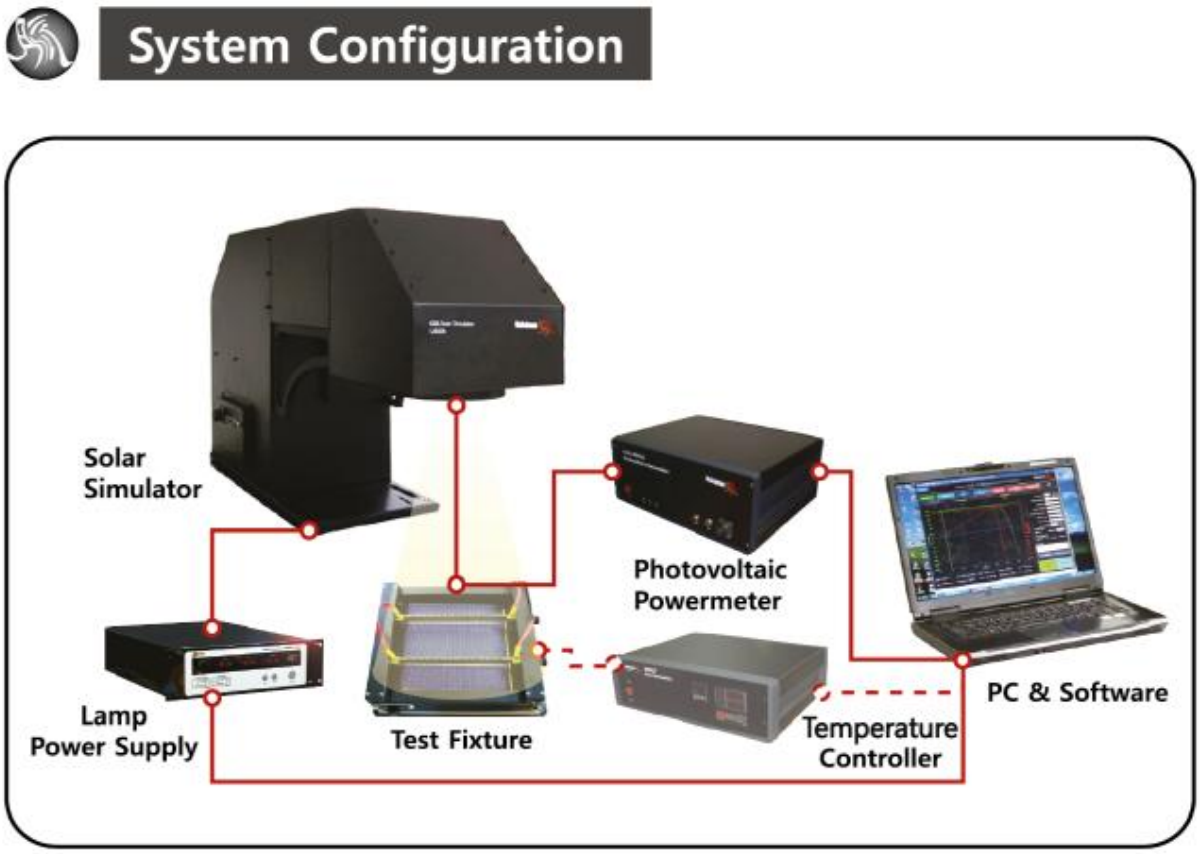

Figure 11 Complete setup of the system [3].

This system, shown in fig.11, is generally meant for the IV measurement of thin films, however due to the flexible mounting jig—measurement of our sample i.e. simple wafer is also possible.

The image of the output of an ideal solar cell/ thin film is shown below in fig.12. For this ideal output a K801 reference cell is used.

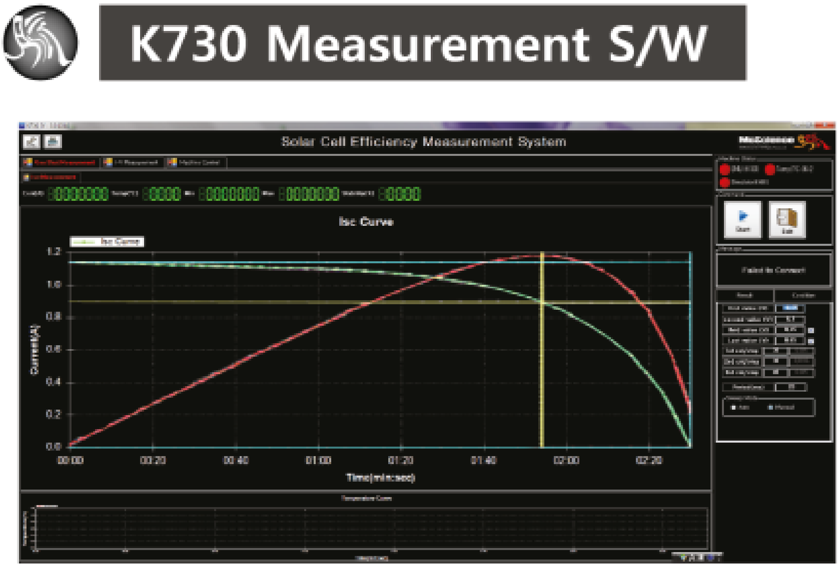

Figure 12 Ideal output of the system [3].

2.2 Readings

Using the mentioned apparatus we measured the efficiency of our solar cell.

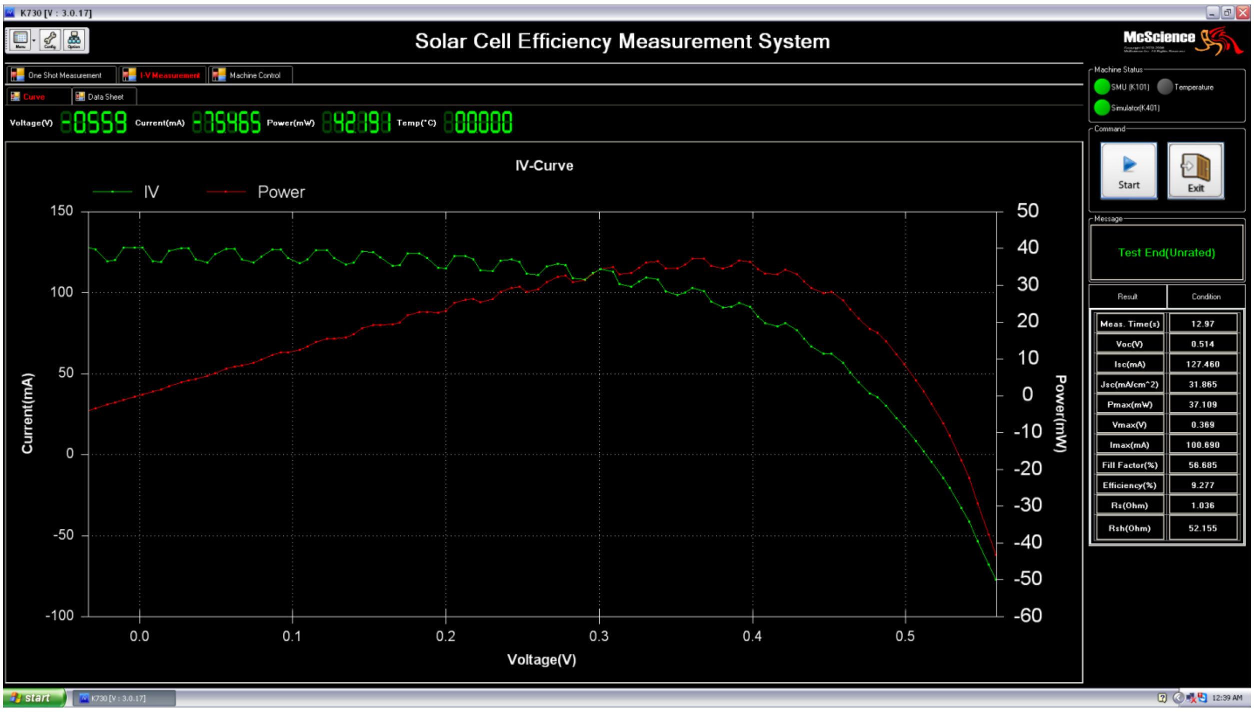

Figure 13 The output IV curve of the solar cell sample under sun simulation system.

Table 9 The obtained values are:

Measured time (s)	12.97
V_{oc} (v)	0.514
I_{sc} (mA)	127.460
J_{sc} (mA/cm^2)	31.865
P_{max} (mW)	37.109
V_{max} (V)	0.369
I_{max} (mA)	100.690
Fill factor (%)	56.685
Efficiency (%)	9.277
R_s (Ω)	1.036
R_{sh} (Ω)	52.155

V_{min} (V)	-0.559
I_{min} (mA)	-75.465
P_{min} (mW)	42.191

Chapter 3: QUANTUM EFFICIENCY MEASUREMENT

3.0 Introduction

From the electron-hole pair production through absorption of photon in a solar cell we know that either of the participants in the pair may contribute to the current in the cell or they may both recombine to pay no contribution to the current in the cell. Quantum efficiency is the percentage of photons that causes the collectable carriers i.e. the percentage of photons that contribute to the current flow under short circuit condition. There are two types of quantum efficiency:

1. Internal quantum efficiency (IQE): is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy that shine on the solar cell from outside *and* are absorbed by the cell.
2. External quantum efficiency (EQE): is the ratio of the number of charge carriers collected by the solar cell to the number of incident photons.

EQE can be mathematically calculated as [4]:

$$EQE = \frac{Electron/sec}{Photons/sec} = \frac{\frac{current}{e}}{\frac{power_{total}}{E_{of\ 1\ photon}}}$$

This can only be determined by the K3100 IPCE measurement systems.

3.1 Machine functionality and specification:

The K3100 EQX spectral IPCE (incident photon to converted electron) measurement system essentially measures the External Quantum Efficiency that consists of multiple components such as the Light Source & Monochromator, Output Signal Detector (DC/AC mode), Test Fixture (Optionally with Thermo-station), Reference Cell and Spectral IPCE Measurement Software.

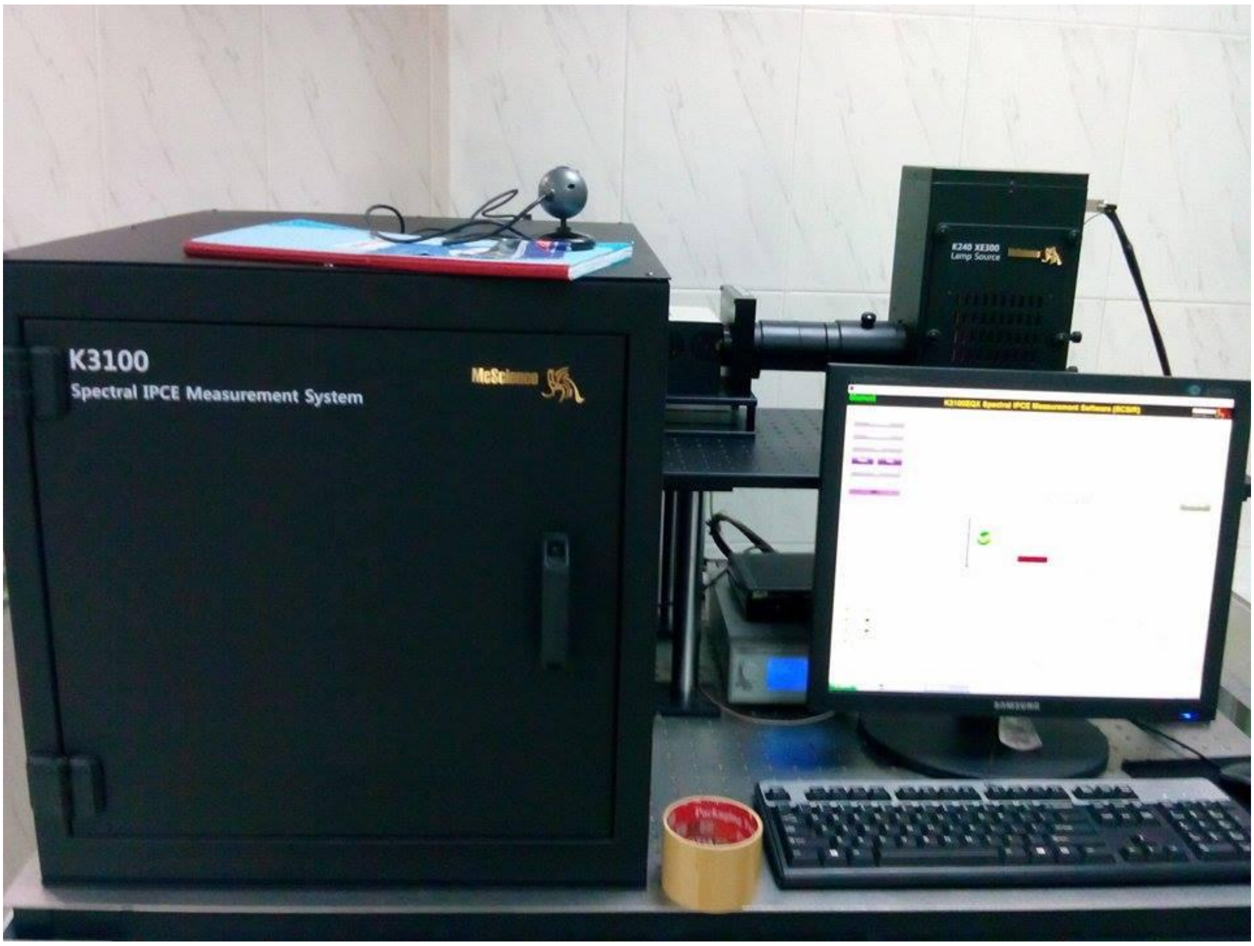

Figure 14 K3100 system.

The configuration of this specific model is given in table 10. Other models of K3100 such as IQX, TQX, ATX and NIR can also measure other aspects of a solar cell or thin film such as internal quantum efficiency, quantum efficiency mapping etc.

Table 10 Configuration of K3100 EQX.

Model	K3100 EQX
Feature	EQE

Light source	Xenon
Mode	Both AC and DC

The system is setup as shown in fig. 17. The internal setup of the system includes components: K102 and K801 shown in fig. 15, and the specifications for these components are given in table 11 and 12.

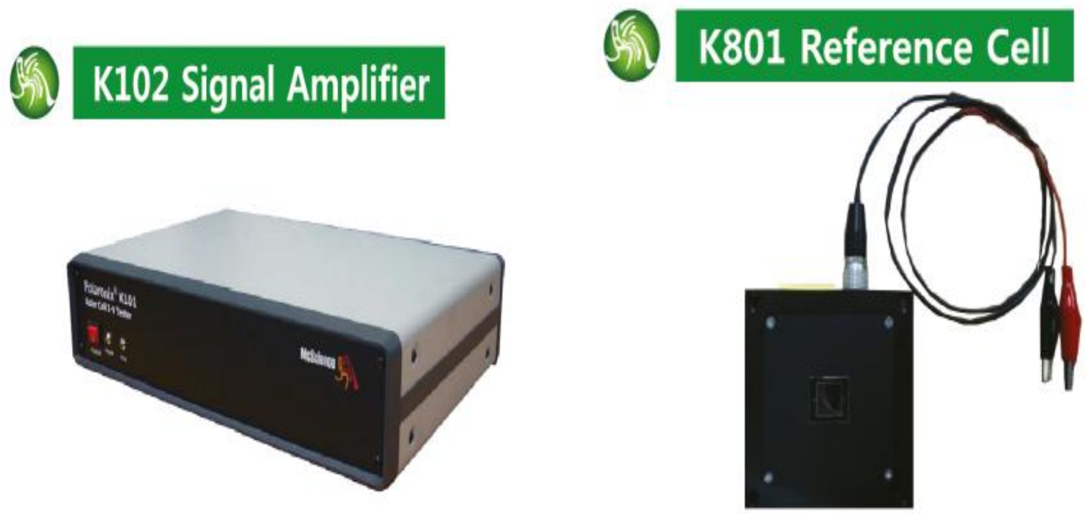

Figure 15 K102—signal amplifier and K801—reference cell [5].

Table 11 K102—signal amplifier specifications [5].

Range of amplification	3 range signal amplification
Gain (V/A)	10^2 to104
Voltage range (V)	0 to 10
Voltage bias	Available

Table 12 K801—reference cell specification.

UV-Vis range	Mono-Si Photodiode

NIR range	InGaAs Photodiode

K731 measurement software is used for this setup to ideally give the following graph:

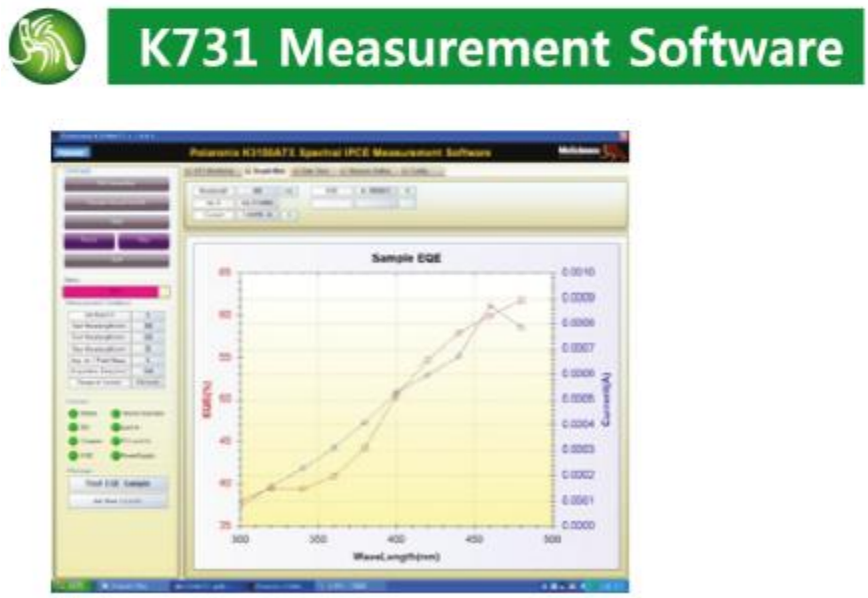

Figure 16 Ideal cell EQE output against wavelength and current [4].

EQE value refers to the amount of current produced in the cell when photons of a particular wavelength are irradiated on it. If the cell’s quantum efficiency is integrated all over the solar electromagnetic spectrum, it can be concluded that the cell produces current readily at being exposed to sunlight.

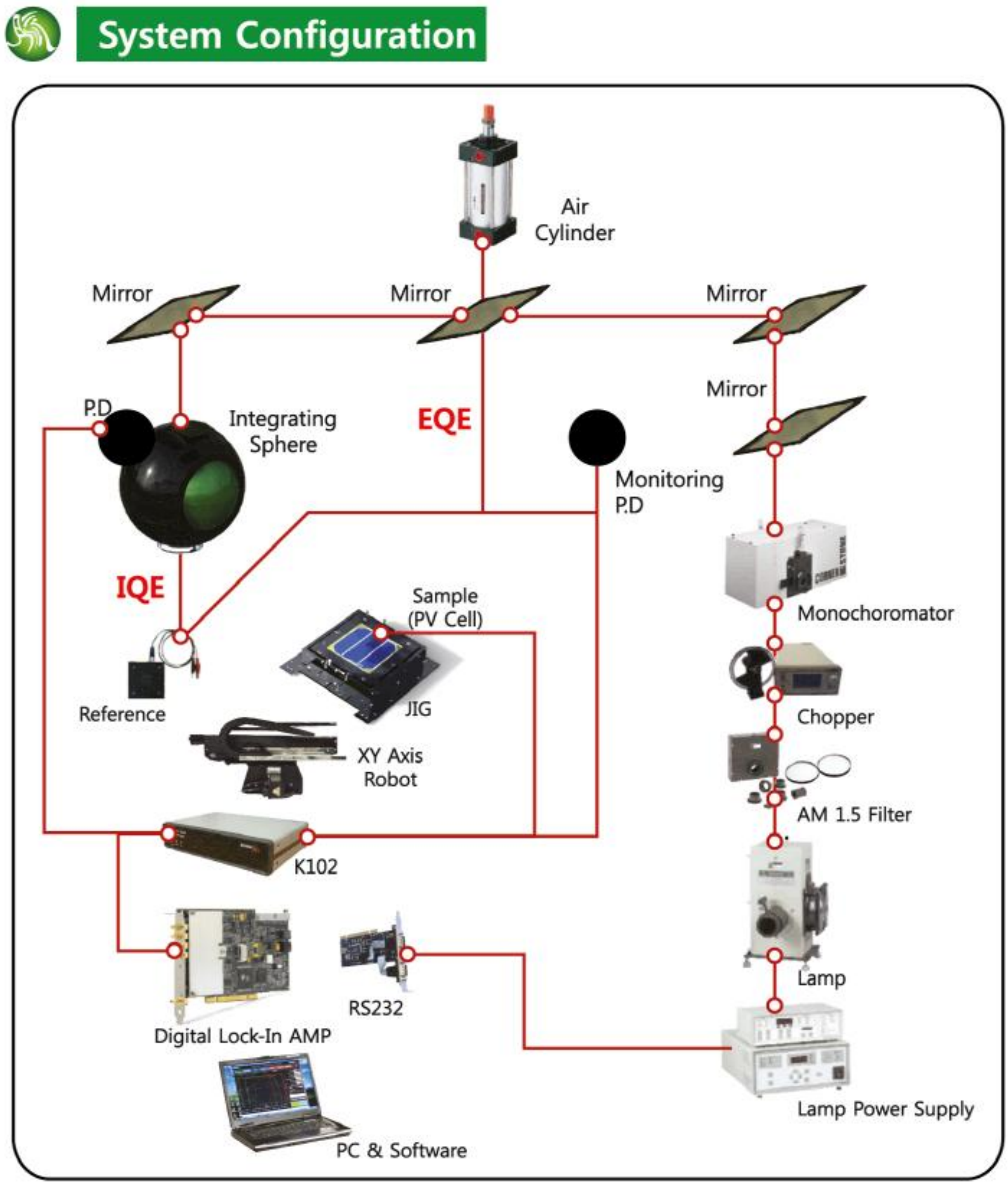

Figure 17 Complete external and internal setup of the system [5].

3.2 Readings:

The system setup specifications are given in table 13.

Table 13 Measurement conditions.

Method	Reflection
Set bias (V)	0
Start Wavelength (nm)	300
End wavelength (nm)	1100
Step wavelength (nm)	20
Acquisition delay (ms)	500
DUT range	5
Halogen lamp	0

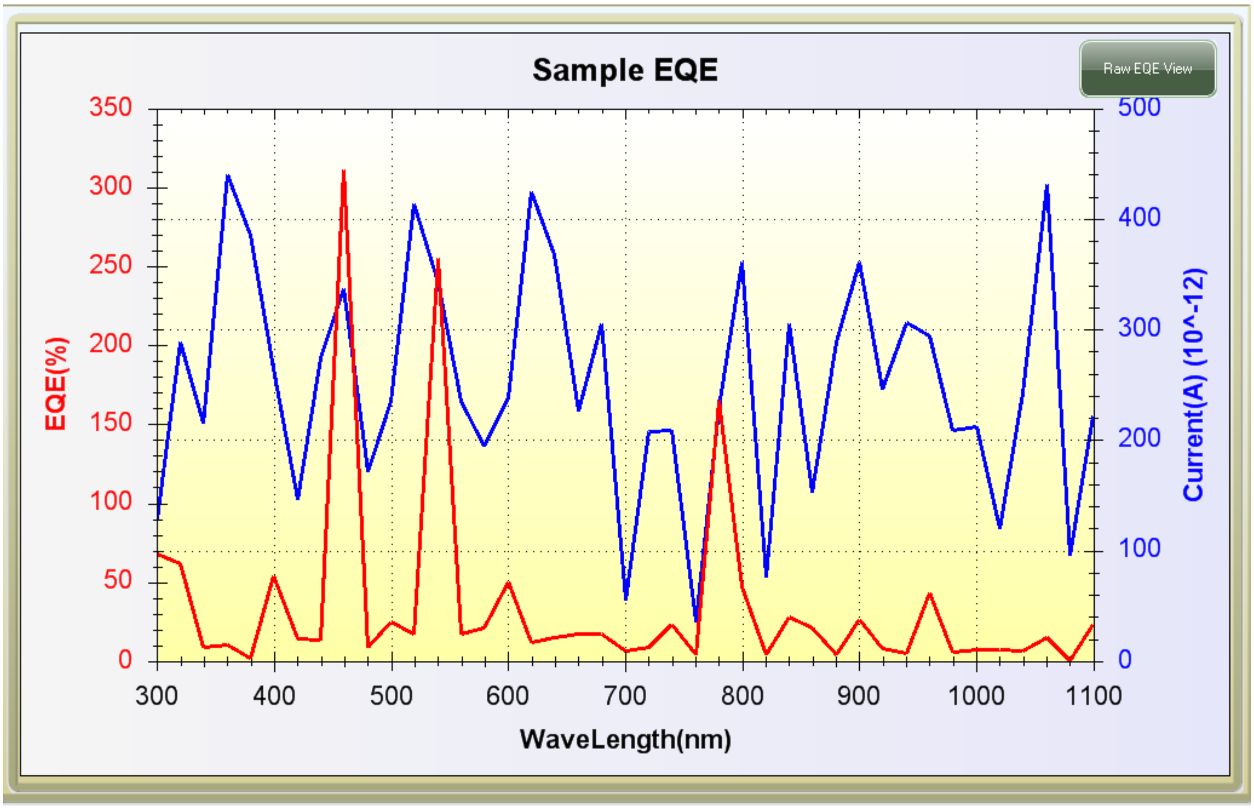

Figure 18 Sample EQE graph against wavelength of light used to test the EQE and current

The EQE value of the sample shown in fig.18, is peaking at particular wavelengths such as 450 nm, 550 nm etc, however despite dropping at multiple wavelengths significantly it is mostly above zero level throughout the range of wavelengths. This shows that upon being exposed to sunlight, this cell will produce current—this is also verified by the same instrument in the fig.18.

EQE is measured in a percentile manner with reference to the ideal cell or reference cell as mentioned before (K801). The results of this test done to our particular sample are given in table 14 and other variable values of the system are given in table 15.

Table 14 EQE results.

Wavelength (nm)	1100
Idp S	4.9880E-12
Current (a)	2.2175E-10
EQE (%)	22.99

Table 15 Other variables of the system.

Power supply	Current	15.50 A
	Voltage	20.20 V
	Power	313.10 W
	Lamp hours	31.52 Hrs
Others	Chopper	20 Hz
	Mono filter	1

	Bias	0 V
	Dut range	5
	Grating	1

Discussions

All the characterisation including the I-V characterisation in Chapter 2, since induced by optical means, falls under the category of optical characterisation. The purpose of this study was to observe and understand the characteristics. Despite all of these being optical characters, there is no connection among the processes by which they are determined.

The SVP measurement system is available and less costly compared to the other two systems; however, the handling of this apparatus can be stressful.

The K3000 and K3100 systems are however very fast and easy to handle and take readings from, the drawback of these systems are their costs and maintenances.

The three types of study mentioned in this paper: 1. determination of minority carrier diffusion length, 2. calculation of efficiency and 3. calculation of EQE, show no direct relation to each other despite being of the same category.

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