Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2014, Article ID 972828, 6 pages
http://dx.doi.org/10.1155/2014/972828

Research Article

Block Textured a-Si:H Solar Cell

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Received 13 March 2014; Revised 5 May 2014; Accepted 26 May 2014; Published 23 June 2014

Academic Editor: Mohammad Yusri Hassan

A series of etching experiments on light trapping structure have been carried out by glass etching. The block structure provides long light traveling path and a constant distance between the cathode and anode electrodes regardless of the block height, which results in higher efficiency of the block textured solar cell. In terms of etching profile of the glass substrate, the addition of NH_4F resulted in the smooth and clean etching profile, and the steep slope of the block was obtained by optimizing the composition of etching solution. For a higher HF concentration, a more graded slope was obtained and the addition of HNO_3 and NH_4F provided steep slope and clean etching profile. The effects of the block textured glass were verified by a comparison of the solar cell efficiency. For the textured solar cell, the surface was much rougher than that of the plain glass, which also contributes to the improvement of the efficiency. We accomplished block shaped light trapping structure for the first time by wet etching of the glass substrate, which enables the high efficiency thin film solar cell with the aid of the good step coverage deposition.

1. Introduction

The demand for renewable energy sources is increasing and the installation of photovoltaic (PV) systems on roofs or the facades of buildings in urban areas is expected to increase. According to the designed concept of esthetics and practicality, it is desirable for PV systems to blend in with the buildings and cityscapes [1]. To realize this, considerable efforts have been made to achieve the low cost of solar cells [2] and high conversion efficiency. Maximum stabilized efficiencies of more than 10% could be achieved for the best modules using the monolithic tandem interconnection of an hydrogenated amorphous silicon (a-Si:H) junction with microcrystalline silicon (μc-Si:H) [3].

Texturing is one way of increasing the solar cell efficiency. Light scattering at textured interfaces is essential for the high efficiency of thin film solar cells [4, 5]. The a-Si:H solar cells considered in this paper are widely accepted thin-film solar cells because (a) silicon is abundant and nontoxic, (b) the process temperature is low, enabling module production on flexible and low cost substrates, (c) the technological capability for large-area deposition exists, such as plasma enhanced chemical vapor deposition (PECVD), and (d) the material requirements are low, 1 to 2 μm, due to the high absorption coefficient compared to crystalline silicon [6–9]. On the other hand, the efficiency of a-Si:H solar cells is approximately 10%, which is still lower than that of other solar cells, and texturing is one way of increasing the efficiency [10].

Reduction of the front surface reflectance, a good back surface reflector, and texturing are important for achieving the full benefits of optical absorption enhancement [11, 12]. In terms of texturing, one method involves etching the substrate. Surface texturing can reduce the light reflectance on the surface of cells quite efficiently and achieve enhanced light absorption inside the cells compared to flat surface cells [13, 14]. A low cost surface texturing method by wet etching using an alkaline solution is used widely for improving the short circuit current of the cells [15, 16]. To achieve the high efficiency, the transmitted light should be trapped in the solar cells to avoid escaping from the solar cell surfaces until it is absorbed [17]. Light trapping structures have been reported such as pyramid structure in crystalline silicon solar cell [16–20]. However, glass etching was not reported for the light trapping structure, and even the antireflection structure by glass etching was reported [21]. Therefore, we investigated etching characteristics of the glass for the block structure, which provides a long light traveling path. Block textured glass was prepared by wet etching a glass substrate

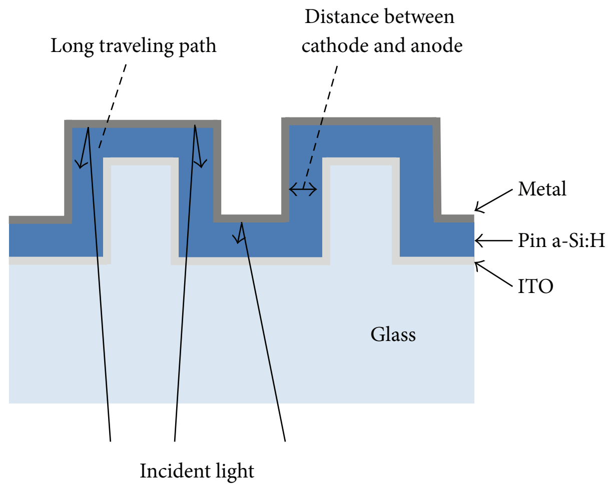


Figure 1: Suggested block textured thin film solar cell that provides long traveling path of the incident light while keeping the distance between the cathode and anode constant.

and a-Si:H solar cells were formed on the textured glass. The block structure as shown in Figure 1 provides a long light traveling path along the sidewall of the block while maintaining the distance between the cathode and anode invariable, regardless of the height of the block which is the traveling path of the light. Therefore, higher efficiency can be obtained using a block structure than that of a solar cell on the conventional plain glass. However, the way to form the block structure for the light trapping was not reported and we succeeded to accomplish a good shape of the block with wet etching. This light trap structure enhances efficiencies while keeping reducing layer thickness which contribute to make a very low cost technology [22, 23].

2. Experiment

For the efficient light trapping, the large height of the block such as 2 to 3 μm is necessary. Large height of the block gives long light traveling path and improves light trapping effect. To obtain the block shape, the glass was etched using chemicals containing hydrofluoric acid (HF) and the etching condition was optimized.

The chemical composition and other etching conditions were varied to obtain the optimal block structure. The etching temperature was fixed at 40°C and the etching time was varied up to 200 s. The etching was carried out at different HF concentrations (10 wt.%, 20 wt.%). The chemicals used for etching were HF, HNO_3, and NH_4F, the compositions of which were optimized for the best block shape. Table 1 lists the etching rate under a range of etching conditions. The Cr was used as the masking material during glass etching [24]. In the case of the HF-only etching solution, the etching rate was high and the Cr mask was unable to endure the process [25, 26]. HNO_3, H_2SO_4, and NH_4F were tested to achieve a clean and high taper angle. Figure 2 shows the etching process by photolithography. Initially, a Cr layer was deposited after cleaning the glass. After Cr mask patterning by lithography, the glass substrate was etched to form a block structure. After glass etching, the photoresist was removed. All experiments were carried out with a constant temperature bath. After etching, the surface of textured glass was examined by scanning electron microscopy (SEM) to observe the surface morphology and determine the etching rate.

After texturing the substrate, a-Si:H solar cell with the structure of ITO (indium tin oxide)/P-type a-Si:H/intrinsic a-Si:H/N-type a-Si:H/Al, was deposited. The silicon layers were deposited by PECVD and Al and ITO layers were deposited by sputtering. Initially, the ITO layer was deposited at a RF power of 50 W, process pressure of 2 mTorr, and 20 sccm of Ar gas. Subsequently, the p-i-n a-Si:H layers were deposited by PECVD at 250°C. The p-layer was prepared from a mixture of $SiH_4/H_2/B_2H_6$ at a flow ratio of 150/120/60. The i-layer was prepared from a mixture of SiH_4/H_2 at a flow ratio of 150/120. The n-layer was prepared from a mixture of $SiH_4/H_2/PH_3$ at a flow ratio of 150/120/30. An Al layer was deposited at a RF power of 125 W, process pressure of 5 mTorr, and 20 sccm of Ar gas. Table 2 lists the processing conditions of the a-Si:H solar cells.

3. Result and Discussion

In the suggested block textured solar cell, the shape of block texturing is important for achieving high conversion efficiency and the etching of the glass was investigated. After etching the glass, the shape was observed by scanning electron microscopy (SEM) for the various etching conditions as shown in Figure 3. HF is a typical glass etching solution; however, it was uncontrollable for high etching rate as it increased the concentration of HF and resulted in nonuniform etching surface profile. Therefore, other chemicals such as H_2SO_4, HNO_3, and NH_4F were investigated for better etching profile. In Figure 3, 1-1 and 1-2 show the etching results without NH_4F, in which the etching surface was not uniform and as it increased the HF concentration etching rate increased as well as the surface roughness and nonuniformity. The effect of H_2SO_4 is shown in 2-1 and 2-2. Addition of

TABLE 1: Etching rates according to the composition of the etching solution.

Number	Time (s)	Etchant (wt.%)				Etching rate (μm/s)
		HF (49%)	HNO_3	H_2SO_4	NH_4F	
1	60	20	15	—	—	0.05
2	60	20	15	—	15	0.04
3	60	10	—	15	—	0.03
4	60	10	—	15	15	0.02
5	60	10	15	—	—	0.01
6	60	10	15	—	15	0.03

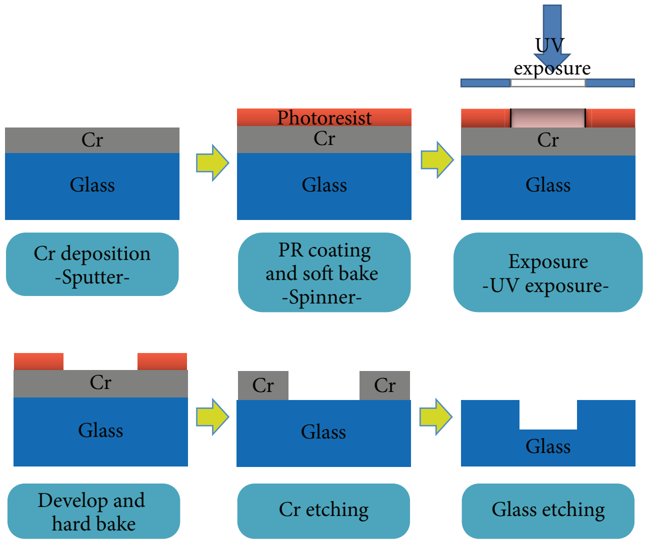


FIGURE 2: Texturing process by wet etching.

H_2SO_4 increased the etching rate compared to the addition of HNO_3 and the etching surface was not much uniform. The addition of NH_4F improved the nonuniformity of the etching surface; however, the surface was still not uniform. The clean etching was obtained at an etching solution with HF, HNO_3, and NH_4F, as shown in 3-1 and 3-2. Without NH_4F, the etching profile was not clean, and the optimal condition was a solution containing 10 wt.% HF, 15 wt. % HNO_3, and 15 wt.% NH_4F under the etching temperature of 40°C.

Under these optimized etching conditions, experiments were conducted at various etching times. The SEM image of Figure 4(a) presents the etching profiles according to the etching times. With increasing etching time, the etched depth increased and isotropic etching was observed. In terms of the etching cross section, the upper part showed a stiff etching profile, whereas the lower part showed a slow etching profile. After an etching time of 200 s, 3.06 μm height of the block was obtained, and the etching depth is shown in Figure 4(b).

At higher HF concentrations, a more graded slope was obtained, and the addition of HNO_3 and NH_4F produced a steeper slope and a clean etching profile. After fine adjustment of the solution, an optimized block-textured surface of the glass was obtained as shown in Figure 5. An a-Si:H solar cell was formed on the block textured glass and compared with the solar cell on the conventional glass substrate. Among the solar cells on the various slope block textured glass, the one with the steep slope did not operate well, which was attributed to a short between cathode and anode electrode due to the steep slope which results in thin layer of deposition material. However, the improved environment free of particles, any other contamination, and optimized PECVD conditions would provide high efficiency even with thin layer of the deposited material. Due to the short fail, the efficiency of the solar cell on the slow slope block textured glass was compared with that of the solar cell on the conventional plain glass. Figures 6(a) and 6(b) show SEM images of each type of solar cell, (a) is the solar cell on the conventional plain glass and (b) is the solar cell on the textured glass. The two types of solar cells were fabricated at the same time to be sure of the same characteristics of the solar cells. The efficiencies were measured under a solar simulator with AM 1.5 (1000 W/m^2). Because the traveling paths of the incident light are different between those two samples, it is expected that the two samples will have different efficiencies. Figure 6(b) shows that the surface is much rougher for the block textured solar cells than that of conventional glass, which increases light scattering when the light is reflected at the metal electrode.

The thickness of the i-layer is a key parameter that can limit the performance of amorphous thin film solar cells because it determines the absorption of the incident light and

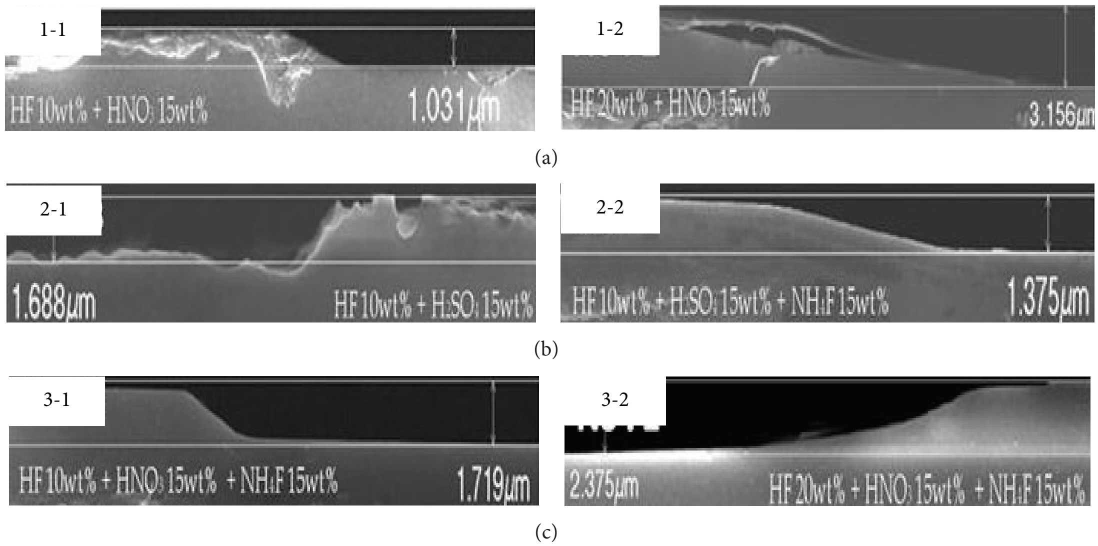


Figure 3: Etching profiles of the glass using different etching solutions; (a) etching results without NH_4F, (b) the effect of H_2SO_4, and (c) without NH_4F.

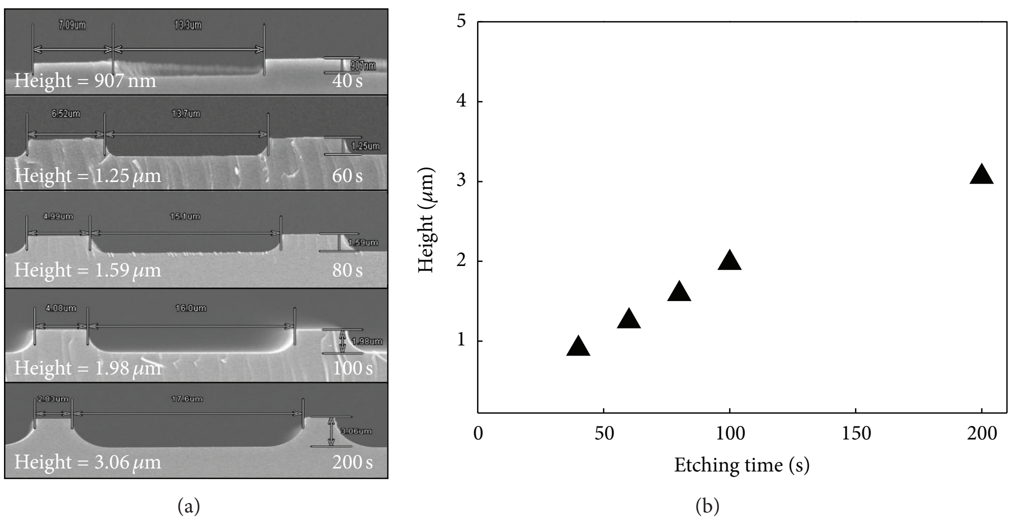


Figure 4: (a) SEM images of the etching profile according to the etching times and (b) the graph as a function of the etching time.

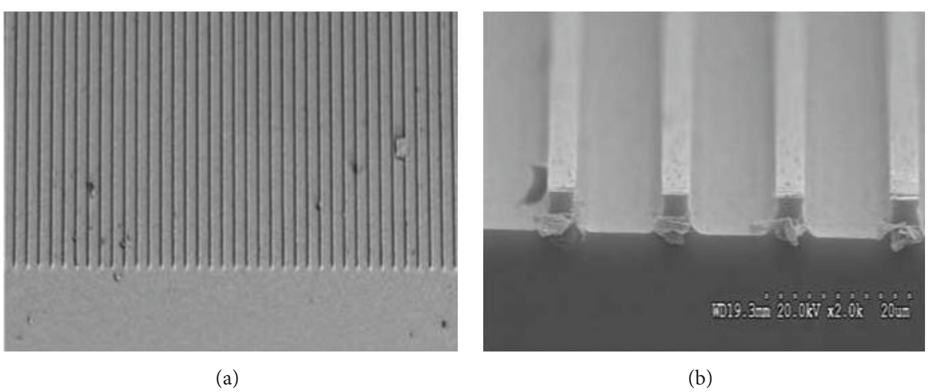
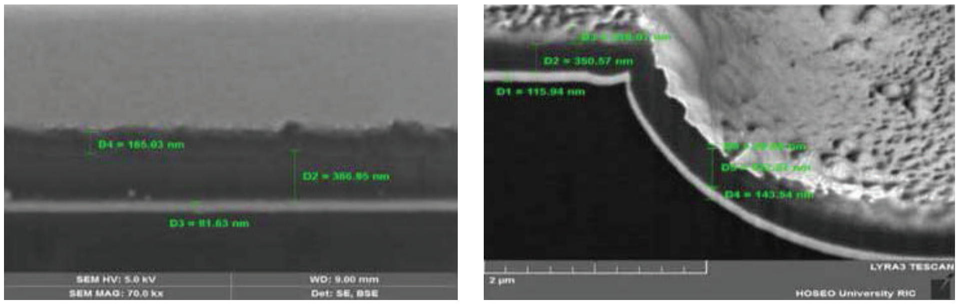


Figure 5: Block textured glass obtained under the optimized etching conditions.

Table 2: Process conditions of a-Si:H solar cell by PECVD.

Layer	Temperature (°C)	Electrode distance (mils)	Working pressure (Torr)	RF power (W)	Gas
N-type	250	1000	1.5	10	SiH_4, H_2, PH_3
Intrinsic	250	1000	1.0	10	SiH_4, H_2
P-type	250	1000	1.5	10	SiH_4, H_2, B_2H_6



(a) (b)

Figure 6: SEM images of a-Si:H solar cell on (a) conventional glass and (b) block textured glass.

Table 3: The comparison of the measured parameters with conventional plain glass substrate and block textured glass substrate.

	V_{oc} (V)	J_{sc} (mA/cm^2)	F.F	Efficiency (%)
Conventional	0.47	6.45	0.43	1.30
Textured	0.54	6.64	0.54	2.00

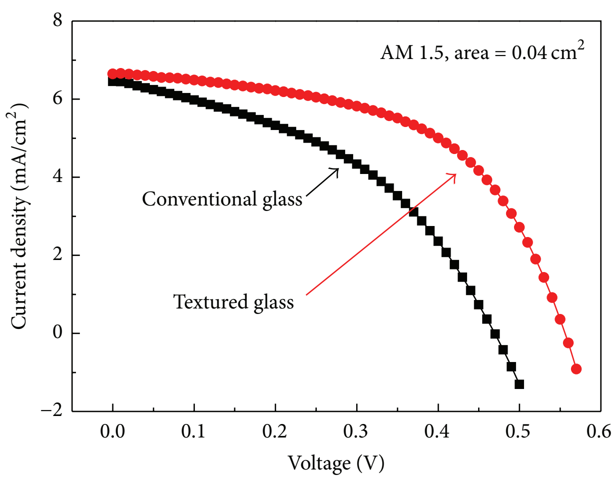


Figure 7: *J-V* curves of the fabricated solar cells.

the drift of the electrons and holes [27]. Since the increased thickness of the i-layer increases the recombination of the carriers, the efficiency decreases. On the other hand, in the suggested block textured structure, the recombination of the carriers can be minimized due to the short electrode distance with thin i-layer, even with the long light traveling path.

Figure 7 shows the *J-V* characteristics of a-Si:H solar cells on conventional glass and textured glass. Although the efficiencies of the solar cells were not high due to nonoptimized environment, a comparison between the two samples was possible because they were fabricated at the same time with the same conditions. The efficiency of the solar cell on the block textured glass was 1.5 times higher than that of the conventional one.

Block textured glass substrate showed higher efficiency than solar cell on the conventional plain glass; measured parameters were shown in Table 3. The short circuit current was not increased as much as the efficiency and can be attributed to the decrease of the short resistance between the cathode and anode due to the rough surface of the solar cell. The rough surface of the block textured solar cell also contributes to the higher conversion efficiency due to the increased light scattering at the back metal electrode. The increased open circuit voltage for the graded block structure was attributed to the decreased contact resistance which can reduce the voltage drop at the contact.

4. Conclusion

To increase the efficiency, we suggested a block textured solar cell, which gives long traveling path of the incident light and maintains the distance between the cathode and anode electrodes invariable. The block structure was obtained by wet etching the glass substrate, and the condition was optimized to obtain a block shape. The addition of NH_4F resulted in the smooth and clean etching profile, and the steep slope of the block was obtained by optimizing the etching solution. For a higher HF concentration, a more graded slope was obtained and the addition of HNO_3 and NH_4F provided steep slope and clean etching profile. After depositing the a-Si:H solar cells on both substrates (conventional and block textured), the efficiencies of the solar cells were compared under the solar simulator with AM 1.5 (1000 W/m^2). For the first time, we developed the etching process for the block textured solar cell for high light trapping. The depth as high as 3.06 μm was achieved with good block shape by optimizing the etching condition. This suggested that block structure provides long light traveling path and low carrier recombination by short distance between cathode and anode.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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