

Stability Enhancement of Silver Nanowire Networks with Conformal ZnO Coatings Deposited by Atmospheric Pressure Spatial Atomic Layer Deposition

Viet Huong Nguyen, Dorina Papanastasiou, Thomas Sannicolo, Sara Aghazadehchors, Afzal Khan, Carmen Jiménez, Ngoc Duy Nguyen, Daniel Bellet, **David Muñoz-Rojas**

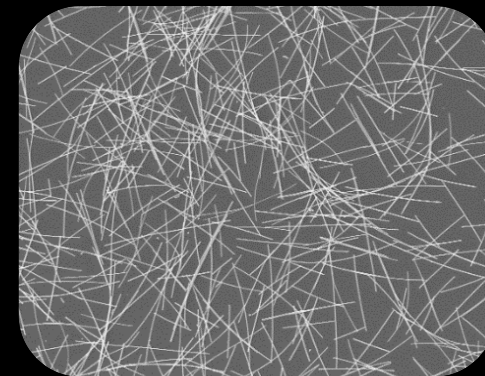
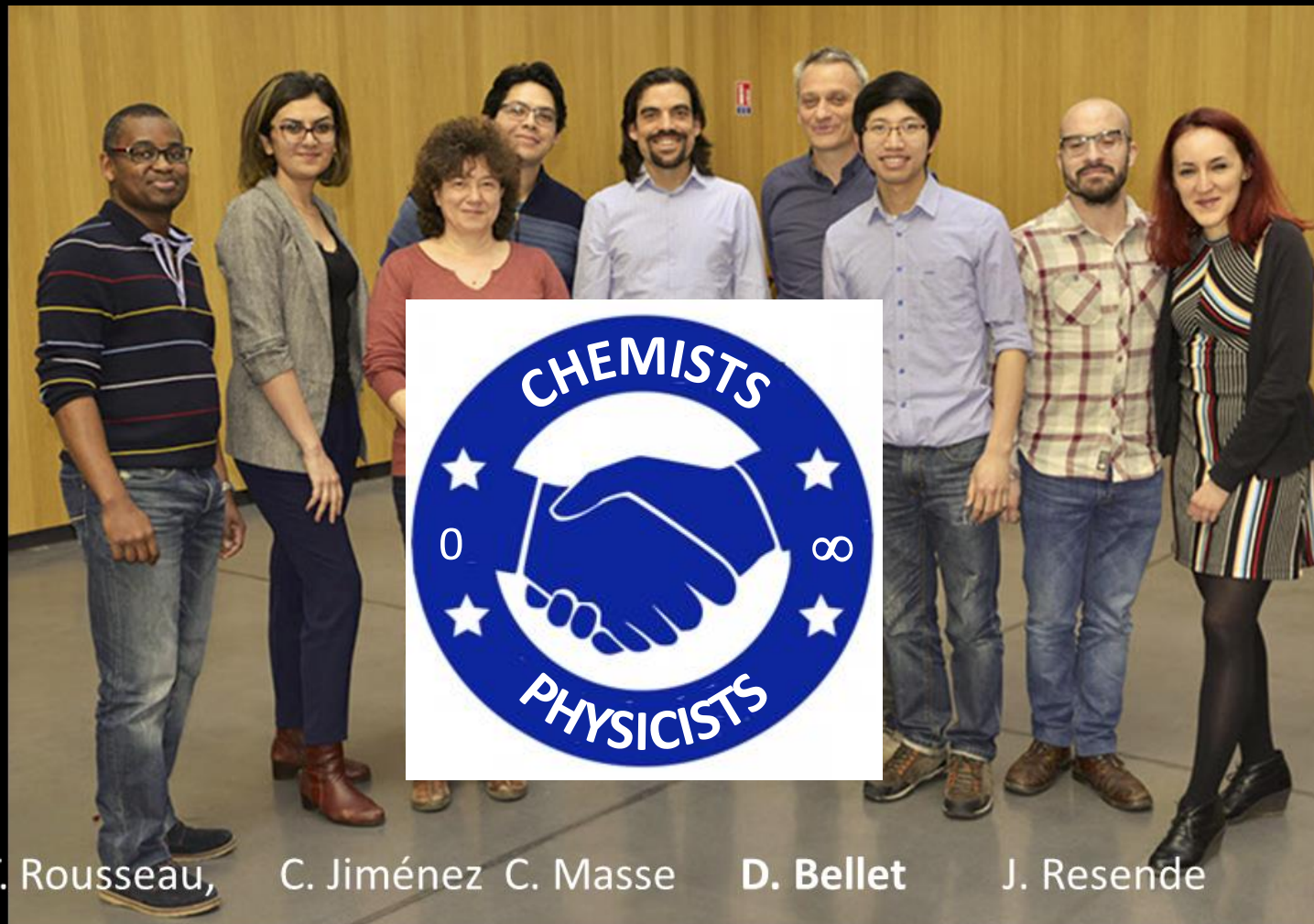
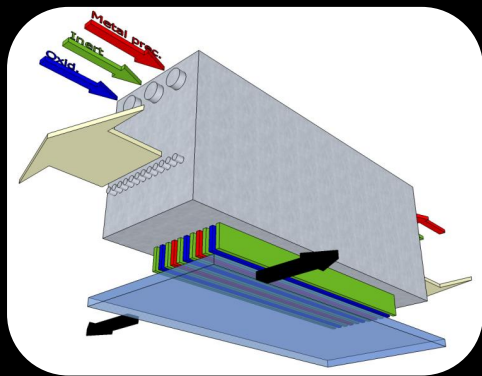
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Laboratoire des Matériaux et du Génie Physique (Grenoble-INP/CNRS)

EuroCVD-BalticALD 2019, 27th June, Luxembourg

SALD Team + AgNWs Team = improved TCM



T. Rousseau, C. Jiménez C. Masse D. Bellet J. Resende

S. AghazadehChors D. Muñoz-Rojas V. Nguyen D. Papanastasiou

Optoelectronic devices



Alternative transparent electrodes are needed...

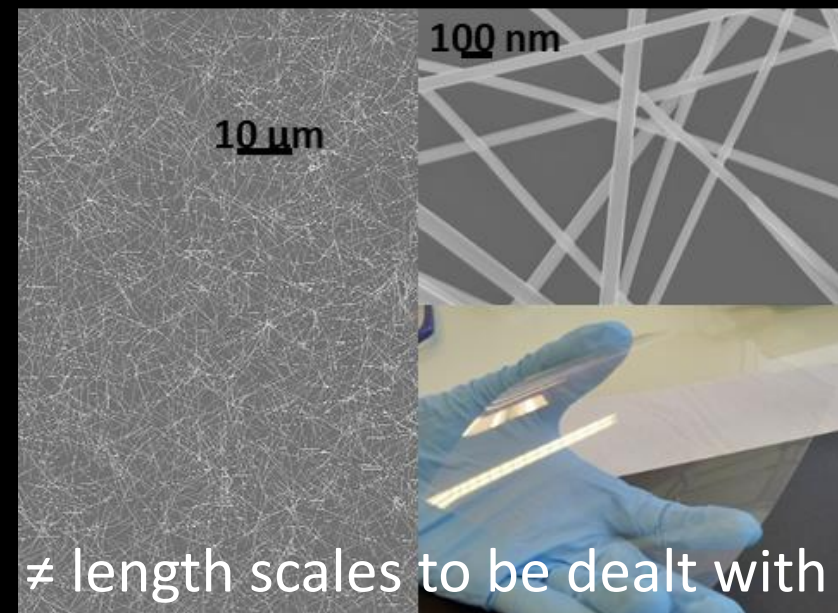
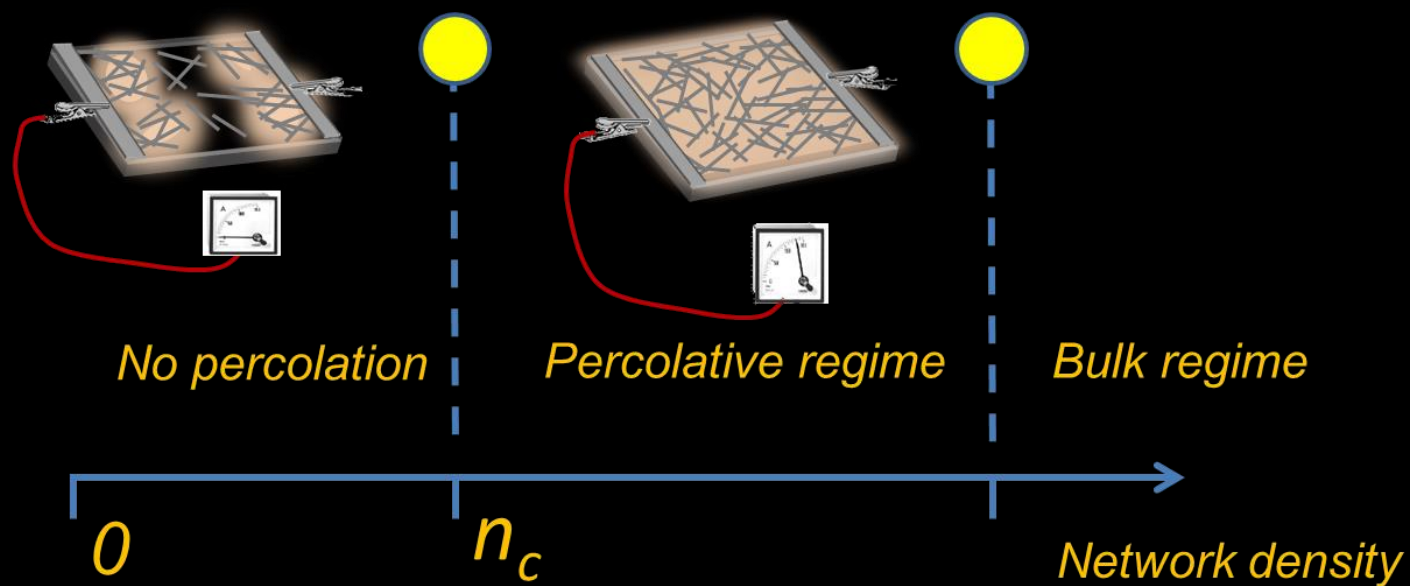
Transparent heaters

Transparent heater for defrosting window

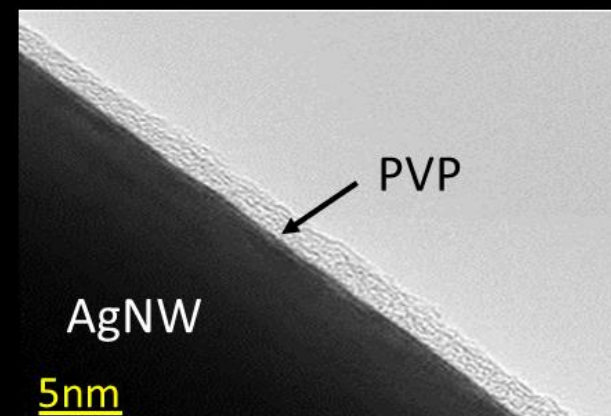
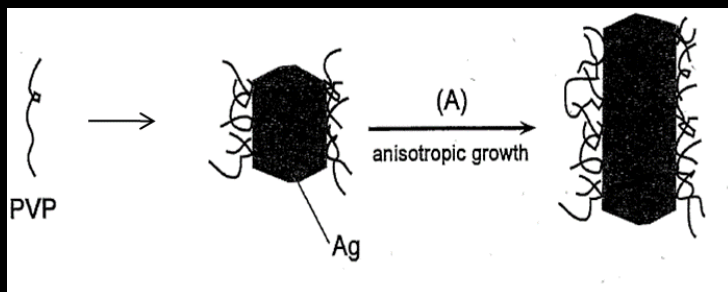
- Indium scarcity
- Brittleness



AgNW Networks as alternative TCM



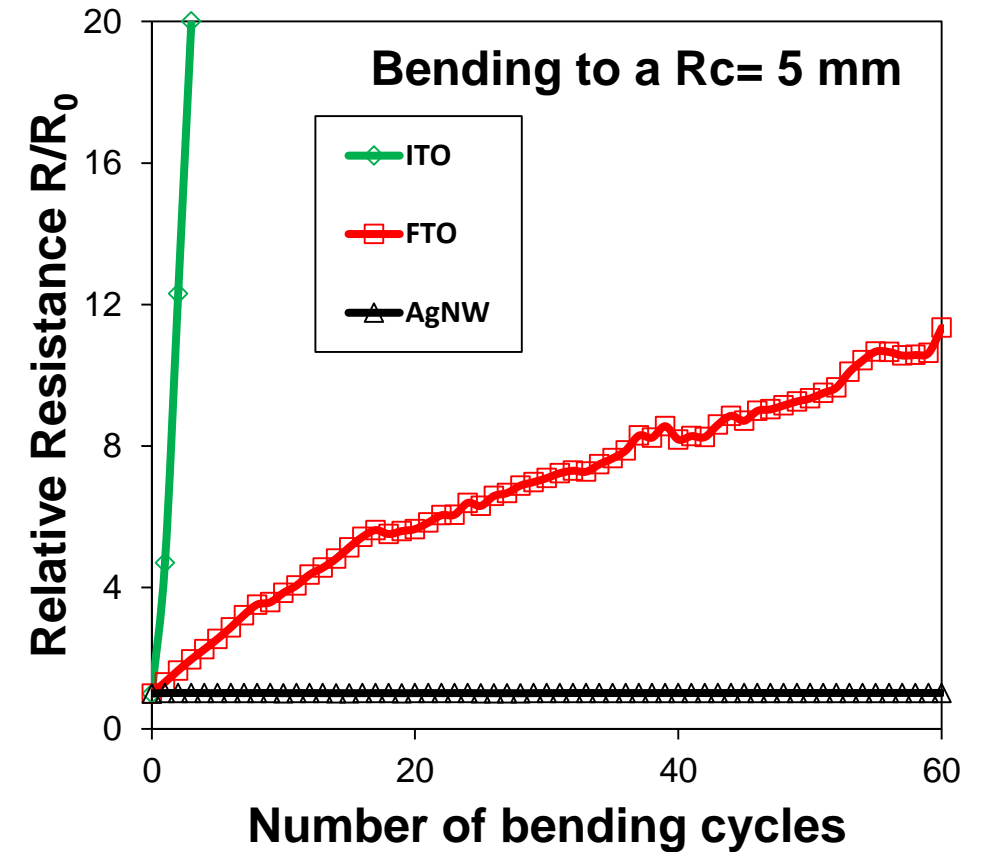
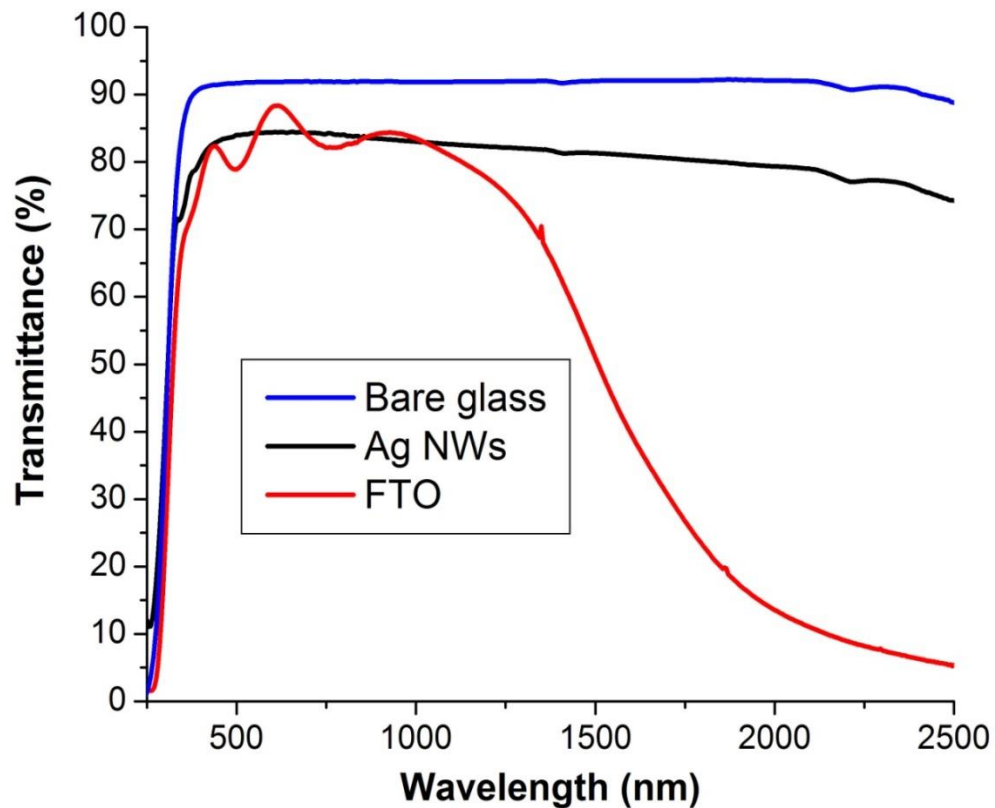
Ag NWs synthesized by the polyol method



AgNW Networks as alternative TCM

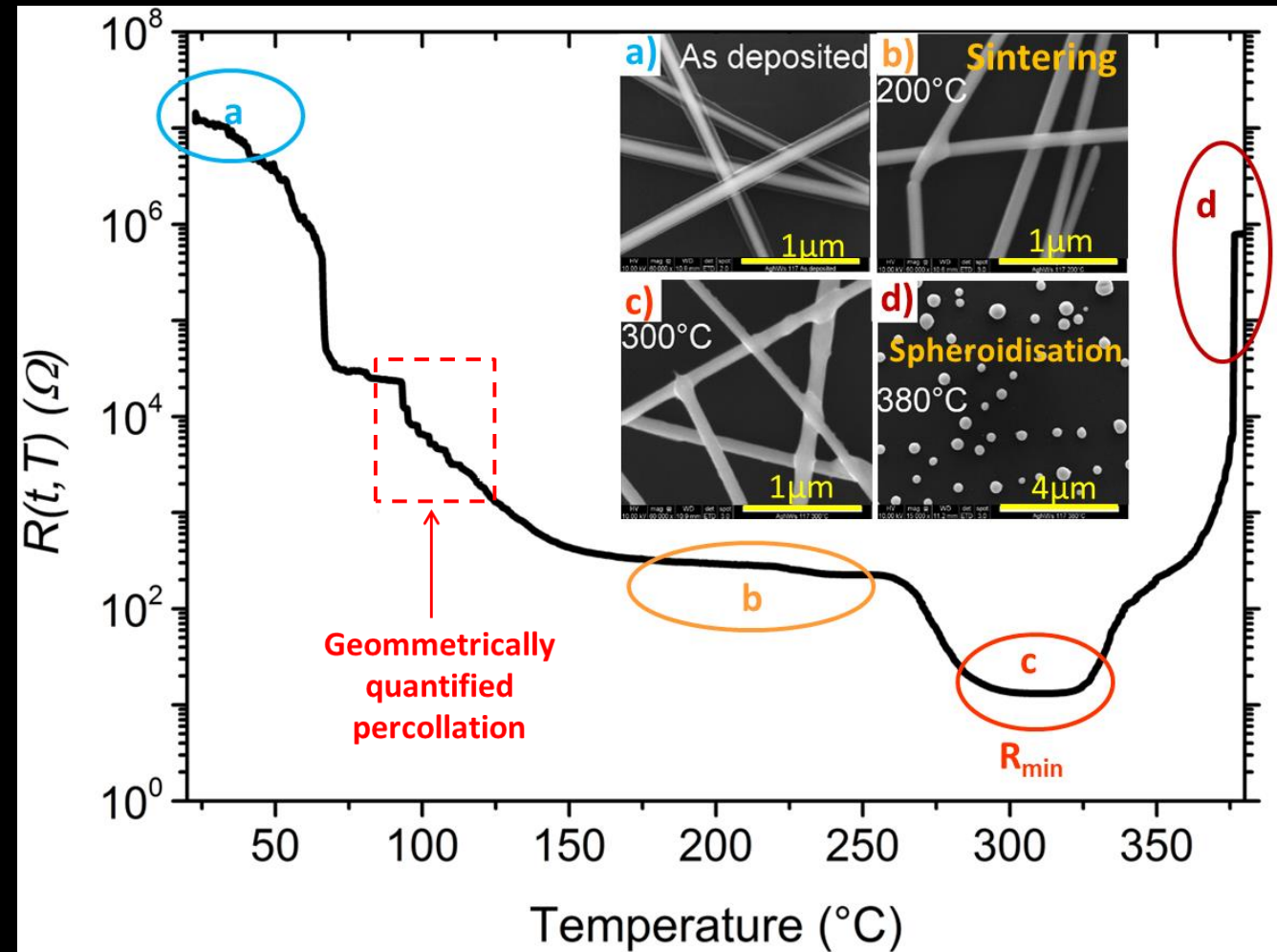
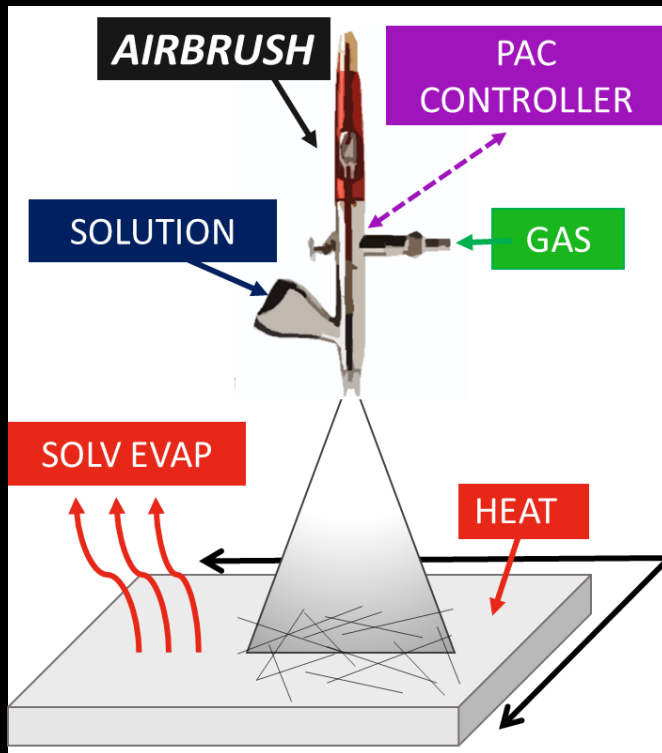
More transparent to IR than TCO and more flexible

For sheet resistance of about $10 \Omega/\text{sq}$:

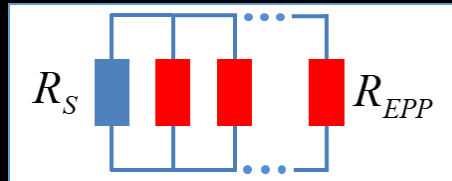
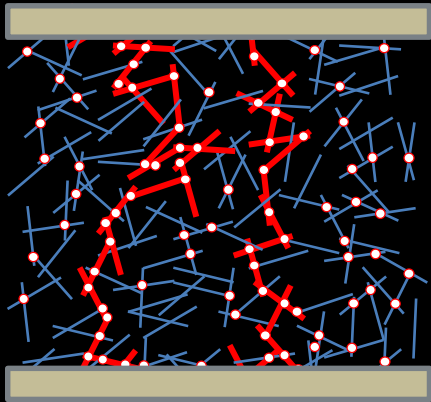


Deposition and optimisation of Ag NW networks

Ag Nanowires Spray Deposition

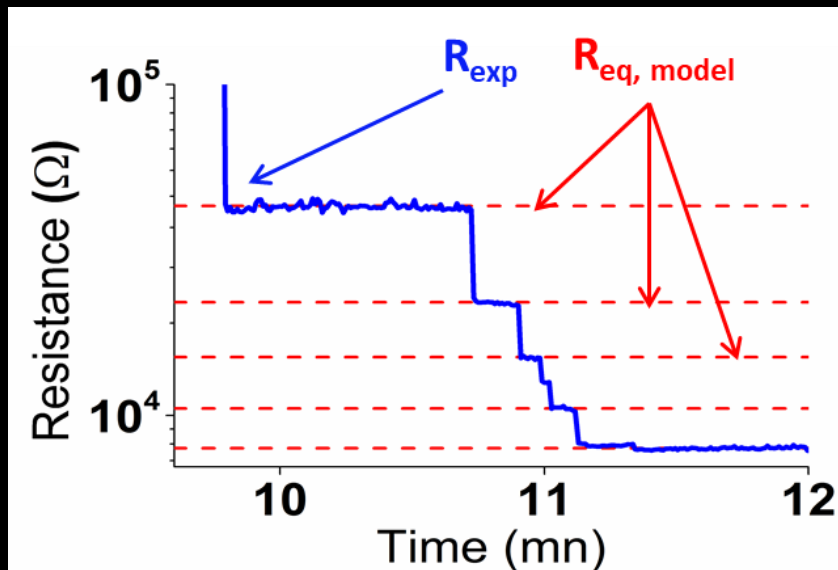


Quatized percolation and antipercolation

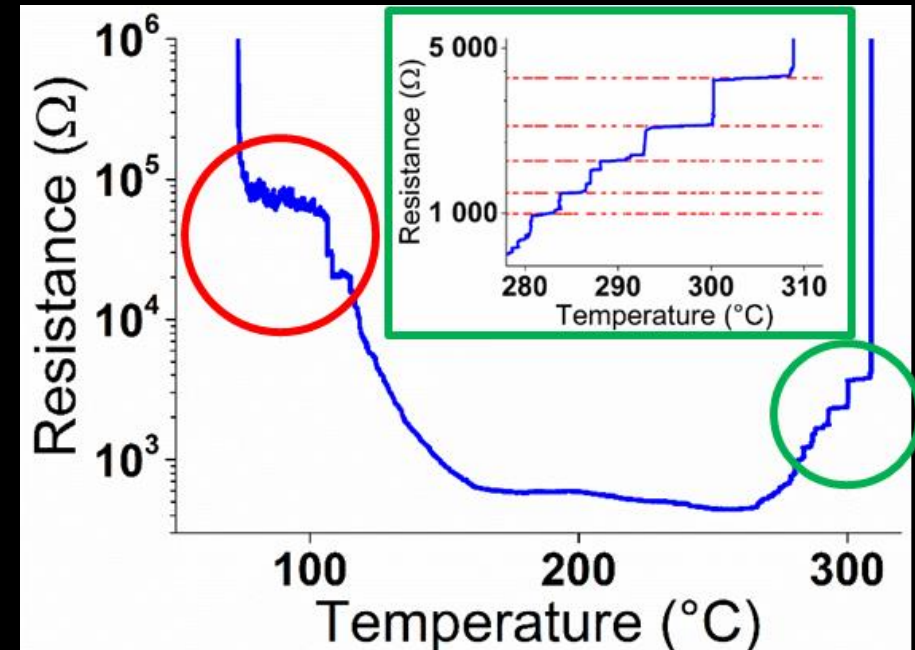
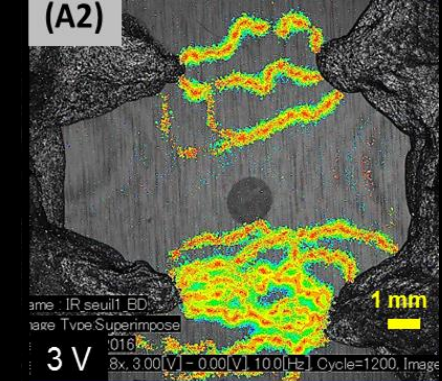
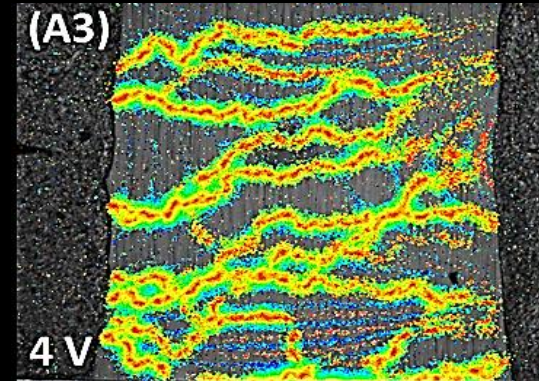


$$\frac{1}{R_{eq.}^n} = \frac{1}{R_S} + \frac{n}{R_{EPP}}$$

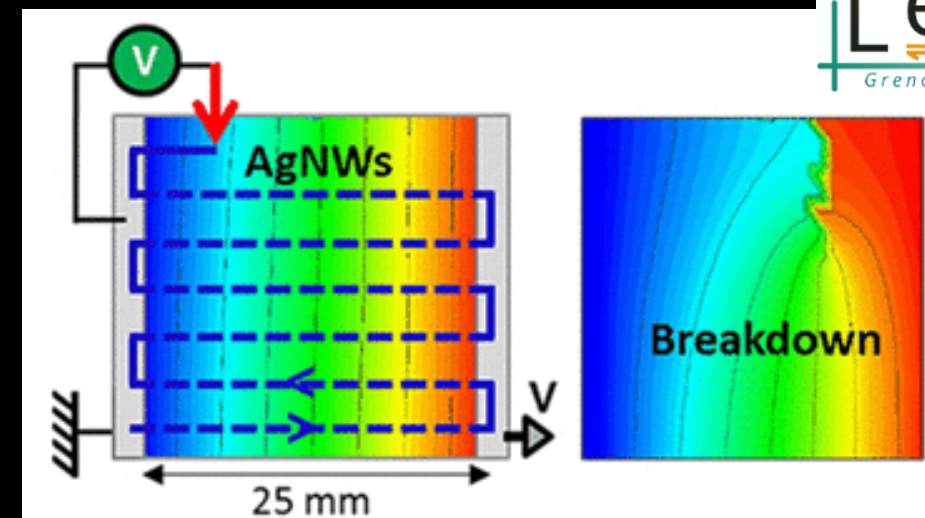
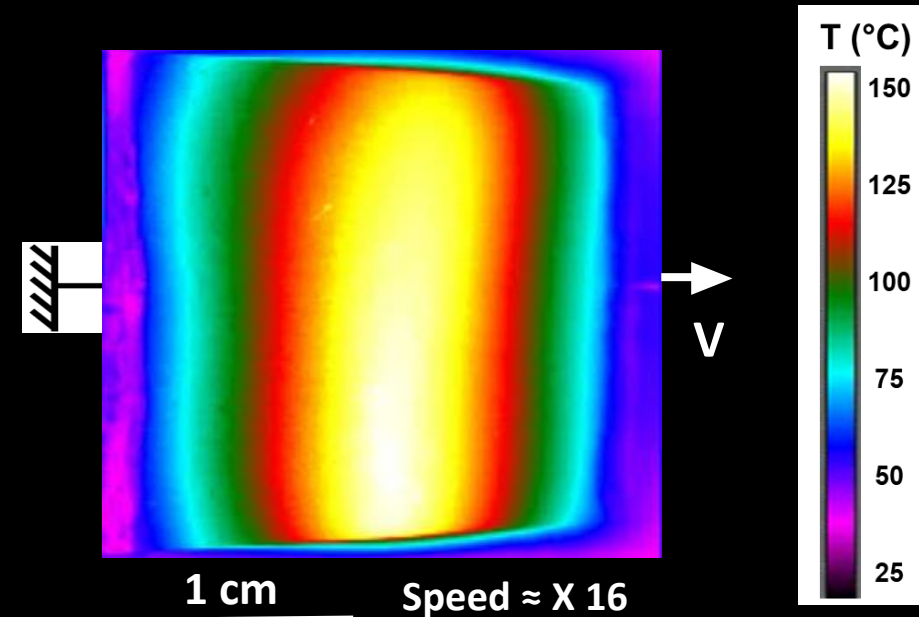
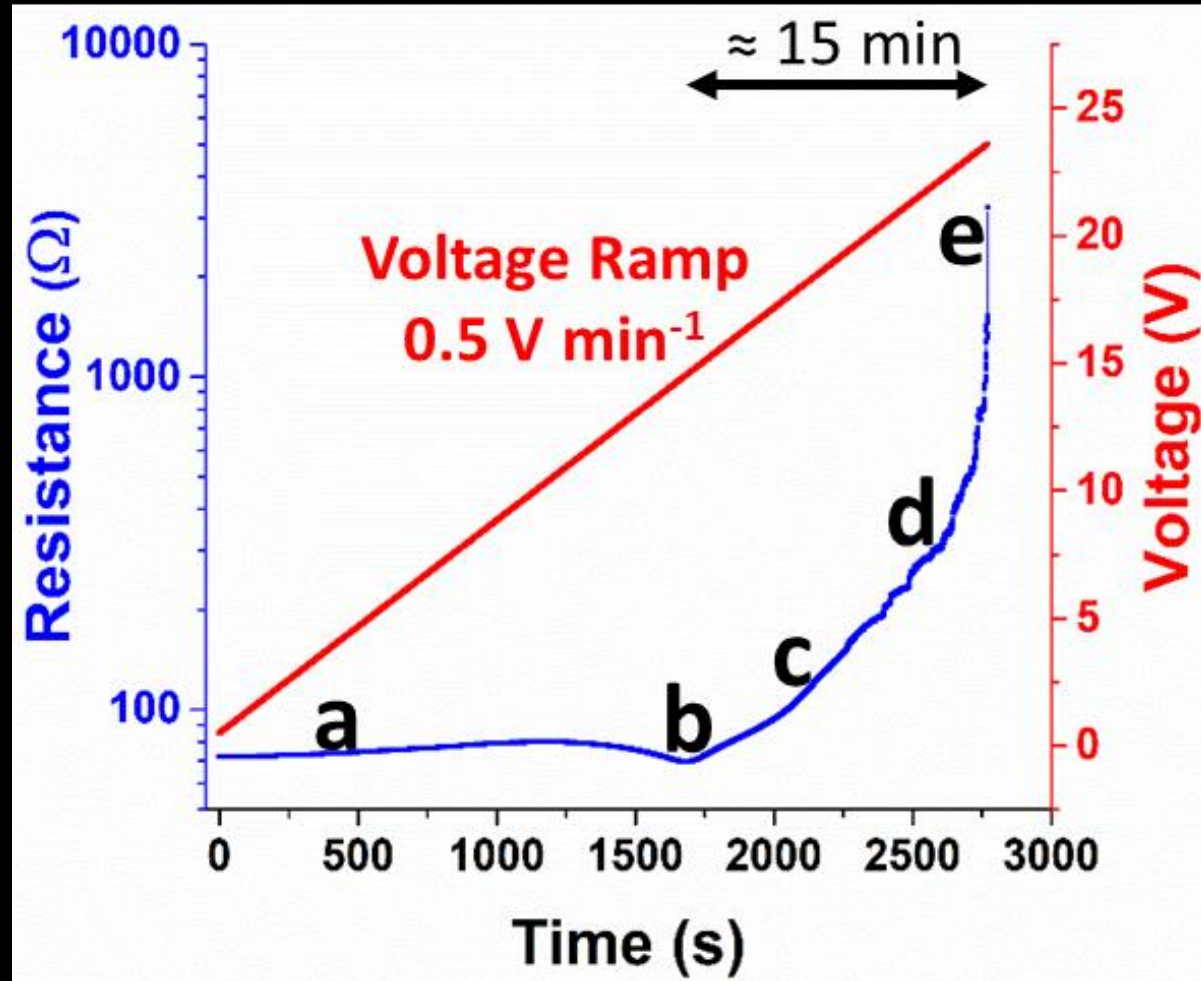
$$R_{EPP} = K \cdot \left(\frac{\rho(D_{NW}) \cdot L}{S} \right)$$



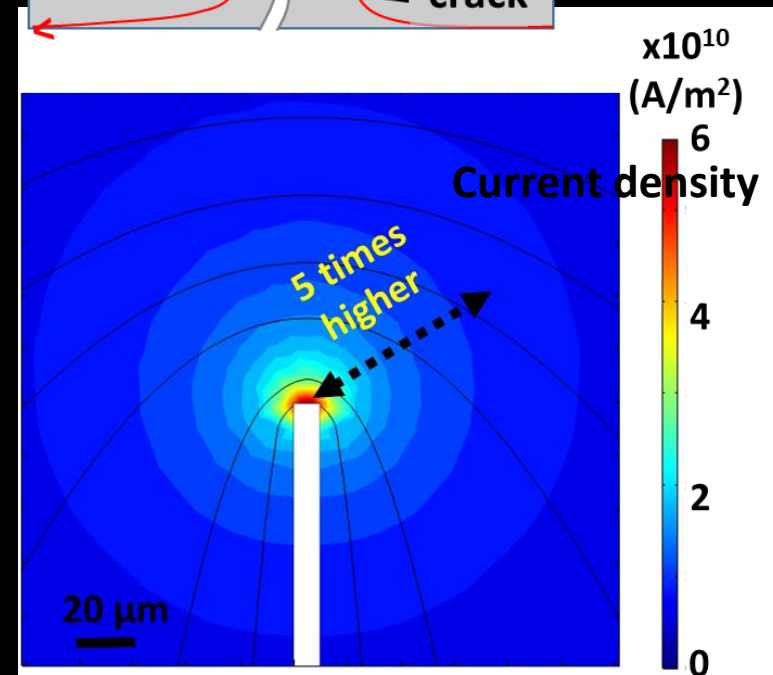
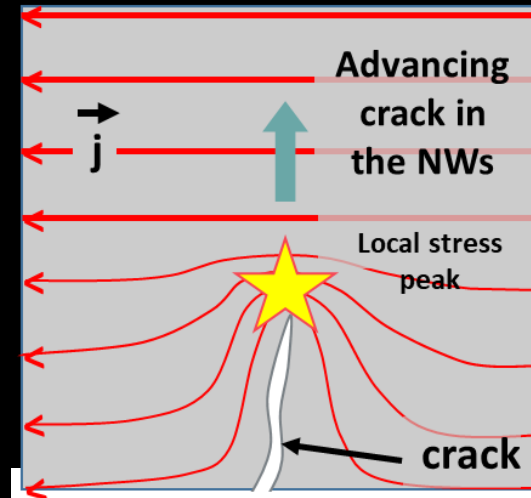
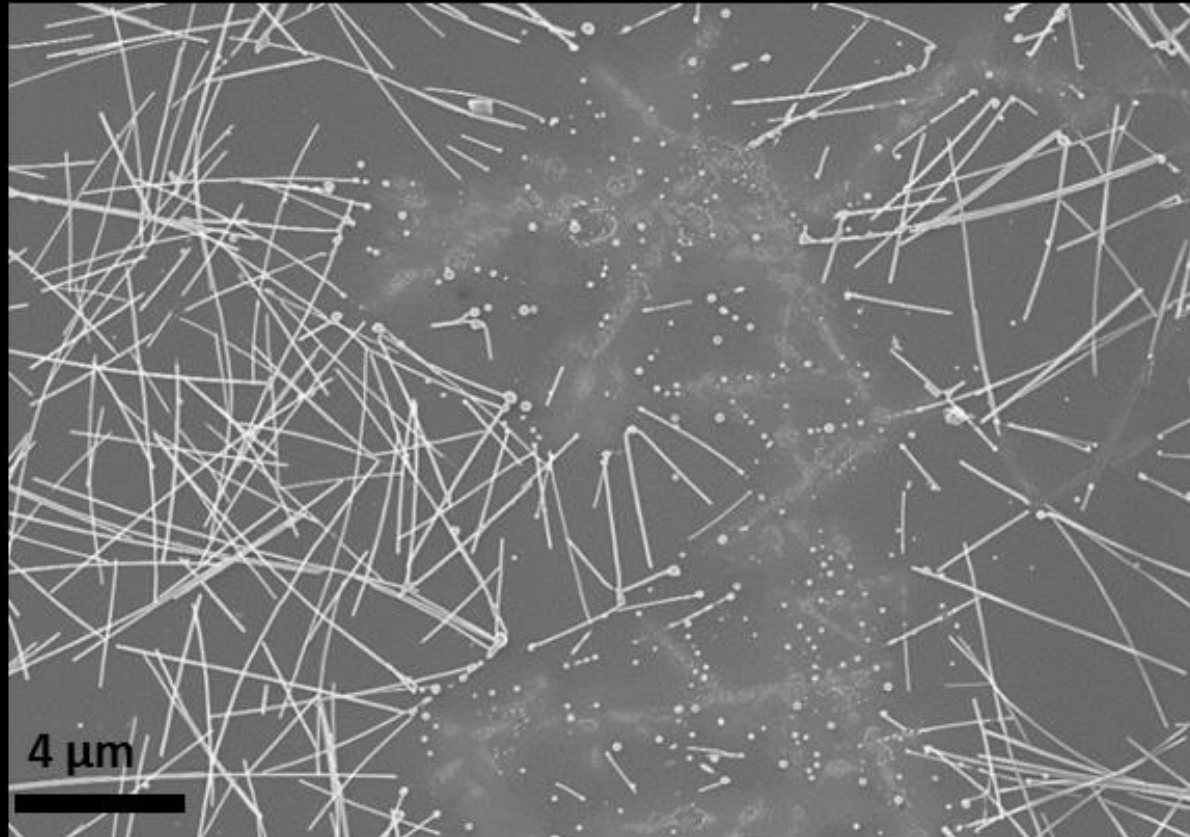
Lock-in IR Thermography



Electrical stress also degrades AgNW networks

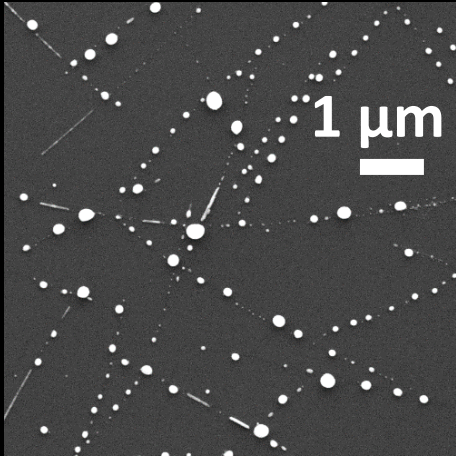


Electrical stress also degrades AgNW networks



Sannicolo et al., ACS Nano 12 (2018) 4648-4659

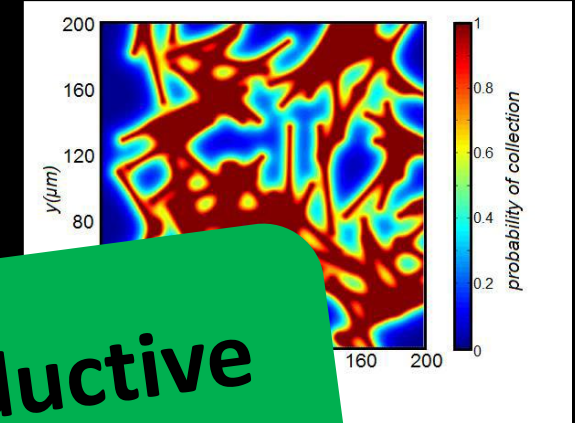
Drawbacks of AgNW networks



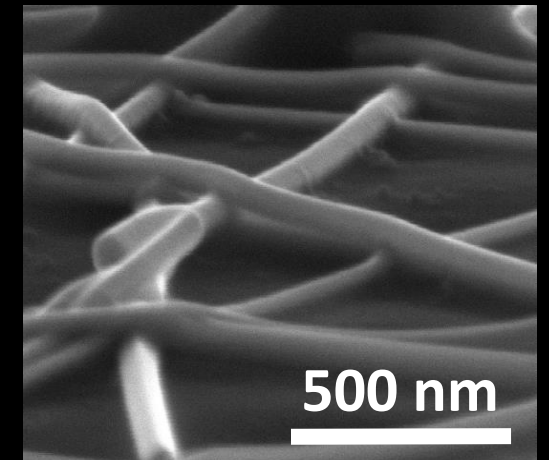
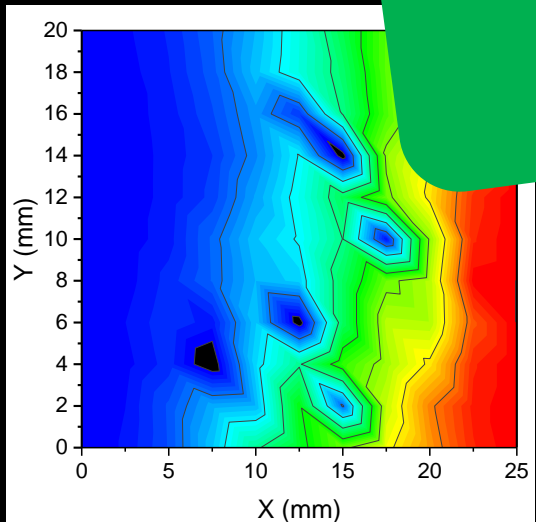
- Low thermal and electrical conductivity
- Poor adhesion to the substrate

Possible solution: Transparent Conductive Nanocomposites

Probability of charge collection

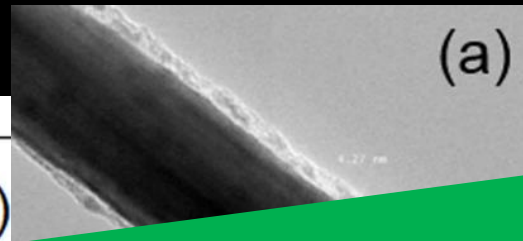
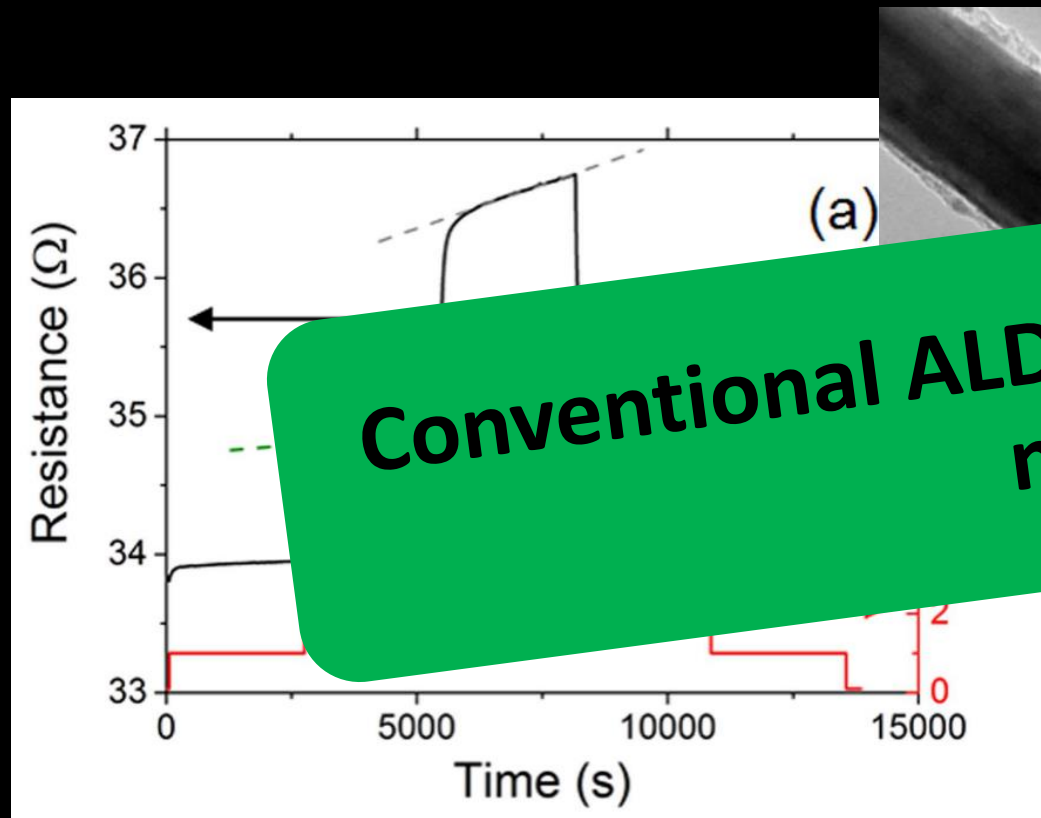


Electrical Mapping

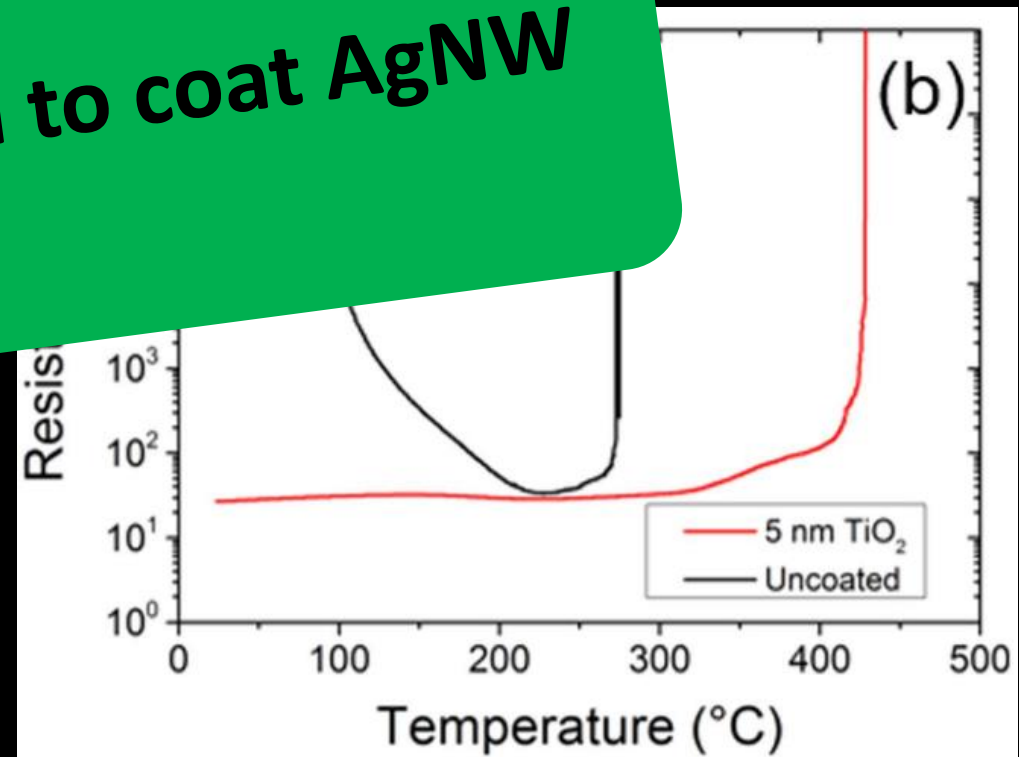




Coating AgNW networks with a thin layer of oxide improves stability



TDMAT + H₂O, 250 °C, Fiji F200



Atmospheric Pressure Spatial ALD (AP-SALD)

Up to 100 times faster, atmospheric pressure, even open-air

Materials Today Chemistry 12 (2019) 96–120



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Speeding up the unique assets of atomic layer deposition

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Cite this: DOI: 10.1039/c3mh00136a

Spatial atmospheric atomic layer deposition: a new laboratory and industrial tool for low-cost photovoltaics


David Muñoz-Rojas^{*abc} and Judith MacManus-Driscoll^c

Spatial Atomic Layer Deposition

David Muñoz-Rojas, Viet Huong Nguyen,
César Masse de la Huerta, Carmen Jiménez and
Daniel Bellet

Additional information is available at the end of the chapter

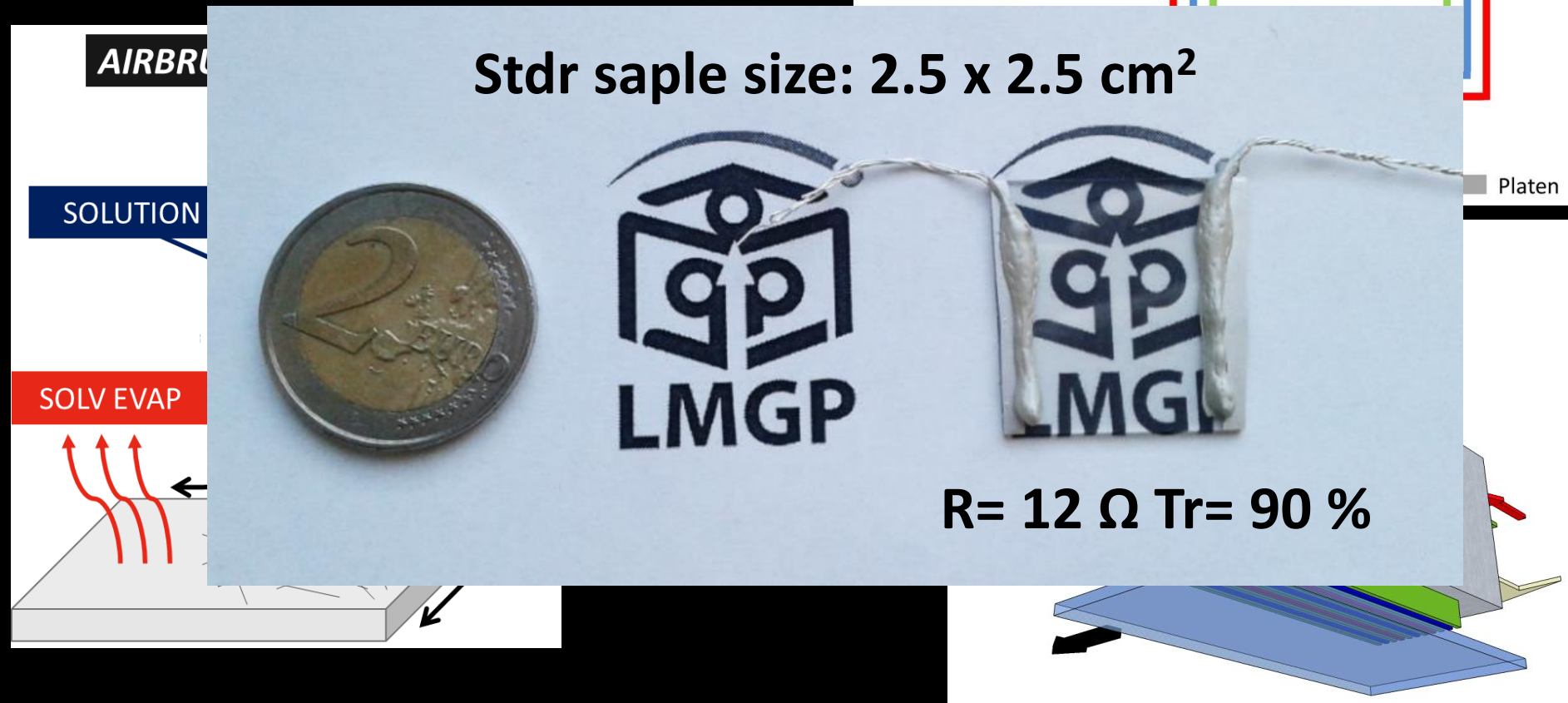
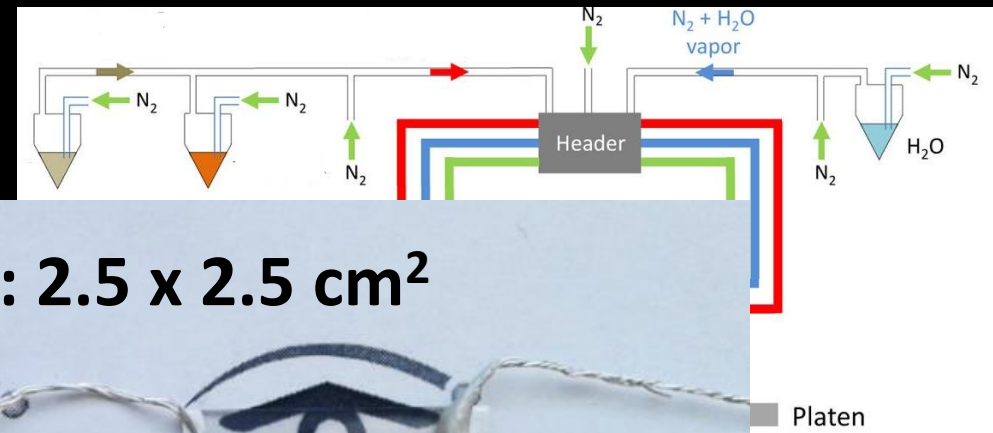
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Atmospheric open-air processing

AP-SALD @ LMGP

Ag Nanowires
Spray Deposition



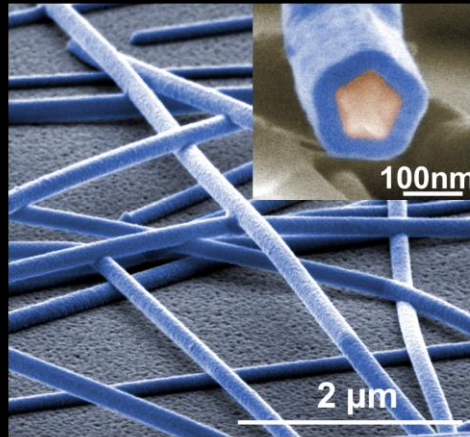
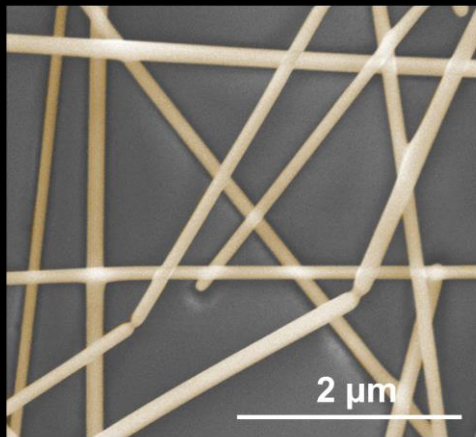
Study of the effect of ZnO coating thickness on stability

DEZ + H₂O, 200 °C

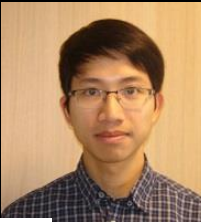
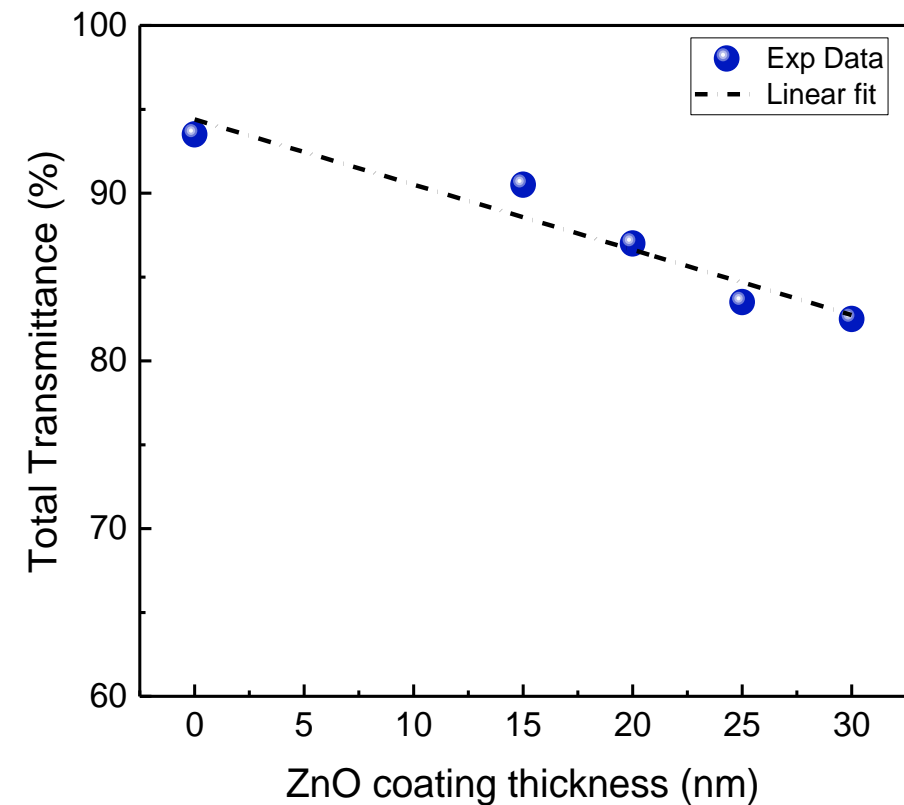
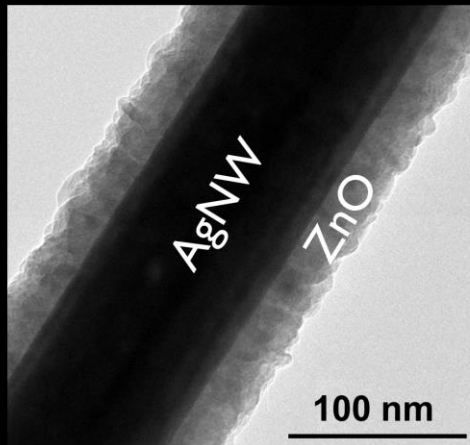
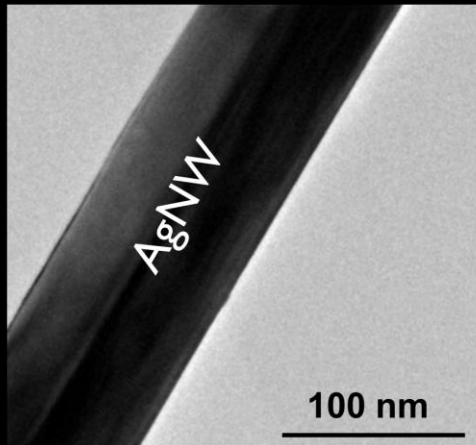
Bare AgNWs

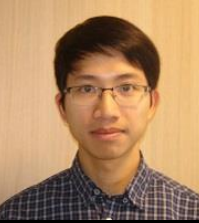
ZnO coated AgNWs

SEM

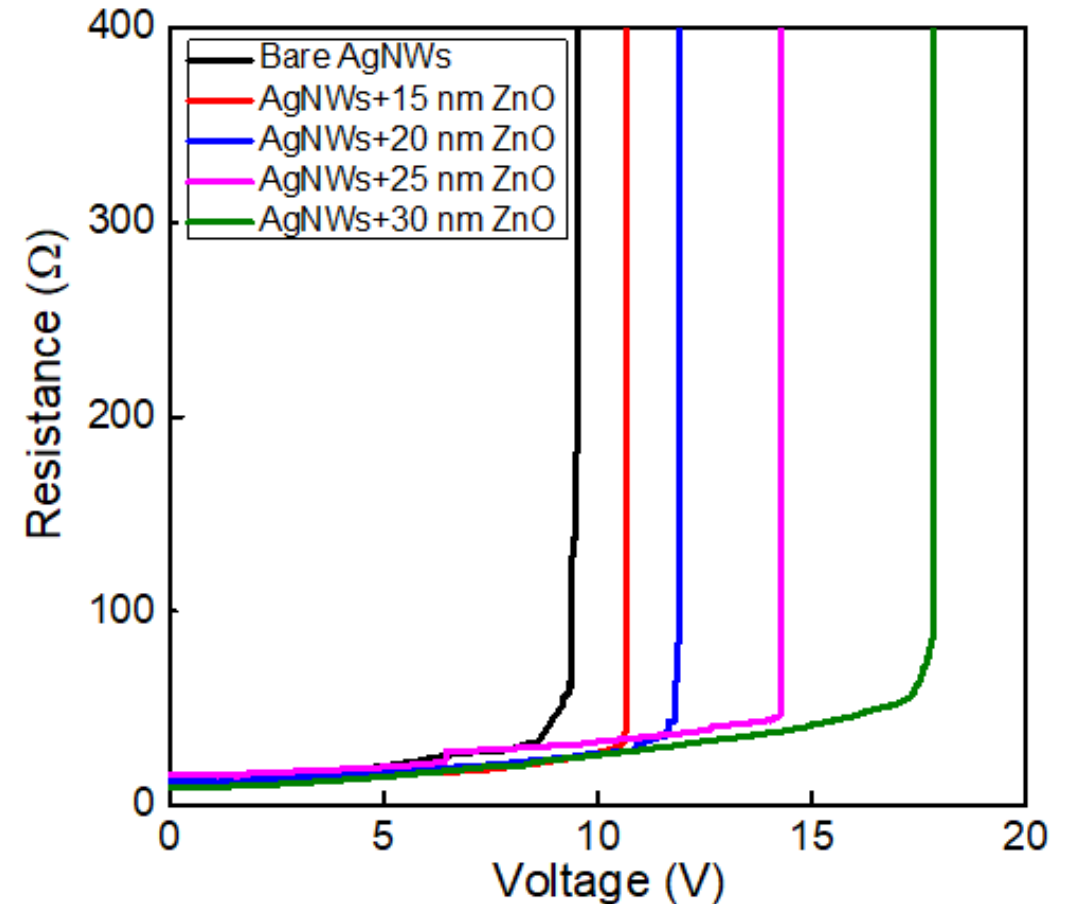
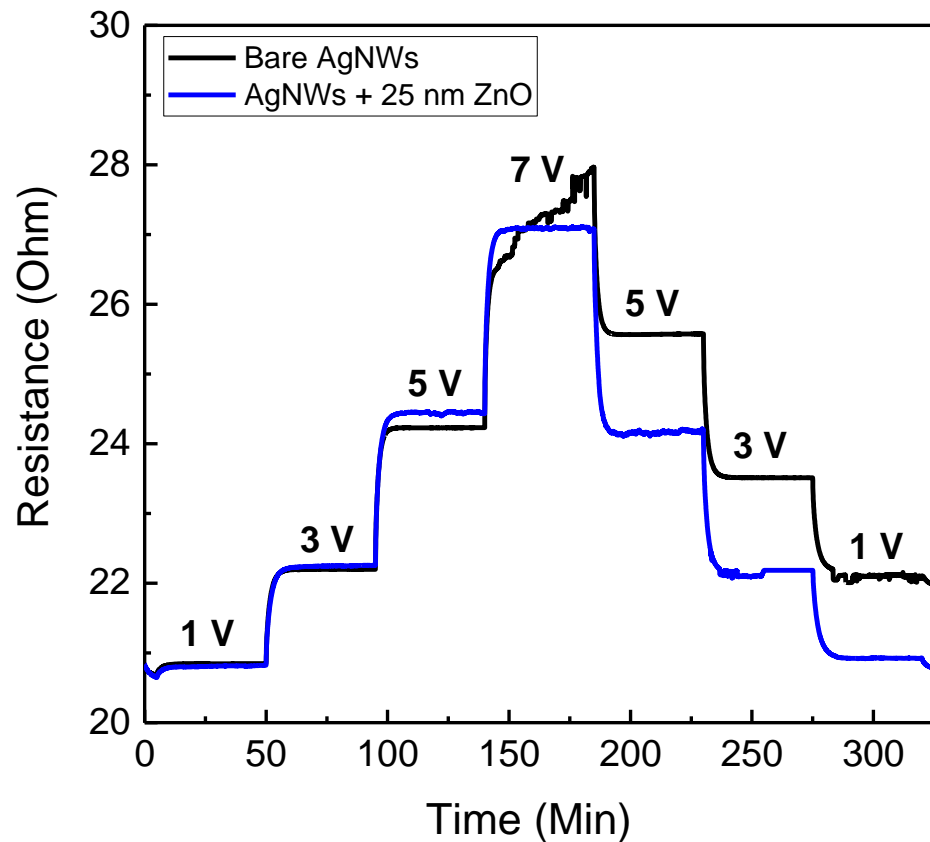


TEM

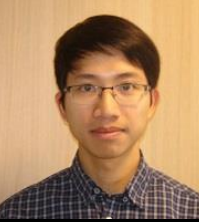




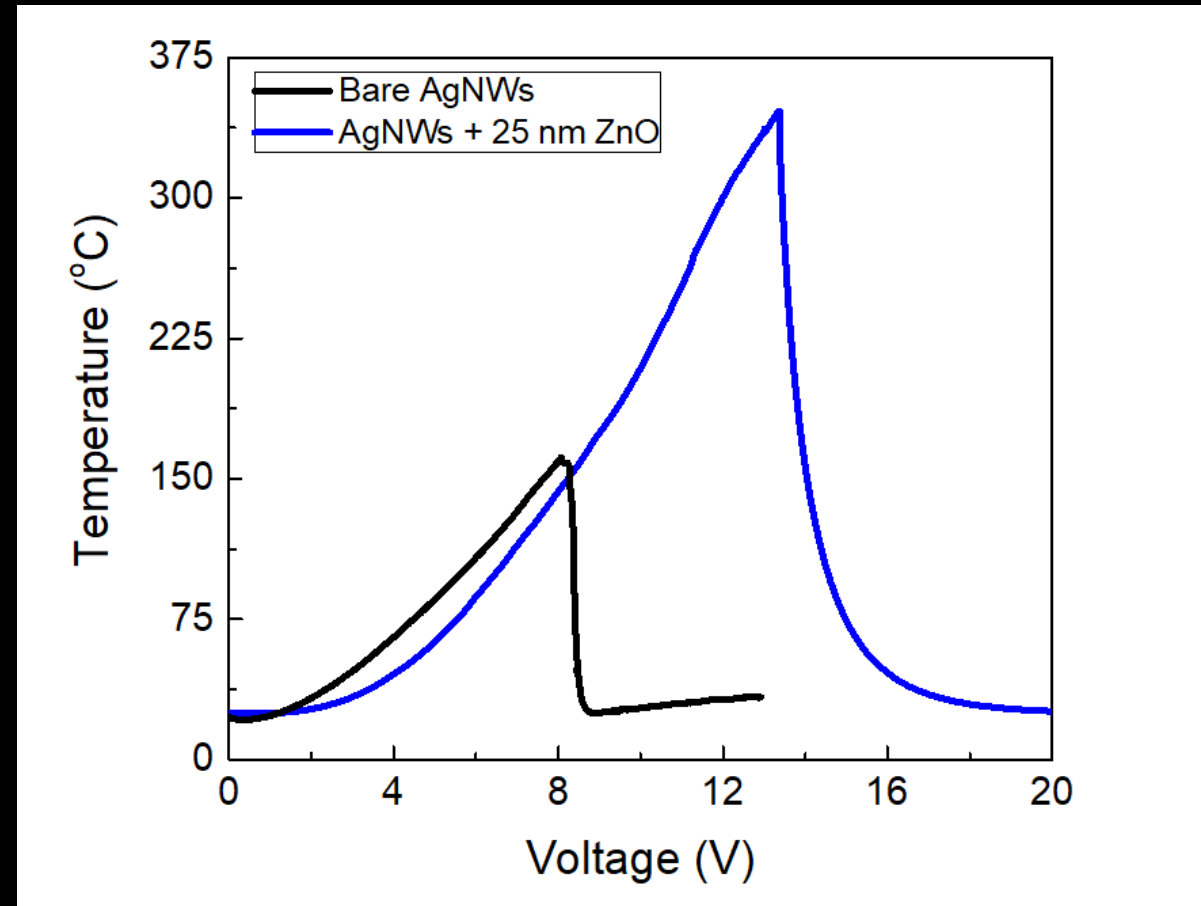
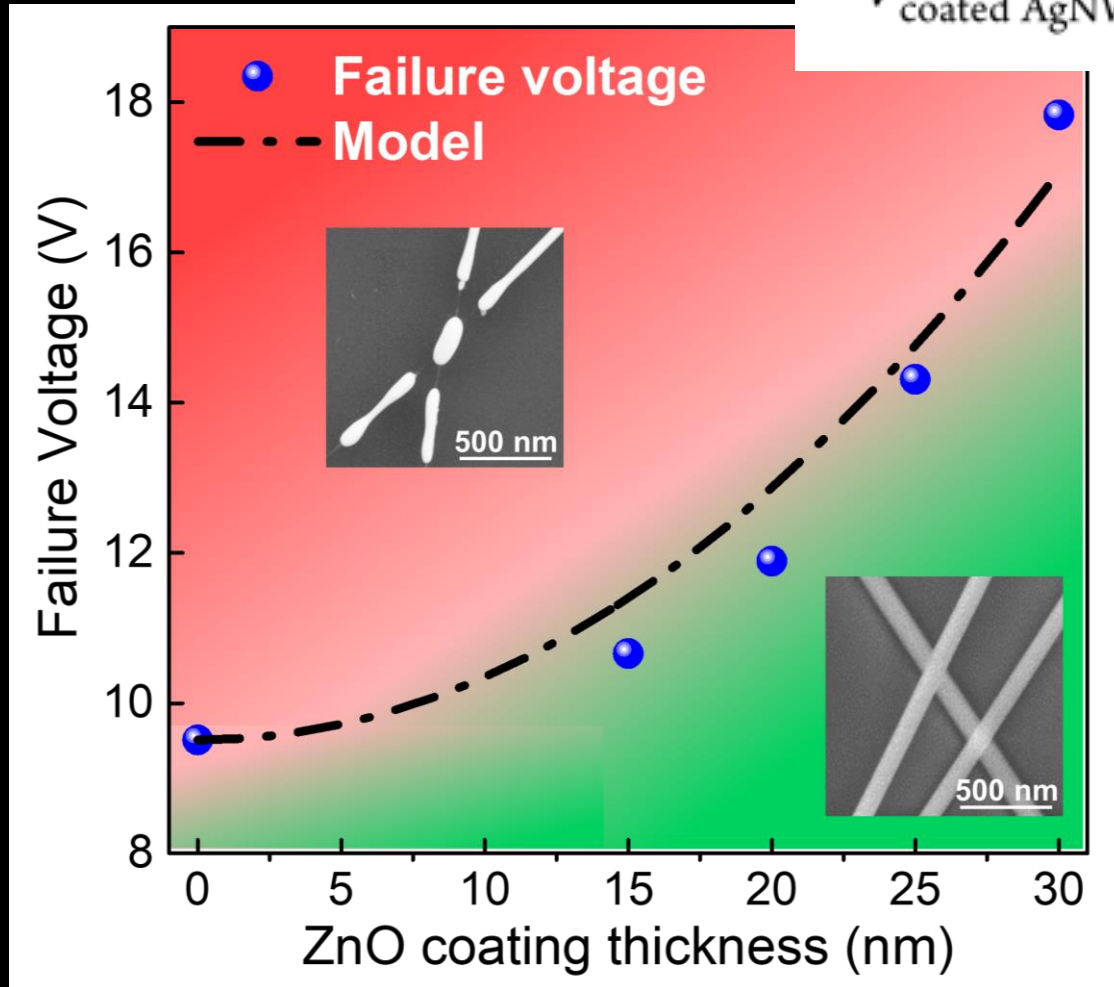
Failure upon thermal ramp increases for thicker coatings



Study of the effect of ZnO coating thickness on stability

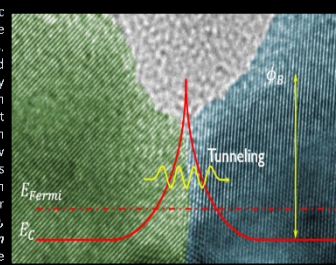


$$V_{\text{coated AgNW}}^{\text{fail}}(L_{\text{ZnO}}) = V_{\text{bare AgNW}}^{\text{fail}} + \frac{\dot{V} \cdot L_{\text{ZnO}}^2}{2D}$$



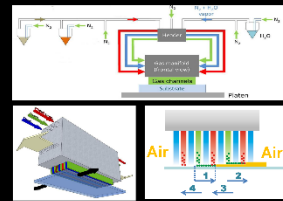
Abstract

Transparent conductive oxides (TCOs) are key components of optoelectronic devices, such as solar cells or LEDs. TCOs, and in general all highly doped polycrystalline semiconductors, present high potential barriers and short depletion layers at the grain boundaries. This results in an increased probability of electron tunneling through the grain boundaries, as opposed to the thermionic emission mechanism observed in low doping semiconductors. Existing conductivity models do not properly account for charge tunneling through the grain boundaries in TCOs, which prevents a proper understanding of the scattering mechanisms limiting their conductivity. We present a new model based on the Airy Function Transfer Matrix Method that allows the numerical calculation of charge mobility through grain boundaries in highly doped polycrystalline semiconductors. The new model has been used to fit experimental data obtained for Aluminum doped ZnO (AZO) samples synthesized by different methods. This has allowed the calculation of the electron trap density at grain boundaries, thus providing the dominant charge scattering mechanisms for the different samples. Our findings show that **AZO films deposited by atm. methods (such as spatial atomic layer deposition, SALD) suffer from a high trap density of traps at the grain boundaries, which limits the mobility in these films.** UV light can be used to improve the mobility by releasing trapped oxygen, and the desorption curves can be used as a simple way to obtain the trap density at the grain boundaries.



AZO deposition by SALD: open air processing, how does it compare to other deposition techniques?

Spatial Atomic Layer deposition: Separation of precursors in space. ALD done at high throughput in the open air.

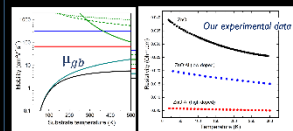


Technique	T °C	t (nm)	μ (cm² V⁻¹ s⁻¹)	N (cm⁻³)	ρ (Ω cm)
PLD	230	280	47.6	1.54x10 ²¹	8.54x10 ⁻⁵
DC Sputt.	RT	350	14.8	8.2x10 ²⁰	3.5x10 ⁻⁴
RF Sputt.	100	680	28	5.9x10 ²⁰	3.7x10 ⁻⁴
MOCVD	450	600	17	4.35x10 ²⁰	8.35x10 ⁻⁴
ALD	300	200	19.7	2.2x10 ²⁰	1.4x10 ⁻³
SALD-TNO	200	320	5	5.0x10 ²⁰	2.0x10 ⁻³
SALD-LMGP	200	210	2.6	4.25x10 ²⁰	5.6x10 ⁻³

Oxygen pressure increasing

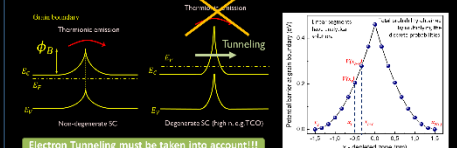
Mobility highly affected by oxygen pressure

New model: tunnelling included



Traditionally used Seto's model, based on thermionic emission, fails to explain the evolution of conductivity with temperature

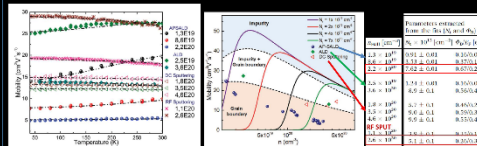
New model needed for degenerate semicon. (TCO) Airy Funct. Transfer Matrix & Discretization



New model predicts diff. behaviour depending on which is the most important scattering factor. Our AZO is Type III, i.e. GB limited

Application to diff. AZOs

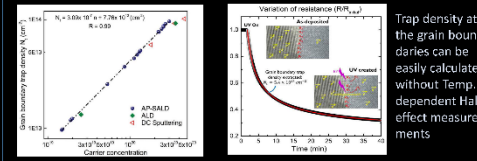
SALD films: the ones with the highest trap density at the GB.



Trap density is proportional to carrier concentration but the relationship is diff. for diff. methods

Can we recover a higher mobility? UV treatment

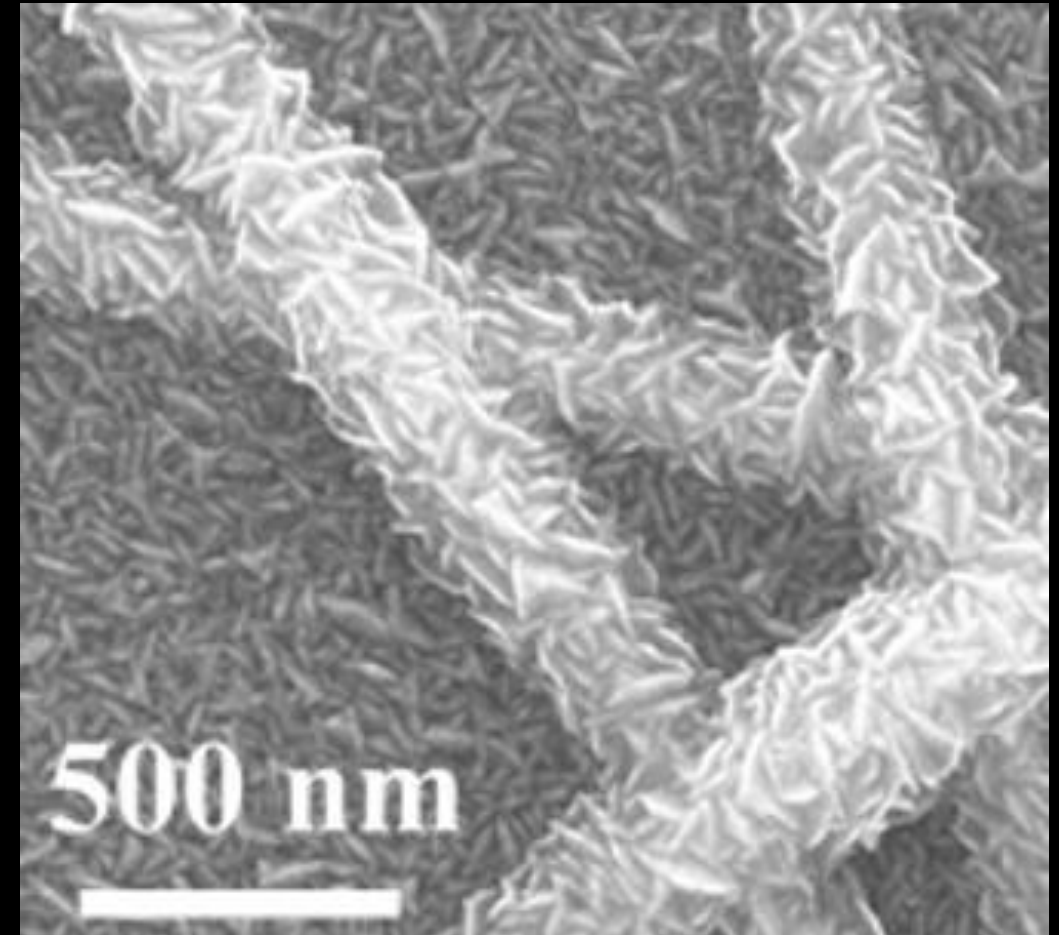
- Clear effect of UV on conductivity (@ mild vacuum at low temp)



V. Nguyen et al. Materials Horizons, 2018, 5, 715-726

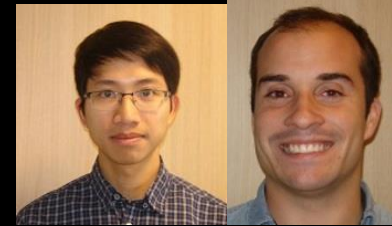
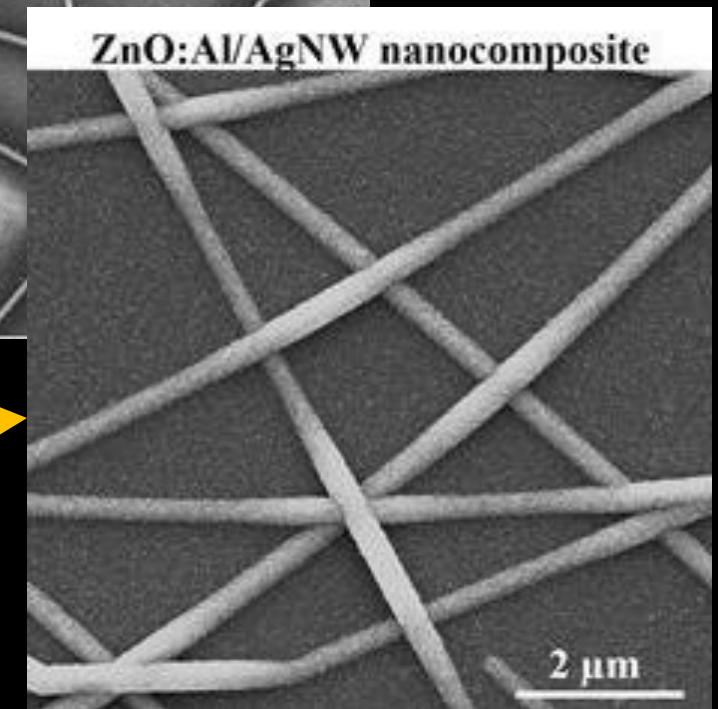
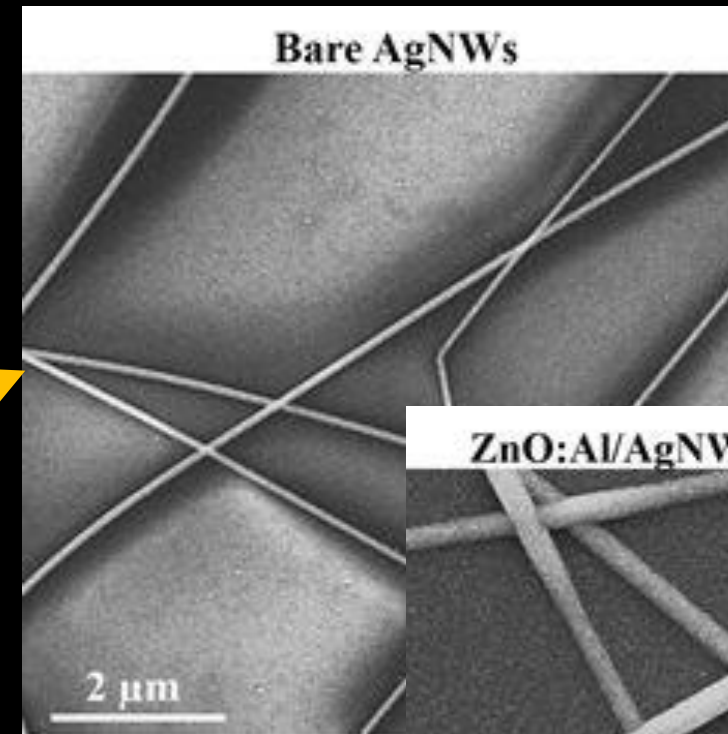
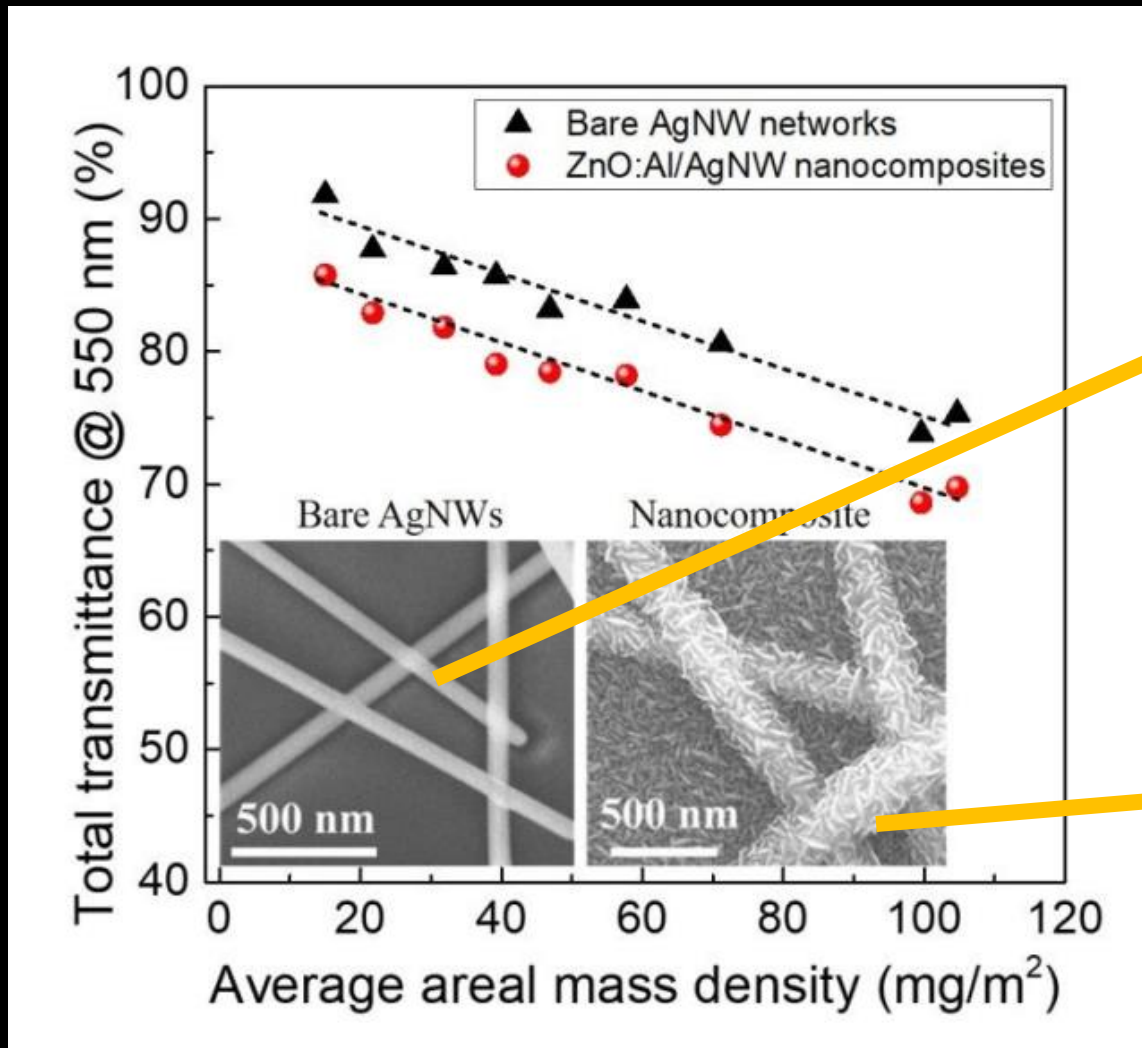
V. Nguyen et al. ACS App. Nano Mater., 2018, 1, 6922-6931

<https://sites.google.com/site/workdmr>

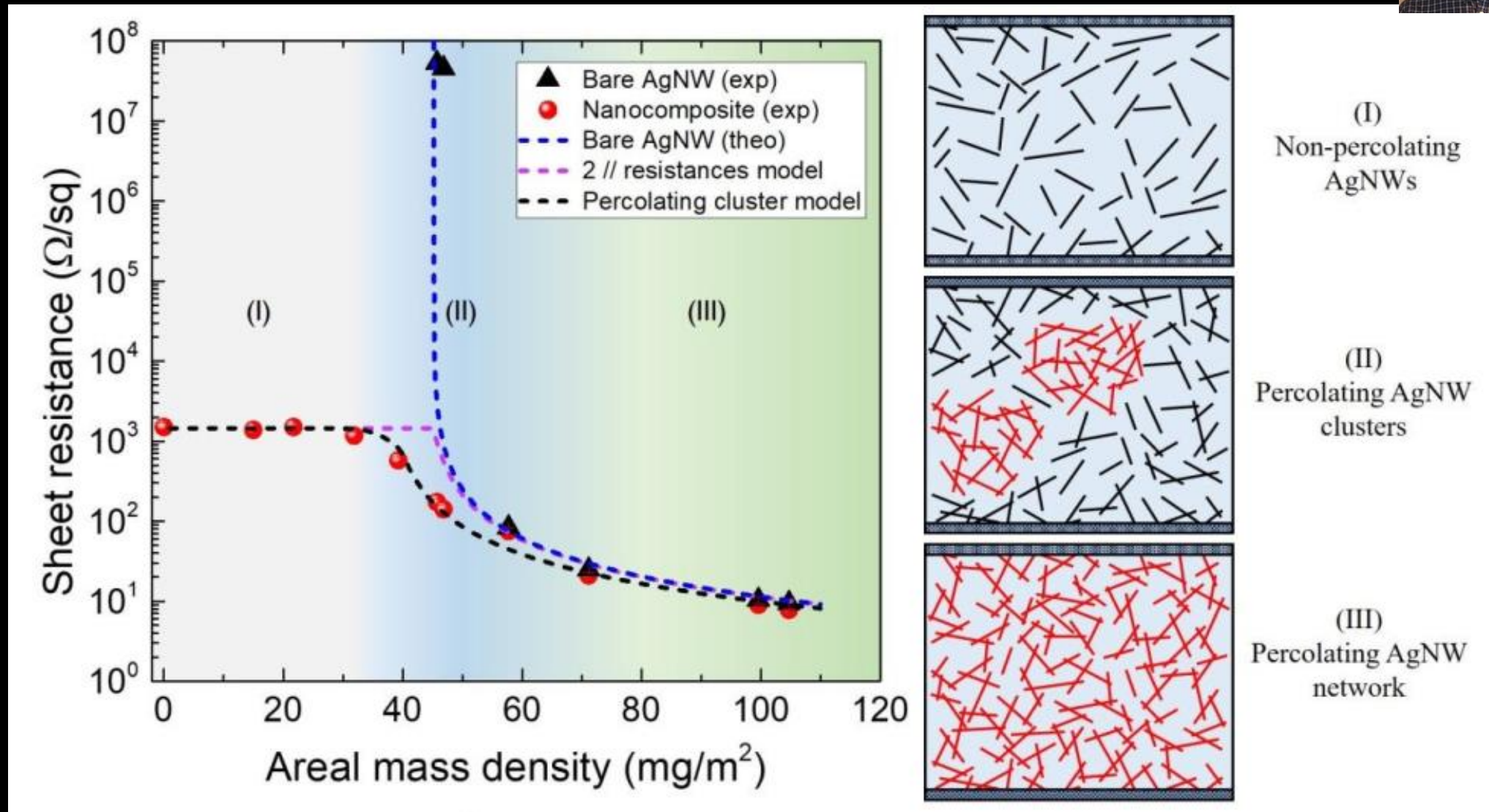
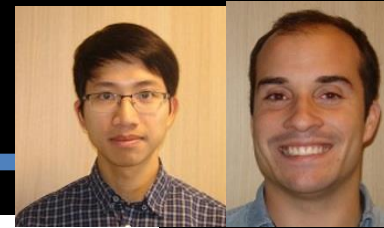


AgNWs + Al:ZnO by AP-SALD DEZ, TMA, H₂O, 200 °C, 150 nm

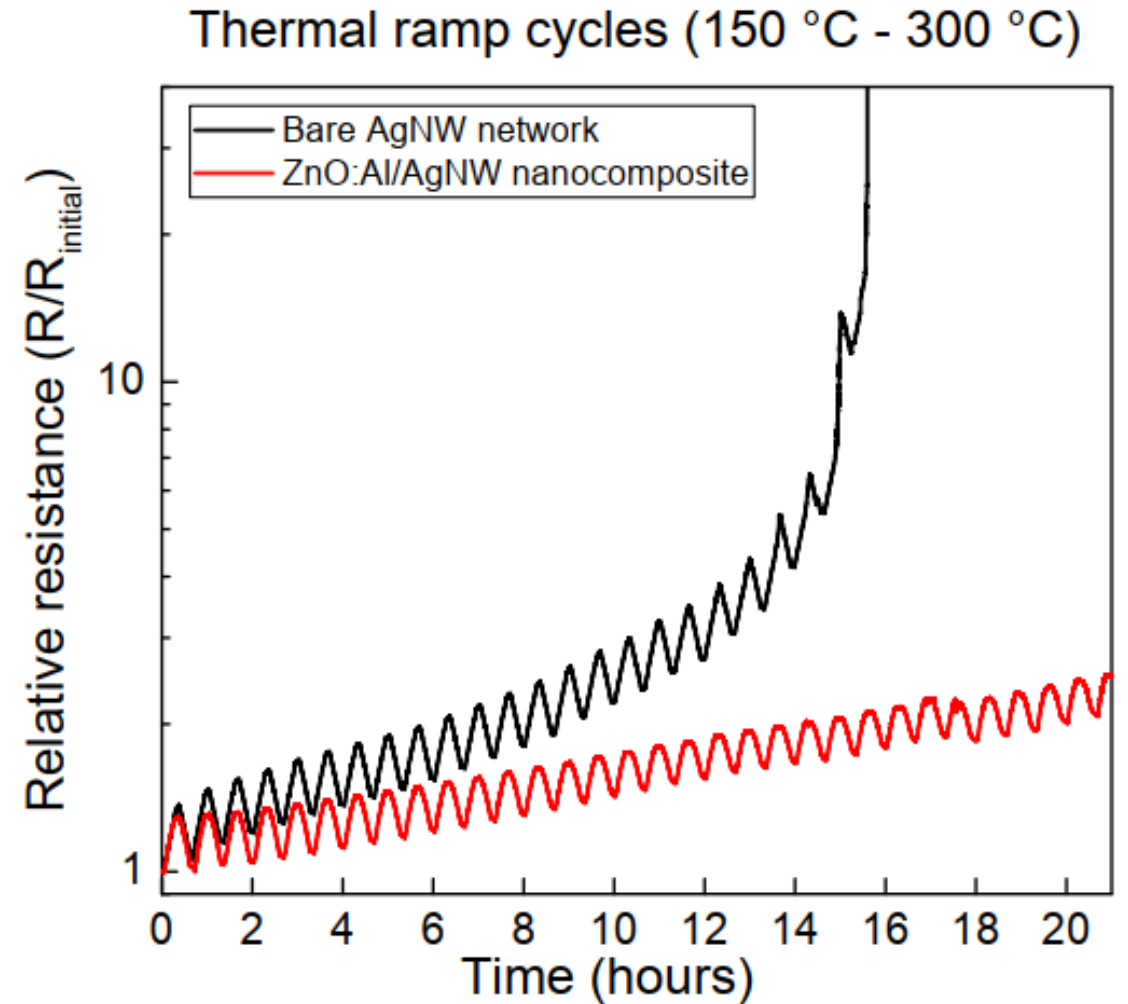
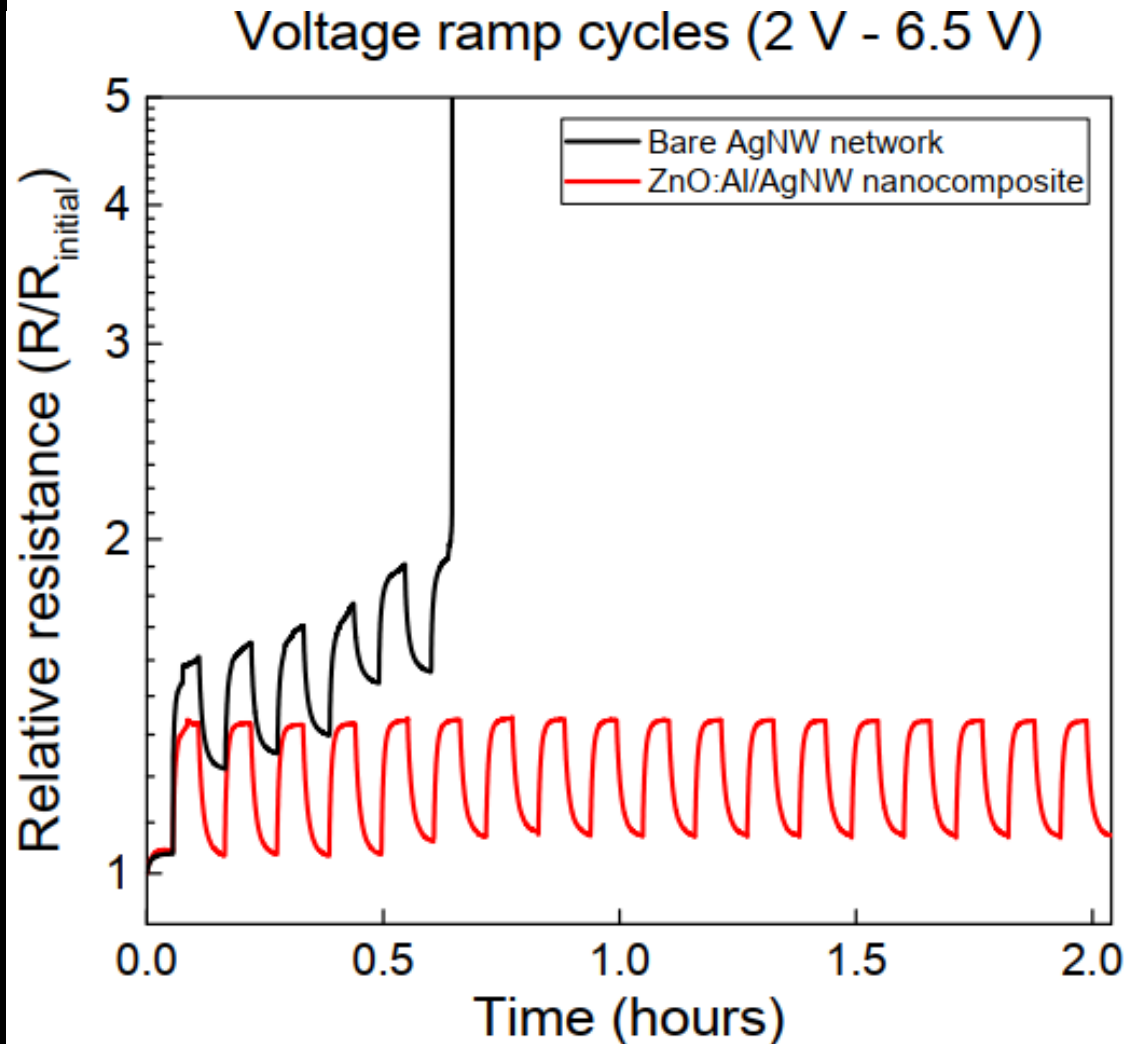
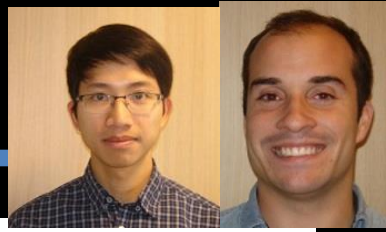
AgNW networks + TCO coating: better collection eff.



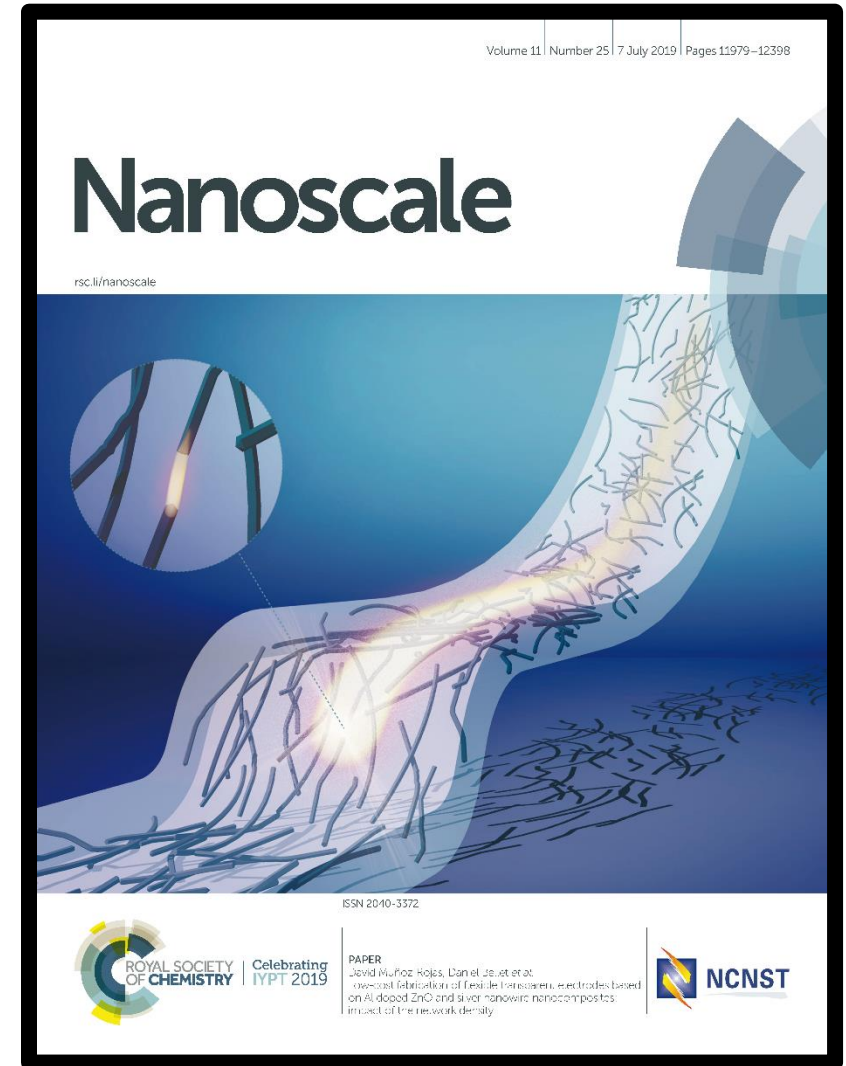
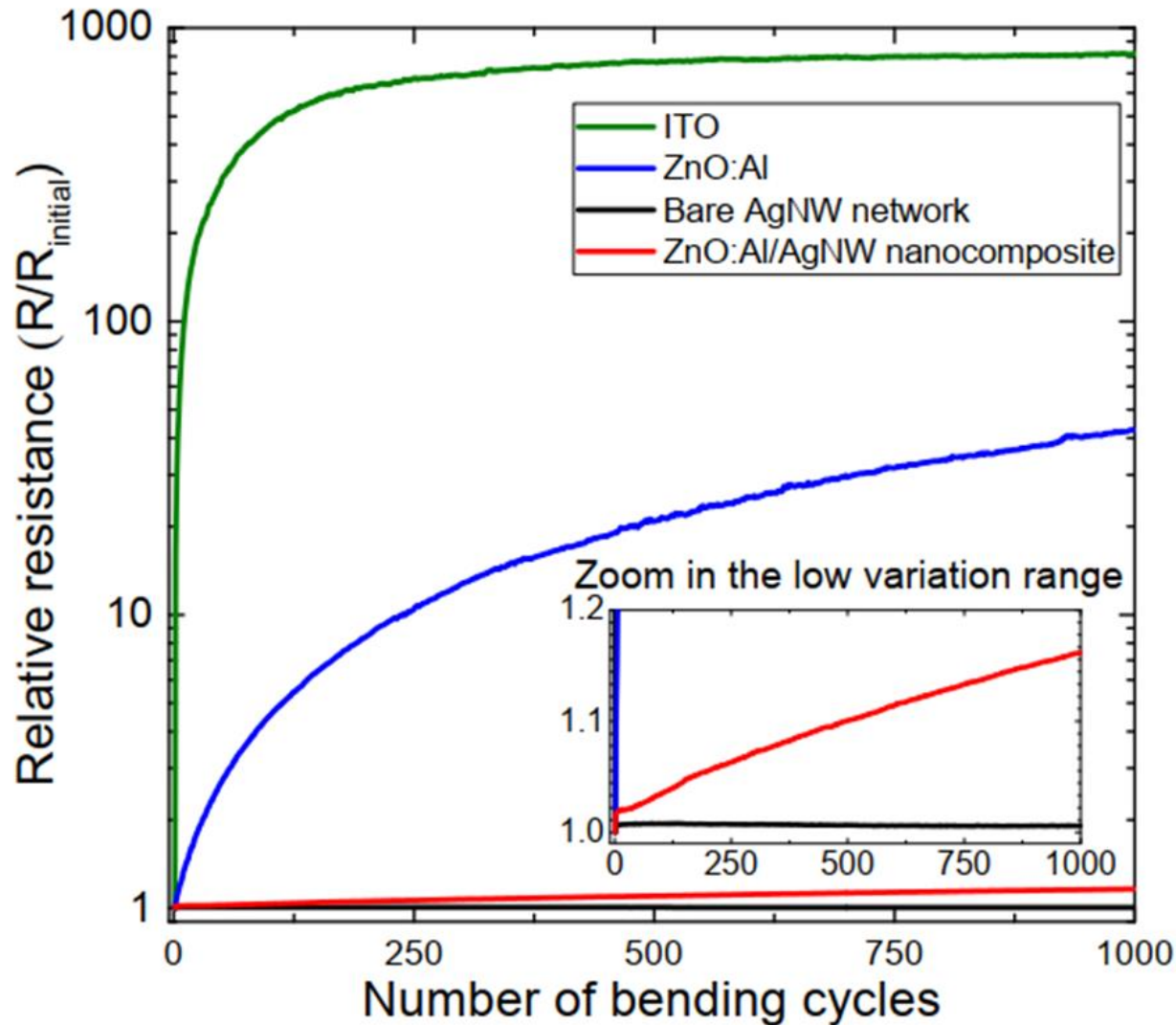
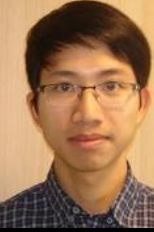
Synergistic effect for low AgNWs areal densities



More stable than bare AgNW networks



More flexible than bare AgNW networks or Al:ZnO



- ***AP-SALD: protective conformal coatings and nanocomposites for AgNW based electrodes: thermal, electrical, chemical and mechanical stability improvement***
- ***Also protection of CuNW networks
(with Al_2O_3 , Celle, C. et al. Nanotechnology, 29 (2018) 085701)***
- ***Coatings & composites contribute to a fundamental understanding of the stability and behavior of AgNWs***

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Thanks for your attention!!!

