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Effects of the hot zone design during the growth of large size multi-crystalline silicon ingots by the seeded directional solidification process

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ABSTRACT

In this study, the installation of insulation blocks in the hot zone is utilized to assist in the growth of multi-crystalline silicon ingots with 800 kg of silicon charge using the seeded directional solidification method. A transient global numerical simulation is carried out to investigate the heat and mass transport during growth process. At a higher solidification fraction, lower concavity of the crystal–melt interface near the crucible wall can be obtained as compared to the standard model. The lowest concavity and highest energy saving is achieved when insulation blocks are added to the side of a directional solidification block and to the low part of the side insulation. The simulation results for this design also show a reduction of the melt velocity. The average oxygen concentration is slightly higher along the crystal–melt interface, compared to the standard one.

1. Introduction

Multi-crystalline silicon (mc-Si) solar cells have the highest market share in the photovoltaics (PV) market. To accomplish the goal of grid parity, the production cost of silicon solar cells must be reduced further and their efficiency has to be improved which is strongly dependent on wafer production and quality. Recently the growth of large size mc-Si ingots with high quality has become the main direction of development in wafer production. As the ingot weight goes up, however, the rate of increase in the height of the ingot becomes less than the rate of increase in the area. Martinuzzi et al. [1] has suggested that the height of large size mc-Si ingots produced from the casting process should not exceed 20 cm in order to avoid the production of extended defects, the expense of crucible use and the production of upgraded silicon waste. Seeded directional solidification (DS) systems have been developed capable of obtaining high quality large size mc-Si crystals. In this technology, the bottom of the quartz crucible is paved with crystalline silicon seed crystals which need to be preserved during the solidification process in order to prevent nucleation from the bottom crucible wall. Grain orientation is important because it significantly affects the conversion efficiency of the solar cells. It is well-known that the crystal–melt (c–m) interface has a great influence on the orientation of the grain size and thermal stress during the growth process. A flat or slightly convex c–m interface is beneficial for an outward grain direction and lower thermal stress in the ingot. To obtain this favored interface, it is very important to reduce heat loss throughout crucible system, especially to control the radial heat flux. Different designs of insulation partitions for optimization of the DS process have been studied [2–6]. The modeling and experimental results have shown that using a partition block can reduce the total heat consumption and improve the shape of the solidification interface during the growth process. This design also has a significant effect on the temperature distribution and thermal stress in the silicon ingots. There is an optimal increase in velocity with a partition block which allows the fabrication of high quality wafers for high conversion efficiency mc-Si solar cells. Ding et al. [7] added an insulated crucible susceptor to the DS furnace to preserve seed crystals to produce a consistently flat or slightly convex seed–melt interface during the melting process, while Chen et al. [8] showed that large energy saving can be achieved with the current DS furnace design with only minor geometric modifications achieved by adding solid blocks to the lower corner of the side insulation. “Pivot surfaces” which were introduced to explain the decrease of total power, act by redirecting the radiation of the heat flux from the hot zone to

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the bottom of the heat exchanger block in the cold zone. The effect of the addition of insulation blocks on the impurity distribution and the melt velocity, however, was not investigated in these studies. This modification of the DS furnace changes the temperature field near the crucible wall and affects convection in the silicon melt. The bottom corner of the crucible is the position where the heat flux becomes highest, therefore it is necessary to add insulation blocks in this region to reduce the heat loss. Teng et al. [9,10] added an insulation block to prevent heat loss from the heat exchanger block to the gap of the insulation cage, which resulted in an interface shape with lower deviation between the crystal edge and the center. They also investigated the thermal flow field and distribution of oxygen and carbon concentration in the silicon melt. A gas flow guidance device installed in a mc-Si crystal growth furnace enhanced the motion of argon gas flow near the free surface [11,12]. As a result, a greater amount of SiO gas is carried out of the furnace by the argon gas.

In this study, a series of transient global numerical simulation are performed with 800 kg of total silicon charge. The effects of the addition of insulation blocks to the side of the DS block and/or to the low part of the side insulation, on the thermal field, the flow field and impurity transport during the growth process are investigated. Moreover, the enhancement of energy saving by these modifications is also discussed.

2. Mathematical model

A schematic illustration of the structure of the seeded industrial DS furnace used to grow 800 kg mc-Si ingots is shown in Fig. 1. The standard furnace is modified by the addition of insulation block A to the side of the DS block and insulation block B to the low part of the side insulation. During the growth process, the temperature at the furnace wall is kept constant at 300 K by a water-cooling system. The side insulation with block B moves upward independently. The melting process is controlled in the studied DS system, so as to preserve the 18mm high seed crystals at the crucible bottom. To save simulation time, the real configuration of a DS furnace with its square crucible is replaced by a 2D axially-symmetric model which is cylindrical in shape. This simplification has been widely used in the literature [2–12] and has been validated by experiments [2,5,7]. The silicon melt is considered to be a Newtonian fluid and the deformation of the free surface is neglected. Argon gas is regarded as an ideal gas with an incompressible flow. Moreover, all of the solid surfaces are assumed to be gray surfaces.

The differential equations governing the fluid flow and heat transfer are given below.

In the fluid flow:

$$\frac{\partial\rho_i}{\partial t}+\nabla\cdot\left(\rho_i\vec{u_i}\right)=0 \tag{1}$$

$$\frac{\partial\rho_i\vec{u_i}}{\partial t}+\left(\vec{u_i}\cdot\nabla\right)\rho_i\vec{u_i}=-\nabla p_i+\nabla\cdot\tau_i+(\rho_i-\rho_{i,0})\cdot\vec{g} \tag{2}$$

$$\frac{\partial\rho_i C_{p,i}T_i}{\partial t}+\nabla\cdot\left(C_{p,i}\rho_i\vec{u_i}T_i\right)=\nabla\cdot(k_i\nabla T_i) \tag{3}$$

$$\frac{\partial(\rho_i C_{p,j})}{\partial t}+\nabla\cdot\left(\rho_i\vec{u_i}C_j\right)=\nabla\cdot(D_j\nabla C_j) \tag{4}$$

$$\rho_g=\frac{p_o M}{RT}, \tag{5}$$

where ρ, ρ_0, C_p, u, τ, g, T, k, C, D, p_0, M and R are density, reference density, specific heat, velocity, stress tensor, gravitational acceleration, temperature, thermal conductivity, concentration, diffusivity, pressure, molecular weight and universal gas constant, respectively. Subscript i represents argon gas (g) or liquid silicon (l), while subscript j stands for silicon monoxide (SiO) in the argon gas region or oxygen (O) in the melt.

In the heater:

$$\nabla(k_h\nabla T_h)=\dot{q}, \tag{6}$$

where $q\cdot$ is the heat generation from the heater.

The thermal conditions on the interface between two opaque surfaces are

$$\left(k\frac{\partial T}{\partial n}\right)_1=\left(k\frac{\partial T}{\partial n}\right)_2; \tag{7}$$

$$T_1=T_2. \tag{8}$$

The radiative heat transfer along the interface between the opaque surface and gas is as follows:

$$\left(k\frac{\partial T}{\partial n}\right)_{opaque}=\left(k\frac{\partial T}{\partial n}\right)_{gas}+\sigma_s\varepsilon T^4-q_{in}, \tag{9}$$

where σ_s is the Stefan–Boltzmann constant, ε is the thermal emissivity and q_{in} is the incoming radiative heat flux.

The heat fluxes at the c–m interface should satisfy the Stefan condition, and the temperature at this interface should be equal to

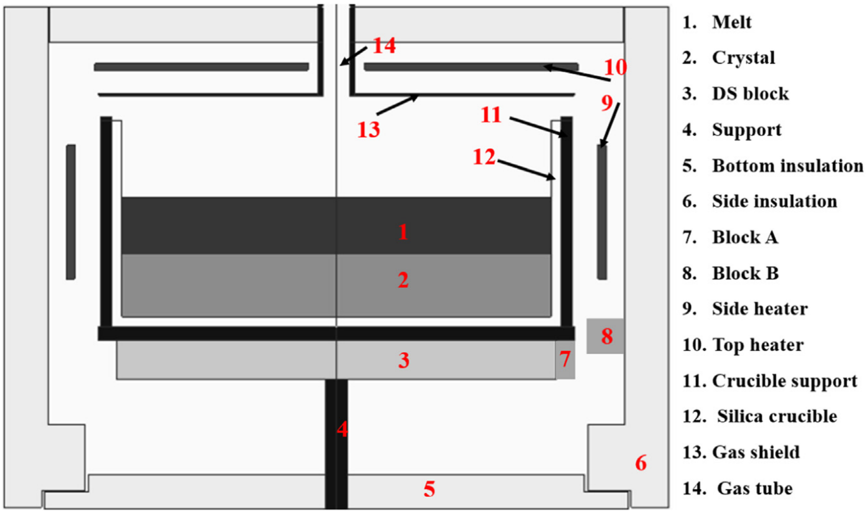

Fig. 1. Schematic diagram of the seeded industrial DSS furnace.

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