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Novel low-cost alkaline texturing process for diamond-wire-sawn industrial monocrystalline silicon wafers

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A R T I C L E I N F O

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A B S T R A C T

Diamond-wire-sawing (DWS) processes have been developed in recent years to overcome the problems of silicon (Si) waste and low throughput of the conventional multi-wire-slurry-sawing (MWSS) process for cutting Si ingots into wafers. However, DWS is not adopted extensively by PV industry as standard alkaline texturing is not directly applicable to these wafers to generate regular pyramidal structure. In the present work we are reporting a novel low-cost alkaline texturing process for industrial DWS monocrystalline silicon (c-Si) wafers. Our process has three novelties; firstly, it uses a low-cost saw damage removal (SDR) process with a new recipe of potassium hydroxide (KOH), sodium hypochlorite solution at 80 °C for slow Si etching. This process also successfully removes the amorphous Si layer normally present on the as-cut DWC Si wafer surface. Secondly, no initial cleaning process is required before our SDR process. Finally, a high throughput KOH/isopropyl alcohol/potassium silicate texturing process was applied successfully for pyramid formation on the DWS c-Si wafers. Small (~2–4 µm in height) and uniform pyramidal structure with reduced surface reflectance is confirmed by scanning electron microscope, Zeta 3D measurement and UV–Vis spectroscopy studies. Further, photoluminescence (PL) imaging of lifetime samples prepared with the present texturisation process, confirmed the uniformity of surface passivation, a prerequisite for solar cell fabrication. Screen-printed solar cells were fabricated in NCPRE cell fabrication laboratory. For our 6 in. pseudo-square CZ p-type c-Si wafers cell efficiencies up to 18.5% were achieved with the new texturing process. This high throughput novel texturing process thus can easily be integrated into the standard industrial process.

1. Introduction

The multi-wire-slurry-sawing (MWSS) monocrystalline silicon (c-Si) wafers is generally the conventional technique to slice large Si ingots into the wafers in the photovoltaic (PV) industry [1]. There are always critical issues like environmental, steel-wire breakage rate, low productivity and high kerf-loss [2,3] associated with this sawing process. Researchers tried to overcome these difficulties by using a new Si wafer sawing method known as diamond-wire-sawing (DWS) [4,5]. With its high throughput, higher yield, longer wire lifetime, convenient cooling liquid recycling and low kerf-loss [6] features, the DWS technology becomes an undoubted candidate to replace the MWSS technology to produce c-Si wafers. However, there are surface morphological differences between the MWSS and DWS c-Si wafers. The MWSS wafers have thick damaged layer (~10 µm) with random distribution of broken crystals [5]. However, the DWS wafers have a less damaged layer (~5 µm) and nearly 10–20 nm amorphous silicon (a-Si) layer (confirmed by Raman spectroscopy [7]) over and above the damaged layer [5]. This amorphous layer originates during the high-speed cutting with the diamond particles adhered on the wire. Besides, highly prominent parallel saw marks with 'pilgrim wave defects' [8] with hard damaged pits on the wafer surface are the basic features of these DWS wafers. These pilgrim waves, had a measurable impact on local current generation across the device largely due to local variations in the front surface reflectance [8]. These are the reasons behind the absence of a proper high yield low reflectance alkaline texturing process [9,10]. So, till date it is not completely adopted in PV industry.

For c-Si solar cells, sodium hydroxide (NaOH) or potassium hydroxide (KOH) based solutions are used for anisotropic selective etching of the < 100 > silicon surface to form a textured surface of random upright pyramids. The textured surface reduces optical reflectance due to the so-called 'double-bounce' effect [11,12]. Isopropyl alcohol (IPA) is generally added to the alkaline solution to achieve good lateral uniformity of the pyramids across the Si wafer surface by modifying the surface wettability in the texturing process [13]. However, presence of the a-Si layer presented on the DWS wafer surfaces, does not allow

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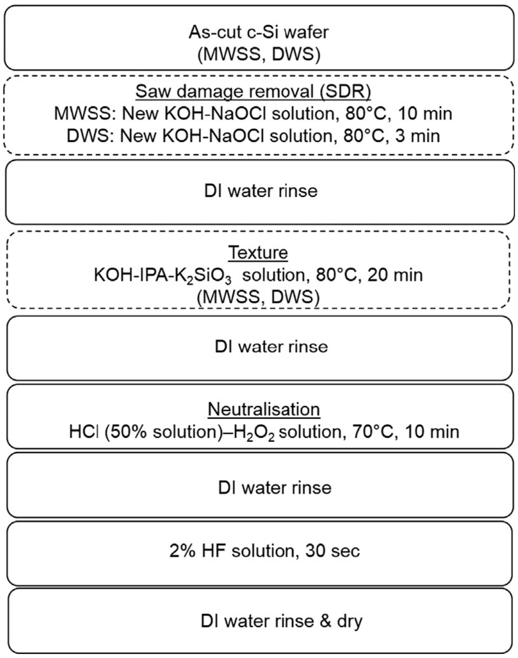

Fig. 1. Process flow diagrams of the novel texturing processes. The modified process steps are shown as dashed boxes in the figure.

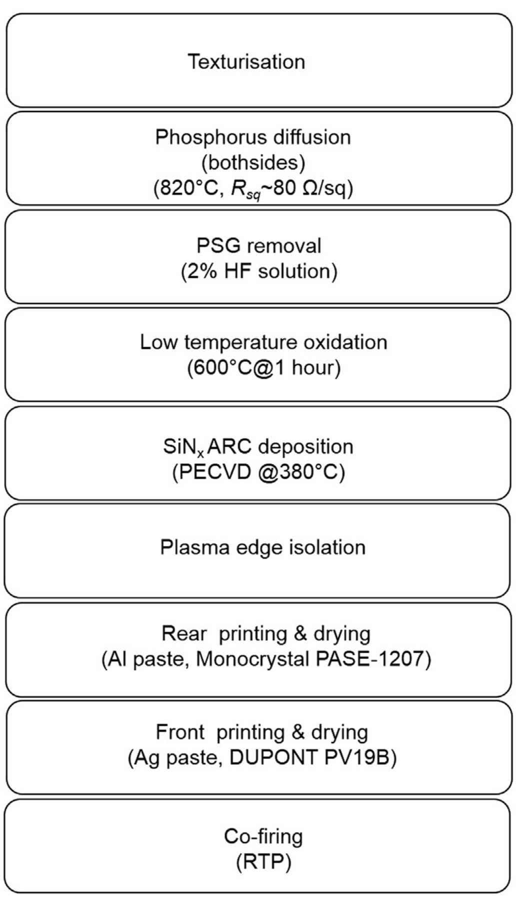

Fig. 2. Schematic illustration of the solar cell processing flow used in this work.

smooth Si-etching [7] as Si etching is generally faster on areas with random distributed pits [5]. Therefore, main concern of the pyramidal texturing is the effective saw damage removal (SDR) process. An effective SDR process must etch the damaged Si-layer and also removes a-

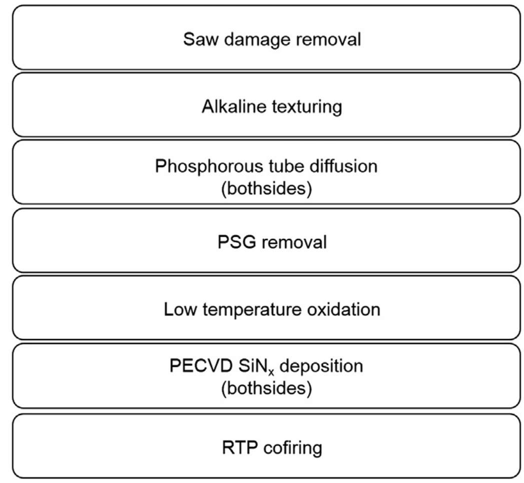

Fig. 3. Lifetime sample fabrication process flow for the MWSS and DWS textured c-Si wafers.

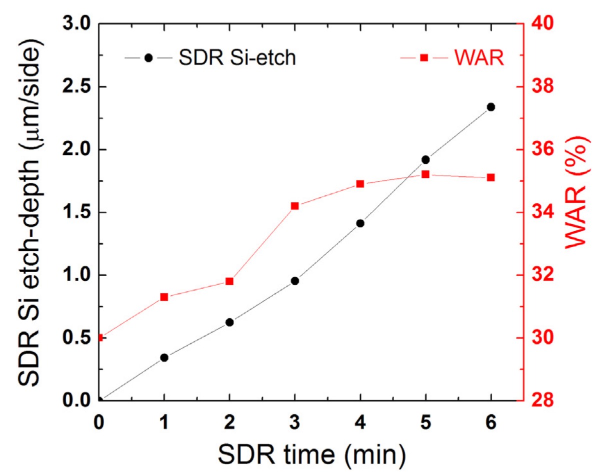

Fig. 4. The variations of Si etch depth per side and the weighted average reflectance (WAR) with the SDR time upto 6 min in the novel SDR process are shown. WAR value is weighted using the AM1.5 G solar spectrum over the 300-1000 nm wavelength range.

Si layer from the as-cut DWS c-Si wafer surface. After successful implementation of the effective SDR process, any standard alkaline texturing process should work to generate a low reflecting uniform pyramidal surface suitable for high efficiency cell fabrication.

Researchers tried to use different chemical processes to solve the above SDR related problems. Pretreatment process using a mixture of hydrochloric (HCl) acid - hydrogen peroxide (H_2O_2) solutions [14], KOH or NaOH based, hydrofluoric (HF) – nitric (HNO_3) acid based [5,15–17] and HF – HCl based [18] SDR solutions had been tried. Equipment vendor RENA GmbH also developed industrial texturing process [19] for the DWS c-Si wafers. However, they are all found to be incapable of removing the saw marks from the surface of DWS c-Si wafers [5]. Chen *et al.* [5] successfully reported a SDR process with 25% (by weight) tetra-methyl-ammonium hydroxide (TMAH) solution at 85–90 °C. However, this still need a pre-SDR wafer clean step [5]. This SDR process was followed by pyramid formation using NaOH solution mixed with commercial additive to achieve uniform pyramidal textured surface. TMAH is comparatively a costly chemical and the requirement of additional pre-SDR wafer clean makes this SDR process out of purview of industry applications.

The present work reports a novel low-cost and industrial approach for anisotropic texturing for the DWS c-Si wafers. Our process combines a novel single step low-cost SDR solution with a new combination of