

## ORIGINAL RESEARCH ARTICLE

## Investigation of PMMA Thin Film as a Low-Cost Anti-Reflective Layer for Crystalline Silicon Solar Cells

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## ABSTRACT

In this paper, we study the effects of a PMMA thin film on the improvement of the output characteristics of a crystalline silicon (C-Si) solar module using a solar simulator and a simple, low-cost spin-coating technique. The results show that the performance efficiency and the corresponding characteristic parameters of the C-Si solar module coated with a PMMA thin film are higher than those of the uncoated module: An open circuit voltage  $V_{OC}$  increased from 531.73 mV to 549.85 mV, while short current  $I_{sc}$  increased from 69.83 mA to 87.45 mA, and the maximum power  $P_{max}$  increased from 22.64 mW to 28.43 mW. Meanwhile, the power conversion efficiency of the C-Si solar module increased from 19.75 % to 22.11 %. Finally, the series resistance decreased by 0.75  $\Omega$ . Thus, a PMMA thin film could be used to replace conventional anti-reflective coatings for silicon solar cells.

## INTRODUCTION

Recently, the development of high-performance and cost-effective anti-reflective coatings (ARCs) has been a major focus of research, especially in the fields of optics and engineering, including optoelectronic devices and solar cells (Zhang et al. 2025). ARCs are widely used in various optical lenses and solar cells. In solar cell applications, ARCs are used to increase absorption and reduce reflection of incident light (Martin A. Green 2024).

The rapid development in the applications of modern optoelectronics devices in the areas of space exploration to consumer electronics, Solar cells and Panels, as well as Biological and Medical fields, led to the growing demand for efficient anti-reflecting coatings that maximize light absorption and transmission (Chiromawa and Ibrahim 2016, Dhimish 2022, Hassan Sayed 2022).

In conventional crystalline silicon solar cells, various transparent films such as;  $SiO$ ,  $SiO_2$ ,  $Si_3N_4$  and  $TiO_2$  among other films, having high refractive indices have been used as ARC (Lin et al. 2014). Films for ARCs are usually prepared using high-technology, high-cost fabrication techniques, such as plasma-enhanced chemical vapour deposition (PECVD), thermal evaporation (Maryam et al. 2012), magnetron sputtering (Pandian et al. 2014), and sol-gel synthesis. Thus, leading to the production of high-cost solar cells. Another drawback of these techniques is that the reflected rays destructively interfere with the incident rays, resulting in a narrow

acceptance angle for anti-reflection coatings at a given wavelength (Yuan et al. 2009).

Recently, it has been reported that crystalline silicon solar cells could attain an efficiency of approximately 27% of the incident solar irradiance. This means it reflects almost one-third of the incident irradiance that could otherwise have contributed to the overall efficiency of silicon solar cells and/or solar panels (Jamaluddin et al. 2024, Martin A. Green 2024). However, in silicon solar cells, considerable efforts have been made to minimize the effects of destructive interference by adding periodic nanostructures to single-layer anti-reflecting coatings (Chang et al. 2011).

Understanding the optical properties of materials and their specifications may lead to the proper selection of anti-reflecting coating materials and, consequently, to better-performing anti-reflecting coatings (Wu et al. 2017, Zhao et al. 2023, Karthick Sekar 2024).

The function of ARCs is dependent upon the reflective index of the material used. Therefore, the effects of ARC are rather limited. To minimize the effects of destructive interference at the surface of solar cells, considerable effort has been made by adding periodic nanostructures to a single-layer ARC. This could also be a costly method, which may increase the cost of solar cells. Among the mentioned coating processes, the sol-gel method is the simplest, cheapest, and offers many other advantages over

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the others, including adjustable refractive index materials, a simple process, low cost, and suitability for special-shaped structures (Chiromawa 2015). In this paper, we have adopted the sol-gel method to fabricate ARC for crystalline silicon solar cells using optical polymer (PMMA films) (Chiromawa 2015, Buskens 2016).

Optical polymers are plastics that transmit incident light very well. These classes of polymers have wide applications in the semiconductor industry, including optical lenses for optical instruments, video and camera lenses, light-emitting diodes, and ophthalmic lenses, among others. Other applications include: optical fibres, fibre couplers and connectors as well as masks in lithography technology (Xiao et al. 2022). The most common polymers used in semiconductor industries are, poly (Methyl Methacrylate) PMMA, Poly Carbonate (PC), and Poly Styrene (PS) (Guo and Ren 2021; Mukherjee et al. 2023).

Poly(methyl Methacrylate) (PMMA) is a synthetic polymer of methyl Methacrylate with molecular formula  $(C_5O_2H_8)_n$ , with the IUPAC name as Poly(methyl 2-methylpropenoate). PMMA is a transparent thermoplastic material that is lighter than inorganic glass and is shatter-resistant (Wu et al. 2022). One of the major advantages of PMMA is that it is easier to handle and process, as it does not contain any harmful or toxic contaminants (Lin et al. 2024).

Pure atactic PMMA is an amorphous plastic with a shiny surface, high brightness, and a transmission efficiency of 92% over the wavelength range of 380-1000nm, with a refractive index of 1.49 (Chiromawa and Ibrahim 2016). In addition to this, PMMA have low absorption band (of wave number between  $2000cm^{-1}$  and  $2750cm^{-1}$ ), availability, and wider applications in engineering, medical, as well as daily-life purposes. Other important property of PMMA is that it has good compatibility with Silicon and its oxide-related compounds, like  $SiO_2$  as well as providing good adhesion, mechanical properties, and optical clarity (Chiromawa and Ibrahim 2015); PMMA is used in the micro-electro-mechanical system (MEMS) process as a positive photo-resist to provide high-contrast and high-resolution images (Wu et al. 2022). In a related development, PMMA is also used for mask formation in micro/nanofabrication of optical lenses and for lithography in semiconductor fabrication technology. Furthermore, PMMA is used in the fabrication of waveguides, Infrared detectors/sensors applicable to many electronic devices, and infrared lenses (Chiromawa and Ibrahim 2017).

This paper focuses on the use of single layer PMMA film as anti-reflecting coating for crystalline silicon solar cells. However, there is limited literature on the use of PMMA film as an ARC. A low-cost non-vacuum spin-coating technique was utilised to deposit a PMMA thin film on the surface of a  $SiO_2$  wafer using a spin-coating machine. The results show that this method can provide a uniform distribution of the PMMA thin film layer on a crystalline silicon wafer and drastically reduce solar flux reflection.

Hence, increased solar flux absorption, leading to enhanced efficiency in crystalline silicon solar cells.

## METHODOLOGY:

Three pieces of  $5cm$  by  $3cm$  ( $15cm^2$ )  $SiO_2$  wafers were cleaned using the Decontamination DECON, a procedure which was adopted from (Chiromawa 2015). The  $SiO_2$  wafers were immersed in to a mixture of ( $H_2SO_4 + H_2O_2$ ) solution in the ratio of (3: 1) at the temperature of  $110^\circ C$  for about 15 to 20 minutes, then inserted in distilled DI, water at the temperature of  $80^\circ C$  and also rinsed with distilled DI, water. Finally, the wafer was blown-dried with Nitrogen gas. Plasma exposure on the surface of the  $SiO_2$  substrate was performed in an Inductive Coupled Plasma etching system (ICP-RIE; Oxford Plasmalab 80 Plus) with a RF power of 100W and a process pressure of 30 mTorr. Because of its effectiveness in surface activation, oxygen ( $O_2$ ) plasma was chosen at a flow rate of 10 sccm for 60 seconds. Wafers were then spun-coated with a PMMA film at 4000 rpm and 500 rpm using a spin coater (Ibrahim 2015). To ensure the total dryness and gas-off, the samples were baked in an oven at a temperature of  $180^\circ C$  for 60 minutes (Chiromawa and Ibrahim 2016).

## Characterizations:

The PMMA layers were analysed using a field emission scanning electron microscope (FESEM) and an (EDX) detector system (model: FEI Nova NanoSEM 450), while the thickness of PMMA film layers on  $SiO_2$  was determined using an optical reflector meter (Filmetrics F-20). Filmetrics F-20 analysis shows that a 250.00 nm-thick layer of PMMA was obtained at 4000 rpm, and a 490.00 nm-thick layer at 500 rpm.

Since the spectral response of crystalline silicon solar cells is critically dependent on the number of incident solar radiation absorbed especially from far infrared (IR) to the red-end region of visible light (vis), we further the spectral study of light transmission with the extended range of wavelengths on PMMA/ $SiO_2$  (Ibrahim 2015). UV-Vis-NIR-Spectrometer (Model: Cary 5000) with the spectral range of (3300 – 175nm) with the resolution of 1nm was used to analyzed the effects of PMMA film layer on crystalline silicon surface. The differences in the reflections of incident irradiance were measured and recorded for an uncoated crystalline silicon surface and a crystalline silicon surface coated with a PMMA film layer. The spectrum was recorded in the wavelength range from 200 nm to 2000 nm with the resolution of 1nm. The results show that uncoated Si has the highest light reflection in this wavelength range, while Si coated with a PMMA film layer has the lowest light reflection. Furthermore, the FTIR spectrometer (Model: Perkin Elmer Spectrum GX) with a spectral range from  $370 cm^{-1}$  to  $7800 cm^{-1}$  and a resolution of  $1 cm^{-1}$  was used to analyze the percentage of infrared transmission through  $SiO_2$  and  $SiO_2$  coated with PMMA film layers of different thickness. The spectrum was recorded in the range from  $370 cm^{-1}$  to  $7800 cm^{-1}$

with a resolution of  $1\text{ cm}^{-1}$ . Fig. 1 shows UV-Vis-NIR reflection spectral analysis of a crystalline silicon wafer coated with 250 nm PMMA film layer and an uncoated Crystalline Silicon wafer (Chiromawa and Ibrahim 2015). Fig. 2 shows the FTIR transmission spectra through SiO<sub>2</sub> and PMMA/SiO<sub>2</sub> with a PMMA film layer of two different thicknesses (Chiromawa 2015).

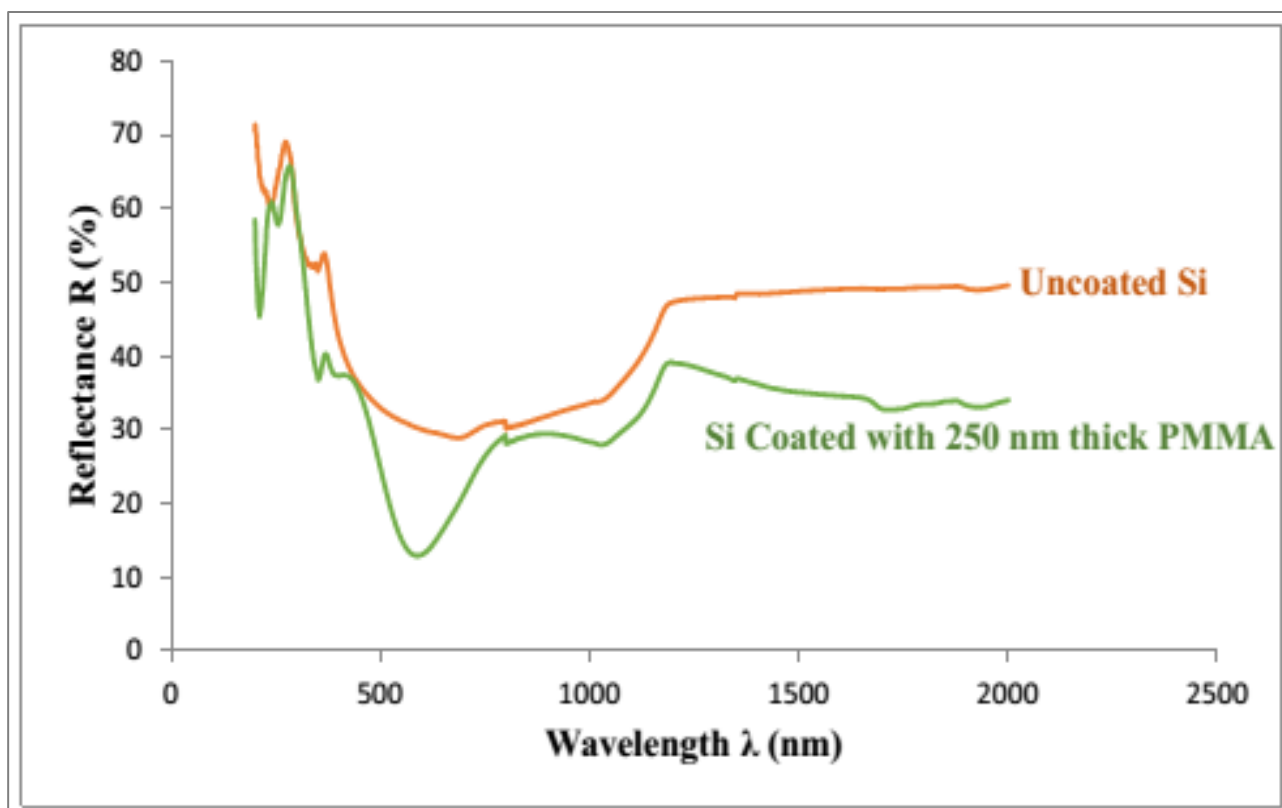
**RESULTS AND DISCUSSIONS**

A single-crystalline silicon solar module (5cm by 3cm) with a power rating of 0.25W was used to study the effects of a PMMA film layer on the out-of-cell characteristics of solar cells. Solar simulator system-IV (Model: KEITHLEY-2400 SOURCE METER) was utilized to study the increase in other characteristics parameters of the Solar Cells, such as: maximum and open circuit voltages ( $V_{max}$  and  $V_{oc}$ ), maximum and short circuit currents ( $I_{max}$  and  $I_{sc}$ ), series and shunt resistances

( $R_{series}$  and  $R_{shunt}$ ), as well as the fill factor ( $FF$ ) when PMMA film was in used and compared to when not used.

The results obtained were then processed and analysed. The experimental steps taken could be described as follows: in the first step of the experiment, IV characteristics of the Si-Solar module were measured and recorded. In the second step of this experimental activity, IV characteristics of the C-Si Solar module with a PMMA film layer were measured and recorded. The results show that the C-Si Solar module with a PMMA thin film layer has greater output power than the Si-Solar module without a PMMA thin film layer.

Table 1: Shows the solar simulator analysis for the effects of PMMA thin film on characteristics parameters of C-Si Solar Module, while Figure 2 shows the same solar simulator analysis for IV-characteristics of C-Si Solar module comparing the results obtained.



**Fig. 1:** shows UV-Vis-NIR reflection spectral analysis of crystalline silicon wafer coated with 250 nm PMMA film layer and uncoated Crystalline Silicon wafer.

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characteristics of C-Si Solar module comparing the results obtained.

FESEM analysis of PMMA/SiO<sub>2</sub> shows the presence of silicon, oxygen, and carbon. In FESEM/EDS analysis, 31.65 % Silicon, 36.67 % Oxygen, and 31.70 % Carbon are the recorded percentage compositions for the PMMA thin film layer on SiO<sub>2</sub>. The presence of carbon indicates the presence of PMMA. However, hydrogen has not been observed; this is because hydrogen is the lightest element in the periodic table.

As seen in Fig. 1, the UV-Vis NIR Spectrometer analysis shows significant differences in optical reflection, with lower light reflection observed on a crystalline silicon

surface coated with a PMMA film layer compared to an uncoated crystalline silicon surface (Chiromawa and Ibrahim 2016). It is evident that the crystalline silicon surface coated with a PMMA film layer has the lowest light reflection across the recorded spectrum, while the bare,

uncoated surface has the highest. This could be due to the thin PMMA film on the silicon surface, thereby decreasing surface reflection and consequently increasing the absorption of incident light.

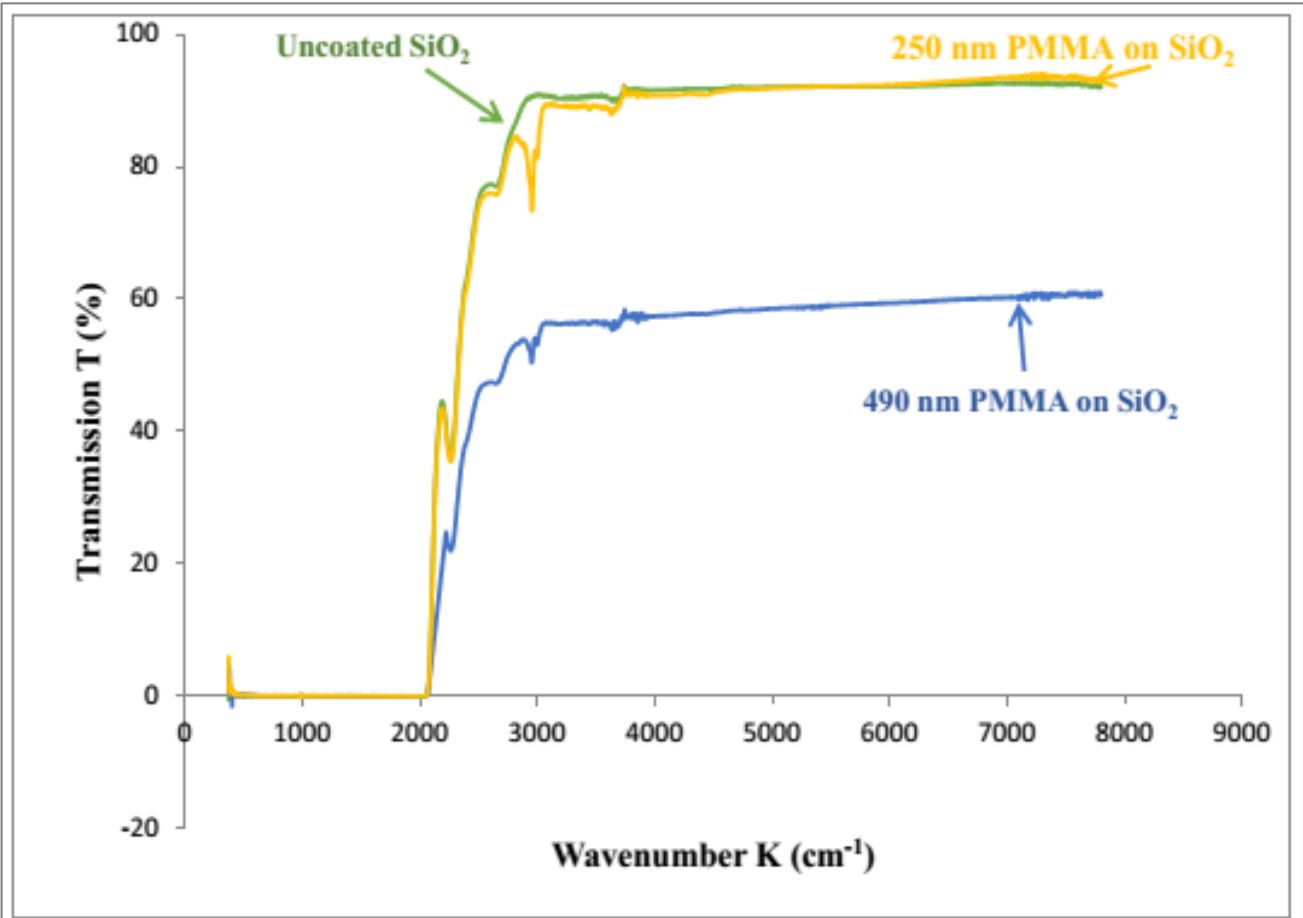


Figure 2: FTIR transmissions spectra through  $SiO_2$  and PMMA/ $SiO_2$  with PMMA film layer of two different thicknesses.

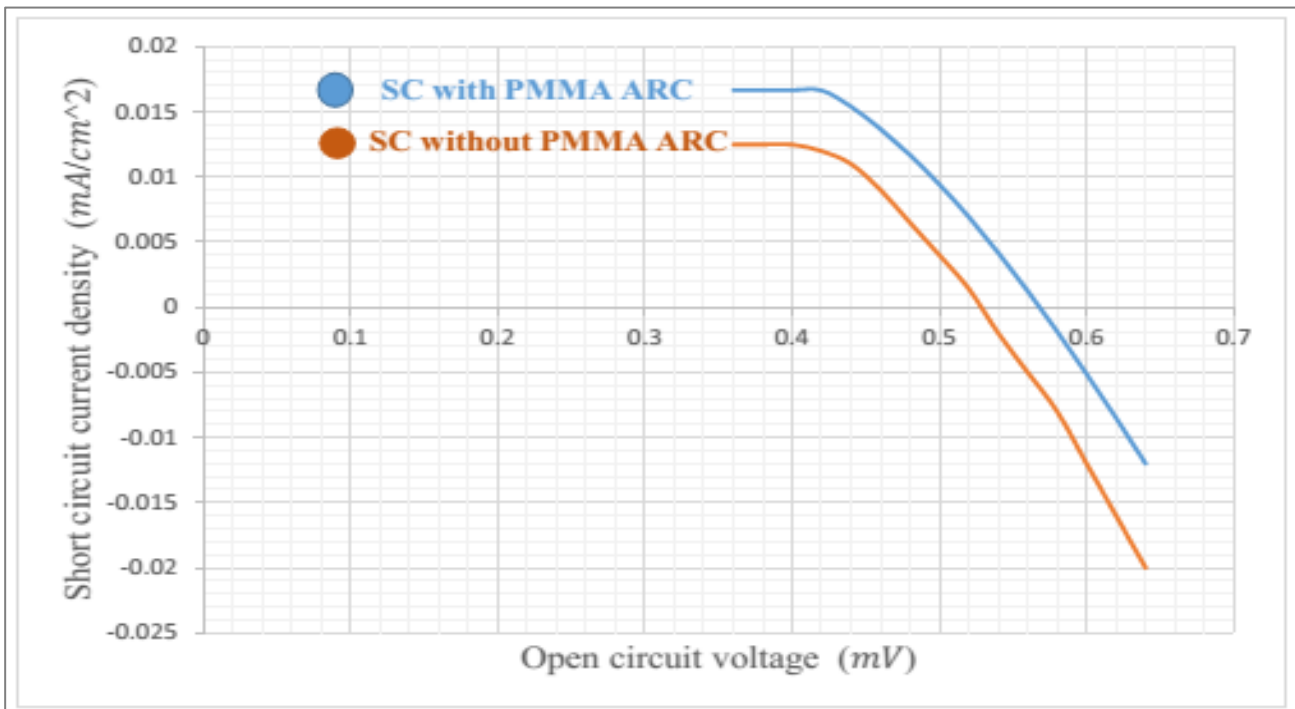


Figure 3: IV-characteristics of Si-Solar cells comparing the results of the two experimental steps taken: (C-Si Solar Cells with PMMA ARC and C-Si Solar Cells without PMMA ARC).

**Table 1: Effects of PMMA thin film on characteristics parameters of C-Si Solar Module**

S/N	Parameter	Unit of measurement	C-Si Solar Module	C- Si Solar Module with PMMA Thin film
1	Short circuit current, $I_{SC}$	mA	69.83	87.45
2	Short circuit current density, $J_{SC}$	mA/cm <sup>2</sup>	12.05	15.39
3	Open circuit voltage, $V_{OC}$	mV	531.73	549.85
4	Maximum current, $I_{max}$	mA	55.75	72.38
5	Maximum current density, $J_{max}$	mA/cm <sup>2</sup>	09.19	12.23
6	Maximum voltage, $V_{max}$	mV	383.00	395.00
7	Maximum Power, $P_{max}$	mW	22.64	28.43
8	Fill Factor FF	-	0.61	0.61
9	Series Resistance, $R_S$	Ohms ( $\Omega$ )	1.95	1.20
10	Shunt Resistance, $R_{Sh}$	Ohms ( $\Omega$ )	205.65	169.32

In a related development, the FTIR spectra show that almost no infrared transmissions are detected in the wave number range from 370 cm<sup>-1</sup> to 2070 cm<sup>-1</sup>, corresponding to the wavelength range between 27.03 μm and 4.83 μm (as depicted in Fig. 2); this could be due to the large wavelength having insufficient power to penetrate the samples. However, rapid increase in transmission efficiencies were observed between 2081 cm<sup>-1</sup> and 2895 cm<sup>-1</sup>, corresponding to the wavelength range of 4.81 μm to 3.46 μm. Meanwhile, high transmissions, which are almost uniform with only slight differences, were recorded between 2900 cm<sup>-1</sup> and 7800 cm<sup>-1</sup>, corresponding to the wavelengths from 3.45 μm and 1.28 μm. In Fig 2, for uncoated SiO<sub>2</sub> and SiO<sub>2</sub> coated with 250 nm PMMA film, at 2895 cm<sup>-1</sup>, the transmission efficiencies of 89.97% and 83.10% were observed, respectively, at 3000 cm<sup>-1</sup>, 90.86% and 81.92% were recorded: at 4000 cm<sup>-1</sup>. The transmission efficiencies rose to 91.64% and 90.89%, respectively. The highest transmittances were at 7800 cm<sup>-1</sup>, where transmission efficiencies of 92.14% and 92.84% were recorded, respectively. This could be due to the high energy of the incident infrared radiation which may increase the excitation of the molecular vibration of PMMA so that the resultant transmitted light will be equal to the sum of the incident and the emitted radiation at 7800 cm<sup>-1</sup>. Thus, it clearly indicates that the effects of a thin PMMA film (250 nm) on attenuating infrared transmission are negligible. Meanwhile, as the thickness of PMMA film was increased to 490 nm (in the same Fig 2), the infrared transmission was drastically reduced, and a transmission of 53.84% was recorded at 2895 cm<sup>-1</sup>; 53.25% at 3000 cm<sup>-1</sup>; and 57.47% at 4000 cm<sup>-1</sup>. Finally, transmission of 60.69% was obtained at 7800 cm<sup>-1</sup>.

As depicted in Table 1; C-Si solar module has the maximum power  $P_{max}$  of 22.64 mW with the short circuit current  $I_{SC}$  of 69.83 mA and open circuit voltage  $V_{OC}$  of 531.73 mV. However, as the single layer PMMA ARC was deposited on its surface, the  $P_{max}$  increased to 28.43 mW, the short circuit current  $I_{SC}$  to 87.45 mA and open circuit voltage  $V_{OC}$  of 549.85 mV. Analysis of solar simulators on a C-Si solar module without PMMA ARC shows that it has an efficiency of 19.75%, while

analysis of a C-Si solar module with PMMA ARC shows that the efficiency rose to 22.11%. Thus, the C-Si solar module with PMMA ARC has the highest power conversion efficiency.

The IV-characteristic curves of Figure 1 are similar to those obtained by (Chang et al. 2011) in that the periodic (biometrics) nano-structures were imprinted on Si-solar cells to enhance the concentrating optics on silicon solar cell. They choose to use high technology and costly techniques (the combinations of colloidal lithography, cast moulding method, and reversal nano-imprint lithography to fabricate spherical periodic nanostructures) while we choose to use simple and cheaper; non vacuum spin coating technique to deposit single layer PMMA film as anti-reflecting coating which allows free passages of incident solar radiation onto solar cells.

**CONCLUSION**

In this paper, we have successfully demonstrated the feasibility of using a non-vacuum spin-coating method to deposit a single-layer PMMA thin film as an anti-reflecting coating for crystalline silicon solar cells. The results obtained show a favourable improvement in the characteristics of the C-Si module. An open circuit voltage  $V_{OC}$  has been increased from 531.73 mV to 549.85 mV, while a short circuit current  $I_{SC}$  increases from 69.83 mA to 87.45 mA. The maximum power  $P_{max}$  has increased from 22.64 to 28.43 mW, and the power conversion efficiency of the C-Si solar module has increased by 2.36%. Therefore, the results clearly indicate the advantage of using the non-vacuum spin-coating method for investigating the effects of a PMMA thin film on improving the output characteristic parameters of crystalline silicon solar cells. Thus, conclusively, PMMA thin films have great potentiality in other material solar cells.

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