ICCG-16 ABSTRACT

Meniscus Shapes in Detached Bridgman Growth

M. P. Volz\textsuperscript{a}, K. Mazuruk\textsuperscript{b}

\textsuperscript{a}NASA, Marshall Space Flight Center, EM30, Huntsville, AL 35812, USA
\textsuperscript{b}University of Alabama in Huntsville, Huntsville, AL 35762, USA

Abstract

In detached Bridgman crystal growth, most of the melt is in contact with the ampoule wall, but the crystal is separated from the wall by a small gap, typically 1-100 micrometers. A liquid free surface, or meniscus, bridges across this gap at the position of the melt-crystal interface. Meniscus shapes have been calculated for the case of detached Bridgman growth in cylindrical ampoules by solving the Young-Laplace equation. Key parameters affecting meniscus shapes are the growth angle, contact angle of the meniscus to the ampoule wall, the pressure differential across the meniscus, and the Bond number, a measure of the ratio of gravitational to capillary forces. In general, for specified values of growth and contact angles, solutions exist only over a finite range of pressure differentials. For intermediate values of the Bond number, there are multiple solutions to the Young-Laplace equations. There are also cases where, as a function of pressure differential, existence intervals alternate with intervals where no solutions exist. The implications of the meniscus shape calculations on meniscus stability are discussed.
Meniscus Shapes in Detached Bridgman Growth

M. P. Volz\textsuperscript{a}, K. Mazuruk\textsuperscript{b}

\textsuperscript{a}NASA, Marshall Space Flight Center, EM31, Huntsville, AL 35812, USA
\textsuperscript{b}University of Alabama in Huntsville, Huntsville, AL 35762, USA
▶ Introduction to detached growth
▶ Experimental results
▶ Detached growth theory
▶ Calculation of meniscus shapes
  - Large Bond numbers $> O(1)$
  - Small Bond numbers $\sim O(10^{-6})$, microgravity case
  - Intermediate Bond numbers
▶ Conclusions
Principles of Detached Bridgman Growth

Sufficient condition for detachment\(^1,2\):
\[ (\alpha + \theta \geq 180^\circ) \]

Advantages
- No sticking of the crystal to the ampoule wall
- Reduced stress
- Reduced dislocations
- No heterogeneous nucleation by the ampoule
- Reduced contamination


Growth Angle and Wetting Angle

Growth angle $\alpha$:

$$\alpha = \arccos \left( \frac{\gamma_{sg}^2 + \gamma_{lg}^2 - \gamma_{sl}^2}{2 \cdot \gamma_{sg} \cdot \gamma_{lg}} \right)$$


Wetting angle $\theta$:

$$\theta = \arccos \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}}$$

(Young equation)

$\gamma_{lg}$: surface energy liquid-gas
$\gamma_{sl}$: surface energy solid-liquid
$\gamma_{sg}$: surface energy solid-gas
Gas Pressure Below Meniscus

Higher pressure below the meniscus by active pressurization

Higher pressure below the meniscus by temperature reduction above the melt

Higher pressure below the meniscus due to segregation at the interface


The gas volumes above the melt and below the meniscus are connected

⇒ $p_2 = p_1$

no pressure difference possible
Growth with Forced Pressure Difference

**T-Profile a)**
\( (p_1=p_2) \)
- Melting of feed material \( (p_1=p_2) \)
- \( \text{T-Profile b)} \)
\( (p_1<p_2) \)
- Translation \( (p_1<p_2) \)

**Diagram:**
- \( T \text{[°C]} \)
  - 750
  - 900
  - 1050
  - 1100
  - 1150
- Distance [mm]
  - 0
  - 50
  - 100
  - 150
  - 200
  - 250
  - 300

- \( p_1 < p_2 \) (red line)
- \( p_1 = p_2 \) (black line)

- **Components:**
  - fused silica
  - graphite ring
  - pBN
  - Ge
  - Si
  - interface
  - graphite
For Ge in an open pBN ampoule, a pressure difference sufficient for detachment cannot develop.
For Ge in a closed pBN ampoule, enough pressure develops in the gap to produce detachment.
Effect of Open Bottom pBN Ampoule (GeSi)

Fig. 1. Experimental system: (a) growth configuration; (b) ampoule with silica crucible; (c) ampoule with pBN insert.
Ge Grown in pBN ampoules

Fig. 5. Micrograph from the detached-grown sample UMC7 and from the attached-grown sample UMC6.
Fig. 6. Localized increased EPD after the crystal attaches partially to the wall.

X-Ray Synchrotron Topography of Detached Ge

220 reflection topograph (\(l = 0.69 \text{ Å}\)) recorded from a detached-grown UMC3 crystal wafer cut parallel to the growth axis (S – scratch, SB – subgrain boundary, D – dislocation).

Fig. 2. Schematic diagram of detached solidification.

\[ \Delta P_o = P_{\text{cold}} - P_{\text{hot}} - h_{\text{pg}} \]

Mathematical Formulation

\[ \frac{d^2 z}{dr^2} + \frac{dz}{dr} \left( 1 + \left( \frac{dz}{dr} \right)^2 \right)^{3/2} \left( 1 + \left( \frac{dz}{dr} \right)^2 \right)^{1/2} \Delta P \quad Bz(r) \]

\[ \Delta P = \frac{\Delta P_m r_0}{\gamma}, \quad \Delta P_m = P_{\text{top}} - P_{\text{bottom}} + \rho g H \]

\[ B = \frac{\rho g_0 r_0^2}{\gamma} \]

\[ B = 3.248; \text{Ge, } r_0 = 6 \text{ mm} \]

\[ B = 4.651; \text{InSb, } r_0 = 5.5 \text{ mm} \]

\[ \frac{\partial r}{\partial s} = \cos \beta, \quad \frac{\partial z}{\partial s} = \sin \beta, \quad \frac{\partial \beta}{\partial s} = -\frac{\sin \beta}{r} + \Delta P - Bz \]

Set of 3 coupled differential equations

Boundary Conditions

\[ z(0) = 0; \quad \beta(0) = 90^\circ - \alpha; \]

\[ \beta(1) = \theta - 90^\circ; \quad r(1) = 1 \]

\[ \alpha: \text{growth angle} \]

\[ \theta: \text{contact or wetting angle} \]
Gap Width vs. Pressure Differential

\[ \theta + \alpha < 180^\circ \]

\[ \theta + \alpha > 180^\circ \]

\( \alpha = 14.3^\circ \)

\( B = 3.248 \)

\( \theta = 140^\circ \)

\( \theta = 152^\circ \)

\( \theta = 164^\circ \)

\( \theta = 172^\circ \)
Meniscus Shapes for several Contact Angles

\[ \Delta P = 2.0 \]

\[ \alpha = 14.3^\circ \]

\[ B = 3.248 \]
Meniscus Shapes vs. $\Delta P$ for $\theta = 140^\circ$

$\alpha = 14.3^\circ$

$B = 3.248$

$z$

$r$
Gap Width vs. Pressure Differential ($g = 1 \times 10^{-6} g_0$)

$\theta + \alpha < 180^\circ$  \(\leftarrow\)  $\theta + \alpha > 180^\circ$

$\alpha = 14.3^\circ$

$B = 3.248 \times 10^{-6}$

$r$

$\Delta P$

- $\theta = 140^\circ$
- $\theta = 152^\circ$
- $\theta = 164^\circ$
- $\theta = 172^\circ$
Evolution of Meniscus Shapes ($\theta = 172^\circ$; $g = 1 \times 10^{-6} g_0$)

$\alpha = 14.3^\circ$

$B = 3.248 \times 10^{-6}$

$\theta = 172^\circ$ ($\theta + \alpha > 180^\circ$)
Evolution of Meniscus Shapes ($\theta = 140^\circ; \quad g = 1 \times 10^{-6} \quad g_0$)

\[ \alpha = 14.3^\circ \]

\[ B = 3.248 \times 10^{-6} \]

\[ \theta = 140^\circ \quad (\theta + \alpha < 180^\circ) \]
Gap Width vs. $\Delta P$ (Intermediate Bond Number)

$\theta + \alpha > 180^\circ$

$\theta = 172^\circ$
$\alpha = 14.3^\circ$
$B = 0.1$
Meniscus Shapes (Intermediate Bond Number)

\[ \theta = 172^\circ, \alpha = 14.3^\circ, B = 0.1 \]

\[ \Delta P = 1.4 \]

\[ \Delta P = 2.0 \]

\[ \Delta P = 2.3 \]

\[ \Delta P = 2.9 \]
Gap Width vs. $\Delta P$ (Intermediate Bond Number)

- $\theta = 164^\circ$
- $\alpha = 14.3^\circ$
- $B = 0.1$
Meniscus Shapes (Intermediate Bond Number)

\[ \theta = 164^\circ, \alpha = 14.3^\circ, \Delta P = 1.75, B = 0.1, \alpha + \theta < 180^\circ \]
Conclusions

- Meniscus shapes in detached Bridgman growth are determined by the growth and contact angles, the pressure differential, and the Bond number.
- Whether $\theta + \alpha$ is less than or greater than $180^\circ$ is the determining factor in whether menisci exist at large positive or negative pressure differentials.
- Gap widths have been determined as a function of $\Delta P$ for several values of $\alpha$, $\theta$, and $B$.
- The largest gap widths are obtained, in general, when $\Delta P$ is on the order of $\gamma/r_0$.
- The existence of the calculated meniscus shapes will depend on both their static and dynamic stability.