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Optimization of the high-performance multi-crystalline silicon solidification process by insulation partition design using transient global simulations

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ABSTRACT

A transient global model was established to investigate the effect of the raise velocities of the partition block on the crystal growth rate, the crystal–melt (C–M) interface and the thermal stress distribution during the solidification process. The simulation results showed that among the different raise velocities of the partition block, initially slowly raising and then rapidly raising the partition block was the most favorable for the solidification process. A slightly convex C–M interface and low thermal stress distribution were obtained, and a fast crystal growth rate was also achieved. Thus, this design was implemented in casting experiments, and the experimental results indicated that this design was beneficial for optimizing the C–M interface in the solidification process. The average conversion efficiencies of high-performance multi-crystalline silicon solar cells was about 0.13% higher with this design (18.18%) than with a fixed partition block design (18.05%).

1. Introduction

Directional solidification (DS) is the main method used to manufacture multi-crystalline silicon (mc-Si) because of its inexpensive production costs, simple operation process, and feedstock tolerance. Many new DS techniques have been developed to meet the product quality requirements of the newly developed photovoltaic market. These techniques include growth of quasi-mono-crystalline silicon ingots [1,2] and granular silicon-seeded growth for high-performance (HP) mc-Si ingots [3–5]. However, several challenges still exist, which leaves much room for the improvement of the quality of industrial silicon ingots. One of these challenges is the optimization of the crystal–melt (C–M) interface in the solidification process, because the C–M interface has a great effect on the quality of silicon ingots [6,7]. Another challenge is reduction of the thermal stress in the silicon ingots, because high thermal stress restrains the solar cell efficiency by causing dislocations.

The preservation of the seed crystals is important in both the growth of quasi-mono-crystalline silicon ingots and granular silicon-seeded HP mc-Si ingots. In the DS furnaces, the partition block is often used to preserve seed crystals and has been studied by many researchers. Ma et al. [7] and Wei et al. [8] compared the temperature distribution and energy usage in the DS systems with and without a partition block. Yu et al. [9] investigated the effect of the parameters of the partition block, including the position, width, and thickness of the partition block, on the temperature distribution in an industrial DS furnace. However, they did not find an optimal design that met both the requirement of preserving the seed crystals and that of optimizing the solidification process. To overcome this problem, a moveable partition block was proposed. Ding et al. [10] and Qi et al. [11] investigated the effect of the type of motion of the partition block on the C–M interface and the stress distribution during the bulk crystal growth process. They found that keeping the partition block at a high position during the melting process, rapidly moving it down to a position below the bottom of the graphite susceptor when the crystal growth process started, and then moving it up as the crystal growth progressed was an effective way to preserve the seed crystals and optimize the solidification process. However, their studies [10,11] were based on the DS furnaces only had a side heater, and there

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are no detailed investigations on how the raise velocities of the partition block affect the C–M interface and the thermal stress distribution during the solidification process. In addition, most of the DS furnaces in factories nowadays have both the top and side heaters, since using top and side two heaters can control temperature distribution for the entire solidification process [12]. Furthermore, the moving profile of the partition block is an important parameter for the solidification process. Thus, studying the effects of the moving profiles of the partition block in the DS furnaces with top and side heaters is important for the application of movable partition block.

Based on previous studies [9–11], the raise velocity of the partition block was investigated under a 1:1 power distribution between the top and side heaters. A transient global model was established to investigate the effect of the raise velocity of the partition block on the hot-zone of the DS system. The crystal growth rate, C–M interface shape and thermal stress distribution in the solidification stage were analyzed in this work.

2. Experimental and numerical methods

2.1. Experimental

A JJL500 directional solidification furnace produced by JingGong Science and Technology Co., Ltd. was used. The industrial-scale DS system used in the experiments is shown in Fig. 1. The DS system consisted of top and side graphite heaters, a quartz crucible, a graphite susceptor, a heat exchange block, a gas shield, insulation, thermocouples, and a movable extruding partition block ("13" in Fig. 1). The volume of the crucible was $840\times840\times420\ \mathrm{mm}^3$. Granular silicon seeds were first paved across the entire bottom of the crucible, the thickness of the seeds was about 20 mm, and then the silicon feedstock was loaded to produce a silicon ingot with a height of 270 mm. The functions of the components of the DS system have been explained in our previous study [13]. The operating conditions of the furnace were: (1) the temperature of the furnace chamber wall was kept at about 300 K via a water-cooling system, (2) the pressure of the furnace was 600 mbar, and (3) the argon flow rate was 30 L/min.

2.2. Numerical model

A transient global model was used to investigate the effect of the different designs with the Crystal Growth Simulator code from the Semiconductor Technology Research Group, which has been used by many researchers to study and optimize the crystal growth process [10,13–15]. In the numerical model, the furnace was assumed to be two-dimensional axisymmetric based on the real structure of the DS system, and was divided into a number of sub-regions for the simulation. The number of the numerical mesh was about 25,000 and consisted of quadrangular and triangular cells. Structured grid and mesh refinement was performed in the area near the free melt surface and the C–M interface. The temperature at the crystallization interface was set to 1685 K. The melt was regarded as a Newtonian fluid. The inert argon gas was treated as an ideal gas and incompressible, and all of the radiative surfaces were assumed to be diffuse gray. Fig. 2 shows the power consumption and temperature variation of TC2 between simulation and experimental results. The maximum difference of power consumption was less than 5 kw and the maximum difference of temperature of TC2 was less than 15 K. It verified that the simulation model matches the practical casting experiments very well.

The model took into account thermal conduction, thermal radiation, melt convection, and the gas flow [13–15]. The calculation of the crystallization front geometry was based on the following steps:

Calculation of the vertical component of the growth velocity at the C–M interface

$$V_{crys}=\frac{1}{|n_x|\rho_c\Delta H}\left(\lambda_c\frac{\partial T_c}{\partial n}-\lambda_m\frac{\partial T_m}{\partial n}\right), \tag{1}$$

Movement of the nodes belonging to the crystallization front:

$$\Delta X=V_{cry}\cdot\Delta t, \tag{2}$$

Refreshment of the computational grid in blocks adjacent to the C–M interface,

where V_{crys}, n, n_x, ρ_c, ΔH, λ, T, ΔX and Δt are the crystallization rate, normal to the interface surface, cosine of the corner between the normal n and the vertical axis, crystal density, latent heat, thermal conductivity, temperature, interface displacement, and transient discretization step, respectively, and the subscripts c and m represent crystal and melt, respectively. Numerical grids for part of the DS furnace are shown in Fig. 3. Quadrangular cells were created in crystal and melt region, and triangular cells were created in gas region, the transient discretization step was 30 s.

The thermoelastic stress model was used to analyze the thermal stress distribution during the solidification process [10,11,14]. The crystal was assumed to be isotropic and the von Mises stress was used to reflect the thermal stress. The Young's modulus was 166 GPa and Poisson's ratio was 0.22. The thermal stress problem was solved under the assumption of zero external pressure and zero gravity, indicating that the influence of crucible deformation, the Si_3N_4 coating on the crucible, and the weight of silicon was ignored.

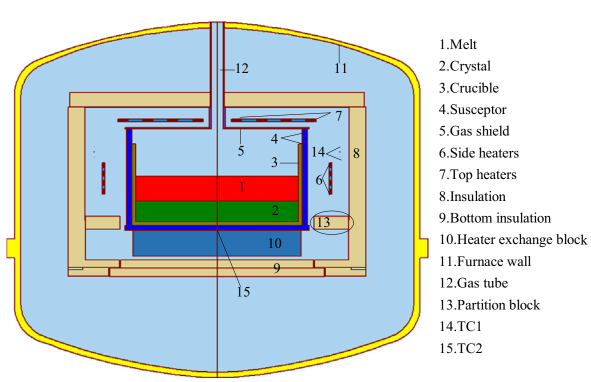

Fig. 1. Configurations of the DS system.

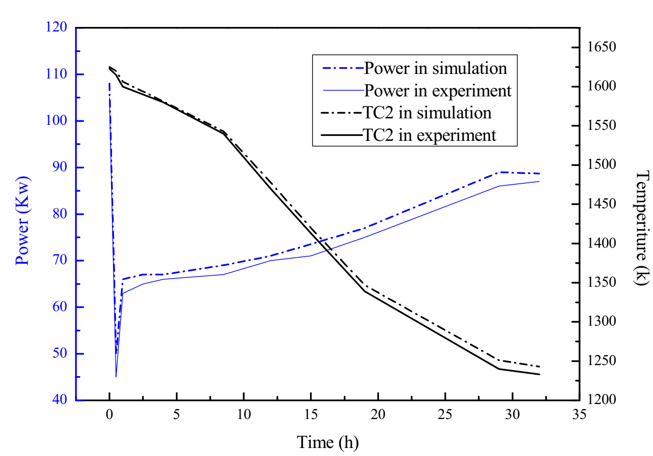

Fig. 2. Validate the model by contrasting the temperature of TC2 and power consumption between simulation and experiment results.