Design of a high temperature superconducting magnet for a single silicon crystal growth system

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Abstract. This paper presents a study on the design of a high-temperature superconducting (HTS) magnet for a Czochralski single silicon-crystal growth system by evaluating the temperature and flow distributions of silicon melt at the cusp magnetic field. A two-dimensional finite element method (FEM) simulation model was built to determine the effects of the magnetic field on the temperature and flow distributions in the silicon melt. The characteristics of the HTS magnet were analyzed using a three-dimensional FEM model. The HTS magnet was designed using 2G HTS wire and the magnet was validated through FEM simulation. The simulation results showed that the melt convection was significantly suppressed by the Lorentz force, and that the temperature distribution was uniform in the silicon melt under the cusp magnetic field. The shape of the HTS magnet was determined as a magnet ring with a magnetic flux density of 0.35 T at the center of the crucible bottom. The fundamental design specifications and the data obtained from this study can be applied to the development of a real silicon-crystal growth system.

1. Introduction
Czochralski (Cz) technology is widely used as a single silicon-crystal growth method, in which a crucible is used to hold the melt from which a crystal is grown. To improve the quality of the crystals, the static magnetic fields of the external magnet around the crucible are used, which are well known for suppressing the melt convection and the temperature fluctuations when the magnetic field strength is 0.1 – 0.5 T [1]–[4]. There are three types of magnetic field used in the Cz method: horizontal magnetic field, vertical magnetic field and cusp magnetic field. The cusp magnetic field, in which the free surface of the melt is centered between two opposite fields generated by two magnets, has the advantages of both horizontal and vertical magnetic fields [3]–[6]. However, to increase crucible size and crystal diameter, the application of a static magnetic field of sufficient strength requires large coil systems that consume a substantial amount of electric power [2]. Thus, the superconducting magnet technique is an attractive solution for reducing the dimensions and energy consumption of crystal growth systems.

Nowadays, low-temperature superconducting magnets (NbTi) for single silicon-crystal growth have already been commercialized and widely used. However, high-temperature superconducting (HTS) magnets will operate efficiently and reliably on magnet quench due to their high critical temperature and high capacity, which can lead to a large temperature margin [7]–[8].

In this paper, a high-temperature superconducting (HTS) magnet was proposed for a 300 mm silicon-crystal growth system, and the temperature and flow distributions of a silicon melt within the cusp magnetic field were analyzed. Based on the physical parameters of the Cz crystal growth system, a two-dimensional (2D) axisymmetric finite element method (FEM) simulation model was built. The velocity field and temperature distribution in the silicon melt were analyzed for two cases: one with no magnetic...
field and one with cusp magnetic field. Then, the magnetic field strength and shape were determined to
design the HTS magnets using 2G HTS wire with an expected operating temperature of 30 K or less.
The metal was insulated using stainless steel tape to provide quench protection and to improve thermal
conduction.
A characteristic analysis of the magnet was conducted using a three-dimensional (3D) FEM
simulation. It was found that melt convection was significantly suppressed by the Lorentz force and that
the temperature gradient of the silicon melt was significantly reduced under the cusp magnetic field. The
magnetic flux density at the center of the crucible bottom was 0.35 T. The operating current of the
magnet was 344 A with four double pancake coils (DPCs). The total wire length was 11.5 km. The
fundamental design specifications and the data obtained from this study can be applied to the
development of a real silicon-crystal growth system.

2. Magnetic fields in a Cz silicon-crystal growth system

2.1. Configuration of a 300 mm single silicon-crystal growth system

![Figure 1. Configuration of a Cz silicon-crystal system](image)

In an industrial Cz single silicon growth process, a crystal is grown from molten silicon contained in a
silica crucible as shown in figure 1. The melt flow in a crucible is determined based on the material
properties of the silicon melt, as shown in table 1. Table 2 shows the parameters of the Cz single silicon-
crystal growth system, which were chosen to model the melt flow with a crucible having a diameter of
900 mm. The crystal has a diameter of 300 mm. The silicon melt has relatively high electric conductivity,
allowing the melt flow in the crucible to be affected by electromagnetic fields [9]-[11].

| Parameters                      | Values   |
|--------------------------------|----------|
| Mass density, \( \rho \)       | 2,580 kg/m\(^3\) |
| Dynamic viscosity, \( \eta \)  | 0.00086 kg/ms |
| Specific heat, \( C_p \)        | 1,000 J/(kg.K) |
| Thermal conductivity, \( k \)  | 67 W/(mK)   |
| Electric conductivity, \( \sigma \)| \( 1.2 \times 10^6 \) S/m |
| Volumetric expansion rate, \( \alpha \) | 0.00014 1/K |
| Melting temperature, \( T_0 \)  | 1,685 K    |
2.2. Magnetic field effects on the silicon melt

Because the silicon melt has high conductivity, the magnetic field has a considerable influence on melt convection through the Lorentz force, $\vec{F}_s$, which is described as

$$\vec{F}_s = j \times \vec{B},$$

where $j$ is the induced current density determined by

$$j = \sigma (\vec{v} \times \vec{B}),$$

where $\vec{v}$ is the melt velocity field and $\vec{B}$ is the magnetic induction. The Lorentz force opposes the direction of the melt flow.

Normal axisymmetric flow is driven by buoyancy, electromagnetic force and heat transfer inside the crucible wall. Assuming that the fluid is incompressible and that the Boussinesq approximation is valid, the time-averaged momentum equation is described as in [2], [12]-[14],

$$\rho (\vec{v}, \nabla) \vec{v} = -\nabla p + \eta \nabla^2 \vec{v} - \rho \hat{g} \alpha (T - T_0) + \vec{F}_s,$$

where $p$ is the pressure, $\rho$ is the reference density, $\eta$ is the dynamic viscosity, $\alpha$ is the coefficient of volume expansion, $\hat{g}$ is the gravitational acceleration, and $T$ is the temperature of the silicon melt.

Mass conservation and energy transport equations with $\nabla \vec{v} = 0$ are

$$\rho C_p (\vec{v}, \nabla) T = \nabla (k \nabla T),$$

where $C_p$ is the specific heat, and $k$ is the thermal conductivity.

In this paper, the simulation results for a cusp magnetic field revealed a coil configuration in which the vertical component of the magnetic field equaled zero at the melt free surface. The distribution of the field inside the melt was very inhomogeneous. For simplicity, the field was modeled with solenoidal analytical expressions and the cusp magnetic field as a linear field [2] given as

$$\vec{B} = \frac{B}{R (r \vec{e}_r + 2 (H - z) \vec{e}_z)},$$

where $R$ and $H$ are the radius and height of the melt in the crucible, respectively. The corresponding unit vectors $\vec{e}_r$ and $\vec{e}_z$ are described in figure 1.

3. Modelling of silicon melt flow with a cusp magnetic field

3.1. 2D FEM simulation model

Based on the parameters of the Cz crystal growth system given in tables 1 and 2, a 2D axisymmetric FEM simulation model was built as shown in figure 2. The temperature and flow distributions in the silicon melt were analyzed without magnetic field and with a cusp magnetic field. The crystal rotation
rate was 15 rpm, and the crucible counter-rotation rate was 5 rpm. The crystal diameter was 300 mm, and the diameter of the crucible inside wall was 900 mm. The melt height was 280 mm. The temperature of the crucible wall heated by AC induction heater was 1,685 K, and the temperature of the crystal surface in contact with the liquid silicon was 1,400 K. The operating conditions of this analysis were recognized as the most appropriate for the Cz crystal growth process [1]-[3].

Figure 2. FEM simulation model and the magnetic flux density results for a cusp magnetic field

The shape, size, and the location of the HTS magnet were determined by the magnetic flux density at points at the center of the free melt surface, $B_{CT}$; the free melt surface in the crucible wall, $B_{CTE}$; and the centre of the crucible bottom, $B_{CB}$, respectively.

3.2. FEM analysis results and discussions

The comparisons of the velocity field and temperature distributions in the crucible without a magnetic field and with a cusp magnetic field in the 2D FEM simulation results are shown in figures 3 and 4, respectively.

For the cusp magnetic field, the melt convection in the crucible wall and the upward melt flow under the crystal were suppressed, while mixing of the melt under the crystal remained strong because the silica dissolution in the crucible wall was reduced. The maximum velocity of the melt flow under the contact surface between the crystal and the free melt surface was 0.158 m/s. Compared to the simulation with no magnetic field case, the temperature distribution in the melt was more homogeneous and the temperature gradient was significantly reduced.

Figure 3. Velocity field of the silicon melt in the FEM simulations
Figure 4. Temperature gradient of the silicon melt in the FEM simulations

The change in the maximum velocity of the melt flow due to the magnetic flux density at the center of the crucible bottom is shown in figure 5. The figure shows that suitable value for magnetic field strength was determined, and the minimum velocity of the melt flow was achieved at the magnetic flux density of 0.35 T at the center of the crucible bottom.

Figure 5. The velocity of the silicon melt at the center of the crucible bottom based on magnetic flux density

4. Design of an HTS magnet for a 300 mm single Si crystal growth system

4.1. Determination of specifications of the HTS magnet

Figure 6 shows the design process for the HTS magnet for a Cz 300 mm single silicon-crystal growth system.
First, the design targets of the HTS magnet were determined. Here, the authors designed the magnet based on the cusp field configuration and selected a ring-shaped coil. The magnet was cooled below 30 K using a cryogenic conduction cooling method, and the target magnetic flux density was 0.35 T at the center of the crucible bottom. Second, the distance from the free melt to the magnet and the size of the magnet rings (inner and outer radius) were decided. Third, the number of turns and number of DPCs were determined. The coil length and cost were considered. Finally, the critical current of the HTS magnet was estimated and the operating current was chosen. The characteristic analysis of the magnets was conducted using FEM simulation.

To estimate the critical current of the HTS magnet, a 3D FEM simulation model was designed. The perpendicular magnetic flux density at an operating current of 1 A was 0.00797 T. The 2G YBCO HTS wires used in the design were manufactured by SuNam company, and were 12 mm wide and 0.22 mm thick. The critical current was 600 A at a temperature of 77 K. The perpendicular magnetic flux density of the magnet was compared to the critical current characteristics curve as shown in figure 7 to determine the critical current of the HTS magnet [15].

![Design flow chart for the HTS magnet](image)

**Figure 6.** Design flow chart for the HTS magnet

![Critical current and field properties of the SuNam conductor (YBCO; Ic = 600 A at 77 K)](image)

**Figure 7.** Critical current and field properties of the SuNam conductor (YBCO; Ic = 600 A at 77 K)
At 30 K, the critical current was 430 A, and the target operating current was 344 A which is 80% of the critical current. Figure 8 shows the configuration of the HTS magnet in the Cz 300 mm single silicon-crystal growth system. The ring-shaped DPCs were applied to the magnet, and four DPCs made up the magnet rings. The inner and outer radii of the HTS magnet were 810 mm and 900 mm, respectively; the distance from the free melt surface to the coils was 400 mm, and the number of turns of one single package coil (SPC) was 500. Table 3 provides detailed specifications for the HTS magnet.

![Figure 8. Configuration of the HTS magnets](image)

| Parameters                                | Values     |
|-------------------------------------------|------------|
| Distance from the free melt surface to coils | 400 mm     |
| Inner radius                              | 800 mm     |
| Outer radius                              | 910 mm     |
| Number of DPCs                            | 4ea        |
| Number of turns of the SPC                | 500 turns  |
| Superconducting wire                      | YBCO       |
| Thickness of HTS tape                     | 0.22 mm    |
| Width of HTS tape                         | 12 mm      |
| Magnetic field direction                  | Cusp magnetic field |
| Magnetic field strength (center of crucible bottom) | 0.35 T |
| Critical current ($I_c$)                  | 430 A      |
| Operating current ($I_{op} = 0.8 \times I_c$) | 344 A      |

### 4.2. Confirmation of the design results

A 3D FEM simulation model was built to analyze the characteristics of an HTS magnet and to confirm the design results as shown in figure 9. The magnetic flux density at the top of the crucible edge and the center of the crucible bottom were 0.3 T and 0.35 T, respectively. The results of the magnetic flux density satisfied the initial goal of the study.

![Figure 9. Confirmation of the desired magnetic field for the HTS magnet](image)
5. Conclusion
This paper presents the results of designing an HTS magnet for a single silicon-crystal growth system. The authors analyzed the effects of static magnetic fields on silicon melting in a single silicon-crystal growth system. Magnetic field strength and shape were determined for an HTS magnet designs, and the characteristics of the designed magnet were analyzed using FEM simulations to determine its specifications. A ring-shaped DPC was applied to the HTS magnet, and the operating current of the HTS magnet with four DPCs was 344 A. The number of turns of one SPC was 500 with a total wire length of 11.5 km. The melt convection was significantly suppressed by the Lorentz force, and the temperature distribution was uniform in the silicon melt under the cusp magnetic field. The magnetic flux density of 0.35 T at the center of the crucible bottom was achieved. The basic design specifications and data from this study can be effectively applied to the development of real silicon-crystal growth systems.

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