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Distribution and propagation of dislocation defects in quasi-single crystalline silicon ingots cast by the directional solidification method

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ABSTRACT

We investigated the distribution and propagation of dislocation defects in quasi-single crystalline (QSC) silicon ingots. The dislocation distributions in both the central single crystalline region and the surrounding polycrystalline region of the ingot are measured and compared. Although the dislocation density in the central single crystalline region is much lower than that in the surrounding polycrystalline region, dislocations in this region propagate and spread with the growth of the silicon crystal, especially at the final stage of solidification. The performances of solar cells made of wafers from different parts of the QSC silicon ingot are also compared. The results show that solar cells made of wafers from the middle part of the ingot have the best performance and those made of wafers from the top part of the ingot have the worst performance.

1. Introduction

Single crystalline silicon rods grown by the Czochralski (CZ) method and multi-crystalline silicon (mc-Si) ingots cast by the directional solidification (DS) method are commonly used substrates for solar cells. By combining the advantages of the above two materials, seed-assisted quasi-single crystalline (QSC) silicon ingots cast by the DS method have been developed [1]. QSC silicon is popular in photovoltaic applications owing to its low manufacturing cost, high throughput and high conversion efficiency for solar cells [2,3]. However, there is still room for improvement in the casting of QSC silicon ingots, such as reusing seed crystals, increasing the single crystalline region, reducing crucible contamination and controlling dislocation propagation [4]. Among these possible improvements, control of dislocations is the main way of improving the ingot quality, because dislocations are the main structural defects in QSC silicon ingots.

Dislocations in the single crystalline region of a QSC silicon ingot usually originate from the split between two seeds and inclusions incorporated into the advancing growth front [5]. Dislocations that form then propagate as solidification proceeds, appearing as a cascade from the bottom to the top of the silicon ingot. This propagation feature has been shown to be extremely detrimental to the minority carrier lifetime [1,5]. Dislocations in the polycrystalline region of the silicon ingot are likely to occur at the grain boundaries (GBs) and they propagate along the crystallographic orientation [6]. To avoid dislocation propagation and to reduce the dislocation density, the thermal field in the casting process is usually optimized to maintain an ideal interface shape and reduce the thermal stress [7–9]. It has been proposed that reducing the dislocation density can also be obtained by controlling impurity transport and avoiding precipitation during crystal growth [10–12]. Irrespective of what method is used, a clear understanding of the distribution and propagation characteristics of dislocations throughout the QSC silicon ingot is essential. However, previous studies have only compared the dislocation density in several sections of an ingot, which is inadequate for understanding the distribution characteristics and propagation mechanism of dislocation defects in cast QSC silicon ingots.

In this study, the dislocation distributions in different sections that are perpendicular to the growth direction of an industrial-size QSC silicon ingot are determined. The basic distribution characteristics of dislocation for both the single crystalline and polycrystalline regions of the ingot are analyzed. Special attention is paid to revealing the propagation mechanism of dislocation in the central large single crystalline region. The cell data for different parts of the silicon ingot are also compared to clarify the influence of dislocation on the solar cell performance.

2. Experiment process

The QSC silicon ingot was cast in an industrial DS furnace [13]. The side length of the ingot was 840 mm and the height was

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approximately 250 mm. The fabricated ingot was cut into 25 bricks with 156 × 156 mm^2 cross section, which is the same size as that of the seed crystals. These bricks were then wire-sawn into wafers with thickness of about 180 μm. The wafers were first etched in HF/HNO$_3$ solution to remove the sawing damage, and then etched in $K_2Cr_2O_7$/HF/$C_2H_4O_2$ solution to observe the dislocations. A confocal laser scanning microscope (CLSM) was used to detect the dislocation distribution in the silicon wafers and photoluminescence (PL) measurements were used to reveal the dislocation propagation in the central single crystalline region of the QSC silicon ingot.

3. Results and discussion

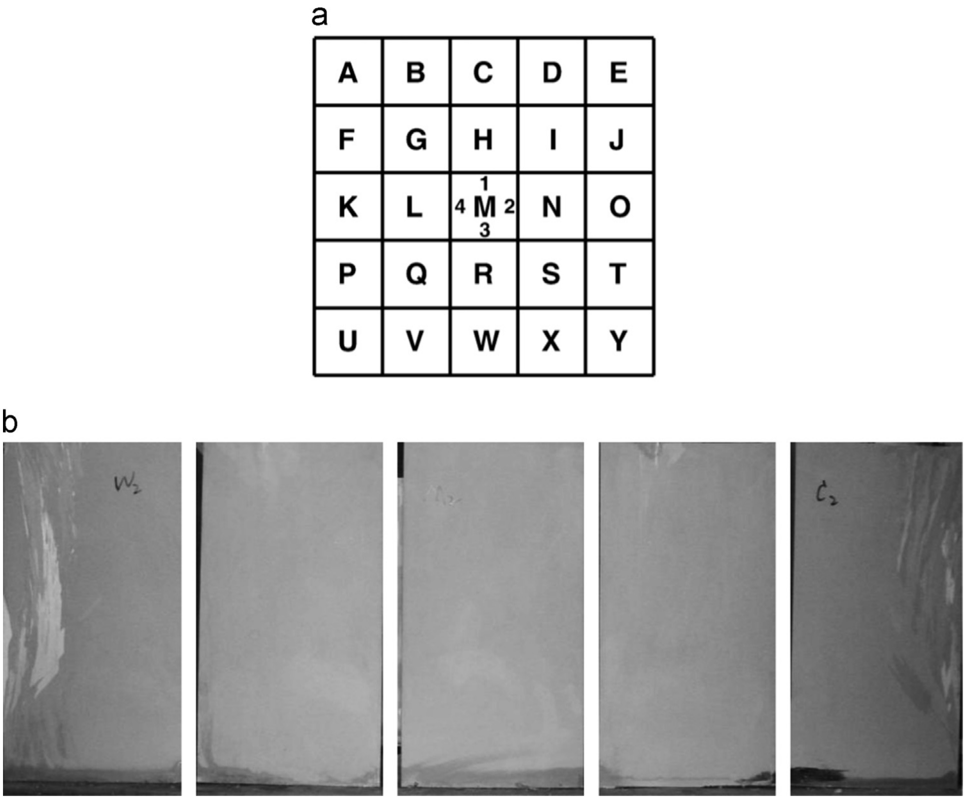
The QSC silicon ingot is cut into 25 bricks, as shown in Fig. 1. Fig. 1(a) shows the numbering of the 25 bricks of the ingot and Fig. 1(b) shows the grain distribution in the central cross section of the ingot. Among these bricks, the nine at the central region of the ingot are single crystalline, and the other 16 in contact with crucible walls contain two parts: a main single crystalline part far away from crucible wall and a minor polycrystalline part consisting of small grains of silicon close to the crucible wall. The small grains usually originate from the crucible wall and propagate toward the center and the top of the ingot.

Fig. 2 shows the defect distribution in a wafer cut from one of the surrounding 16 bricks. From the picture of the silicon wafer shown in Fig. 2(a), the polycrystalline region lies along the top edge of the wafer, which is close to the crucible wall during the ingot solidification process. Many small grains and GBs exist in this region. Dislocations are likely to form at these GBs and propagate along the crystallographic orientation [6]. The color below the polycrystalline silicon region is uniform, which means that the lower part of the silicon wafer is one large grain (single crystalline silicon).

Fig. 2(b) shows the PL imaging of the silicon wafer shown in Fig. 2(a). The bright area in the PL imaging indicates low dislocation density, whereas the dark patterns, such as spots, lines and loops, indicate regions of high dislocation density [14,15]. The top region in Fig. 2(b) corresponds to the polycrystalline silicon in Fig. 2(a) and is dark in color. This indicates that the dislocation density is high in this region and the solar cell performance will be markedly influenced. For the single crystalline region, there are still dark patterns, as shown in the lower part of Fig. 2(b). This is mainly due to the formation and propagation of dislocations in the bulk grain during ingot solidification. The dark patterns in the single crystalline region are dense along the edges of the wafer and sparse in the central part. This is because the generation mechanisms of dislocation are different for the two regions. The above distribution characteristic will be studied in detail in Fig. 4, and it is important for understanding the dislocation propagation mechanism in the casting of QSC silicon ingots.

To observe the dislocation distribution in the surrounding 16 bricks in detail, an enlarged view of the structural defects in the transition region from polycrystalline silicon to single crystalline silicon is shown in Fig. 3. The structural defects are observed by CLSM. Two GBs exist in Fig. 3: one is located at the bottom left and the other spans the whole region. Dark spots are etching pits corresponding to scattered dislocations. It is clear that the dislocation densities on the two sides of the GBs are greatly different. The region with low density is single crystalline silicon and the region with high density is polycrystalline silicon.

After investigating the dislocation distribution in the surrounding 16 bricks, we now focus on the dislocation propagation in the nine single crystalline bricks. Fig. 4(a)–(f) shows the PL imaging of six silicon wafers taken from the bottom to the top of the central single crystalline brick. The six wafers are equidistantly spaced in the brick. The wafer in Fig. 4(a) is located near the bottom of the ingot. No dark patterns are present in the central region of the



A	B	C	D	E
F	G	H	I	J
K	L	1 4 M 2 3	N	O
P	Q	R	S	T
U	V	W	X	Y

Fig. 1. Bricks cut from a QSC silicon ingot: (a) numbering of bricks of the ingot and (b) grain distribution in the central cross section of C2–H2–M2–R2–W2 of the ingot.