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Optimization of heat transfer by adjusting power ratios between top and side heaters for casting high-performance multi-crystalline silicon ingots

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ABSTRACT

Numerical simulations were applied to analyze the effects of the power ratios between top and side heaters on the crystal–melt (c-m) interface and the thermal stress distribution during the solidification process. The simulation results showed that among the different increase velocities of the power ratio, increasing the power ratio uniformly provided a most favorable solidification process: a slightly convex c–m interface shape and low thermal stress were obtained. The optimized design was implemented in casting experiments, which showed that the high-performance multi-crystalline silicon ingot had a vertical columnar structure and a lower dislocation density. The average conversion efficiency of solar cells was about 0.08% higher with this design (18.24%) than with the original design (18.16%).

1. Introduction

Multi-crystalline silicon (mc-Si) remains the main material used in the manufacture of silicon solar cells because its reduced casting costs. For example, the annual PV installation was over 50 GW in 2015, and the mc-Si solar cells shared the market at nearly 60% [1]. Directional solidification (DS) has emerged as a key production technology for the growth of mc-Si ingots over past decade. Many new DS techniques have been developed for the seed-assisted growth for the high-performance (HP) mc-Si ingots [2–7], and the seeds consist of silicon particles (homo-seeded) [3,6] or quartz granules (hetero-seeded) [7] in the mc-Si industrial production. However, the optimization of the c–m interface and the reduction of the thermal stress remain the key challenges for the promotion of the quality of industrial silicon ingots in the solidification process.

Heaters directly provide heat for the hot zone and are an important factor in controlling the thermal field. With increased ingot size, multiple heaters were preferred for better control of the thermal field in the furnace. Ma et al. [8] indicated that a relatively flat growth interface could be obtained by optimizing the powers of the top and side heaters. Li et al. [9] found that raising power ratio between the top and side heaters could change the melting sequence, enlarge the axial temperature gradient in the crystal. However, the DS furnaces had the power ratio fixed at a certain value in their studies [8,9], and good control of the thermal field cannot always be maintained throughout the entire solidification process. A variable power ratio was necessary for improving the control of the thermal field. Wu et al. [10] proposed a continued variable power ratio ranging from 4:6 (0.67) to 6:4 (1.5) in an upgraded generation-six (G6) DS furnace from a G5 one. The effects in reduction of the casting costs, promotion of the production efficiency and the silicon ingot quality were remarkable after upgrading the hot-zone. However, in that previous study, only one pattern of power ratio was investigated, with the variation range was limited from 0.67 to 1.5. Furthermore, no detailed studies on the effects of variation of the power ratio on the c–m interface shape and the thermal stress distribution have been conducted.

In this paper, numerical simulations were applied to investigate the effects of power ratio variations with multiple patterns and a larger variation range on the c–m interface shape and the thermal stress distribution during the solidification process. Experiments were also conducted, the dislocation agglomerates density of silicon wafers and the conversion efficiency of solar cells were evaluated.

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2. Experimental and numerical methods

2.1. Experimental

The industrial-scale JJL500 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 an extruding partition block. The power ratio between the top and side heaters can be set at any value than 0. The functions of the system components and the operating conditions have been described in our previous studies [10,11]. Specially processed quartz granules were first paved across the entire bottom of crucible with a volume of $880 \times 880 \times 480\ mm^3$, and then a Si_3N_4 coating was processed onto the inner wall of the crucible. About 520-kg silicon feedstock was loaded into the prepared crucible to produce a silicon ingot with a height of 310 mm.

2.2. Numerical model

A transient global model (CGSim) was employed to analyze the effects of the designs, and it has been verified in our previous studies [10–13]. In the numerical model, the furnace was assumed to be 2-D axisymmetric based on the real structure of the DS system, and divided into a number of sub-regions for simulation. The numerical mesh settings have been described in our previous report [12]. The model took into account the thermal conduction, thermal radiation, melt convection and gas flow. The melt was regarded as a Newtonian fluid, and the inert argon gas was treated as an ideal gas and incompressible, all of the radiative surfaces were assumed to be diffuse gray. The algebraic turbulence model was used to investigate the melt convection, the turbulent Prandtl and Schmidt number were set to 0.9, and the weight of the wall functions was set to 1. The temperature at the crystallization interface was set to 1685 K, steady global simulation first be carried out, after that unsteady global simulation were carried out with the input parameters of the power ratio and the position of bottom insulation. Thermo-elastic stress model was used to analyze the thermal stress distribution during the solidification process [14,15]. The crystal was assumed as isotropic and the Von Mises stress was used to reflect the thermal stress. The Poisson's ratio was 0.25 and Young's modulus was 1.66 GPa. The thermal stress problem was solved under the assumption of zero gravity and zero external pressure [13]. Unsteady computations were performed with taking into account the stress relaxation. The process of dislocation formation related to plastic deformation was quantitatively described by the Haasen-Alexander-Sumino model [16,17]. The physical parameter settings of the material properties of each furnace part were confirmed by the casting experiments, as published in our previous paper [11].

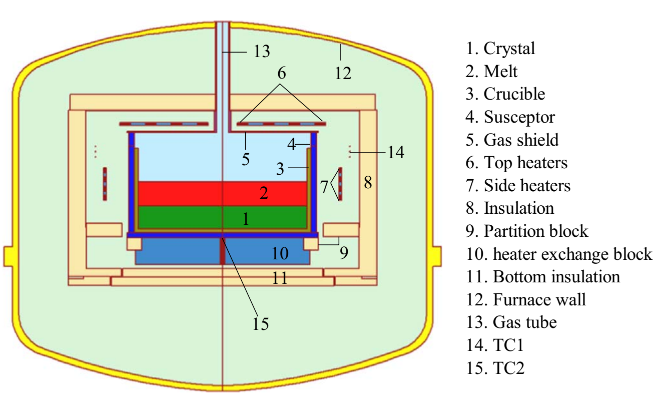

Fig. 1. Configurations of the DS furnace.

3. Analysis

First, a series of simulations with power ratio between the top and side heaters were implemented to investigate the c–m interface shape. The power ratios were fixed at 0.2, 0.3, 0.4, 0.5, 0.8, 1, 1.2 and 2 in these simulations, respectively. Fig. 2(a) shows the horizontal deflections of the c–m interface with the growth height. The interface being convex toward melt is the convex interface, and concave toward melt is the concave interface. The deflection is the interface height difference between the central and the outermost edge regions, positive and negative values represent convex and concave interfaces, respectively. With increased power ratio, the c–m interface transformed from convex to concave, and the height of the turning point was lower. Another turning point from concave to convex appeared and the height was higher. It is already shown that the flat or slightly convex c–m interface is most beneficial for the crystal growth.

The deflections were within an acceptable range at the early stage of solidification when the power ratio was 0.3, and it was very large at the later stage, as shown in Fig. 2(a). Fig. 2(b) shows the crystal height of the central regions with the growth time for the power ratio of 0.3. The minimum deflection appeared near 12th hour, as shown in Fig. 2. To reduce the deflection, the power ratio should be increased [10]. Thus, three new designs of the

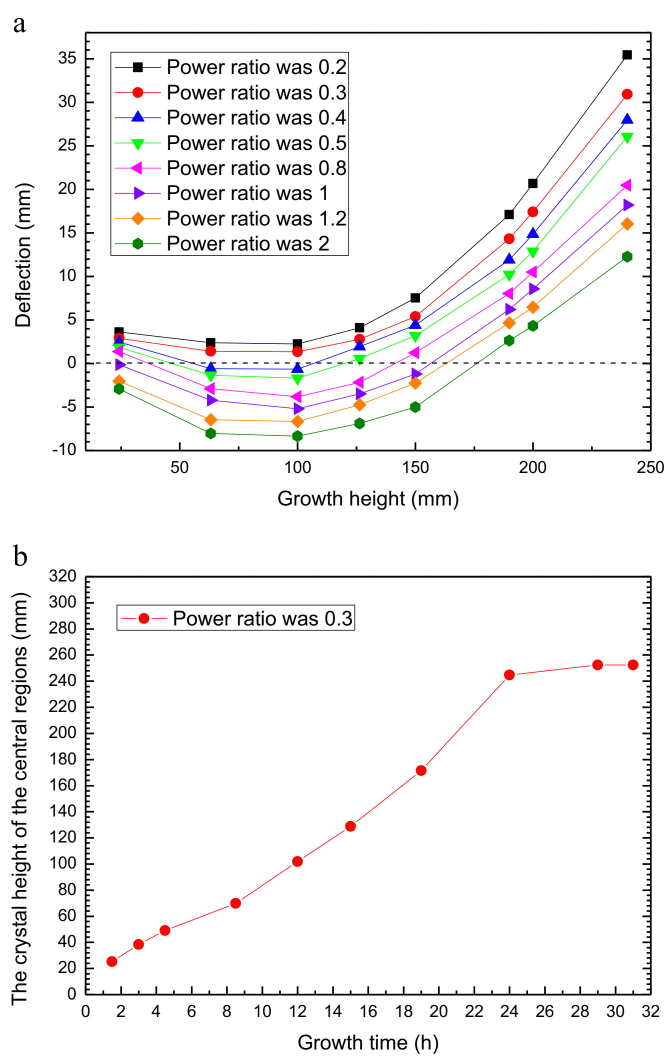

Fig. 2. (a) Comparison of deflections of the c–m interface with the growth height; (b) the crystal height of central regions with the growth time for the power ratio of 0.3.