Scaling Analysis of Semiconductor Crystal Growth from the Liquid Phase in an Axis Static Magnetic Field

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A formulation of the relation between static magnetic induction and Reynolds number in liquid, for vertical Bridgman and LPE growth processes of semiconductors in axial static magnetic field was derived based on a scaling analysis, and the validity of the estimation was experimentally investigated. The calculated values of the effective segregation coefficients for Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ crystals grown by the Bridgman method agreed well with the experimentally measured ones from 0 to 6 T of the magnetic induction. In the case of LPE growth on GaP(111)B, nearly diffusion-controlled condition in the liquid was achieved at 6 T. It was shown by *in situ* observation using a near-infrared (NIR) microscopic interferometer that the static magnetic field reduced the LPE growth rate, and as a result, suppressed appearance of macro-steps and hillocks.

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1. Introduction

The quality of semiconductor crystals is mainly influenced by the concentration and distribution of dopants and defects, which are controlled by mass and heat transfer in environment and by interface kinetics. On the terrestrial condition, buoyancy convection yielded by density gradient in liquid often generates defects like growth striations or segregation of dopant in the grown crystal due to the oscillatory flow.

Convection in molten semiconductor is typically vigorous and affects heat transfer, mixing of solutes, and microstructure of the grown crystal. The oscillatory flow in the melt can result in periodic inhomogeneities in the crystals.¹⁻³⁾ And if we want to produce a bulk crystal from melt whose concentration profile is homogeneous, the effective segregation coefficient should be changed from an equilibrium segregation coefficient to unit along the growth direction by means of damping of the convection.⁴⁾ However, it is not easy to attain to a pure diffusive mass transport state in the liquid during the bulk crystal growth on the terrestrial condition. Therefore, an application of magnetohydrodynamic (MHD) effect of static magnetic field to a conductive fluid is one of the promising methods to damp the convection during Czochralski and Bridgman growths.⁵⁻⁷⁾

As another subject of semiconductor crystal growth, macrosteps are frequently observed on the surface of crystals grown from solution, *e.g.*, liquid phase epitaxy (LPE) and traveling heater method (THM) growths. Macrostep has a terrace structure which is generally described in terms of a flat tread and a steep riser. Macrostep varies with the growth conditions morphologically and induces the segregation of dopant atoms. Many investigators have studied the characteristics of macrosteps, their morphologies and their relationships with dopant distribution.⁸⁻¹⁰⁾ Nishinaga¹¹⁾ pointed out

qualitatively that the non-uniformity of dopant distribution is attributed to the difference of the atomic step velocity between at a terrace and a riser parts. However, the dynamics of formation, migration and coalescence of macrosteps have not been revealed precisely and the quantitative relation between the segregation of dopant atoms and the atomic step velocities have been still in veil. It is difficult to understand the interface phenomena, because usually temperature and concentration gradients in liquid phase become driving forces of convection in the liquid.

Therefore, achievement of extremely weak and steady states of natural convection was regarded as a method which led us to investigate the influence of convection on growth process from liquid phase under the gravity. It is well-known that the presence of a uniform static magnetic field tends to stabilize and damp this undesired convective flow. When a magnetic field is applied to an electrically conducting liquid, the liquid motion is reduced because of the interaction between the imposed magnetic field and the induced electric current. Until now there is few reports of simplified but fruitful formulation for the solute concentration distribution in crystals, although a great number of large-scale numerical calculations using computers have been performed to identify the potentiality of the MHD effect in order to damp the convection.¹²⁻¹⁴⁾

In the present research, a formulation of the relation between static magnetic induction and Reynolds number in liquid for vertical Bridgman and LPE growth processes of semiconductors in axial static magnetic field was derived based on a scaling analysis, and the validity of the estimation was experimentally investigated.

2. Experimental Procedure

2.1 Principle arrangement

An axial static magnetic field, B_0 , was produced by a liquid helium free superconducting magnet with a bore 300 mm in diameter and 600 mm in length, which was designed to gener-

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Fig. 1 Schematic drawings of the experimental setup: (a) for melt growth by a vertical Bridgman method, and (b) for solution growth with an NIR microscopic interferometer.

ate a homogeneous magnetic field with maximum induction of 6 T at the center. Homogeneity of the magnetic field in a cylindrical volume with $\phi 100$ mm and 20 mm in height at the center of the bore was less than 1.5%. The direction of the bore axis could be rotated horizontally or vertically to the gravity vector.

An image furnace for crystal growth experiments was mounted into the bore. The reasons for using a monoellipsoidal mirror furnace for heating of a growth ampoule included the following two points: (1) It is necessary to keep a distance between the optical system and the heat source to prevent thermal damage to the measurement system. (2) It is easy to make high temperature gradient in the ampoule axisymmetric. The lower part of the furnace was made up of gold-coated parts, which included a flat mirror and a displacement stage for the ampoule. A thermal-protection mirror was put on the boron nitride plug of the heating lamp to elongate the lifetime of the lamp. A halogen lamp with maximum power of 1 kW was used as a heating source. Output of the heat lamp was steered by a high-precision control DC power supply. DC current is essential to avoid an interaction of the filament and the external Lorentz force in case of magnetic fields. The positions of the furnace and the electromagnetic facility were fixed during the growth, and those of the ampoule and an optical system for solution growth experiment in the z -directions was able to be controlled by drive components independently. The ampoules were evacuated up to $\sim 10^{-4}$ Pa, subsequently sealed by flame, and set at the center of the magnet afterwards. The temperature distribution in the ampoule was measured using a dummy ampoule, and

the temperature program during growth was decided based on these data. Schematic drawing of the experimental setups are shown in Fig. 1.

2.2 Vertical Bridgman growth experiment

Vertical Bridgman growth was realized by pulling down the ampoule from 1 mm/h to 10^2 mm/h with a drive mechanism. Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ crystals were grown by a vertical single-zone Bridgman method, because the melt of the former material has a higher conductivity and lower density difference between the components than those of the latter. The feed material and the seed single crystals were included in a cylindrical quartz-glass ampoule of 8 mm in inner-diameter. To prevent the influence of Marangoni convection on the heat and mass transports in the melt, a quartz-glass rod of $\phi 7.5$ mm was put on the melt as a rid and it was slightly pushed by quartz-glass wool filled in the ampoule. The growth direction and the vector of the magnetic induction were parallel to the gravity vector. The other growth conditions and the physical properties of the materials were shown in Table 1.

After growth, the samples were cut along the growth directions using a thin wheel with diamond particles, and polished mechanically to be mirror surfaces. The concentration profiles in the crystals were characterized by a four point probe method and an EDX for Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, respectively.

2.3 LPE growth experiment

There was no report of *in situ* observation for crystal growth processes of semiconductors until 1980. Chikawa¹⁵⁾

Table 1 Physical properties of the materials and growth conditions.

Symbol	Ga _x Ge _{1-x}			Pb _{1-x} Sn _x Te
C ₀ (at%)	0.1	0.2	1	20
k ₀	0.087	0.087	0.061	0.58
σ (Ω ⁻¹ ·m ⁻¹)	1.5 × 10 ⁶			1.6 × 10 ⁵
α (at% ⁻¹)	-7.3 × 10 ⁻⁴			-2.3 × 10 ⁻³
β (K ⁻¹)	1.1 × 10 ⁻⁴			1.1 × 10 ⁻⁴
ν (m ² /s)	1.4 × 10 ⁻⁷			2.8 × 10 ⁻⁷
ρ ₀ (kg/m ³)	5.5 × 10 ³			7.8 × 10 ³
D (m ² /s)	1.9 × 10 ⁻⁸			5.3 × 10 ⁻⁹
G _C (at%/m)	-40	-80	-400	-3.8 × 10 ³
G _T (K/m)	3.0 × 10 ³			3.0 × 10 ³
m	0.12			0.36
V _G (m/s)	8.3 × 10 ⁻⁶			2.2 × 10 ⁻⁶
L (m)	2.6 × 10 ⁻²			
r (m)	4.0 × 10 ⁻³			
B ₀ (T)	0.0–6.0			

visualized the behavior of dislocations in a thin Si plate, with a thickness of 300 μm, by X-ray topography. A visualization experiment of flow pattern in a melt was performed during Cz growth of Si, where the trace of tungsten particles in the melt was observed directly with X-ray radiography.¹⁶⁾

For a semiconductor a transmission threshold wavelength, λ_C, can be calculated with the certain band gap. The λ_C's at room temperature are roughly estimated as 1.1 μm for Si, 0.93 μm for InP, 0.87 μm for GaAs, 0.83 μm for CdTe, 0.55 μm for GaP, respectively. It is known that the λ_C shifts to a longer wavelength at high temperature. If a solid-liquid interface can be observed with infrared light from the solid phase side of the semiconductor, *in situ* observations of the solution growth processes become possible,^{17–19)} because the solutions, *e.g.*, Ga for GaAs, In for InP and Te for CdTe, reflect optically like metals. By utilizing the transparent properties of semiconductors for infrared radiation, the authors succeeded in directly observing the morphological changes of the solid-liquid interface during solution growth in high static magnetic field.

This optical system was adjusted to focus on the solid-liquid interface through the substrate placed inside the tube. The both of the fringe pattern and the bright field image could be observe simultaneously. The displacement of the S/L interface was measured by counting the amount of the interference fringe displacement on the facet region using an NIR microscopic interferometer. A 5 mW laser diode with wavelength of λ = 0.78 μm was used to a light source for the interferometer. The interference fringe pattern corresponds to contour lines with 0.120 μm in height difference of S/L interface at growth temperature.²⁰⁾ A typical image of the interference fringe pattern is shown in Fig. 2. The image beam reflected at the S/L interface was received by a CCD camera, and digitally calculated and recorded to a computer through an image processor. The substrate used for the experiment was sulfur-doped GaP crystals, 300 μm in thickness and ϕ7.8 mm, with orientations of (111)B ± 0.1. The quality of the observed image was strongly influenced by the optical transmittance of the seed crystal, and therefore the bottom of the substrate was

Fig. 2 Typical image of an interference fringe pattern on a growing facet region in a GaP(111)B crystal. The fringe pattern corresponds to contour lines with 0.120 μm in height difference.

lapped and polished mechanochemically as a mirror surface. LPE growth experiments were performed in a quartz glass ampoule consisting a graphite crucible, a GaP substrate and a Ga solvent. The radius and the length of the solution were 3.8 mm and 13 mm, respectively.

The dissolution and growth processes were carried out by linear heating and cooling methods with the rates of 0.5 K/min, respectively. The temperature range for the procedures was from 973 to 993 K. To sufficiently saturate the solute distribution in the liquid before growth was started, B₀ was held at 0 T for 2 h to stir the liquid with the help of the convective flow currents, and then at the target value of B₀ for an additional 2 h.

3. Results and Discussion

3.1 Estimation of Reynolds number in liquid

The influence of the buoyancy force on natural convection was studied by Camel and Favier using a scaling analysis.²¹⁾ Friedrich *et al.*²²⁾ modified the scaling analysis to estimate the fluid behavior on the centrifuge, where the centrifugal force and the Coriolis force were taken into account. In the present research, the scaling analysis was applied to the Navier-Stokes equation taking account of thermal convection and Lorenz force in axisymmetric flow and axial static magnetic fields based on the Friedrich's procedure.

The Navier-Stokes equation for an incompressible fluid in the Boussinesq approximation, the continuity equation, and the governing equations of heat and mass transport can be written with the aid of Ohm's law and the continuity of electric current density as follows:

$$(\partial \mathbf{u} / \partial t) + (\mathbf{u} \cdot \nabla) \mathbf{u} = -(1/\rho_0) \nabla P + \nu \nabla^2 \mathbf{u} + \mathbf{F}, \quad (1a)$$

$$\mathbf{F} = \{\beta(T - T_0) + \alpha(C - C_0)\} \mathbf{g} - (\sigma/\rho_0) \{\mathbf{j} \times \mathbf{B}\}, \quad (1b)$$

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}), \quad (2)$$

$$\mathbf{B} = (0, 0, B_0) \quad (3)$$

$$\nabla \cdot \mathbf{j} = 0 \quad (4)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (5)$$

$$(\partial T / \partial t) + \mathbf{u} \cdot \nabla T = \kappa \nabla^2 T, \quad (6)$$

$$(\partial C / \partial t) + \mathbf{u} \cdot \nabla C = D \nabla^2 C. \quad (7)$$

When the curl operators were applied to eqs. (1a) and (1b), the following equations for the steady state condition of the fields were derived:

$$\begin{aligned} \nu \nabla \times \{ \nabla \times (\nabla \times \mathbf{u}) \} \\ + \nabla \times \{ (\mathbf{u} \cdot \nabla) \mathbf{u} \} - \nabla \times \mathbf{F} = \mathbf{0}, \end{aligned} \quad (8a)$$

$$\begin{aligned} \nabla \times \mathbf{F} = \mathbf{g} \times (\beta \nabla T + \alpha \nabla C) \\ - (\sigma / \rho_0) \nabla \times \{ (\mathbf{u} \times \mathbf{B}) \times \mathbf{B} \}. \end{aligned} \quad (8b)$$

Here it has to be mentioned that $\mathbf{E}$ vanishes in eq. (8b) for axisymmetric flow and axial magnetic fields in an electrically-insulated growth ampoule,¹²⁾ because $\mathbf{E}$ satisfies Maxwell equations and the continuity condition derived from eq. (4) as follows:

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t = \mathbf{0}, \quad (9)$$

$$\nabla \cdot \mathbf{E} = 0. \quad (10)$$

The radius of the liquid phase, r , and the unknown velocity, u_r , were introduced as the characteristic length and flow velocity into eqs. (8a) and (8b). The differential operator, the flow velocity, the buoyancy and Lorentz forces, and the gravity vector were respectively normalized by the absolute values as follows:

$$\begin{aligned} (\nu u_r / r^3) \hat{\nabla} \times \{ \hat{\nabla} \times (\hat{\nabla} \times \hat{\mathbf{u}}) \} + (u_r^2 / r^2) \hat{\nabla} \times \{ (\hat{\mathbf{u}} \cdot \hat{\nabla}) \hat{\mathbf{u}} \} \\ - |\nabla \times \mathbf{F}| (\hat{\nabla} \times \hat{\mathbf{F}}) = \mathbf{0}, \end{aligned} \quad (11a)$$

$$\hat{\nabla} \equiv r \nabla, \quad \hat{\mathbf{u}} \equiv \mathbf{u} / u_r, \quad |\hat{\nabla}| = |\hat{\mathbf{u}}| = 1. \quad (11b)$$

The radius temperature and concentration gradients were assumed to be proportional to the product of the interface gradient against the growth direction, m , and the axial temperature and concentration gradients in the vicinity of the solid/liquid interface, G_T and G_C , respectively. Therefore, the following approximation were applied to the buoyancy term in eq. (8b):

$$|\mathbf{g} \times \nabla T| \approx m g_0 G_T, \quad |\mathbf{g} \times \nabla C| \approx m g_0 G_C. \quad (12)$$

The relative importance of the body forces on u_r in eq. (11a) can be given by the dimensional coefficients in front of the normalized vector terms which should be on the order of unit:

$$\begin{aligned} (\nu u_r / r^3) + (u_r^2 / r^2) \\ - m g_0 (\beta G_T + \alpha G_C) + (\sigma u_r B_0^2 / \rho_0 r) \approx 0. \end{aligned} \quad (13)$$

From eq. (13), Reynolds number, Re , was derived by Hartmann number, Ha , and thermal and solute Grashof numbers, Gr_T and Gr_S :

$$Re^2 + (1 + Ha^2) Re \approx |m (Gr_T + Gr_S)|. \quad (14)$$

The solution of eq. (14) for Re was given by:

$$Re \approx -(1 + Ha^2)/2 + \sqrt{(1 + Ha^2)^2/4 + |m (Gr_T + Gr_S)|}, \quad (15)$$

where the requirement $Re > 0$ was taken into consideration.

3.2 Vertical Bridgman growth

The influence of convection on the mass transport is usually evaluated with an effective segregation coefficient, K_{eff} , which is the ratio of the solute concentration in the solid, C_S , to that in the melt.^{23–26)} According to the model of Pfann,⁴⁾ C_S can be described as the following function of solidified fraction, f :

$$C_S = K_{\text{eff}} C_0 (1 - f)^{K_{\text{eff}} - 1}, \quad (16)$$

where C_0 : initial concentration in the liquid. If we want to produce a bulk crystal from melt whose concentration profile is homogeneous, K_{eff} should be changed from an equilibrium segregation coefficient, k_0 , to unit along the growth direction by means of damping or acceleration of the convection due to the external force.

According to the model of Ostrogorsky and Müller,²⁷⁾ the relation between K_{eff} and the segregation parameter, Δ , was:

$$K_{\text{eff}} = k_0 / \{1 - (1 - k_0) \Delta\}, \quad (17)$$

where (a) $\Delta = 1$: pure diffusive mass transport, and (b) $\Delta = 0$: complete mixing with strong convection. At low Gr_S and Gr_T , the normalized solute boundary layer thickness in the melt, X_C^* , can be regarded as a constant value, $2D/(rV_G)$ where V_G is the growth rate. Introducing of Schmidt number, Sc , Peclet number, Pe , X_C^* , and Re yields Δ as:²²⁾

$$\Delta = \{1 + Sc X_C^* Re / (6Pe)\}^{-1}, \quad (18)$$

where the velocity profile was approximated as linear. In the result, K_{eff} can be simply estimate from the experimental condition, the physical properties of the materials, and eqs. (15)–(18). It was assumed that k_0 was constant over the entire range of f .

Figure 3 shows the normalized solute concentration profiles in the grown crystals versus f in eq. (16) for Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$. The mass transport in Ge melt attained to the diffusive regime at $B_0 = 6$ T, whereas the transport was governed by strong mixing due to the convection at $B_0 = 0$ T. The Lorentz force in the Ge melt was thought to be obviously effective to damp the convection due to the weak buoyancy force and the large conductivity of the melt. On the other hand, the solute transport was strongly governed by the convection at $B_0 = 0$ T and 6 T for $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$, and therefore the Lorentz force in the melt was weak to damp the convective flow in contrast with the case of the Ga-doped Ge.

The calculated K_{eff} based on eqs. (15)–(18) was shown in Fig. 4, and we can see the values agreed well with the experimental ones which were calculated by the following equation:

$$K_{\text{eff}} = 1 - [(dC_S/df)/(2C_S)]_{f=0.5}. \quad (19)$$

Even if Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ crystals will be grown with the same experimental conditions shown in Table 1 in a low gravity environment, it will not so easy to realize a diffusive mass transport in the melts due to residual buoyancy convection in term of segregation in the grown crystals. Figure 5

Fig. 3 Normalized concentration profile in the crystal, C_s/C_0 , along the growth direction.

shows estimated K_{eff} for the materials as function of gravity acceleration without magnetic field, which was derived from eq. (14). An unmanned mission on a satellite ($\sim 10^{-6}g_0$) will be suitable for the Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ crystal growth experiments in diffusion-dominated.

3.3 LPE growth

The growing interface showed a convex shape toward the solution. The facet spread laterally as time went on, and at the same time small steps moved to the peripheral region of the seed crystal. The morphological change of the S/L interface was mainly observed and measured on the ellipsoidal facet region, which usually appeared at the center of the substrate after back-melting.

Danilewsky *et al.*²⁸⁾ reported the relationship between the dumping effect of convection and magnetic strength during solution growth in semiconductors determined by the traveling heater method (THM) through the estimation of critical thermal and solute Rayleigh numbers and observation of the striation on a grown crystal using an optical microscope. They pointed out that the convective flow changed from time-dependent to time-independent under an axial magnetic field

Fig. 4 Calculated K_{eff} as a function of magnetic induction, B_0 . The marks, $\bullet$ and $\circ$, correspond to the experimental values for 0.2 at% Ga-Ge and $\text{Pb}_{0.8}\text{Sn}_{0.2}\text{Te}$.

Fig. 5 Estimated K_{eff} as a function of gravity acceleration without a magnetic field.

of 0.44 T in Ga-Sb and Ga-As systems. Inatomi *et al.* reported the influence of vertical magnetic field of 0.44 T on THM growth rate on GaAs(111)B seed crystal¹⁸⁾ and that of horizontal magnetic field of 0.8 T on LPE growth rate on GaP(111)B substrate.²⁹⁾ Those magnetic induction were not enough to damp the convection, though behavior of convection might changed from time-dependent to time-independent.

We assumed that the influence of j in the crucible upon the distribution of E in the solution was negligible, because the electrical conductivity of the graphite ($9.1 \times 10^4 \Omega^{-1}\cdot\text{m}^{-1}$ at 293 K) was much lower than that of molten Ga ($3.4 \times 10^6 \Omega^{-1}\cdot\text{m}^{-1}$ at 1073 K). The term of solute convection in eq. (14) can be neglected for the growth, because the solution has the concentration of phosphorus less than 0.1 at% at 923 K³⁰⁾ and therefore the thermal convection was considered as a dominant flow. A hypothetical gravity level, $g_h = g/g_0$, in which Re was the same value as that in static magnetic

Fig. 6 Hypothetical gravity level, g_h , as a function of magnetic induction, B_0 .

induction B_0 , was estimated based on eq. (14) as shown in Fig. 6, where the calculated value of g_h approached that of Ha^{-2} asymptotically as the induction increased. When we assumed $g_h = 10^{-6}g_0$ as the same order of residual gravity level in an artificial satellite experiment, applying of magnetic induction of 6 T was expected to be enough to damp the convection as a near-diffusive mass transport state.

Since growth rate during LPE growth process are usually too small to consider the moving boundary condition at the S/L interface, a diffusion equation with no flow in a one-dimensional system where a liquid phase has a finite length can be described from eq. (7) as follows:

$$\partial C / \partial t = D \partial^2 C / \partial x^2. \quad (20)$$

We can assume that the mass flux of the solute atoms to the graphite crucible is negligible, and the concentration on the S/L interface is increased by linear-cooling method for growth as follows:

$$\partial C / \partial x|_{x=L} = 0, \quad \partial C / \partial x|_{x=0} \approx C_S V_G(t) / D, \quad (21a)$$

$$C(0, t) = C_0 - pt, \quad C(x, 0) = C_0, \quad (21b)$$

where p : (dC_e/dt) as a constant, and C_e : equilibrium concentration in the solution at the S/L interface, respectively. The displacement of the interface, $H(t)$, can be expressed as a Fourier series of time by solving eq. (20) with eqs. (21a) and (21b) as a similar way reported by Tiller,³¹⁾

$$H(t) = (Lp/C_S) \left[t + 2 \sum_{n=1}^{\infty} (L/a_n^4 D) \exp(-a_n^2 D t / L) \right], \quad (22)$$

$$a_n = (2n - 1)\pi/2.$$

The sign of p in eq. (22) for growth and dissolution were defined as positive and negative, respectively.

Figure 7 shows the dissolution and growth thickness of GaP(111)B as functions of time in 0 and 6 T. The curve fitting for the measured values was based on the least squares method. The curves of the both processes at 6 T were close to

Fig. 7 Displacement of S/L interface in a GaP(111)B crystal as a function of time.

Fig. 8 Bright field images of growing facet regions in a GaP(111)B crystals.

the calculated values based on eq. (22) with the parameters as $L = 13$ mm, $p = 6.8 \times 10^{21} \text{ m}^{-3} \cdot \text{s}^{-1}$, $C_S = 2.5 \times 10^{28} \text{ m}^{-3}$, and $D = 7.8 \times 10^{-10} \text{ m}^2/\text{s}$, whereas the values at 0 T clearly deviated from the calculated ones. A possible explanation for the difference between the growth and dissolution thickness at 6 T may be the existence of weak solute convection, because density of phosphorous ($2.4 \times 10^3 \text{ kg/m}^3$ at 293 K) has to be smaller than that of molten gallium ($5.9 \times 10^3 \text{ kg/m}^3$ at

298 K) at 1173 K. In contrast to the growth process the transport of phosphorous in the solution during dissolution process is considered to be unstable from a viewpoint of fluid dynamics due to the rejection of phosphorous from the solid-liquid interface. Gel'fgat and Gorbunov³²⁾ reported the possibility of additional forced thermoelectromagnetic (TEM) convection in semiconductor melt in a magnetic field with a sharp temperature gradient. The TEM convection, which is caused by coupling effect of temperature gradients in solid and liquid phases, and magnetic field, might be dominant flow at 6 T. We should also consider another possibility of surface kinetics influence on growth and dissolution rates.

During the growth, macrosteps and hexagonal-shaped hillocks generated at the dislocations in the substrate appeared at $B_0 = 0$ T. On the other hand, the large facet region with few macrosteps and hillocks was observed at 6 T as shown in Fig. 8. It was supposed that the morphology of the growth interface at 6 T was more stable than that at 0 T. The concentration and temperature gradients in the vicinity of the S/L interface might increased as the magnetic induction increased. Consequently, the constitutional supersaturation ahead of the interface, which is known as a driving force to make the morphology unstable, decreased as the magnetic induction increased.

4. Conclusions

In the present research, a formulation of the relation between static magnetic induction and Reynolds number in liquid, for vertical Bridgman and LPE growth processes of semiconductors in axial static magnetic field was derived based on a scaling analysis, and the validity of the estimation was experimentally investigated.

The calculated values of the effective segregation coefficients for Ga-doped Ge and $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ crystals grown by the Bridgman method agreed well with the experimentally measured ones from 0 to 6 T of the magnetic induction. The mass transport in Ge melt attained to the diffusive regime at $B_0 = 6$ T, whereas the transport was governed by strong mixing due to the convection at $B_0 = 0$ T. The Lorentz force in the Ge melt was thought to be obviously effective to damp the convection due to the weak buoyancy force and the large conductivity of the melt.

The *in situ* observation setup for solution growth of semiconductor was developed in static magnetic field up to 6 T. In case of LPE growth on GaP(111)B, nearly diffusion-controlled condition in the liquid was achieved at 6 T. The morphological change of GaP(111)B growth surface was measured directly by NIR microscopic interferometry. In the result, it was shown that static magnetic field reduced growth rate, and suppressed appearance of macrosteps and hillocks, because the morphology of the S/L interface was stabilized by damping of the convective flow due to the Lorentz force.

Nomenclature

- g vector of acceleration of gravity, $g_0 = |g| = 9.81 \text{ m/s}^2$
 g_h hypothetical low-gravity level
 t time

- P pressure
 T temperature
 κ thermal diffusivity
 ρ_0 density of solution at reference temperature
 D diffusion coefficient of solute atom
 σ electrical conductivity
 u flow velocity vector in liquid
 u_r characteristic velocity in liquid
 r radius of liquid phase
 B magnetic induction vector, $B_0 = |B|$
 E electric field vector
 j vector of electric current density
 α solute expansion coefficient
 β thermal expansion coefficient
 ν kinematic viscosity
 G_T axial temperature gradient in the vicinity of S/L interface
 G_C axial concentration gradient in the vicinity of S/L interface
 Δx_i maximum deviation of interface from planarity
 m gradient of S/L interface, $\Delta x_i/r$
 f solidified fraction
 k_0 segregation parameter
 K_{eff} effective segregation coefficient
 Δ segregation parameter
 V_G growth rate
 L initial length of liquid phase
 p (dC_e/dt) as a constant
 C_0 initial concentration in liquid
 C_e equilibrium concentration in solution at S/L interface
 C_s solute concentration in the solid
 $H(t)$ displacement of S/L interface
 X_C^* normalized solute boundary layer thickness in melt
 Pr Prandtle number, ν/κ
 Sc Schmidt number, ν/D
 Re Reynolds number, $u_r r/\nu$
 Ha Hartmann number, $B_0 r (\sigma/\rho_0 \nu)^{1/2}$
 Gr_T thermal Grashof number, $\beta G_T g_0 r^4/\nu^2$
 Gr_S solute Grashof number, $\alpha G_C g_0 r^4/\nu^2$
 Pe Peclet number, $V_G r/D$

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