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Next-generation multi-crystalline silicon solar cells: Diamond-wire sawing, nano-texture and high efficiency

Fang Cao, Kexun Chen, Jingjiao Zhang, Xiaoya Ye, Jianjiang Li, Shuai Zou, Xiaodong Su*

College of Physics, Optoelectronics and Energy, Collaborative Innovation Center of Suzhou Nano Science and Technology, Photovoltaic Research Institute of Soochow University & Canadian Solar Inc., and Jiangsu Key Laboratory of Thin Films, Soochow University, 1 Shizi Street, Suzhou 215006, China

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ABSTRACT

The absence of an effective texturing technique for diamond-wire sawn multi-crystalline silicon (DWS *mc*-Si) solar cells has hindered commercial upgrading from traditional multi-wire slurry sawn silicon (MWSS *mc*-Si) solar cells. In this paper, a nano-texture technique has been developed to achieve 18.31% efficient DWS *mc*-Si solar cells on a pilot production line. Their unique pyramidal nanostructure, which has the most close-packed {111} surface of Si diamond crystal, not only benefits both light-trapping and electric properties but also can effectively remove the saw-marks and amorphous layer of the cells. Therefore, the short-circuit current I_{sc} of a nano-textured DWS *mc*-Si solar cell is ~324 mA higher than that of a micron-textured one, while its open-circuit voltage V_{oc} does not show an evident decrease with the increase of its surface area. The technique has paved the way for the mass production of DWS *mc*-Si solar cells by satisfying the exact requirements of the PV industry for high efficiency and low cost.

1. Introduction

In the past few decades, multi-wire slurry sawing (MWSS) has been a mainstream technique for slicing large ingots of single/multi-crystalline silicon (*sc*-Si/*mc*-Si) into thin wafers in the PV industry [1,2]. However, as its production increased to several hundred thousand tons each year, MWSS shortages eventually emerged, including low productivity, high breakage of steel-wire, and high material consumption and industrial waste (i.e., non water-soluble cutting fluid, slurry and disposable wires). Therefore, several research groups have demonstrated that diamond wire sawing (DWS) has several superiorities over MWSS, i.e., 2.5-fold slicing speed, half the thickness of the saw-damage layer, and water-soluble coolant without any slurry [3,4]. More importantly, DWS showed great potential for cutting thin wafers down to 60 μm [5]. Therefore, DWS is expected to become a next-generation slicing technique for fabricating wafer-based Si solar cells. In fact, DWS *sc*-Si solar cells that are fabricated in production lines have shown comparable photovoltaic properties to MWSS ones [6].

Unfortunately, DWS *mc*-Si solar cells are still unpopular and unacceptable in the PV industry mainly due to the lack of an effective texture technique. In general, the normal texture process for MWSS *mc*-Si wafers, which is based on the isotropic acidic etching of a HNO_3/HF system, can reduce the reflection of a wafer down to ~23%. In our preliminary works, the reflection loss of a DWS *mc*-Si wafer after the same texture process is still as high as ~28%, resulting in a 0.4% lower power conversion efficiency (η) than that of an MWSS wafer. Unlike the randomly and homogeneously fractured surface in MWSS wafers, the existence of directional saw marks and an incompletely covered amorphous Si layer in DWS wafers will result in an undesirable texture, as will be discussed later. Because *mc*-Si solar cells have occupied more than 80% of the photovoltaic (PV) market, it is an urgent requirement for PV researchers and the industry to develop an effective texture technique for efficient DWS *mc*-Si solar cells.

Recent progress in nanostructure textured black silicon has attracted intensive attention due to its great potential for applications in silicon-based solar cells [7–11]. There are several advantages of black silicon solar cells: excellent light trapping in a wide spectrum ranging from 300 to 2000 nm [7]; the possibility of removing the need for expensive plasma-enhanced-chemical-vapor-deposition (PECVD) processing; and wider acceptance angle of light [12]. There are three main types of techniques for fabricating black silicon: laser texturing [9,10], reactive ion etching (RIE) [13–16], and metal-catalyzed chemical etching (MCCE) [17,18]. For mass production, the RIE and MCCE techniques have high expectations, but obviously MCCE is much more suitable for the current industry product line where the texturing process is also based on chemical solutions due to their low-cost and stability. It is worth mentioning that the efficiency of the

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* Corresponding author.
E-mail address: xdsu@suda.edu.cn (X. Su).

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nanostructured MWSS *mc*-Si solar cells have reached over 18% in our group through the use of an MCCE technique [19].

In this work, we demonstrate that DWS *mc*-Si solar cells can achieve an efficiency as high as 18.31% after being nano-textured and having their saw marks eased.

2. Experiments

A standard process for producing *mc*-Si solar cells consists of four main steps, i.e., obtaining a micron-textured surface by using acid etching in an HNO_3/HF mixture solution, forming a p–n junction emitter by diffusing phosphorus into silicon, depositing the SiN_x antireflection/passivation layer by PECVD, and metalizing the top/bottom electrodes by screen printing and firing. In this work, one group of MWSS *mc*-Si wafers and two groups of DWS *mc*-Si wafers from same batch (20 pieces each, $156 \times 156 \times 0.18\ mm^3$, *p*-type, specific resistance $\rho = 1–3\ \Omega\ cm$, GCL company, China) had normal acid etching applied first to obtain the micron-texture (labeled as MT-MWSS *mc*-Si and MT-DWS *mc*-Si). Then, one group of MT-DWS *mc*-Si wafers underwent a nano-texture process (as detailed elsewhere [19]) to incorporate a nano-pyramid structure onto the surface (labeled as NT-DWS *mc*-Si). In this process, the wafer was first loaded with Ag nanoparticles on the surface by using an electroless plating method, was then placed in a mixture solution of H_2O_2 and HF to form an array of nano-pores, and was finally post-etched in an alkali solution, such as NaOH, to convert the nano-pore texture into a unique nano-pyramid texture. Finally, three groups of wafers (MT-MWSS *mc*-Si, MT-DWS *mc*-Si and NT-DWS *mc*-Si) were fabricated into solar cells in a pilot product line with the same parameters.

The microstructure, reflection, external quantum efficiency (EQE), doping concentration, surface sheet resistance, lifetime of minority carrier and IV curves of the resulted DWS *mc*-Si wafers or solar cells were measured by SEM (Hitachi, S4800, Japan), TEM (FEI Tecnai G2F20S-Twin,USA), Reflectometer (Radiation Technology D8, China), PV Measurements (QEX7, USA), ECV Pro (Nanometrics, UK), 4 Probe sheet resistance tester (Napson RT-70V, Japan), IV measurement system (Berger PSL-SCD, Germany), and WT2000 (Semilab WT2000, Hungary), respectively.

3. Results and discussion

3.1. The comparison of as-cut DWS and MWSS mc-Si wafers

The surface microstructure of as-cut silicon wafers has a strong influence on the etching behavior. Fig. 1 shows photos and SEM images of DWS and MWSS *mc*-Si wafers. Different from the homogeneously distributed rough, dentate, and fractured surface of gray MWSS *mc*-Si wafers, shiny silver DWS *mc*-Si wafers feature smooth areas, individual fractures, parallel grooves and many cracks (Fig. S1, Supporting information) [4]. In principle, the cutting mechanisms of MWSS and DWS wafers are quite different: the former was sliced by rotating free-SiC particles driven by a high-speed moving wire [2], and the latter was sawn by fixed-diamond particles adhered to a high-speed moving wire [3]. Obviously, the clearly visible parallel grooves with lateral cracks on the surface of DWS wafers were the trace lines of the kerfs of diamond blades, the smooth areas may be the bottom parts of the grooves after their laterals were scratched by later incoming diamond blades, and the disperse fractures were mainly formed by

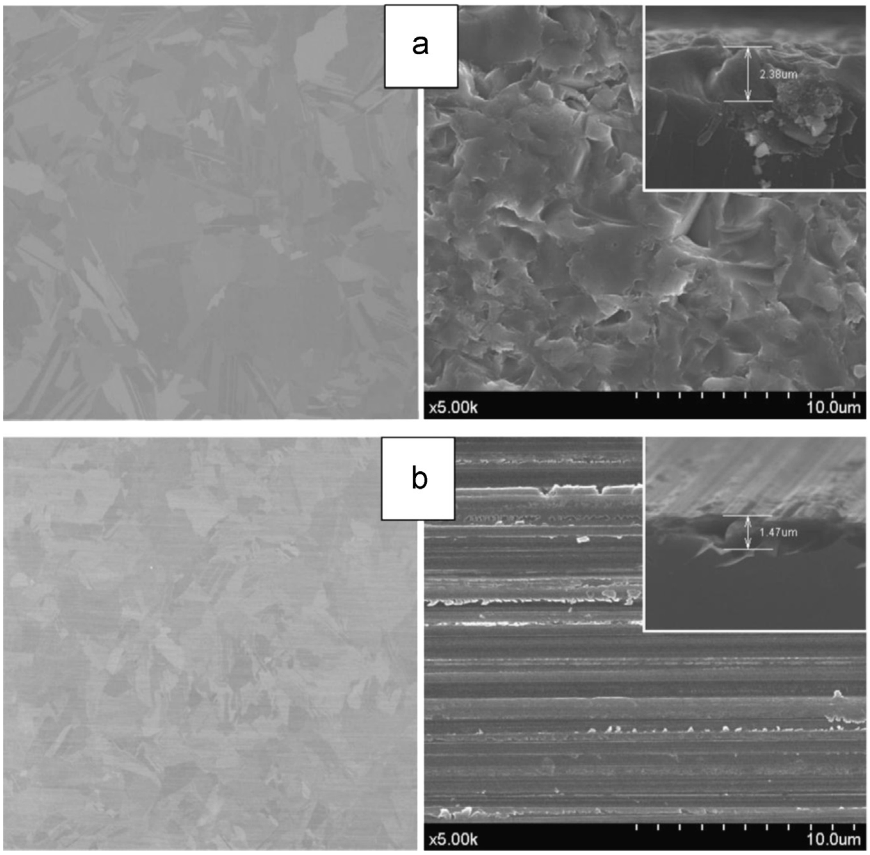

Fig. 1. Surface photos (left) and SEM images (right) of (a) MWSS and (b) DWS *mc*-Si as-cut wafers. Insets: the cross-section images of the wafers.