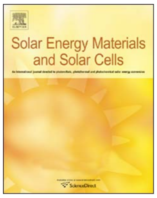
Solar Energy Materials and Solar Cells 180 (2018) 173–183

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat



A continuous, single-face wet texturing process for industrial multicrystalline silicon solar cells using a surfactant treated photoresist mask

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ARTICLE INFO

Keywords:
Multicrystalline silicon solar cells
Honeycomb-like textured surface
Multicrystalline silicon texturization
Masked wet etching
High efficiency
Single-face texturing

ABSTRACT

In this paper, a high-throughput continuous, single-face texturing method was introduced into the fabrication process for industrial multicrystalline silicon solar cell production. With a patterned photoresist film as the mask for the wet etching, wafers without back protection were transported by rollers and only the masked face could contact the etching solution and be etched through the mask openings. The first etching results indicated that serious heat aggregation and poor wettability of the acid solution on the mask surface resulted in a seriously uneven and uncontrolled etching reaction. However, after applying a surfactant to the photoresist mask to improve the mask's hydrophility, a stable and uniform etching reaction could be achieved. A honeycomb-like textured surface with a pitch of 18 μm was fabricated successfully. The etched pits had a nearly smooth spherical segment surface and a surface occupancy of 70%. This regular textured surface had a low in-plane average reflectivity of approximately 20% and greatly increased the carrier lifetime. Compared with multicrystalline silicon solar cells textured by conventional acid etching, the average efficiency increased from 18.31% to 18.57%. In addition, this texturing technique is expected to promote the application of diamond-wire cut multicrystalline silicon wafers in the future.

1. Introduction

A high efficiency and low cost solar cell is highly desired by the photovoltaic industry. Recently, multicrystalline silicon (mc-Si) solar cells have taken the largest market share because of their low cost and high productivity [1–3]. However, compared to monocrystalline silicon, mc-Si has a higher surface carrier recombination and higher surface reflectance, which leads to lower efficiency [4,5]. For industrial production of mc-Si solar cells, isotropic acid etching on the base of saw damage patterns which acts as a starting point for etching is the best common texturing process to reduce surface reflectance [6,7]. However, this technique is not yet effective enough for texturing high quality damage-less mc-Si wafers, such as diamond-wire cut wafers [8–10]. Therefore, to further improve the efficiency of mc-Si solar cells, it is necessary to develop new approaches to achieve a textured surface with low reflectance and good electrical properties.

Several new techniques have been suggested to texture mc-Si, including diamond-wire sawn mc-Si solar cells, such as laser ablation [11,12], mechanical scribing [13], dry chemical etching [14], reactive-ion etching (RIE) [15,16], metal catalyzed wet etching [17–20], and masked dry [21–24] and wet [25–31] etching. In recent years, the concept "black Si" with a very low surface reflectance often appears in the research of mc-Si solar cells [32–34]. RIE and metal catalyst wet chemical etching are 2 mainstream ways to fabricate black Si. However, RIE requires large-area vacuum devices, and metal nanoparticle-catalyzed etching cannot avoid problems of metal contamination [34]. Although a very low surface reflectance can be obtained, neither of those 2 processes can fabricate a strictly regular textured structure, and they lead to serious surface defects [32,33]. To remove the porous layer and improve the efficiency of solar cells, subsequent processes are required, which lead to increased reflectance [19,32].

Besides the black Si with a nanostructure surface, masked wet etching techniques were proposed more than a decade ago that used an inorganic film of SiO_2 or SiN_x as an etching mask to fabricate a honeycomb-like microstructure textured surface for Si solar cells [26–28]. That technique could achieve not only a low surface reflectance but also good electrical properties for both slurry and diamond-wire cut mc-Si solar cells, and attracted much attention. However, further application

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https://doi.org/10.1016/j.solmat.2018.03.003
Received 15 April 2017; Received in revised form 27 February 2018; Accepted 1 March 2018

for industrial production is limited by its low throughput and complexity in the formation and patterning process of the etching mask [26–28]. Recently, as the large-area lithographic technique has developed, a soft mask based on photoresist film has been also applied to the texturization of mc-Si solar cells in the dry plasma etching process [22,23]. For the wet etching process, although the weak strength and adhesion of the resist film on the rough mc-Si surface are critical deficiencies, photoresist film masked wet etching is an attractive solution for texturing the mc-Si silicon solar cell due to its low cost, reduced damage, appropriate imaging resolution, and high throughput process [29–31].

We have previously described a new technique for texturing mc-Si solar cells by a masked wet etching process using a negative photoresist as a mask [31]. Normally, masked wet etching for Si wafers uses an immersion process in which the entire wafer is immersed in the etching solution [25–31]. We fabricated a honeycomb-like structure successfully by a batch immersion process. However, to avoid excessive etching in the immersion process, the rear surface of the mc-Si had to be protected by a resist or other film. Single-face etching is more suited to industrial production, because the protection and follow-up cleaning process can be omitted to reduce costs. In this paper, we describe a true single-face texturing process for mc-Si solar cells using a masked wet etching method. With optimized processing parameters, we fabricated a large-area, honeycomb-like, textured surface for mc-Si wafers. Compared to mc-Si solar cells textured by common acid etching, improvements in photocurrent and efficiency were clearly achieved.

2. Experimental details [31]

2.1. Fabrication of the photoresist mask

The basic substrates used were slurry-cut, p-type, boron-doped 2–3 Ω mc-Si wafers of 180–200 μm thickness and 156 mm × 156 mm area. The wafers were first processed to remove damaged layers and impurities.

A negative photoresist film (Beijing Kempur, BN308) was formed on the front surface of the wafers by screen printing. Then a photoresist mask was fabricated using photolithography. Array of holes which uniformly spaced in a hexagonal layout was used as the mask pattern. A prebake and hard bake were used to improve the adhesion and strength of the resist mask. The best baking conditions were 100 °C for 3 min for the prebake, and 130 °C for 5 min for the hard bake.

2.2. Fabrication of honeycomb textured surface

After the photolithography patterning process, the wafers were etched in a mixture of 68% nitric acid (HNO_3) and 49% fluoric acid (HF) aqueous solution. In a batch immersion process, masked wafer was dipped in the etching solution and the rear surface was protected by the organic film. In this paper, a continuous, single-face masked texturing system in which masked mc-Si wafers are transported continuously through the etching solution on a roller array was introduced. Fig. 1 is a schematic diagram of the single-face texturing process. Unlike the conventional industrial acid texturing process in which the entire wafer is below the liquid surface and both faces of the wafer are etched, in this process the height of the rollers ensures that the masked surface of the Si wafer just touches the etching solution, and the rear surface is exposed to the air. Two pinch rollers are used to prevent the wafers from drifting during the etching process. Only the front surfaces of the wafers are etched by the etching solution through the mask openings. In our process, the wafers were transported 800 mm, and we adjusted the transport speed to achieve an appropriate etching time.

After the etching process, to remove the residual photoresist the wafers passed through a chain sintering furnace with a peak temperature above 500 °C. Then the textured wafers were cleaned in a standard process comprising alkali cleaning (NaOH), acid cleaning (HCl), and pure water rinsing, and then dried by an air knife.

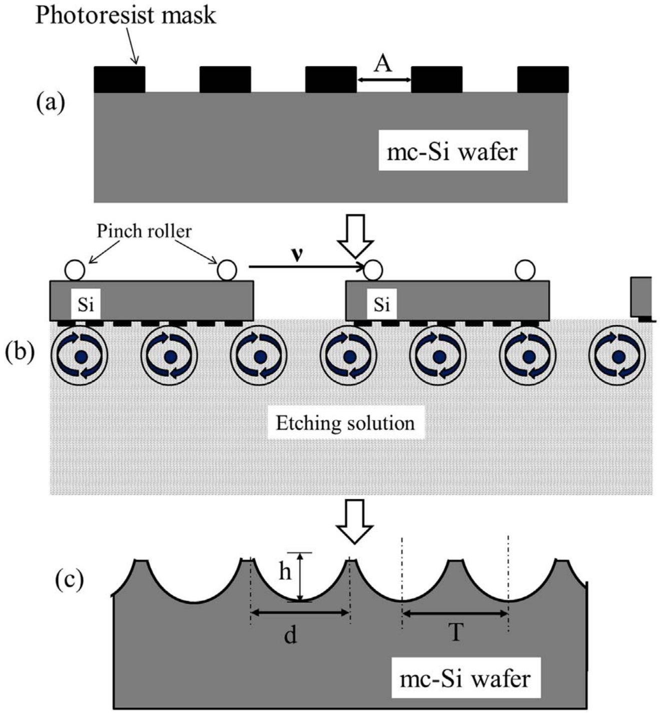

Fig. 1. Continuous single-face masked wet chemical texturing process (chain process) to fabricate a honeycomb-like textured structure. (a) Masked wafer before etching. (b) Wafer during etching. (c) Wafer after etching. Dimensions are d, the aperture diameter of the etched pits; h, the depth of the etched pits; T, the pitch of the mask pattern and the textured structure; and A, the diameter of the mask apertures; v, the transport speed of the wafers.

2.3. Fabrication of solar cells

Fig. 2 shows the solar cell fabrication process. Except the texturing process, the almost same conventional process steps were used for both solar cells textured by conventional acid etching and single-face masked wet etching process.

The throughput of solar cell production depends on the rate of the photolithograph process, which in turn is limited by the exposure process. In our study, the exposure time of one piece of mc-Si wafer was approximately 0.5–0.8 s, and transport time was 0.5 s. Therefore, the highest throughput could reach approximately 2700 pieces per hour.

2.4. Measurement and evaluation

During the etching process, a thermal imager (ARTCAM-320-THERMO) was used to monitor the wafer temperature which could indicate the rate of etching reaction or whether the etching occurred because it was an exothermic reaction. The surface morphology of the photoresist mask and the textured structure of the mc-Si wafers were examined using a scanning electron microscope (SEM) and a 3D optical microscope (Zeta 20). A standard diffusion 8° integration sphere spectroscopic-reflectometer (D8SR, Ridatech LLC, Shanghai) was used to measure the surface reflectivity in the wavelength range of 350–1050 nm. The optical and sampling apertures of the reflectometer were 20 mm and 25 mm. The carrier lifetime was determined by the microwave photoconductivity decay method (Semilab μ-PCD). In addition, the surface contact angle was analyzed by a contact angle meter (Data Physics DCA21). The solar cell performance measurement was made by a cell test and sorting system (Fortix FCTS-400, Korea).