Solar Energy Materials & Solar Cells 159 (2017) 128–135

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Different nucleation approaches for production of high-performance multi-crystalline silicon ingots and solar cells

Iryna Buchovska [a,*], Oleksandr Liaskovskiy [b], Timur Vlasenko [b], Sergey Beringov [b], Frank M. Kiessling [a]

[a] *Leibniz Institute for Crystal Growth, Max-Born-Str. 2, D-12489 Berlin, Germany*
[b] *Pillar Ltd, member of Pillar Group, Severo-Syretskaya Str. 3, 04136, POB 42, Kiev, Ukraine*

ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form
27 July 2016
Accepted 29 August 2016
Available online 15 September 2016

Keywords:
Directional solidification
Seeded nucleation
Dislocation
Multi-crystalline silicon
Solar cells
Conversion efficiency

ABSTRACT

Two different process approaches for growing high-performance multi-crystalline silicon (HPM-Si) material for photovoltaic applications are presented. Assisted nucleation was achieved by seeding on fine polycrystalline silicon chunks and on a rough silica crucible bottom, respectively. For each of the two methods industrially sized ingots of 650 kg were directionally solidified. Wafers of these ingots and those from conventionally solidified multi-crystalline (mc) silicon ingots were used to produce solar cells on industrial line. Solar cell parameters were analyzed and compared.

Both assisted nucleation methods are suitable for industrial growing of HPM-Si ingots. The grain size is more homogeneously distributed resulting in improved material quality. Less dislocation clustering results in higher average conversion efficiency of solar cells compared to those made of conventionally solidified mc-Si material. Moreover, it is also experimentally proven that assisted nucleation procedure is effective for both Siemens polysilicon feedstock and cheaper solar grade silicon. Further improvements of nucleation procedures, which can be used to achieve higher conversion solar cell efficiency and lower product cost, are proposed.

1. Introduction

Silicon based solar cell technology has been developed continuously showing significant increase in efficiency year by year. However, it is obvious that further increase of efficiency is also related to the quality of the used wafer material. It is well known that structural imperfections [1] are strongly influencing the cell performance and hence, the structural properties of the material have to be controlled. For many years directional solidification has been the leading technology for production of silicon ingots for PV application. Due to relative simplicity and low production cost, multi-crystalline (mc-Si) silicon material got the main part of the crystalline wafer based market leaving behind rather expensive single crystalline material [2,3]. During latest years PV experienced gradual improvement in efficiency of mc-Si based solar cells by upgrading solar cell production: cell design, high-efficiency paste etc.

Shifting the focus to wafer quality, it becomes obvious that many improvements can be done by upgrading the bulk properties of crystalline material. With regard to the targets set by photovoltaic to reduce the cost per Wp in the nearest future, standard growing technology of multi-crystalline silicon ingots by directional solidification faces certain challenges, some of which are hard to overcome. Despite the unquestionable advantages of directional solidification, such as low cost, high equipment automation and easy operation, there is a huge disadvantage compared to monocrystalline material: structural imperfections, such as high dislocation densities, electrically active grain boundaries, random crystalline orientations and e.g. grain borders of crystallites containing parasitic impurities (metals, silicon nitride, silicon carbide etc.). These structural properties are crucial for final solar cell performance [1,4–8,21]. Therefore, the overcoming of above mentioned imperfections is the main task for the current technology of directional solidification.

High-performance multi-crystalline (HPM) silicon wafers lately became a dominating product on the photovoltaic market as they ensure significantly higher conversion efficiency and power output of solar cells and solar modules in comparison to conventional multi-crystalline silicon products, while utilizing the same equipment and method of directional solidification. Advanced defect engineering of HPM ingot growth results in considerable changes of crystalline structure, consequently in noticeably improved performance of HPM material even without any upgrade of solar cell or solar module design [9,10]. However, so far HPM material itself does not imply a certain approach to crystallization conditions, but

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.solmat.2016.08.038
0927-0248/© 2016 Elsevier B.V. All rights reserved.

refers to final material properties characterized by small grain sizes, high quantities of random grain boundaries, low densities of dislocation clusters and a method that ensures dislocation clusters, which are formed during columnar growth, to annihilate shortly after their formation [11].

Normally defect engineering of HPM material is based on two main approaches: provoking a desirable crystal grain structure at the beginning of the growth process and preservation of this structure along the ingot height. It was shown that small initial grains of random orientations are advantageous for low dislocation densities [12] and dislocation clusters terminate during growth by interaction with random angle grain boundaries [11]. At present, numerous approaches to initial growth condition for provoking nucleation of small random grains were proposed and widely studied, such as enhanced cooling, spot cooling, notched crucibles, silicon chunk seeding, rough crucible coating [10,13–18]. Currently many of these methods are successfully utilized for provoking and preserving improved crystalline structure while enabling the use of existing industrial crystallization equipment with minor changes in design or even without ones. However, being a relatively new technology, HPM ingot growing has no identical approach in application of various procedures during the growth process. The optimal choice of methods remains unclear and depends on specific equipment, feedstock and final purpose.

In this paper, the authors compare two approaches for growing HPM ingots by provoking small random grains utilizing industrial DS (directional solidification) furnaces: seeding on fine polycrystalline silicon chunks and heterogeneous nucleation on a rough silica crucible bottom. These directionally solidified ingots were used for production of solar cells on industrial line. Material parameters and conversion efficiency of solar cells of both HPM ingots are measured and compared with each other as well as with those made of conventional multi-crystalline silicon material. In order to reduce costs HPM material was also obtained from less expensive solar grade feedstock. Special attention is paid to the difference in material quality across ingot footprint and along ingot height.

2. Experimental procedures

Two HPM silicon ingots were grown in identical industrial DS G5-sized furnaces using the same materials and consumables, except for the bottom of the silica crucibles: one utilizing seeding on fine polycrystalline silicon chunks (referred as HPM1) and the other using heterogeneous nucleation on a rough silica crucible bottom (referred as HPM2). A schematic diagram of the growth set-ups is shown in Fig. 1. Industrial polycrystalline silicon produced by Siemens method was used as feedstock and 650 kg solar grade silicon was loaded into the silica crucibles with dimensions of $840 \times 840 \times 540\ \text{mm}^3$. Prior to loading, both crucibles were covered inside with the same Si_3N_4 coating to prevent sticking and to reduce silica erosion and impurity dissolution. Ingots were doped with equal quantities of boron to ensure p-type conductivity and resistivity ranging from 1.0 to 3.0 Ω cm. Except for the seeding procedure at the very beginning of the growth process, both ingots were produced employing identical growth recipes including gas flow, power of heaters and temperature profiles. The growth recipe was adjusted for HPM material in order to keep the specific structure with small grains with random orientation along the ingot height.

2.1. Seeding on polycrystalline silicon chunks

To provoke seeding in the HPM1 ingot, a modified method of directional solidification was used that allows growing multi-crystalline silicon ingots with predefined grain sizes. The method is accomplished by using fine polycrystalline silicon chunks as seeds, which completely cover the bottom of the silica crucible, followed by loading the crucible with silicon feedstock on the top of this seed layer. In this experiment commercially bought polycrystalline silicon chunks were used as seeds with sizes ranged from 0.5 to 5 mm in diameter and random shape. The thickness of the seed layer was ~25 mm. The feedstock was melted completely while keeping the chunk layer totally or partially solid and provoking nucleation from these seeds at the start of ingot growth.

In order to control the melting and seeding process by preventing the chunks from melting, the axial temperature gradients at the crucible bottom were increased using an additional cooling system at the bottom [20]. The designed cooling system is appropriate to be installed on industrial DS furnace without any special redesign and does not violate the basic modes of DS furnace operation. The cooling system was switched on at a pre-final stage of melting when all silicon feedstock except for chunks was completely melted. This procedure provokes crystallization starting from fine polycrystalline chunks.

2.2. Heterogeneous nucleation on rough silica crucible

Ingot HPM2 was grown in an industrially produced rough silica crucible. The side walls of the crucible were relatively smooth similar to those used in experiment HPM1, while the bottom of the

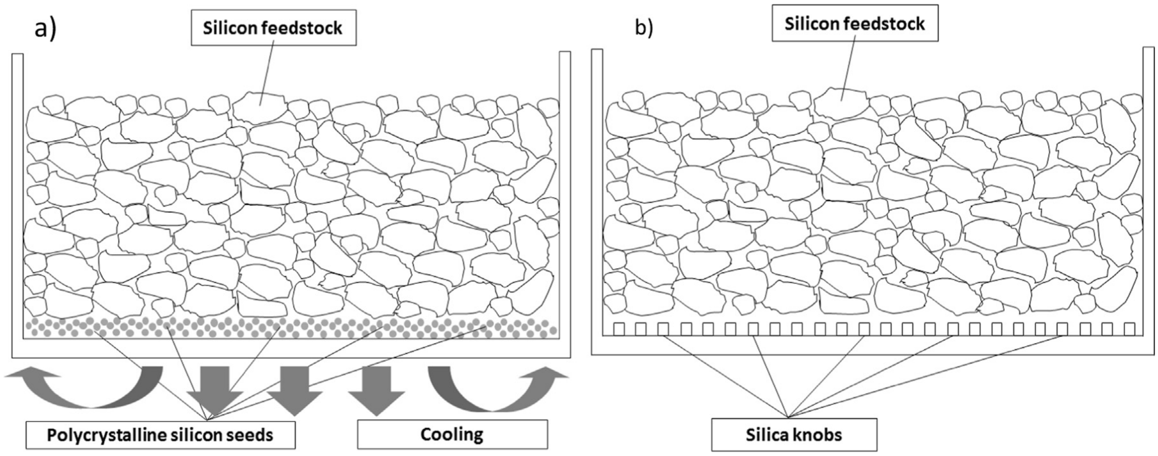

Fig. 1. Schematic diagram of nucleation procedure: (a) HPM1approach - seeding on fine polycrystalline silicon chunks, (b) HPM2 approach - heterogeneous nucleation on rough silica crucible bottom.