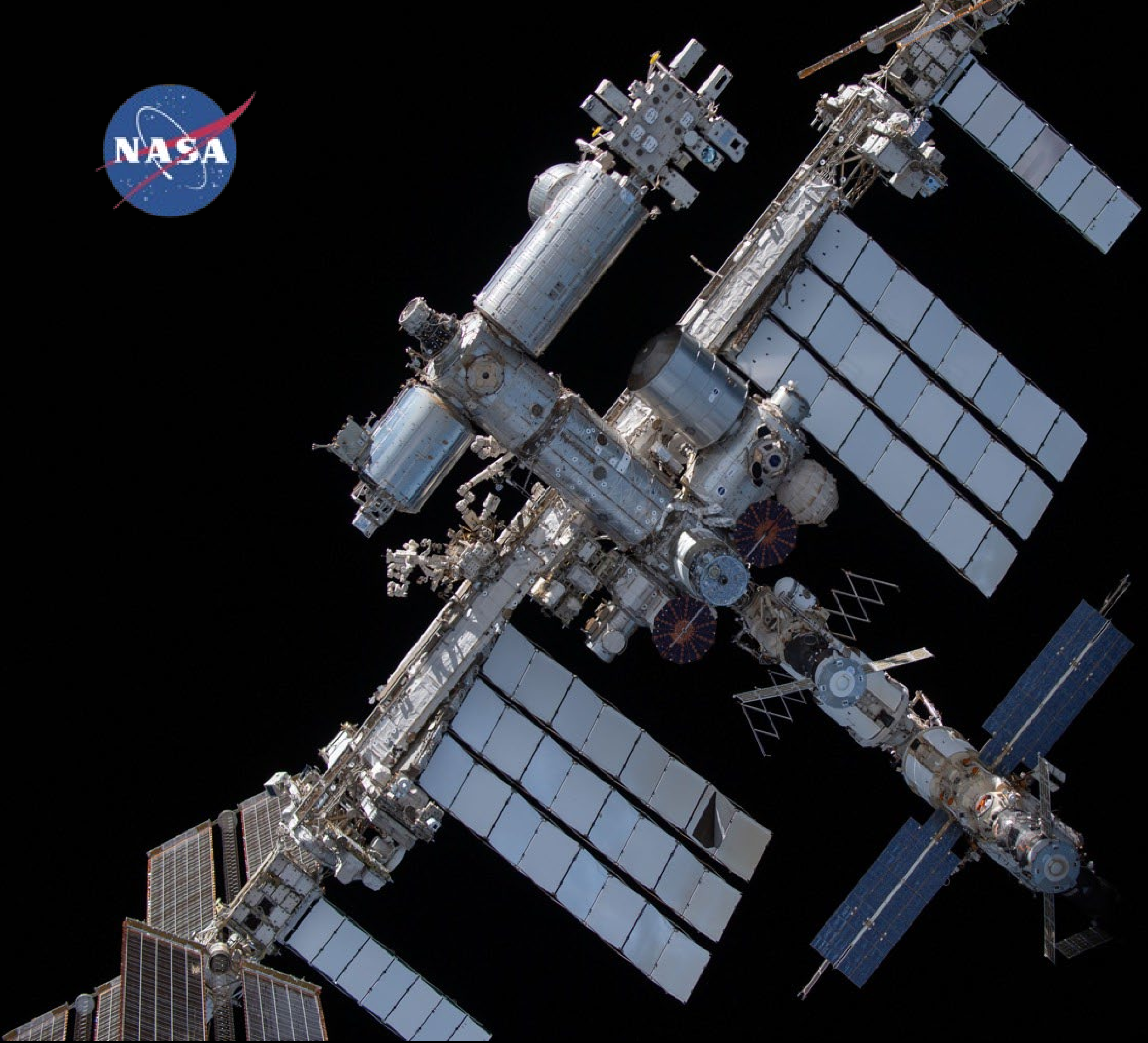


Semiconductor ICs for Space Applications: Powering the Future of Exploration

On Demand Manufacturing of Electronics (ODME)

Curtis Hill

NASA MSFC - ESSCA

Principal Investigator

ODME Project and InSPA Space Economy

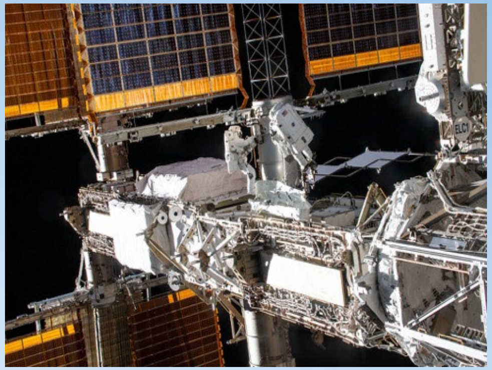
NASA ODME Technology Areas

In Space for Space ***EXPLORATION***	In Space for Earth ***COMMERCIALIZATION***	Ground Development ***TECH MATURATION***
Microelectronics	Semiconductor Fabrication	Printed Semiconductors & Components
Sensors	Semiconductor Crystals/ Wafers	Next-Generation Deposition Systems
Power & Energy	Semiconductor 2D Materials	Advanced Toolplate Tools for ISS Multimaterial Printer
		Lunar Surface Inkless Deposition Systems

ISM ODME Technology Development Approach

Ground Development

Parabolic Flights - Test



Microgravity – Demonstrate

Lunar Habitat – Use

CLDs – Commercialize

ISM is maturing advanced manufacturing capabilities through microgravity demonstrations on STMD Flight Opportunities enabled Parabolic Flights.

- Six parabolic flight campaigns prior to FY25, with four more planned in 2025.
- Working with ISS NL and multiple Integration Partners for planned microgravity demonstrations of semiconductor technologies.
- Working with CLD partners to mature semiconductor technology with plans for eventual demo on their platforms.

In Space Production Applications

In Space for Earth

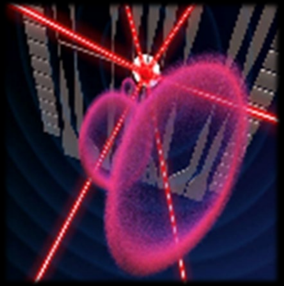
- Investing in scalable & sustainable manufacturing of microgravity enhanced products that support large markets on Earth
  - U.S. **competitiveness** in industries that serve national interests
  - Direct **benefits to humanity** by returning products to Earth
  - U.S. leadership of a **robust LEO economy**

- Aligned to **National Priorities**
  - CHIPS & Science Act
  - Cancer Moonshot
  - Domestic Biomanufacturing
  - Maintaining U.S. Preeminence in LEO

In-Space Production Applications Value Creation:

In-SPA builds on 50+ years of µg research in space to accelerate the application of new technologies on Earth that benefit humanity, from subatomic through global scale.

Quantum Subatomic

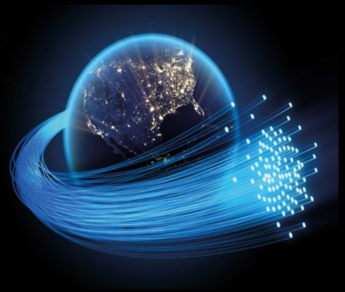


Cold Atom Lab

Atomic-Molecular

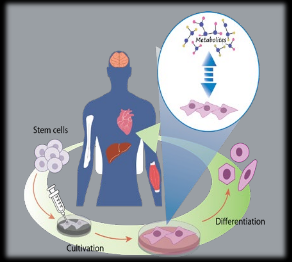
Crystals
Pharma
Industrial
Semiconductors

Alloys and Photonics



ZBLAN Optical Fibers
Semiconductors

Cells and Tissues



Cancer
Neurodegenerative
Stem Cells
3D Tissues

Thin Films

Artificial Retinas
Medical Devices

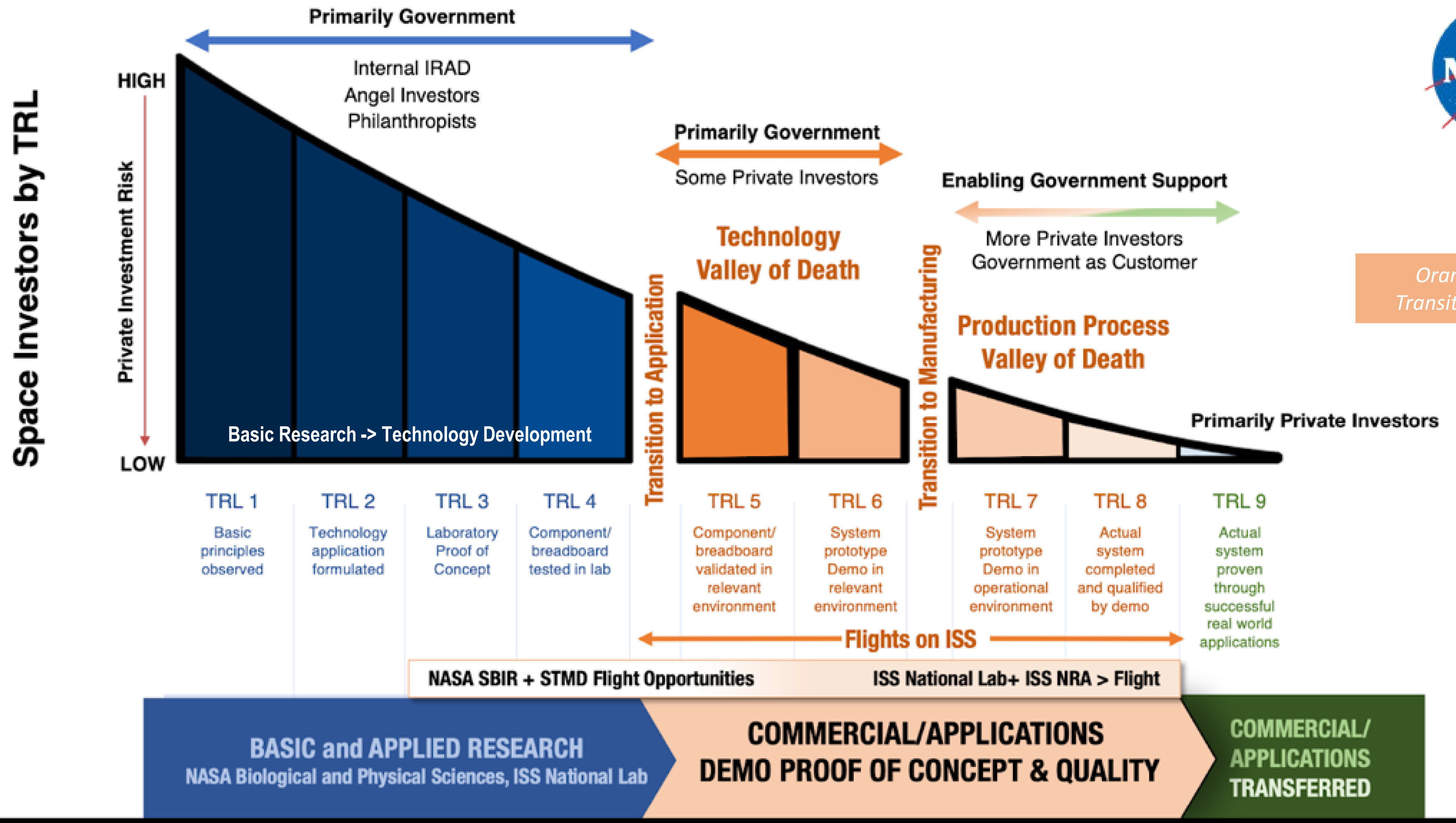
On-Demand Manufacturing

Microelectronics
Sensors
Tools

- Space-manufactured artificial retinas ready for animal trials; semiconductors in parabolic testing; wearable sensors; 3D printed human knee meniscus.
- Medical Advances
- High-throughput heavy metal optical fiber manufactured on the ISS to commercial lengths
- 90% of crystals manufactured in space since 1973 improved in structure, uniformity, size, or reduction of defects
- Manufacturing Bose-Einstein condensates in space near absolute zero since 2019

FEED THE PIPELINE FOR US LEADERSHIP AND SUCCESS

Approach: Build. Fly. Learn. Fix. Improve. Iterate. Repeat. Succeed. Through the Valleys of Death to Applications via Practice

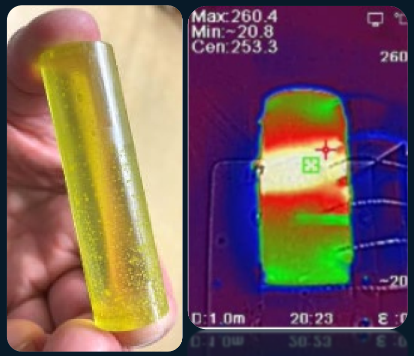


Orange shows Transition to InSPA

FROM DISCOVERY TO APPLICATION

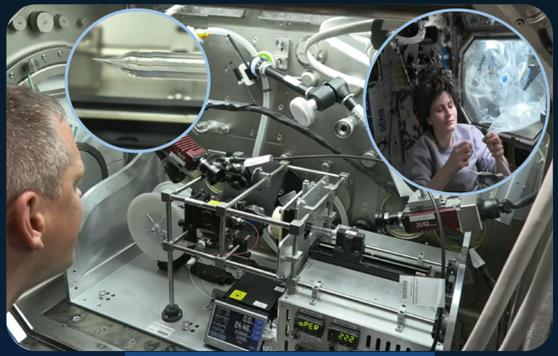
Current InSPA Portfolio

-Advanced Materials-



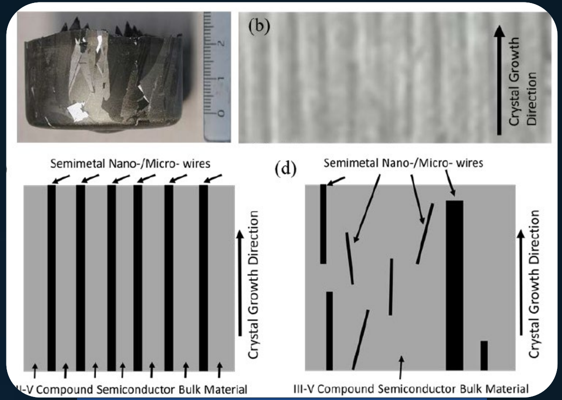
Microgravity-Enhanced Molten-Core Fibers. DSTAR (SBIR)

Specialty optical fibers.
Mercury Systems

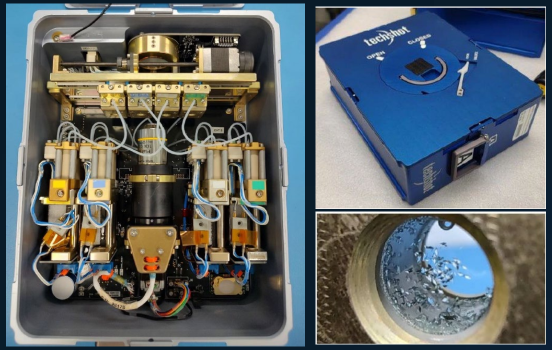


Specialty optical fibers.
Apsidal LLC

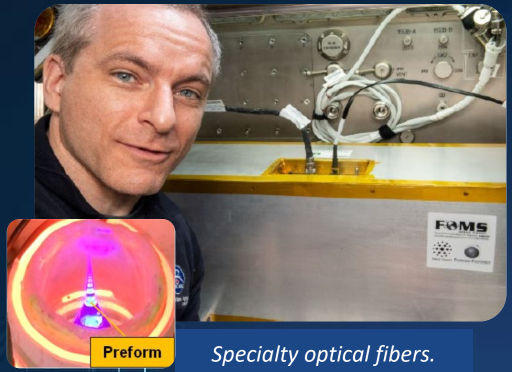
Industrial Crystallization Facility
Redwire – Made In Space



Bulk Semiconductor Crystals.
United Semiconductors

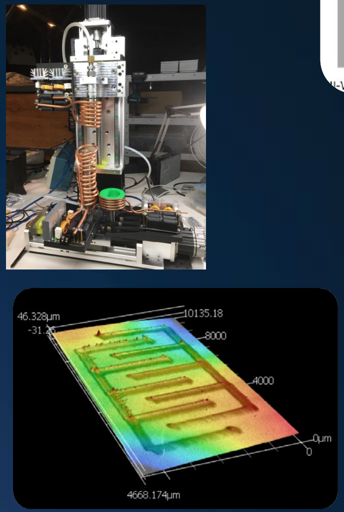


Protein Crystal Growth for Pharmaceuticals.
Redwire-Techshot

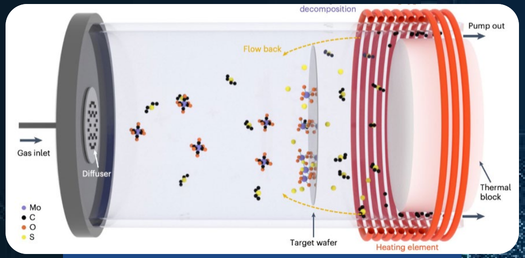


Specialty optical fibers.
FOMS

Specialty optical glass.
Flawless Photonics



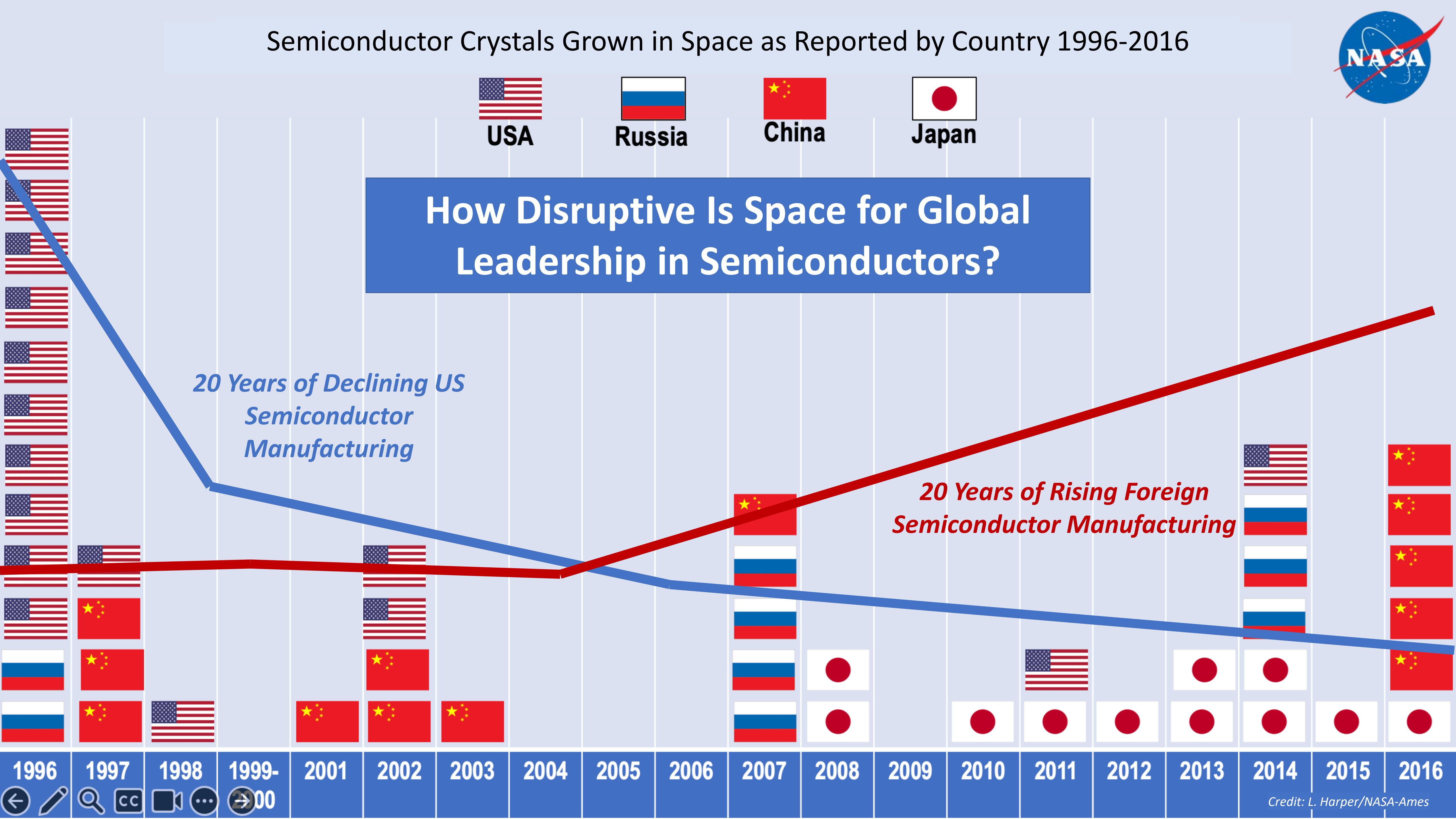
Plasma Growth of Diamond Semiconductor in Microgravity for Quantum Applications.
Space Foundry (SBIR)



2D MoS_2 Semiconductors.
Goeppert LLC (SBIR)

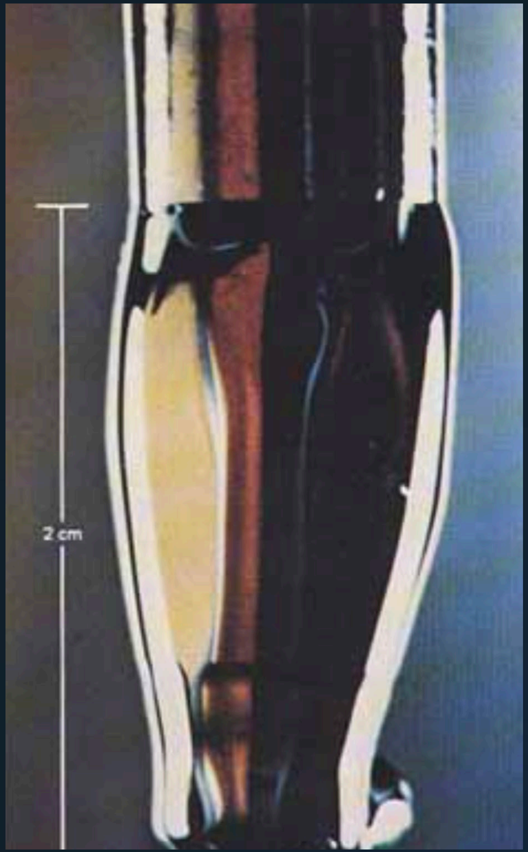
Italics - have flown to ISS on one or more missions

Semiconductor Devices. MSTIC.
Redwire-Made In Space



Semiconductor Crystals Grown in Space as Reported by Country 1996-2016
NASA
USA
Russia
China
Japan
How Disruptive Is Space for Global Leadership in Semiconductors?
20 Years of Declining US Semiconductor Manufacturing
20 Years of Rising Foreign Semiconductor Manufacturing
1996
1997
1998
1999-
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Credit: L. Harper/NASA-Ames

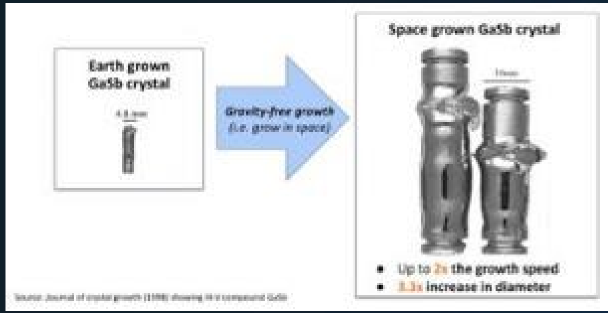
Regaining the Lead in µg Crystal Growth



- InSPA study shows >80% of 120 semiconductor crystals grown in space since 1973 improve in structure, uniformity, or size.
- Before 1998, the U.S. dominated R&D in space semiconductors.
- After 1998, China, Russia, and Japan took the lead.
- In 2016, China implemented 9 semiconductor crystal investigations.
- NASA has 2 InSPA semiconductor crystal investigations in progress and many more proposals in review.
- Need investment in an advanced furnace with capability for larger bulk crystal / wide bandgap semiconductors

Butler University Study of Microgravity Crystal Research:

Dr. Anne Wilson, amwilson@butler.edu or 317-940-940



~20% improvement in crystal growth through greater uniformity and increased size

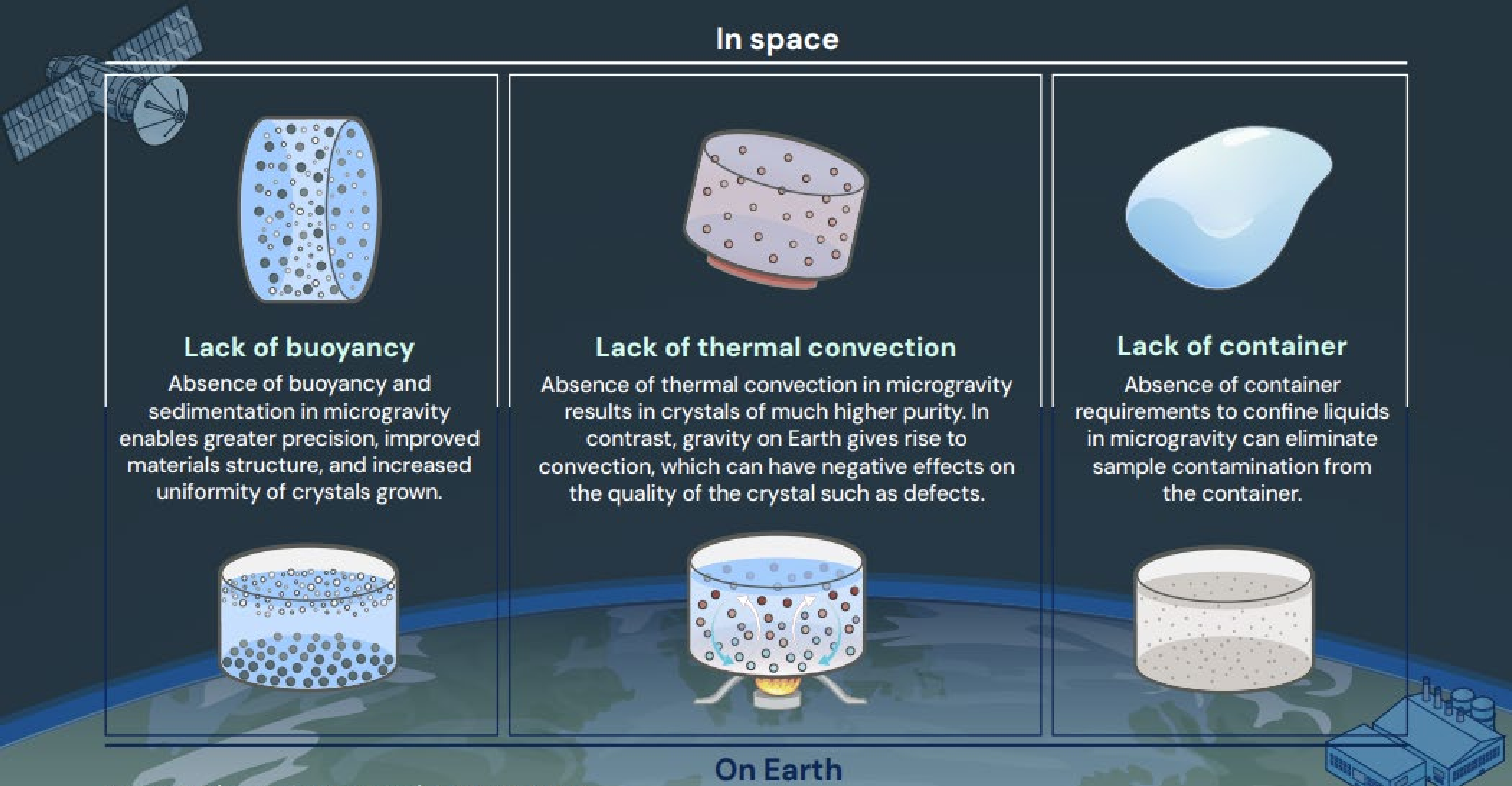
BUTLER UNIVERSITY

Crystals grown in microgravity show improvement

	Macromolecules/ Organics (n = 318)	Inorganics (n = 189)	Semiconductors (n = 140)
Improved in at least one metric*	288; 88%	164; 87%	120; 86%
Improved in two or more metrics	229; 72%	99; 48%	69; 49%
Improved in three or more metrics	155; 49%	38; 20%	22; 16%

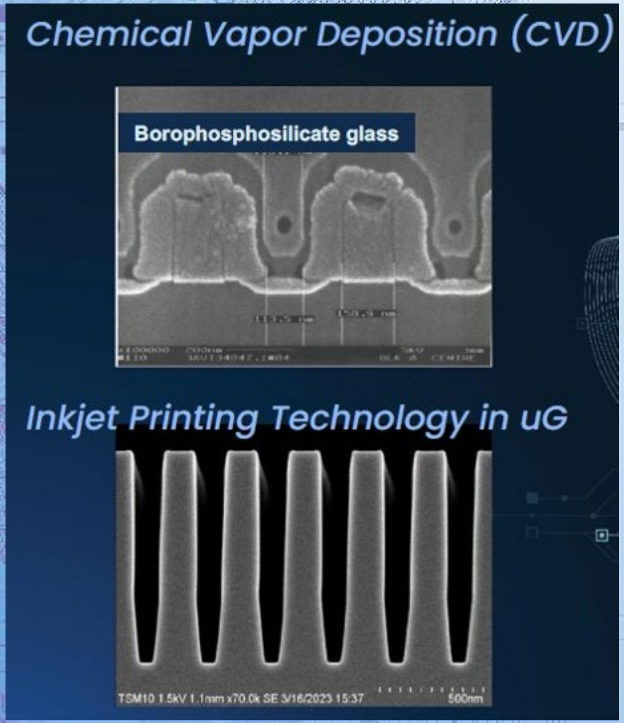
**Metrics that were improved: size, structure, uniformity, resolution limit, mosaicity, and/or performance*

**Most reports do not include more than one or two metrics*



Source: GAO (analysis and illustrations). | GAO-25-107542

Space Enabled Advanced Devices & Semiconductors (SEADS)



13x Increase in Yield

Potential production cost savings of ~$1/chip

- NASA (InSPA & ODME) are bringing U.S. semiconductor R&D and pilot-scale manufacturing to the ISS for higher yields, higher performance, and lower cost
  - Four existing awards for semiconductor crystal and device manufacturing;
  - Additional awards pending
  - Joint funding of Inkjet Printer development with Intel, ASU, etc.
- Collaborating with NSF to support emerging ecosystem
  - Anticipate SBIR awards for high-throughput science and EAGER award for private sector consortium development
- Collaborating with State of Texas
  - Texas A&M and InSPA/ODME have partnered on a Space Act Agreement for semiconductor research; 3-way funding of MoS_2 material development for Goeppert furnace
- Pursuing collaboration with SRC and DoD next.

This is a Must-Win for the U.S.

Areas of In Space Semiconductor Commercial Development

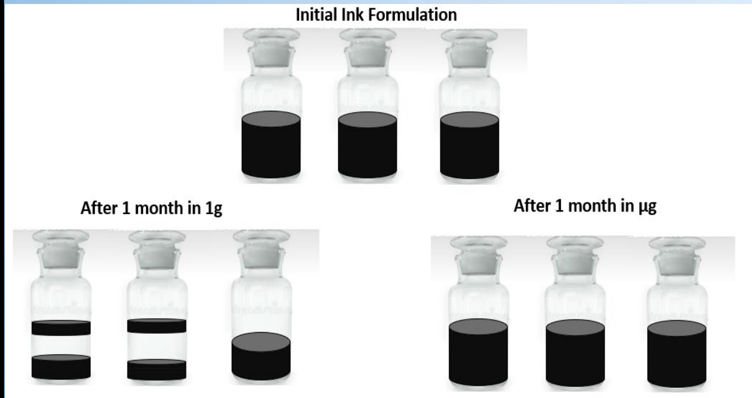
- Crystal growth – leverage known microgravity crystal growth advantages for Si and new materials
    - New project/study in process with Butler University on Wide Bandgap Semiconductor Crystals
- Fabrication processes and materials
    - Replace bulky, expensive terrestrial processes with Space-Enabled processes and materials – 3D printing with EHD inkjet
    - 2D materials for transistor scaling and heterogeneous integration – combines crystal growth advantages with new fab processes

Additional Interagency Initiatives in Space Manufacturing/Semiconductors

- Interagency Working Groups for Space Economy, Working Capital, & Semiconductors
- Partnership with NSF / Space TIP for SBIRs
- New potential application and funding with Space Force, DARPA, and DoE

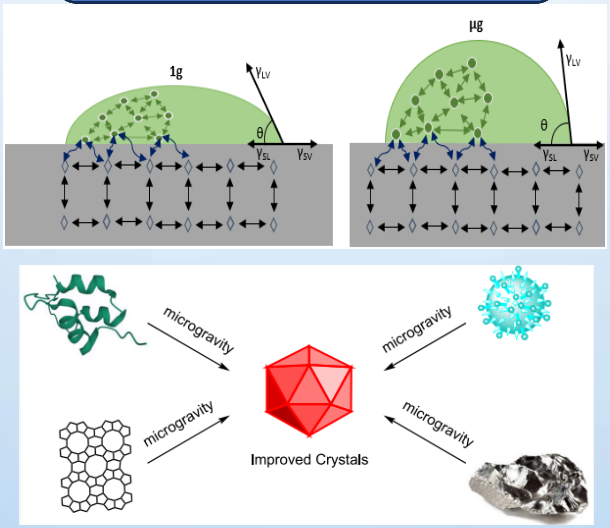
Materials-related mg Impacts

Sample preparation stage (before printing)



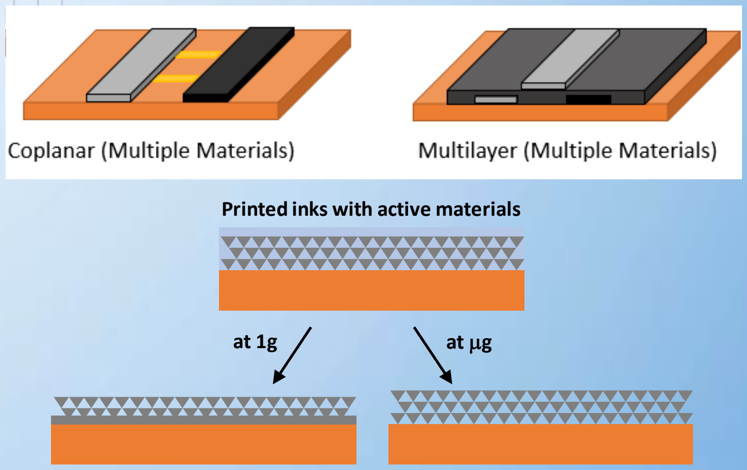
- µg removes convection, sedimentation, and buoyancy that can disrupt physical and chemical processes.
- Less aggregation and sedimentation of colloidal active materials → higher stability and longer ink shelf life
- Higher stability allows more loading of active materials (less additives).

Manufacturing stage (during printing/fab)



- Diffusion and surface tension-dominant processes enables more uniform structures at individual molecule level.
- In printing, µg allows less spread of the printed layers → higher resolution
- In crystal growth, µg allows larger crystal size & fewer defects → high quality

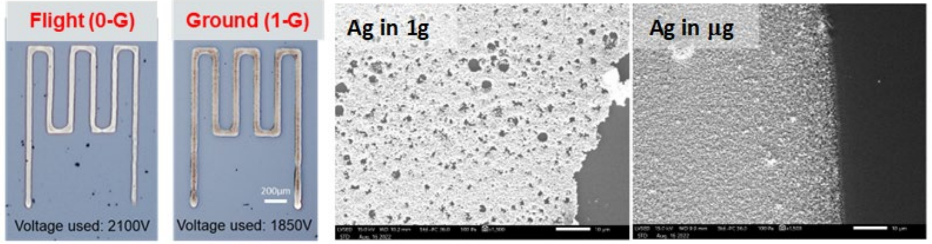
Application stage (after printing)



- In printing, higher concentration of the active material in inks allows superior performance and operation stability.
- In crystal growth, better crystal quality gives superior efficiency and lifetime.
- Multilayer fabrication is enabled to form integrated systems with multiple functional devices. More complex devices.

Demonstration Examples of mg Impacts

Inkjet and EHD printing in mg



Dec-2021 flight test

ISU-Silver-35s1 (S35s1)	
Silver content (wt.%)	35 ± 2
Average particle size (nm)	150 - 200
Viscosity (cP)	300 - 500
Solvent	DMSO
Surfactant (wt.%)	1%
Aged (months)	Fresh

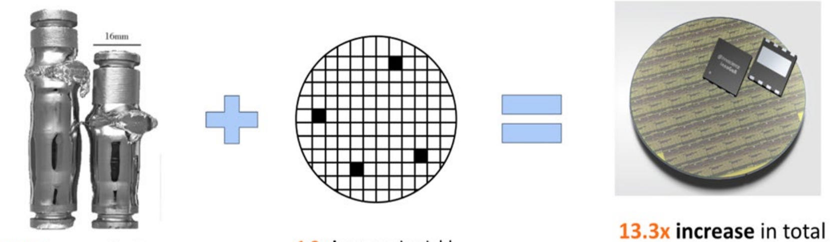
May-2022 flight test

ISU-Silver-35s1 (S35s1)	
Silver content (wt.%)	50 ± 2
Average particle size (nm)	150 - 200
Viscosity (cP)	300 - 500
Solvent	DMSO
Surfactant (wt.%)	0.6-1%
Aged (months)	Fresh

Resistivity (µΩ·cm) Bulk Silver = 1.59 µΩ·cm		
Sintering (30 min)	35% Ink	50% Ink
50 °C	4.27E+8	19795
100 °C	1.06E+7	2213
150 °C	123.3	15.27
200 °C	19.68	2.98

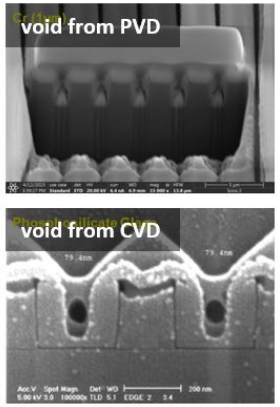
- Micro-structures of printed patterns results in denser structure with less porosity
- Silver loading can be increased from 35% (at 1g) to 50% (at mg) due to less agglomeration → 8.1 times higher conductivity
- Under mg, larger voltage can be used for reducing printed line width (higher resolution) for EHD mechanism.

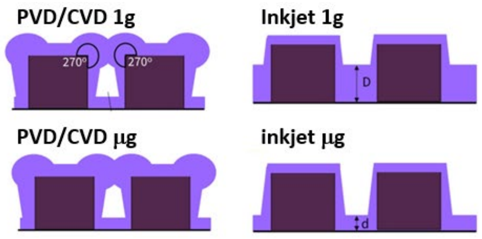
Crystal growth



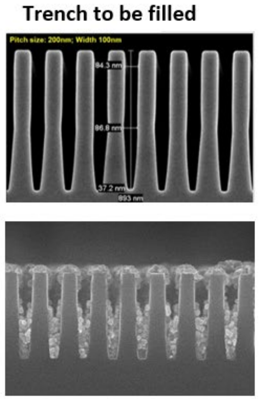
- From the studies of 500 entries in last 50 years, 89% of macromolecules crystals, 79% of inorganic crystals, and 81% of semiconductor crystals reported improved crystal structures in mg.

Trench filling - Fabrication

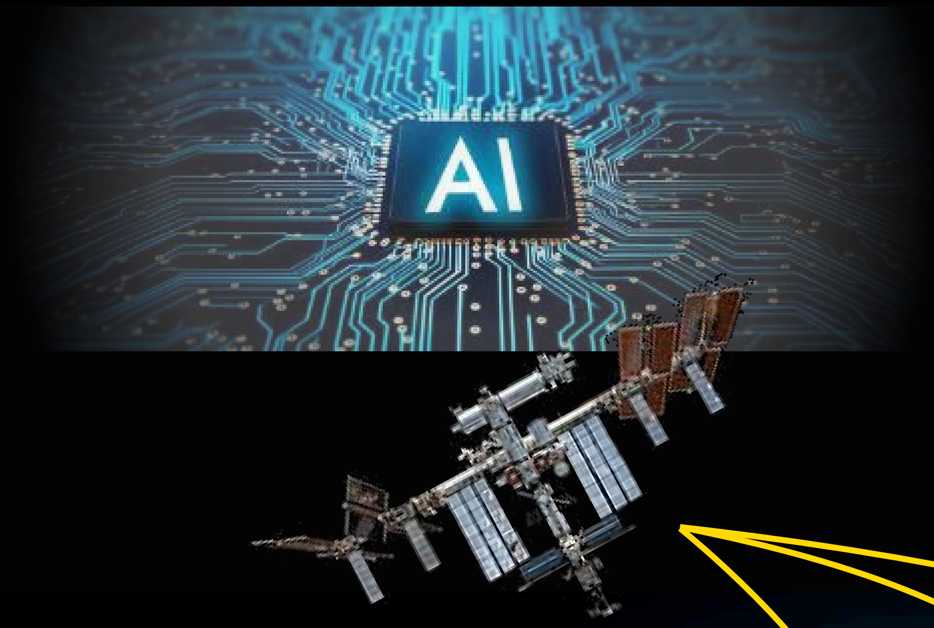




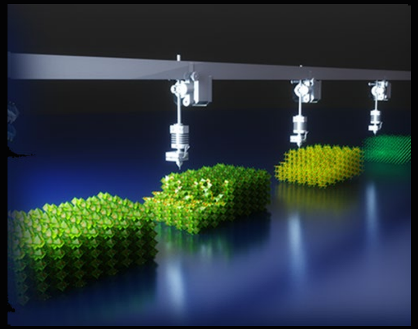
Combination of inkjet printing and mg offer high step coverage without voiding problem. Beneficial for 3D memory fabrication with high density and high performance



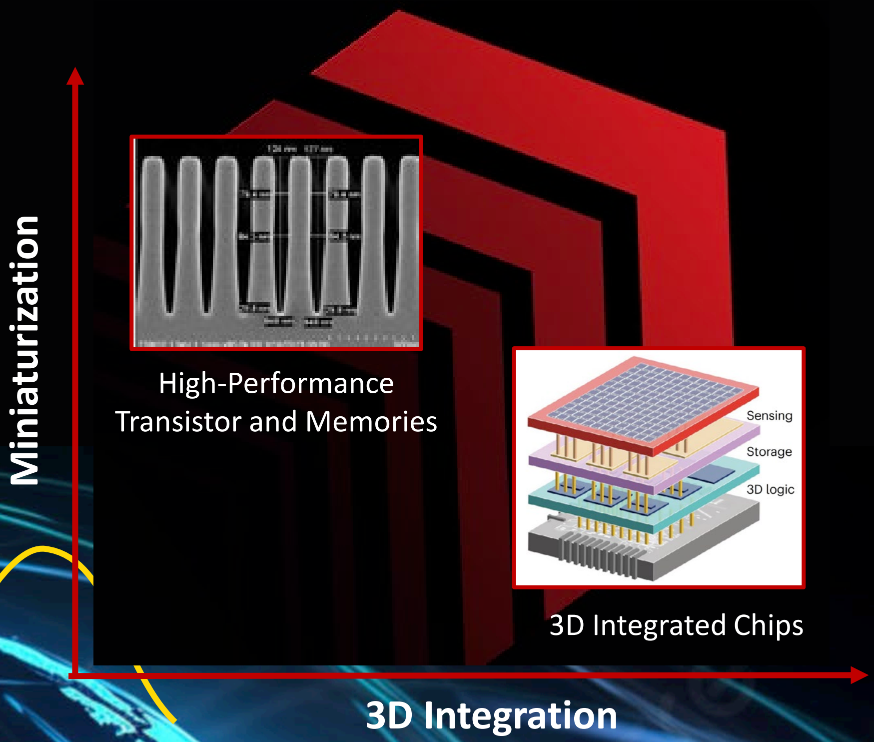
In-Space Semiconductor Manufacturing



In-Space Semiconductor Manufacturing



µG semiconductor offers opportunities to manufacture better chips



Manufacturing of Next-Generation Microelectronics/AI Chips:

- 100-1000 times power reduction
- Smarter and general AI
- AI for radiation-hard space applications

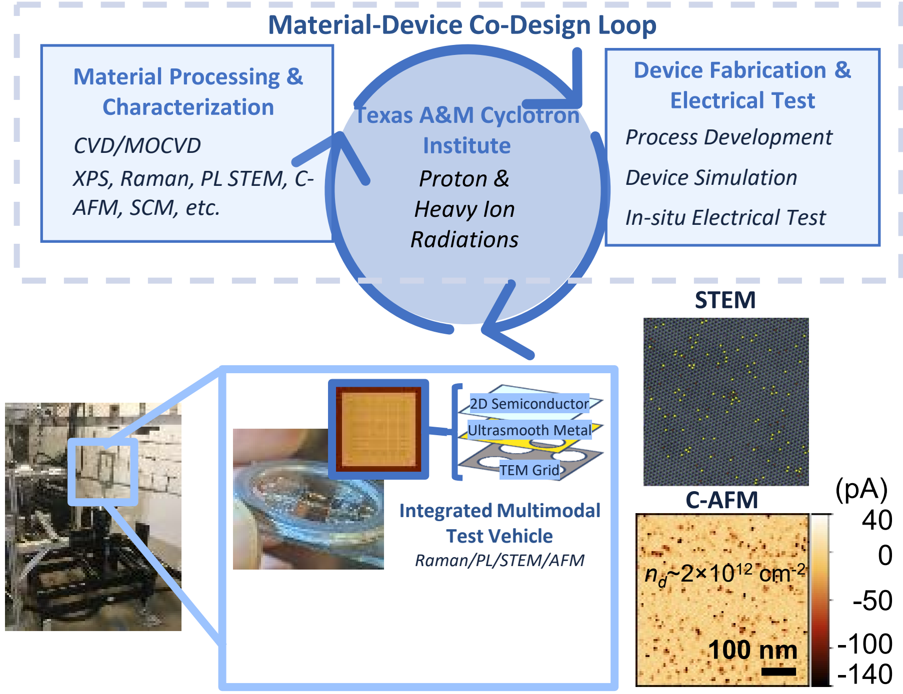
Manufacturing of Emerging Semiconductor:

- Low defect density semiconductor growth
- Thin film growth on high aspect-ratio nanostructures

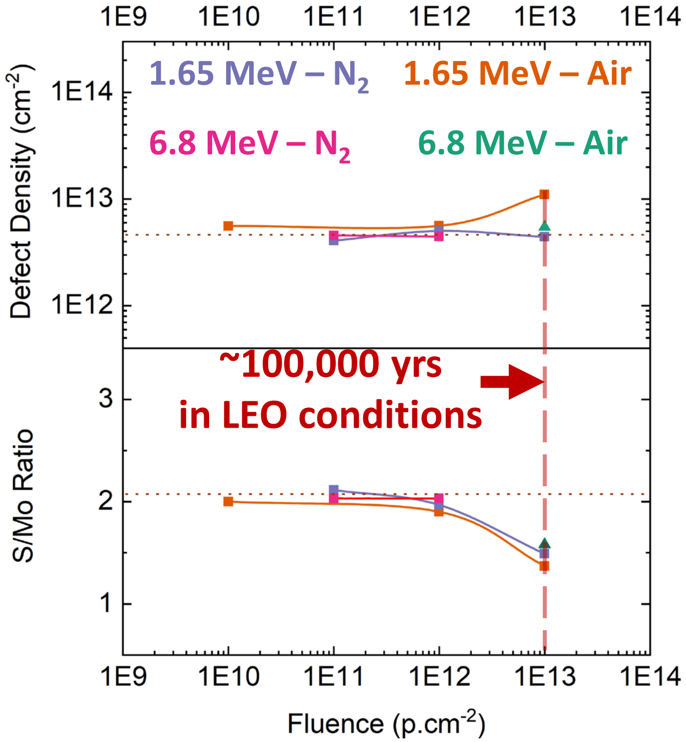
TAMU – NASA Project Year 1 – Summary of Key Results

- Protocols for sample preparation and irradiation experiments were developed.
- Comprehensive material/device characterization methods were developed, with special focus on the characterization of irradiation-induced defect densities and their impact on the device performance. The tools include: Raman, PL, XPS, STEM, C-AFM, SCM, C-V, etc.
- SRIM/device simulation was conducted, and a transistor design that balance the performance, scaling, and radiation tolerance was provided.
- ***Key experimental result:*** We do not see significant increase in defect density for a harsh proton radiation condition (1-7 MeV, 10^{13} cm^2 fluence). This condition is equivalent to ~100,000 years proton radiation in the low-earth orbit (LEO).
- ***Key simulation result:*** Device simulation results predicted a greatly improved radiation tolerant and scaling trend for 2D-material-based transistors.

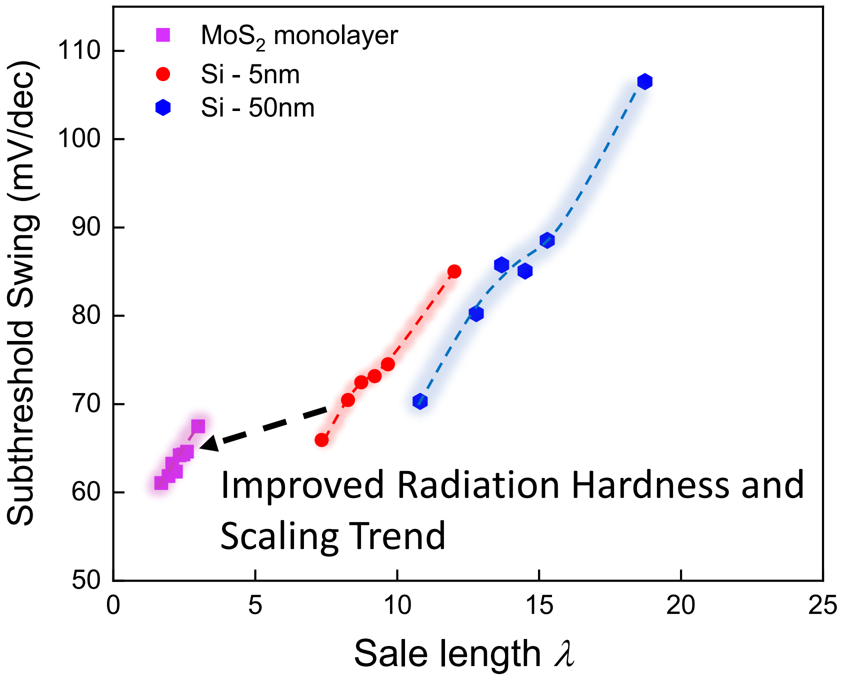
Rad.-Hard. 2D Transistors Experimental Platform



Proton Radiation Hardness

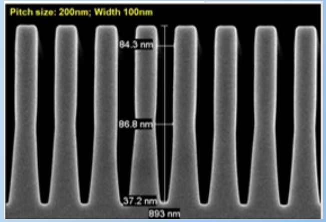


Device Simulation & Benchmark

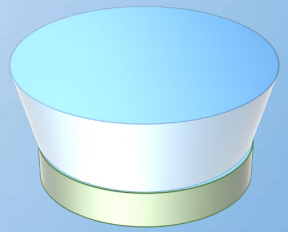


ODME Technology Maturation to support InSPA Commercialization of Electronics Manufacturing in Microgravity

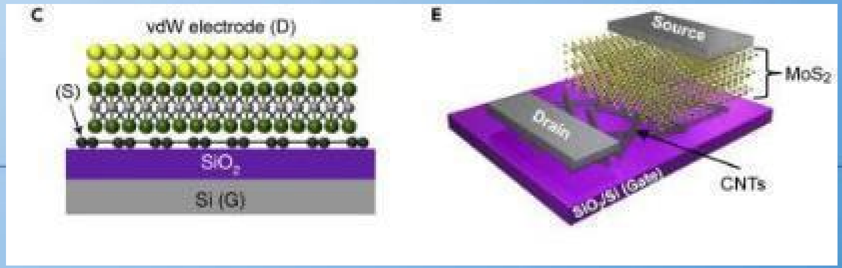
- **Development of EHD inkjet for precision microelectronics & semiconductor printing**
  - Microgravity enables higher yields for semiconductors & microelectronics.
  - Eliminate secondary etching needed with conventional CVD process.
- **Integration into the ODME Flight Printer**
- **Demonstration of new semiconductor crystal fabrication and device optimization in microgravity**
- **Development of advanced 2D semiconductor materials enabled by microgravity for next-gen devices**



EHD Printing in Semiconductor Trench



Microgravity grown diamond wafer



2D Semiconducting Materials for Ultimately-Scaled Transistors

Capability Gaps – Current LEO Infrastructure

- **As InSPA technologies mature from "R&D" to precision manufacturing, ISS NL capabilities must evolve from a Research Lab to a Manufacturing Lab, including new enabling infrastructure and analytics to accelerate learning (reduce time between iterations) and reduce downmass via increased in-situ quality monitoring**
  - Multiple new Glovebox(es) with imaging and analytics adhering to FDA GMP processes
  - More capable furnaces (higher temp, multiple zones, larger work volume, precise temp control)
  - Conditioned stowage
  - Containerless processing
  - Public and Proprietary Databases with Artificial Intelligence and Machine Learning to make past research available

- **NASA and ISS National Lab have worked with industry/academia to define technology needs**
  - Wet Lab White Paper
  - Study on Microgravity Crystal Growth Research by Butler Univ

- **On-Demand Return and free-flyer manufacturing platforms to supplement ISS capabilities**
  - ISS cargo vehicle launch and return cadence is not adequate for a thriving manufacturing economy in LEO
  - ISS throughput is limited, and some technologies are not ideal for a crewed environment

- **Industry needs Government support of early commercial development**
  - CLD Providers and ISS Commercial Service Providers are establishing teaming and talking concepts .

Questions?