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Improvement of conversion efficiency of multicrystalline silicon solar cells by incorporating reactive ion etching texturing

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ABSTRACT

The reactive ion etching in combination with acidic etching (acidic+RIE) is applied to form the front surface texturing of 156 × 156 mm^2 multicrystalline silicon (mc-Si) wafers in order to improve the cell efficiency. The scanning electron microscope (SEM) analyses indicate that the RIE process produces dense nanoscale ridge-like structures based on the acidic textured surfaces, and these structures generate an excellent antireflection effect. The matching processes including the post-cleaning, the phosphorus diffusion, and the deposition of silicon nitride (SiN_X) antireflection coating are optimized. The acidic+RIE textured surfaces in combination with high sheet resistance emitters result in a remarkable enhancement in short wavelength response and then improve the short circuit current density (J_{SC}) significantly. The absolute conversion efficiency of acidic+RIE textured solar cells is improved 0.51% on average compared to the acidic textured solar cells in mass production, and a maximum full-area cell efficiency of 18.49% is achieved on the mc-Si solar cell with a conventional cell structure.

1. Introduction

Front surface texturing in multicrystalline silicon (mc-Si) solar cells plays a significant role in improving the cell efficiency, because the texturing is useful for reducing the light reflectance of the silicon surface and increasing the light trapping. Most commonly, wet texturing, including acidic etching [1–3] and alkaline etching [4–6], is used in conventional production line for the surface texturing owing to the advantages of being easy to implement and of low cost. However, wet texturing will not only induce a large amount of silicon loss which is contrary to the purpose of cost reduction, but also cannot reduce the surface reflectance sufficiently for mc-Si because of its various crystal orientations. Therefore, several other methods have been developed to texture the mc-Si wafers in recent years including mechanical V-groove texturing [7–9], laser texturing [10,11] and masked or maskless reactive ion etching (RIE) texturing [12–14]. RIE can be utilized to create nanoscale ridges on surfaces of mc-Si wafers using plasma and reactive gases, the subtle ridges can considerably reduce surface reflectance and provide excellent light trapping without introducing significant damage. In the RIE process, it is relatively easy to control all process parameters, thus a good reliability and reproducibility can be obtained. Furthermore, RIE possesses high rates of isotropic etching which provides a potential large production capacity, and then it is feasible to be integrated into industrial cell production line.

In this paper, the maskless RIE in combination with acidic etching (acidic+RIE) is adopted for the front surface texturing of 156 × 156 mm^2 mc-Si wafers in mass production. The scanning electron microscope (SEM) analyses indicate that the RIE texturing produces dense nanoscale ridge-like surface structures regardless of the grain orientations of mc-Si wafers. The matching processes, including the post-cleaning, the diffusion for high sheet resistance emitter, and the deposition of silicon nitride (SiN_X) antireflection coating on acidic+RIE textured surface are investigated. We integrate all the optimized processes and achieve a full-area efficiency of mc-Si solar cell with a conventional cell structure of up to 18.49%.

2. Experimental

All experiments were performed on boron-doped *p*-type mc-Si wafers with resistivity, thickness and size of around 2 Ω cm,

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180 μm, and 156 × 156 mm^2, respectively. The surface texturing of mc-Si wafers was carried out by acidic etching and acidic+RIE separately for comparative study. Acidic texturing was carried out by using a mixture of HF, HNO_3 and deionized (DI) water in the volume ratio of 1:3:2.5, the acidic solution was maintained at 9 °C, and the etching duration was 2 min. The maskless RIE texturing was performed on the acidic textured wafers using a parallel plate reactor manufactured by Jusung Engineering Inc. The reactive gases were SF_6, O_2 and Cl_2 in the volume ratio of 2:2:1, and the plasma was excited by radio frequency (RF, 13.56 MHz) with power density of about 1 W/cm^2, pressure of 0.3 Torr and time of 80 s at room temperature. The acidic+RIE textured wafers were again cleaned in acidic solution containing HF, HCL and DI water in the volume ratio of 1:1:8 for 5 min at room temperature. After the texturing process, solar cells were fabricated by utilizing conventional fabrication techniques. Phosphorous diffusion using $POCl_3$ was performed at 840 °C for 15–25 min to form the *N*-type emitters with sheet resistances from 60 to 90 Ω/sq. The phosphorus silicate glass (PSG) was removed by a diluted HF solution (9% by volume). The SiN_X antireflection coating was deposited by plasma enhanced chemical vapor deposition (PECVD). Finally, the front and back metal contacts with low resistances were formed by screen printing and co-firing in a furnace system at 910 °C.

The texturing microstructures of mc-Si wafers were analyzed using a SEM equipped with a field emission gun (Quanta-400 FEG). The silicon surface reflection was examined by an UV–vis–NIR spectrophotometer using the integrating sphere in the range of 375–1075 nm. External quantum efficiency (EQE) measurement was made in the range of 300–1100 nm using a xenon lamp. Spectroscopic ellipsometry was used to determine the optical property and thickness of the SiN_X antireflection coatings. The electrical characteristic of the mc-Si solar cells was investigated by photocurrent–voltage (*I*–*V*) measurement under the illumination of AM1.5 using a solar-simulated light source. All of these measurements were performed at room temperature.

3. Results and discussion

For comparison, the SEM images of mc-Si wafers with acidic texturing and acidic+RIE texturing are both prepared. Fig. 1 shows the surface structure of acidic textured mc-Si wafer, it can be clearly seen that the smooth and bowl-like structures with a feature size of 2–6 μm are formed. Fig. 2 shows the SEM images of acidic+RIE textured mc-Si wafer without the post-cleaning process. As shown in Fig. 2(a), the acidic+RIE textured surface morphology in the order of several micrometers is the same as the acidic textured surface shown in Fig. 1(a). Meanwhile, as shown in Fig. 2(b) and (c), the dense nanoscale ridge-like structures based on the microscale bowl-like surfaces are formed regardless of grain orientations of mc-Si wafer.

During the RIE process performed on the acidic textured wafers, SF_6 and O_2 gases generate $F^{\bullet}$ and $O^{\bullet}$ radicals, respectively. $F^{\bullet}$ radicals provide the chemical etching of silicon materials by producing volatile SiF_4, $O^{\bullet}$ radicals passivate the silicon sidewall surfaces with the absorbed $Si_xO_yF_z$. As shown in Fig. 2(b) and (c), the adsorbates $Si_xO_yF_z$ are located at both the top of ridge-like structures and the borders of bowl-like structures, which protect the wafers against etching and then act as a randomly perforated mask, so the $Si_xO_yF_z$ can help to control the etching profiles [15]. However, the $Si_xO_yF_z$ are detrimental to the electrical performance of cells. It is necessary to remove the adsorbates and other residues produced

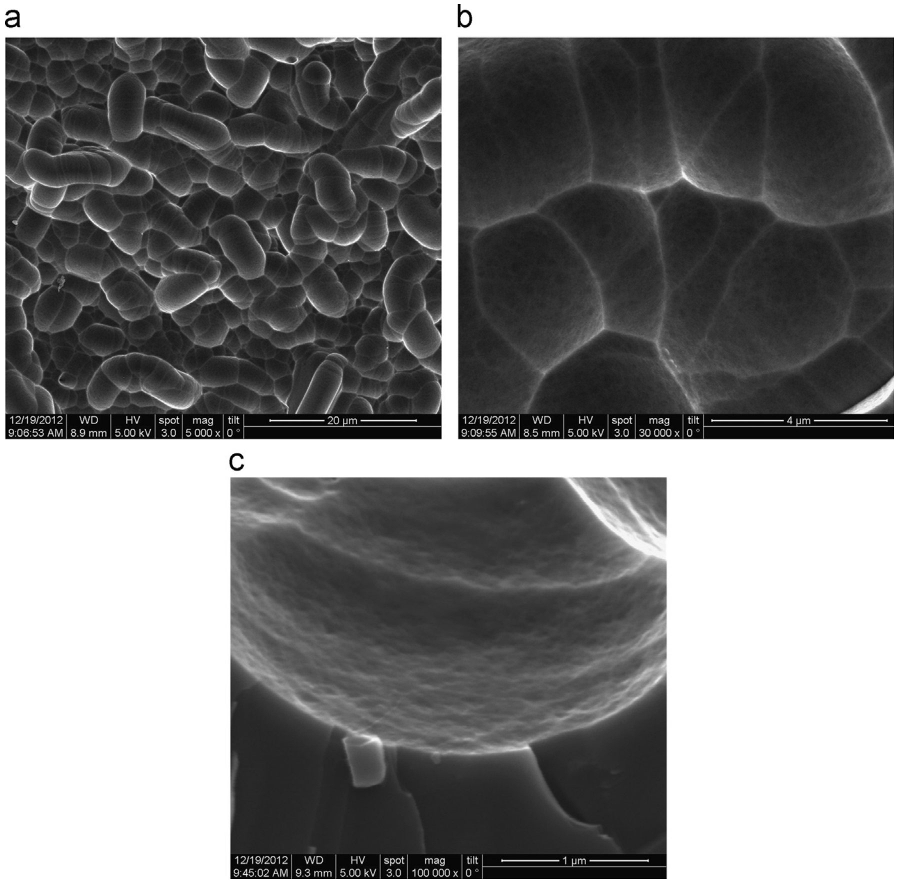

Fig. 1. SEM images of acidic textured mc-Si wafer: (a) 5000× , (b) 30,000× , and (c) cross-sectional image 100,000× . The smooth and bowl-like structures with a feature size of 2–6 μm are formed.