Enhanced oxidation stability of transparent copper films using a hybrid organic-inorganic nucleation layer

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Supporting information

Table S1: The sheet resistance of the different electrode structures investigated. Sheet measurements were made immediately after electrode fabrication.

Abbreviations	**Full Structure (Glass Substrates)**	**Average Sheet Resistance ± Standard Deviation (Ω sq^{-1})** *(Champion)*
MM | Cu	Mixed APTMS:MPTMS monolayer (1:1) | 9 nm Cu	**10.8 ± 0.2** *(10.5)*
MM | Al | Cu	Mixed APTMS:MPTMS monolayer (1:1) | 0.8 nm Al | 9 nm Cu	**8.7 ± 0.1** *(8.6)*
Glass | Cu	9 nm Cu directly on glass	**13.8 ± 0.6** *(13.3)*
Glass | Al | Cu	0.8 nm Al | 9 nm Cu directly on glass	**9.0 ± 0.3** *(8.8)*
PEI | Ag*	PEI (spin coated) | 9 nm Ag	**9.4 ± 0.3** *(9.0)*

*Matching 9 Ω sq^{-1} reported by Kang *et. al.*[5]

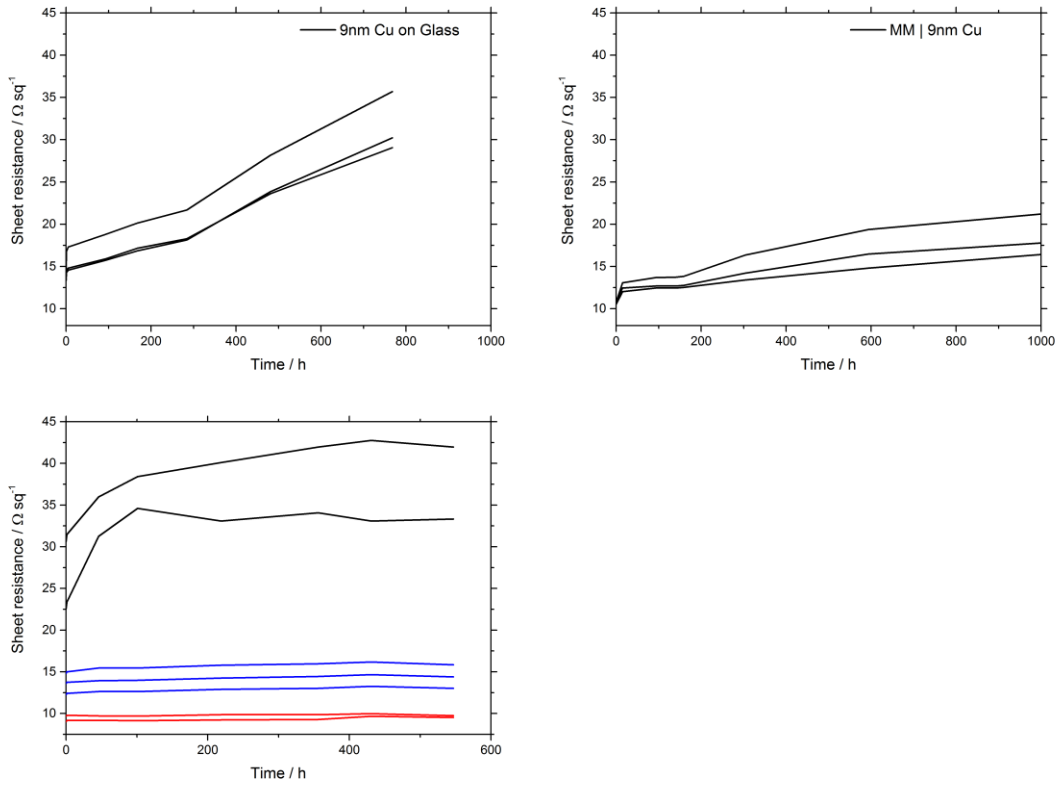

Figure S1: Graphs showing the change in sheet resistance with time exposed to ambient air for the five reference electrode structures given in Table S1. Bottom left graph: (red) 9 nm Ag on PEI; (blue) 9 nm Ag on MPTMS; (black) 9 nm Ag on glass.

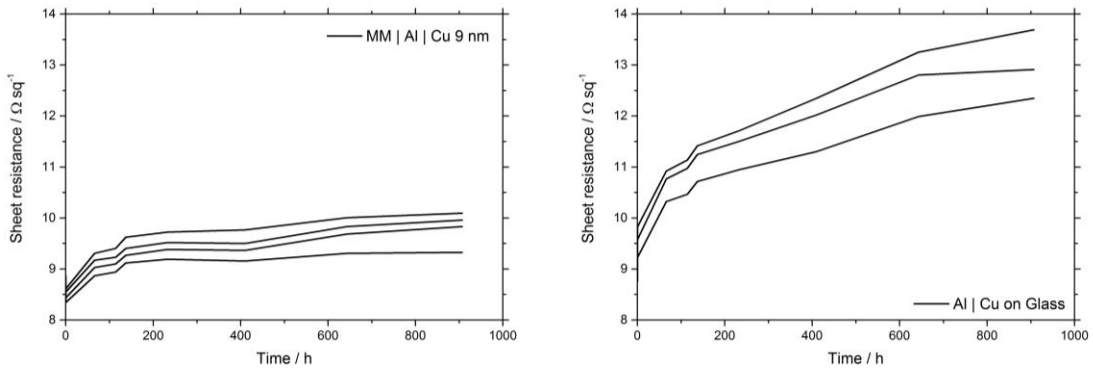

Figure S2: Graphs showing the change in sheet resistance with time exposed to ambient air for Al | Cu films fabricated with and without a mixed monolayer for adhesion (APTMS:MPTMS, 1:1) as in Table S1.

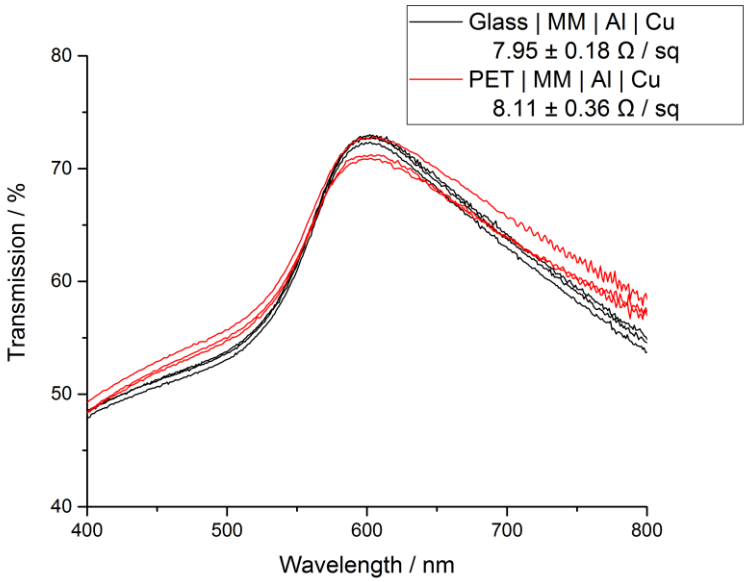

Figure S3: Transmission spectra of evaporated 9 nm Cu films on glass (black) and PET (red) modified with a mixed monolayer (MM) / 0.8 nm Al seed layer. The transparency and initial sheet resistance on both substrates are equivalent.

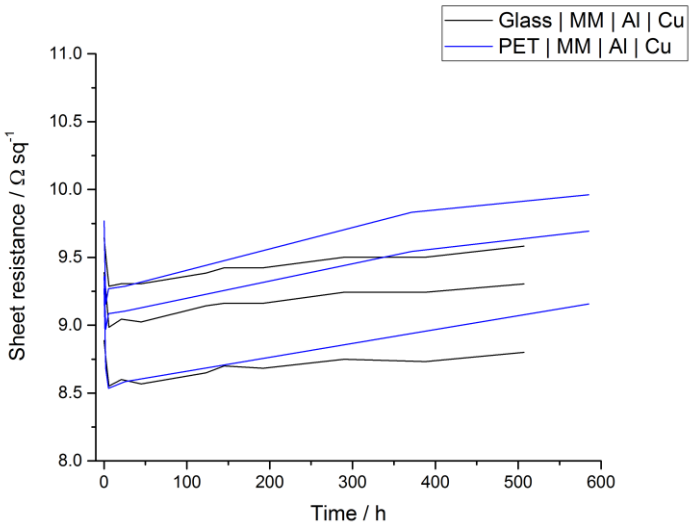

Figure S4: Evolution of sheet resistance with time exposed to air for 9 nm Cu films on glass (black) and PET (blue) modified with a mixed monolayer (MM) | 0.8 nm Al seed layer.

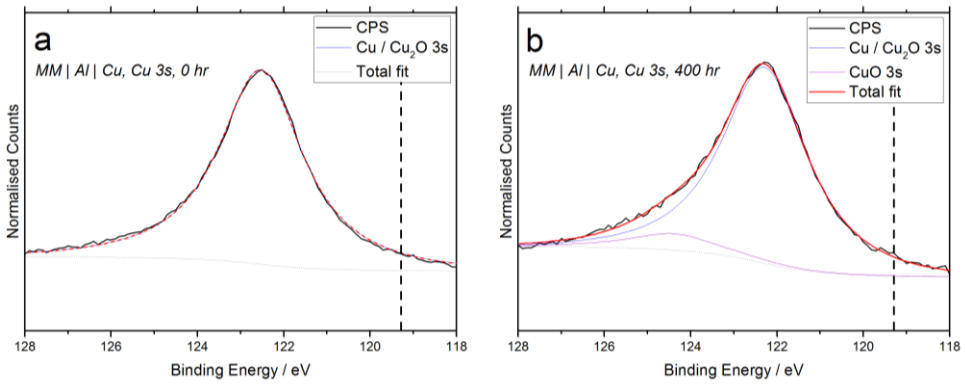

Figure S5: High resolution X-ray photoelectron spectroscopy (XPS) spectra of the Cu 3s and Al 2s region for a glass | mixed monolayer | Al (0.8 nm) | Cu (9 nm) electrode; before (a) and after (b) exposure to ambient air for 400 hrs. The dotted line at 119.3 eV indicates where Al 2s peak associated with aluminum oxide would appear if present. The X-ray beam was incident normal to the substrate and so the sampling depth is approximately 6 nm.

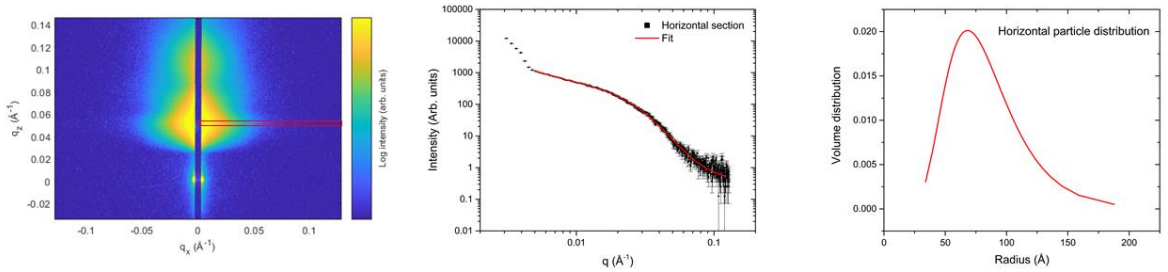

Figure S6: (Left) An example 2D detector image from GISAXS of a MM | Cu (9 nm) film, with the horizonal section used to extract particle radii highlighted in red. (Centre) The results of fitting the horizontal sub-section using a model based upon a monolayer of spherical particles. (Right) The resultant particle size distribution.

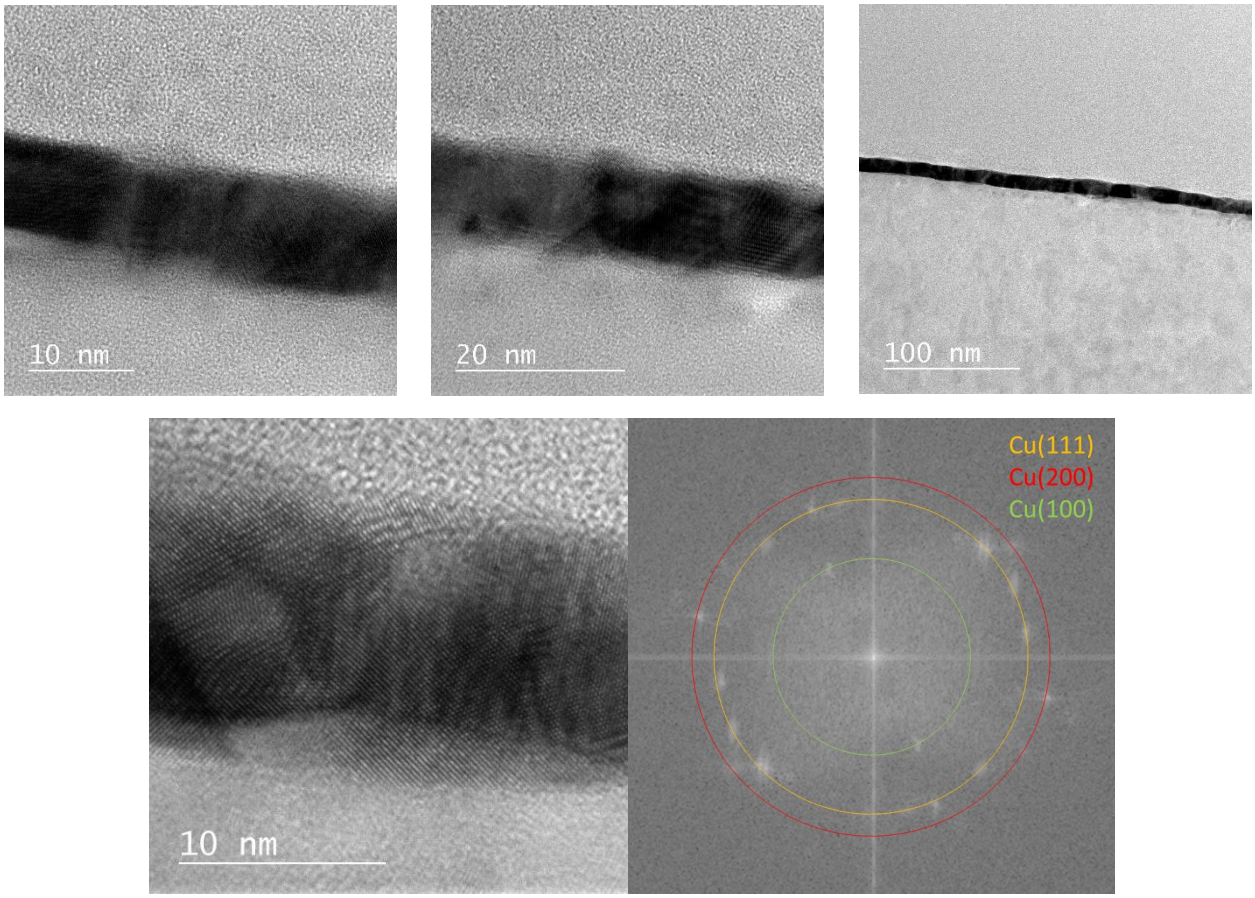

Figure S7: TEM images of the MM | Al | Cu film cross-section which show copper crystallites extending from the upper surface of the film to the underlying substrate. The lower image shows a close up of the section and the corresponding fast Fourier transform. The extracted d-spacings are Cu(111): 0.21 nm, Cu(200): 0.18 nm and Cu(100): 0.35 nm.

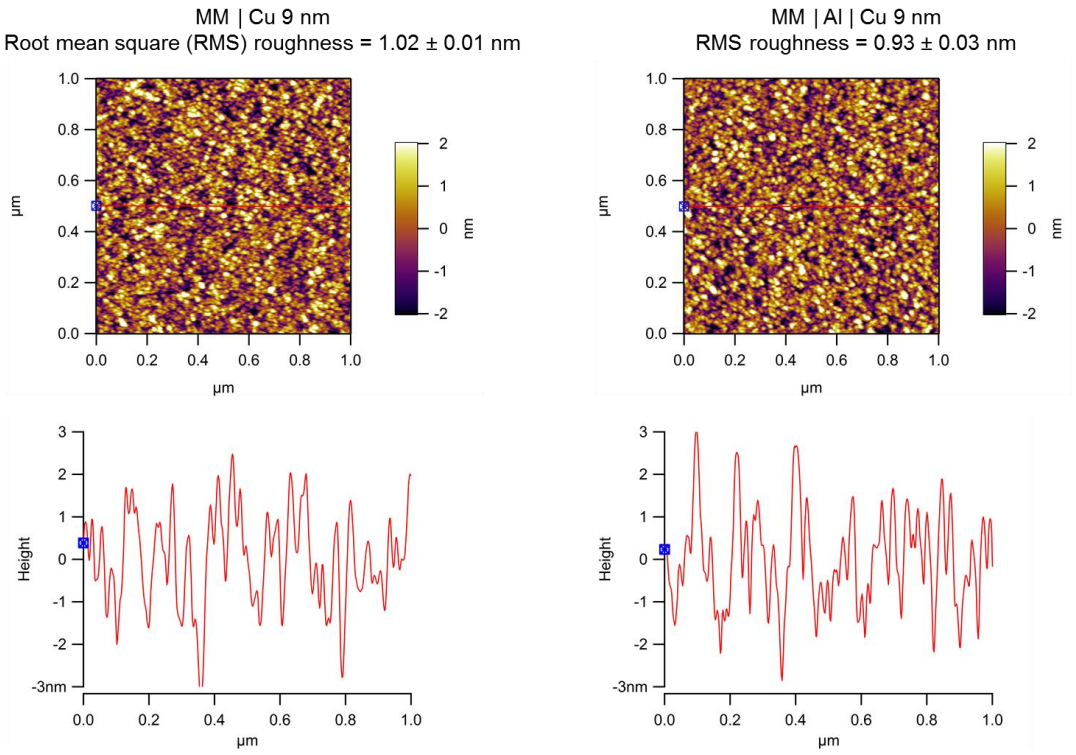

Figure S8: AFM images comparing the surface roughness of two electrode structures; MM | Cu 9 nm and MM | Al 0.8 nm | Cu 9 nm. In the experiment a glass substrate derivatized with a mixed molecular adhesive layer over its whole surface was loaded into the thermal evaporator. One half of the substrate was masked during the 0.8 nm Al evaporation, and then 9 nm copper was deposited over the whole sample without breaking vacuum. In this way the samples are identical in every respect except for the inclusion of the 0.8 nm Al layer.

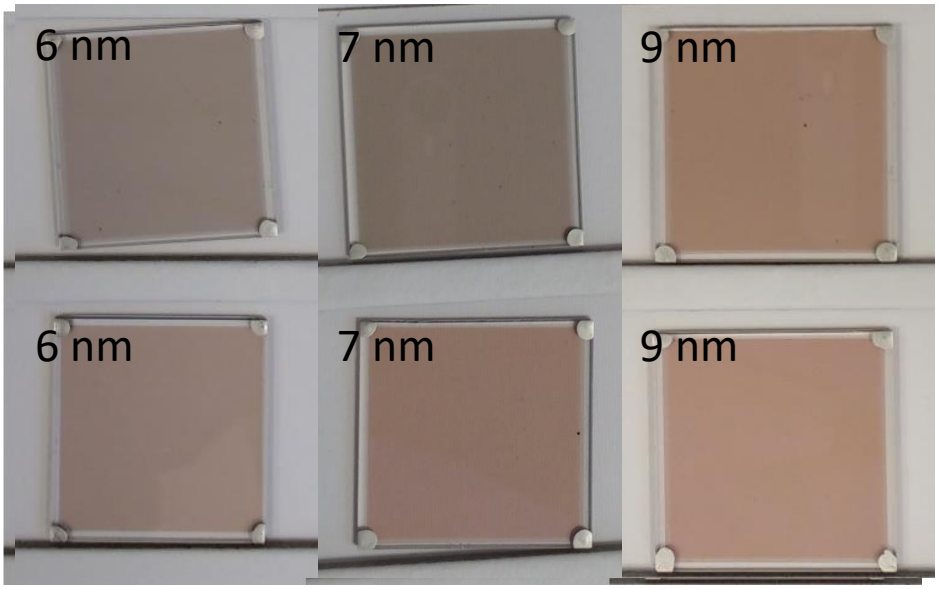

Figure S9: Photographs of two series of copper-based electrodes (Top 3 – MM | X nm Cu, Lower 3 – MM | 0.8 nm Al | X nm Cu). The higher percolation thickness of Cu on MM without an 0.8 nm Al is evident from the dark colouration for films with a Cu film thickness ≤ 7 nm, which is due to excitation of localised surface plasmons associated with a particulate film morphology. The photographs were taken in air within 5 minutes of removal of the glove box.

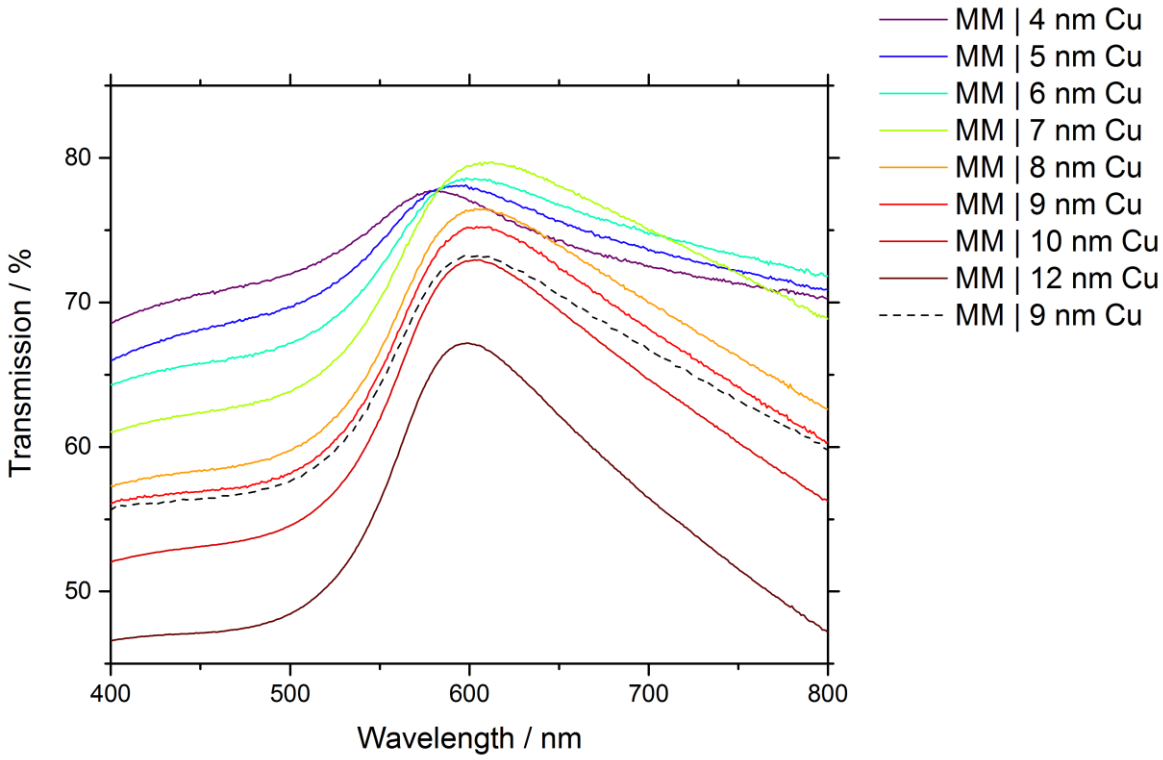

Figure S10: The evolution of the transmission spectrum of thin MM | 0.8 nm Al | X nm Cu electrodes. Measurements referenced to glass substrate to exclude reflection from the glass/air interface.