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Article

Keywords:

Posted Date: September 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10807879/v1>

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Additional Declarations: No competing interests reported.

Laser Sintering Gold Platinum Conductivity Sensors for Water Reclamation Processes in Space

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1. Abstract

Sustaining life outside our atmosphere has been of interest for some time. Astronauts can live in outer space for six to twelve months at a time; however, sustaining life in space long-term requires extending this timeframe. A major process that allows extended time in space is water reclamation. Water supply is limited due to human demand, the cost of supply missions, and rocket payload capacities; therefore, recycling and reusing water is essential. This work focuses on additive manufacturing of liquid conductivity sensors for use in water reclamation processes in Environmental Control and Life Support Systems. The sensor uses a direct ink write printer to make ink deposition viable under microgravity conditions. This work investigates laser sintering to achieve connectivity and conductivity in gold-platinum-palladium printed ink, reducing power consumption and space for in-space manufacturing. The laser investigated is a 445 nm fiber-coupled diode laser. The sensor substrate is alumina, and the ink contains gold, platinum, and palladium particles for their conductive properties and robustness in harsh environments. The sensors are laser-sintered using various laser powers, scanning speeds, and beam diameters, and then tested for conductivity while submerged in a standard conductivity solution. These results demonstrate a pathway to autonomous, on-demand sensor fabrication for long-duration space missions.

2. Introduction

The National Aeronautics and Space Administration's (NASA) current vision, with Artemis and the Moon-to-Mars architecture, has created an urgent need for manufacturing techniques that transition from Earth-dependent supply chains to autonomous in-space manufacturing (ISM). One of the critical technologies for deep space exploration is the Environmental Control and Life Support System (ECLSS), which maintains, manages, and recovers resources on the International Space Station (ISS) to support human life. One major domain of ECLSS is water recovery, in which wastewater, such as urine, is purified and recycled into the water supply. The water supply is limited since supply missions are costly and humans need ample water to survive.

The primary parameter in current water monitoring techniques in space is conductivity. Additional sensors such as voltammetric, temperature, dissolved oxygen, pH, redox potential, and turbidity sensors [2-4] are also used for general water monitoring on Earth; however, conductivity sensors are used in space because of their simplicity. Urine contains high levels of dissolved salts, making it highly conductive compared to purified water; urine typically has a conductivity of 15–20 mS/cm [5], whereas potable water has a conductivity range of 10–800 μ S/cm [6]. More specifically, conductivity sensors ensure that sufficient pretreatment acid is used for each urine purification event. However, the chemical pretreatment used in the water reclamation process on the ISS, such as chromic and phosphoric acid, is extremely corrosive and can rapidly destroy sensors. Therefore, a sensor is needed that can withstand the solution and be replaced quickly. Technology is needed to create sensors with ISM constraints in mind, such as gravitational and payload limitations, while achieving rapid production.

To achieve these goals, our previous work [7, 8] investigated direct ink write (DIW) and electrohydrodynamic (EHD) inkjet printing as additive manufacturing technologies for printed electronics (PE), using silver-palladium (AgPd) and silver (Ag) as conductive materials. DIW and EHD printing are practical for ISM, given the gravitational constraints. Neither technique relies on gravity to deposit ink: DIW uses mechanical pressure to push ink through a nozzle onto a substrate [9], and EHD applies a voltage difference between the nozzle and the substrate, drawing ink directly from the nozzle to the substrate using an electric field [10, 11]. Additionally, laser sintering is used because of its high feature selectivity and sintering capabilities [12-14]. EHD-printed Ag was laser-sintered under microgravity and lunar-gravity conditions, demonstrating the technique's viability for ISM [8]. However, DIW printing is better suited for conductivity sensors because of its larger feature size. In comparison, EHD printing achieves sub-micron resolution widths, whereas DIW can achieve up to hundreds of microns in a single pass. The conductivity sensors are about 5 mm wide and 15 mm long.

In our previous work, DIW-printed AgPd nanoparticle (NP) and terpeneol solvent ink on an alumina substrate were tested for conductivity sensor fabrication for on-demand manufacturing of electronics (ODME) in space [7]. The sensor design comprised three electrodes, whose ends were rounded toward each other but did not touch, forming a probe submerged in the solution. The laser sintering parameters were investigated using a variety of laser systems with wavelengths including continuous-wave (CW) 445 nm, 808 nm, 915 nm, and 1064 nm, as well as femtosecond-pulsed 1040 nm. Laser sintering proved to be a viable alternative to conventional furnace sintering, reducing power consumption and producing the AgPd film required for the conductivity sensors. Laser-sintered AgPd using a 445 nm laser achieved a conductivity of approximately 9×10^5 S/m, whereas furnace-sintered AgPd at 850 °C for 60 min comparatively achieved 2.8×10^6 S/m [7]. However, the experimentation encountered system limitations due to the 445 nm laser's maximum output power of 6 W [7].

Unfortunately, after experimentation, AgPd was found unsuitable for the ODME device. When subjected to a solution of pretreated urine mix containing chromic and phosphoric acid, urea, added amino acids, water, and added salts to mimic astronaut urine (e.g., CaCl_2 , KH_2PO_4 , and Na_2SO_4), a corrosion layer formed, preventing sensor-fluid contact. This is hypothesized to result from weakening of the Ag-Pd bonds under the oxidizing conditions of the chromic acid, causing water-soluble PdSO_4 to form from AgPd and Na_2SO_4 . The Ag was then free to react with the chlorine to form solidified AgCl on the probes. NASA Marshall Space Flight Center (MSFC) determined that gold-platinum (AuPt) was preferred over AgPd because of its higher corrosion resistance. This work builds upon the AgPd laser sintering results to develop a DIW-printed and laser-sintered conductivity sensor made from AuPt (containing <5% palladium). AuPt has the same Technical Data Sheet (TDS) drying and sintering parameters as AgPd: 150 °C for 15 min and 850 °C for 60 min, respectively. This work builds on the laser sintering parameters used for AgPd [7] and uses a 445 nm laser to sinter AuPt ink lines and sensors at varying laser power, scanning speeds, and beam spot sizes to improve connectivity and adhesion to the alumina. In addition, the 445 nm laser system in this work delivers up to 30 W of output power; however, 12 W is sufficient for this study. NASA MSFC personnel designed the sensors, while our team at Oregon State University (OSU) conducted the laser sintering trials. In addition to laser sintering, the samples are initially dried to test whether the sensor can be dried with a laser, whether the TDS drying temperature is necessary, or whether a laser can replace this step. The printer planned for use in space for ISM is an nScript DIW printer, with a limited platen temperature of 100°C. Therefore, this work tests the drying parameters using either a furnace at 150°C for 15 min (the TDS recommendation), the V-One platen at 150°C for 15 min and 100°C for 15 min, or a defocused laser. An nScript printer is not available to print sensors for this study; however, a Voltera V-One DIW printer is available and used. Three sensor sets were tested in this work: the first set was printed using the V-One and has an average thickness of ~40 µm; the second set was printed

using the V-One and has an average thickness of $\sim 10\ \mu\text{m}$; and the last set was screen-printed and has an average thickness of $\sim 6\ \mu\text{m}$. Because of the three variations in sample thickness and drying conditions, the laser sintering parameters vary for each to achieve optimal adhesion and connectivity. Finally, the sensors are submerged in conductivity standard solutions to test their accuracy in measuring conductivity.

3. Methods

a. Sample Preparation

Three sensor thicknesses were tested in this work: the first set was printed using a Voltera V-One, pictured in Figure 1a, and has an average thickness of $\sim 40\ \mu\text{m}$; the second set was printed using the V-One and has an average thickness of $\sim 10\ \mu\text{m}$; and the last set was screen-printed at NASA MSFC and has an average thickness of $\sim 6\ \mu\text{m}$. The V-One-printed samples were dried using a platen and laser, while the screen-printed samples were furnace-dried. The V-One is designed to fabricate printed circuit boards with specific inks and substrates; however, it was used with the substrates and inks of choice for this research. Figure 1b shows the V-One printing AuPt ink on an alumina substrate through a 0.23 mm inner diameter nozzle. The nozzle is directly connected to an ink syringe and mechanically pressurized to extrude ink onto the substrate.

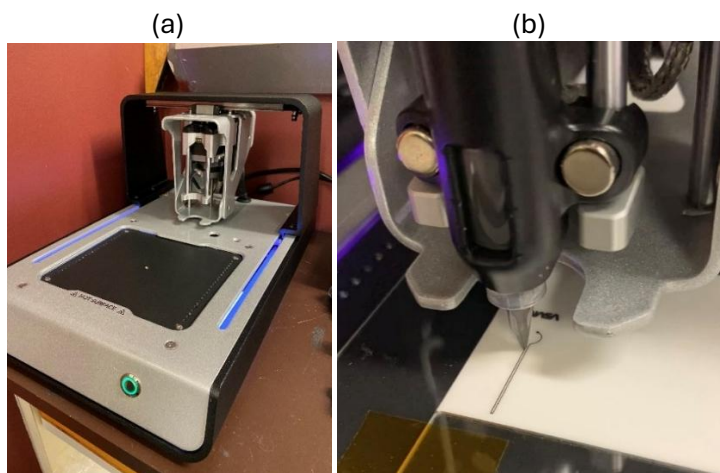


Figure 1. Pictures of the (a) Voltera V-One printer and (b) printing AuPt ink on alumina.

The AuPt ink was purchased from Insulectro (Micromax 4597R (formerly known as DuPont 4597R) with Micromax 9180R as the solvent (composition unknown) and solid content of gold 45 – 50 %, platinum 25 – 30 %, and palladium 2 – 5 %, for a total solid content of 80.1 – 81.4 %) and printed on alumina substrates. Figure 2(a) shows 15 mm AuPt lines on alumina used for preliminary laser sintering tests for the V-One samples. Figure 2(b) shows a V-One-printed sample with one AuPt sensor printed on alumina. Figure 2(c) shows a screen-printed sample with three sensors printed on an alumina substrate. The Voltera-printed and screen-printed sensors differed in overall thickness, which affects the required laser sintering parameters. Two sets of Voltera-printed sensors were tested. The first set of Voltera-printed sensors had an average thickness of $\sim 40\ \mu\text{m}$; however, to have a one-to-one comparison with the screen-printed sample, a second set with an average thickness of $\sim 10\ \mu\text{m}$ was printed. The screen-printed sensors had an average thickness of $\sim 6\ \mu\text{m}$.

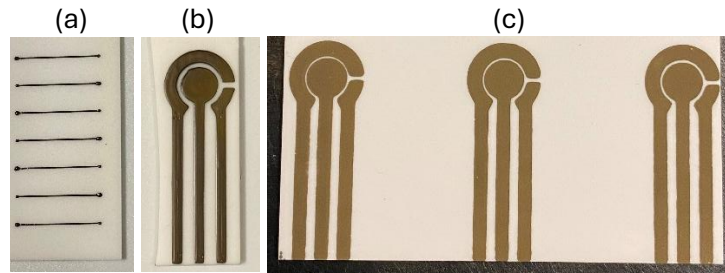


Figure 2. (a) V-One printed AuPt lines on alumina, (b) V-One printed conductivity sensors, and (c) furnace-dried conductivity sensors screen-printed at NASA MSFC.

b. Laser Sintering Experimental Setup

A CW 445-nm, fiber-coupled diode laser was used for laser sintering experiments. Figure 3 shows the laser sintering setup with the laser fiber input to a lens tube with XYZ stages beneath it. The lens tube contains a 20 mm focal-length lens to collimate the fiber output and a 15 mm focal-length lens to focus the laser on the sample. The focused beam spot diameter, approximately 11.75 mm from the lens tube, is 177 μm . The XYZ stages beneath the lens tube translate the sample beneath the laser beam. The Z-axis stage controls the distance between the sample and the laser output, thereby changing the beam spot size. The samples printed with the Voltera at OSU and at NASA MSFC were placed in the laser sintering setup for drying and sintering.

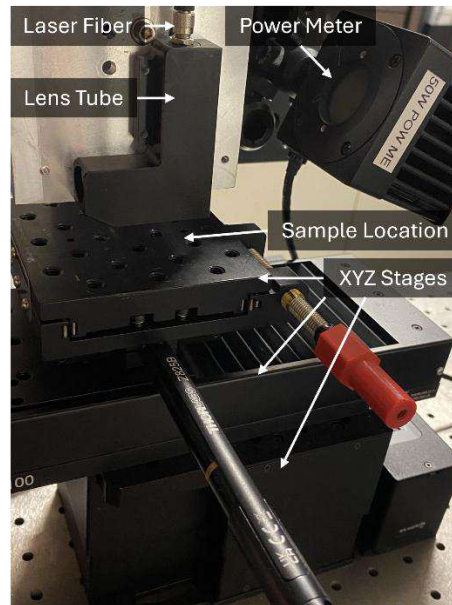


Figure 3. Picture of the laser sintering setup with components labeled.

The parameters in Table 1 were used to dry and sinter the sensors. The conventional methods outlined in the ink's TDS are 150 $^{\circ}\text{C}$ for 15 min for drying, and a 60 min cycle with a peak temperature of 850 $^{\circ}\text{C}$ for sintering. The sensors were dried at 100 $^{\circ}\text{C}$ due to the nScript's limited platen temperature. Therefore, four sintering methods were tested: 100 $^{\circ}\text{C}$ for 15 min; 100 $^{\circ}\text{C}$ for 15 min with a defocused 445 nm laser; 150 $^{\circ}\text{C}$ for 15 min; and a defocused 445 nm laser only. The screen-printed samples were furnace-dried at NASA MSFC and could not be tested with additional drying methods, but they were tested for laser-sintering capabilities.

Table 1: Printer used for the AuPt sensors, average thickness of the sensors, and the drying and sintering methods used.

Printer	Average Film Thickness (μm)	Drying Method	Sintering Method
V-One	40, 10	100°C 15 min	445 nm Laser
V-One	40, 10	100°C 15 min + 445 nm Laser	445 nm Laser
V-One	40, 10	150°C 15 min	445 nm Laser
V-One	40, 10	445 nm Laser	445 nm Laser
Screen	6	150°C 15 min	445 nm Laser

c. Characterization

The sensors were characterized using scanning electron microscopy (SEM) to examine their morphology before and after sintering. A stylus profilometer was used to measure the thickness of the printed films. A multimeter was used to measure the resistance of each of the three electrodes of each sensor, as well as each line. If films are non-conductive, they are labeled NC. The SEM images of the lines are paired with their laser parameters and resistances to compare the morphology between parameters. After drying or sintering the sensors, the parameters and sensor characteristics are summarized in a table format. The table cells are color-coded: green indicates conductive sensors with a uniform film; yellow indicates a non-uniform or non-conductive film; and red indicates sensors that are either conductive or non-conductive but have poor film quality. The sensors are characterized by their ability to measure conductivity when submerged in standard potassium chloride (KCl) solutions (Fisher Scientific) of varying conductivity. Equation 1 is used to calculate the probe conductivity, σ .

$$\sigma = \frac{K}{|Z|} \quad (1)$$

Where K is the probe constant, 0.4 cm^{-1} , found using the dimensions of the sensors, and Z is the complex impedance. Pins are soldered to the sensor electrodes and connected to an embedded device programmed in C to measure the complex impedance of the sensors. Variations in drying and sintering methods are tested for soldering performance. Successful soldering is determined by whether the pins remain attached to the sensor during handling and testing. Failed soldering is determined by whether the pins fall off or have inadequate connection, as determined by a multimeter voltage reading between the sensor and the pins. The sensors are submerged in conductivity standard solutions with conductivities of 84, 430, 600, 1,000, 10,000, 25,000, and 50,000 $\mu\text{S/cm}$.

4. Results

a. Screen-printed AuPt with 10 μm thickness

AgPd ink has the same baseline drying and sintering requirements as AuPt ink, as recommended by their technical data sheets. As a result, the laser sintering tests for AgPd from our previous work [7] are used as preliminary data to determine the laser sintering parameters for AuPt in this work. In summary, the laser sintering parameters ideal for achieving conductivity comparable to furnace-sintered samples were determined to be CW 445 nm, 0.5 mm/s, and 3 W. Figure 6 shows the different morphology and resistance between unsintered screen-printed AuPt samples provided by NASA MSFC and samples exposed to 3 W and 4 W at a 0.5 mm/s scanning speed using a focused

beam with a 177 μm diameter. Not only does the ink form continuity between NPs, but the resistance is reduced from 79 Ω to 2.5 Ω .

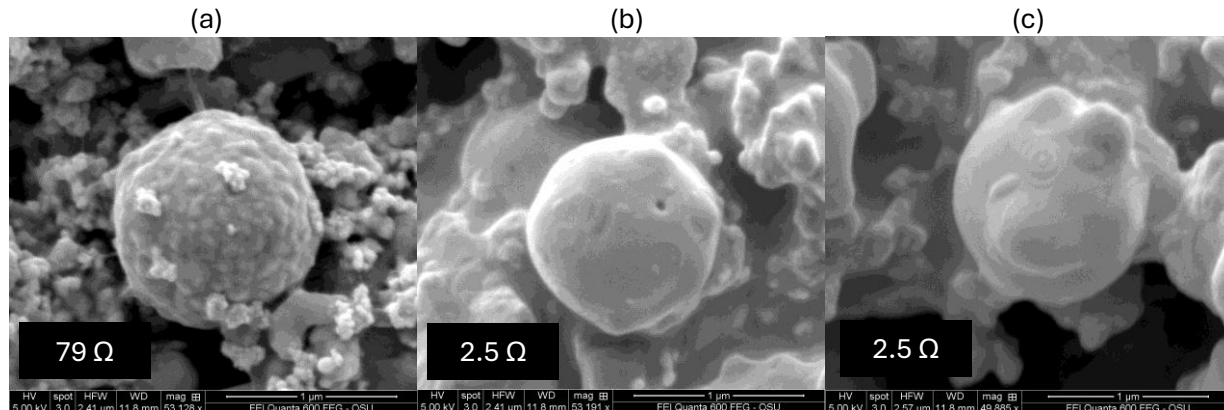
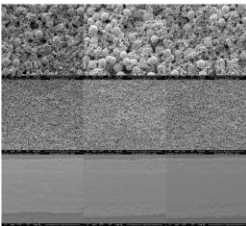
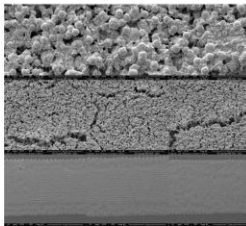
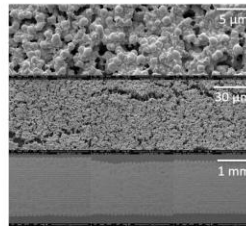
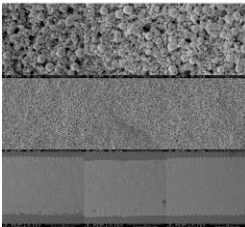
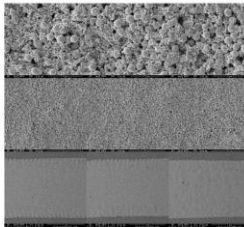
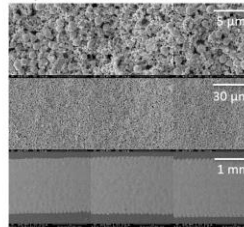
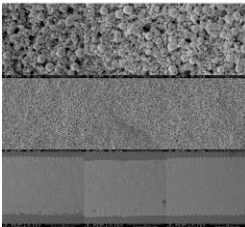
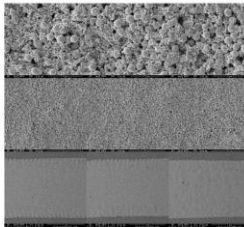
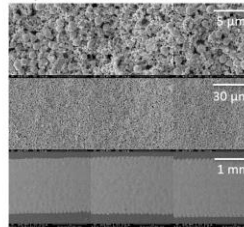
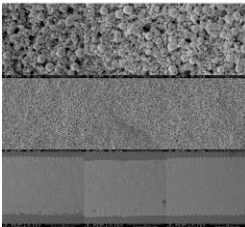
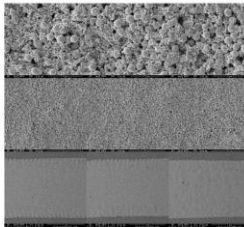
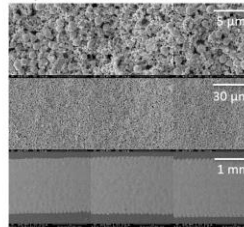
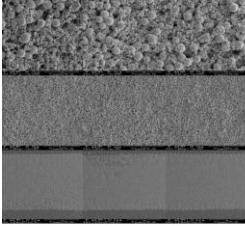
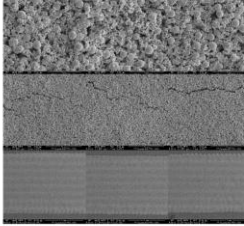
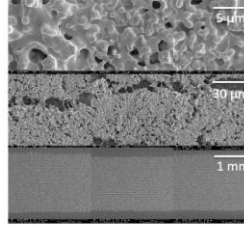
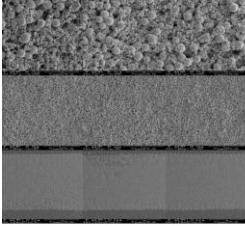
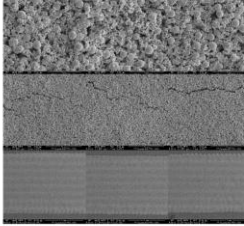
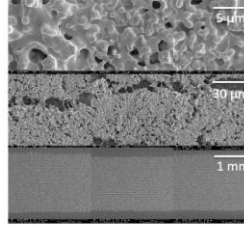
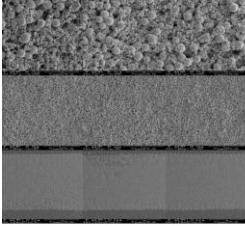
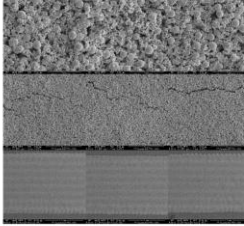
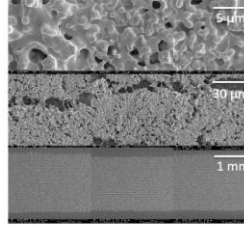
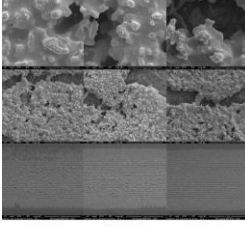
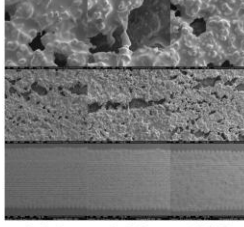
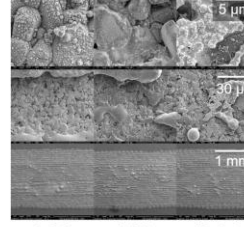
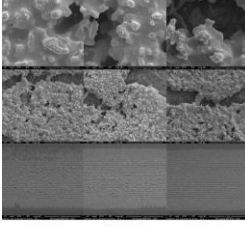
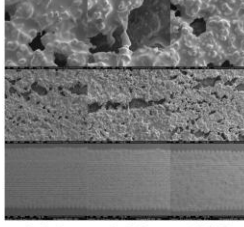
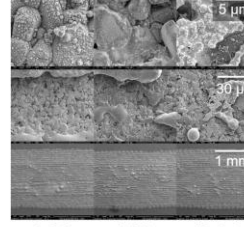
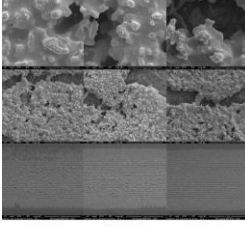
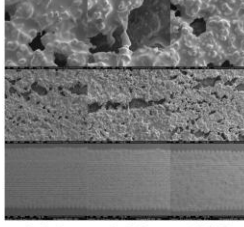
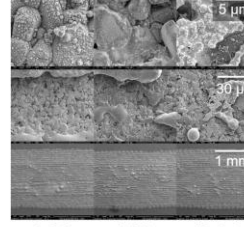
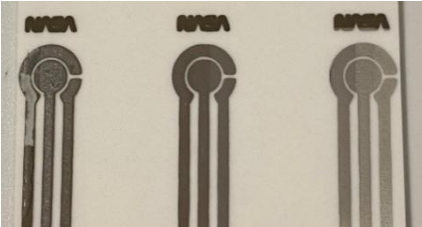
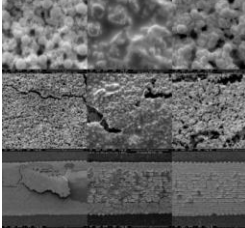
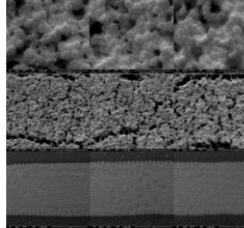
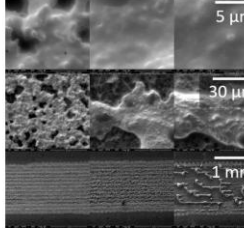
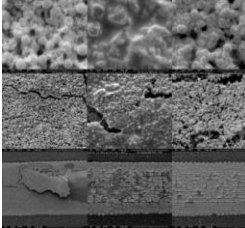
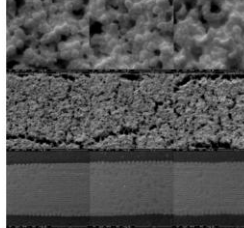
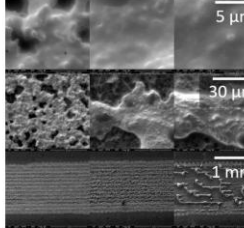
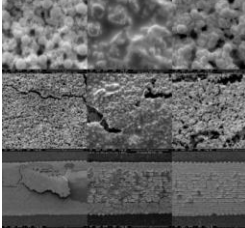
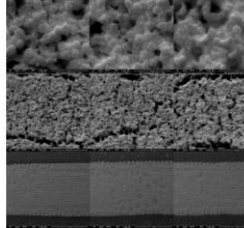
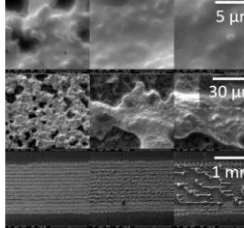
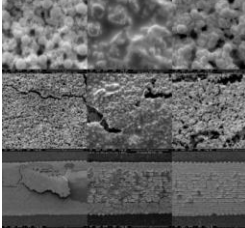
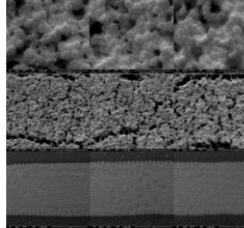
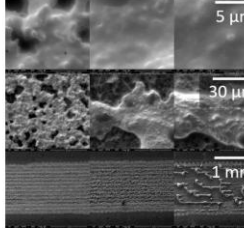
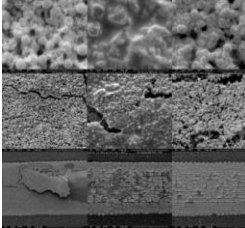
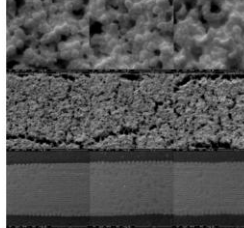
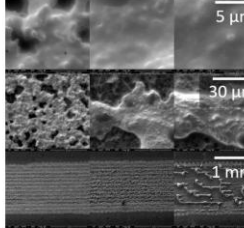
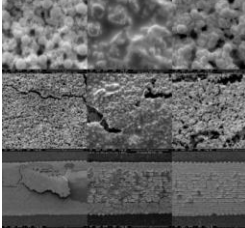
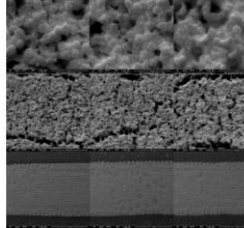
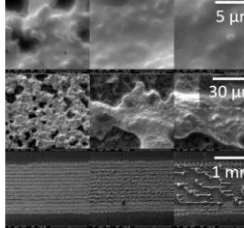
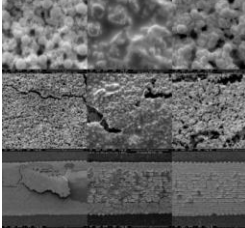
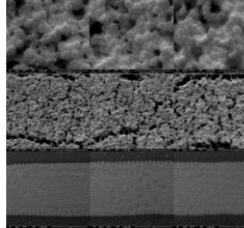
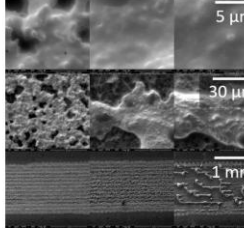
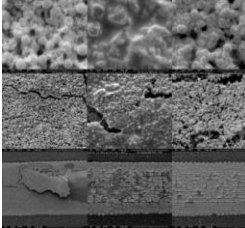
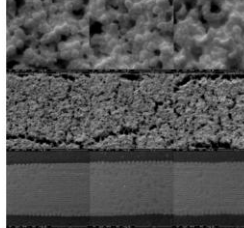
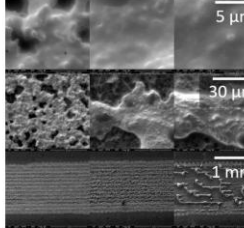
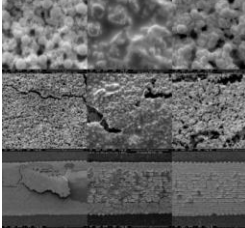
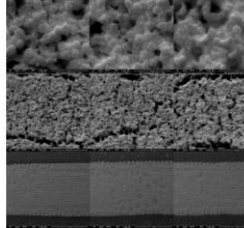
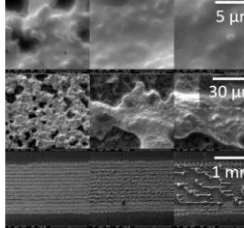


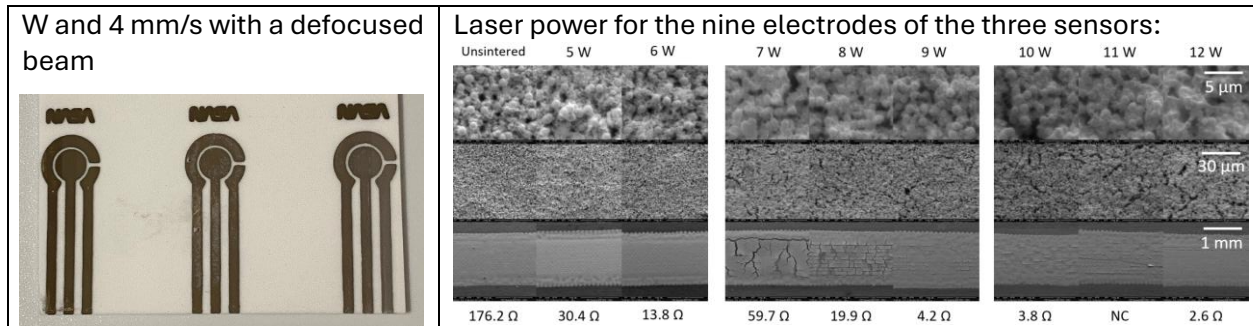
Figure 6. SEM images of dried AuPt ink from screen-printed sensors (a) unsintered, (b) after 3 W at 0.5 mm/s, and (c) after 4 W at 0.5 mm/s.

To determine the optimized parameters for AuPt sensors based on the predetermined parameters from AgPd results [7], we first identified the laser parameters required to sinter the dried screen-printed AuPt sensors provided to us by NASA MSFC. The samples were initially dried at 150 $^{\circ}\text{C}$ for 15 min and have a thickness of approximately 6 μm . The 0.5 mm/s scanning speed is considered slow for ISM efficient and rapid prototyping; therefore, higher speeds, up to 10 mm/s, were tested. With the increased scanning speed, the laser power is also increased to expose the sample to higher intensities and achieve sintering similar to the 0.5 mm/s results. In previous work, the 445 nm laser used had a maximum output power of 6 W [7]; and higher power and scanning speed could not be achieved as in this study. Table 2 presents the SEM and resistance results for the screen-printed samples laser-sintered with variations in laser power, scanning speed, and beam spot diameter (D).

Table 2. SEM images and resistance measurements for laser-sintered screen-printed samples that were dried using 150 $^{\circ}\text{C}$ for 15 min.

Sample	Sample SEM Images and Resistance
1) The first sensor was left unsintered, the second and third were laser sintered with 3 and 4 W at 0.5 mm/s	Scanning Speed: 0.5 mm/s Focused Beam: D = 165 μm Laser power and scanning speed for the nine electrodes of the three sensors: Unsintered  82.5 Ω 79 Ω 75.9 Ω 3 W, 0.5 mm/s  2.2 Ω 2.5 Ω 2.7 Ω 4 W, 0.5 mm/s  2.4 Ω 2.5 Ω 2.2 Ω

2) Defocused beams of different diameters were used at 3, 4, and 6 W at 0.5 mm/s 	Scanning Speed: 0.5 mm/s Defocused Beam: Diameters below Laser power and scanning speed of two laser passes for the nine electrodes of the three sensors: <table><tr><th>Unsintered</th><th>3 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 1 mm beam</th><th>4 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 0.5 mm beam</th></tr><tr><td></td><td></td><td></td></tr><tr><td>76.1 Ω 81.3 Ω 79 Ω</td><td>69.4 Ω 80.6 Ω 84.6 Ω</td><td>18.8 Ω 18.7 Ω 15.9 Ω</td></tr></table>	Unsintered	3 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 1 mm beam	4 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 0.5 mm beam				76.1 Ω 81.3 Ω 79 Ω	69.4 Ω 80.6 Ω 84.6 Ω	18.8 Ω 18.7 Ω 15.9 Ω																		
Unsintered	3 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 1 mm beam	4 W, 0.5 mm/s with 1 mm beam 6 W, 0.5 mm/s with 0.5 mm beam																										
																												
76.1 Ω 81.3 Ω 79 Ω	69.4 Ω 80.6 Ω 84.6 Ω	18.8 Ω 18.7 Ω 15.9 Ω																										
3) Focused beam at 6 W at different scanning speeds of 0.5 mm/s and 0.05 mm/s 	Scanning Speed: 0.5, 0.05 mm/s Focused Beam: D = 165 μm Laser power and scanning speed for the nine electrodes of the three sensors: <table><tr><th>Unsintered</th><th>6 W, 0.5 mm/s with 0.4 mm beam</th><th>6 W, 0.05 mm/s with 165 μm beam</th></tr><tr><td></td><td></td><td></td></tr><tr><td>73.5 Ω 69.1 Ω 69.8 Ω</td><td>6.5 Ω 7.5 Ω 9.4 Ω</td><td>2.9 Ω 3 Ω 2.9 Ω</td></tr></table>	Unsintered	6 W, 0.5 mm/s with 0.4 mm beam	6 W, 0.05 mm/s with 165 μm beam				73.5 Ω 69.1 Ω 69.8 Ω	6.5 Ω 7.5 Ω 9.4 Ω	2.9 Ω 3 Ω 2.9 Ω																		
Unsintered	6 W, 0.5 mm/s with 0.4 mm beam	6 W, 0.05 mm/s with 165 μm beam																										
																												
73.5 Ω 69.1 Ω 69.8 Ω	6.5 Ω 7.5 Ω 9.4 Ω	2.9 Ω 3 Ω 2.9 Ω																										
4) Three sensors laser sintered with 6 W at varying scanning speeds of 1, 4, and 10 mm/s 	Scanning Speed: 1, 4, 10 mm/s Focused Beam: D = 165 μm Laser power and speed for the three sensors: <table><tr><th>6 W, 1 mm/s</th><th>6 W, 4 mm/s</th><th>6 W, 10 mm/s</th></tr><tr><td></td><td></td><td></td></tr><tr><td>2.5 Ω 2.3 Ω 2.3 Ω</td><td>2.1 Ω 2.3 Ω 2.6 Ω</td><td>9.8 Ω 14 Ω 12.8 Ω</td></tr></table>	6 W, 1 mm/s	6 W, 4 mm/s	6 W, 10 mm/s				2.5 Ω 2.3 Ω 2.3 Ω	2.1 Ω 2.3 Ω 2.6 Ω	9.8 Ω 14 Ω 12.8 Ω																		
6 W, 1 mm/s	6 W, 4 mm/s	6 W, 10 mm/s																										
																												
2.5 Ω 2.3 Ω 2.3 Ω	2.1 Ω 2.3 Ω 2.6 Ω	9.8 Ω 14 Ω 12.8 Ω																										
5) Each of the nine electrodes was laser sintered using 4 – 12 W and 4 mm/s with a focused beam 	Scanning Speed: 4 mm/s Focused Beam: D = 177 μm Laser power for the nine electrodes of the three sensors: <table><tr><th>4 W</th><th>5 W</th><th>6 W</th><th>7 W</th><th>8 W</th><th>9 W</th><th>10 W</th><th>11 W</th><th>12 W</th></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>NC</td><td>9.1 Ω</td><td>3.8 Ω</td><td>2.2 Ω</td><td>2.4 Ω</td><td>2.7 Ω</td><td>3.1 Ω</td><td>19.1 Ω</td><td>NC</td></tr></table>	4 W	5 W	6 W	7 W	8 W	9 W	10 W	11 W	12 W										NC	9.1 Ω	3.8 Ω	2.2 Ω	2.4 Ω	2.7 Ω	3.1 Ω	19.1 Ω	NC
4 W	5 W	6 W	7 W	8 W	9 W	10 W	11 W	12 W																				
																												
NC	9.1 Ω	3.8 Ω	2.2 Ω	2.4 Ω	2.7 Ω	3.1 Ω	19.1 Ω	NC																				
6) Each of the nine electrodes was laser sintered using 4 – 12	Scanning Speed: 4 mm/s Defocused Beam: D = 1 mm																											



An interplay between speed, beam diameter, and power was needed to determine the best laser parameters. Table 3 details the laser sintering parameters and characteristics of the screen-printed sensors listed in Table 2. For example, at a higher scanning speed of 4 mm/s, a focused laser at laser powers between 6 – 9 W achieves $<3 \Omega$. Although at 6 W, large cracks are present. Similarly, at a slower scanning speed of 0.5 mm/s at lower laser powers of 3 and 4 W, $<3 \Omega$ is achieved. However, at speeds up to 10 mm/s, a focused beam ablates the AuPt ink from the alumina substrate, and powers exceeding 6 W at 0.5 mm/s melt the ink, resulting in large cracks.

Table 3. Summary table of the laser sintering parameters and resulting characteristics.

Scanning Speed (mm/s)	Laser Power (W)	Spot Size	Resistance (Ω)	Characteristics
0.05	6	165 μ m	~ 3	- Melted particles - Large gaps present, but still conductive and adhered to the substrate
0.5	3	165 μ m	~ 2.5	- Cracks present - Gold and platinum particles adhering to each other but not completely melted
	4	165 μ m	~ 2.4	- Cracks present - Gold and platinum particles adhering to each other but not completely melted
	6	0.4 mm	~ 7.8	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted
1	6	165 μ m	~ 2.4	- Melted particles - Large gaps present, but still conductive and adhered to the substrate
4	4	177 μ m	NC	- Cracks present – ink flakes off substrate - Gold and platinum particles adhering to each other but not completely melted
	5	177 μ m	9.1	- Cracks present – ink flakes off substrate - Melted particles
		1 mm	30.4	- No cracks present - Gold and platinum particles adhering to each other but not completely melted
	6	165 μ m	~ 2.3	- Melted particles

				- Large gaps present, but still conductive and adhered to the substrate
		177 μm	3.8	- Cracks present – ink flakes off substrate - Partially melts particles
		1 mm	13.8	- No cracks present - Gold and platinum particles adhering to each other but not completely melted
	7	177 μm	2.2	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted
		1 mm	59.7	- Cracks present – ink flakes off substrate - Partially melts particles
	8	177 μm	2.4	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted
		1 mm	19.9	- Cracks present – ink flakes off substrate - Partially melts particles
	9	177 μm	2.7	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted
		1 mm	4.2	- Minor cracks present - Partially melts particles
	10	177 μm	3.1	- Melted particles - Large gaps present, but still conductive and adhered to the substrate
		1 mm	3.8	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted
	11	177 μm	19.1	- Melted particles - Large gaps present, reducing conductivity
		1 mm	NC	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted - Substrate cracking
	12	177 μm	NC	- Melted particles - Large gaps present, ink ablating from the substrate
		1 mm	2.6	- Minor cracks present - Gold and platinum particles adhering to each other but not completely melted - Substrate cracking
10	6	165 μm	~12.2	- Melted particles - Large gaps present, ink ablating from the substrate

Overall, a focused laser beam is optimal for laser sintering the ~6 μm -thick AuPt samples. Depending on the scanning speed (0.5 or 4 mm/s), laser power varies between 3 – 4 W and 7 – 9 W, respectively.

At a higher speed of 10 mm/s, melting occurs, resulting in large gaps and discontinuities. Similarly, at the slowest speed of 0.05 mm/s, melting results in large gaps, and discontinuities are present. At laser powers exceeding 9 W, melting and cracking of the film occur.

b. V-One-printed AuPt with 40 μm thickness

The second set of samples for which laser sintering parameters were determined was for approximately 40 μm -thick samples printed using the V-One. The screen-printed samples were dried at 150 °C for 15 min, as described in the ink's TDS. However, the nScript printer, designed for space use, has a limited platen temperature of 100°C. To address this challenge, four drying methods were tested: 100°C for 15 min; 100°C for 15 min with a defocused 445 nm laser; 150°C for 15 min; and a defocused 445 nm laser only. Table 4 outlines the drying methods used for V-One-printed sensors with an average thickness of $\sim 40 \mu\text{m}$, along with before-and-after images of the sensors and the resistance of each electrode for each sensor.

Table 4. Drying method and resulting resistances for V-One-printed sensors with an average thickness of $\sim 40 \mu\text{m}$.

Drying Method	Before Drying		After Drying	
150°C 15 min		NC		Resistance (Ω)
				60.9
				57.8
				49.6
100°C 15 min		NC		NC
100°C 15 min + Defocused Beam D = 4 mm 6 W 1 mm/s		NC		Resistance (k Ω)
				3.40
				1.34
				0.54

100°C 15 min + Defocused Beam D = 4 mm 9 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>45.0</td></tr><tr><td>77.3</td></tr><tr><td>49.4</td></tr></table>	Resistance (Ω)	45.0	77.3	49.4
Resistance (Ω)								
45.0								
77.3								
49.4								
6 Passes Defocused Beam D = 4 mm 6 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 6 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>162.4</td></tr><tr><td>200.1</td></tr><tr><td>169.3</td></tr></table>	Resistance (Ω)	162.4	200.1	169.3
Resistance (Ω)								
162.4								
200.1								
169.3								
10 Passes Defocused Beam D = 5.2 mm 9 W 1 mm/s		NC		<table><tr><th>Resistance (kΩ)</th></tr><tr><td>242.1</td></tr><tr><td>185.0</td></tr><tr><td>217.2</td></tr></table>	Resistance (k Ω)	242.1	185.0	217.2
Resistance (k Ω)								
242.1								
185.0								
217.2								
1 Pass Defocused Beam D = 5.2 mm 9 W 0.5 mm/s		NC		<table><tr><th>Resistance (kΩ)</th></tr><tr><td>3.1</td></tr><tr><td>17.0</td></tr><tr><td>43.0</td></tr></table>	Resistance (k Ω)	3.1	17.0	43.0
Resistance (k Ω)								
3.1								
17.0								
43.0								
2 Passes Defocused Beam D = 4 mm Pass 1: 9 W 1 mm/s Pass 2: 10 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>206.4</td></tr><tr><td>160.3</td></tr><tr><td>361.9</td></tr></table>	Resistance (Ω)	206.4	160.3	361.9
Resistance (Ω)								
206.4								
160.3								
361.9								
1 Pass Defocused Beam D = 4 mm 5 W 2 mm/s		NC		NC				

According to the ink's TDS drying parameters, AuPt was dried for 15 min at 150 °C, resulting in a sample with a resistance of 60 Ω . Drying the AuPt at 100 °C for 15 min alone results in nonconductive

electrodes; however, adding a defocused laser at 6 W yields a resistance on the order of k Ω . Increasing the laser power to 9 W with a defocused beam reduces the resistance to <100 Ω , similar to drying the AuPt at 150 °C for 15 min. One pass with a defocused laser at 9 W and 0.5 mm/s achieves k Ω resistance; however, the ink spreads, causing shorts in the circuit. Multiple passes with a defocused laser at a higher scanning speed of at least 1 mm/s reduce ink spreading while achieving < 300 Ω . Table 5 summarizes the drying results from Table 4, including resistances and notes on the quality of the printed film after drying.

Table 5. After-drying characteristics of V-One-printed sensors with ~40 μm thickness.

Drying Method	After Drying	
100°C 15 min	Nonconductive - No ink spreading observed - More post-processing is needed to achieve conductivity	
150°C 15 min	- No ink spreading observed - Film appears completely dried and even	Resistance (Ω)
		60.9
		57.8
100°C 15 min + Defocused Beam D = 4 mm 6 W 1 mm/s	- No ink spreading observed - More post-processing is needed to achieve better conductivity	Resistance (k Ω)
		3.40
		1.34
100°C 15 min + Defocused Beam D = 4 mm 9 W 1 mm/s	- Ink spreading is observed	Resistance (Ω)
		45.0
		77.3
6 Passes Defocused Beam D = 4 mm 6 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 6 W 1 mm/s	- No ink spreading observed	Resistance (Ω)
		162.4
		200.1
10 Passes Defocused Beam D = 5.2 mm 9 W 1 mm/s	- No ink spreading is observed - More post-processing is needed to achieve better conductivity	Resistance (k Ω)
		242.1
		185.0
1 Pass Defocused Beam D = 5.2 mm 9 W 0.5 mm/s	- Ink spreading is observed	Resistance (k Ω)
		3.1
		17.0
		43.0

2 Passes Defocused Beam D = 4 mm Pass 1: 9 W 1 mm/s Pass 2: 10 W 1 mm/s	- Minimal ink spreading is observed	Resistance (Ω)
		206.4
		160.3
		361.9
1 Pass Defocused Beam D = 4 mm 5 W 2 mm/s	Nonconductive	
	- Minimal ink spreading is observed	
	- More post-processing is needed to achieve conductivity	

For the ~ 40 μm -thick samples, the optimal drying conditions include drying at 150 $^{\circ}\text{C}$ for 15 min, followed by multiple passes with a defocused beam at 9 W and 1 mm/s. Although samples dried on a platen at 100 $^{\circ}\text{C}$ for 15 min and a defocused beam produced an even film, the resistance did not fall below $\text{k}\Omega$, indicating that the sample was not fully dry.

The screen-printed AuPt sensors could be sintered at 7 – 9 W at a higher speed of 4 mm/s; therefore, in this study, AuPt lines were printed using the V-One and laser-sintered at 5 – 10 W at 4 mm/s to test similar capabilities. Figures 7 and 8 show the SEM images of the ~ 40 μm thick AuPt lines printed using the V-One after drying at 100 $^{\circ}\text{C}$ and 150 $^{\circ}\text{C}$ for 15 min on the V-One platen and sintered with laser powers of 5 – 10 W at 4 mm/s using a focused beam of 177 μm . Figure 7 shows the SEM images at 5, 30, and 200 μm magnifications, and the resulting resistance after drying at 100 $^{\circ}\text{C}$ and subsequent laser sintering. In the AgPd results [7], melting was not achieved as in furnace-sintered samples; however, at higher power, melting is achieved, but once the laser power exceeds 5 W, the ink is ablated from the substrate, and the samples are no longer conductive.

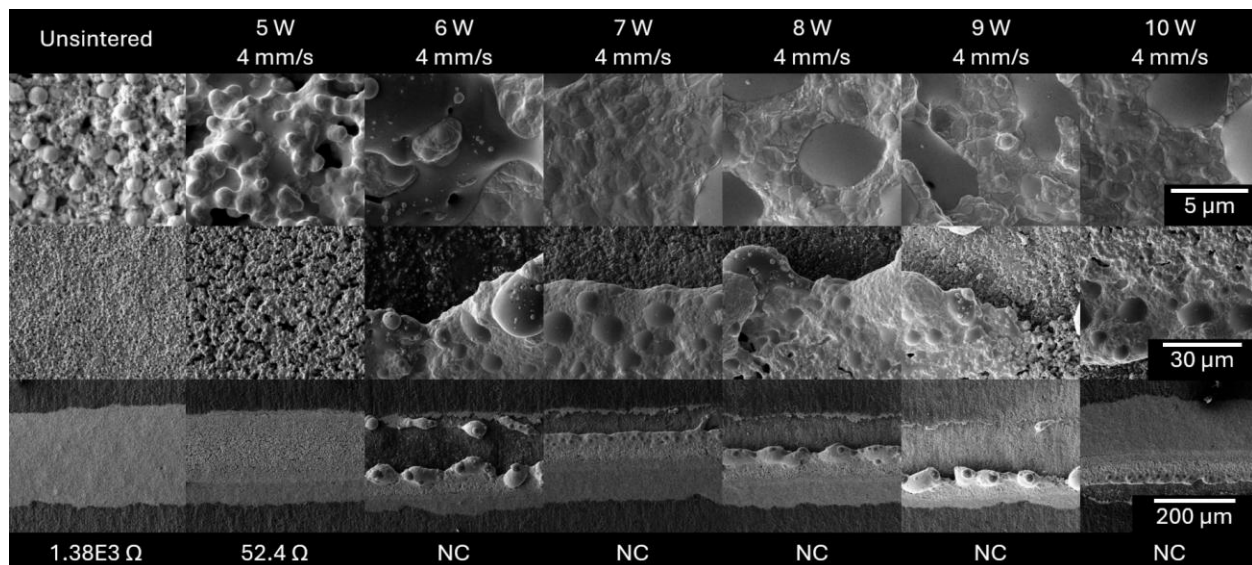


Figure 7. SEM images of AuPt lines on alumina after drying at 100 $^{\circ}\text{C}$ for 15 min on the V-One platen and laser sintered using the laser power and scanning speed described in the top row. The resistance of the printed line is shown in the last row for each column.

Figure 8 shows the SEM images at magnifications of 5, 30, and 200 μm of AuPt lines on alumina, dried on the V-One platen at 150 $^{\circ}\text{C}$ for 15 min as recommended by the TDS, and laser-sintered with laser powers of 5 – 10 W at 4 mm/s using a focused beam.

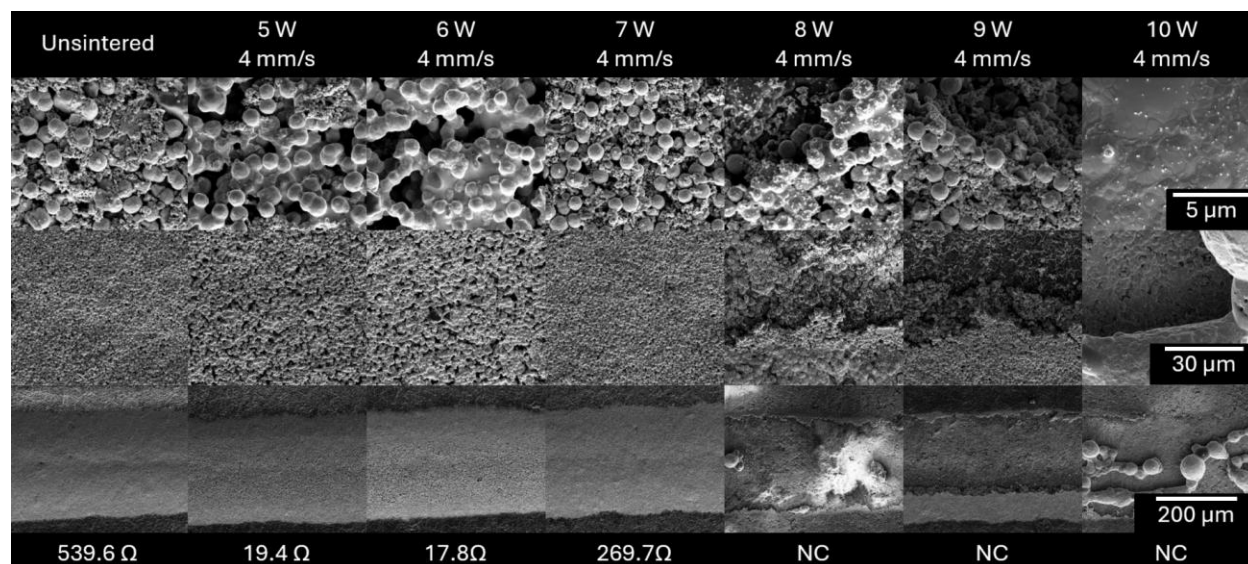
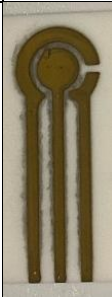


Figure 8. SEM images of AuPt lines on alumina after drying at 150 $^{\circ}\text{C}$ for 15 min on the V-One platen and laser sintered using the laser power and scanning speed described in the top row. The resistance of the printed line is shown in the last row for each column.

Figures 7 and 8 show that a 150 $^{\circ}\text{C}$ drying temperature improves the resistance of AuPt lines sintered at higher laser power and scanning speed. However, even when dried using the V-One platen at 100 $^{\circ}\text{C}$ or 150 $^{\circ}\text{C}$, the ink melts and ablates from the substrate. The resistance also does not compare to that of the $\sim 6\text{ }\mu\text{m}$ -thick AuPt sensors dried at 150 $^{\circ}\text{C}$ and laser sintered using 7 – 9 W at 4 mm/s, which achieved $<3\text{ }\Omega$. Therefore, a study on the laser sintering parameters for the V-One-printed AuPt is required. The required sintering parameters are tested on V-One prints to determine whether a defocused beam at higher laser power and scanning speed performs better than a focused beam. Table 6 displays the laser parameters used to sinter the $\sim 40\text{ }\mu\text{m}$ -thick V-One-printed sensors dried using the various techniques listed in Table 5, along with their corresponding resistances.

Table 6. Laser sintering parameters and the corresponding drying method and electrode resistances.

Sintering Parameters	Drying Method		After Sintering	
1 Pass Defocused Beam D = 1.44 mm 5 W 4 mm/s		100°C 15 min		Resistance (Ω)
		NC		9
				12.8
				50.9

1 Pass Defocused Beam D = 5.2 mm 9 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s		150°C 15 min <table><tr><th>Resistance (Ω)</th></tr><tr><td>60.9</td></tr><tr><td>57.8</td></tr><tr><td>49.6</td></tr></table>	Resistance (Ω)	60.9	57.8	49.6	 <table><tr><th>Resistance (Ω)</th></tr><tr><td>2.4</td></tr><tr><td>2.2</td></tr><tr><td>2.1</td></tr></table>	Resistance (Ω)	2.4	2.2	2.1
Resistance (Ω)											
60.9											
57.8											
49.6											
Resistance (Ω)											
2.4											
2.2											
2.1											
7 Passes Defocused Beam D = 5.2 mm 9 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s		100°C 15 min + Defocused Beam D = 4 mm 6 W 1 mm/s <table><tr><th>Resistance (kΩ)</th></tr><tr><td>3.40</td></tr><tr><td>1.34</td></tr><tr><td>0.54</td></tr></table>	Resistance (kΩ)	3.40	1.34	0.54	 <table><tr><th>Resistance (Ω)</th></tr><tr><td>5.1</td></tr><tr><td>6.4</td></tr><tr><td>4.5</td></tr></table>	Resistance (Ω)	5.1	6.4	4.5
Resistance (kΩ)											
3.40											
1.34											
0.54											
Resistance (Ω)											
5.1											
6.4											
4.5											
3 Passes Defocused Beam D = 1.44 mm 6 W 1 mm/s		6 Passes Defocused Beam D = 4 mm 6 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 6 W 1 mm/s <table><tr><th>Resistance (Ω)</th></tr><tr><td>162.4</td></tr><tr><td>200.1</td></tr><tr><td>169.3</td></tr></table>	Resistance (Ω)	162.4	200.1	169.3	 <table><tr><th>Resistance (Ω)</th></tr><tr><td>9.3</td></tr><tr><td>11.8</td></tr><tr><td>11.2</td></tr></table>	Resistance (Ω)	9.3	11.8	11.2
Resistance (Ω)											
162.4											
200.1											
169.3											
Resistance (Ω)											
9.3											
11.8											
11.2											

Regardless of the sintering parameters used for the ~ 40 μm -thick samples, resistance decreased; however, some samples exhibited uneven surfaces, ink spreading, or ink flaking off the substrate. Table 7 summarizes the drying and sintering results from Table 6, including resistance and notes on printed-film quality.

Table 7. Summary and color coding of sintering parameters and resulting film quality and resistance for V-One-printed sensors with ~ 40 μm average thickness.

Drying Method	After Sintering	
100°C 15 min NC - No ink spreading observed - More post-processing is needed to achieve conductivity	1 Pass Defocused Beam D = 1.44 mm 5 W 4 mm/s	Resistance (Ω)
		9
		12.8
	5 W 4 mm/s No ink spreading	50.9

		- Uneven film surface	
150°C 15 min - Even film surface	Resistance (Ω)	1 Pass	Resistance (Ω)
	60.9	Defocused Beam	2.4
	57.8	D = 5.2 mm	2.2
	49.6	9 W 1 mm/s	2.1
		+	
		1 Pass	
		Defocused Beam	
		D = 2.3 mm	
		9 W 1 mm/s	
		- Even film surface	
		- Flaking off of ink	
100°C 15 min + Defocused Beam D = 4 mm 6 W 1 mm/s - No ink spreading observed	Resistance (k Ω)	7 Passes	Resistance (Ω)
	3.40	Defocused Beam	5.1
	1.34	D = 5.2 mm	6.4
	0.54	9 W 1 mm/s	4.5
		+	
		1 Pass	
		Defocused Beam	
		D = 2.3 mm	
		9 W 1 mm/s	
		- No spreading of ink	
		- Flaking off of ink	
		- Surface inconsistencies	
6 Passes Defocused Beam D = 4 mm 6 W 1 mm/s + 1 Pass Defocused Beam D = 2.3 mm 6 W 1 mm/s - No ink spreading observed	Resistance (Ω)	3 Passes	Resistance (Ω)
	162.4	Defocused Beam	9.3
	200.1	D = 1.44 mm	11.8
	169.3	6 W 1 mm/s	11.2
		- Ink spreading observed	
		- Surface inconsistencies	

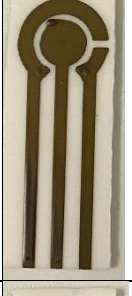
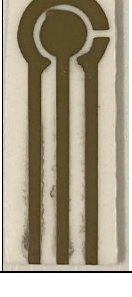
The ~40 μm thick V-One samples could not achieve even film surfaces and $<3 \Omega$. Drying the samples at 150 °C for 15 min and sintering with a defocused beam achieved $<3 \Omega$; however, the ink was not fully adhered to the substrate and would delaminate. This is due to the thick structure of these samples.

c. V-One-printed AuPt with 10 μm thickness

The ~40 μm V-One sample adhesion showed that a small amount of solvent was necessary to ensure adhesion, which might reduce the sensor's sensitivity. Thinner V-One-printed samples were tested to determine whether solvent was necessary for adhesion. Sensors were made with an average thickness of ~10 μm . The laser drying and sintering parameters were repeated for the ~10 μm thick sensors. Table 8 outlines the drying conditions used and presents before-and-after pictures of

the samples, along with their resistances. All the drying conditions are compared against the TDS requirement to dry the ink at 150 °C for 15 min.

Table 8. Drying method and resulting resistances for V-One-printed sensors with an average thickness of ~10 μm .

Drying Method	Before Drying		After Drying	
150°C 15 min		NC		Resistance (Ω)
				119.9
				137.6
				133.2
100°C 15 min		NC		Resistance ($\text{k}\Omega$)
				NC
				11.83
				1.19
100°C 15 min + Defocused Beam D = 4 mm 6 W 1 mm/s		NC		Resistance ($\text{k}\Omega$)
				NC
				7.01
				0.526
100°C 15 min + Defocused Beam D = 2.3 mm 9 W 1 mm/s		NC		Resistance (Ω)
				42.1
				49.9
				27.9

1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>488.3</td></tr><tr><td>344.4</td></tr><tr><td>294.3</td></tr></table>	Resistance (Ω)	488.3	344.4	294.3
Resistance (Ω)								
488.3								
344.4								
294.3								
2 Passes Defocused Beam D = 2.3 mm 9 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>178</td></tr><tr><td>178</td></tr><tr><td>141</td></tr></table>	Resistance (Ω)	178	178	141
Resistance (Ω)								
178								
178								
141								
4 Passes Defocused Beam Passes 1 – 3: - D = 2.3 mm - 9 W 1 mm/s Pass 4: - D = 1.75 mm - 9 W 1 mm/s		NC		<table><tr><th>Resistance (Ω)</th></tr><tr><td>46.6</td></tr><tr><td>42.4</td></tr><tr><td>51.1</td></tr></table>	Resistance (Ω)	46.6	42.4	51.1
Resistance (Ω)								
46.6								
42.4								
51.1								

Overall, resistance could be measured for all $\sim 10\text{ }\mu\text{m}$ -thick AuPt samples when drying them using a heated platen at $150\text{ }^{\circ}\text{C}$ for 15 min, $100\text{ }^{\circ}\text{C}$ for 15 min, $100\text{ }^{\circ}\text{C}$ for 15 min with an additional laser pass, and using the laser only. However, $100\text{ }^{\circ}\text{C}$ for 15 min alone resulted in a $\text{k}\Omega$ resistance, indicating that the sample was not fully dry, unlike with the other drying methods. Table 9 summarizes the drying results, including resistances and notes on film quality, from Table 8 for V-One-printed sensors with an average thickness of $\sim 10\text{ }\mu\text{m}$.

Table 9. After-drying characteristics of V-One-printed sensors with $\sim 10\text{ }\mu\text{m}$ thickness.

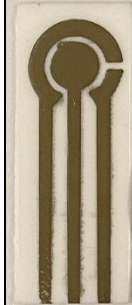
Drying Method	After Drying	
100°C 15 min	The majority of print is conductive down to $\text{k}\Omega$ resistance - No ink spreading observed - More post-processing is needed to achieve conductivity	
150°C 15 min	- No ink spreading observed - Film appears completely dried and even	Resistance (Ω)
		119.9
		137.6
100°C 15 min + Defocused Beam D = 4 mm	- No ink spreading observed - More post-processing is needed to achieve better conductivity	Resistance ($\text{k}\Omega$)
		NC
		7.01
		0.526

6 W 1 mm/s						
100°C 15 min + Defocused Beam D = 2.3 mm 9 W 1 mm/s	- Slight spreading of ink, but no shorts - Film appears completely dried and even	<table><tr><th>Resistance (Ω)</th></tr><tr><td>42.1</td></tr><tr><td>49.9</td></tr><tr><td>27.9</td></tr></table>	Resistance (Ω)	42.1	49.9	27.9
Resistance (Ω)						
42.1						
49.9						
27.9						
1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s	- No ink spreading observed	<table><tr><th>Resistance (Ω)</th></tr><tr><td>488.3</td></tr><tr><td>344.4</td></tr><tr><td>294.3</td></tr></table>	Resistance (Ω)	488.3	344.4	294.3
Resistance (Ω)						
488.3						
344.4						
294.3						
10 Passes Defocused Beam D = 5.2 mm 9 W 1 mm/s	- No ink spreading is observed - More post-processing is needed to achieve better conductivity	<table><tr><th>Resistance (kΩ)</th></tr><tr><td>242.1</td></tr><tr><td>185.0</td></tr><tr><td>217.2</td></tr></table>	Resistance (kΩ)	242.1	185.0	217.2
Resistance (kΩ)						
242.1						
185.0						
217.2						
2 Passes Defocused Beam D = 2.3 mm 9 W 1 mm/s	- No ink spreading is observed	<table><tr><th>Resistance (Ω)</th></tr><tr><td>178</td></tr><tr><td>178</td></tr><tr><td>141</td></tr></table>	Resistance (Ω)	178	178	141
Resistance (Ω)						
178						
178						
141						
4 Passes Defocused Beam Passes 1 – 3: - D = 2.3 mm - 9 W 1 mm/s Pass 4: - D = 1.75 mm - 9 W 1 mm/s	- No ink spreading is observed	<table><tr><th>Resistance (Ω)</th></tr><tr><td>46.6</td></tr><tr><td>42.4</td></tr><tr><td>51.1</td></tr></table>	Resistance (Ω)	46.6	42.4	51.1
Resistance (Ω)						
46.6						
42.4						
51.1						

The thinner V-One samples dried more easily than the thicker ones, as shown by more green rows in Table 9 than in Table 5. Slight ink spreading was observed when the samples were dried at 100 °C, whereas drying at 150 °C and using the laser produced smooth films with no ink spreading. As with the 40 μm samples, the laser sintering parameters are tested after drying. Table 10 presents the laser parameters used to sinter the dried V-One-printed sensors having an average thickness of $\sim 10\text{ }\mu\text{m}$, along with their corresponding resistances. A defocused and focused 445 nm laser was used.

Table 10. Laser sintering parameters and their before and after pictures and resulting resistances for V-One-printed sensors with $\sim 10\text{ }\mu\text{m}$ average thickness.

Sintering Parameters	Drying Method		After Sintering									
2 Passes Defocused Beam D = 2.3 mm 9 W 1 mm/s + 1 Pass Defocused Beam D = 1.75 mm 9 W 1 mm/s		150°C 15 min										
		<table><tr><th>Resistance (Ω)</th></tr><tr><td>119.9</td></tr><tr><td>137.6</td></tr><tr><td>133.2</td></tr></table>		Resistance (Ω)	119.9	137.6	133.2	<table><tr><th>Resistance (Ω)</th></tr><tr><td>6.3</td></tr><tr><td>7.9</td></tr><tr><td>7.8</td></tr></table>	Resistance (Ω)	6.3	7.9	7.8
Resistance (Ω)												
119.9												
137.6												
133.2												
Resistance (Ω)												
6.3												
7.9												
7.8												

1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s		100°C 15 min + Defocused Beam D = 2.3 mm 9 W 1 mm/s									
		<table><tr><th>Resistance (Ω)</th></tr><tr><td>42.1</td></tr><tr><td>49.9</td></tr><tr><td>27.9</td></tr></table>	Resistance (Ω)	42.1	49.9	27.9	<table><tr><th>Resistance (Ω)</th></tr><tr><td>39</td></tr><tr><td>31.9</td></tr><tr><td>18.9</td></tr></table>	Resistance (Ω)	39	31.9	18.9
Resistance (Ω)											
42.1											
49.9											
27.9											
Resistance (Ω)											
39											
31.9											
18.9											
1 Pass Focused Beam D = 177 μ m 8 W 1 mm/s		4 Passes Defocused Beam Passes 1 – 3: - D = 2.3 mm - 9 W 1 mm/s Pass 4: - D = 1.75 mm - 9 W 1 mm/s									
		<table><tr><th>Resistance (Ω)</th></tr><tr><td>46.6</td></tr><tr><td>42.4</td></tr><tr><td>51.1</td></tr></table>	Resistance (Ω)	46.6	42.4	51.1	<table><tr><th>Resistance (Ω)</th></tr><tr><td>5.1</td></tr><tr><td>3.3</td></tr><tr><td>3.3</td></tr></table>	Resistance (Ω)	5.1	3.3	3.3
Resistance (Ω)											
46.6											
42.4											
51.1											
Resistance (Ω)											
5.1											
3.3											
3.3											

For all three laser sintering parameters, low resistance was achieved; however, some ink was ablated from the alumina substrate when a focused beam was used, and ink spreading occurred on the samples dried at 100 °C for 15 min. Table 11 summarizes the drying and sintering results from Table 10 for the V-One-printed sensors with an average thickness of $\sim 10 \mu\text{m}$, with the resistances and notes on the quality of the printed film.

Table 11. Summary and color coding of sintering parameters and resulting film quality and resistance for V-One-printed sensors with $\sim 10 \mu\text{m}$ average thickness.

Drying Method		After Sintering	
150°C 15 min - Even film surface	Resistance (Ω)	2 Passes	Resistance (Ω)
	119.9	Defocused Beam	6.3
	137.6	D = 2.3 mm	7.9
	133.2	9 W 1 mm/s	7.8
		+ 1 Pass Defocused Beam D = 1.75 mm 9 W 1 mm/s - No spreading of ink	

100°C 15 min + Defocused Beam D = 2.3 mm 9 W 1 mm/s - Even film surface - Slight spreading of ink, but no shorts	Resistance (Ω)	1 Pass Defocused Beam D = 2.3 mm 9 W 1 mm/s - Even film surface - Slight spreading of ink, but no shorts	Resistance (Ω)
	42.1		39
	49.9		31.9
	27.9		18.9
4 Passes Defocused Beam Passes 1 – 3: D = 2.3 mm 9 W 1 mm/s Pass 4: D = 1.75 mm 9 W 1 mm/s - Even film surface	Resistance (Ω)	1 Pass Focused Beam D = 177 μ m 8 W 1 mm/s - Ablation of some of the film - Low resistance – a larger laser beam may be required	Resistance (Ω)
	46.6		5.1
	42.4		3.3
	51.1		3.3

Overall, the ~10 μ m-thick samples dried at 150 °C for 15 min produced the most consistent film after drying and laser sintering, while reducing resistance to <10 Ω .

d. Adhesion testing by soldering the samples

As the final adhesion test, pins were soldered onto the sensors and tested in a conductivity standard solution. Table 12 shows the sample preparation method and its soldering results for attaching pins for conductivity testing. The pins were successfully soldered on for the samples dried at 150°C for 15 min and dried using a laser; however, the samples dried at 100°C for 15 min were unsuccessful.

Table 12. The soldering results for the different printing methods, drying, and sintering techniques.

Sample Preparation Methods	Soldering Results
V-One-printed Drying: 150°C for 15 min on the V-One platen Sintering: 445 nm laser	Soldering successful
V-One-printed Drying: 100°C for 15 min on the V-One platen Sintering: 445 nm laser	Soldering unsuccessful
V-One-printed Drying: 445 nm laser Sintering: 445 nm laser	Soldering successful
Screen-printed Drying: 150°C for 15 min in a furnace Sintering: 445 nm laser	Soldering successful

Figure 9 shows three of the sensors with their pins soldered that were successful. The results were repeatable, as other samples with the same laser parameters were soldered. Figure 9a shows the screen-printed sensor laser-sintered with a focused beam at 8 W and 4 mm/s. Figure 9b shows a V-

One-printed sensor dried at 150°C for 15 min and laser-sintered at 9 W at 1 mm/s, with pins soldered on. Figure 9c shows a V-One-printed sensor dried with multiple passes of a defocused 445 nm laser at 9 W and 1 mm/s, and sintered with a single pass of a focused 445 nm laser at 8 W and 1 mm/s.

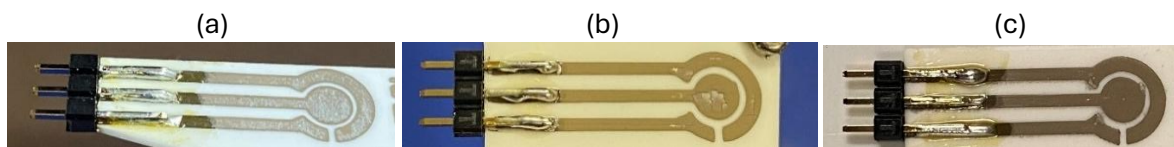


Figure 9. Sensors with leads soldered on: (a) a screen-printed sensor, (b) a V-One-printed sensor dried at 150 °C for 15 min and laser sintered, (c) a V-One-printed sensor laser dried and sintered.

e. Testing the conductivity sensors in solution

Once the pins were attached to the sensors, the sensors could be tested in KCL conductivity standard solutions. The soldered-on leads were connected to a C-programmed device provided by NASA MSFC and run using Python, shown in Figure 10.

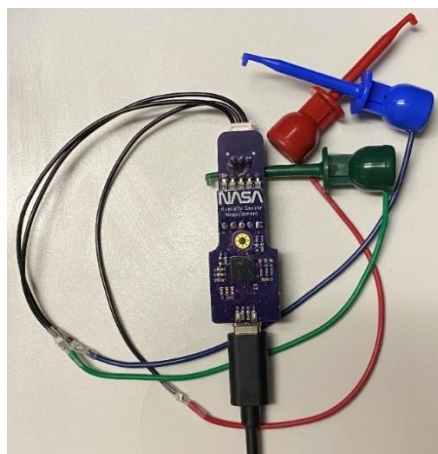


Figure 10. Device connected to the conductivity sensors to measure their impedance in the KCL standard conductivity solutions.

The conductivity standards tested were KCl solutions with conductivities of 84, 430, 600, 1,000, 10,000, 25,000, and 50,000 $\mu\text{S}/\text{cm}$. Figure 11 shows two sensors and the measurement setup. Figures 11a and 11b show a screen-printed sensor and a V-One-printed sensor submerged in solution, with the measurement device connected, respectively.

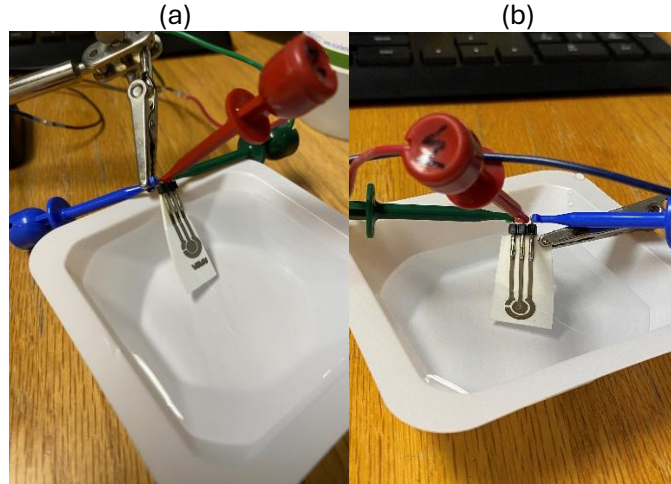


Figure 11. (a) A laser-sintered screen-printed sensor submerged in a KCl conductivity standard solution. (b) A V-One-printed sensor dried at 150°C for 15 min and laser sintered using a defocused beam at 9 W and 1 mm/s, submerged in a KCl conductivity standard solution.

Table 13 shows the results for sensors submerged in the conductivity standard solutions, including the solution conductivity measured with a standard conductivity probe, the complex impedance, the sensor conductivity, and the standard deviation of the measurements for each solution. The conductivity of each standard solution was measured using a commercially purchased conductivity sensor to verify the conductivity of the standards purchased.

Table 13. Probe conductivity results for the three sample sets: Screen-printed and laser-sintered, V-One-printed and dried at 150°C for 15 min, and V-One-printed and dried using a laser.

Screen-Printed, 150°C for 15 min and 8 W at 4 mm/s			
Solution (μS/cm)	Average Z (Ω)	Probe Conductivity (μS/cm)	Standard Deviation (μS/cm)
83	7341.6	5.45E-01	6.78E-04
430	1818	2.20E+00	1.49E-02
593	1377.1	2.90E+00	8.98E-03
997	757.89	5.28E+00	3.86E-02
10100	105.25	3.80E+01	1.38E-01
22700	53.058	7.54E+01	3.15E-01
40000	36.35	1.10E+02	5.80E-01
V-One-Printed, 150°C for 15 min and 9 W at 1 mm/s			
Solution (μS/cm)	Average Z (Ω)	Probe Conductivity (μS/cm)	Standard Deviation (μS/cm)
85	9678.78	4.13E-01	2.84E-03
433	2066.949	1.94E+00	2.61E-02
592	1371.455	2.92E+00	3.87E-02
988	950.115	4.21E+00	1.81E-02
9900	91.679	4.36E+01	1.98E-01
22500	35.519	1.13E+02	2.73E-01
39500	20.67	1.94E+02	3.30E-01

V-One-Printed, defocused 9 W at 1 mm/s and focused 8 W and 1 mm/s			
Solution ($\mu\text{S/cm}$)	Average Z (Ω)	Probe Conductivity ($\mu\text{S/cm}$)	Standard Deviation ($\mu\text{S/cm}$)
85	8156.149	4.90E-01	1.47E-03
427	1952.564	2.05E+00	2.96E-03
587	1331.993	3.00E+00	1.99E-02
990	851.463	4.70E+00	9.91E-03
9800	102.02	3.92E+01	1.77E-01
20300	60.172	6.65E+01	2.75E-01
35000	45.073	8.87E+01	9.49E-01

Figure 12 shows the sensor conductivity plotted against the standard solution conductivity. The more linear the relationship, the more sensitive the sensor is to changes in the solution conductivity.

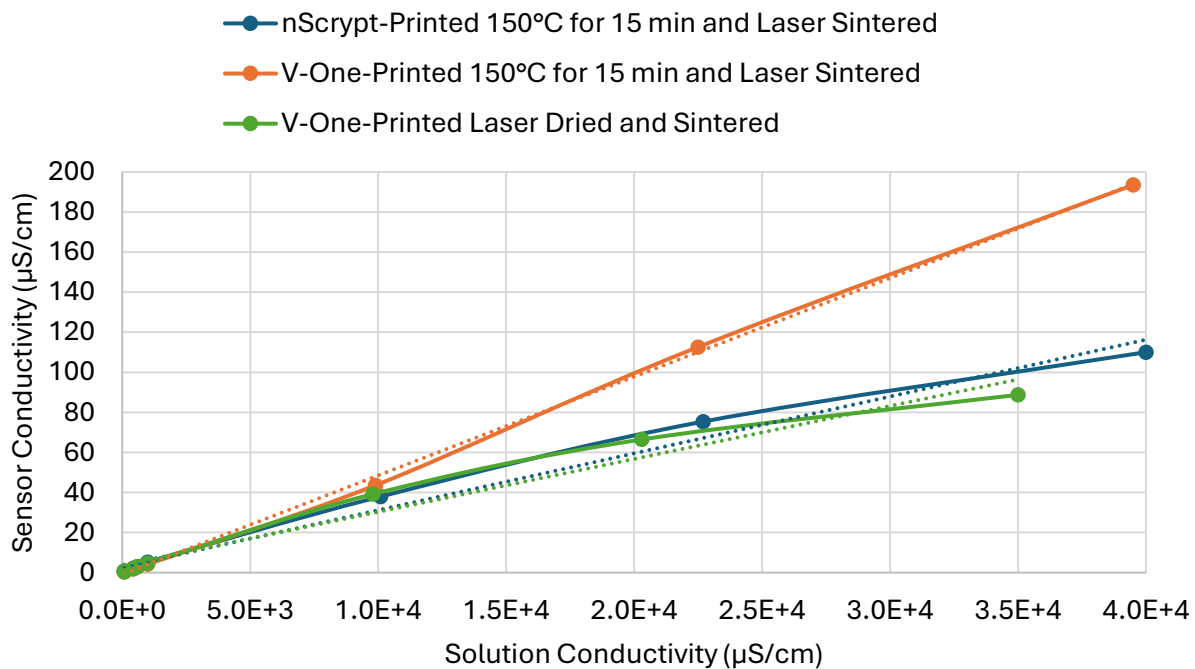


Figure 12. Plot of the conductivity of the three sensors relative to the conductivity of the standard solution.

5. Discussion

The results of this work showcase the printing and laser sintering requirements for fabricating conductivity sensors that meet the constraints of ISM, particularly for applications such as water monitoring aboard the ISS and future Artemis missions. In our previous studies with AgPd, we highlighted how variations in laser power, scanning speed, and beam diameter affect resistance and film morphology, and the need to modify these parameters. In this work, we added the complexity of determining whether a 445 nm laser can eliminate the need for a platen or the drying conditions required by many high-temperature inks, which typically evaporate a solvent. The AuPt ink presents challenges related to solvent evaporation, adhesion, and achieving sufficient particle connectivity

when using a laser rather than the TDS-recommended thermal drying and sintering processes. Because ISM systems cannot rely on conventional furnace sintering or extended thermal cycles, understanding how drying and sintering conditions interact with ink composition and film thickness is essential for producing reliable sensors.

Across all three sample sets with average thicknesses of ~6, ~10, and ~40 μm , it was found that drying at 100 °C was insufficient to remove the solvent from the AuPt ink. This aligns with the TDS recommendations for both AgPd and AuPt, which specify a drying temperature of 150 °C for complete drying. Introducing a defocused laser beam provided the additional thermal input needed to evaporate the solvent; however, it also caused film spreading due to the broader heat distribution. Surface morphology showed that multiple passes with a defocused beam produced more uniform drying than combining platen heating with laser exposure, indicating that gradual, spatially distributed heating is more effective for maintaining a consistent film. The films could be effectively dried using a 100 °C platen combined with a defocused laser, a fully defocused laser alone, or the TDS-recommended 150 °C drying step.

The ~6 μm -thick AuPt films provided by NASA MSFC were received dried by conventional furnace heating at 150 °C for 15 min. Once received, the ~6 μm -thick sensors were successfully sintered using a range of laser parameters. Focused-beam sintering at 3 – 4 W and 0.5 mm/s, as well as higher-power sintering at 7 – 9 W and 4 mm/s, produced conductive films. For dried ~40 μm -thick AuPt, a defocused beam at 9 W was sufficient to sinter the material, demonstrating that AuPt can be processed using multiple optical configurations as long as the energy density threshold is met. However, the film delaminated from the alumina substrate and flaked off. Adhesion testing highlighted that for thicker films, adhesion was strongest when a small amount of solvent remained, suggesting that partial solvent retention may promote adhesion. In contrast, the thin films (~10 μm) exhibited different behavior. The films were sintered with a defocused laser beam at 8 – 9 W and 1 mm/s or a focused laser beam at 8 W and 1 mm/s. None of the samples flaked after sintering; however, a focused beam ablated the surface slightly due to the rapid interaction between solvent evaporation and NP melting, whereas multiple defocused passes allowed the solvent to escape gradually, preventing damage.

However, solderability revealed a key distinction between thin and thick films. For the thin films, only samples fully dried by laser alone or at 150 °C supported reliable pin soldering. This differs from the thicker films, where a small amount of retained solvent improved adhesion. The difference suggests that thin films rely more heavily on complete NP consolidation, whereas thicker films benefit from solvent-assisted bonding between the NPs and the alumina. These findings demonstrate that drying and sintering conditions must be tailored to film thickness to achieve optimal adhesion, conductivity, and solderability. They also confirm that laser-based processing can replace furnace sintering for AuPt inks, enabling rapid, selective, and low-power fabrication compatible with ISM constraints.

The successful operation of three AuPt conductivity sensors in standard conductivity solutions further validates the feasibility of DIW-printed and laser-sintered AuPt sensors for ECLSS water monitoring applications in space. The linear response to the conductivity standards verifies their ability to sense changes in solution conductivity. As NASA continues to develop autonomous manufacturing capabilities for long-duration missions, these results provide a pathway to producing corrosion-resistant, rapidly replaceable sensors directly in orbit.

6. Acknowledgment

This study was funded by NASA under requisition No. 80NSSC23PB039. The funder helped design the sensors, analyze AgPd sensor failures, and review this manuscript.

7. Competing Interests

All authors declare no financial or non-financial competing interests.

8. Data Availability

All data generated or analyzed during this study are included in this published article.

9. Author Contributions

ES fabricated the V-One-printed sensors, executed laser sintering and drying experiments, tested the sensors in standard conductivity solutions, wrote the manuscript, and analyzed and interpreted the data. AF designed the conductivity sensors and the measurement methods, contributed to the main concept of the research, and reviewed the manuscript. NK is the main PI of the project, contributing to the initial concept, editing and proofreading the manuscript, and advising ES.

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