Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information for

Curving Silver Nanowires Using Liquid Droplets for Highly Stretchable and Durable Percolation Networks

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Estimation of gas velocity

The gas velocity can be estimated using Bernoulli's equation. Bernoulli's equation is defined as:

$$\frac{v^2}{2} + \frac{K}{K-1}\frac{P}{\rho} + gz = \frac{v_1^2}{2} + \frac{K}{K-1}\frac{P_1}{\rho_1} + gz_1$$

$$A_1 v_1 = Av$$

where v_1 is the velocity of compression gas in near the air compressor, v is the air current speed near the nozzle, K is the ratio of specific heat at air, P is the compressor gauge pressure, P_1 is the atmospheric pressure, ρ_1 and ρ_2 are air densities evaluated at corresponding pressure, A is the annulus area of air path in nozzle, and A_1 is the tube area of the air compressor.

The air current speed near the nozzle region v can be obtained as:

$$v = \sqrt{\frac{\frac{2K}{K-1}\left(\frac{P}{\rho} - \frac{P_1}{\rho_1}\right)}{\left(\frac{A^2}{A_1^2} - 1\right)}}$$

and v was calculated to be $130\ m/s$.

Estimation of Weber and Ohnesorge numbers

Deformation and breakup of the liquid droplet in the spray coating is determined by the Weber number (We) and Ohnesorge number (Oh).

We is defined as:

$$We = \frac{\rho_g v^2 D}{\sigma}$$

where ρ_g is the density of air, v is the current speed in the near-nozzle region, D is the diameter of a droplet, and σ is the surface tension of the liquid.

Oh is defined as:

$$Oh = \frac{\mu_L}{\sqrt{\rho_L D \sigma}}$$

where μ_L is the viscosity of the liquid and ρ_L is the density of IPA.

If We is more than 10 and Oh is less than 0.1, it is possible to small spherical liquid droplet generation from the breakup. In our spray systems We and Oh are calculated 280 and 0.04, respectively.

Derivation of elasto-capillary length

Here, we assume that IPA completely wet Ag NW. If the length of the NW is longer than the droplet average diameter, the surface energy of droplet can be comparable to the bending deformation energy of NW.

Surface energy (E_S) is defined as:

$$E_S = \sigma \pi d l$$

where σ is the surface tension, d is the diameter of NW, l is the length of the rod. The shape of NW was assumed to be the circle.

The bending energy (E_b) is defined as:

$$E_b = \frac{EIl}{2R^2}$$

where E is Young's modulus, I is the second moment of inertia, and R is the radius of a droplet.

When the surface energy is larger than the bending energy, the NW can be curved and the critical radius of the droplet can be deduced as:

$$R \geq l_{EC} = \sqrt{\frac{EI}{2\sigma \pi d}}$$

where l_{EC} is the elasto-capillary length. If the radius of droplet is larger than l_{EC}, NW can be deformed.

Derivation of buckling length

As the size of the droplet decreases due to the breakup process during spray, the NW inside the droplet should experiences a compressive force. Since both ends of the NW are not supported or fixed, the force applied to both ends can be approximated by the simple Euler buckling theory.

The critical buckling load (F^*) is:

$$F^* = \frac{\pi^2 EI}{l^2}$$

where E is Young's modulus, I is the second moment of inertia, and l is the length of NW.

The maximum compressive force (F_{cross}) from the surface tension under the complete wetting assumption is:

$$F_{cross} = \sigma \pi d$$

where σ is the surface tension, d is the diameter of NW.

The bending deformation can occur when the maximum compressive force overcomes the critical load, and the characteristic length for the buckling (l_b) can be deduced as:

$$l_b = \sqrt{2} \pi l_{EC}$$

where l_{EC} is the elasto-capillary length. In the NW examples used in Figure 1 and 2, l_b was estimated to be 5.3 μm.

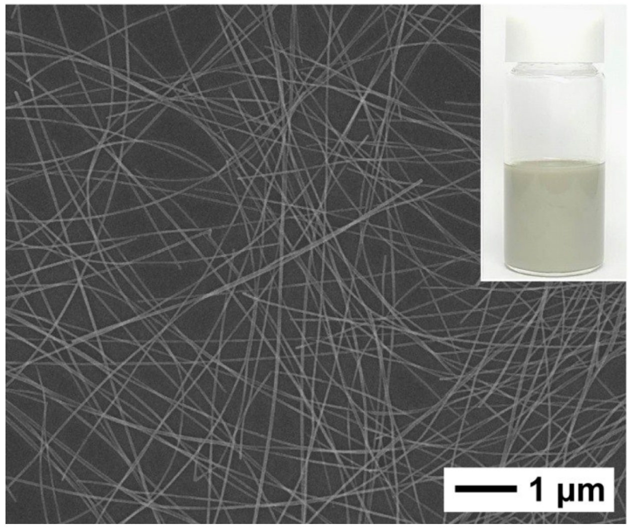

Figure S1. SEM image of commercially available Ag NWs with an average length of 15 μm used in this study. The inset shows a photograph of a Ag NW dispersion in IPA.

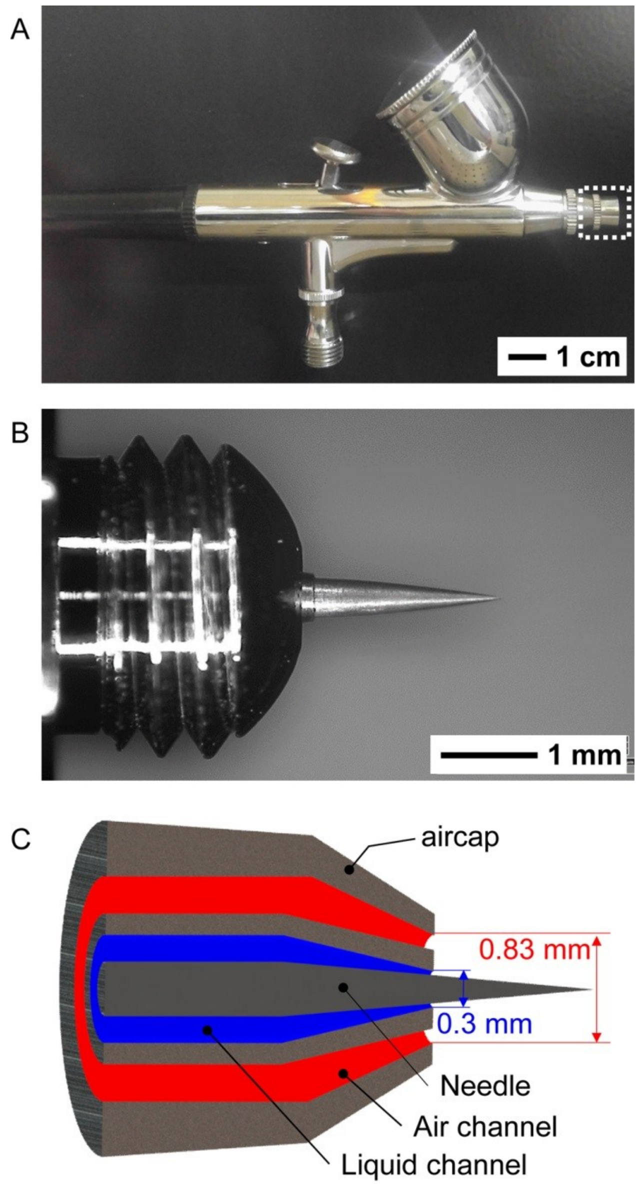

Figure S2. (A) Photograph of an air brush. (B) OM image of the air brush nozzle head (without air cap). (C) Schematic illustration of a cross section of the air brush nozzle head.

Figure S3. Photograph of Spraytec laser diffractometer used for the measurement of droplet sizes.

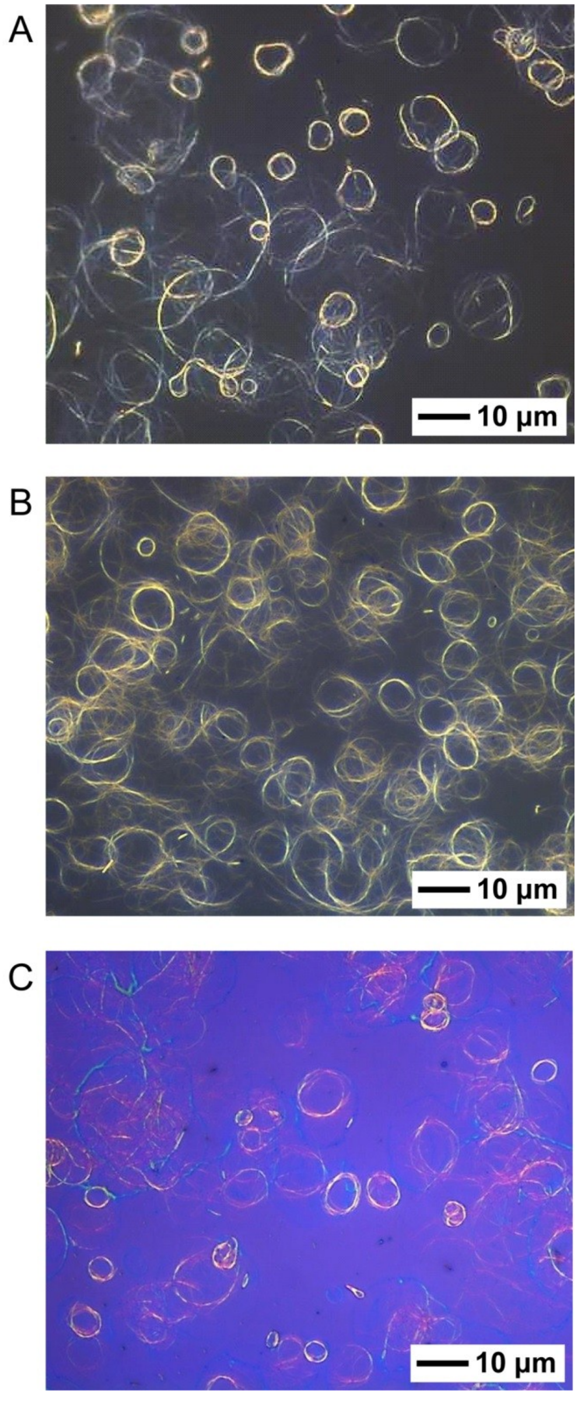

Figure S4. OM images of Ag NW rings deposited on (A) PDMS, (B) PET, and (C) SiO_2 wafer.

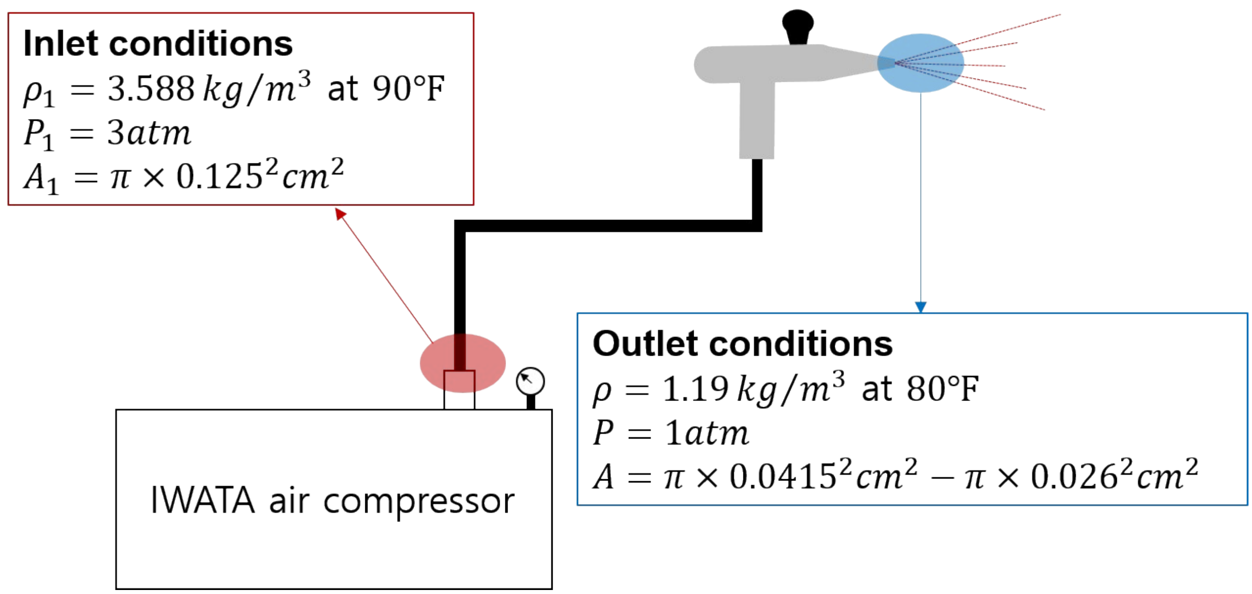

Figure S5. Schematic illustration of spray system, material properties, and operating conditions.

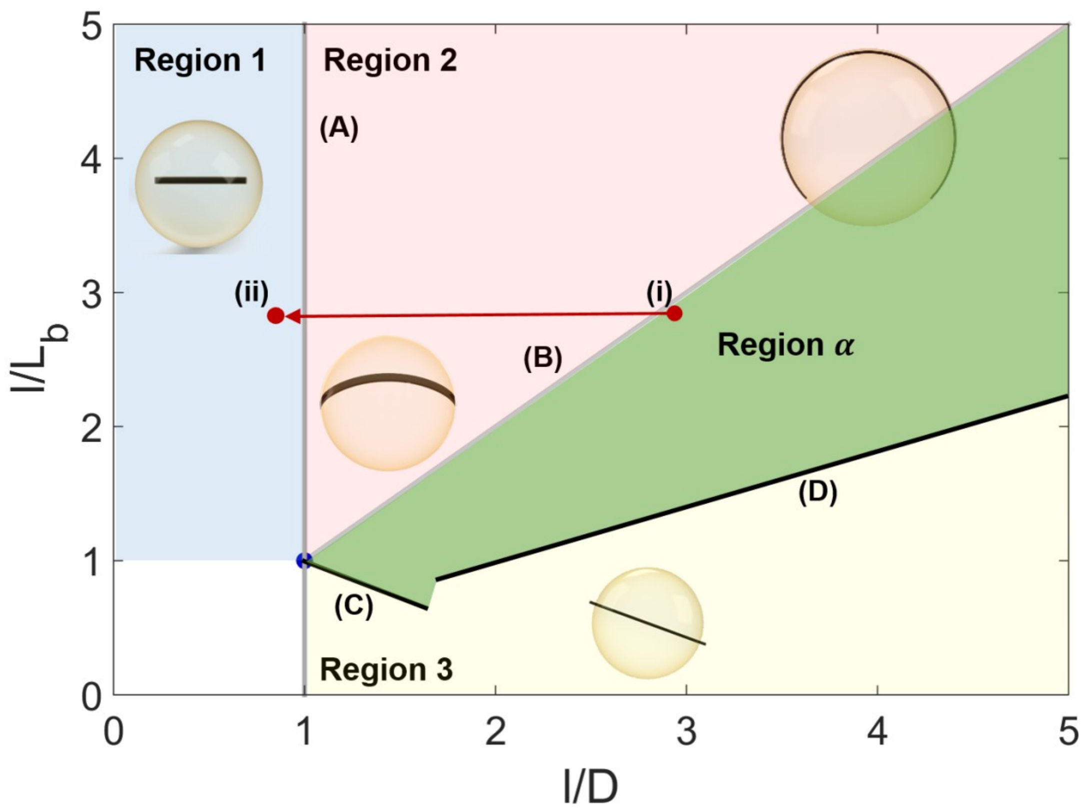

Figure S6. Stability diagram of NW in the droplet based on the model proposed by Cohen and Mahadevan. l_b is the buckling length of our system, l is the Ag NW length and D is the droplet diameter. When the drop size is larger than the length of Ag NW ($l < D$, the left side of the line A), the NW will have straight configuration. When l is relatively smaller than or close to l_b, the NW can penetrate through the drop (region 3, under the line C and D). When the NW is long enough (region 2, $l > l_b$ and $l > D$), it will curved to form a ring pattern. According to Cohen and Mahadevan, both curved and straight configurations are allowed in the region α (below the line B, and above the line C and D). The average length of Ag NW used in Figure 2 and the average size of droplet by the spray system corresponds to the state (i), which strongly suggests that the NW will be curved inside the most of the droplets. If the droplet merged, as explained in the main text, D can increases (l/D decreases), the state (i) can be shifted to the state (ii), which cross the line A. The NW experiences a transition from curved to straight configurations.

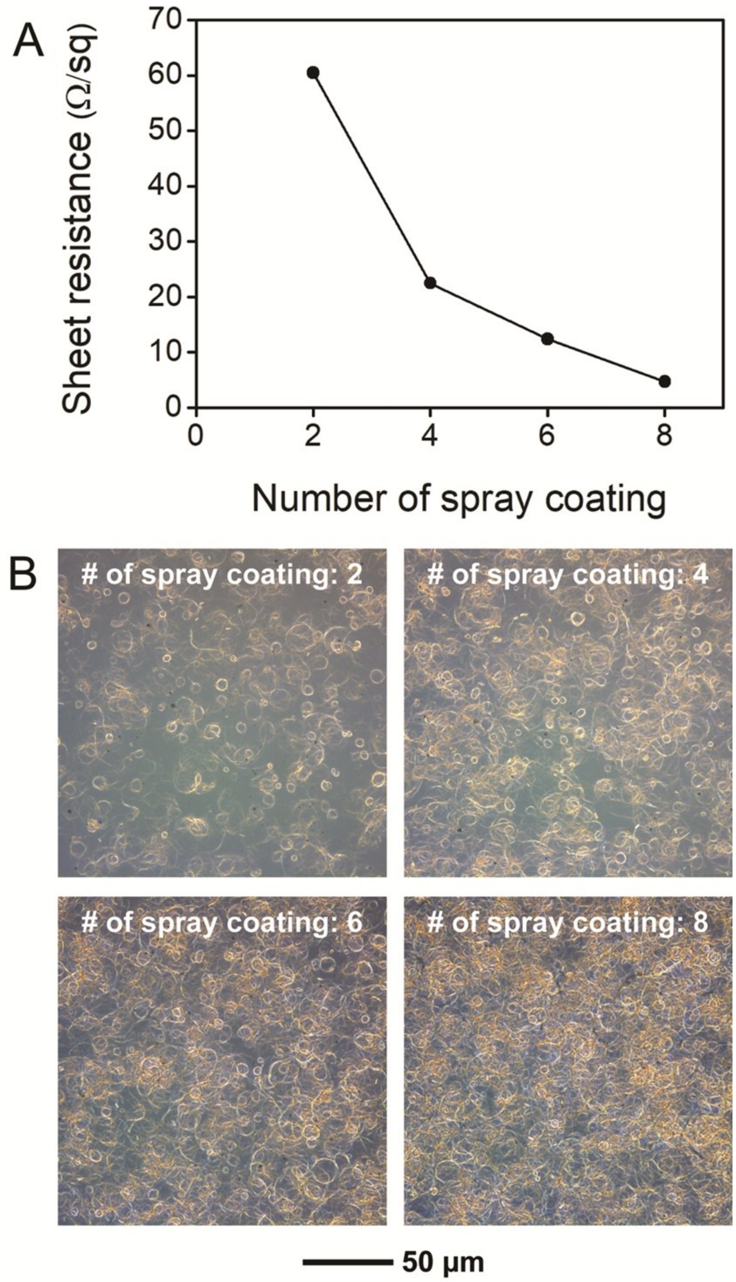

Figure S7. (A) Sheet resistances and (B) optical microscopy images of Ag NW ring films prepared with the different number of spray coating.

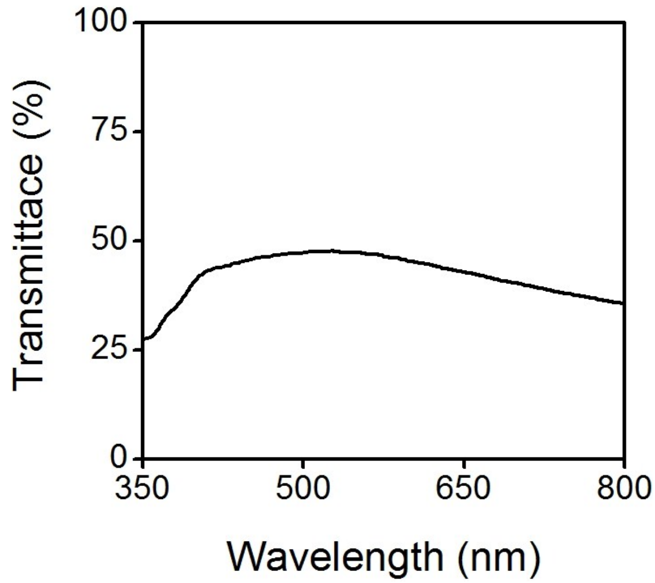

Figure S8. Plot of transmittance versus wavelength for the ring-structured Ag NW electrode shown in Figure 4b.