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I-V Characteristics of Photovoltaic under 10ms Pulsed Irradiance

of Light Emitting Diode Arrays

I-V Characteristics of Photovoltaic under 10ms Pulsed Irradiance of Light Emitting Diode Arrays

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ABSTRACT

I-V characteristics of PV solar cells are general information under standard test condition (STC), the solar simulator using standard light source. Commercial solar simulators use Xenon or Halogen lamps which are short-life and expensive. The study has been proposed I-V characteristics of PV under pulsed irradiance of the Light Emitting Diode (LED). It is commonly recognized that LED is long-life, light weight, low energy consumption, and cheap light source. Experimental 1024 LEDs used five arrays as light source (Red, Green, Blue, White and RGBW) were pulsed with 10ms duration which has the amplitude of 8 to 10 times of rated current. The irradiance of Red and Blue arrays was 1,000 $W \cdot m^{-2}$. The RGBW irradiance was 800 $W \cdot m^{-2}$ and another monochromatic irradiance was 400 $W \cdot m^{-2}$. Advantageously, the pulsed technique is easier to control the LED temperature than the continuous operation. As the result, the measurement of I-V characteristics under Red, Blue and RGBW irradiation were difference to the STC and there were corrected by STC, the errors of parameters within 5 %.

Index Terms—Photovoltaic, Light Emitting Diode, I-V characteristics

1. INTRODUCTION

I-V characteristics of PV solar cells are general information which refers to standard test condition (STC). From I-V Curve, the series shunt and the dynamic resistances of PV solar cells can be determined [1]. The STC I-V characterization using commercial solar simulators used Xenon or Halogen lamps, which are short-life and high cost.

Light Emitting Diode (LED) is a modern optoelectronics solid-state light source which has high intensity with low power consumption, long lifetimes, light of weight, and cheapness. With the highest efficiency of visible range light source, LEDs will be replaced the conventional lamps in the next lighting revolution [2].

Recently, LEDs has been applied to experiment with static parameters of the photovoltaic (PV). Multi-colors LEDs arrays were constructed to be the solar simulators and used for estimating the absolute spectral response of solar cell [3]. A fundamental experiment for discrete-wavelength LED solar simulator was conducted so that the spectral response and I-V characteristic of x-Si solar cell was measured [4]. The accuracy of the calculating I-V characteristics which measured by LED solar simulator was improved [5]. New generation of PV module rating by LED solar simulator and spectral response fitting model was developed to achieve 2 percent uniformity, 0.42 sun intensity specifications and reach the practically useable level of the experimental results of the x-Si solar cell [6]. Short-circuit current density, open-circuit voltage and fill factor of n^+p silicon solar cell were simulated and measured by three monochromatic wavelengths flash light sources [7]. A LED-based photovoltaic measurement system [8] which according to class AAA was constructed.

We propose a novel technique, pulsed LED irradiance, which reaches $800Wm^{-2}$ and 1000Wm-2 irradiance. A 10ms period up to 10 times of LED rated current is injected LED array to irradiate pulsed light. Nevertheless, the I-V characteristics of a 12.5*12.5 cm2 mono-crystalline silicon PV solar cell will test under the pulsed LED irradiance, correction and comparison to STC to fulfill the existence techniques and contribute to the next generation LED solar simulator.

2. I-V CHARACTERISTIZATION OF PV

2.1. PV Solar Cell I-V Characterization

I-V characteristics of PV solar cells have to measure under IEC 60904-1 standard [9] procedures that cover the measurements in natural sunlight, steady-state simulated sunlight, or in pulsed simulated sunlight. I-V characteristics are not measured under STC (1000 $W \cdot m^{-2}$, AM1.5, 25 °C), they need to corrections using the procedure under IEC 60891 [10].

2.2. Pulsed Technique

Generally, LEDs are operating in temperature range of -40 to 80 °C with 125 to 150 °C junction temperature approximately. Power consumption and heat loss of LEDs array are controlled to maintain the operating or junction temperature that is not over the limit of specifications. Sometime, the manufacturers are permitted to pulse the current of LED for multiply the luminous flux output or digital works using duty cycle technique under the limitation of operating and junction temperature.

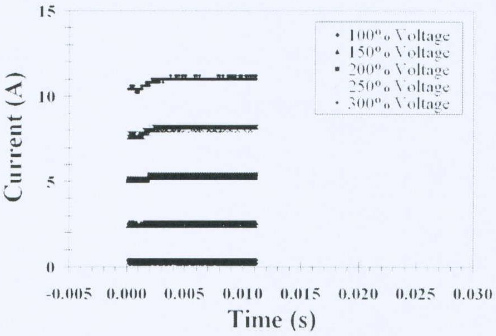
If we control the junction temperature to less than the limitation using the special cooling and the duty cycle of pulse, the LEDs can pulse the higher current that shine the higher luminous flux. So, the design of LED experiment for pulsed technique should test the limitations: forward input current, forward input voltage and output irradiance.

3. EXPERIMENT SETUP

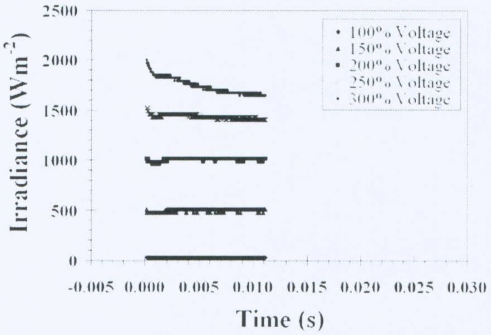
Five LED arrays were constructed, R, G, B, W, and RGBW. T1¾ Diameter of 632nm red (LTL2F3VEKNT), 525nm green (TOL-50bUGdCTa-M4), 468nm blue (TOL-50aUBdCEa-ETB6) and white (LTW-2S3D7) LEDs were selected to assemble the LED arrays. Each array consists of 1024 LEDs which is 64 parallels of 16 LEDs and a current limiting resistor. Each of RGBW strings were arrangement 128 circuits of series 8 LEDs.

Firstly, the I-V characteristics samples of each diode were tested in the range of 0 to 5 times of the rated forward voltage. They were approximately generated to13 to15 times of the rated current before broken. In the experiment, the high performance of DC power supply (Santrex) gave the high voltages to the LEDs array which was controlled pulse width using IGBT.

The gate of the IGBT (IRG4PH50UDPbF) switch was controlled at 10 ms triggering. The pulse amplitude can manually adjust the voltage (approximate 3 times of LED rated voltage). The LED solar simulator has 3 layers. The top of it is the LED array putting on the turbid glass diffuser and the bottom is the test plan. The distance between them was 3 mm and 3 cm, respectively. A photodiode detector (13DAS003, and 13AMP003) was calibrated by a Pyranometer (Kipp & Zonen, CM11) at about 100Wm^{-2} with continuous irradiance. An audio amplifier signal input was 100Hz sinusoidal. It was connected to a PV cell (12.5*12.5 cm^2, glass-EVA-cell-EVA-back sheet capsulated, mono-crystalline) to operate the specimen in photovoltaic and diode mode alternately. The current, voltage and irradiance signals were measured synchronously during 10 ms by a current probe (Fluke I30s), voltage probes and photodiode respectively. The output signals were monitoring and acquisition by the oscilloscope (Tektronix 2014).



a) Pulse Input current of red LED array



b) Pulse Output irradiance of red LED array

Fig. 1 Pulse current input and pulse irradiance output

Then, I-V characteristics under pulsed irradiance of LED arrays were plotted. The tested results were corrected to STC by using a method under IEC 891 [10]. The corrected I-V characteristics were compared and evaluated with the STC results. Finally, LED array temperatures were measured continuous and pulse operation by IR thermo-photographer (NEC TH7700N).

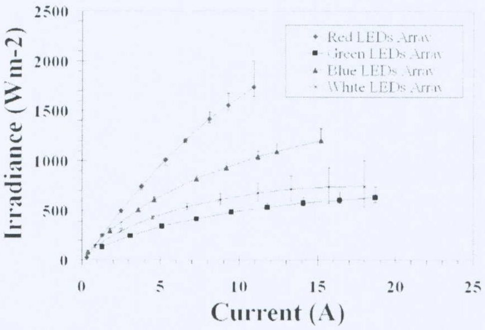


Fig. 2 Current-Irradiance (I-G) Characteristics

4. RESULT AND DISCUSSION

The uniformity of irradiance of 3 cm test plane was less than 10%, which corresponds to class C of IEC 60904-9 [11]. Fig. 1 shows higher current higher irradiance. According to the power supply recovered the current; the current pulse was unstable during 2 ms after the rise edge. The power supply was stable at the lower current, so that the irradiance was stable.

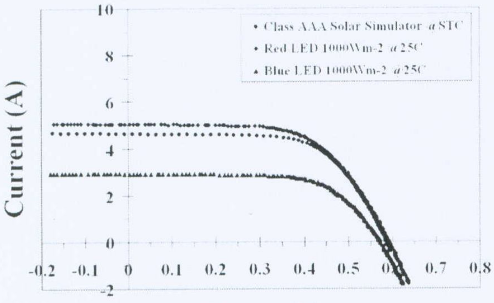


Fig. 3 I-V characteristics under 1000 W·m^{-2}

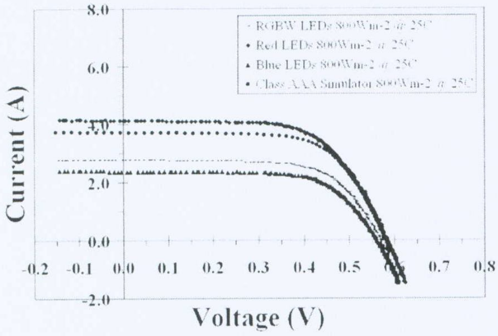


Fig. 4 I-V characteristics under 800 W·m^{-2}

Table 1 Irradiance and Temporal Instability

LEDs Arrays	10 ms duration			After 2 ms		
	Average Irr.	Temporal Instability		Average Irr.	Temporal Instability	
	(W·m^{-2})	%	Class	(W·m^{-2})	%	Class
Red	1009	2.99	B	1011	1.47	A
Red	815	3.70	B	820	1.82	A
Red	427	3.57	B	431	1.75	A
Blue	1012	3.45	B	1008	1.41	A
Blue	812	3.51	B	812	2.61	B
Blue	409	5.26	C	412	3.45	B
Green	410	3.53	B	408	2.38	B
White	423	2.86	B	420	2.86	B
RGBW	801	4.17	B	804	4.10	B
RGBW	405	4.76	B	408	4.02	B

Table 1 shows the instability of LED pulse irradiance can classify in class A of 1000 W·m^{-2}in the red and blue arrays. In the case of stable 8A and 11A currents of a red LED array, at 1500 and 2000 W·m^{-2} of red light were decreased that may cause by an internal temperature effect [12]. Irradiance-current (G-I) characteristics of the red LEDs were plotted base on 10ms pulsed width, which shows in Fig. 2. All LEDs were not perfect isotropic of emitters and may cause by quantum well [12].

The results of short-circuit current (I_{sc}) of PV solar cell under 3 different wavelength conditions of LED array is shown in Fig. 3. I_{sc} under the red array is approximately 10 percent more than I_{sc} at STC. I_{sc} under the blue array is about 60 percent of the STC. I_{sc} under the RGBW array closes to 75 percent that shows in Fig 4. At the same irradiance, the I_{sc} under each wavelength is difference therefore the spectral response: the number of photons, the generation rate, the recombination rate, the quantum efficiency.

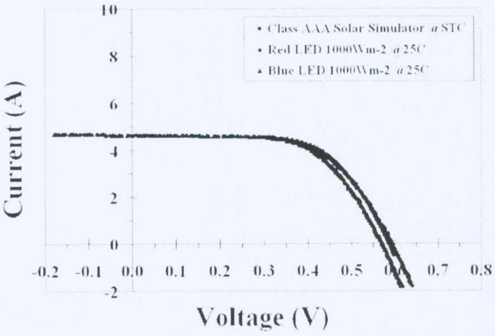


Fig. 5 Correction to STC I-V characteristics form LED 1000 W·m^{-2} irradiance

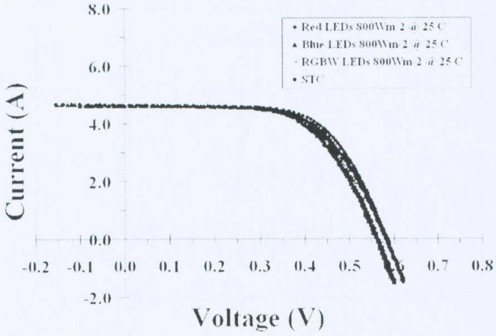
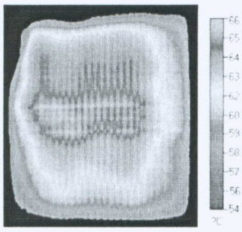


Fig. 6 Correction to STC I-V characteristics form LED 800 W·m^{-2} irradiance

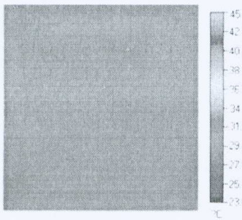
However, the I-V characteristics of 1000Wm^{-2} (Fig. 5) and 800 W·m^{-2} (Fig.6) under each red and blue light and 800 W·m^{-2} under RGBW light which were corrected to STC, all parameters of PV solar cell is 5 percent of error. Fig. 7 shows LED array's temperature of the continuous and pulsed operations. The LED temperature from the pulsed operation (27 °C) is lower than the continuous operation (63 °C). The pulsed LED array has low power consumption so that it is easier to control the temperature.

Table 2 Correction to STC parameters of a PV solar cell

Parameters	**Light Sources**					
	800 W·m^{-2} **Red LED**	**800** W·m^{-2} **Blue LED**	**800** W·m^{-2} **RGB W LED**	**1000** W·m^{-2} **Red LED**	**1000** W·m^{-2} **Blue LED**	**AAA Sim @ STC**
V_{oc} (V)	0.58	0.56	0.56	0.59	0.57	0.58
I_{sc} (A)	4.63	4.63	4.66	4.63	4.63	4.63
P_{max} (W)	1.66	1.61	1.63	1.69	1.65	1.72
V_{mp} (V)	0.41	0.39	0.40	0.41	0.41	0.42
I_{mp} (A)	4.11	4.11	4.03	4.11	4.03	4.06
FF (%)	61.9	61.7	62.0	61.9	62.1	63.5
η (%)	11.4	11.0	11.1	11.5	11.1	11.4
R_s (Ω)	0.03	0.03	0.03	0.03	0.03	0.03
R_{sh} (Ω)	5.00	5.00	5.00	5.20	5.20	5.20



a) Non-uniformity of 63 °C average temperature of the continuous operation



b) Uniformity of 27 °C average temperature of the pulse operation

Fig. 6 LED array temperature of the continuous and pulse operations

5. CONCLUSION

In the conclusion, monochromatic R and B LED arrays have 1000 W·m^{-2} of irradiance and the instability of class A in 8ms duration therefore the pulse amplitude is 8 or 10 times of the rated current. The RGBW LED array achieved 800 W·m^{-2} of class B instability. The G and W was irradiance of 400 W·m^{-2} in class B. The correction I-V characteristics close to the STC within 5%. The pulsed LED array is easier to control the LED temperature.

6. ACKNOWLEDGEMENT

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Light Dependent Series and Shunt Resistances of Photovoltaic Cells under Light Emitting Diode Illumination

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Abstract

In designing photovoltaic (PV) or solar cell systems, one requires static and dynamic parameters of PV cells and modules, as well as balance of systems. Static parameters are series resistance (R_s) and shunt resistance (R_{sh}), determined by I-V characterization. The parameters are obtained under the standard test condition (STC), i.e. 1000 W·m^{-2}, AM 1.5, 25 °C, such parameters can be called the parameters at STC. In this paper, we review recent works and explore possibility of determining static parameters using monochromatic lights, using recently developed and commercialized high luminosity light emitting diodes –LED , or combination of them instead of white light, that have been previously reported. Parameter determination is done at STC and non-STC conditions. Using LEDs for I-V characterization of cells and modules at STC and non-STD conditions, if found to yield correct results compared to characterization based on white light and at STC conditions, would permit less expensive and flexible characterization methods. In our study, I-V curves of mono-crystalline cells (12.5 *12.5 cm^2) are determined using different natures of light, i.e. sunlight, Class B pulsed solar simulator, monochromatic blue, green, and red LEDs. Apart from different nature of light, e.g. white and monochromatic, light intensity is varied from 400-1,000 W/m^2. From our results, we find that R_s is virtually independent of light wavelength and irradiance, while R_{sh} is light-wavelength and irradiance dependence. It is possible to derive STC parameters from non-STC parameters.

Keywords: Photovoltaic, Series resistance, Shunt resistance

1. INTRODUCTION

Photovoltaic (PV) device is a semiconductor that converts sunlight directly to electricity. In designing PV solar cell systems, one requires static and dynamic parameters of PV cell and modules, as well as balance of system: inverter, converter, charger, and etc. Static parameters are the voltage-dependent diode resistance (R_d), series (R_s) and shunt (R_{sh}) determined by I-V characterization [1]. The parameters are obtained under the standard test condition (STC), i.e. 1000 W·m^{-2}, AM 1.5, 25 °C, such parameters can be called the parameters at STC. However, non-STC temperatures and irradiances of I-V measurements can correctable to STC using IEC 891 [2] procedures. Parameter determination is done at STC and non-STC conditions. Using LEDs for I-V characterization of PV cells at STC and non-STD conditions, if found to yield correct results compared to characterization based on white light and at STC conditions, would permit less expensive and flexible characterization methods.

Recently, I-V characteristics of PVs were measured under the white light, the monochromatic light, and the multi-color LEDs solar simulators. The continuous light approximate 100 W·m^{-2} multi-color of red, blue, infrared, and white LEDs solar simulator was used for I-V characterization of PV that shows the measurement differ from the STC characteristics and compensation to STC [3]. A novel style, I-V characteristic of PV cell was characterization using flash light 800 W·m^{-2} of multi-color red green, blue, and white LEDs, and 1000 W·m^{-2} of monochromatic red or blue Pulse LEDs solar simulators [4]. At higher level, the results shows that the different spectral wavelength irradiances the different I-V characteristics. However, the correction to STC I-V characteristics was within 5% of STC.

This paper, we propose the light dependent R_s and R_{sh} of photovoltaic cells under light emitting diode illumination. To compare the values of R_s and R_{sh} between the STC and non-STC conditions is a main objective of the study. 400 to 1000 W·m^{-2} of Class AAA, red, and blue light were study in conditions of irradiances and spectral wavelengths. 400 W·m^{-2} of red, green, blue, and white LEDs, natural sunlight, halogen lamp lights were used for verify the effects of spectral wavelengths. So, the applications of the pulse monochromatic and multi-band light-wavelengths LEDs solar simulator were demonstrate.

2. SERIES AND SHUNT RESISTANCES OF PV

PV solar cell DC equivalent circuit [5] consist of photo-current source, voltage-dependent diode resistance, series resistance (R_s) and shunt (R_{sh}) resistance show in Fig 1. PV parameters are temperature dependent. R_s is consist from contact resistance, p-layer sheet resistance, n-layer bulk resistance, and parasitic transition region resistance. Auger recombination, recombination in traps and surface are causes of R_{sh} [6].

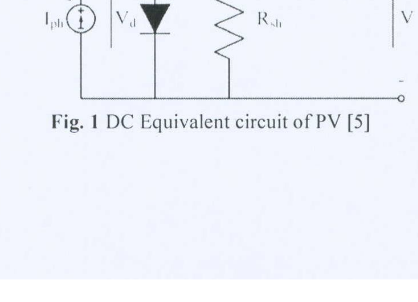


Fig. 1 DC Equivalent circuit of PV [5]

Table 1 Parameters of a x-Si PV cell under STC, non-STC, and Correction to STC conditions (* the maximum error)

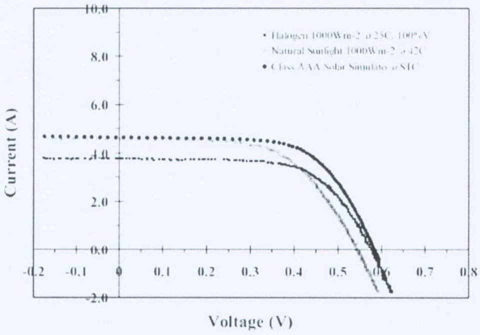
Parameters	Experiments				Correction to STC			
	Class AAA	Natural Sunlight	W-halogen Lamps	Error *	Class AAA	Natural Sunlight	W-halogen Lamps	Error *
Irradiance, G (Wm^{-2})	1002	1021	1004	-	1002	1002	1002	-
Temperature, T (C)	25	40	26	-	25	25	25	-
Area, A (cm^2)	146.13	146.13	146.13	-	146.13	146.13	146.13	-
OC Voltage, V_{oc} (V)	0.59	0.55 *	0.57	-6.8 %	0.59	0.55 *	0.58	-6.8 %
SC Current, I_{sc} (A)	4.64	4.59	3.74 *	-19.4 %	4.64	4.56 *	4.63	-1.7 %
Max Power, P_{max} (W)	1.72	1.45	1.32 *	-23.3 %	1.72	1.73	1.60 *	-6.5 %
Max Voltage, V_{mp} (V)	0.41	0.39 *	0.41	-4.9 %	0.41	0.45 *	0.39	9.7 %
Max Current, I_{mp} (A)	4.20	3.35	3.23 *	-23.1 %	4.20	3.83 *	4.11	-8.8 %
Fill Factor, FF (%)	63.3	55.4 *	61.7	-12.5 %	63.3	68.4 *	59.9	8.1 %
Efficiency, η (%)	11.70	9.69	8.97 *	-11.7 %	11.70	11.80	11.0 *	6.0 %
R_s (Ω)	0.03	0.03	0.04 *	0.01 Ω	0.03	0.03	0.03	0.00 Ω
R_{sh} (Ω)	4.74	5.00	5.20 *	0.76 Ω	4.74	4.67 *	4.70	-0.07 Ω

3. EXPERIMENT

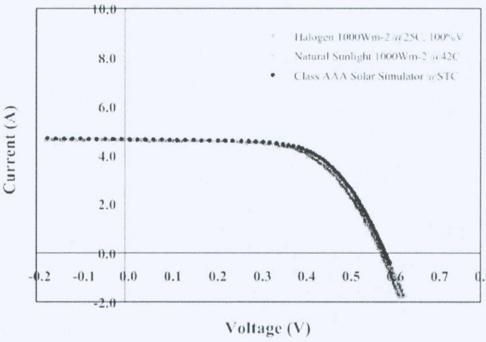
First, a 12.5*12.5 cm^2 capsulated mono-crystalline silicon (x-Si) PV cell was measurement I-V characteristics using procedures in IEC 60904-1 [7] under STC by using Class AAA solar simulator (PASAN) for the control I-V characteristics. Secondly, non-STC I-V characteristics of the specimen was tested under 400 and 1000 $W{\cdot}m^{-2}$ of natural sunlight and a Tungsten-halogen lamp solar simulator (according to IEC 60904-9 [8] class C uniformity, and class A instability) to compare static parameters under effect of spectral wavelength. Thirdly, the tests under 400 to 1000 $W{\cdot}m^{-2}$ of Class AAA solar simulator were examined to compare the effects of the irradiances. Then, to test the influences of wavelengths and irradiances, a PV cell was characterization under 25 °C, 400 to 1000 $W{\cdot}m^{-2}$, monochromatic red and blue lights by using class B uniformity and instability Pulse LEDs Solar Simulator. To test the effects of wavelengths, the green and white lights of LEDs solar simulator were tested the specimen at 25 °C and 400 $W{\cdot}m^{-2}$ conditions. After that, The I-V characteristics were plot and calculated the static parameters, the R_s and R_{sh} were determined by using the Single-curve method [1]. Finally, R_s and R_{sh} of a x-Si PV cell were analyzed in various conditions.

4. RESULTS AND DISCUSSION

The testing results under the various conditions of irradiance and wavelength are STC, non-STC 1000 $W{\cdot}m^{-2}$ of sunlight and solar simulator, non-STC 400 to 1000 $W{\cdot}m^{-2}$ of LEDs.



a) At 1000 $W{\cdot}m^{-2}$, 25 °C



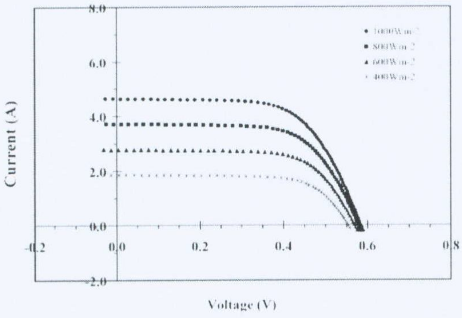
b) The correction to STC

Fig. 2 STC and non-STC I-V Characteristics of x-Si PV Cell

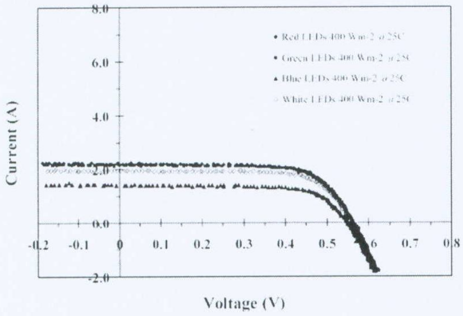
I-V characteristics of x-Si VP cell under 1000 $W{\cdot}m^{-2}$ STC and non-STC conditions show in Fig. 2 a). According to the matching of the wavelengths, the short circuit current (I_{sc}) of a x-Si PV cell under the natural sunlight close to the STC I-V characteristics. Fig. 2 b). shows The spectral were unmatched so I_{sc} under the Tungsten-halogen solar simulator less than the STC condition. As results, the correction of non-STC I-V characteristics to STC by applying the procedures of IEC 891 [2] can perform not only the temperature and the irradiance but also the wavelength.

Table 1 shows the experimental results of static parameters changing by light sources, the error of each parameter and light sources are much different from Class AAA such as the errors of Tungsten-halogen lamps, -19.1 % of I_{sc}, -23.3 % of, P_{max}, -12.5 % of FF and -11.7 % of η because of the spectral mismatch. The STC correction results show the parameter error within 10%.

Fig. 3 a) shows the STC and non-STC I-V characteristics at different irradiances of class A solar simulator under 400 to 1000 $W{\cdot}m^{-2}$, the higher irradiance the higher I_{sc}. Therefore, the irradiance is proportional to the number of photon which generated the photo-current.



a) At 400 to 1000 W·m^{-2}, Class AAA Wavelength



b) At 400 W·m^{-2} of LEDs Lights

Fig. 3 STC and Non-STC I-V Characteristics of x-Si PV cell

The different wavelength the different I_{sc} shows in Fig 3 b). At the same irradiance, the different wavelengths enhance the energy of photon, absorption rate and generation rates in a unit area of specimen x-Si PV cell. However, the measurement I-V characteristics can correct and close to 5% to STC. So the different continuous or band wavelengths of the pulse white LEDs, pulse monochromatic LEDs solar simulators, or non-STC, can used for the x-Si PV cell I-V characteristics and STC correction.

Table 2 Parameters under Class AAA Solar Simulator

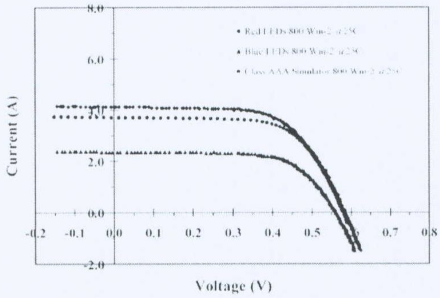
Parameters	Irradiance (W·m^{-2})			
	400	600	800	1000
Rs (Ω)	0.05	0.04	0.03	0.03
Rsh (Ω)	7.96	7.50	6.79	4.74

Table 2 shows that the higher irradiance the lower R_s and R_{sh}. The R_s were 0.05 Ω, 0.4Ω, 0.03Ω and 0.03 Ω at 1000, 800, 600, and 400 W·m^{-2} respectively. The changing of R_s may cause the parasitic series resistivities of the p-n junction and the bulk material of x-Si. Furthermore, the R_{sh} were 7.96 Ω, 7.50 Ω, 6.79 Ω, and 4.74 Ω. At different irradiances 1000, 800, 600, and 400 W·m^{-2} respectively. In accordance with the most recombination at 1000 W·m^{-2} irradiance is highest number of photon. The recombination is a reverse process of the generation depends on the number of photon, the wavelength absorption of the x-Si, and the distance of absorptions. R_{sh} of materials is low, therefore the higher irradiance the higher recombination.

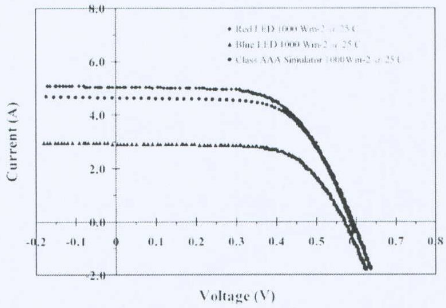
Table 3 Series and Shunt Resistances at 400 W·m^{-2}

Solar Simulators	Parameters			
	Series Resistance		Shunt Resistance	
	R_s (Ω)	$\bar{X}$, *SD*	R_{sh} (Ω)	$\bar{X}$, *SD*
Class AAA	0.05	0.05 ± 0.00	7.96	7.96 ± 0.00
Sunlight	0.03	0.04 ± 0.008	5.00	5.27 ±0.19
Halogen	0.05		5.40	
White LEDs	0.04		5.40	
Red LEDs	0.03	0.04 ± 0.008	6.50	5.90 ± 0.54
Green LEDs	0.05		5.20	
Blue LEDs	0.04		6.00	
ANOVA Statistic	F = 0.643		F = 16.893 **	
** 99th percentiles significant				

Table 3 shows the values of R_s and R_{sh} at low irradiance, 400 W·m^{-2}. The changing of R_s was 0.05 Ω to 0.03 Ω and 0.04 Ω at different wavelength of the solar simulators. To analyze the difference of R_s of a specimen, there were divided into 3 groups of solar simulator, Class AAA, continuous wavelength and monochromatic wavelength of pulse LEDs. As the assumption of R_s of x-Si PV cell is a normal distribution. By using ANOVA statistic, R_s of those 3 groups light sources were not significantly difference. Therefore, R_s were essentially independent of light wavelength at low irradiance. R_{sh} of 3 groups light source were 7.96 Ω to 5.00Ω. As a result, R_{sh} at various wavelengths were significantly difference thus R_{sh} is the light-dependent parameter.



a) At 800 W·m^{-2}



b) At 1000 W·m^{-2}

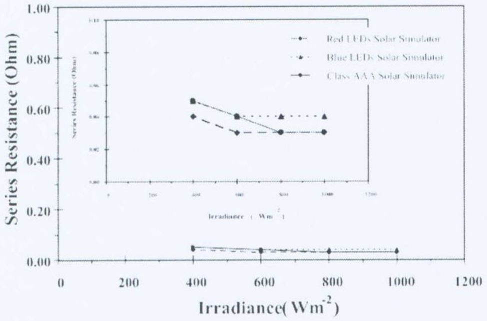
Figure 4 Samples of I-V curves at 400 to 1000 W·m^{-2}, 25 °C

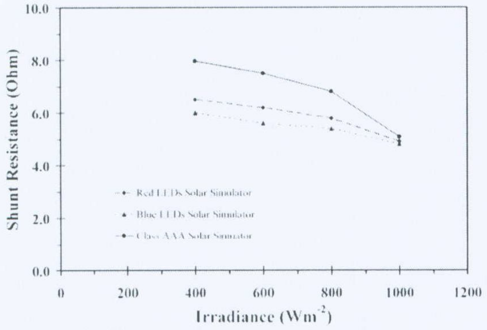
Fig. 4 shows samples of I-V Characteristics under Class AAA and Pulse LED Solar Simulators at 400 to 1000 W·m^{-2}, 25 °C. Trends of R_s and R_{sh} at this conditions shows in Fig. 5.

Fig 5 a) shows the decreasing of R_s at the increasing of irradiance. Red LEDs solar simulator, R_s decreased from 0.4 Ω to 0.3Ω, 0.3 Ω and 0.3Ω at different irradiance and the blue light LEDs, R_s decreased from 0.5 Ω to 0.4Ω, 0.4 Ω and 0.4Ω. Both of monochromatic LEDs decreased at 400, 600, 800 and 1000 W·m^{-2} respectively but they don't significantly change, 0.5 Ω to 0.3 Ω.

Fig. 5 b) shows the decreasing R_{sh} the increasing irradiance of Class AAA, monochromatic red and blue Pulse LEDs solar simulators. At 400 W·m^{-2}, R_{sh} of x-Si PV cell of the red light was 6.50Ω, and the blue light was 4.80Ω and Class AAA light source was 7.96Ω. In this case, the specimens were characterized at the same light power such as 400 W·m^{-2} on 12.5*12.5 cm^2, x-Si absorbed the blue light more than the red light which more generated electron-hole pair in p-n junction because the higher electron-hole pair generation the higher recombination. According to R_{sh} at class AAA solar simulator matched AM 1.5 spectral wavelengths, R_{sh} is more complex combination at each wavelength. At the highest irradiance 1000 W·m^{-2}, R_{sh} decreased from 5.08 Ω to 4.90 Ω of the red light and 4.70 Ω of the blue light. Even though R_s of red and blue light closed to the STC, the error of them at 1000 W·m^{-2} were 3.5 % and 7.5 % respectively. So R_{sh} is the light-dependent parameter. It is lower R_{sh} at higher irradiance.

a) Series resistance versus irradiances





b) Shunt resistance versus irradiances

Fig. 5 Irradiance Dependent Resistances

5. CONCLUSION

In conclusion, I-V characteristics of non-STC differ from the STC and it is possible to derive STC parameters from non-STC parameters. At higher irradiance of class AAA, monochromatic red and blue, R_s and R_{sh} were low. Furthermore, the light sources were classified into 3 groups, Class AAA, continuous wavelength, and monochromatic wavelength, R_s was not significantly difference. R_s were virtually independent of light wavelength at low irradiance. In addition, R_{sh} at low irradiance of each groups were significantly difference. R_s of Class AAA, monochromatic red and blue LEDs wavelengths at 400 to 1000 W·m^{-2} decreased when the irradiance increased but not significantly. R_{sh} decreased, increased irradiance. The R_{sh} error of red and blue light were 3.5 % and 7.5 % respectively. Generalization, R_s is independent of wavelength and irradiance whereas R_{sh} is the wavelength and irradiance dependence.

5. ACKNOWLEDGMENTS

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เรื่อง

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Research Article

Construction of Tungsten Halogen, Pulsed LED, and Combined Tungsten Halogen-LED Solar Simulators for Solar Cell I-V Characterization and Electrical Parameters Determination

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I-V characterization of solar cells is generally done under natural sunlight or solar simulators operating in either a continuous mode or a pulse mode. Simulators are classified on three features of irradiance, namely, spectral match with respect to air mass 1.5, spatial uniformity, and temporal stability. Commercial solar simulators use Xenon lamps and halogen lamps, whereas LED-based solar simulators are being developed. In this work, we build and test seven simulators for solar cell characterization, namely, one tungsten halogen simulator, four monochromatic (red, green, blue, and white) LED simulators, one multicolor LED simulator, and one tungsten halogen-blue LED simulator. The seven simulators provide testing at nonstandard test condition. High irradiance from simulators is obtained by employing elevated supply voltage to tungsten halogen lamps and high pulsing voltages to LEDs. This new approach leads to higher irradiance not previously obtained from tungsten halogen lamps and LEDs. From I-V curves, electrical parameters of solar cell are made and corrected based on methods recommended in the IEC 60891 Standards. Corrected values obtained from non-STC measurements are in good agreement with those obtained from Class AAA solar simulator.

1. Introduction

Solar simulators for solar cell testing can be broadly classified into 3 groups, namely, AM 1.5 G terrestrial system solar simulators, AM 1.5 D concentrating PV solar simulators, and AM 0 space system solar simulators. Major building blocks of solar simulators, are light sources and light quality control components, such as filters and lenses, rendering AM 1.5 spectrum as specified in the IEC 60904-3 Standards and ASTM G173-03 Standards or AM 0 specified in ASTM E490-00a [1–3]. The IEC 60904-9 and ASTM E927-10 classify solar simulators in terms of spectral match, uniformity and temporal stability into simulator classes [4, 5].

Solar simulators have been continuously developed for nearly five decades, with differing approaches on lamp selection, combined light sources and filtering. Xenon arc lamps and metal halide arc lamps are employed in commercial solar simulators. Research solar simulator works during the last two decades are reported on light emitting diodes (LED) as they are inexpensive, consume small power and can be combined to produce required spectrum outputs, and promising a new approach to low cost. Current-voltage characterizations of solar cells are done at standard test condition (STC) (1,000 W$\cdot$m^2, 1.5 AM spectrum, cell at 25°C) as specified in IEC 60904-1 Standards [6]. As there are simulators not conforming to AM 1.5 G, notably simulators based on metal halide lamps and LEDs, the IEC 60891 Standards provide correction methods to convert the non-STC test results to the STC [7]. During the present decade the major research trend in solar simulators for terrestrial solar cells is on low cost and high intensity LED solar simulators and translation of non-STC results. This paper focuses on construction and characteristics of simulators not conforming to AM 1.5 G, with emphasis on LED-based simulators, and applications of the IEC 60891 Standards on non-STC results.

Solar simulators using Xenon lamps and metal halide sources were reported over forty years ago, initially for space radiation simulation and afterwards for terrestrial solar cell characterization. An excellent review on early works is undertaken by Emery [8]. Compact source iodide (CSI) lamps were introduced in 1980s, as reported by Beeson [9]. After that multi-CSI solar simulators for large scale testing have become commercially available. On pioneering LED-based solar simulators, Kohraku and Kurokawa measure spectral responses of solar cells using 4-color and 6-color LED simulators [10]. Potential low cost and simplicity of LED-based simulators are pointed out. During the past decade, numbers of research work are published on LED simulators, all showing low intensity limitations of LED-based simulators. Bliss et al. develop an LED-based solar similar prototype producing light at variable flash speeds and pulse shapes [11]. Color and UV LEDs and halogen light sources are employed.

This paper is on construction and testing of seven solar simulators for solar cell characterization using tungsten halogen lamps and monochromatic red, green, blue, and white LEDs. High irradiance is achieved by operating lamps at elevated supply voltage above rated voltage, and in LEDs by applying voltage high pulses. This approach leads to higher irradiance that has not been previously obtained. Solar cell electrical parameters are derived and corrected according to the IEC 60891 Standards for I-V characterization at non-STC obtained under the seven simulators.

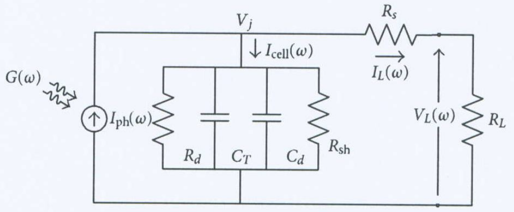

FIGURE 1: AC equivalent circuit of a solar cell.

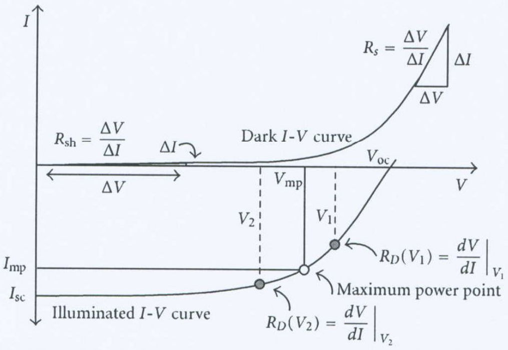

FIGURE 2: Dark and illuminated I-V curves of a solar cell.

2. Electrical Parameters of Solar Cells

In representing solar cells (and modules) one uses a DC equivalent circuit or an AC equivalent circuit. The DC circuit consists of three resistances, namely, series resistance (R_S), shunt resistance (R_{sh}), and internal dynamic resistance (R_d). The AC equivalent circuit has two additional parameters, that is, junction capacitance (C_T) and diffusion capacitance (C_D). C_T is voltage dependent whereas C_D is voltage and frequency dependent. **Figure 1** shows an AC equivalent circuit.

Series and shunt resistances are determined from dark I-V characteristics or dark IV curves. Dark or illuminated IV curves are employed to determine internal dynamic resistance. The IEC 60904-1 Standards provide guidelines on performing I-V characteristics measurements under natural sunlight, steady-state simulated sunlight, and pulsed simulated sunlight [6].

Impedance spectroscopic techniques, not covered in this paper, are employed to determine dynamic parameters. Spectroscopic measurements can be done by expensive impedance spectroscopy equipment, reported by Kumar et al. [12]. Alternatively, Chenvidhya et al. has determined dynamic parameters utilizing laboratory equipment, with small periodic signals superimposing on AC signal as inputs to solar cells and FFT analysis of output signals [13].

From a dark I-V curve as showen in **Figure 2**, R_S is a slope in the first quadrant and depends on resistances of bulk semiconductors and contacts. R_{sh} can be derived from a slope at near-zero voltage, and depends on defects and traps in semiconductors. For each solar cell, R_S and R_{sh} are constant at all operating conditions. On the other hand, R_d is operating point dependent and is a slope at of an I-V curve (under dark or illumination) at a particular operating point.

In comparing performance of solar cells, apart from series and shunt resistance, other electrical parameters are also required. These are open circuit voltage (V_{OC}), short circuit current (I_{SC}), maximum power (P_{pm}) (and corresponding current and voltage), solar cell efficiency (η), and fill factor (FF).

3. Equipment

For characterization of solar cell under Class AAA simulator according to IEC 60904-9 Standards [4], natural sunlight and seven solar simulators fabricated in this study, we use a solar cell obtained from a local module manufacturer. It is a monocrystalline silicon solar cell with a dimension of 12.5 × 12.5 cm^2. The solar cell is encapsulated with EVA and has a Tedlar backsheet.

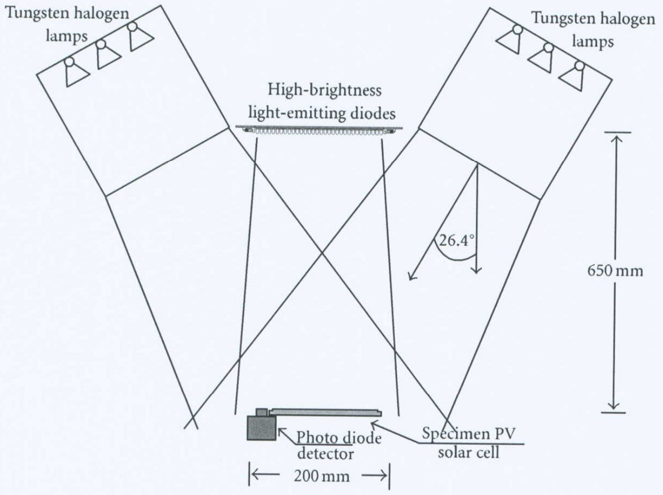

FIGURE 3: A schematic structure of combined tungsten halogen and blue LED solar simulator.

3.1. Solar Simulators

3.1.1. Tungsten Halogen Solar Simulator. The basic lamp array consists of 3 × 3 Philips tungsten halogen lamps, each rated at 12 V and 50 W. The array is naturally ventilated. Supply voltages can be varied from 100%, 120%, and 140% of rated voltage to increase lamp light outputs. This, however, affects color temperature of lamps, and resultant spectra.

As lamp supply voltage increases, lamp light outputs increase and the spectra are blueshifted. To maintain a constant irradiance of 1,000 $W\cdot m^{-2}$ on a test plane, spacing distances between the array and the test plane are adjusted. For supply voltages at 100%, 120%, and 140% of rated voltage, the spacing distances are 42 cm, 62 cm, and 78 cm, respectively.

3.1.2. LED Solar Simulators. Study on five LED simulators, four monochromatic LED arrays, and one combined color LED array, used in this work, has been reported by Namin et al. [14]. Four monochromatic LEDs are red-R at 632 nm, green-G at 525 nm, blue-B at 468 nm and white-W. Each array has 1,024 LEDs and is 227.5 mm × 227.5 mm. The LED array is 3 mm above a glass diffuser, under which is a test plan. Supply voltages to LEDs are pulse signals whose amplitudes are increased above rated voltages to raise light outputs. Amplitudes of pulse signals can be continuously varied from 0–150 V with a pulse width of 10 ms and a period of 1 s. Heat from LEDs is removed with LED heat sinks and forced air cooling. This helps maintain steady temperature of heat sink at 25°C.

3.1.3. Combined Tungsten Halogen-Blue LED Solar Simulator. Tungsten halogen lamp light outputs are deficient in the blue part of the spectrum. To augment the blue part, we incorporate a blue LED array with tungsten halogen lamps as shown in Figure 3. The simulator combined light sources consisting of two 3 × 3 tungsten halogen lamp arrays and one blue LED array, similar to the one described above. The blue LED array is located directly 65 cm above the test plane. Two tungsten halogen lamp arrays are placed along opposite sides of the blue LED array, and at an inclined angle of 26 degrees with respect to the horizon.

3.1.4. Class AAA Solar Simulator. PASAN Class AAA Sun Simulator IIIc is used as a reference solar simulator. It is a commercial short-pulse solar simulator employing 4 flash Xenon lamps. Light pulses can be varied between 2–10 ms. Up to 2 × 2 m solar cells modules can be tested.

4. Measurements and Analysis

4.1. Measurements on Solar Simulator Characteristics. The following measurements are made.

Tungsten Halogen Solar Simulator. Spectral characteristics, irradiance spatial uniformity, and temporal stability are maintained when lamps are supplied at 100%, 120%, and 140% of rated voltage.

LED Solar Simulators. The above-mentioned study of Namin et al. covers

(i) thermal characteristics of LED arrays under continuous and pulsed operations. This is to compare temperature profiles of arrays under the two operating conditions. Infrared pictures of LED heat sinks are taken and used to determine corresponding temperature,

(ii) continuous and pulsed operations of LEDs at different amplitudes, pulse widths, and pulse periods. The

Table 1: Irradiance uniformity and temporal instability of seven solar simulators.

Light sources	Average irradiance (Wm^{-2})	Uniformity		Temporal instability	
		% Uniformity	Uniformity class	% Temporal instability	Temporal instability class
Tungsten halogen lamps					
Supply voltage and separation distance					
100% rated voltage, 42 cm	1004	9.8	C	1.25	A
120% rated voltage, 62 cm	1006	4.85	B	1.25	A
140% rated voltage, 78 cm	1005	2.60	B	1.25	A
Tungsten halogen lamps with blue LEDs					
120% rated voltage, 62 cm	1,040	3.60	B	0.47	A
Light emitting diodes					
Blue LED	1,015	2.68	B	1.40	A
Red LED	1010	2.60	B	1.50	A
Green LED	410	3.92	B	2.50	B
White LED	415	2.92	B	2.75	B
Combined R-G-B LED	810	3.84	B	3.10	B

shortest pulse duration that can be used would be governed by the sweeping time from the short circuit condition to the open circuit condition in I-V curve measurement,

(iii) spatial uniformity and temporal stability of irradiance are examined.

Table 1 shows irradiance levels, uniformity, and temporal stability of the seven solar simulators. Averaged irradiance levels are calculated from measured irradiance at 64 locations on the test plane.

4.2. Determination of IV Curves. The seven solar simulators used to measure I-V curves are (i) one tungsten halogen simulator, (ii) four monochromatic LED solar simulators, (iii) one combined RGB LED solar simulator, and (iv) one combined tungsten halogen-blue LED solar simulator. IV curves of a solar cell are made under STC condition PASAN Class AAA solar simulator, non-STC conditions (seven simulators) and under natural sunlight. The I-V characterization method follows the IEC 60904-1 Standards [6].

4.3. Analysis of Electrical Parameters

STC Condition. Calculations are made on solar cell electrical parameters (I_{SC}, V_{OC}, P_{mp}, efficiency, fill factor) and resistances (R_S, R_{sh}, R_d).

Non-STC Conditions. At present, there are correction methods based on the IEC 60891 Standards for measurements at non-STC conditions. I-V curves at different irradiances and temperatures were characterized by Class AAA solar simulator. The R_S and temperature coefficients of current (α) and voltage (β) and curve correction factor (κ) are determined.

The equations to translate or correct the non-STC results are as follows:

$$\begin{aligned} I_2 &= I_1 + I_{SC}\left[\frac{I_{SR}}{I_{MR}} - 1\right] + \alpha(T_2 - T_1), \\ V_2 &= V_1 - R_s(I_2 - I_1) - \kappa I_2(T_2 - T_1) + \beta(T_2 - T_1). \end{aligned} \quad (1)$$

In the above equations, I_1, V_1 are measured current and voltage at non-STC; I_2, V_2 are corrected current and voltage; I_{SC} is the short circuit current of the test solar cell; I_{MR} is the short circuit current of the reference cell; I_{SR} is the short circuit current of the reference cell under standard light intensity; T_1 is the measured temperature of the test solar cell; T_2 is the standard temperature or other specified temperatures; α and β are temperature coefficients of current and voltage, respectively; κ is the curve correction factor.

Based on the equations outlined above, we correct results obtained from seven solar simulators using the IEC 60891 Standards and compared with the STC results. Figure 4 is a flowchart on solar simulator construction and corrections of electrical parameters using the IEC 60891 Standards.

5. Results and Discussions

5.1. Spectral Irradiance of Tungsten Halogen and Combined Tungsten Halogen-Blue LED Solar Simulators. For simplicity, we herein will use the term "spectral irradiance" of solar

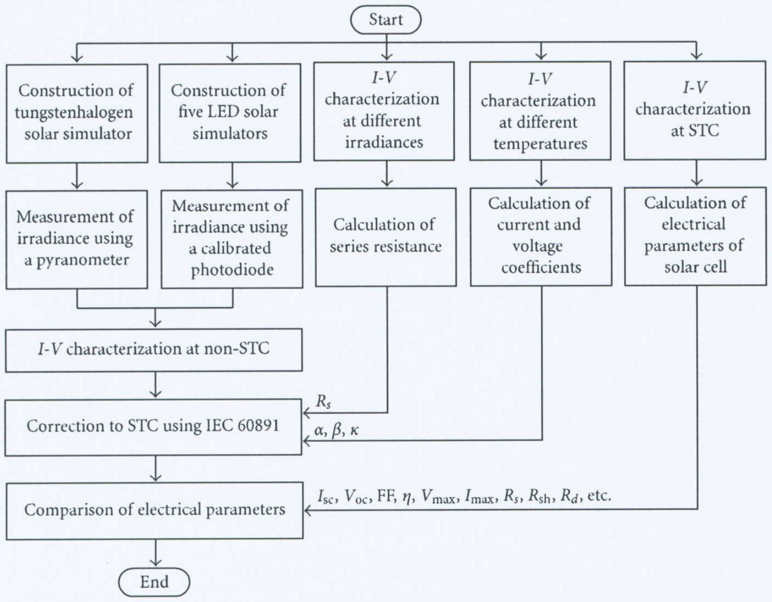

Figure 4: Flowchart of solar simulator construction and corrections of electrical parameters using IEC 60891 Standards.

simulator instead of spectral intensity. It can be seen from Figure 5 that spectra of the tungsten halogen simulator are different from the reference spectral irradiance [1]. The spectra are more "red" in contents. As the supply voltages are increased, the lamps get hotter and the output light spectra shift towards shorter wavelengths—blue-shifting. As a consequence, better spectrum matching with the AM 1.5 spectrum can be expected at elevated supply voltages. Thus, one can improve the spectral match of tungsten halogen solar simulators by raising supply voltages. The disadvantages would be higher power consumption and shorter lamp life. Adopting pulsed supply voltages would reduce such disadvantages, permit even higher supply voltages, and improve spectral match. We do not pursue such idea with tungsten halogen lamps, but carrying this out with LED simulators. The results are reported in later parts of the paper.

The spectral irradiance and intensity of a combined tungsten halogen-blue LED solar simulator is shown in Figure 6. The spectral match is improved by adding a blue irradiance component in the range of 400–500 micron. Temporal stability of irradiance of tungsten halogen solar simulators, obtained from an ordinary power supply with simple rectifier and a high quality power supply, shown in Figure 7, are compared and evaluated. It is seen that a Class A temporal stability is achieved using a high quality power supply.

Tables 2 and 3 compare spectral matches obtained from the tungsten halogen solar simulators using three supply voltages, and a combined tungsten halogen-blue LED solar simulator.

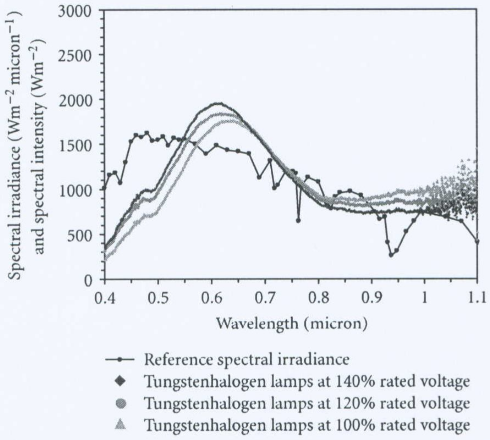

Figure 5: Reference spectral irradiance [1] and spectral intensity of tungsten halogen simulator under various supply voltage.

It is clearly seen form Tables 2 and 3 that combining blue LEDs with tungsten halogen lamps produce a better spectral match. Better I-V characterization and more accurate electrical parameters can be expected. This opens new avenues for low cost solar simulator construction.

5.2. LED Array Characterization. Followings are salient features on LED array characterization undertaken by Namin et al.

TABLE 2: Spectral match of tungsten halogen solar simulator at three different supply voltages.

Wavelength range (nm)	Supply voltage at 100% of rated voltage		Supply voltage at 120% of rated voltage		Supply voltage at 140% of rated voltage	
	Spectral match	Class	Spectral match	Class	Spectral match	Class
400–500	0.40	C	0.49	C	0.55	C
500–600	0.84	A	0.95	A	1.04	A
600–700	1.21	A	1.25	A	1.28	B
700–800	1.05	A	1.04	A	1.00	A
800–900	0.94	A	0.88	A	0.82	A
900–1100	1.65	C	1.38	B	1.29	B
Classification	1,010 W·m^{-2}	C	1,009 W·m^{-2}	C	1,010 W·m^{-2}	C

Note: In the IEC 60904-9 Standards, six wavelength ranges are used to determine a spectral match with standard AM 1.5 G [9].

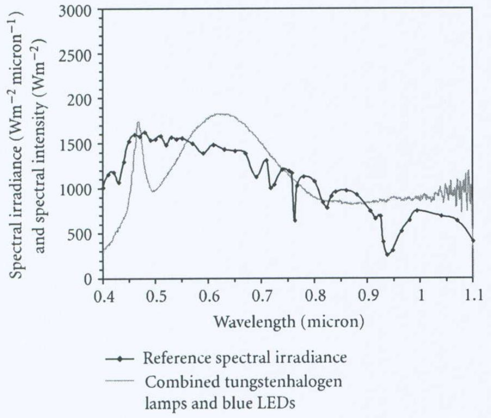

FIGURE 6: Reference spectral irradiance [1] and spectral intensity of combine tungsten halogen operated at 120% rated voltage and blue LEDs.

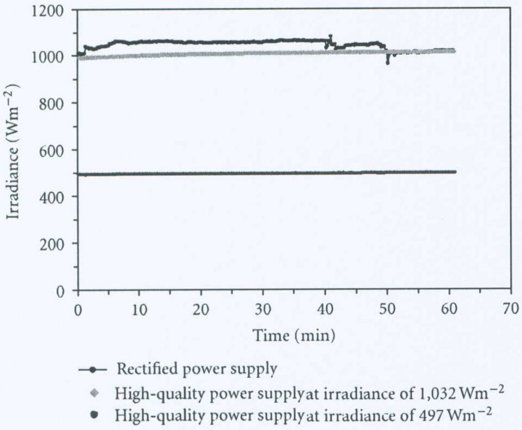

FIGURE 7: Temporal stability of irradiance of tungsten halogen solar simulator under different supply voltages.

TABLE 3: Classification of tungsten halogen solar simulator and combined tungsten-halogen blue LED solar simulator.

Classification	Light sources at irradiance of 1,000 Wm^{-2}	
	Tungsten halogen lamps at 140% rated voltage	Combined tungsten halogen lamps (120% rated voltage) and blue LEDs
Spectral match class	C	B
Nonuniformity class	B	B
Temporal instability class	A	A
Standard classification	CBA	BBA

Thermal Characteristics of LED Arrays. Under continuous voltage, heat sink temperature rises substantially (63°C). However, under pulse operation mode the array remains cool at room temperature (27°C). The merit of the pulse operation mode is evident.

Stability of Irradiance from LED Arrays under Pulse Operations. Irradiance stability of the R, G, B, and W LED arrays and the RGB array under 10 ms pulse operations is studied. Pulse amplitudes at one, two, and three times LED-rated voltages are applied, and irradiance stability is recorded. It is found that amplitudes of pulses can be increased to at least twice the rated voltage, and the array still provides a stable light output. Temporal stability is under 5%, and, the 5 simulators are Class B.

Spatial Uniformity of Irradiance. On the test plane, the spatial uniformity is better than 5%. The 5 simulators are Class B.

Relationship between the LED Current and Irradiance. LED light outputs and irradiance levels initially increase with increasing LED current but level off, due to temperature rises. Among the four monochromatic R, G, B, and W arrays and the combined RGB array, only R and G arrays provide irradiance higher than 1000 Wm^{-2}. Less than 1000 W·m^{-2} is available from G, W, and RGB arrays. Blue and white LEDs

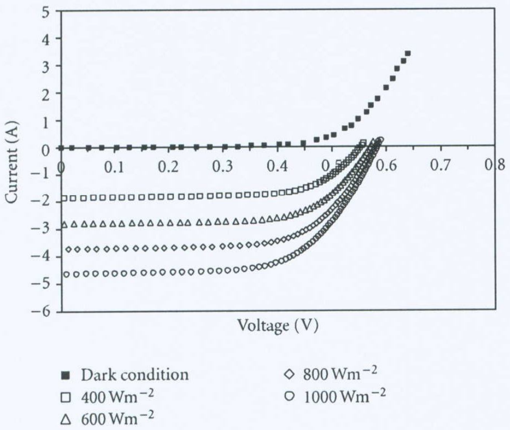

Figure 8: Dark and illuminated I-V curves of an X-Si solar cell obtained from Class AAA solar simulator.

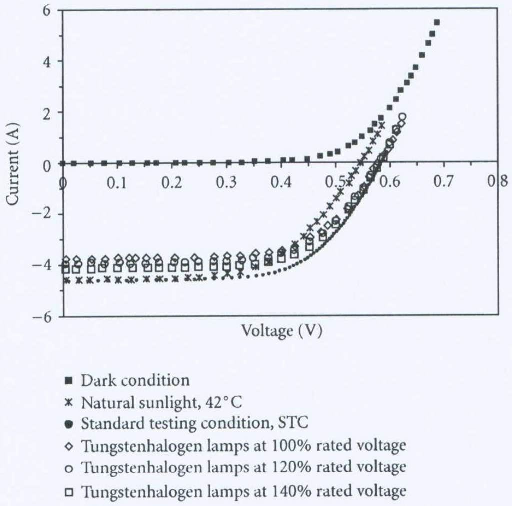

Figure 9: Uncorrected I-V curves obtained from tungsten halogen simulator under three supplied voltages, natural lighting, and Class AAA solar simulator at irradiance of 1,000 W·m^{-2}.

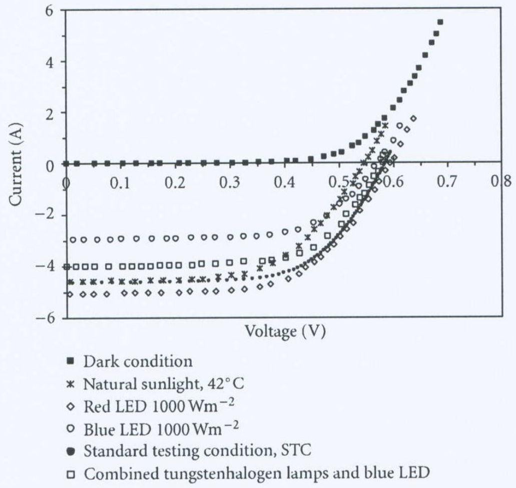

Figure 10: Uncorrected I-V curves from natural sunlight, Class AAA solar simulator, red LED, blue LED, and combined tungsten halogen-blue LED simulators at irradiance of 1,000 W·m^{-2}.

are more temperature dependent and are less efficient as their light outputs rapidly fall with increasing supply current.

In principle we can further increase LED light outputs by using higher pulse amplitudes while keeping LED temperature down. Chilled air, instead of room temperature air, could possibly be used in the cooling. But LED array structures would be complex and more expensive.

5.3. *I-V Characteristics Obtained from the Seven Solar Simulators*

5.3.1. Uncorrected I-V Curves Obtained from the Non-STC Simulators. We compare I-V curves obtained from seven non-STC solar simulators with I-V curves from a reference STC solar simulator (PASAN Class AAA Sun Simulator IIIc). Results are plotted in Figures 10 and 11.

From the Figures 8, 9, and 10, we note the following.

(a) PASAN Sun Simulator can be adjusted to provide an irradiance over 400–1,000 W·m^{-2}, Figure 8.

(b) Tungsten halogen simulator supply voltage can be adjusted to 140% of rated voltage, resulting in changes in irradiance and spectrum shift.

(c) For all 5 LED simulators, voltages and current can varied to provide irradiance in the range of 400–1,000 W·m^{-2}, and light spectra being different from AM 1.5. Out of the 5 simulators, only the red and blue LED simulators provide an irradiance of 1,000 W·m^{-2}. Results are previously reported and not shown here [14].

For the tungsten halogen simulator, at the irradiance level of 1,000 W·m^{-2}, Figure 10, uncorrected I-V curves measured with the three supply voltages are of the same shape as the I-V curve of the Class AAA simulator, with some deviations. The curve of the simulator operated at 140% rated voltage is the best fit. This is understandable as at elevated voltages, the lamp temperature increases with accompanying spectrum shift towards the short wavelength. On the other hand, I-V curves of the red and blue LED simulators are significantly different from that of the Class AAA simulator, Figure 11. Red LED simulator results in higher current than blue LED simulator. This could be explained partly by the fact that at the same irradiance there are more red photons

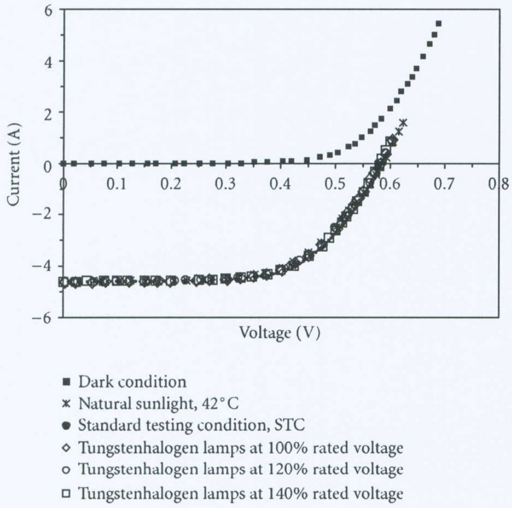

Figure 11: Corrected I-V curves measured under natural sunlight, Class AAA solar simulator, and tungsten halogen simulator (at 100%, 120%, and 140% rated voltage) after IEC 60891 Standards correction.

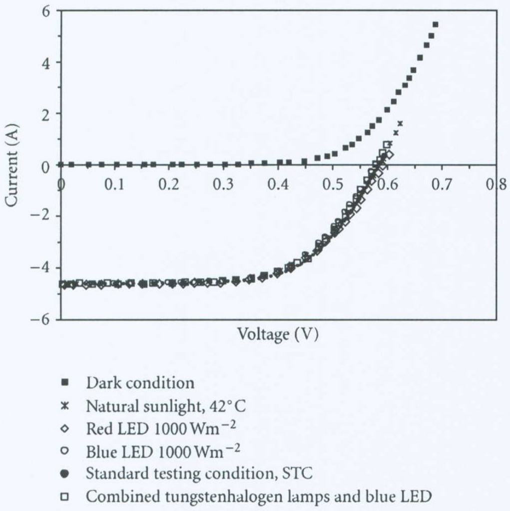

Figure 12: Corrected I-V curves measured under natural sunlight, Class AAA solar simulator, red LED simulator, blue LED simulator, and combined tungsten halogen-blue LED simulator after IEC 60891 Standards correction.

(at lesser energy) than blue photons. Hence, photocurrent due to red photons is greater.

5.3.2. Corrected I-V Curves at STC Based on the IEC 60891 Standards. We undertake corrections of the non-STC measurements of the seven non-STC simulators using the IEC 60891 Standards, outlined in Section 4.3, and plot results as Figures 11 and 12.

The corrected I-V curves and that of the Class AAA simulator are quite similar. We wish to point out that this is the first instance that the IEC 60891 correction method is applied for tungsten halogen, LED and tungsten halogen-LED simulators. Kohraku and Kurokawa have proposed a different correction method, called the Two-curve method.

5.3.3. Electrical Parameters of Solar Cell at STC. From the corrected I-V curves of the tungsten halogen simulator, the red and blue simulators, and the tungsten halogen-blue LED simulator at 1,000 W·m^{-2}, we derive electrical parameters (I_{SC}, V_{OC}, P_{mp}, efficiency, fill factor) at the STC. The results are shown in Table 4.

Comparing electrical parameters obtained from the seven non-STC simulators after corrections based on the IEC 60891 Standards and those obtained from Class AAA simulator, very good agreement is seen. Differences in values of electrical parameters are about 2% or less. This level of result accuracy is essential in adopting tungsten halogen lamps, LED and combined tungsten halogen-LED simulators in solar cell characterization. Less expensive but yet excellent-performance solar simulators can be constructed from these light sources.

6. Conclusions

We construct and test seven solar simulators with tungsten halogen lamps and LEDs as light sources for solar cell characterization. The seven simulators are one simulator using tungsten halogen lamps, four simulators using monochromatic red, green, blue, and white LEDs, one with combined red-green-blue LEDs and one tungsten halogen lamps—blue LEDs. Higher irradiance are achieved with tungsten halogen lamps and LEDs, by operating lamps at elevated supply voltage above rated voltage and pulsing LEDs by at voltage, respectively. Irradiance uniformity and instability qualify the seven simulators as Class B. Their spectral match with air mass 1.5 is varied. Using these simulators, I-V curves of solar cell are measured under non-STC conditions. Solar cell electrical parameters are derived. Applying correction methods recommended in the IEC 60891 Standards, for I-V characterization at non-STC, results on electrical parameters obtained with the tungsten halogen simulator, the combined tungsten halogen-blue LED simulator, and the monochromatic red and blue LED simulators are in good agreement with Class AAA simulator. Less expensive and excellent performance solar simulators can be fabricated with tungsten halogen lamps and LEDs as light sources.

Acknowledgments

The authors wish to acknowledge supports from their two universities for research facilities and research funds. They wish to acknowledge supports from the CSSC for excellent research facilities. Valuable advices have been given by

Table 4: Electrical parameters of solar cell measured under natural sunlight, Class AAA solar simulator, and non-STC solar simulators after IEC 60891 Standards correction.

Parameters	Light sources							
	Tungsten halogen lamps under three supply voltages							
	100% rated voltage	120% rated voltage	140% rated voltage	Red LED	Blue LED	Combined tungsten halogen and LEDs	Natural sunlight	Class AAA (STC)
G $(\text{W}\cdot\text{m}^{-2})$	1000	1000	1000	1000	1000	1000	1000	1002
T (C)	25	25	25	25	25	25	25	25
V_{oc} (V)	0.58	0.58	0.58	0.59	0.57	0.58	0.58	0.58
I_{sc} (A)	4.63	4.63	4.63	4.63	4.63	4.63	4.59	4.63
P_{max} (W)	1.65	1.68	1.67	1.69	1.65	1.68	1.66	1.72
V_{mp} (V)	0.41	0.42	0.41	0.41	0.41	0.42	0.41	0.42
I_{mp} (A)	4.07	4.04	4.07	4.11	4.03	4.04	4.07	4.06
FF (%)	61.8	62.7	62.8	61.9	62.1	62.7	62.2	63.5
η (%)	11.3	11.5	11.4	11.5	11.1	11.5	11.4	11.7
R_s (Ω)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
R_{sh} (Ω)	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.08
R_d @ V_{mp} (Ω)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Assistant Professor Proapran Plienpoo, Associate Professor Dr. Koarakot Wattanavichean, and Dr. Veerapon Monyakul.

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ภาคผนวก ง

ประสิทธิภาพควันตัมของเซลล์แสงอาทิตย์ และผลตอบสนองความยาวคลื่นของโฟโตไดโอด

ภาคผนวก ง.

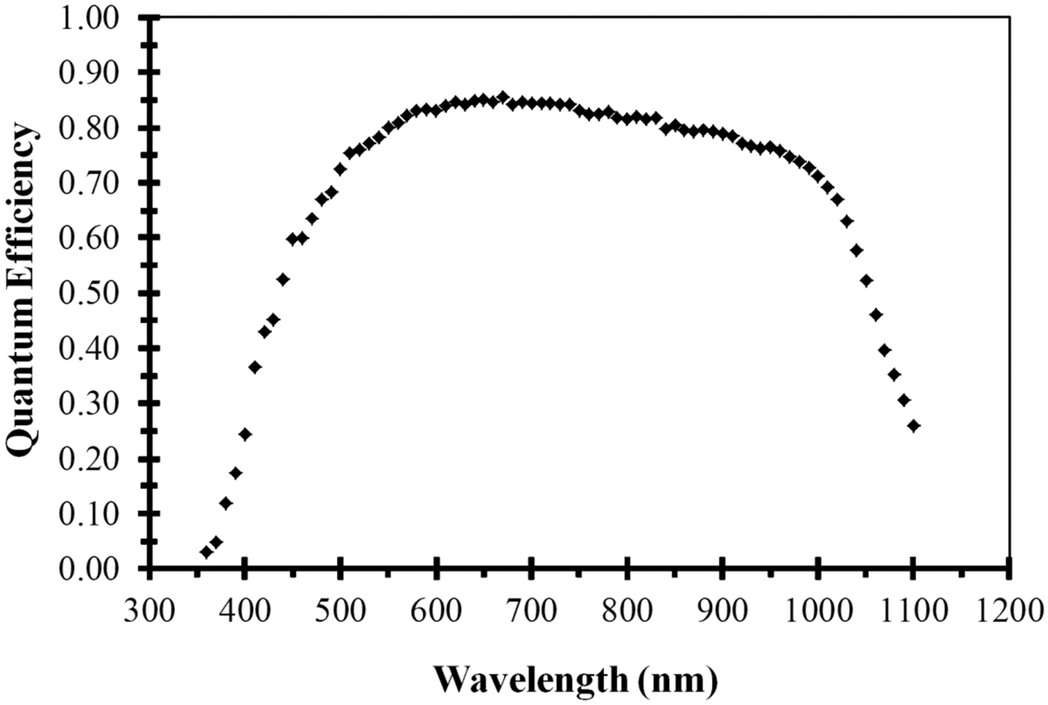
ประสิทธิภาพควันตัมของเซลล์แสงอาทิตย์ และผลตอบสนองความยาวคลื่นของโฟโตไดโอด

ง.1 ประสิทธิภาพควันตัมของเซลล์แสงอาทิตย์

ประสิทธิภาพควันตัม (Quantum Efficiency) เป็นสัดส่วนระหว่างจำนวนโฟตอนแสงในแต่ละความยาวคลื่น ต่อจำนวนประจุพาหะของเซลล์แสงอาทิตย์ ที่กำเนิดจากโฟตอนแต่ละความยาวคลื่นนั้นๆ เมื่อแสงแต่ละความยาวคลื่นตกกระทบเซลล์แสงอาทิตย์ในความเข้มที่เปลี่ยนแปลงไป ย่อมทำให้จำนวนประจุพาหะรวมหรือค่ากระแสของเซลล์แสงอาทิตย์มีค่าเปลี่ยนแปลงไปนั่นเอง

การวัดประสิทธิภาพควอนตัมของเซลล์ตัวอย่างที่ใช้ในงานวิจัยนี้ ใช้เครื่องวัดประสิทธิภาพควันตัม (PV Measurements, Inc. QEW7 Solar cell measurement system) โดยความอนุเคราะห์การวัดทดสอบจากห้องปฏิบัติการเทคโนโลยีแสงอาทิตย์ (STL) ศูนย์เทคโนโลยีอิเล็กทรอนิกส์และคอมพิวเตอร์แห่งชาติ (เนคเทค) อุทยานวิทยาศาสตร์ประเทศไทย) แสดงได้ดังรูปที่ ง. 1

จากรูปที่ ง. 1 ประสิทธิภาพควอนตัมของเซลล์แสงอาทิตย์ชนิดซิลิกอนผลึกเดี่ยว Cell #029 มีค่าต่ำประมาณ10 % ในช่วงความยาวคลื่นน้อยกว่า 400 nm ค่าเพิ่มขึ้นมากจนถึงประมาณ 70 % ในช่วง 400 – 500 nm แล้วเพิ่มขึ้นเพียงเล็กน้อยไปถึงค่า 80 % ในช่วง 500 – 600 nm โดยมีค่าสูงสุด 85.6 % ที่ความยาวคลื่น 670 nm แล้วค่าลดต่ำลงเหลือประมาณ 80 % ที่ 700 nm ลดลงเหลือประมาณ 70 % ตลอดช่วง 700 – 1,000 nm และมีค่าลดลงอย่างมากจนเหลือประมาณ 30 % ที่ความยาวคลื่น 1,100 nm

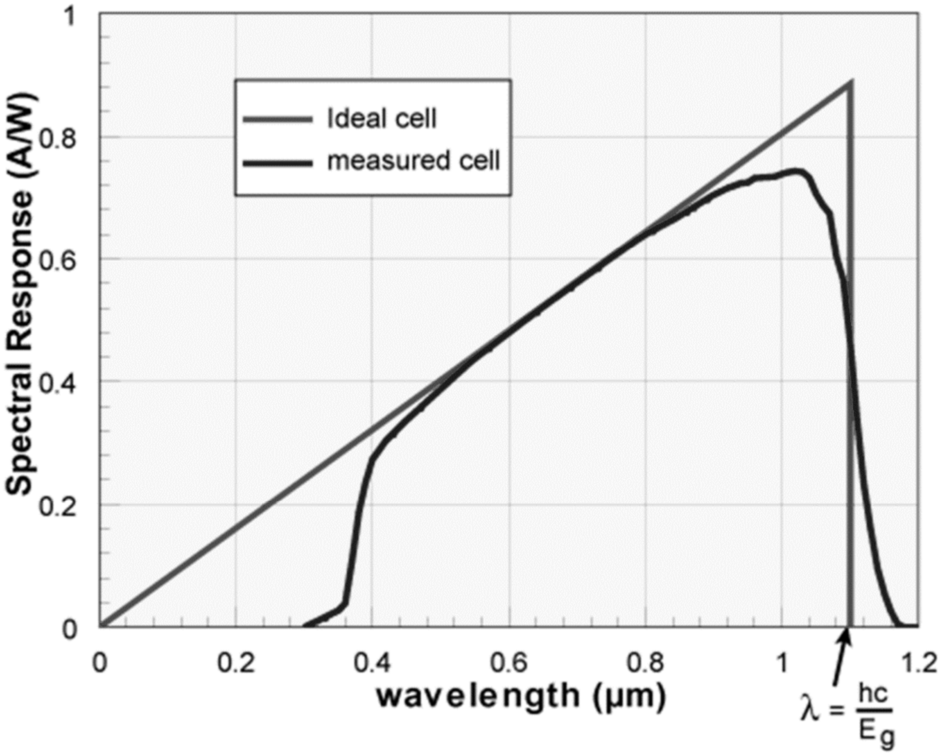


รูปที่ ง.1 ประสิทธิภาพควอนตัมของเซลล์แสงอาทิตย์ชนิดซิลิกอนผลึกเดี่ยวที่ใช้ในการศึกษานี้

ง.2 ผลตอบสนองความยาวคลื่นของเซลล์แสงอาทิตย์ชนิดซิลิกอน

ผลตอบสนองความคลื่น (Spectral responsivity) เป็นสัดส่วนระหว่างกระแสที่เซลล์แสงอาทิตย์หรือโฟโตไดโอดจ่ายออก ต่อกำลังงานแสงในแต่ละความยาวคลื่น (wavelength) ที่ตกกระทบหรือป้อนเข้า

เซลล์แสงอาทิตย์ซิลิกอนผลึกเดี่ยวที่ใช้ในการศึกษานี้ ไม่ได้ถูกวัดผลตอบสนองความยาวคลื่น เนื่องจากข้อจำกัดด้านเครื่องมือ จึงอนุมานว่า มีผลตอบสนองความยาวคลื่นเช่นเดียวกันหรือคล้ายกันกับผลตอบสนองความยาวคลื่นของเซลล์แสงอาทิตย์ชนิดซิลิกอนโดยทั่วไป ดังตัวอย่างในรูปที่ ง.2



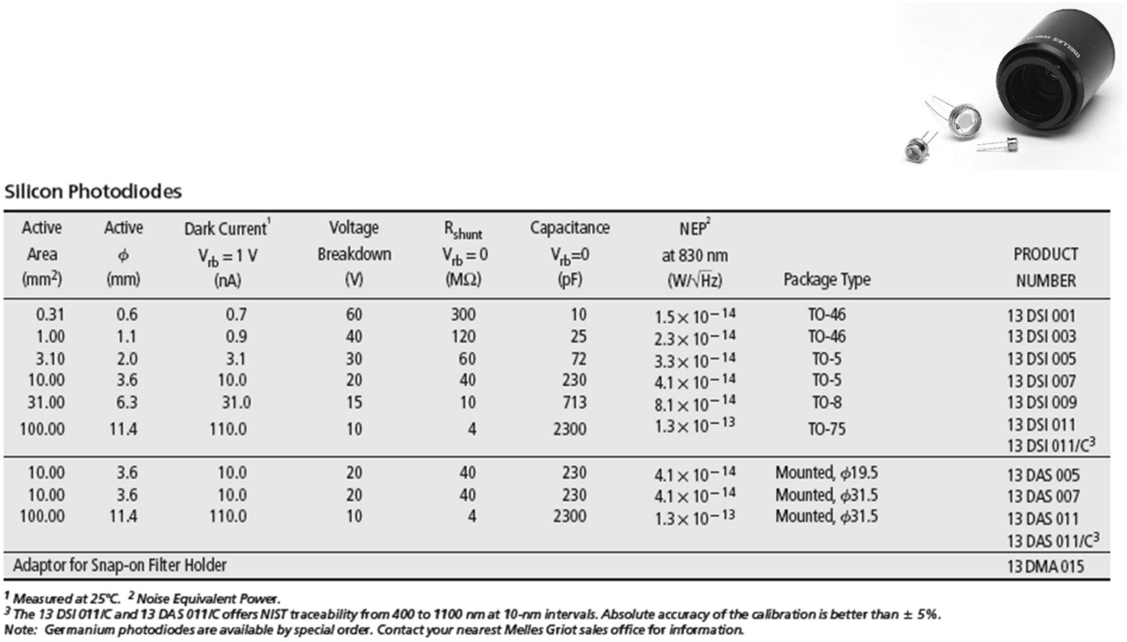
รูปที่ ง.2 ตัวอย่างผลตอบสนองความยาวคลื่นของเซลล์แสงอาทิตย์ชนิดซิลิกอนโดยทั่วไป

(http://pvcdrom.pveducation.org/CELLOPER/spectral.htm)

ง.3 ผลตอบสนองความยาวคลื่นของโฟโตไดโอด

โฟโตไดโอดที่ใช้ในการศึกษานี้ (13DSI003 และ 13AMP003) เป็นชนิดพีไอเอ็น ซิลิกอนโฟโตไดโอด (PIN silicon photodiode) มีพื้นที่รับแสง 1 ตารางมิลลิเมตร มีค่าคาปาซิแตนส์ที่แรงดันศูนย์ (ขณะลัดวงจร) เท่ากับ 45 pF ดังแสดงในรูปที่ ง.3

โฟโตไดโอดที่ใช้ในการศึกษานี้ ไม่ได้ถูกวัดผลตอบสนองความยาวคลื่น เนื่องจากข้อจำกัดด้านเครื่องมือเช่นกัน จึงอนุมานว่า มีผลตอบสนองความยาวคลื่นเช่นเดียวกันหรือคล้ายกันกับผลตอบสนองความยาวคลื่นของโฟโตไดโอดชนิดซิลิกอนโดยทั่วไป ดังตัวอย่างในรูปที่ ง.4 และ ง.5



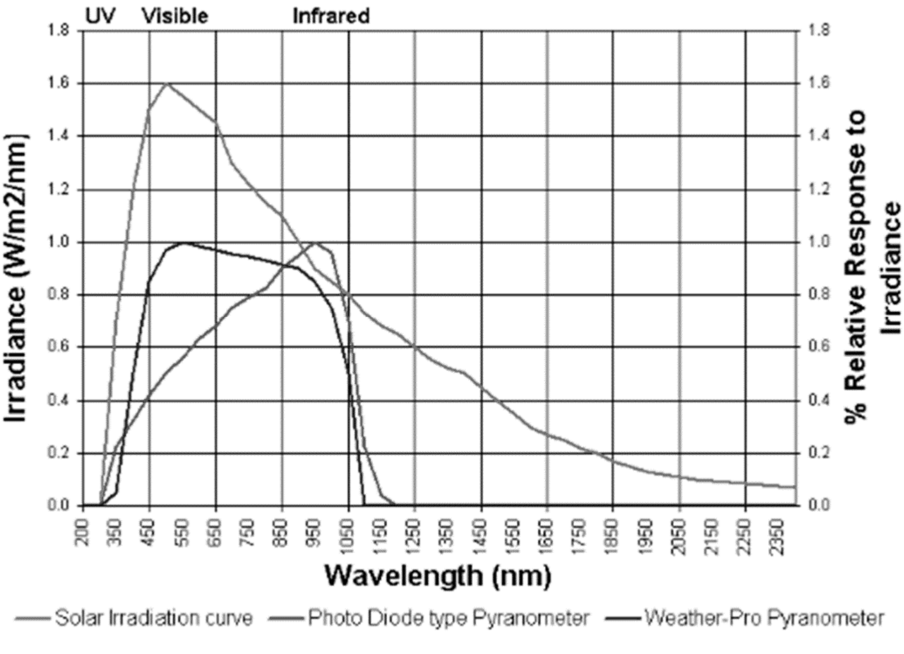
Silicon Photodiodes

Active Area (mm^2)	Active ϕ (mm)	Dark Current[1] $V_{rb} = 1$ V (nA)	Voltage Breakdown (V)	R_{shunt} $V_{rb} = 0$ (MΩ)	Capacitance $V_{rb}=0$ (pF)	NEP[2] at 830 nm (W/√Hz)	Package Type	PRODUCT NUMBER
0.31	0.6	0.7	60	300	10	1.5×10^{-14}	TO-46	13 DSI 001
1.00	1.1	0.9	40	120	25	2.3×10^{-14}	TO-46	13 DSI 003
3.10	2.0	3.1	30	60	72	3.3×10^{-14}	TO-5	13 DSI 005
10.00	3.6	10.0	20	40	230	4.1×10^{-14}	TO-5	13 DSI 007
31.00	6.3	31.0	15	10	713	8.1×10^{-14}	TO-8	13 DSI 009
100.00	11.4	110.0	10	4	2300	1.3×10^{-13}	TO-75	13 DSI 011 13 DSI 011/C[3]
10.00	3.6	10.0	20	40	230	4.1×10^{-14}	Mounted, ϕ19.5	13 DAS 005
10.00	3.6	10.0	20	40	230	4.1×10^{-14}	Mounted, ϕ31.5	13 DAS 007
100.00	11.4	110.0	10	4	2300	1.3×10^{-13}	Mounted, ϕ31.5	13 DAS 011 13 DAS 011/C[3]
Adaptor for Snap-on Filter Holder								13 DMA 015

[1] Measured at 25°C. [2] Noise Equivalent Power.
[3] The 13 DSI 011/C and 13 DAS 011/C offers NIST traceability from 400 to 1100 nm at 10-nm intervals. Absolute accuracy of the calibration is better than ± 5%.
Note: Germanium photodiodes are available by special order. Contact your nearest Melles Griot sales office for information.

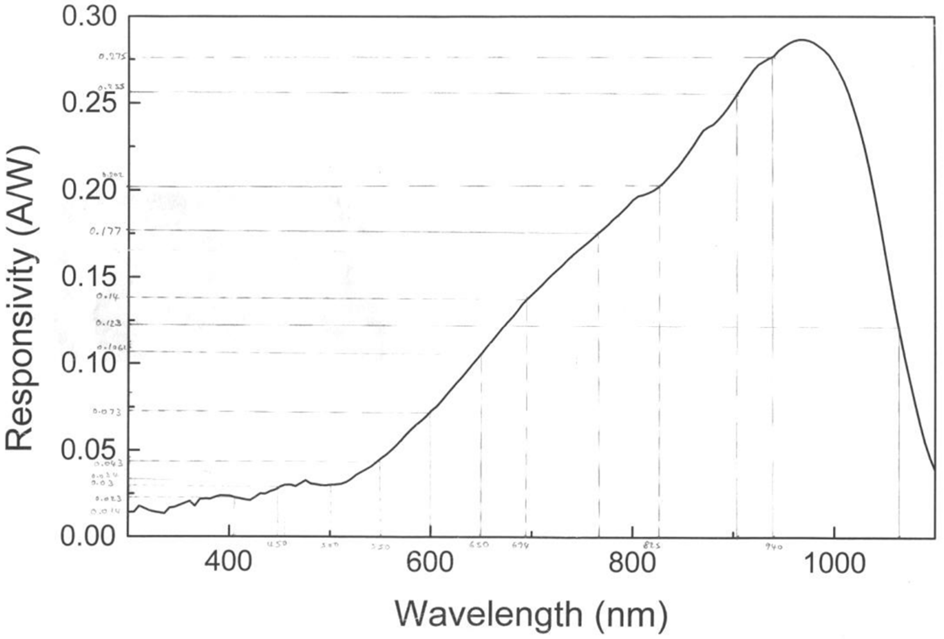
รูปที่ ง.3 คุณสมบัติของโฟโตไดโอด รุ่น 13DSI003

(http://www.datasheetarchive.com/13DSI003-datasheet.html)



รูปที่ ง.4 ตัวอย่างผลตอบสนองความยาวคลื่นของโฟโตไดโอดชนิดซิลิกอน เทียบกับไพรานิมิเตอร์และแสงอาทิตย์

(http://www.trutrack.com/intech/light_probe.html)



รูปที่ ง.5 ตัวอย่างผลตอบสนองความยาวคลื่นของโฟโตไดโอดชนิด PIN silicon