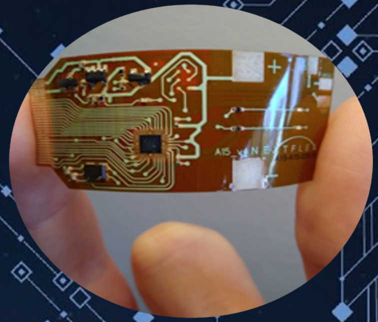
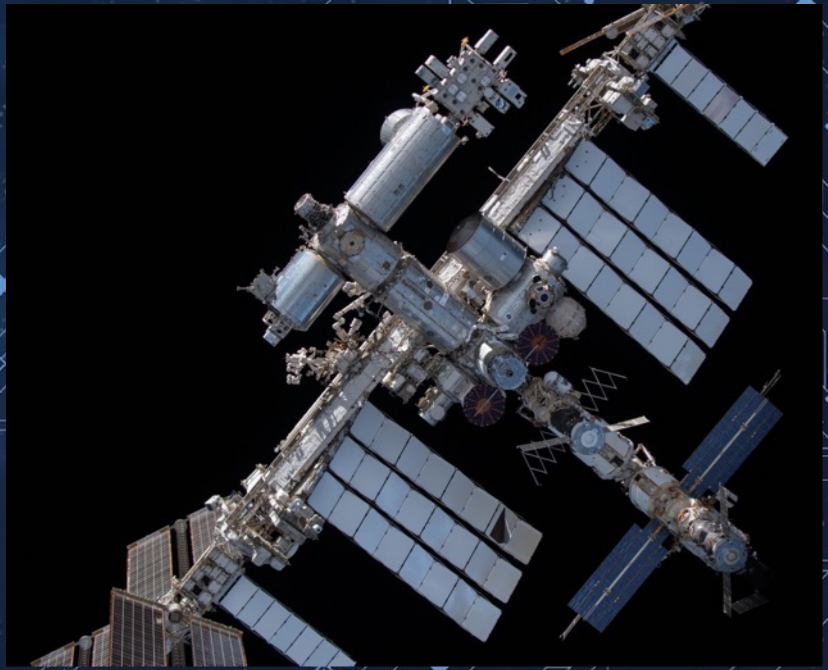
MICROGRAVITY MANUFACTURING
OF SEMICONDUCTORS & MICROELECTRONICS





Stanford Semiconductor Workshop| 3.28.23 | curtis.w.hill@nasa.gov
Curtis Hill MSFC ESSCA / ODME PI & InSPA SME for Semiconductors

NASA IN-SPACE MANUFACTURING

PORTFOLIOS

In Space Manufacturing (ISM)

In Space for NASA Exploration

In Space Servicing, Assembly, and Manufacturing (ISM)

In Space for Space (Govt. & Private)

NASA Research Announcement (NRA)

ISS-OZ

In Space Production Applications (InSPA)

In Space for Earth

AWARDS AND SPONSORSHIP

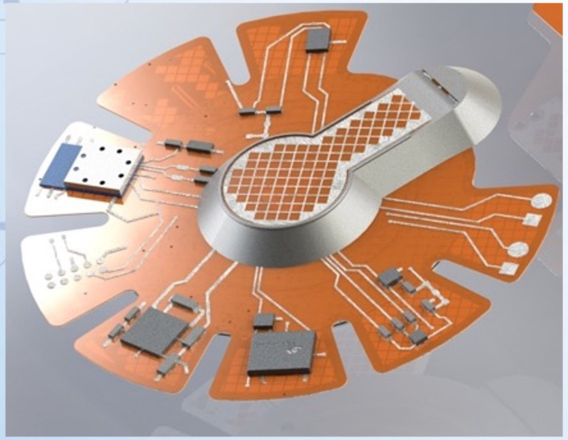
ISS National Lab Research Announcement (NLRA)

CASIS

Many opportunities for synergy between portfolios

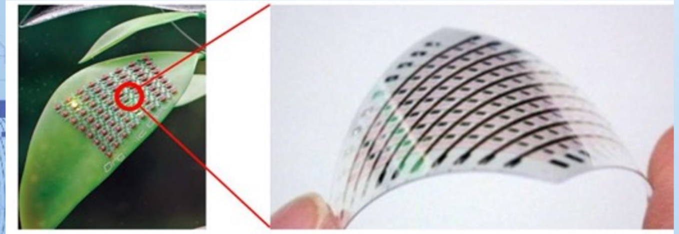
CASIS - Center for the Advancement of Science in Space
Non-Profit Operator of the ISS National Lab

ON-DEMAND MANUFACTURING OF ELECTRONICS *ODME*

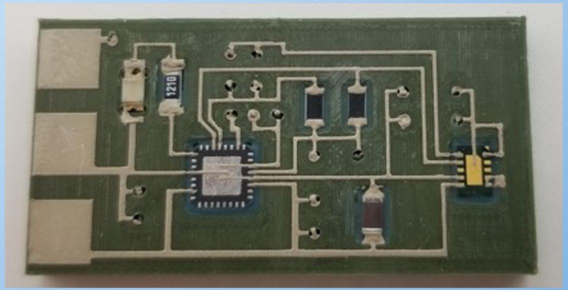


Crew Health Wearable Wireless Sensor

- Objective 1: Development of ODME capabilities for microgravity manufacturing
  - ISS demo– FabLab with Advanced Toolplate
- Objective 2: Development of electronics devices sensors for in-space manufacturing
  - Primarily for **Use In Space**



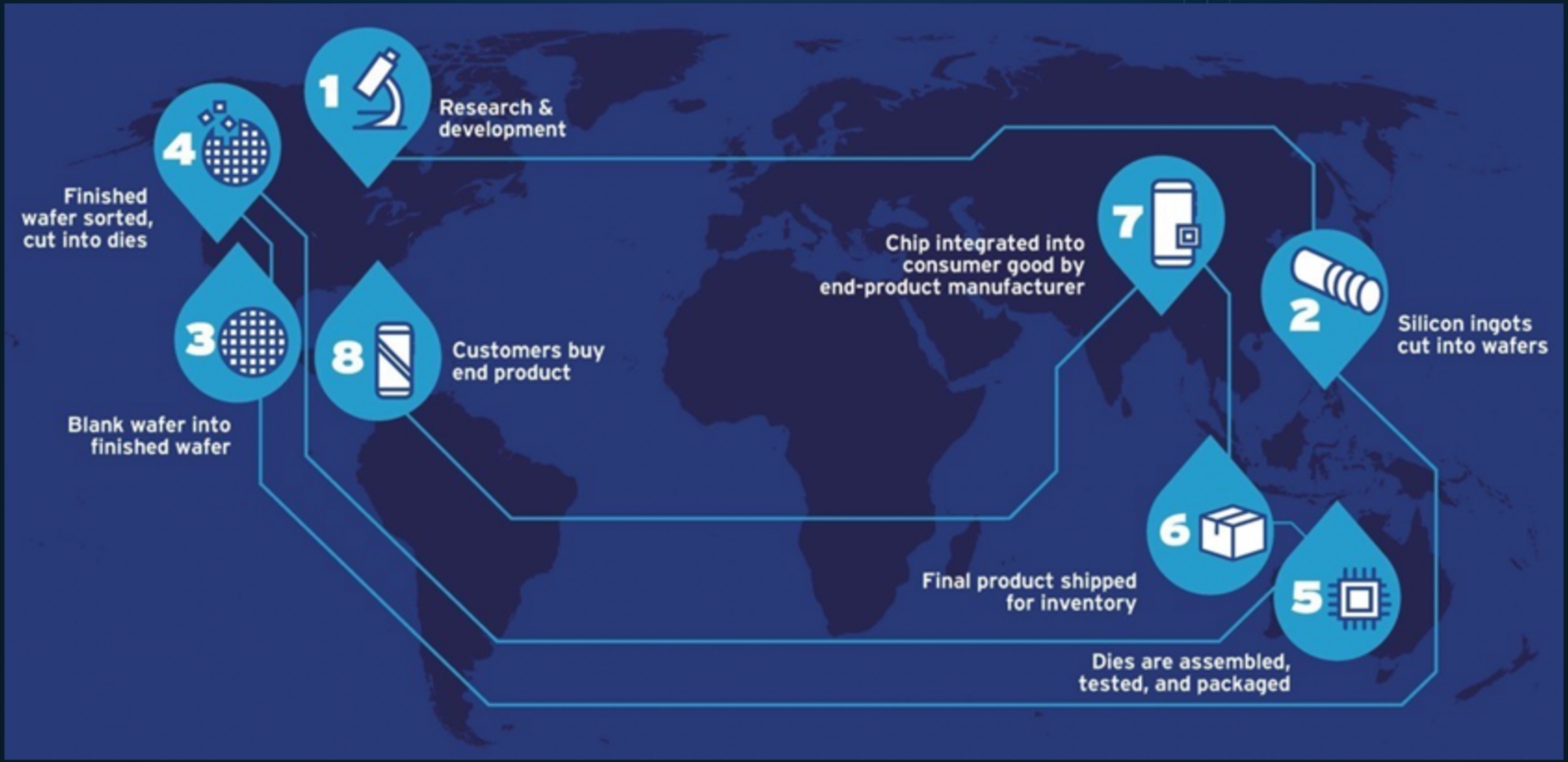
Plant growth strain sensor



Additively-printed CO_2 Sensor

WHAT IS THE 'SEMICONDUCTOR DEVICE SUPPLY CHAIN'?

WORLD MAP OF THE SI-BASED SUPPLY CHAIN:



Global Semiconductor Value Chain Map (Source: Semiconductor Industry Association)

Microgravity Development of Optimized Semiconductor Crystal Growth and Optimized Semiconductor Fabrication Processes

NASA FOCUS ON SEMICONDUCTOR MANUFACTURING IN SPACE AND THE CHIPS ACT OF 2022

Technology Maturation through:

- SEADS research awards for focused topics
- Continuation and parallel awards in InSPA
- NASA Internal Parallel and Focused Research in Advanced Manufacturing

Workforce Development through:

- SEADS research awards with specific workforce development
- Partnerships and awards with Universities focused on workforce development

LEO Infrastructure Development through:

- CLD Support and Collaboration
- Additional Transportation support

SEADS – *Space-Enabled Advanced Devices & Semiconductors*

PROPOSED NEW SEADS AWARD PHASES
FOR SEMICONDUCTOR RESEARCH AWARDS

SEADS Phase 1a – Modelling and Sim, Ground Fab and Printing

SEADS Phase 1b – Flight Campaign for proof of concept

SEADS Phase 2 – ISS Demo iterations

SEADS Phase 3 – CLD Demo

SUMMARY OF ~60 SEMICONDUCTOR CRYSTALS GROWN IN SPACE COMPARED TO EARTH

Macromolecules (Organic) Space Results

- 79% of experiments showed improved uniformity
- 83% of experiments showed improved structure 78% of experiments grew larger crystals
- 78% of experiments showed improved resolution
- 76% of experiments had improved mosaicity

Inorganics

- 79% of experiments showed improved uniformity
- 75% of experiments showed improved structure
- 70% of experiments grew larger crystals

Macromolecules & Inorganics

- 79 of all experiments showed improved uniformity
- 75% of all experiments grew larger crystals
- 81% of all experiments showed improvement in structure

Semiconductors

- 83% of experiments showed improved uniformity
- 89% of experiments showed improvement in structure
- 47% of experiments grew larger crystals

Overall

- 90% of all crystals improved in at least one metric
- 74% showed improvement in two, and
- 49% showed improvement in three or more

Source: Butler University Study for NASA InSPA

HOW CAN MICROGRAVITY PROCESSING BENEFIT THIS INDUSTRY?

An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types

Hannah Wright, Amari Williams, Ashley Wilkinson, Lynn Harper, Ken Savin, and Anne M. Wilson*

Cite This: *Cryst. Growth Des.* 2022, 22, 6849–6851 Read Online

Semiconductor Specific Investigations*:

- **2.2x** the diameter
- **100-1000x** fewer defects
- Up to **2x** the growth speed

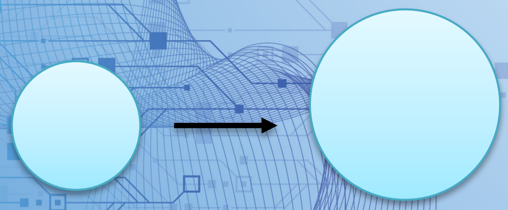
*Analysis of database performed by Dr. Jessica Frick/Stanford University

HOW CAN MICROGRAVITY PROCESSING BENEFIT THIS INDUSTRY?

CASE STUDY | CADMIUM TELLURIDE (CDTE)

Translation into an Earth-based application…

120% increase in area

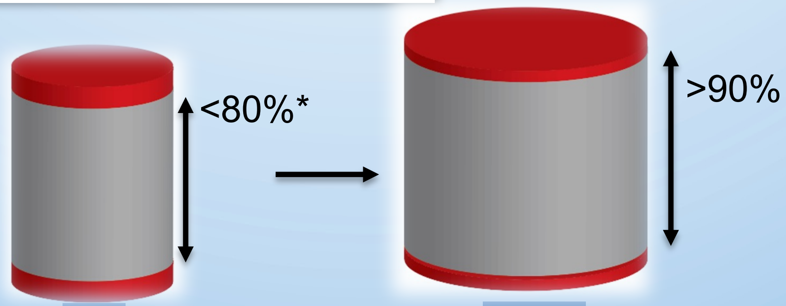


g μg

(1) 2.2x increase in crystal size

+

>10% increase in usable volume



g μg

(2) 10-1000x fewer defects

(3) Uniform dopant distribution

=

>150% increase in product

Other potential benefits include:

- Extended product lifetime
- Increase in solar efficiency
- Wider operating ranges

CASE STUDY

CADMIUM TELLURIDE (CDTE)

Ref.	Mission	Year	Process Temp.	Process Time
Nuc. Instrum. Methods Phys. Res. A283 (1989) 363-369	Spacelab D-1	1985	1050 °C	21 hours
J. Mater. Res., Vol. 17, No. 12, 2002	STS-95	1998	1170 °C	26 hours
IEEE Nucl. Sci. Symp. Conf. Rec. (2008) R05-5, 122-125	Foton-M3	2007	1175 °C	12 hours

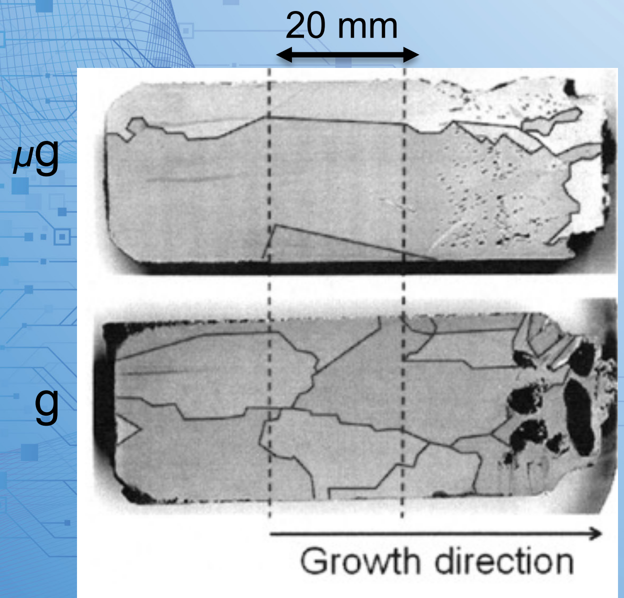
Summary of Results

(1) 2.2x increase in crystal size

(2) 10-1000x fewer defects

(3) Uniform dopant distribution

(1) Crystal Size

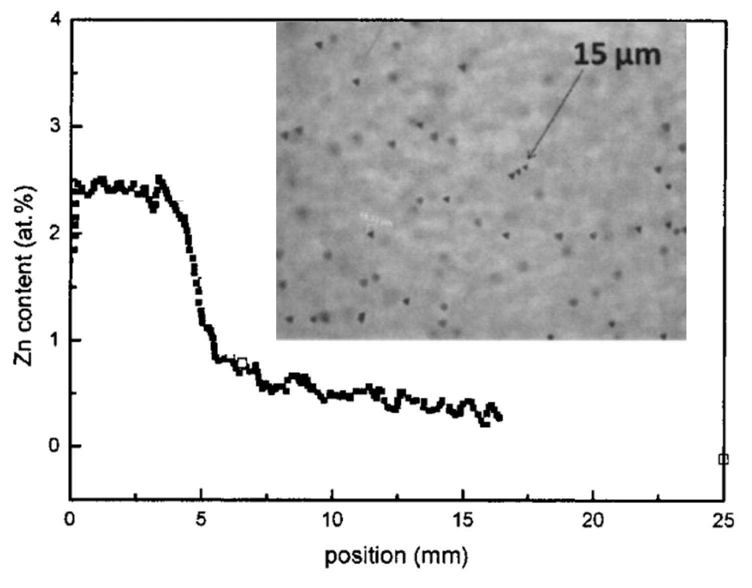


(2) Defect Concentration

Defect concentration [cm^{-3}]

Space crystal samples 1.3	Earth crystal ref. samples
$4.8\times10^{+14}$	$8\times10^{+14}$
$2\times10^{+13}$	$6\times10^{+13}$
$2\times10^{+13}$	$6\times10^{+13}$
–	–
–	–
–	–
–	$7\times10^{+13}$
$8\times10^{+13}$	$1.1\times10^{+14}$
$7.8\times10^{+13}$	$1.4\times10^{+15}$
$6\times10^{+14}$	$1.1\times10^{+15}$
$1\times10^{+13}$	$1\times10^{+13}$
$1\times10^{+12}$	$1\times10^{+15}$

(3) Dopant Content & Density



BENEFITS OF MICROGRAVITY FOR SEMICONDUCTOR FABRICATION

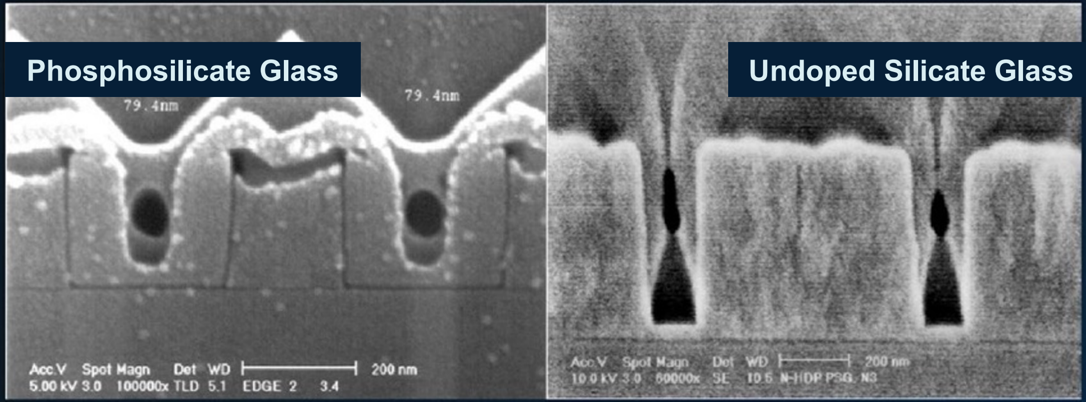
Semiconductor chip performance improvement and cost reduction from microgravity processing which should:

- Provide better trench filling and avoid voiding (defect-reduction) in pattern structures by inkjet printing.
- Enable the mask-free and etching-free process for 3-dimensional memory and advanced devices due to thinner printing in microgravity environment.

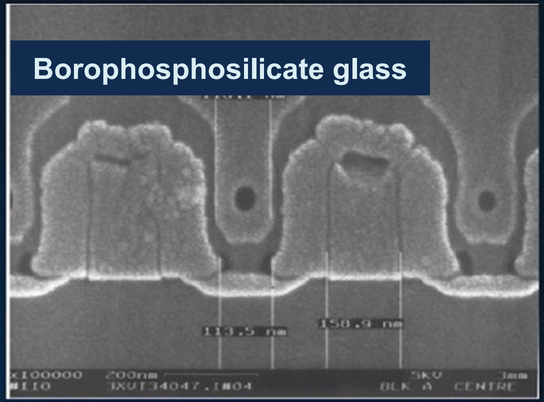
SPACE ENABLED ADVANCED DEVICES & SEMICONDUCTORS (SEADS):

ENHANCEMENT OF FABRICATION PROCESS

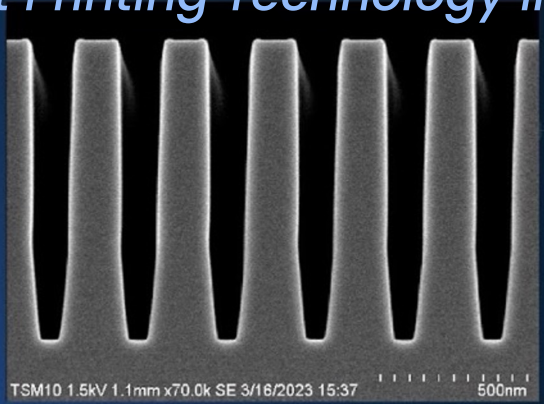
High Density Plasma (HDP-CVD)



Chemical Vapor Deposition (CVD)



Inkjet Printing Technology in uG



- ✓ Mask-free / Etching-free
- ✓ High Fabrication Efficiency
- ✓ Cost Reduction
- ✓ High Density / High Performance

BENEFITS OF MICROGRAVITY FOR EHD INKJET PRINTING

FROM 120 PARABOLAS ON TWO ODME PARABOLIC FLIGHT CAMPAIGNS FY22

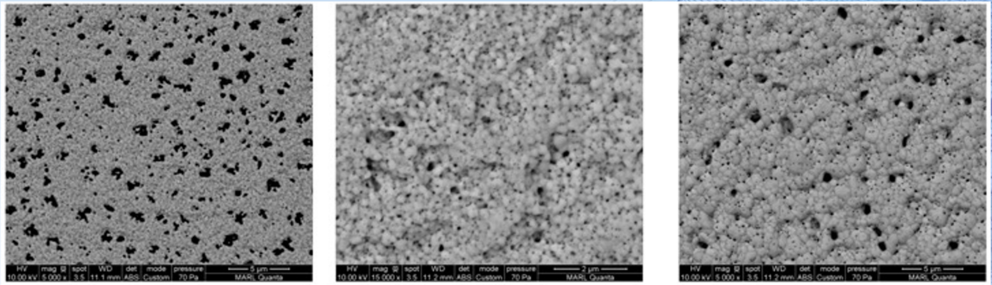
- Benefits of microgravity for ink formulation
  - Under microgravity, risks of ink agglomeration are minimized
  - Increase of silver loading from 35% to 50%
  - Micro-structures of printed patterns: fewer pores and denser
  - Electrical performance: 50% loading is ~two times bulk silver
- Benefits of microgravity for EHD printing process
  - For ground-test, higher voltage = ***increased feature size***
  - Under 0-G, apply higher voltage yields a significant reduction of printed line width – ***increased feature resolution***

For future devices:

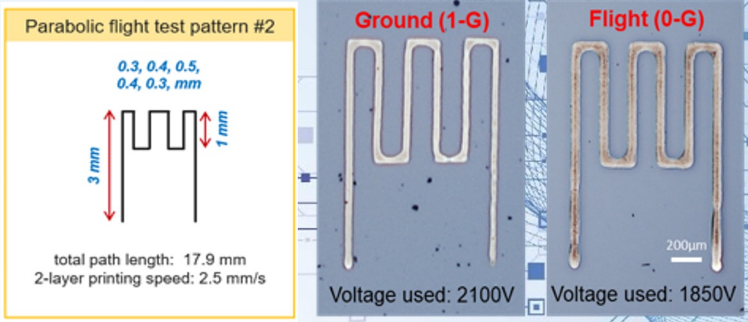
- higher-resolution ? improved manufacturability of complex structures ? increased electrical performance of devices

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



35% particle loading (2 layers) | 46% particle loading (2 layers) | 57% particle loading (2 layers)



PROVING THE CONCEPT: *SPACE ENABLED DEVICES AND SEMICONDUCTORS (SEADS) TECHNOLOGY MATURATION AND LEO DEMONSTRATION PREPARATION*

PHASE 1

Modelling and Simulation
Jan-May 2023

- NRA and NLRA White Papers
- Analysis of Technical Approach
- Design & Prep Flight Experiments

Ground Fabrication of Devices and Printing
Mar-July 2023

- Design of Device and Stackup (NAU)
- Fabrication of Device and Stackup (TEL)
- Inkjet Material Selection and Printing

PHASE 2

Flight Campaign 1
Aug 2023

- Flight Test of Initial Designs for Optimization
- Demo Multiple Patterns

Flight Campaign 2
Late 2023

- Print Multiple Patterns
- Optimize EHD inks & parameters

PHASE 3

ISS Microgravity Demo
TBD

- Iterate till optimized
- Demo and Optimize Entire Fabrication Process

PHASE 4

CLD Commercial Mfg Demo
TBD

- Full Process Commercial Demo

KEY CHIPS ACT INITIATIVES

AT UNIVERSITY PARTNERS WORKFORCE DEVELOPMENT

Building and expanding on research efforts in areas that include:

AI-enabled design and modeling

Sustainable semiconductor manufacturing and materials development

Heterogeneous integration and packaging

Nanolithography

Establishing state-wide and regional academic – university – college partnerships in workforce development

Supporting a semiconductor technology innovation ecosystem

What’s Next?

Let’s look at the intersection of microgravity and semiconductors more closely … together.

NASA and **CASIS are investigating implementation options.**

We are looking to work with NIST and the broader Space and Semiconductor communities to develop **strategies for** in-space manufacturing and encourage collaborations and consortia to accelerate progress and inform priorities.

ISS NATIONAL LABORATORY