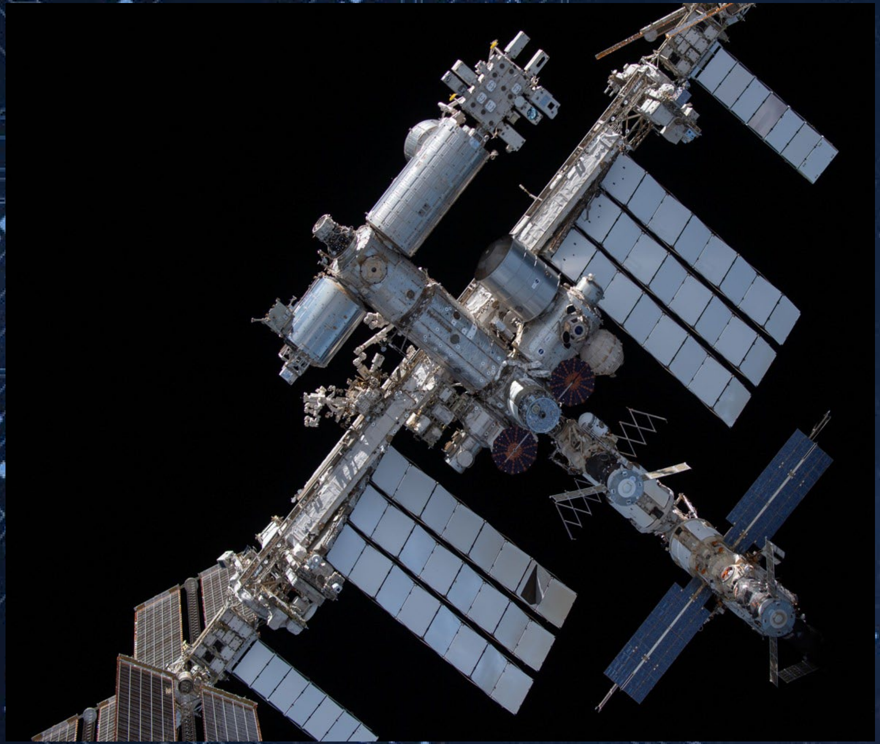
On Demand Manufacturing of Electronics (ODME)

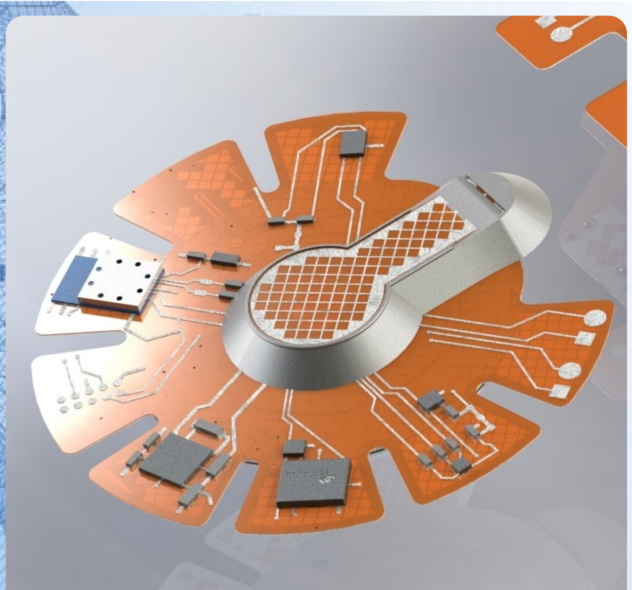


Presentation to:
2024 Manufacturing Problem Prevention Program Conference
October 22, 2024

Curtis Hill, MSFC-ESSCA
Principal Investigator, On Demand Manufacturing of Electronics (ODME)
Subject Matter Expert – Semiconductors, InSPA NASA LEO Commercialization

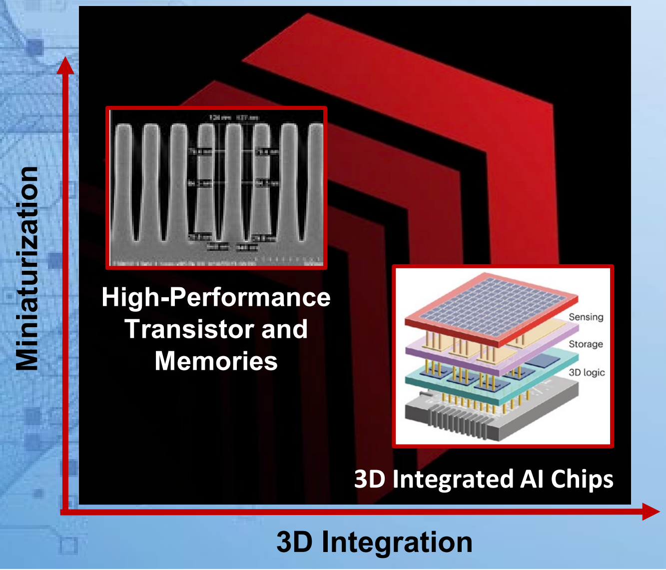
ON-DEMAND MANUFACTURING OF ELECTRONICS *ODME*

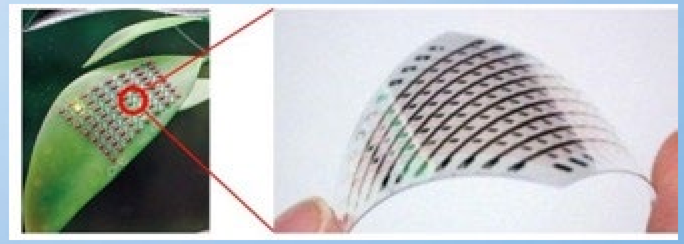
- Objective 1: Development of electronics devices & sensors for in-space manufacturing
  - Primarily for **Use In Space**
- Objective 2: Development of ODME capabilities for microgravity manufacturing of electronics, sensors, and semiconductors
  - Primarily for **Use on Earth**



Crew Health Wearable Wireless Sensor

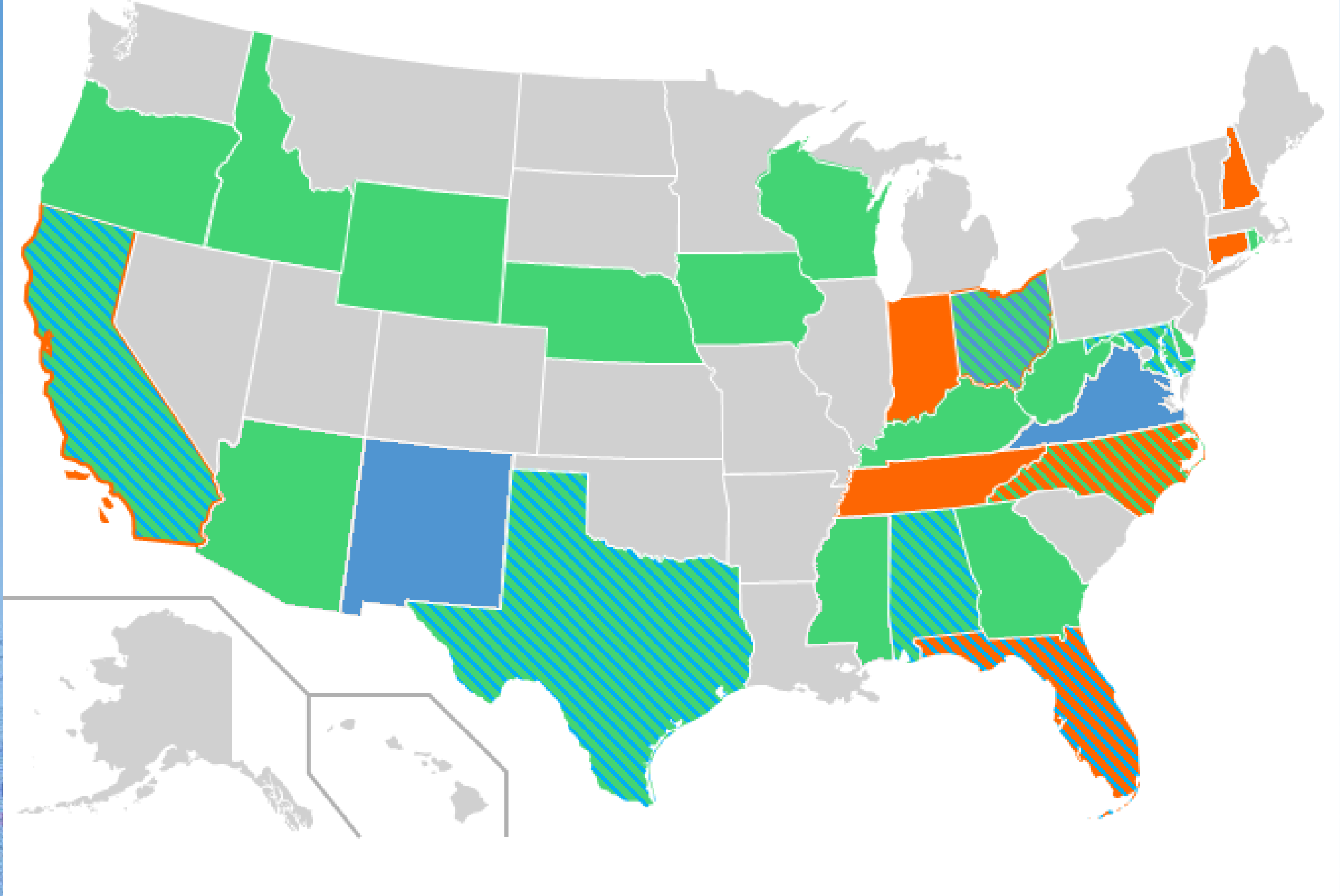
μG semiconductor offers opportunities to manufacture better AI chips





Plant growth strain sensor

ODME Partnership Map



Academic

- University of Louisville
- University of Alabama Huntsville
- Appalachian State
- Auburn University
- Boise State
- Georgia Tech
- CalTech
- Iowa State University
- Florida A&M University
- Oregon State University
- West Virginia University
- Youngstown State University
- University of Wisconsin
- University of Wyoming
- University of Delaware
- University of Texas El Paso
- Mississippi State
- Arizona State University
- University of Delaware
- Stanford University
- Wichita State

NASA Centers

- Marshall Space Flight Center
- Ames Research Center
- Johnson Space Center
- Kennedy Space Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Glenn Research Center
- Langley Research Center
- Armstrong Flight Research Center

Industry/Government

- NSF
- AFRL
- Oak Ridge National Labs
- Techshot
- Redwire Space
- Cornerstone Research Group
- LambdaVision
- Faraday Incorporated
- Laboratory for Physical Sciences
- Intel
- Fujifilm
- Axiom Space
- Space Tango
- ISS National Lab
- Goeppert
- United Semiconductors
- NextFlex
- nScrypt
- Multi3D

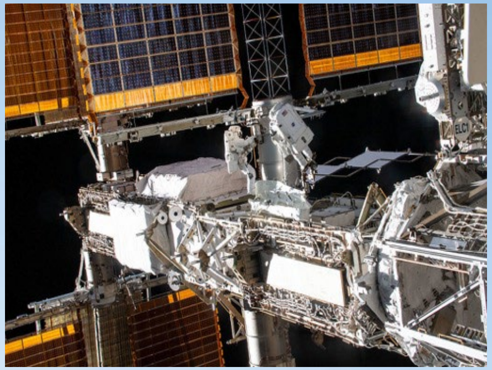
NASA ODME Technology Areas

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.

- **Three parabolic flight campaigns prior to FY24, with five more planned in 2024.**
- **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.**

NASA ODME Technical Maturation Plan

Objective: Document the engineering and programmatic approach to maturing On Demand Manufacturing of Electronics through infusion into architecture or commercialization

Scope: Electronics manufacturing of multilayer circuits and semiconductors within a pressurized, temperature-controlled environment

Phases:

1. **Concept Study and Process Evaluation:** Focus on a survey and evaluation of potential technologies.
    - **Entrance:** Start of Program (TRL 2)
    - **Exit:** Down selection of Deposition Technologies (TRL 3)
2. **Hardware Integration and Process Development:** Focus on hardware maturation and process development
    - **Entrance:** Selection of Primary Deposition Techniques (TRL 3)
    - **Exit:** Parabolic flights demonstrating critical elements and successful integration (TRL 4-5)
3. **Process Optimization:** Focus on understanding microgravity effects and optimization of processes
    - **Entrance:** Authorization to manufacture flight hardware (TRL 4-5)
    - **Exit:** Incorporation into mission architecture (multilayer deposition) and/or commercialization (semiconductors) (TRL 6-7)

In Space Production Applications

In Space for Earth

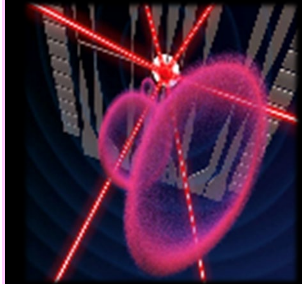
- Investing in scalable & sustainable manufacturing of microgravity enhanced products that support large markets on Earth
  - U.S. *competitiveness* in industries that serve national interests
  - Direct *benefits to humanity* by returning products to Earth
  - U.S. leadership of a *robust LEO economy*

- 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

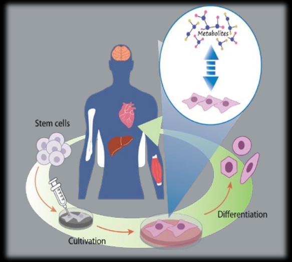
Atomic-Molecular

Crystals
Pharma
Industrial
Semiconductors

Alloys and Photonics

ZBLAN Optical Fibers
Semiconductors

Cells and Tissues



Cancer
Neurodegenerative
Stem Cells
3D Tissues

Thin Films

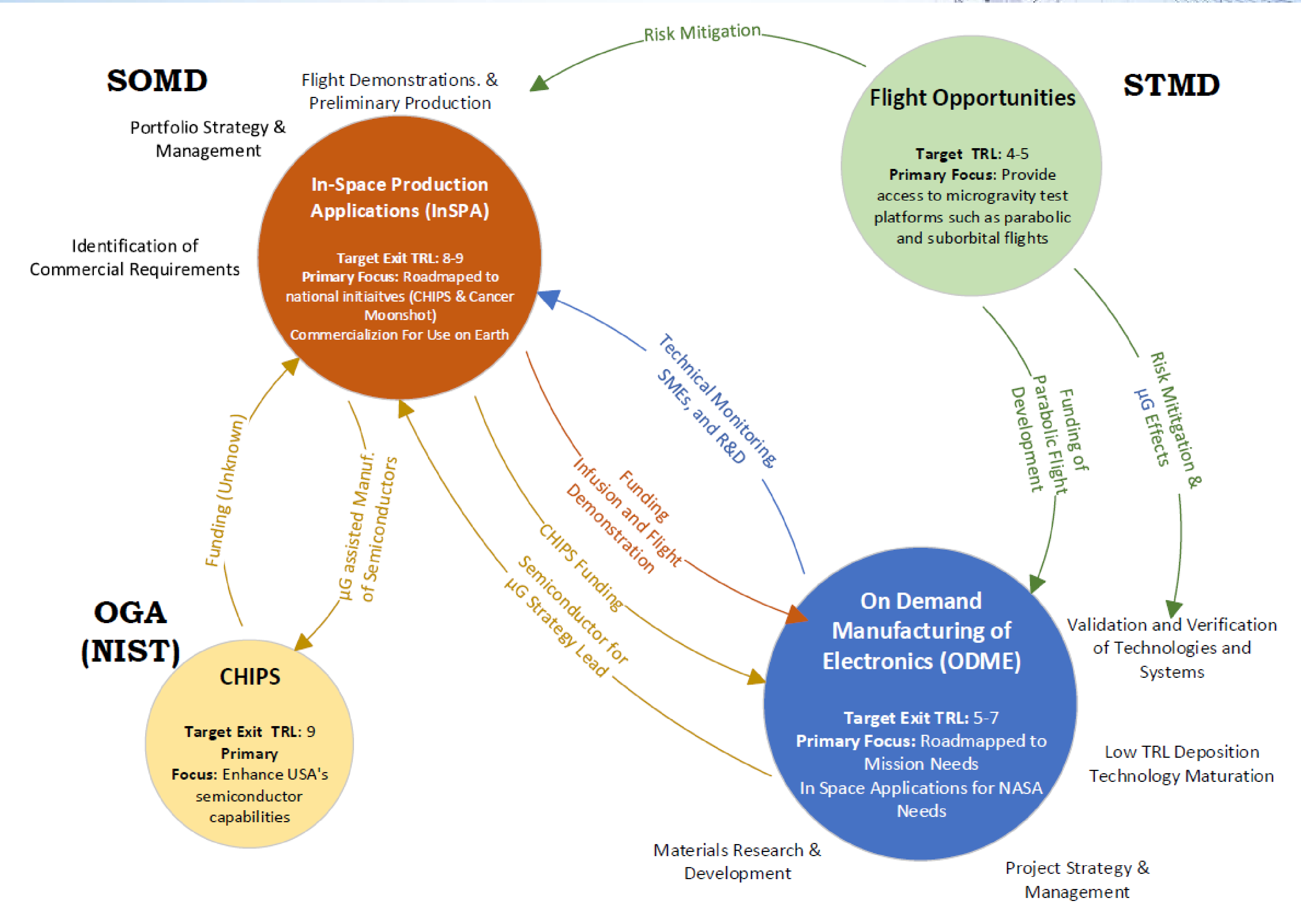
Artificial Retinas
Medical Devices

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

ODME as Tech Dev Hub for Commercialization

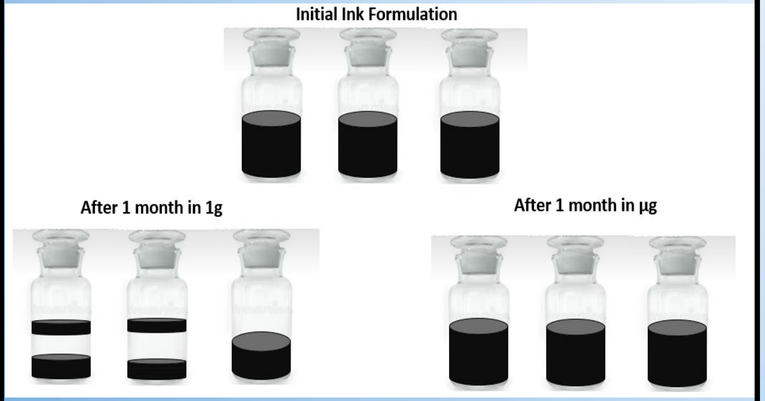


Utilization of Microgravity Advantages for Manufacturing of Microelectronics and Semiconductors

- Process and materials development of new precision deposition processes
- Development of optimized microgravity-enabled materials for high value applications
- Pushing the state of the art for semiconductors with space-enabled materials

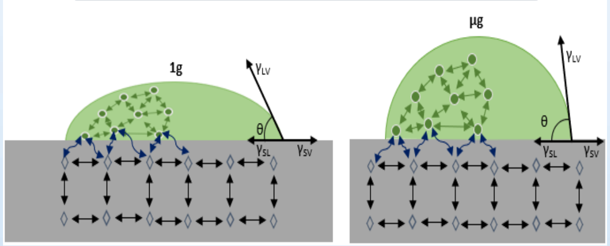
Materials-related µg impacts

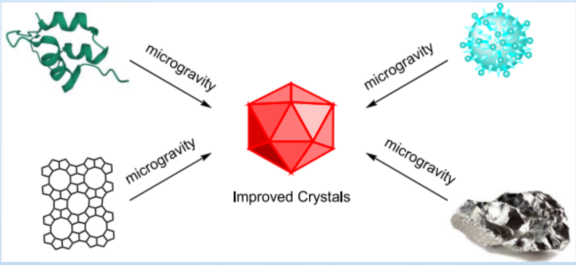
Sample preparation stage (before printing)



- 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).

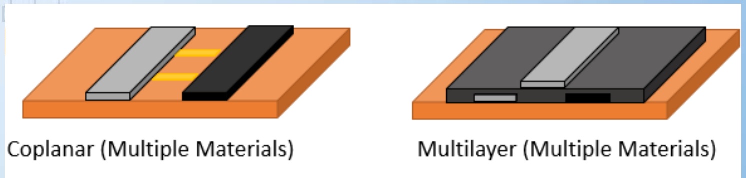
Manufacturing stage (during printing/fab)

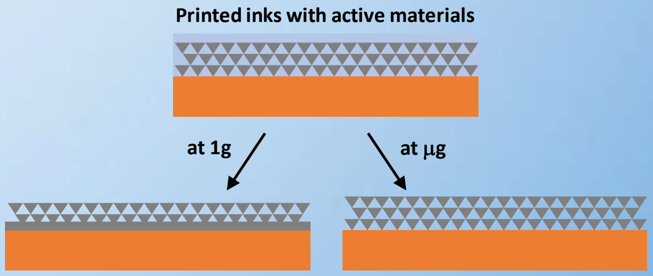




- Diffusion and surface tension-dominant processes enables more uniform structures at individual molecule level.
- In printing, µg allows less spread of the printed layers → higher resolution
- In crystal growth, µg allows larger crystal size and fewer defects → high quality

Application stage (after printing)

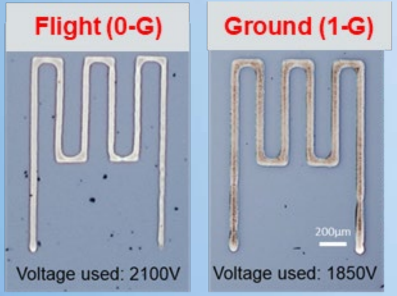


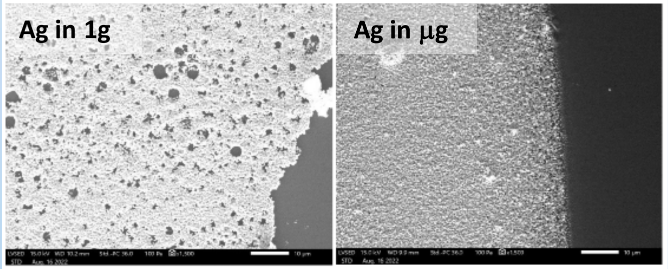


- In printing, higher concentration of the active material in inks allows superior performance and operation stability.
- In crystal growth, better crystal quality gives superior efficiency and lifetime.
- Multilayer fabrication is enabled to form integrated systems with multiple functional devices.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

Demonstration examples of μg impacts

Inkjet and EHD printing in μg



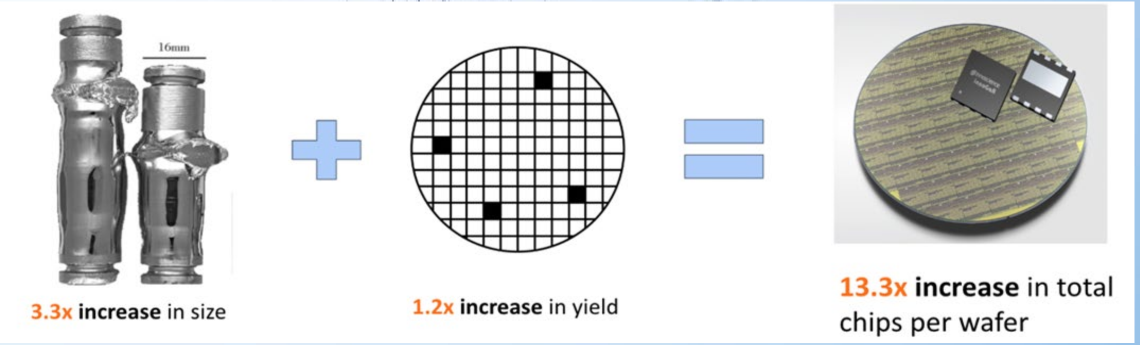


Dec-2021 flight test		May-2022 flight test	
ISU-Silver-35s1 (S35s1)		ISU-Silver-35s1 (S35s1)	
Silver content (wt.%)	35 ± 2	Silver content (wt.%)	50 ± 2
Average particle size (nm)	150 - 200	Average particle size (nm)	150 - 200
Viscosity (cP)	300 - 500	Viscosity (cP)	300 - 500
Solvent	DMSO	Solvent	DMSO
Surfactant (wt.%)	1%	Surfactant (wt.%)	0.6-1%
Aged (months)	Fresh	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

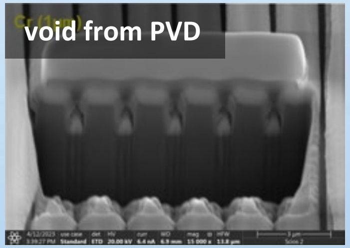
- Micro-structures of printed patterns results in denser structure with less porosity
- Silver loading can be increased from 35% (at 1g) to 50% (at μg) due to less agglomeration → 8.1 times higher conductivity
- Under μg, larger voltage can be used for reducing printed line width (higher resolution)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

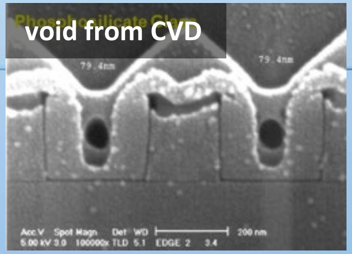
Crystal growth

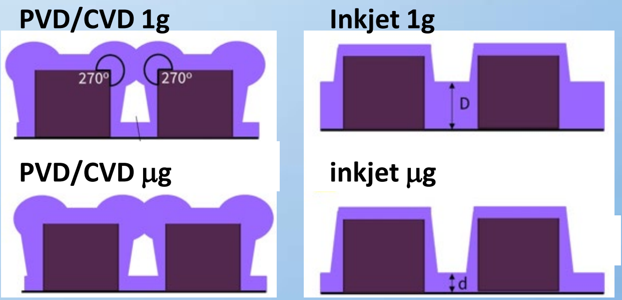


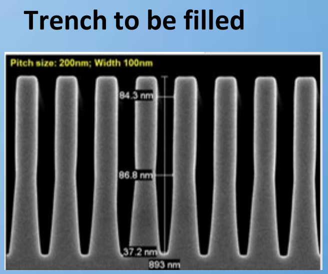
- From the studies of 500 entries in last 50 years, 89% of macromolecules crystals, 79% of inorganic crystals, and 81% of semiconductor crystals reported improved crystal structures in μg.

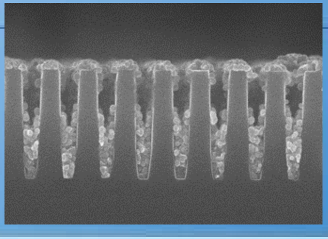
Trench filling







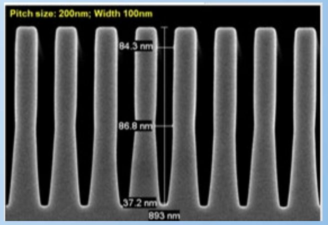




- Combination of inkjet printing and μg offer high step coverage without voiding problem. Beneficial for 3D memory fabrication with high density and high performance

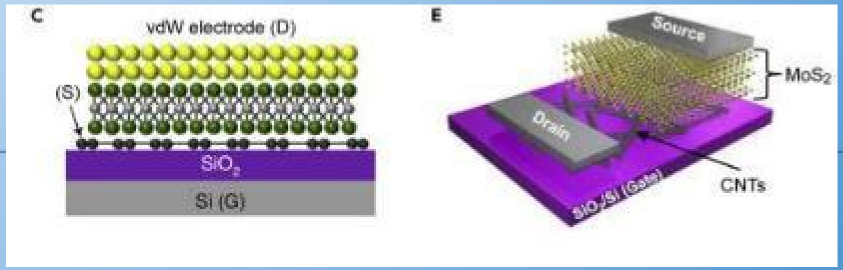
ODME Technology Maturation to support InSPA Commercialization of Electronics Manufacturing in Microgravity

- Development of EHD inkjet for precision microelectronics & semiconductor printing
  - o Microgravity enables higher yields for semiconductors & microelectronics.
  - o 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

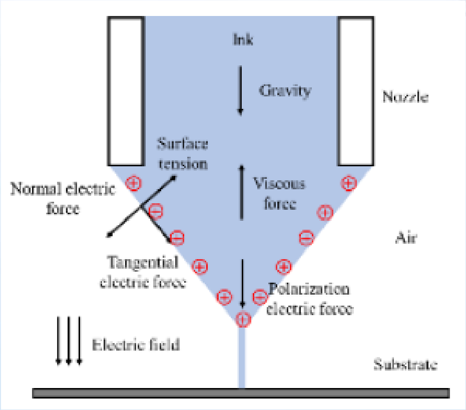
Wide bandgap diamond semiconductor

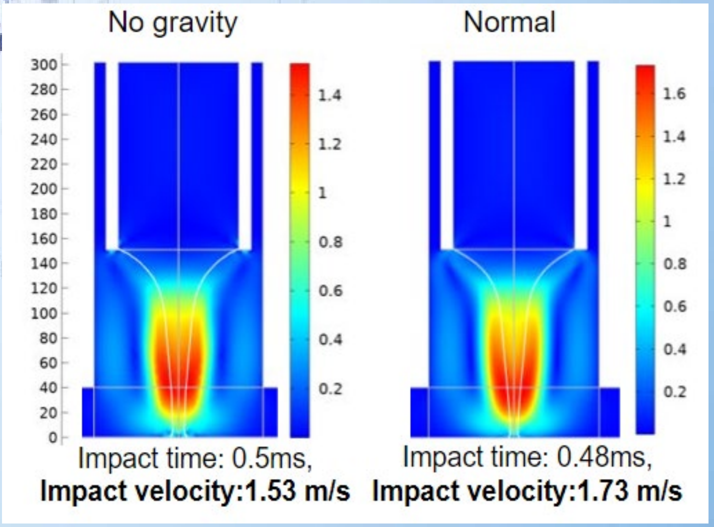


2D Semiconducting Materials for Ultimately-Scaled Transistors

Electrohydrodynamic Inkjet Technology Overview

- An Electrohydrodynamic (EHD) Inkjet printer uses a combination of hydraulic and electronic forces to deposit ink onto a substrate.
  - The electric field generated enables printing in microgravity environments; the effects of the electric field on the droplet are much greater than the effects of gravity.
- Multiple materials can be printed.





Modeling indicates no significant changes in droplet dynamics with and without gravity.

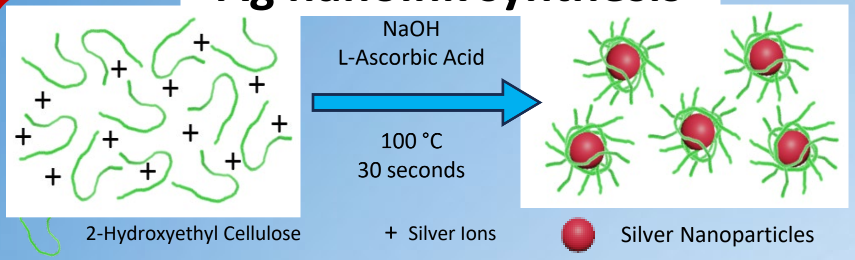
EHD is a thin film printing technology that is distinct from traditional ink jet and well suited for use in µG.

SPEC	DMP-2850 IJ (Industry Std)	EHD Inkjet
Minimum feature size	30 microns	0.5 microns
Ink viscosity	4-8 centipoise	0.1 - 500 centipoise
Ink surface tension	28-32 dynes/cm	1 - 800 dynes/cm
Droplet size	1pL - 10pL	0.1fL - 10pL

EHD ink platform development

Iowa State University, Jiang Research Lab
Patent disclosures: 900.330US, 900.340PRV

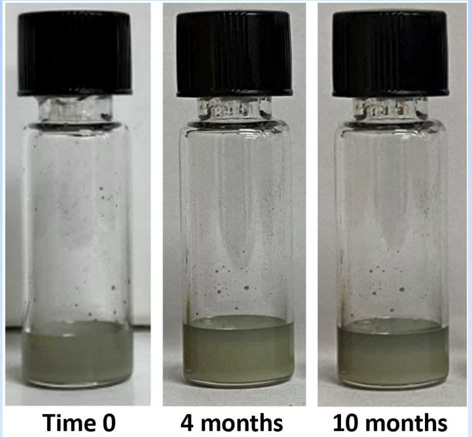
Ag nanoink synthesis



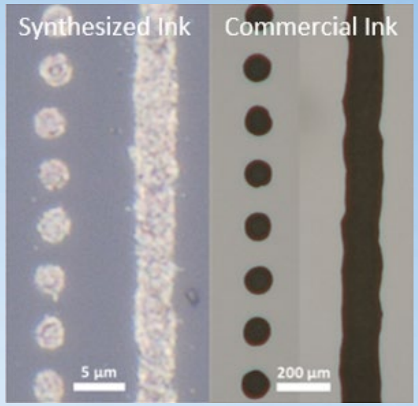
- **Highly stable with long shelf-life**
- **Better conductivity**
- **Lower sintering temperature**
- **10x higher printing resolution**

(benchmarked against commercial ink)

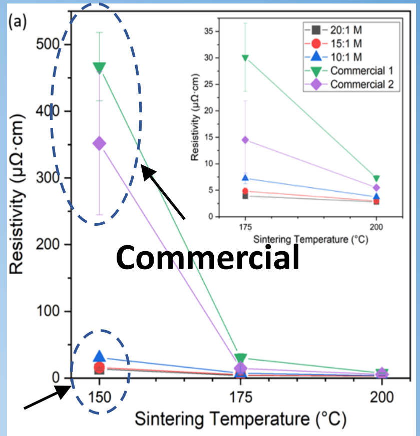
Highly stable with long shelf-life

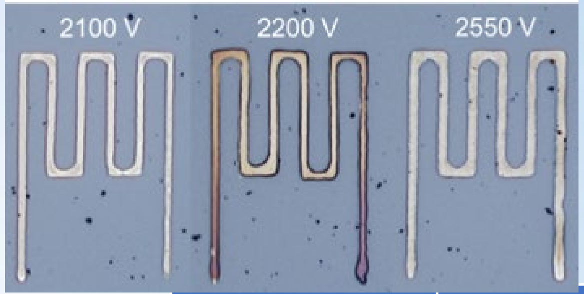


10x higher resolution



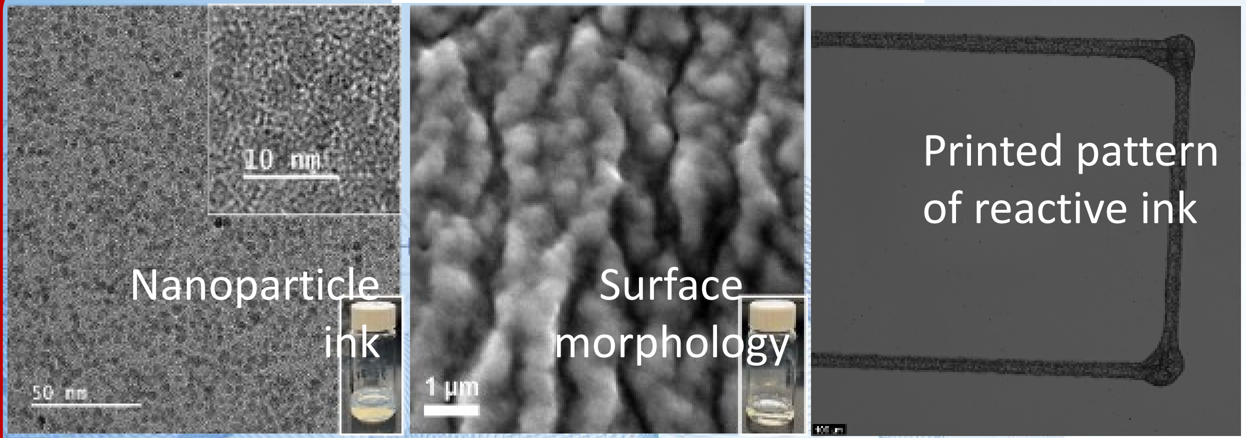
Better conductivity at lower sintering temperature





High quality prints during flight test

ZnO semiconductor ink

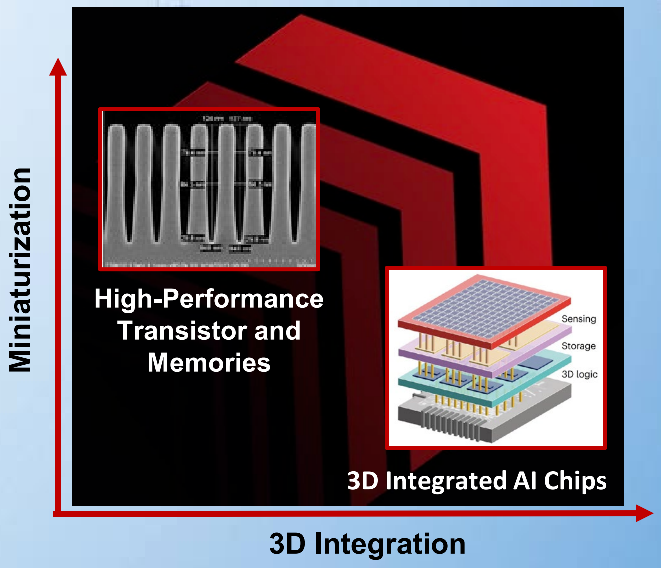


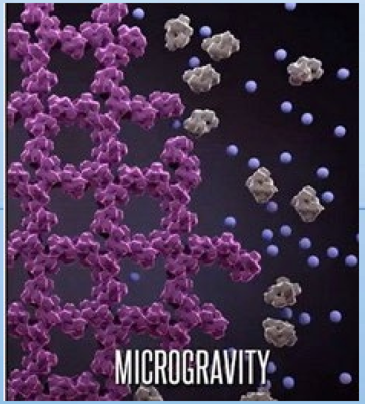
	Pros	Cons
Nanoparticle ink	• Film continuity • High film density	• Instability • Possible nozzle clogging • Contamination
Reactive ink	• No nozzle clogging • Smooth printing • Various solvent options	• Impurity • Thick film is hard to achieve

Areas of In Space Semiconductor Commercial Development

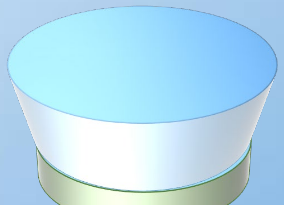
- Crystal growth – leverage known crystal growth advantages for Si and new materials
- Fabrication processes and materials
  - Replace bulky, expensive terrestrial processes with Space-Enabled processes and materials
  - 2D materials for transistor scaling and heterogeneous integration – combines crystal growth advantages with new fab processes

μG semiconductor offers opportunities to manufacture better AI chips





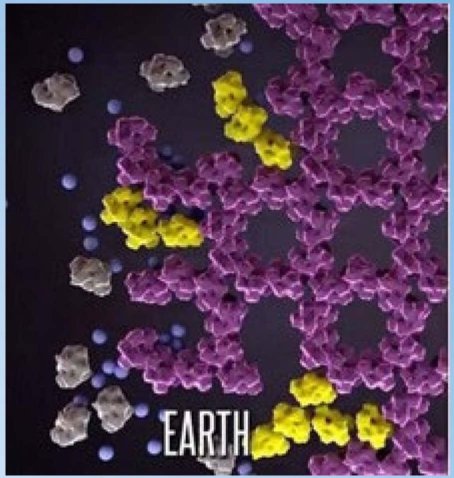
2D material grown in microgravity



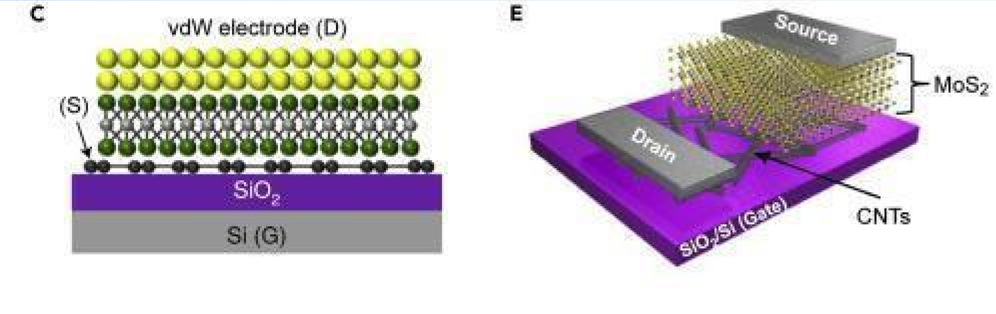
Microgravity grown diamond wafer

Why Microgravity Environment Matters for 2D Material Growth

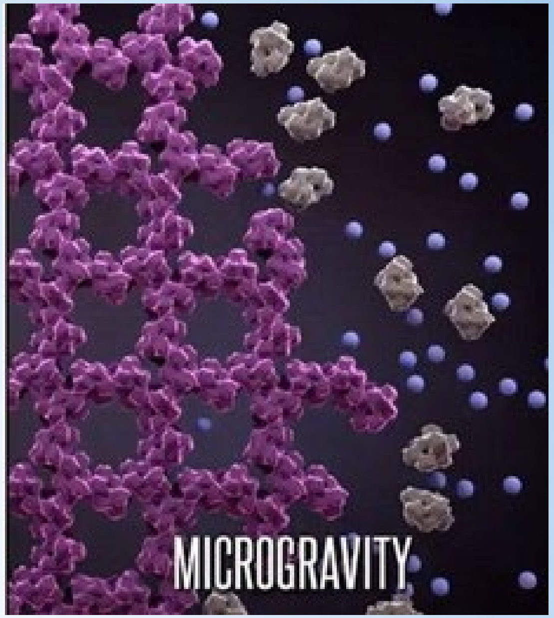
- Microgravity **reduces** the influence of heat convection, particle movement, buoyancy and sedimentation
- Crystals grow more slowly and often in a more equilibrium manner that **reduces structural defects**.



Credits: NASA



2D Semiconducting Materials for Ultimately-Scaled Transistors

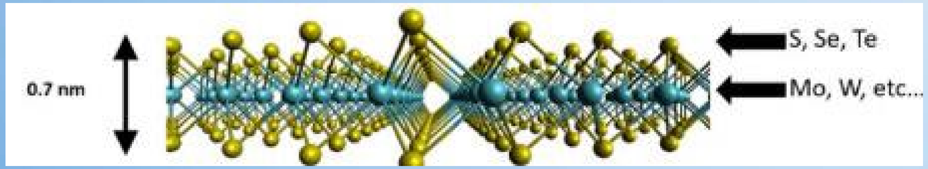


In Space Production of MoS_2 for silicon integration

2D materials development team:
PI: Goeppert, Inc (Phase III SBIR)
Support Co-Is:
Arizona State, Texas A&M

Technical Approach

- Build CMOS-compatible terrestrial MOCVD system for low-temperature MoS2 film growth.
- Modify Design for In-Space Use
  - Identify required modifications (weight, power consumption, safety, etc)
  - Use simulations to model fluid flow and thermal gradients for improved growth performance
  - Test design modifications on terrestrial model
  - Evaluate payload resources for ISS implementation
  - Collaborate with NASA engineering experts on flight qualification

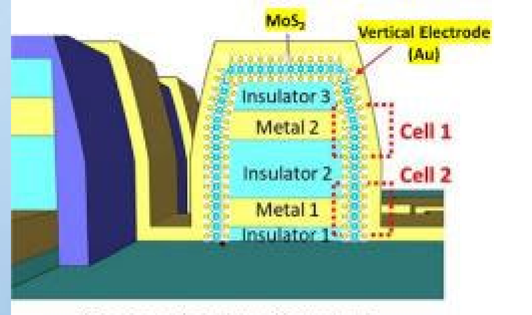


Market

- Global semiconductor market $550 billion by 2023
- 2D material market $3 billion by 2027
- CVD equipment $22 billion by 2027

Applications

- High-performance transistors, integrated circuits, sensors
- Next-generation logic and memory devices
- Flexible and wearable electronics
- Quantum computing components



Cross-section view of structure

Potential Advantages

- Improved film uniformity and crystallinity by minimizing gravity-driven convection and sedimentation
- Ability to finely tune defect densities and locations by precisely controlling growth kinetics
- Possibility to grow films not achievable on Earth due to thermal or compositional constraints
- Scalability to larger wafer sizes due to reduced boundary layer effects
- Strengthens US leadership in strategic advanced logic devices and semiconductor supply chain

Questions?

Curtis Hill
Tel: (256) 655-6876
Email: curtis.w.hill@nasa.gov