A Cost Effective Solution for Large Area Transparent Conductive Coatings for Solar Cells

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ABSTRACT

A vertical in-line DC sputtering system with rotary magnetron sputtering source has been designed and developed for the deposition of aluminum-doped zinc oxide (AZO) on Gen 5.5 glass substrates. An in-line conveyorized chemical bath for post-deposition texturing of the AZO films has also been developed. By optimization of the sputtering process parameters, and the chemical texturing, substrates suitable for front contact applications have been fabricated. Single junction amorphous silicon solar cells and modules fabricated on the substrates are found to give comparable performance to that of commercial fluorine-doped tin oxide (FTO) substrates. The details of the processes developed are given, and other possible applications of the system are outlined.

INTRODUCTION

Transparent Conductive Oxide coatings find applications in numerous areas such as solar cells, architectural glasses, electrochromic coatings, displays, etc. Considerable work has being going on in the development of Aluminum doped Zinc Oxide (AZO) based TCO films for solar cells due to its low cost, high electrical conductivity, and optical transparency in the visible and the NIR region. Also, the fact that controlled texturization of the AZO surface can be established by chemical means makes it ideally suited for solar cell applications [1].

Continuing on the earlier developments of in-line coating systems for solar applications [2], a vertical in-line DC sputtering system with rotary magnetron sputtering source has been developed and the deposition of aluminum-doped zinc oxide (AZO) films has been carried out on Gen 5.5 glass substrates. In order to texturize the as-deposited AZO films for them to be effective for solar cell applications, a post-deposition chemical etching process is carried out in a conveyorized etching/ cleaning machine. The sputter deposition conditions and texturizing parameters have been optimized to obtain AZO films suitable for top contacts in amorphous silicon solar cells. Single junction amorphous silicon solar cells and modules have been fabricated on the AZO substrates and commercial FTO substrates for a comparison of performance.

EXPERIMENTAL

The system developed for carrying out the TCO coatings is shown in figure 1. The system consists of a loading/unloading station, and 3 vacuum chambers. Since the system is run in the developmental mode, both the loading of the glass substrates, and the unloading of the coated substrates are done at the same end of line. The first of the 3 chambers is used as the load-lock chamber for entry/exit while the other 2 process chambers are maintained at high vacuum. The rotary magnetron is located in the central chamber, i.e. process chamber 1. During the course of deposition, all the 3 chambers are combined and the glass is swept back and forth the required number of times in front of the magnetron to obtain the desired thickness.

Figure 1. Vertical in-line sputtering system for large area TCO coatings

An important design feature is the frame-less glass holding, making the entire area of the substrate useful for coating, and more importantly simplifying the manufacturing cycle as there is no requirement to move the substrate holder back to home position following deposition in industrial setups. The entire system is tilted by an angle of 10 ° w.r.t the vertical for this purpose. The system employs a rotary magnetron with a hollow cylindrical target (AZO, 2 wt % Al_2O_3) for the deposition of the AZO films. The target consists of cylindrical segments whose dimensions are ID of 132.5 mm and a thickness of 16 mm and total length of 1500 mm. The distance between the target and the substrate is ~ 70 mm. The substrates used are float glass sheets of thickness 3 mm. For the transportation of glass inside the vacuum chamber, the system employs graphite pads on which the glass substrate rests, and a chain and belt arrangement compatible with high deposition temperatures which supports and moves the glass. The pumping system includes dry roughing pumps and turbo molecular pumps, and the base vacuum is of the order of 5 x 10^{-6} mbar. The sputtering trials have been carried out a pressure of 2 x 10^{-3} mbar with the introduction of Argon gas.

The post-deposition texturization of the sputtered AZO films is carried out by uniformly spraying a diluted HCl solution onto the face of the films as the glass is moved across the conveyorized chemical etching system. Subsequent rinsing, cleaning, and blow drying sections are built in to the machine to clean the glass following the etching step.

Figure 2. The conveyorized etching/glass cleaning machine.

The thickness of the deposited films have been determined using a Stylus Profiler (Dektak 6M, Veeco Instruments). The optical properties of the AZO films were characterized using a UV-Vis-NIR double beam Spectrometer (Perkin Elmer, Lambda 750) with a 60 mm Integrating Sphere attachment. The sheet resistance of the films was measured using a four probe sheet resistivity meter (NAGY SD-510). The surface morphology has been studied using a Zeiss Ultra-55 FESEM. The hall measurements were done in van der Pauw configuration using a Ecopia HMS 5300 system. The I-V characteristics of small area cells (active area: 1cm^2) were measured under a 100 mW/cm^2 intensity light source using a Keithley 6487 Electrometer. The I-V characteristics of 1 ft x 1 ft modules were measured in a module tester Model No. SNMTA-XP 105-9 from Spectranova, Canada.

RESULTS AND DISCUSSION

The films have been deposited at substrate temperatures ranging from room temperature to 300 ° C, and the resultant electrical and optical properties have been studied. In all the cases, the thickness of the AZO films is in the range of 1.25 ± 0.2 microns.

Table 1. Electrical and optical properties of AZO films deposited at different substrate temperatures. The average transmission values given are glass compensated values i.e., the transmission value for the film only.

Temperature	**Carrier Concentration (x 10^{20}/cc)**	**Mobility (cm^2/V.s)**	**Resistivity (Ω.cm)**	**Avg Transmission % (380 – 780 nm)**	**Avg Transmission % (380 – 1100 nm)**
RT	3.13	17.7	1.12E-03	74.1	75.8
150	3.16	20.2	9.79E-04	71.2	72.5
200	5.13	22.9	5.30E-04	78.0	76.0
250	4.71	19.9	6.66E-04	84.4	80.3
300	3.14	20.8	9.56E-04	90.3	86.5

It is found that the lowest resistivity values are obtained at a substrate temperature of 200 °C, but the corresponding optical transmission is poor, and the best combination of transmission and resistivity are obtained at a substrate temperature of 300 °C.

The addition of small amounts of oxygen of up to 2 % of the gas mixture results in reduced resistivity, beyond which the resistivity values start increasing.

Upon etching in diluted HCl solution, the surface gets texturized resulting in the formation of uniformly distributed craters on the surface. The optimized etchant concentrations used in this case is ~ 0.02 wt % which is much lower than the values of ~ 0.5 wt % reported by other works

[3,4]. The lower concentrations of HCl required in this case compared to the values reported by others could be resulting from the use of the spray technique which is effective at removing the precipitates formed on the surface from to the etching, thereby exposing a fresh film surface to the etchant solution, and thus increasing the etching potential of the solution. In addition, the lower concentration of the HCl solution also leads to a greater control over the etching and the resultant sheet resistance of the textured films. The etching time is adjusted in order to maintain a sheet resistance of 10 Ω/□ after the texturization. The HRSEM image of the textured sample is given in figure 3. The surface features are of the order of ~ 300 nm, and the resultant haze value @ 600 nm is ~ 16.9 %. The Haze value can be further increased by increasing the etching time or the acid concentration, or both.

Figure 3. HRSEM image of the textured AZO sample taken with a 60 ° sample tilt.

In order to check the effectiveness of the texture for thin film solar cells, single junction amorphous silicon solar cells have been fabricated on the AZO substrates, and on commercially procured fluorine-doped tin oxide (FTO) substrates for comparison. The depositions of the solar cell layers have been done in a home built in-line PECVD system capable of handling two substrates of size 1 ft x 1 ft simultaneously. The recipe adopted for the solar cell structure is based on oxygen alloyed p, and buffer layers that was optimized earlier in the group [5]. For small area solar cells fabricated with an active area of 1 cm x 1 cm, fill-factors comparable to FTO substrates and higher have been obtained on AZO substrates with the use of oxide-alloyed hydrogenated amorphous silicon p-layers without the need for intermediate micro/nano crystalline layers [6]. The current densities and corresponding efficiencies obtained on both substrates are also comparable showing the suitability of the texture for solar cells.

Figure 4. I-V Curves of best efficiency small area solar cells with thermally evaporated back contacts on FTO and AZO substrates.

Following the fabrication of small area solar cells, modules have been fabricated on 1 ft x 1 ft substrates, using IR (1064 nm) and Green (532 nm) laser scribing for integration. It is observed that the P1 scribing using IR laser which is effective for the case of FTO substrates is not effective in the case of the AZO layers leading to lowering of module fill-factors. But the current densities obtained on AZO substrates are found to be slightly higher resulting in an overall comparable performance between the two substrates.

CONCLUSIONS

A vertical in-line rotary magnetron sputtering system and a conveyorized chemical etching machine has been developed for fabrication of AZO based TCO substrates for solar cells. The process recipe has been optimized for obtaining substrates with suitable electrical, optical and surface properties for fabrication of amorphous silicon solar cells. In order to establish the suitability of the substrates, small area solar cells and 1 ft x 1 ft solar modules have been fabricated on the AZO substrates and commercially procured FTO substrates. Comparable performances are obtained on both substrates.

With the use of cost effective manufacturing technology refined over several years of research, coating equipments are offered at competitive costs for the deposition of large area coatings such as TCO films for CIGS, CdTe, HIT, a-Si, low emissivity coatings, and for various other metallic and dielectric coatings.

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REFERENCES

1. B. Rech and H. Wagner, "Potential of amorphous silicon for solar cells,"Appl. Phys. A: Mater. Sci. Process. 69 (2), 155 – 167, 1999.
2. C. Banerjee, P.M. Ratheesh Kumar, K. Mohanchandran, S. Prasanth, and A.K. Barua, "Realization of a Cost Effective Production Technology for Single Junction Amorphous Silicon Solar Modules," Conference Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition (EU-PVSEC), 2011.
3. J. Muller, G. Schope, O. Kluth, B. Rech, M. Ruske, J. Trube, B. Szyszka, X. Jiang and G. Brauer, "Upscaling of texture-etched zinc oxide substrates for silicon thin film solar cells," Thin Solid Films 392, pp. 327 – 333, 2001.
4. Jurgen Hupkes, Jorj I. Owen, Sascha E. Pust, and Eerke Bunte, "Chemical Etching of Zinc Oxide for Thin-Film Silicon Solar Cells," ChemPhysChem 13, pp. 66 – 73, 2012.
5. Gourab Das, Sourav Mandal, M. Rajive Tomy, Chandan Banerjee, Sumita Mukhopadhyay, and A. K. Barua, "Development of oxide based window and buffer layer

for single junction amorphous solar cell: Reduction of light induced degradation," Materials Science in Semiconductor Processing 24, pp. 50–56, 2014 .

6. M. Kubon, E. Boehmer, F. Siebke, B. Rech, C. Beneking, and H. Wagner, "Solution of the ZnO/p contact problem in a-Si:H solar cells," Solar Energy Materials and Solar Cells 41/42, pp. 485-492, 1996.