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Research paper

Controlling solidification front shape and thermal stress in growing quasi-single-crystal silicon ingots: Process design for seeded directional solidification

Lijun Liu [a, *], Qinghua Yu [a], Xiaofang Qi [a], Wenhan Zhao [a], Genxiang Zhong [a, b]

[a] *Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China*
[b] *Donghai JA Solar Technology Co., Ltd., Lianyungang, Jiangsu 222300, China*

HIGHLIGHTS

- Different moving partition blocks are designed and compared for a seeded DS furnace.
- Small-grain region in silicon ingots can be notably reduced via moving partition designs.
- Lower thermal stress in silicon ingots can be achieved with moving partition designs.
- The process with a down-up moving partition block is the most favorable.

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ABSTRACT

To control the solidification front shape and thermal stress in the growing silicon ingot and reduce the small-grain region at its periphery, a moving insulation partition block was designed in an industrial seeded directional solidification furnace for quasi-single-crystal silicon ingots. We propose several moving process designs of the partition block. A transient global model of heat transfer in which all types of heat transfer are included was established to investigate the thermal field, solidification front evolution, and thermal stress in the growing ingot. Corresponding experiments were conducted to validate the simulation results through the relationship between solidification front shape and the small-grain region. It was found that the moving process can significantly influence the thermal field, solidification front shape, and thermal stress in the growing ingot during the solidification process. The moving partition block design is feasible to control the solidification front shape and reduce the small-grain region at the periphery of the solidified ingot. A favorable moving process design of the partition block was obtained that can simultaneously achieve a small small-grain region and low thermal stress in the solidified ingot.

1. Introduction

Directional solidification (DS) of quasi-single-crystal silicon (QSC-Si) ingots for high efficiency solar cells has emerged as a new technology in photovoltaic (PV) industries [1–4]. In this technology, the entire bottom of the crucible is paved with single crystalline silicon bricks as seed crystals, which have a minimum thickness of 10 mm and uniform crystal orientation, whereas no seed crystals are used in the conventional DS technology for producing multi-crystalline silicon (mc-Si) ingots. The seeds prevent random nucleation at the crucible bottom, and lead to subsequent crystal growth with the same crystal orientation as the seeds [1]; thus, the seeds need to be well preserved during the melting process [4–6]. This seeded DS technology is theoretically beneficial for single-crystal growth. However, experimental results have shown that nucleation always occurs along the crucible wall, and the generated silicon grains move into the interior of the ingot, eventually forming a small-grain region at the periphery of the solidified ingot [7,8]. The small-grain region should be as small as possible to improve the average efficiency of solar cells made from wafers of the ingot. To obtain this goal, it is crucially important to control the axial

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* Corresponding author. Tel./fax: +86 29 82663443.
E-mail address: ljliu@mail.xjtu.edu.cn (L. Liu).

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temperature gradient and the melting front shape during the melting process of feedstock, preserve the seeds and the solidification front shape during the solidification process, prevent nucleation from the crucible sidewalls, and reduce the thermal stress in the growing ingot.

To obtain a large axial temperature gradient and a favorable seed-melt interface shape during the seed preservation process, an insulation partition block (labeled 8 in Fig. 1) has been designed to control the temperature distribution in the hot zone of the seeded DS furnace [8]. The partition block is installed in the space between the heat exchange block and the heater. Li and Liu et al. [6] investigated the melting process in a seeded DS furnace for seed preservation. Their results showed that the melting process progresses from the periphery, top, and bottom to the center of the silicon region without a partition block, while it progresses from the top to the bottom of the silicon region with the partition block. Some other studies [8–11] have investigated the effect of the partition block on the solidification front shape, thermal stress, growth rate, and power consumption during the solidification process in DS furnaces. These studies showed that the design of the partition block is effective to preserve the seeds during the melting process, and it is also beneficial for increasing the growth rate and reducing power consumption. However, it is unfavorable for obtaining a flat or slightly convex solidification front shape and reducing thermal stress in the growing ingot during the solidification process. It is difficult to design a fixed partition block to maintain a favorable melting/solidification front shape through the whole process (both the melting and solidification processes).

Considering that a fixed partition block can effectively maintain a favorable seed-melt interface shape during the seed preservation process [6], an appropriate design of the moving insulation partition block might be effective to maintain a favorable melting/solidification front shape through the whole process. That is, to establish a sufficiently large upward axial temperature gradient during the melting process and a flat or slightly convex solidification front during the solidification process. In our previous studies [6,8], we installed a partition block at a favorable position in the DS furnace and successfully controlled the seed-melt interface shape, and thus preserved the seeds during the melting process. In this study, based on the above idea, a few moving processes of this partition block are proposed to control the solidification front shape and thermal stress in the growing ingot during the solidification process. A transient global model of heat transfer was developed to investigate the evolution of the thermal field during the solidification process for each moving process of the partition block. Experiments were conducted to validate the simulation results through the relationship between the solidification front shape and the small-grain region.

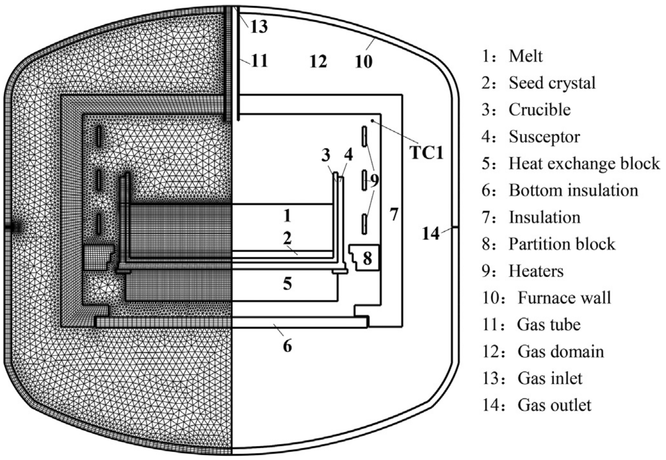

Fig. 1. Configuration and computational grids of the seed-assisted industrial DS furnace.

2. Experimental methods

2.1. Directional solidification process

The configuration of the industrial seeded DS furnace for growing QSC-Si ingots is shown in Fig. 1. In the industrial production process, the dimensions of the square crucible were $84 \times 84 \times 42$ cm^3 with a silicon feedstock capacity of approximately 430 kg. Twenty-five pieces of single crystals with a cross section of 156×156 mm^2 and a thickness of about 10 mm were used as crystal seeds. Thermocouple 1 (TC1) was installed near the outer wall of the graphite resistance heater to monitor the temperature, which was used to control the heater power during the whole process. The bottom insulation (labeled 6 in Fig. 1) gradually moved down when the solidification process began. The evolution of the temperature of TC1 and the moving velocity of the bottom insulation were prescribed and kept the same for all of the designed DS processes. The histories of the TC1 temperature and bottom insulation position are shown in Fig. 2(a).

2.2. Moving processes of the partition block

To preserve the seed crystal, the initial position of the partition block (labeled 8 in all designed moving processes) was kept the same, as shown in Fig. 1. This position is referred to as 0 mm. Fig. 2(b) shows the four moving processes of the partition block: stationary, slow-down, fast-down, and down-up processes. Fig. 2(c) shows the position of the insulation partition block versus solidification time. In the case of stationary process, the position of the partition block was fixed in space all the time as that it is in the feedstock melting process [6]. In the slow-down process, the partition block was moved downwards along with the bottom insulation at a slow rate. In the fast-down process, the partition block was moved downwards at a fast rate. When it moved downwards by 80 mm, the partition block was keep stationary for both the slow-down and fast-down processes. In the down-up process, the partition block was moved downwards by 80 mm at the same rate as that in the fast-down process, and then moved upwards by 120 mm at a slow rate. The movement of the partition block does not cause disturbances on the melt since the partition block does not contact with the crucible and the fastest moving speed is as small as 8.0 cm per hour.

Experiments were conducted in the industrial DS furnace (Fig. 1) for the stationary, slow-down, and down-up processes after linking the partition block to the transmission mechanism. The grown silicon ingots were cut into bricks with a square cross-section by wire sawing. The grain morphology of the brick side was highlighted by an infrared detector (IRB-30, Semilab).

3. Numerical models

The DS process under consideration in this research for growing quasi-single-crystal silicon ingots indeed is in 3D. However, the thermal field in the silicon domain, the solidification front shape and the quality of the finally grown ingot are dominated by the radial interaction between the silicon melt/crystal and the quartz crucible through the crucible inner wall rather than its asymmetry in the circumferential direction because of the huge difference in thermal properties of the silicon material and quartz crucible as well as the possibility of nucleation on the crucible inner wall