Shape Evolution of Detached Bridgman Crystals Grown in Microgravity
Research Motivation

• What are the conditions for detachment in microgravity and how do they depend on the governing parameters?
  ➢ Growth angle
  ➢ Contact angle
  ➢ Pressure differential
  ➢ Bond number (ratio of gravity to capillarity)

• Which detached growth solutions are dynamically stable?

• How does an initial crystal radius evolve to one of the following states?
  ➢ Stable detached gap
  ➢ Attachment to the crucible wall
  ➢ Meniscus collapse

• What are the effects of angular dependence on the crystal shape (faceting effects)?
Detached Crystal Growth
α: growth angle
θ: contact or wetting angle
ΔP = PH - PC: Dimensionless pressure differential across the meniscus
z(r): meniscus shape
Z(r): crystal shape

$$\Delta P = \Delta P_{\text{external}} + \rho gh + 2 \frac{\gamma}{r_{tm}}$$

where
$\Delta P_{\text{external}}$: external gas pressure differential
$\rho gh$: weight of melt (pressure head)
$2 \frac{\gamma}{r_{tm}}$: capillary pressure from top meniscus
Equations in Zero Gravity

\[ \frac{\partial z}{\partial r} = \pm \frac{\Delta P(r^2 - 1) - 2 \cos \theta}{\sqrt{4r^2 - (\Delta P(r^2 - 1) - 2 \cos \theta)^2}} \]

Meniscus shape equation, \( z(r) \): 2 possible solutions for \( g = 0, \, B = 0 \)

\[ \frac{dZ}{dr} = \tan(\alpha + \beta) \]

Crystal shape equation, \( Z(r) \): 2 possible solutions in zero gravity

\[ \frac{dZ^\pm}{dr} = \frac{\sqrt{4r^2 - y^2} \tan \alpha \pm y}{\sqrt{4r^2 - y^2} \mp y \tan \alpha} , \quad y = \Delta P(r^2 - 1) - 2 \cos \theta \]
Crystal Evolution for $\theta + \alpha > 180^\circ$; $Z^+$ solution

Ge

$\alpha = 14.3^\circ$

$\theta = 172^\circ$

$P_0 = 2.5$

$P = 1.9$

$P = 1.4$

$P = 1.3$

$P = 1.2$
Ge Crystal Evolution for $\theta + \alpha > 180^\circ$; $Z^+$ solution

Material: Ge  
Growth Angle: 14.3°  
Contact Angle: 172°  
$\Delta P = 1.4$

(a) Radius decreases until meniscus collapses

(b, c) Radius increases or decreases until stable growth with a constant radius is reached
Ge Crystal Evolution for $\theta + \alpha > 180^\circ$; $Z^-$ solution

Material: Ge  
Growth Angle: $14.3^\circ$  
Contact Angle: $172^\circ$

For $Z^-$ solutions, all crystals decrease in radius until the menisci collapse.
Existence Region for $\theta + \alpha > 180^\circ$
Crystal Evolution for $\theta + \alpha < 180^\circ$

$Z^+$ solutions

$Z^-$ solutions

$\alpha = 14.3^\circ; \theta = 140^\circ$
Crystal Evolution for $\theta + \alpha < 180^\circ$

Material: Ge  
Growth Angle: 14.3°  
Contact Angle: 140°  
$\Delta P = 1.0$

(a, c) Radius decreases until meniscus collapses

(b) Radius increases or decreases until attachment at the crucible wall
Existence Region for $\theta + \alpha < 180^\circ$
• “Influence of Containment on the Growth of Silicon-Germanium” (ICESAGE) is a collaborative investigation between NASA and the European Space Agency (ESA)
• The ICESAGE experiments will be conducted in the Low Gradient Furnace (LGF) in the Materials Science Laboratory on the International Space Station (ISS)

• ICESAGE will test the theories of crystal shape evolution in detached Bridgman growth
• Dependence on the parameters $\Delta P$, $\theta$, and the crystal starting position $r_0$ will be examined
• Launch is currently planned on a SpaceX flight in 2016
• A theory describing the shape evolution of detached Bridgman crystals in microgravity has been developed
• A starting crystal of initial radius $r_0$ will evolve to one of the following states:
  ➢ Stable detached gap
  ➢ Attachment to the crucible wall
  ➢ Meniscus collapse
• Only crystals where $\alpha + \theta > 180^\circ$ will achieve stable detached growth in microgravity
• Results of the crystal shape evolution theory are consistent with predictions of the dynamic stability of crystallization (Tatarchenko, *Shaped Crystal Growth*, Kluwer, 1993)
• Tests of transient crystal evolution are planned for ICESAGE, a series of Ge and GeSi crystal growth experiments planned to be conducted on the ISS