In-Space Manufacturing of Semiconductors – History and Future Vision

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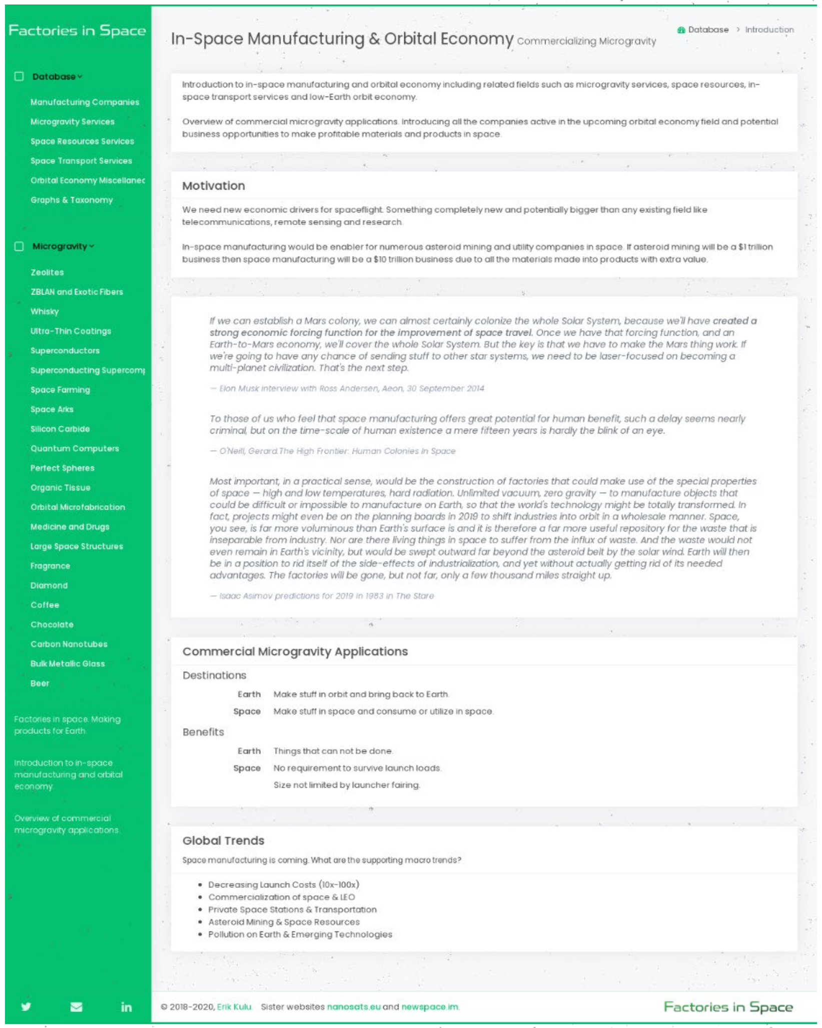
Factories in Space

Factories in Space

www.factoriesinspace.com

- Public database of commercial entities in the in-space economy, space resources and microgravity manufacturing fields.
- Started in 2018 and currently has over 700 entries.
- ZBLAN was the inspiration after realizing the kick-starter potential.
- It was first created to provide an overview of commercial microgravity applications but soon expanded to other in-space economy fields due to large overlap.
- At the time, similar sources found, and new content starting points, were Lynn Harper's CMAPP and Microgravity Applications and Ioana Cozmuta's Space Portal presentations.
- Driven by the need to find new revenue sources from space to drive the development of new space technologies and enable faster Solar System exploration.
- Strong belief that in-space manufacturing, and related in-space economy services, will be the largest space industry in the future.



[*] https://sites.google.com/site/cmapproject/home
[*] https://sites.google.com/site/microgravityapplications/
[*] https://www.nasa.gov/sites/default/files/ioana_hq_spaceportal_presented1.pdf

Outline

- Background & Scope
- History of In-Space Materials Production
- History of In-Space Semiconductor Production
- Historical Commercial Entities
- Vision for the Future

Scope

- **Semiconductors** - materials which have a conductivity between conductors (generally metals) and nonconductors or insulators (such as most ceramics). Semiconductors can be pure elements, such as silicon or germanium, or compounds such as gallium arsenide or cadmium selenide. [1]
  - **Growing wafers (crystals)**
- **Microfabrication** - process of fabricating miniature structures of micrometer scales and smaller.
  - Historically, the earliest microfabrication processes were used for integrated circuit fabrication, also known as **"semiconductor manufacturing".**
  - Semiconductor crystals often require post-processing to make them usable in devices.
  - In the last two decades microelectromechanical systems (MEMS), microfluidics/lab-on-a-chip, optical MEMS have re-used, adapted or extended microfabrication methods. Flat-panel displays, and solar cells are also using similar techniques. [2]
  - Processes like deposition and removal can have own applications (e.g., ultra-thin films).

[1] https://depts.washington.edu/matseed/mse_resources/Webpage/semiconductor/semiconductor.htm
[2] https://en.wikipedia.org/wiki/Microfabrication

History of In-Space Materials Production

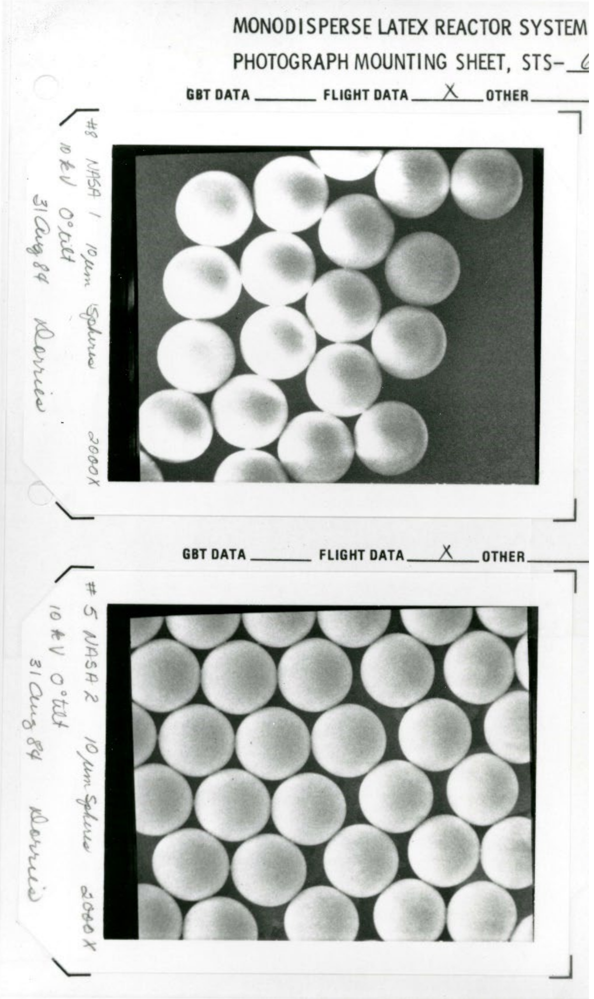
Commercial activities for advanced materials and pharmaceuticals, in addition to semiconductors and microfabrication.

NB! This overview is non-exhaustive, there are more examples in the fields of tissue engineering etc, but likely not yet sold commercially.

Perfect Spheres (1984)

John W. Vanderhoff, a chemistry professor at Lehigh University, worked with NASA to design an instrument Monodisperse Latex Reactor (MLR).

- A plastic mixture contained in four furnaces congeals and grows around tiny seeds to produce plastic spheres of uniform size.
- In one space shuttle experiment, these furnaces produced ten billion identical tiny spheres.
- The National Bureau of Standards certified that the size of these spheres is ten micrometers in diameter, varying by only a tenth of a percent.
- One could buy these in a 5-milliliter vial for $384.
- Plastic beads were worth between $4-12 million per kilogram.
- The idea of making spheres in space was behind one of the oldest proposals for space manufacturing: making ball bearings in space (drop towers).
- NASA planned to make more latex balls in larger sizes. They have published estimates that the market for larger 100-micron spheres could be $200 million to $300 million annually.

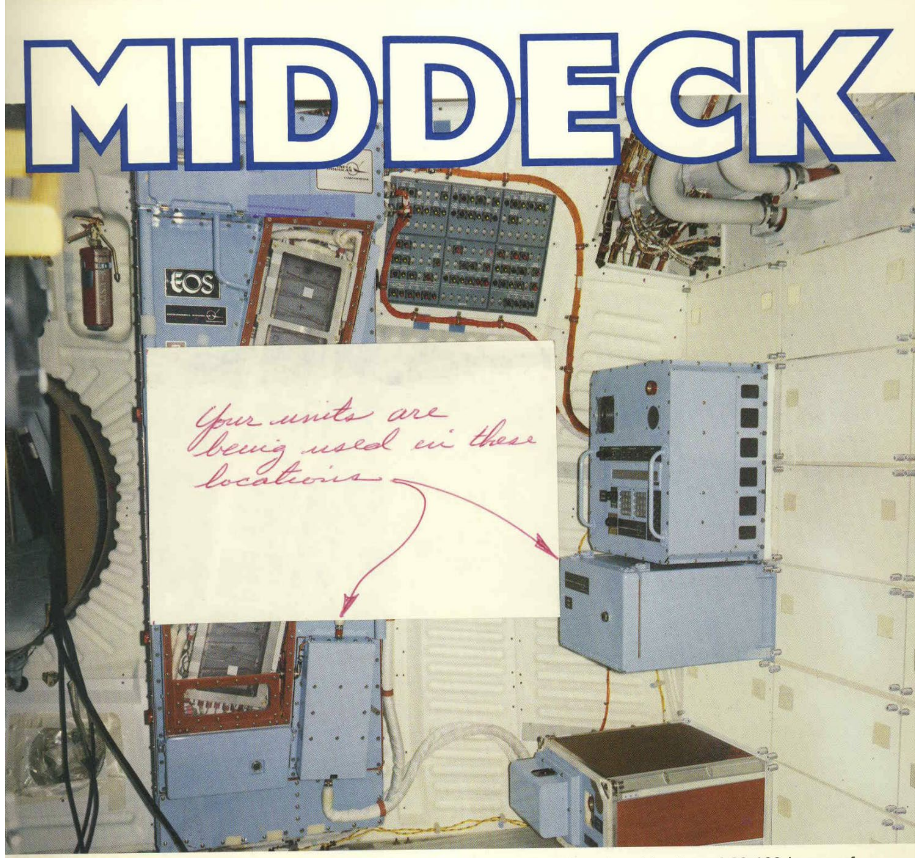


[*] *Harry L. Shipman. Space 2000: Meeting the Challenge of a New Era, 1987.*
[*] *https://commons.wikimedia.org/wiki/File:SpaceBeadsSRM_034.jpg*

Pharmaceutics (1982-1985)

EOS (Electrophoresis Operations in Space)

- A joint venture of McDonnell Douglas and Johnson & Johnson.
- Drug called erythropoietin, a human hormone that controls the production of red blood cells. Before, it was available in very small quantities for laboratory research and had not been used clinically.
- The first flight in June 1982, demonstrated that the expected improvement in volume and purity of product would happen.
- In April 1985, 1 gram of drug was produced, and testing started.
- In July of 1985, McDonnell Douglas planned to fly an EOS production unit in the payload bay of the Space Shuttle. This 5,000-pound unit will be 3.5 feet wide and 14 feet long and have 24 times the separation capacity.
- McDonnell Douglas's had a shopping list of ~20 drugs for space manufacturing. One had been announced: the production of beta cells in space as a possible cure for diabetes, in collaboration with Washington University in Saint Louis.
- „Johnson & Johnson seems to have got discouraged.“

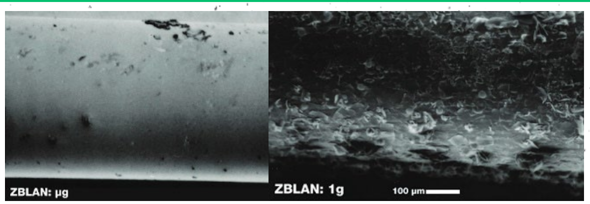


The two remaining middeck flights of the EOS unit are scheduled for June and October of 1984. A McDonnell Douglas engineer, Charles Walker, will ride aboard the first (and possibly the second) of these flights to ensure the unit meets its objective of 80-100 hours of continuous separation. When the Space Shuttle Discovery is launched, Walker will make history as America's first industry representative to fly in space.

[*] Harry L. Shipman. Space 2000: Meeting the Challenge of a New Era, 1987.
[*] https://www.thermoelectric.com/2010/archives/library/Electrophoresis%20in%20Space%201985.PDF

ZBLAN Optical Fiber (2017+)

- News in 1998 estimated ZBLAN commercial potential at $2.5 billion.
- Optical fiber ZBLAN was started to be publicly called in many news articles as the first likely profitable product made in space in about 2016-2017.
- NASA's awarded contracts to FOMS, Physical Optics Corporation (Mercury Systems), Apsidal and DSTAR starting from 2016.
- Made in Space launched internally funded demonstration missions in 2017 and 2019.
- FOMS reported high-quality production on ISS in 2019.
- In 2020, NASA selected further proposals from Made In Space, Apsidal and DSTAR.
- In July 2022, two NASA-supported optical fiber manufacturing payloads arrived at the ISS aboard CRS-25: Space Fibers 3 developed by FOMS and the Orbital Fiber Optic Production Module (ORFOM) from Mercury Systems (Physical Optics Corporation).
- Jeff Foust wrote in September 2022 that experiments in ZBLAN fiber production have yet to convert into commercial production and producing such fibers in space was turning out to be harder than expected. Apsidal's De says a breakthrough is still possible, given enough effort.



FOMS Inc

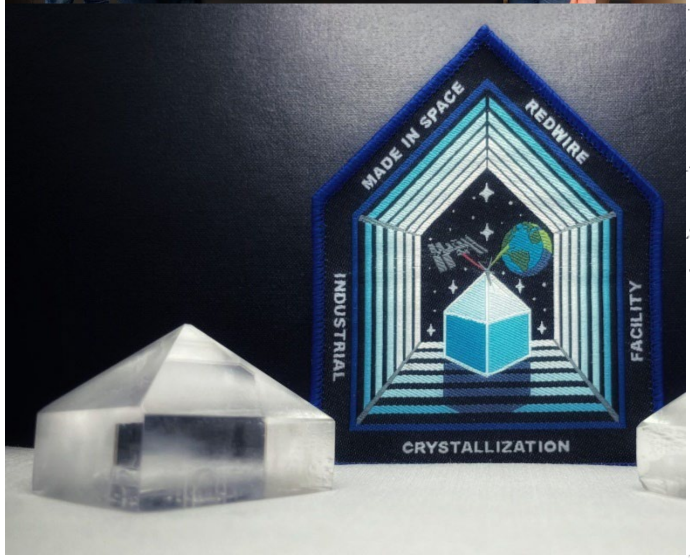
Mercury Systems

[*] Gary L. Workman. ZBLAN Microgravity Study. Technical report, April 1995.
[*] Dave Dooling. ZBLAN Has Great Commercial Potential. February 1998.
[*] https://spacenews.com/foust-forward-manufacturing-a-low-earth-orbit-economy/.
[*] https://www.space.com/made-in-space-second-zblan-optical-fiber-space-factory.html
[*] https://www.nasa.gov/directorates/spacetech/flightopportunities/NASA_Supported_Optical_Fiber_Manufacturing_Arrives_at_Space_Station

Optical Crystals (2022)

In 2022, Redwire announced the first sale of its space-manufactured optical crystal.

- To researchers at the Center for Electron Microscopy and Analysis (CEMAS), a leading electron microscopy facility, at The Ohio State University.
- The space-enabled optical crystal was manufactured in Redwire's Industrial Crystallization Facility (ICF) onboard the International Space Station (ISS).
- Space-manufactured optical crystals could improve laser system performance because they have a higher laser damage threshold due to fewer inclusions and defects because of the space manufacturing process.
- Two grams of the space-manufactured crystal were sold.
- The approximate value is $2 million per kilogram.



[*] https://redwirespace.com/newsroom/redwire-opens-new-commercial-market-for-in-space-production-with-first-sale-of-space-manufactured-optical-crystal/
[*] https://redwirespace.com/newsroom/space-crystals-developing-laser-optics-products-in-space/

History of In-Space Manufacturing of Semiconductors

Activities and publications in chronological order. Not completely exhaustive, please see the Butler University 2022 study and database for all semiconductor experiments

H. Wright et al. Cryst. Growth Des. 2022, 22, 12, 6849–6851 https://pubs.acs.org/doi/abs/10.1021/acs.cgd.2c01056

NB! More historical activities of NASA, especially during the ISS lifetime, and current activities are expected to be covered by other presenters.

1973, Skylab 3

- Five experiments involving the processing of semiconductor materials were performed during the Skylab 3 mission.
- The primary purpose was to examine the influence of gravity-driven flows on the solidification process, with emphasis on the distribution of the dopant atoms that give the semiconductors its desired electrical properties.

1978, Materials Processing in Space

- The Committee examined as an example the possible importance of growing semiconductor crystals in space for commercial use. It was particularly appropriate because it also involves solidification and containerless processing.
- Among the advantages claimed for growing semiconductor electronic crystals in space are improved homogeneity, greater purity, reduction of the number of physical defects and imperfections, ability to grow large-diameter crystals, and ability to grow crystals as flat ribbons.
- Two assumptions are implied: first, that semiconductor crystals have stringent requirements for purity, uniformity. and perfection; second, that the availability of electronic materials with fewer imperfections or greater purity will permit making electronic devices with improved characteristics.
- It has been said that better starting material leads to better device performance, but, in fact, the quality of starting material is not the limiting consideration for most devices presently manufactured. Even if starting material were perfect, most fabrication processes for devices involve steps at high temperatures that induce physical and chemical defects far in excess of those originally present.

1980, Materials Processing in Space: Early Experiments

- Another problem in the technology of silicon and semiconductors is that of obtaining very uniform dopant distribution, particularly in the relatively high concentrations needed for applications such as infrared detectors.
- Another class of semiconductors in which a high degree of chemical homogeneity is essential is the class of alloy or solid solution semiconductors. In these materials the electrical characteristics are determined by the ratio of the components that make up the alloy. No dopants are necessary.

[*] National Research Council 1978. Materials Processing in Space. Washington, DC: The National Academies Press. https://doi.org/10.17226/20033 .
[*] Materials Processing in Space: Early Experiments, NASA, 1980. https://ntrs.nasa.gov/api/citations/19810007559/downloads/19810007559.pdf

1982, Civilian Space Policy and Applications, Materials Science and Engineering in Microgravity

- Commercially valuable crystals for sensitive infrared sensors, most difficult to grow on Earth, may be enhanced by melt growth in a microgravity environment.
- The absence of gravity opens new possibilities for the growth of large, flat, pure crystals by vapor technique.
- The program includes the investigation of Hg12 nuclear detector crystals that can be used at ambient temperature.

1984, Producing Gallium Arsenide Crystals in Space (Microgravity Research Associates)

- The production of high-quality crystals in space is a promising near-term application of microgravity.
- Gallium Arsenide (GaAs) is the material for initial commercial production because of its inherent superior electronic properties, wide range of applications and broad base of on-going device development effort.
- Entered joint endeavor agreement with NASA in April 1983 to develop the electroepitaxial method for growing semiconductor crystals in space.
- Epitaxial crystal growth avoids many of the problems of bulk processing. Here the crystal material is deposited layer upon layer on a crystal seed. The process achieves more uniform crystal structure but is very slow and produces only thin layers of small diameter (3 inch) crystals. Typically, epitaxial crystals have been layered upon slices of bulk crystal to fabricate devices and is not compatible with growth of bulk quantities.

1987, Space 2000: Meeting the Challenge of a New Era

- Popular science book with a review chapter on Materials Processing in Space.
- Source for the early companies: Microgravity Research Associates and EOS.

[*] Civilian Space Policy and Applications, June 1982, NTIS order #PB82-234444
[*] Randolph, R. L., "Producing Gallium Arsenide Crystals in Space", Space Industrialization Opportunities, edited by Jernigan, C. M. and Pentecost, E., 1985.
[*] Harry L. Shipman. Space 2000: Meeting the Challenge of a New Era. 1987.

1985+, Battelle's Advanced Materials Center for the Commercial Development of Space (CCDS)

1985, Microgravity Materials Processing for Commercial Applications

- Formed in November 1985, the Advanced Materials Center for the Commercial Development of Space, located at Battelle Memorial Institute in Columbus, Ohio.
- Established to utilize the microgravity environment in the commercial development of composite and mixed-phase materials with substantially improved properties.
- The Center is conducting research in catalysts (variant-phase chlorides, zeolites, and mixed oxides), polymer systems, **electronic materials (float-zone crystal growth on Type II-VI semiconductor crystals, particularly Cadmium telluride, CdTe)**, and controlled-porosity glass.
- The present program focuses on a proof of principle for each research thrust, utilizing ground-based and suborbital facilities, together with modeling to demonstrate the potential for producing commercially important materials.
- As of 1990, focus had turned to polymer processing in space, which constitutes the most active microgravity program at the Advanced Materials CCDS. Three areas: membrane processing, multiphase composite behavior, and plasma polymerization. Current work in microgravity crystal growth is discussed with reference to the development of the Zeolite Crystal Growth facility.

[*] Centers for the Commercial Development of Space https://ntrs.nasa.gov/api/citations/19900004835/downloads/19900004835.pdf

[*] https://www.cambridge.org/core/journals/mrs-online-proceedings-library-archive/article/abs/microgravity-materials-processing-for-commercial-applications/3FC74D4706E5BB9AAAFF8709343110EC R. Kohli, P. L. Brusky, S. Diamond, A. J. Markworth, V. D. McGinniss, P. J. Melling, E. D. Spinosa, and E. W. Collings Advanced Materials Center for the Commercial Development of Space, Battelle Columbus Division, 505 King Avenue, Columbus, Ohio 43201-2693

[*] Mccauley, Lisa A., Microgravity polymer and crystal growth at the Advanced Materials Center for the Commercial Development of Space, 1990.

1980+, Germany, Freiburg (1)

1980, The first results University of Freiburg researchers gained from crystal growth experiments in μg were achieved on a SKYLARK-7 sounding rocket in the TEXUS program of the DLR (German Aerospace Center) in the framework of the TEXUS-3 mission. The sounding rocket launched in 1980 from Sweden and provided 6 min of μg.

1985, Floating zone growth of silicon under microgravity in a sounding rocket

- A phosphorus-doped silicon crystal of 8 mm by 10 mm length has been grown by the floating zone method at a rate of 5 mm/min.
- Concluded that time-dependent thermocapillary flows, driven by surface tension gradients, are the predominant cause for dopant inhomogeneities.

1985, German Space Shuttle flight, STS-61-A (also known as Spacelab D-1)

1993, German Space Shuttle flight, STS-55, or Deutschland 2 (D-2)

- In 1993, the German Spacelab mission D-2 GaAs crystal growth experiments have been launched by the German Space Agency. Using floating-zone technique the obtained sample contained significantly lower amount of dislocation networks with relatively larger cell size than its Earth-growth counterpart (Herrmann and Müller 1995, pp. 350–360).
- In the same mission, Cröll et al. also reported about decreasing dislocations in the case of GaSb using floating-zone method.

1999, Semiconductor crystal growth under microgravity: Results of Float-zone technique

- Semiconductor crystal growth experiments performed in Germany often used the Floating-zone technique (FZ). Recent Results of the FZ growth of Silicon, Si and Galliumantimonide, GaSb in connection with fluid dynamics will be reported.
- FZ-GaAs within a quartz ampoule up to 25 mm in diameter has been grown for the first time during the German Spacelab mission D2.
- Three FZ-GaSb single crystals have been successfully grown on Spacehab-4 during the STS-77 Space Shuttle flight, May 1996.

[*] A. Eyer, H. Leiste, R. Nitsche, Kristallographisches Institut der Universität, Hebelstrasse 25, D-7800 Freiburg, Fed. Rep. of Germany
[*] K.W. Benz, A. Croell Kristallographisches Institut, Universitaet, D-79104 Freiburg, Germany https://www.sciencedirect.com/science/article/abs/pii/S0273117799007188?via%3Dihub
[*] K.W. Benz, P. Dold. 2002 https://www.researchgate.net/publication/228463554_Crystal_growth_under_microgravity_Present_results_and_future_prospects_towards_the_International_Space_Station

1980+, Germany, Freiburg (2)

2012, Crystal growth under microgravity: Present results and future prospects towards the ISS

- Semiconductor materials have wide interest in the Industry. Enhancing the optical, electrical, and magnetic properties of them.
- The role which microgravity plays for the understanding of the growth of semiconducting materials is reviewed. Main emphasis is placed on the interaction of fluid flow and mass transport phenomena during different growth processes, the character and strength of surface tension driven flows, the limitations of diffusive transport regimes, and possibilities provided by magnetic fields to support or replace microgravity conditions.
- **None of the achievements of microgravity research into the growth of crystals to date can be said to be spectacular. But crystal growth is not a field where spectacular advances often occur**. Rather it is one where detailed studies of mechanisms and the coupling between the many parameters controlling the process progressively improve y that process.
- In terms of gaining a better understanding of solidification processes, the research under microgravity made valuable contributions, e.g. for the judgement of STD flows, for the knowledge about mass transport mechanisms towards the growth front, for the investigation of containerless growth or the study of crucible detachment.

2017, 30 Years of Crystal Growth Under Microgravity Conditions in Freiburg: An Overview of Past Activities

- The focus of material research in Freiburg was and is still in semiconducting materials; elemental semiconductors like Si, Ge, and GeSi as well as various compound semiconductors like InP, GaAs, and CdTe.
- **The responsibility of µg research is to provide insight into the occurring processes and to transfer this to the processes under gravity conditions on earth. A lot of applications during crystal growth and their influence on the growing material, i.e. the use of rotating, travelling, and static magnetic fields, vibrations, plastic skins to cover liquids, etc. were investigated and resulted in improved methods for optimized crystallization.**
- The experiments under the special conditions of microgravity allowed insights into the crystal growth itself, the growth kinetics directly at the phase boundary, and the detailed evaluation of different convectional phenomena.

[*] A. Eyer, H. Leiste, R. Nitsche, Kristallographisches Institut der Universität, Hebelstrasse 25, D-7800 Freiburg, Fed. Rep. of Germany
[*] K.W. Benz, A. Croell Kristallographisches Institut, Universitaet, D-79104 Freiburg, Germany https://www.sciencedirect.com/science/article/abs/pii/S0273117799007188?via%3Dihub
[*] K.W. Benz, P. Dold. 2002 https://www.researchgate.net/publication/228463554_Crystal_growth_under_microgravity_Present_results_and_future_prospects_towards_the_International_Space_Station

1987+, Russia (1)

1989, Experiments on crystallization of semiconductor materials, eutectic alloys and crystal growth from water solution in microgravity

- In July 1987 on-board the Mir orbital complex, two experiments on direct crystallization of the eutectic A1-Ni alloy were carried out with the use of the "Crystallizer CSK-I".
- This paper gives results about crystallization of Al-Ni eutectic alloys, of GaSb and of hydroxyapatite and calcium sulphate, under microgravity.
- When the flight was over, two capsules with the experimental space samples and the cassette or the record of space experimental parameters were brought back to Earth.

2001, Crystallization of semiconductors in microgravity, Current state, problems and prospects (25-years results)

- Attempt to sum up the more than 25-years our (ICPM) experience in the field of semiconductor crystals growth in microgravity.
- Carried out more than 60 experiments on Ge and GaSb single crystals growth, undoped and doped with various impurities, aboard Photon and Mir.
- Application of magnetohydrodynamical (MUD) stirring for crystallization process control. It should be noted that heat and mass transfer is easy to control in space, since the level of mass forces in this case is several orders of magnitude lower than on the Earth.
- Our experimental data (Photon-5, 1989) on growth of high-purity germanium by the floating-zone technique in microgravity showed that the use of a 0.2 mT **rotating (400 Hz) magnetic field provided the steady-state melted zone** of a length equal to the diameter of initial ingot, During the experiment, the power consumption of inductor system was 18 VA. To obtain similar results on Earth, magnetic fields 100 times greater must be used.
- Low power, contactlessness and efficiency are the factors defining the prospectivity of rotating magnetic fields application in space-based growth processes. The spacebom growth facility Polyzone specially designed for Russian segment of ISS, already equipped with magnetic inductor.
- **Pioneering experiments on the growth of semiconducting crystals in space were performed more then 20 years ago. However, since then, device-grade space-grown single crystals with properties surpassing those of the best terrestrial counterparts have not been obtained.**
- Nevertheless, efforts have had some success. The specific features of weightlessness as a unique technological medium have been demonstrated, and the strategy of preparing and conducting space experiments has been worked out. It has been shown that in-depth analysis of basic laws of heat-mass transfer and crystallization under zero-gravity conditions, including the specific microgravitational situation aboard spacecraft, and reliable methods of controlling these processes are vital for tackling the problem of obtaining good space crystals. The possibility of effectively using results obtained in space to refine growth technologies on the Earth has been demonstrated.

[1] L.L. Regel, O.V. Shumaev, I.V. Vidensky, I.M. Safonova, A.A. Vedernikov, I.V. Melikhov, V.F. Komarov, A.I. Ivanov Space Research Institute, U.S.S.R. Academy of Sciences, U.S.S.R. Received 22 March 1989,
[2] Mil'vidskii Mikhail, Kartavykh Andrey, Rakov Valerii https://adsabs.harvard.edu/full/2001ESASP.454..395M

1987+, Russia (2)

2001, Gravity Application to Anisotropic Semiconductor Materials: from, to Microgravity Conditions

- We have studied the properties of tellurium crystals, Te-Se and Te 80Si 20 alloys grown under different gravity levels by a modified Bridgman method using a Te crystal seed. We examined the influence of gravity from microgravity up to 10 g on the distribution of electrically active intrinsic defects and dopants.
- The data on solidification of the glassy alloy Te 80Si 20 in space and at normal gravity on earth indicate that microgravity suppresses cluster nucleation during the solidification and promotes ideal glass formation.

2012, Some results of semiconductor crystal growing under microgravity conditions

- It has been shown using Ge(Ga), GaSb(Si), and GaSb(Te) crystals as an example that the formation of segregation growth striations can be avoided during their recrystallization by the vertical Bridgman method in conditions of physical simulation of microgravity on the Earth, mainly due to the essential weakening of the thermal gravitation convection. By their structure and impurity distribution, they approach the crystals grown in space.
- In general, first results were encouraging and showed that obtaining of higher quality crystals in weightlessness conditions is possible in principle. However, the structure of the crystals of the Ge solid solutions with 1 at % Si and 0.001 at % Sb, which were obtained by directional crystallization on the Apollo– Soyuz space complex, turned out lower quality than for the terrestrial analogs.
- **However, obtaining of semiconductor crystals with microcrystalline uniform structure is possible, which is inadmissible in conditions of normal gravity. Such experiment was realized on Mir during the complete remelting of the Te crystal with the subsequent cooling down to the transition into the supercooled state and homogeneous spontaneous crystallization. The sample had finecrystalline uniform structure with a minimal grain size down to 5 µm, which cannot be realized in terrestrial conditions**. The fine crystalline state of tellurium made it possible to observe the phenomena associated with scattering at grain boundaries, which were not observed in bulk and large grained samples.

2016, Ge:Ga Crystal Growth Within an RMF During the Foton-M4 Mission

- One of the important problems of applied MHD is the stability of the flow induced by a rotating magnetic field (RMF). In spite of many theoretical studies, there is no experimental evidence consistent with theoretical results. During the FOTON-M4 mission in 2014, two germanium crystals doped with gallium were grown both without application of RMF and within the RMF.

[1] Parfeniev, R. V. (A.F. Ioffe Physico-Technical Institute RAS, Russia); Regel, L. L. (International Center for Gravity Materials Science and Applications, Clarkson University, USA); https://ui.adsabs.harvard.edu/abs/2001AcAau..48..163P/abstract
[2] Shulpina, I.L et al., 2012. Some results of semiconductor crystal growing under microgravity conditions. Phys. Solid State 54 (7), 1264. https://www.researchgate.net/publication/257855636_Some_results_of_the_growth_of_semiconductor_crystals_in_microgravity_conditions_to_the_50th_anniversary_of_Yuri_Gagarin's_flight_into_space
[3] Alexander S. Senchenkov, Russian Federal Space Agency. Nikolai N. Kolesnikov & V. I. Orlov, Institute of Solid State Physics RAS https://www.researchgate.net/publication/304539960_GeGa_CRYSTAL_GROWTH_WITHIN_AN_RMF_DURING_THE_FOTON-M4_MISSION

1989+, China

1999, Structural properties of SI-GaAs grown in space

- A new flight experiment for growing semi-insulating gallium arsenide (SI-GaAs) single crystal in space was successfully performed in Oct. 1996 in cooperation with the Lanzhou Institute of Physics, CAST and the Institute of Physics, CAS. The starting ingot was a 20 mm diameter bar cut and ground from a SI-GaAs single crystal terrestrially grown by liquid-encapsulated Czochralski (LEC) technique.

2001, Comparison of field effect transistor characteristics between space-grown and earth-grown gallium arsenide crystal substrates

- Experiments for growing semiconducting crystals in space have been performed for more than 20 years. The species of semiconducting crystals grown from melt in space include germanium, silicon, gallium antimonide, indium phosphide, indium antimonide and gallium arsenide.
- Although the characteristics of semiconductors grown in space have been studied extensively, the device-grade semiconductor grown in space surpassing terrestrial counterparts has not yet been found in literature.
- The SI–GaAs crystal ingot grown in space is 20 mm in diameter and 100 mm in length in a recoverable satellite. The ingot was sliced into 0.5 mm thick wafers, which were ground and polished.
- Some of the processed wafers were selected to **fabricate low noise field effect transistors and analog switch integrated circuits** using direct ion-implantation technique at Hebei Semiconductor Research Institute.
- In conclusion, all the electrical properties of the low noise FETs and analog switch ICs made by direct ion implantation technique in space-grown SI–GaAs wafers have surpassed those made from conventionally terrestrial grown SI–GaAs. This result shows that the device-grade space-grown semiconducting single crystal surpassed the best terrestrial counterparts.

2002, Space grown semi-insulating gallium arsenide single crystal and its application

2017, Microgravity Growth of Semiconductor Materials

[*] N.F. Chen, Y.T. Wang, X.R. Zhong, L.Y. Lin, Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences https://www.sciencedirect.com/science/article/pii/S0273117799007218
[*] Mian Zhang, Yunsheng Wang, Xiwei Bai, and Jing Zhao, Hebei Semiconductor Research Institute https://aip.scitation.org/doi/10.1063/1.1342201
[*] https://www.sciencedirect.com/science/article/abs/pii/S0273117701006627
[*] https://www.researchgate.net/publication/319943550_Microgravity_Growth_of_Semiconductor_Materials
[*] http://www.mat-china.com/Upload/PaperUpLoad/8aa2ef43-7bfa-4686-b419-c0d4bc3d7fc4.pdf

1992+, Japan

1992, Survey report of JSUP Space Environment Utilization Research Committee in 1992: Functional New Materials Session

- Space is considered to be a favorable environment for: semiconductor joining by atomic adhesion, fabrication of thin films of diamond and amorphous silicon alloys, CVD processes, production of super-minute grains. Although there has not been an experiment utilizing the merit of high-vacuum environment, the environment is essential for film fabrication, from spattering to MBE (Molecular Beam Epitaxy) and plasma CVD.
- Taking advantages of microgravity environment, amorphous semiconductors made a remarkable improvement in quality and quantity.

1993, Fabrication of Si-As-Te ternary amorphous semiconductor in the microgravity environment

- **Ternary chalcogenide Si-As-Te** system is an interesting semiconductor from the aspect of both basic physics and technological applications. Since a Si-As-Te system consists of a IV-III-II hedral bonding network, it has a very large glass forming region with a wide physical constant controllability. For example, its **energy gap can be controlled in a range from 0.6 eV to 2.5 eV**, which corresponds to the classical semiconductor Ge (0.66 eV), Si (1.10 eV), GaAs (1.43 eV), and GaP (2.25 eV). It would be a suitable system to investigate the compositional dependence of the atomic and electronic properties in the random network of solids.
- A big barrier impending the wide utilization of this material is the huge difficulty encountered in the material preparation which results from large differences in the weight density, melting point, and vapor pressure of elements used for the alloying composition.
- The objective of the FMPT/M13 experiment is to fabricate homogeneous multi-component amorphous semiconductors in the microgravity environment of space, and to make a series of **comparative characterizations** of the amorphous structures and their basic physical constants on the materials prepared both in space and in normal terrestrial gravity.

1994, Fabrication of a new type of synthetic semiconductor in space

- Fabrication of a ternary Si-As-Te amorphous semiconductors in the Spacelab J is introduced together with essential advantages
- In a final part, a large area thin film growth in space and its application to a bioproductive solar power generation is proposed.

[*] Y. Hamakawa https://ntrs.nasa.gov/citations/19940009272
[*] Y. Hamakawa, Faculty of Engineering Science, Osaka University, Toyonaka, Osaka, Japan, https://ieeexplore.ieee.org/document/519800
[*] https://www.sciencedirect.com/science/article/abs/pii/S027311770100672X Y. Hiraoka a, K. Ikegami a, T. Maekawa a, S. Matsumoto b, S. Yoda b, K. Kinoshita b, Toyo University, 2100, Kujirai, Kawagoe, Saitama 350-8585, Japan, National Space Development Agency of Japan, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505, Japan

1994-1996, Wake Shield Facility (WSF)

- Wake Shield Facility (WSF) was a NASA experimental science platform that was placed in LEO by the Space Shuttle. It was a 3.7 m diameter, free-flying stainless steel disk. The WSF operated at a distance from the Space Shuttle to avoid contamination.
- The WSF was sponsored by the NASA's Office of Life and Microgravity Sciences and Applications. It was designed by the Space Vacuum Epitaxy Center, (renamed to Center for Advanced Materials), at the University of Houston, a NASA Commercial Space Center with Space Industries Inc.
- The WSF Flight Program was a series of missions **aimed at determining the feasibility of the space wake vacuum environment for the industrial production of thin film semiconductor material.** Using a low-cost approach, WSF-01 went to orbit in <5 years for <$15M.
- The WSF's orbital speed was at least three to four times faster than the speed of thermospheric gas molecules in the area, which resulted in a cone behind the WSF that was entirely free of gas molecules. The WSF thus **created an ultrahigh vacuum in its wake.**
- The thin film growth apparatus included 8 source cells (small furnaces) for the evaporation of elemental atoms for molecular beam epitaxy (MBE) thin film growth, and two gas nozzles for the effusion of organometallic gaseous species for chemical beam epitaxy (CBE) thin film growth. The MBE/CBE apparatus allowed for growths on seven separate substrate wafers, with the growths supported by total pressure gauge and a mass spectrometer measurements of the residual vacuum environment at the growth regioon.
- These missions produced the first characterization of vacuum wake formation and **epitaxial growth in that wake by growing the first-ever crystalline semiconductor thin films of record purity gallium arsenide (GaAs) and carbon-free aluminum gallium arsenide (AlGaAs) thin films.**
- WSF-03 continued experiments in thin films for transistors, lasers, and solar cells, by growing material for device fabrication.
- Funding ran out in 1997. In May 1998, SVEC granted license to SPACEHAB to market, and operate the Wake Shield Facility.

[*] https://web.archive.org/web/20191017172744/http://www.svec.uh.edu/wsfp.html
[*] https://en.wikipedia.org/wiki/Wake_Shield_Facility
[*] A. Ignatiev et al http://www.cam.uh.edu/projects/space-materials

1996, Technology Thresholds for Microgravity: Status and Prospects

- **The production yield of integrated circuits and optoelectronic devices is, to a certain extent, a direct result of the quality of the starting materials. Although there are numerous processing steps in the fabrication of such devices, any one of which can affect the overall yield, it is generally accepted that as the process engineering is improved, the starting material will eventually become the yield-limiting step.**
- Yoe reviewed the results of 11 flight experiments on germanium-based crystals formed by both chemical and physical vapor transport methods and concluded that the results were internally consistent, that bigger and more microhomogeneous crystals were observed in every case, and that in some cases crystals 100 times larger were achievable in space compared to Earth.
- Weidemeier has reviewed 13 different experiments encompassing the spectrum of chemical (CVT) and physical-vapor transport (PVT) and crystal growth of diverse materials (IV-VI compounds).
- Reviewed results demonstrated "a considerable improvement of the surface and bulk chemical and structural microhomogeneity of space-grown GeSe crystals relative to ground controls. The space crystals are much larger and grew in the ampoule without direct wall contact.
- In 1993, the technologically important (II-VI) compounds, such Hg-Cd-Te, demonstrated nearly defect-free crystal surfaces, with at least a 1,000-fold reduction in crystalline defects compared to Earth grown references. Two space-grown crystals used in devices for infrared energy detection showed infrared radiation transmission levels approaching the theoretical maximum. **These crystals have traditionally been considered good microgravity candidates because of their extreme sensitivity to very minute fluid disturbances.**
- The milestones for near-term growth of semiconductor crystals include:
    - (1) production of defined, chemically homogeneous standards of silicon for resisitivity and chemical analyses;
    - (2) high resistivity, homogeneous, defect-free silicon, with diameters up to 15 cm for high-voltage, high-current power rectification;
    - (3) large dislocation-free, homogeneously doped silicon for infrared-detector arrays or very large sensor integration (VLSI);
    - (4) intrinsic and extrinsic (indium-doped) Si-Ge alloy crystals with chemical homogeneity for infrared (IR) detectors;
    - (5) highly perfect III-V (e.g., GaAs) substrates for heterostructures;
    - (6) ternary semiconductor compounds (e.g., Cdl.xZnxTe, Hgl.xCdxTe, PbSnTe) for R&D; and
    - (7) quaternary semiconductor compounds such as GaInAsP, InPAsSb, GaPAsSb, and A1GaInSb for R&D.
- **Independent projections for electronic materials have estimated a long-term, space-based economic contribution of between $6 billion annually (Rockwell International) and $31 billion annually.**

[*] D.A. Noever, NASA Marshall Space Flight Center, https://ntrs.nasa.gov/api/citations/19970005379/downloads/19970005379.pdf

2001, Microgravity Effects on Materials Processing: A Review

- The dreams of manufacturing "perfect" crystals using "zero gravity" began in the 1960's during the Apollo era. Talk of manufacturing other substances continued through the 1970's and much of the 1980's. **Then reality set in, particularly with the Challenger disaster.**
- **The space environment was not magic, and the materials were not sufficiently better to warrant the costs.**
- **On the other hand, an immense amount was learned about gravitational effects on materials process**, both through the results of space experiments and through related ground-based research. In fact, many results were unanticipated, and some await full explanation. This knowledge has proven to be extremely useful in improvement and innovation of materials processing on Earth.
- When the dream of manufacturing in space began in the 196O's, a major problem in semiconductor device manufacturing was variation in impurity doping, on both macroscopic and microscopic scales.
- In Czochralski growth, periodic variations in impurity concentration arose from the rotation of the crystal while it was being pulled from the melt.
- Bridgman growth in space seemed to offer the perfect solution to this problem -- utilizing zero gravity to eliminate convection, and, thereby, to give a constant impurity concentration. **It was realized the acceleration is not zero in an orbiting spacecraft.**
- **The steady acceleration level was estimated to be one-millionth of Earth's gravity.** Thus, the term "zero gravity" died and " microgravity" was born. Measurements showed considerably larger fluctuating accelerations, averaging one thousandth of earth's gravity. These arose from movements of the crew, equipment, spacecraft attitude adjustment. The residual acceleration in spacecraft always causes buoyancy-driven convection. In recent years, it has become increasingly recognized that some microgravity experiments require reduced acceleration levels in order to be fully successful. **Consequently, both passive and active vibration-damping systems have been devised.**
- The original motivation for Bridgman growth in space was to produce **semiconductor crystals with completely uniform doping**. Homogeneous crystals were sometimes produced in flight experiments, but only when the freezing rate was much greater than the convective velocity of the nearby melt. Reduced gravity was much more successful at eliminating compositional striations than at avoiding radial or macroscopic longitudinal variations.

[*] William R. Wilcox and Lira L. Regel, Clarkson University https://ntrs.nasa.gov/api/citations/20030056609/downloads/20030056609.pdf

2000-2001, Space Microchip Fabrication

G. H. Chapman and N. Pfeiffer published papers on commercial space-based microchip fabrication

- Standard terrestrial fabrication techniques are optimized for in-situ resources: water, power, air pressure and gravity that are plentiful on Earth.
- Current research has been concentrated on orbital fabrication of single high vacuum processes, such as Wakeshield's silicon epitaxial growth.
- Yet, even the simplest semiconductor devices require the combination of many microfabrication steps, such as thin film deposition, patterning (photolithography), and etching. With the right choice of processes, native vacuum greatly reduces the number of microfabrication process steps, and equipment complexity, mass and power.
- Investigated a wide range of microfabrication processes for orbital environmental compatibility. An alternative microfabrication process has been developed using the native vacuum environment, which could replace wet terrestrial based microfabrication, with significant savings in equipment size, mass and consumables, while reducing cycle time. More importantly these dry space processes remove significant sources of contaminants thus eliminating many manufacturing steps.
- To create true structures, an important step is the introduction of a vacuum based process inorganic resist for photolithographic patterning of films. The elimination of organic resists almost eliminates local contamination thus reducing cleaning steps, which consume lots of water, acids and organic solvents. It also increases throughput and improves quality. Plasma/ion cleaning further eliminates liquid consumables.
- The base case, production of 5,000 ASIC wafers per month, indicates that orbital fabrication is 103% more expensive than commercial facilities. Modelling indicates that the cost of orbital fabrication can be decreased to 58% that of a future Earth-based facility.

2000, N. Pfeiffer Thesis

- The thesis examined the feasibility of fabricating semiconductors in orbit through the use of process and economic models.
- The semiconductor fabrication processes are represented in a detailed, step-by-step, numerical model.
- A system for the transport and fixturing of wafers in the orbital environment using magnetic levitation, is modelled in this thesis.

[*] Prof. Glenn H. Chapman http://www2.ensc.sfu.ca/~glennc/microspace.html
[*] G. H. Chapman, N. Pfeiffer https://www.researchgate.net/publication/269218499_A_comparison_of_microfabrication_and_WakeShield's_processing_requirements
[*] N. Pfeiffer https://core.ac.uk/download/pdf/56371746.pdf
[*] J. S. Johnson, G.H. Chapman, N. Pfeiffer, 2000 https://www.researchgate.net/publication/268460992_Feasibility_of_commercial_space-based_microchip_fabrication
[*] G. H. Chapman N. Pfeiffer, J. S. Johnson, "Synergy of Combining Microfabrication Technologies in Orbit

2002, Crystal Growth of Semiconductors in Microgravity [1]

- Good list of references.

2005, Solar Cells on the Moon [2]

- Moon and asteroids have conditions that allow for in-situ energy generation. No atmosphere — i.e. a high vacuum surface environment, and they contain most all elements required for the fabrication of solar cells — e.g., semiconductors, metals, and optical coating materials.
- These conditions allow for the possibility of fabricating thin film solar cells on the surface given the appropriate tools.
- The vacuum of the lunar surface is ideally situated for vapor deposition of the thin film structure required to make silicon solar cells.
- The lunar regolith can be processed to extract silicon and metals needed to fabricate the thin film solar cells and can also be solar-thermally melted to form a nano-smooth high resistivity glass to act as a substrate for cell growth. A metal bottom contact layer can then be sequentially solar-thermally evaporated onto the lunar glass substrate followed by evaporation of p- and n-doped silicon to form the solar cell. Such a thin film deposition on glass results in microcrystalline Silicon.

2007, Numerical modeling of the semiconductor alloys solidification by using a baffle under microgravity and terrestrial conditions [3]

- Some experiments on Te-doped InSb solidification by using a baffle in sealed ampoules performed under microgravity conditions in the Glovebox of the ISS are numerically investigated in order to analyze the baffle effect on the solute distribution.

2010, Space Research Results Purify Semiconductor Materials [4]

- After years in the lab preparing for the launch of the Wake Shield Facility, to grow semiconductor crystals, researchers advanced an existing epitaxy technique called molecular beam epitaxy—the process of depositing a thin layer of material on top of another thin layer of material.
- **In 1997, the researchers formed a company to fabricate optical devices using the advanced techniques and knowledge.** "Research in the lab at the Commercial Space Center, in preparation for on-orbit research, allowed some advances that wouldn't have been discovered otherwise,". It's still the foundation technology that AOI uses to make all of its laser products."

[1] Rachel A. Taylor, Literature Seminar, 2002, https://chemistry.illinois.edu/system/files/inline-files/Taylor.Abstract.LitSeminar.pdf
[2] Prof. Alex Ignatiev http://www.cam.uh.edu/projects/space-materials
[3] C. Stelian, West University of Timisoara, Romania, https://www.sciencedirect.com/science/article/pii/S0022024807012122
[4] https://spinoff.nasa.gov/Spinoff2010/ip_8.html

2020, Toward on-board Microchip Synthesis of CdSe vs PbSe Nanocrystalline Quantum Dots as a Spectral Decoy for Protecting Space Assets [1]

- Quantum dots (QDs), also called semiconductor nanocrystals, are semiconductor particles a few nanometres in size.
- Quantum dots were suggested as a means of spectral decoy to divert rocket attacks from flying objects such as satellites. By dispersion of a cloud of quantum dots with electro-optical properties. This approach encompasses a passive countermeasure tailored to the to-be-protected space asset that can deceive and dazzle the incoming attacker.
- Challenges are that these nanomaterials are unstable in the long-term under the forces exhibited on a flying object and the nanoparticles might agglomerate to form larger microparticles, which have a different spectral footprint.
- This work proposes an on-board real-time synthesis of quantum dots on a satellite as a result of an interdisciplinary innovation that combines nanomaterial chemistry, heating, and mixing with batch microfluidics, and microfabrication of a miniaturized chip.
- Additionally, quantum dots need to be tailored in the type of material and size to replicate the spectral signal of the to-be-protected space asset while the synthesis process needs to be robust and resilient to work reliably and automatically under the demanding conditions of a flying object.
- In this study, we selected cadmium selenide (CdSe) and lead selenide (PdSe) as the materials of choice.
- Our synthesis process aims to simplify and tailor CdSe and PdSe quantum dots to match the above demands. Results show that both CdSe and PdSe quantum dots have been successfully synthesized within a maximum of 10 minutes.
- The synthesized PdSe QDs were able to reach the mock-spectrum and could produce an emission wavelength peak from 1,200 to 1,400 nm. This work finally provides insights into the limits of batch synthesis in a microfabricated nanodot chip, such as the need to improve reproducibility and enhance particle growth.
- Based on this learning, we propose a self-priming flow microchip synthesis that can capitalize on mixing as a key asset.

[1] J, Nijhuis et al. Eindhoven University of Technology, 2020, https://pubs.rsc.org/en/content/articlelanding/2021/RE/D0RE00327A
[2] https://en.wikipedia.org/wiki/Quantum_dot
[3] Hyungsuk Moon, Changmin Lee, Woosuk Lee, Jungwoo Kim, Heeyeop Chae, 2019, https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201804294

Companies

Historical or little-known companies relevant for semiconductor manufacturing in space.

Microgravity Research Associates (1979)

Microgravity Research Associates

- A retired US Air Force officer, a retired NASA manager, and a Harvard MBA joined forces to establish Microgravity Research Associates, with the backing of a dozen venture capitalists.
- Plans to grow crystals in space, starting with gallium arsenide. The high-quality gallium arsenide crystals could, in principle, be used to make chips that would be much faster than the silicon chips used in most applications.
  - There are people who would be willing to spend $100,000 to put a supercomputer on their desks.
  - NASA is responsible for providing seven flight opportunities without charge and for furnishing integration services.
  - The last several flight missions of the endeavor in the 1987-1989 time period will produce quantities of space grown crystals sufficient for wide-scale distribution to electronic materials laboratories for their evaluation, as well as to support initial sales to users of semiconductor crystal materials.
  - These services will support the growth of 15, and possibly up to 20 kilograms of GaAs crystal on flights which do not need to accommodate other significant users of electrical power. These production quantities will be sufficient for initial commercial production.
- (1984) Microgravity Research Associates had no easy time raising about $1.5 million for research on gallium arsenide.
- (1984) By one estimate, the intake from space-produced gallium-arsenide devices alone might hit $3.1 billion by the year 2000. It has seven shuttle flights planned to produce the crystals. Its first commercial product may be hatched by 1989.
- "Within the next decade or two, people will look back and say, 'How could we have gotten along before without making crystals in space,' " says President Richard Randolph.
- (1986) Experiments for space manufacturing in small scale are scheduled for 1986 and 1989, which will be carried out by NASA's Space Shuttle.

[*] Harry L. Shipman. Space 2000: Meeting the Challenge of a New Era, 1987.
[*] https://commons.erau.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=2497&context=space-congress-proceedings
[*] https://www.csmonitor.com/1984/0702/070216.html
[*] https://www.inc.com/magazine/19841101/2049.html
[*] http://www.ibiblio.org/gautam/GC_ByLines/Space%20Industrialisation%20Not%20a%20Distant%20Dream.pdf

ACME Advanced Materials (2014)

- In 2013, patent filed for Wide Band Gap Semiconductor Wafers Grown and processed in a Microgravity Environment and Method of Production (the only one relevant patent found, expired due to fee)
  - The application discloses and claims a method to process silicon carbide and other similar wide band gap semiconductors in a microgravity environment. The wafers are placed onto stackable containment systems that create an appropriate gap between each wafer to allow for homogeneous heating and processing.
- In 2014, announced first production of Silicon Carbide wafers in microgravity using parabolic flights.
  - Process to produce large quantities of low loss, electrically defect free Silicon Carbide (SiC) wafers in a microgravity.
  - This development creates a new grade of SiC wafer, S Grade, that are electrically defect free of the mid-gap states known to cause power loss and reliability issues in SiC devices by impeding current flow through these electrical scattering centers.
  - During the brief periods of microgravity, the Silicon Carbide wafers undergo a heating process that anneals them.
- Raised a total funding of $1.6 million in 2014-2015.
- In 2015, CASIS agreement for Investigation: SiC Microgravity Enhanced Electrical Performance (MEEP) to determine whether longer-duration spaceflight can provide additional defect reduction in SiC wafers.
- In 2016, announced that they have decided to use parabolic aircraft to produce their first generation of Silicon Carbide (SiC) semiconductor material instead of suborbital rockets.
- The founder Rich Glover has marked on LinkedIn that he stopped working there in 2018. Previous company name was Masterson Industries as listed on the patent.

[*] https://patents.google.com/patent/US20140353682
[*] https://www.crunchbase.com/organization/acme-advanced-materials/company_financials
[*] https://twitter.com/ACMEmicroG
[*] https://parabolicarc.com/2014/09/10/acme-advanced-materials-produces-commercial-sic-wafers-micogravity/
[*] https://parabolicarc.com/2015/10/27/casis-awards-research-agreements-companies/
[*] https://parabolicarc.com/2016/01/14/acme-advanced-materials-selects-aircraft-microgravity-processing/
[*] https://newspaceglobal.com/more-about-flights-used-sic-production-acme-advanced-materials/

UniversityWafer (1997, 2021)

Space Based Semiconductor Material Fabrication Service

UniversityWafer, Inc. with partners are working on providing researchers with a vehicle that allows not only testing theories but actual production in the low orbit of space.

In 2021, announced plans to build a system capable of producing power wideband semiconductor materials in low earth orbit.

The system will reportedly work through Chemical Vapor Deposition (CVD), with a range of growth temperatures up to 800C and continuous growth time up to six months.

Composite semiconductor materials including Gallium Nitride (GaN), Silicon Carbide (SiC) or even more exotic materials are possible to grow in space.

[*] https://www.universitywafer.com/space-based-semiconductor-fabrication.html
[*] https://eepower.com/news/universitywafer-looks-to-implement-semiconductor-production-in-low-earth-orbit/#

Other Commercial Entities

Listing current companies from the Factories in Space database for overview and awareness in case some are missed or when some are missing from this list:

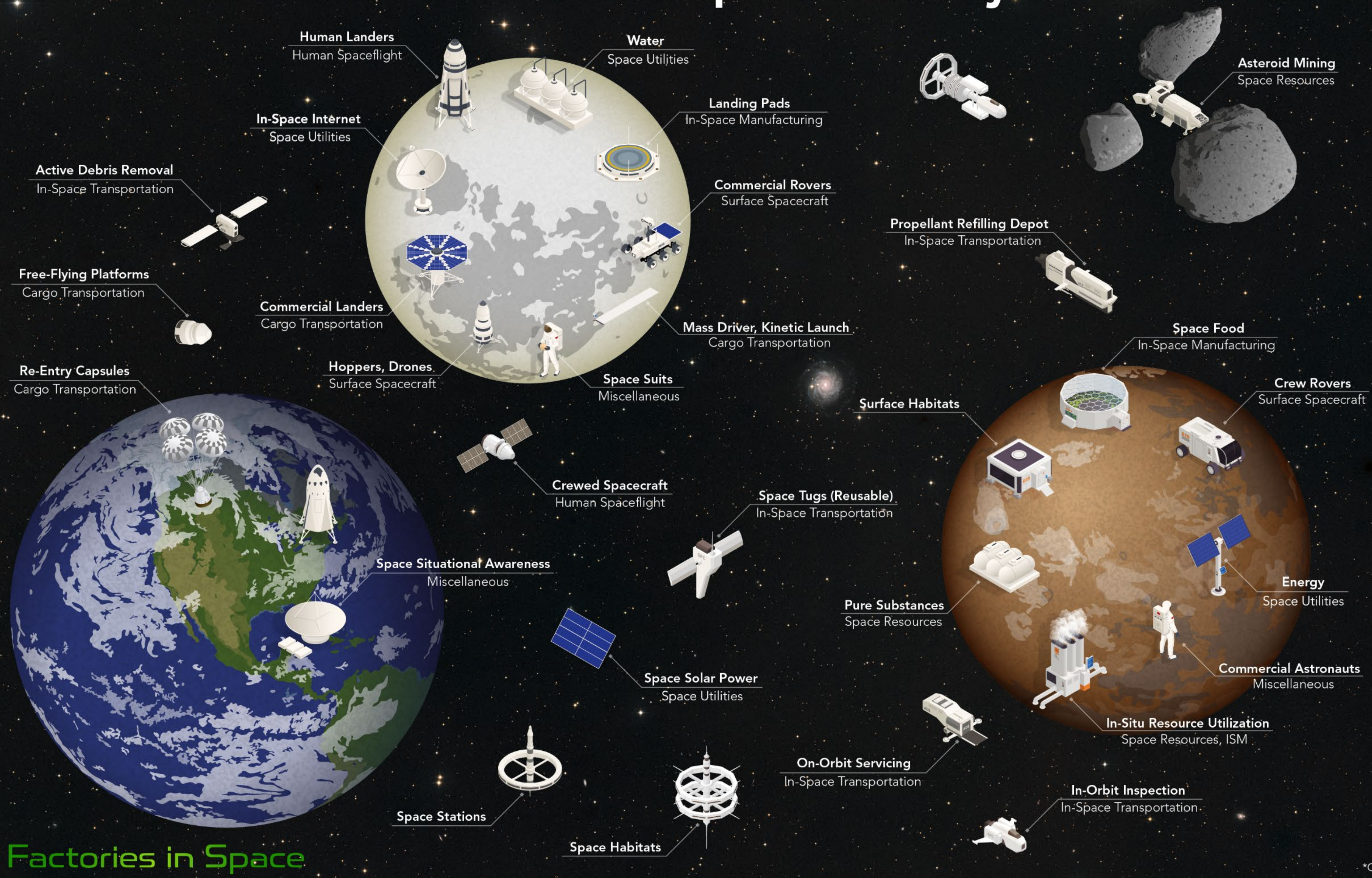
- **Astrobotic**
- **Blue Origin**
- **Faraday Technologies**
- **GOEPPERT**
- **Maana Electric**
- **Nebula Interplanetary Systems**
- **Redwire**
- **Space Foundry**
- **Space Forge**
- **United Semiconductors**

Vision of the Future

Large-scale semiconductor manufacturing possibilities in space.

In-Space Economy

factoriesinspace.com
2023-02-26



In-Space Economy Classification:

1) Human Spaceflight
   - Crewed Spaceships & Shuttles
   - Human Landers
2) Cargo Transportation & Landers
   - Robotic Landers (Moon, Mars)
   - Re-Entry Capsules (Earth, Mars)
   - Cargo Resupply
   - Reusable Satellites
3) Surface Spacecraft
   - Crew Rovers
   - Robotic Rovers
   - Drones, Hoppers
4) Space Stations & Habitats
5) Surface Habitats & Structures
6) In-Space Manufacturing (ISM)
   - In-Space Production
   - Space Food, Space Agriculture
   - Microgravity Manufacturing
   - Additive Manufacturing
   - In-Space Assembly, Construction, etc.
7) Space Resources
   - ISRU (In-Situ Resource Utilization)
   - Pure Substances (Ice, Oxygen, Metals)
   - Space, Lunar & Asteroid Mining
   - Prospecting, Processing, Recycling
8) Space Utilities
   - Energy, Power-Beaming
   - In-Space Internet, Data Relay
   - Navigation
   - Water, Propellant
9) In-Space Transportation
   - Space Tugs, Space Trucks
   - Orbital Transfer Vehicles (OTV)
   - On-Orbit Servicing, Maintenance
   - Propellant Reload Stations (Depots)
   - Active Debris Removal
   - In-Orbit Inspection
   - Space Mobility, Space Logistics
10) Miscellaneous
   - Microgravity Services
   - In-Orbit Computing, Storage
   - Space-Flown Items
   - Space Suits & Garments
   - Commercial Astronauts
   - Space Entertainment & Advertising
   - Space Traffic Management
   - Space Tourism Support, etc.

Factories in Space

*Original creation by Erik Kulu since 2020 inspired by E2MC

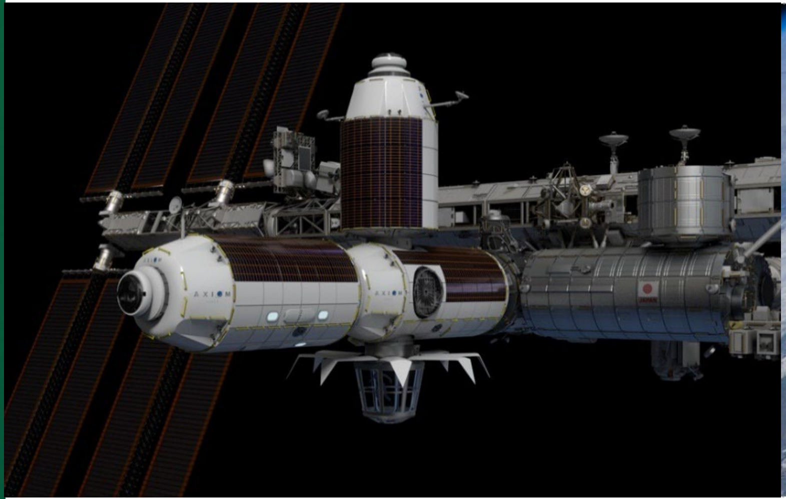
Vision for the Future (1)

Proliferation of lower cost and responsive microgravity flight opportunities:

- Microgravity end-to-end flight services using the ISS
- Free-flyers with return-to-Earth capabilities
- Commercial space stations and modules

Many more semiconductor experiments are very likely across the world. Scientific breakthroughs can happen unexpectedly.

- Hopefully find more materials that are worthwhile to make in space, e.g. crystals for use in commercial sensors etc.
- Perform more end-to-end process and economic studies, for example which existence likely helped to popularize ZBLAN.

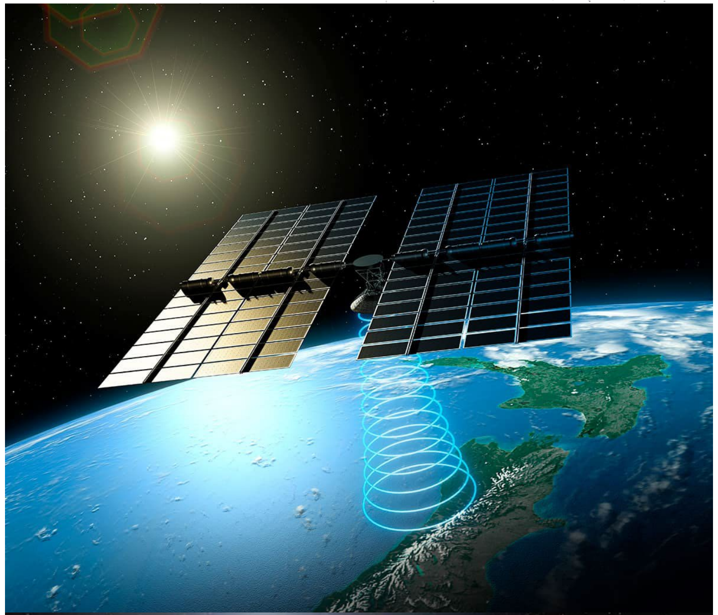

Axiom Space

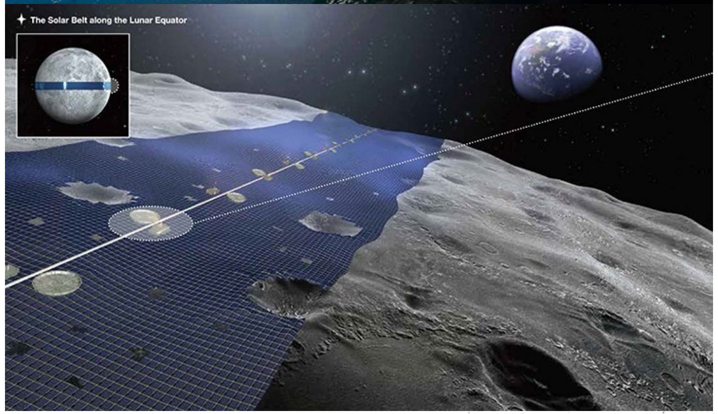
Varda Space

NanoRacks Nanolab

Vision for the Future (2)

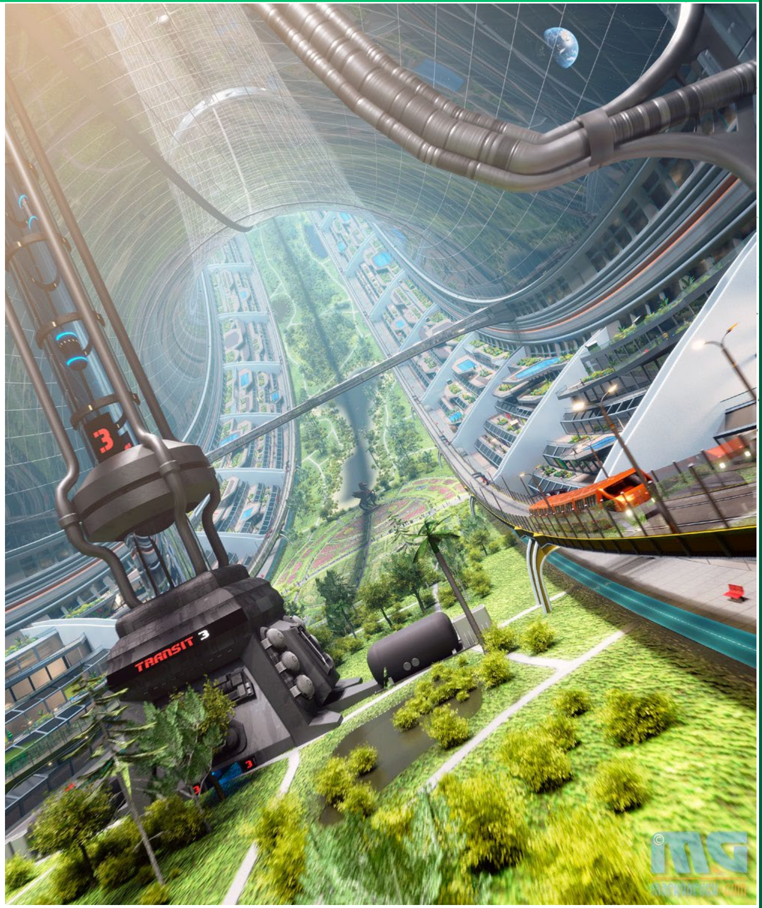
- **Space-based solar power** – enabling trends are converging for the first time (e.g. Starship). It could offer abundant clean energy while being cost competitive with terrestrial power generation; thus, it has the potential to become one of the largest space industry while having a big positive impact to Earth.
- **Solar panels on the Moon** – for example, Blue Origin, Maana Electric, and The Solar Belt array on Moon's equator.
- **In-situ manufacturing** of solar cells is likely to happen in the next decade at minimum even when Earth is not the target market.





Vision for the Future (3)

1. **New environmentally sustainable manufacturing processes for Earth to save water and/or electricity**
   - TSMC accounts for 6% of Taiwan's electricity demand. In 2025, it is forecast to rise to 12.5%. [2]
   - "Finding ways to manufacture chips in more environmentally sustainable ways may be possible, but there's little appetite for slowing down the industry's expansion." [3]
2. **Moving manufacturing to space to protect the Earth's biosphere**
   - Most of space is a hostile place with no life to harm.
   - Jeff Bezos "You shouldn't be doing heavy energy manufacturing on Earth. We can build gigantic chip factories in space." [1]



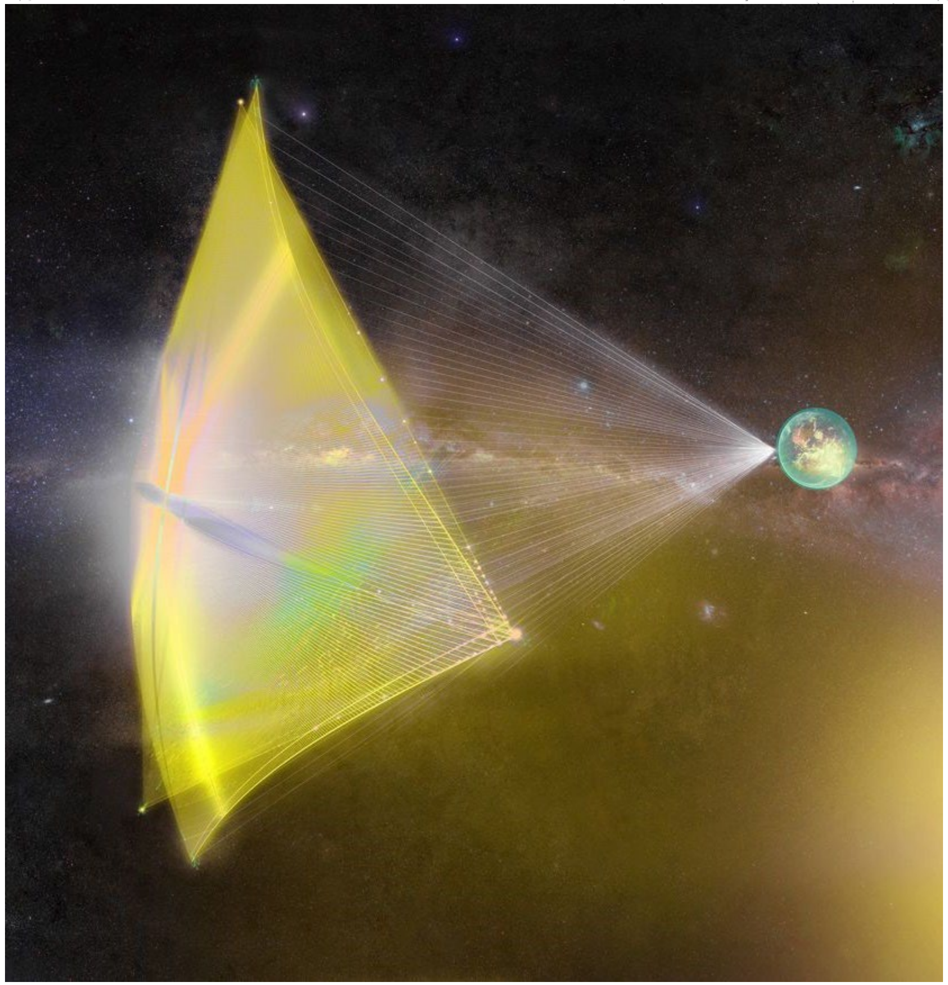
Mark A. Garlick, @SpaceBoffin

[1] https://futurism.com/jeff-bezos-wants-to-move-our-factories-to-space-to-protect-earth
[2] https://www.cleanenergywire.org/news/net-zero-targets-could-force-taiwans-chipmakers-abroad
[3] https://www.bloomberg.com/news/articles/2022-08-25/energy-efficient-computer-chips-need-lots-of-power-to-make?leadSource=uverify%20wall

Vision for the Future (4)

Interplanetary & Interstellar Travel

- **Solar sails steering** - electrically tunable metasurfaces and devices are gaining interest due to their ability to manipulate optical phase and amplitude. These semiconductor and liquid crystal devices are of a particular interest.
- **Laser sailing** – High refractive index semiconductors like Si and MoS2 may be used for laser sails. They are highly absorbing across the solar spectrum and cannot be used for regular solar sailing. To avoid folding, the very large sails are perhaps best made in space.
- **Space-made semiconductor lasers array** and wireless power beaming stations to create an „interplanetary highway"?



Breakthrough Starshot

[*] Artur R. Davoyan et al. Photonic materials for interstellar solar sailing, 2021
[*] Breakthrough Starshot https://breakthroughinitiatives.org/initiative/3

Factories in Space

www.factoriesinspace.com

Thank you for the attention
and invitation!

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