3D numerical simulation with experimental validation of a traveling magnetic field stirring generated by a Bitter coil for silicon directional solidification process

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Abstract. Silicon is the most widely used raw material in photovoltaic industry; however, the quality of the silicon photovoltaic solar cells depends on the quality of the raw material (i.e. metallurgical silicon or poly-silicon) and the solidification methods used for the production of the silicon ingot from which the solar cells are produced. This study is related to how improve the quality of the final ingot in the directional solidification process; it is necessary to control the impurity segregation of silicon raw material during the processing. This control can be accomplished by adding an electromagnetic Bitter coil which can generate an external traveling magnetic field (TMF) stirring to control the hydrodynamic flow of silicon melt during the solidification process without contaminating it. To carry out this study, we used a Bridgman vertical directional solidification furnace, equipped with a cylindrical Bitter coil stirrer in order to have the control of the silicon melt convection on the principal parameters of the solidification process, such as the growth rate, the thermal gradient and the natural convection of silicon melt. For the electromagnetic, heat exchange and silicon melt flow modelling, we used 3D numerical Multiphysics coupled models. Parallel to the numerical results we carried out experimental investigations relating to the characterization of the electromagnetic parameters. This study shows a promising effect of the applied traveling magnetic field on the final ingot quality; indeed, we have the ability to control the silicon melt flow which can affect the thermal configuration, the solidification interface shape and the segregation of impurities by changing the electric current input configuration of the Bitter coil stirrer.

Key words: Bitter coil, silicon melt stirring, travelling magnetic field, vertical directional solidification.

1. Introduction

Many kinds of silicon solar cells are available in the market and the best in quality is made from high raw material quality like poly-silicon. This raw material increases the cost of the solar cells due to the fact that the raw material is the most expensive constituent. Our goal is to find a way to reduce this cost by using a cheap raw material, such as the upgraded metallurgical (UMG) silicon as solar-grade silicon (SoG) [1]. This silicon is less expensive than polysilicon due to its quality according to the impurities level; but it can be used for solar cells production with proper production process [2]. In addition, the growth rate, thermal gradient and fluid convection (natural or forced) are predominant
factors that may affect the segregation of impurities in the final solidification process, whether for alloys [3-5] or pure material production. Based on this, it is necessary to control these factors in order to optimize the solar cells properties according to the purity level of the used raw material. The main important key investigated in this study is to control the segregation phenomena by controlling the silicon melt hydrodynamic flow and optimizing the shape of the silicon solid/liquid interface. Our approach is based on a numerical simulation coupled model supported by an experimental characterization. The study focuses on the different possibilities of controlling the hydrodynamic of the silicon melt using the interaction between the thermal configuration, imposed by the furnace, and the travelling magnetic field, imposed by the Bitter coil stirrer.

2. Materials and methods

To reach our goal, we used in this study a vertical Bridgman (2 Inches) furnace, denoted VB2, which operates in the resistive mode. VB2 is a cylindrical solidification furnace with an axisymmetric vertical axis [6-7]. In order to study deeply the directional solidification process of metallurgical photovoltaic silicon under the solidification key parameters, such as: thermal gradient and convection, VB2 furnace was equipped with specific thermal and hydrodynamic controls to modify the thermal gradient and the silicon melt convection. The thermal control is carried out by an instrumented heating system composed by two separate resistors; in the upper part of the furnace for the hot zone and in the lower part of the furnace for the cold zone. By this design, we have a separate thermal control over two zones that can generate a precise thermal gradient in the central zone of the furnace. The central zone, between the two resistors, was thermally insulated in order to create an adiabatic zone for the silicon melt charge according to the principle of Bridgman solidification process. For the hydrodynamic part, the control was obtained by the incorporation of an electromagnetic Bitter coil stirrer in the central zone (figure 1) which can generate a TMF configuration. This Bitter coil is composed of six blocks of ten disks to build the coils (figure 1 (b) and (c)); powered by a three-phase electric currents at frequency \( f_0 = 50 \text{ Hz} \) and with a pulsation \( \omega \) equal to \( 2\pi/T \) (\( T = 1/f_0 \) represent the period). All the components of the Bitter coil are installed in a stainless steel enclosure (figure 1 (a)) with the following dimensions: the internal radius is equal to 10 cm and the height is equal to 25 cm.

![Figure 1. (a) Bitter coil stirrer (b) and (c) pictures of the six blocks that make up the coil.](image)

The model was carried out by COMSOL Multiphysics software based on the presented design in figure 1; the schematic of 3D numerical model of the Bitter coil stirrer is shown in figure 2. This coupled model offers the possibility of analysing numerically the configurations of the electromagnetic field and the hydrodynamic flow of the silicon melt.
As illustrated in figure 2, the silicon is contained in a fused silica cylindrical crucible and positioned in the central axis of the Bitter coil stirrer with the following dimensions: the radius $R = 2.5$ cm and the height $H = 30$ cm. The Bitter coil is composed of 6 blocks of 10 disks; each block is separated with an insulating layer, the whole system is assembled by well insulated fixing screws. For simulation purposes, the silicon charge was considered as liquid at a temperature above the silicon melting point ($T_m = 1687$ °K). The used model allowed us to perform different numerical configurations in order to discern the ability of the designed Bitter coil stirrer to generate an acceptable TMF configuration; which in turn, creates a better control of the silicon melt movement during the solidification process for the purpose to improve the segregation of the impurities in the final ingot. Our tests show that without the contamination of silicon melt, the TMF configurations can be changed externally by modifying the electromagnetic input parameters.

3. Traveling magnetic field (TMF)

The obtained traveling magnetic field is created by the three-phase alternating electric current with a phase shift of 120 degrees ($2\pi/3$) with adequate input currents. Base on this, the input current of the three phases ($I_A$, $I_B$ and $I_C$) are expressed, in the equation system (1) figure 3, as function of the generator input currents ($I_1$, $I_2$ and $I_3$) and $\omega$ the pulsation [8].

$$\begin{align*}
    I_A &= I_1 \cdot \cos(\omega t) \\
    I_B &= I_2 \cdot \cos(\omega t + \frac{2\pi}{3}) \\
    I_C &= I_3 \cdot \cos(\omega t + \frac{4\pi}{3})
\end{align*}$$

(1)

**Figure 3.** Illustration of the poly-phase input currents in the Bitter coils for upward and downward TMF configurations.
For the purpose of controlling the hydrodynamic flow of the silicon melt, we chose two specific configurations of TMF, the first one with a TMF upward and the second one with a TMF downward. These two configurations can be obtained by changing the distribution of the phases in the input current of the Bitter coil stirrer as illustrated in figure 3. Due to this three-phase system connection; the maximum value of the magnetic field density moves vertically in the middle of the Bitter coil stirrer, and therefore over the crucible and the melt silicon charge, as shown in figures 4 and 5 for the used conditions: $f_0 = 50$ Hz and the input currents of the three-phase are: $I_1 = I_2 = I_3 = 300$ A.

4. Results and discussions

4.1. Numerical simulation results

For the numerical results, we started with the presentation of the electromagnetic filed configuration. In figure 4, we can see the numerical results of the 3D field configuration of the magnetic flux intensity.

![3D simulation results](image)

**Figure 4.** 3D simulation results of the configuration of the magnetic flux streamline of the TMF downward case for the following operating conditions: $f_0 = 50$ Hz and the input currents are: $I_1 = I_2 = I_3 = 300$ A.

Since the Bitter coils are placed along the OZ axis; the created magnetic field is directed along this axis; the streamlines of the magnetic flux intensity show the existence of two loops along the Bitter stirrer (see figure 5). If the coils of the Bitter stirrer are correctly supplied by a poly-phase electric source with a pulsation $\omega t$ (as presented in equation (1) and illustrated in figure 3), the magnetic field propagation should be in form of a traveling wave parallel to the OZ axis. To understand this result, figure 5 shows the geometry of the central section of the system by the illustration of the vertical cutting median plane through the Bitter coils and the silicon melt charge in the centre. These results are for the downward case, they show the TMF configuration with the norm of the magnetic flux intensity at the following operating conditions for the Bitter coil: the frequency $f_0 = 50$ Hz and the input currents for the three-phase are: $I_1 = I_2 = I_3 = 300$ A. The difference between the three cases illustrated side by side pictures in figure 5 is related to three different spatial presentation of the magnetic field; suggesting that the designed Bitter coil stirrer has the ability to generate an acceptable movement of the TMF wave that can be used for the stirring purpose of the silicon melt charge.
Figure 5. Numerical results of the spatial evolution of arrow vectors field of the magnetic flux intensity norm for the downward TMF case for the following operating conditions: $f_0 = 50 \text{ Hz}$ and the input currents are: $I_1 = I_2 = I_3 = 300 \text{ A}$.

The three pictures in figure 5 show the numerical results of the arrows field of the magnetic flux intensity norm. Those pictures, from left to right, illustrate three consecutive instant in the same period ($T$). The maximum of the magnetic flux intensity is located near the coils and moves from the top to the bottom of the Bitter coil as shown by the dotted circles in black colour (TMF downward case). This movement is related to the phase shift in the input parameters of the three-phase system between the three instants. To present this phase shift configuration, in figure 6 we plotted the dimensionless current from the equation system (1) as a function of time for the three-phase.

Figure 6. Dimensionless configuration of the three-phase current as a function of time according to the system phase shift for one period $T = 1/f_0$.

As we can see, according to the system equation (1), figure 6 shows the phase shift and the variation of the electric input current as a function of time between the three-phase, the result of this phase shift configuration with the connections system used in figure 3 allow the creation of the adequate TMF movement.

This Bitter coil conception offers the ability to control the value of the magnetic field intensity in the
silicon melt by varying the values of the input currents; moreover, it is also possible to change the
direction of the TMF effect by modifying the shift of the positions of the three phases of the Bitter
coils. Likewise, for the upward case, the TMF wave has the same movement but from the bottom
to the top of the Bitter coil (upward). Therefore, the control of the hydrodynamic flow in the silicon melt
is possible by magneto hydrodynamic coupled interaction for both cases: a TMF and hydrodynamic
flow upward and a TMF and hydrodynamic flow downward in the vicinity of the crucible wall. The
3D numerical results of the magneto hydrodynamic flows of molten silicon for the two TMF
configurations are presented in figure 7:

As shown in figure 7, we can see the direction of the silicon melt convection and the velocity obtained
for two hydrodynamic flow configurations: the result on the right illustrates the downward
hydrodynamic flow for the TMF downward configuration and the result on the left illustrates the
upward hydrodynamic flow for the TMF upward configuration. For both cases and for the same input
parameters of currents we obtained the same maximum value of the flow velocity with the installation
of two pairs of vortices. Consequently, depending to the initial imposed thermal configuration and
natural hydrodynamic flow; the Bitter coil stirrer effect can provide better control over the key
parameters of the impurities segregation phenomena, such as: the velocity of the silicon melt and the
shape of the solid-liquid interface during the solidification process. By having sufficient flow velocity
of silicon melt and an almost plan and horizontal solid/liquid interface shape, we can significantly
improve the segregation of impurities in the final ingot [6-7].

4.2. Experimental validation
In this section, we present the validation of the electromagnetic parameters of our Bitter coil stirrer.
The numerical results of the magnetic intensity are compared to the electromagnetic experimental
measurements (figure 8). The Bitter coil stirrer is powered by a three-phase AC with the frequency $f_0 =
50$ Hz.
Figure 8. Comparison between numerical results and experimental measurements of the magnetic intensity on the vertical direction $OZ$ at the centre position of the Bitter coil stirrer for: $R = 0$ cm and $R = 4$ cm with $f_0 = 50$ Hz and $I_1 = I_2 = I_3 = 400; 600$ and $800$ A. 

Figure 8 shows the results of the electromagnetic intensity in z-positions (i.e. in vertical direction) for the two following positions: (a) for the z position equivalent to the radius $R = 0$ mm and (b) for the z position equivalent to the radius $R = 40$ mm. To ensure that the same results are obtained regardless the input current, measurements were carried out for different applied values: $I_1 = I_2 = I_3 = 400; 600$ and $800$ A. The electromagnetic results obtained by the model are in concordance with the experimental results; consequently, they can be used for the validation of a future experimental investigation on the generated hydrodynamic flow in the silicon melt.
5. Conclusions
The electromagnetic configuration and the hydrodynamic flow in the silicon melt were numerically and experimentally investigated. The obtained results show clearly the possibility to control the silicon melt convection, by adding an external traveling magnetic field stirring apparatus, to control the silicon melt convection without physical contact through the magneto hydrodynamic volume forces (i.e. Lorentz forces). Good concordance between the obtained numerical results and experimental results validated our numerical model that can be used as an efficient tool to investigate and predict the possible forced configuration using our traveling magnetic field Bitter coil stirrer. The Bitter coil stirrer has been designed to generate different modes of traveling magnetic field (i.e. upward or downward stirring); each configuration giving a specific electromagnetic force pattern with a particular hydrodynamic flow affecting directly the thermal configuration and the shape of the solid/liquid interface. It was shown that it is possible to change the melt flow convection by using either upward or downward stirring configuration; such result will have then a direct effect on the impurity segregation as well. Further investigation will be useful to quantify the effect of such melt flow modification on the segregation and the distribution of impurities on the scale of the whole silicon ingot.

6. References
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