STUDY OF 3D PHENOMENA IN CZOCHRALSKI LARGE DIAMETER SILICON SINGLE CRYSTAL GROWTH IN A TRANSVERSE MAGNETIC FIELD

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Introduction. The transverse magnetic field is known to control the oxygen concentration and to decrease the micro non-uniformities in dopant and impurity distribution over the crystal diameter in the actual silicon single crystal growth. Yet, the influence by a transverse magnetic field should obviously cause axial asymmetry of the melt flow and temperature field thats affect negatively the quality of produced crystals. Therefore, the obtained positive results require a thorough study of the transverse magnetic field action on the hydrodynamics and heat/mass transfer in the melt because they could allow to find optimal patterns of the hydrodynamic flows and temperature field aimed at the production of high quality single crystals.

Direct observation of the melt flow in molten silicon is very complicated. Real insight into the molten silicon is given by Watanabe *et al.* [1] using the X-ray radiography in a small crucible (75 mm diameter). Some information about the melt flow can be derived from the temperature measurements in molten silicon during the crystal growth [2]. Most investigations of the melt flow in large crucibles are based on numerical simulation. Several papers have presented three-dimensional (3D) solutions for CZ systems with static horizontal magnetic fields, e.g., [3, 4, 5].

Physical modeling is more expensive than numerical modeling, but has fewer simplifications and therefore it shows better agreement with the processes in industrial facilities. Modeling in low temperatures and in non-aggressive melts is possible. Most works on physical modeling are done in very small crucibles, e.g. [6], using a cusped magnetic field [7]and an axial magnetic field, both in the crucible of 160 mm in diameter filled with mercury.

1. Experimental set-up and procedure of experiments.

1.1. Experimental set-up. InGaSn alloy (Fig. 1 – (1)) with the melting temperature of 10.5 degree C was used for physical modelling in a 500-mm-diameter silica crucible (2); the diameter of the water cooled crystal model of stainless steel (3) was 165 mm, the melt height was 150 mm. The crucible was heated by a nickel-chrome heater (5) mounted directly on the crucible. Heat losses from the melt free surface were considered using a heat exchanger (4). The magnet (6) with two vertical coils produces a horizontal field in the crucible zone. The experimental setup is described in detail in [8].

1.2. Measurement system. A multi-channel set of probes was used to measure and process the obtained data. The set consisted of 32 thermocouples arranged either in meridional or azimuthal planes of the crucible. Probe sampling time was 1000 seconds and 1000 instant temperature distributions were registered, which, after averaging, showed the mean temperature distribution, temperature pulsations and were composed as video animations. Since the action by a transverse magnetic fields results in asymmetry of the temperature field, the set of

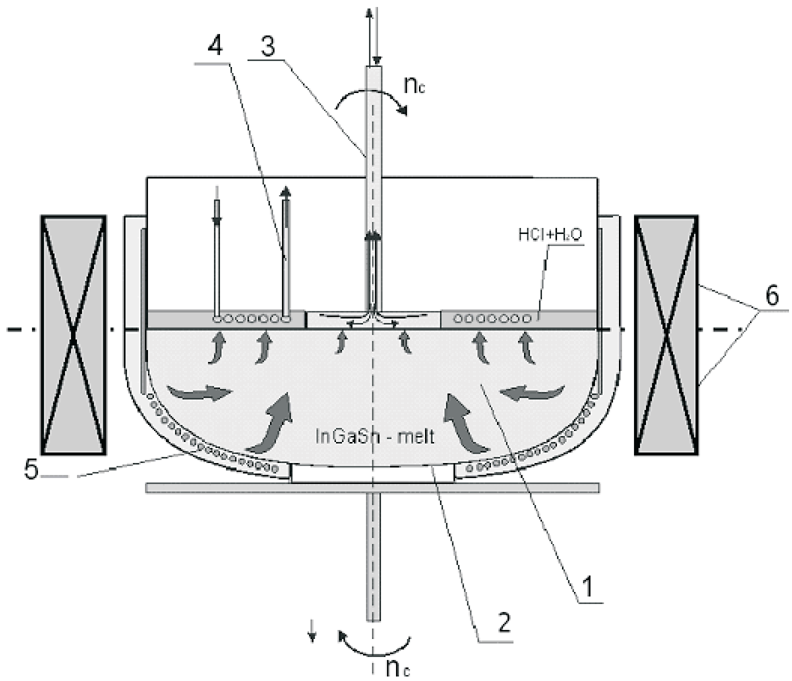


Fig. 1. Principal schematic of the experimental facility. 1- melt, 2 – crucible, 3 –crystal model, 4 – heat exchanger, 5 – heater, and 6 – magnetic system.

probes was arranged in meridional planes either parallel to the vector of magnetic field induction or perpendicular to it.

2. Results without crucible and crystal rotation. The transverse magnetic field influence on the thermogravity convection (TGC – no crystal/crucible rotation) has been studied in detail. The melt flows upwards along the hot crucible wall and downwards under the cold crystal causing turbulent convection and intensive mixing in the melt bulk, which reduces the temperature drop (temperature difference between the "coldest" point in the subcrystal zone and the "hottest" one on the crucible wall). The magnetic field suppresses this convection and reduces temperature fluctuations. The obtained results evidence that the transverse magnetic field suppresses the melt flow much stronger in a plane perpendicular to the field and increases the temperature drop in this plane more than in the parallel plane, as shown in Fig. 2 (TGC case is depicted as 0 / 0). The isolines of the mean temperature for a field intensity of 80 mT are shown in Fig. 3 in meridional planes parallel (a) and perpendicular (b) to the vector of magnetic field. The isolines in the parallel plane are more curved that testifes the higher velocity in this plane. The result is a disturbed rotational symmetry of the temperature field. This is in good agreement with the widely known MHD statement that the vortical patterns, whose axes of rotation match with the direction of the magnetic field induction vector, are less suppressed. The figures with mean temperatures, e.g., Fig. 3, and video animations show that the influence by a transverse magnetic field on thermogravity convection excites classical MHD phenomena, i.e., the suppression of the mean melt flow and velocity as well as temperature fluctuations. The temperature fluctuations in the parallel plane are sufficiently suppressed already at 40 mT, whereas in the perpendicular plane, the fluctuations first increase with the magnetic field intensity and decrease only at 160 mT (Fig. 2, case 0 / 0).

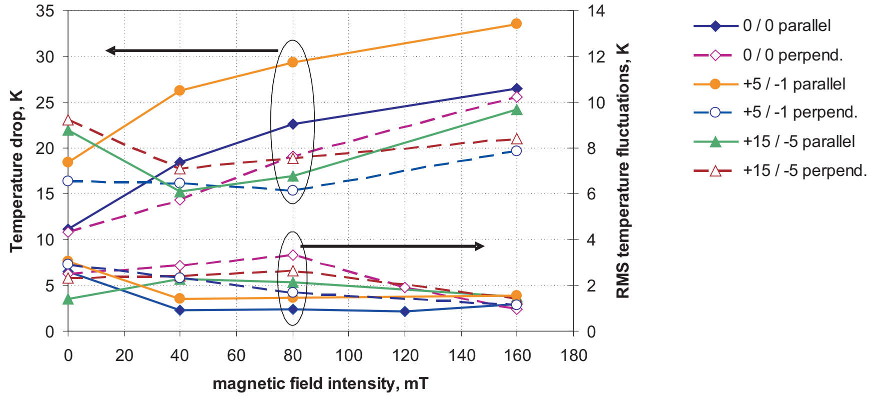
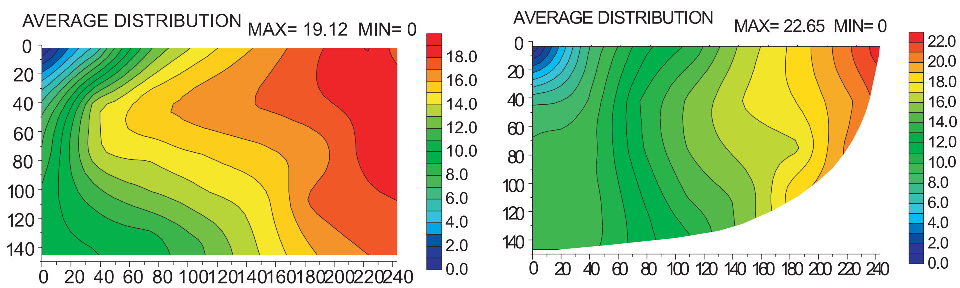


Fig. 2. Temperature difference and root mean square (RMS) temperature fluctuations in vertical planes parallel and perpendicular to the magnetic field, depending on the magnetic field intensity.

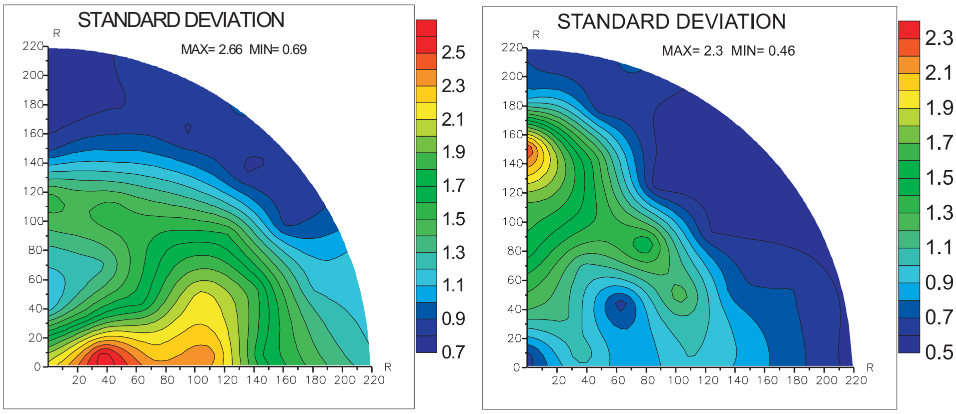
3. Results with crucible and crystal rotation. The rotation of crystal and crucible, especially the counter-rotation, is a typical case for Czochralsky crystal growth. The influence by a steady transverse magnetic field on the temperature field at combined convection (TGC and crystal/crucible rotation) is more complicated. With the crystal rotating alone, the action of the magnetic field restricts to the suppression of the meridional melt flow driven by TGC in the melt bulk. At actual rates, the effect of crystal rotation is comparatively small and manifests itself only under the crystal. Apparently, the strongest MHD phenomena could be related to the rotation of the melt bulk (i.e., rotation of the crucible) in the transverse magnetic field. At crystal and crucible rotation rates of $+15/-5$ rpm and without the magnetic field the temperature drop is about 22 K and it is much higher than 11 K in the case without rotation, because the rotation of the melt bulk suppresses the meridional convection (Fig. 2). Increasing the magnetic field to 40 mT decreases the temperature drop in the both planes because the symmetry of the azimutal flow is broken and the meridional components of velocity are present in the melt.

The increasing of the magnetic field at high crystal and crucible rotation rates increases the temperature fluctuations in the both planes (Fig. 2). The analysis of video animations reveals the nature of these fluctuations. This regime is characterized by periodic injections of cold melt from the subcrystal zone into the zone under the melt free surface. Sometimes "cold tongues" from the subcrystal zone achieve even the crucible wall. This ensures a permanent modification of the temperature field pattern and enhances the instability of flow and temperature.



(*a*) (*b*)

Fig. 3. Isolines of the mean temperature in meridional planes parallel (a) and perpendicular (b) to the magnetic field direction at the field intensity of 80 mT.



(*a*) (*b*)

Fig. 4. Isolines of RMS temperature fluctuations in the azimutal plane 10 mm under the melt surface at crystal/crucible rotation rates $+15/-5$ rpm and with the transverse magnetic field of 80 mT (*a*) and 160 mT (*b*) (the field is directed parallel to the vertical axis.

The distribution of temperature fluctuations over 1/4 of the azimutal plane for 80 mT is shown in the Fig. 4*a* and for 160 mT in Fig. 4*b*. The plane is located 10 mm below the melt surface, therefore, the absolute values are different from those in Fig. 2. The fluctuations have their maximum value under the crystal, and a pronounced maximum in the middle of the crucible over the whole azimutal direction. The increase of magnetic field induction to 160 mT and of the crucible rotation rate just strengthens such phenomena. Yet, the decrease of the crucible rotation rate decreases the hydrodynamic instability at the melt free surface, in particular.

So the crucible rotation in a transverse magnetic field results in a new instability mechanism, whose influence on the hydrodynamics and temperature field enhances, as the crucible rotation rate and the magnetic field induction increase.

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