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Characterization of defects in mono-like silicon wafers and their effects on solar cell efficiency

Longfei Gong [a,*], Fengzhen Wang [a], Qing Cai [a], Da You [b], Bing Dai [a]

[a] GCL Applied Industrial Research Institute (Suzhou), Ltd., No. 158 Ren'ai Road, SEID, SIP, Suzhou, China
[b] Jiangsu GCL Silicon Material Technology Development Co., Ltd., No.88 Yangshan Road, Xuzhou Economic Development Zone, Xuzhou, China

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ABSTRACT

Cell efficiency distribution of mono-like silicon ingot was investigated. And a long low-efficiency tail was found in the efficiency distribution chart, which degraded the cost-effectiveness of this material. Highly spatial resolved photoluminescence and electron back-scattered diffraction characterizations of the mono-like silicon wafers were performed to investigate the low-efficiency reasons. In the experiments, we found that lots of sub-grains, invisible with naked eyes, formed by low angle grain boundaries and high density of dislocations. Relationship of low angle grain boundaries, dislocations and cell efficiency were also investigated and calculated. It is found that the density of dislocations and low angle grain boundaries increase rapidly in the directional solidification of mono-like silicon ingot. Wafers from the top side of the ingot had high density of dislocations and low angle grain boundaries, which led to low-efficiency cell performance and long low-efficiency tail distribution.

1. Introduction

Silicon is the main material for the expanding photovoltaic (PV) products. In PV field, solar cells are mainly manufactured on multi-crystalline silicon (mc-Si) wafers and single crystalline silicon wafers. Compared with the single crystalline silicon wafers, mc-Si wafers are limited in lower conversion efficiency since there are much more crystal defects such as dislocations, grain boundaries and metallic impurities [1]. These defects can act as the recombination center for minority carriers, degrading the bulk lifetime of silicon wafers and solar cell performance.

To improve the solar cell performance of mc-Si, effect of micro-structures of grain and grain boundary, dislocation density and impurity content on cell efficiency are widely and intensively investigated [2,3,4–8]. Micro-structures of mc-Si could be improved by controlling the initial growth conditions and cooling rate of silicon dendrites. So, some larger grain silicon ingot with lower density of defects will be obtained in high efficiency solar cell applications. By cast technology with seeds covering the crucible, some obtain an ingot with one large dominating grain in the center and small grains surrounded. These ingots are called mono-like silicon or quasi-single crystalline (QSC) silicon. It is reported that mono-like silicon solar cell could give much higher cell efficiency performance than mc-silicon solar cell, which is even closed to the efficiency behavior of the single-crystal solar cell [1,9].

Compared with random grain boundary defects in mc-Si wafers, Low angle boundaries have been reported as serious defects to deteriorate solar cell performance [2,6].

For further investigation of the effect of defects on solar cell performance, photo-luminescence (PL) spectroscopy was used to observe the characterization of defects in mono-like wafers, which was proved to be a useful non-contacting and non-destructive technique in characterizing the distribution of defects and harmful impurities in semiconductor or solar wafer materials [10,11]. Electron back-scattered diffraction (EBSD) technology was also introduced in the experiments and used to characterize the grain angle, grain orientation and other grain parameters. Our investigation showed that large quantity of low angle grain boundaries with relative angle of less than 10° were found in mono-like silicon wafers, on which no grains or grain boundaries could be observed with naked eye.

In this work, we gave the defect distribution chart from bottom side to top side of one silicon block. We also showed the relationship of these defects and solar cell efficiency performance. We hope these results will help to understand the reasons of low-efficiency in mono-like silicon materials and enhance the application of the mono-like silicon in industry.

2. Materials and methods

A mono-like Si ingot was casted by directional solidification technology, boron-doped with the resistivity of 1.0–3.0 Ω-cm and the growth direction of ⟨100⟩. 16 blocks from the center part of the

* Corresponding author. Tel.: +86 18915598686.
E-mail address: deeplevel2005@gmail.com (Longfei Gong).

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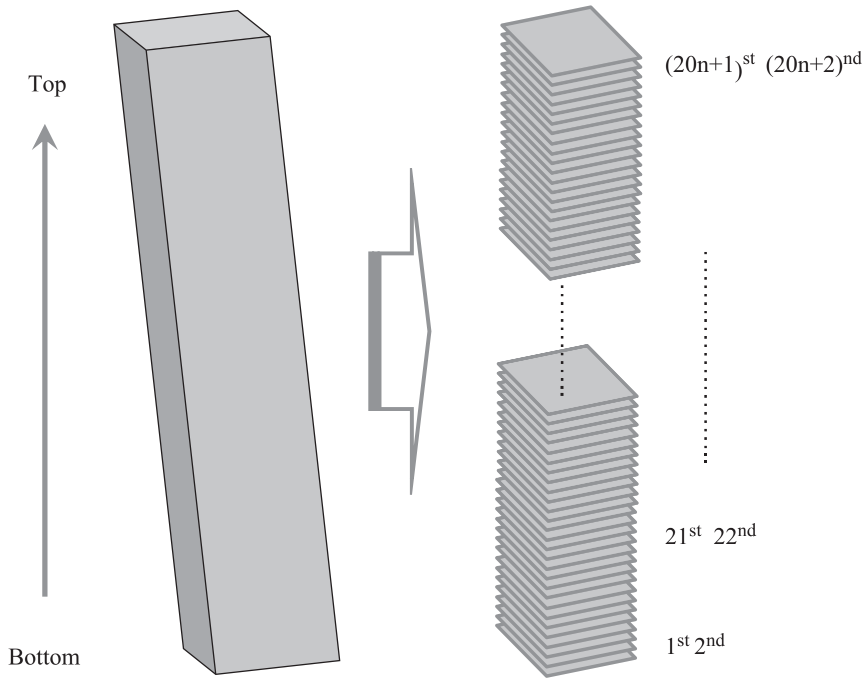

Fig. 1. Sketch showing the selection of wafers from the mono-like silicon block.

ingot are mono-like silicon and the 20 blocks from the edge part of the ingot are partly mono-like silicon or multi-Si. In the experiments, 16 blocks from the center part of the ingot were used. Wafers were sliced with the thickness of 200 μm and the dimension of 156 mm × 156 mm. As shown in Figs. 1 and 2 sample wafers were selected every 20 wafers by sequence from bottom side to top side of the block. One of the two wafers is used for PL test and some destructive experiments, such as dislocation etch and EBSD investigation. The other one is made into solar cell for cell efficiency performance investigation. It can be concluded that the characters of the two neighboring wafer are nearly the same.

PL images of as-cut wafer and finished solar cell made by the neighboring wafer have been acquired using the commercially available PL system equipped with a laser of 808 nm and a silicon CCD camera with a resolution of approximately 1 mega pixel [10]. For PL imaging of as-cut wafers, 5 V laser voltage and 20 s acquisition time were used, and for solar cell test, PL image was recorded by using 5 V and 3 s acquisition time.

For EBSD test, samples are chemically polished for about 3.5 min in HNO_3–HF mixture solutions (HNO_3: HF = 6:1) to remove the damaged layer, and then cleaned in DI water to remove the contaminations. EBSD images are investigated by Zeiss Sigma FESEM and Oxford HKL Nordlys S detector with voltage 20 KV and step length 50 μm. Large samples with area up to 156 mm × 15 mm, are scanned in EBSD test experiment for statistically significant of the measured data.

Dislocations and grain boundaries are observed by optical microscope, after the wafers were mirror-polished by chemical-mechanical polishing machine, cleaned by DI water and etched for 5 min in sirtl etchant solution (HF(49%): CrO_3(5 M/L) = 1:1). The fraction of dark line and defect networks on as-cut wafers' PL image was calculated by area, in which the wafer PL image was divided into 100 parts to estimate and calculate the fractions of dark line networks areas.

All the other wafers from the center 16 blocks of the ingot were made into solar cell to investigate the cell efficiency distribution. In the solar cell process, alkali solution was used to form 'inverted pyramid' texture.

3. Results and discussion

Fig. 2 shows the optical photograph and the PL image of mono-like wafer used in this study. In Fig. 2(a), no grains or grain boundaries could be observed in naked eyes on the wafer and the wafer has only one grain. In Fig. 2(c), EBSD test results also showed that only one grain orientation was found and the orientation is ⟨100⟩, which was the same as seed crystal silicon orientation. Fig. 2 (a) and (c) can tell that mono-like silicon has only one large silicon crystal grain, and the grain orientation inherits from the original seed orientation like CZ-Si. Fig. 2(b) is PL image of the wafer, on which we found some dark line and network pattern in the image. It is reported that dark contrast means strong recombination centers of minority carries [11] in PL image, and the recombination centers are always induced by heave metal impurities or defects. In the paper, these dark lines and network defects in PL images are named Recombination Active Network defects (RAN defects).

To study the solar cell efficiency distribution of the whole mono-like ingot, we made all the wafers from the ingot into solar cells, in which alkali solution was used to form 'inverted pyramid' texture and a SiN_x layer was used to form a uniform antireflection film by PECVD.

Fig. 3 showed the cell efficiency distribution of the whole 16 sample blocks in the experiment. We found that it was a non-normal distribution and there exists a long tail on the low efficiency side. There must be something with strong recombination electrically centers do harmful effect on the cell efficiency performance of the wafers. To investigate the low-efficiency tail details reasons and location of the low efficiency wafers in the ingot, we investigate the detail trends of cell efficiency from bottom side to top side of the ingot. One mono-like silicon block was chosen and the wafers from the block were laser marked in sequence. And then, we made them into solar cells. Efficiency trend chart of the solar cells was showed in Fig. 4.

It could be found that the cell efficiency decreased rapidly as the cell wafers approach to the top of the ingot. In other words, the cell efficiency decreased along with the crystal ingot growth direction quickly. The cell efficiency difference of the top wafer