NUMERICAL MODELING OF CONVECTION INDUCED BY ALTERNATING MAGNETIC FIELDS IN SEMICONDUCTOR MELTS

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Introduction. Alternating magnetic fields can be used in order to increase the level of convection and to mix the doped semiconductor alloys in crystal growth processes. The Bridgman growth method uses a resistive heating of the sample, so in this case, the electromagnetic heating of the sample must be avoided. A numerical analysis of the electromagnetic induced convection in GaInSb semiconductor melts is performed by using the software package CrysVUn. The magnetic field parameters are varied in order to obtain a maximum efficiency of the induced convection with a minimum quantity of the heat released in the melt. The influence of the electric current frequency on the convection intensity is analyzed for samples with various radii ($R = 0.5 - 4$ cm) and as long as $L = 5$ cm.

1. Physical and numerical model. The use of alternating magnetic fields for the stirring of GaInSb high doped alloys (10%–20% indium concentration) grown in a vertical Bridgman configuration, has been proposed in [1]. In this method, the melted sample contained in a crucible is pulled with a constant rate in a thermal field characterized by an axial temperature gradient (see Fig. 1). Numerical simulation of thermo-solutal convection in GaInSb melts shows a strong solutal damping effect of the flow near the solid-liquid interface in the case of concentrated alloys. This leads to a huge increase of the radial variation of indium concentration and of the interface curvature. The quality of highly doped crystals can be improved by applying an alternating magnetic field produced by

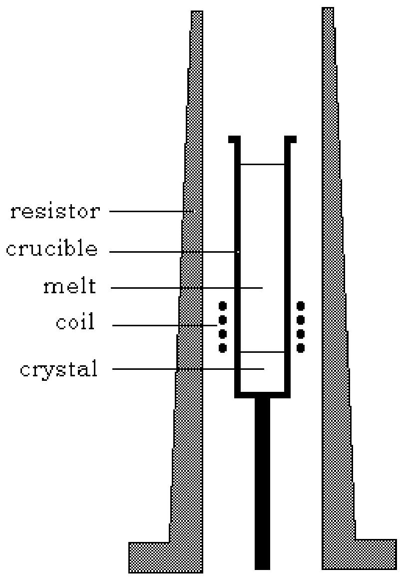


Fig. 1. Vertical Bridgman configuration equipped with an electromagnetic coil.

a coil placed around the crucible in the vicinity of the interface, as is shown by previous numerical simulations [1]. In this case the level of convection is increased in order to obtain a strong mixing of the solute near the solid-liquid interface and to improve the chemical homogeneity of the sample. The optimal magnetic field parameters (frequency f and magnetic induction amplitude B_0) for which the electromagnetic convection has a maximum efficiency and the induced heat in the sample is negligible are numerically carried out in [2]. The analysis was performed in the case of a GaInSb sample with the radius $R = 0.6$ cm and length $L = 6$ cm.

In this work, the numerical analysis of the convective intensity as a function of the electrical current frequency, is performed for samples with various radii $R = 0.5 - 4$ cm and length $L = 5$ cm. In order to validate the numerical procedure, in a first step the modeling was performed for mercury samples and the results are compared with the experimental data given by [3], which show a maximum stirring for a magnetic skin $\delta = 0.2R$ in the case of a mercury sample with the radius $R = 10$ cm. This maximum corresponds to a shielding parameter $R_\omega = 40$.

The transient modeling is performed by using the finite volume software CrysVUn [4]. The momentum, heat transfer and magnetic induction equations are numerically solved in order to analyze the effect of an alternating magnetic field on the buoyancy convection.

The electric current induced in the liquid sample by the alternating magnetic field interacts with the external magnetic field and creates electromagnetic forces, which produce the fluid flow. The amplitude of the magnetic field B_0 given by the Nagaoka's formula, determines the Alfven's velocity as follows:

$$u_A = \frac{B_0}{\sqrt{\mu\rho}}\,. \tag{1}$$

The electromagnetic forces are concentrated in the magnetic skin of thickness:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \tag{2}$$

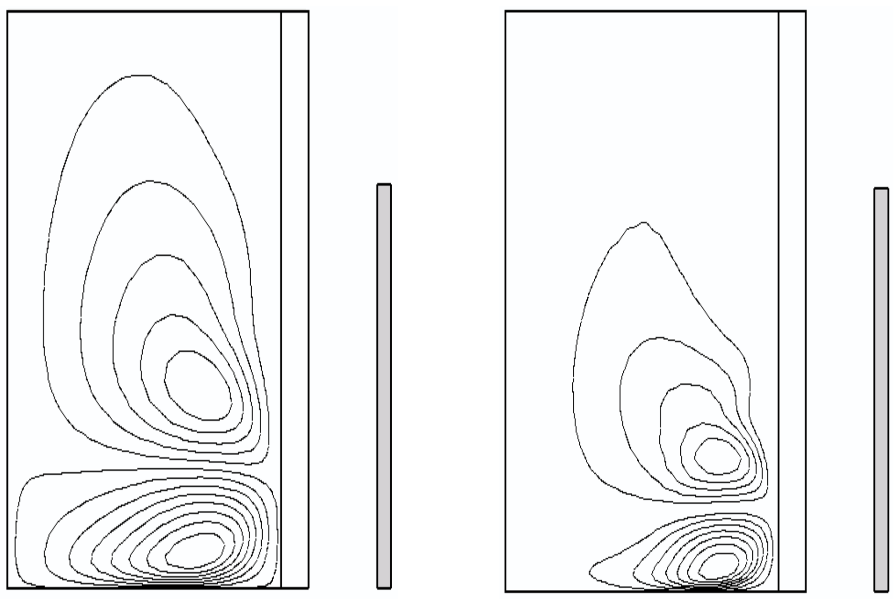
The magnetic skin effect can be characterized in terms of a dimensionless parameter called the shielding parameter:

$$R_\omega = \mu\sigma\omega R^2 = 2\frac{R^2}{\delta^2} \tag{3}$$

2. Numerical results. The simulation domain contains a GaInSb sample, a crucible, a coil and the surrounding domain. The configuration is similar to that used in the experimental Bridgman set-up equipped with an electromagnetic coil [2]. The magnetic field amplitude is $B_0 = 5$ mT and corresponds to the optimal value carried out from previous numerical simulations [2]. Only the liquid sample is taken into account in the simulation by considering a flat solid-liquid interface.

The thermal field in the sample is characterized by an axial temperature gradient. The isotherms are almost flat in the absence of the electromagnetic induced convection, so the intensity of the buoyancy convection is very small. When the electromagnetic induced convection deforms the isotherms, the buoyancy flow increases and damps the electromagnetic convection.

The flow field computed for a sample with the radius $R = 2$ cm in the case of $R_\omega = 2(\delta = R)$ and $R_\omega = 32(\delta = R/4)$ is shown in Fig. 2. Two opposite cells characterize the electromagnetic induced flow with a maximum convective intensity for the lower one. In the case of large magnetic skin ($\delta = R$), the flow



(*a*) (*b*)

Fig. 2. Flow field in the GaInSb sample with $R = 2$ cm radius: (*a*) Shielding parameter $R_\omega = 2$; (*b*) Shielding parameter $R_\omega = 32$.

is extended over the whole volume of the sample (see Fig. 2*a*), while for a small magnetic skin ($\delta = R/4$), the convection is located near the crucible wall (see Fig. 2*b*).

The influence of the electric current frequency on the convection intensity is analyzed for samples with various radii $R = 0.5 - 4$ cm. The electric current frequency is varied between 0.1 and 40 kHz that corresponds to the shielding parameter values $R_\omega = 0.5 - 130$. In Fig. 3, the rate $u_{\max}/u_A$ is represented as a function on the shielding parameter R_ω in the case of various radii of the sample.

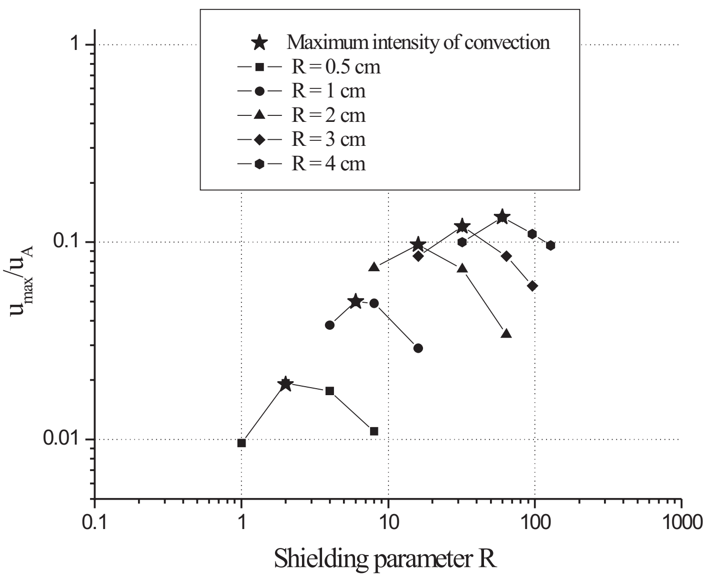


Fig. 3. Maximum convective velocity versus the shielding parameter.

It can be observed that the shielding parameter value, for which the convective intensity reaches the maximum, depends on the sample radius and increases from $R_\omega^{\max} = 2$ in the case of $R = 0.5$ cm to $R_\omega^{\max} = 60$ for $R = 4$ cm. This result is important in the case of samples with a small radius. As, for example, for a $R = 0,5$ cm sample, the maximum intensity of the convection is obtained for the frequency $f^{\max} = 10$ kHz, which is much lower that the huge frequency $f = 100$ kHz corresponding to the shielding parameter $R_\omega = 40$. At this lower value of frequency, the induced heat in the liquid sample is negligible, so the thermal field produced by the Bridgman furnace is not modified.

3. Conclusions. The use of alternating magnetic fields for an efficient stirring of the semiconductor melts during the crystal growth processes necessitates optimization of the magnetic field parameters in order to obtain a maximum intensity of the electromagnetic convection with a minimum of the induced heat in the sample. Numerical analysis of the electric current frequency influence on the convective intensity for samples with various radii is performed by using the CrysVUn software.

¿From the numerical analysis a dependence of the shielding parameter is found for which the induced convection has its maximum intensity $R_\omega^{\max}$ on the sample radius. These results are important for samples with a small radius when an optimal stirring is obtained at frequencies much lower than those corresponding to $R_\omega^{\max} = 40$, and in this case the electromagnetic heating of the sample is negligible.

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