Low-Cost and Robust Printing of Resistance Thermometer Sensors using the Voltera

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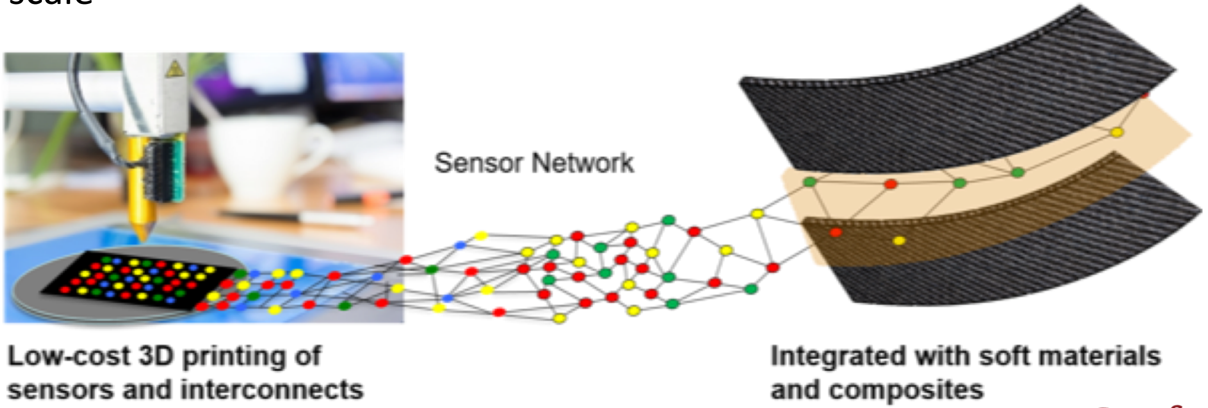
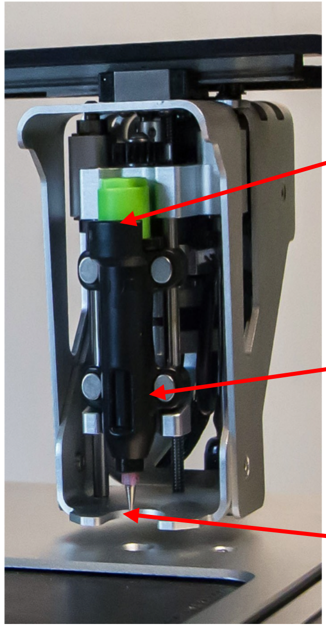
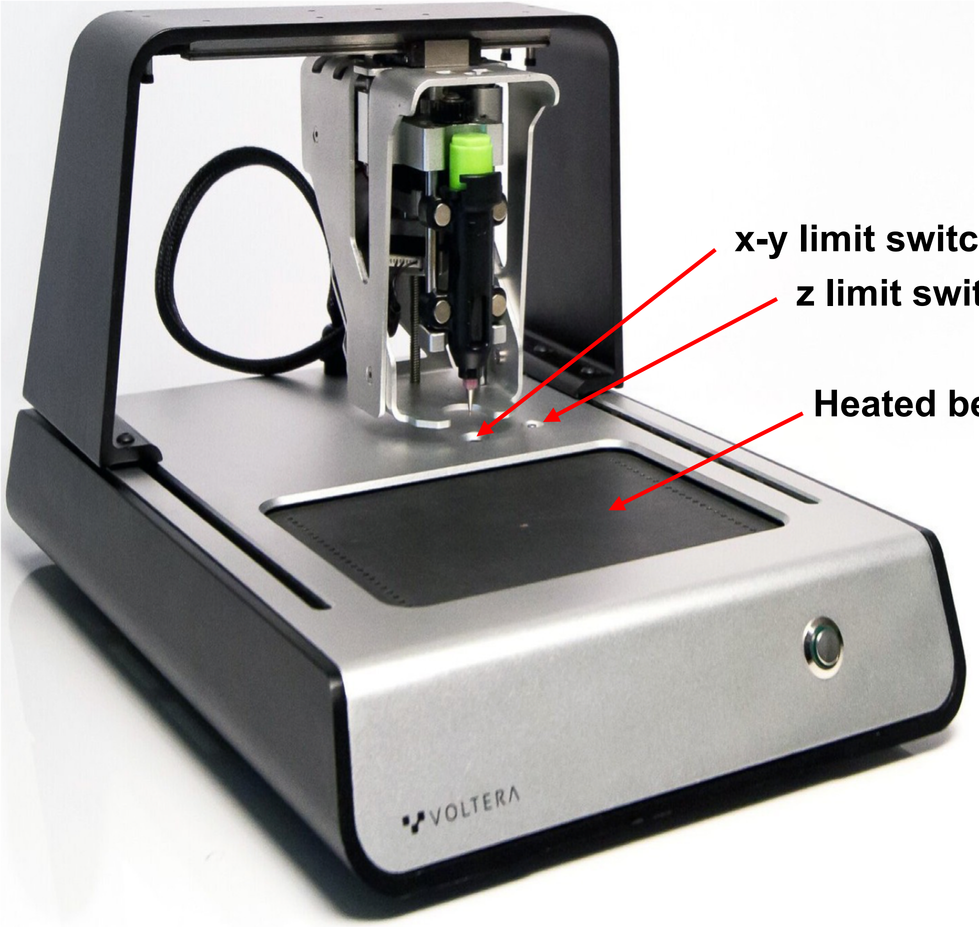
Motivation:

- Sensor networks utilize arrays of sensors to monitor and control systems
- Scaling up is difficult using traditional semiconductor fabrication techniques
- Issues often arise during network development and deployment:
  - Subtractive process causes waste
  - Conforming to curved surfaces
- Additive manufacturing allows sensor networks to be quickly prototyped and implemented on a large scale

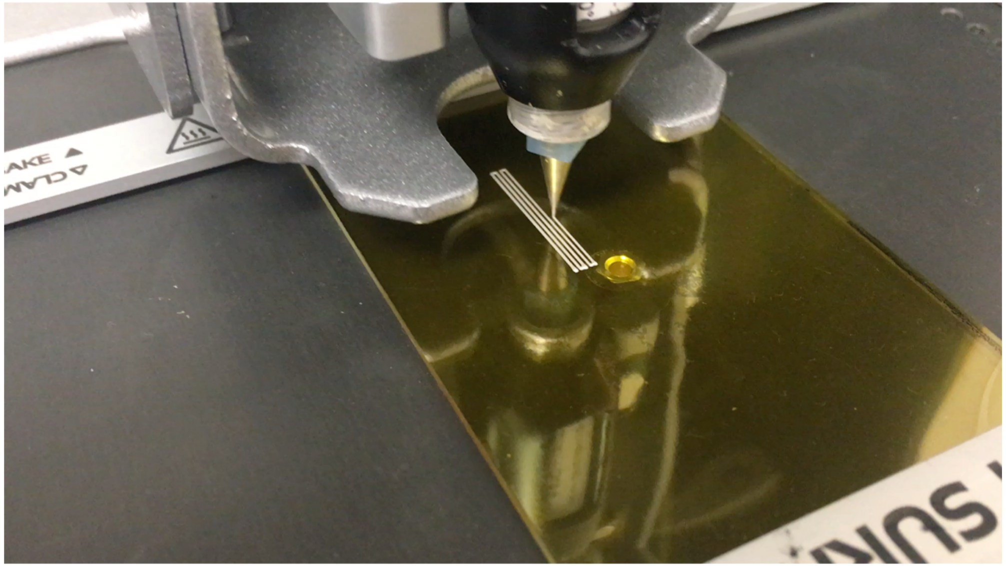


Voltera V-One





Voltera V-One



Cartridge Z-probe

100um 150um 225um

Objective:

This project will look at fabricating and testing Resistance Temperature Detector sensors (RTD) in order to characterize useful parameters for sensor network printing:

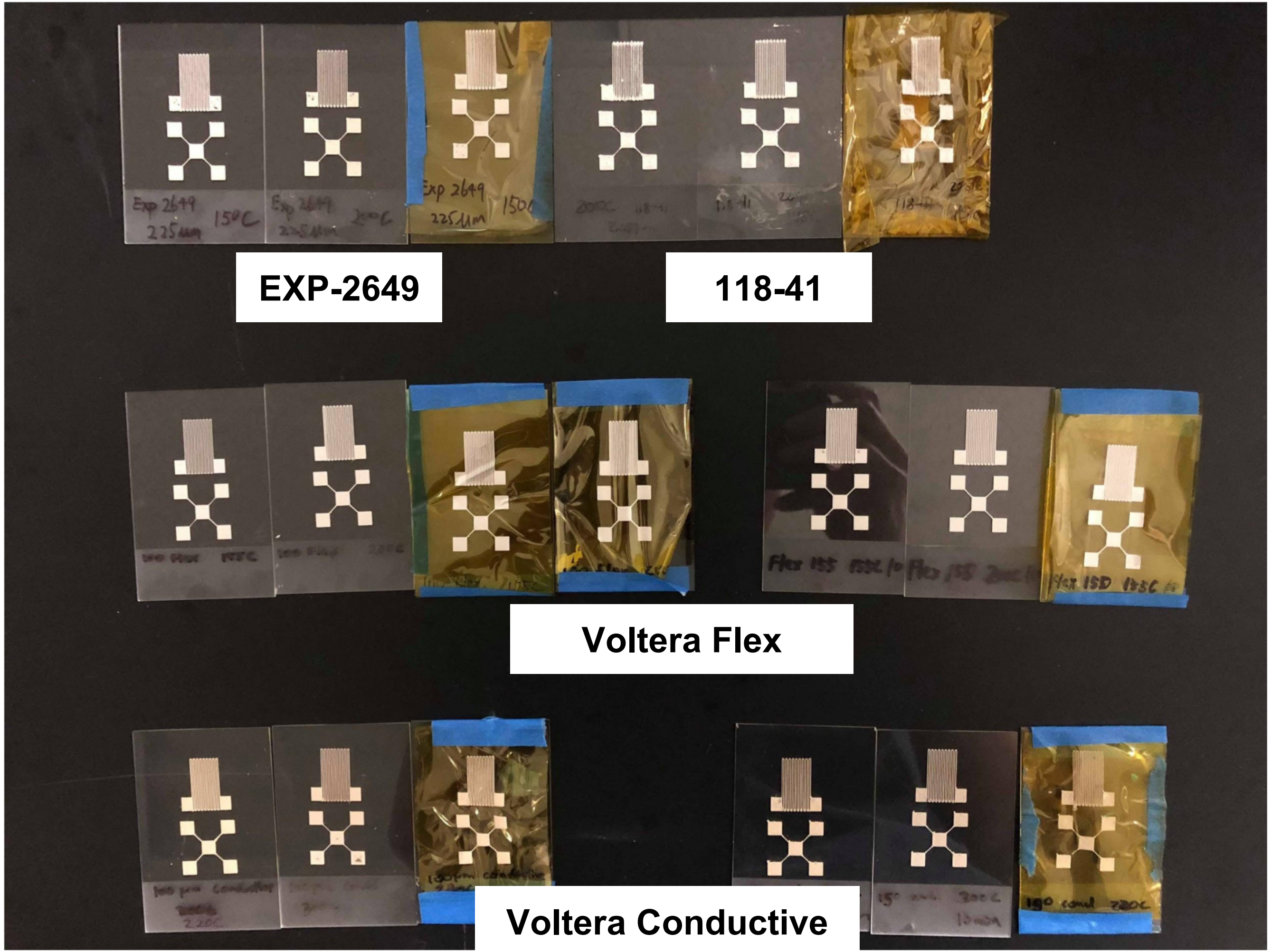
- Ink (4)
- Substrate (2)
- Nozzle size & Sensor geometry (2)
- Anneal temperature (2)

Outputs:

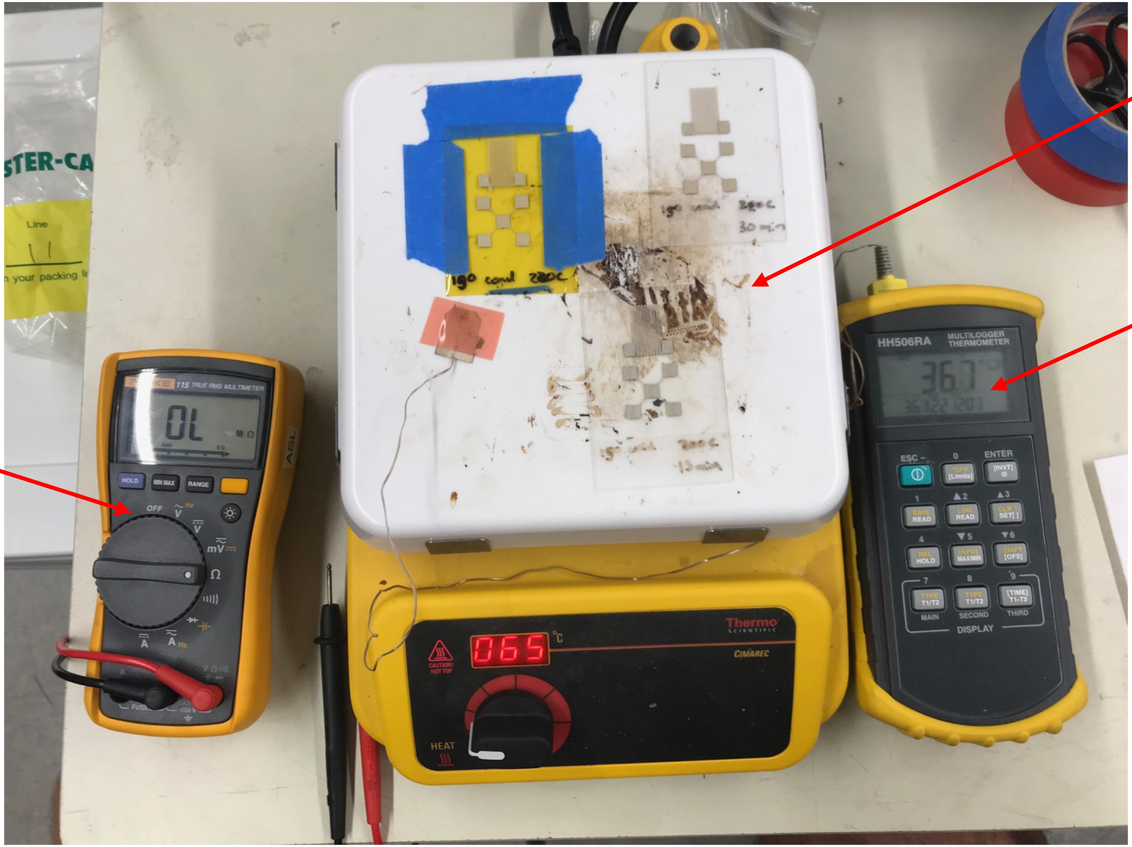
- Temp vs resistance
- Sheet resistance / bulk resistivity
- Thickness, width

Design of Experiments Table

Ink	Substrate	Nozzle Size (um)	Anneal Temp (C)
Voltera Conductive	Glass	150	220
Voltera Conductive	Glass	150	300
Voltera Conductive	Glass	100	220
Voltera Conductive	Glass	100	300
Voltera Conductive	Kapton	150	300
Voltera Conductive	Kapton	150	220
Voltera Conductive	Kapton	100	300
Voltera Conductive	Kapton	100	220
Voltera Flexible	Glass	150	155
Voltera Flexible	Glass	150	200
Voltera Flexible	Glass	100	155
Voltera Flexible	Glass	100	200
Voltera Flexible	Kapton	150	155
Voltera Flexible	Kapton	150	200
Voltera Flexible	Kapton	100	155
Voltera Flexible	Kapton	100	200
CM EXP-2649	Glass	225	150
CM EXP-2649	Glass	225	200
CM EXP-2649	Kapton	225	150
CM EXP-2649	Kapton	225	200
CM 118-41	Glass	225	175
CM 118-42	Glass	225	220
CM 118-43	Kapton	225	175
CM 118-44	Kapton	225	220


EXP-2649
118-41
Voltera Flex
Voltera Conductive

Resistance / Temp Measurements

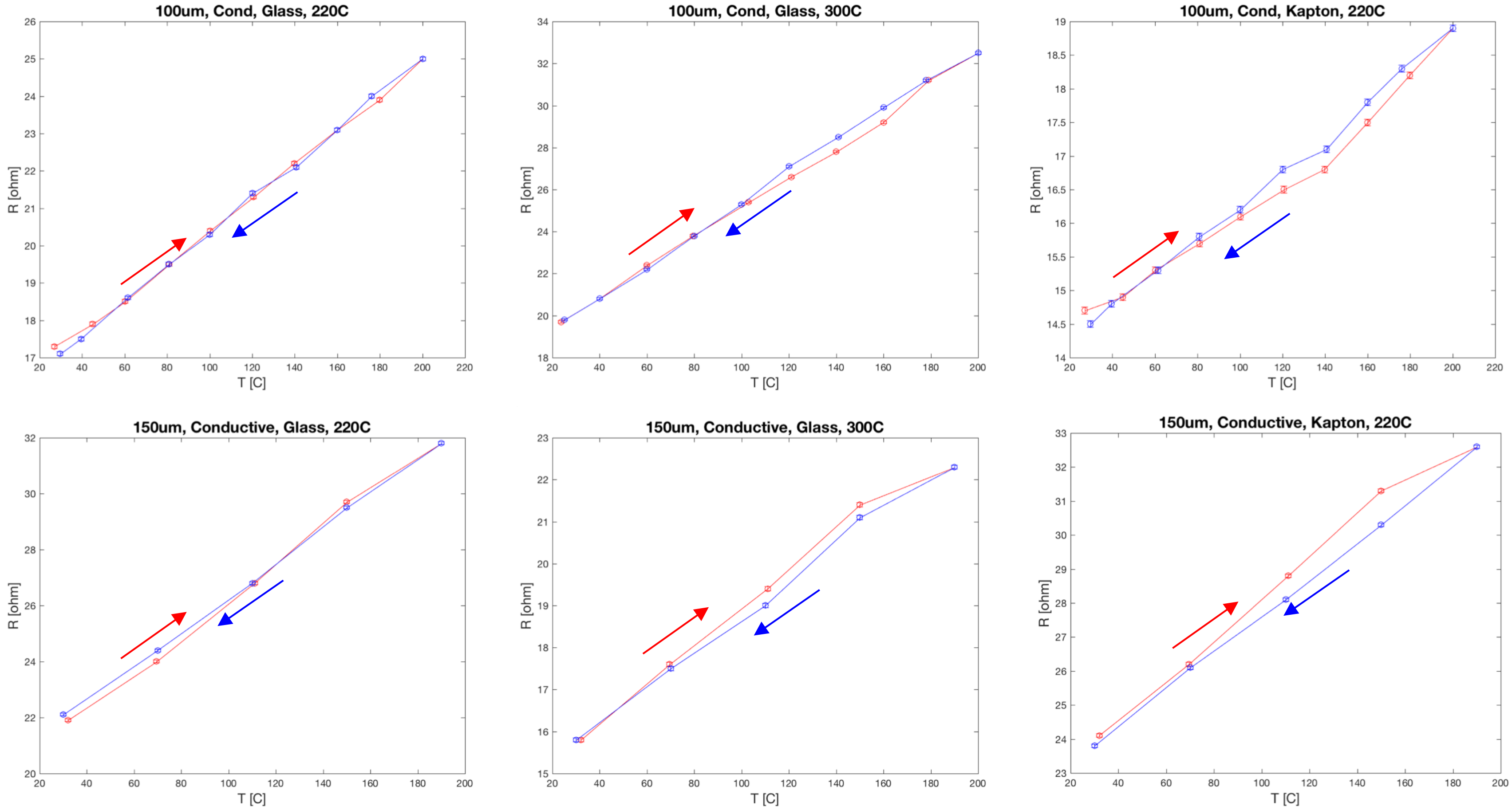


Hotplate

Thermocouple

Voltmeter

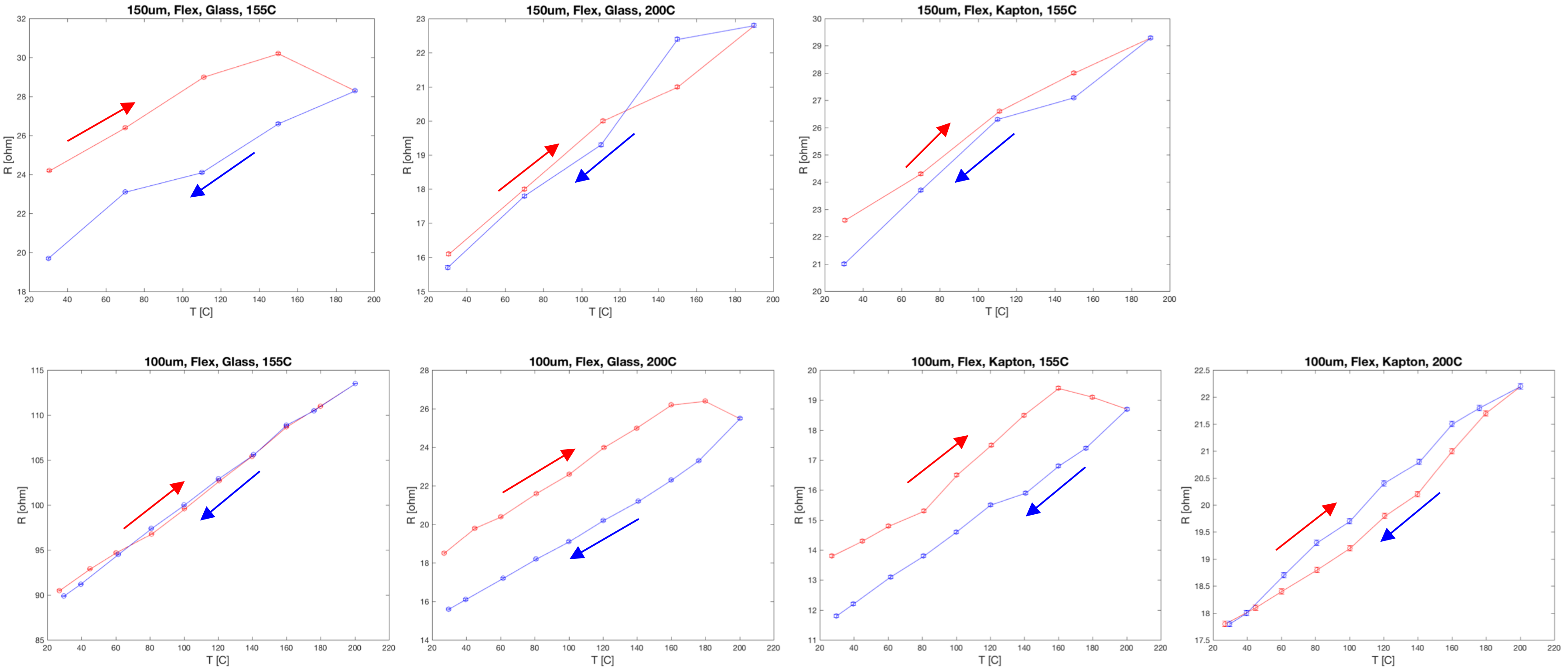
Voltera Conductive Ink R-T curves



Increasing temp.

Decreasing temp.

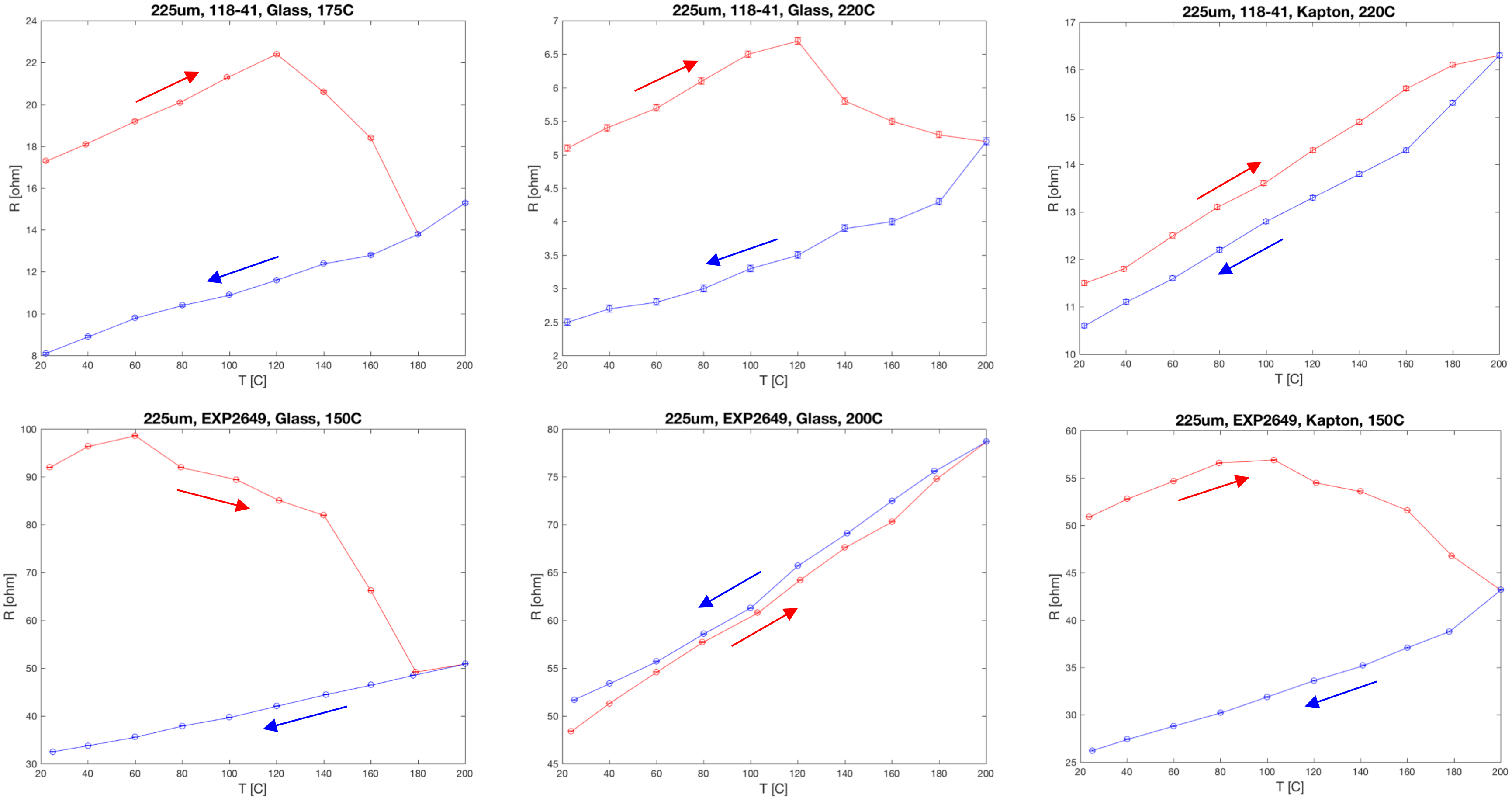
Voltera Flexible Ink R-T curves



Increasing temp.

Decreasing temp.

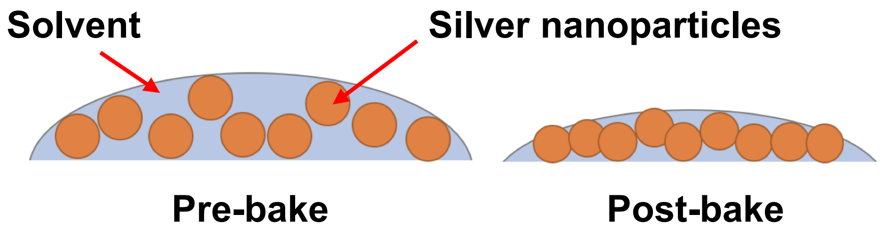
Creative Materials Inks R-T curves



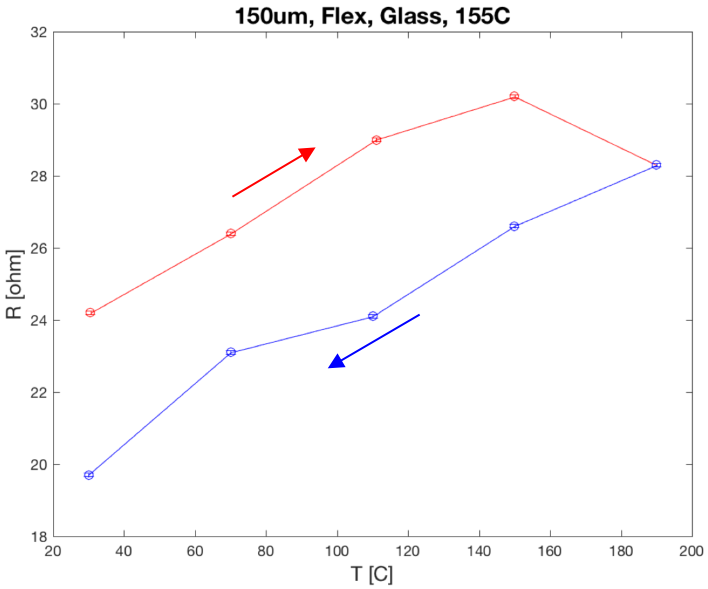
Increasing temp. Decreasing temp.

Conclusions: Anneal Temperature

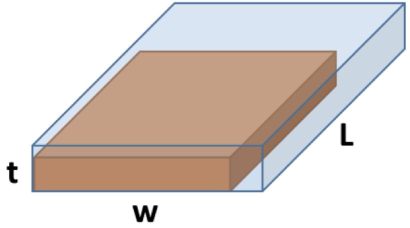
- In some cases, we notice especially large hysteresis
- Due to testing RTD at higher temperature than these samples were annealed at, resistance further decreased while test performed



Higher bake temperature burns off more solvent → silver particles closer together → conductivity increases

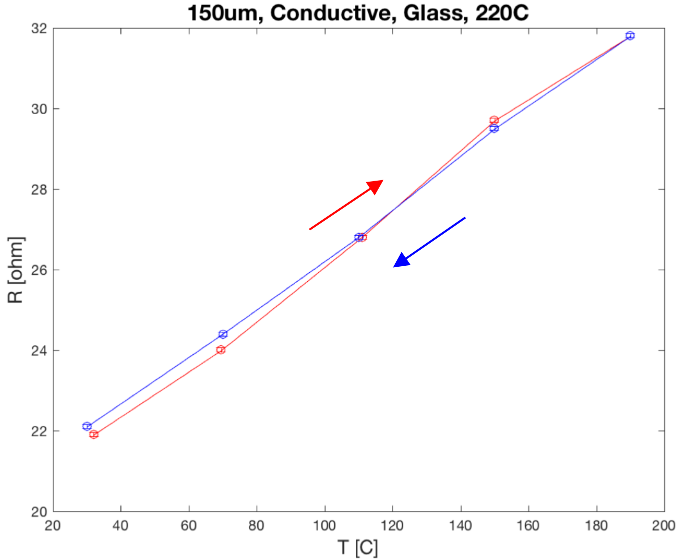


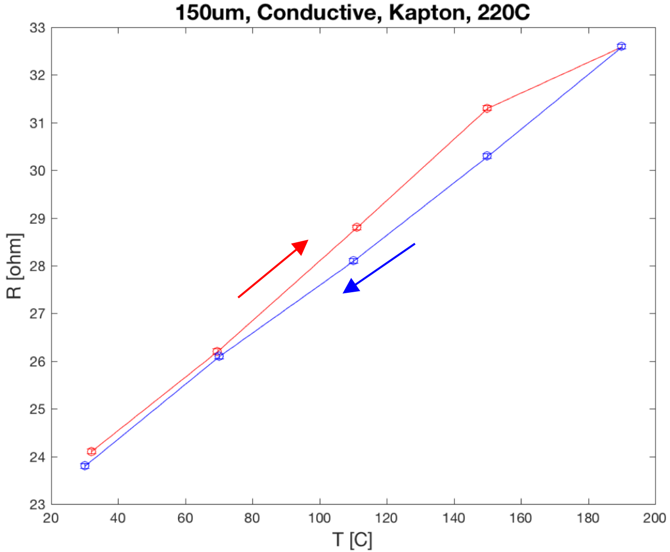
Conclusions: Substrate Thermal Expansion



- More hysteresis on Kapton than glass due to thermal expansion (assumning ink isotropic)

$$R_{\text{initial}} = \rho \frac{L}{wt} \quad \rightarrow \quad R_{\text{thermal expansion}} = \rho \frac{(1+\alpha\Delta T)L}{(1+\alpha\Delta T)w * (1+\alpha\Delta T)t} = \rho \frac{L}{wt} \frac{1}{(1+\alpha\Delta T)}$$



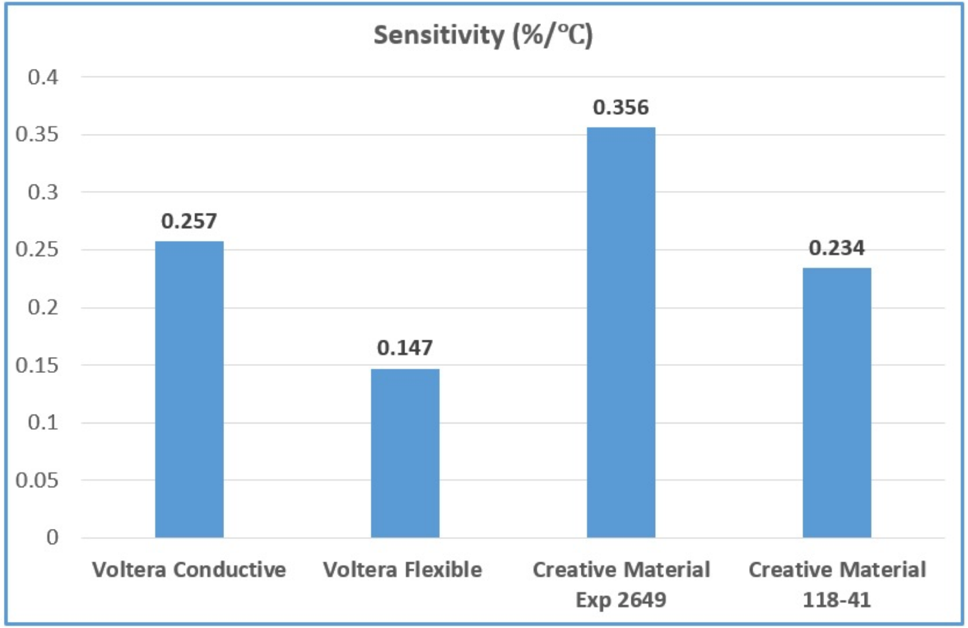


Conclusions: Sensor sensititivity

- 2 methods to represent sensitivity:

$$\frac{\Delta R}{\Delta °C}$$ **Unit**: Ohm / ℃

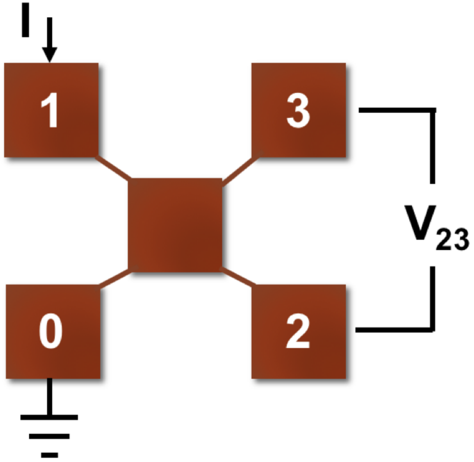
$$\boxed{\frac{\Delta R / R}{\Delta °C}}$$ **Unit**: % / ℃



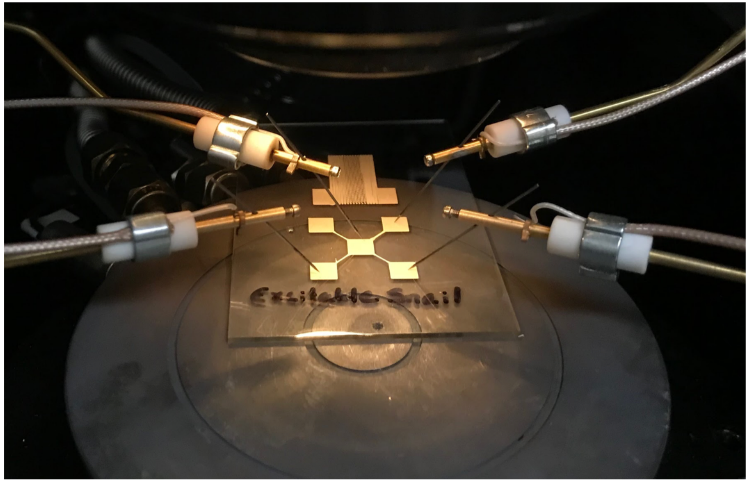
Reference:
A platinum based RTD sensor has a sensitivity of 0.385 (%/℃)

Sheet Resistance

- Independent of sensor geometry, so good for comparison



$$V_{23} \rightarrow R_{01,23} = \frac{V_{23}}{I}$$



Sheet resistance:
resistivity, thickness

$$R_s = \frac{\pi R_{01,23}}{\ln 2} \quad [\Omega/sq]$$

RTD resistance:
resistivity, thickness, width, length

$$R = \rho \frac{L}{w\,t} = R_s \frac{L}{W} \quad [\Omega]$$

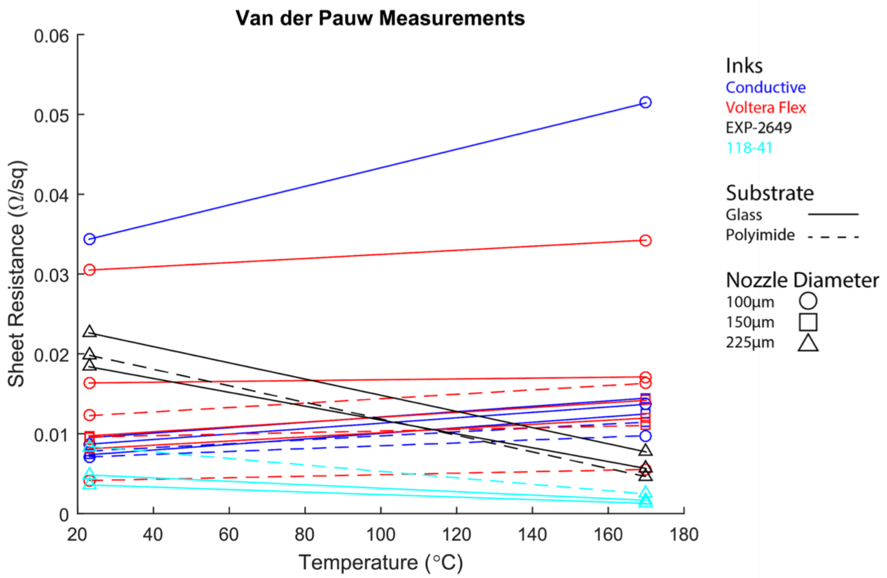
Sheet Resistance

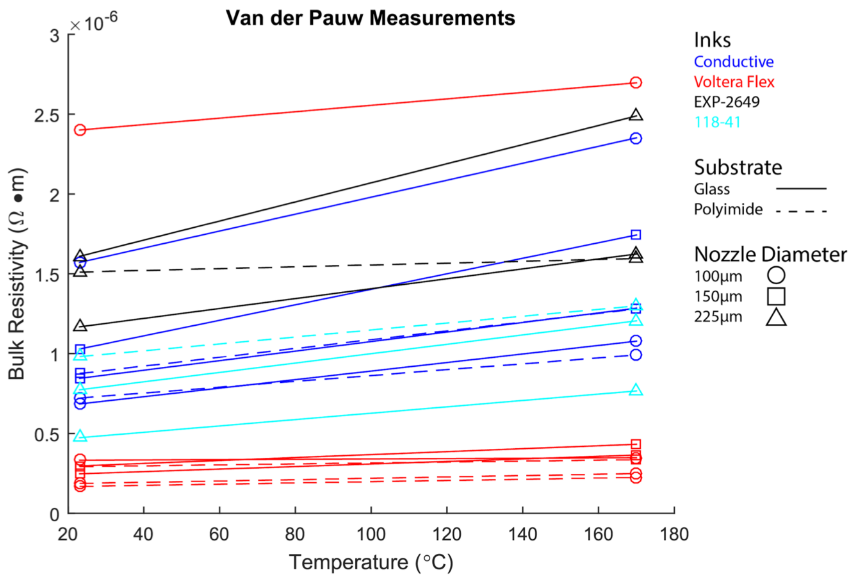
Nozzle (um)	Ink	Substrate	Cure Temp (C)	Sheet Resistance (mOhm/sq)	Bulk Resistivity (Ohm*m)
150	Conductive	Glass	220	9.51	8.45E-07
150	Conductive	Glass	300	7.36	1.03E-06
150	Conductive	Polyimide	220	7.83	8.75E-07
100	Conductive	Glass	220	8.70	6.85E-07
100	Conductive	Glass	300	34.36	1.57E-06
100	Conductive	Polyimide	220	7.10	7.22E-07
150	Flex	Glass	155	9.73	2.97E-07
150	Flex	Glass	200	8.12	2.47E-07
150	Flex	Polyimide	155	9.59	2.92E-07
100	Flex	Glass	200	16.36	3.32E-07
100	Flex	Glass	155	30.49	2.40E-06
100	Flex	Polyimide	155	12.26	1.87E-07
100	Flex	Polyimide	200	4.14	1.68E-07
225	EXP-2649	Glass	200	22.63	1.61E-06
225	EXP-2649	Glass	150	18.39	1.17E-06
225	EXP-2649	Polyimide	150	19.83	1.51E-06
225	118-41	Glass	200	4.83	7.73E-07
225	118-41	Glass	175	3.58	4.73E-07
225	118-41	Polyimide	175	8.39	9.81E-07

(Voltera conductive ink datasheet lists 12 mOhm / sq)

Thickness measurement with micrometer

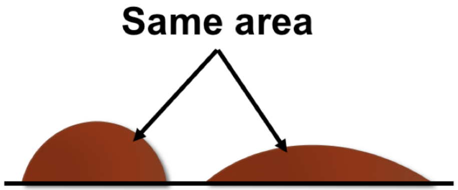
Sheet Resistance

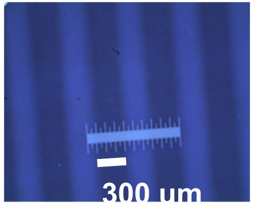




Printing Challenges: Line Width

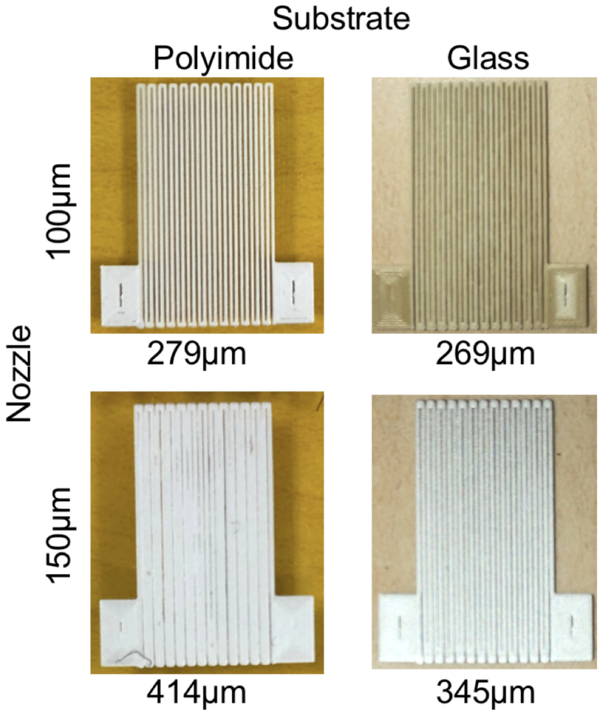
Line Width / Nozzle Diameter		
	Glass	**Polyimide**
Conductive	2.058	2.792
Flex	2.158	3.678
EXP-2649	1.033	1.267
118-41	1.000	0.911





Thickness measurement under microscope

Substrate wettability

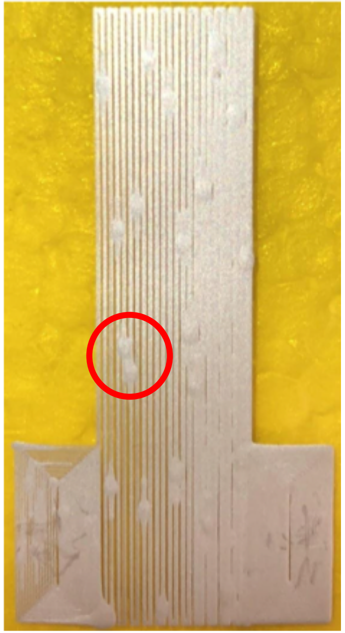


Trim length thinning because plunger turns only once
This is a problem when trying to print with long trim

Printing Challenges: Trim length & Thinning

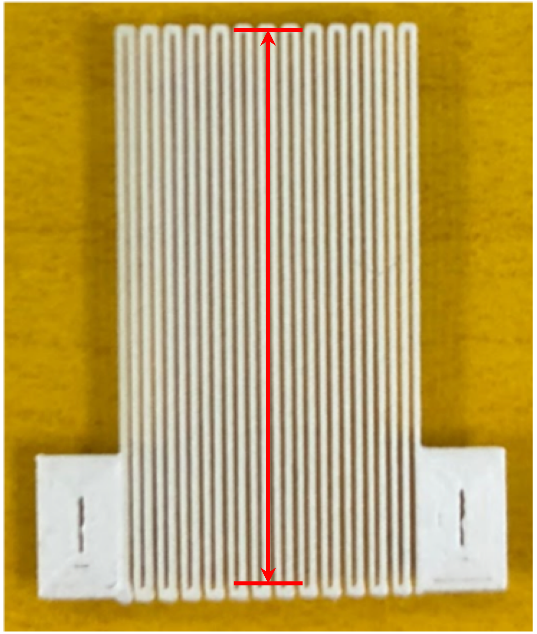
Anti-stringing distance

(retrace distance per trim)



Trim length

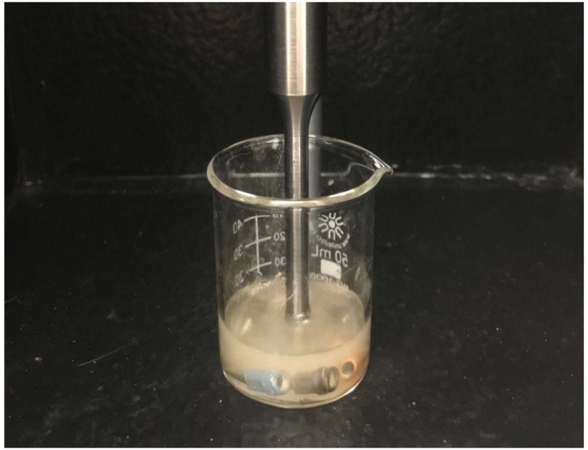
(max distance in one path)



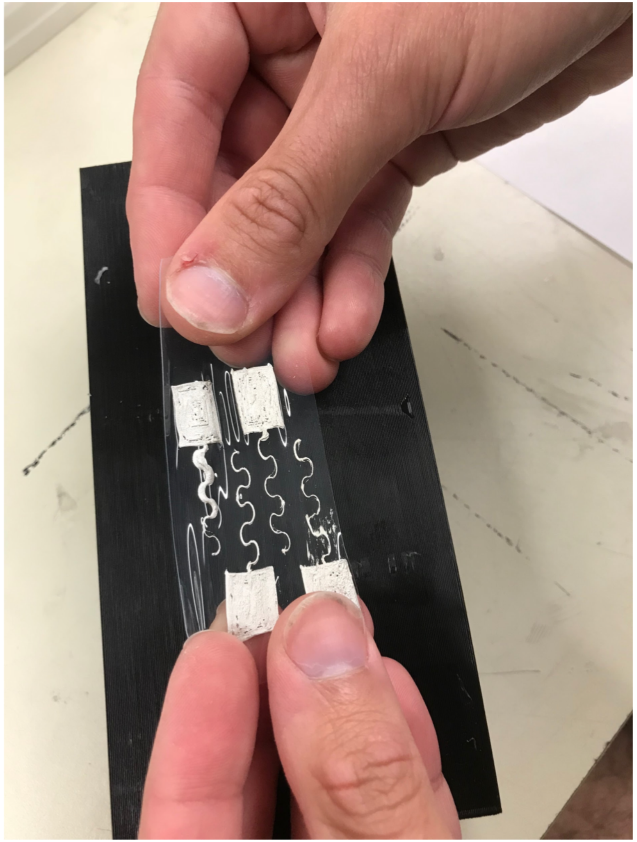
Printing Challenges: Nozzle Clog

Nozzle clogging

- Syringe purge
- **Sonicate in acetone**
- Leave in solvent
- Refrigerate



Printing Challenges: Silicone substrate



Acknowledgements

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