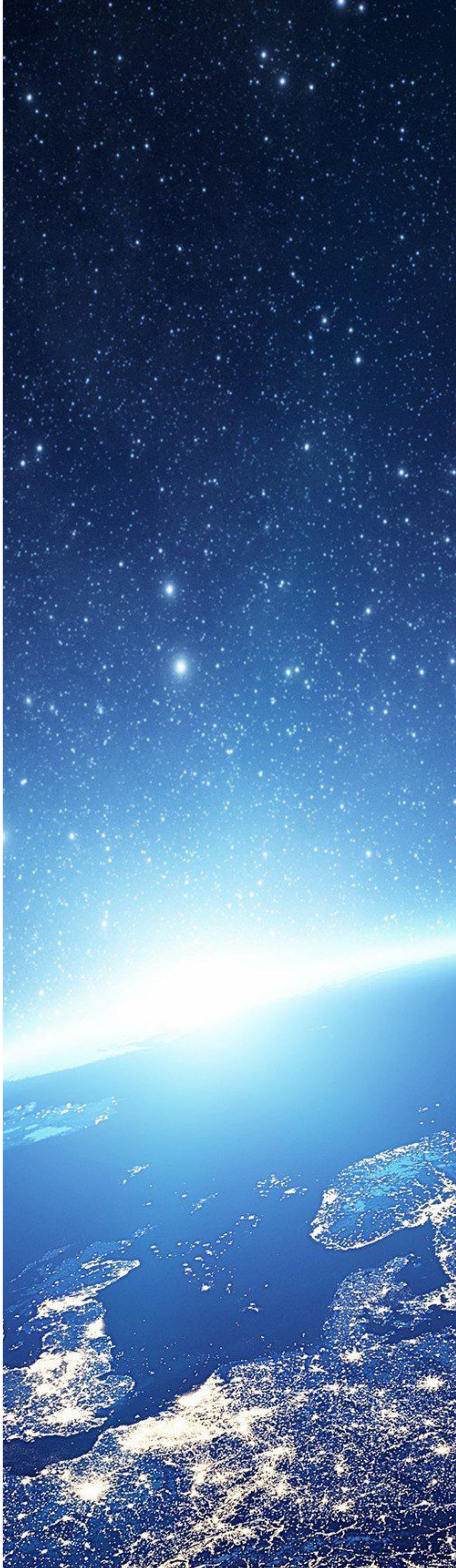
Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use



Jessica J. Frick, Stanford University, XLab
Erik Kulu, Factories in Space
Gary Rodrigue, Allbright Consulting
Curtis Hill, NASA, Jacobs
Debbie G. Senesky, Stanford University, XLab

Contents

Contributors and Acknowledgments

The authors would like to acknowledge the efforts of all the participants of the Stanford University Workshop on Semiconductor Manufacturing in the Space Domain, whose valuable contributions informed the key recommendations of this paper.

Navid Alinejadian
KTH Royal Institute of Technology

Christopher Allison
Sierra Space

Tanvi Arey
Purdue University

Zakaria Al Balushi
University of California, Berkeley

Salil Bapat
Purdue University

Alain Berinstain
Space Tango

Brock Birdsong
Auburn University

Ellen Bock
Northrop Grumman

John Chen
Silfex

Rachel Clemens
Axiom Space

Sergio Cordero
Stanford University

Jasmine Cox
Stanford University

Ioana Cozmuta
G-Space

Rituparna Curt
Stanford University

Michael Curtis
Boise State University

Sahil Dagli
Stanford University

Amrit De
Apsidal

Alexander van Dijk
NASA

Partha Dutta
United Semiconductors

Vivek Dwivedi
NASA

Sana Elyas
Orbital Composites

Kevin Engelbert
NASA

Joe Epstein
Lockheed Martin

Noah Feingold
Stellar Ventures

Jessica J. Frick
Stanford University

Ram Gandhiraman
Space Foundry

Daniel Gutierrez
Space Foundry

Lynn Harper
NASA

Rose Hernandez
ISS National Lab

Michael Heuken
AIXTRON

Zahra Nenna Heussen
Stanford University

Curtis Hill
NASA

Micheal Holguin
Nanoracks

Roger Howe
Stanford University

Mitchell Hsing
InchFab

Steven Huning
NASA

Han Jansen
G-Space

Kuang-Han Ke
Gran Systems

Vinay Kenny
Purdue University

Jessica Koehne
NASA

Katheryn Kornegay
Stanford University

Jason Krizan
Independent

Erik Kulu
Factories in Space

Simon Lancaster
Omni Venture Labs

Rick Lazansky
Silicon Catalyst

Zhou Li
Stanford University

Alex Li
Nvidia

Roya Maboudian
University of California, Berkeley

Masoud Mahjouri-Samani
Auburn University

Robert Malakhov
NextFlex

Arturo Mateos
Northrop Grumman

Ajay P. Malshe
Purdue University

Alastair McGibbon
Space Forge

Matt Napoli
NASA

Ranga Narayanan
University of Florida

Adrian Nosek
Apsidal

Rachel Ormsby
Redwire

Remus Osan
G-Space

Youkabed Ostadhossein
PARC

Heidi Parris
NASA

Shaun Peiffer
ISS National Lab

Greg Pitner
TSMC

Bruce Pittman
Skycorp

Jackson Pitts
Apsidal

Ovi Popescu
AeroPro

Craig Pritsky
BryceTech

J Provine
Aligned Carbon

Geeta Rajagopalan
Oracle

Monsuru Ramoni
Navajo Technical University

Dan Rasky
NASA

Somilkumar Rathi
Independent

Gary Rodrigue
ALLBRIGHT Consulting

Tara Ruttley
Orbital Reef

Ashwyn Sam
Stanford University

Myeonglok Seol
NASA

Ashwin Seshia
University of Cambridge

Sadas Shankar
Stanford University

Roger Smith
Sierra Turbines

Debbie G. Senesky
Stanford University

Miki Sode
Futurity Systems

James Stott
NASA

Chen-li Sun
National Taiwan University

Gaurav Thareja
Applied Materials

Sudhanshu Tiwari
Purdue University

Raghav Vanga
Lumentum

Jonathan Volk
Sierra Space

Martin Volz
NASA

Taylor Waddell
NASA

Jacky Wan
University of California, Riverside

Tiffany Wang
Stanford University

Noor Ward
ISS National Lab

David Wiliams
The Ohio State University

Todd Younkin
Semiconductor Research Corporation (SRC)

Ellen Zeng
Stanford University

Wenlong Zhang
Arizona State University

Charles Zhang
3M

The authors would like to acknowledge the contributions of key sponsors of the Stanford University Workshop on Semiconductor Manufacturing in the Space Domain, the results of which are captured in this white paper.

Finally, the authors would like to recognize key inputs from colleagues across the industry whose expertise contributed to this white paper.

This white paper was compiled and designed by Nexight Group.

Acronyms and Abbreviations

Acronyms and abbreviations and their definitions.

ACRONYM	DEFINITION
AAS	American Astronautical Society
ACCGE	American Conference on Crystal Growth and Epitaxy
ACS	American Chemical Society
AFOSR	Air Force Office of Scientific Research
AI	Artificial Intelligence
ASGSR	American Society for Gravitational and Space Research
ASTP	Apollo-Soyuz Test Project
CASIS	Center for the Advancement of Science in Space
CCDS	Centers for the Commercial Development of Space
CHIPS Act	Creating Helpful Incentives to Produce Semiconductors Act
CLD	Commercial LEO Destination
COSMIC	Consortium for Space Mobility and ISAM Capabilities
CVD	Chemical vapor deposition
DARPA	Defense Advanced Research Projects Agency
DGCM	Discovery and growth of crystalline materials
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ELF	Electrostatic Levitation Furnace
ESA	European Space Agency
EU	European Union
FY	Fiscal Year
HV	High vacuum
IC	Integrated circuit
InSPA	In-Space Production Applications
IP	Intellectual property
ISAM	In-space servicing, assembly, and manufacturing
ISS	International Space Station
ISSRDC	International Space Station Research and Development Conference

ACRONYM	DEFINITION
JAXA	Japan Aerospace Exploration Agency
kg	Kilogram
kW	Kilowatt
LEO	Low-Earth Orbit
LGF	Low Gradient Furnace
MFER	Material Furnace Experiment Rack
MRL	Manufacturing Readiness level
MRS	Materials Research Society
MSFC	Marshall Space Flight Center
MSL	Materials Science Laboratory
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NLRA	National Lab Research Announcement
NPJ	Nature Portfolio's Journal
NSF	National Science Foundation
OMVPE	Organometallic Vapor Phase Epitaxy
Pa	Pascal
PCB	Printed circuit board
PI	Principal investigator
PVD	Physical vapor deposition
R&D	Research and development
SBIR	Small Business Innovation Research
SQF	Solidification and Quenching Furnace
STEM	Science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer
SUBSA	Solidification Using a Baffle in Sealed Ampoules
SVEC	Space Vacuum Epitaxy Center
TRL	Technology Readiness Level
μg	Microgravity
UHV	Ultra-high vacuum
UK	United Kingdom
USSR	Union of Soviet Socialist Republics
WSF	Wake Shield Facility

Chemical elements, formulas, and compounds

FORMULA	COMPOUND
AlGaAs	Aluminum gallium arsenide
AlSb	Aluminum antimonide
BiSb	Bismuth antimonide
CdTe	Cadmium telluride
GaAs	Gallium arsenide
GaN	Gallium nitride
GaSb	Gallium antimonide
Ge	Germanium
GeSe	Germanium monoselenide
InSb	Indium antimonide
MoS2	Molybdenum disulfide
PbTe	Lead telluride
$RbAg_4I_5$	Rubidium silver iodide
Si	Silicon
SiC	Silicon carbide
SiO	Silicon monoxide
SiO_2	Silicon dioxide

1 Executive Summary

In-space manufacturing offers technological innovation, advancements, and discoveries unbound by Earth's gravitational forces. To harness the full potential of manufacturing in low-Earth orbit (LEO), industry leaders gathered at Stanford University in March 2023 at the inaugural Semiconductor Manufacturing in the Space Domain Workshop to discuss the past, present, and future of the field. This workshop brought together a community of experts to explore the rich history of semiconductor and in-space manufacturing. These experts and their foundational research and collaboration are the driving force behind this paper.

The workshop's priority was to identify the 2030 goals that must be reached to make in-space semiconductor production a reality by 2050. **The consensus was that the field needs to take the remaining years to de-risk investment from semiconductor corporations and private investors.** To do that, the community needs to obtain more iterative data on promising semiconductor R&D in LEO. This would include the whole range of experiments in the semiconductor production phases such as crystal growth, wafer processing, epitaxial growth, circuit patterning, etc. Beyond synthesizing the takeaways from the workshop, the report describes the current state of semiconductor manufacturing in space and carves out a path for the future.

Over the past three decades, the deteriorating discovery and growth of crystalline materials (DGCM) capacity in the United States has significantly stalled the domestic semiconductor industry. This report intends to regain U.S. attention to space-based semiconductor manufacturing and bring the field back from hibernation. The Vision for 2050 and Call to Action sections, informed by both industry and history experts, propose actionable solutions that can awaken the semiconductor industry from nearly 25 years of inactivity in space.

The benefits of semiconductor manufacturing in LEO are clear. Earth's gravitational forces pose substantial barriers to quick, high-yield semiconductor production. Beyond the scientific benefits of microgravity, there are substantial practical benefits to incorporating LEO-based manufacturing into the supply chain. Transitioning this industry into space is the only path forward if the United States is to keep pace with the technological arms race unfolding across the globe.

This report identifies opportunities to strengthen U.S. leadership in the LEO-based semiconductor manufacturing field. The industry urgently needs a roadmap for both immediate and long-term funding strategies that can support various components. Long-term government investments can help de-risk additional private investments, and funding student fellowship programs will drive workforce development.

Beyond a need for funding, the industry needs a designated collaborative community ecosystem. This field is currently situated alongside several related fields, and gaining traction in established fields is certainly necessary. However, there is a clear need for a designated "home" and community that can draw on knowledge from academia, the space sector, and the semiconductor industry. A push towards this collaborative environment will only benefit the industry at large and give the United States a competitive edge in this growing field.

This paper will explain the scientific basis for this industry in the proceeding sections. Discussions of the past and present of semiconductor manufacturing in LEO will provide the necessary context for the various author recommendations to develop the industry.

1.1 Definitions of Key Terms

Semiconductor. This is a class of advanced materials that possess unique electrical properties which can be regulated to allow for tasks like information storage and processing in electronic circuits. They are the crucial foundation of a wide range of electronic devices, such as smartphones, computers, and even advanced military systems. The significance of semiconductors cannot be overstated. They underpin the technological advancements that shape modern society, impacting everything from communication and transportation to healthcare and national defense.

LEO. Low-Earth orbit is one type of Earth-centered orbit that is defined as having an altitude of 1,200 miles or less. For context, this is approximately the straight-line distance between Chicago, IL and Miami, FL. LEO is the nearest type of orbit around Earth and therefore requires the lowest amount of energy for satellite and space station placement and is the most accessible orbit for crew and servicing. LEO is home to the International Space Station (ISS, ~250 miles above Earth), the Hubble Space Telescope (~340 miles above Earth), and numerous telecom satellites (for smartphone communications) and Earth observation satellites (for environmental monitoring).

Microgravity. Gravity is one of the four fundamental forces of nature. It is a force of attraction between any two objects with mass. The gravity we experience on the surface of the Earth is referred to as "g". The gravity in LEO is referred to as microgravity, or "μg", because the gravitational force is much weaker compared to that on Earth. Therefore, any science performed on the ISS or in LEO is considered to be in a μg environment. "Zero gravity" is a common misnomer for this environment. Additionally, a microgravity environment cannot be replicated in a laboratory on Earth. There are techniques that can afford short durations (1–20 sec) of low g (acceleration < g), such as drop towers, skydiving, parabolic flights, and suborbital flights which can achieve up to 4 minutes of microgravity. However, prolonged periods of microgravity, in the order of hours, are typically required to produce robust, iterative data for semiconductor manufacturing; therefore, semiconductor processing experiments in microgravity must be performed in LEO.

Terrestrial Use. This term, often referred to in the field as "in-space, for Earth," encompasses the goal of using the unique environment of microgravity to improve upon, address challenges of, or discover technologies that can be used to benefit life on Earth. **This report is specifically focused on what manufacturing verticals within the global semiconductor supply chain should be executed in LEO and sold as products for Earth use.**

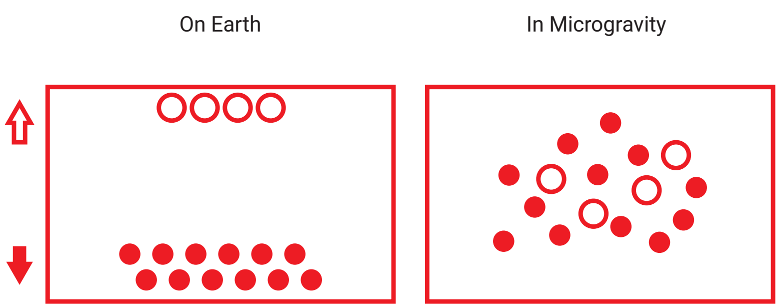
Beyond Silicon. Electronics have traditionally relied on silicon-based semiconductors for devices like computers and smartphones. However, silicon cannot fundamentally keep up with the rapidly increasing market demands. The industry must move "beyond silicon" and incorporate new materials to meet this demand. Industries like electric vehicles and the Internet of Things require more efficient devices made of other semiconductor materials like diamond, gallium nitride (GaN), graphene, and silicon carbide (SiC). These materials offer enhanced performance, efficiency, and power handling; the results are benefits like longer battery life, higher operating frequencies, and improved thermal performance.

Establishing a robust LEO environment for semiconductor manufacturing is of the utmost importance as humanity's dependence on semiconductors goes "beyond silicon." This is because the immense benefits LEO has to offer are those that cannot manifest anywhere on Earth due to detrimental effects of gravity. In brief, the benefits include improving known, terrestrial-based semiconductor manufacturing processes which can result in physically larger and higher-quality semiconductors. Simply put, these benefits have the potential to translate into increased production volumes of semiconductor devices with increased efficiency and performance. This can provide a competitive edge to companies that know how to use it. In addition to improving known processes, semiconductor manufacturing in LEO unlocks a new degree of freedom (i.e., gravity) in research and development (R&D), enhancing the probability of science and technology advancement through "surprise" for future U.S. innovation.[1] The following sections will review in detail what specifically about the LEO environment—where one of the four fundamental forces of nature is removed—is beneficial to semiconductor manufacturing.

2.1 The Behavior of Liquids and Gases in Microgravity

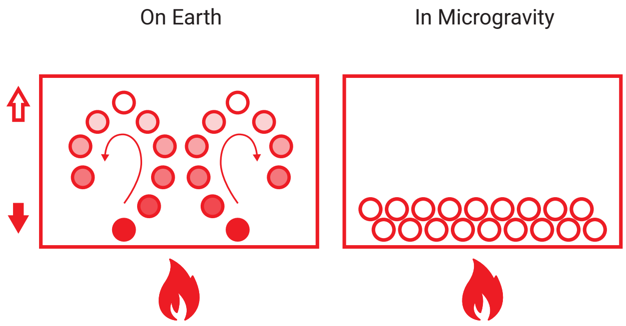
Many, if not all, of advanced material manufacturing processes involve liquid and/or gaseous states of matter. For example, casting, injection molding, and 3D printing involve the use of liquid materials or molten metals to create intricate shapes. The underlying principle of these processes rely on human's innate understanding of liquid behavior under gravity. Pouring a cup of tea guarantees the liquid will take its shape and remain in the container, unless knocked over. Similarly, various deposition techniques, such as chemical vapor deposition (CVD) and physical vapor deposition (PVD), rely on gaseous states of matter to deposit thin films and coatings onto surfaces. Again, the underlying principle for these processes relies on human understanding of how gases behave under gravity—for instance, the resistance and buoyancy of air provides a bird with the necessary lift and thrust to take off. Moreover, in industries like pharmaceuticals, food processing, and chemical refining, liquid and gas phases are frequently employed in manufacturing processes for mixing, separation, and purification purposes.

What is it specifically about the *behavior of liquids and gases* that changes when the effects of gravity are significantly reduced? There are four key factors to consider:

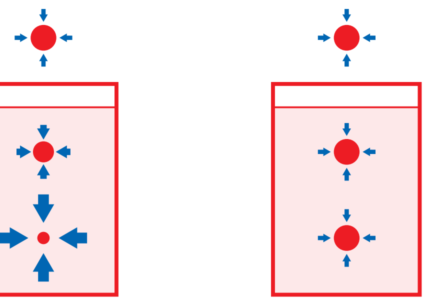


1. **Absence of Buoyancy & Sedimentation.** On Earth, a material's density (mass per unit volume) determines whether it will float (buoyancy) or sink (sedimentation). For example, when adding honey and olive oil to a glass of water, the honey will sink to the bottom of the glass while the olive oil will float on top. In microgravity, the relative density of substances does not matter—meaning that the mixture of honey, olive oil, and water will disperse much more evenly. This enables greater precision, improved materials structure, and increased uniformity in microgravity.

1 Yin, Z., Zhang, X., Wang, W., Li, X., & Yu, J. (2019). Melt Growth of Semiconductor Crystals Under Microgravity. *Physical Science Under Microgravity: Experiments on Board the SJ-10 Recoverable Satellite*, 327–360. https://doi.org/10.1007/978-981-13-1340-0_13



2. **Absence of Convection.** This is the most complicated and technical consideration. The best way to understand this phenomenon is to consider thermal convection, which relies on understanding the relative densities of a substance. On Earth, when heating a pot of water, for example, the water closer to the heat source gains energy (i.e., becomes warmer), and therefore becomes less dense and rises to the top. This cycle of warm liquid rising and cool liquid falling creates the cycle called convection. This phenomenon is alleviated in microgravity because of the absence of buoyancy and sedimentation. For a more thorough discussion, review "Convection Phenomena of Importance for Materials Processing in Space" by Prof. Simon Ostrach.[2]



3. **Absence of Hydrostatic Pressure.** This is the pressure exerted by a fluid in a confined space due to the weight of the fluid itself. Atmospheric pressure is mostly approximated by the hydrostatic force due to the weight of the air on the surface of the Earth. The closer an object is to Earth's surface, the more air that is above it, resulting in higher atmospheric pressure. This phenomenon is completely dependent on gravity and is therefore weakened in microgravity, helping with precision placement of materials.

4. **Absence of Container Requirements.** Without costly and intricate methods of intervention, liquids cannot be confined on Earth without the use of containers, with which they must be in direct contact. Microgravity alleviates the need for containers, which on Earth can create disadvantages in semiconductor processing such as size limitations and sample contamination.

In addition to the four key physical considerations listed above, there are several advantages to manufacturing semiconductors in LEO:

- **Access to 'Free' Vacuum.** The vacuum in LEO ranges from 10^{-5} to 10^{-8} Pascal (Pa). For context, many semiconductor manufacturing processes occur at high vacuum (HV) and ultra-high vacuum (UHV), below 10^{-1} Pa and 10^{-6} Pa, respectively. One can imagine easily evacuating a process chamber through a port built into the side of a LEO manufacturing platform.

- **Access to Solar Energy.** In LEO, there is no atmosphere to scatter or absorb the Sun's radiation, enabling direct exposure to the Sun's solar energy. Therefore, efficient energy harvesting to use and store can take place when an orbiting body is exposed to direct sunlight.

- **Access to Low Environmental Impact Location.** Semiconductor manufacturing can incur air pollution, and the energy consumption itself uses sources that contribute to greenhouse gas emissions. Emissions from processes performed in LEO can mitigate effects to the environment and human health on Earth. Additionally, the proximity to solar renewable energy sources (as mentioned above) cuts dependence on greenhouse gas emissions.

---

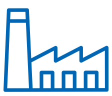
2 Ostrach, S. (1977). Convection Phenomena of Importance for Materials Processing in Space. *Materials Sciences in Space with Application to Space Processing*, 3–32. https://doi.org/10.2514/5.9781600865268.0003.0032

2.2 LEO Benefits to the Semiconductor Supply Chain

Understanding the fundamental alterations in the behavior of liquids and gases in microgravity informs which processes within the global semiconductor supply chain derive advantages from being conducted in LEO. These advantages can potentially reach a level at which the benefits outweigh the costs associated with off-planet operations.

To establish the current global semiconductor supply chain landscape, the following example uses a smartphone as the consumer end product whose core processing depends on semiconductor devices. Figure 1 gives a graphical representation of the following stages of production:

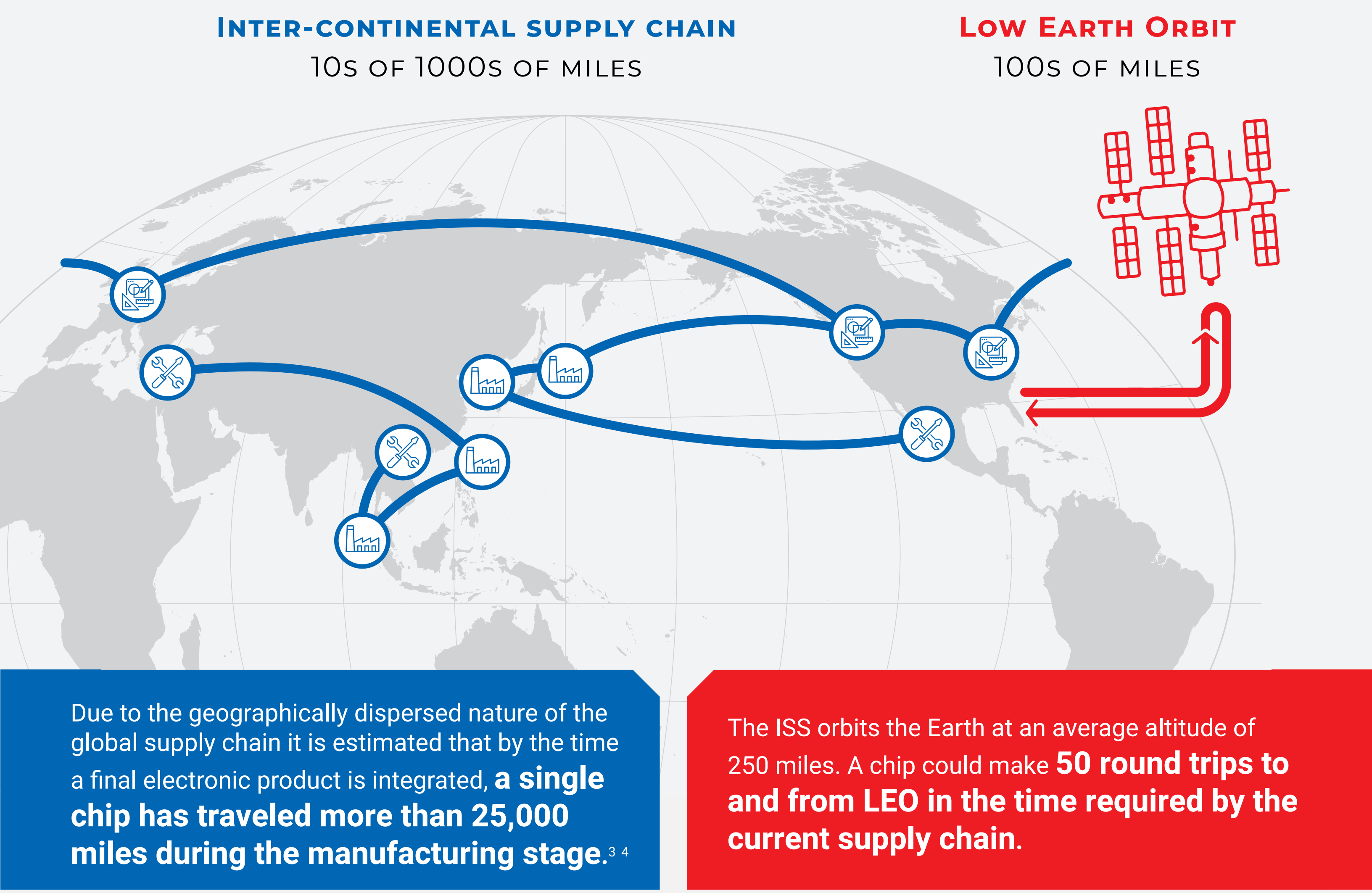
1. **Design.** Semiconductor companies design integrated circuits (ICs) that serve specific functions within the smartphone (e.g., memory, image sensors, filters). This stage is primarily performed in the United States and the European Union (EU).



2. **Manufacturing.** This is the actual physical manifestation of the devices. Most of this stage is performed in China, Taiwan, South Korea, Japan, and Malaysia. Manufacturing encompasses many important steps, including:

    a. **Substrate Production.** Typical silicon-based technology requires growth of silicon (Si) crystals to be cut and polished into wafers. These wafers are used as the substrate, or building foundation, for the device fabrication.

Figure 1. *Inter-Continental Semiconductor Supply Chain*



b. **Device Fabrication.** On top of the substrate, processes such as epitaxial layer deposition and circuit patterning (a series of 20–30 steps involving photolithography, deposition, etching, and implantation techniques), are executed to create the ICs.

c. **Chip Creation.** Once the wafer is patterned, it is sliced into chips; these are individual semiconductor devices. Depending on the size of the wafer, the size of the designed ICs, and rejection rate, one can achieve anywhere from several hundred to a few thousand chips per wafer.

d. **Packaging.** Individual chips are encapsulated into protective casings and connected to external leads to provide the necessary connections for power and data transfer.

3. **Integration.** The packaged devices are integrated into the smartphone during the assembly of the device. They are mounted onto the smartphone's printed circuit board (PCB), along with other necessary components. The PCB acts as a central brain that connects all the neurons (semiconductor chips) that work together to form a functioning electronic device. This stage is primarily performed in China, Taiwan, and Vietnam.

Within the manufacturing stage of semiconductor device development, aspects of the Substrate Production and Device Fabrication steps that can benefit from being conducted in LEO have been identified. These aspects are discussed below.

2.2.1 Substrate Production

The Neglected 2009 Report

In 2009, The National Research Council of the National Academies convened the Committee for an Assessment of and Outlook for New Materials Synthesis and Crystal Growth. The goal was to assess current work and new opportunities in the United States in the field of DGCM.[5] Semiconductors were a major focus area of this study, and the committee found that over the past 20 years, "the US' capabilities in DGCM has seen a substantial deterioration." They stressed the point that "if these trends continue, U.S. scientists, engineers, and industrial facilities either will become dependent on materials developed and grown outside the United States or will not have access to needed materials at all." Unfortunately, the findings of this report were ignored. The trend since this publication in 2009 continued, leading to what the committee feared: complete U.S. dependence on Asia for all Si crystalline substrates. **Today, Asia dominates the single crystal Si wafer market, holding a market share of over 70 percent in 2021.[6] If the United States does not act now on DGCM in next-generation semiconductors materials (e.g., diamond, silicon carbide (SiC), GaN), it will meet the same fate as Si.**

Documented Benefits of Semiconductor Crystal Growth in LEO

The microgravity environment of LEO offers a major opportunity for DGCM. In 2022, a team of researchers led by Professor Anne Wilson of Butler University published, "An Analysis of Publicly Available Microgravity

3 Do we see an end to the chip shortage? (2022, April 20). *Electronics Sourcing*. https://electronics-sourcing.com/2022/04/20/do-we-see-an-end-to-the-chip-shortage/

4 In-depth Analysis of the Global Semiconductor Supply Chain [Blog post]. (2022, January 20). *Utmel*. https://www.utmel.com/blog/categories/semiconductor/in-depth-analysis-of-the-global-semiconductor-supply-chain

5 National Research Council of the National Academies of Science. (2009). *Frontiers in Crystalline Matter: From Discovery to Technology*. The National Academies Press: Washington, DC. https://doi.org/10.17226/12640

6 GlobeNewswire. (2023, February 8). Single Crystal Silicon Wafers Market to Cross USD 14.6 Billion by 2028, at a CAGR 5.50% from 2022–2028 Thanks to Increasing Trend of Digitization and Electronic Mobility. *SkyQuest*. https://www.globenewswire.com/news-release/2023/02/08/2603935/0/en/Single-Crystal-Silicon-Wafers-Market-to-Cross-USD-14-6-Billion-by-2028-at-a-CAGR-5-50-from-2022-2028-Thanks-to-Increasing-Trend-of-Digitization-and-Electronic-Mobility.html

Crystallization Data: Emergent Themes Across Crystal Types."[7] This study was pivotal in understanding exactly how widespread and intense the benefits of a microgravity growth environment are to semiconductor crystals. The database comments on the improvements of microgravity-grown semiconductors in terms of size, structure, and uniformity. It is updated every Friday and publicly available.[8] At the time of publication, more than 160 semiconductor crystals were identified in the Butler database (July 2023). Over the past decade, most came from outside the US. The study reported that for semiconductor crystals processed in LEO compared to terrestrial samples, more than 80 percent improved in either one or a combination of structure, uniformity, reduction of defects, and/or electrical and optical properties–and some by orders of magnitude.[9] [10]

One analysis of these results on cadmium telluride (CdTe) crystals grown in microgravity (n = 9) concluded that improvements in crystal size and uniformity, combined with a decrease in orders-of-magnitude of defects, has the potential to increase yield of the final CdTe solar cell by greater than 150 percent.[11] How exactly this increase in yield could affect the revenue gains along the semiconductor supply chain is still not known. An increase in yield by just 3 percentage points can be worth as much as 6 percent in gross revenue, and it is hypothesized that a 150 percent increase in semiconductor yield from LEO manufacturing could have game-changing monetary advantages.[12] To reiterate, this is just considering how the microgravity environment of LEO increases product yield, not the additional benefits in crystal quality. Those benefits could lead to extended product lifetimes, increased solar efficiency, and wider operating ranges, which themselves would lead to monetary benefits along the semiconductor supply chain.

Learning From the Past 70 Years of Silicon Crystal Growth

Society today is heavily reliant on silicon (Si) technology, the development of which started when Si crystals were first grown in 1950, two years after the invention of the transistor on germanium (Ge).[13] Since then, Si crystal growth technology has evolved from producing ingots of 10s of mm (~10 kg) to ingots up to 450 mm in diameter (550-600 kg).[14] Without this 45,000 percent increase in production scale, the Si-based society of today would simply not exist.

Along this 70-year road of evolution, intricate systems were needed for the simple crystal growth method to fight the detrimental effects of gravity. Buoyancy and convection (discussed in Section 2.1) are responsible for many gravity-induced issues in Si crystal growth including dopant striation, interface instability, and oxygen impurity transport, among others. To combat these issues, Si crystal growers employ crystal rotation and strong magnetic fields which add significant cost and complexity to the growth system.[15] Additionally, the massive weight of the molten Si itself adds cost and system complexity from the methods employed to physically support crystal growth.

Other gravity-facilitated issues concern contamination by container interaction. This requires maintaining a high vacuum and argon flow to remove silicon monoxide (SiO) gas and prevent oxygen defects. SiO gas is

7 Wright, H., Williams, A., Wilkinson, A., Harper, L., Savin, K., & Wilson, A. M. (2022). An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types. *Crystal Growth & Design, 22*(12), 6849–6851. https://doi.org/10.1021/acs.cgd.2c01056

8 Official Semiconductor Data Set—Butler University [Google Docs]. (n.d.). (Butler University). https://docs.google.com/spreadsheets/d/1Zl_B_IbC_UFx4VfFamhCQcGgUdtk64r6wOdQ_wO3lHU/edit

9 Harper, L. (2023, March 27-28). What is happening now? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

10 Wright, H., Williams, A., Wilkinson, A., Harper, L., Savin, K., & Wilson, A. M. (2022). An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types. *Crystal Growth & Design, 22*(12), 6849–6851. https://doi.org/10.1021/acs.cgd.2c01056

11 Frick, J. (2023, March 27-28). What is happening now? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

12 Bohn, R. E., & Terwiesch, C. (1999). The economics of yield-driven processes. *Journal of Operations Management, 18*(1), 41–59. https://doi.org/10.1016/S0272-6963(99)00014-5

13 Dukat, F. M. (2019, February 19). The Transistor in Industry. (RFCafe). : https://www.rfcafe.com/references/radio-news/transistor-industry-may-1956-radio-television-news.htm

14 Shimura, F. (2007). Single-Crystal Silicon: Growth and Properties. *Springer Handbook of Electronic and Photonic Materials*, 255–269. https://doi.org/10.1007/978-0-387-29185-7_13

15 Chen, J. (2023, March 27–28). Demystifying semiconductor device fabrication [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

created when the molten Si reacts with the quartz (SiO_2) growth container. Unfortunately, the requirement of a container to hold the molten Si will invariably lead to impurity concentrations of oxygen (~$5x10^{17}$ cm^{-3}) and carbon (~$5x10^{15}$ cm^{-3}) and microdefects in the range of $1x10^6$ to $1x10^7$ cm^{-3}.

Instead of adding complexity and cost to the system of single crystal growth to fight against gravity (i.e., prevent buoyancy and thermal convection, combat container contamination, and physically support a molten mass), production should move to the ideal environment of space. In the short term, a large investment will be required to establish crystal growth infrastructure in LEO; in the long term, the more amenable crystal growth environment has the potential for substantial benefits.

Concerning cost, it is difficult to put a dollar amount on the investments made specifically to Si crystal growth infrastructure over the last 70 years. However, the recent investments of global leaders in Si wafer production can help estimate the order of magnitude:

In July 2022, GlobalWafers, a Taiwanese company, announced it is building a $5 billion facility in Texas to "shore-up" Si wafer production for their customers such as Intel and Texas Instruments.[16] In July 2023, Japan announced that it would subsidize SUMCO up to $530 million for their new Si wafer factories in the south of Japan.[17] For context, one of the private space stations in development, Orbital Reef, is expected to cost in the range of $10 billion.[18]

At this point in society's dependence on Si technology, it does not make economic sense to shift production of single crystal Si to space; 10s of billions, if not 100s of billions of dollars' worth of infrastructure is established on Earth. However, as humanity evolves beyond Si technologies, the United States can begin the process of moving next generation semiconductors (e.g., diamond, SiC, GaN) to space and gain a competitive edge from the start. In this way, perfecting mass scale production of next generation semiconductors could be condensed into a single decade rather than the 70 years it took to fight gravity for Si boules.

2.2.2 Device Fabrication

The way in which the microgravity environment scientifically benefits device fabrication is not as well-known as substrate production. This is purely because there have been only a handful of these studies in LEO over the past 50 years, as opposed to the over 160 crystal growth experiments documented. One set of experiments, to be discussed in Section 3.1, includes epitaxial growth of III-V semiconductors in the 1990s as part of the Wake Shield Facility program. Nevertheless, there are aspects of device fabrication that could, in theory, scientifically benefit from a microgravity environment. These aspects are discussed below; however, substantial R&D efforts are still required to pinpoint where exactly along the production line microgravity manufacturing could benefit the most.

Within the umbrella of device fabrication, there exists two complementary technologies: conventional and printed devices, with the latter being the more nascent field. For reference, conventional devices are key components of products on the market today, like consumer electronics (e.g., smartphones, laptops, gaming consoles), whereas most printed device applications are still in the prototyping and development stages. Sixty flight iterations on parabolic aircraft are currently planned to test the printer before the experiments are conducted on the ISS.

16 Morra, J. (2022, July 8). GlobalWafers to Build $5 Billion Facility in U.S. to Shore Up Wafer Supply. *Electronic Design*. https://www.electronicdesign.com/technologies/analog/article/21246073/electronic-design-globalwafers-to-build-5-billion-facility-in-us-to-shore-up-wafer-supply

17 Nagao, R. (2023, July 11). Japan to give $530m for new Sumco silicon wafer plants at home. *Nikkei Asia*. https://asia.nikkei.com/Business/Tech/Semiconductors/Japan-to-give-530m-for-new-Sumco-silicon-wafer-plants-at-home

18 Boyle, A. (2021, October 25). Blue Origin teams up with Sierra Space, Boeing and others on 'Orbital Reef' space station project. *GeekWire*. https://www.geekwire.com/2021/blue-origin-teams-sierra-space-boeing-others-orbital-reef-space-station-project/

There are numerous techniques that exist within conventional or printed device fabrication, many of which are employed multiple times throughout the fabrication of a modern semiconductor device. For context, a non-exhaustive list of conventional and printed Device Fabrication techniques is presented to the right.[19]

The technological benefits of performing device fabrication in microgravity are not as clear-cut as those found for crystal growth. It is not that they do not exist, but rather that this is an emergent field that still requires much fundamental work.

For printed device fabrication, microgravity offers benefits to non-contact printing techniques, including, but not limited to:[20]

- Less aggregation and sedimentation of colloidal active materials enables significantly higher stability and longer ink shelf life.
- Higher stability of materials allows more loading of active materials (fewer additives to remove by post-processing).
- Higher concentrations of the active material in inks allow superior electrical and mechanical performance and long-term device stability.

For context, current collaborations between NASA and Intel estimate that the benefits of microgravity processing of printed devices could save up to $1 per chip. This could scale to billions of dollars in savings, making microgravity semiconductor manufacturing research as economically lucrative as it is scientific. This would scale to billions of dollars in savings, making microgravity semiconductor manufacturing research as economically lucrative as it is scientific.

Conventional Device Fabrication Techniques

Piranha cleaning
Ion implantation
Atomic layer deposition
Thermal annealing
Surface passivation
Etching
Physical layer deposition
Electrochemical deposition
Photolithography
Chemical vapor deposition
Molecular beam epitaxy
Chemical-mechanical polishing

Printed Device Fabrication Techniques

Screen*
Inkjet
Gravure*
Aerosol jet
Magnetohydrodynamic
Electrohydrodynamic

* Contact printing techniques; all others are non-contact printing techniques.

3 The Past: Background & History of Semiconductor Manufacturing in LEO

The origins of in-space manufacturing began with symposiums and conferences to discuss the future of the field. The first Space Processing Symposiums were held in 1968, 1969, and 1974, and the first Space Manufacturing conferences at Princeton University began in 1975. In the early years, space manufacturing was often called “space processing” or “materials processing in space.”[21] These symposiums laid discussion groundwork which subsequently consolidated into roadmaps that established goals and methods of advancement for manufacturing in space.

Eventually, these space manufacturing roadmaps progressed into networks and centers of excellence for research in the area. In 1985, the National Aeronautics and Space Administration (NASA) initiated Centers

19 Šakalys, R., Mohammadlou, B. S., & Raghavendra, R. (2022). Fabrication of multi-material electronic components applying non-contact printing technologies: A review. *Results in Engineering, 15*, 100578. https://doi.org/10.1016/j.rineng.2022.100578

20 Hill, C. (2023, March 28). The Future of Semiconductor Processing in Space – How do we spend money to make money (in Space)? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

21 Wuenscher, H. F. (1970). Unique Manufacturing Processes in Space Environment. (Space Congress: Session 7 – Manufacturing Processes in Space). https://commons.erau.edu/space-congress-proceedings/proceedings-1970-7th/session-7/4

for the Commercial Development of Space (CCDS), a handful of which focused on space-based materials processing. These included:[22]

- Battelle's Advanced Materials Center for the Commercial Development of Space
- The Vanderbilt Center for the Space Processing of Engineering Material
- The Consortium for Materials Development in Space, established at the University of Alabama in Huntsville
- The Clarkson University Center for Commercial Crystal Growth
- The Space Vacuum Epitaxy Center (SVEC) at the University of Houston.

Figure 2 represents NASA's funding strategy for these five CCDS from 1986 to 1989. The goal of these centers was to bring academia, industry, and government together to develop commercialization of advanced materials in space. However, starting in the 1990s with the development of the crewed International Space Station, there was a notable shift in investigative priorities to fields with experimental requirements more amenable to human presence. The U.S. government's deprioritization of this field resulted in space-based materials processing communities losing precious momentum. A loss of institutional knowledge on the subject commenced over the next two decades.

There is no one reason for the slow-down of semiconductor manufacturing work in space, and there was no true consensus from the workshop participants. However, it can be theorized what factors led to the loss of momentum and what has changed in the past few decades to make now the right time to bring the field out of hibernation.

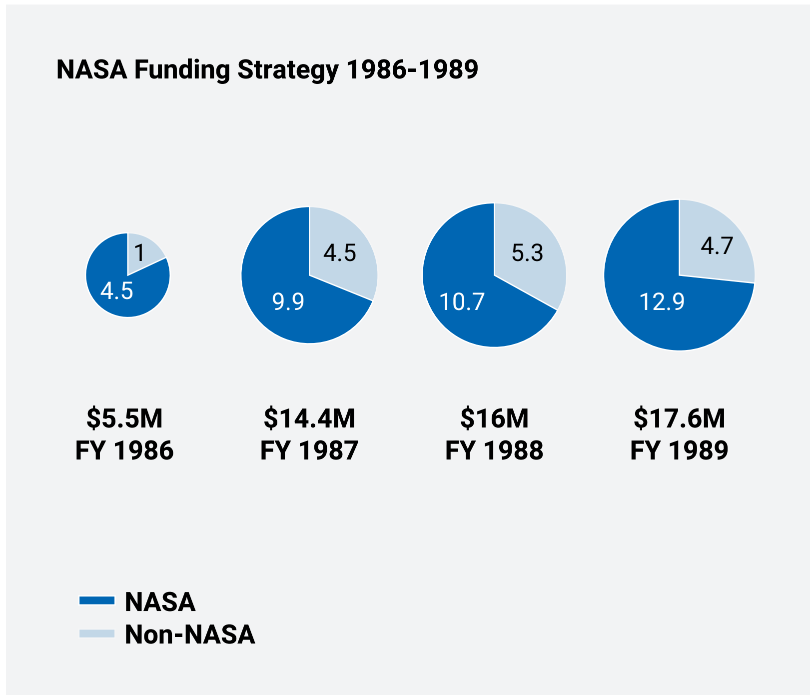


Figure 2. *Percentage of the total funding for the first five Centers for the Commercial Development of Space derived from NASA and non-NASA sources from 1986-89*

3.1 Before the International Space Station

In-space semiconductor research began with a desire to understand the effects of microgravity on crystal physical properties. The growth of crystals requires much longer processing times (on the order of hours to days) and smaller vibrations, which could only be achieved with orbital spaceflight, as opposed to drop towers, parabolic flights, and sounding rockets whose duration of weightlessness is on the order of seconds to minutes.[23] It was hoped that commercially attractive processes would be identified by the mid-1970s and a dedicated space manufacturing space station module would be justified by the late 1970s.[24]

22 Walker, S. E. (1989). Centers for the commercial development of space. *NASA*; Washington, DC. https://ntrs.nasa.gov/citations/19900004835

23 Kohli, R., Brusky, P. L., Diamond, S., Markworth, A. J., & Mcginniss, V. D. (1987). Microgravity materials processing for commercial applications. *NASA*: Boston, MA. https://ntrs.nasa.gov/citations/19880041344

24 Space processing and manufacturing. (1969). *NASA*. https://ntrs.nasa.gov/citations/19710002226

The first semiconductor crystal growth experiments in space were conducted on the Skylab space station in 1973. These experiments included crystal growth of:

1. **Ge**, led by researchers of Texas Instruments Inc.;
2. **InSb** (indium antimonide), led by The University of Alabama in Huntsville; and
3. **GeSe** (germanium monoselenide), led by Rensselaer Polytechnic Institute.

Dr. Rocco A. Petrone, Director of Marshall Space Flight Center (MSFC), said of these results, *"If the promise shown by Skylab experiments is an indicator, then the possibility of manufacturing more highly purified material for making more efficient semiconductors for use in the field of communications, [...] awaits only the availability of [the Space Shuttle program] and Spacelab."*[25]

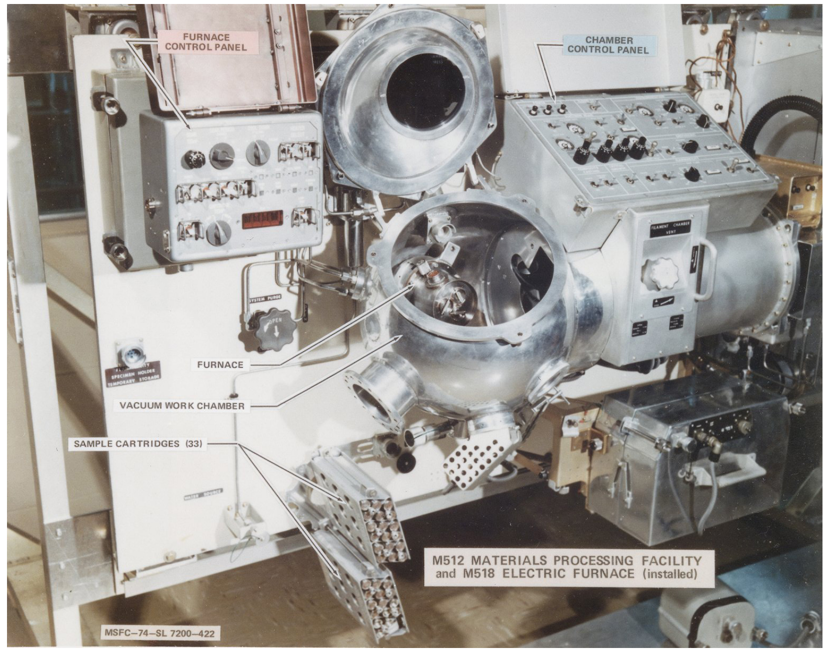


Figure 3. *Skylab Furnace*

Shortly after the Skylab mission came the Apollo-Soyuz Test Project (ASTP), which modified the furnace used on Skylab to reach a maximum process temperature of 1200 °C. This enabled the 1975 semiconductor investigations on aluminum antimonide (AlSb). Additionally, iterative semiconductor crystal growths of Ge and GeSe were conducted as follow-ups to the Skylab studies.[26] The USSR Salyut-6 space station then hosted a handful of semiconductor experiments starting in 1977, on bismuth antimonide (BiSb), gallium antimonide (GaSb), and lead telluride (PbTe), noting benefits to microgravity growth such as undisturbed growth kinetics.[27]

Reports coming out in the late 1970s continued to outline numerous benefits and potential advantages to manufacturing semiconductors in space.[28] This led to the first commercial venture seeking production of semiconductors in space for use on Earth, Microgravity Research Associates, founded in 1979. The company was backed by venture capitalists and a series of NASA Small Business Innovation Research (SBIR) awards to grow gallium arsenide (GaAs) crystals in space. The first small experiments were scheduled for 1986, but no further records have been found after the Space Shuttle Challenger disaster.[29]

Experiments through the 1980s were hosted on either Spacelab, as part of the U.S. Space Shuttle program, or recoverable satellites put into orbit by China and Russia. China's first semiconductor manufacturing experiments were performed on GaAs, focusing on crystal growth of semi-insulating GaAs, Si-doped GaAs, and Te-doped GaAs.[30] China's focus on in-space GaAs experiments would resume in the '90s.

25 Taylor, K. R. (1974). Proceedings of the third Space Processing Symposium on Skylab Results, volume 2. *NASA*. https://ntrs.nasa.gov/citations/19740021792

26 Page, L. W., & Page, T. (1977). Apollo-Soyuz Pamphlet No. 8: Zero-G Technology [PDF]. *NASA*. https://ntrs.nasa.gov/api/citations/19780019210/downloads/19780019210.pdf

27 Soviet Salyut-6 Scientific Space Station: The First Manned Phase—September 1977-March 1978 [PDF]. (1979). *National Foreign Assessment Center*. https://nsarchive2.gwu.edu/NSAEBB/NSAEBB501/docs/EBB-29.pdf

28 Naumann, R. J., & Herring, H. W. (1980). Materials processing in space: Early experiments. *NASA*: Washington, DC. https://ntrs.nasa.gov/citations/19810007559

29 Shipman, H. L. (1987). Space 2000: Meeting the challenge of a new era. *NASA, University of Delaware*. https://ntrs.nasa.gov/citations/19880058378

30 Hu, W. (Ed).. (1997). Space Science in China. *Routledge & CRC Press*. https://www.routledge.com/Space-Science-in-China/Hu/p/book/9789056990237

The 1990s primarily consisted of in-space investigations on either the continued U.S. Space Shuttle program using Spacelab or the Soviet Union/Russian space station, Mir. The Mir space station, in orbit from 1988 to 2001, hosted 14 Soviet Union/Russian experiments on semiconductor manufacturing.[31] These studies ranged from iterative crystal growths of single Ge crystals to ternary semiconductors like rubidium silver iodide ($RbAg_4I_5$) where, "The effect [of microgravity] manifests itself in the better homogeneity of samples and decrease of structural defects and inclusions."[32] [33]

Figure 4. *Wake Shield Facility STS-80*

In the mid-1990s, the SVEC at the University of Houston developed the Wake Shield Facility (WSF), a 12-foot-diameter disk-shaped platform, using the low-pressure environment in the wake of the space shuttle. The WSF flew on three missions, the first attached to the exterior of the Space Shuttle to leverage the high vacuum environment in LEO. During the last two missions, the facility was released after launch to become a freeflyer.[34] These studies resulted in two peer-reviewed publications on GaAs and aluminum gallium arsenide (AlGaAs) crystalline thin-film growth by epitaxial growth. The space-grown samples were fabricated into photocells with superior performance, compared to control samples made on Earth.[35] [36]

China was the first to investigate producing ICs out of semiconductor crystals grown in space. Microgravity-grown GaAs crystals, processed on a recoverable Chinese satellite in 1996 were sliced into wafers and low noise field effect transistors and analog switch ICs were fabricated using direct ion-implantation technique at the Hebei Semiconductor Research Institute.[37] The properties of these devices were superior to the ones produced terrestrially.[38]

3.2 ISS National Laboratory

Since its launch in 1998, the ISS has hosted more than 3,000 research experiments.[39] However, only 13 of these 3,000 experiments have resulted in peer-reviewed publications on semiconductor manufacturing experiments (e.g., crystal growth and recrystallization). Moreover, out of the 177[40] total peer-reviewed publications on in-space semiconductor manufacturing experiments in its 50-year history, only 7 percent

31 Official Semiconductor Data Set—Butler University [Google Docs]. (n.d.). (Butler University). https://docs.google.com/spreadsheets/d/1Zl_B_IbC_UFx4VfFamhCQcGgUdtk64r6wOdQ_wO3lHU/edit?usp=embed_facebook

32 Buhrig, E., Schwichtenberg, G., & Pätzold, O. (2000). Growth of Zn-doped Germanium under Microgravity. *Crystal Research and Technology, 35*(8), 911–919. https://doi.org/10.1002/1521-4079(200008)35:8<911::AID-CRAT911>3.0.CO;2-Y

33 Popov, A. S., Kostadinov, I. Z., Mateev, M. D., Regel, L. L., & Baturin, N. A. (1992). The influence of the front of crystallization upon the phase content in RbAg4I5 bulk crystals grown in microgravity. *Solid State Ionics, 57*(3), 211–215. https://doi.org/10.1016/0167-2738(92)90150-N

34 Space Research Results Purify Semiconductor Materials. (2010). *NASA Spinoff*. https://spinoff.nasa.gov/Spinoff2010/ip_8.html

35 Ignatiev, A. (2001). Advanced thin-film materials processing in the ultra-vacuum of space. *Acta Astronautica, 48*(2), 115–120. https://doi.org/10.1016/S0094-5765(00)00148-X

36 Freundlich, A., Horton, C., Vilela, M. F., Sterling, M., Ignatiev, A., Neu, G., & Teisseire, M. (2000). Photoluminescence of GaAs grown by metallorganic molecular beam epitaxy in space ultra-vacuum. *Journal of Crystal Growth, 209*(2), 435–439. https://doi.org/10.1016/S0022-0248(99)00586-2

37 Chen, N., Zhong, X., Lin, L., Xie, X., & Zhang, M. (2000). Semi-insulating GaAs grown in outer space. *Materials Science and Engineering: B, 75*(2), 134–138. https://doi.org/10.1016/S0921-5107(00)00348-2

38 Chen, N. F., Zhong, X., Lin, L., Zhang, M., Wang, Y., Bai, X., & Zhao, J. (2001). Comparison of field effect transistor characteristics between space-grown and earth-grown gallium arsenide single crystal substrates. *Applied Physics Letters, 78*(4), 478–479. https://doi.org/10.1063/1.1342201

39 Guzman, A. (2021, December 17). Station Research Results Contributing to Exploration. *NASA*. http://www.nasa.gov/mission_pages/station/research/news/five-ISS-research-results-deep-space-exploration

40 As of July 28, 2023. The database is updated every Friday by Prof. Anne Wilson and her team at Butler University.

were performed on the ISS. Of that percentage, only half attributed to U.S. experiments, and the other half to Japan.[41] To give an even deeper perspective, **the United States has lost the lead on semiconductor manufacturing investigations to China since the birth of the ISS**. This is illustrated in Figure 5, which plots the number of semiconductor manufacturing experiments performed by country, before and after the ISS was established in orbit.

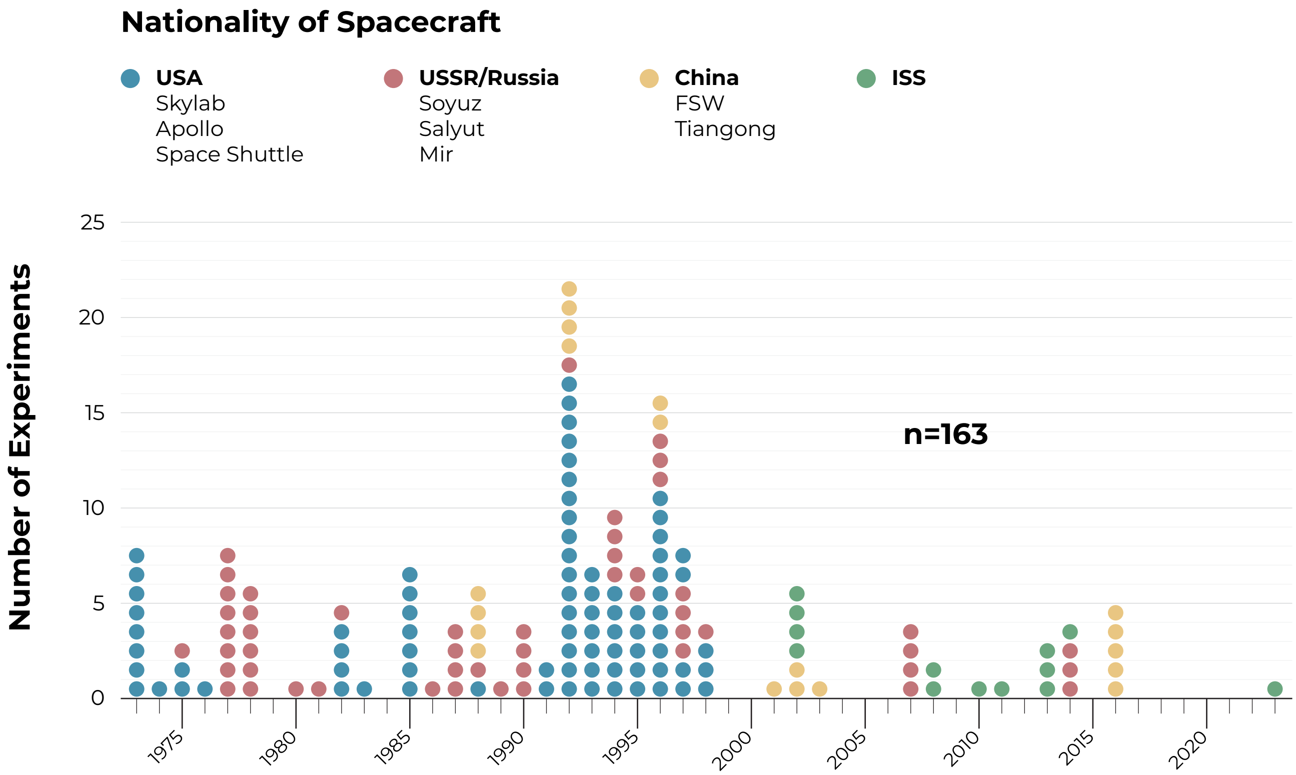


Figure 5. *In-Space Semiconductor Crystal Growth Experiments*

While the ISS is appropriate for early stages of development, the temperatures, volumes, power, toxicity, and risk involved in later-stage R&D are not suitable for a crewed spacecraft. Limited advocacy for developing the free flyers or other vehicles necessary for semiconductor experiments, along with the period's shifting priorities, could explain this correlation.

The Chinese space station Tiangong, set to host over 1,000 experiments over the next decade, is outfitted with a "high-temperature furnace" as part of a Material Furnace Experiment Rack (MFER).[42] Currently, the ISS has only two facilities that can achieve temperatures suitable for semiconductor manufacturing, and only one can sustain these temperatures for lengths appropriate for a manufacturing scale.[43] Past experience suggests that accessing these high-temperature furnaces can take several years, which is untenable in such a demanding industry.[44] China's lead in semiconductor manufacturing experiments may grow if the ISS and future U.S. commercial space stations do not meet the standards required for semiconductor work.

41 Official Semiconductor Data Set—Butler University [Google Docs]. (n.d.). (Butler University). https://docs.google.com/spreadsheets/d/1Zl_B_IbC_UFx4VfFamhCQcGgUdtk64r6w0dQ_w03lHU/edit?usp=embed_facebook

42 Mallapaty, S. (2022). China's space station is almost complete—How will scientists use it? *Nature*. https://doi.org/10.1038/d41586-022-03462-5

43 Frick, J. J., & Senesky, D. G. (2022). Metal Alloy Synthesis in Microgravity. *In-Space Manufacturing and Resources: Earth and Planetary Exploration Applications*. 269–284. https://doi.org/10.1002/9783527830909.ch14

44 Frick, J. (2023, March 27-28). What is happening now? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

It is important to note that there have been several experiments performed on the ISS that use semiconductors to extract their thermophysical properties (e.g., density, surface tension, viscosity). These include experiments performed on the Japan Aerospace Exploration Agency's (JAXA) Electrostatic Levitation Furnace (ELF).[45] However, these experiments are not of direct interest in this report because they are fundamental property experiments as opposed to experiments on one of the four main areas of semiconductor manufacturing (substrate production, device fabrication, chip creation, and packaging), as outlined in Section 2.2.

The ISS is set to cease operations by 2030. In the limited time left with the ISS, industry must act now to not only take advantage of the remaining lifespan, but to begin thinking about in-space experiments, research, and manufacturing in a post-ISS landscape. With manufacturing processes still in relatively early stages, improvements must first be made so that when commercial stations/platforms/free flyers are operational, large-scale manufacturing processes can be readily implemented.

45 Tamaru, H., Koyama, C., Saruwatari, H., Nakamura, Y., Ishikawa, T., & Takada, T. (2018). Status of the Electrostatic Levitation Furnace (ELF) in the ISS-KIBO. *Microgravity Science and Technology, 30*(5), 643–651. https://doi.org/10.1007/s12217-018-9631-8

3.3 The Neglected 2015 NASA Report

In April 2014, a NASA MSFC Materials Lab Workshop was held in Arlington, VA to facilitate collaboration between scientists, engineers, academics, industry leaders, government agencies, and international space agencies to discuss the future of science experiments aboard the ISS.[46] NASA MSFC Materials Lab subsequently published a strategic plan in February 2015, outlining the goals for the future of in-space manufacturing, research, and experiments before the retirement of the ISS.[47] It is important to note that it was not until September 2015 that Boeing was tasked to extend the primary structural hardware of the ISS past 2020 to the end of 2028.[48]

The workshop and subsequent report pointed to needs in prioritizing semiconductor experiments in space. Other priorities identified by the report include bulk growth of semiconductors for high value sensors and detectors, meniscus-defined and semi-containerless semiconductor processing, high temperature processing of industrially relevant semiconductors, and thermophysical property measurements.

Despite the report on this workshop being publicly available since 2015, as with the 2009 report, it was ignored and decision makers neglected to take action. Few people at the most recent 2023 workshop were even aware of its existence. While this former report provides a great foundation for the topic, it exemplifies a need for advancement in this field. With the ISS ceasing operations by 2030, the 2015 report's prioritization of greater space station utilization is waning. The report was not used to its maximum potential at the time of publication, and addresses many of the issues raised at this year's workshop. It has been almost a decade since the workshop convened, and the only options for high-temperature work on the ISS remain the Low Gradient Furnace (LGF), Solidification and Quenching Furnace (SQF), and Solidification Using a Baffle in Sealed Ampoules (SUBSA) furnace. The re-discovery of this report underscores the long overdue push to take greater advantage of the long duration microgravity environment in space.

Beyond the importance of the content within the neglected workshop and report lies the issue with internal record keeping and database accessibility. Most participants in this workshop being unaware of such a substantial, publicly available document points to a need for a more robust database where foundational work and literature can be found easily. The demand that exists within this industry cannot afford a continuous re-invention of the wheel, and this paper should not be shelved like the 2015 report.

46 Report of the NASA MaterialsLab Workshop. (2014).

47 NASA MaterialsLab Strategic Plan. (2015). *National Aeronautics and Space Administration*.

48 Maass, R. (2015, September 30). NASA extends Boeing contract for International Space Station. *Space Daily*. https://www.spacedaily.com/reports/NASA_extends_Boeing_contract_for_International_Space_Station_999.html

The present Space Landscape can be summarized by the following areas:

Increased Access to LEO. In the 1980s, launching to LEO using the U.S. Space Shuttle was around (in fiscal year [FY] 21 USD) $54.5k per kilogram (kg). Today, in the 2020s, the cost has decreased by two-orders-of-magnitude to $951 using Falcon Heavy.[49] For context, it costs about $200 to ship 1kg of chocolates from Venice, Italy to Palo Alto, CA. In addition to the big names, like Northrop Grumman, SpaceX, Blue Origin, Virgin Galactic, and Rocket Lab, there are exciting newcomers to the area like Vast Space and Firefly Aerospace. NanoRacks and Space Tango are additional examples of end-to-end microgravity service providers. With increased competition in launching payloads to LEO, costs will only decrease.

Planned Commercial LEO Stations. There are many plans in place from various companies for future LEO space stations: Axiom Space Station, Northrop Grumman, Orbital Reef, Starlab, and the newly announced Haven-1 from Vast.[50] These stations have yet to come to fruition, but the field is optimistic. These, however, are not the first commercial station plans put in place. Prior to these station announcements, which began in 2020, Bigelow Aerospace pursued the stations Galaxy, Sundance, and B330, but all were canceled due to financial difficulties. Additionally, Excalibur Almaz, a private spaceflight company based in the United Kingdom (UK), pursued the station Alma Commercial, but never launched due to lack of funds.[51]

Commercial Free Flyers. These experimental platforms are in various stages of implementation, from concept to flight testing. Some commercial entities in this area include Sierra Space, Varda, Space Forge, and In-Orbit Aerospace.[52] For the semiconductor sector, these may offer a stepping-stone to proof-of-concept experiments that offer prolonged microgravity (on the order of hours to days).

The present Semiconductor Landscape, similarly, features the following main components:

Need for 'Beyond-Silicon'. The time has come in which the replacement of Si can no longer be avoided in fields such as telecommunications, automotive, cloud services, and virtual or augmented reality. Next-generation semiconductor device materials, like diamond, SiC, GaN, graphene, molybdenum disulfide (MoS2), etc. are just a few examples of new materials with the potential to improve performance. There are countless academic, industrial, and government initiatives shifting the focus on these "beyond-silicon" materials. For example, in 2018 the U.S. Department of Defense (DOD) Advanced Research Projects Agency (DARPA) rolled out a $1.5 billion program over five years to support industry and academic researchers to design new electronic materials and devices.[53] The semiconductor community will need to expand their R&D and production horizons (possibly above Earth!) to tackle these materials challenges through innovative challenges yet to be overcome by current R&D and production methods.

Global Supply Chain. As discussed in Section 2.2, the supply chain for semiconductor devices spans the entire globe. It is an international effort to keep society functioning with the electronic devices available today. There is no exact data on the global dollar investment amount that it took to get Si-based technology where it is today, but it is safe to say that this value is within the range of hundreds of billions to possibly trillions of U.S. dollars across all the sectors and regions of the world. By some estimates, it is thought that the semiconductor industry will need to invest ~$3 trillion in R&D and capital expenditure

49 Giulianotti, M., Sharma, A., Clemens, R., Garcia, O., Taylor, L., Wagner, N…Wagner, W. (2021). Opportunities for Biomanufacturing in Low Earth Orbit: Current Status and Future Directions. *Preprints*. https://doi.org/10.20944/preprints202108.0044.v1

50 List of commercial space stations. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=List_of_commercial_space_stations&oldid=1171641757

51 List of space stations. (2023). *Wikipedia*. https://en.wikipedia.org/w/index.php?title=List_of_space_stations&oldid=1171029312

52 Kulu, E. (2022, September 21). In-Space Manufacturing—2022 Industry Survey and Commercial Landscape. *Factories in Space*. https://www.researchgate.net/publication/364107062_In-Space_Manufacturing_-_2022_Industry_Survey_and_Commercial_Landscape

53 Service, R. F. (2018, July 24). Beyond silicon: $1.5 billion U.S. program aims to spur new types of computer chips. *Science*. https://www.science.org/content/article/beyond-silicon-15-billion-us-program-aims-spur-new-types-computer-chips

over the next 10 years just to keep up with increasing demand.[54] The point stands that the semiconductor industry as it exists now has the means and know-how to add LEO destinations to their global supply chain if microgravity truly offers the solution to challenges currently faced in the semiconductor industry (e.g., high-purity, large scale substrates of next generation semiconductor materials). It is important to find out now how disruptive space semiconductors can be in the future; assessing U.S. competitive vulnerabilities will be key should another nation make a hard push for LEO-based semiconductor manufacturing.

US Leadership Prioritization. The 2022 U.S. CHIPS and Science Act will provide roughly $280 billion in funding to boost domestic research and manufacturing of semiconductors and develop an industry workforce.[55] The act is aimed at competing with China to secure the semiconductor supply chain in the U.S. and create an innovation "boom" to jumpstart the next generation of semiconductor devices. From this Act, the American semiconductor manufacturing industry is reinvigorated. The sector is primed to invest in innovative and new approaches (or maybe those coming out of hibernation!) to current challenges.

4.1 Current Advanced Material Processing Capabilities on the ISS

The ISS is essential for proof-of-concept level R&D. However, as stated in Section 3.2, the ISS has only two facilities that can achieve temperatures suitable for semiconductor manufacturing (with respect to substrate processing, Section 2.2), and only one can sustain these temperatures for lengths appropriate for a manufacturing scale.[56] These facilities include the SUBSA furnace and the Materials Science Laboratory (MSL) which hosts an exchangeable furnace core. The SUBSA furnace can theoretically reach a process temperature of 850 °C, but it has only demonstrated a maximum process temperature of 800 °C for just 1 hour in orbit.[57] The furnaces hosted in the MSL can theoretically go to 1400 °C, but they have not demonstrated this capability in orbit since installation. The two furnaces used in the MSL are the SQF and the LGF. The SQF was designed for metallurgical research (i.e., non-semiconductor work) and has had many successful programs implemented by the European Space Agency (ESA).[58] The LGF was "designed mainly for Bridgman crystal growth of semiconductor materials" but has never been used for this purpose since its installation in 2011.[59] In fact, most samples processed in the LGF have been metal alloy sintering experiments, unrelated to semiconductors.[60] However, the inability for the LGF to perform semiconductor crystal growth (as it was intended for) is not due to the inadequacy of the hardware, but rather the inability of the funded projects to pass the current flight safety level expectations on a crewed station.

The current state of semiconductor crystal growth on the ISS is constrained by stringent safety level ratings. In truth, most semiconductor work is not appropriate for crewed vehicles unless appropriate safeguards are in place. The ISS is currently well-suited for work other fields of work (e.g., cancer research, biomanufacturing, pharmaceutical synthesis), but for semiconductors and other advanced materials, alternative platforms (e.g., external platforms, free-flyers, uncrewed vehicles) are required.

54 Varas, A., Varadarajan, R., Palma, R., Goodrich, J., & Yinug, F. (2021, March 28). Strengthening the Global Semiconductor Supply Chain in an Uncertain Era. *BCG Global*. https://www.bcg.com/publications/2021/strengthening-the-global-semiconductor-supply-chain

55 Rep. Ryan, T. [D-O.-13. (2022, August 9). H.R.4346 - 117th Congress (2021-2022): Chips and Science Act (2021-07-01) [Legislation]. *Congress*. http://www.congress.gov/bill/117th-congress/house-bill/4346

56 Frick, J. J., & Senesky, D. G. (2022). Metal Alloy Synthesis in Microgravity. *In-Space Manufacturing and Resources: Earth and Planetary Exploration Applications*. 269–284. https://doi.org/10.1002/9783527830909.ch14

57 Redwire Space, & Ormsby, R. (2023, March 28). The Future of Semiconductor Processing in Space – Q&A with future LEO destinations [Q&A]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

58 Frick, J. J., & Senesky, D. G. (2022). Metal Alloy Synthesis in Microgravity. *In-Space Manufacturing and Resources: Earth and Planetary Exploration Applications*. 269–284. https://doi.org/10.1002/9783527830909.ch14

59 Materials Science Laboratory (MSL): Material physics research facility in Destiny. (n.d.). *ERASMUS Centre - Directorate of Human Spaceflight and Operations, European Space Agency*. http://wsn.spaceflight.esa.int/docs/Factsheets/15%20MSL%20LR.pdf

60 NASA/Johnson Space Center. (2018, May 31). Sintering solutions aboard the International Space Station. *ScienceDaily*. https://www.sciencedaily.com/releases/2018/05/180531135306.htm

NASA InSPA understands in order to accelerate semiconductor work in space, these experiments must be performed outside of the habitable volume of the ISS. To facilitate this work, NASA leaders are investigating the Bishop Airlock for ISS external platform access and the use of ISS re-supply capsules as experimental platforms operating as free flyers. It should be noted that most, if not all, of these experiments will be required to be returned to Earth for further analysis and processing.

To reiterate, China's lead on semiconductor manufacturing experiments may grow if the ISS and future U.S. commercial space infrastructure (e.g., space stations, uncrewed platforms, free flyers) do not meet the standards required for semiconductor work.

4.2 Current Funding Routes

The only formal analytical research on end-to-end manufacturing of microchips in space was conducted in 2000-2001 by Chapman and Pfeiffer. This research investigated processes and resource constraints of both crystal growth and microfabrication. Even the simplest semiconductor devices require many microfabrication steps, as highlighted in Section 2.2. An alternative microfabrication process was developed using the native vacuum environment, which could replace wet terrestrial based microfabrication and eliminate many steps. They also explored expected in-space production rates and economics and concluded orbital manufacturing could eventually become cheaper. This was the first study exploring the unit economics of microchip manufacturing.[61]

However, the common conclusion from the early 2000s seems to have been that the space-grown semiconductor crystals were better, but not sufficient to warrant the additional costs at the time.[62] With the possible exceptions of growing unique crystals that cannot be made on Earth or with new dry microfabrication processes, which are superior in microgravity. A lot was learned about gravitational effects on materials, which has proven to be very useful in improving materials processing on Earth. Twenty years later, the context and situation have changed; we need new end-to-end microgravity production studies.

4.2.1 In-Space Production Applications (InSPA) Solicitation

In Space Production Applications (InSPA) provides financing and support for researchers seeking to get their work out of a lab and into space.[63] These efforts help avoid productivity lulls when funding dries up at mid-level Technology Readiness Levels (TRLs), but it is the only government-funded program on the level of funding actually capable of making a dent in in-space start-up funds. SBIR grants are inadequate in this area; they can barely fund one parabolic flight experiment, let alone get into orbit.

InSPA, came out of a desire for an agency meant to leverage space for the benefit of Earth. The focus was on accelerating development cycles and finding products that are superior when developed in space. InSPA is meant to award funding to companies with the goal of raising the technological readiness level of certain products and moving them to market.[64]

TRLs are ranking systems used to measure the maturity level of certain technologies. The range is between TRL 1, basic principles observed and reported, and TRL 9, actual system "flight proven" through successful mission operations. Often, when technologies reach TRL 3, where researchers are working in a lab, there tends to be limited funding allocation until the technology matures more. InSPA seeks to overcome this "valley of death" by funding these technologies for in-space research and experimentation.[65]

---

61 Pfeiffer, N. (2000). Process Development for Fabrication of Silicon Semiconductor Devices in a Low Gravity, High Vacuum, Space Environment. *Simon Fraser University*. https://www2.ensc.sfu.ca/grad/theses/masters/Pfeiffer_2000.pdf

62 Wilcox, W. R., & Regel, L. L. (2001). Microgravity Effects on Materials Processing: A Review. (Conference Proceedings of EUROMAT 2001. NASA). https://ntrs.nasa.gov/api/citations/20030056609/downloads/20030056609.pdf

63 In Space Production Applications. (n.d.). *NASA*. https://www.nasa.gov/international-space-station/space-station-research-and-technology/in-space-production-applications/

64 Guzman, A. (2022, August 31). What is In Space Production Applications? *NASA*. http://www.nasa.gov/mission_pages/station/in-space-production-applications/what-is-in-space-production-applications

65 Tzinis, I. (2015, May 6). Technology Readiness Level. *NASA*. http://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

InSPA supports companies in their first flights, allowing researchers to assess their in-space hardware needs and identify potentially overlooked areas. InSPA funding also supports developing the hardware to the point that the resulting products are vastly superior to what can be produced on earth. This is the final hurdle necessary before the technology can be scaled and attract private investors.

Semiconductor manufacturing thus involves coordination across numerous fields to achieve market readiness. Even understanding the current body of semiconductor data requires working through international findings, some of which are outdated. This is an ongoing effort that is vital in identifying problems that have already been solved and what has yet to be improved. InSPA is meant to stimulate and accelerate the development of the space economy.

To date, there has only been one solicitation award dedicated to semiconductor manufacturing. In April 2022, United Semiconductors was selected for their proposal to produce semimetal-semiconductor composite bulk crystals with the goal of developing a processing technology for creating device-ready wafers from space-grown crystals.[66]

NASA and CASIS are developing strategies to support semiconductor manufacturing programs in space, and are eager to work alongside other government agencies (e.g., the National Science Foundation [NSF], the National Institute of Standards and Technology [NIST], DOD) to accelerate in-space manufacturing activities and collaborate across different research groups.

The ISS National Lab Research Announcement (NLRA) 2023-6 was recently put forward to "solicit proposals for applied research and development seeking to demonstrate space-based manufacturing and production activities in microgravity."

4.3 Current Community

Alongside the developing funding routes lies the industry community. This landscape is presently without much organization and established community, consisting mostly of conferences, workshops, and journals. There are several organizations supporting community development, but coordination is limited. Stanford's inaugural Semiconductor Manufacturing in the Space Domain workshop is just one part of this growing industry.

The American Society for Gravitational and Space Research (ASGSR) is a non-profit organization that focuses on advancing biological and physical sciences research "in, of, and for space." They intend to achieve this through coordinating various professional communities, encouraging cross-industry collaboration to further gravitational research.[67]

This year was the 12th annual International Space Station Research and Development Conference (ISSRDC). This conference spotlighted the ISS and the microgravity environment's potential to advance R&D goals in a variety of fields. The conference is hosted by the Center for the Advancement of Science in Space, Inc. (CASIS); NASA; and the American Astronautical Society (AAS). At the event, a half-day workshop on semiconductor manufacturing in space was well attended.

Several microgravity journals routinely publish industry-specific articles. These include the Nature Portfolio's Journal (NPJ) published by Nature,[68] *Springer's Microgravity Science and Technology: An International Journal for Microgravity and Space Exploration Related Research*,[69] as well as ASGSR's journal Gravitational and Space Research.[70]

---

66 Gilder, C. (2022, April 15). NASA Selects Proposals to Enable Manufacturing In Space for Earth. *NASA*. http://www.nasa.gov/mission_pages/station/research/news/nasa-selects-phase-1-proposals-for-inspa

67 ASGSR. (2023). About ASGR. *American Society for Gravitational and Space Research*. https://asgsr.org/about/

68 Npj. (2023, February 3). Microgravity. *Nature*. https://www.nature.com/npjmgrav/

69 Microgravity Science and Technology. (n.d.). *Springer*. https://www.springer.com/journal/12217

70 ASGSR. (2019). Gravitational and Space Research. *De Gruyter Poland*. https://sciendo.com/journal/GSR

This year was also the 23rd American Conference on Crystal Growth and Epitaxy (ACCGE-23) and the 21st US Workshop on Organometallic Vapor Phase Epitaxy (OMVPE-21). These events are part of a larger community adjacent to the LEO semiconductor manufacturing industry. Additional organizations like the American Chemical Society (ACS), SEMICON West, and the Materials Research Society (MRS) are part of this larger, established ecosystem. Participation in events, workshops, and conferences, such as the Ohio Aerospace Institute's Biocene conference, help the industry gain early traction with key players.

While there are opportunities to participate in these key areas, none are dedicated exclusively to in-space manufacturing of semiconductors. Carving out space within these established communities is beneficial, but further highlights the need for a dedicated industry community.

5 The Future: Setting Up the LEO Semiconductor Manufacturing Industry for Success

The workshop's priority was to identify the 2030 goals that must be reached to make in-space semiconductor production a reality by 2050. The consensus was that the field needs to take the remaining years to de-risk investment from semiconductor corporations and private investors. To do that, the community needs to obtain more iterative data on promising semiconductor R&D in LEO. This would include the whole range of experiments in the semiconductor production phases such as crystal growth, wafer processing, epitaxial growth, circuit patterning, etc.

The workshop participants identified three key areas to strengthen by 2030 to acquire more iterative data, intending to de-risk non-government investment in LEO semiconductor manufacturing by 2050: infrastructure, funding, and ecosystem. It bears repeating that as competition increases, US leadership in LEO-based semiconductor manufacturing is critical. The following subsections investigate the key elements required to adequately strengthen the target areas.

5.1 The U.S. Government Outlook on LEO and the Semiconductor Industry

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 is intended to strengthen American manufacturing, supply chains, and national security. Keeping the United States at the helm of science and technology progress requires substantial investment into the necessary research, development, and workforce demands. The main goal of this act is to bolster domestic-based semiconductor research, development, and production. The United States currently relies on East Asia for most semiconductor needs. Shifting reliance from foreign entities to domestic is vital in national security concerns and supports U.S. economy and innovation. This act provides the funding and government support that allows for far more progress in the U.S.-based semiconductor industry.

Additionally, the Biden Administration issued a commitment to Maintaining U.S. Preeminence in Low-Earth Orbit in March 2023. The National Low-Earth Orbit Research and Development strategy outlined the Biden-Harris Administration's "vision for U.S. leadership in the future research and development in LEO." This vision focuses on supporting an interagency strategy and action plan enabling government-wide collaboration and support of public-private partnerships. Realizing and institutionalizing the scientific, economic, diplomatic, and educational benefits of LEO research is critical to U.S. leadership in LEO. Five key policy objectives were identified by the report:[71]

1. **Advance groundbreaking science and technology** by conducting transformational R&D and enabling rapid, repeatable science in space.
2. **Strengthen U.S. government collaboration and partnerships** by encouraging new entrants in R&D through a LEO National Laboratory, promoting data sharing, and prioritizing sustainable access to LEO.

71 Maintaining U.S. Preeminence in Low Earth Orbit. (2023, March 31). *The White House*. https://www.whitehouse.gov/ostp/news-updates/2023/03/31/maintaining-u-s-preeminence-in-low-earth-orbit/

3. **Promote market opportunities, innovation, and sustainability** by adapting non-traditional use cases, enabling equitable access on future platforms, and addressing economic and regulatory barriers to market space-based R&D.
4. **Expand international cooperation** by exploring more opportunities for collaboration and implementing human spaceflight safety coordination.
5. **Stimulate science, technology, engineering, and mathematics (STEM) education and workforce development**, including by increasing opportunities for people from backgrounds underrepresented in STEM, and building capacity in institutions.

Practical applications stand on the shoulders of foundational research; proper funding and support of such R&D is vital if the field is to grow and stabilize.

5.2 Vision for 2050

In the year 2050, the in-space economy has blossomed into a thriving and dynamic ecosystem, encompassing a multitude of interconnected sectors. At its core lies a revolution in in-space manufacturing, transportation, and space launch capabilities, marked by fully reusable spacecraft that have vastly reduced the barriers to access space. The Moon, Mars and asteroids have become not just destinations for exploration, but hubs of economic activity, with human settlements and mining operations tapping into the vast resources they offer. The expansion of microgravity access opportunities has unlocked new frontiers for R&D, catalyzing groundbreaking discoveries and innovations.

Figure 6. *Commercial LEO Destination - Axiom* [72]

Moreover, the establishment of commercial space stations has become a norm, serving as pivotal hubs for scientific endeavors and commercial ventures alike. The entire in-space ecosystem acts as both an enabler and a powerful demand driver for the manufacturing of advanced technologies like semiconductors. As a result, numerous new revenue sources have emerged, bolstering the global economy, and propelling human civilization into an era of unparalleled progress and opportunity. We are forging a path towards a future where the boundless potential of space is harnessed for the betterment of all.

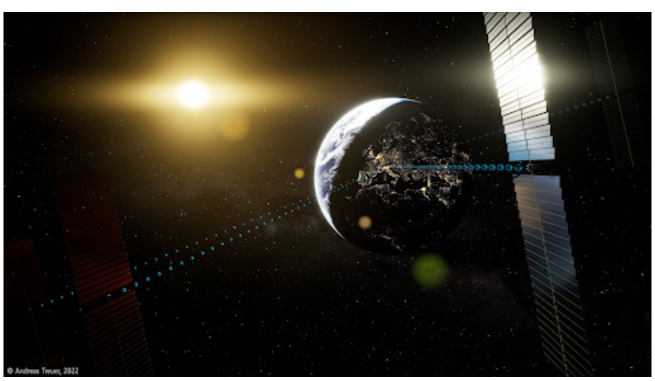


Figure 7. *ESA SOLARIS* [73]

In the context of in-space manufacturing of semiconductors, the production of solar cells is likely to come to fruition, driven by a different economic calculation. Harnessing the Moon's resources, in-situ manufacturing can enable the creation of solar cells on site. This would reduce the cost and logistical complexities associated with transporting prefabricated panels from Earth. The concept of space-based solar power is emerging as a viable solution to meet the ever-increasing energy demands on Earth. Capturing solar energy in space and beaming it back to Earth unlocks an inexhaustible, green energy source revolutionizing the approach to power generation and distribution.

72 Axiom Space selected by NASA for access to International Space Station port. (2020, January 27). *Axiom Space*. https://www.axiomspace.com/news/axiom-selected-by-nasa-for-access-to-international-space-station-port

73 SOLARIS activity plan. (n.d.). *ESA*. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/SOLARIS_activity_plan

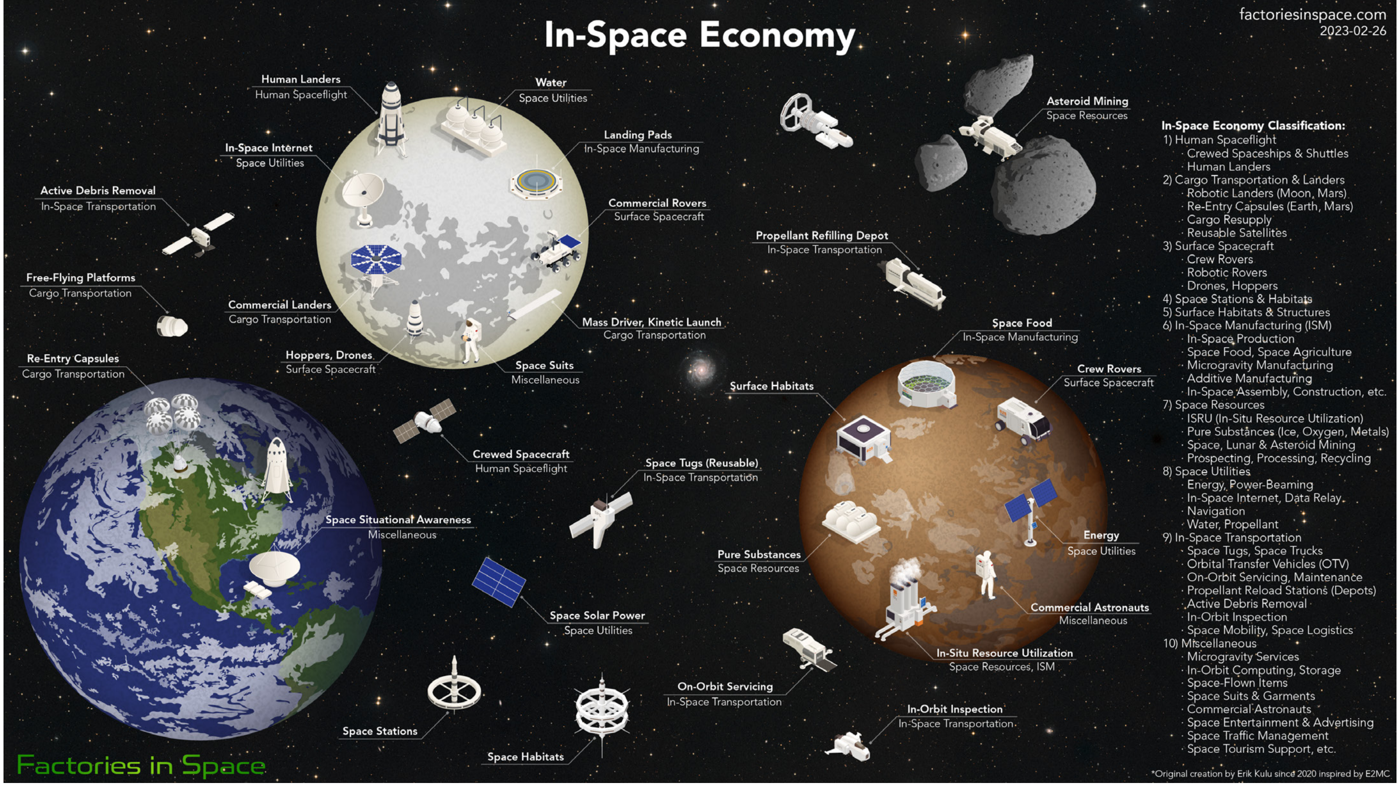


Figure 8. *Factories in Space - In-Space Economy*

On Earth, the semiconductor industry's rapid expansion poses a significant challenge to environmental sustainability. Manufacturing giants like TSMC account for a substantial portion of national electricity consumption. TSMC accounts for 6 percent of Taiwan's electricity demand, and by 2025 it is forecast to rise to 12.5 percent.[74] In-space manufacturing holds the potential to address these environmental concerns while also driving technological progress. Among the promising approaches is 3D inkjet printing, which has garnered attention with NASA planning to demonstrate its viability for producing memory chips.[75] This innovative process not only offers greater environmental benefits on Earth, such as reduced water and electricity consumption, but also thrives in microgravity conditions, streamlining production steps, making it even more suited for space-based applications.

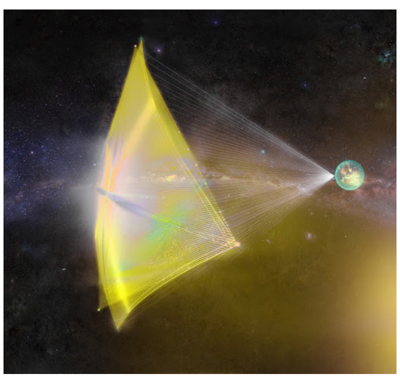


Figure 9. *Breakthrough Starshot*[78]

By 2050, other space-made semiconductors may start to find alternative use in solar sails. Solar sails or laser sails together with wireless power beaming stations placed at strategic locations throughout the Solar System could be used for efficient propellant-less transportation and even interstellar travel as planned by Breakthrough Starshot.[76] As described by Davoyan et al., electrically tunable meta surfaces, which may be semiconductors, are gaining interest for solar sail steering due to their ability to manipulate optical phase and amplitude. Moreso, high-refractive index semiconductors like Si and MoS_2 may be used for laser sails.[77] Given the considerable size of such sails and the delicate intricacies of their folding and deployment, space-manufacturing these semiconductor-based laser sails and the large semiconductor laser power beaming arrays emerge as the most likely approaches.

---

74 Liu, K. (2022, December 15). Net zero targets could force Taiwan's chipmakers abroad. *Clean Energy Wire*. https://www.cleanenergywire.org/news/net-zero-targets-could-force-taiwans-chipmakers-abroad

75 Hill, C. (2023, March 28). The Future of Semiconductor Processing in Space – How do we spend money to make money (in Space)? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

76 Starshot. (n.d.). *Breakthrough Initiatives*. https://breakthroughinitiatives.org/initiative/3

77 Davoyan, A. R., Munday, J. N., Tabiryan, N., Swartzlander, G. A., & Johnson, L. (2021). Photonic materials for interstellar solar sailing. *Optica, 8*(5), 722–734. https://doi.org/10.1364/OPTICA.417007

78 Starshot. (n.d.). *Breakthrough Initiatives*. https://breakthroughinitiatives.org/initiative/3

5.3 What needs to happen now to support the vision for 2050?

The vision demands developing the necessary skills and infrastructure to produce the best semiconductor materials and devices that can be made on Earth or in space. To do this, there must be support for transportation, in-space manufacturing spacecraft, the ability to iterate and learn, and the means to develop the skill of the national workforce in remote manufacturing. These initiatives will require funding, and financial concerns remain paramount in the progress of the industry. On the investor side, there are several handoffs along the funding chain between different groups of investors, each with their own investment timeframes. There is concern for an investment timeline mismatch between semiconductor investors, typically 5 years, and space investors, typically 15 years.

Engaging and inspiring a new generation to supply this industry with the workforce capable of this undertaking is also of concern. Funding for academic education and training programs, research, and salaries is necessary to even begin innovating. The field is complex and draws from other industries, making cross-industry incentives vital in driving interest to join the effort.

Perhaps the largest barrier to progress in the industry is the tendency to set long-term goals with short-term timeframes. Efforts must be made to mitigate the risk on projects that will not be profitable in the short term. These projects need support to achieve long-term success. Industry and investors should be informed that this work is generally long-term.

Collaboration is invaluable in the effort to advance the industry. There is no need or time for various companies to reinvent the wheel and make the same mistakes. There is a current hesitation in sharing findings and shortcomings as companies don't want to lose their competitive advantage. The industry must move forward together, and the government should facilitate a consortium to unite various groups. NASA's funding of the Butler study, allowing free and open access to readily available data, was a key step in this direction. All players in the industry must collaborate to overcome the barriers presented by this complex industry and undertaking.

Figure 10. *Vision 2050 Roadmap*

5.3.1 Platforms and Infrastructure through 2050

Most of the necessary equipment needs to truly leverage microgravity, as opposed to terrestrially designed equipment slightly adapted for microgravity use. The semiconductor industry was able to grow so quickly because SEMATECH provided a safe forum for all whole ecosystem partners to understand new technology node requirements. In some cases, legacy equipment was used, but new equipment was needed most. All the equipment had to come together, including the right environment (e.g., a clean room). If one component was missing, the whole technology node evolution would come to a halt. This is necessary to handle the hundreds of steps in semiconductor fabrication.

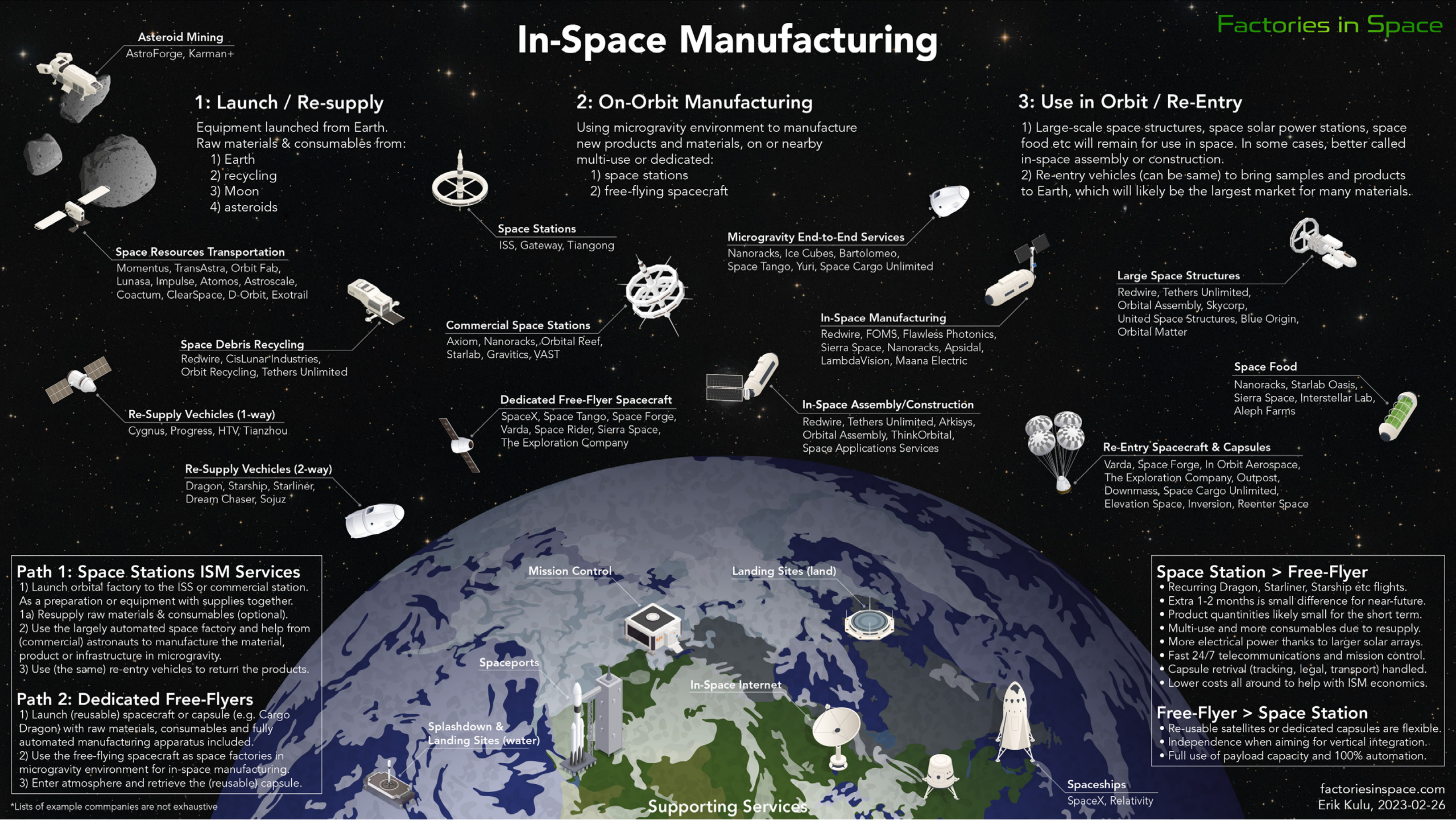


Figure 11. *Factories in Space - In-Space Manufacturing*

In the context of manufacturing semiconductors in space, the LEO environment is just another technology node evolution. New equipment is needed to address the unique requirements of this technology node and maximize yield and opportunity.

The ISS is not suitable for long term, high--yield semiconductor manufacturing. The ISS will conduct proof-of-concept experiments with the ultimate goal of transitioning facilities from ISS to Commercial LEO Destinations (CLDs). These experiments will take advantage of external platforms and different modules on board to adequately isolate payloads and experiments. Free flyers offer additional opportunities to develop proof of concept in a sustained microgravity environment without relying on the ISS.

There are various logistical and environmental barriers for performing semiconductor processing experiments. Workshop participants identified the following areas to strengthen:

- Increased time
- Increased power
- Uncrewed facilities
- Terrestrial prototyping facilities
- Vibrationally isolated facilities

These areas currently prevent the platform from achieving commercial-scale production or manufacturing. However, there is still much to be done in terms of R&D, especially regarding early stage TRL products. The utilization of the ISS as a pilot lab for R&D will provide important evidence to support the launch of commercial industries and pilot-scale manufacturing in space.

There are four key recommendations that would help support required infrastructure:

More Time. Increased processing time in orbit (in the order of hours to days).

- Right now, experiments don't spend enough time in space to truly harness the benefits of LEO.

More Power. Laboratory scale instruments can use 1 to 10s of kilowatt (kW) per experiment.

- Right now, experiments don't have access to adequate power levels to push the field forward.

Uncrewed Facilities. External or uncrewed orbital platforms with automation will alleviate human involvement.

- An external or uncrewed platform will reduce or eliminate vibrations to ensure higher success rates.

Earth Facilities. Easily accessible terrestrial replicates of space hardware with access to microgravity "simulators" (e.g., parabolic flights, drop shafts, skydiving) for trial and error.

- Increased access to environmental replicas will ensure that experiments in space are more successful.
- Academia can leverage access to these facilities to improve education and further expand the workforce.

Additionally, workshop participants identified four semiconductor candidates to target for near-term, proof-of-concept experiments:

- Diamond
- Graphene
- Silicon carbide (SiC)
- Gallium nitride (GaN)

5.3.2 Roadmap to Funding through 2050

A sustainable funding pipeline is required to bring this field to practice and profitability. More specifically, government- and industry-led programs should be strategically designed to seed and foster the LEO semiconductor manufacturing sector. This funding pipeline should support TRL and manufacturing readiness level (MRL) maturity. Funding pathways for early-stage research, as well as proof-of-concept experimentation, are required to validate physics and complex engineering concepts. In addition, follow-on resources to support eventual translation and widespread adoption by the commercial sector are critical. Market viability and the current state of microgravity and Earth infrastructure should be considered at all stages of program development.

The recommended near-term funding strategy (over the next one to three years) is outlined below.

NEAR TERM

next one to three years

- **Funding for techno-economic and market analysis is required to identify the costs, benefits, and risks of this technology focus area.** These studies may be conducted by established or new institutes/consortia, as well as by the private sector. However, the outcome of these studies should be made public to positively impact and influence the ecosystem.
- **Accelerator grants to support validation of ambitious and high-impact activities** (e.g., growth of competitive "beyond silicon" semiconductors). This high-risk, high-reward funding strategy may be critical to the continuation of this field. A few key and well-funded demonstration projects may pave the way to address critical human needs and therefore high-impact markets. Program topics should be selected via input from both the semiconductor and space sectors. In addition, funding duration should be selected to ensure and support competitiveness.

NEAR TERM

next one to three years

- **Funding for research programs in the $5M to $15M range** is required to conduct proof-of-concept studies aboard the ISS and near-ready CLDs. The programs should include sufficient support for modeling, flight opportunities for hardware advancement, implementation partners for compatibility with ISS and/or CLD protocols, external platforms, and industry-academic partnerships, as well as training of students from various fields. Programs should be selected for potential synergy, as well as risk mitigation.
- **Intra-agency programs** should address the potential interdisciplinary/cross-cutting benefits of the semiconductor-space sector. The semiconductor industry supports the advancement of healthcare, energy, industry, transportation, defense sectors and more. Therefore, intra-agency programs should be considered. NASA, which does not allocate a significant budget to semiconductors, should not be challenged to fund this interdisciplinary sector alone.[79] Unique and joint partnerships with non-NASA and non-ISSNL agencies (e.g., DOD, National Institutes of Health [NIH], U.S. Department of Energy [DOE], Air Force Office of Scientific Research [AFOSR], Space Force) should be formed to support large-scale and poignant research efforts. In addition, agencies that aim to advance science (e.g., NSF) and economic growth (e.g., U.S. Department of Commerce [DOC], NIST) should partner to harness the new space economy. The authors suggest an initial investment of $100M of the NIST $50B and DOD $2B budgets into LEO platforms.
- **SBIR and Small Business Technology Transfer (STTR) programs** should be awarded to enable new companies to form from academia and small businesses. This will enable translation of early-stage, semiconductor-space research to the commercial sector. However, the appropriate flight opportunities and infrastructure should be made available to enable the organizations to flourish.

The recommended long-term and sustainable funding strategy to reach the vision for 2050 is outlined below.

LONG TERM

sustainable funding strategy to reach vision for 2050

- **Follow-on grants for the aforementioned programs** should be implemented to continue to advance high-value programs to scale. "One-off" programs without a continued pathway to commercialization and implementation of "lessons learned" should be avoided. In addition, sufficient funding to execute and scale-up prototype concepts should be made available.
- **Annual seed grants coupled with implementation and flight support** should be provided by the government and private sectors to enable the exploration of "breakthrough" ideas. These grants can be used to catalyze and validate high-risk concepts. However, proper support (implementation, hardware, upmass/downmass) must be provided to ensure the success of these programs.
- **Fellowships for undergraduate and graduate student researchers** should be provided to encourage research activity and awareness of this field. In addition, these fellowships can further amplify the support of faculty that aim to explore this field.
- **STEM Programs for K-12** are foundational to a long term sustainable Semiconductor Industry. Working with organizations like Rosie Riveters may develop programs targeting K-12 to develop early knowledge and interest in the field.
- **Early-career awards for newly appointed faculty members** to encourage participation and advancement of semiconductor-space science and engineering. Funding early-stage research via new faculty members can help further promote and seed the field and lay the groundwork for more research activity (e.g., publications) in this sector.
- **Center grants (>$15M)** should be developed to enable multi-institutional activities, as well as close partnerships with industry. These large center grants should include industrial input and participation from both the semiconductor and aerospace industries. In addition,

79 Foust, J. (2022, July 20). NASA authorization included in CHIPS Act. *SpaceNews*. https://spacenews.com/nasa-authorization-included-in-chips-act/

LONG TERM

sustainable funding strategy to reach vision for 2050

interdisciplinary research teams should be encouraged. A five-plus year duration of the programs should be considered to enable multiple demonstrations and implementation of lessons learned. Furthermore, these programs should aim to conduct education, outreach, and workforce development to train the next generation of scientists and engineers.

- **Large- and mid-scale infrastructure grants for Earth- and space-based facilities and equipment** should be used to catalyze and enable programs. These grants may support the design and procurement of critical facilities (e.g., external station platforms, Earth-based analogs) to conduct pilot-scale research programs. Without the appropriate infrastructure, as well as plans for upmass/downmass these programs will not be successful or reach maturity.

5.3.3 Roadmap to Community Development through 2050

To advance the future of in-space semiconductor manufacturing, there is a critical need to build a community to support this effort and each other. This community needs to encompass research and academia, government institutions, and innovative industry members.

Six key goals of a community-based consortium:

- **Prioritize.** Identify semiconductor R&D opportunities with the most critical needs (e.g., National Security) and those with profitable unit economics.
- **Advise.** Work with space infrastructure/instrumentation entities so in-space facilities cater to the priority areas (power, size, etc.).
- **Connect.** Bring together industry/academic communities of relevant expertise to develop partnerships.
- **Standardize.** Set intellectual property (IP) expectations and create infrastructure guidelines for facile integration between in-space facilities.
- **Share.** Host databases and conferences for all players in the community (and particularly in academia) to share R&D findings.
- **Translate.** Understand and communicate how the R&D results will create market value.

Participants noted that a collaborative community-based ecosystem, such as a public-private partnership or consortium, would serve to further prioritize and de-risk space-based semiconductor R&D and translate results into commercial products for use in a host of terrestrial applications. The consortium should combine traditional government-funded R&D with the requirements to raise and execute private-sector funding streams (commercial entities, venture capital, and startups) that could support not only individual space-based Semiconductor projects, but also the companies that will execute those projects on the ISS. The Consortium for Space Mobility and ISAM Capabilities (COSMIC) is a recent example of a nationwide coalition intended to invigorate domestic in-space servicing, assembly, and manufacturing (ISAM).[80] This is a NASA-organized community focused on in-space manufacturing, but is not dedicated exclusively to semiconductors.

The next steps of a potential consortium fall into four areas:

1. **Secure** five-year funding commitments from government agencies such as NIST, NSF, DOD.
2. **Develop** a structure and governance model to expedite the development and translation of semiconductors in LEO.
3. **Establish** an integrated process outlining the role of the consortium from discovery to commercialization of a LEO-based product.
4. **Recruit** the right set of members for the consortium.

80 *COSMIC – Consortium for Space Mobility and ISAM Capabilities*. (n.d.). https://cosmicspace.org/

The structure and governance for the consortium should include an oversight board that sets priorities, provides resources, manages knowledge capture, and serves as a single point of contact for its membership and external key stakeholders. The board should include advisory committees of experts in industry and commerce, science, and LEO-based operations.

The consortium should follow a staged commercialization or a TRL process going from a discovery/concept stage to taking a product to market. Each stage would have specific activities and critical milestones that must be met before a project could advance to the next stage. The advisory committees would be responsible for overseeing each stage and reporting back to the oversight board.

Recruiting the right set of expert members for the consortium is foundational to its success. Representation from five key groups will be needed on the oversight board and advisory committees:

Commercial implementers such as semiconductor companies, contract development, and manufacturing organizations;

Technology developers such as universities, institutes, and R&D organizations;

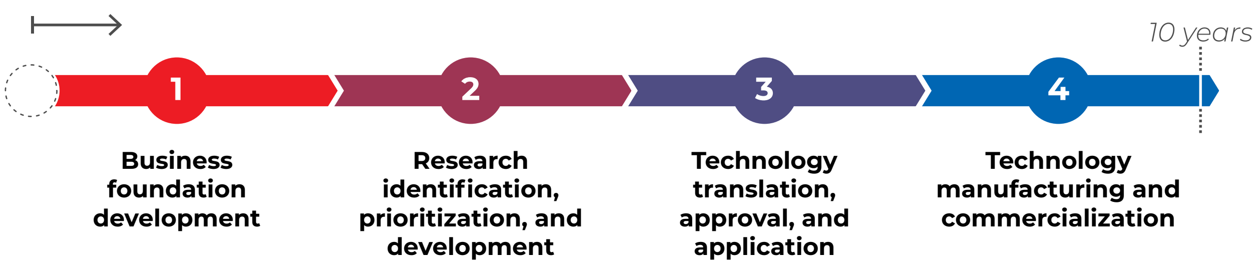
Technology enablers such as companies and organizations with a focus on artificial intelligence (AI), robotics, and automation;

Launch and payload operations experts; and

Public agencies such as Science, Space, and Defense.

An ideal member would have knowledge and resources in multiple groups.

Commercialization for any semiconductor platform will take time and trial and error. The consortium could be defined by four phases that, taken together, span 10 years:



Based on discussions in the workshop, many of the key opportunities for semiconductors in space are in the second phase. For this reason, a productive consortium, as measured in commercial success, would require a minimum lifetime of five years (although ideally 10 years).

Workforce development is a necessary component of supporting this industry. Attracting a competent and extensive workforce for semiconductor manufacturing is difficult on earth, but space offers an exciting opportunity that may be leveraged to develop a workforce. Computer science is currently a much more attractive job in terms of advertising, and the industry is struggling to compete for personnel. Facilities are not in the most appealing locations to live, and knowledge about the field is only disseminated in higher levels of academia. Undergraduate experiences, while incredibly valuable, are quite limited and high schoolers are never taught about semiconductors. Future workforce interests are established by middle school, so Elementary STEM programs are needed to catch students while their brains and interests are highly adaptable. Space has the potential to appeal to wide audiences and involve them in a cutting-edge industry primed for innovation and advancement.

5.4 Call to Action

In the mid-1980s, the U.S. semiconductor industry was faltering. Japan was leading the industry in both market share and product quality. This crucial U.S. industry was on the precipice and the United States was on the verge of relinquishing an innovative industry that supplied components crucial for everything from computers to weapons systems.

In 1988, a consortium of 14 American chip makers was born. SEMATECH (Semiconductor Manufacturing Technology) was formed to revitalize the U.S. semiconductor industry. By the early to mid-1990s, the decline had reversed, and U.S. chip makers regained the lead. By the mid-1990s, SEMATECH, with its ambitious plans for chip miniaturization and reduction of defects and cost, was on its way to becoming a model for collaboration between industry and government to advance American leadership. The consortium not only propelled the electronics industry forward, but brought the entire U.S. economy along.

SEMATECH was able to convince the DC ecosystem to fund a five-year commitment of $100 million in annual funding from DARPA, matched by consortium members. Today, it is fair to say that the U.S. semiconductor industry is in a crisis, with broad implications for the U.S. economy. However, crises can bring innovation and opportunity.

The United States has a leadership in space and can regain its leadership in semiconductor R&D and manufacturing, but there must be urgency. Bringing together America's unique skill set will help develop a new transformative platform to propel the United States into the future. An unseized moment will relinquish advantages to China, India, and others; the United States and its economy will be relegated to the sidelines.

The last two decades have seen remarkable advances in semiconductor technology. Additionally, exponential advancement in space technologies enable new opportunities to access and commercialize space for terrestrial benefit. There is now an inflection point where these areas can converge to capitalize on the unique advantages each confers.

Under the umbrella of a consortium, much like SEMATECH, this report proposes a union of thought leaders and subject matter experts from both government and industry. The group will identify the most promising opportunities, current gaps, and pathways to realizing the full potential of the LEO environment for the semiconductor industry.

Backed by new data, it is believed that the next great discoveries to improve semiconductors will come from research and manufacturing off Earth. Investment in space-based semiconductor manufacturing R&D and a national infrastructure in LEO will be critical in maintaining U.S. leadership in this area during the transition to future commercial LEO platforms. The Stanford University Workshop on Semiconductor Manufacturing in the Space Domain was a first step toward this future, and this report is intended as the next. This is the call to implement the roadmap outlined herein to establish a successful and sustainable market for semiconductors manufacturing in space.

Appendix: Works Cited

ASGSR. (2023). About ASGR. *American Society for Gravitational and Space Research*. https://asgsr.org/about/

ASGSR. (2019). Gravitational and Space Research. *De Gruyter Poland*. https://sciendo.com/journal/GSR

Axiom Space selected by NASA for access to International Space Station port. (2020, January 27). *Axiom Space*. https://www.axiomspace.com/news/axiom-selected-by-nasa-for-access-to-international-space-station-port

Bohn, R. E. & Terwiesch, C. (1999). The economics of yield-driven processes. *Journal of Operations Management, 18*(1), 41–59. https://doi.org/10.1016/S0272-6963(99)00014-5

Boyle, A. (2021, October 25). Blue Origin teams up with Sierra Space, Boeing and others on 'Orbital Reef' space station project. *GeekWire*. https://www.geekwire.com/2021/blue-origin-teams-sierra-space-boeing-others-orbital-reef-space-station-project/

Buhrig, E., Schwichtenberg, G., & Pätzold, O. (2000). Growth of Zn-doped Germanium under Microgravity. *Crystal Research and Technology, 35*(8), 911–919. https://doi.org/10.1002/1521-4079(200008)35:8<911::AID-CRAT911>3.0.CO;2-Y

Chen, J. (2023, March 27–28). Demystifying semiconductor device fabrication [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

Chen, N., Zhong, X., Lin, L., Xie, X., & Zhang, M. (2000). Semi-insulating GaAs grown in outer space. *Materials Science and Engineering: B, 75*(2), 134–138. https://doi.org/10.1016/S0921-5107(00)00348-2

Chen, N. F., Zhong, X., Lin, L., Zhang, M., Wang, Y., Bai, X., & Zhao, J. (2001). Comparison of field effect transistor characteristics between space-grown and earth-grown gallium arsenide single crystal substrates. *Applied Physics Letters, 78*(4), 478–479. https://doi.org/10.1063/1.1342201

COSMIC – Consortium for Space Mobility and ISAM Capabilities. (n.d.). https://cosmicspace.org/

Davoyan, A. R., Munday, J. N., Tabiryan, N., Swartzlander, G. A., & Johnson, L. (2021). Photonic materials for interstellar solar sailing. *Optica*, 8(5), 722–734. https://doi.org/10.1364/OPTICA.417007

Do we see an end to the chip shortage? (2022, April 20). *Electronics Sourcing*. https://electronics-sourcing.com/2022/04/20/do-we-see-an-end-to-the-chip-shortage/

Dukat, F. M. (2019, February 19). The Transistor in Industry. *RFCafe*. : https://www.rfcafe.com/references/radio-news/transistor-industry-may-1956-radio-television-news.htm

Foust, J. (2022, July 20). NASA authorization included in CHIPS Act. *SpaceNews*. https://spacenews.com/nasa-authorization-included-in-chips-act/

Freundlich, A., Horton, C., Vilela, M. F., Sterling, M., Ignatiev, A., Neu, G., & Teisseire, M. (2000). Photoluminescence of GaAs grown by metallorganic molecular beam epitaxy in space ultra-vacuum. *Journal of Crystal Growth, 209*(2), 435–439. https://doi.org/10.1016/S0022-0248(99)00586-2

Frick, J. (2023, March 27-28). What is happening now? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

Frick, J. J., & Senesky, D. G. (2022). Metal Alloy Synthesis in Microgravity. *In-Space Manufacturing and Resources: Earth and Planetary Exploration Applications*. 269–284. https://doi.org/10.1002/9783527830909.ch14

Gilder, C. (2022, April 15). NASA Selects Proposals to Enable Manufacturing In Space for Earth. *NASA*. http://www.nasa.gov/mission_pages/station/research/news/nasa-selects-phase-1-proposals-for-inspa

Giulianotti, M., Sharma, A., Clemens, R., Garcia, O., Taylor, L., Wagner, N…Wagner, W. (2021). Opportunities for Biomanufacturing in Low Earth Orbit: Current Status and Future Directions. *Preprints*. https://doi.org/10.20944/preprints202108.0044.v1

Globe Newswire. (2023, February 8). Single Crystal Silicon Wafers Market to Cross USD 14.6 Billion by 2028, at a CAGR 5.50% from 2022–2028 Thanks to Increasing Trend of Digitization and Electronic Mobility. *Skyquest*. https://www.globenewswire.com/news-release/2023/02/08/2603935/0/en/Single-Crystal-Silicon-Wafers-Market-to-Cross-USD-14-6-Billion-by-2028-at-a-CAGR-5-50-from-2022-2028-Thanks-to-Increasing-Trend-of-Digitization-and-Electronic-Mobility.html

Guzman, A. (2021, December 17). Station Research Results Contributing to Exploration. *NASA*. http://www.nasa.gov/mission_pages/station/research/news/five-ISS-research-results-deep-space-exploration

Guzman, A. (2022, August 31). What is In Space Production Applications? *NASA*. http://www.nasa.gov/mission_pages/station/in-space-production-applications/what-is-in-space-production-applications

Harper, L. (2023, March 27-28). What is happening now? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

Hill, C. (2023, March 28). The Future of Semiconductor Processing in Space – How do we spend money to make money (in Space)? [Presentation]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

Hu, W. (Ed). (1997). Space Science in China. *Routledge & CRC Press*. https://www.routledge.com/Space-Science-in-China/Hu/p/book/9789056990237

Ignatiev, A. (2001). Advanced thin-film materials processing in the ultra-vacuum of space. *Acta Astronautica*, *48*(2), 115–120. https://doi.org/10.1016/S0094-5765(00)00148-X

In-depth Analysis of the Global Semiconductor Supply Chain [Blog post]. (2022, January 20). *Utmel*. https://www.utmel.com/blog/categories/semiconductor/in-depth-analysis-of-the-global-semiconductor-supply-chain

In Space Production Applications. (n.d.). NASA. https://www.nasa.gov/international-space-station/space-station-research-and-technology/in-space-production-applications/

Kohli, R., Brusky, P. L., Diamond, S., Markworth, A. J., & Mcginniss, V. D. (1987). Microgravity materials processing for commercial applications. *NASA*; Boston, MA. https://ntrs.nasa.gov/citations/19880041344

Kulu, E. (2022, September 21). In-Space Manufacturing—2022 Industry Survey and Commercial Landscape. *Factories in Space*. https://www.researchgate.net/publication/364107062_In-Space_Manufacturing_-_2022_Industry_Survey_and_Commercial_Landscape

List of commercial space stations. (2023). *Wikipedia*. https://en.wikipedia.org/w/index.php?title=List_of_commercial_space_stations&oldid=1171641757

List of space stations. (2023). *Wikipedia*. https://en.wikipedia.org/w/index.php?title=List_of_space_stations&oldid=1171029312

Liu, K. (2022, December 15). Net zero targets could force Taiwan's chipmakers abroad. *Clean Energy Wire*. https://www.cleanenergywire.org/news/net-zero-targets-could-force-taiwans-chipmakers-abroad

Maass, R. (2015, September 30). NASA extends Boeing contract for International Space Station. *Space Daily*. https://www.spacedaily.com/reports/NASA_extends_Boeing_contract_for_International_Space_Station_999.html

Maintaining U.S. Preeminence in Low Earth Orbit. (2023, March 31). *The White House*. https://www.whitehouse.gov/ostp/news-updates/2023/03/31/maintaining-u-s-preeminence-in-low-earth-orbit/

Mallapaty, S. (2022). China's space station is almost complete—How will scientists use it? *Nature*. https://doi.org/10.1038/d41586-022-03462-5

Materials Science Laboratory (MSL): Material physics research facility in Destiny. (n.d.). *ERASMUS Centre - Directorate of Human Spaceflight and Operations, European Space Agency*. http://wsn.spaceflight.esa.int/docs/Factsheets/15%20MSL%20LR.pdf

Microgravity Science and Technology. (n.d.). *Springer*. https://www.springer.com/journal/12217

Morra, J. (2022, July 8). GlobalWafers to Build $5 Billion Facility in U.S. to Shore Up Wafer Supply. *Electronic Design*. https://www.electronicdesign.com/technologies/analog/article/21246073/electronic-design-globalwafers-to-build-5-billion-facility-in-us-to-shore-up-wafer-supply

Nagao, R. (2023, July 11). Japan to give $530m for new Sumco silicon wafer plants at home. *Nikkei Asia*. https://asia.nikkei.com/Business/Tech/Semiconductors/Japan-to-give-530m-for-new-Sumco-silicon-wafer-plants-at-home

NASA/Johnson Space Center. (2018, May 31). Sintering solutions aboard the International Space Station. *ScienceDaily*. https://www.sciencedaily.com/releases/2018/05/180531135306.htm

NASA MaterialsLab Strategic Plan. (2015). *National Aeronautics and Space Administration*.

National Research Council of the National Academies of Science. (2009). Frontiers in Crystalline Matter: From Discovery to Technology. *The National Academies Press*: Washington, DC. https://doi.org/10.17226/12640

Naumann, R. J., & Herring, H. W. (1980). Materials processing in space: Early experiments. *NASA*; Washington, DC. https://ntrs.nasa.gov/citations/19810007559

Npj. (2023, February 3). Microgravity. *Nature*. https://www.nature.com/npjmgrav/

Official Semiconductor Data Set—Butler University [Google Docs]. (n.d.). *Butler University*. https://docs.google.com/spreadsheets/d/1Zl_B_IbC_UFx4VfFamhCQcGgUdtk64r6wOdQ_wO3lHU/edit?usp=embed_facebook

Ostrach, S. (1977). Convection Phenomena of Importance for Materials Processing in Space. *Materials Sciences in Space with Application to Space Processing*, 3–32. https://doi.org/10.2514/5.9781600865268.0003.0032

Page, L. W., & Page, T. (1977). Apollo-Soyuz Pamphlet No. 8: Zero-G Technology [PDF]. *NASA*. https://ntrs.nasa.gov/api/citations/19780019210/downloads/19780019210.pdf

Pfeiffer, N. (2000). Process Development for Fabrication of Silicon Semiconductor Devices in a Low Gravity, High Vacuum, Space Environment. *Simon Fraser University*. https://www2.ensc.sfu.ca/grad/theses/masters/Pfeiffer_2000.pdf

Popov, A. S., Kostadinov, I. Z., Mateev, M. D., Regel, L. L., & Baturin, N. A. (1992). The influence of the front of crystallization upon the phase content in RbAg4I5 bulk crystals grown in microgravity. *Solid State Ionics*, 57(3), 211–215. https://doi.org/10.1016/0167-2738(92)90150-N

Redwire Space, & Ormsby, R. (2023, March 28). The Future of Semiconductor Processing in Space – Q&A with future LEO destinations [Q&A]. *The Workshop on Semiconductor Manufacturing in the Space Domain*, Stanford University. https://semispace.sites.stanford.edu/

Report of the NASA MaterialsLab Workshop. (2014).

Rep. Ryan, T. [D-O.-13. (2022, August 9). H.R.4346 - 117th Congress (2021-2022): Chips and Science Act (2021-07-01) [Legislation]. *Congress*. http://www.congress.gov/bill/117th-congress/house-bill/4346

Šakalys, R., Mohammadlou, B. S., & Raghavendra, R. (2022). Fabrication of multi-material electronic components applying non-contact printing technologies: A review. *Engineering*, 15. https://doi.org/10.1016/j.rineng.2022.100578

Service, R. F. (2018, July 24). Beyond silicon: $1.5 billion U.S. program aims to spur new types of computer chips. *Science*. https://www.science.org/content/article/beyond-silicon-15-billion-us-program-aims-spur-new-types-computer-chips

Shimura, F. (2007). Single-Crystal Silicon: Growth and Properties. *Springer Handbook of Electronic and Photonic Materials*, 255–269. https://doi.org/10.1007/978-0-387-29185-7_13

Shipman, H. L. (1987). Space 2000: Meeting the challenge of a new era. *NASA, University of Delaware*. https://ntrs.nasa.gov/citations/19880058378

SOLARIS activity plan. (n.d.). *ESA*. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/SOLARIS_activity_plan

Soviet Salyut-6 Scientific Space Station: The First Manned Phase—September 1977-March 1978 [PDF]. (1979). *National Foreign Assessment Center*. https://nsarchive2.gwu.edu/NSAEBB/NSAEBB501/docs/EBB-29.pdf

Space processing and manufacturing. (1969). *NASA*. https://ntrs.nasa.gov/citations/19710002226

Space Research Results Purify Semiconductor Materials. (2010). *NASA Spinoff*. https://spinoff.nasa.gov/Spinoff2010/ip_8.html

Starshot. (n.d.). *Breakthrough Initiatives*. https://breakthroughinitiatives.org/initiative/3

Tamaru, H., Koyama, C., Saruwatari, H., Nakamura, Y., Ishikawa, T., & Takada, T. (2018). Status of the Electrostatic Levitation Furnace (ELF) in the ISS-KIBO. *Microgravity Science and Technology*, *30*(5), 643–651. https://doi.org/10.1007/s12217-018-9631-8

Taylor, K. R. (1974). Proceedings of the third Space Processing Symposium on Skylab Results, volume 2. *NASA*. https://ntrs.nasa.gov/citations/19740021792

Tzinis, I. (2015, May 6). Technology Readiness Level. *NASA*. http://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

Varas, A., Varadarajan, R., Palma, R., Goodrich, J., & Yinug, F. (2021, March 28). Strengthening the Global Semiconductor Supply Chain in an Uncertain Era. *BCG Global*. https://www.bcg.com/publications/2021/strengthening-the-global-semiconductor-supply-chain

Walker, S. E. (1989). Centers for the commercial development of space. *NASA*; Washington, DC. https://ntrs.nasa.gov/citations/19900004835

Wilcox, W. R., & Regel, L. L. (2001). Microgravity Effects on Materials Processing: A Review. *Conference Proceedings of EUROMAT 2001, NASA*. https://ntrs.nasa.gov/api/citations/20030056609/downloads/20030056609.pdf

Wright, H., Williams, A., Wilkinson, A., Harper, L., Savin, K., & Wilson, A. M. (2022). An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types. *Crystal Growth & Design*, *22*(12), 6849–6851. https://doi.org/10.1021/acs.cgd.2c01056

Wuenscher, H. F. (1970). Unique Manufacturing Processes in Space Environment. *Space Congress: Session 7 – Manufacturing Processes in Space*. https://commons.erau.edu/space-congress-proceedings/proceedings-1970-7th/session-7/4

Yin, Z., Zhang, X., Wang, W., Li, X., & Yu, J. (2019). Melt Growth of Semiconductor Crystals Under Microgravity. *Physical Science Under Microgravity: Experiments on Board the SJ-10 Recoverable Satellite*, 327–360. https://doi.org/10.1007/978-981-13-1340-0_13