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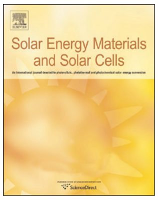

Higher quality mono-like cast silicon with induced grain boundaries

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ABSTRACT

Sub-grain boundaries related to dislocation clusters are seriously detrimental to the quality of mono-like cast silicon, which reduce the efficiency of the solar cells. Here, we have developed a novel technique to grow the mono-like cast silicon by forming special grain boundaries. The special grain boundaries are induced by controlling the placing method of seeds at the bottom of crucible. It is found that the sub-grain boundaries in the new ingots are completely suppressed, which are clarified by the measurements of photoluminescence and electroluminescence. Therefore, compared to the conventional mono-like ingot, the minority carrier lifetime of the new ingots is significantly increased, and the internal quantum efficiency of corresponding solar cells gets obviously improved. As a result, the power conversion efficiency of the solar cells is averagely 18.1%, which is much higher than that of conventional ones by a value of 0.6% absolutely. These results are of significance for the quality improvement of mono-like silicon and their application in photovoltaics.

1. Introduction

Crystalline silicon (c-Si) is the main substrate material for the manufacture of solar cells in the photovoltaics (PV) industry. In recent years, mono-like (ML) cast silicon, also known as quasi-single crystalline (QSC) silicon, has received much attention due to its high quality and low cost [1–3]. Compared to common multicrystalline silicon (mc-Si), the ML cast silicon has the higher minority carrier lifetime and avoids the formation of grain boundaries (GBs). Meanwhile, the alkaline texturing can be applied for the ML c-Si solar cell fabrication for reducing the sunlight reflectance, which is not possibly used for the mc-Si solar cells. Compared to Czochralski (CZ) silicon, the ML c-Si has also some advantages. Except for the lower cost, the light induced degradation in ML c-Si solar cells is much low due to its low oxygen concentrations [4], and meanwhile, the square shape of ML c-Si wafers increases the effective area ratio in the cell modules, which are beneficial for the improvement of the electricity output in the practical PV application.

Defects including grain boundaries (GBs) and dislocations in c-Si materials are usually considered to be the main factors that degrade solar cell performance. They can cause deep levels in silicon band gap and become the recombination centers for minority carriers [5]. For the ML c-Si, since the GBs can be avoided, the dislocations become the most important defects. It has been reported that the scattered dislocations in ML c-Si have no significant influence on the solar cell performance. However, the dislocations in ML c-Si can easily multiply and then form the clusters, which are detriment for the solar cell [3]. Recently, Gong et al. have verified that the high density dislocations (called as recombination active network, RAN) in ML c-Si can significantly reduce the efficiency of solar cells [6]. Zhang et al. have found that the density of dislocations is exponentially increased in the ML c-Si along the growth direction [7]. In our previous report [8], it has been found that the orientation of the region near the dislocation clusters in the ML c-Si is slightly different from its neighbor region, and therefore the so-called “sub-grain” is actually formed. The sub-GBs consisting of dislocation clusters originate from the lattice mismatch between adjacent seeds at the bottom of crucible. These sub-GBs in ML c-Si have severe influences on the solar cell performance [8–10], which hinder the practical application of ML silicon in photovoltaic industry. Recently, Birkmann et. al have reported that the formation of sub-GBs can be effectively suppressed by inducing the GBs using the seeds with tilt angular deviation [11]. However, this method requires a complicated seed process and meanwhile the orientation of the c-Si is not consistent for the application of alkaline texturization in the solar cell process.

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In this paper, we will report a novel technique to induce GBs during the ML c-Si growth by using seeds with radial angular deviation. The GBs can effectively avoid the effect of the inevitable mismatch between adjacent seeds at the bottom of crucible, and therefore the sub-GBs in ML c-Si can be suppressed. Both the crystal quality of ML c-Si and the solar cell efficiency get significantly improved. This new technique is interesting for the practical application of ML c-Si in PV industry.

2. Experiments

Two boron-doped, ⟨100⟩-oriented ML c-Si ingots were grown in a GT-450 DSS furnace from GT Advanced Technologies Co. Ltd. The size of ingot was 870 × 870 × 300 mm^3, and the weight was about 500 kg. One ingot is the regular ML c-Si with sub-grains by a common process, labeled as ingot A, which is used as a reference here. The other one is the ML c-Si with induced grain boundaries (GBs), labeled as ingot B. The GBs were induced by keeping an intentional twist angular deviation of 10–45° between the adjacent (100)-oriented seeds. The angular deviation should be larger than the maximum deviation value of the sub-grains. After solidification, the ingots were cut into wafers. The resistivities of wafers determined by the four probe method are in the range of 1.7–1.4 Ω cm, which decreases along the solidified direction from the bottom to the top of the ingot. The wafers were fabricated into the solar cells on an industrial line by a conventional screen printing process, including the alkaline texturization, phosphorus diffusion, Al BSF and Ag metal electrodes.

The defects in both kinds of wafers were characterized by a PL imaging system (BT imaging, LIS-R1), and a minority carrier lifetime scanning system (Semilab WT-2000). The orientation of ingots was tested by an X-ray orientation tester (Dandong ray instrument Co. Ltd., YX-2). After the solar cell fabrication, the electrical-luminescence (EL) signals of the solar cells were measured by a NELC-140H solar battery testing equipment (Shanghai Juna Co. Ltd.), and the performances of the solar cells were measured by a HALM equipment (H.A.L.M Elektronik GMBH).

3. Results and discussions

Fig. 1 shows the surface of the reference ingot A observed from an oblique angle. The feature caused by the sub-grains can be obviously found on the surface of ingot A. The measurements of X-ray orientation tester indicate that these areas indeed contain many small sub-grains, with a slight deviation from (100) orientation. The angular deviations of the sub-grain regions are ± 0.7°, ± 1° and ± 2.8° at the typical bottom, middle and top positions of the ingot, respectively [8]. This means that the deviation of sub-grain orientation increases along the ingot height, even though it is smaller than 3°.

Fig. 1. Optical photo of the top surface of reference ML silicon ingot (ingot A) from an oblique angle. Sub-grains could be observed, as indicated by the circle.

Fig. 2 shows the optical, PL and minority carrier lifetime images of the cross-section of a block from ingot A. The sub-grains can be seen at the block section, corresponding to the cascade dark pattern in the PL image. Macroscopic sub-grains, along with large amount of defects, start from the seed junctions, and their region becomes larger along the ingot height. The dark patterns in the PL image are responsible for the lower carrier lifetime. The lower carrier lifetime should be caused by the sub-GBs, which are the deep levels for carrier recombination [5]. As a result, the intensity of PL and the minority lifetime decrease obviously in the sub-grain regions.

Fig. 3 shows the optical, PL and minority carrier lifetime images of the cross-section of a block from ingot B. It can be seen that a macroscopic grain boundary is induced at the seed junction by using a seed cutting with intended angular orientation. Compared with the ingot A, the sub-grain boundaries disappear in the ingot B. Therefore, the minority carrier lifetime is increased near the GB regions, as shown in Fig. 3c. One may also notice that at the top of the ingot B, there are other dark patterns with lower carrier lifetime, see Fig. 3b and c. These dark patterns are not related to the sub-GBs originated from the seed junctions at the bottom of crucible, but maybe related to the dislocations or dislocation clusters generated by impurity inclusions.

The PL images of the wafers from the bottom, middle and top of ingot A and B are shown in Fig. 4. For both kinds of ingots, the defect region with darker patterns in the wafer from the bottom is much less than that from the top. However, the distribution of defects in the ingot B is much different from that in the ingot A. For ingot A, the sub-grain boundaries are the major defects. The ratios of defective area over the wafer area are ~50% and ~90% for the middle and top of ingot A, respectively. Compared to ingot A, the defective area ratio in ingot B is much smaller. The ratio of defective area for the wafer from the top of ingot B is only around 30%. Therefore, it is believed that the quality of the ingot B should be better than that of the ingot A, due to its less defective area. This point is also confirmed by the carrier lifetime mapping of two ingots, as shown in Fig. 5. It is obviously seen that the carrier lifetime of ingot B without sub-GBs is averagely higher and more uniform than that of the ingot A.

Fig. 6 shows the EL images of solar cells based on the wafer from the middle part of ingot A and B. In Fig. 6a, lots of dark clusters caused by serious carrier recombination can be seen for ingot A, which are correlated with sub-GBs. However, there were only two slightly dark lines for ingot B, which are related to the intentionally induced GBs, see Fig. 6b. This result indicates that the quality of ingot B without sub-GBs is better than that of ingot A. Fig. 7 shows the internal quantum efficiency (IQE) of the solar cells based on the wafers from the middle part of two ingots. Note that small angular deviation in ML c-Si usually cannot have obvious influence for the alkaline texturization during the solar cell fabrication. Therefore, the sunlight reflectivity of the solar cells based on ingot A should be quite similar to that of the solar cells based on ingot B, as reported in our early work [8]. It can be seen that from Fig. 7, the IQE of the solar cell based on ingot B is higher in the whole spectrum, especially in the long wavelength range. For the short wavelength (UV) range, the minority carriers injected by the sunlight are close to the surface, and therefore the surface recombination plays a more important role in the carrier collection efficiency of solar cell. Thus, one can only see a slight improvement