SAND2022-9758C

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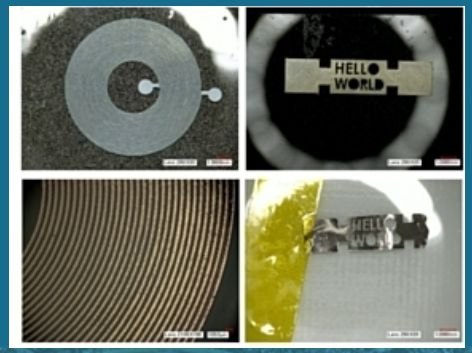
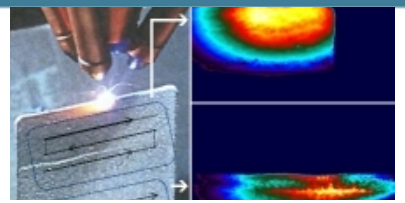
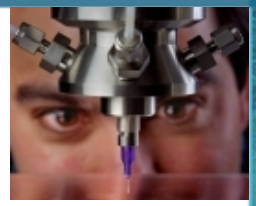
Assessing Aerosol Jet Printed Gold Inks for Printed Electronics Applications







Yongkun Sui, Lok-kun Tsui, Chowdary R. Koripella, Andrew Sanford, and Judith M. Lavin

7/25/2022

Solid-freeform Fabrication Symposium

U.S. DEPARTMENT OF ENERGY NNSA

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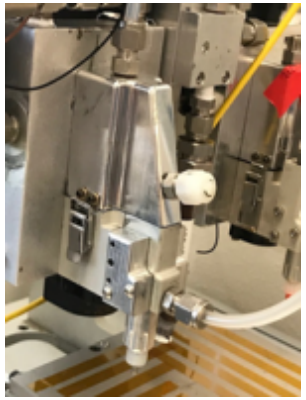
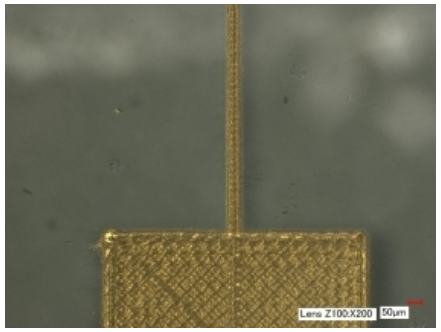
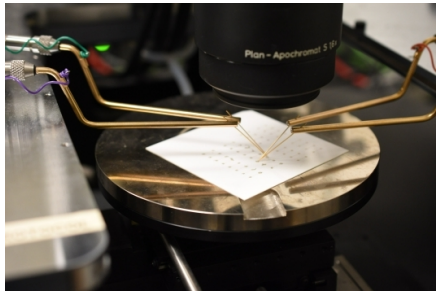
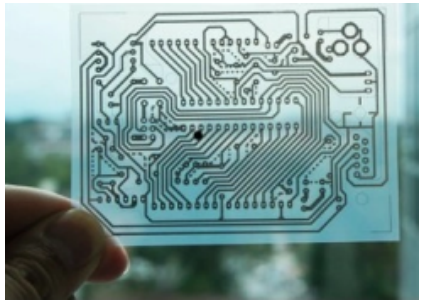
Outline

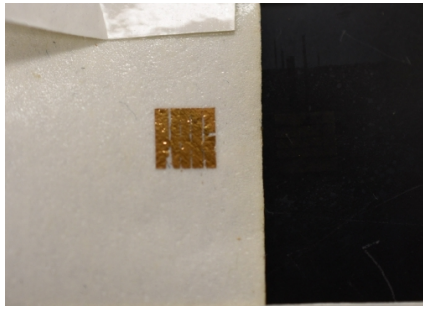






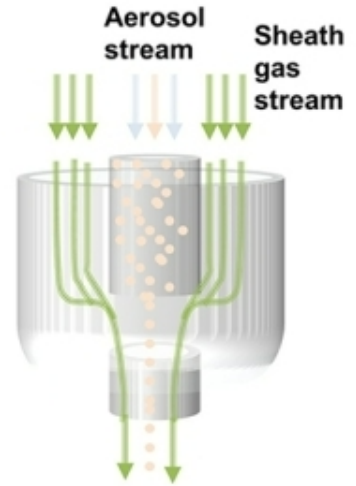
- Brief overview of aerosol-jet printing
- Applications of printed gold
- Printing quality optimization
- Thermal sintering
- Conductivity measurement
- Adhesion test
- Summary and conclusion



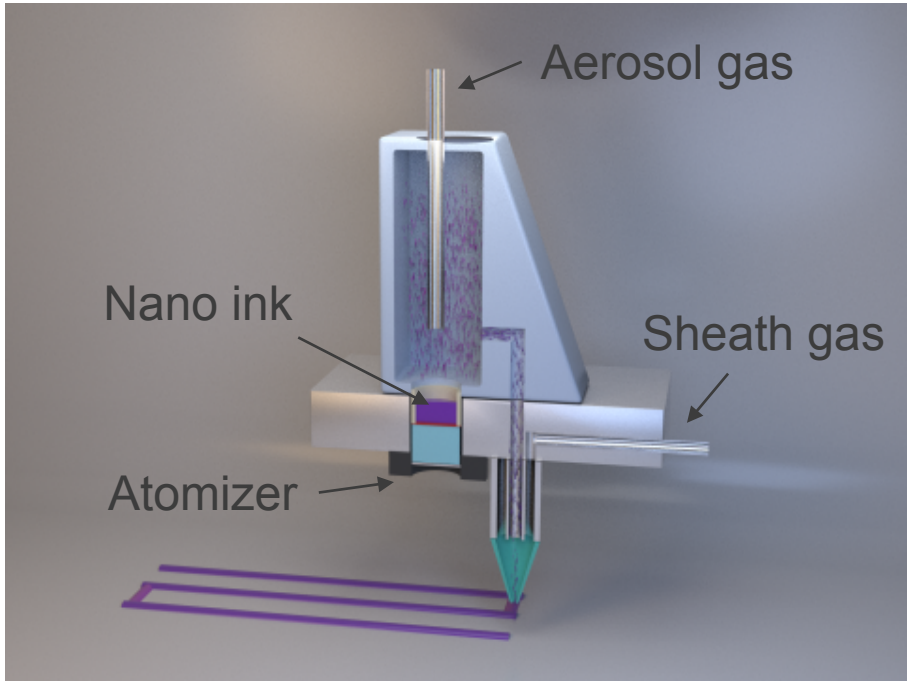


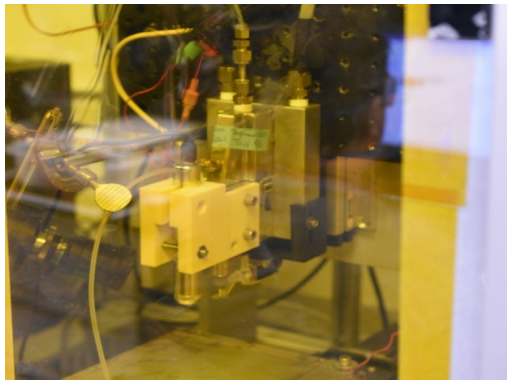
What is Aerosol-Jet Printing?

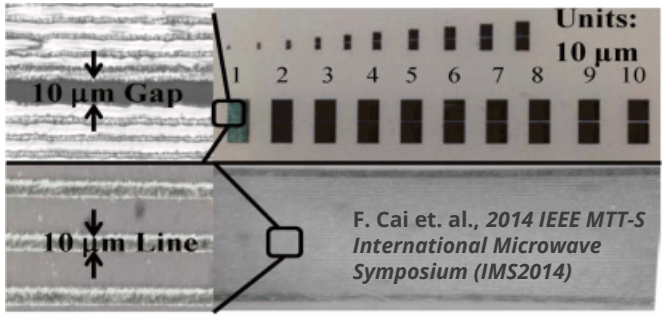
- Use **aerodynamic focusing** to precisely and accurately deposit electronic inks onto substrates
- The ink is placed into a vial; ink mist generated through **ultrasonic atomization**
- The aerosol mist is then carried by the **aerosol gas** to the print head where it is focused by a **sheath gas**
- Advantages: high-resolution, non-contact, rapid-prototyping



MAS.865 2018 How to Make Something that Makes (almost) Anything, MIT







F. Cai et. al., *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*

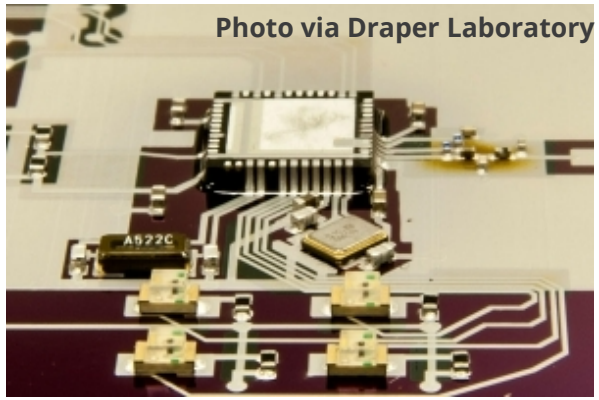
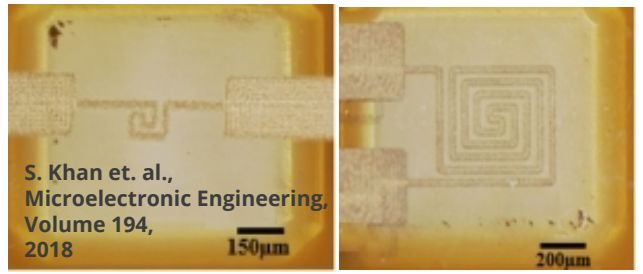


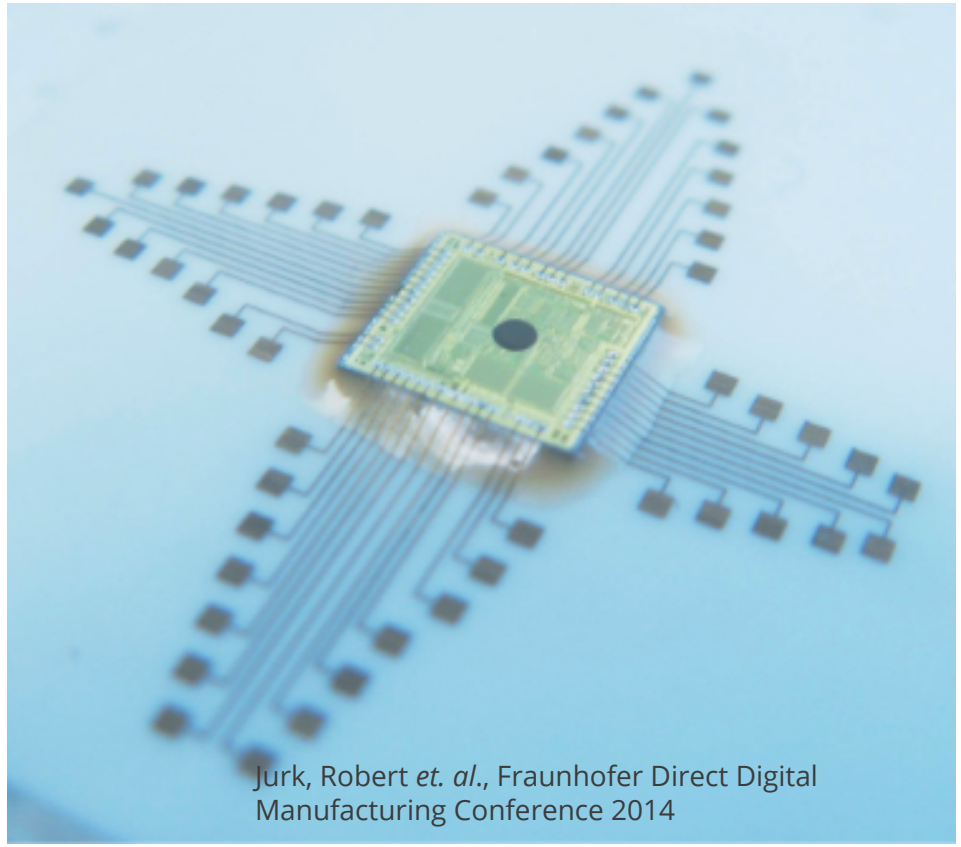
Photo via Draper Laboratory



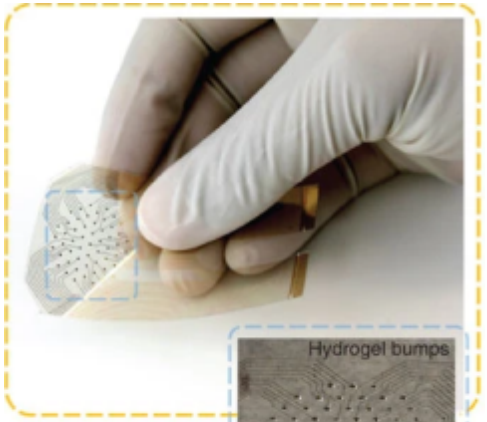
S. Khan et. al., Microelectronic Engineering, Volume 194, 2018

Printed Gold Applications

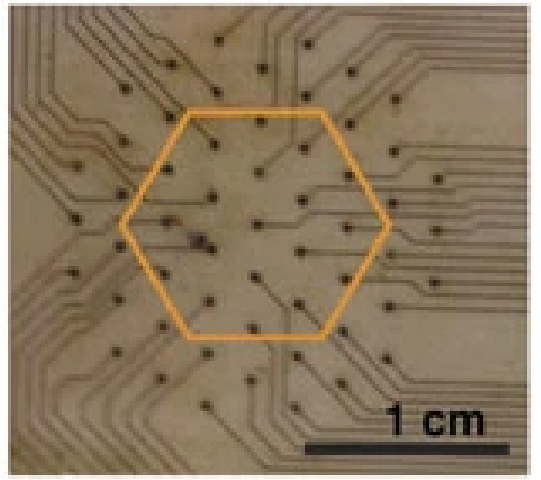
- Silver is the most popular material for printed electronics
- Advantages of gold compared to silver
  - **Chemical inertness**, more suitable for harsh environment applications
  - **Biocompatibility**, medical applications

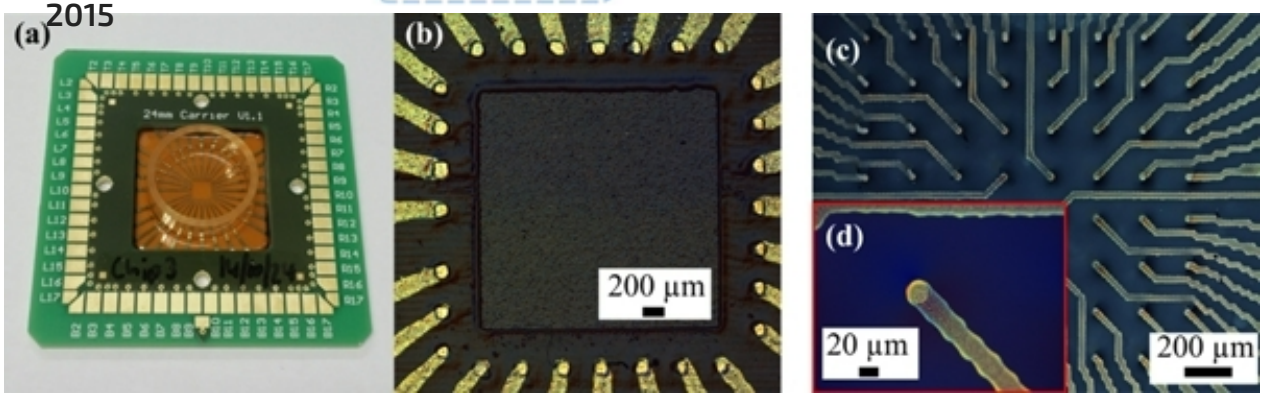


Jurk, Robert *et. al.*, Fraunhofer Direct Digital Manufacturing Conference 2014



Swisher, S. *et. al.*, *Nature Communication* **6,** 6575, 2015





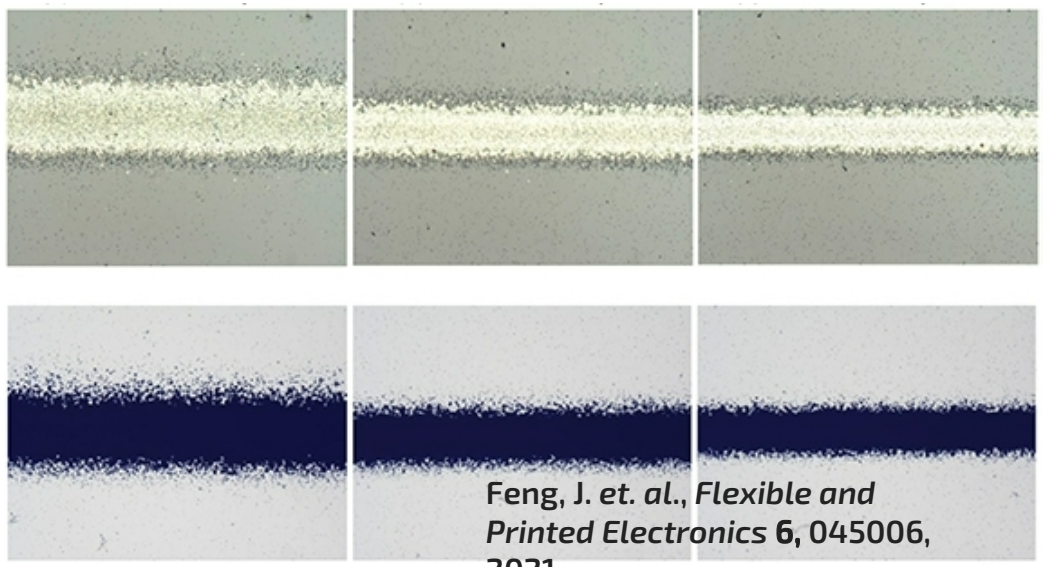
Bachmann *et. al.*, Flexible and Printed Electronics, 2017

Ink Candidates

	UTDots Au40X	UTDots Au25X	NovaCentrix 25% Au
Solvent	Xylenes	Xylenes	Water
Loading (w/v)	40%	25%	25%
Dilution (v/v)	ink:xylenes:terpineol = 2:2:1	ink:xylenes:terpineol = 10:2:1	ink:water = 2:1
Loading after dilution	16.0%	19.2%	16.7%

Parameters to consider:

- Line and infill resolution
- Overspray
- Conductivity
- Stability
- Adhesion (ASTM D3359-17)

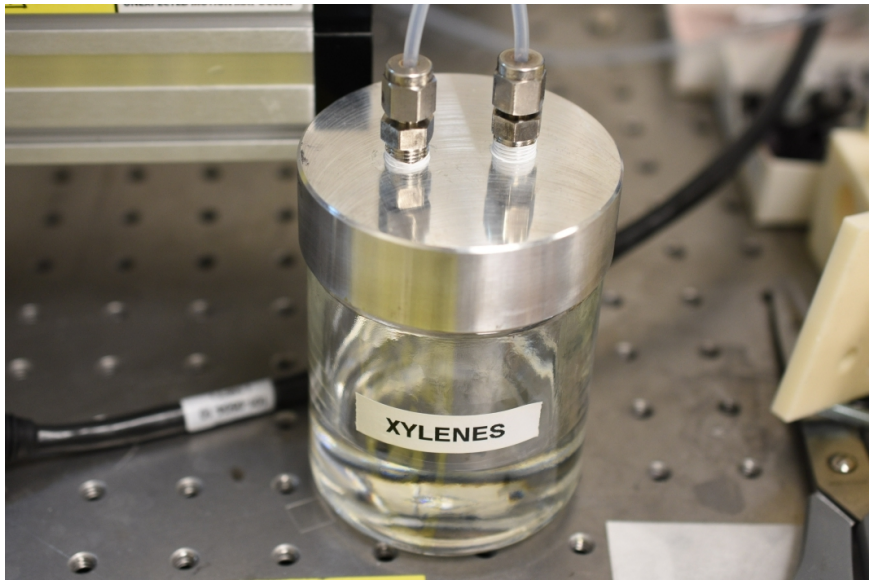


Feng, J. *et. al.*, *Flexible and Printed Electronics* **6**, 045006, 2021

Optimizing Print Quality

Three main parameters to tune:
- Atomization voltage
- Aerosol gas flow rate
- Sheath gas flow rate

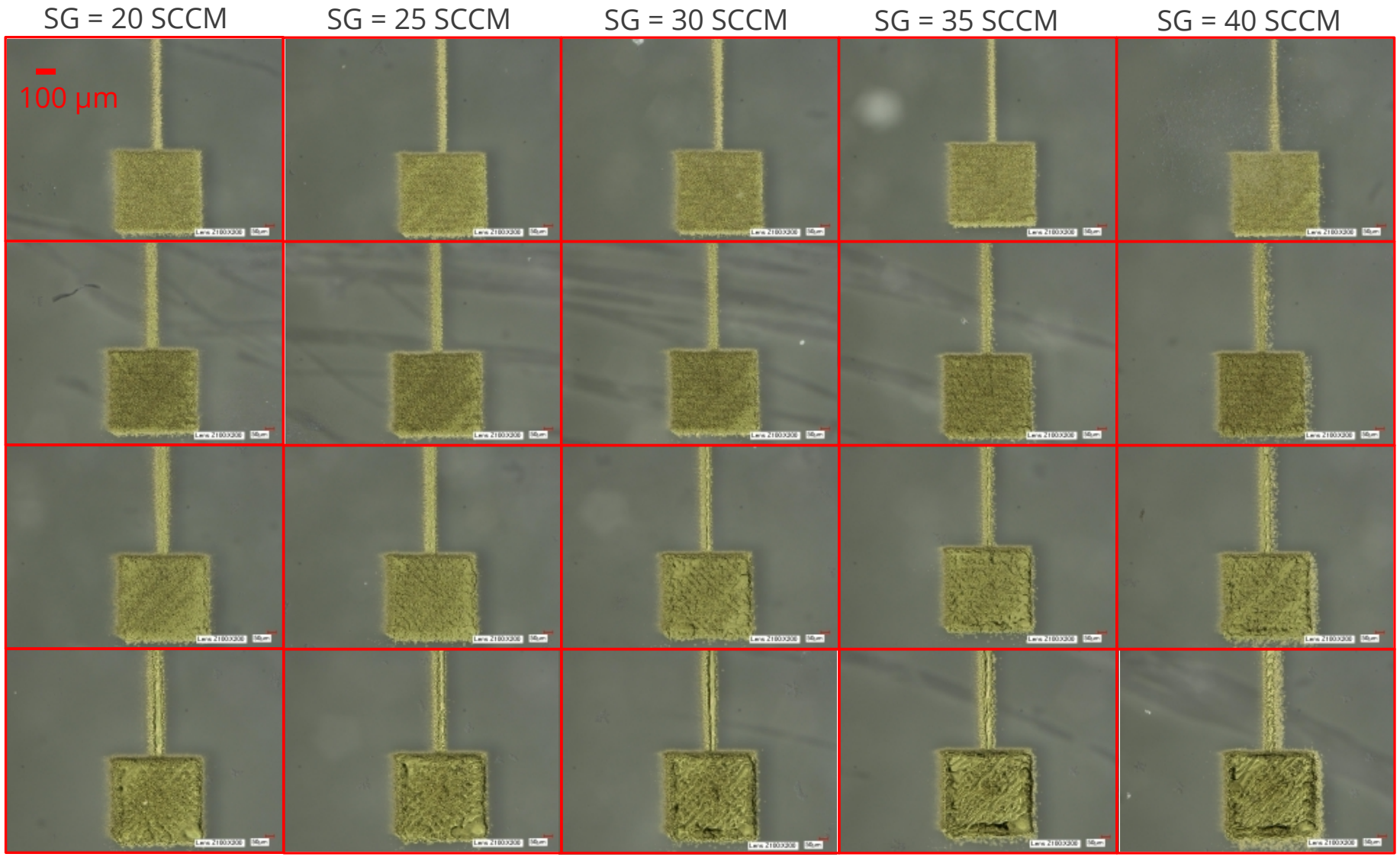
Fixed parameters:
- Printing platen temperature - 100 °C
- Printing speed - 300 mm/min
- Number of layers - 4 layers
- Nozzle orifice - 150 µm (Fisnar)
- Vapor jar
  - Xylenes for the xylenes-based inks
  - DI water for the water-based ink



Line and Pad Quality as a Function of Focusing Ratio

Focusing Ratio (FR) = SG/AG

UTDots Au25X, atomization voltage (AV) = 35 V

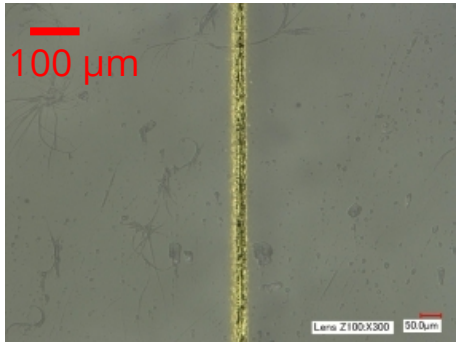


Line and Pad Quality with Optimized Print Conditions

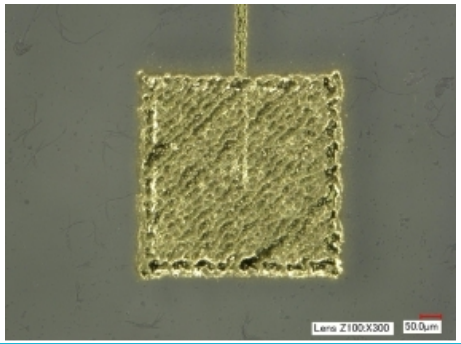
	AG range (SCCM)	SG range (SCCM)	AV range (V)
UTDots Au 40X	3-5	20-40	20
UTDots Au 25X	3-4.5	20-40	34-37
NC 25% Au	3-4	25-35	18.5-23.5

UTDots Au40X

- AG 3 SG 25 AV 20
- Slight overspray

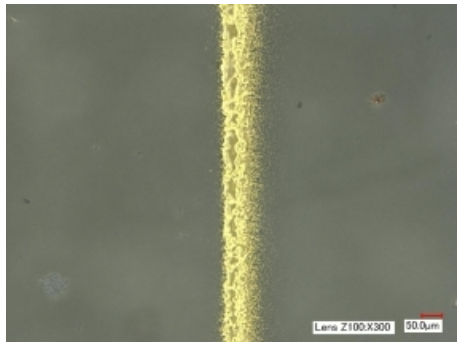


- Moderate overspray
- Rough texture

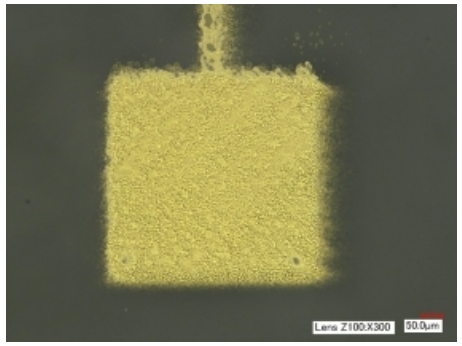


UTDots Au25X

- AG 4 SG 25 AV 35
- Severe overspray
- Line spreading

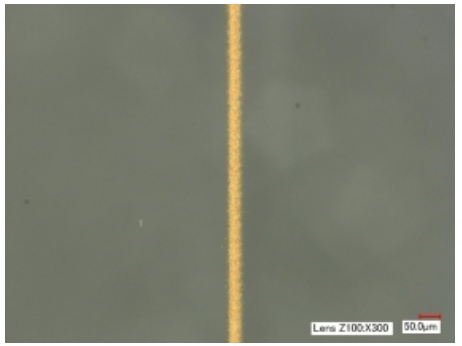


- Severe overspray

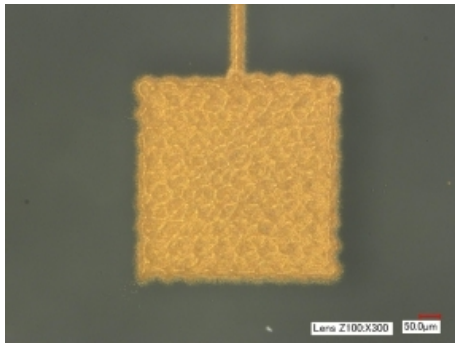


NC 25% Au

- AG 4 SG 35 AV 23.5
- Slight overspray



- Slight overspray
- Smooth texture



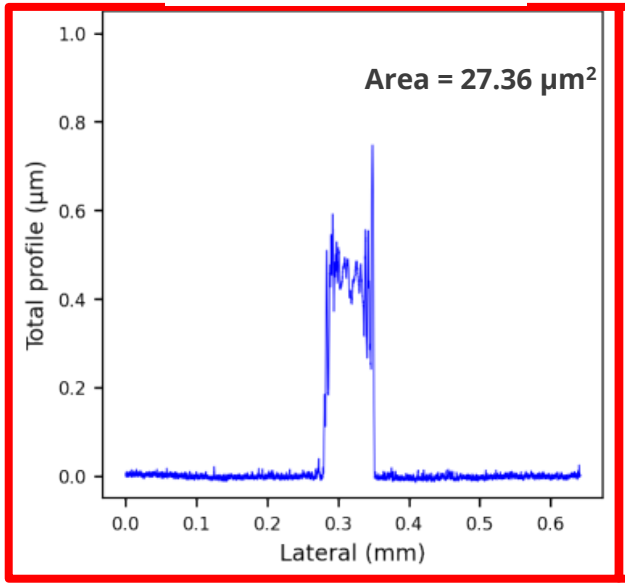
	UTDots Au 40X	UTDots Au 25X	NC Au 25%
Line quality	+	-	+
Pad quality	+	-	++

Profilometry

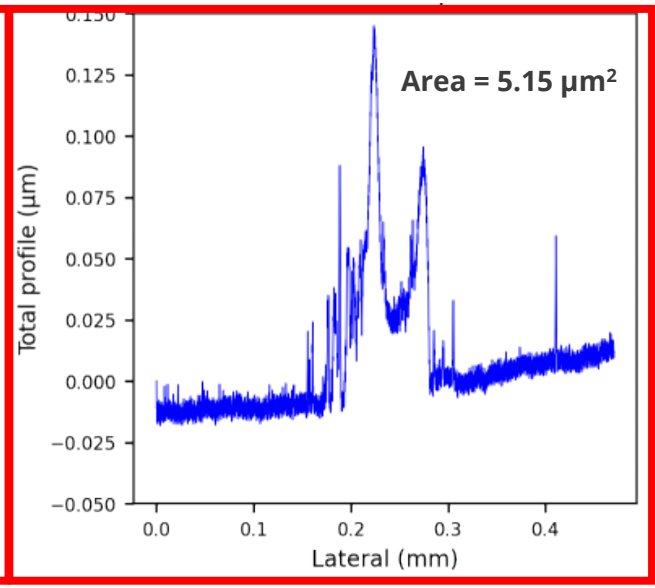
- Stylus profilometer (Bruker Dektak)
- 3 spots per line and 3 lines measured for each ink

	UTDots Au40X	UTDots Au25X	NC 25% Au
Avg. area (μm²)	27.1	5.2	19.1
Std. dev. Area (μm²)	1.2	0.3	5.8

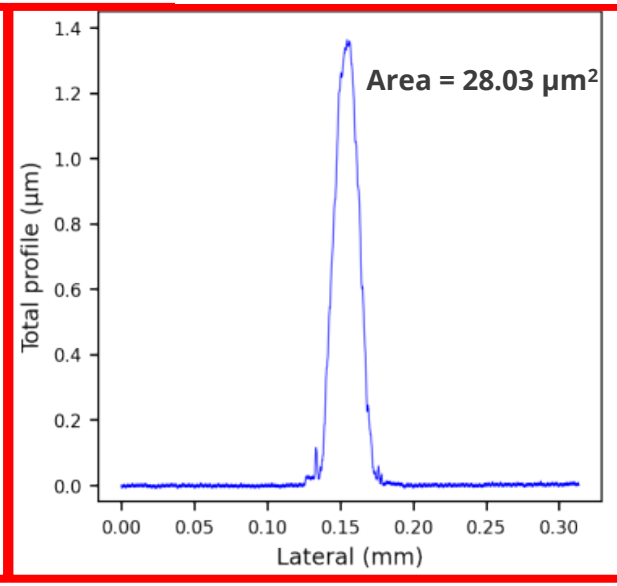
UTDots Au40X

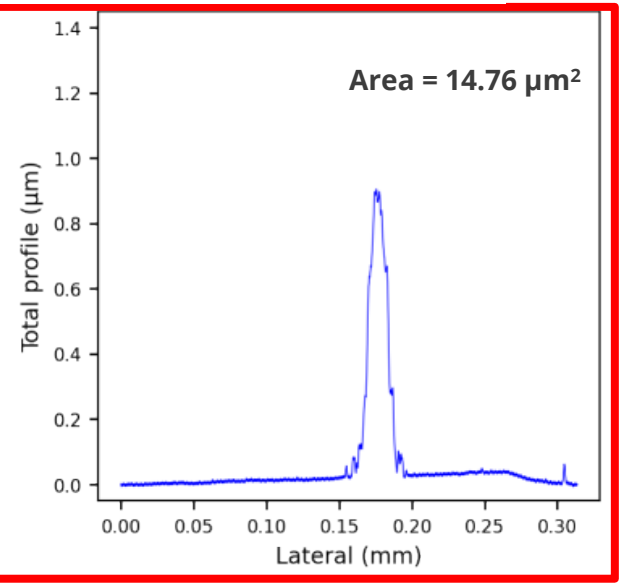


UTDots Au25X



NC 25% Au

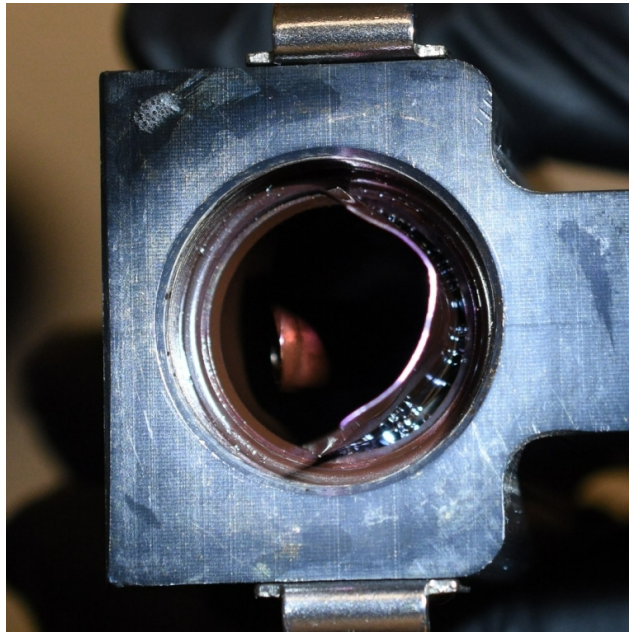




Ink Stability

- NC 25% Au has a low surface tension and foams after 10-15 min of continuous atomization
- UTDots Au25X was atomized at 35 V, which may have some instability issue

PEEK cartridge



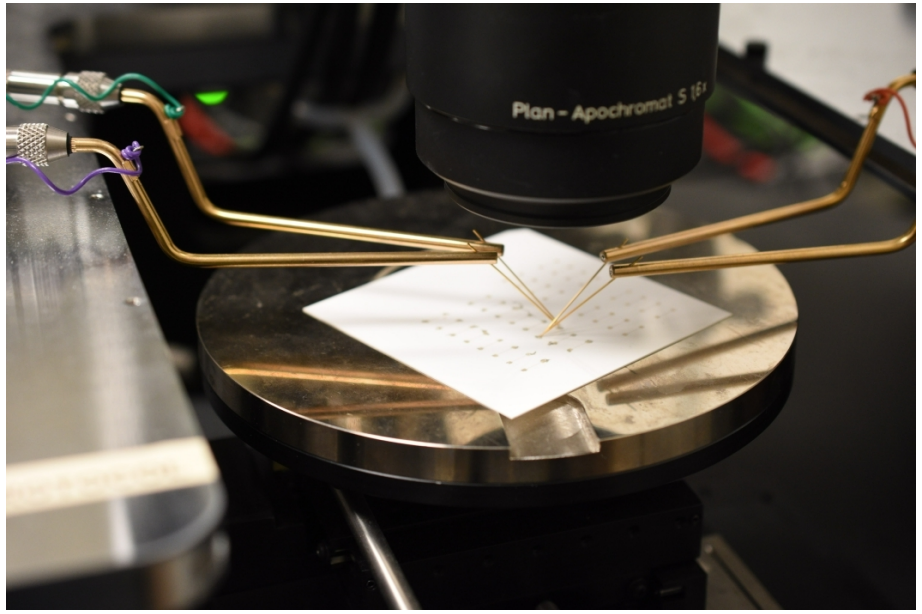
Ink vial

Metal cartridge

	UTDots Au 40X	UTDots Au 25X	NC Au 25%
Atomization stability	++	+	-

Electrical Conductivity Measurements

- Inks were thermally sintered 1 °C /min from ambient temperature to 300 °C, held at 300 °C for 3 hours, then cooled to ambient temperature
- Test setup: Keithley 2400 source meter; 4-wire connection; sourcing I and measuring V
- Silver epoxy applied to the gold pads, cured at 100 °C for 1 hour
- 4 mm lines



	UTDots Au40X	UTDots Au25X	NC Au 25%
Avg. Resistance (Ω)	10.4	90.4	16.4
Std. dev. Resistance (Ω)	0.5	9.0	4.5
Resistivity (mΩ·μm)	71.5	128.8	78.3
x bulk Au resistivity	3.3 x	5.8 x	3.6 x
% bulk Au conductivity	**30.8%**	**17.1%**	**28.1%**

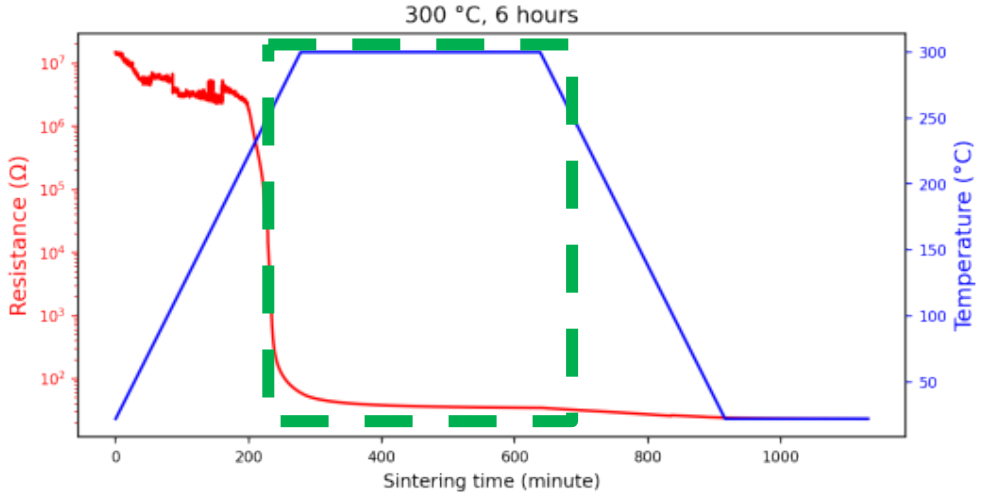
Performance Comparison

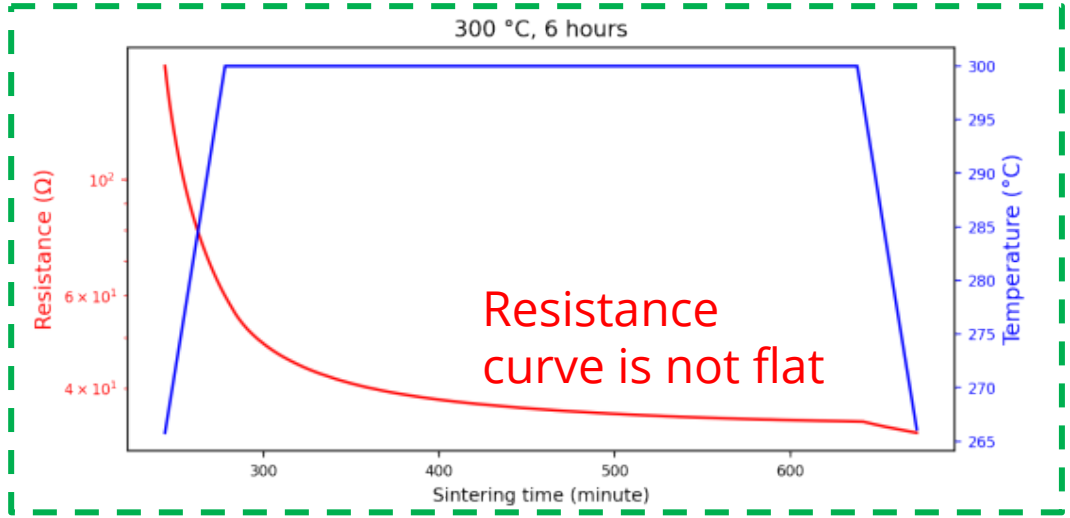
- UTDots Au40X showed the best performance
- Test data collected on *ultrasonic atomization*-based aerosol jet printers

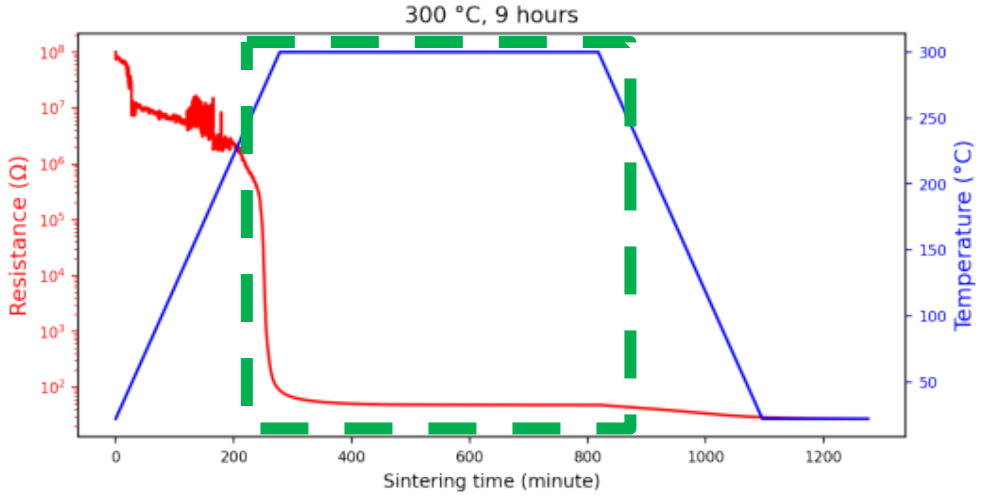
	UTDots Au40X	UTDots Au25X	NC Au 25%
Line resolution	+	-	+
Infill quality	+	-	++
Deposition rate stability	++	+	-
Atomization stability	++	+	-
% bulk Au conductivity	30.8%	17.1%	28.1%
Price (per gram of Au)	$446	$466	$571
Shelf-life	3 months	3 months	2 weeks
Storage condition	Ambient	Ambient	Fridge

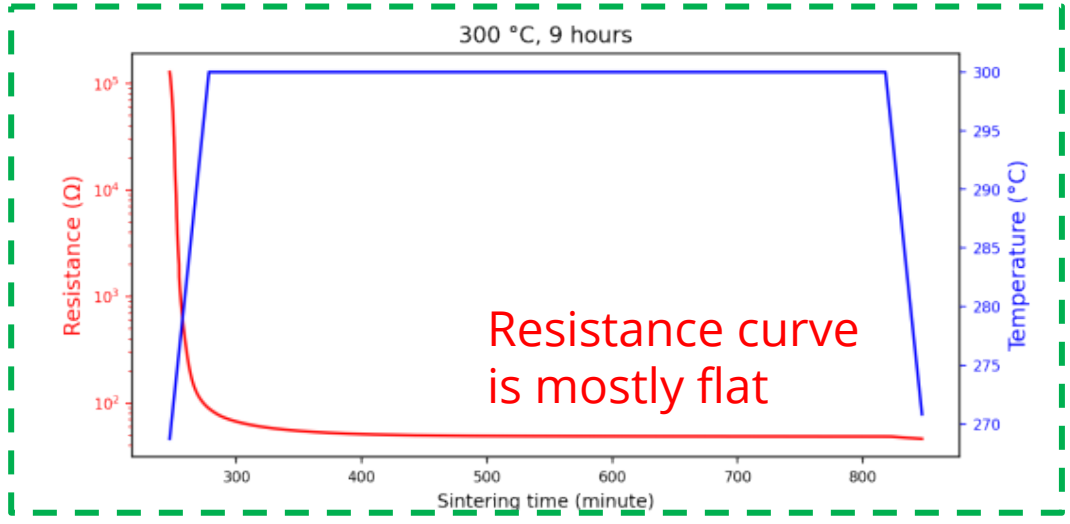
In-situ Resistance Monitoring while Sintering

- Sintering for 6 and 9 hours at 300 °C
- Final resistivity 0.050 Ω·µm after 9 hours at 300 °C
- 44% bulk Au conductivity





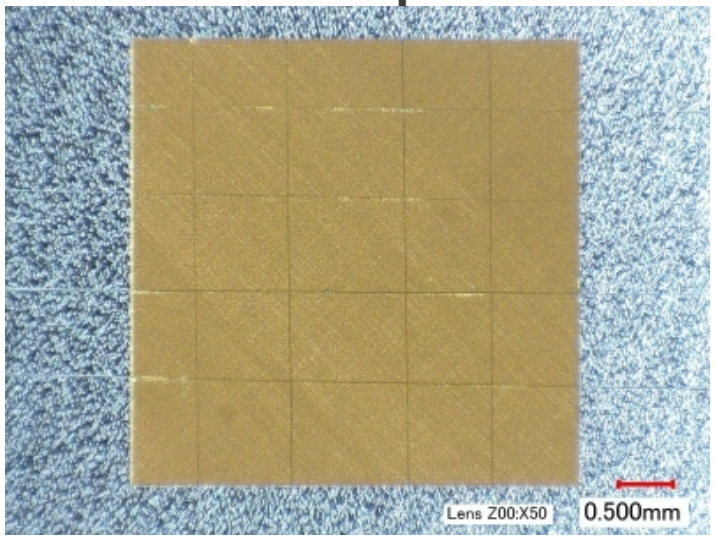




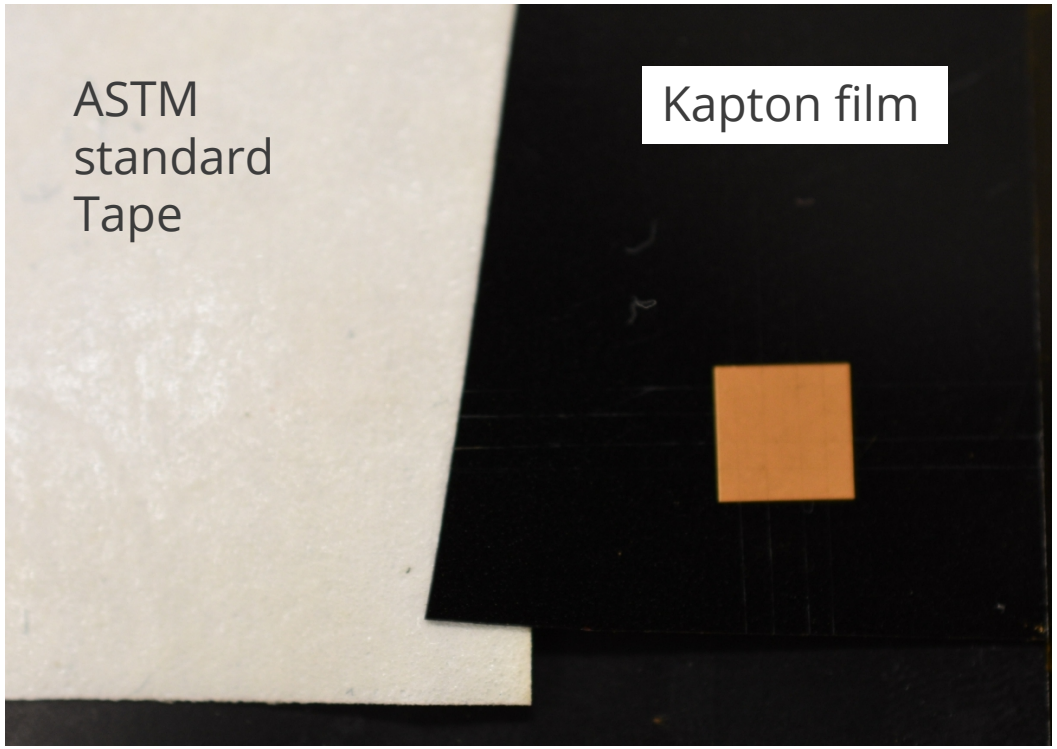
Adhesion Test

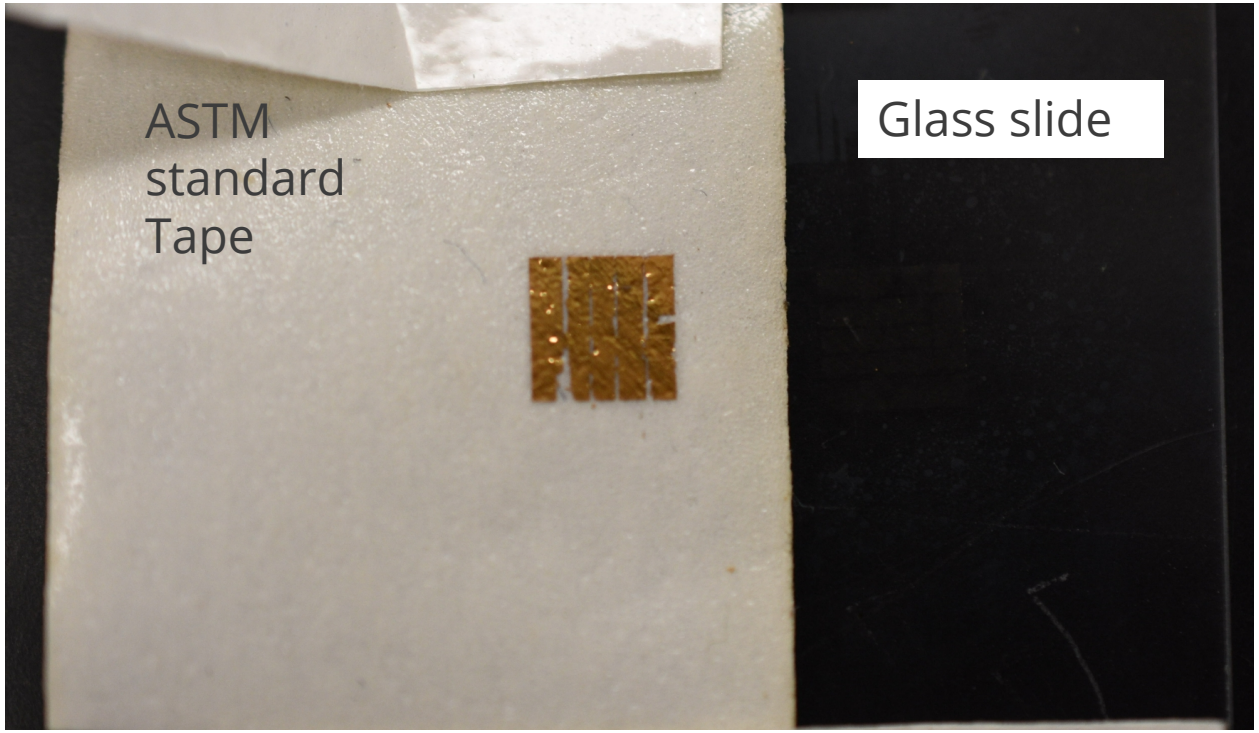
- ASTM D3359-17
- Printed Au pad cross-cut
- Rating 5B for printing on Kapton film
- Rating 0B for printing on glass slide

Before Tape Test



Post Tape Test





Conclusion

- UTDots Au40X out of the three inks has the best overall performance for ultrasonic atomization-based aerosol jet printing
  - High resolution (~30 μm line width)
  - Good stability and long shelf life
  - High electrical conductivity
- 44% bulk Au conductivity after sintering at 300 °C for 9 hours
- A promising technique for making interconnects, high-frequency circuits, etc. at chip level, especially for harsh environment applications

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