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Characterization of high-efficiency multi-crystalline silicon in industrial production

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ABSTRACT

A new technique for the directional solidification growth of multi-crystalline silicon (mc-Si) ingot was developed by GCL-POLY Energy Holdings Ltd. This technique is called as S2 and has been used recently for industrial production. The average conversion efficiency of the solar cells fabricated by S2 mc-Si wafers is increased by 0.62% compared with the traditional mc-Si solar cells using conventional solar cell processing. In order to understand the origin of the high cell performance, ensure the process reproducibility and further improve the technique, this paper analyzes the grain structures of the S2 mc-Si wafers by light microscopy and scanning electron microscopy supported with electron back scatter diffraction. Our analysis indicates that the increased performance of the S2 mc-Si solar cells is contributed to low dislocation density, uniform and highly oriented grains with high percentage of electrically inactive grain boundary (∑3 grain boundary).

1. Introduction

Single- and multi-crystalline silicon are the mainstream materials for the fabrication of the commercial solar cells at present and they will still be in the future [1,2]. The production volume (60%) of the multi-crystalline silicon (mc-Si) solar cells is lager than that (40%) of the single-crystal silicon (sc-Si) solar cells due to its lower cost. There are various techniques [3] for the mc-Si production, such as electromagnetic casting, edge-defined film feed method, casting technique, directional solidification, etc. Among them, the directional solidification [4] is a widely used method owing to its good tolerance to the feedstock impurities, mass productivity, easy operation, and specially cost effectiveness. It is well known that the inferior performance of the mc-Si solar cells compared with the sc-Si is mainly due to the presence of crystal defects, for example, dislocations and grain boundaries. Recombination of the minority carriers at the crystal defects significantly reduces the energy conversion efficiency of the mc-Si solar cells [5,6]. However, not all defects are harmful to the charge carrier lifetime, such as the so-called ∑3 grain boundary, especially twin boundary, which is electrically inactive. Therefore, they have weaker recombination activity than high-∑ and random grain boundaries. It is possible that the mc-Si solar cells achieve similar conversion efficiency to the sc-Si solar cells as long as the grain growth is well controlled to preferred orientations and boundaries [7,8]. The seed and dendrite castings are proposed to reduce grain boundaries and enlarge grain size along with more homogeneity of grain orientation. In the former method [9], the pre-arranged seed crystals (such as sc-Si seeds) are set at the bottom of a crucible before crystallization, which initiates from the seed crystals. But, the critical issue is the initial dislocations originated from the junctions of the seed crystals. Moreover, the seed crystal cost and yield also are issues for industrial application. In the latter method, seed crystals are generated from the melt during crystallization by inducing dendrite growth at the bottom of the crucible. For inducing the dendrite growth, the nucleation site is fast cooled by water [10] or argon flow [11], as well as with different thermal conductivity materials [12] in the initial stage of casting. However, it is difficult to have a sufficient undercooling in industrial-scale furnace, because the bottom area of the crucible is large, the graphite heat exchanger block is thick, and the nitride coating is isolated. Based on the directional solidification, GCL-POLY Energy Holdings Limited (referred as GCL) developed a new technique, named as S2, for mc-Si ingot growth in industrial production. The average energy conversion efficiency of the solar cells fabricated by S2mc-Si wafers is significantly increased compared with the traditional mc-Si solar cells using conventional solar cell

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processing. In order to understand the origin of the high cell performance, ensure the process reproducibility and further improve the technology, this paper characterizes the S2 mc-Si wafers with respect of dislocation densities, grain size, grain orientation and grain boundaries by light microscopy (LM), and scanning electron microscopy (SEM) supported with electron back scatter diffraction (EBSD). Moreover, solar cells have been fabricated from the S2 mc-Si wafers for the solar cell parameter measurements.

2. Experiments

Two ingots are grown in industrial production for this investigation: one with the standard conditions of the directional solidification (referred as Ref ingot) and the other with the new technology of GCL (referred as S2 ingot). In our new process, the geometry modification of the furnace and the optimization of the heat field are made on directional solidification system for better control of grain uniformity and grain orientation [4]. The detail with associated process is not disclosed here. It is worth noting that the crystallization speed is the same for both ingots. The ingots are doped by boron. A block cut from the center region of each ingot is prepared for the characterization purposes. Wafers are sliced from the blocks by the wire sawing process (the slicing is vertical to the growth direction). The wafer has a cross-section area of 156 × 156 mm^2 and a thickness of about 200 μm. We divide the wafers, from the top (solidified last) of the block to its bottom (solidified first), into two groups, i.e. odd and even groups. The odd group is used for the physical characterization, and the even one is fabricated as solar cells for the electrical parameter measurements.

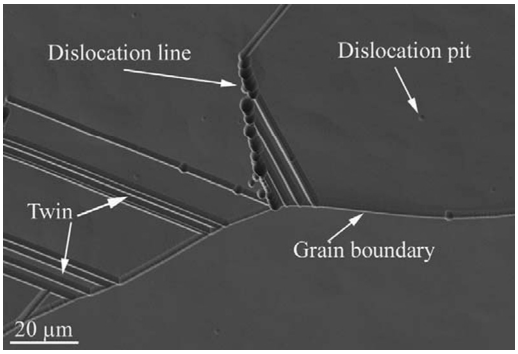

Fig. 1. A scanning electron microscope image of a polished and etched mc-Si wafer clearly shows dislocation lines, dislocation pits, grain boundaries and twins.

3. Physical characterization

3.1. Dislocations

Dislocations are one of the most important efficiency limiting defects in mc-Si solar cells since they act as recombination centers and consequently reduce minority carrier lifetime. In order to measure dislocation density, the as-cut mc-Si wafers are first chemically polished by HNO_3 (75 %)/HF (49 %) solution with (6:1) concentration for removing the saw damage and slurry residues on the wafer surfaces. After 3.5 min of polishing, the wafers are rinsed with deionized water and dried under a nitrogen gun. Then, we select Secco etch solution, $K_2Cr_2O_7$ (0.15 M/L)/HF (49 %) with (1:2) concentration, for delineating the crystalline defects of the wafer surfaces. Fig. 1 shows a SEM image of Secco defect delineation. Dislocation lines, dislocation pits, grain boundaries and twins are clearly distinguished. With Image J software, dislocation density is estimated by counting etch pits in high magnification LM and SEM images. The measurements are carried out over areas up to 310 × 550 μm^2 at several locations across each wafer in order to obtain meaningful statistical data and the dislocation density is found to remain relatively constant. A typical dislocation region of the S2 mc-Si wafer from the middle of the block is shown in Fig. 2a (LM image) and b (SEM image). Twin boundaries which are electrically inactive, shown by arrows, appear as parallel straight lines. Fig. 2c (LM image) and d (SEM image) illustrates a typical dislocation region of the Ref mc-Si wafer in the same height as the S2 mc-Si wafer. A summary of the dislocation observation and analysis from a large number of LM and SEM images is as follows. (i) The dislocation density is higher in the Ref mc-Si wafer (≈1.2 × 10^6 cm^{-2}) than that in the S2 mc-Si wafer (≈2.5 × 10^5 cm^{-2}); (ii) the dislocation distribution is highly inhomogeneous among grains and small size grains (micro-grains) possess high dislocation densities; (iii) the areas with twin boundaries contain either no dislocation or only fewer dislocations; and (iv) the total twin area is larger in the S2 mc-Si wafer (58 mm^2) than that in the Ref mc-Si wafer (25 mm^2).

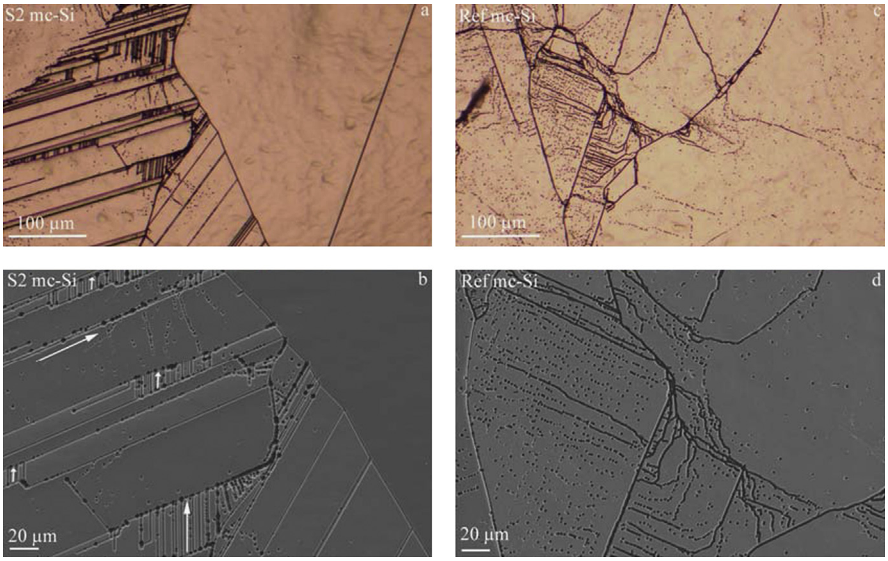

Fig. 2. A typical dislocation region for a S2 mc-Si wafer (a) light image and (b) scanning electron microscope image, arrows appear as parallel straight lines showing electrically inactive twin boundaries. A typical dislocation region for a Ref mc-Si wafer (c) light image and (d) scanning electron microscope image.