Nanostructured Silicon Oxide Film for Enhanced Crystalline Solar Cell

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Abstract— **In this study, we investigate the potential use of silicon oxide layer as one possible way to increase the silicon solar efficiency at low cost. The layer is fabricated on top of commercially available monocrystalline silicon (mc-Si) solar cells by low temperature Plasma Enhanced Chemical Vapour Deposition (PECVD) using Tetramythyle–Silane (TMS), ($C_4H_{12}Si$) precursor and oxidized by means of potassium permanganate ($KMnO_4$) agent. This study compares the electrical and optical characteristics of monocrystalline silicon cells before and after coating. The PV cells surface chemical composition was analyzed using Scanning Electron Microscopy (SEM). Reflectance and transmittance analysis results are also presented. The experimental results show a relative enhancement of about 10% (from 12.14% to 13.34%) in the monocrystalline cell electrical efficiency conversion.**

Index Terms — monocrystalline solar cell, nanoparticles, PECVD, silicon oxide.

I. INTRODUCTION

Silicon (Si) is the leading material used in the commercial production of low cost solar cells given the non-toxicity, raw material cost and abundance of Si [1]. The cost effectiveness of solar cells can be further reduced by improving the solar cell efficiency while maintaining low fabrication costs.

The main spectral losses in a single junction solar cell are high due to the mismatch between the incident solar spectrum and the spectral absorption properties of the material leading to the thermalisation of the charge carriers [2]. Enhancing the energy conversion of the conventional solar cell above the theoretical limit of ~30% calculated by Shockley and Queisser could be approached by preventing the thermalisation of the charge carries with the help of down conversion materials [3,4]. Silicon oxide film can serve as down conversion layer on the Si solar cells due to its optical property of absorption ultraviolet radiation and reemitting the absorbed energy by these films as red light where the Si solar cell has greater response [5]. In recent decades, silane has been widely used as a raw material when preparing silicon containing thin films using PECVD systems [6,7]. Currently, organosilicon compounds such as liquid/vapour-phase TMS has been adopted as a source of silicon instead of hazardous silane gas

for the deposition onto plastic substrates. Furthermore, TMS also has the cost advantage of not requiring heating apparatus due to its high vapour pressure at room temperature [9].

In this paper, we report the growth of silicon oxide nanoparticles layer on commercial monocrystalline silicon solar cell using TMS as a precursor and oxidized by means of Potassium Permanganate with no significant increase in the cost of fabrication. Also, we show the effects of the oxygen diffusion in the silicon nanoparticles layer on the electrical energy conversion efficiency of the solar cell. In addition, the reflectivity, chemical composition and structure of the silicon nanoparticle have been investigated.

II. EXPERIMENTAL

The deposited layers were grown on the top of commercial monocrystalline solar cells XS156B3 with a dimension of $156{\times}156$ mm^2 from MOTECH. Prior to deposition, the cells were cleaned using Isopropyl alcohol (IPA) solution. The cleaning continues inside the PECVD chamber by argon ion bombardment. The argon flow rate was 30 cm^3/min for 5 minutes with a 100V DC bias for each experiment.

The argon treatment displaces impurities on the substrates through energetic argon ion bombardment. The solar cells were placed on an electrode, whose configuration was designed to provide a uniform plasma environment and to ensure the good film uniformity across the entire area of the cell.

The cells were introduced into the process chamber of the PECVD reactor and reaction species are ionized at radio frequency of 13.56 MHz. The precursor used for the deposition of silicon nanoparticles is TMS. The TMS entering the chamber is ionized and strikes the substrate placed on a supporting cathode table. The flow of the process gas is controlled and monitored using mass flow controllers; and the chamber pressure is maintained at -4 Bar is controlled and monitored using a capacitance manometer and pressure control unit. One monocrystalline cell was placed inside the chamber for each experiment. The coating parameters during the experiments were; the time of deposition, the DC bias voltage, and the flow of TMS. Those parameters remained constant for each experiment while the mass of potassium permanganate was varied for each experiment. The coating

conditions are summarized in Table 1. Comparative current versus voltage (I-V) and Power versus voltage (P-V) curves of the solar cells were produced under halogen light at temperature of 20 °C and light intensity of 290W/m^2. Only 8.544 cm^2 of solar cell surface area was illuminated. Also, the electrical conversion efficiency of the cell was tested under UV light with an intensity of 75 W/m^2 with surface illumination area of 32 cm^2. Prior to the measurements, the light intensity was measured with a reference cell calibrated by GBSOL and solar power meter (Di LOG-model:S102) instrument to check the visible irradiance and UV light meter (LT Luton-model:UV-340) instrument was used to check ultraviolet irradiance. All the samples were tested using the same conditions. The electrical characteristics of the solar cells were obtained by connecting the cell with a resistive load (Array Electronics). All the cells were tested using the same conditions.

TABLE 1
SUMMARY OF COATING CONDITIONS

Coating	C_1	C_2	C_3	C_4	C_5	C_6
TMS Flow Rate (cm^3/min)	25	25	25	25	25	25
Time (minutes)	15	15	15	15	15	15
DC Bias (volts)	100	100	100	100	100	100
KMnO$_4$ (gram)	5	10	20	30	40	50

The reflectivity spectra were obtained using PerkinElmer Lambda 650 UV/Vis spectrophotometer equipped with an integrating sphere and operating in the range of (200-850) nm. Structural and composition analysis of the solar cells were carried out before and after the silicon nanoparticles deposition process using a ZEISS SUPRA 35VP field emission Scanning Electron Microscopy (SEM).

III. RESULTS AND DISCUSSION

Figure 1 shows the reflectance spectra of the uncoated cell and coated cell at maximum performance under visible light (C_3). The reflectance of the coated cell was reduced in the UV and short wavelength part of the visible light region whereas the reflectance of the remained part of the visible light and near infrared region was slightly increased. The reduction in the reflectance of the coated cell in the UV region indicates that more photons that generate charge carries absorbed and could be attributed in the increase of the electrical conversion efficiency.

The characteristics of the current-voltage (I-V) curve of the solar cell after PECVD coating with 20g mass of KMnO$_4$ is shown in Figure 2. (I-V) curve obtained before coating is also shown for comparison. This coating provides with the best results when the cell is measured under halogen light. In case of the uncoated cell, it was found that I_{sc}=524 mA and V_{oc}=82 mV while the coated cell (C_3) the results were I_{sc}=86 mA and V_{oc}=427 mV. The formation of the silicon oxide layer on the solar cells resulted in clear relative enhancement of (~4.9%) in the short circuit current (I_{sc}). However, the open circuit voltage (V_{oc}) was slightly improved.
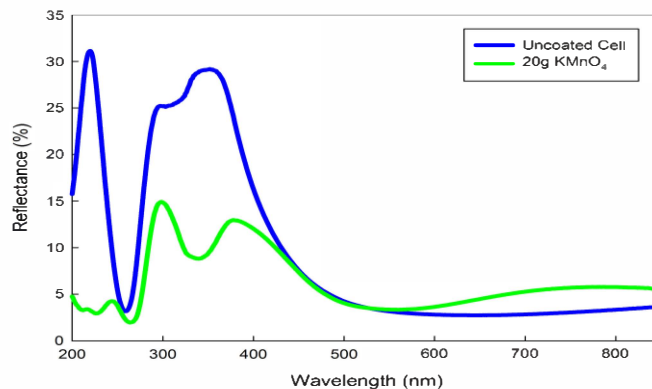

Fig. 1. Reflectance spectrum of the uncoated and coated solar cell with maximum electrical output enhancement.

Table 2 summarizes the electrical characteristics of the uncoated solar cell and the other six coated cells with silicon particles oxidized by different weight masses of KMnO$_4$. It can be seen from the table that the efficiency of all the coated cells were improved. The improvement is dominated by current rather than voltage.

This indicates that the optical properties of the SNPs have contributed to an enhancement in the light response of the silicon solar cell while the unchanged or slightly increased values of V_{oc} shows that deposition of the silicon oxide layer by the PECVD process was successful without damaging the surface of the crystalline solar cell due to the deposition of the silicon oxide layer at low temperature.
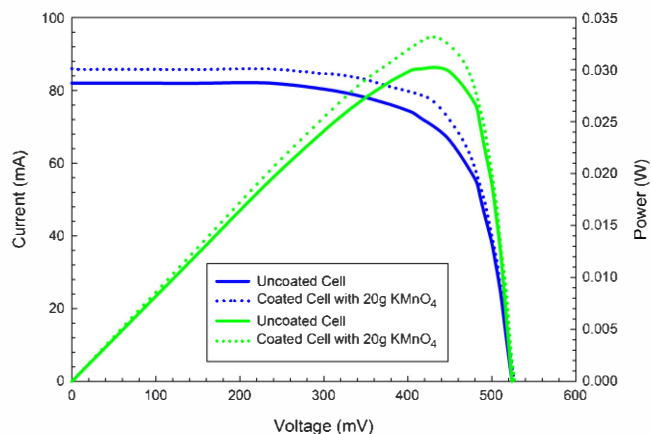

Fig. 2. I-V & PV curves of the coated and uncoated cell under visible light source.

Figure 3 shows the electrical conversion efficiency of the cells against the weight mass of the KMnO$_4$ under Ultraviolet (UV) and Visible (Vis) Light. Under Visible light illumination, it can be seen from the graph that the efficiency increases with the increasing value of the KMnO$_4$ until it reaches an optimum value then it is starting to decrease. An increase of the mass weight of KMnO$_4$ introduced in the coating chamber increases the amount of oxygen released due to thermal decomposition of KMnO$_4$. Since the coating parameters were similar for all the coated cells. It means that the oxygen diffusion within the silicon nanoparticle affects significantly the electrical conversion efficiency of the cell. For the purpose of proving the photon down-conversion effects present during the I-V measurements, the cells were tested with a high energy excitation UV light illumination, the measurements resulted in

higher values of the short circuit current compared to the measured results under halogen light. This improvement in current can be ascribed to absorption within Si-nps embedded in the oxide matrix [8].

TABLE 2
ELECTRICAL CHARACTERISTICS OF THE UNCOATED AND COATED CELLS AT 290W/M^2 AND 20 ˚C

Coating	V_{oc} (mV)	I_{sc} (mA)	P_{max} (W)	FF (%)	η (%)
Uncoated	524	82	0.30096	0.70	12.14
C_1	527	81	0.30816	0.72	12.43
C_2	527	88	0.32560	0.70	13.14
C_3	527	86	0.33072	0.72	13.34
C_4	524	83	0.30587	0.70	12.34
C_5	527	81	0.28544	0.66	11.52
C_6	524	77	0.27537	0.68	11.11

Also, an important increase in the open circuit voltage for the coated solar cells is observed. This increase is directly related to the rise in photocurrent. This increase in the open circuit voltage corresponds to the results obtained in [5].
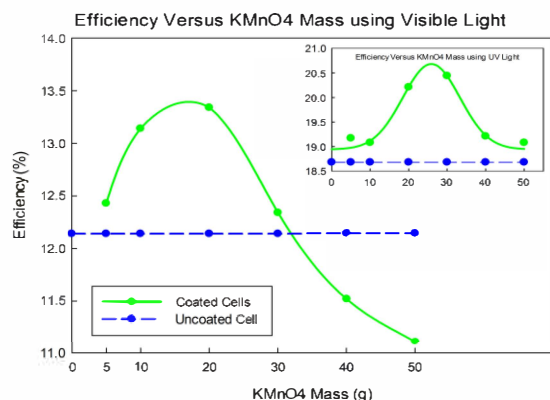

Fig. 3.   Efficiency versus KMnO$_4$ mass under visible and ultraviolet light.

Figure 4 shows a schematic of the coated and uncoated cells and the chemical composition of the deposited element on the surface of the solar cell. It can be seen for the uncoated cell the presence of N and Si because the commercial cell is coated with antireflection layer of Si$_3$N$_4$. However, the uncoated cell shows presences of C, O and Si due to using TMS precursor during PECVD process and the presence of the O is because the oxidizing potassium permanganate. The electrical conversion efficiency could be further enhanced by optimizing the PECVD deposition process growth parameters to lower the impurity content of silicon nanoparticles that are incorporated in the compound such as carbon during the PECVD process.

IV.   CONCLUSION

In this study, we investigated the effects of applying silicon nanoparticles on top of pyramidal textured mono-crystalline Si solar cells fabricated by PECVD using TMS precursor and oxidized with potassium permanganate on the electrical conversion efficiency. With optimized oxygen diffusion in the silicon nanoparticles, a relative increase in the power conversion efficiency of the mc-Si solar cell by about 10% is achieved due to the improvement in the spectral response and

short circuit current in the coated cell caused by the absorption of high energy photons within the silicon oxide layer and the remission of red light to the body of the solar cell.
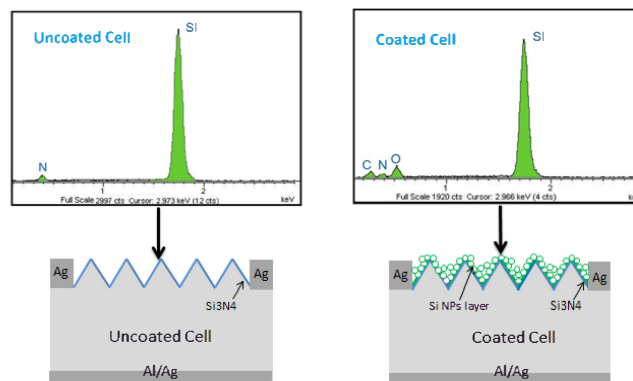

Fig. 4.   A schematic of the coated and uncoated cell and SEM surface composition analysis spectrum.

This study demonstrates that nanoparticles films contribute significantly to efficiency enhancement of solar cells at low manufacturing cost.

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