Electronic Supplemental Information

Wired for Stability: Evaluating Electrical Performance in Zinc Oxide-Modified Silver Nanowire Solution-Processed Transparent Electrode

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Experimental

Formation of AgNW/ZnO transparent electrodes. Transparent electrodes (TE) were deposited using spin coating at various speeds and concentrations of AgNW/IPA dispersions as to determine the optimal transmittance/sheet resistance and the concentration of the percolation threshold. AgNW/IPA dispersion with a ratio of 1:1 was coated at 1000 rpm for 30s on previously cleaned glass substrates, after which it was thermally annealed for 15 minutes at 230°C to induce welding at AgNW junctions i.e., between AgNW in contact. Subsequently, ZnO NPs/DI water dispersion (ZnO NPs were synthesized through a modified sol-gel approach according to Sun et al. [1]) was coated at 2000 rpm on top of AgNW. The number of coating ZnO layers 1 (AgNW/1x ZnO), 2 (AgNW/2x ZnO) and 3 (AgNW/3x ZnO), with the system being annealed after each ZnO deposition at 140°C for 1h to ensure the removal of any excess solvent.

Sample preparation. Scanning electron microscopy was performed on FEI Helios Nanolab 660 DualBeam FIB (2–20kV operating voltage, 0.1 and 1.6 nA operating current). A carbon coating followed by a platinum coating were deposited prior to FIB milling in order to protect the AgNW/ZnO networks upon exposure to the gallium ion beam, which would otherwise amorphize the structure. FIB was used for lamella lift out from sample (cross-section of AgNW coated with ZnO layer), which was thinned down below 100 nm in thickness. This was performed in order to enable high quality TEM and scanning transmission electron microscopy (STEM) investigations on the TITAN3 Themis 60–300 double aberration corrected microscope, equipped with the Super-X energy dispersive spectrometry system controlled with Bruker Esprit software.

Method for determination of crystallite size. The average crystallite size of 22.11 ± 8.29 nm was calculated from the XRD peak pattern from the Debye Scherrer equation such that multiple peaks are used to give an estimate of the crystallite size with taking account the many factors affecting peak broadening:

$$D = \frac{K\lambda}{\beta_{hkl} cos\theta} \quad (1)$$

where D is the crystal length, β_{hkl} is the full width at half maximum of the peak, K is the constant related to the crystalline shape in the range of 0.87 - 1.0 (for the hexagonal wurtzite the k constant was taken to be 0.9) and θ is the Bragg angle of diffraction. Analysis of SEM and TEM micrographs gave insight to the size of ZnO NPs to be 29.06 ± 11.78 and 27.34 ± 7.55 nm, respectively. It must be noted that the value attained from crystallite size from the XRD pattern is not the same as particle diameter.

Surface roughness measurements. The mean surface roughness (Ra) and root mean square of the surface roughness (Rq) was done using a Dektak150 Veeco profilometer for a hills and valleys profile with a duration for each scan being 120s, a resolution of 0.139 μm/sample and a length of scan of 5000 μm.

Voltage ramp measurements. To determine the behavior of TE under electrical stress, voltage ramp measurements provide a way to apply a gradually increasing voltage to the electrode while measuring its electrical properties. The samples analyzed were subjected to a constant voltage ramp of 0.6 V/min, where the sudden increase in resistance of the TE means irreversible degradation to the samples.

Plateau voltage ramp measurements. Applying a constant voltage in steps at a set interval gives more insight into the electrical stability of a TE. The voltage plateau measurements were applied for 15 minutes each, with a total of 7 steps, with the maximum voltage being 7V. The current fluctuation of the plateau at 5V for AgNW sample (Figure 9b, black line) indicates degradation present, whereas for the AgNW/ 3x ZnO sample the degradation starts at 7V. During the first 4 plateaus, the TE samples exhibit increased heating which leads to degradation, whereas on the last 3 plateaus they cool down.

Cyclic voltage ramp measurements. Voltage ramp cycles provide more insight into the working principle of a TE in a device when the device is working under bias and when there is no bias present. The AgNW and AgNW/3x ZnO samples were measured under high current conditions to test the stability, where the voltage values for each peak were from 4V - 10V and each cycle lasted 2.5 minutes. As the current

increases and the sample reaches a bias of 10V, the AgNW are heated through Joule's law thus welding previously unwelded junctions. This is shown through a decrease in the relative change in electrical resistance as a downward trend for the maximums of these peaks, where the maximums represent the moment the sample exhibits the highest amount of current passing through. The degradation of the uncoated sample of AgNW can be seen as a deviation from the linear maximum that are exhibited for other peaks.

Supplementary Data

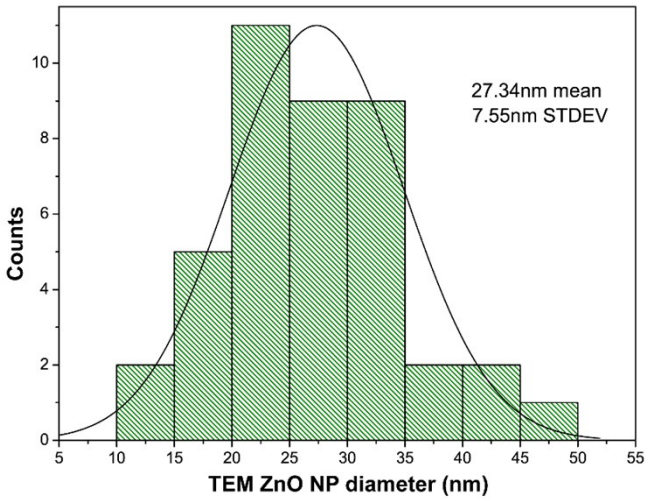

Fig. S1 Histogram of ZnO nanoparticle size distribution acquired from TEM images

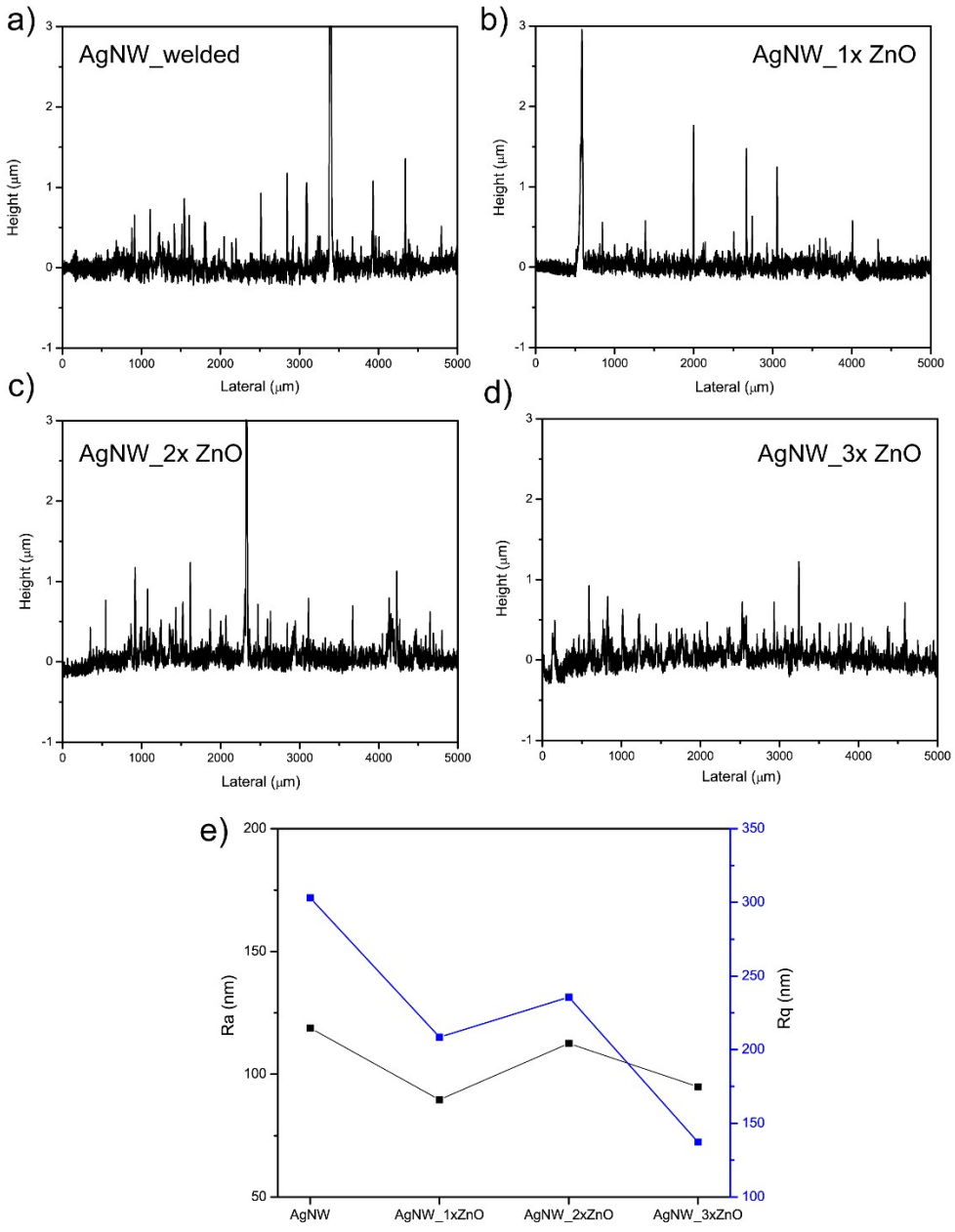

Fig. S2 Surface roughness profilometer measurements for a) welded AgNW, b) AgNW/ 1x ZnO NP, c) AgNW/ 2x ZnO NP, d) AgNW/ 3x ZnO NP and e) Ra and Rq values for these samples.

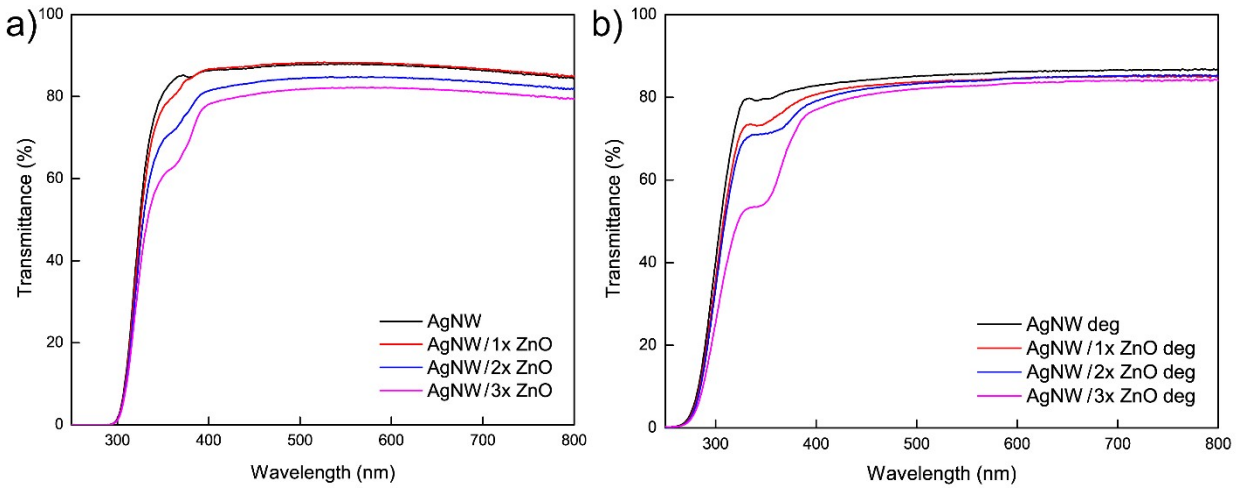

Fig. S3 Optical transmittance of AgNW/ZnO a) before and b) after voltage ramp tests.

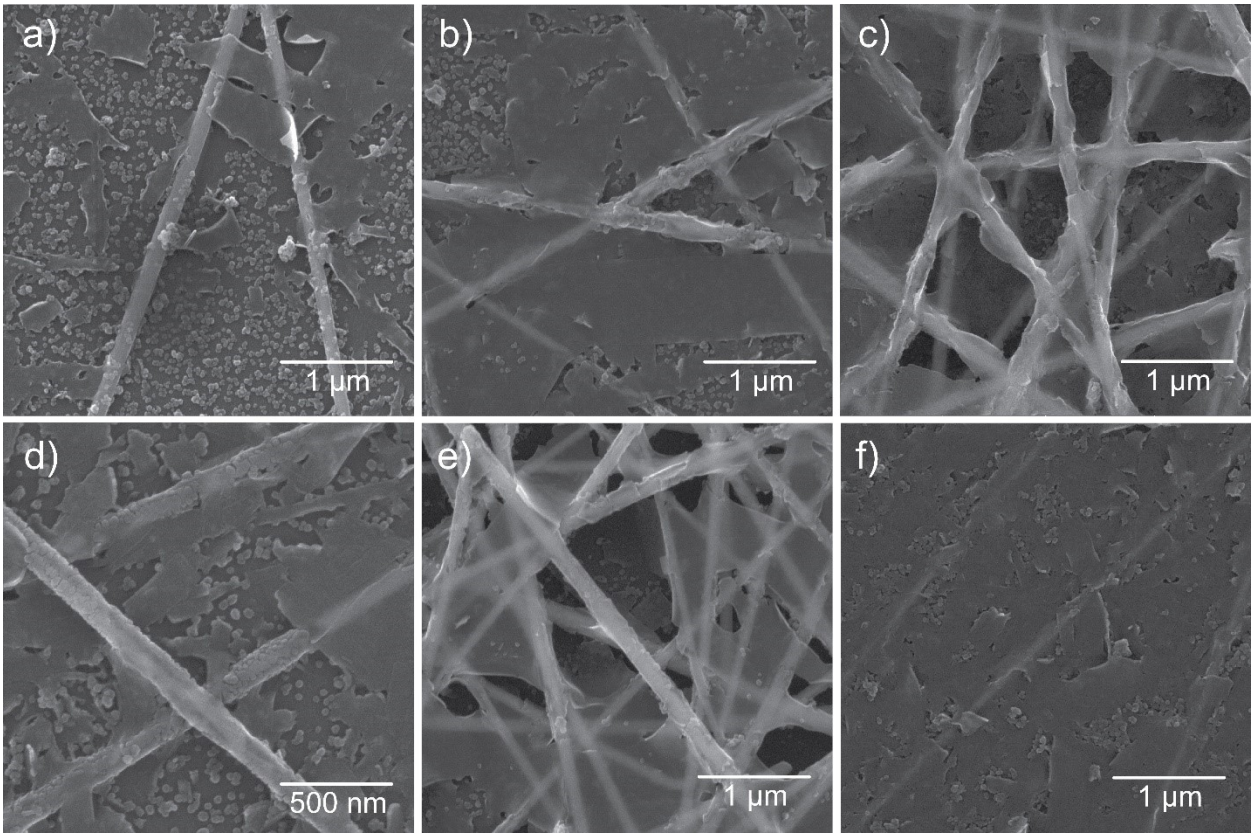

Fig. S4 SEM micrographs of spin coated TE of pristine a) AgNW/ 1x ZnO NP, b) AgNW/ 2x ZnO NP, c) AgNW/ 3x ZnO NP and degraded samples of d) AgNW/ 1x ZnO NP, e) AgNW/ 2x ZnO NP and f) AgNW/ 3x ZnO NP after voltage ramp measurements.

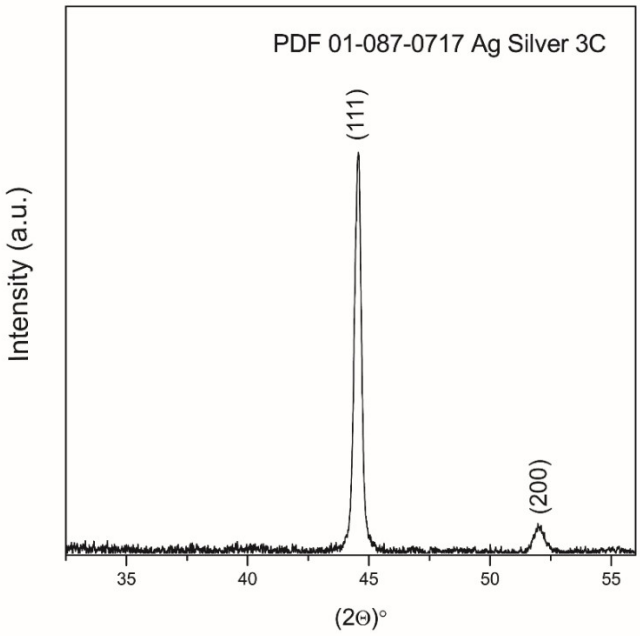

Fig. S5 XRD pattern of welded AgNW, showing characteristic peaks of (111) and (200).

Reference

1 B. Sun and H. Sirringhaus, *Nano Lett.*, 2005, **5**, 2408–2413.