

NASA-TN-112524

Reprinted from

11-76-711  
(C. W. M. J. D.)  
043 497

JOURNAL OF **CRYSTAL  
GROWTH**

---

Journal of Crystal Growth 167 (1996) 478–487

Magneto-hydrodynamic damping of convection during vertical  
Bridgman–Stockbarger growth of HgCdTe

D.A. Watring <sup>\*</sup>, S.L. Lehoczky

*Space Sciences Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA*

Received 3 April 1995; accepted 26 January 1996



ELSEVIER

# Journal of Crystal Growth

## EDITORIAL BOARD

M. SCHIEBER (Principal Editor)  
Dept. Mater. Sci., School Appl. Sci. & Technol.  
Hebrew University, Jerusalem 91904, Israel  
Telefax: +972-2-666 804

R. KERN  
CRMC<sup>2</sup>, CNRS, Campus Luminy, Case 913  
F-13288 Marseille Cedex 9, France  
Telefax: +33-91-418 916

R.S. FEIGELSON  
Ctr. Materials Res., 105 McCullough Bldg.  
Stanford Univ., Stanford, CA 94305-4045, USA  
Telefax: +1-415-723 3044

T. NISHINAGA  
Dept. Electron. Eng., Univ. of Tokyo  
7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan  
Telefax: +81-3-5684-3974

D.T.J. HURLE  
H.H. Wills Phys. Lab., Univ. Bristol  
Tyndall Avenue  
Bristol BS8 1TL, UK

G.B. STRINGFELLOW  
Dept. Mater. Sci., 304 EMRO, Univ. of Utah  
Salt Lake City, UT 84112, USA  
Telefax: +1-801-581 4816

## ASSOCIATE EDITORS

A. BARONNET (*Industrial, Biological, Molecular Crystals*)  
CRMC<sup>2</sup>, CNRS, Campus Luminy, Case 913  
F-13288 Marseille Cedex 9, France  
Telefax: +33-91-418 916

K.W. BENZ (*Microgravity, Electronic Materials*)  
Kristallographisches Inst., Universität  
Hebelstr. 25, D-79104 Freiburg, Germany  
Telefax: +49-761-203 4369

A.A. CHERNOV (*Kinetics of Crystallization, Protein Crystallization*)  
Inst. Crystallography, Acad. of Sciences  
Leninskii Prosp., Moscow 117333, Russian Fed.  
Telefax: +7-095-135 1011

A.Y. CHO (*Molecular Beam Epitaxy*)  
Room 1C-323, AT&T Bell Laboratories  
Murray Hill, NJ 07974-2070, USA  
Telefax: +1-908-582 2043

B. COCKAYNE (*IOCG News*)  
School of Metallurgy and Mater.  
Univ. Birmingham, P.O. Box 363, Edgbaston, Birmingham  
B15 2TT, UK  
Telefax: +44-121-471 2207

S.R. CORIELL (*Theory*)  
A153 Mater. Natl. Inst. of Standards & Technol.  
Gaithersburgh, MD 20899-0001, USA

D. ELWELL (*Priority Communications, Superconductivity*)  
Hughes Aircraft Company  
P.O. Box H, M/S A2408, 500 Superior Avenue  
New Port Beach, CA 92658-8908, USA  
Telefax: +1-714-759 2868

M.E. GLICKSMAN (*Solidification*)  
School of Eng., Mater. Eng. Dept., Rensselaer Polytechnic  
Inst., Troy, NY 12180-3590, USA  
Telefax: +1-518-276 8554

M.A.G. HALLIWELL (*X-ray Diffraction*)  
Philips Analytical X-ray, Lelyweg 1  
7602 EA Almelo, The Netherlands

T. HIBIYA (*Oxides, Melt Thermophysical Properties, Microgravity*)  
Fundamental Res. Labs., NEC CORPORATION  
34, Miyukigaoka, Tsukuba 305, Japan  
Telefax: +81-298-566 136

H. KOMATSU (*Proteins Molecular Crystallization, Growth from Solutions*)  
Inst. Mater. Res., Tohoku Univ.  
Katahira 2-1-1, Sendai 980, Japan  
Telefax: +81-22-215 2011

T.F. KUECH (*Thin Films and Electronic and Optical Devices*)  
Dept. Chem. Eng., Univ. Wisconsin-Madison  
Madison, WI 53706, USA  
Telefax: +1-608-265 3782

A. McPHERSON (*Protein Growth*)  
Dept. Biochemistry, Univ. of California  
Riverside, CA 92521, USA  
Telefax: +1-909-787 3790

P.A. MORRIS HOTSENPILLER (*Electrooptical Crystals, Book Reviews, Oxide Thin Films*)  
E.I. du Pont de Nemours & Co., Exp. Station  
Wilmington, DE 19888-0358, USA  
Telefax: +1-302-695 1664

J.B. MULLIN (*Semiconductors*)  
EMC, "The Hoo", Brockhill Road  
West Malvern, Worcs., WR14 4DL, UK  
Telefax: +44-1684-575 591

K. NAKAJIMA (*Liquid and Vapor Phase Epitaxy*)  
Integrated Mater. Lab., Fujitsu Labs. Ltd.  
Morinosato-Wakamiya 10-1, Atsugi 243-01, Japan  
Telefax: +81-462-48 3473

H. OHNO (*Epitaxy*)  
Research Inst. of Electrical Commun.  
Tohoku Univ., Sendai 980 77, Japan  
Telefax: +81-22-217 5553

K. PLOOG (*Molecular Beam Epitaxy*)  
Paul-Drude-Inst. für Festkörperelektronik  
Hausvogteiplatz 5-7, D-10117 Berlin, Germany  
Telefax: +49-30-203 77201

F. ROSENBERGER (*Protein Crystallization, Fluid Dynamics*)  
Center for Microgravity and Materials Research  
Univ. Alabama, Huntsville, AL 35899, USA  
Telefax: +1-205-895 6791

R.W. ROUSSEAU (*Solution Growth, Industrial Crystallization*)  
School of Chem. Eng., Georgia Inst. of Technol.  
Atlanta, GA 30332-0100, USA  
Telefax: +1-404-894 2866

K. SATO (*Biocrystallization and Organic Crystals*)  
Fac. Appl. Biol. Sci., Hiroshima Univ.  
Higashi-Hiroshima 724, Japan  
Telefax: +81-824-227 062

L.F. SCHNEEMEYER (*Superconductivity, Oxides, Novel Materials*)  
Room 1A-363, AT&T Bell Labs.  
Murray Hill, NJ 07974-2070, USA  
Telefax: +1-908-582 2521

D.W. SHAW (*Semiconductors, Epitaxy, Devices*)  
Texas Instruments Inc., P.O. Box 655936, MS 147  
Dallas, TX 75265, USA  
Telefax: +1-214-995 7755

I. SUNAGAWA (*Minerals*)  
3-54-2 Kashiwa-cho, Tachikawa-shi  
Tokyo 190, Japan  
Telefax: +81-425-35 3637

G. VAN TENDELOO (*Electron Microscopy, Fullerenes, Superconductivity*)  
University of Antwerp, RUCA  
Groenenborgerlaan 171, B-2020 Antwerp, Belgium  
Telefax: +32-3-2180 217

A.F. WITT (*Semiconductor Crystals*)  
Dept. of Metall. & Mater. Sci., Massachusetts  
Inst. of Technol., Cambridge, MA 02139, USA  
Telefax: +1-617-253 5827

A. ZANGWILL (*Theory (Epitaxy)*)  
School of Physics, Georgia Inst. of Technol.  
Atlanta, GA 30332, USA  
Telefax: +1-404-894 9958

### Scope of the Journal

Experimental and theoretical contributions are invited in the following fields: Theory of nucleation and growth, molecular kinetics and transport phenomena, crystallization in viscous media such as polymers and glasses. Crystal growth of metals, minerals, semiconductors, magnetics, inorganic, organic and biological substances in bulk or as thin films. Apparatus, instrumentation and techniques for crystal growth, and purification methods. Characterization of single crystals by physical and chemical methods.

### Abstracted/Indexed in:

Aluminium Industry Abstracts; Chemical Abstracts; Current Contents: Physical, Chemical and Earth Sciences; EI Compendex Plus; Engineered Materials Abstracts; Engineering Index; INSPEC; Metals Abstracts; Physics Briefs.

### Subscription Information 1996

Volumes 158-169 of Journal of Crystal Growth (ISSN 0022-0248) are scheduled for publication. (Frequency: semimonthly.) Prices are available from the publishers upon request. Subscriptions are accepted on a prepaid basis only. Issues are sent by SAL (Surface Air Lifted) mail wherever this service is available. Airmail rates are available upon request. Please address all enquiries regarding orders and subscriptions to:

Elsevier Science B.V., Order Fulfillment Department  
P.O. Box 211, 1000 AE Amsterdam, The Netherlands  
Tel: +31 20 485 3642; Fax: +31 20 485 3598

Claims for issues not received should be made within six months of our publication (mailing) date.

**US mailing notice** - Journal of Crystal Growth (ISSN 0022-0248) is published semimonthly by Elsevier Science B.V., Molenwerf 1, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Annual subscription price in the USA is US \$65.35 (valid in North, Central and South America only), including air speed delivery. Periodicals postage paid at Jamaica NY 11431. US postmasters: Send address changes to Journal of Crystal Growth, Publications Expediting, Inc., 200 Meacham Avenue, Elmont NY 11003. Airfreight and mailing in the USA by Publications Expediting.

Ⓜ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper)

PRINTED IN THE NETHERLANDS

North-Holland, an imprint of Elsevier Science



ELSEVIER

Journal of Crystal Growth 167 (1996) 478–487

JOURNAL OF  
**CRYSTAL  
GROWTH**

# Magneto-hydrodynamic damping of convection during vertical Bridgman–Stockbarger growth of HgCdTe

D.A. Watring<sup>\*</sup>, S.L. Lehoczky

*Space Sciences Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA*

Received 3 April 1995; accepted 26 January 1996

## Abstract

In order to quantify the effects of convection on segregation,  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  crystals were grown by the vertical Bridgman–Stockbarger method in the presence of an applied axial magnetic field of 50 kG. The influence of convection, by magneto-hydrodynamic damping, on mass transfer in the melt and segregation at the solid–liquid interface was investigated by measuring the axial and radial compositional variations in the grown samples. The reduction of convective mixing in the melt through the application of the magnetic field is found to decrease radial segregation to the diffusion-limited regime. It was also found that the suppression of the convective cell near the solid–liquid interface results in an increase in the slope of the diffusion-controlled solute boundary layer, which can lead to constitutional supercooling.

## 1. Introduction

For nearly four decades, the usefulness of applied magnetic fields in crystal growth from the melt has been recognized. The fundamental basis for the interaction between magnetic fields and convection was first discussed in Refs. [1–5]. The basic mechanism for the interaction of an applied magnetic field and a molten semiconductor involves the electrical currents induced by the movement of a conductor in the presence of a magnetic field. Early experiments by Utech and Flemings [6,7] investigated the effects of a magnetic field on tellurium-doped indium antimonide grown in a horizontal furnace by directional solidification. Their results indicated that vertical

magnetic fields of 1300 and 1750 G were sufficient to suppress turbulence in the melt. This eliminated the temperature fluctuations which caused melting and resolidification of the growth interface and an associated fluctuation in the dopant concentration in the crystal grown in zero field.

Temperature and solutal gradients in the melt during growth almost always result in buoyancy-driven convection. Frequently, this convective flow is oscillatory [8] and gives rise to a fluctuating rate of crystal growth, which, in turn, produces a microscopically non-uniform distribution of dopant in the crystal. The universal effect of an applied magnetic field is the damping of the convective turbulence in the melt, which produces a more homogenous dopant distribution [9–13].

The majority of the experimental studies with magnetic fields has been focused on the growth of GaAs, Si and Ge by the Czochralski growth process.

<sup>\*</sup> Corresponding author.



In these systems, small (2–5 kG) fields were applied to suppress turbulent convection. Limited work [6,12–16] has been conducted on the magnetic effects of crystal growth in a vertical Bridgman–Stockbarger configuration and out of these experiments only two involved the II–VI compounds of HgCdTe and HgZnTe.

The Hg-based II–VI semiconductor compounds are important for application of infrared detection and imaging applications for a broad range of wavelengths from 0.8  $\mu\text{m}$  to the far-infrared spectrum beyond 30  $\mu\text{m}$ . The crystal growth of these Hg-based II–VI systems is characterized by a destabilizing horizontal temperature gradient due to a difference in the thermal conductivities of the melt and the crystal at the growth interface in the presence of a containing crucible and the release of latent heat. Additionally, a stabilizing vertical solutal gradient is produced by the rejection of the denser constituent (HgTe in the case of HgCdTe) into the melt. These phenomena, coupled with a large solutal-to-thermal expansion coefficient ratio ( $\beta_c C_0 / \beta_l \Delta T_r \approx 100$ ) and a large thermal-to-solutal diffusion coefficient ratio ( $\alpha_T / D_L \approx 200$ ), give rise to double diffusive convection during the growth of these binary semiconductors, where  $\Delta T_r$  is the radial temperature difference,  $C_0$  is the starting composition,  $\beta_c$  and  $\beta_l$  are, respectively, the solutal and thermal expansion coefficients and  $\alpha_T$  and  $D_L$  are the thermal and solutal diffusion coefficients, respectively. If this buoyancy-induced convection is large as compared to the solidification velocity, it can interfere with segregation near the solid–liquid interface resulting in a non-homogenous crystal. It is believed that the reduction of convection should be advantageous in maintaining the solid–liquid interface shape required to minimize the crystal defect densities while minimizing compositional variation transverse to the crystal growth direction.

This paper focuses on the influence of the magnetic field on mass transfer in the melt and radial segregation at the solid–liquid interface. We begin with a description of the charge crucible configuration, followed by a brief discussion of the Bridgman–Stockbarger growth system used for the experiments. Results of the axial and radial compositional distributions with and without the presence of the magnetic field are, then, described.

## 2. Experimental procedure

### 2.1. Sample preparation

The starting materials were triple-distilled instrument grade Hg from Bethlehem Apparatus and six nines grade Cd and Te from Johnson Matthey. The ampoules were made from 8 mm ID  $\times$  12 mm OD commercial grade, T08, fused silica quartz. A tapered section was formed on the quartz ampoule to enhance the probability of single crystal growth. An internal layer of graphite was formed on the ampoule as described in Ref. [16] to prevent the adhesion of HgCdTe to the ampoule walls. The elements were weighed out for  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  ( $x = 0.2$ ), loaded into the ampoules and sealed off under a  $10^{-4}$  Torr vacuum. The  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  ingots were compounded by a homogenization process that has been described in detail elsewhere [16]. The formed ingots were 14 cm long and weighed approximately 47 g.

### 2.2. Directional solidification growth system

The ingots were regrown by directional solidification in the presence of a stationary axially aligned magnetic field as shown schematically in Fig. 1a. The Bridgman–Stockbarger crystal growth system consisted of five heated zones with the booster and cold zone separated by a 2 cm adiabatic zone. A 0.3 cm thick heat extraction plate was placed between the adiabatic zone and cold zone to produce high axial gradients. The ampoule was supported by an inconel 625 cartridge assembly shown in Fig. 1b and remained stationary during crystal growth. Translating the furnace instead of the cartridge minimized any movement and vibrations of the sample and allowed the crystallization to take place in the homogenous region of the magnetic field. The superconducting magnet is manually set to the desired field strength (up to 50 kG) and is held constant during the entire growth process. The thermal profile was chosen in order to produce a gradient of approximately 80°C/cm on the ampoule wall at the position of 706°C, the solidus temperature for the steady-state growth [17]. The thermal profile was translated at a relatively slow rate of 0.2  $\mu\text{m/s}$  in order to avoid constitutional supercooling [18].

### 2.3. Characterization

The effect of convection on segregation was determined by measuring radial and axial compositional variations in the grown crystals. For this study, the average  $x$  values ( $x$  is the mole fraction of CdTe) of wafers cut transverse to the growth direction were determined by high precision density determinations and the values of the crystal lattice constant published by Woolley and Ray [19] as described in detail elsewhere [20,21].

For  $x$  values of 0.18 or larger, the radial microdistribution of cadmium telluride was quantitatively determined from the transmission edge of the IR transmission spectrum. The details of this highly automated transmission-edge mapping technique are described in Ref. [22]. Briefly, the hardware consists of a Fourier transform spectrometer specially equipped with a software controllable  $xy$  stage driven by stepper motors. The stage can position the sample throughout a 2.54 cm square in 50  $\mu\text{m}$  steps. Spectra are then analyzed to obtain the cut-on wavelength

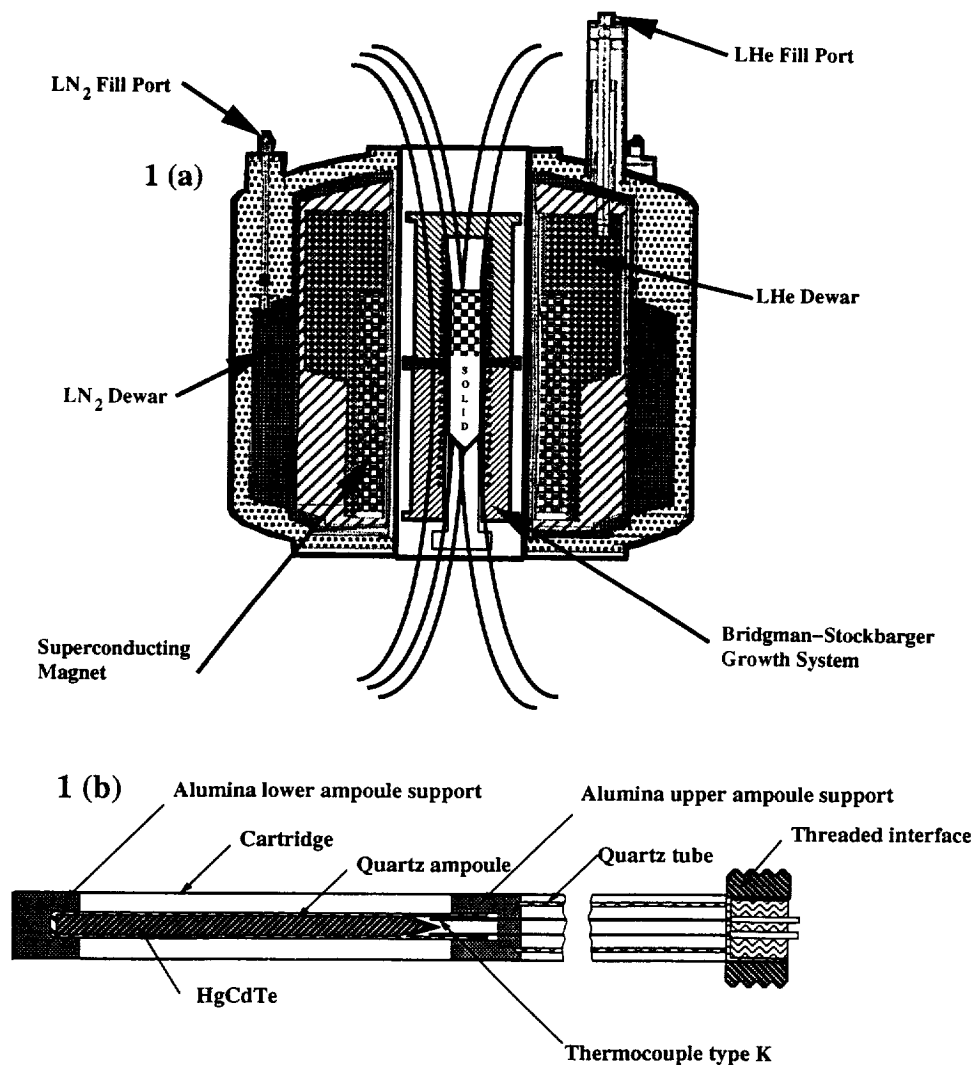


Fig. 1. (a) Schematic representation of the magnetic Bridgman-Stockbarger growth system. (b) Containment cartridge utilized for the magnetically stabilized growth of HgCdTe.

and the mole fractions of CdTe are calculated from the compositional dependence of the energy bandgap. For those samples with a cadmium telluride content of less than  $x = 0.18$ , the radial compositional variations were determined by energy dispersive X-ray spectroscopy analysis (EDX) using pseudo-binary solid solutions as standards [23].

### 3. Results and discussions

#### 3.1. Axial compositional distributions

Fig. 2 shows the limiting axial compositional distributions for directional solidified HgCdTe. The two experimental curves [21], illustrate the effects of varying translation rates. The translation rates for ingots MCT-L6 and MCT-L7 were 0.310 and 0.068  $\mu\text{m/s}$ , respectively. Solidification at the slower rate results in the build up of a much longer solute boundary layer. Hence, the stabilizing solutal forces are expected to be less during the growth. This reduced stabilizing force can lead to the increase of natural convective mixing, which results in a more uniform radial segregation. However, the axial com-

positional profile never reaches a steady-state value. Therefore, improved radial segregation is gained at the expense of less uniform axial composition. If the translation rate is increased, as in MCT-L6, shorter transients result in steady-state axial compositional distribution, but radial segregation increases by two orders of magnitude. These results are in qualitative agreement with the numerical calculations of Motakef [24,25]. His results indicate that radial segregation increases initially with decreasing Peclet mass transfer number reflecting the reduction in the mixing of the melt, which results in increased non-uniformity of melt composition at the growth interface. This suggests that improved material compositional uniformity requires sufficiently fast growth rates to produce short initial transients and a simultaneous reduction of radial segregation caused by convective effects.

Fig. 3 shows the axial compositional distribution profiles for two crystals: curve MCT-D2 was obtained for growth without a magnetic field and curve MCT-4 for growth with melt stabilization by a 50 kG axial magnetic field. The theoretical curve based on a one-dimensional diffusion equation is also shown.

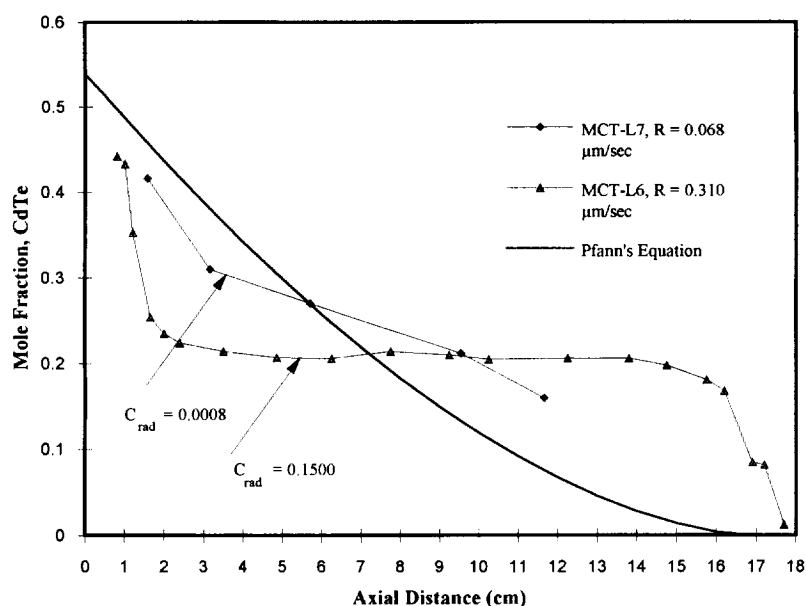


Fig. 2. Axial compositional limits of directional solidification for HgCdTe.

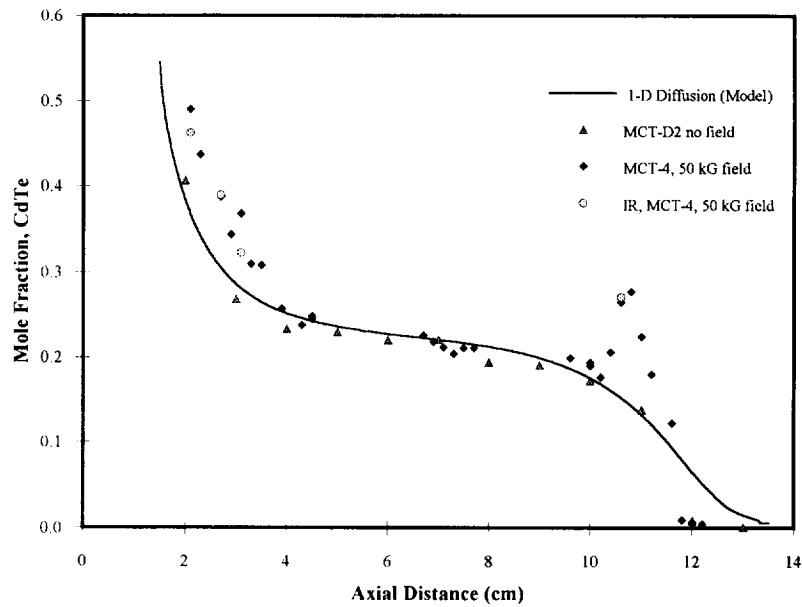


Fig. 3. Comparison of the experimental axial compositional distribution to the one-dimensional diffusion model.

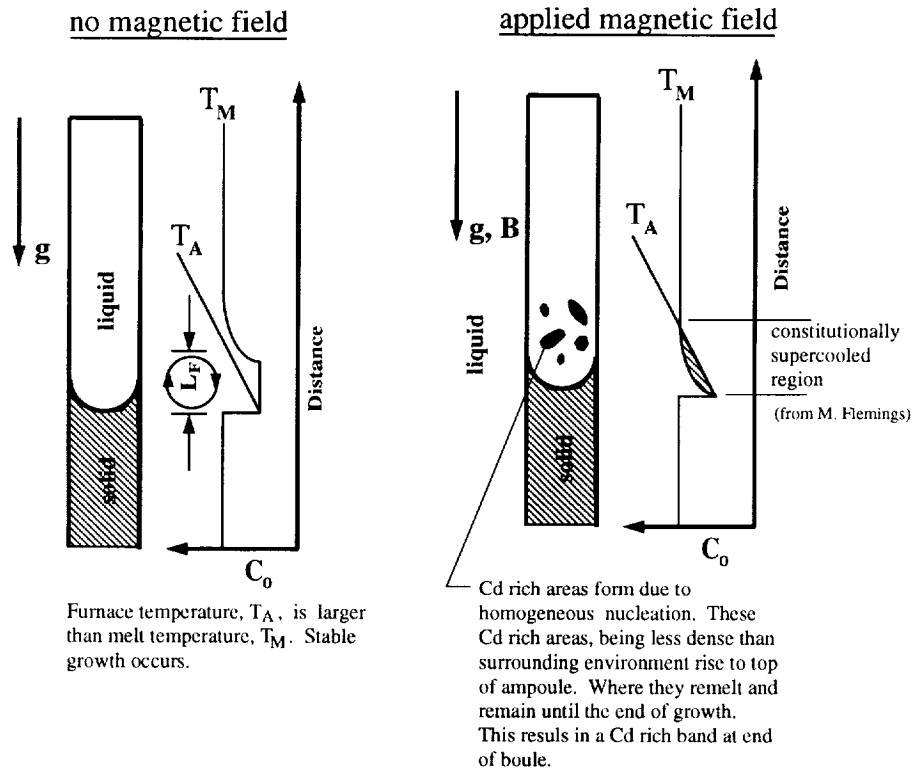


Fig. 4. Schematic representation of the convective melt flows and solute boundary layer configurations for directional solidification growth of HgCdTe with and without magnetic stabilization.



The curve for MCT-D2 indicates that, as expected, during solidification in zero field the distribution of CdTe undergoes an initial transient, then a steady-state region followed by a final transient. This compares well with the curve calculated from an exact numerical solution to the one-dimensional diffusion equation for an  $x = 0.2$  alloy [26,27]. The curve for MCT-4 (50 kG field) shows a similar initial transient and steady-state section. However, a sharp increase in the CdTe content is observed near the last-to-freeze end just before the final transient. To ensure that this rise was not due to measurement error, IR compositional measurements were taken at various axial locations. There was excellent agreement between the two measurement techniques, see Fig. 3. This rise in CdTe content may be explained by constitutional supercooling ahead of the interface. Fig. 4, shows a schematic of the convective melt flows and solute boundary layer configurations for the no-field and field cases. In the no-field case, a region with intense convection (as compared to the growth rate) caused by radial thermal gradients is assumed to occur between a bulk of diffusion-controlled melt and the growth interface as proposed by Kim and Brown [28] to explain axial segregation patterns seen in HgCdTe crystal growth experiments by Szofran and Lehoczky [29]. Hence, the axial temperature gradient in the melt is sufficient to avoid constitutional supercooling due to the flatness of the compositional profile and normal solidification proceeds. In the case of growth in the presence of a stabilizing magnetic field, the elimination or reduction of convection allows for the build up of the diffusion-controlled solute boundary layer closer to the solid–liquid interface. As the axial temperature gradient is held constant, this stiffer solutal boundary layer produces a region in the liquid ahead of the interface that is at an actual temperature below its equilibrium liquidus temperature. Accordingly, this can lead to homogeneous nucleation of solid-phase particles, richer in Cd (higher  $x$ ) than the bulk melt, which float upwards because their densities are less than those of the melts. This phenomenon of buoyant rising of solid particles, or Stokes migration, has been observed during vertical Bridgman–Stockbarger growth experiments of HgCdTe [30,31] and HgCdSe [32] and is consistent with the results from the growth of the MCT-4 ingot. Conclusive evidence

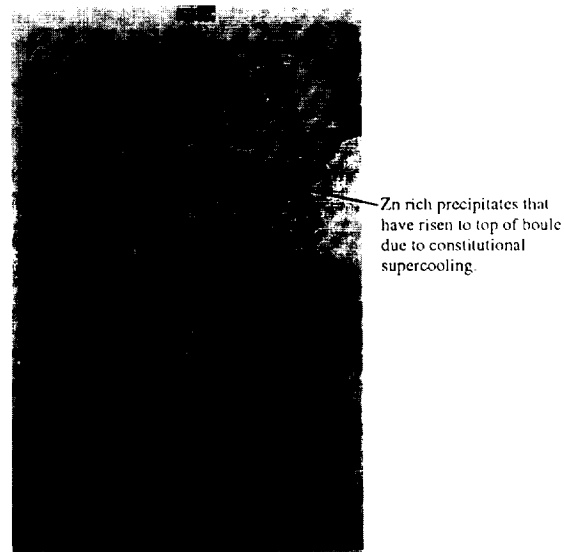


Fig. 5. Back-scatter micrograph of a quenched HgZnTe ingot showing Zn-rich precipitates that have migrated to the top of the boule due to Stokes migration brought about by constitutional supercooling [33].

of this phenomenon is demonstrated in Fig. 5, which illustrates a back-scattering electron micrograph of a quenched HgZnTe ingot grown by Lehoczky et al. [33]. It clearly shows Zn-rich precipitates that have migrated to the top of the boule due to Stokes migration resulting from constitutional supercooling.

### 3.2. Radial compositional distributions

#### 3.2.1. Radial segregation: initial transients

Fig. 6 shows the radial compositional variations for wafers 2.5 cm from the first-to-freeze portion of ingots MCT-D2 (zero field) and MCT-4 (50 kG field) as determined by IR transmission-edge measurements. The pattern of low Cd content at the center (high Hg content) and high Cd content along the edge of wafer #2.2, prepared from the MCT-D2 ingot, is consistent with other results obtained previously in the absence of a magnetic field. As noted earlier, the vertical directional solidification of Hg-based II–VI systems is characterized by double diffusive convection and a concave (toward the solid) growth interface. Thus, the denser Hg-rich melt tends to accumulate at the center of the crucible resulting in the radial compositional profile shown in Fig. 6a.

Fig. 6b shows the radial profile for growth in the presence of the stabilizing magnetic field. The order of magnitude improvement in radial homogeneity clearly indicates that the magnetic field was efficacious in suppressing convective effects on segregation. Fig. 6c shows the composition variation across the diameter of the two samples. Compositional variations in other wafers in the initial transient region show similar behavior.

### 3.2.2. Radial segregation: steady-state region

In an effort to quantify the effects of the magnetic field on the radial segregation, the experimental results were compared to the analysis of the lateral solute segregation associated with a curved solid–liquid interface during steady-state unidirectional solidification of a binary alloy as derived by Coriell and Sekerka and described in detail in Ref. [34].

Briefly, they solved the species continuity equation for the radial solute concentration in the solid crystal at the solid–liquid interface with the assumptions of no convection in the liquid and that the solid–liquid interface could be represented by a Fourier series. Their work showed that in the limiting case, the transverse segregation in the solid is proportional to the deviation of the interface from planarity, the proportionality factor being just the product of the unperturbed concentration gradient and the distribution coefficient given by

$$\Delta C/C_0 = (k - 1)(R/D_L)\Delta\zeta, \quad (3.1)$$

where  $\Delta C$  is the difference in composition at the edge and center of the wafer,  $k$  is the equilibrium segregation coefficient,  $R$  is the translation rate and  $\Delta\zeta$  is the interface deflection. These calculations are applicable for crystal growth in a stabilizing mag-

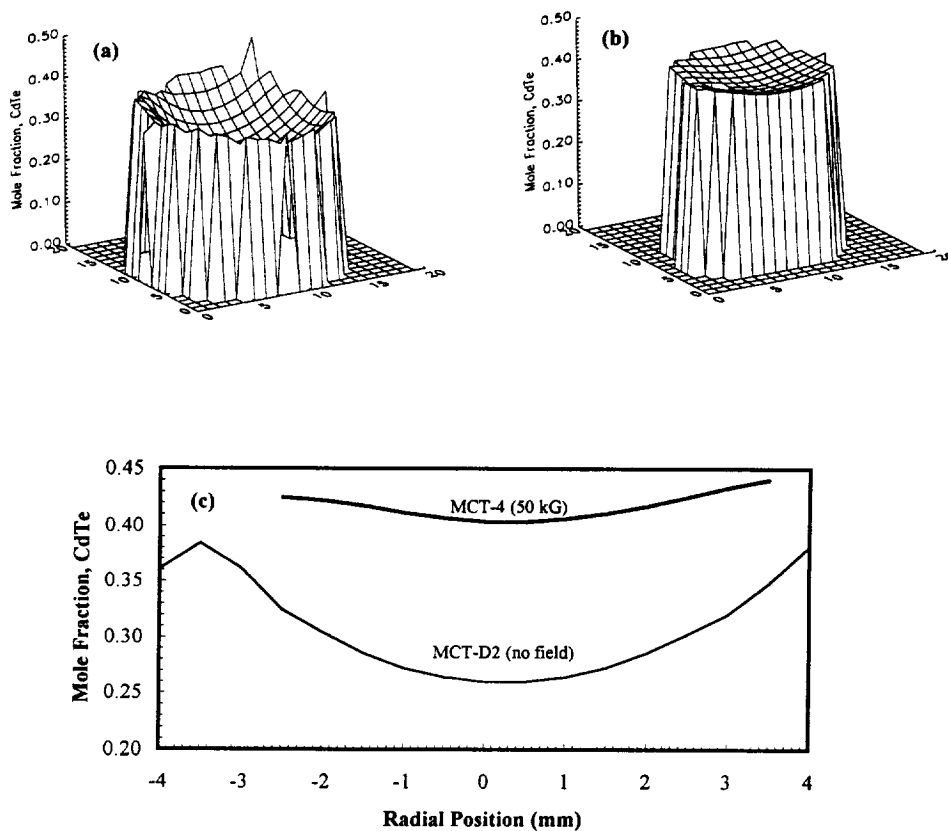
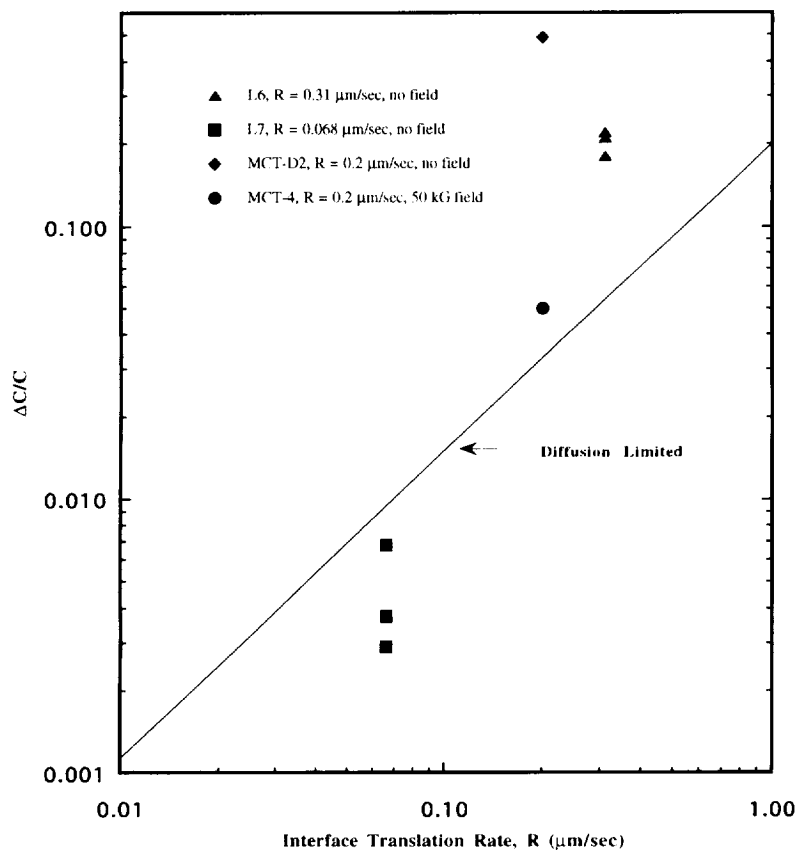


Fig. 6. Compositional profiles for (a) MCT-D2 (wafer #2.2) 2.5 cm from first to freeze, grown without a magnetic field, (b) MCT-4 (wafer #4) 2.5 cm from first to freeze, grown with a 50 kG stabilizing magnetic field and (c) comparison of radial profiles.

netic field where the field strength is sufficient to suppress convection. The solid–liquid interface deflection necessary for the calculations was determined experimentally by quenching samples with and without a magnetic field. The quenched interface obtained in the presence of a magnetic field was symmetric about the growth axis and had a maximum deflection (concave toward the solid) of 1.1 mm, which was a factor of 3 less than that obtained without the magnetic field. Similar effects on the solid–liquid interface were found in gallium-doped germanium grown in the presence of a 30 kG axial magnetic field [35].

Fig. 7 shows a comparison of the experimental and the calculated diffusion-limited radial segregation, where the diffusion-limited regime was determined by varying the translation rate in Eq. (3.1).

For this calculation, the steady-state equilibrium segregation coefficient,  $k = 4.2$ , was determined experimentally by measuring the compositional change across a quenched interface in the steady-state region of crystal growth. The mass diffusion coefficient,  $D_L = 5.5 \times 10^{-5} \text{ cm}^2/\text{s}$ , was determined by a best fit of the experimental axial composition data to the one-dimensional diffusion-limited model of Clayton et al. [36] and is consistent with the value obtained by Lehoczky et al. [21]. The figure summarizes previous data for MCT-L6 and MCT-L7, as well as, the data from MCT-D2 and MCT-4. The multiple data points for MCT-L6 and MCT-L7 are for three wafers analyzed in the steady-state region and are described in Ref. [21]. The comparison of the various experimental and calculated results strongly suggest nearly diffusion-limited growth and, thus, signifi-



cantly improved compositional homogeneity can be obtained with magnetically stabilized Bridgman–Stockbarger growth systems.

#### 4. Conclusions

An axial magnetic field was applied during crystal growth experiments in order to damp the velocity of the melt via magneto-hydrodynamic interactions. The resulting reduction in convection significantly altered the overall mass transfer and redistribution process. The primary influence of convection on mass transfer in the melt and segregation at the solid–liquid interface can be summarized as follows:

(1) The axial compositional distribution was relatively unaffected during the initial transient and steady-state growth portions of the solidification process. An abrupt rise in the CdTe content was observed near the end of the ingot and has been attributed to constitutional supercooling brought about by the magnetic suppression of convection near the solid–liquid interface, which results in an increase in the slope of the diffusion-controlled solute boundary layer.

(2) In conventional growth, the Hg-based II–VI systems are characterized by double diffusive convection and a concave growth interface. This results in the accumulation of Hg-rich material at the center of the melt just ahead of the growth interface, which in turn increases the interface curvature because of the nature of the HgTe–CdTe pseudo-binary phase diagram. These effects tend to enhance the radial segregation.

(3) For growth in a 50 kG magnetic field, the convection intensity was sufficiently damped, which allowed the interface curvature and radial composition to approach diffusion-limited growth conditions.

It should be remarked that the present study indicates that the interaction of the thermal, solutal and momentum fields in HgCdTe systems are highly coupled. The modification of these complex interactions, through, for example, the application of a magnetic field can significantly alter the interface morphology and compositional homogeneity. Therefore, any attempts at modeling these systems should involve the fully coupled form of the governing equations.

#### Acknowledgements

The investigation was supported by the Microgravity Science and Applications Division of NASA. The authors wish to thank Mr. Curtis Bahr, Mr. Rens Ross, Mr. Leroy Mullaley and Mr. Don Lovell for their invaluable technical assistance in the experimental portion of this work. The authors are also indebted to Dr. Gillies, Su, Szofran, Volz and Motakef for their helpful discussions and suggestions during the characterization portion of this work.

#### References

- [1] S. Chandrasekhar, *Hydrodynamics and Hydromagnetic Stability* (Clarendon, Oxford, 1961).
- [2] W.B. Thomson, *Philos. Mag.* 42 (1951) 1417.
- [3] B. Lehnert and N.C. Little, *Tellus* 9 (1957) 97.
- [4] G.Z. Gershuni and E.M. Zhukhovitskii, *Zh. Eksperim. Teor. Fiz.* 34 (1958) 465.
- [5] H.P. Utech and J.G. Early, *Acta Met.* 15 (1967) 1238.
- [6] H.P. Utech and M.C. Flemings, *J. Appl. Phys.* 37 (1966) 2021.
- [7] H.P. Utech and M.C. Flemings, in: *Crystal Growth*, Ed. H.S. Peiser (Pergamon, Oxford, 1967) p. 651.
- [8] J.-C. Han, S. Motakef and P. Becla, *J. Mater. Process. Manufactur. Sci.* 1 (1992) 195.
- [9] W.W. Fowles, *Low Gravity Sciences*, Vol. 67, Science and Technology Series (1987).
- [10] R.W. Series and D.T.J. Hurle, *J. Crystal Growth* 113 (1990) 305.
- [11] D.T.J. Hurle and J.D. Hunt, *The Solidification of Metals*, ISI P110 (Iron and Steel Institute, 1968) p. 162.
- [12] K.M. Kim, *J. Electrochem. Soc.* 129 (1982) 427.
- [13] D.H. Matthiesen, M.J. Wargo, S. Motakef, D.J. Carlson, J.S. Nakos and A.F. Witt, *J. Crystal Growth* 85 (1987) 557.
- [14] S. Sen, R. Lefever and W. Wilcox, *J. Crystal Growth* 43 (1978) 526.
- [15] C.-H. Su, S.L. Lehoczy and F.R. Szofran, *J. Crystal Growth* 109 (1991) 392.
- [16] C.H. Su, S.L. Lehoczy and F.R. Szofran, *J. Appl. Phys.* 60 (1986) 3777.
- [17] F.R. Szofran and S.L. Lehoczy, *J. Electron. Mater.* 10 (1981) 1131.
- [18] J.W. Rutter and B. Chalmers, *Can. J. Phys.* 31 (1953) 15.
- [19] J.C. Woolley and B. Ray, *J. Phys. Chem. Solids* 13 (1960) 151.
- [20] H.A. Bowman and R.M. Schoonover, *J. Res. Natl. Bur. Std. (US)* 71C (1967) 179.
- [21] S.L. Lehoczy, F.R. Szofran and B.G. Martin, *Advanced Methods for Preparation and Characterization of Infrared Detector Materials*, Part I, NASA CR-161598 (1980).
- [22] F.R. Szofran, G.L.E. Perry and S.L. Lehoczy, *J. Crystal Growth* 86 (1988) 20.

- [23] D.C. Gillies, *J. Electron. Mater.* 11 (1982) 689.
- [24] S. Motakef, *J. Crystal Growth* 102 (1990) 197.
- [25] S. Motakef, *J. Crystal Growth* 104 (1990) 833.
- [26] J.C. Clayton, *Transient and Diffusion Analysis of HgCdTe*, NASA CR-162049, 1982.
- [27] J.C. Clayton, M.C. Davidson, D.C. Gillies and S.L. Lehoczy, *J. Crystal Growth* 60 (1982) 374.
- [28] D.H. Kim and R.A. Brown, *J. Crystal Growth* 96 (1989) 609.
- [29] F.R. Szofran and S.L. Lehoczy, *J. Crystal Growth* 70 (1984) 349.
- [30] C.H. Su, G.L.E. Perry, F.R. Szofran and S.L. Lehoczy, *J. Crystal Growth* 91 (1988) 20.
- [31] F.R. Szofran, D. Chandra, J.-C. Wang, E.K. Cothran and S.L. Lehoczy, *J. Crystal Growth* 70 (1984) 343.
- [32] C.R. Whitsett, J.G. Broerman and C.J. Summers, *Semicond. Semimet.* 16 (1981) 53.
- [33] S.L. Lehoczy, F.R. Szofran, D.C. Gillies, S.D. Cobb, C.-H. Su, Y.-G. Sha and R.N. Andrews, *NASA Conf. Publ.* 3272, Vol. I (1994) pp. 163–222.
- [34] S.R. Coriell and R.F. Sekerka *J. Crystal Growth* 46 (1979) 479.
- [35] D.H. Matthiesen et al., *J. Crystal Growth* 85 (1987) 557.
- [36] J.C. Clayton, M.C. Davision, D.C. Gillies and S.L. Lehoczy, *J. Crystal Growth* 60 (1982) 374.



# Journal of Crystal Growth

## Instructions to Authors (short version)

### Submission of papers

Manuscripts (one original + two copies), should be sent to a member of the Editorial Board or preferably to an appropriate subject Associate Editor. Priority communications should be sent to D. Elwell. News or announcements should be submitted through the Principal Editor; a duplicate should be sent directly to Elsevier Science B.V., address given below.

*Original material.* Submission of a manuscript implies it is not being simultaneously considered for publication elsewhere and that the authors have obtained the necessary authority for publication.

### Types of contributions

Original research papers, Letters to the Editors and Priority communications are welcome. They should contain an Abstract (of up to 200 words) and a Conclusions section, which particularly in the case of theoretical papers translates the results into terms readily accessible to most readers.

As a guideline: *experimental papers* should not be longer than 16 double-spaced typed pages, and 8 figures + tables; for *theoretical papers* a maximum of 20 pages and 10 figures + tables is suggested.

*Letters and Priority communications* should not be longer than 5 double-spaced typed pages, and 3 figures + tables. They will be given priority in both the refereeing and production processes. The faster production schedule may preclude sending proofs of Letters and Priority communications to authors.

### Manuscript preparation

Contributions may be written in English, French or German. They should have an abstract in English. The paper copies of the text should be prepared with double line spacing and wide margins, on numbered sheets.

*Structure.* Please adhere to the following order of presentation: Article title, Author(s), Affiliation(s), Abstract, PACS codes and keywords, Main text, Acknowledgements, Appendices, References, Figure captions, Tables.

*Corresponding author.* The name, complete postal address, telephone and fax numbers and the e-mail address of the corresponding author should be given on the first page of the manuscript.

*Classification codes/keywords.* Please supply one to four classification codes (PACS and/or MSC) and up to six keywords of your own choice that describe the content of your article in more detail.

*References.* References to other work should be consecutively numbered in the text using square brackets and listed by number in the Reference list. Please refer to the more detailed instructions for examples.

### Illustrations

Illustrations should also be submitted in triplicate: one master set and two sets of copies. The *line drawings* in the master set should be original laser printer or plotter output or drawn in black india ink, with careful lettering, large enough (3–5 mm) to remain legible after reduction for printing. The *photographs* should be originals, with somewhat more contrast than is required in the printed version. They should be unmounted unless part of a composite figure. Any scale markers should be inserted on the photograph itself, not drawn below it.

*Colour plates.* Figures may be published in colour, if this is judged essential by the Editor. The Publisher and the author will each bear part of the extra costs involved. Further information is available from the Publisher.

### After acceptance

*Important.* When page proofs of the accepted manuscripts are made and sent out to authors, this is in order to check that no undetected errors have arisen in the typesetting (or file conversion) process. At the proof stage only printer's errors may be corrected. No changes in, or additions to, the edited manuscript will be accepted.

*Notification.* The authors will receive the final answer of acceptance or rejection from the Office of the Principal Editor and will be invited to supply an electronic version of the accepted text, if this is not already available.

*Copyright transfer.* In the course of the production process you will be asked to transfer the copyright of the article to the Publisher. This transfer will ensure the widest possible dissemination of information.

### Electronic manuscripts

The Publisher welcomes the receipt of an electronic version of your accepted manuscript. If there is not already a copy of this (on diskette) with the journal editor at the time the manuscript is being refereed, you will be asked to send a file with the text of the accepted manuscript directly to the Publisher by e-mail or on diskette (allowed formats 3.5" or 5.25" MS-DOS, or 3.5" Macintosh) to the address given below. (When e-mailing a non-ASCII word-processor file, you should encode it, e.g. with UUEncode or BinHex, so as to retain all formatting codes.) The name and version of the word-processing program and the type of operating system should always be indicated. Please note that no deviations from the version accepted by the Editor of the journal are permissible without the prior and explicit approval by the Editor. Such changes should be clearly indicated on an accompanying printout of the file.

### Author benefits

*No page charges.* Publishing in Journal of Crystal Growth is free.

*Free offprints.* The corresponding author will receive 50 offprints free of charge. An offprint order form will be supplied by the Publisher for ordering any additional paid offprints.

*Discount.* Contributors to Elsevier Science journals are entitled to a 30% discount on all Elsevier Science books.

### Further information (after acceptance)

Elsevier Science B.V., J. Crystal Growth  
Issue Management Physics  
and Materials Science  
P.O. Box 2759, 1000 CT Amsterdam  
The Netherlands  
Fax: +31 20 485 2319/+31 20 485 2704  
E-mail: matsci-de-f@elsevier.nl

