

Research Article

Micro Array of Fresnel Lenses Concentrator Photovoltaic System on Crystalline Silicon Solar Cells

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Abstract

Using the combination of the electron beam lithography (EBL), the reactive ion etching (RIE) and the Polydimethylsiloxane (PDMS) replica molding techniques the author have fabricated the micro-array of PMMA/SiO₂ Fresnel lenses concentrator photovoltaic CPV-system for high efficiency silicon solar cells. Fresnel rings units containing eleven concentric rings were created on PMMA layer with the outermost Fresnel ring having an external diameter of 45.24 μm and are located ≈200 μm away from each other. The CPV-system consists ≈3025-Fresnel lens units per cm² with approximate focal length f of ≈45 μm and the optical concentration ratio (OCR) of ≈95X. The resulting CPV-system when placed at the location ≈45 μm from the surface of silicon solar cells (Si-Solar cells) increased the open circuit voltage V_{OC} by 17.9 mV, short current density J_{SC} by 5.2 mA/cm² and the maximum power P_{max} by 11.42 mW. Meanwhile, this system enhanced power conversion efficiency of Si-Solar cells by 0.17% and decreased the series resistance R_s of Si-Solar cells by 0.81 Ω.

Keywords

Micro-Fresnel Lens, Photovoltaic, Solar Cells, PMMA, PDMS

1. Introduction

The spectral response of crystalline silicon solar cells is critically dependent on the number of incident photons absorbed especially from far infrared to the red-end region of visible light [1-8]. Fresnel lenses find wider applications in modern actively developing photovoltaic systems and they are becoming the backbone of the solar concentrators in different photovoltaic solar cells and panels [9-12]. Fresnel lenses used in concentrator photovoltaic (CPV) applications are almost universally Plano-convex in which solar radiations are focused by means of a series of concentric grooves (also referred to as point focus) or parallel grooves (known as line focus) [13, 14]. When parallel rays of light are passing

through the aperture of the Fresnel lens, each ring of the prisms refracts the light at a slightly different angle and focuses on a focal point [15-18]. However, Fresnel lenses used in CPV applications suffers from long focal distance, non-uniform illumination on the solar cells and it occupies a larger area compared to that of solar cells [19, 20]. In the principles of PV-effects, non-uniform solar flux distribution on the solar cells results in creation of hot spots thereby increasing the recombination chances lowering its efficiency and increases the life time degradation of the solar cells [21, 22].

To achieve a high magnitude light trapping system which

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Received: 7 November 2025; **Accepted:** 19 November 2025; **Published:** 17 December 2025



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can improve the internal quantum efficiency of crystalline silicon solar cells, micro array of Fresnel lenses CPV-system could be a better solution. Micro array of Fresnel lenses CPV-system can also suppress surface reflection, enhancing the absorption of light and could replace conventional CPV-systems in crystalline silicon solar cells, detectors and other photosensitive devices [23, 24].

In this paper, we fabricated PMMA/SiO₂ micro-array Fresnel lenses CPV-system using the combination of the electron beam lithography EBL, the reactive ion etching RIE and the Polydimethylsiloxane PMDS, replica molding techniques for high efficiency crystalline silicon solar cells. However, there is no literature reported on the use of these combined methods for silicon solar cells. Unlike other conventional photovoltaic concentrators in which the concentrator systems have large surface area compared to that of solar cells and hence, are placed far away from the surface of the solar cells, this system have the same size as solar cells and hence, is placed on the surface of the solar cells without occupying any additional surface area in the space [25]. The overall size of the cell is 5 cm by 5 cm, however, the array has the same size as that of the cell as illustrated in Figure 1.

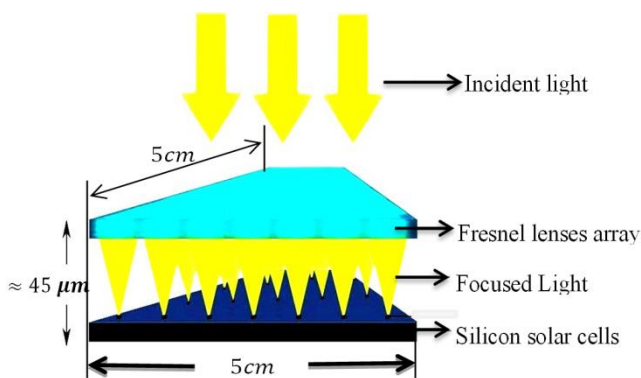


Figure 1. Schematic illustration of Micro array of PMMA/SiO₂ Fresnel lenses CPV-system on Si solar cells.

2. Fabrication Process

The most important steps adopted in the fabrication process of PMMA/SiO₂ Fresnel lenses CPV-system is the making of a master mold or stamp, which is also sometimes called the template [26-29]. In this process, a negative profile of micro-scale Fresnel lens with concentric circular rings was fabricated on Si substrate. Figure 2: Shows the schematic illustration of the brief outline steps of this process. As seen in the first stage of this process (Figure 2A-C), the process started by the RCA cleaning of the Si wafer by having immersed in to the mixture of (H₂O:NH₄OH:H₂O₂) in the ratio of 5:1:1 (by volume) at the temperature range from 75 °C to 80 °C for a duration of 10 to 15 minutes. This followed by immersing the wafers into a mixture of (HF:H₂O) in the ratio of 1:50 for approximately 10 to 20 seconds. Then the wafer was im-

mersed in to the mixture of (HCl:H₂O₂:H₂O) in the ratio of 1:1:6 at the temperature of 75 °C for the duration 10 to 15 minutes. Finally, the samples were rinsed with DI water and then blown dried with nitrogen gas (N₂). Followed by spin-coating process, in this step; to obtain 200 nm thickness of PMMA resist layer on Si substrate, the wafer was spun coat at 4000rpm for the duration of 90s using spin coater. Meanwhile, to ensure the total dryness and off-gassing, the sample was baked in an oven at temperature 180°C for 60 mins. The EBL process was then used to define circular pattern of Fresnel rings on the layer of PMMA. The e-beam exposed layer of PMMA was developed in a mixture of Methyl Iso-butyl Ketone MIBK, and Isopropyl Alcohol IPA, (MIBK: IPA) in the ratio of 1:3 (by volume) at the temperature of 23°C for the duration 35 sec. The wafer was then inserted into the solution of IPA for the duration of 35 seconds as a stopper and the sample was then blown dried with N₂. This was followed by metal deposition technique and lift off process (Figure 2D and E). In these steps, 50 nm Nickel (Ni) was deposited on developed structures using an RF-sputtering system (Auto RF-Sputter Coater, model: Auto 500), while the PMMA photoresist layer was removed by soaking the sample in acetone for the duration of 30 min; resulting in a negative of micro-scale Fresnel lens profiles from Ni on the Si substrate. In Figure 1F, the reactive ion etching process with a SF₆ etchant gas was used for transferring the pattern onto the Si substrate by a Ni mask and the remaining Nickel (Ni) mask was removed by wet-chemical etching technique using mixture solution of sulfuric acid and water (H₂SO₄: H₂O) in the ratio of (3:7) by volume.

The second stage of this process begins with PDMS mixture preparation and poured the prepared liquid PDMS on the Si-mold [30-32]. In Figure 2H, the PDMS base was mixed with the curing agent in the ratio of 10:1 (by weight): To obtain 80 μm thickness [33], the PDMS mixture was spun coat on Si-Mold at 1000 rpm for the duration of 60 sec and let the PDMS solidify at room temperature for 48 hours. Although heating of PDMS would shorten the solidification time, but it might also cause defects due to thermal expansion or bubbles, which may eventually affect the optical performance of the fabricated Fresnel lens. After congealed, the PDMS replica was carefully released from the Si-Mold as illustrated in Figure 2I. In Figure 2J: To increase the adhesive force between PMMA and SiO₂ interface; SiO₂ was prepared by cleaning and plasma treatment. The surface treatment on SiO₂ was achieved by using a plasma cleaner (PLASMA- PREP. 100, Nanotech), and then the PMMA was spun coat on SiO₂. Immediately after PMMA/SiO₂ spin coating, PDMS-Mold with imprinted Fresnel lenses array was then carefully aligned on PMMA/SiO₂ with the support of glass as illustrated in Figure 2K. To ensure a damage free PMMA/SiO₂ Fresnel lenses, for solidification and total gas off, the PMMA was heated at the temperature between 95°C to 105°C for the duration of 5mins. The PDMS mold was carefully tore off (Figure 2L), and the PMMA Fresnel lens was obtained

without damaging PMMA structures (Figure 2M). Finally, the PMMA/SiO₂ micro-array Fresnel lenses CPV-system was placed on two different locations from the surface of Si-solar

cells to study both the actual focal point of the system and the improvements in the characteristics parameters of solar cells.

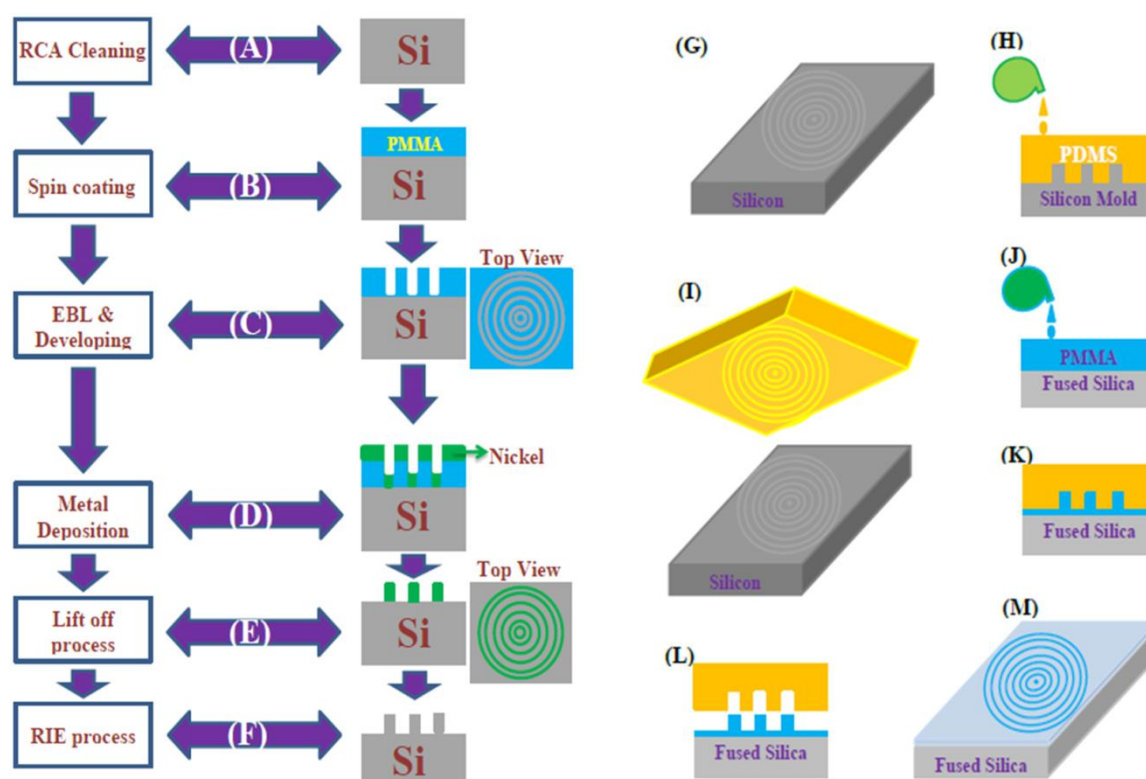


Figure 2. Schematic illustration of the fabrication process of Micro-array of Fresnel lenses CPV-System by PDMS replica molding method; (A) RCA cleaning process of Si substrate (B) Spin coating of PMMA photoresist on the Si substrate and baking (C) EBL process and Developing (D) Metal deposition (E) Lift off process (F) Reactive ion etching process (G) Silicon (master) Mold (H) PDMS mixture preparation and Poured on Si-Mold (I) Tearing of PDMS from Si-Mold (J) Clean the fused silica (SiO₂) and spin coating of PMMA on SiO₂ (K) Imprint PDMS-Mold on PMMA/SiO₂ (L) Tear the PDMS from PMMA/SiO₂ to obtain PMMA/SiO₂ Fresnel lens of Figure 2M.

3. Characterization Process

After e-beam exposure and development (Figure 2C), the developed structures were characterized using Field Emission Scanning Electron Microscope FESEM and EDS/EBSD detector system (model: FEI Nova NanoSEM 450) and the Atomic force Microscope AFM, (Dimension EDGE, BRUNKER; Shimadzu) system. Figure 3: Shows the FESEM images and EDX spectrum of the developed structures on PMMA/Si surface. The Energy-dispersive X-ray spectroscopy (EDX) results of the PMMA/Si spun coat at 4000 rpm shows the presence of silicon, oxygen and carbon at the surface of the sample (Figure 3A). The presence of carbon and Oxygen confirmed the existence of PMMA and its decomposition products. The FESEM analysis on the other hand, shows clearly, the formation Fresnel rings units on its surface (Figure 3B-E).

The developed structures were then coated with Nickel (Ni) by using RF-sputtering system (Auto RF-Sputter Coater,

model: Auto 500). Figure 4: Shows the FESEM images of pattern Fresnel rings on Ni/Si at different magnifications and the EDX spectrum confirming the existence of Ni/Si on its surface. The FESEM images shows the Fresnel rings on Si at different magnifications, the appearance of Fresnel rings are less clearer compared to those of Figure 3. This may be due to the thin film layer of nickel Ni sputtered on the patterned samples. However, the EDX spectrum confirmed the presence of silicon, nickel, oxygen, and carbon compositions on Si surface. This implies that, there is the existence of PMMA and its deposition products as well as Nickel metallic material on Si surface.

The reactive ion etching (RIE) system (Oxford Instruments, PlasmaLab 80 RIE) was utilized in the fabrication of micro-array of Fresnel rings on Si using SF₆/O₂ as the main etching gases. The AFM analysis corresponds to the experimental analysis shows that, vertical sidewall profiles or U-groove sidewall shapes of Si-Fresnel rings was achieved with the average depth of about 117 nm. Atomic force microscope (AFM) systems with tapping mode: Dimension

EDGE- BRUKER, Shimadzo and NanoNavi II (using SI-DF40 as a cantilever) were used to measure the surface profile of the RIE-etched Si-Fresnel rings array. The system has the capability of measuring the profile of the surface topography and waviness as well as surface roughness in micro/nano-meter range of a square field which covers the maximum surface area of $(100\ \mu\text{m})^2$. **Figure 5:** Shows the AFM images of surface topography and the etching profiles of

Si-Fresnel rings array. In **Figure 5A and B**, the 2 and 3-dimensional topography of Fresnel rings in $(100 \times 100)\mu\text{m}^2$ field are respectively shown, while **Figure 5C** shows 2-dimensional topography of RIE-etched Si-Fresnel rings in $(10 \times 10)\mu\text{m}^2$ field and **Figure 5D** represents the etching profile of **Figure 5C**. In **Figure 5C and D**, vertical sidewalls or U-grooves can clearly be seen. This could be due to the addition of oxygen O_2 in to the main etching gas (SF_6).

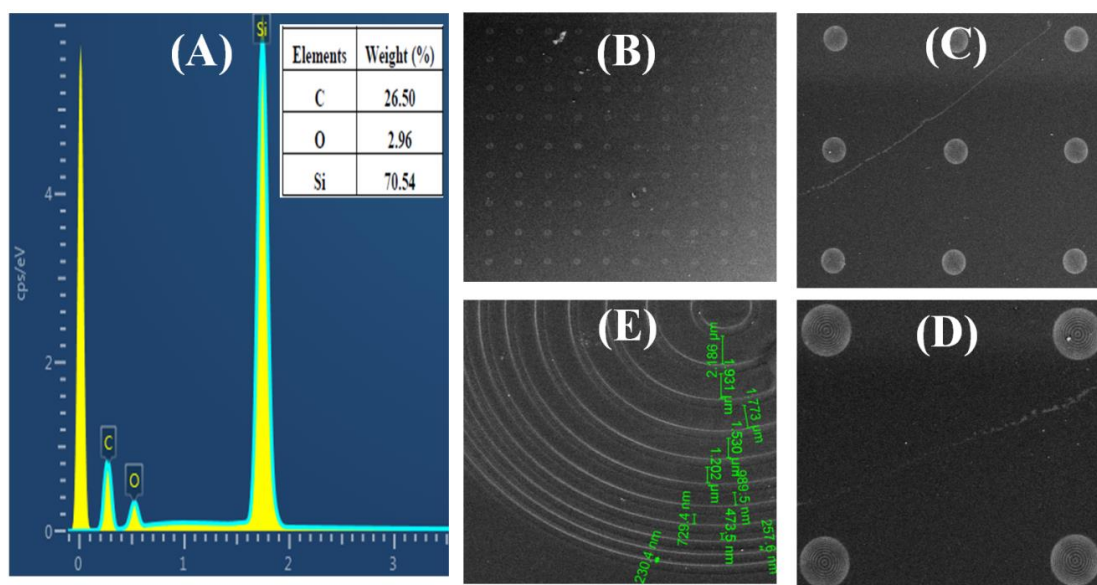


Figure 3. FESEM images (at different magnifications) and EDX spectrum of the developed structures on PMMA/Si surface (A) EDX spectrum (B) FESEM image at 130X (C) FESEM image at 500X (D) FESEM image at 1KX (E) FESEM image at 8KX.

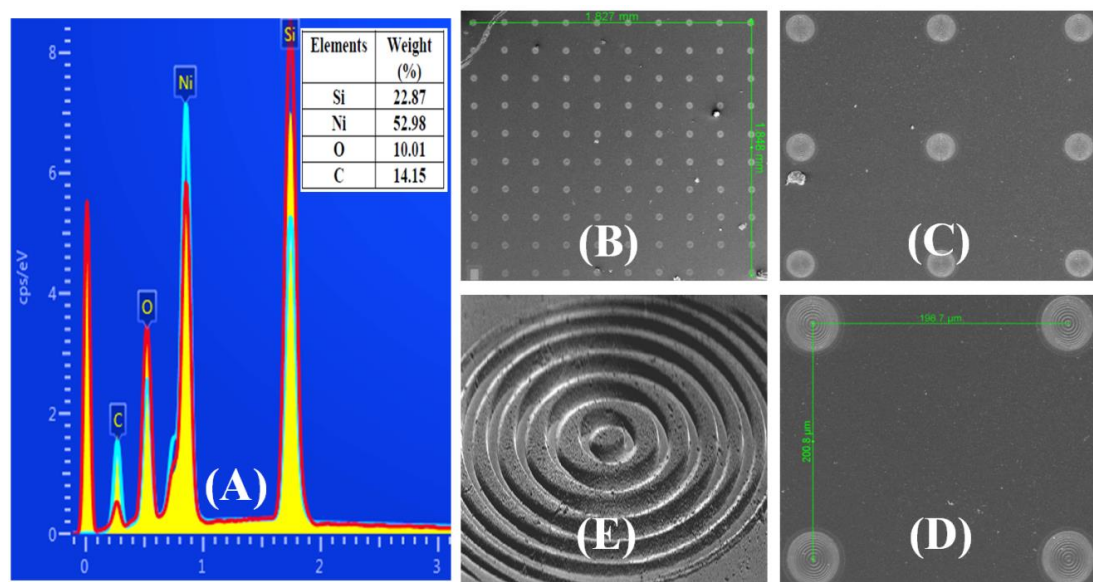


Figure 4. EDX spectrum and the FESEM images pattern of Fresnel rings on Ni/Si at different magnifications (A) EDX spectrum (B) FESEM image at 130X, (C) FESEM image at 500X, (D) FESEM image at 1KX, (E) 3-D FESEM image at 10KX.

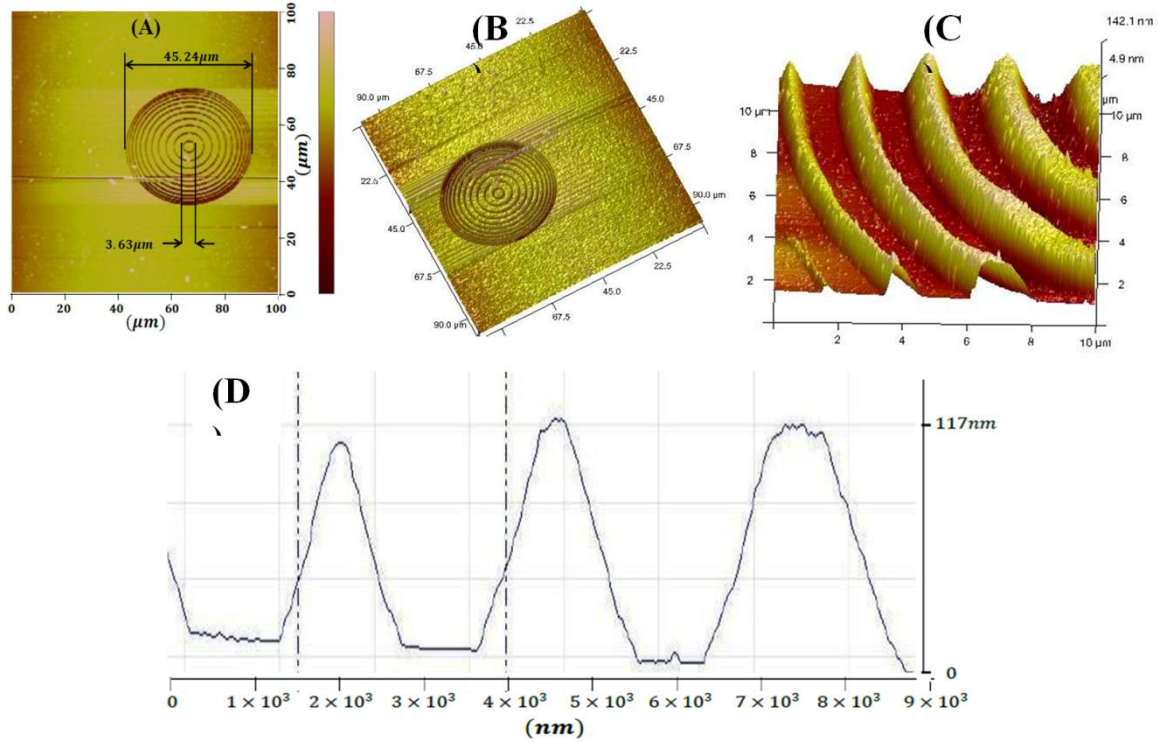


Figure 5. AFM images of surface topography and the etching profiles of Si-Fresnel rings array at different magnifications (A) 2-D view of the developed structures $(100 \mu\text{m})^2$ (B) 3-D view of the developed structures $(100 \mu\text{m})^2$ (C) 3-D view of the RIE-etched structures $(10 \mu\text{m})^2$ (D) Etching profiles.

4. Results and Discussions

Optical and Geometrical Analyses

Geometrical profile of Fresnel lenses could be considered as approximately has rectangular in shape (Figure 5). Starting from the optical center; each Fresnel ring is built up by internal and external diameters (*i.e.* D_{n-ext} and D_{n-int}). If A_1 is the increase in surface area of a Fresnel ring of depth d , and the radius R_1 , then A_1 can be obtained by the following equation:

$$A_1 = 2\pi(R_{1-ext} + R_{1-int}) \times d = 2\pi d(R_{1-ext} + R_{1-int}) \quad (1)$$

Therefore, in general, the increase in the surface area of n -rings can express as:

$$A_n = 2\pi(R_{n-ext} + R_{n-int}) \times d = 2\pi d(R_{n-ext} + R_{n-int}) \quad (2)$$

Since each unit of Fresnel lens consist of eleven concentric rings (Figure 3E, 5A and 5B), then the increase in surface area of a complete unit of Fresnel lens is the sum of the increase in surface area of the individual Fresnel ring. Mathematically, the increase in surface area of a complete unit of Fresnel lens is express as:

$$A_{F-rings \text{ unit}} = A_1 + A_2 + A_3 + \dots + A_{11} \quad (3)$$

From the FESEM analysis, the thickness of each Fresnel ring is found to be approximately 680 nm (0.68 μm), this means that, the difference between R_{n-ext} and R_{n-int} is 0.68 μm . Furthermore, from AFM analysis, the depth d of the ring for Si etched is about 117 nm (0.117 μm). These values were used in equations (1), (2) and (3) above to calculate the increase in the surface area of one complete unit of Fresnel rings. Table 1: Shows the calculated values of the increase in surface area of each of the eleven concentric rings of a Fresnel lens unit. The total increase in surface area of a unit of Fresnel rings is 214.03 μm^2 . Therefore, for 100 units of Fresnel lens (Figure 4B); there will be increase in surface area of 21403 μm^2 . Therefore, the approximate surface area of a square containing 10 by 10 array Fresnel lens units can be estimated as;

$$A_{s\cong} = 1827 \mu\text{m} \times 1848 \mu\text{m} = 3376296 \mu\text{m}^2 \quad (4)$$

The effective area A_{eff} of this square will be the sum of the area of the square $A_{s\cong}$ and increase in area due to the formation of 100 units of Fresnel lenses expressed in equation (5);

$$A_{eff} = 3376296 \mu\text{m}^2 + 21403.2 \mu\text{m}^2 = 3397700.2 \mu\text{m}^2 \quad (5)$$

Furthermore, for a square with the length of one side as 1 cm there will be $(\frac{10\text{mm}}{1.827\text{mm}} \times 10 = 5.473454)$ units of Fresnel lenses along one side. Therefore, there are

$\approx (55)^2 = 3025$ -Fresnel lenses for every 1 cm^2 .

Fresnel lens used in concentrator photovoltaic applications works on the principles that, when parallel rays of light are passing through the aperture of the Fresnel lens, each ring of the prisms refracts the light at a slightly different angle and focuses on a focal point (Figure 6). The radiation beam incident normal at the surface of the Fresnel lens is refracted at an angle β at the facets underneath the plane of the lens which can be expressed as [1];

$$\beta = \tan^{-1} \left(\frac{R_{ext}}{f} \right) \quad (6)$$

Where f is the focal length of the Fresnel lens concentrator system, however, the sloped facets angle α , can be obtained from Snell's law of refraction as;

$$\alpha = \sin^{-1} \left(\sqrt{\frac{\sin^2 \beta}{(n^2 - 2n \cos \beta + 1)}} \right) \quad (7)$$

The transmission efficiency, the optical concentration ratio, and the uniformity of solar fluxes distribution on the surface of the solar cells were determined using the ray tracing simulation. The transmission of light at the immediate surface of Fresnel lens T_{IS} was obtained by assuming that the angle of incidence to be very negligible ($\theta_i \approx 0$) from the Fresnel equation as:

$$T_{IS} = \frac{4n}{(n+1)^2} \quad (8)$$

However, for a given Fresnel lens with a slope facet angle α and a transmission angle β , the surface transmission T_{RS} , at the rear surface, can be obtained from equation (9):

$$T_{RS} = \left(\sqrt{\frac{1}{2} \left(1 - \frac{\tan^2 \beta}{\tan^2(2\alpha + \beta)} \right)^2 + \left(1 - \frac{\sin^2 \beta}{\sin^2(2\alpha + \beta)} \right)^2} \right) \quad (9)$$

Where n is the refractive index of PMMA (1.49). Meanwhile, the geometrical concentration ratio (GCR) of this system can be obtained from equations (10), and hence, be expressed as:

$$GCR = \frac{A_{eff}}{A_{in}} \quad (10)$$

And the optical concentration ratio (OCR) can be obtained by the following equation:

$$OCR = GCR \times T_{RS} \quad (11)$$

The monochromatic flux distribution ϕ_λ at the surface of the solar cells formed by lens block is the sum of the incidence fluxes of the individual lens blocks of the entire array system multiplied by transmission efficiency T_{RS} [34, 35]. Hence, the total flux distribution can be expressed as:

$$\phi_\lambda = T_{RS} \sum \phi_{(\lambda)} A_{eff} \quad (12)$$

The effective transmission versus the angle of incidence is given in the graph of Figure 7. As seen, the transmission is decreasing with the increase in the incidence angle, where this shows that high transmission can be obtained at small angle of incidence. The highest transmission efficiency ($\approx 94\%$) corresponds to the smallest incident angle was achieved at $\theta_i \approx 0^\circ$.

Thus, micro-array of Fresnel lenses CPV-system consists of 10 by 10 array Fresnel lenses per $337629 \mu\text{m}^2$ (refer to Figure 4B with the help of equation (4)) or 55 by 55 array Fresnel lenses per cm^2 . Since the depth of the each Fresnel ring is approximately $= 0.117 \mu\text{m}$, then the increase in area due to formation of 100 units of Fresnel rings is $= 21403 \mu\text{m}^2$ or due to formation of 3025 units of Fresnel rings is $= 64744680 \mu\text{m}^2$. Therefore, the approximate geometric concentration ratio GCR of the system is 1.01 and the approximate optical concentration ratio OCR is 95X at an angle of incidence of ($\theta_i \approx 0^\circ$). Meanwhile, the approximate focal length f , of the CPV-system was obtained to be $45 \mu\text{m}$ and the approximate gratings pitch on the periphery of 680 nm . Overall, a shorter focal length corresponds to a shorter wavelength can be obtained when the index of refraction is less. This is consistent with the Snell's law of refraction.

Table 1. Calculated values of the increase in surface area of eleven concentric Fresnel rings.

Number of rings	Measured radius	Radius (μm)		Increase in Surface Area (μm^2)		Total increase in Area (μm^2)
		$R_{int.}$	$R_{ext.}$	$A_{int.}$	$A_{ext.}$	
1	1.82	1.48	2.16	1.0878	1.5876	2.6754
2	5.02	4.68	5.36	3.4398	3.9396	7.3794
3	7.76	7.42	8.1	5.4537	5.9535	11.4072
4	10.43	10.09	10.77	7.41615	7.91595	15.3321

Number of rings	Measured radius	Radius (μm)		Increase in Surface Area (μm^2)		Total increase in Area (μm^2)
		$R_{int.}$	$R_{ext.}$	$A_{int.}$	$A_{ext.}$	$A_{int.} + A_{ext.}$
5	11.84	11.50	12.18	8.4525	8.9523	17.4048
6	13.12	12.78	13.46	9.3933	9.8931	19.2864
7	15.08	14.74	15.42	10.8339	11.3337	22.1676
8	17.48	17.14	17.82	12.5979	13.0977	25.6956
9	19.51	19.17	19.85	14.08995	14.5898	28.6797
10	20.92	20.58	21.26	15.1263	15.6261	30.7524
11	22.62	22.28	22.96	16.3758	16.8756	33.2514
Total increase in surface area for a complete unit of Fresnel rings (μm^2)						214.032

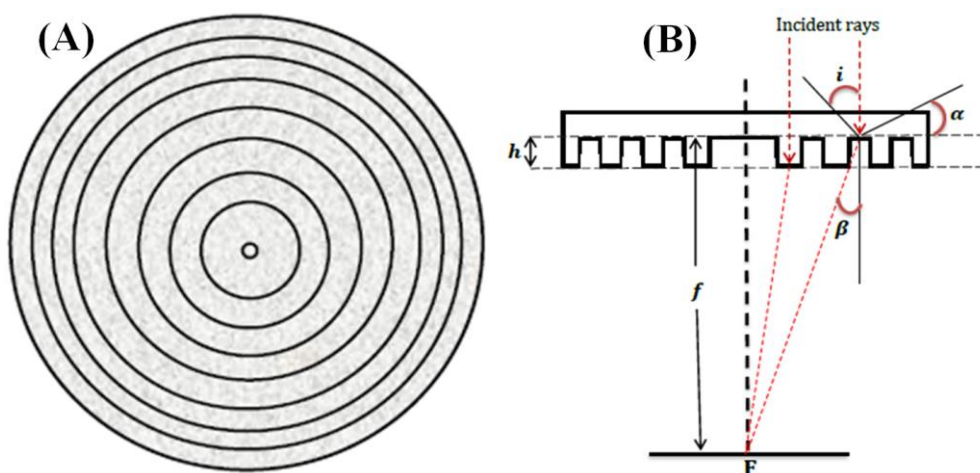


Figure 6. Schematic illustration of Fresnel lens (A) 2-dimensional view showing the concentric rings of Fresnel lens (B) Side view showing the optical Parameters of Fresnel lens as a concentrator PV system.

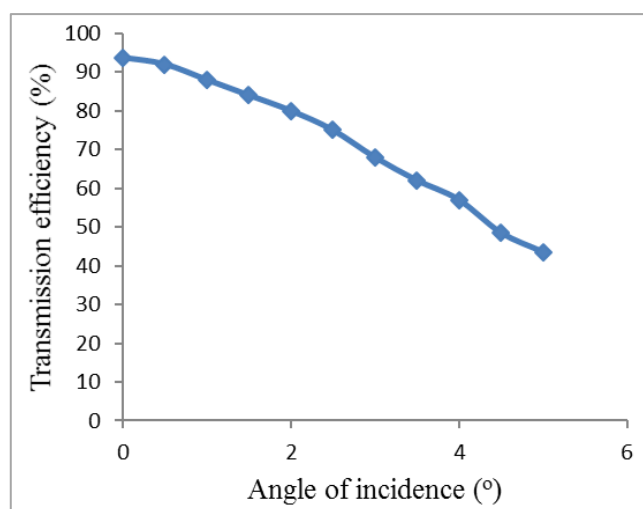


Figure 7. Transmission efficiency T (%) against incidence angle ϕ_i ($^\circ$).

Solar Simulator Analysis

Commercially available mono-crystalline silicon solar cells (rated 0.25W) ordered through <http://www.ebay.com/> was used to study the increase in the output power and the efficiency when the PMMA/ SiO_2 micro-array Fresnel lenses CPV-system was brought in contact to the surface of Si-solar cells. Solar simulator system-IV (Model: KEITHLEY-2400 SOURCE METER) was used to study the increase in other characteristics parameters of the Si-solar Cells such as: maximum and open circuit voltages (V_m and V_{oc}), maximum and short circuit currents (I_m and V_{sc}), series and shunt resistances (R_s and R_{sh}), as well as the fill factor (FF) when the CPV-system was in used. The results obtained were then analyzed and compared to that obtained when the CPV-system was not in used. The experiment was taken in three different stages; in the first stage of the experiment, IV-characteristics of Si-Solar Cells was measured and recorded. In the second stage of this experiment, PMMA/ SiO_2 micro-array Fresnel lenses CPV-system was brought at a distance of $\approx 20 \mu\text{m}$

from the surface of Si-Solar cells to study the difference in the output characteristics, while in the third stage of this experiment, CPV-system was brought at a distance of $\approx 45 \mu\text{m}$ to the surface of Si-solar cells to study the effects of the focal distance of the Fresnel lens in the improvements of the output power and the efficiency of Si-solar cells. The result obtained shows that the solar panel has the maximum power P_{max} of 21.63 mW with the short circuit current I_{SC} of 68.73 mA and open circuit voltage V_{OC} of 538.83 mV. But as the CPV-system was brought at $20 \mu\text{m}$ from its surface, the P_{max} increased to 27.43 mW, the short circuit current I_{SC} to 86.38 mA and open circuit voltage V_{OC} of 547.85 mV. However, the maximum power P_{max} obtained on the cells with the CPV-system placed $45 \mu\text{m}$ from the surface of the solar cells is 33.06 mW while the values of I_{SC} and V_{OC} were respectively changed to 99.95 mA and 556.73 mV. **Table 2:** Shows the summary of the Solar Simulator's analysis on the effects of this CPV-system as well that of its focal distance on the output characteristic parameters of Si-Solar Cells and **Figure 8:** Shows the solar simulator analysis for IV-characteristics of Si-Solar Cells of three different experimental stages.

Solar simulators' analysis on Si-solar cells without CPV-system shows that, the Si-solar cells has the efficiency of 9.01% while the analysis on Si-solar cells with CPV-system placed at $20 \mu\text{m}$ from its surface shows that the efficiency increased to 9.14%. However, as CPV-system was placed $45 \mu\text{m}$ away from the surface of Si-Solar Cells, the efficiency rose to 9.18%. Thus, the Si-Solar Cells with CPV-system placed at focal point ($\approx 45 \mu\text{m}$) has the highest efficiency.

We suggested that the major reasons for lower increase in efficiency is that, the design of micro-array of Fresnel lens

units are sparse, hence the used CPV-system on Si-solar cell could result to high concentration of incident light thereby creating hot spots on some selected points. These may cause the lattice vibrations to interfere with free passage of charge carriers and the junction begins to lose power to separate charge carriers leading to increase in chances of recombination. These negative effects may be reduced by using array of Fresnel lenses at shorter distances to each other by modernizing the geometric design of the system and by producing a cooling system to the cell".

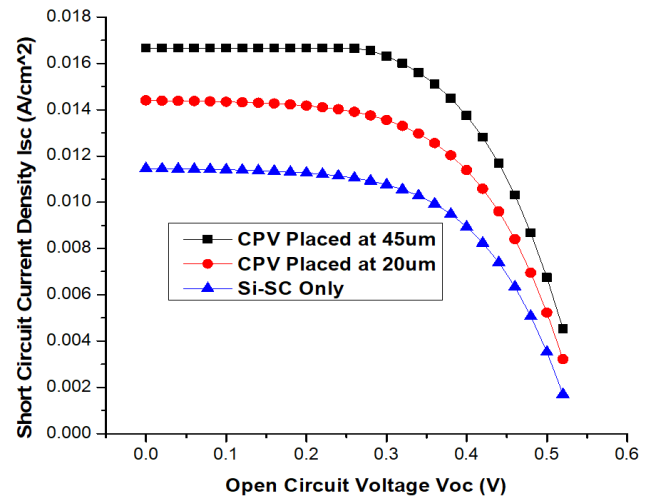


Figure 8. IV-characteristics of Si-Solar cells comparing the results of the three experimental stages (A) Si-Solar Cells only (B) Si-Solar Cells with PMMA/SiO₂ Fresnel lenses array CPV-system placed at $20 \mu\text{m}$ away from solar cells (C) Si-Solar Cells with PMMA/SiO₂ Fresnel lenses array CPV-system placed at $45 \mu\text{m}$ away from solar cells.

Table 2. Effects of CPV-system on characteristics parameters of Si-Solar Cells.

S/N	Parameter	Unit of measurement	Si-Solar Cells (Si-SC)	Si-SC with CPV-system placed at $20 \mu\text{m}$ apart	Si-SC with CPV-system placed at $45 \mu\text{m}$ apart
1	I_{SC}	mA	68.73	86.38	99.95
2	J_{SC}	mA/cm^2	11.46	14.40	16.66
3	V_{OC}	mV	538.83	547.85	556.73
4	I_{max}	mA	56.94	72.18	86.99
5	J_{max}	mA/cm^2	9.49	12.03	14.50
6	V_{max}	mV	380	380	380
7	P_{max}	mW	21.64	27.43	33.06
8	FF	-	0.58	0.58	0.59
9	R_S	Ω	1.95	1.77	1.41
10	R_{Sh}	Ω	203.89	172.71	240813.73

5. Conclusion

In this paper, we have successfully fabricated micro-scale array of PMMA/SiO₂ Fresnel lenses CPV-system using the combination of the EBL, the RIE and the PDMS replica molding techniques. The results of ray tracing analysis on Fresnel lenses array CPV-system shows that, CPV-system consists of 3025-Fresnel lens units per cm² with the approximate focal length f of 45 μ m. The transmission efficiency of 93.7% was achieved at an angle of incidence of $\approx 0^\circ$ with f – number ≤ 1 and the optical concentration ratio (OCR) of 95X. The resulting CPV-system when placed at the location $\approx 45 \mu$ m from the surface of Si-solar cells (i. e. approximately on the focal point of the CPV-system); an open circuit voltage V_{OC} increases from 538.83 mV to 556.73 mV, short circuit current I_{SC} from 68.75 mA to 99.95 mA and the maximum power P_{max} from 21.64 to 33.06 mW. Finally, the power conversion efficiency of Si-solar cells when the Si-solar cells were placed at the focal point of the CPV system increases by 0.17%. In general, these results clearly indicate the advantage of using small size CPV-system in investigating the improvement in the output characteristic parameters of silicon solar cells. Thus, conclusively, the system has the great potentiality in other material solar cells.

Abbreviations

EBL	Electron Beam Lithography
RIE	Reactive Ion Etching
CPV	Concentrator Photovoltaic
PDMS	Polydimethylsiloxane
OCR	Optical Concentration Ratio
PMMA	Poly (Methyl Methacrylate)
V_{OC}	Open Circuit Voltage
I_{SC}	Short Circuit Current

Acknowledgments

This work was performed at the Nano-Optoelectronics Research and Technology (NOR) Laboratory of the School of Physics, Universiti Sains Malaysia (USM) during my PhD studentship. Therefore, the author wishes to acknowledge the financial support and contributions from Umaru Musa Yar'adua University, Katsina (UMYUK) via the Tertiary Education Trust Fund (TETFund) Scheme for the financial sponsorship of my PhD research work.

Author Contributions

Nura Liman Chiromawa: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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