European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

3% absolute efficiency gain on multicrystalline silicon solar cells by TiO_2 antireflection coatings derived by APCVD process

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Abstract. This paper reports about the adaptation of the CVD thin films technology to the fabrication process of multicrystalline silicon (mc-Si) solar cells which is the key issue of modern method of photovoltaic power generation. In this contribution, the higher reflection of a mc-Si solar cell surface is strongly reduced by the deposition of TiO_2 antireflection coating (ARC) on the front using CVD method at atmospheric pressure (APCVD). The surface morphology and elemental composition of the TiO_2 antireflective layers were revealed using Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive X-ray Spectroscopy (EDS). The reflectivity was then reduced from 35% to 8.6% leading to the increase of the short circuit current J_{sc} which was about 33.86 mA/cm² with a benefit of 5.23 mA/cm² (surface area = 25 cm²) compared to reference cell (without ARC). This simple and low cost technology induces a 14.26% conversion efficiency which is a gain of + 3% absolute in comparison to reference cell. These results are encouraging and prove the effectiveness of the APCVD method for efficiency enhancement in silicon solar cells.

Keywords

Titanium dioxide, APCVD, solar cell, antireflection coating, efficiency.

1. Introduction

There is a variety of viable renewable energy resources in progress; among them photovoltaics is the most promising as a future clean and sustainable energy technology to replace fossil fuels. The increase in the photovoltaic (PV) market requires the development of high and cost-effective silicon solar cells processing technologies based on the optimization of the "cost" to "efficiency" ratio for larger scale mass production. Recently, multicrystalline silicon (mc-Si) solar cells predominate the market share and account for 50 % of all the PV modules manufactured worldwide [1] because of its lower manufacturing cost at the mass production level [2] combined with relatively high conversion efficiency and high reliability. However, the efficiency of these photovoltaic devices is limited by a number of factors including optical losses caused by the reflection of solar radiations from the cell surface. So, the cost-effective fabrication of an indispensable antireflection coating which should be included at the top surface of solar cells, still the most important manufacturing steps of silicon solar devices. In this context, the adaptation of the CVD thin films technology to the fabrication process of multicrystalline silicon solar cells is the key issue of modern method of photovoltaic power generation. In fact, due to its cost effectiveness, the CVD processing technology becomes an important issue for the large-scale spread of photovoltaic technology across the energy market. CVD is simple, low cost and very effective technology for efficiency improvement in silicon solar cells by reducing reflection and improving the light-generated current. The APCVD or Atmospheric Pressure Chemical Vapor Deposition is the most promising variant of CVD methods for antireflection coatings manufacturing steps due to its compatibility with industrial requirements such as high throughput deposition, high process speed, suitability to large area and mass production. In fact, Wong [3] demonstrates the capability of the APCVD system of depositing TiO_2 onto 580 solar cells per hour. Moreover, as the name implies, there are no requirements of vacuum. Usually, the most widely used materials as ARC in silicon solar cells are: Titanium dioxide (TiO_2), Tin dioxide (SnO_2), Zinc oxide (ZnO), Silicon nitride (Si_3N_4), Zinc sulphide (ZnS) [4], [5], [6]. Among them, TiO_2 appears as the best choice for this application in industrial use due to its excellent antireflection properties such as a high refractive index [7], [8] and excellent transmittance in the visible and near infrared region of the solar spectrum [9], [10]. Since TiO_2 is highly transparent, it acts like a window for the transmission of solar radiations. In addition, it presents a very good chemical resistance and an excellent stability at high temperature [11]. The use of such TiO_2 layers derived by APCVD in multicrystalline silicon solar cell production depends on the possibility of improving the photovoltaic device performance.

In this paper we report the results of a study assessing the impact of the TiO_2 antireflection coating derived by APCVD process on the electrical performance (open circuit voltage, short circuit current, fill factor and efficiency) of multicrystalline silicon n^+/p structure solar cell. For this purpose, these solar cells were characterized by current-voltage *(I-V)* measurements in the dark and under illumination (AM 1.5 solar spectrum, 100 mW/cm², 25°C) using a sun simulator. We demonstrated that significant improvement in short-circuit current and thus efficiency of the cells were possible and the related results were compared to reference cells (without antireflective layers). Furthermore, the TiO_2 antireflective layer deposited on the front surface was characterized by Scanning Electron Microscopy (SEM), and its reflectance was measured by UV-Vis Reflectance Spectrophotometry.

2. Experimental details

A. TiO_2 antireflection coating formation

In this work, we present a simplified and fast procedure for increasing the efficiency of mc-Si solar cells. For this study, we performed our experiments on mc-Si solar cells without antireflection coatings (as reference cells) originate from UDTS Institute (Algiers, Algeria). The solar cell of 10 × 10 cm² was divided into 5 × 5 cm² samples using a diamond cutter. Each sample has a bus bar which is perpendicular to the finger electrodes. Those fingers have the width of 161.6 µm and were aligned with intervals of 2.29 mm on each sample. The cells have a conventional n^+/p structure, a thickness of 300 µm and a junction depth of 0.5 µm. A 60 nm thin film of TiO_2 as the antireflective layer was deposited on the front surface of these cells from the titanium tetrachloride ($TiCl_4$) precursor using an APCVD equipment at 450°C.

Our APCVD system consisted of three (03) parts interconnected of:

- APCVD reactor consisting of a reaction chamber equipped with a substrate holder, and a heating system with temperature control;
- Chemical vapor precursor supply system;
- Gas system consisting of oxygen (O_2) and nitrogen (N_2).

The formation of the TiO_2 antireflection coating proceeds as follow:

a) Generation of the $TiCl_4$ vapor precursor delivered to the CVD reactor;
b) Transport of the $TiCl_4$ vapor into the reaction chamber by oxygen as a carrier gas;
c) The reaction of the $TiCl_4$ vapor with oxygen gas and TiO_2 formation by oxidation taking place by the reaction:

$$TiCl_4(g) + O_2(g) \rightarrow TiO_2 + 2Cl_2(g)$$

The TiO_2 antireflective layers were deposited in the standard conditions presented in Table I.

Table I. Deposition conditions of APCVD for the TiO_2 antireflection coatings

APCVD process parameter	Value
O_2 flow rate	1 L min^{-1}
N_2 flow rate	0.5 L min^{-1}
$TiCl_4$ heating temperature	68°C
Deposition temperature	450°C
Deposition time	15 min

B. Solar cell characterization

We used solar simulator to get *I-V* curves of the solar cells with/without antireflective layers. Furthermore, we observed the TiO_2 surfaces with a scanning electron microscope (SEM) which is equipped with Energy Dispersive X-ray Spectrometer (EDS). We also performed the optical reflection measurements in the wavelength range 300-1150 nm by means of “VARIAN Cary 500 Model ultraviolet-visible-near infrared (UV-Vis-NIR) spectrophotometer equipped with an integrating sphere.

3. Results and discussion

A. SEM-EDS analysis

The surface morphology and elemental composition of the TiO_2 antireflective layers were revealed using Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive X-ray Spectroscopy (EDS). We have taken one film of TiO_2 from the deposited films as representative for the SEM study. A typical TiO_2 film grown at optimum conditions using $TiCl_4$ is shown in Fig. 1. The TiO_2 film shows compact, uniform and dense surface morphology with small grains homogeneous in size. Typically, the corresponding EDS spectrum is presented in Fig. 2, which expressly confirms that the layers contain titanium (Ti) and oxygen (O) elements. A similar EDS pattern was obtained by [12]. No chlorine element was detected in the spectrum, it implies that the $TiCl_4$ precursor have been decomposed completely before the deposition.

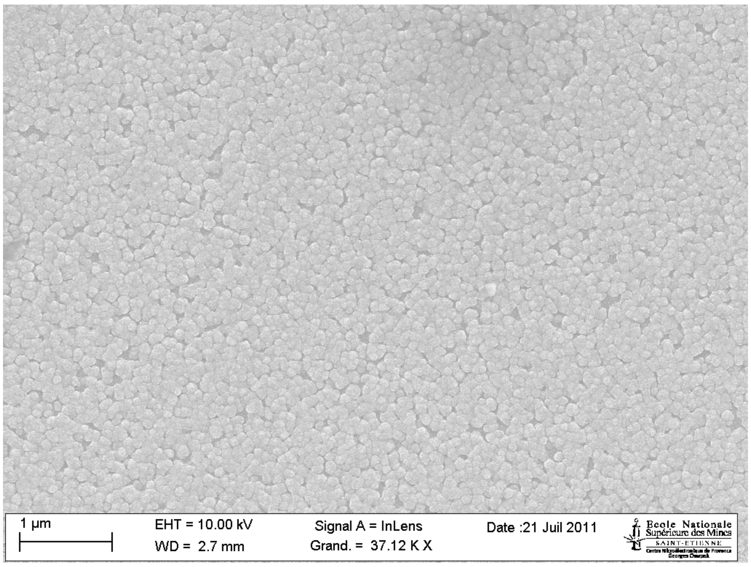

Fig.1. SEM image of surface morphology of a typical TiO_2 thin film deposited by APCVD

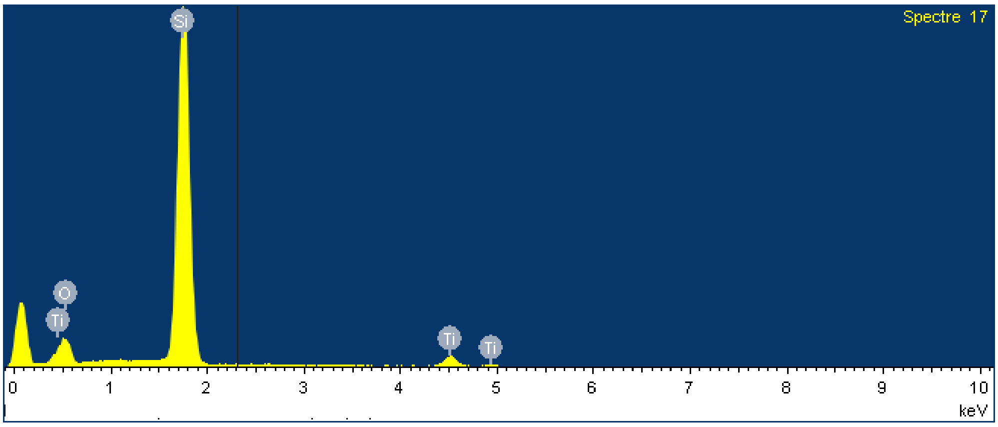

Fig.2. The corresponding EDS spectrum of the TiO_2 thin film

B. Reflectance measurements

The mc-Si solar cell suffers from a high natural reflectivity at the surface which reduces the short circuit current and thus the efficiency of the device. Therefore, the reduction of optical losses consisting in reflection of the part of incident light from the front surface of the cell is extremely important for efficient solar device. The UV-Vis reflectance spectra for the TiO_2 thin films in the wavelength range from 300 nm to 1150 nm, are shown in Fig. 3. The reflection of the bare multicrystalline silicon substrate is about 35%, and the value was reduced to 8.61% as the minimum average reflectance after the deposition of the TiO_2 antireflection coating. Similar value of reflectance was obtained by B.S. Richards [13] for TiO_2 as antireflection coating.

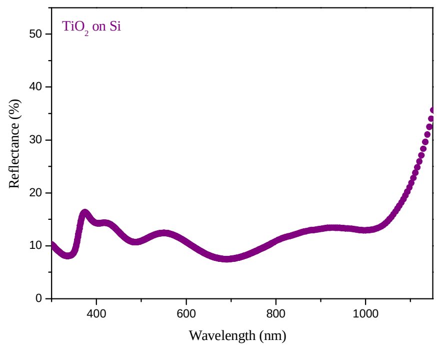

Fig.3. UV-Vis Reflectance spectra of the APCVD deposited TiO_2 thin film

C. Solar cell results

The light I-V characteristics of mc-Si solar cells with/without antireflection coatings were measured; the typical experimental results are summarized in Table II, and the resulted curve is shown in Fig.4 for an optimum conditions.

The most important electrical parameter for the solar cell industry is efficiency η because it incorporates the open circuit voltage (V_{co}), short circuit current (J_{cc}) and fill factor (FF) as given by equation (1).

$$\eta = V_{co}.I_{cc}.FF/P_{in} \quad (1)$$

where P_{in} is the incident light intensity.

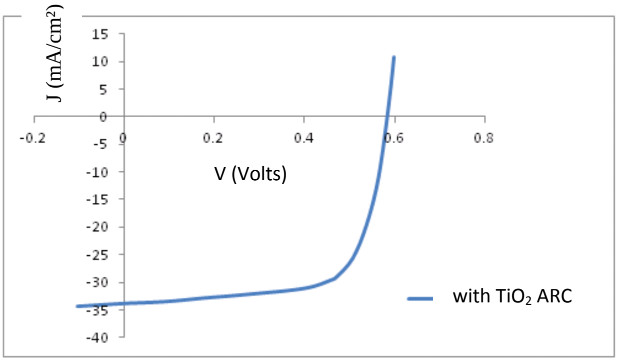

Fig.4. Light I-V characteristic of a typical mc-Si solar cell with TiO_2 antireflection coating (ARC)

From the data given in Table II, the solar cell with antireflection coating has shown the best photovoltaic performance, in particular, a short circuit current J_{sc} of 33.86 mA/cm² which increases by ΔJ_{sc}= 5.23 mA/cm² compared to reference cell (without ARC). This consequently gives a maximum cell efficiency of 14.26% which is a gain of + 3% absolute in comparison to reference cell. According to these results, the improvement in conversion efficiency of solar cells is mainly attributed to the increase in the short circuit current due to the reduction of reflectivity from the front surface and the enhancement of light transmission by the TiO_2 antireflective layer. From [14], the industrial solar cells fabricated from multicrystalline silicon have conversion efficiency around 14%. The photovoltaic parameter results obtained for our solar cells are in good agreement with those reported by [15].

Table II: Evolution of the experimental electrical parameters for mc-Si solar cells with and without antireflection coating.

Cell	**J_{sc} (mA/cm²)**	**V_{oc} (mV)**	**FF**	**η (%)**
mc-Si solar cell without ARC (reference cell)	28.63	561	0.70	11.24
mc-Si solar cell with TiO_2 ARC	33.86	585	0.72	14.26

Conclusion

The use of the APCVD technique for the formation of the TiO_2 antireflective layer on the front surface of mc-Si solar cell can enhance its power conversion efficiency by 3% in absolute value (surface area = 25 cm²). The improvement in efficiency of mc-Si solar cell from 11.24% to 14.26% is mainly attributed to the increase in short circuit current density from 28.63 mA/cm² to 33.86 mA/cm² with a benefit of ΔJ_{sc} = 5.23 mA/cm² due to the reduction of reflectivity from the front surface and the enhancement of light transmission by the TiO_2 antireflection layer.

The results confirm the effectiveness of the CVD technology for efficiency improvement in mc-Si silicon solar cells which is compatible with industrial requirements. Thanks to cost reduction and improved efficiency, the CVD technology offers a way to increase the competitiveness of mc-Si solar cells and has a great potential for large commercial scale production.

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