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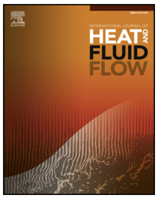

Parameter study of traveling magnetic field for control of melt convection in directional solidification of crystalline silicon ingots

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ABSTRACT

Melt convection plays a critical role in the quality of crystalline silicon ingots produced by directional solidification (DS), through influencing the solidification front shape and impurities distribution. The utilization of a traveling magnetic field (TMF) is a promising way to control melt convection pattern. Lorentz forces induced by a TMF will present various characteristics under different imposed electric current parameters, such as current amplitude, frequency and phase shift. Understanding the effects of current parameters on melt convection pattern is crucial for the selection of suitable parameters to achieve the enhancement of melt mixing and a preferable solidification front. Based on a coupled model of global heat transfer, this paper explores the effects of these current parameters on the melt convection pattern in a DS furnace of crystalline silicon ingots under the action of a downward TMF. The melt mixing effect and solidification front shape are further elucidated based on different melt convection patterns. The results indicate that the effects of current parameters on the melt mixing effect and solidification front shape is quite complicated, which is not monotonous. By precisely tailoring the combination of current parameters, a flat or slightly convex solidification front and decent melt mixing are simultaneously obtained. This study can facilitate the successful and optimum utilization of a TMF in the DS process of crystalline silicon ingots.

1. Introduction

Directional solidification (DS) of multi-crystalline or quasi-single crystalline silicon ingots is the main method for manufacturing photovoltaic silicon wafers for solar cells (Aravindan et al., 2017; Buchovska et al., 2017; Gu et al., 2012; Lan et al., 2017; Nguyen et al., 2016). The flow pattern of silicon melt in the DS process directly influences the transfer of heat and impurities, further determining the solidification front shape and impurities distribution in silicon ingots (Ansari Dezfoli et al., 2017; Bouabdallah and Bessaïh, 2012; Dennis and Dulikravich, 2002; Liu et al., 2017). A concave or extremely convex solidification front will lead to bad verticality of grain boundary, large thermal stress and defect propagation (Qi et al., 2014; Yang et al., 2016). High impurities concentration will result in defect generation, minority carrier lifetime reduction and even precipitate formation (Gan et al., 2017; Yu et al., 2013). All these disadvantage situations will significantly decrease the silicon ingot quality and eventually cause degradation of solar cell efficiency. Therefore, the precisely tailoring of the melt convection pattern in the DS process is of vital importance for improving silicon ingot quality and eventually obtaining high-efficiency solar cells.

The melt convection is primarily driven by the buoyancy force arising from horizontal thermal gradient in the conventional DS furnace. It is very difficult to achieve favorable melt flow patterns only by adjusting hot zone configurations to control the buoyancy force. It is required to introduce the assistance of external forces. A very promising means of exerting external forces to control melt convection pattern is the use of a traveling magnetic field (TMF) (Dropka et al., 2016b; Lin et al., 2014; Qin et al., 2017; Rudolph and Kakimoto, 2011; Yeckel and Derby, 2013). A TMF will present notably different characteristics under different imposed electric current parameters, such as current amplitude, frequency and phase shift. Comprehensive understandings of the effects of imposed current parameters on melt convection and solidification front are crucial to making full use of the advantage of a TMF to improve the DS process for high-quality silicon ingot.

As the supplement to casting experiment of silicon ingots in the high temperature, model experiments with low-melting materials (Dadzis et al., 2017, 2013a; Galindo et al., 2012; Meier et al., 2017) and numerical simulations (Dadzis et al., 2013b; Dropka et al., 2011; Sivasankaran et al., 2011) have become powerful tools to explore melt convection under the action of TMF with visualized images.

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Dadzis et al. (2016) performed model experiments based on DS of gallium under a TMF for silicon processes combined with numerical simulations. They observed distinctly different influences on the melt flow of an upward TMF and a downward TMF, which results in a more concave solidification front and a more convex front, respectively, both with local opposite deflections in the corner region. They therefore concluded that it is very challenging to obtain a flat solidification front in DS processes of silicon. Cablea et al. (2014) compared the effects of different orientations of TMF on the segregation of impurities and the orientation of grain boundaries for DS of silicon. The simulation and experimental results in their study indicated that a downward TMF is more beneficial to melt mixing to remove impurities from the solidification front vicinity and obtaining a flat solidification front to increase the verticality of grain boundaries. Vizman et al. (2013) predicted the effects of the current amplitude on the melt flow pattern and solidification front shape in DS of silicon ingots under an upward TMF based on a local model with idealized thermal boundary conditions. They found that the rise of current amplitude can only increase maximum velocity of melt flow but not change the melt flow pattern when the melt flow is dominated by the Lorentz force and can increase the concavity of the front. Dropka et al. (2016a) analyzed the effects of TMF on melt stirring and solidification front shaping in DS of silicon at various scales by local simulations with the thermal boundary conditions obtained from global simulations without considering melt convection. The stepwise solving methodology applied in their study cannot couple the change of heat transfer in the melt caused by TMF into the global heat transfer, so a coupled model of global heat transfer is required to accurately reveal the effects of TMF. They only presented effects of the imposed current parameters on the maximum Lorentz force and effects of two different frequencies on the spatial distributions of Lorentz force in the melt with various sizes. It is inadequate to comprehensively understand the effects of imposed current parameters for a TMF on the melt convection and solidification front.

The above literatures presented multiple studies on the effects of a TMF on the melt convection and solidification front. However, they did not clearly address the following issues: (a) the interaction between the melt flow driven by TMFs and the thermal boundary of melt region, which needs to be tackled by a coupled global heat transfer model; (b) the detailed effects of all imposed current parameters on the Lorentz force distribution, melt convection pattern, thermal field and solidification front shape in DS of silicon; (c) selection of suitable current parameter combination to obtain a flat or slightly convex solidification front and enhanced melt mixing. In this study, we filled the above mentioned gap in the literature. We explored DS of silicon under a downward TMF with different current parameters based on a coupled model of global heat transfer, such as current amplitude, frequency and phase shift. The Lorentz force distributions in the melt were illustrated under different current parameters. The convection pattern and temperature distribution in the melt were also compared between different current parameters. The effects of different current parameters on solidification front shape were elucidated in detailed. The effects of combinations of different parameters, which can maintain the maximum Lorentz force same, on the melt mixing and front shape were also examined. Several optimized parameter combinations were eventually proposed to simultaneously obtain enhanced melt mixing in the whole melt region and a relatively flat or slightly convex solidification front. This paper offers a significant guidance on selection of current parameters for a TMF to obtain decent melt mixing and a favorable solidification front shape in the DS process of crystalline silicon ingots.

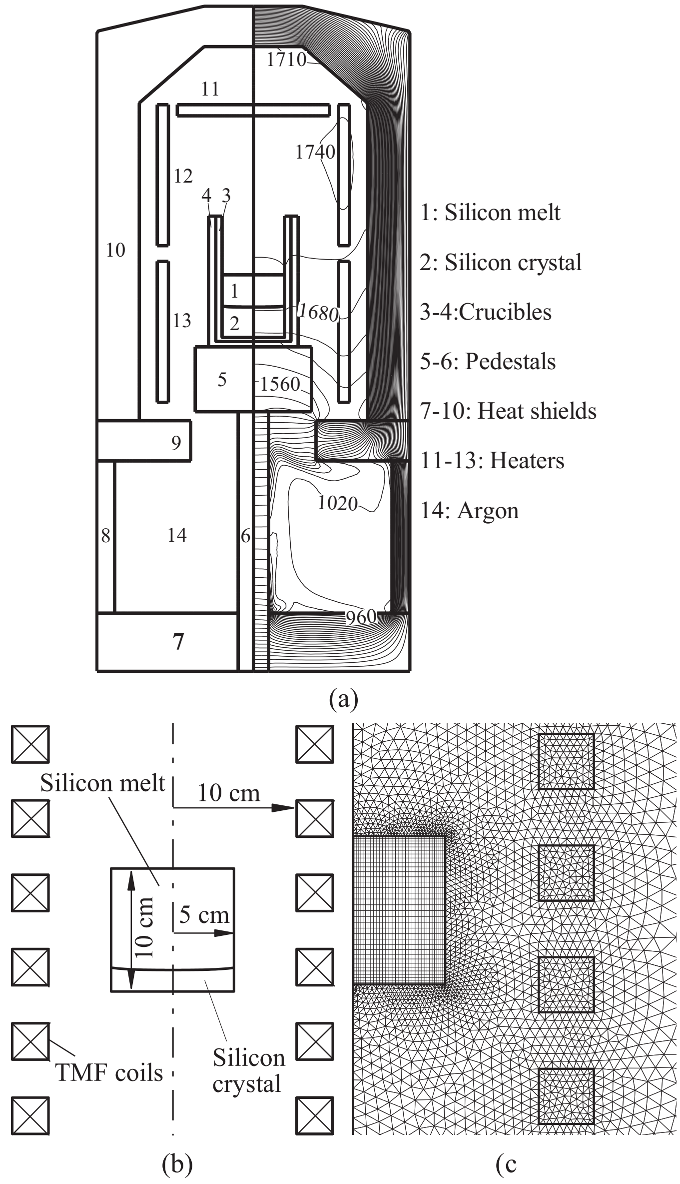

Fig. 1. (a) Configuration of a DS furnace (left) and temperature distribution (right, 30 K between two contour lines); (b) configuration of coil system for generating TMFs; and (c) the local grids for solving TMFs (left side is symmetric axis).

2. Model description

2.1. Physical problem and assumptions

The configuration of a DS furnace for producing crystalline silicon ingots is shown in Fig. 1(a). The DS furnace includes silicon region (melt and crystal), crucibles, pedestals, heat shields, heaters, and argon region, which are all included in the coupled global heat transfer calculation. The silicon ingot produced by the DS furnace has a diameter of 10 cm and a height of 10 cm. More details can be found in our previous work (Li et al., 2012). In order to guarantee the calculation accuracy and efficiency simultaneously, some major assumptions in the model of global heat transfer are made as follows: (1) the geometric configuration of the furnace is axisymmetric; (2) the growth system is in the quasi-steady state; (3) the melt convection is laminar and incompressible; (4) the Boussinesq approximation is applicable to tackling the variation of melt density with the temperature; (5) the radiative heat transfer is modeled as diffuse-gray surfaces; and (6) the argon gas in the furnace chamber is ideal and completely transparent. According to the simulation results as depicted in Section 3, the mass-weighted average velocity of melt flow was 0.32–8.59 mm/s among all cases of this study, which can be used as the characteristic velocity. The characteristic length of melt flow was defined as $(V_m)^{1/3}$, where V_m denotes the melt volume (Dropka et al., 2016a). The calculated characteristic length was about 7.32 cm. The density and dynamic viscosity of the