Atmospheric Pressure and Ambient Temperature Plasma Jet Sintering of Aerosol Jet Printed Silver Nanoparticles

Nazli Turan,§ Mortaza Saeidi-Javash,§ Jiahao Chen, Minxiang Zeng, Yanliang Zhang,* and David B. Go*  

**ABSTRACT:** Atmospheric pressure nonthermal plasmas hold great promise for applications in environmental control, energy conversion, and material processing. Even at room temperature, nonthermal plasmas produce energetic and reactive species that can initiate surface modifications at a plasma–surface interface, including thin-film nanoparticle assemblies, in a nondestructive and effective way. Here, we present the plasma-activated sintering of aerosol jet printed silver thin films on substrates ranging from glass to delicate materials including blotting paper, fruits, and flexible plastic. We characterize the microstructural evolutions and electrical properties of printed films along with the electrical, thermal, and optical properties of an argon plasma jet. We demonstrate an electrical conductivity as high as $1.4 \times 10^6$ S/m for printed films sintered under atmospheric conditions in which the surface temperature stays below 50 °C. These results highlight a future direction where additive manufacturing of electronic devices can be achieved on flexible and low-melting-point materials under ambient conditions without requiring additional thermal processing by utilizing nonthermal plasmas.

**KEYWORDS:** plasma jet sintering, atmospheric pressure, low temperature, flexible electronics, aerosol jet printing

1. INTRODUCTION

In the past decade, interest has surged in developing materials and techniques for manufacturing flexible electronics. Traditional methods such as photolithography and vacuum deposition require expensive equipment, include multistage processes, and are incompatible with the fabrication of devices on conformal surfaces. Additive manufacturing of flexible electronics using screen printing, inkjet printing, and aerosol jet printing (AJP) has received tremendous interest due to its low cost, rapid processing capability, and high efficiency.1–3 AJP, in particular, has been implemented to fabricate a large variety of electronic devices using a wide range of nanoparticle (NP)-based inks, including metals, semiconductors, and dielectrics, on conformal surfaces.4,5 In this method, the printable ink is first aerosolized using a pneumatic or ultrasonic atomizer, and the aerosol is then aerodynamically focused by a sheath gas through a fine nozzle and deposited onto a substrate. AJP enables printing functional NPs and dispersants with a feature size as small as 10 μm.

Achieving a densified, continuous film of printed NPs typically requires thermal sintering at temperatures higher than 200 °C for several hours, where the elevated temperature leads both to the removal of solvents/surfactants and enables the NPs to diffuse and consolidate, resulting in films with improved mechanical, thermal, and electrical transport properties.6–8 The removal temperature of typical stabilizing agents [e.g., polyvinyl chloride (PVC)] ranges from 100 to 260 °C,9 and to achieve sintering, the temperature needs to be elevated above this range. For printing flexible and wearable electronics, exploiting flexible/stretchable substrates with low melting temperatures [e.g., fabrics and plastics such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN)] is necessary. Therefore, a method enabling both the removal of surfactants and sintering at near ambient temperatures presents a technological need.

Recently developed sintering methods including laser sintering, photonic sintering, and plasma sintering have been implemented to meet the requirements of fast and roll-to-roll manufacturing of functional thin films.4,10,11 Spark plasma sintering (SPS) has been the most common plasma-based sintering technique and is well-recognized for being rapid, combining high pressure and high current, and activation by energetic plasma species.12–22 However, this technique utilizes a plasma spark, where the plasma is thermalized (i.e., in equilibrium) and thus acts primarily as a heating source, leading to a rapid increase in system temperature.

Received: July 28, 2021  
Accepted: September 10, 2021
Nonthermal plasmas are an alternative plasma regime characterized by nonequilibrium, where the electrons are energetic (∼1−10 eV or ∼10,000 K), but the ions and surrounding gas are much colder and can even stay around ambient temperature. They offer an attractive alternative to SPS because they can overcome the temperature restrictions required of delicate and flexible materials. In this case, low-temperature sintering is presumed to be driven by energetic plasma species mobilizing the surfaces of NPs rather than a temperature. Low pressure nonthermal plasma sintering has been implemented in vacuum chambers with pressures of 0.1−2000 mTorr and with powers of 10−900 W using radio frequency (rf) plasmas. Others have demonstrated atmospheric pressure plasma sintering utilizing rf-powered electrodes or plasma jets with heated plates (<150 °C) and obtain electrical conductivities close to bulk values.

Near-room-temperature (∼60 °C) chemical sintering of silver (Ag) NPs has been proven effective depending on major factors such as NP size, the amount of surfactant, sintering temperature, and film morphology. Studies have also showed that sintering is even possible at room temperature with the presence of charged photoelectrolytes and chloride ions, while others have demonstrated that aqueous Ag NP inks can be utilized to obtain conductive films by drying for 24 h in air at room temperature. These studies demonstrated electrical conductivities on the order of 10^7 S/m, which is similar to conductivities achieved with the various aforementioned plasma sintering methods. The advantage of utilizing plasma systems in sintering is their adaptability for high quantity processing without requiring synthesizing or washing steps to adjust a specific amount of chemicals and solvents.

Here, we present a plasma jet processing method for sintering aerosol jet printed silver NPs at temperatures suitable for delicate substrates including papers and fruits. A plasma jet is composed of flow-guided ionization waves that are weakly ionized, highly reactive, and low temperature, suitable for interacting with sensitive surfaces. Plasma jets have been used extensively for tissue engineering and wound healing and for treatment of liquids. The propagation and electrical characterization of plasma jets have been studied and well-described in the literature. Therefore, fundamental knowledge of plasma jets can easily be adapted for sintering within the context of plasma–surface interactions.

In this work, we demonstrate the capability of atmospheric pressure, ambient temperature plasma jets to sinter printed Ag NPs without the need for external pressurizing equipment, vacuum chambers, or heating sources. Our studies show that the substrate temperature can be maintained below 50 °C throughout the process by applying the plasma periodically (on/off). With a deposited power of 12 W during the on period and a total sintering time of 100 min, we achieve an electrical conductivity of 1.1×10^6 S/m for printed films on glass. Moreover, sintering of the printed films on PEL blotting paper produced an electrical conductivity of 1.4×10^6 S/m using a plasma power of only 6 W, implying improved energy transfer from plasma species to a film printed on porous paper. Finally, we also demonstrate sintering on delicate substrates including the flesh of a ripe tomato, a leaf, and flexible plastic, with no apparent damage. These results reveal the potential for atmospheric pressure and low temperature sintering for printed flexible electronics.

2. RESULTS AND DISCUSSION

Colloidal silver NP inks were printed using the AJP technique. Silver ink with 30−50 nm particles was printed on various substrates (Figure 1a), including glass (∼1 mm thick) and PEL P60 blotting paper (∼0.1 mm). After printing, the films were...
sintered with a plasma jet and the electrical conductivity of the sintered films was measured using the van der Pauw method (details in the Experimental Section).

The plasma sintering apparatus consisted of a plasma jet that operates in a cylindrical volume dielectric barrier discharge configuration using a quartz tube, with an external concentric copper tape as a ground electrode and a 1.2 mm diameter axially centered stainless-steel rod inside the tube as a powered electrode (Figure 1b). To form the plasma jet, argon (Ar) was flowed through the quartz tube at 1500 mL/min into a continuously filled (10 mL/min) nitrogen (N$_2$) cubic plexiglass chamber (40 × 40 × 40 mm$^3$) to control the gas composition (Figure 1c). A 7.5 kV peak-to-peak sinusoidal voltage at 50 kHz was applied to the powered electrode, resulting in 6–12 W of power deposited into the plasma, depending on the substrate. See additional electrical characterization details in the Experimental Section. The ignited Ar plasma jet propagated down the tube for 35 mm and then expanded in N$_2$ at a gap of 5 mm from the substrate such that the diameter of the impinging jet on the substrate was roughly 4 mm.

A typical experiment included in situ substrate temperature measurements using an infrared (IR) camera. To avoid possible interference with IR radiation from the plasma itself, the sample substrate was mounted on a 0.2 mm black tape with an emissivity of 0.92, and the IR camera was directed at the back of the tape. The temperature difference between the front surface and back surface of the substrate was determined to be around 0.6 °C based on both experimental measurements and COMSOL simulations. Note that the camera accuracy is calibrated within ±2 °C or ±2% of the reading. Therefore, the camera measurements at front and back surfaces are within the given uncertainty values, and the back-surface temperatures can effectively approximate the front surface temperature of the substrate. The IR image was calibrated in preliminary tests against a thermocouple mounted on a sample itself, enabling us to deduce sample temperatures from IR images (Figure 1d). The plasma jet was also characterized by optical emission spectroscopy (OES) detecting Ar emission lines showing that the electron temperature in the plasma was approximately 0.79 eV (see Supporting Information S1 for details), consistent with typical values reported for plasma jets.50

The plasma jet sintering process consisted of cycles in which the plasma jet was turned on and off periodically. One cycle consisted of an active plasma time (30 s) followed by a cooling time (30 s), for a duty cycle of 50%. To achieve uniform sintering across the printed film, we printed 2 × 2 mm$^2$ thin films (Figure 1b) that were entirely covered by the plasma jet impinging on the surface. Aerosol jet printed silver NP films were printed with a single pass, and the printing parameters are presented in Table S1 of Supporting Information.

As illustrated in Figure 1e,f, the low-temperature nature of the plasma sintering process enabled printing and sintering on highly delicate substrates, such as plastics, or even biomaterials such as leaves and tomatoes. Figure 1g,h shows scanning electron microscopy (SEM) images of the silver NP films before and after plasma sintering for 100 min, illustrating that the plasma effectively densifies particles, which is the key for obtaining conductive films.

Under periodic plasma jet operation, the electrical resistance of the printed film was reduced over 6 orders of magnitude in the first 20 min of plasma exposure, as shown in Figure 2, and then continued to decrease by another order of magnitude over 80 min, plateauing at a final value. The initial rapid drop in the sheet resistance is likely due to the removal of surfactants in the ink by energetic plasma ions and electrons that dissociate chemical stabilizers. Energy-dispersive X-ray (EDX) analysis revealed an almost 50% decrease in carbon mass after 20 min of pulsed operation, which can be correlated to the removal of organic compounds (Table S2 in Supporting Information).

The corresponding electrical conductivity of the printed silver films continuously increased as the sintering time progressed, achieving a maximum electrical conductivity of 1.1 × 10$^6$ and 1.4 × 10$^6$ S/m for films printed on glass and PEL respectively. We attribute this slightly higher electrical conductivity on PEL to the porosity of the PEL paper. It is known that nonthermal plasmas can propagate through porous media via both surface ionization waves and microfilaments,51−54 and thus, the plasma jet likely penetrates into the PEL, allowing for greater exposure to the silver NPs. It is notable that the measured conductivity values are lower than bulk silver conductivity (6.3 × 10$^7$ S/m55), suggesting that the films were not fully sintered. However, conductivity values ~10$^6$ S/m are comparable to other plasma-based techniques (see Table 1). Sintering occurs by NPs constructing bridges at their grain boundaries facilitating mass transport and eventually forming a continuous medium leading to enhanced electrical conductivity. Figure 3 shows densification of silver NPs on both glass and PEL paper. While the NPs generally preserved their shapes on the glass substrate, a more dispersed appearance and potentially redeposited particles were observed after 100 min of operation. Conceivably, films on glass experienced a structural transition between 50 and 100 min of operation that led to larger NP clusters and distributed atoms on top of them. In contrast, films on PEL paper formed structures filling the gaps between NPs after 20 min and advanced to a fully continuous medium after 100 min, possibly due to the porous nature of the substrate permitting penetrating energy transfer from the plasma propagating through the pores. SEM images show that the sintering procedure on different substrates may undergo different densification mechanisms over time.

The temperature variation on both the glass and PEL substrates during plasma on and off periods was captured with the IR camera. Figure 4a shows the temperature rising and falling with the corresponding plasma on/off periods for the first 10 cycles. The maximum temperature on glass stayed
below 50 °C, while the thinner PEL paper diffused the heat away more effectively during the cooling period, resulting in lower maximum temperature around 45 °C. Since this is not primarily a thermal process, it is likely that the cooling down time during the plasma-off portion of the cycle does not affect sintering or the conductivity considerably. However, the potential effect of relocation of atoms through necking growth driven by capillary pressure during the plasma-off time cannot be ruled out.\textsuperscript{56}

To confirm that the low-temperature plasma sintering process was not thermally driven, two control tests were conducted by thermally processing similarly printed samples in an Ar oven. A maximum electrical conductivity of 2.65 ± 0.33 × 10\textsuperscript{7} S/m (42% of bulk silver\textsuperscript{55}) was achieved for a thermally sintered film at 300 °C for 2 h. On the contrary, thermally processed films at 50 °C for 100 min were nonconductive, which supports the conclusion that plasma sintering activates the NP ink nonthermally, illustrating its potential for low-temperature surface functionalization applications.

The plasma jet enabled sintering into the submicron film thickness, with effective energy transfer from plasma species to surface NPs propagating to deeper layers. Figure S2 in Supporting Information shows cross-sectional analysis of films on both substrates. A silver film on glass demonstrated interconnected NP islands up to 20% of the entire thickness from the top layer toward the bottom after sintering. For the

### Table 1. Comparison of Different Argon Plasma Sintering Conditions for Silver NP Films on Various Substrates

<table>
<thead>
<tr>
<th>Plasma application</th>
<th>Plasma power (W)</th>
<th>Particle size (nm)</th>
<th>Film thickness (μm)</th>
<th>Process time</th>
<th>Electrical conductivity (S/m)</th>
<th>Maximum operation temperature (°C)</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure Ar plasma</td>
<td>900</td>
<td>23</td>
<td>1</td>
<td>60 min</td>
<td>1.14 × 10\textsuperscript{7}</td>
<td>150</td>
<td>Ma, et al. 2014\textsuperscript{25}</td>
</tr>
<tr>
<td>Low pressure Ar plasma</td>
<td>300</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low pressure Ar plasma</td>
<td>300</td>
<td>5−12 nm</td>
<td>0.5</td>
<td>30 min (pre-drying at 100 °C for 60 min)</td>
<td>1.89 × 10\textsuperscript{7}</td>
<td>100</td>
<td>Pabst, et al. 2013\textsuperscript{50}</td>
</tr>
<tr>
<td>Atm pressure Ar plasma pencil</td>
<td>&lt;20</td>
<td>20−30 nm</td>
<td>0.18</td>
<td>60 min</td>
<td>1.85 × 10\textsuperscript{7}</td>
<td>70</td>
<td>Wolf, et al. 2013\textsuperscript{51}</td>
</tr>
<tr>
<td>Atm pressure Ar plasma jet</td>
<td>6</td>
<td>30−50 nm</td>
<td>0.36</td>
<td>50 min (50 cycles)</td>
<td>6.21 × 10\textsuperscript{6}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Top-view SEM images of (a−d) unsintered and plasma sintered silver films on glass and (e−h) unsintered and plasma sintered Ag NP films on PEL paper. Scale bars are 50 nm.

Figure 4. (a) Maximum surface temperature during sintering with cyclic plasma on and off periods (30 s on/off) on glass and PEL paper. The IR camera has an uncertainty of ±2%. (b) Sinusoidal plasma current measured during the plasma on period of a single cycle for an applied peak-to-peak voltage of 7.5 kV at 50 kHz.

ACS Applied Materials & Interfaces
PEL substrates, almost the entire film transformed into a
unified new phase with larger clusters that were denser at the
top layers. After 100 min of sintering, wavy structures on the
top surface and a thickness reduction of 4–5% were observed.
This deeper penetration of the sintering likely led to achieving
a higher conductivity value on PEL paper than on glass.

For both substrates, we generated the plasma jet using an
applied sinusoidal voltage of 7.5 ± 0.7 kV at 50 kHz to the
powered electrode. Notably, the plasma power for the glass
substrates was calculated to be 11.7 ± 0.2 W, whereas the
power for films on PEL substrates was 6.1 ± 0.6 W. We
attribute this difference in power to the electrical permi-
tivity of the two substrates (\( \epsilon_{\text{glass}} = 11.4, \epsilon_{\text{PEL}} = 1.5 \)), which in turn
affects surface ionization wave propagation for impinging
plasma jets.\(^{16,57,58}\) Surfaces with a larger dielectric permi-
tivity drop more voltage across the plasma column, while surfaces
with a smaller permittivity more effectively enable lateral
expansion of the plasma jet on the surface as surface ionization
waves, until the ionization waves quench due to a lack of
accumulated charges. The change in plasma properties was also
evident in the plasma current traces, as observed in Figure 4b.
The current during the negative half-cycle was substantially
higher on glass compared to PEL paper, resulting in the higher
deposited power for glass substrates.

Plasma jets and similar nonthermal plasmas have emerged as
promising candidates for roll-to-roll processing of value-added
materials.\(^{1,2}\) In terms of applying nonthermal plasmas to
sintering, a number of studies have explored low pressure Ar
plasmas. Compared to these, our plasma jet provides a
significant reduction in power and operating temperature while
also enabling atmospheric pressure processing (Table 1),
which reduces complexity, time, and cost. We note that an
atmospheric pressure plasma pencil study achieved comparable
electrical conductivity values to those we report here, while
improving the film conductivity by 2 orders of magnitude in 2
min.\(^{28,59}\) While the 2 min was remarkably fast, their initial
conductivity, prior to sintering, was orders of magnitudes
higher than ours, possibly due to their ink formulation and
particle size. Our plasma jet also increases the conductivity by
2 orders of magnitude in the first few minutes, which we
attribute primarily to surfactant removal. We note that the
plasma sintering results shown in Table 1 are comparable to
other, primarily chemical, low-temperature sintering meth-
ods.\(^{30–53}\) One advantage of the plasma jet is that it is a
localized process (as shown in Figure 1) and thus offers the
potential for scanned sintering to produce graded conductiv-
ities, which cannot be achieved with purely chemical low-
temperature sintering.

We have also applied this plasma jet sintering approach to
highly curved and delicate substrates. As shown in Figure 5,
a continuous Ar plasma jet with a power of 3 W can successfully
sinter silver NP films on a tomato without any damage to its
surface. Note that the initial data point with the highest sheet
resistance shows that the film was not conductive prior to
sintering. We measured unsintered samples with a two-point
probe multimeter, and the resistance values were above the
measurable scale of our multimeter for all samples. Therefore,
the first point (at 0 min) is an artificial representation of a
nonconductive sample. Figure 5a shows the printed silver film
on a tomato before sintering, and Figure 5b shows the sintered
film after 45 min. Moreover, ambient temperature plasma
sintering can be used for sintering printed pattern on low-
melting-temperature substrates such as PDMS or silicone

Figure 5. Sheet resistance of the printed silver NP film on a tomato. Insets show (a) printed silver film (1 × 5 mm²) before sintering, (b) surface of the tomato after sintering, (c) printed pattern on a silicone substrate attached to human skin during plasma sintering, and (d) aerosol jet printed University of Notre Dame logo (interlocking ND) on a grape. The initial data point at 0 min reflects the upper limit of the multimeter and is only included in the figure to convey the magnitude of improvement in resistance after sintering.

3. CONCLUSIONS

We have developed a low-temperature plasma jet process to
sinter aerosol jet printed silver NP films. An argon plasma jet
sintered the removal of the surfactants surrounding the NPs
and redistributed and densified the remaining particles. The
printed NP films achieved a conductivity of 1.4 × 10⁶ S/m
under ambient plasma operation. Continuously cycling the
plasma jet on and off for 30 s allowed us to control the
substrate temperature below 50 °C. Operating the plasma jet at
a lower power (3 W) enabled sintering of printed structures on
delicate substrates such as tomatoes and human skin under
continuous operation, confirming the feasibility of room-
temperature plasmas for processing electronics on biomaterials.
While the achieved electrical conductivities were not as high as
conventional sintering or the bulk material, it is likely that
sintering is a strong function of the plasma power, as is the
substrate temperature. There is therefore a trade-off between
sintering performance and substrate temperature. Still, these
results show that nonthermal plasma jet sintering has the
potential to facilitate manufacturing processes for flexible
electronic applications on temperature-sensitive components.
Future work by integrating the plasma jet and printing process
holds promise in advancing printing and in situ sintering for
scalable and low-cost additive manufacturing.

4. EXPERIMENTAL SECTION

4.1. Aerosol Jet Printing of Silver NPs. Silver NP films were printed using an aerosol jet printer (AJ 300 system, Optomec, Inc.,
Albuquerque, NM). Clariant’s PRELECT TPS nanosilver conductive
ink with 30–50 nm NPs was diluted with DI water at a ratio of 1:2.5
(ink to water), followed by bath sonication for 30 min. The average
silver NP size was 30–50 nm, and the ink contained ethylene glycol
with 50% solid content. The density, viscosity, and surface tension of
the ink were 1.8 g/mL, 25 ± 2 mPa s, and 35 ± 3 mN/m, respectively.
Prior to printing, an AutoCAD schematic design of the
pattern was loaded onto the printer to generate a toolpath for
printing. An ultrasonic atomizer created a mist of droplets with a size
range of ~1–5 μm that were directed by a carrier gas (N₂) and

ACS Appl. Mater. Interfaces XXXX, XXX, XXX–XXX
https://doi.org/10.1021/acsami.1c14049
deposited onto the substrate. Table S1 in Supporting Information presents the printing parameters. We used glass slides (VWR plain and frosted microslides, USA) with a thickness of 1 mm and PEL P60 paper (Printed Electronics Ltd., UK) with a thickness of ~0.1 mm as substrates. Before printing, the glass slides were first washed with deionized water and isopropyl alcohol, followed by O₂ plasma treatment for 7 min (Harrick Plasma, PDC-001-HP (115 V)/PDC-002-HP (230 V), New York, USA).  

4.2. Characterization. 4.2.1. Plasma Generation and Characterization. The applied sinuousoidal voltage was controlled using a transformer (CMI-5533) and a power amplifier (Powertron, model 50A, RF Amplifier), and the frequency was set using a function generator (Agilent 33220A). The frequency can be varied between 50 and 100 kHz, and the applied peak-to-peak voltage to the entire circuit ranged from 5 to 8 kV. The applied voltage was measured using a high-voltage probe (Tektronix P6015A) and monitored on a digital oscilloscope (Tektronix TBS 2000) with a time resolution of 2 ns. The current trace was recorded across an external resistor (Rᵋ) of 10 kΩ. Charge accumulation was measured across a capacitor Cₛ (2.2 nF). Oscilloscope data were extracted with 8-bit resolution and a sampling rate of 250 MΩ/s. The average deposited power to the plasma was calculated via

\[
P_{\text{plasma}} = \frac{1}{T} \int_{a}^{T} V(t)I(t)\,dt - \frac{1}{2} Cₛ Vᵋ^2
\]

where \(T\) is the period of one sinusoidal cycle, \(Vᵋ\) is the total applied voltage, \(V(t)\) is the voltage across the resistor, and \(I(t)\) is the total current. OES was conducted with a Shamrock 303i Andor spectrometer with 0.1 nm wavelength resolution and a high-speed Andor iStar Intensified CMOS camera.

4.2.2. Thermal Characterization. A FLIR T420 IR camera was utilized to measure the spatiotemporal evolution of the surface temperature on the back side of substrates. The camera has a thermal sensitivity of < 0.015°C with an uncertainty of 3% that is calculated using the Student distribution.

4.2.3. Electrical Resistivity Characterization. Silver NP films were printed in square patterns (2 × 2 mm²) with four pads on the corners to connect copper leads for electrical conductivity measurements using the van der Paww method. The electrical leads were connected to the printed film using silver paint (Flash-dry silver conductive paint, SPI, USA). After measuring the sheet resistance, the thickness of each film was measured at five different locations using a 2D profilometer (DektakXT, Bruker, USA). The reported conductivities are the average value of five measurements with a corresponding uncertainty of 3% that is calculated using the Student’s t distribution at 95% confidence for all values. Repeatability was assessed by conducting a series of tests for different sintering times (\(N = 3\) at each time) under slightly different conditions (4000 sccm of Ar and 10 sccm of N₂ in the environment, yielding 4.5 W and 7.5 W for PEL and glass substrates, respectively) and determining the coefficient of variation for the measured sheet resistance (see Figure S3). The coefficient of variation for the sheet resistance ranged from 73 to 62% for glass and PEL substrates, for 20 min time due to partial sintering, to 8 and 20%, respectively, for 75 min when the film was fully sintered.

4.2.4. Scanning Electron Microscopy. A scanning electron microscope (Helios G4 Ux DualBeam (FEI), USA), with a working voltage of 15 kV and a working distance of 4.5 mm, was used for top-view and cross-sectional imaging of the printed silver NP films.

**ASSOCIATED CONTENT**  

Supporting Information  
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.1c14049.  

OES of argon (Ar) plasma jets; cross-sectional SEM images of thin films; AJP conditions; EDX spectroscopy analysis of unsintered and sintered films; and coefficient of variation for the measured sheet resistance (PDF).

**AUTHOR INFORMATION**  

Corresponding Authors  
Yanliang Zhang — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States; orcid.org/0000-0001-7423-8001; Email: yzhang45@nd.edu  
David B. Go — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States; Department of Chemical and Biomolecular Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States; orcid.org/0000-0001-8948-1442; Email: dgo@nd.edu  

Authors  
Nazli Turan — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States; orcid.org/0000-0002-1915-3125  
Morteza Saeidi-Javash — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States  
Jiahao Chen — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States  
Minxiang Zeng — Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, Indiana 46556, United States; orcid.org/0000-0002-3513-9200

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acsami.1c14049

Author Contributions  
N.T. and M.S.-J. contributed equally to this work.

Notes  
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**  
This material is based upon work supported by the US Air Force Office of Scientific Research under Award no. FA9550-18-1-0157, the Department of Energy under Award no. DE-EE0009103, and the National Science Foundation under award CMMI-1747685. N.T. and D.B.G. thank Jinyu Yang for assistance with the OES analysis.

**REFERENCES**  

[https://pubs.acs.org/doi/10.1021/acsami.1c14049](https://pubs.acs.org/doi/10.1021/acsami.1c14049)  
ACS Appl. Mater. Interfaces XXXX, XXX, XXX--XXX


