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Numerical investigation of the effect of a crucible cover on crystal growth in the industrial directional solidification process for silicon ingots

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ABSTRACT

We carried out transient global simulations of heating, melting, growing, annealing and cooling stages for the industrial directional solidification (DS) process. Two separate DS processes were performed with a covered crucible and an uncovered crucible to investigate the effect of a crucible cover on global heat transfer and silicon crystal growth. It is found that the cover blocks heat transfer from the heaters to the silicon domain significantly, and therefore influences the crystal growth through the entire DS process. For the melting of silicon feedstock, covering the crucible can lead to a significant increase in melting time, whereas it has little effect on the melting sequence. During the growing stage, the solidification time for the process with a crucible cover is much shorter than the process without a cover. The cover can also influence the melt convection near the free surface center, but it hardly changes the melt flow pattern deep in the crucible. For the annealing and cooling processes, heat transfer is not significantly affected by covering the crucible and the isotherm shapes in the silicon ingots are similar with and without a cover.

1. Introduction

Directional solidification (DS) is the main method for manufacturing multi-crystalline and quasi-single crystalline silicon ingots for solar cells [1]. The DS process is a highly coupled nonlinear thermal system with complex heat and mass transport. It includes solid thermal conduction, melt convection, argon flow, thermal radiation, phase change, as well as transport of oxygen, carbon and other impurities [2,3]. These transport characteristics can influence the crystal growth of silicon ingots significantly [4]. Therefore, many techniques, such as process optimization and structural improvement, are implemented to control the heat and mass transport in the DS process and to optimize the crystal growth and improve the ingot quality. Among these measures, adding a cover above the crucible is used to prevent the silicon melt from being contaminated by the impurities in the furnace chamber [5]. In addition, the crucible cover can also separate the insulations and heaters from the silicon domain, and therefore influence the temperature distribution in the melt.

A few studies have been carried out to investigate the effect of a crucible cover on heat and mass transport in the DS process for crystalline silicon ingots. Gao et al. [6] numerically compared the oxygen and carbon concentrations in the furnaces with and without a cover. The results indicated that the cover could influence the impurities in the silicon crystal significantly. They also found that a cover made from nonreactive material is beneficial to the carbon control [7]. Teng et al. [8,9] studied the effects of a specially designed cover on heat and mass transport in the DS process. They found that the cover could guide the argon gas flow and influence the silicon melt convection, which would also influence the oxygen and carbon distributions in the furnace. These studies are helpful in understanding the important role of the crucible cover in controlling the impurities during the DS process. However, they are not sufficient to reveal the effect of the cover on heat transfer and crystal growth. The DS is a complex process including heating, melting, growing, annealing and cooling stages [10]. The cover must affect the heat transferred from the heaters to the silicon during these stages. Therefore, it is essential to study the effects of the crucible cover on heat transfer and crystal growth during the entire DS process.

In this paper, we chose an industrial DS furnace that can produce 450 kg ingots to perform the numerical study. Transient simulations of

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global heat transfer, including melt convection, argon flow, thermal conduction, radiation and phase change, were carried out for the heating, melting, growing, annealing and cooling stages of the DS process. Based on the global modeling, we investigated the characteristics of heat transfer for DS furnaces with and without a crucible cover. The heating power consumption, temperature distribution, melting time and sequence, solidification front surface shape and other process parameters were analyzed and compared. The study can help us to understand the cover effects on silicon crystal growth by the DS method.

2. Model description

The configuration, dimensions and computational grids of an industrial-size DS furnace for crystalline silicon ingots are shown in Fig. 1(a). The side length of the square crucible is 840 mm and the silicon ingot is about 250 mm high. The thermocouple TC1 located close to the top heater is used to control the heating power by monitoring the temperature evolution. Another thermocouple TC2 is used to monitor the temperature at the crucible base. The crucible cover labeled with no. 12 is made of graphite and it can be easily installed or removed in the production process. The entire furnace is divided into a number of sub-domains for simulation

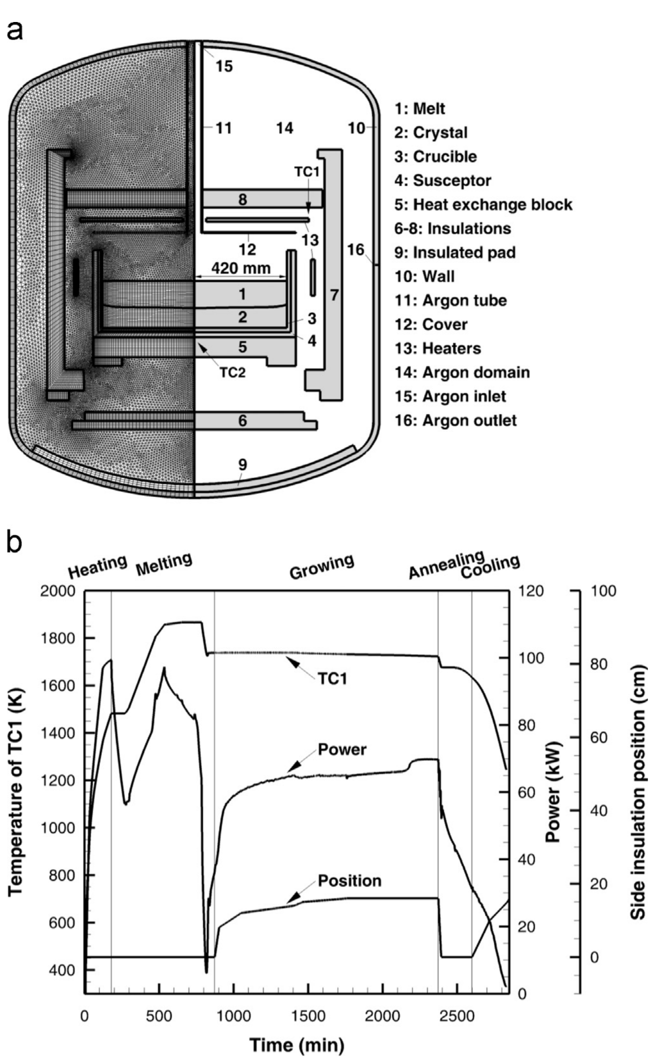

Fig. 1. Model of an industrial-size DS furnace: (a) configurations and computational grids and (b) process parameters.

and the structured/unstructured combined mesh scheme is applied to improve the computation efficiency. The basic assumptions and governing equations for the transient global modeling of heat transfer in a DS process have been published elsewhere [2,10].

The control parameters for the entire DS process are shown in Fig. 1(b). Four vertical thin solid lines divide the curve sections into heating, melting, growing, annealing and cooling stages. The side insulation is closed to prevent heat loss during the heating, melting and annealing stages. It is opened to allow heat to escape for the growing and cooling stages. The heating power increases automatically in the heating stage and it is then controlled by the preset temperature of TC1 until the end of the process. The transient heat transfer model for the above DS process has been validated by comparing the numerical results with the experimental data in a previous study [10]. DS processes with and without a crucible cover are performed to investigate the effect of the cover on heat transfer and crystal growth. The TC1 settings, the side insulation moving velocity, the furnace pressure and the argon flow rate are maintained the same for the two processes.

3. Results and discussion

3.1. Effect of a crucible cover in the heating and melting stages

Fig. 2 shows the evolution of temperature and heating power in the heating and melting stages for DS processes with and without a crucible cover. The vertical thin solid line in Fig. 2(a) is the transition point of these two stages. The heating stage lasts from 0 to 180 min and the heating power increases automatically to guarantee that the temperature of TC1 can reach 1480 K at the end of this stage, as shown in Fig. 1(b). The melting stage lasts from 180 to 870 min and the variations of TC1 to control the heating power are preset the same for the two processes. It can be seen from Fig. 2(a) that both the temperature at the silicon top surface and that of TC2 are lower for the process with a crucible cover than without a crucible. This is mainly due to the crucible cover blocking heat transfer, which will decrease the temperature in the silicon domain.

To study the effect of a crucible cover on the melting of silicon feedstock in more detail, Fig. 2(b) shows the partial enlarged view of the zone indicated in Fig. 2(a). There are three main stages in Fig. 2(b): heating of the silicon feedstock, melting of the silicon feedstock and heating of the melt. Taking the DS process with a crucible cover as an example, the temperature at the silicon top surface increases rapidly until 460 min. At 460 min, the temperature reaches the melting point of 1685 K and the feedstock begins to melt from the top. The temperature increases relatively slowly from 460 to 760 min, as the feedstock absorbs heat while melting. There exists another turning point at about 760 min when the temperature begins to increases rapidly again after complete melting. Therefore, the time spent melting the feedstock is about 300 min for the process with a crucible cover. For the DS process without a crucible cover, the melting stage lasts from 450 to 710 min and the total time is about 260 min. It is obvious that more time is needed for feedstock melting in the case with a crucible cover.

Fig. 3 shows the evolution of the solid–liquid interface during melting for the DS processes with and without a crucible cover. Fig. 3(a1) and (b1) shows that the feedstock melts from top to bottom for both processes at the initial stage. Next, the feedstock near the crucible side wall begins melt. Then, the feedstock located near the crucible bottom wall melts before complete melting, as shown in Fig. 3(a3) and (b3). The above analyses indicate that the crucible cover has little effect on the melting sequence. The