Original Research

Efficiency Improvement through Electro-Spraying Process of Hybrid SiO_2-VO_2 Anti-Reflection Coating for Monocrystalline Silicon Photovoltaic Cells

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Abstract: Utilizing the incident solar radiation into electrical energy through monocrystalline silicon solar cells has recently gained great interest in the field of advanced manufacturing. Reflection loss is a critical optical loss affecting solar cells performance. Through the process of antireflection coating, some of the scattered incident photons could be transmitted into the solar cells which leads to better utilization of incident light rays and improves efficiency. In the present work, antireflective materials such as SiO_2, VO_2 and SiO_2-VO_2 mixture films were coated over the silicon solar cell through an electro-spraying process. Characterization techniques such as XRD, AFM and FESEM were exploited to evaluate the efficiency of the electro-spraying process through the film's crystalline properties, agglomeration formation and surface property of the films formed over the solar cells. The results demonstrated that SiO_2-VO_2 blended solar cell showed a minimum reflectance of 6.55% compared to bare cell. After coating the solar cell with SiO_2-VO_2, it exhibited higher power conversion efficiency of 24.87% under regulated environment. It acquires the narrow length of visible spectrum and serves as a yellow/green filter in visible spectrum. This electro-spraying process improves the capability of the cells to transmit the light as in sunlight with uniform radiation. It increased the photon transmission which reached the depletion region. The minimum resistivity of 5.37×10^{-3} Ω·cm was achieved when the electro-spraying process applies a film of SiO_2-VO_2 blend on the cell, which is lower than all other samples. The electro-spraying process of SiO_2-VO_2 blend decreased reflection by reducing sunlight scattering.

Keywords: electro-spraying process; advanced manufacturing; antiglare coatings; monocrystalline Si solar cells; renewable energy

1. Introduction

Sunlight can be utilised as electrical energy, heat energy and hybridised chemical energy. Some of the solar energy conversion devices were PV cells, thermal collector devices and solar-chemical devices. In all these devices, energy conversion was affected mainly due to the surface reflection. Around 5–10 % of incident solar light gets reflected back from the solar cell surface resulting in the 9–14 % decrease in the solar energy conversion into electrical or heat energy, more specifically in the visible spectrum [1]. Anti-glare surface coatings were key factors for the overcoming the light reflection due to optical losses. By the proper selection and coating of anti-glare layers with refractive index lying better the optimal working range, some scattering photons can be trapped and been transmitted into the depletion layer of solar cell [2]. Conventional antireflection coating was implemented in single or multilayer thin films either with single or multiple materials. It is usually a dielectric material with transparent nature, which holds refractive index between the specified

range [3]. The anti-glare coatings were performed through various techniques such as physical and chemical vapour deposition and sol gel synthesis. However, these techniques were preferred in laboratory scale due to its high equipment cost, complex operating environment and low scale operation.

Further, micro and nano texturing of silicon substrates has also become a trending technology of reducing reflection and maximizing trapping of light in photovoltaic devices alongside the thin-film antireflection coatings. Such texturing techniques create irregular or pyramidal features, surface structures, which permit multiple interior reflections and improvement of the optical path length and absorbs photon within the active layer [4]. Etching micro-pyramid alkaline and metal-assisted chemical etching (MACE) nanoscale structure have all demonstrated the capability to reduce surface reflectivity to less than 10% at the entire solar light wave length range [5]. The optical performance of the textured surface with antireflection coating is superior to that of individual methods in that, the textured surface has the benefit of geometrical light trapping and coating work on the gradient of the refractive index. However, the texturing processes may be expensive to the other chemical treatments, sensitive to control of the etching parameters, and may cause surface defects or significant recombination losses unless passivated. Therefore, the development of cost effective, standardized processes of coating such as electro-spraying is highly crucial in increasing the effectiveness of solar cells in large scale manufacturing.

As seen, some of the large-scale anti-glare thin film coating can be obtained through blade coating, knife edge coating, brush coating, screen printing etc., Uniform and good adherence of coated films cannot be achieved easily [6]. This drawback can be overcome through electro spraying coating technique. The setup has syringe with needle loaded with the coating material dispersed with ethanol. High voltage supply, preset mass flow rate, spinneret velocity, plate velocity and distance between the needle and plate were the crucial operating parameters. The coating was performed by charging the needle tip with positive charge and deposition plate with negative charge separated at very small distance [7]. With the influence of strong electrostatic force of attraction, the ejected coating material gets split into finer droplets and gets adhered over the plate surface. This coating technique can be performed under atmospheric temperature and pressure which make it as low-cost operation resulting in better morphology and control over coating thickness. It is mainly suited for hybrid material coating over selected substrates [8].

Combined effect of two anti-reflective materials with refractive index closer to each other showed better photon transmission and declined reflectance resulting in elevated performance of solar cell. Also, blended anti-glare materials exerts long term sustainability. The present works, as illustrated in Figure 1, aims to utilise the thin film transparent antiglare coatings of SiO_2, VO_2 and SiO_2-VO_2 mechanical blends through electro-spray technique [9]. The power output performance of purchased, SiO_2, VO_2, SiO_2-VO_2 blended solar cells were evaluated through variety of characterisation techniques. Some of the inspection methods for determining the optical, structural, electrical, thermal and morphological studies through FESEM, AFM, Four-probe method, IR thermal imaging, UV-Vis spectroscopy. With the optimal coating parameters, the anti-glare coatings hold progressive optical performance in addition to thermal performance. Thus, blended antireflection coating found to be promising antireflection layer capable of delivering the high-power output with subsequent reduction in optical reflectance. Antireflection coatings made of oxides can as well lead to long term reliability of photovoltaic devices. The silicon surface is shielded against the infiltration of moisture and contaminants in the air by the SiO_2-VO_2 layer creating a dense and smooth shield. This protection is effective in reducing the degradation at the surface as well as stabilizing electrical characteristics in the long runs of illumination. Also, the thermal and chemical stability of oxide coating promotes performance stability in the operating conditions. These properties show that the coating applied is not only efficient, but also increases the reliability of devices [10].

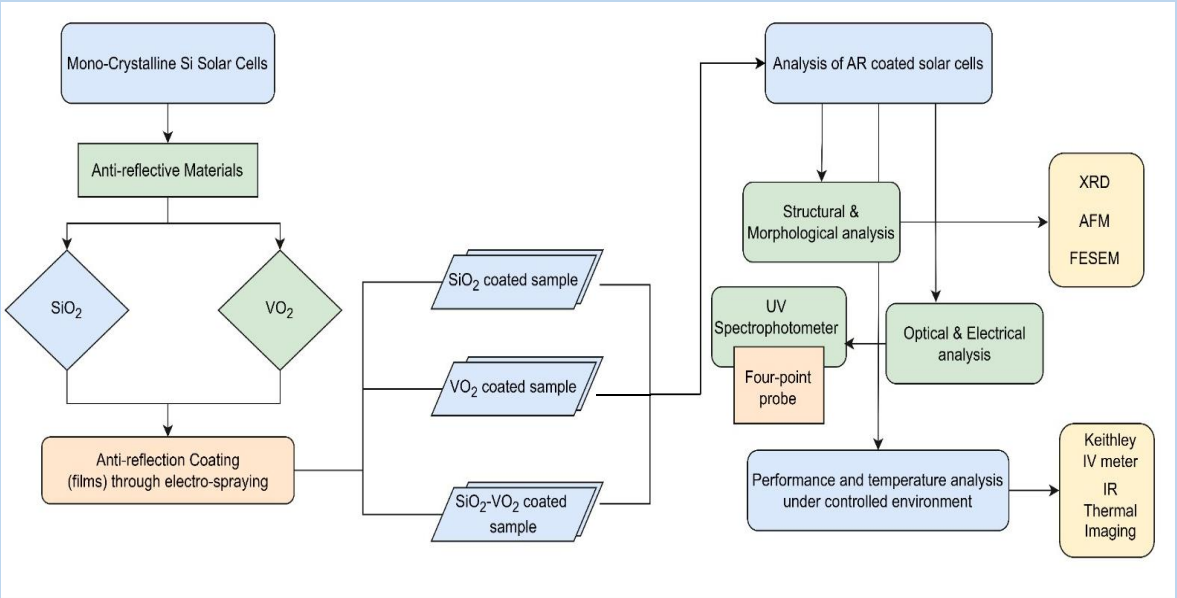

Figure 1. Flowchart of research work flow.

2. Materials and Methods

2.1. Materials

The Monocrystalline silicon solar cells of dimensions 38×52 mm (obtained from Vikram Solar) were used for the investigation. SiO_2 and VO_2 and Ethanol with 99.9% purity (provided by Spectrum Reagents and Chemicals Pvt. Ltd.) were also used as reflective coating materials. A 99.9% pure Ethanol (a product of Herenba Instruments and Engineers) was used as blending medium.

2.2. SiO_2-VO_2 Blend Mixture Preparation

SiO_2-VO_2 blend was prepared using ball milling technique which was found to be more effective for the preparation of homogenous mixture. This technique also helps to reduce the particle size. With the help of planetary ball mill, the materials were mixed together under normal atmosphere for up to 240 minutes. This prolonged process led to the formation of different metastable phases resulting in the better mixing of selected anti-glare materials. The rotational speed was maintained as 1500 rpm. Finally, the prepared mixture was collected and thoroughly washed using deionised water and followed by alcohol. The washed homogenous mixture was then dried in hot air oven at 75 °C.

2.3. SiO_2-VO_2 Blend Mixture Coating

The prepared SiO_2-VO_2 mixture was taken in the beaker along with 100 ml of ethanol. Afterwards, it was thoroughly mixed using magnetic stirrer for 40 minutes. The obtained mixture was sonicated using ultrasonicator. The sonication process was performed for 30 minutes resulting in deagglomeration of mixture particles. Lastly, the obtained mixture was loaded into the 5 ml syringe with a spraying tip. With the pre-set mass flow rate, the syringe was pressed and the dispersed fluid was ejected and sprayed out in very finer droplets. Because of the electrohydrodynamic atomisation, the ejected droplets were deposited over the solar cells leading to uniform deposition, through electro-spraying. The coating was performed for SiO_2, VO_2 and SiO_2-VO_2 mechanical blends over the solar cell surface by the use of the same electro-spraying process.

2.4. Characterization Methods to Analyse the Anti-reflective Materials Coated Solar Cell

Different characterization methods were employed to evaluate the efficiency of bare cell and the SiO_2, VO_2, and SiO_2-VO_2 coated photovoltaic samples by the electro-spraying process. X-Ray Diffraction was used to characterize the phase and crystalline nature of the solar cell samples. Field Emission Scanning Electron Microscopy (FESEM) was performed using a ZEISS GEMINI SEM 500 (Carl Zeiss, Germany) to investigate the cross-section and surface morphologies of the solar cells. Atomic Force Microscopy was used in tapping mode under atmospheric condition for analysing the surface roughness of bare and coated cell. UV–visible absorption spectra were recorded using a Shimadzu UV-1800 and UV–visible spectrophotometer (Shimadzu Corp., Japan) was employed for recording the reflectance spectra in the wavelength between 300–1200 nm. Four-point probe technique was used to measure the electrical properties such as resistivity, hall mobility and carrier concentration of the solar cells. A Keithley 2400 SourceMeter® (Keithley Instruments Inc., USA) was employed for I–V measurements to measure the photocurrent-voltage parameters like current density, open-circuit voltage and fill factor of the photovoltaic samples. The cell temperature of bare cell, SiO_2, VO_2 and SiO_2-VO_2 coated samples were measured using Infra-Red Thermal Imaging technique [11].

3. Results and Discussions

3.1. XRD Analysis

The crystal arrangement and position of pure SiO_2, VO_2, and SiO_2-VO_2 coated by the electro-spraying process on a Silicon photovoltaic substrate is analysed using XRD and shown in Figure 2. There is a silicon peak could be found, that is because the anti-reflective materials like SiO_2 and VO_2 coated on a Si surface. As illustrated in XRD peaks of Figure 2, VO_2 on Si substrate affirmed only monoclinic diffraction pattern. The SiO_2-VO_2 peaks exhibited a single-phase VO_2 and the peaks were sharp. Hence, it is proved that the SiO_2 with higher amorphous was found. No peaks of any other phases or impurities were found, showing the higher level of purity of the coating materials [12]. The average size of the crystallite and width of the peaks were corelated. Various parts of the sample were evaluated and exhibited the same properties, demonstrating the uniformity in their crystallization and composition.

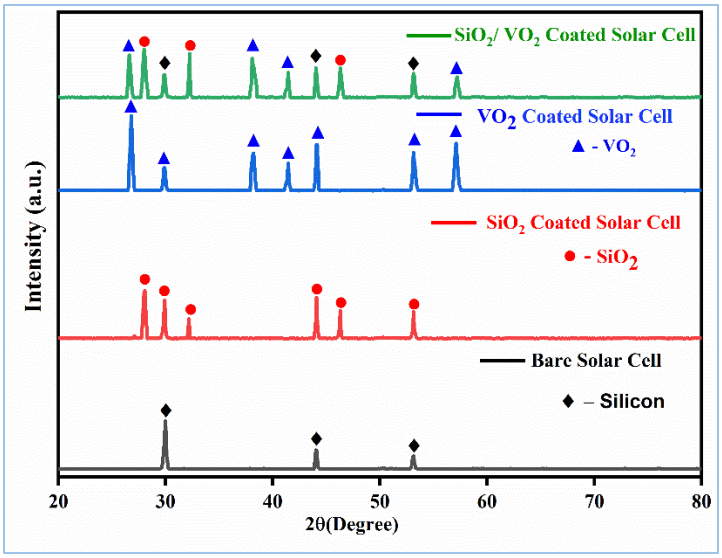

Figure 2. XRD of SiO_2-VO_2 coated over silicon solar cell by the electro-spraying process.

3.2. Surface Roughness Analysis

Figure 3 illustrates the surface roughness images of SiO_2 and VO_2 films coated by the electro-spraying process. The AFM analysis was performed under atomic force microscope (Dimension Icon, Bruker, USA) to evaluate the regularity of materials on coated substrates and to unestand the coating thiclness. The surface roughness of SiO_2, VO_2 and SiO_2-VO_2 is observed as 38 nm, 44 nm and 50 nm. The particle agglomeration, grain refinement and grain growth were observed. For the SiO_2-VO_2 coating film, the AFM morphology gives a comparably fine-granulated microstructure. The size distribution of the particles differs from 30 to 70 nm, demonstrating the increased uniform surface morphology. Disregarding of the less variation in surface roughness, SiO_2 and VO_2 coatings firmly attach to the Si surface, thus promoting the sunlight propagation [13]. The SiO_2, VO_2 and SiO_2-VO_2 films displayed an impenetrable structure having higher thickness therefore improving their capacity to efficiently trap the reflected photons.

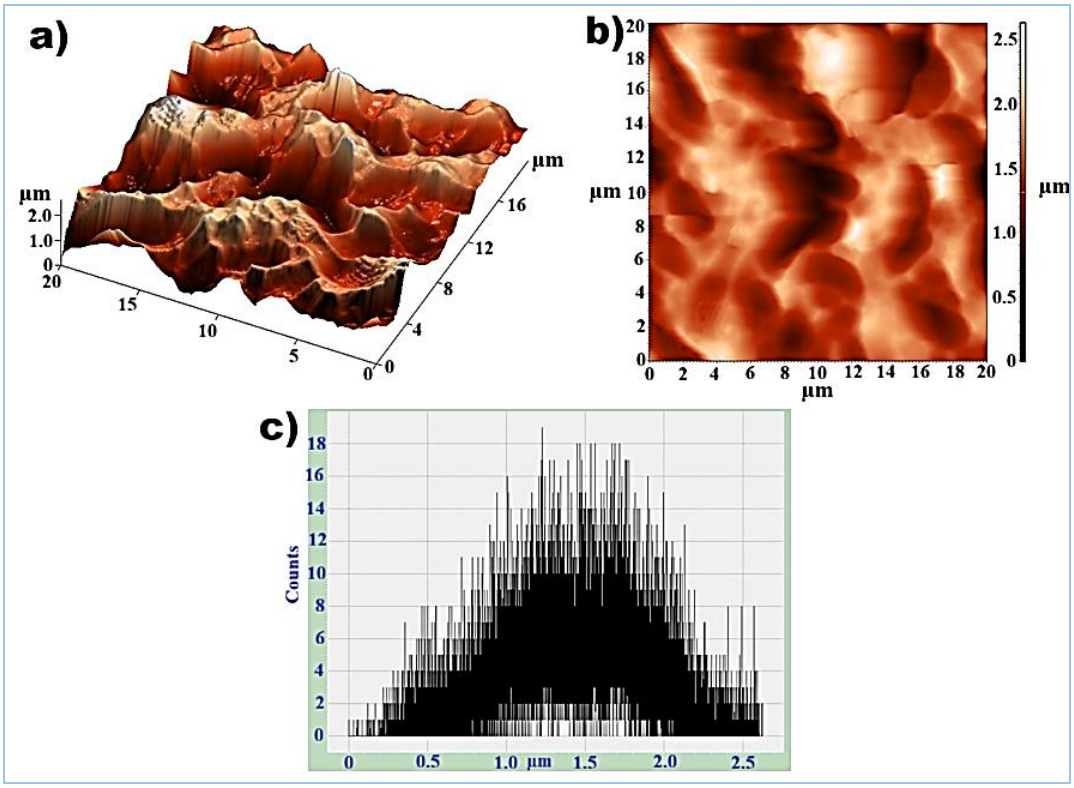

Figure 3. Morphology of AFM of SiO_2-VO_2 blend coated solar cell by the electro-spraying process. (a) 3D topography; (b) 2D topography; (c) Histogram analysis.

3.3. FESEM Analysis

The sectional view and morphological characteristics of the samples were evaluated using FESEM method. The SEM images of SiO_2, VO_2 and SiO_2-VO_2 coated on the photovoltaic cells by the electro-spraying process were shown in Figure 4. The coatings have optically dense structure. The thicknesses of the SiO_2, VO_2 and SiO_2-VO_2 films were found as to be 223 nm, 303 nm and 390 nm, respectively. The SiO_2-VO_2 coating exhibited a fine structure having well-proportioned grains homogenously growing over the entire Si photovoltaic surface as seen in Figure 4. The particle clusters formation and interconnected pores were observed among particles and smooth surface observed across the particle surface. As shown in Figure 4, the surface of SiO_2 and VO_2 film is uniform and compress with grain size. The substrate to nozzle distance, voltage supply and rate of flow were

the factors which affects the coating's quality. The surface defects were not found in the samples. Certainly, the smooth and even surface achieved by the electro-spraying process of SiO_2-VO_2 film improved the absorption of sunlight in active sites and consequently increases the absorption ability [14]. The electro sprayed materials were completely attached with the frontal area of solar cell because of strong electrostatic attractive force.

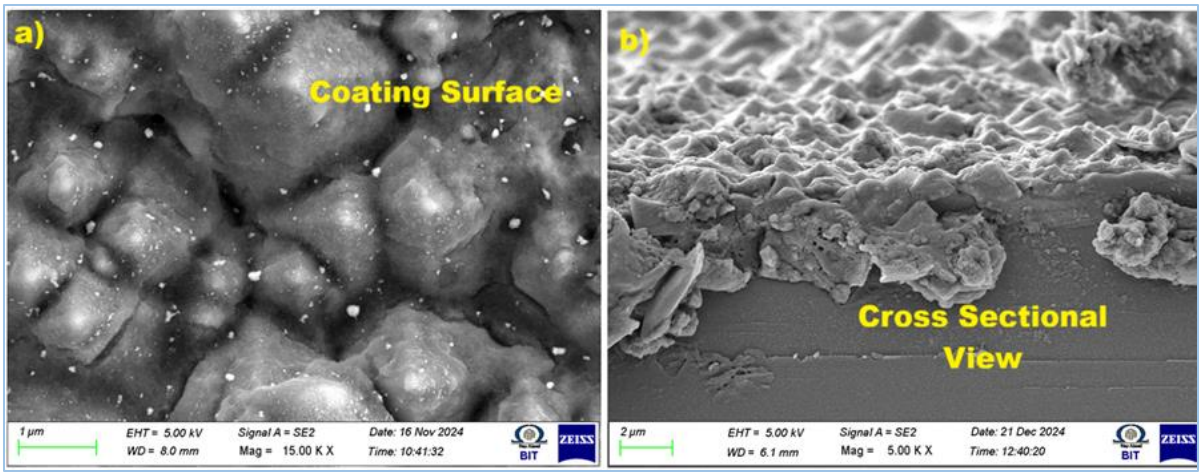

Figure 4. FESEM of blended SiO_2-VO_2 coated solar cell by the electro-spraying process. (a) Surface morphology; (b) Cross-sectional view.

3.4. Optical Reflectance and Quantum Efficiency Analysis

In Figure 5 reflectance curve and External Quantum efficiency (EQE) is illustrated for bare cell, SiO_2, VO_2 and SiO_2-VO_2 coated photovoltaic samples. UV Visible spectroscopy was employed for measuring the optical property like reflectance of the solar cells. The reflectance value of bare cell, SiO_2, VO_2 and SiO_2-VO_2 coated cell were measured as 16.36%, 12.17%, 10.24% and 6.55%, respectively. The reflection values are reduced after coating by the electro-spraying process using antireflective materials as shown in Figure 5. Compared to all samples, blended SiO_2-VO_2 showed minimum reflectance. The absorbed electrons per incident photons gives the External Quantum efficiency. The External Quantum efficiency data showed that the electrons and photons combined with photovoltaic surface. The SiO_2-VO_2 coated solar cell sample exhibited the highest quantum efficiency as compared to other samples. The quantum efficiency values for bare cell, SiO_2, VO_2 and SiO_2-VO_2 was measured as 80.17%, 85.71%, 91.09% and 96.45%, respectively. It is due to the minimum reflection of incident rays in the photovoltaic cell. The rough surface and ideal coating thickness increased the light propagation and decreased the light scattering [15]. The existence of Silicon and Vanadium facilitated more sunlight to penetrate through the solar cells. Table 1 gives the summary of reflectance and EQE data analysed using UV spectroscopy. In order to have optimum antireflection on silicon the refractive index of the coating would ideally between n≈1.9–2.0. The refractive index of the materials used separately is SiO_2 (n≈1.46) and VO_2 (n≈2.8), which are not in the close range of this ideal value. TheVO_2 mixture in SiO_2 introduces a more realistic range of refractive index (n≈1.8–2.2) that lies much closer to the optimum range and provides much closer matching impedance between silicon and air. This is why the blended coating presents the least reflectance (6.55%) as compared to that of SiO_2 (12.17%) and VO_2 (10.24%).

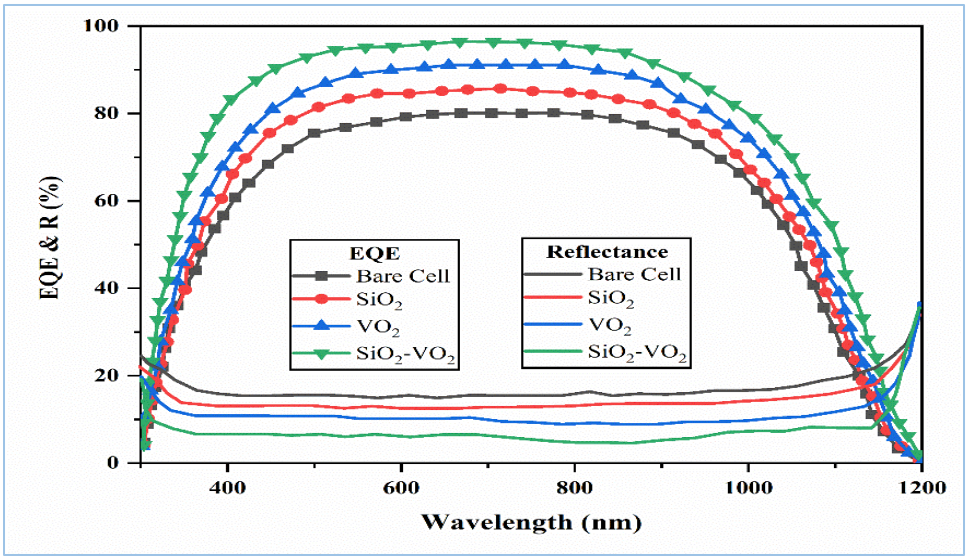

Figure 5. Optical reflectance and EQE curve of bare, SiO_2, VO_2 and blended SiO_2-VO_2 coated cell using the electro-spraying process.

Table 1. Reflectance and EQE measurements of bare cell, SiO_2, VO_2 and SiO_2-VO_2 coated solar cells.

Specimen	Reflectance (%)	EQE (%)
Bare cell	16.36	80.17
SiO_2	12.17	85.71
VO_2	10.24	91.09
Blended SiO_2-VO_2	6.55	96.45

3.5. Performance Analysis in Regulated Environment

The efficiency of solar cell is measured under a controlled environment employing solar simulator. The evaluated photocurrent–voltage property of the solar cell is shown in Figure 6. The efficiency characteristics of coated solar cell using the electro-spraying process, that are extracted from the I–V graph, are summarized in Table 2. With the anti-reflection coating of SiO_2, VO_2 and SiO_2-VO_2, the power conversion efficiency of solar cell is increased from 17.22% to 24.87%. The enhancement is primarily because of the increased short-circuit current and open-circuit voltage. There is a decrease in efficiency of 17.22% for bare cell with other parameters like J_{SC} = 35.75 mA/cm^2, V_{OC} = 0.61 V and Fill factor = 74%, respectively. The single material such as SiO_2 and VO_2 coated cells exhibited a power conversion efficiency of 19.99% and 20.76%, respectively. In comparison with all other samples, the blended SiO_2-VO_2 coated sample provided the maximum efficiency of 24.87% with increased J_{SC} of 44.92 mA/cm^2, V_{OC} of 0.692 V and improved FF of 80, respectively. The enhancement in efficiency is because of the transmitted sunlight is transformed more effectively in solar cells. Thus, decreased reflectance could have higher effect on overall efficiency in solar cells [16]. Even though the reduction of the optical reflections is directly proportional to the enhancement of the J_{SC}, the increment of the V_{OC} and FF is attributed to other electrical improvements by the antireflection coating. The electro-sprayed SiO_2-VO_2 film also reduces the surface recombination by formation of smooth and dense interface resulting in improved quality of the junction. Besides, the surface passivation effect, decrease in series resistance, and an enhancement of the hall mobility can enhance the efficiency of charge carrier transport. The combination of these effects leads to a reduced loss in recombination and results in increased V_{OC}, FF and J_{SC} [17].

Table 2. Photocurrent-voltage results of bare cell, SiO_2, VO_2 and blended SiO_2-VO_2 coated solar cell by the electro-spraying process under regulated environment.

Sample	J_{SC} (mA/cm²)	V_{OC} (V)	FF (%)	PCE (%)
Bare cell	35.75	0.651	74	17.22
SiO_2	39.67	0.663	76	19.99
VO_2	40.06	0.673	77	20.76
SiO_2-VO_2	44.92	0.692	80	24.87

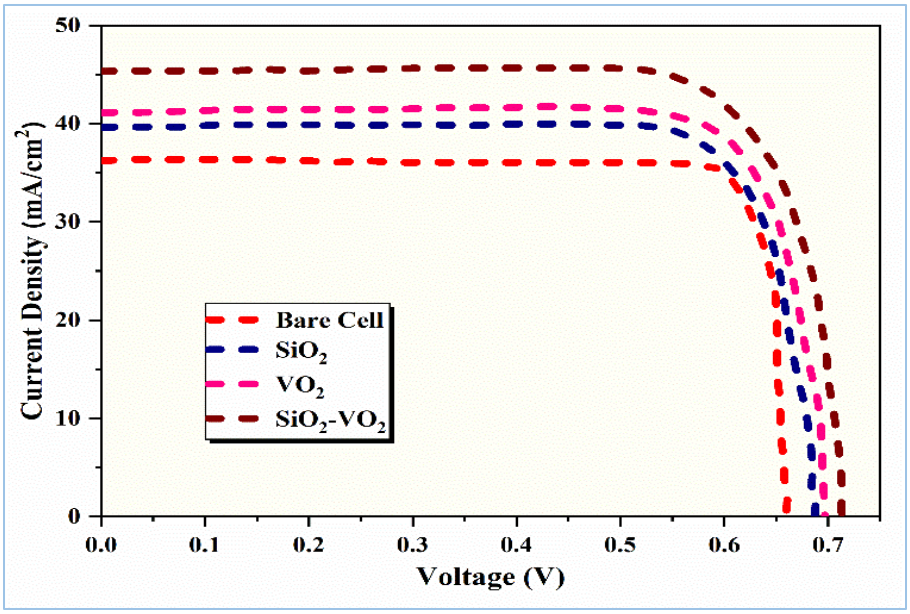

Figure 6. I-V graph of bare, SiO_2, VO_2 and blended SiO_2-VO_2 coated cell by the electro-spraying process.

3.6. Electrical Analysis

The electrical properties of bare, SiO_2, VO_2 and SiO_2-VO_2 coated cell using the electro-spraying process were measured using four-probe technique as illustrated in Figure 7. The resistivities of bare, SiO_2, VO_2 and SiO_2-VO_2 coated sample were measured as 9.23×10^{-3} Ω·cm, 8.44×10^{-3} Ω·cm, 6.76×10^{-3} Ω·cm and 5.37×10^{-3} Ω·cm, respectively. It is clear that bare cell exerts more resistivity than SiO_2-VO_2 coated cell. it is primarily because of increased size of grains and lower grain boundaries. It is proved that when the layers of ARC increases, the resistivity decreases, finally lead to increased conductivity in SiO_2 and VO_2 coated photovoltaic sample and also improves mobility of electrons. The carrier concentration of various ARC coated samples varies from 25.48×10^{20} to 37.36×10^{20} cm^{-3}. The hall mobility also increased from 11.22 cm^2/Vs to 15.35 cm^2/Vs for bare cell to blended SiO_2-VO_2 coated cell. When compared to other solar sample, the photo-generated current and conductivity is increasing for double layer coated cell. Table 3 shows the measurements of electrical parameters.

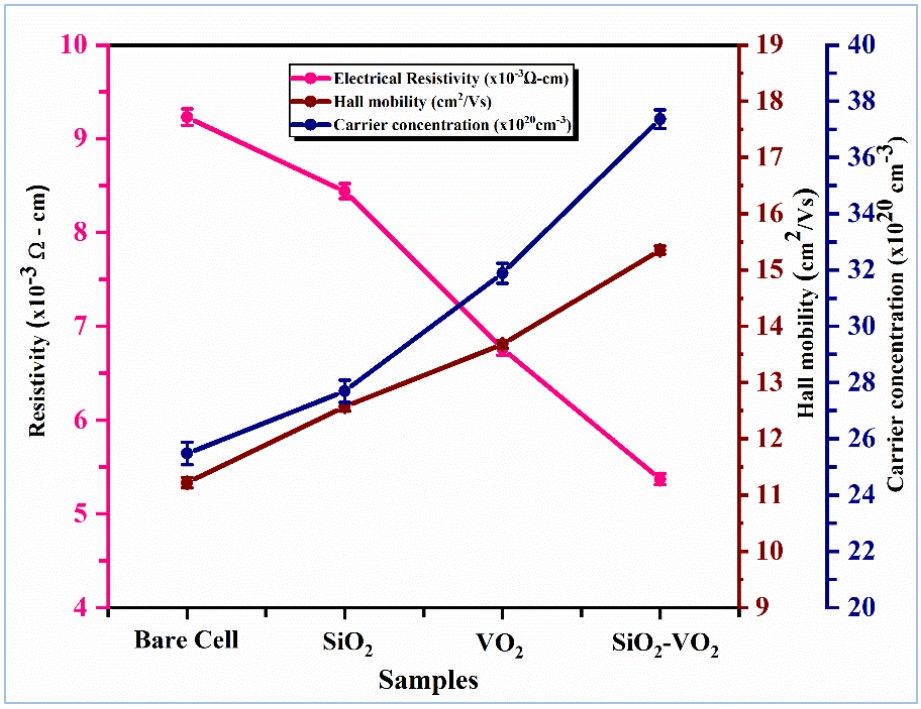

Figure 7. Electrical resistivity, carrier concentration and hall mobility analysis curve of bare, SiO_2, VO_2 and blended SiO_2-VO_2 coated solar cells by the electro-spraying process.

Table 3. Electrical resistivity, carrier concentration and hall mobility of bare, SiO_2, VO_2 and blended SiO_2-VO_2 coated Si solar cells the electro-spraying process.

Samples	Resistivity (Ω·cm)	Carrier concentration (cm^{-3})	Hall mobility ($cm^2\ V^{-1}s^{-1}$)
Bare cell	9.23×10^{-3}	25.48×10^{20}	11.22
SiO_2	8.44×10^{-3}	27.69×10^{20}	12.57
VO_2	6.76×10^{-3}	31.88×10^{20}	13.68
SiO_2-VO_2	5.37×10^{-3}	37.36×10^{20}	15.35

3.7. Cell Temperature Analysis in Controlled Atmosphere

The efficiency of solar cell is primarily affected by the cell temperature. The performance of solar cell decreases as the cell temperature increases. The power production in photovoltaic cells is also affected by increased resistivity because of increased heat flux [18]. In controlled environment, the temperature of bare cell, SiO_2, VO_2 and SiO_2-VO_2 coated cell by the electro-spraying process were measured. An IR thermal imager combined and presented both IR and visible images to a single image as illustrated in Figure 8. It is clear from the Figure 8, that the blended SiO_2-VO_2 coated cell exhibited lower cell temperature of 41.9°C when compared to bare cell.

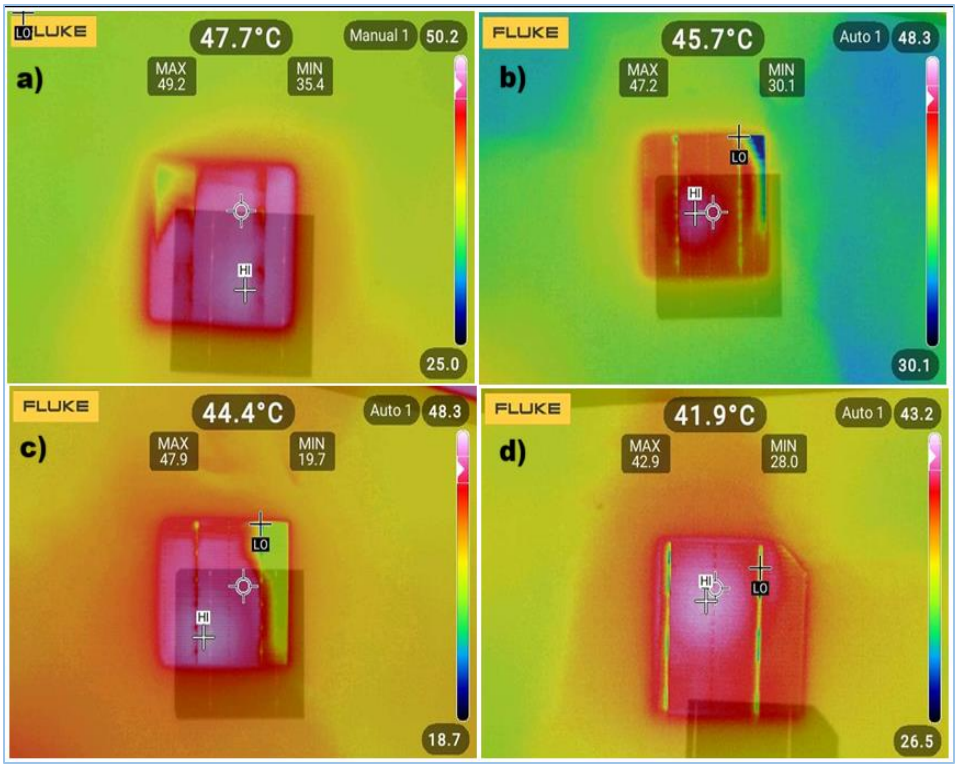

Figure 8. Thermal images of (a) bare, (b) SiO_2, (c) VO_2 and (d) blended SiO_2-VO_2 coated solar cells by electro-spraying under regulated light source.

The SiO_2 and VO_2 coated cell showed a minimum temperature of 45.7 °C and 44.4 °C, respectively. It might be due to larger effective surface area of the coated films as compare to the uncoated sample. This decreasing operating cell temperature of the coated samples can be attributed not only due to the influence of antireflection behavior alone. The SiO_2-VO_2 coating also results in an increased light transmission, reduced non-radiative recombination loss and this limited the excess heat that could be produced within the cell. Moreover, the coating structure is homogeneous and finely-grained, which increases the quantity of the effective surface area, which is beneficial to thermal dissipation when illuminated. This decreases the internal heat generation and increases the heat spreading which in turn reduces the steady-state operating temperature [19]. Larger effective surface area leads to better cooling of the coated samples and hence SiO_2-VO_2 coated films performance is significantly higher which might result in longer service life of the photo-voltic cells. The electro-spraying process of double layer coating of SiO_2-VO_2 increased the power conversion efficiency of solar cell as confirmed by the structural, electrical, optical and thermal analysis.

4. Conclusions

Using electro-spraying process, silicon dioxide and vanadium oxide were deposited as an anti-reflective coating on mono-crystalline solar cells. The SiO_2 and VO_2 were coated as a single material and also coated as a combined material that is blended SiO_2-VO_2 on solar cells. The crystalline orientation of SiO_2 and VO_2 peaks were obtained using XRD. Using FESEM analysis, the cross-sectional view and thickness of the samples were found as 223 nm, 303 nm and 390 nm for SiO_2, VO_2 and blended SiO_2-VO_2 coated solar cells. The surface roughness of the samples was obtained by AFM investigation. Anti-reflection coating is primarily employed to reduce the reflection loss in photovoltaic cells. It is proved that the blended SiO_2-VO_2 coated as AR coating on solar sample exhibited minimum reflectance of 6.55% as confirmed by UV-Vis spectroscopy analysis. Also, the

SiO_2, VO_2 and SiO_2-VO_2 coated cells showed a minimum resistivity of $8.44 \times 10^{-3}\Omega\cdot cm$ and $6.76 \times 10^{-3}\Omega\cdot cm$ compared to bare cell ($9.23 \times 10^{-3}\Omega\cdot cm$). As resistivity reduces, the conductivity and photon to power conversion increases which ultimately leads to increased efficiency of solar cell. therefore, the blended SiO_2-VO_2 coated cell with minimum resistivity exhibited the highest power conversion efficiency of 24.87%. This blended layer allows more photons to penetrate through the solar cells by reducing the light scattering. The temperature of the SiO_2-VO_2 is also minimum which shows a corelation to the above results. The process of electro-spraying of SiO_2 and VO_2 as an anti-reflection coating on solar cells shows potential to increase the overall performance of solar cell, therefore rendering them sustainable in widespread applications.

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Conflict of Interest: The author declares no conflict of interest.

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