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Performance of solar cells fabricated from cast quasi-single crystalline silicon ingots

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Abstract

We comprehensively investigated the performance of solar cells made from quasi-single crystalline silicon (QSC-Si) cast by the seed-assisted directional solidification (DS) method and its relationship with the area ratio of $\langle 100 \rangle$ -oriented single crystal of a QSC-Si wafer. It is found that the cell performance improvement triggered by alkaline texturing is more notable for the QSC-Si wafers with a morphology of higher $\langle 100 \rangle$ -oriented single crystal ratio, and the difference in cell efficiency between alkaline and acidic texturing is up to an absolute value of 1.05%. As the single crystal ratio of the QSC-Si wafer decreases from 100% to 50%, the cell efficiency decreases from 18.15% to 17.04%. We also compared the performance of typical CZ-Si solar cells and the QSC-Si solar cells made from wafers with fully $\langle 100 \rangle$ -oriented single crystal. It is found that the average efficiency of QSC-Si solar cells is about 0.8% absolutely lower than that of the CZ-Si solar cells, and it has a substantially wider range of distribution due to dislocation propagation.

Keywords: Energy conversion efficiency; Seed-assisted directional solidification; Quasi-single crystalline silicon; Solar cells

1. Introduction

Quasi-single crystalline silicon (QSC-Si) cast by the seed-assisted directional solidification (DS) method has emerged as a promising material for low-cost, high-efficiency solar cells (Gu et al., 2012; Stoddard et al., 2008, 2009). On the one hand, QSC-Si offers lower manufacturing cost and higher throughput for silicon wafers than single-crystalline silicon rods grown by the Czochralski (CZ) method. On the other hand, it produces solar cells with higher conversion efficiency than those produced with multi-crystalline silicon (mc-Si) ingots cast by the conventional DS method. Many studies have devoted to the improvement of QSC-Si ingots through optimizing the hot-zone of furnace and growth process (Black et al., 2012; Gao et al., 2012; Ma et al., 2012). Much attention has also devoted to the performance of QSC-Si solar cells, and considerable conversion efficiency has been obtained based on the $\langle 100 \rangle$ -orientated QSC-Si wafers (Gu et al., 2012; Kaden et al., 2012; Prajapati et al., 2009; Stoddard et al., 2009). However, on the other hand, several challenges have emerged for the QSC-Si ingots, chief among which are the formation of mc-Si grains (Gu et al., 2012; Wu and Clark, 2011), high defect density (Hu et al., 2012; Tachibana et al., 2012), and long low carrier lifetime zone at the bottom of ingot (Yu et al., 2013). Particularly, the formation of mc-Si grains in the QSC-Si ingot make the

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QSC-Si wafers have special morphology, which has obvious influence on the performance of solar cells with different texturing methods. Therefore, the area ratio of the largest single grain of a QSC-Si wafer becomes a new concept for classifying the quality of product and for matching the subsequent cell process.

However, the detailed relationship between cell efficiency and morphology of QSC-Si wafers remains unclear. The influence of texturing technology on the performance of solar cells made from QSC-Si wafers with different morphological structures is also unknown. These issues need to be resolved to improve QSC-Si ingot quality and solar cell performance.

In this study, various aspects of the performance of solar cells made from QSC-Si ingots cast by the seed-assisted DS method are investigated. The effect of texturing technology on cell performance is comparatively analyzed to properly select texturing technology for wafers with different area ratios of $\langle 100 \rangle$ -oriented single crystals. Attention is paid to the quantitative relationship between cell efficiency and the area ratio of $\langle 100 \rangle$ -oriented single crystal in the QSC-Si wafer. Furthermore, the solar cell efficiency distribution of wafers of the QSC-Si ingot is investigated and compared with that of a typical CZ-Si and a mc-Si ingot.

2. Fabrication and measurement of the QSC-Si ingot and solar cells

A QSC-Si ingot was cast in an industrial Jinggong JJL500 DS furnace with $\langle 100 \rangle$ -oriented single crystal seeds closely placed at the base of the crucible (Yu et al., 2012). The cross section of the ingot was 840 × 840 mm and its height was approximately 275 mm. The ingot was cut into 25 bricks with a square cross section of 156 × 156 mm. These bricks were then transversely sawn with wire into wafers with a thickness of about 180 μm. A laboratory off-line photoluminescence (PL) instrument (BT imaging, LIS-R1) and industrial online PL instrument (Hennecke, HE-WI-04) were used to observe the dislocation distribution in the wafers. The solution containing HNO_3 and HF was used for isotropic acidic texturing and the solution containing KOH and C_2H_5OH was used for anisotropic alkaline texturing. The wafers were classified into several groups according to the area ratio of $\langle 100 \rangle$ -orientated single crystal calculated with the help of a self-designed latticed tool. For each group, we used more than 4000 samples. Batch production of solar cells was conducted online using a standard manufacturing process, then the performances of the solar cells were measured by online I–V measurement systems (HALM).

3. Results and discussion

The seed crystals were $\langle 100 \rangle$ oriented, so the grown QSC-Si ingot mainly consisted of $\langle 100 \rangle$ -oriented single crystals. However, mc-Si grains inevitably form at the corners and sides of QSC-Si ingots during mass production, because of the defective shape of the solidification interface and free nucleation at the crucible walls during the solidification process. Fig. 1(a) shows the numbering of the 5 × 5 bricks cut from the produced QSC-Si ingot. Fig. 1(b) shows longitudinal cross-sectional images of the blocks in the central line; namely, Nos. B11, C12, C13, C14 and B15. Fig. 1(c–e) shows the wafers obtained from blocks at different positions in the QSC-Si ingot; namely, Nos. A1, B3 and C13, respectively. The wafer from the ingot corner (No. A1) has mc-Si grains near the two sides that contacted with the crucible walls. The wafer from the ingot side (No. B3) has mc-Si grains near the side that contacted with the crucible wall. The wafer from the center (No. C13) has $\langle 100 \rangle$ -oriented single-crystal morphology without any mc-Si grains.

Typically, mc-Si wafers are textured using the isotropic acidic texturing method because of their randomly oriented crystal grains (Cheng et al., 2011), while a pyramidal structure with low reflectance can be obtained in $\langle 100 \rangle$ -oriented CZ silicon (CZ-Si) wafers using the alkaline texturing method (Barrio et al., 2012), which is one of the important factors that result in the high efficiency of CZ-Si solar cells. For the wafers cut from the QSC-Si ingot, the area ratios of $\langle 100 \rangle$ -oriented single crystals differed. Obviously after alkaline texturing, the QSC-Si wafer with fully $\langle 100 \rangle$ orientation possesses a surface with pyramidal structures, which have excellent light trapping ability (Gu et al., 2012). The QSC-Si wafers containing mc-Si grains were subjected to the two texturing methods introduced above. After isotropic acidic texturing, the color of wafer surface was uniform and the reflectance measured at the mc-Si and $\langle 100 \rangle$ -oriented single crystal regions remained consistent with that of mc-Si wafers, as shown in Fig. 2(a). In contrast, after anisotropic alkaline texturing, the QSC-Si wafer did not possess uniform surface texture. Fig. 2(b) shows that there is obvious color variation in different regions of the wafer, and a reflective surface is obtained in the mc-Si region. We randomly selected five separate points in the $\langle 100 \rangle$ -oriented and mc-Si regions to measure reflectance with a wavelength range of 300–1050 nm. The results are shown in Fig. 2(c). The reflectance of the $\langle 100 \rangle$ -oriented regions in the QSC-Si wafers after alkaline texturing showed little difference from that of CZ-Si, while high reflectance of the mc-Si region was induced by alkaline texturing. The reflectance of this region was much higher than that of an acidic-textured conventional mc-Si wafer. Such mc-Si regions with high surface reflectance after alkaline texturing will lower the efficiency of QSC-Si solar cells.

Table 1 shows the differences in solar cell performance between QSC-Si wafers with various $\langle 100 \rangle$ -oriented single crystal ratios subjected to alkaline and acidic texturing methods. We can see that the texturing technology used has a marked effect on the cell performance for all QSC-Si wafers with $\langle 100 \rangle$ -oriented single crystal ratios of over 50%. Compared with the acidic texturing method, the alkaline texturing method can notably increase the cell efficiency, and improve the short-circuit current (Isc) and