ROTATING MAGNETIC FIELD INFLUENCE ON HEAT AND MASS TRANSFER DURING AXIAL HEATING PROCESS SEMICONDUCTOR CRYSTAL GROWTH

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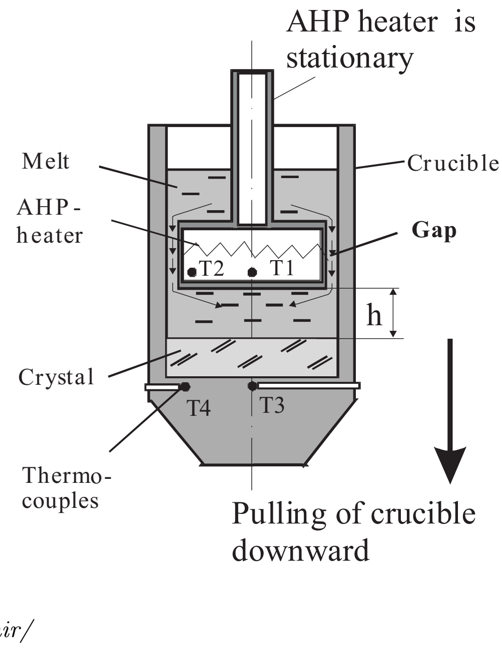
Introduction. Axial Heating Process (AHP) method [1] of crystal growth is basically a modified Bridgman technique with an additional submerged heater placed above the solid-liquid interface at a certain distance, which is kept constant during the growth. The purpose of this is threefold. First, the AHP heater functioning as a baffle separates the near-interface domain, the growth chamber, from the bulk of the melt leaving less room for convective motion in the area of interest. Second, it provides additional means to control the growth by imposing a specific temperature distribution and vibrational or rotational movements. And the last, a constant offset of the AHP heater during the whole growth process makes it possible to avoid end point effects. The gap between the AHP heater and the crucible wall provides the inflow of species-rich fluid from the bulk of the melt to the growth chamber.

Laboratory experiments have shown that AHP technique with submerged heater is capable of noticeably decreasing the flow intensity and, in the end, of increasing the quality of grown crystals [2].

Magnetic field is an effective method of controlling the motion of electroconductive fluid. Given the fact that the motion of such a fluid is hampered in the direction normal to magnetic force line, it is to be expected that the static magnetic field can dampen the buoyancy-driven flow. Meanwhile, the rotating



magnetic field (RMF) acts in an entirely different way: in case of vertical Bridgman furnace with the rotation axis of magnetic field coaligned with the furnace axis, it induces recirculating azimuthal flow which is coupled with meridional flow via the Eckman effect. RMF is then capable of both damping and intensifying meridional convective motion at the same time in different parts of the melt [3].

The purpose of present study is to investigate the combined effect of RMF and submerged heater in AHP configuration on heat and mass transfer during semiconductor crystal growth.

1. Problem formulation. The AHP furnace setup and problem geometry and boundary conditions are taken from [4] with minor modifications. A cylindrical crucible with radius R and a sidewall of finite thickness is filled with two phases of material: the bottom is occupied by a crystal with a fluid over it. But, since the pseudo-steady state approach is implemented, we exclude the crystal from consideration. Although the solid/liquid interface is generally curved, we consider it as planar. A submerged heater is mounted over the interface at a distance δ_z, separating the growth chamber from the bulk of the melt. There is a small gap δ_r between the heater and the crucible. The RMF is induced by a single pole magnet. The rotation axis for the magnetic field is coaligned with the crucible axis of symmetry.

The melt is assumed to be Newtonian and isothermally incompressible; the steady axisymmetric Navier–Stokes equations in the Boussinesq approximation [4] with an additional term – Lorentz body force $\mathbf{F}_{\mathrm{L}}$ [5] are used.

The external rotating magnetic field is assumed to be orthogonal to the symmetry axis. The period of rotation is much less than the characteristic hydrodynamic time scale, which allows averaging of the Lorentz force. On the other hand, the rotation frequency is small enough such that a skin depth exceeds the characteristic ampoule size. Provided that this requirement is satisfied, the RMF can be treated as spatially uniform [5]. The only force component that survives to the averaging is the azimuthal one, thus making it possible to introduce a scalar function f and to treat the Lorentz force as follows:

$$\mathbf{F}_{\mathrm{L}} = \frac{1}{2}\sigma B^2 \left(1 - \frac{1}{r}\frac{\partial f}{\partial z}\right)[\mathbf{\Omega} \times \mathbf{r}]\,, \qquad \Delta f - \frac{f}{r^2} = 0.$$

The boundary conditions for the scalar function f assume that the crucible is perfect electrical insulator and the fluid and submerged heater have the same electrical conductivity such that the boundary condition of the heater surface can be dropped:

$$r = R : \frac{\partial f}{\partial r} = 0; \qquad z = 0,\, H : \frac{\partial f}{\partial z} = r\,.$$

Following [4], the boundary conditions for the temperature are set to:

on the inner crucible wall (crucible sidewall is excluded from consideration in this particular series of simulations):

$$0 < z < \delta_z : \frac{\partial T}{\partial r} = 0; \qquad \delta_z < z < H : T = T_h;$$

linear temperature gradient on heater bottom:

$$T = T_a + (T_b - T_a)\frac{r}{R_h}\,;$$

zero flux on the rest of the heater:

$$\frac{\partial T}{\partial \mathbf{n}} = 0;$$

melting temperature on the interface and fixed temperature on the top:

$$z = 0 : T = T_m; \qquad z = H : T = T_h\,.$$

Boundary conditions for the dopant concentration are conventional, with a kind of artificial boundary condition on top, as suggested in [6].

2. Numerical procedure. We performed a set of numerical experiments to investigate the influence of RMF on heat and mass transfer during AHP crystal growth with physical material parameters corresponding to gallium-doped germanium [[6]. The crucible geometry parameters are R = 1.6 cm, H = 0.8 cm. Numerical experiments were performed for two values of heater offset δ_z, 0.8 and 0.4 cm, and a magnetic induction B in range of $0 \div 0.5$ mT. In all cases the pulling rate V_f is 3.6 cm/h and initial Ga concentration is 0.5%.

To solve the problem, a self-developed 2$^{\text{nd}}$ order fully implicit finite-difference solver is employed.

3. Numerical results. In spite of employed temperature conditions, the upper part of melt lies in isothermal zone, a fact that explains the absence of convective motion in that region which we observed. A single vortex comprising the flow pattern in the growth chamber is driven by the temperature gradient imposed on bottom surface of the heater. Due to low Prandtl number, ~ 0.01, the case for liquid semiconductors, the heat transfer is dominated by diffusion; we found the temperature field mostly unaffected by the flow induced by combined actions of the buoyancy and RMF. On the contrary, the species transport (Schmidt number is ~ 10) is convection-dominated.

The effect of RMF is the generation of an azimuthal flow, which is coupled with a meridional flow via the Eckman effect. The latter is clearly seen in the upper part of the melt free of buoyancy-driven flow. The flow pattern there is comprised of two almost symmetrical vertically stacked vortices (with the symmetry slightly disturbed by the gap between heater and crucible wall). The vortices' cores are pulled towards horizontal surfaces. In the growth chamber RMF-induced force is

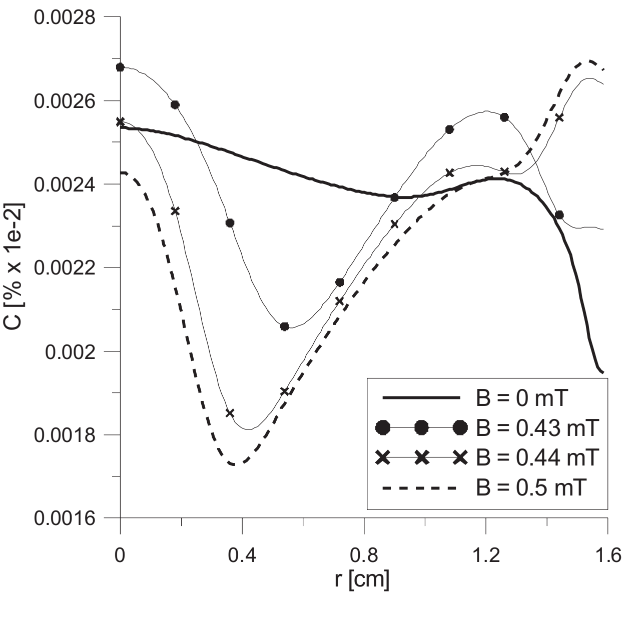


Fig. 1. Dopant concentration profile along the interface for $\delta_z = 0.4$ cm.

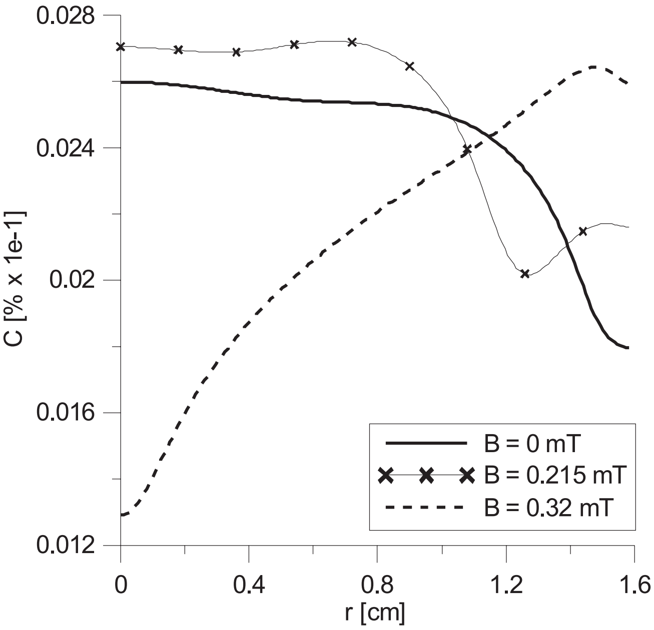


Fig. 2. Dopant concentration profile along the interface $\delta_z = 0.8$ cm.

superimposed on the buoyancy force and is acting against it. As a result, the flow pattern gets changed to a double-vortex one with the new vortex originating at the interface and pushing the old one upwards. This change has a clear effect on the dopant distribution measured along the solid/liquid interface, as seen in Figs. 1–2.

For all examined cases it is found that the application of RMF radically changes the dopant distribution. However, the problem requires further studying to take in account the non-planarity of the solid/liquid interface due to the difference in heat conductivities of phases and the heat of fusion.

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