Humidity Sensing via Cellulose Nanofibril Films with Printed Silver Electrodes

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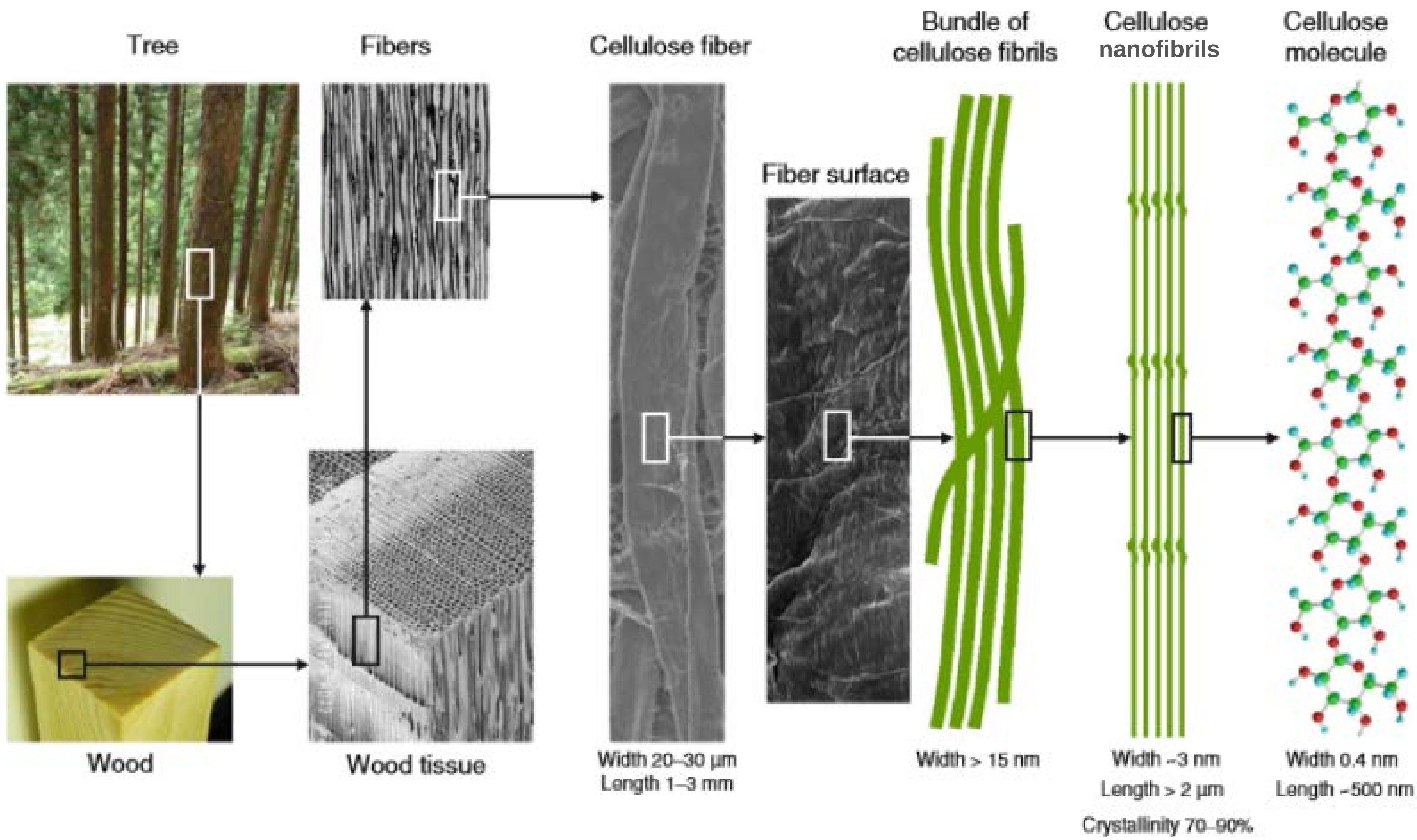
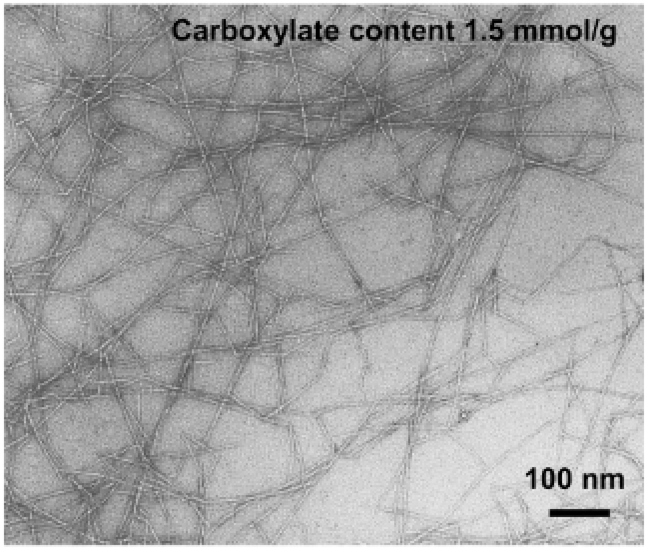
Cellulose is abundant, renewable, and biodegradable.



Wood cellulose is composed of bundled cellulose fibrils, which are in turn composed of individual cellulose nanofibrils (CNFs).
Adapted from Isogai, J Wood Sci ***2013****.*

Cellulose nanofibrils (CNF) show promise for exciting applications.

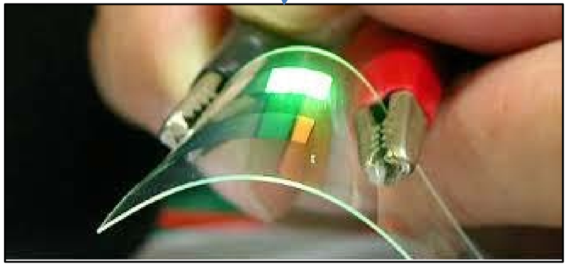
CNF Network



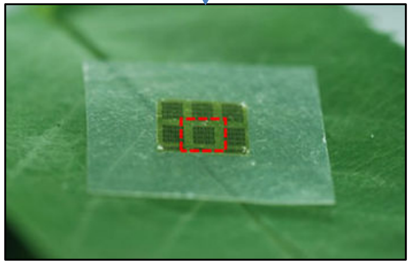
*TEM image of aqueous dispersion of 2,6,6-tetramethylpiperidinyloxy (TEMPO)-oxidized CNFs. Reproduced from Saito et al., Biomacromolecules **2007**.*

Flexible displays and electronics

Aerogels



OLED. Chris Rongione. Public domain.



Microwave active GaAs electronic devices on CNF paper. Yei Hwan Jung et al. Fig. 3s. CC BY 4.0

Aerogel. Courtesy NASA/JPL-Caltech. Public domain.

Thin cellulose nanofibril (CNF) films respond rapidly to humidity.

A piece of 0.5 wt.% CNF film exhibits hygroscopicity, swelling and curling with absorbed moisture while resting on a lightly dampened sponge.

1. Swell but do not disintegrate with moisture absorption.
2. Conductivity changes with fluctuating humidity.

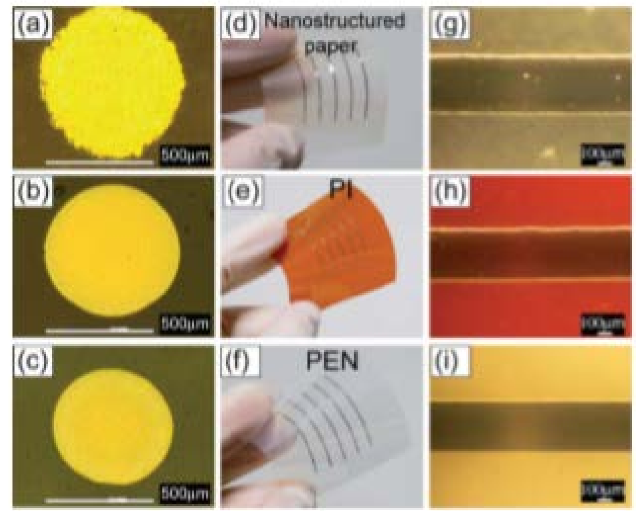
*Eyebe et al., Sensors and Actuators B: Chemical **2017***

Prior studies support the idea of printed CNF thin-film humidity sensors.

Eyebe et al. used thin CNF films to sense humidity in microwave frequencies.

Humidity sensor prototypes consisting of CNF films taped atop coplanar waveguide (CPW) circuits. *Reproduced from Eyebe et al., Sensors and Actuators B: Chemical* ***2017***

Nge et al. demonstrated that CNF films were superior substrates for silver nanoparticle (AgNP) inkjet printing.



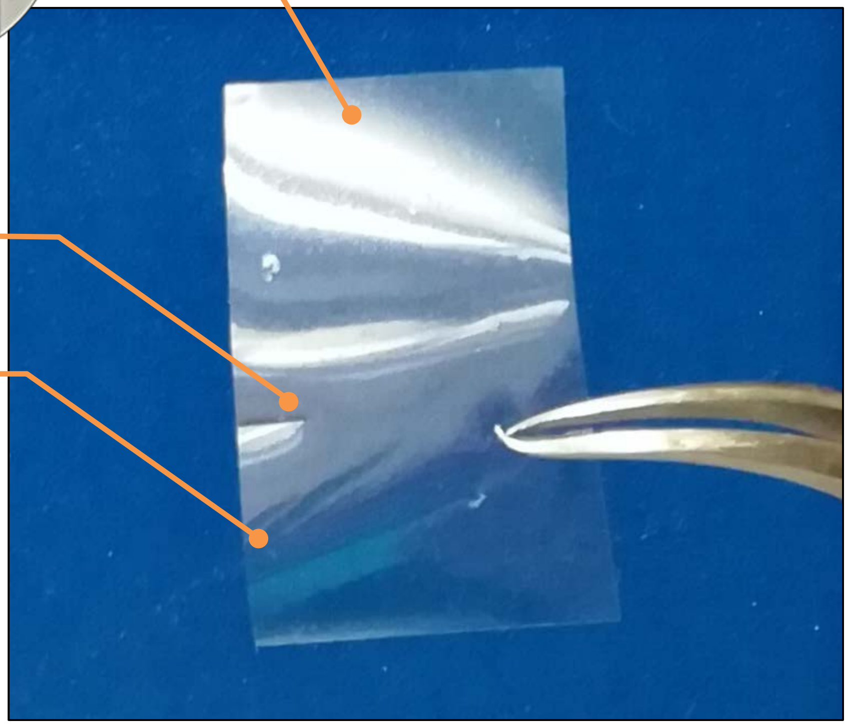
Comparison of inkjet-printed silver nanoparticles on CNF films, polyimide (PI), and poly(ethylene napthalate). 1st column: printed dots; 2nd column: printed tracks; 3rd column optical images of printed tracks. *Reproduced from Nge, et al., J. Mater. Chem. C* ***2013***

Fabrication and characterization of CNF films

Dish-dried from aqueous 2,6,6-tetramethylpiperidinyloxy (TEMPO)-oxidized CNFs

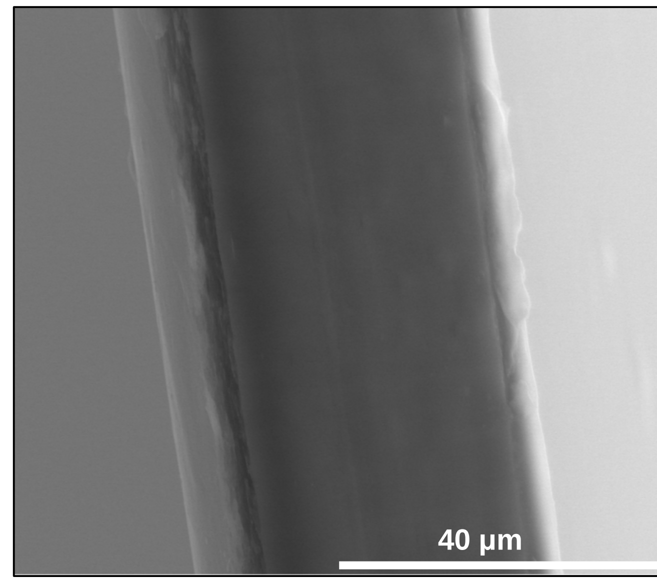
0.5 wt.%

26-43 μm thick

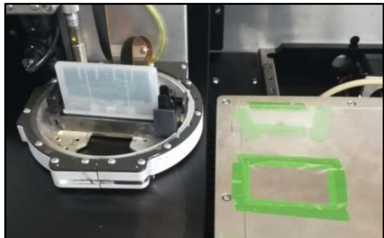


Free-standing CNF film

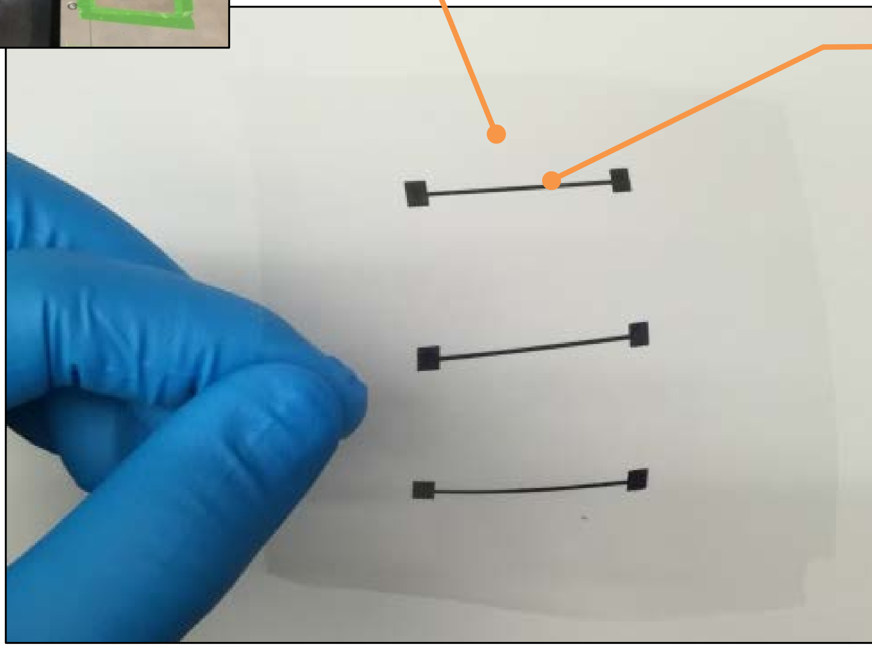
ESEM image:
CNF film cross-section



Fabrication and characterization of silver nanoparticle (AgNP) electrodes

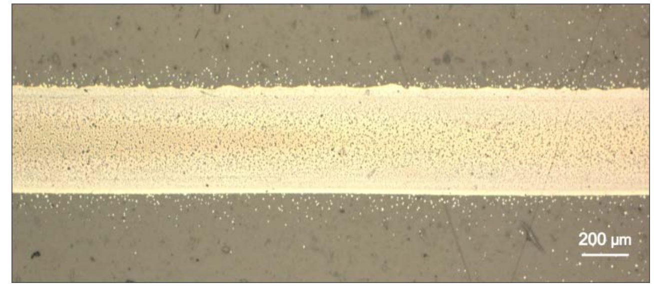


AgNP electrodes printed using Dimatix DMP-2831 piezoelectric inkjet printer (Fujifilm)



Humidity sensor prototype

Optical image: AgNP electrode



Sintered in oven for 2 hours at 100 °C.

Sheet Resistivity of AgNP Electrodes

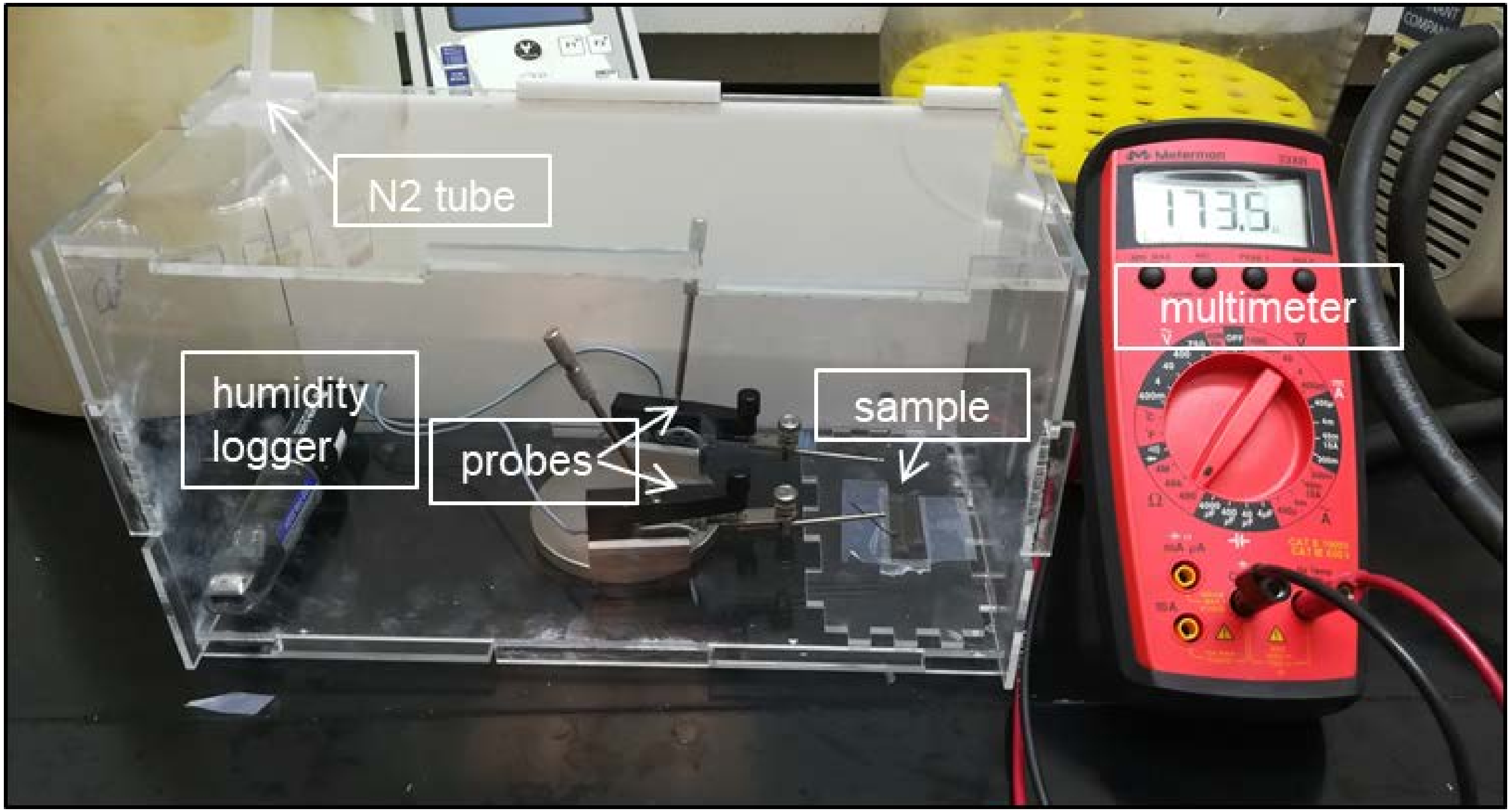
Specimen	ρ_{sheet} [Ω/sq.]
1	1.10 (±0.02)
2	2.50 (±0.01)
4	2.10 (±0.03)
5	3.10 (±0.01)
6	2.20 (±0.01)

Average sheet resistivity [$\rho_{sheet} = \frac{resistance}{length} \times width$] of all specimens: 2.2 Ω/sq. (±0.7). Values of 0.02 Ω/sq. – 70 Ω/sq. have been reported for silver nanowires.

Kalakonda, Nanomaterials and Nanotechnology ***2016***
Gebeyehu et al., RSC Advances ***2017***

Resistance of AgNP electrodes increased with humidity.

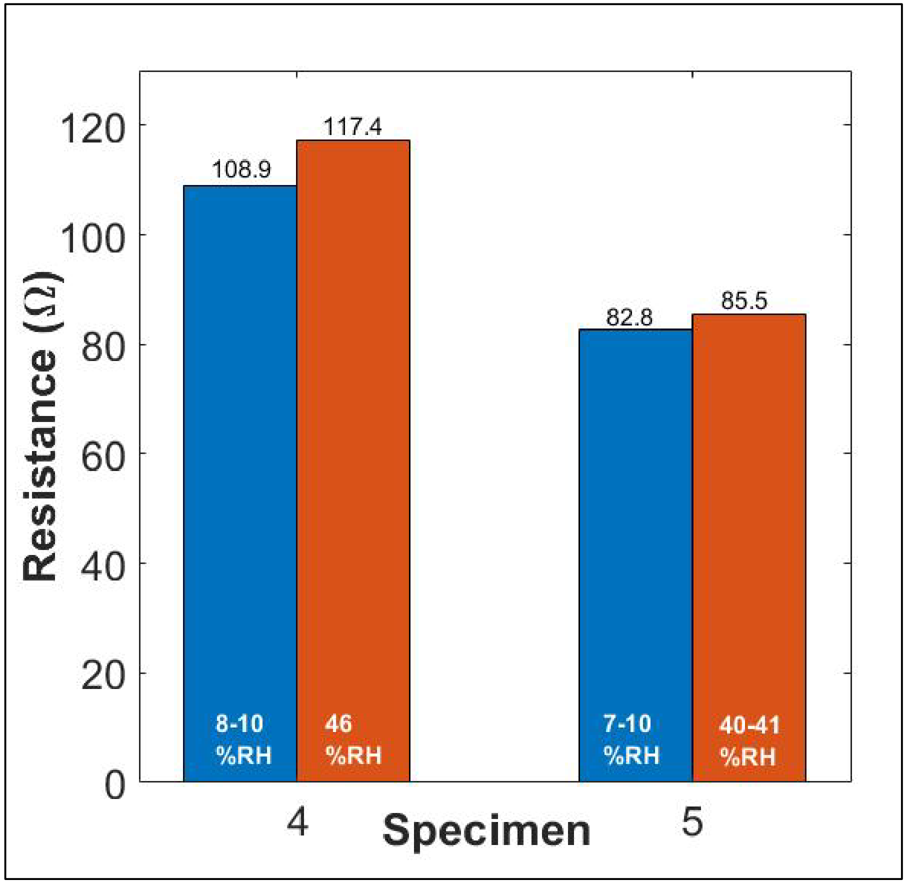
Humidity chamber set-up



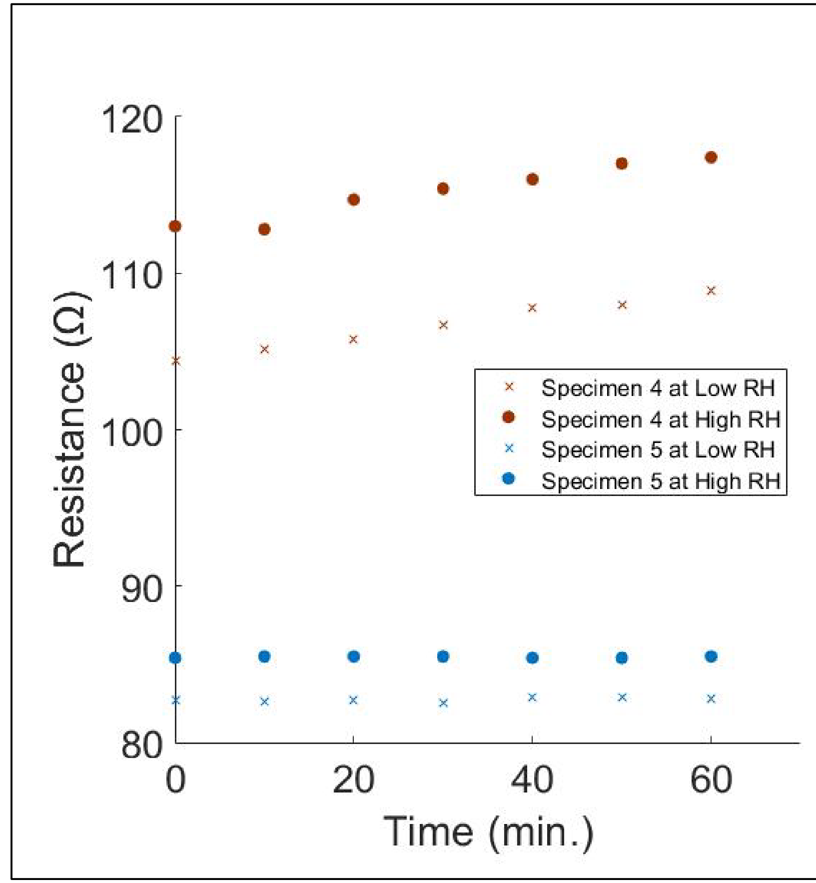
- Electrical resistance recorded for AgNP electrodes every 10 min. for 1 hour at low and high relative humidity (RH).
- RH controlled by flowing nitrogen into chamber.

Resistance of AgNP electrodes increased with humidity.

Resistance vs. Relative Humidity (RH)



Resistance vs. Time at Low or High RH

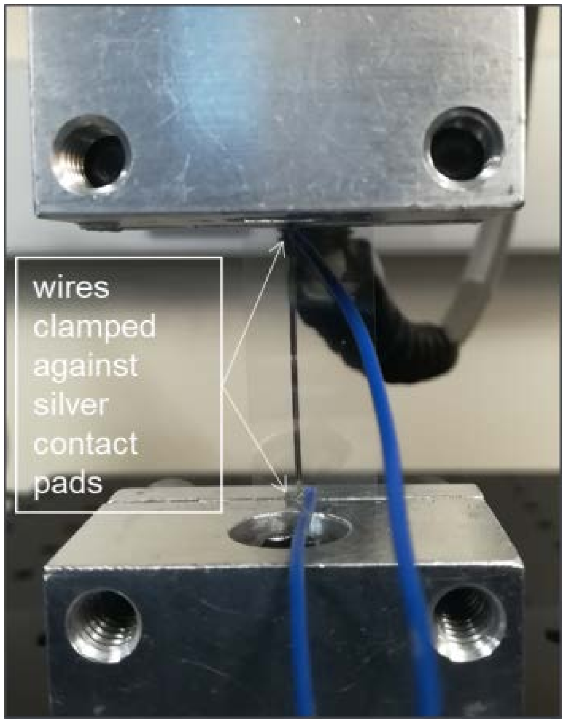


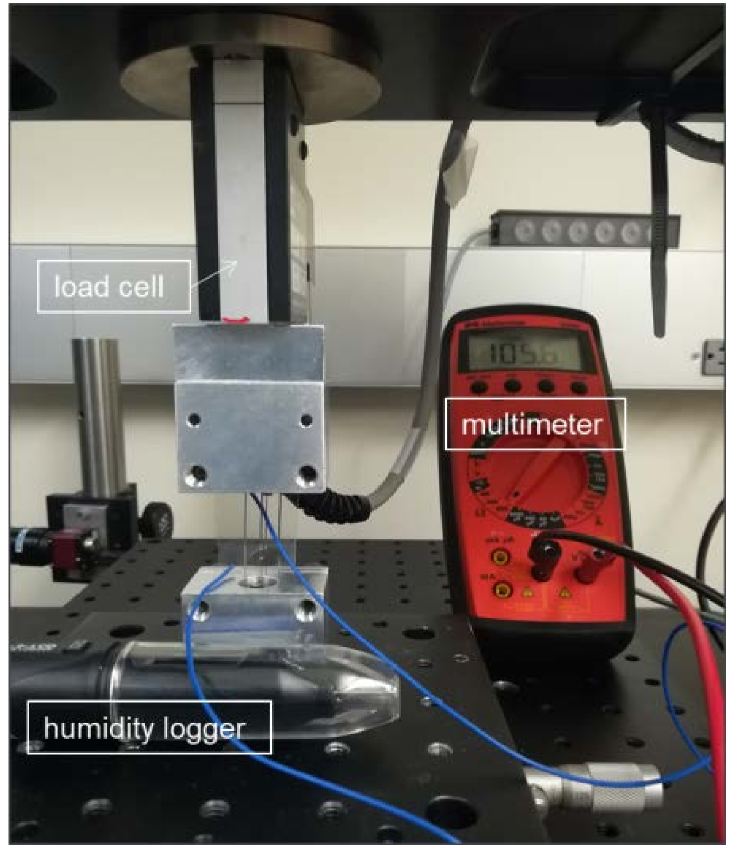
Specimen 4: 8% increase in resistance when RH increased from 8-10% to 46%.

Specimen 5: 3% increase in resistance when RH increased from 7-10% to 40-41%.

Resistance of AgNP electrodes did not increase from 0-0.65% strain.

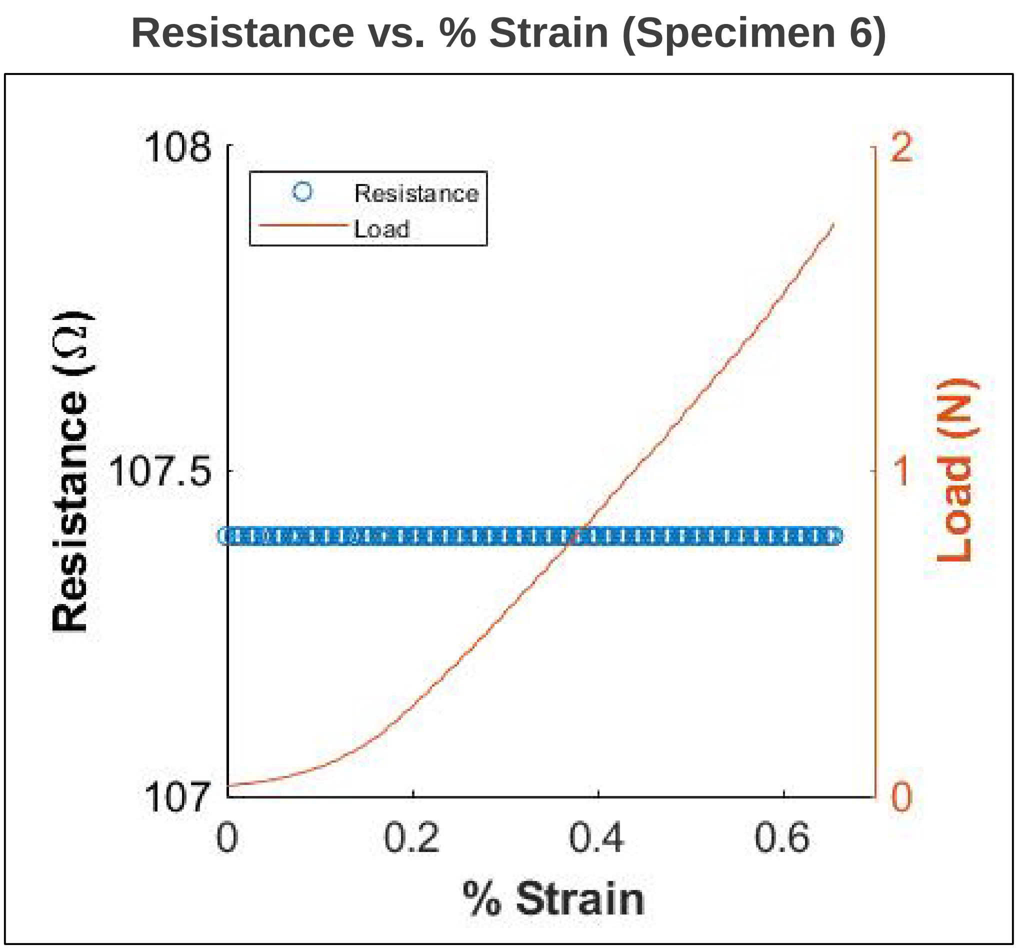
Tensile test set-up





- Tensile specimen mounted on MTS machine.
- Electrical resistance recorded for AgNP electrodes while applying a crosshead displacement of 1% strain/min.

Resistance of AgNP electrodes did not increase from 0-0.65% strain.



Room humidity was 43% RH throughout test.

Preliminary result: no change in resistance up to ~0.65% mechanical strain.

Summary / Future Work

- Fabricated simple humidity sensors by inkjet-printing silver nanoparticle electrodes on cellulose nanofibril films.
- Sheet resistivity falls inside range found for silver nanowires in literature.
- Resistance of AgNP electrodes increased with humidity, but did not change with strain up to ~0.65%.
- Resistance of AgNP electrodes on CNF films may respond to changing humidity due to moisture content, but not strain along axes of electrodes.
- Future work will investigate higher mechanical strains and a wider range of humidities.

Acknowledgments

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