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Improved seeded directional solidification process for producing high-efficiency multi-crystalline silicon ingots for solar cells

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ABSTRACT

We proposed an improved process design for the industrial mc-Si seeded directional solidification process to produce high-quality multi-crystalline silicon ingots for high-efficiency solar cells. A transient global model of heat transfer was employed to investigate the effects of the process design parameters on the melt–crystal interface shape, thermal field, and thermal stress distribution in the solidified silicon ingot during the solidification process. Ingot casting experiments were carried out and the solar cell performance was measured. The results show that the melt–crystal interface shape in the improved process design remains convex during almost the whole solidification process, and the thermal stress level at the bottom of the solidified ingots is significantly lower than in the original process design. Based on the experimental results, the quality of grown silicon ingots and the conversion efficiency of solar cells were analyzed. The shadow region present in the silicon ingot produced with the original process design disappears and the morphology of the ingot is improved with a more homogeneous distribution of grain orientation using the improved process design. The average yield rate of the solidified silicon ingot is 8.18% higher with the improved process design. The average conversion efficiency of solar cells is higher with the improved process design (17.59%) than with the original process design (17.48%).

1. Introduction

High-quality multi-crystalline silicon (mc-Si) solar cells are the ultimate goal in photovoltaic applications. However, the photoelectric conversion efficiency of conventional mc-Si solar cells is usually less than that of mono-crystalline solar cells because of structural defects, such as dislocations and grain boundaries, in the mc-Si ingots [1]. To reduce structural defects, as well as quasi-mono casting [2–5], dendrite casting [6,7], and using notched crucibles [8], a new technique which is identified as high-efficiency mc-Si casting has recently emerged. In this technique, high-quality silicon ingots for solar cells are fabricated by paving mc-Si crystal seeds at the bottom of the crucible to favorably initiate nucleation at the start of crystal growth.

Although high-efficiency mc-Si has been achieved in industrial applications [9,10], there is still scope to increase the quality of silicon ingots. To produce mc-Si ingots with a weight more than 600 kg in industrial manufacture, the problems of unsatisfactory morphology and infrared shadow region in the solidified silicon ingots are involved, which definitely affect the quality of the silicon ingots and the conversion efficiency of the obtained solar cells. It is well known that the quality of silicon ingots is significantly affected by the thermal history of the solidification process, such as the evolution of the melt–crystal (m–c) interface shape [11–13] and thermal stress [14,15]. During the directional solidification (DS) process, the furnace configuration [16,17] and solidification process operating parameters are the main factors that influence the thermal conditions. Among these factors, controlling the solidification process parameters is the most efficient way to obtain optimal growth conditions for producing high-quality silicon ingots in industrial production. However, little research could be found in existing literatures on the study of solidification process parameters prescribing. To effectively improve the silicon ingots quality and popularize the new technique, improvement in the design of the solidification process parameters for growing high-efficiency mc-Si ingots is required.

In this paper, we proposed an improved design of solidification process for an industrial mc-Si seeded DS furnace. The m–c interface and thermal stress in the silicon ingots between the improved design and the original one are compared. The effects of the process parameters on the quality of the silicon ingots and the conversion efficiency of solar cells made with it are analyzed.

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2. Process improvement design

A schematic diagram of the seeded DS furnace for growing high-efficiency mc-Si ingots with a weight of 600 kg is shown in Fig. 1. To control the nucleation and grain growth, proper mc-Si seeds were paved at the bottom of the crucible with a thickness of approximately 20 mm. The silicon feed materials were loaded into a silica crucible with a volume of 840 × 840 × 580 mm^3. The argon flow rate is 30 L/min and the furnace pressure is 0.6 bar. In the temperature-controlled DS furnace, thermocouple 1 (TC1) is installed at the middle of the top heater to control the heating power consumption. Thermocouple 2 (TC2) is installed at the upper center of the heat exchange block to monitor the temperature of the crucible bottom.

During the solidification process, on the one hand, the time-evolution of the temperature of TC1 can maintain the thermal condition of the hot zone through controlling the heating power consumption. On the other hand, the time-evolution of the upward side insulation position can control the solidification rate of the silicon ingot through affecting the heat transfer between the chamber wall and the bottom of the heat exchange block. Obviously, these two parameters (evolution of the temperature of TC1 and the side insulation position) will determine the history of thermal condition in the furnace, and thus affect the quality of the solidified silicon ingot. However, in the current furnace under the original process design, there are two problems that decrease the quality of the silicon ingot: an unfavorable morphology and the infrared shadow region, which are probably caused by the m–c interface shape and the thermal stress, respectively, during the solidification process. Given this situation, we attempt to redesign the process parameters to obtain suitable thermal conditions for mc-Si ingot growth.

For the process design, we supposed to decrease the excessive temperature gradient in the silicon region and the radiation heat loss between the heat exchange block and the chamber wall by slowing down the variation of the temperature of TC1 and the position of side insulation. Fig. 2 shows the specific prescribed process parameters for both the temperature variation of TC1 and the position variation of side insulation during the whole solidification process. As shown in Fig. 2(a), the temperature of TC1 in the new process design is about 7 K lower than that in the original process design at the beginning of the solidification process. Additionally, the variation rate of TC1 in the improved process design is also slower than that in the original process design during the followed process. As shown in Fig. 2(b), the side insulation moves slower and the final position of the side insulation is 4 cm lower than in the original process design. Because the two process parameters have a complicated correlative effect on heat transfer in the DS furnace, we first carried out coupled global simulations of heat transfer in the whole furnace and thermal stress distribution in silicon ingot. Then we conducted ingots casting experiments to verify the predictions.

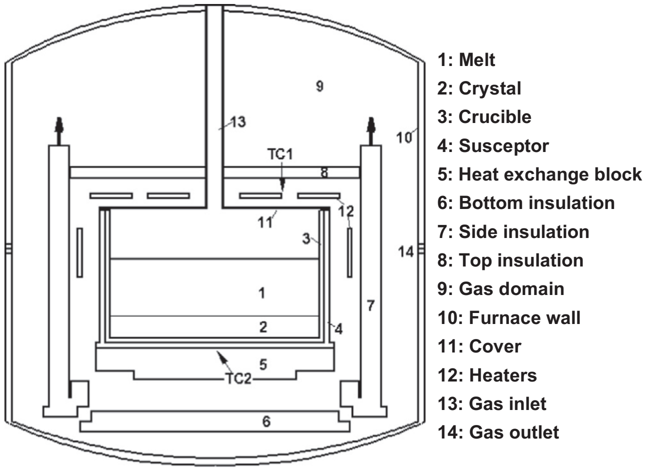

Fig. 1. Schematic diagram of an industrial mc-Si seeded DS furnace.

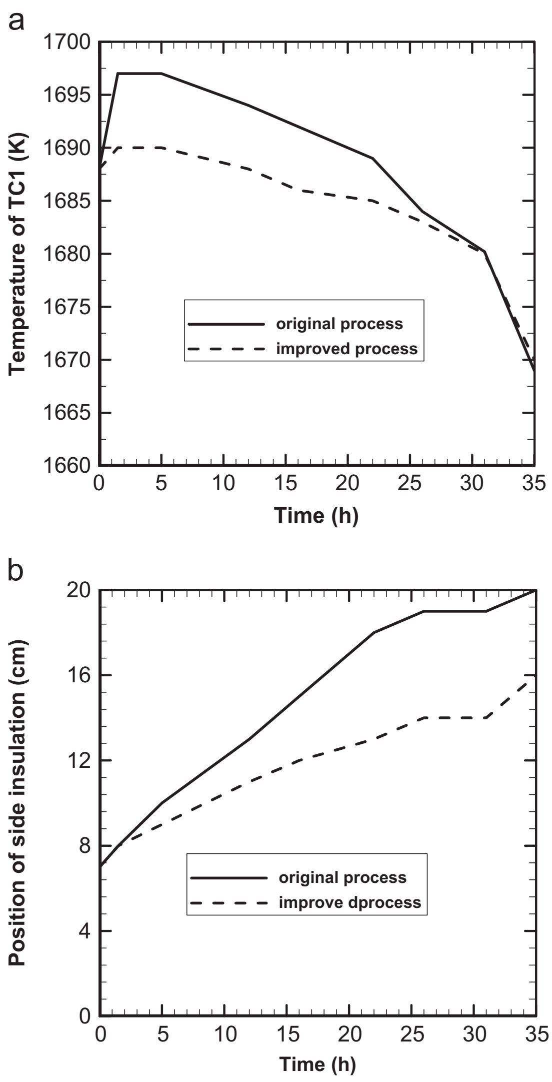

Fig. 2. Evolutions of (a) the monitor temperature of TC1 and (b) the position of the side insulation.

3. Comparison of the improved and original process designs

3.1. Melt–crystal interface shape and thermal stress distribution

The heat transfer under the original and improved processes was first studied by transient global simulations. The transient global model of heat transfer in the seeded DS furnace, involving thermal conduction, thermal radiation, melt convection, and gas flow, as well as the phase change, has been validated in our previous papers [3,18]. For growing mc-Si ingots, the control of m–c interface shape is one of the most important factors, and it affects the thermal stress and the grain growth. The m–c interface shape is identified by the isotherm line at 1685 K. Fig. 3 shows the m–c interface shape at three solidification stages for both process designs. The results indicate that the interface shape is convex to the melt at the initial stage of the solidification process, and then it