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Broadband spectral response of diamond wire sawn mc-Si solar cell with omnidirectional performance and improved appearance

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ABSTRACT

Highly efficient diamond wire sawn (DWS) multi-crystalline Si (mc-Si) solar cells with a satisfactory visual appearance are expecting to dominate the photovoltaic industry soon. Here, we report the realization of broadband spectral response of DWS mc-Si solar cells with omnidirectional performance and improved appearance. The success lies in the effective surface texturization based on MACE technique followed by post acid modification and the introduction of SiO_2/SiN_x stack layers on the rear side. Bowl-like pits with an open size of about 1 μm are uniformly formed on the Si surface regardless of the crystallographic directions, which significantly enhances the antireflection ability in the short wavelength and makes the grain boundaries less noticeable. We have also shown that the bowl-like textured cells possess exceptional optical absorption over wide angles of incidence from 0° to 70°. Moreover, the SiO_2/SiN_x stack layers enhance the rear internal reflection and passivation, effectively increasing the long wavelength absorption and suppressing the electrical losses. We have successfully mass-produced DWS mc-Si solar cells with an average efficiency of 19.1%, which is 1.2% absolutely higher than that of the conventional micro-textured counterparts.

1. Introduction

In recent years, multi-crystalline silicon (mc-Si) solar cell has occupied large percent of the photovoltaic industry market for its low cost. Nevertheless, the spectral responses in both short wavelength (< 600 nm) and long wavelength (> 900 nm) of industrial mc-Si solar cells are not sufficiently high, which are mainly attributed to the relatively high reflectance at the front surface and severe parasitic absorption as well as severe carrier recombination at Al rear reflector. This leads to a low conversion efficiency (η), especially for diamond wire sawn (DWS) mc-Si solar cells. The η of conventional acid textured DWS mc-Si solar cells is about 0.4% absolutely lower than that of multi-wire slurry sawn ones [1], which sets significant barriers in promoting the industrialization of DWS mc-Si solar cells. Since DWS technique has several advantages including higher productivity, higher precision in cutting thin wafers and lower material waste [2–6], it is expected to occupy more than 50% in slicing mc-Si in the industry by 2020 [7]. Therefore, it is an urgent affair to realize high efficient DWS mc-Si solar cells with excellent spectral responses in both the short wavelength and long wavelength.

Many researches have demonstrated that Si nanostructures, such as nanowire arrays, have excellent broadband antireflection ability including in the short wavelength region [8–12]. However, the performances of such nanostructures based cells are not satisfactory due to the severe surface and Auger recombination that lead to strong electrical losses [13–15]. Recently, there are lots of reports demonstrating that metal-assisted chemical etching (MACE) technique combined with post alkaline modification is effective to overcome these disadvantages [1,16,17]. By employing this method, we have fabricated micro/nano composite structures with satisfactory antireflection properties and acceptable electrical losses, and an absolute increase of 0.57% in η was achieved on DWS mc-Si solar cells [18]. Nevertheless, owing to the anisotropic etching property of alkaline solution, different micro- or nano-structures are formed on different crystallographic planes, leading to the unsatisfactory appearance of DWS mc-Si solar cells. Therefore, it is urgent to develop a surface texture that can effectively improve short wavelength spectral responses with an acceptable appearance for DWS mc-Si solar cells.

In addition, it is also necessary to further improve the optical and electrical properties in the long wavelength range by rational design of cell structures. Through introducing dielectric thin films (SiO_2, SiN_x, or SiO_2/SiN_x stack layers) at the rear surface, Holman et al. [19]

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demonstrated that parasitic absorption in the Al rear reflector in the long wavelength range can be effectively suppressed when the thickness of the dielectric film is more than 100 nm, resulting in enhanced spectral response in the long wavelength and cell performances. Moreover, these dielectric films can effectively passivate the rear surface, reducing the photogenerated carrier loss at the rear surface [20]. These advantages have been verified in our 20% efficient nanostructures textured single-crystalline Si solar cells [21] and the industrial single-crystalline Si solar cells with a high η of 22.13% [22].

In this study, by employing MACE technique with post acid modification, and the introduction of SiO_2/SiN_x stack layers at the rear surface, we have successfully fabricated bowl-like structures textured DWS mc-Si solar cells with an improved visual appearance and a high η of 19.1% with a large wafer size of 156 × 156 mm^2. The achieved η of our samples is 1.2% absolutely higher than that of the conventional micro-texture (CM-T) based counterparts. In addition, our cells possess excellent broadband spectral response due to the outstanding antireflection performance in short wavelength and suppressed parasitic absorption in long wavelength together with reduced carrier recombination at the rear surface. Furthermore, the cells also possess exceptional optical absorption over wide angles of incidence (AOI) from 0° to 70°, exhibiting omnidirectional property, which is beneficial to the electric power generation since the AOI changes with the rotation of the earth. We believe that DWS mc-Si solar cells with appropriate surface texture and rational rear design will soon become the mainstream in the mc-Si solar cell industry.

2. Experimental

2.1. Texturization and fabrication of the DWS mc-Si solar cells

In this work, the used Si wafers were p-type DWS mc-Si with a size of 156 × 156 mm^2, a thickness of 200 ± 20 µm and resistivity of 1–3 Ω cm. The texturization and cell fabrication processes are shown in Fig. 1. Deionized water (DIW) cleaning was performed after every step. Firstly, saw damage etching was employed by acid solution. After that, the wafers were immersed into MACE solution (2.4 M HF/1.7 M H_2O_2/0.0002 M $AgNO_3$) for 4 mins at 50 °C. In this process, Ag nanoparticles were deposited onto the Si substrate and nano-pores were formed. Then the nano-pores were enlarged by immersing the wafers into the mixed solution of HF:HNO_3:DIW = 1:6:3 (volume ratio) for different modification times of 30 s, 50 s, 100 s (labeled as T_{30}, T_{50}, and T_{100}), respectively, at the temperature of 8 °C. Finally, all the textured wafers were immersed in the solution of HNO_3:DIW = 1:1 (volume ration) for 8 mins to remove the residual metal impurities, followed by rinsing with DIW and spin-drying. In addition, CM-T samples were prepared as the reference by dipping the wafers into the mixed HF/HNO_3/DIW (1:5:4) solution for 3 mins at 8 °C.

After the texturization and industrial cleaning processes, one group of the wafers underwent a standard industrial solar cell fabrication process, including n-type diffusion on one side with $POCl_3$ as diffusion source (M5111-4WL/UM, CETC 48th Research Institute), removal of the phosphorous silicate glass (PSG) in dilute HF solutions, deposition of SiO_2/SiN_x layers on the front surface by plasma enhanced chemical vapor deposition (PECVD) system (M82200-6/UM, CETC 48th Research Institute), the fabrication of front and back electrodes by screen printing technique (PV1200, DEK) and co-firing process (CF-Series, Despatch).

Another group of the wafers underwent a distinct cell fabrication process. Firstly, the rear surface was polished by NaOH/H_2O_2 solution. Then the SiO_2/SiN_x stack layers were deposited on the rear side by PECVD at 450 °C for 40–100 mins. Subsequently, n^+-emitter was formed on the front side during the diffusion process for about 100 mins at 800 °C. After the PSG removing process, local line openings were formed on the rear SiO_2/SiN_x stack layers by laser ablating (DR-LA-Y40, DR Laser), followed by an annealing process at 700 °C for 60 mins. After that, SiO_2/SiN_x stack layers were deposited on the front side by PECVD for about 40 mins at 400 °C. Finally, the wafers underwent the same screen printing and the co-firing processes as mentioned above. The diagram of the cell structure is illustrated in the middle part of Fig. 1.

2.2. Fabrication of the samples for recombination comparison

For the study of effective minority carrier lifetime (τ_{eff}), SiO_2/SiN_x stack layers were symmetrically deposited on both sides of the polished wafers by PECVD at 450 °C for 100 mins and followed by an annealing process at 550 °C to 850 °C for 60 mins.

2.3. Characterization

The morphologies of the wafers were investigated by field emission scanning electron microscopy (Zeiss Ultra Plus). The reflectance spectra and external quantum efficiency (EQE) were measured by QEX10 (PV MEASUREMENTS). Minority carrier lifetime measurements were carried out by quasi-steady state photoconductance decay method in Semilab WT1200 equipment. And the electrical parameters of the solar cells were measured under AM1.5 spectrum at the temperature of 25 °C.

2.4. Simulations of reflectance

The surface reflectance of CM-T over the AOIs from 0° to 80° was simulated by setting the periodic grooves with 2 µm in width and 400 nm in height on the surface of 180 µm Si substrate by online wafer ray tracer provided by PV light house, which is a professional optical simulator for the Si microstructures-textured solar cells. AM1.5 spectrum was used in our cases and the max total rays were set to 50,000 to enhance the accuracy. The surface reflectance of our bowl-like structures was numerically calculated by Lumerical finite difference time

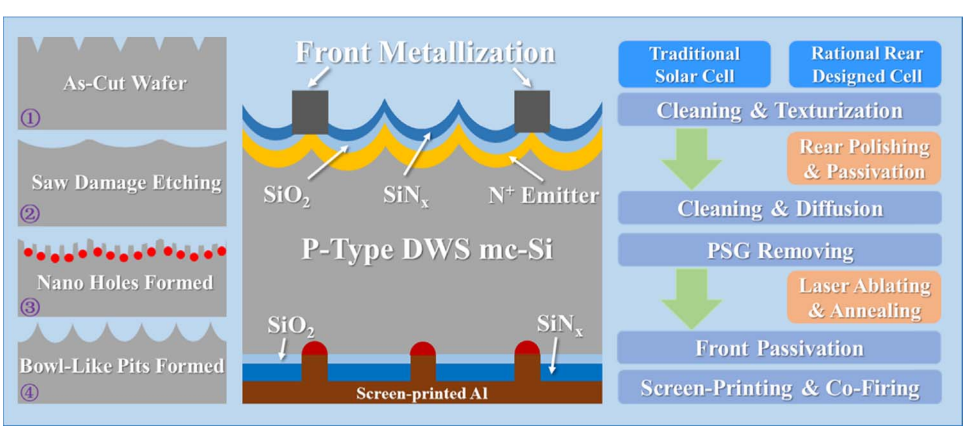

Fig. 1. Schematic illustration of the main steps for texturization (left) and fabrication (right) of the DWS mc-Si solar cells, together with the diagram of the cell structure (middle).