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A design of crucible susceptor for the seeds preservation during a seeded directional solidification process

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ABSTRACT

A special insulated crucible susceptor in a directional solidification (DS) furnace was designed to preserve seed crystals during the melting process and to optimize the thermal field in the hot-zone during the seeded solidification process. A global numerical model was established to investigate the effects of the transformation, and the model has been validated by comparing the simulation to the experimental measurements. The results of the simulation indicated that the crucible susceptor described here can facilitate the preservation of seed crystals very effectively and that it does so by constructing a suitable temperature gradient and a flat seed–melt (s–m) interface. The casting experiments confirmed that the variations in the height of the preserved seed crystals had changed from 10 mm in the original system to 2 mm in the new susceptor system.

1. Introduction

Directional solidification (DS) technology is widely used for multi-crystalline silicon (mc-Si) production because of its cost performance, flexibility tolerance of feedstock, and simple operation process. New DS technology has been developed to meet the product quality requirements of the newly developed photovoltaic market. These technologies include seeded DS technology, which is used to produce the quasi-monocrystalline silicon ingots or the high-efficiency mc-Si ingot. About 1% or 0.3% higher values of solar cell conversion efficiency were obtained in the current process than in conventional silicon ingots subjected to the same cell process. In the seeded DS process, the bottom of the quartz crucible must first be paved with seed crystals of silicon, but there is no need for this in the conventional DS process. It is clear that covering the whole bottom of the crucible with seed crystals is important to the suppression of random nucleation from the bottom of the crucible. The preservation of seed crystals is, in this way, a significantly effective seeded DS process, in which high numbers of seed crystals must remain unmelted during the melting process. In this way, a consistent flat or slightly convex seed–melt (s–m) interface during the melting process is required, and this depends on precise control of the thermal field in the silicon [1].

Due to recent developments of computer technology and computation techniques, numerical simulation has become a powerful tool for the investigation and optimization of the DS technology [2–6]. Many studies have used numerical simulation methods on seeded DS processes in various DS systems [7–16]. For example, it has been used in the design of an insulation partition block in an industrial DS furnace meant to produce quasi-monocrystalline silicon ingots [15]. The influence of general parameters, including the position, width and thickness of the added insulation partition block, has been investigated using numerical method analysis [16].

In the present paper, a crucible susceptor was designed for use in an industrial DS furnace. Part of the conventional graphite susceptor was replaced by a low-thermal-conductivity material. The effects of the design on the hot-zone during silicon melting period and crystal growth period were analyzed. A global simulation was established for a basic ingot casting environment involving argon flow, thermal conduction, thermal radiation, and melt convection. The numerical model was validated using experimental measurements. The investigation focused mainly on the design of the susceptor, which affected the temperature gradient and the s–m interface. The design process was then correlated with the preservation of the seed crystal during the melting process. The effects on the temperature fields and the crystal–melt (c–m) interface during the crystal growth process were also studied.

2. Mathematical model description

2.1. Seeded DS system description

A JJL500 directional solidification system (DSS) furnace produced by JingGong Science and Technology Co., Ltd. was used. As shown in

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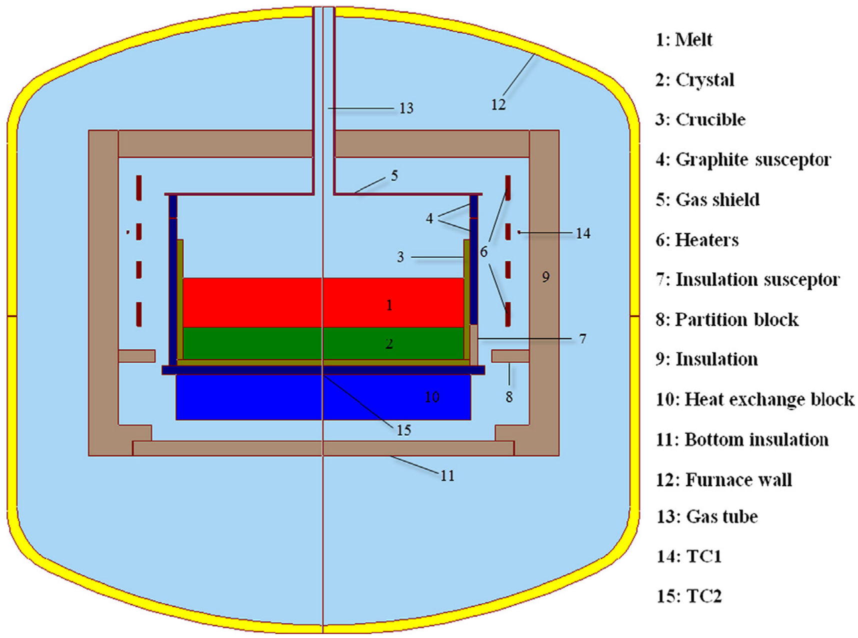

Fig. 1. Configurations of the two different DS systems.

Fig. 1, two different industrial-scale DS systems were involved in the experiments. The left side of Fig. 1 shows one of the most popular redesigned structures used for seeded DS silicon ingot produce in JJL500 furnace. An extruding insulation partition block was installed in order to protect unmelted seed crystals during the melting period (index 8 in Fig. 1). The right side of Fig. 1 shows some improvements made to the design shown on the left. Part of the graphite susceptor was replaced by low-thermal-conductivity materials like the carbon felt (index 7 in Fig. 1). The length and thickness of the insulated susceptor were identical with the side graphite susceptor, and the height was about 70–130 mm. The material properties were the same with the insulation material which was shown in Table 1. Both of the two DS hot-zones consist of graphite heaters, quartz crucible, crucible susceptor, heat exchange block, gas shield, insulations, and thermocouples. The volume of crucible used in the experiment was $840 \times 840 \times 420$ mm^3 and 440 kg silicon feedstock was loaded in, obtaining an ingot with a height of about 270 mm. Graphite susceptors were applied to the area surrounding the crucible to prevent it from deforming at high temperatures. The heaters provided heat for the hot-zone and the insulation contained the heat within a small area. During the growth period, the bottom insulation was moved downwards to ensure that the silicon would solidify in a directional manner beginning from the bottom of the crucible. The heat exchange block that was used to support the crucible acted as the heat exchange with the outside hot-zone. The gas shield separated the silicon from most of graphite materials, which reduced carbon contamination. Thermocouple 1 (TC1) and Thermocouple 2 (TC2) were installed as shown in Fig. 1 to monitor the temperature of the hot-zone. Inert argon gas was used to purify the growth environment. The temperature of the furnace chamber wall was kept at about 300 K via a water-cooling system.

Seed crystals were first paved across the entire bottom of the crucible. The thickness of the seeds was about 20 mm, and they could be polycrystalline or single-crystalline, as determined by the ingot type of the mc-Si or the quasi-monocrystalline silicon. Once the melting process was complete, the temperature at the s–m interface was decreased below the melting point by adjusting the heat and opening a vent at the bottom of the insulated area. Then the crystal growth started from the residual seed crystals, retaining the same crystal orientation. The temperature gradient in the silicon region had to be accurately controlled throughout the casting process. During the silicon melting period, a sufficiently large vertical temperature gradient near the top side of the seed crystals and a relatively flat s–m interface should be controlled to preserve the seeds. During the bulk crystal growth period, an appropriate vertical temperature gradient and a slightly convex c–m interface were required to optimize the growth rate, filter out impurities, and prevent nucleation of the side wall of the crucible.

2.2. Mathematical model

A global numerical simulation method was used to analyze the effects of this design using commercial software CGSim from STR Group, which has been used by many researchers to study and optimize crystal growth processes [17–20]. In the numerical model, the furnace was assumed to be symmetrical about a 2D axis based on the real structure of the DSS furnace and following the principle of equivalent simplified model. The melt was presumed to be a Newtonian fluid, and the inert argon gas was treated as an ideal gas and incompressible, all of the radiative surfaces are assumed as diffuse-gray. Physical parameters of the material properties of each furnace parts have been confirmed by the ingot casting experiments are shown in Table 1. The heat transfer is described by the following equation:

$$-\nabla(\lambda_{ik}\nabla T) = Q, \tag{1}$$

where T is the temperature, λ_{ik} is the thermal conductivity tensor, and Q is the heat flux. Radiative heat exchange between the solid surfaces through a non-participating medium is computed in terms of diffusive-gray surface radiation. The total radiative flux incoming to a given surface element is calculated using the configuration factors F_{ij} (the view factors). Then the total radiative flux incoming and outgoing at the elementary surface element i can be calculated as follows:

$$q_i^{in} = \sum q_j^{out} F_{ij}, \tag{2}$$

$$q_i^{out} = q_i^{em} + (1-\varepsilon_i)q_i^{in}, \quad q_i^{em} = \varepsilon_i \sigma T^4, \tag{3}$$

where q^{in} and q^{out} are the radiation flux incoming and outgoing at the surface element, respectively, q^{em} is the heat emission from the