Space Enabled Advanced Devices and Semiconductors (SEADS) – a New Era for In-Space Manufacturing of Electronics

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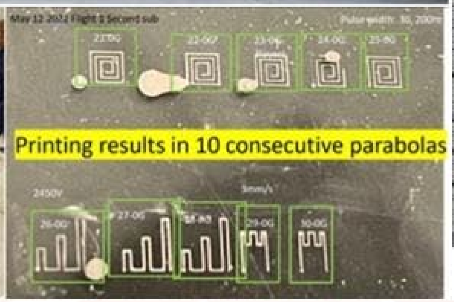
Space Enabled Advanced Devices and Semiconductors (SEADS)

- **NASA initiatives**
  - NASA On Demand Manufacturing of Electronics (ODME)
- **Goal**
  - develop and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for advanced semiconductor electronic devices on the ISS
  - ODME is partnering with various groups (Intel/ASU/TEL/ISU/WISC)
- **Current phase**
  - Advance testing on parabolic flights prior to deployment to the ISS.
- **Semiconductor device manufacturing in ISS**
  - Creation of both printed electronics and metals/semiconductor materials with advanced functional device manufacturing
- **Manufacturing technique**
  - Electrohydrodynamic inkjet printing (EHD printing) and post-sintering

Technology Description (EHD printing)

- University of Wisconsin team: lab-developed EHD printer
- Completed parabolic flights demonstration successfully (11/2021, 05/2022, 03/2024)
- Scheduled parabolic flights demonstration (08/2024, 11/2024)
- In-situ monitoring of flexible sensors, semiconductors, batteries, 3D metal patterns at micro-scale.



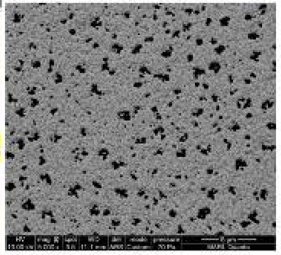
Dec-2021 flight test

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

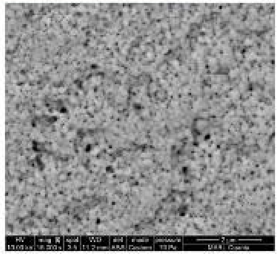
May-2022 flight test

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

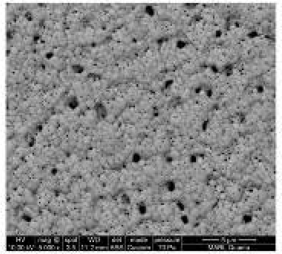
Resistivity (μΩ·cm) Bulk Silver = 1.59 μΩ·cm		
Sintering (30 min)	35% Ink	50% Ink
50 °C	4.27E+8	19795
100 °C	1.06E+7	2213
150 °C	123.3	15.27
200 °C	19.68	2.98



35% particle loading (2 layers)



46% particle loading (2 layers)

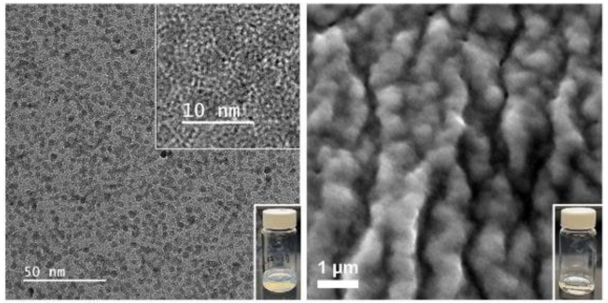


57% particle loading (2 layers)

Technology Description (Ink & Device)

- Iowa State team Semiconductor oxide (ZnO) and Arizona State device team
  - Reactive inks shows feasible modulation (material & EHD printer parameters)
  - The performance meet expectation, and more innovation solutions in place.

	Pros	Cons
ZnO nanoparticle ink	• Ultra-small particle size • Smooth printing • Uniform and continuous film	• Carbon contamination • Challenge in stability • Possible nozzle clogging
ZnO reactive ink	• No nozzle clogging issue • Smooth printing • Various solvent options	• Impurities due to low temperature sintering • Thick film is hard to achieve • Film continuity



ZnO nanoparticle ink
- Particle size < 10 nm
- Organic solvent based

ZnO reactive ink
- Particle free
- Ultra-stable

(a) (b)

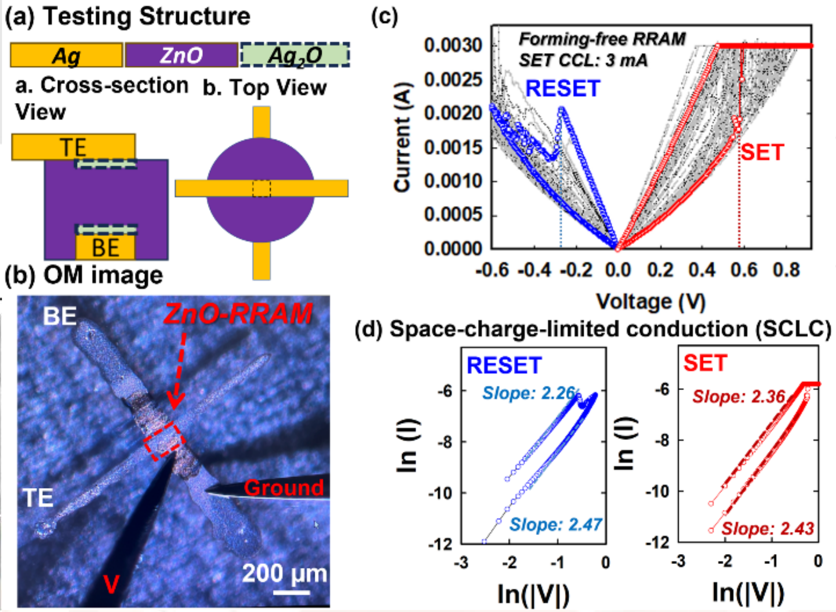
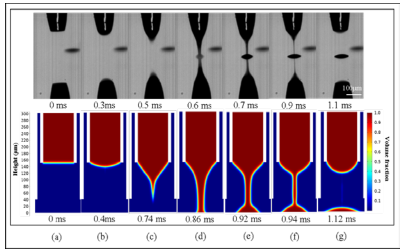


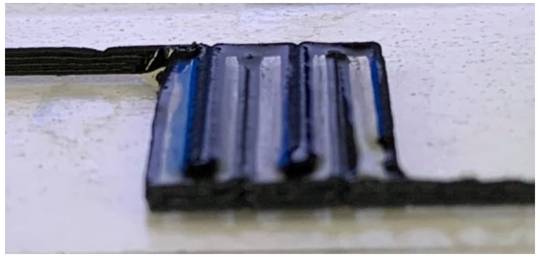
Table 1. Comparison of Inkjet Printed Memory

Device stacks (TE/AL/BE)	Deposition method	Switching polarity	SET	RESET	On/off Ratio
Al/ZnO/ZnO_{1-x} /ZnOAl [Ceram. Int. 2017]	PVD	Bipolar	1.4 V	-1.5 V	4.8 @1V
Ag/WO_{3-x}/Au [AFM 2023]	Inkjet printing	Bipolar	1 V	-0.5 V	$<10^2$
Ag/TiO2/Carbon/ Paper [VLSI 2014]	Inkjet Printing	Bipolar	2 V	-4 V	$10\sim10^2$
Ag/ZnO/Ag (This Work)	**EHD printing**	**Bipolar**	**0.6 V**	**-0.27 V**	**~50@0.1 V (Forming-free)**

Results of most recent 0-g flight test in 03/2024

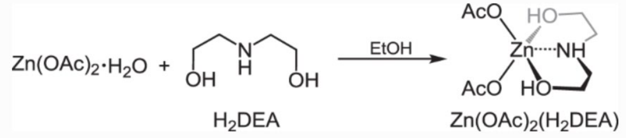
- Electrohydrodynamic (EHD) printing is a specialized printing that involves the use of electric fields to dispense and control the behavior of liquid droplets.
- It relies on the principle of electrostatic forces where the electric field is applied to a conductive fluid causing it to form a jet.
- It is affected by the interaction between the electric field, surface tension, and the liquid's properties.



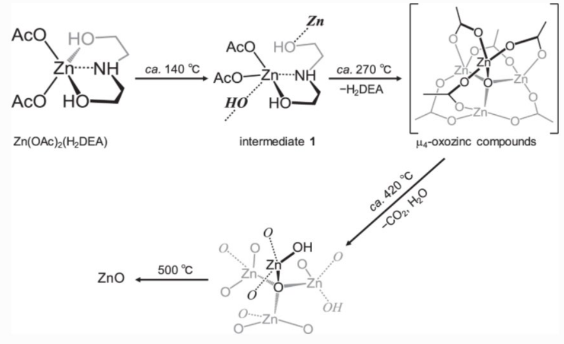


Results of most recent 0-g flight test – material and inks

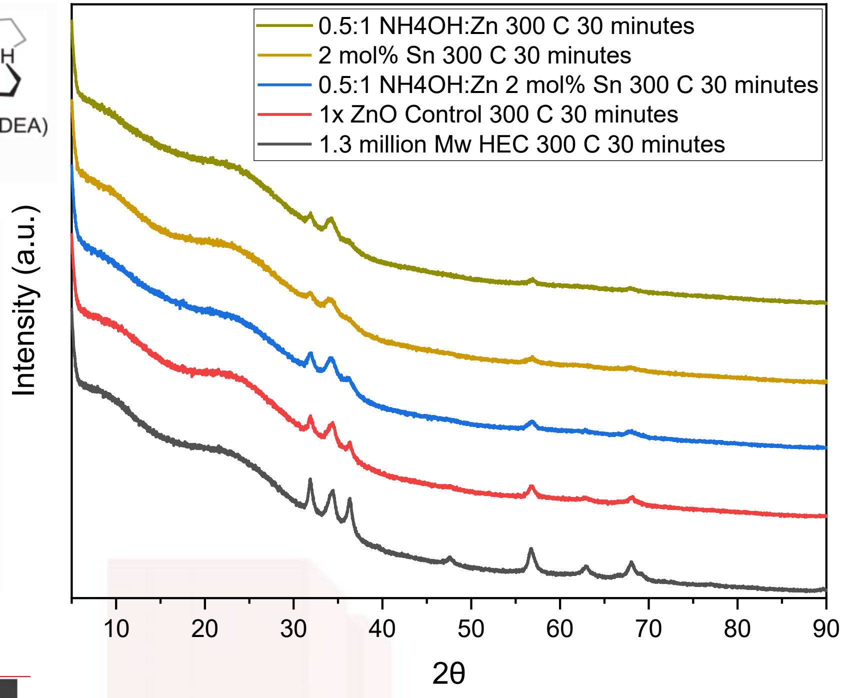
- Reactive ZnO Ink
  - Zinc acetate dihydrate
  - Tin (II) chloride dihydrate (tin source for doping)
  - ethanolamine
  - ammonium hydroxide (0.5:1 molar NH4OH : Zn^{2+})
  - Methanol or ethanol as solvent
  - Heat at 70 °C for 20 minutes
  - Forms a zinc-amine complex
  - Degrades into ZnO when heated



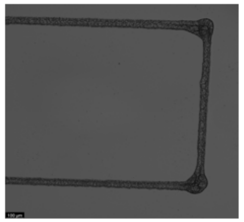
Synthesis of $Zn(OAc)_2(H_2DEA)$



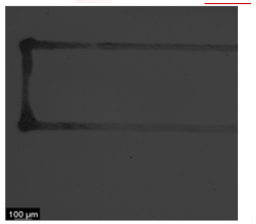
A possible thermal decomposition pathway from $Zn(OAc)_2(H_2DEA)$ to ZnO



Able to consistently produce ZnO even when changing the composition of out inks.



Base ZnO

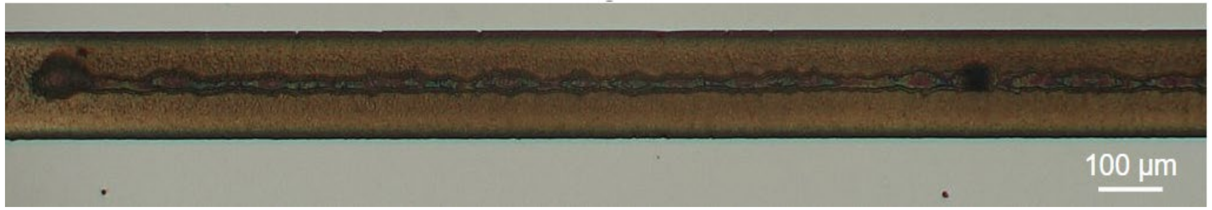


0.5:1 NH4OH:Zn

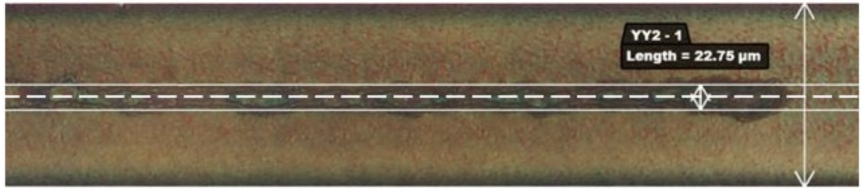
Hayami, R.; Endo, N.; Abe, T.; Miyase, Y.; Sagawa, T.; Yamamoto, K.; Tsukada, S.; Gunji, T. Zinc–Diethanolamine Complex: Synthesis, Characterization, and Formation Mechanism of Zinc Oxide via Thermal Decomposition. *J. Solgel Sci. Technol.* **2018**, *87* (3), 743–748.

Results of most recent 0-g flight test – printing results

- PDMS results & selected ZnO results



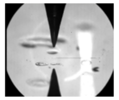
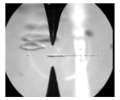
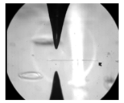
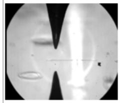
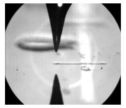
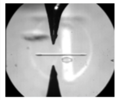
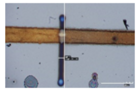
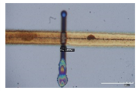
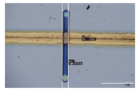
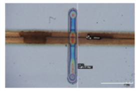
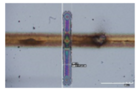
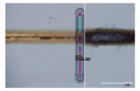
Zoom in:



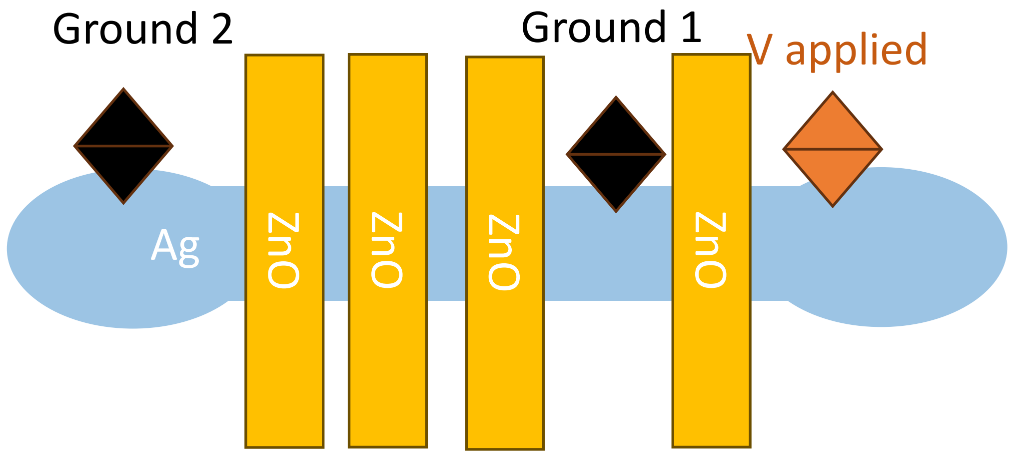
Center PDMS line on the top of silver

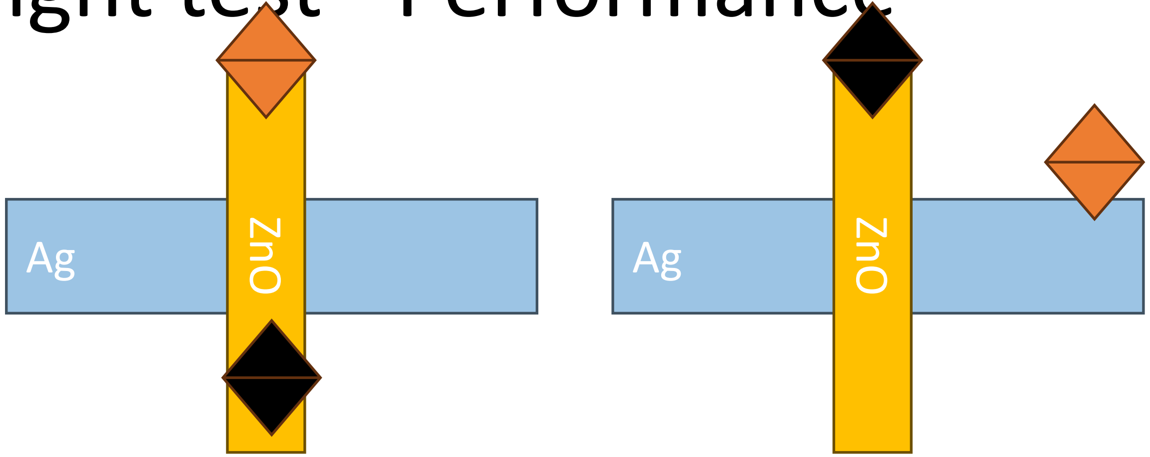
Result:

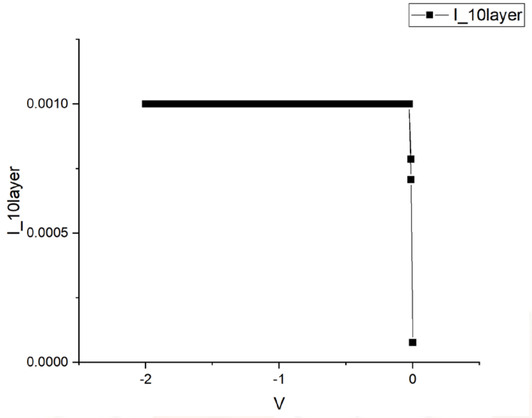
6 PDMS patterns printed with good centering.

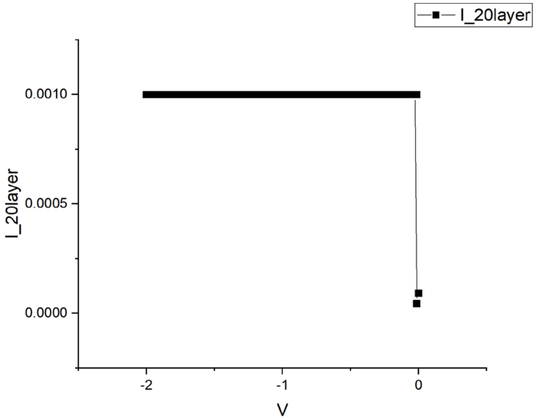
Parabola #	Parabola 11 (A)	Parabola 11 (B)	Parabola 12 (A)	Parabola 12 (B)	Parabola 13 (A)	Parabola 13 (B)
Camera Shots						
Printed Pattern						
Voltage (Pulse)	1300 V	1300 V	1300-1400 V	1300-1400 V	1400 V	1400 V
Frequency (Hz)	200 Hz	200 Hz	200 Hz	200 Hz	200 Hz	200 Hz
Duty Ratio (%)	60%	60%	60%	60%	60%	60%
Nozzle size	28 µm	28 µm	28 µm	28 µm	28 µm	28 µm
Printing Speed (x-stage movement)	1	1	1	1	1	1
Standoff distance (with respect to nozzle size in the screen)	x3.75	x3.75	x3.75	x3.75	x3.75	x3.75
Quality	Thin Line	Thin Line	Thin Line	Good	Good	Good

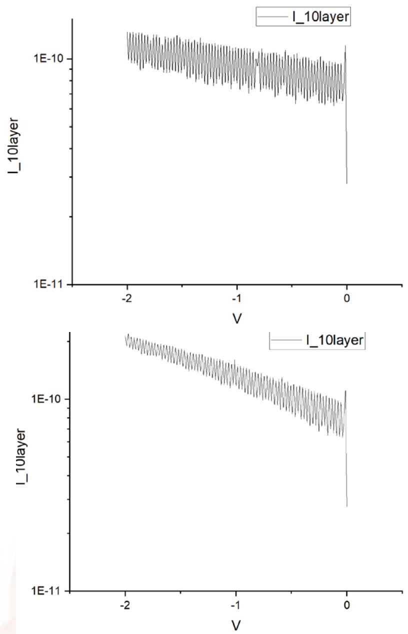
Results of most recent 0-g flight test - Performance











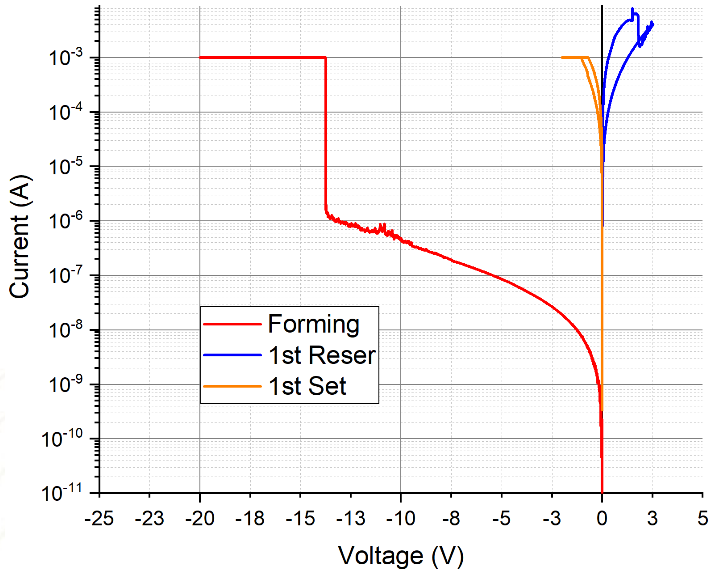
Semiconductor
Industrial standard
Probe S200

- Identical conductivity on Ground 1 and 2, Reach CCL in mV region, not affect by parasitic resistance → **Good conductive Ag**
- Low initial current of ZnO (1E-10 @0.1 V)

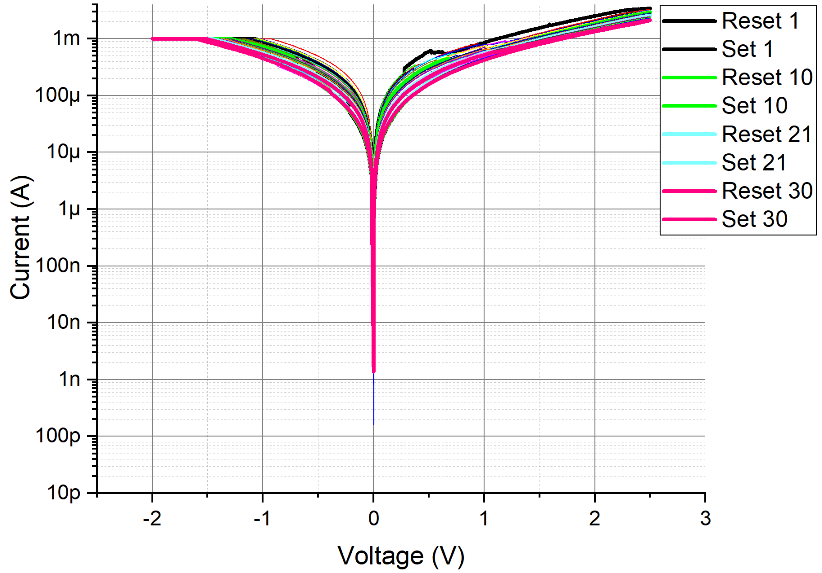
→ **Good switching layer**

Optimized RRAM Programming Algorithms for Semiconductor Storage Technology

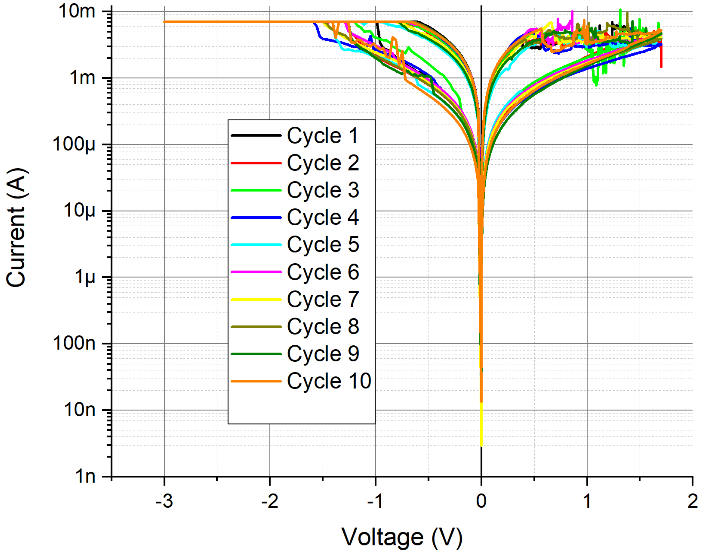
- Comparable low switching voltage to current on-ground cleanroom fabricated memory with simple fabrication and cost
- Good switching yield (Writing “1”: 60% yield; Writing “0”: 50% yield; Writing “1”: 40% yield)
- After optimized algorithms, improved switching reliabilities to multicycle operations → For both AI computing and semiconductor memory storage.



1.Initial forming, 1st RESET, 1st SET (1 mA)

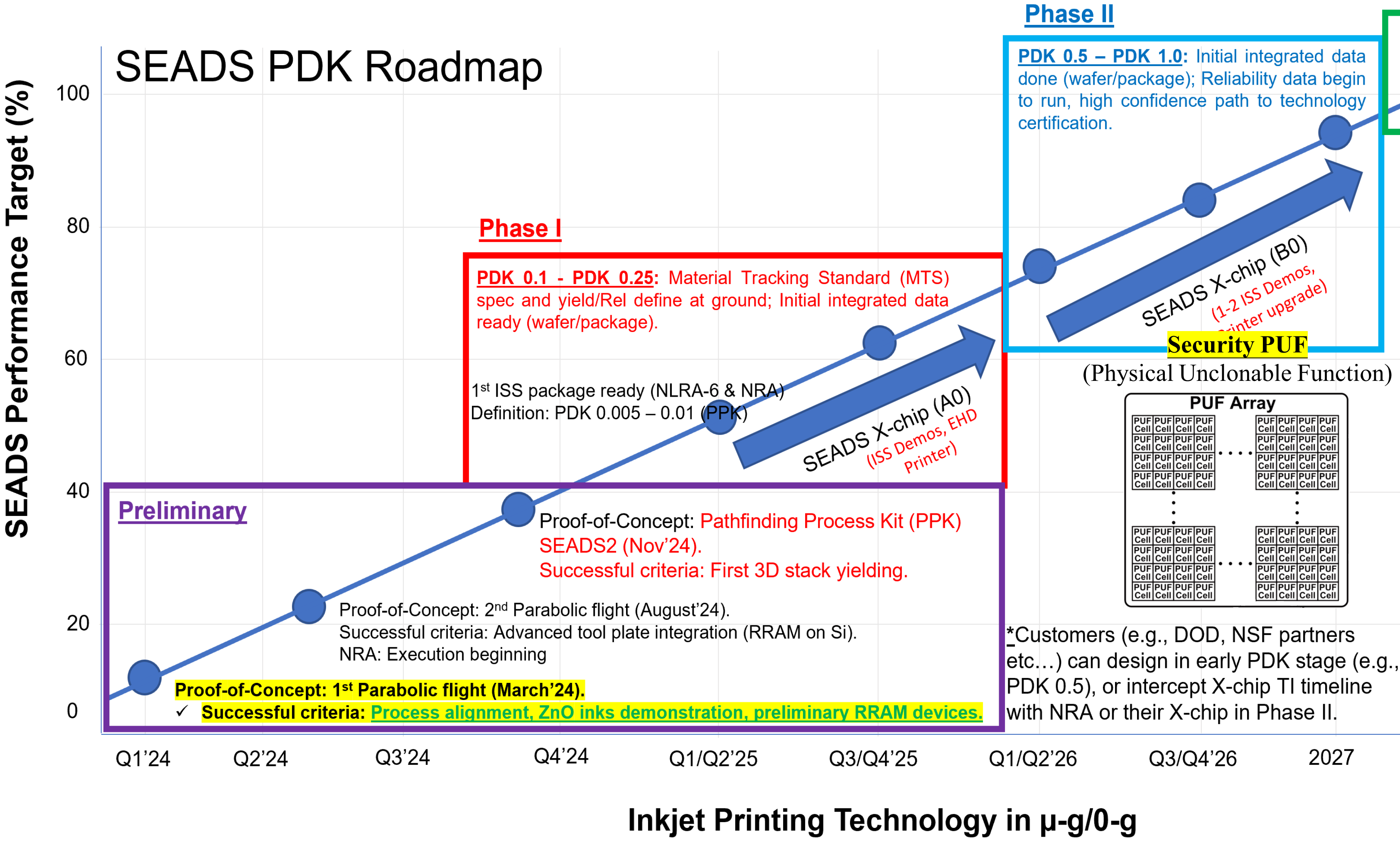


2. Cycling at SET CCL of 1 mA (30 seasoning cycles)



3. Increase SET CCL to 10 mA, successful 10 cycles (good repeatability, reasonable range of variation)

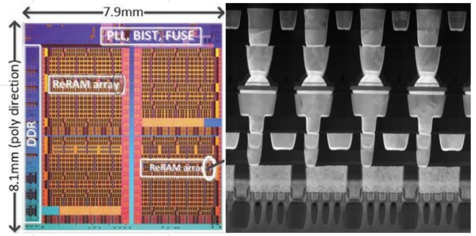
Objectives: SEADS Process Design Kit (PDK) Roadmap



Phase III

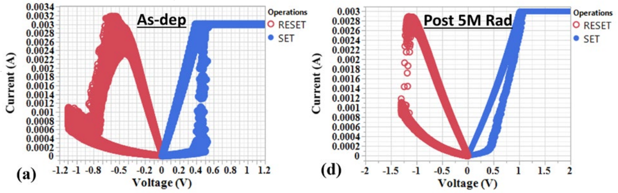
Risk Production/Volume Production (RP/VP): Reliability goal met, HVM quality systems ready; 1st Product TI.

Intel – Embedded RRAM



Security PUF
(Physical Unclonable Function)

Advanced Next Generation Strategic **Radiation hardened Memory** (ANGSTRM)



Memristor-Based Artificial Chips

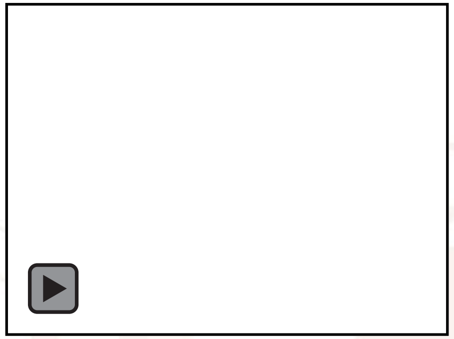
Current effort on **AI-aided** In-space Manufacturing

1. **Autonomous EHD printing** – development of AI and machine learning algorithms for image processing, control and decision-making
2. **Materials development** – a thorough material database to be used for various applications
3. **Device design, fabrication, and testing**
4. **Commercialization and contribution to Low Earth Orbit Economy**
   - Intel, Chips Act, SBIR, STTR, etc.
5. **Education and workforce development**

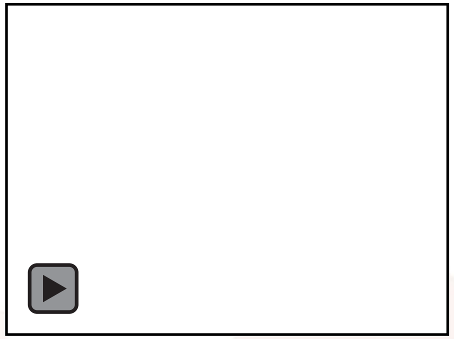
Current Achievements

Working towards real-time in-situ monitoring and decision-making

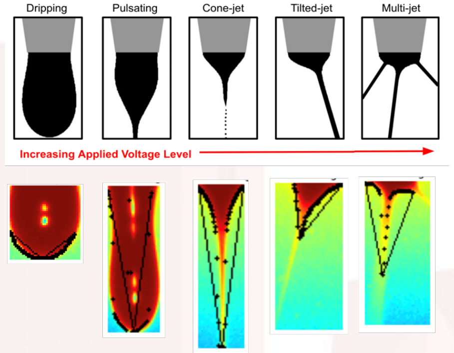
Video-1



Video-2



Stable Printing vs. Unstable Printing
(data are out of pre-set quality boundaries)



Machine vision and machine-learning algorithms for printing conditions

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NASA Award No. 80NSSC21M0360

NASA Award No. 80NSSC20M0107

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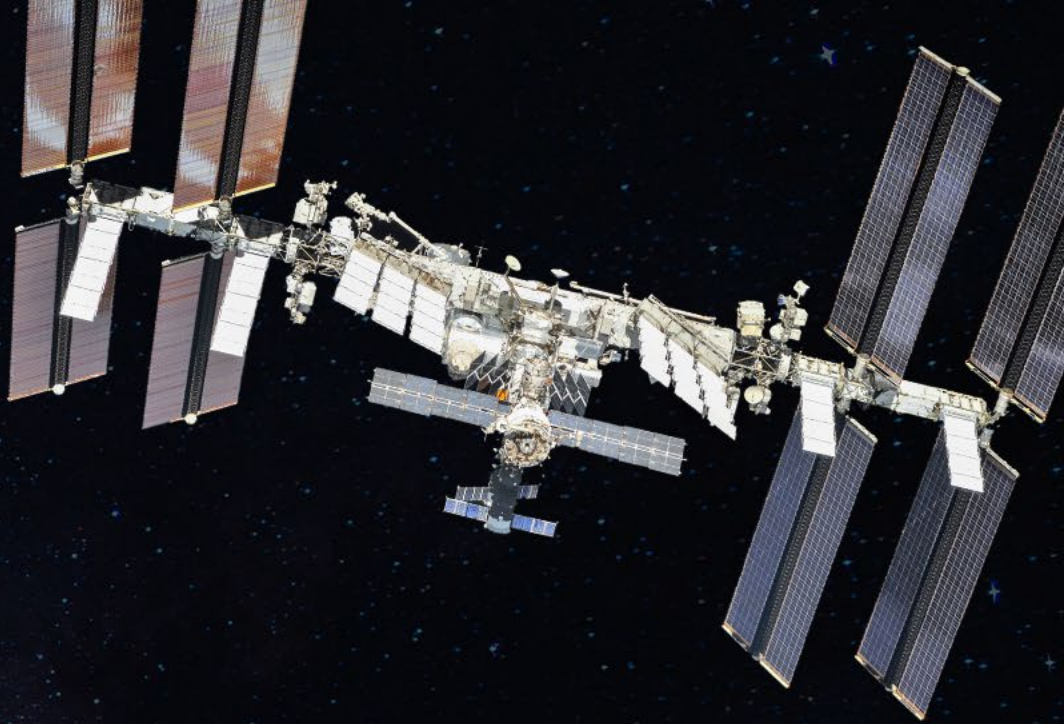

Q&A?