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Preferred grain orientations in silicon ribbons grown by the string ribbon and the edge-defined film-fed growth methods

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ABSTRACT

Silicon ribbons for photovoltaic applications grown under typical industrial processing conditions by the String Ribbon and the Edge-defined Film-fed Growth (EFG) methods were quantitatively analyzed by newly developed scanning technologies with respect to the grain structure and orientation. As a result the grain structure consists typically of elongated grains with a ⟨2 1 1⟩ orientation nearly parallel to the growth direction and a {1 1 0} ribbon surface. These grains are mainly separated by Σ3 twin boundaries which are nearly perpendicular to the {1 1 0} ribbon surface. This result is found to be independent from the orientation of seed crystals and is in agreement with earlier studies on silicon ribbon growth. The experimental observations will be explained by a growth model which considers the surface energies of the growing grains and the need for undercooling in front of the phase boundary.

1. Introduction

The String Ribbon (SR) [1] and Edge-defined Film-fed Growth (EFG) [2] methods are of great interest for the photovoltaic industry because they allow a kerfless production of silicon wafers. The high yield of transforming the poly-silicon feedstock into wafers of proper thickness and dimensions for solar cell fabrication is the main advantage of the SR and EFG growth techniques. The main disadvantage of the growth of ribbons by SR and EFG is that both methods resulted so far only in multi-crystalline silicon wafers with relatively high defect densities which limits the efficiency of solar cells compared to mono crystalline silicon [3].

Already in very early studies on SR and EFG [4,5] it was reported that the silicon ribbons grow typically with elongated grains nearly parallel to the pulling direction. The elongated grains are mostly separated by twin boundaries of Σ3-type and oriented closely to the ⟨2 1 1⟩ orientation in growth direction. The ribbon surface was observed to be preferably a {1 1 0} face [4–7].

This result is of actual interest, because the occurrence of twin boundaries together with the preferred orientations can be useful for an increased solar cell performance if they can be grown reproducibly for most of the ribbon width and length [8].

The present study will extend the earlier work on SR and EFG and present new quantitative results on the grain structure of silicon ribbons which were grown by current industrial SR and EFG production processes, after several years of optimizing. Furthermore, special experiments were carried out in order to investigate the influence of the seed orientation on the resulting grain structure of the ribbons. The grain structure of the ribbons was analyzed quantitatively with respect to the crystallographic orientations of the elongated grains by using a new characterization tool, called "Laue scanner" [9]. It will be discussed how the results of the occurring grain structure can be explained by considering the surface energy of the growing grains and the growth morphology in the vicinity of twin boundaries also considering the recently published model of Fujiwara [10].

2. Ribbon growth and preparation of samples

The examined silicon ribbons were either grown by the String Ribbon (SR) technique at the former production facilities of Sovello GmbH in Thalheim (Germany) or by the EFG technique at the former production facilities of Wacker Schott Solar GmbH in

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Alzenau (Germany). The SR technique is described in [11]; the EFG growth is explained in [12]. The SR and EFG ribbons used in this study have a thickness of 100–300 μm and were grown at a pulling speed of 10–30 mm/min.

In order to visualize the grain structure of the ribbons by a reflectivity measurement (grain detector from Intego GmbH) the ribbon samples were chemically treated (SR samples by a 0.2 mol/l NaOH etchant at 70 °C, EFG samples by an etchant based on HF/HNO_3). Afterwards the crystal orientation of each detected grain was measured by using white X-rays with the Laue scanning apparatus from GE Inspection Technologies [9]. For the EFG samples the detected grains were too small and the grain orientation was determined by a Laue scanning technique in an area of 40 × 20 mm² at measurement intervals of 0.5 mm, which was the resolution limit of the used collimator. Therefore grain boundaries which are separated by less than 0.5 mm cannot be resolved. For optical visibility of grain boundaries samples were etched by a Secco etchant [13].

3. Results of ribbon characterization

The results will be presented for SR and EFG ribbons in two separate Sections 3.1 and 3.2.

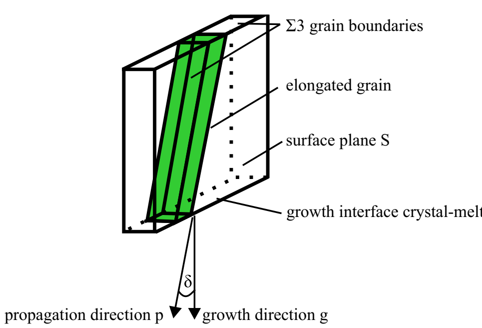

Fig. 1. Schematic drawing of a ribbon with growth direction g, containing an elongated grain with propagation direction p and two grain boundaries reaching from the front surface plane (S) to the backside surface plane. The propagation direction p of the grain is defined by the direction of the line which is given by the two parallel grain boundaries cutting the surface S (see text). δ is the angle between p and g.

In the following the orientation of the grains along the pulling direction and of their surface plane with respect to the ribbon surface will be shown. The plotted orientations are the main orientations {1 0 0}, {1 0 1}, {1 1 1}, {1 1 2}, {1 1 3}, {1 1 5}, {3 1 3} and {3 1 5} with respect to the growth direction g and the surface plane S (compare Fig. 1) respectively with the actual Laue patterns in an agreement by at least 50% with simulated Laue patterns. The deviations from the "exact" orientations are below 14°.

The pulling direction for all results shown in the figures is upwards. As illustrated in Fig. 1, the surface plane of the ribbon is defined as S and the growth direction of the ribbon as g. Since ribbons typically exhibit elongated grains restricted by two parallel grain boundaries we are furthermore introducing the direction p, which represents the propagation direction of the elongated grains. p is defined by the direction of the line given by the two parallel grain boundaries cutting the surface S with an angle δ between p and g (see Fig. 1).

3.1. String ribbon samples

Fig. 2 shows typical results for the grain orientation with respect to g and S of two SR samples. The results show that the majority of the elongated grains in the center of the sample have a propagation direction p almost parallel to the growth direction g (g is anti-parallel to the pulling direction). They are oriented near the ⟨1 1 2⟩ direction (Fig. 2a and c) and their surface planes S are near the {1 1 0} orientation (Fig. 2b and d). Grains too small to be detected by the grain detection system are given in white or gray. These small grains mainly occur near the strings but seem not to interrupt the growth of the elongated grains in the center of the ribbons.

3.2. EFG samples

In this work it could be demonstrated that the "preferred" ⟨2 1 1⟩ – {1 1 0} grain orientations are dominating regardless of the preset seed orientation. Fig. 3 shows the results of EFG seeding experiments with two seeds of different grain orientations. In both cases a part of an EFG sample was used as seed. In case 1 (Fig. 3a) the ribbon seed had the typical as-grown orientation (regular seed) and in case 2 (Fig. 3c) the as-grown ribbon was rotated

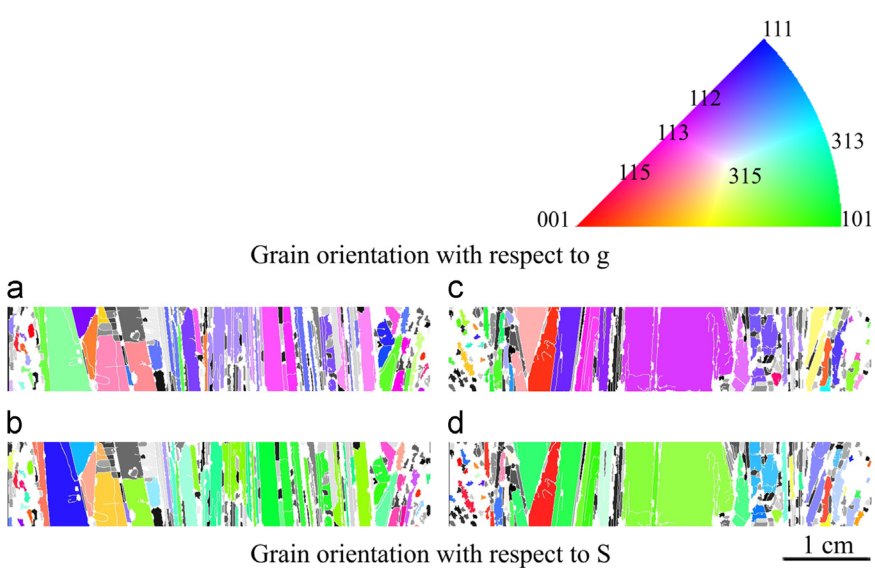

Fig. 2. Crystallographic orientations of two SR samples in the colors of the inverse pole figure in the direction of the growth direction g (a) and (c) of the surface plane S (b) and (d). Gray and white areas are not determined regions.