Preparation and topography analysis of randomly textured glass substrates

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Randomly textured glass sheets in combination with a transparent conductive layer are promising as front contacts for silicon based thin-film solar cells. The authors have developed a novel method to create randomly textured glass surfaces. For the fabrication a wet chemically textured zinc oxide (ZnO) film is used as three dimensional etch mask and its surface topography is transferred to the glass substrate by ion beam etching. The typical texture of the sputtered and etched ZnO film exhibits craterlike features, which can be tuned by a variation of the initial ZnO film thickness and the etching time. Thus, the surface features of the resulting rough glass can be varied within a wide range. Its topography exhibits a maximum root mean square roughness of more than 200 nm with a lateral correlation length around 1500 nm. Microcrystalline silicon solar cells on the textured glass substrates show an increase of the short circuit current density by 36% compared to cells on flat glass. This proves the improvement of the so-called “light-trapping” effect in the solar cells by the glass texture. © 2010 American Vacuum Society. [DOI: 10.1116/1.3480338]

I. INTRODUCTION

Regularly or randomly textured surfaces with feature sizes in or below the micrometer range are of interest for various applications such as optical diffusers and antireflective, refractive, or diffractive elements. Especially in thin-film solar cells, diffractive layers or interfaces are used to scatter the impinging light. This may lead to a “light-trapping” effect, which can significantly improve the conversion efficiency of such a device.1 For amorphous and microcrystalline silicon solar cells, usually a randomly textured transparent front electrode on a flat substrate is applied for this purpose.2–4 Magnetron sputtered aluminum doped zinc oxide (ZnO) textured by wet-chemical etching,2 as-grown textured boron doped zinc oxide by low pressure chemical vapor deposition3 and fluoroine doped tin oxide (SnO2) prepared by atmospheric pressure chemical vapor deposition4 have achieved good light scattering and light trapping in silicon thin-film solar cells. Also attempts have been undertaken to create periodic gratings in the transparent front electrode.5,6

An alternative possibility to improve the light-trapping in thin-film solar cells is the use of textured glass substrates. For sputtered ZnO films, the wet chemically etching behavior of ZnO films strongly depends on the sputtering conditions.7 Thus, by using textured glass as substrate the wet-chemical etching process would be obsolete and thus, the film development is simplified. The ZnO films would “only” have to be optimized in terms of transparency and conductivity—but not etching behavior.

Numerous methods to create textured glass surfaces have been investigated in recent years, e.g., sandblasting, powder blasting,8 sol-gel based methods,9,10 dry-etching through a nanostructured metal mask,11 wet-chemical etching with hydrofluoric acid based solutions, aluminum induced texturization,12 hot embossing.13 Furthermore, the foundation of ripples when treating a glass by ion beam has gained interest.14 In Ref. 15, a transfer of a photoresist mask into a calcium fluoride (CaF2) substrate by ion milling is used to create microlenses.

II. FABRICATION PRINCIPLE

Based on this latter method, we have developed a process to create nanotextured glass surfaces with feature sizes in a range which is promising for efficient light trapping in thin-film solar cells.15 The rough glass is produced by continuous argon ion beam etching (IBE) of wet chemically textured ZnO films on glass substrate. Figure 1 shows the fabrication process schematically. The textured ZnO film on glass [Fig. 1(a)] forms a three dimensional mask, which is subsequently milled by IBE. In the deepest valleys of the textured ZnO film, the glass is exposed. At these positions the glass is also etched by the impinging argon ions [Fig. 1(b)]. By prolonged ion beam etching, more ZnO is eroded and thus additional glass surface is uncovered [Fig. 1(c)]. By continuous etching, the features of the ZnO etch mask are subsequently transferred into the glass substrate [Fig. 1(d)]. Variations of the surface features in the glass can be realized by changing (i) the ZnO film thickness, (ii) the ZnO wet-chemical etching time, (iii) the incidence angle of the impinging ions, or (iv) the ion beam etching time.

III. EXPERIMENT

For the fabrication, first, an aluminum doped ZnO layer was prepared on glass substrates by radio frequency (rf) magnetron sputtering from planar ceramic targets with 1 wt. % aluminum oxide (Al2O3) content.17 A low sodium glass type (Corning Eagle XG) was used to avoid effects by
sodium migration. Films with thicknesses of 800 and 1500 nm were etched for different times (between 30 and 330 s) in 0.5 wt. % hydrochloric acid (HCl). The following IBE process was carried out by an anode layer ion source with argon as process gas. The mean incidence angle of the ions can be varied between 0° and 40° in order to achieve maximum sputtering yield. The IBE process was carried out until the ZnO film was totally removed. The ion source was operated at maximum voltage of 3 kV, high argon gas flow of 40 SCCM (SCCM denotes cubic centimeter per minute at STP), and pressure of $1 \times 10^{-3}$ mbar in order to achieve highest possible sputtering yield. At these conditions and an ion incidence angle of 40°, ZnO and glass are removed with etch rates of 6 nm m/min (Ref. 19) and 5.4 nm m/min, respectively. These etch rates were determined on smooth as-deposited ZnO films and bare glass substrates, respectively. The substrate size is 10 \times 10 \text{ cm}^2; however, the preparation method can in principle be transferred to larger substrate sizes (>$m^2$), since all applied technologies are available on large areas. Atomic force microscopy (AFM) was carried out for all samples before and after the IBE process to investigate the evolution of the surface topography. The AFM scan size was $30 \times 30 \mu m^2$. Root mean square (rms) roughness and lateral correlation length ($\xi$) were extracted from the height-height correlation function which was derived from the AFM data. Furthermore, the crater depth ($c_d$) was determined as vertical peak to valley distance. $c_d$ and rms roughness are used to characterize the vertical feature size, while $\xi$ describes the lateral feature size of the investigated surfaces.

On selected textured glass substrates, ZnO:Al films were deposited by radio frequency magnetron sputtering. A flat glass was codeposited as reference. ZnO:Al film thickness was around 400 nm. The sheet resistances were derived from four-point-probe measurements. Subsequently, microcrystalline silicon solar cells were deposited by plasma enhanced chemical vapor deposition. The active cell area was 1 cm² and the absorber layer thickness was around 1.1 μm. The applied back contact consists of a ZnO:Al/silver (Ag) double layer. The solar cells were characterized by current-voltage (IV) measurements under standard test conditions [air mass (AM) 1.5 illumination at 25 °C].

IV. RESULTS AND DISCUSSION

In Fig. 2, the AFM images of different sample surfaces are depicted. Note that the scan size of the images is $30 \times 30 \mu m^2$. As an example for a three dimensional ZnO mask, Fig. 2(a) shows an AFM image of a wet chemically texture etched ZnO film. Craters with typical diameter of 1–2 μm and opening angles between 120° and 135° are uniformly distributed over the surface. Figure 2(b) shows the resulting glass surface after complete removal of this three dimensional ZnO mask by IBE under a mean incidence angle of 0°. In principle, the glass surface shows similar features as the originating ZnO mask. However, the sharp ridges between the craters of the ZnO surface appear smoothened on the glass surface. In Fig. 2(c), a glass surface with asymmetric features is shown. This shape of the craters can be attributed to the incident angle of 40° of the ion beam, which was applied during fabrication of this sample. The lateral dimension of the features is similar to the originating ZnO surface. By prolonged wet-chemical etching of the initial ZnO layer, in the deepest craters the glass is uncovered. After the dry-etching process, the glass surface exhibits flat regions in the crater bottoms. An example for this type of surface is shown in Fig. 2(d). Again, the asymmetry of the raised features is the result of the ion incidence angle of 40°. By stopping the IBE process before the complete removal of the ZnO mask [situation as illustrated in Fig. 1(c)] and subsequent wet-chemical etching of the ZnO residues, features with truncated vertices are created (not shown).

For detailed surface characterization, AFM data of two wet-etching time series were analyzed. The ZnO surfaces after wet-chemical etching as well as the corresponding glass topographies after IBE at 40° ion incidence angle are investigated. Figure 3(a) shows the crater depth $c_d$ of 800 nm (full

![Image](https://example.com/figure1.png)

**Fig. 1.** Fabrication of the textured glass by subsequent ion beam etching of a textured ZnO on glass substrate: (a) initial ZnO surface, (b) after short IBE process, (c) after prolonged IBE process, and (d) resulting textured glass surface after complete removal of the ZnO film.

![Image](https://example.com/figure2.png)

**Fig. 2.** (Color online) Atomic force micrographs (scan size: $30 \times 30 \mu m^2$) of wet chemically etched ZnO surface (a) and resulting glass topography after transfer of the ZnO surface structure to the glass by ion beam etching at 0° incidence angle (b) and at 40° incidence angle for 70 s (c) and 110 s (d) wet-chemical etching durations of the ZnO layer.
squares) and 1500 nm (full circles) thick ZnO films wet etched between 30 and 330 s, respectively. In principle, with longer etching time, deeper craters evolve in the ZnO surface. However, if first valleys reach the underlying glass surface. Thus, the use of thicker films allows creating deeper craters in the glass. The crater depth in the glass is reduced by 40–80% for glass features that are eroded by ion beam, supports the reduction of the vertical dimensions of the glass features. Note that the rms roughness of an untreated glass substrate is around 3 nm only.

Figure 3(c) reveals the lateral correlation lengths. With longer wet-chemical etching, the crater diameter expands and thus also the lateral correlation length increases. The lateral correlation length of textured ZnO and glass are comparable, indicating similar lateral feature sizes. This proves the shrinking in only vertical direction.

Even though the topography for perfect light-trapping is still unknown, the presented glass surfaces exhibit structures with feature sizes, which are promising for application as diffractive element at the front contact of silicon based thin-film solar cells. Furthermore, the asymmetric shape of the glass features might be favorable for light trapping.

ZnO:Al films were deposited onto the textured glass substrates as conductive window layer. A typical sheet resistance of these films was $10 \ \Omega$. Thus, the resistivity is around $4 \times 10^{-4} \ \Omega \cdot \text{cm}$, which means an increase compared to the reference film on untextured glass substrate, where resistivities below $3 \times 10^{-4} \ \Omega \cdot \text{cm}$ are obtained. This increase is attributed to different growth conditions of the films. Note that the sheet resistance of the ZnO:Al films on textured glass is sufficient for silicon thin-film solar cells and, e.g., no significant degradation of the fill factor is to be expected.

To test the performance of the textured glass substrates, microcrystalline silicon solar cells were prepared on selected samples. The best efficiency of $36\%$ was achieved on textured glass even an increase by 48% was achieved.

**V. CONCLUSIONS**

An up-scalable method to create a variety of randomly nanotextured surface features on glass was described. The topography of textured ZnO films was transferred to glass substrates by ion beam etching. Vertical and lateral sizes of the glass feature can be adjusted in a certain range by varying initial ZnO film thickness and wet-etching time. The developed glass textures show good light-trapping properties: For microcrystalline silicon solar cells, an improvement of the short circuit current of up to 36% was achieved.

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