Supporting Information for "A Robust, Gravure-Printed, Silver Nanowire/Metal Oxide Hybrid Electrode for High-Throughput Patterned Transparent Conductors"

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Images of Gravure Printing Cylinder and Gravure Printer

(a) (b)

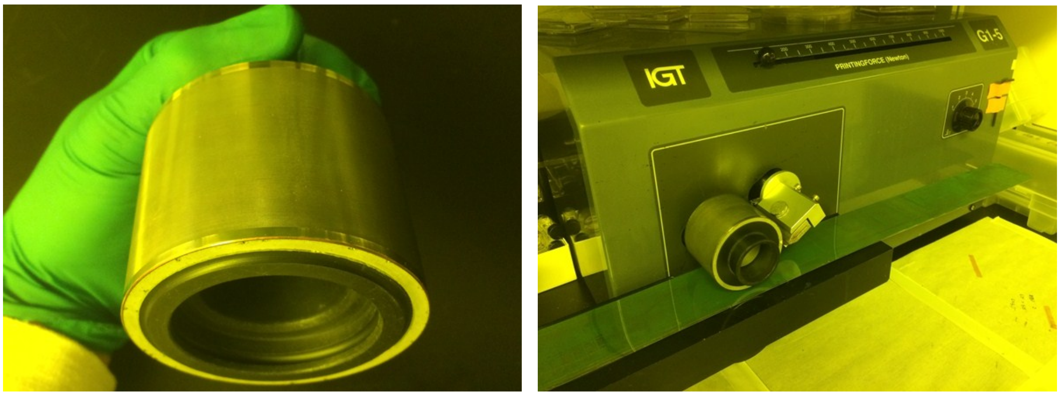

Figure S1 – Image of chrome-coated engraved copper gravure roller (a) and IGT G1-5 benchtop gravure printer (b).

Thickness Measurements of Printed Composite Films:

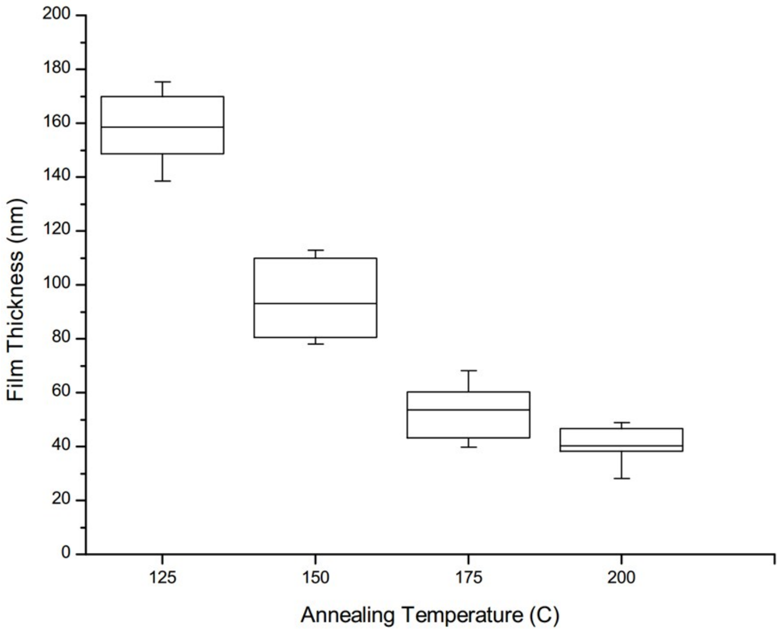

Figure S2 – Thickness of gravure-printed sol-gel IZO films measured by stylus profilometry vs annealing temperature.

Optical Micrographs of printed NW Films:

(a) (b)

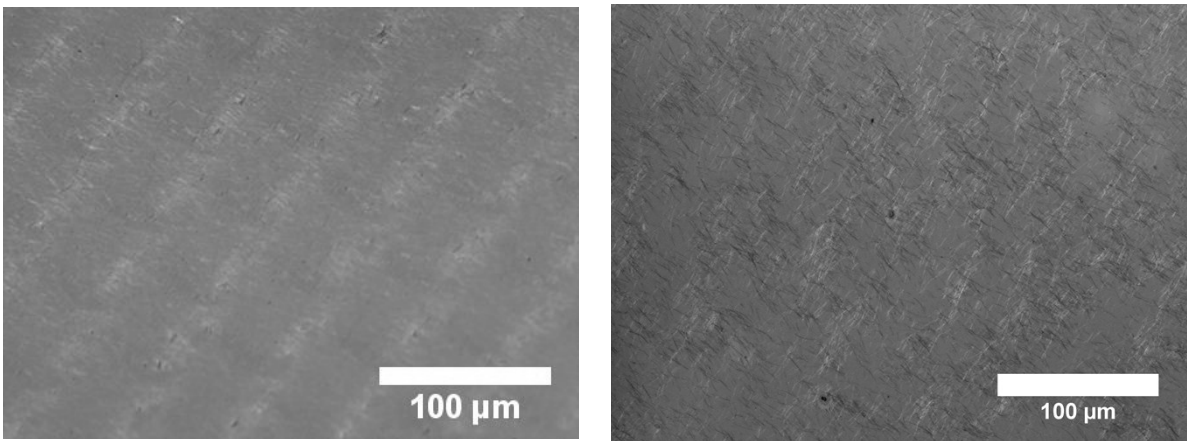

Figure S3 – Textured nanowire film printed from pure Ag NW solution (a). Hybrid film printed from IZO / Ag NW ink (b).

Nanowire Network Modeling:

Each nanowire was modeled as having a resistance per unit length, r_{length}, given by,

$$r_{\text{length}} = \frac{4\rho_{\text{Ag}}}{\pi D^2}$$

where D is the nanowire diameter and ρ_{Ag} is the resistivity of the silver.

A random network of nanowires was then generated with various areal densities of wires, n, nanowire lengths and length distributions. See Figure S3 for examples of generated networks. Each nanowire start, end, and intersection with another wire was taken as a node for the network model. The resistance, r_{ij}, between node i and node j is modeled as,

$$r_{ij} = d_{ij} r_{\text{length}} + R_{\text{int}}$$

for nodes connected by a nanowire and,

$$r_{ij} = R_{\text{matrix}} \frac{N}{2}$$

for nodes connected by the matrix material. In these equations d_{ij} is the distance between nodes, R_{int} is the junction resistance between two nanowires, R_{matrix} is the sheet resistance of the matrix material, and N is the number of nodes.

The conductance matrix, c_{ij}, is generated from $1/r_{ij}$ and the Laplacian matrix, **L**, calculated as,

$$\mathbf{L} = c_i\mathbf{I} - c_{ij}$$

$$c_i \equiv \sum_{j=1}^{N} c_{ij}$$

The resistance between any two nodes α and β is then given by,

$$R_{\alpha\beta} = \sum_{i=2}^{N} \frac{1}{l_i} |\varphi_{i\alpha} - \varphi_{i\beta}|^2$$

where l_i and φ_{ij} are the non-zero eigenvalues and eigenvectors of **L**. Two-point resistances were then calculated for different nodes and different networks and averaged to provide an estimate of the sheet resistance of the composite.

The composite resistance was modeled for various values of n, R_{int} and R_{matrix}. Materials parameters for the silver nanowires were taken from those used in the experimental films (see Table S1). For each condition 4 random networks and 6 two-point resistances were generated giving 24 values to average over. The modeled area of each nanowire network was 50×50 µm^2 or 100×100 µm^2.

Parameter	Value	Unit
ρ_{Ag}	0.0159	Ω.µm
D	0.033	µm
Average NW length	14	µm
Standard deviation of NW lengths	4	µm

Table S1 – Parameters used in nanowire network model

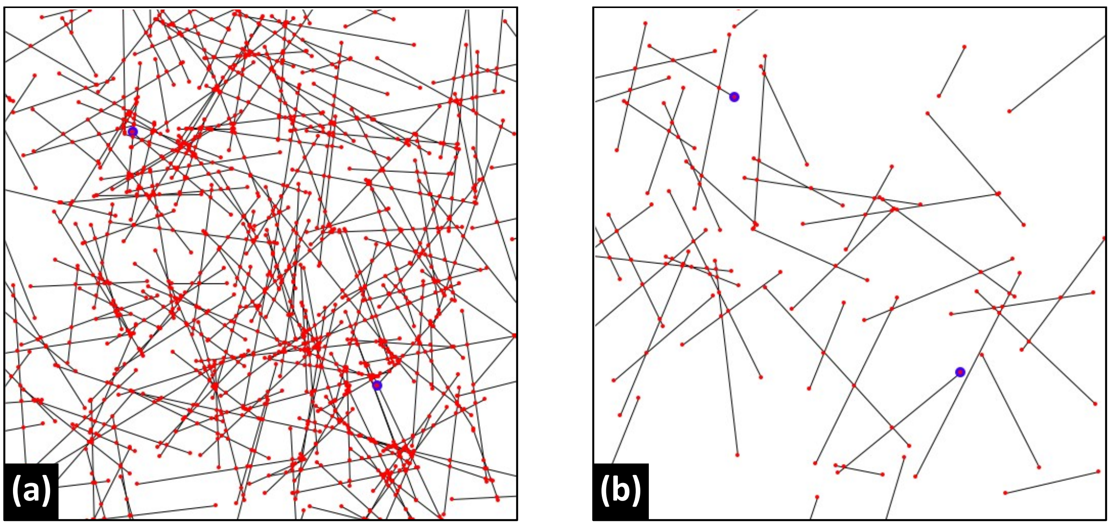

Figure S4 – Examples of nanowire networks generated using the described model. (a) n = 0.1 μm^{-2}, (b) n = 0.02 μm^{-2}. Substrate areas are 50×50 μm^2 in both cases. Every node in the model is marked by a red dot; example 2-point resistance test nodes are also marked with blue dots.

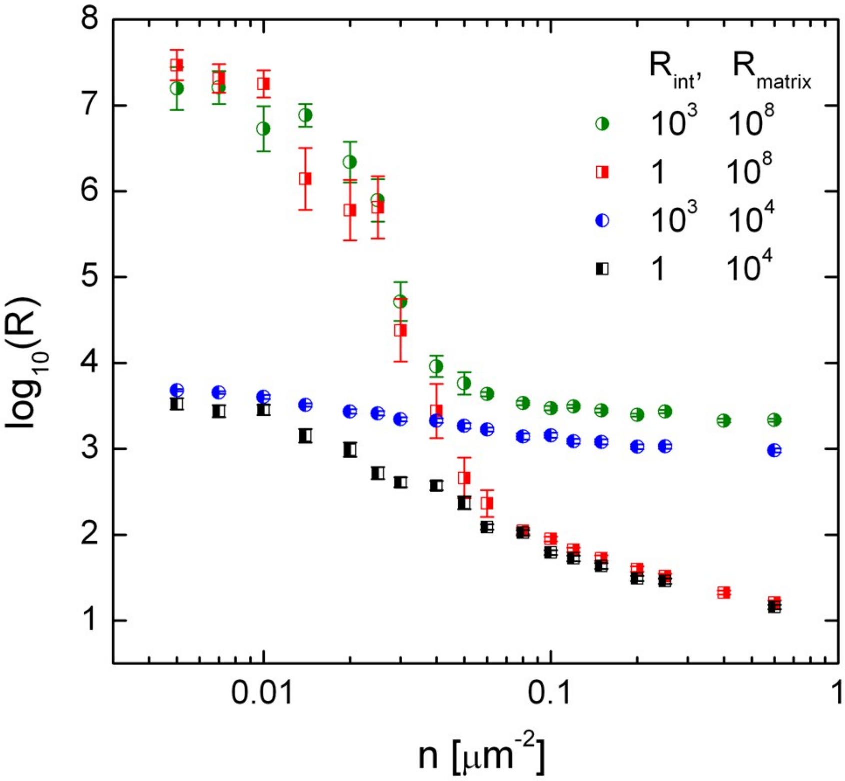

Figure S5 – Results of computational models for nanowire networks. The average resistance, R, is shown as a function of the areal density of wires, n, for four conditions with different matrix resistances, R_{matrix}, and junction resistances, R_{int}.

(a) (b)

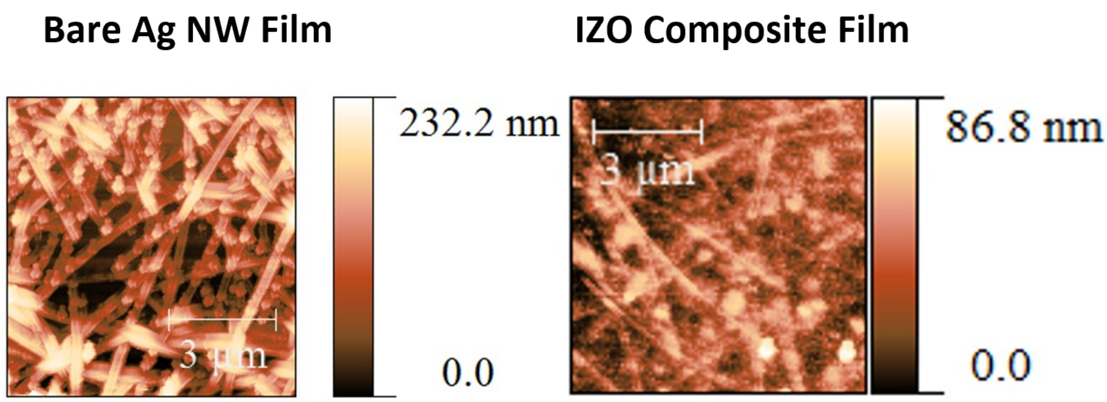

Figure S6 – AFM scans of gravure printed bare Ag NW films (a) and hybrid IZO / Ag NW films (b) printed from 5 mg/mL Ag NW mass-loading inks.