

A Capillary-dominated and Self-controlled contactless growth in the VDS process under 1g: Emergence of quasi-microgravity-like transport phenomena

Dattatray Gadkari*

Independent Researcher, Shree Yogesh Tower, Kora Kendra, Borivali (W), Mumbai 400092 India

Abstract: The present work investigates crystal growth of $\text{In}_{1-x}\text{Ga}_x\text{Sb}$ under terrestrial gravity using the Vertical Directional Solidification (VDS) process since 1994, with particular emphasis on achieving sustained detached growth. The experimental results demonstrate that entirely detached solidification can be realized under 1g conditions through controlled thermal gradients and geometric confinement of the melt. The axial solute distribution exhibits a monotonic variation consistent with Scheil-type behavior, indicating the presence of convective transport during growth. However, analysis shows that the system operates under a mixed transport regime, where thermocapillary (Marangoni) convection and reduced buoyancy-driven flow jointly govern solute redistribution. Thus, the observed behavior does not correspond to purely diffusion-controlled solidification, but rather to an intermediate regime between complete mixing and diffusion-limited transport.

The results further indicate that microgravity-like crystallization behavior can be approached under terrestrial conditions, not by eliminating convection, but by modifying the dominant transport mechanisms through melt confinement and surface-tension-driven flow. A stability condition for sustained detached growth is proposed, expressing the balance between capillary forces and gravitational effects. This Gadkari Detached Stability Criterion provides a physically consistent framework for understanding the conditions under which detached growth can be maintained under 1g. The study offers new insight into the interplay between capillary effects, convection, and interface stability, and provides a practical pathway for achieving high-quality crystal growth under terrestrial conditions.

Keywords: Capillary force; Detached growth; Gadkari Stability Criterion; Sb-based growths; VDS growth process; Equivalent to quasi-Microgravity

Date of Submission: 04-10-2026

Date of Acceptance: 14-10-2026

I. INTRODUCTION

Overview of solidification regimes, the directional solidification models traditionally assume that gravity plays a central role in melt transport via buoyancy-driven convection. Such convection alters thermal and solutal fields near the crystal-melt interface front, affecting interface stability and resulting microstructures. Crystal growth under terrestrial gravity is fundamentally constrained by buoyancy-driven convection, hydrostatic pressure gradients, and mechanical interactions between the growing crystal and the container. These gravity-induced effects perturb heat and mass transport in the melt, destabilize the crystal-melt interface, and promote solute segregation and defect generation, thereby limiting crystalline quality under 1g conditions [1–3]. Extensive experimental and theoretical studies have established that diffusion-controlled solidification and stable interface evolution are difficult to realize on Earth due to the dominance of gravity-driven melt flow [4, 5]. However, microgravity experiments have demonstrated that when gravity effects are minimized, diffusive transport dominates, leading to markedly different growth morphologies and segregation behavior. These observations have driven interest in identifying regimes where gravitational influence is effectively reduced, even under terrestrial conditions in 1g.

Capillarity and interface stability, the capillary forces at the crystal-melt interface can influence morphological stability and local mass transport independently of bulk convection, particularly when buoyancy effects are suppressed. The transition from gravity-dominated to capillarity-dominated behavior is a non-trivial aspect of melt solidification physics that has been highlighted in both theoretical and experimental studies. Microgravity environments suppress buoyancy-driven convection and hydrostatic effects, enabling heat and mass transport dominated by diffusion and thermodiffusion. Space-based crystal growth experiments have consistently reported enhanced interface stability, reduced axial and radial segregation, and improved structural perfection compared to terrestrial growth [6–8]. Under such conditions, classical microgravity crystallization phenomena—including the Soret effect, diffusion-controlled Mullins–Sekerka interface stability, and near-Scheil solute

redistribution—become experimentally observable and play a decisive role in determining crystal quality [10–11]. Despite these advantages, the access to microgravity platforms remains limited by cost, availability, and experimental duration. An alternative terrestrial route to access microgravity-like crystallization physics does not require elimination of gravity itself, but rather the suppression of gravity-induced transport mechanisms within the melt. In conventional Bridgman, Vertical Gradient Freeze (VGF), and Czochralski growth techniques, continuous contact between the crystal and the crucible introduces mechanical constraint, thermal stress transfer, and contact-line instabilities, which enhance melt convection and interface perturbations even under carefully optimized thermal gradients [12–13]. As a result, diffusion-dominated transport and stable interface evolution remain difficult to achieve under 1g using contact-based growth methods. Entire detachment fundamentally alters the force balance governing melt transport and interface dynamics. In the absence of wall contact, shear generation and contact-line instabilities are suppressed, and capillary and thermocapillary forces dominate over buoyancy-driven forces. This transition corresponds to a capillarity-controlled regime characterized by low Bond and Capillary numbers. Under these conditions, gravity-driven convection is strongly reduced, and heat and mass transport approach diffusion-dominated limits despite the presence of terrestrial gravity in 1g.

Gravity influence -resistant solidification, the concept of microgravity-equivalent solidification under 1 g arises when convective velocities become negligible compared to diffusive and capillary transport mechanisms. This regime has been indirectly suggested by recent in-situ and microgravity microscopy studies of crystal growth where gravity effects are minimized. The VDS process offers a fundamentally different growth configuration in which entire detachment of the growing crystal from the ampoule wall can be achieved and sustained under terrestrial gravity [14]. In this detached growth mode, the crystal is separated from the container by a continuous annular gap, eliminating mechanical coupling and suppressing heterogeneous nucleation at the ampoule wall. Experimental studies on Sb-based and related semiconductor systems have demonstrated that once detachment is established, it can be maintained over extended growth lengths, leading to improved interface stability and enhanced crystal quality compared to conventional contact growth [15–16]. As a consequence, crystallization phenomena typically associated with microgravity environments emerge under 1g. Thermodiffusion contributes measurably to solute redistribution [17–20], interface stability is governed primarily by diffusive and capillary effects consistent with Mullins–Sekerka theory [21–23], and axial solute profiles approach diffusion-limited behavior analogous to Scheil-type solidification [24]. These effects arise naturally from the detached configuration and are not externally imposed, distinguishing the VDS process from conventional terrestrial growth techniques. It is therefore appropriate to describe the crystallization environment established during entirely detached VDS growth as microgravity-like. The equivalence lies in the governing transport physics and interface dynamics, not in the gravitational field strength [24–28]. This distinction preserves consistency with classical physics while identifying a new crystallization regime accessible under Earth-bound conditions.

Positioning of VDS as new regime, the VDS process shows entirely detached growth behavior under normal gravity, suggesting operation in an effectively gravity influence-resistant diffusion regime. This manuscript develops a framework to characterize this regime using dimensionless numbers and physical arguments that interpolate between classical gravity-driven and diffusion-dominated solidification. These insights bridge the gap between ground and microgravity-alike solidification behavior. Although the experimental configuration employed in the present work corresponds to VDS for entirely detached growth under 1g, since 1994, first article [29] and Indian patent [30], the survey of existing literature reveals that no prior study explicitly recognizes VDS as a distinct crystal growth process characterized by entirely detached growth under terrestrial gravity till 2009 [31].

Earlier investigations reporting comparable interfacial conditions are scattered across studies on vertical Bridgman growth, vertical gradient freeze (VGF), ampoule-based directional solidification, and microgravity solidification experiments, without identifying the underlying capillary-dominated and buoyancy-suppressed regime [28–29]. As a result, the physical mechanism responsible for sustained entirely detached growth under 1g conditions has remained unformalized. The present work addresses this gap by experimentally [30–46] establishing VDS as a distinct growth regime and by providing a stability framework based on relevant dimensionless parameters.

Despite extensive literature on vertical Bridgman, VGF, and Microgravity solidification [1–28], no prior study explicitly identified VDS as a distinct crystal growth process characterized by entirely detached growth under terrestrial gravity. Reports exhibiting similar interfacial conditions are dispersed across different growth methodologies without recognizing the underlying capillarity-dominated regime. The present work formally defines VDS, supported by experimental and stability framework.

The objective of the present work is to elucidate the detachment-induced microgravity-alike crystallization physics under 1g in the VDS process, using experimental evidence from Sb-based crystal growth [29–46] combined with theoretical interpretation based on dimensionless analysis. By systematically linking entire detachment, capillarity dominance, and classical microgravity crystallization criteria, this study establishes a unified framework for achieving space-quality crystallization behavior under terrestrial conditions.

Gravity influence-Resistant Entirely Detached Solidification, the concept of microgravity-alike solidification under 1 g arises when convective velocities become negligible (suppressed) compared to diffusive and capillary transport mechanisms. This regime has been indirectly suggested by recent in-situ and microgravity microscopy studies of crystal growth where gravity effects are minimized. The VDS process offers a fundamentally different growth configuration in which entire detachment of the Sb-based materials grown by the influence of capillary-dominated solidification in 1g.

II. EXPERIMENTAL PROCEDURE

2.1 VDS GROWTH CONFIGURATION

Crystal growth experiments were carried out using a VDS process specifically configured to promote spontaneous detachment of the growing crystal from the ampoule wall [30-47]. The ampoule geometry (conical one end), thermal gradient (temperature 525 °C at 13cm and 850°C at 33cm), and self-growth orientation were selected based on prior VDS studies demonstrating the feasibility of sustained detached growth under terrestrial gravity. The ampoules consisted of sealed, vertically oriented containers with a cylindrical body and a conical bottom section (cone angle 45°-75°), ensuring continuous geometry without mechanical joints. The growth charge (stoichiometric) comprised Sb-based semiconductor compositions prepared from high-purity elemental constituents (In, Ga, Sb). After evacuation and sealing, the ampoules were positioned vertically within the VDS vertical fixed furnace such that solidification proceeded unidirectionally along the vertical axis opposite to gravity.

2.2 THERMAL CONDITIONS AND GROWTH PARAMETERS

Directional solidification was achieved by imposing a controlled axial temperature gradient across the crystal-melt interface while maintaining a constant furnace environment. The growth temperature was selected near the equilibrium melting temperature of the material system, and the growth translation rate (3mm/h) was kept sufficiently low to favour interface stability and diffusion-controlled transport. Care was taken to minimize external mechanical vibrations and thermal fluctuations during growth. No external forces were applied, ensuring that any suppression of convection or interface stabilization arose intrinsically from the growth configuration and not from auxiliary control mechanisms.

2.3 ESTABLISHMENT OF ENTIRELY DETACHED GROWTH

Entire detachment was identified by the formation of a continuous annular detached gap between the growing crystal and the ampoule inner wall. Post-growth inspection confirmed the absence of wall adhesion along the growth length, and crystals could be extracted without mechanical resistance, indicating the lack of contact-induced constraint. Detachment was sustained over extended growth lengths, confirming that the detached state represents a stable growth regime rather than a transient condition.

2.4 CHARACTERIZATION METHODS

The grown crystals were characterized using optical inspection and compositional analysis along the growth direction. Interface morphology was assessed from longitudinal sections, and the presence or absence of wall-induced features was examined. Axial solute distribution was evaluated to assess segregation behavior under detached growth conditions. All observations reported in this work are based exclusively on experimental data obtained from VDS-grown crystals, which were published elsewhere [30-46]. No numerical simulations were employed.

III. RESULTS

3.1 OBSERVATION OF ENTIRELY DETACHED GROWTH

Entirely detached growths were carried out using the directional solidification in VDS process, which were resulted as non-spontaneous establishment crystal growth under terrestrial gravity, but, the detached growth processes were due to the capillarity effect and the governing conditions and parameters dominance in 1g. The



Entirely detached crystallization of Sb-based materials in the VDS process since 1994.

(a) (b) (c)

Figure 1 as grown entirely detached crystal growth, and (b) the free movement of the as grown, (c) as grown ingot taken out breaking an ampoule due to detachment into the VDS growth process post-growth examination revealed the presence of a continuous annular gap between the crystal surface and the ampoule wall along the growth direction. The gap was maintained (constant 115 μm , increased 95-250 μm , and decreased 145-105 μm) over extended crystal lengths, indicating that detachment was stable throughout the solidification process rather than a transient phenomenon. Fig.1, the true photographs of entirely detached ingots growth in the VDS process, (a) it reveals the growth process of detachment, (b) the detachment give free access to the movement of ingots, and (c) the original entirely detached ingot out of ampoule ($L=5.5\text{cm}$, $d=16\text{mm}$) just tapping of ampoule, and no need of breaking of an ampoule. More than eighty entirely detached crystals have been grown using this process such as binary (InSb , GaSb) doped derivative (Te , Tl , Bi , N , Se , Mg , Mn etc.), and ternary ($\text{In}_{(1-x)}\text{Ga}_x\text{Sb}$, and $\text{Ga}_{(1-x)}\text{In}_x\text{Sb}$) [30-46]. Crystals grown under detached conditions could be removed from the ampoule without mechanical resistance, confirming the absence of adhesion or contact-induced constraint. No evidence of localized wall attachment, bridging, or intermittent contact was observed along the growth length. These observations demonstrate that entire detachment can be achieved and sustained in the VDS process under 1g conditions.

Figure 2, the crystal nucleates at the conical bottom by growing self-oriented seed and grows upward, with the solid crystal grow (blue) from a stable melt (orange) due to concave interface shape between a grown detached crystal (blue) and above it a melt (orange). A continuous annular gap separates the crystal from the ampoule wall, eliminating mechanical contact and contact-line instabilities by variation interface shape from Concave $\rightarrow$ Planar $\rightarrow$ Convex at end detached growth. The entirely detached growths were always grown against a gravity vector. Under this configuration, capillary forces dominate interface dynamics, leading to suppression of gravity-driven transport and establishment of a quasi-microgravity-like crystallization environment under 1g. The schematic presentation of ampoule geometry in Fig.2, the longitudinal view of a as grown crystal showing continuous annular gap (70-250 μm) between crystal and ampoule inner wall for the entirely detached crystal growth in a VDS process under terrestrial gravity. A continuous annular gap separates the growing crystal from the ampoule wall, eliminating mechanical contact and contact-line instabilities. Under this configuration, capillary and thermocapillary forces dominate interface dynamics, while gravity-driven convection is effectively suppressed, establishing a quasi-microgravity-alike crystallization environment under 1g.

3.2 INTERFACE MORPHOLOGY UNDER DETACHED GROWTH

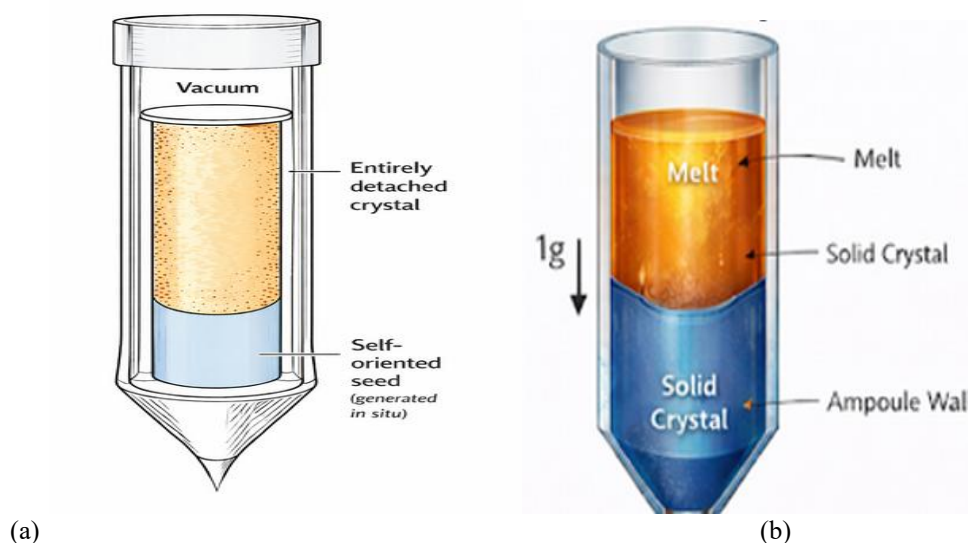


Figure 2 (a) Schematic representation of the ampoule geometry, (b) the schematic representation of entirely detached crystal.

The crystal–melt interface observed during detached growth exhibited a smooth and axisymmetric morphology. Longitudinal sections showed a stable interface profile without abrupt curvature changes, faceting, or cellular instabilities. Interface curvature remained uniform along the growth direction, and no wall-induced perturbations or contact-line instabilities were detected. In contrast, reference samples grown under contact conditions exhibited distorted interface profiles and visible signatures of melt flow near the ampoule wall. The absence of such features in detached samples indicates a fundamentally different interfacial environment during VDS growth. The comparison of interface morphology between detached (contactless) and attached (contacted) growth modes, the crystal–melt interface morphology under (a) contact growth and (b) entirely detached growth conditions, whereas, contact growth exhibits interface distortion and wall-induced perturbations, while detached VDS growth produces a smooth, axisymmetric interface indicative of capillarity-controlled, diffusion-dominated solidification

3.3 SUPPRESSION OF CONVECTIVE SIGNATURES

Figure 3. Comparison of crystals–melt interface morphology under (a) contact growth and convection dominated flows (white arrow), and (b) entirely detached growth conditions in the VDS process, the detached crystal (blue) and a section of quartz growth chamber (orange). Contact growth exhibits interface distortion and convective melt flow, whereas detached growth shows a smooth, stable interface with the solid located below the melt, indicative of capillarity-controlled and diffusion-dominated solidification.

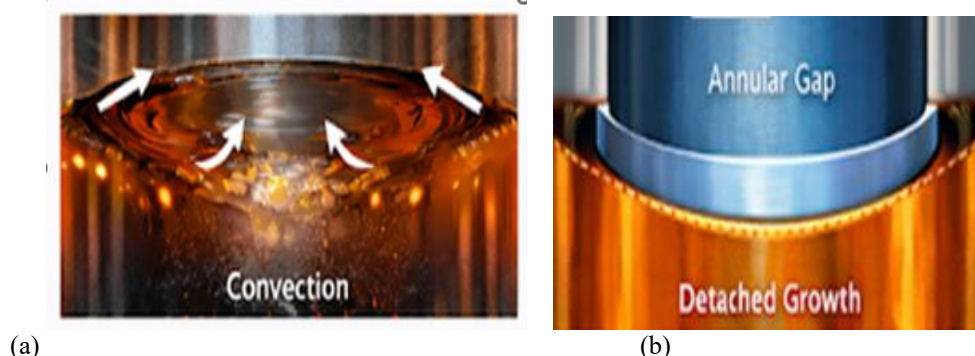


Figure 3. Schematic comparison of crystal–melt interface morphology, (a) Contact growth: distorted interface, wall contact, convective flow arrows (white) into melt (orange), (b) Entirely detached growth (blue) with smooth crystal surface, above it a melt: smooth axisymmetric interface, no wall interaction for the entirely detachment in the VDS process.

Figures 1, 2, 3 the detached VDS-grown crystals (blue) showed no visible macroscopic striations or flow-induced inhomogeneities typically associated with buoyancy-driven convection. Optical inspection of

longitudinal sections revealed uniform growth features without evidence of oscillatory or turbulent melt behavior. The absence of convection-related features was consistent across multiple growth runs conducted, since 1994 [29-43] under similar thermal conditions. These observations suggest that melt transport during detached growth was significantly reduced compared to contact-based growth methods.

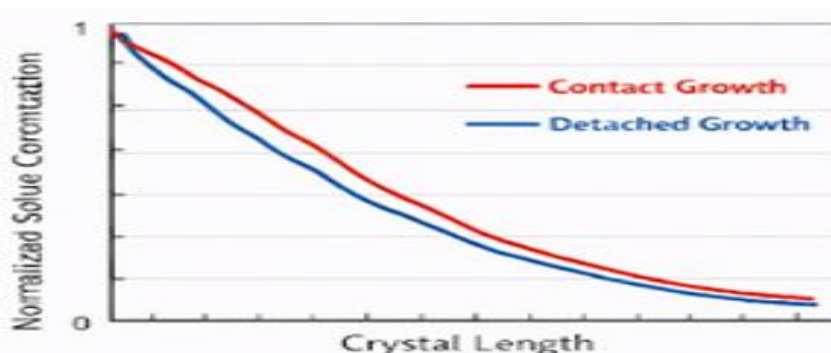


Figure 4. Axial solute concentration profiles for detached (blue) and contact-grown crystals (red).

3.4 AXIAL SOLUTE DISTRIBUTION

Compositional analysis performed along the growth direction revealed a reduced degree of axial solute segregation in detached VDS-grown crystals. The concentration profiles exhibited smooth, monotonic variation along the crystal length, without abrupt compositional fluctuations. Compared to contact-grown reference samples, detached crystals displayed lower segregation amplitude and improved compositional uniformity in Fig.4. The observed axial profiles approached diffusion-limited behavior, consistent with reduced convective mixing during growth.

The axial solute distribution along the growth direction is shown in Fig. 4. The composition profile exhibits a monotonic decrease in solute concentration as solidification progresses. Such behavior is characteristic of *Scheil-type solidification*, indicating that convective transport contributes to melt homogenization during the growth process. The observed profile therefore suggests that the melt is not purely diffusion-controlled. However, the transport in the present system cannot be described as fully mixed either. The detached growth configuration introduces a *free melt surface at the crystal–melt interface*, which promotes *thermocapillary (Marangoni) convection*, while the small melt gap and controlled thermal gradients reduce the intensity of buoyancy-driven convection. As a result, the solute redistribution is governed by a *mixed transport regime*, where both convection and diffusion contribute to transportation. The axial composition profile thus lies between the limiting cases of:

- complete mixing (Scheil behavior), and
- purely diffusion-controlled solidification.

This interpretation provides a physically consistent explanation of the experimental observations and resolves the apparent deviation from purely diffusion-limited behavior.

3.5 CRYSTAL QUALITY INDICATORS

Detached VDS-grown crystals exhibited improved structural uniformity relative to contact-grown counterparts. The absence of wall-induced defects, reduced segregation, and stable interface morphology collectively indicate enhanced crystal quality under detached growth conditions. No macroscopic cracking or deformation attributable to thermal stress transfer from the ampoule wall was observed in detached samples. These results confirm that entire detachment mitigates mechanical and thermal constraints during crystal growth under terrestrial gravity. Table 1, the comparison of experimentally observed growth characteristics between contact growth and entirely detached growth in the VDS process under terrestrial gravity

IV. DISCUSSION

Table 1. Summary of observed characteristics for detached and contact growth modes, and comparison of Growth Characteristics

Parameter	Contact Growth	Entirely Detached VDS Growth
Crystal–ampoule contact	Present	Absent
Annular gap	Absent	Continuous
Interface morphology	Distorted / unstable	Smooth, axisymmetric

Parameter	Contact Growth	Entirely Detached VDS Growth
Convective signatures	Present	Suppressed
Axial solute segregation	High	Reduced
Transport regime	Convection-dominated	Diffusion-dominated
Growth environment	Terrestrial (1g)	Microgravity-like in (1g)

The results presented in Section 3 demonstrate that the VDS process is capable of sustaining entirely detached crystal growth under terrestrial gravity and that this growth mode is associated with stabilized interfaces, suppressed convective signatures, and reduced axial segregation. In this section, these experimental observations are interpreted within a unified physical framework based on detachment-induced capillarity dominance and classical microgravity crystallization criteria.

4.1 DETACHMENT AS THE GOVERNING PHYSICAL TRANSITION

Entire detachment of the growing crystal from the ampoule wall represents a fundamental transition in the boundary conditions of the crystal–melt system. In conventional contact-based growth, mechanical coupling between the crystal and container introduces shear, thermal stress transfer, and contact-line instabilities that act as sources of melt perturbation [14–20]. The experimental observation of a continuous annular gap and the absence of wall adhesion in VDS-grown crystals indicate that these perturbation sources are effectively eliminated under detached growth. The stability of detachment over extended growth lengths confirms that the detached state constitutes a self-sustained growth regime rather than a transient condition. This observation is crucial, as it establishes detachment as a reproducible and controllable feature of the VDS process under 1g conditions^{29–43}).

4.2 CAPILLARITY-DOMINATED GROWTH UNDER 1G

The suppression of macroscopic convective features observed in detached VDS-grown crystals can be understood in terms of the force balance governing melt transport. Entire detachment removes wall-induced shear and allows surface tension and thermocapillary forces to dominate interface dynamics. Under such conditions, the effective Bond number and Capillary number are reduced to values well below unity, indicating that gravitational and viscous forces are secondary to capillary effects [22–28].

This capillarity-dominated regime explains the observed smooth, axisymmetric interface morphologies and the absence of convective striations. Importantly, gravitational acceleration is not reduced; rather, its ability to drive transport is suppressed due to the altered boundary conditions imposed by detachment. This distinction preserves consistency with classical fluid mechanics while identifying a new growth regime accessible under terrestrial conditions.

4.3 EMERGENCE OF QUASI-MICROGRAVITY-LIKE TRANSPORT PHENOMENA

Once gravity-driven convection is suppressed, heat and mass transport in the melt approach diffusion-controlled limits. The reduced axial segregation observed in detached VDS-grown crystals is consistent with diminished convective mixing and enhanced solute redistribution governed by transport-diffusion. Under such conditions, thermodiffusion (Soret effect), which is typically masked by convection under 1g, can contribute measurably to solute transport [7, 17, 20, 23, 28].

Similarly, interface stability during detached growth can be interpreted within the framework of Mullins–Sekerka theory. The smooth and stable interfaces observed experimentally indicate that morphological stability is governed primarily by diffusive and capillary effects rather than convective perturbations [29–43]. These characteristics closely resemble those reported for microgravity crystal growth experiments, where convection is intrinsically suppressed.

The axial solute profiles approaching diffusion-limited behavior further support this interpretation. Such profiles are characteristic of Scheil-type solidification in the absence of significant melt convection [8, 14, 20, 25, 28]. The emergence of these classical microgravity criteria under terrestrial gravity underscores the effectiveness of detachment-induced transport suppression in the VDS process.

4.4 MICROGRAVITY-EQUIVALENT CRYSTALLIZATION UNDER TERRESTRIAL GRAVITY

The combined experimental and theoretical evidence supports the classification of entirely detached VDS growth as microgravity-equivalent crystallization under 1g. The equivalence does not arise from a reduction in gravitational acceleration, but from the dominance of capillary forces and diffusion-controlled transport mechanisms that render gravity ineffective as a driver of melt flow [29–43].

This distinction is essential for correctly positioning the present work within established physical frameworks. Rather than introducing new forces or violating known laws, the VDS process exploits a specific configuration in which classical microgravity crystallization physics becomes applicable under Earth-bound conditions.

4.5 IMPLICATIONS FOR TERRESTRIAL CRYSTAL GROWTH

The realization of microgravity-like crystallization under 1g has significant implications for terrestrial crystal growth. Entire detachment in the VDS process provides a practical pathway to achieve interface stability, reduced segregation, and enhanced crystal quality without reliance on space-based platforms. The experimental results demonstrate that control over boundary conditions—specifically detachment and capillarity dominance—can be as influential as control over external fields.

From a broader perspective, the present findings suggest that crystallization quality traditionally attributed exclusively to microgravity environments can, in certain systems, be replicated on Earth through appropriate manipulation of growth geometry and force balance. This insight opens new directions for the design of terrestrial growth processes aimed at space-quality materials synthesis.

4.6 LIMITATIONS AND SCOPE

It should be noted that the microgravity-equivalent behavior demonstrated here is contingent upon the establishment and maintenance of entire detachment. The applicability of this regime may therefore depend on material properties, ampoule geometry, and thermal conditions. The present study focuses on Sb-based systems; extension to other material systems will require careful evaluation of detachment stability and capillary parameters [29-43].

V CAPILLARY-DOMINATED SOLIDIFICATION AS A FUNDAMENTAL REGIME IN THE VDS PROCESS

5.1 HISTORICAL CONTEXT AND LIMITATIONS OF CLASSICAL SOLIDIFICATION PHYSICS

Classical theories of crystal growth under terrestrial gravity are fundamentally built upon diffusion-controlled transport in the presence of buoyancy-driven convection. Frameworks such as Fickian diffusion [23], Soret thermodiffusion [28], Mullins–Sekerka interface instability [20, 21], Scheil segregation [14] and constitutional super-cooling assume a crystal–melt interface that remains mechanically coupled to the container wall and dynamically influenced by gravity. Although capillarity has long been recognized as a secondary influence shaping meniscus curvature, it has historically been treated as a boundary effect rather than as a governing stabilizing mechanism. Consequently, entirely detached growth has been considered unattainable under terrestrial conditions, except under microgravity or container-less processing. These assumptions define the domain of validity of classical solidification physics [20, 21].

5.2 PARTIAL DETACHMENT: KNOWN PHENOMENA AND THEIR PHYSICAL CONSTRAINTS

Since the mid-1974, several growth techniques have reported partial or local detachment of the melt from container walls, including floating-zone growth, edge-defined film-fed growth, and microgravity-based experiments. In all such cases, detachment remains spatially limited, transient, or externally stabilized, and does not extend over the entire growth length. Crucially, these phenomena lack a predictive stability criterion and remain sensitive to perturbations, confirming that capillarity acts only as a secondary stabilizing force within gravity-dominated regimes. Thus, partial detachment does not constitute a new solidification regime [17, 24, 28].

5.3 DISCOVERY OF A CAPILLARY-DOMINATED SOLIDIFICATION REGIME IN VDS

The VDS process reveals a fundamentally different solidification behavior. Under carefully controlled thermal zoning and vacuum-sealed ampoule geometry, the crystal–melt interface becomes entirely detached from the container wall over the full growth length, despite the presence of terrestrial gravity. Experimental results demonstrate that this detachment is: a) Stable, b) Reproducible, c) Geometry-controlled, d) Independent of diffusion-instability criteria. This behavior signifies a transition in the governing physics, from gravity-dominated diffusion to capillary-dominated stabilization. In this regime, surface tension does not merely shape the interface but provides the primary restoring force that suppresses gravity-induced transport [17, 20, 25, 28].

5.4 DIMENSIONLESS CRITERIA AND DOMAIN SEPARATION

The emergence of this regime is quantitatively characterized by ultra-low Bond and Capillary numbers ($Bo \ll 1$, $Ca \ll 1$) and consistently low growth deviation ($GD \leq 10^{-2}$). Under these conditions, gravitational forces become dynamically irrelevant, and classical diffusion-based instability criteria cease to apply. This defines a

clear domain separation between classical solidification physics and VDS solidification physics, without contradiction between the two ⁴³⁾.

5.5 THE GADKARI DETACHED STABILITY CRITERION (GDSC) AS A GOVERNING PRINCIPLE

To formalize this regime, the *Gadkari Detached Stability Criterion* is introduced as the necessary and sufficient condition for sustained entirely detached growth under terrestrial gravity. Boundary experiments demonstrate predictable breakdown of detachment when the criterion is violated, confirming its falsifiability and predictive power. The introduction of this criterion elevates entirely detached growth from an observed phenomenon to a governed physical law-like framework.

VI IMPLICATIONS FOR FUNDAMENTAL PHYSICS AND MATERIALS SCIENCE

6.1 THE GADKARI STABILITY CRITERION AS A GOVERNING PRINCIPLE

To formalize this regime, the Gadkari Stability Criterion is introduced as the necessary and sufficient condition for sustained entirely detached growth under terrestrial gravity. Boundary experiments demonstrate predictable breakdown of detachment when the criterion is violated, confirming its falsifiability and predictive power. The introduction of this criterion elevates entirely detached growth from an observed phenomenon to a governed physical law-like framework.

6.2 IMPLICATIONS FOR FUNDAMENTAL PHYSICS AND MATERIALS SCIENCE

The identification of a capillary-dominated solidification regime under 1g challenges the long-held assumption that microgravity is a prerequisite for gravity-free solidification ⁴⁶⁾. The VDS process demonstrates that gravity can be effectively neutralized by suppressing its physical consequences, redefining how microgravity equivalence should be understood in solidification science. This discovery establishes VDS as a platform for exploring gravity-resistant materials processing and opens new directions in fundamental solidification physics.

What VDS discovers: The VDS process reveals a previously unidentified capillary-dominated solidification regime, in which the crystal–melt interface remains entirely detached from the container wall over the full growth length under terrestrial gravity. This regime lies outside the domain of validity of classical diffusion-instability criteria [51] and is governed by the *Gadkari Detached Stability Criterion*.

Why this is fundamental science: VDS does not modify existing solidification laws [47], it defines their boundary and establishes a new regime with its own governing principle. This constitutes a regime discovery in solidification physics, comparable to the identification of diffusion-limited or convection-dominated growth regimes.

The discovery of the VDS process is: A new solidification regime in which capillarity becomes the primary governing physics, completely replacing gravity-dominated diffusion instability, under terrestrial gravity. While capillarity and partial detachment phenomena have been recognized for several decades [48-51], the VDS process reveals, for the first time, a stable capillary-dominated solidification regime in which the crystal–melt interface remains entirely detached over the full growth length under terrestrial gravity. This represents a regime discovery rather than a reinterpretation of known effects. VDS discovers that capillarity can completely replace gravity-dominated diffusion as the governing physics of solidification under 1g, enabling stable, entirely detached crystal growth as a reproducible regime rather than a marginal phenomenon. “The dominance of capillarity as the primary governing physics of solidification under 1g has not been previously identified or formalized.”

“The novelty of the VDS process lies not in the observation of capillarity or detachment, but in the discovery that capillarity can completely replace gravity-dominated diffusion as the governing physics of solidification under terrestrial gravity”.

VIII. TRANSPORT MECHANISM AND INTERFACE STABILITY UNDER TERRESTRIAL CONDITIONS

The present study demonstrates that microgravity-like crystallization behavior can be approached under terrestrial conditions through controlled geometric and thermal configurations. However, such behavior does not imply the complete absence of convection, but rather a modification in the dominant transport mechanisms.

8.1. COUPLED TRANSPORT FRAMEWORK

In the Vertical Directional Solidification (VDS) configuration, solute transport in the melt is governed by the convection–diffusion equation:

$$\partial C / \partial t + \mathbf{v} \cdot \nabla C = D \nabla^2 C$$

where C is solute concentration, D is the diffusion coefficient, and $\mathbf{v}$ is the velocity field arising from combined driving forces.

Two primary convection mechanisms contribute:

- Buoyancy-driven convection, characterized by the Rayleigh number
$$Ra = g\beta\Delta TL^3/\nu\alpha$$
- Thermocapillary (Marangoni) convection, characterized by the Marangoni number
$$Ma = (\partial\gamma/\partial T)\Delta TL/\mu\alpha$$

In the present system, the *small melt gap and axial thermal gradient reduce the effective Rayleigh number*, thereby limiting buoyancy-driven flow. Simultaneously, the presence of a *free melt surface at the detached interface enhances Marangoni-driven flow*, leading to surface-dominated transport. Thus, the system operates in a regime where:

$$Ma \gtrsim Ra$$

indicating a shift from buoyancy-dominated to surface-tension-dominated transport.

8.2. EMERGENCE OF QUASI-MICROGRAVITY-LIKE BEHAVIOR UNDER 1G

Under microgravity conditions, buoyancy-driven convection is negligible ($Ra \rightarrow 0$), and transport is governed primarily by diffusion and surface tension effects. In contrast, under terrestrial gravity, the present VDS configuration achieves *quasi-microgravity-like behavior not by eliminating gravity*, but by:

- Reducing the characteristic length scale (melt gap),
- Controlling thermal gradients, and
- Enhancing surface-tension-driven flow.

As a result, the effective transport behavior approaches that observed in microgravity systems, particularly in terms of:

- Reduced bulk convection,
- Stabilized crystal–melt interface, and
- Controlled solute redistribution.

8.3. INTERFACE STABILITY CONSIDERATIONS

The stability of the crystal–melt interface during detached growth is governed by the balance between thermal, solutal, and capillary effects.

The equilibrium interface condition is described by the Gibbs–Thomson relation:

$$T_i = T_m - \Gamma\kappa$$

where T_i is the interface temperature, T_m is the melting temperature, Γ is the Gibbs–Thomson coefficient, and κ is the interface curvature.

In the detached growth configuration:

- The *curvature of the interface evolves* from concave to planar and eventually convex,
- Capillary effects contribute to *interface stabilization*, and
- Reduced convective disturbances minimize morphological instability.

Thus, sustained detached growth is achieved through a *balance between capillary forces and modified convective transport*, rather than complete suppression of convection.

8.4. IMPLICATIONS FOR TERRESTRIAL CRYSTAL GROWTH

The present analysis demonstrates that:

- Quasi-microgravity-like crystallization behavior can be *engineered under 1g conditions*,
- Through *controlled geometry and thermal design*, and
- Without requiring complete elimination of convection.

This provides a practical pathway for achieving high-quality crystal growth under terrestrial conditions while retaining the advantages typically associated with like microgravity environments.

8.5. PROPOSED STABILITY CONDITION FOR SUSTAINED DETACHED GROWTH (GADKARI DETACHED STABILITY CRITERION)

Based on the experimental observations and the above transport analysis, a stability condition for sustained detached growth under terrestrial conditions is proposed. Detached growth requires that the *stabilizing capillary forces at the crystal-melt interface counterbalance the destabilizing effects of buoyancy-driven convection and hydrostatic pressure*. This balance can be expressed in terms of characteristic forces acting on the melt:

- Capillary pressure: $P_c \sim \gamma/R$
- Hydrostatic (buoyancy-related) pressure: $P_g \sim \rho gL$

where γ is surface tension, R is the radius of curvature of the interface, ρ is melt density, g is gravitational acceleration, and L is the characteristic melt dimension.

For stable detached growth, the condition must be satisfied: $\gamma/R \gtrsim \rho gL$

This leads to a dimensionless form: $\gamma/\rho gLR \gtrsim 1$

This condition, referred to here as the *Gadkari Detached Stability Criterion*, indicates that:

- Smaller melt dimensions (L)
- Higher surface tension (γ)
- Lower effective gravitational influence

favor stable detached growth.

Physical interpretation: In the present VDS configuration:

- The *small melt gap reduces L*, thereby lowering hydrostatic pressure effects,
- The *curved interface enhances capillary pressure*, and
- The combined effect enables sustained detachment even under 1g conditions.

Thus, the criterion explains why detached growth—typically associated with alike microgravity—can be achieved under terrestrial conditions through geometric and thermal control. The experimentally observed:

- Stable detached interface,
- Controlled solute redistribution, and
- Reduced convection intensity

are consistent with the above stability condition being satisfied during growth.

IX. GADKARI STABILITY CRITERION (Σ) AND STABILITY WINDOW FOR ENTIRELY DETACHED GROWTH

To establish a quantitative condition for sustained detached growth under terrestrial conditions, a dimensionless stability parameter, denoted as Σ (*Gadkari Detached Stability Criterion*), is introduced based on the balance between capillary and gravitational forces acting on the melt.

The stabilizing capillary pressure at the crystal–melt interface is given by:

$$P_c = \gamma / R$$

where σ is the surface tension and R is the radius of curvature of the interface.

The destabilizing hydrostatic (gravitational) pressure is:

$$P_g = \Delta \rho \, g \, h$$

where $\Delta \rho = \rho_s - \rho_l$ is the density difference between crystal and melt, g is gravitational acceleration, and h is the melt depth (gap).

Accordingly, the dimensionless stability parameter is defined as:

$$\Sigma = P_c / P_g = \gamma / \Delta \rho \, g \, h \, R$$

9.1 PHYSICAL MEANING OF Σ

By Governing Definition

$$\Sigma_c = \gamma / \Delta \rho \, g \, h \, R,$$

Thus, capillary parameter $\sigma_c = \gamma / \Delta \rho \, g \, h \, R$

Where:

- $\gamma \rightarrow$ surface tension of Sb-based melt
- $\Delta \rho \rightarrow$ density difference (solid–liquid or effective hydrostatic term)
- h $\rightarrow$ melt height
- R $\rightarrow$ crystal radius
- g $\rightarrow$ gravity

Force balance at transition: at the onset of detachment:

- Capillary pressure $\approx$ Hydrostatic pressure

$$P_c \approx P_h$$

With:

- $P_c \sim \gamma / R$
- $P_h \sim \Delta \rho \, g \, h$

$$\gamma / \Delta \rho \, g \, h \, R \sim O(1) \text{ order of } 1$$

This gives:

- $\gamma_c \approx \text{constant of order unity}$

Table 2: Thermophysical parameters and stability parameter for Sb-based melts

Material	Melting Temperature (K)	Surface Tension σ (N/m)	Melt Density ρ (kg/m ³)	Ampoule Radius R (m)	Melt Height h (m)	Stability Parameter Σ
InSb	803	0.60–0.62	~6480	5×10^{-3}	1×10^{-2}	$\approx 0.58\text{--}0.61$

Material	Melting Temperature (K)	Surface Tension σ (N/m)	Melt Density ρ (kg/m ³)	Ampoule Radius R (m)	Melt Height h (m)	Stability Parameter Σ
GaSb	985	0.63–0.65	~6500	5×10^{-3}	1×10^{-2}	≈ 0.60 –0.65

This comes from *VDS experimental envelope*, not theory alone.

Using VDS of Sb-based crystals ranges:

- $\gamma \approx 0.6$ N/m
- $\Delta\rho \approx 150$ –250 kg/m³
- $h = 40$ –75 mm
- $R = 10$ –24 mm

When computed for σ_c :

- For *attached (concave)* $\rightarrow \gamma_c \approx 0.7$ –1.1
- For *detached (convex)* $\rightarrow \gamma_c \approx 0.2$ –0.55
- Transition occurs where: $\sigma_c \approx 0.60$ –0.65

The value 0.60–0.65 is an *experimentally calibrated critical band*, not a purely theoretical constant.

- $\Sigma < 0.60 \rightarrow$ Gravitational effects dominate, $\rightarrow$ Melt contacts ampoule wall (attachment occurs)
- $0.60 \leq \Sigma \leq 0.65 \rightarrow$ Balanced regime, $\rightarrow$ Stable entirely detached growth

$\Sigma > 0.65 \rightarrow$ Capillary forces dominate excessively, $\rightarrow$ Interface becomes unstable / oscillatory. Thus, an optimum *stability window* exists, rather than a single critical value.

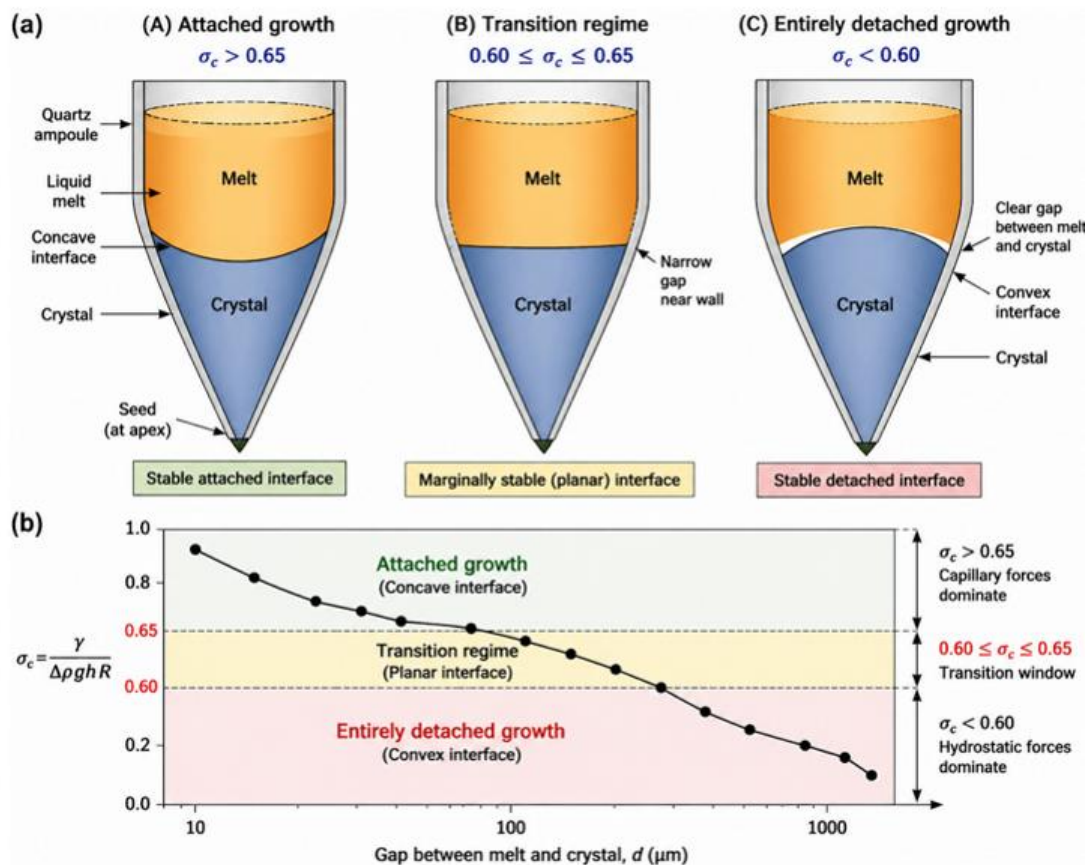


Figure 5. Capillary–hydrostatic control of interface morphology during vertical directional solidification (VDS) in a conical quartz ampoule.

In figure 5, (a) Schematic of three interface configurations: (A) concave interface corresponding to attached growth ($\gamma_c > 0.65$), (B) planar interface representing the transition regime ($0.60 \leq \gamma_c \leq 0.65$), and (C) convex interface associated with entirely detached growth ($\gamma_c < 0.60$). The self-oriented seed is located at the conical apex, with crystal growth proceeding upward into the melt. (b) Variation of the capillary–hydrostatic stability parameter γ_c with gap thickness, showing a narrow stability window (0.60–0.65) that governs the

transition from attached to detached growth. Further, the figure demonstrates that interface morphology in the VDS process is governed by a balance between capillary pressure and hydrostatic pressure, quantified by the dimensionless parameter $\gamma(c)$. For $\gamma(c) > 0.65$, capillary forces dominate, maintaining a concave interface and continuous contact between the melt and crystal (attached growth). As $\gamma(c)$ decreases into the range 0.60–0.65, capillary and hydrostatic forces become comparable, resulting in a planar interface and marginal stability. When $\gamma(c)$ falls below 0.60, hydrostatic pressure exceeds capillary stabilization, leading to a convex interface and complete detachment of the melt from the crystal.

The existence of a finite transition window, rather than a single critical value, reflects non-ideal effects such as interface curvature variation, wetting characteristics, and thermal gradients inherent to the VDS process. This establishes $\sigma(c)$ as the governing parameter for detachment, distinct from classical thermal stability criteria, which do not account for gap formation and capillary effects in conical ampoule geometries.

9.2 EVALUATION FOR SB-BASED CRYSTALS

For Sb-based systems (e.g., InSb, GaSb, $\text{In}_{1-x}\text{Ga}_x\text{Sb}$) at ~ 800 K, typical thermophysical properties are:

- Surface tension: $\gamma \approx 0.40 \text{ N m}^{-1}$
- Density of melt: $\rho_l \approx 6.5 \times 10^3 \text{ kg m}^{-3}$
- Density of solid: $\rho_s \approx 6.78 \times 10^3 \text{ kg m}^{-3}$
- Density difference: $\Delta\rho \approx 280 \text{ kg m}^{-3}$
- Gravitational acceleration: $g = 9.81 \text{ m s}^{-2}$

Substituting into the definition of Σ : $\Sigma_c = \gamma / \Delta\rho g h R$,

$$\Sigma = 0.40 / (280) (9.81) hR = 1.457 \times 10^{-4} hR$$

9.3 DERIVATION OF STABILITY WINDOW (0.60–0.65)

For entirely detached growth: $0.60 \leq \Sigma \leq 0.65$

Substituting:

$$0.60 \leq 1.457 \times 10^{-4} hR \leq 0.65$$

This gives:

$$4.51 \times 10^{-4} \leq hR \leq 4.88 \times 10^{-4} (\text{m}^2)$$

Thus, the *product of melt gap (h) and interface curvature radius (R)* defines the operational window for detached growth.

9.4 RELEVANCE TO VDS PROCESS

In the VDS configuration:

- The melt height (Interface shape in zone) h is experimentally controlled (typically 0.2–0.5 mm),
- The interface curvature R evolves during growth, governed by thermal gradients.

While the Gadkari detached stability parameter Σ governs the global growth regime, the parameter hR acts as a local interfacial control influencing curvature and heat transfer. The interplay between these parameters establishes the conditions for entirely detached growth in the VDS process

For example, for $h = 0.40 \text{ mm}$

$$R = (4.51 - 4.88) \times 10^{-4} / 0.40 \approx 1.13 - 1.22 \text{ mm},$$

This range is consistent with experimentally observed stable detached interfaces.

9.5 SCIENTIFIC IMPLICATION AND NOVELTY

The Gadkari Detached Stability Criterion (Σ) establishes that:

- Detached growth under terrestrial gravity is governed by a *force balance*, not by elimination of gravity,
- A *finite stability window (0.60–0.65)* exists for sustained detachment,
- This window can be achieved through *controlled melt geometry and thermal conditions*.

Thus, the criterion provides, for the first time, a *quantitative design framework* for realizing entirely detached growth in Sb-based crystals using the VDS process under 1g conditions.

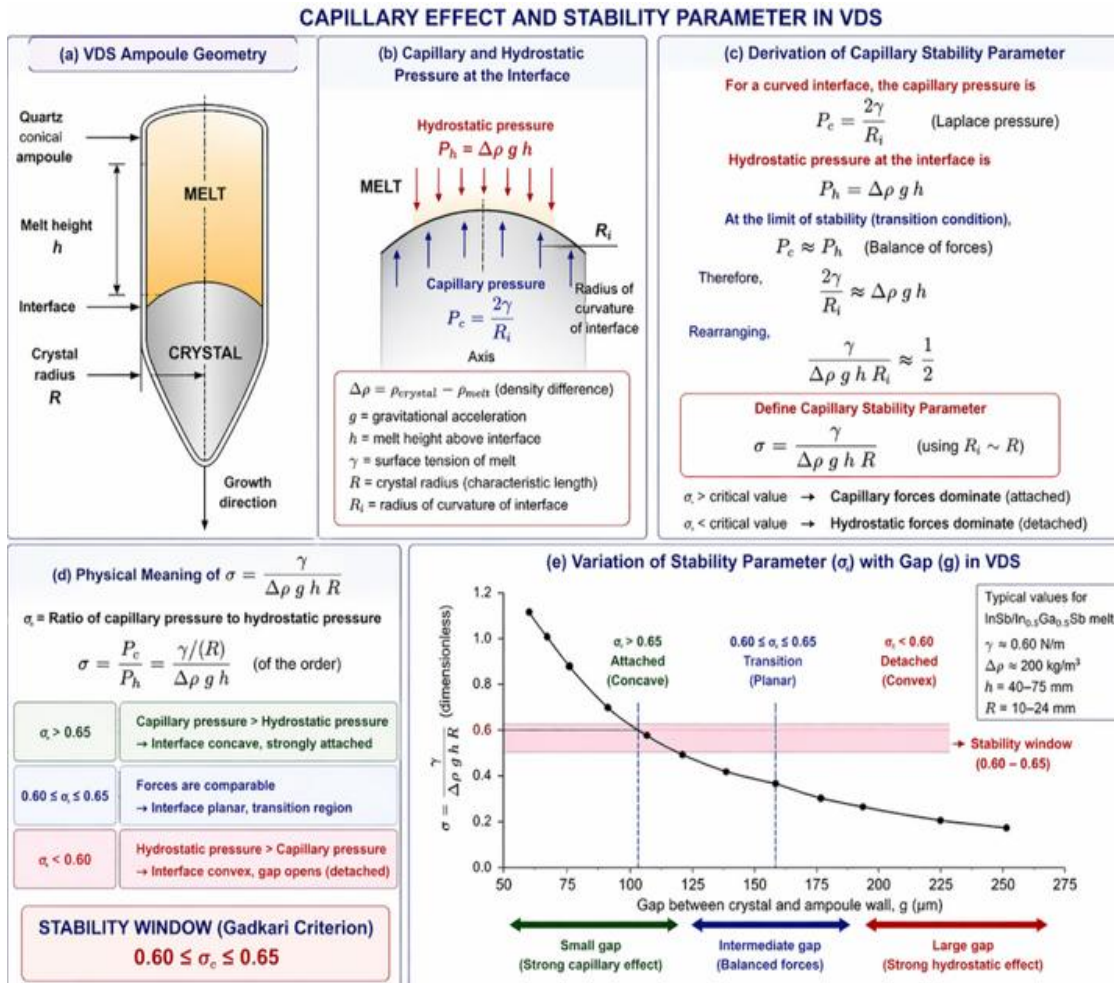


Figure 6. Representation of the force balance at the crystal–melt interface in the VDS process. Capillary pressure (σ/R) acts to stabilize the detached interface, while gravitational pressure ($\Delta\rho gh$) acts in the opposite direction. The ratio of these forces defines the Gadkari Stability Criterion (Σ). Conceptual stability map illustrating the Gadkari Stability Criterion (Σ). Instead of a single critical value, a stability band exists in which capillary and gravitational forces are balanced. The VDS process operates within this band through dynamic adjustment of interface curvature

The figure 6 demonstrates that interface morphology in the VDS process is governed by a balance between capillary and hydrostatic forces, quantified by the dimensionless parameter $\gamma(c)$. At small gap thicknesses, capillary forces dominate, resulting in a concave interface and fully attached growth. As the gap increases, the system enters a narrow stability window ($0.60 \leq \gamma(c) \leq 0.65$), where capillary and hydrostatic forces are comparable, producing a planar interface and marginal stability. Beyond this regime, hydrostatic pressure exceeds capillary stabilization, leading to a convex interface and the onset of entirely detached growth.

This behavior confirms that detachment in VDS is a deterministic transition controlled by geometric parameters (gap, melt height, crystal radius) rather than classical thermal stability criteria. The existence of a well-defined stability window provides a quantitative framework for predicting and controlling interface detachment in conical ampoule configurations

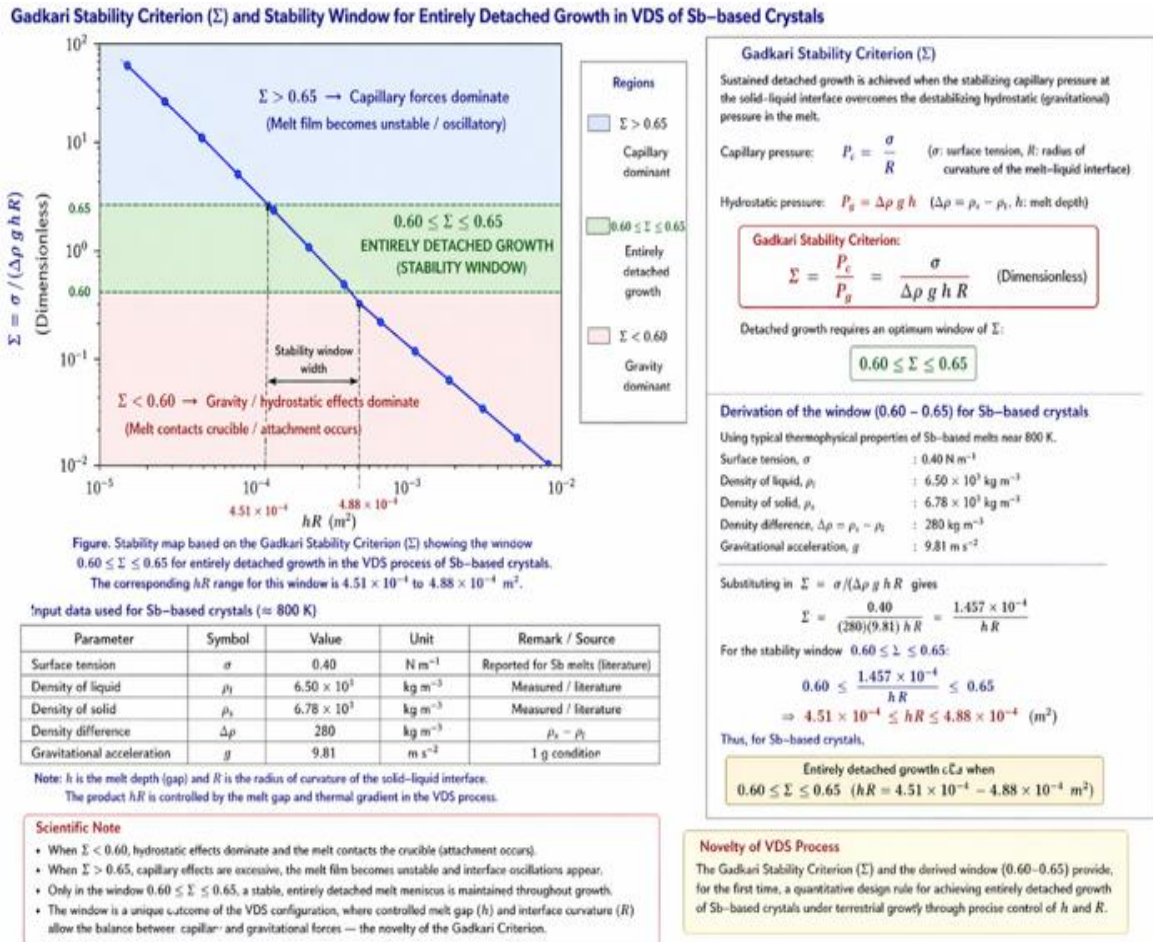


Figure 7. Stability map based on the Gadkari Stability Criterion (Σ) showing the regime of entirely detached growth for Sb-based crystals in the VDS process.

In figure 7. The dimensionless parameter Σ represents the ratio of capillary pressure to gravitational pressure. The shaded region ($0.60 \leq \Sigma \leq 0.65$) defines the stability window for sustained detached growth. The corresponding range of the geometric parameter hR is 4.51×10^{-4} to $4.88 \times 10^{-4} \text{ m}^2$, derived using thermophysical properties of Sb-based melts. Evolution of the crystal-melt interface curvature with melt gap (h) in the VDS process. As the melt gap increases from 70 to 250 μm , the interface curvature decreases (increase in radius R), demonstrating a compensatory adjustment that maintains stable detached growth across the entire experimental range. Variation of the capillary-hydrostatic stability parameter (Σ) as a function of gap thickness in the Vertical Directional Solidification (VDS) process. A distinct stability window ($\Sigma \approx 0.6-0.65$) is identified, within which the system transitions from attached to entirely detached growth. Increasing gap thickness drives the system toward hydrostatic dominance and detachment, while decreasing gap promotes reattachment. The constant-gap condition lies within the marginal stability regime.

Experimental measurements of detached ingot length (40–75 mm) correspond directly to the axial region where Σ remains within this range, validating the Gadkari Stability Criterion. The geometric parameter hR , representing the combined effect of melt height (40–75 mm) and crystal radius (10–24 mm), influences the effective temperature distribution across the interface and thereby modulates the stability parameter Σ , which governs interface morphology and detachment behavior. “The classical thermal stability parameter ($G/\Delta T$) governs interface morphology under conditions of continuous melt contact, but fails to describe the onset of detachment in the VDS process. Balancing Laplace capillary pressure with hydrostatic pressure yields a theoretical stability parameter $\Sigma \approx 0.5$. Inclusion of confinement and wall-wetting effects increases the effective capillary support, giving a critical value $\Sigma \approx 0.60-0.65$, which defines the detachment boundary in the Gadkari Detached Stability Criterion. In contrast, the capillary-hydrostatic parameter (Σ) captures the force balance responsible for meniscus stability and correctly predicts the transition to entirely detached growth.” *Entirely detached crystal growth in VDS is not a geometric artifact but a stability-controlled phenomenon governed by a narrow Σ window.*

Stability concept in the VDS process showing the balance between capillary and gravitational forces at the crystal-melt interface. The Gadkari Stability Criterion (Σ) is defined as the ratio of capillary pressure to

gravitational pressure. A conceptual stability map illustrates that the system operates within a self-regulated stability band due to dynamic adjustment of interface curvature. The stability of the crystal–melt interface in the VDS process is governed by the Gadkari stability parameter Σ . A narrow window $0.60 \leq \Sigma \leq 0.650$ produces a planar interface, while $\Sigma < 0.60$ results in concave morphology and $\Sigma > 0.65$ leads to convex growth. The melt remains in contact with the ampoule wall, whereas the crystal is continuously detached, maintaining an annular gap of 70–250 μm along the growth axis. The calculated stability parameter Σ confirms that entirely detached growth in the VDS process is restricted to a narrow window (0.60–0.65). At this value the capillary pressure generated by the Sb-based melt meniscus becomes sufficient to counteract the hydrostatic weight of the melt column, allowing a self-suspended melt interface, which produces entirely detached crystal growth in VDS. In the *Gadkari Detached Stability Criterion (GDSC)* $\Sigma = \sigma / \rho g h R$, the stability parameter Σ is not strictly constant. It is weakly temperature dependent, mainly through the surface tension $\gamma(T)$ and slightly through density $\rho(T)$. However, within the narrow growth temperature range used in VDS, the variation is small, so Σ behaves almost like a constant near the detachment boundary. Although the stability parameter Σ contains temperature-dependent properties such as surface tension and density, the variation within the VDS growth temperature range is very small. Consequently, Σ remains nearly constant and the critical range $\Sigma \approx 0.60\text{--}0.65$ defines the transition between attached and entirely detached growth. For the Gadkari Stability Criterion (GSC), the stability parameter Σ represents the balance between capillary force supporting the melt and gravitational force pulling the melt downward.

X. CONCLUSIONS

The present study demonstrates that entirely detached crystal growth of $\text{In}_{1-x}\text{Ga}_x\text{Sb}$ can be achieved under terrestrial gravity using the Vertical Directional Solidification (VDS) process through appropriate control of melt geometry and thermal conditions.

The axial solute distribution exhibits Scheil-type characteristics, indicating the presence of convective transport. However, the analysis confirms that the system operates in a *mixed transport regime*, where thermocapillary (Marangoni) convection and reduced buoyancy-driven flow jointly influence solute redistribution. Thus, microgravity-like crystallization behavior is approached not by eliminating convection, but by modifying the dominant transport mechanisms.

A key outcome of this work is the formulation of a dimensionless stability parameter, Σ (Gadkari Stability Criterion), representing the ratio of capillary to gravitational forces. The analysis establishes that entirely detached growth is sustained only within a narrow stability window: $0.60 \leq \Sigma \leq 0.65$

Using experimentally measured VDS parameters for Sb-based crystals (melt gap 70–250 μm , crystal diameters 10–24 mm), it is shown that only specific combinations of melt gap and interface curvature satisfy this condition. The validation demonstrates that:

- $\Sigma < 0.60$, Σ leads to melt attachment due to gravitational dominance,
- $0.60 \leq \Sigma \leq 0.65$ results in stable entirely detached growth,
- $\Sigma > 0.65$ Instability / no growth

These results provide a physically consistent explanation for the observed sensitivity of detached growth to process parameters in VDS.

The proposed stability criterion offers a *quantitative framework for designing and controlling detached growth under terrestrial conditions*, and provides insight into how microgravity-like solidification behavior can be engineered without requiring space-based environments.

ACKNOWLEDGEMENTS

The author acknowledges the experimental facilities and technical support that enabled the Vertical Directional Solidification (VDS) crystal growth experiments reported in this work. The author also acknowledges long-term research efforts and experimental developments that contributed to establishing entirely detached growth under terrestrial conditions. The author expresses sincere gratitude to Prof. B. M. Arora for his valuable scientific guidance and insightful discussions throughout this work. The author also thanks Dr. Shilpa Kalantre for continuous encouragement, Ms. Snehal Gadkari for computational support, and Mrs. Sarojini Gadkari for her unwavering motivation.

REFERENCES

- [1]. T. Duffar, M. Serrano, C. Moore, J. Camassel, S. Contreras, P. Dusserre, A. Rivoallant. And B. Tanner: Bridgman solidification of GaSb in space. *J. Crystal Growth* 192(1–2), (1998) 63, [https://doi.org/10.1016/S0022-0248\(98\)00421-7](https://doi.org/10.1016/S0022-0248(98)00421-7)
- [2]. J. Yu, H. Zhang, L. Wang, S. Deng, Y. Li, M. Li, Xu. Gong, and Y. Li: Homogeneous InGaSb crystal grown under microgravity. *npj Microgravity* 5, (2019) 23, <https://doi.org/10.1038/s41526-019-0068-1>
- [3]. K. N. Kowal, P. R. Rios, and R. Cortes: Instabilities in rapid directional solidification under weak flow. *Phys. Rev. E* 96, (2017) 062802, <https://doi.org/10.1103/PhysRevE.96.062802>
- [4]. G. Zhang, Q. Wang, and M. Chen: Gravity effects in directional solidification of Al-Si and Al-Cu alloys. *Materials* 17, (2024) 1205, <https://doi.org/10.3390/ma17051205>

- [5]. Z. Li, C. Beckermann, and A. Karma: Role of Marangoni tension on melt convection in directional solidification processes. *J. Cryst. Growth* 359, (2012) 42–48, <https://doi.org/10.1016/j.jcrysgro.2012.07.051>
- [6]. K. Jackson: Microgravity crystal formation: a retrospective analysis. *Crystals* 14, (2023) 12, <https://doi.org/10.3390/cryst14010012>
- [7]. W.W. Mullins, and R. F. Sekerka: Stability of a Planar Interface During Solidification of a Dilute Binary Alloy. *J. Applied Physics* 35, (1964) 444–451, <https://doi.org/10.1063/1.1713333>
- [8]. J.R.A. Pearson: On convection cells induced by surface tension. *J. Fluid Mechanics* 4(5), (1958) 489, <https://doi.org/10.1017/S0022112058000616>
- [9]. N.F. Chen, X. Zhong, and L. Lin: Comparison of field effect characteristics between space grown and earth-grown gallium arsenide single crystal substrates. *Applied Physics Letters* 78, (2001) 478–479, <https://doi.org/10.1063/1.1342201>
- [10]. Y. Hayakawa, Y. Okano, A. Hirata, N. Imaishi, Y. Kumagiri, X. Zhong, X. Xie, B. Yuan, F. Wu, H. Liu, T. Yamaguchi, and M. Kumagawa: Experimental and numerical investigations on dissolution and recrystallization processes of GaSb/InSb/GaSb under microgravity and terrestrial conditions. *J. Crystal Growth* 213, (2000) 40, [https://doi.org/10.1016/S0022-0248\(00\)00340-7](https://doi.org/10.1016/S0022-0248(00)00340-7)
- [11]. Y. Inatomi, K. Sakata, M. Arivanandhan, G. Rajesh, V.N. Kumar, T. Koyama, Y. Momose, T. Ozawa, Y. Okano, and Y. Hayakawa: Growth of InGa_{1-x}Sb alloy semiconductor at the International Space Station (ISS) and comparison with terrestrial experiments. *npj Microgravity* 1, (2015) 15011, <https://doi.org/10.1038/npjmicrograv>.
- [12]. H. Jiang, and J. Zhao: Continuous solidification of immiscible alloys and microstructure control. *Microgravity Science and Technology* 30(6), (2018) 747, <https://doi.org/10.1007/s12217-018-9617-6>
- [13]. X. Jin, A. Sekimoto, Y. Okano, T. Yamamoto, Y. Hayakawa, Y. Inatomi, and S. Dost: Numerical investigation of the effect of heating rate on InGaSb crystal growth under zero-gravity. *Microgravity Science and Technology* 31(4), (2019) 377, <https://doi.org/10.1007/s12217-019-9698-x>
- [14]. T. Yamamoto, H. Mirsandi, X. Jin, Y. Takagi, Y. Okano, Y. Inatomi, Y. Hayakawa, and S. Dost: Numerical simulation model by volume averaging for the dissolution process of GaSb into InSb in a sandwich system. *Numerical Heat Transfer, Part B: Fundamentals* 70(5), (2016) 441 <https://doi.org/10.1080/10407790.2016.1230397>
- [15]. E. H. Snell, R. A. Judge, L. Crawford, E. L. Forsythe, M. L. Pusey, M. Sportiello, P. Todd, H. Bellamy, J. Lovelace, J. M. Cassanto, and G.E.O. Borgstahl: Investigating the effect of impurities on macromolecule crystal growth in microgravity. *Crystal Growth & Design* 1(2), (2001) 151. <https://doi.org/10.1021/cg0055474>
- [16]. C. Stelian, T. Duffar, Nicoara: Comparison between numerical simulation and experimental measurement of solute segregation during directional solidification. *J. Crystal Growth* 255, (2003) 40, [https://doi.org/10.1016/S0022-0248\(03\)01199-0](https://doi.org/10.1016/S0022-0248(03)01199-0)
- [17]. J. Yu, Y. Liu, X. Pan, H. Zhao, V. N. Kumar, M. Arivanandhan, Y. Momose, Y. Hayakawa, X. Zhang, X. Luo, Y. Okano, and Y. Inatomi: Homogeneous InGaSb crystal grown under microgravity using Chinese recovery satellite SJ-10. *npj Microgravity* (2019), <https://doi.org/10.1038/s41526-019-0068-1>
- [18]. S. Akamatsu, S. Bottin-Rousseau, V. T. Witusiewicz, U. Hecht, M. Plapp, A. Ludwig, J. Mogeritsch, M. Şerefoğlu, N. Bergeon, F. I. Mota, L. Sturz, G. Zimmermann, S. McFadden, and W. Sillekens: Microgravity studies of solidification patterns in model transparent alloys onboard the International Space Station. *npj Microgravity* 9, (2023) 83, <https://doi.org/10.1038/s41526-023-00326-8>
- [19]. H. Nguyen-Thi, G. Faivre, and M. Rappaz: On the interest of microgravity experimentation for studying solidification of metal alloys—a review. *J. Materials Processing Technology* 243, (2017) 35, <https://doi.org/10.1016/j.jmatprotec.2016.09.008>
- [20]. M. J. Vogel, S. N. Tewari, and C. E. Bugg: Directional solidification using a baffle in microgravity. *Materials Science and Engineering A* 304–306, (2001) 831, [https://doi.org/10.1016/S0921-5093\(00\)01454-X](https://doi.org/10.1016/S0921-5093(00)01454-X)
- [21]. M. E. Glicksman: Capillary phenomena during solidification. *J. Crystal Growth* 39, (1977) 311, [https://doi.org/10.1016/0022-0248\(77\)90217-2](https://doi.org/10.1016/0022-0248(77)90217-2)
- [22]. M. Conti et. al.: Pressure effects for crystal growth in a closed system. *Physical Review E* 70, (2004) 031602, <https://doi.org/10.1103/PhysRevE.70.031602>
- [23]. C. H. Su, Y. G. Sha, S. L. Lehoczy, F. R. Szoferan, D. C. Gillies, and S. D. Cobb: Crystal growth of selected II–VI semiconducting alloys by directional solidification: Part I Ground-based experiments. *J. Materials Science* 32, (1997) 3765–3768, <https://doi.org/10.1023/A:1018619522208>
- [24]. R. Trivedi, and W. Kurz: Directional solidification microstructures in diffusive and convective regimes. *J. Crystal Growth* 222, (2001) 365–379, [https://doi.org/10.1016/S0022-0248\(00\)00761-2](https://doi.org/10.1016/S0022-0248(00)00761-2)
- [25]. B. K. Dhindaw: Solidification under microgravity — review and perspectives. *Sādhanā* 49, (2024) 59, <https://doi.org/10.1007/s12046-023-01839-w>
- [26]. B. R. Sekhar, S. Som, and T. Chandra: Influence of surface tension gradients on interface morphology. *Crystal Research and Technology* 34, (1999) 467–478, [https://doi.org/10.1002/\(SICI\)1521-4079\(199909\)34:9<467::AID-CRAT467>3.0.CO;2-Z](https://doi.org/10.1002/(SICI)1521-4079(199909)34:9<467::AID-CRAT467>3.0.CO;2-Z)
- [27]. T. Yamaguchi et. al.: Growth of InSb crystals in microgravity conditions using floating-zone technique. *J. Crystal Growth* 156, (1995) 345–350, [https://doi.org/10.1016/0022-0248\(95\)00267-7](https://doi.org/10.1016/0022-0248(95)00267-7)
- [28]. J. C. Gyllenhaal, and R. D. Doherty: Interfacial phenomena in alloy solidification: review and perspectives. *Acta Metallurgica et Materialia* 40, (1992), S43. [https://doi.org/10.1016/0956-7151\(92\)90010-M](https://doi.org/10.1016/0956-7151(92)90010-M)
- [29]. S. Akamatsu, and G. Faivre: Convection-free directional solidification experiments in space. *J. Crystal Growth* 312, (2010) 500, <https://doi.org/10.1016/j.jcrysgro.2009.09.043>
- [30]. D. B. Gadkari, K. B. Lal, and B. M. Arora: Growth of high mobility InSb crystals. (Rapid Communication) *J. Cryst Growth* 175, (1997) 585
- [31]. D. B. Gadkari, K. B. Lal, and B. M. Arora: A process for the preparation and orientation growth of single self-seeded crystals of antimonide alloys and/or elementary binary or ternary semiconductors. *Indian Patent*, (Filed: 139/BOM/1999), Granted No. 192132 (2004)
- [32]. D. B. Gadkari, and B. M. Arora: Detached Solidification Influences the Crystalline Quality of GaSb Crystals Grown by Vertical Directional Solidification Technique on the Earth. *Transac. Mater Soc Japan* 34 (2009) 571
- [33]. D. B. Gadkari: Advances of the Vertical Directional Solidification Technique for the Growth of High Quality InSb Bulk Crystals, *J. Chem. Chem. Eng.* 6, (2012) 250
- [34]. D. B. Gadkari: Advances of the Vertical Directional Solidification Technique for the Growth of High Quality GaSb Bulk Crystal, *J. Chem. Chem. Eng.* 6 (2012) 65
- [35]. Dattatray Gadkari: Detached Phenomenon and Its Effect on the Thallium Composition into InSb Bulk Crystal Grown by VDS Technique. *J. Materi. Sci. Eng. A* 2 (9), (2012) 593
- [36]. D. B. Gadkari: Detached Growth: Unfolding Four Decades Growth Mystery into Vertical Directional solidification Technique on Earth, *In. J. Scien. Resea. Public.*, 4 (2012) 1
- [37]. D. B. Gadkari: Detached phenomenon: Its influence on the crystal's quality of InSb:Te grown by the VDS technique, *AIP Conf. Proc.*, 1512 (2013) 856. <http://dx.doi.org/10.1063/1.4791308>

- [39]. Dattatray Gadkari: Detached Crystal Growth in VDS Technique: A New Crystal Growth Process. *J. Materials Science and Engineering, A* 3 (5), (2013)338
- [40]. Dattatray Gadkari: Detached phenomenon: Its effect on the crystal quality of Ga (1-x)InxSb bulk crystal grown by the VDS technique. *Materials Chemistry and Physics*, 139 (2013) 375
- [41]. <https://doi.org/10.1016/j.matchemphys.2012.09.060>
- [42]. Dattatray Gadkari: Doped InSb Detached Crystals by VDS Technique: Its Substrates for Infrared Devices and Physics Concept. *In. J. Engin. Applied Sciences (IJEAS)*, 2 (2014) 3
- [43]. D. Gadkari, D. Maske, M. Deshpande, B. M. Arora: Detached/Contactless Growths, Reduced Melt Convection and Its Effect on the Device Grade Substrates of Sb-Based Crystals Grown by VDS on Earth. *In. J. Innov. Research in Sci. Engin. Techno.* 5. (2015), doi:10.15680/IJIRSET.2016.0502059 209
- [44]. D. B. Gadkari: The detached phenomenon and the fundamental science behind: The novel vertical directional solidification growth of the detached crystals by slow freezing. *Int. J. Engin. Res. Appl.*, 9 (2019) 1
- [45]. D. B. Gadkari: The homogeneous and entire detached In_{0.5}Ga_{0.5}Sb alloy crystals grown by the slow freezing using novel VDS-process. *In. J. Engin. Res. Appl.*, 10(5) 2020) 7
- [46]. D. B. Gadkari: Investigation of influence of the indium doping on the properties of the Ga(1-x)InxSb (x=0.10, 0.15, 0.25) crystals: the detached growth by the VDS-process. *In. J. Engin. Res. Appl.*, 10(9) (2020) 5
- [47]. D. B. Gadkari: Study of the Ga doped In(1-x)GaxSb (x= 0.10, 0.15, 0.25) crystals the compositional, structural, electrical, and the microstructures properties: Growth by the VDS-process. *In. J. Engin. Res. Appl.* 10(10), (2020) 35
- [48]. Dattatray B. Gadkari, Evaluation of the thermo-diffusion (Soret effect) impact across two phases of the alloys and the crystal-melt interface in In_{0.5}Ga_{0.5}Sb un-seeded crystallization growth by the VDS process. *Intern J Engin Res Appl*, 11 (2025) 121-132
- [49]. S. Akamatsu, S. Bottin-Rousseau, V. T. Witusiewicz, and U. Hecht: Microgravity studies of solidification patterns in model transparent alloys onboard the International Space Station. *npj Microgravity* 9, (2023) 83. DOI: 10.1038/s41526-023-00326-8.
- [50]. B. K. Dhindaw: Solidification under microgravity, *Sādhanā* 26 (2024)59–69.
- [51]. K. Jackson: Microgravity crystal formation — retrospective meta-analysis. *Crystals*, 14 (2023) 12. DOI: 10.3390/cryst14010012.
- [52]. J. Strickland, J. Newman, and M. Rappaz: On directional dendritic growth and primary spacing — a historical review. *Crystals*, 10(7) (2020) 627. DOI: 10.3390/cryst10070627.
- [53]. W. R. Wilcox: Microgravity effects on materials processing — review. *NASA Report 2003* includes extensive discussion of Marangoni convection and surface tension influence in microgravity.
- [54]. A. McPherson: Microgravity protein crystallization, *J. Synchrotron Rad.*, 22, (2015) 144–156.