Rapid Development of Electrically Conductive Materials for Additive Manufacturing Feasibility and Applications

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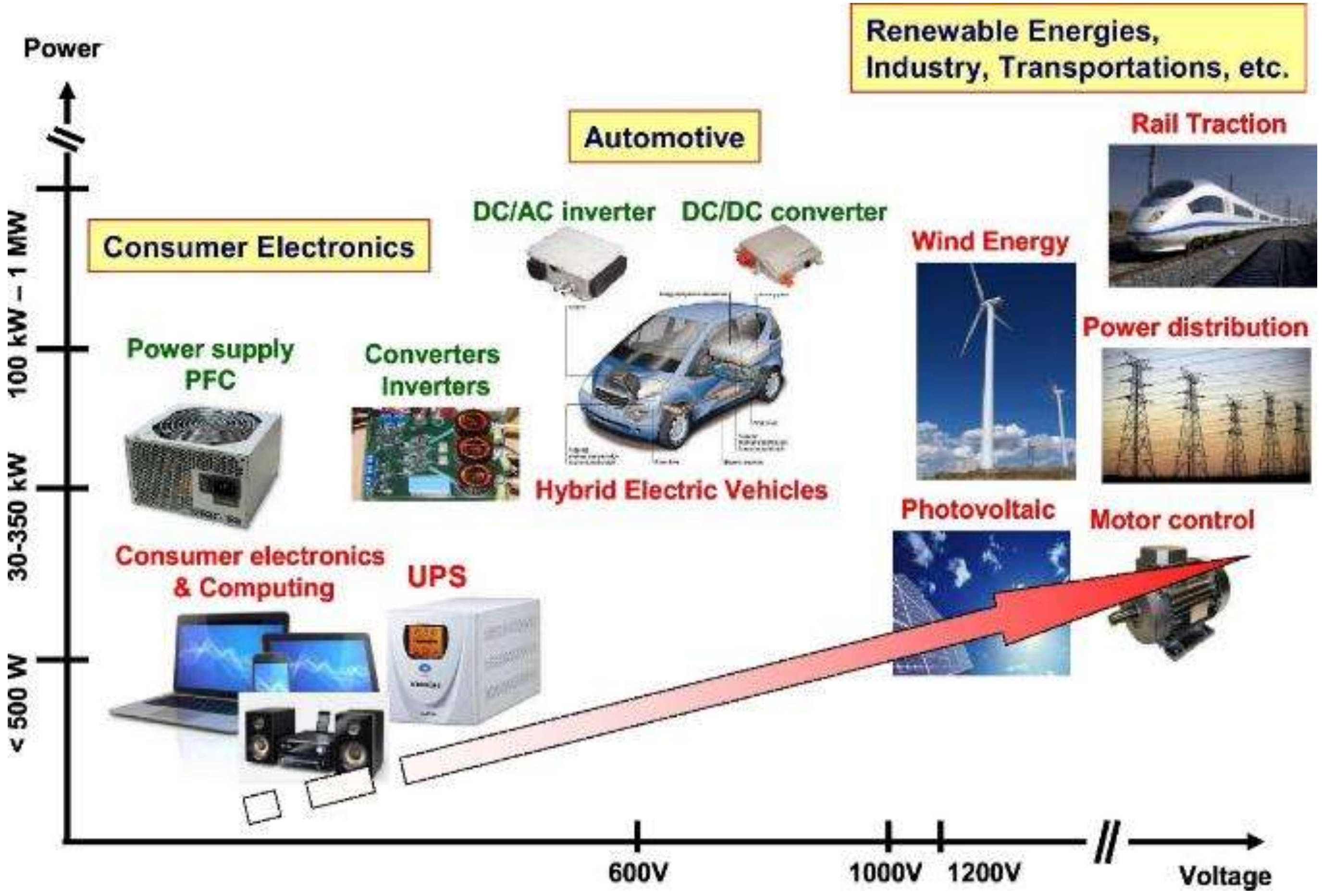
3D-PEIM
INTERNATIONAL SYMPOSIUM ON 3D POWER ELECTRONICS INTEGRATION AND MANUFACTURING

UNIVERSITY OF MARYLAND 1856
CALCE CENTER FOR ADVANCED LIFE CYCLE ENGINEERING
ncms National Center for Manufacturing Sciences
AMMP

Motivation

- Power electronics applications
- RoHS Pb-Free
- Harsh environments
- **Rapid and robust Additive Manufacturing applications**

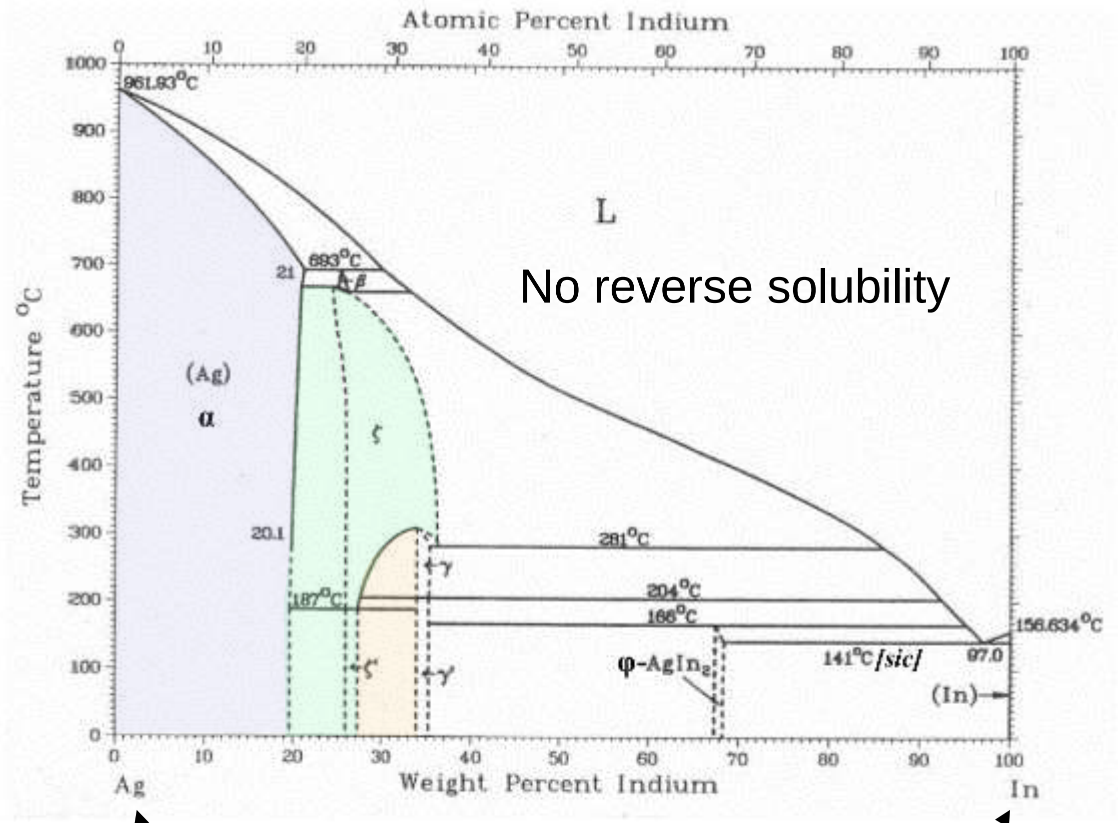
B. A. and G. M., "Electric Power Systems in More and All Electric Aircraft: A Review," IEEE, vol. 8, pp. 169314-169332, 2020.



F. Roccaforte, P. Fiorenza, G. Greco, R. Nigro, F. Giannazzo, F. Lucolano and M. Saggio, "Emerging trends in wide band gap semiconductors (SiC and GaN) technology for power devices," *Microelectronic Engineering,* Vols. 187-188, no. 5, pp. 66-77, 2018.

TLPS Processing

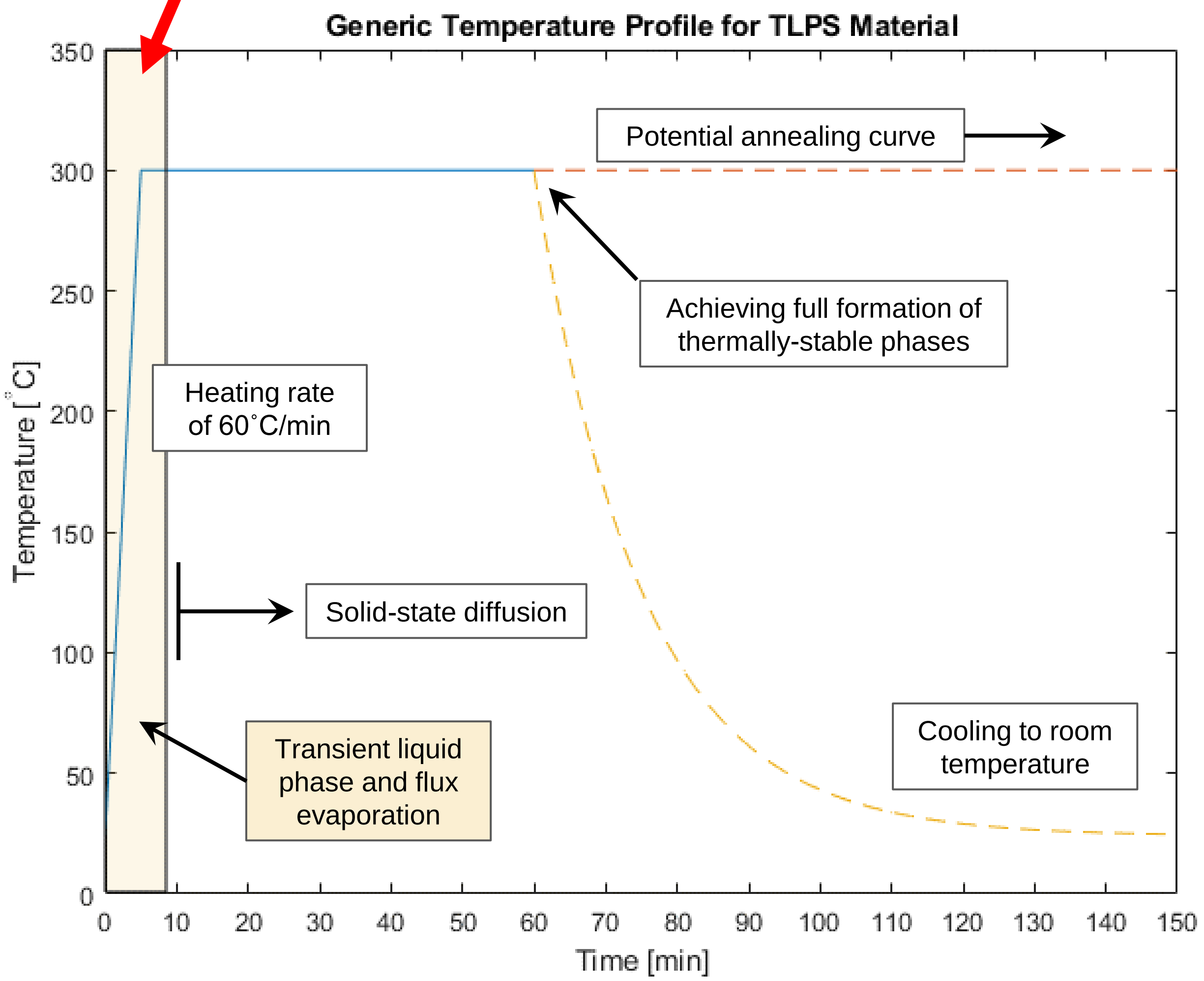
Ag-In Binary Phase Diagram



HMP: High Melting Particles

LMP: Low Melting Particles

Suggested time-frame of focus



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Effects on Electrical Conductivity, and Structure Formation

First-stage-processing category-considerations for temperature profile design, and paste formulation

Flux Performance

Behavior Below Melting Temperature of LMP

- Printability
- Contributes to densification of green structure

Activation and Removal of Oxides

- Links directly to the wetting performance
- Activation time w/respect to melting point of LMP
- Activation time w/respect to evaporation kinetics

Evaporation Kinetics and Escape Routes

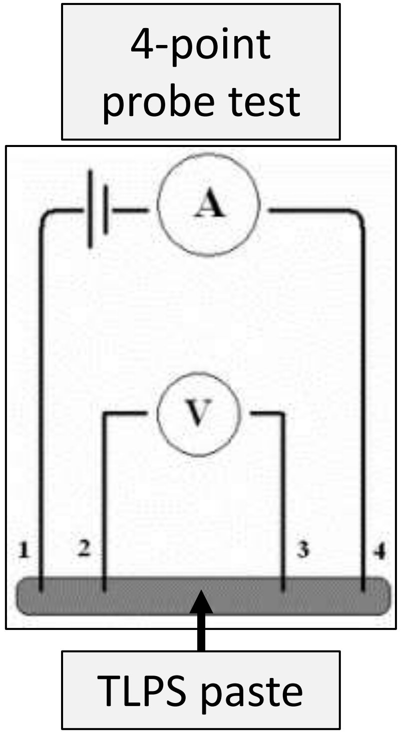
- When to evaporate?
- At what rate?
- How can we control the evaporation routes?

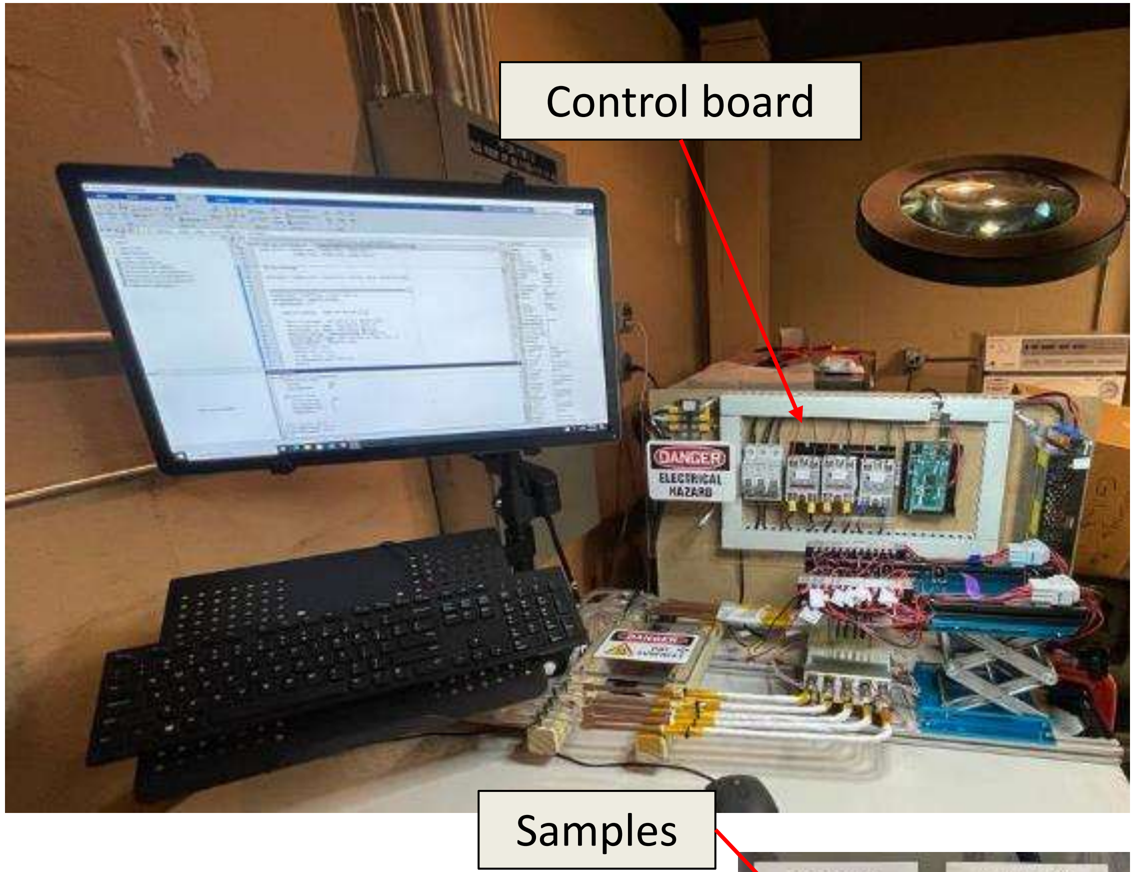
LMP Liquid Phase Performance

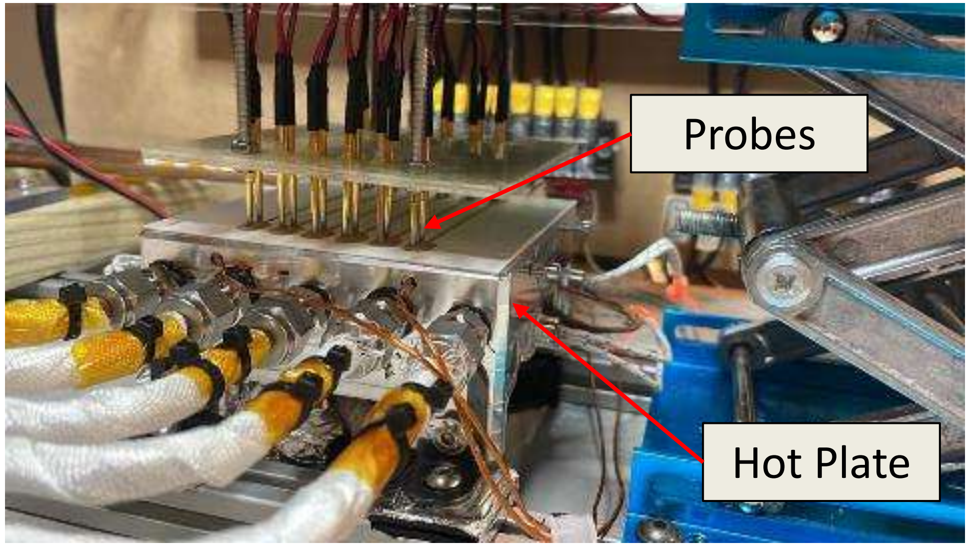
- Amount of liquid phase present at a given time
- Wetting performance
- Liquid state diffusion kinetics
- Sintering-onset

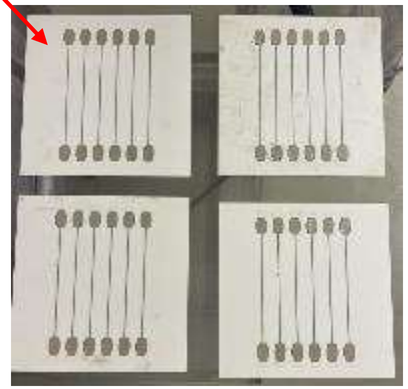
LMP: Low Melting Particles

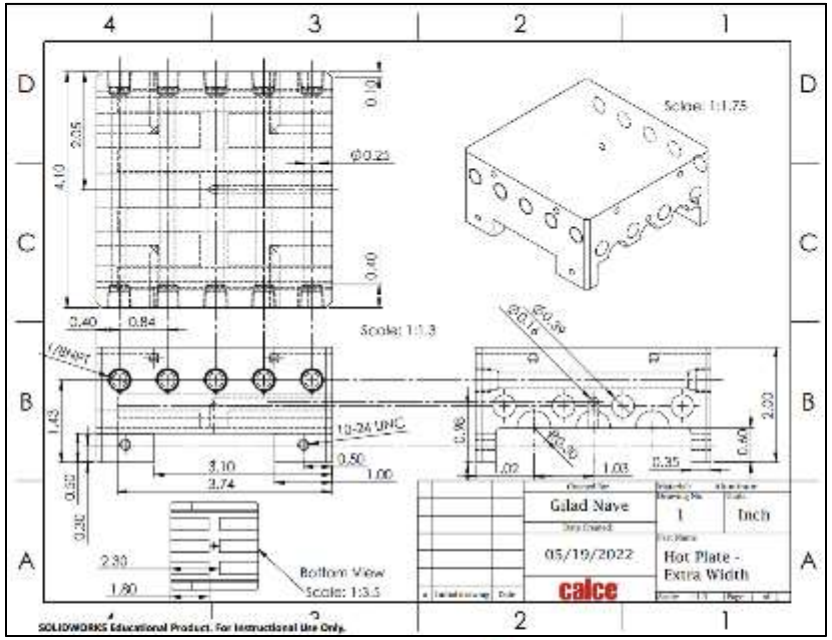
Dynamic Resistivity Test (DRT) Apparatus and Test Design











- Hot plate design and manufacturing
- Stencil design
- Control unit design
- Probe configuration design

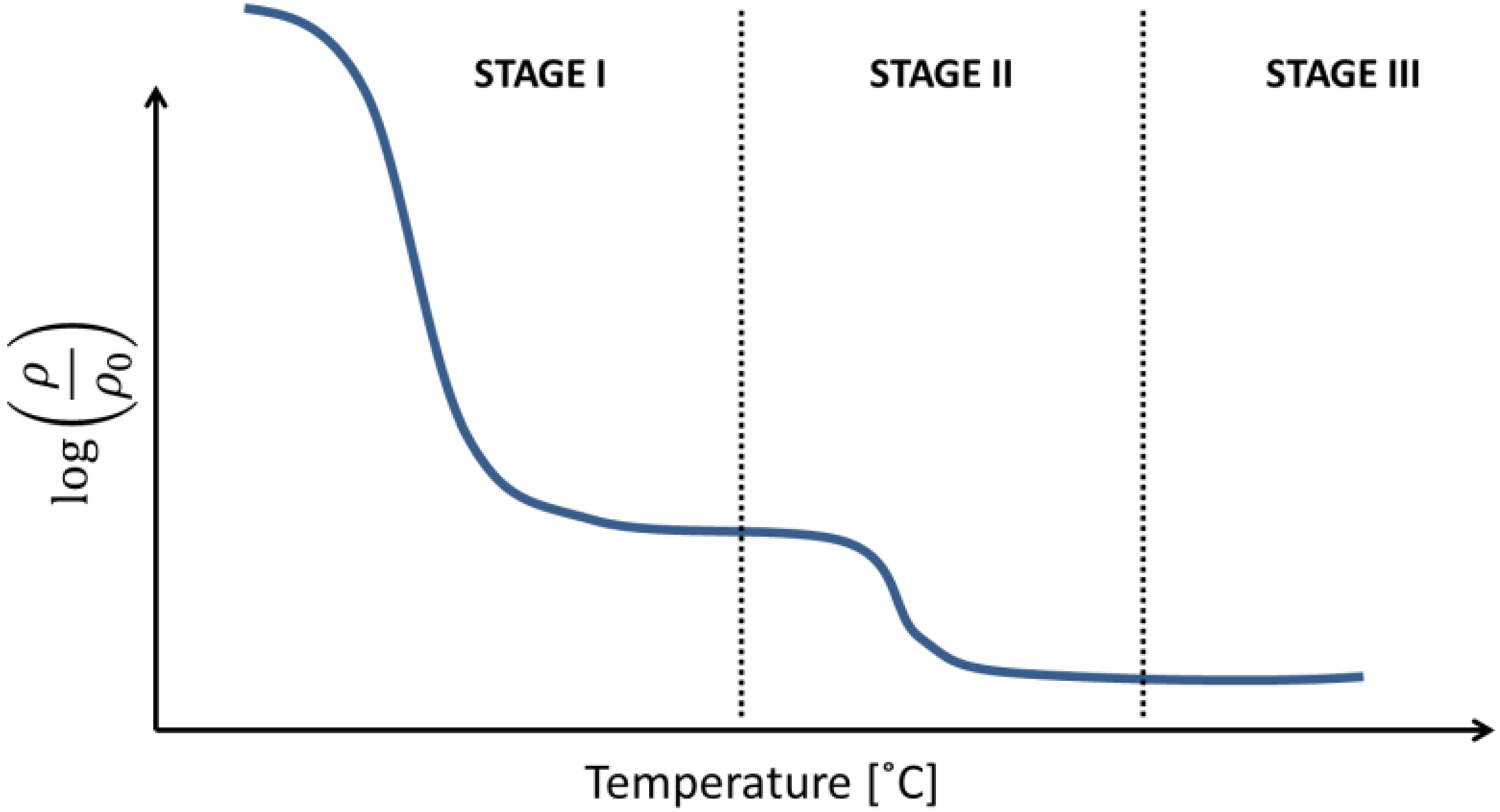
DRT: Schematics Resistivity Curve Evolution

- **STAGE I:** Organic related evaporation, capillary forces. Beginning of percolation network.

- **STAGE II:** Melting of TLPS's Low Melting Particles (LMP). Closer to eutectic melting point. Liquid-state diffusion.

- **STAGE III:** Solid-state diffusion.

$$\log\left(\frac{\rho}{\rho_0}\right) \; Vs. Temperature$$



$$Resistivity = \rho(T, A(T,t), Holding\ Time, \%LMP, \%Flux, LMP\ Selection, Flux\ Selection, etc..)$$

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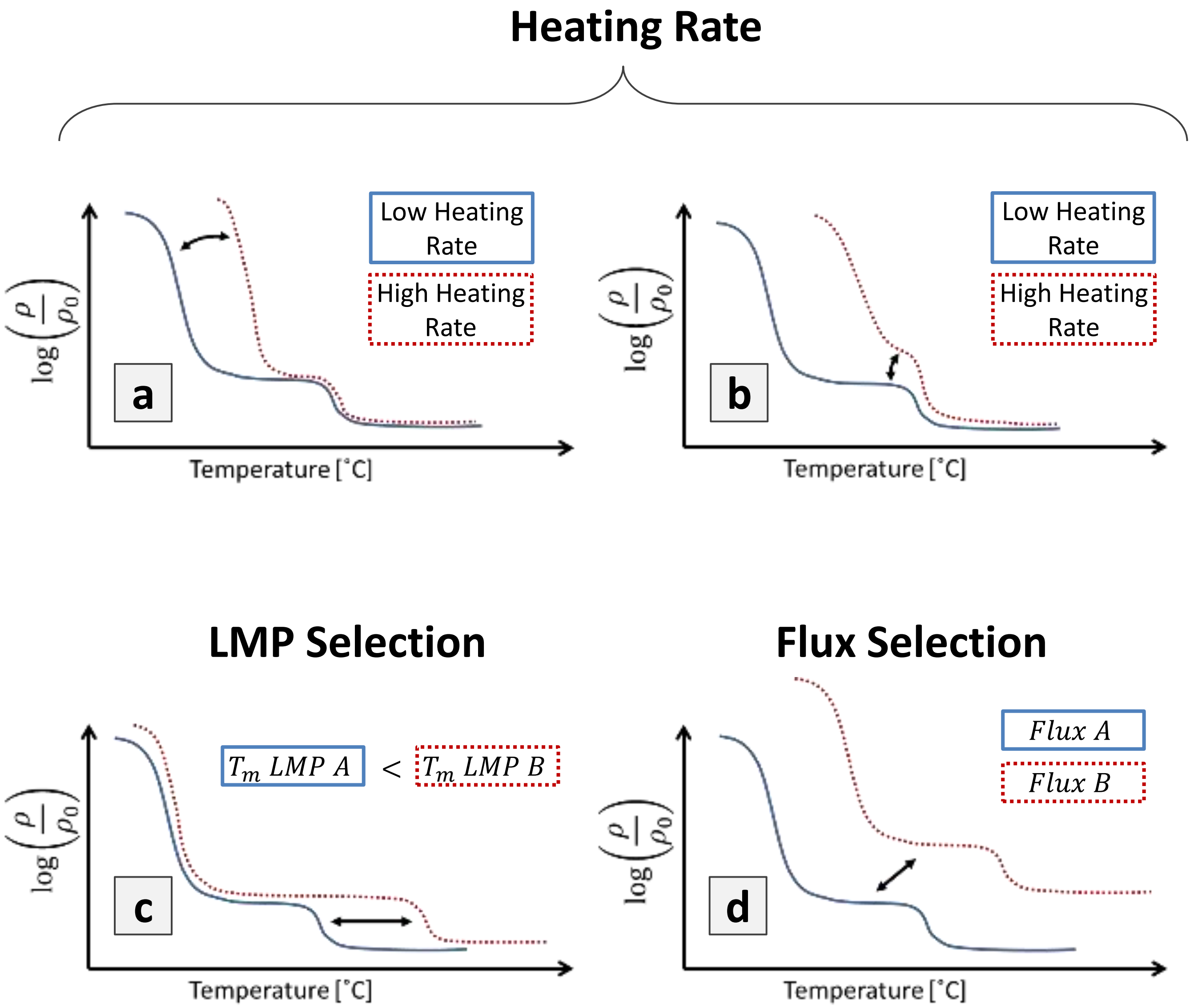
DRT: Schematics of Effects

- **<u>Heating Rate:</u>** Has a major effect over stage I (a). In addition, when combining with specific flux and LMP selection, heating rate has an effect over stage II (b).

- **<u>LMP Selection:</u>** The LMP selection determines the temperature of the secondary major decrease in the resistivity curve (stage II).

- **<u>Flux Selection:</u>** Has the potential to completely shift the resistivity curve (stage I, II, and III).



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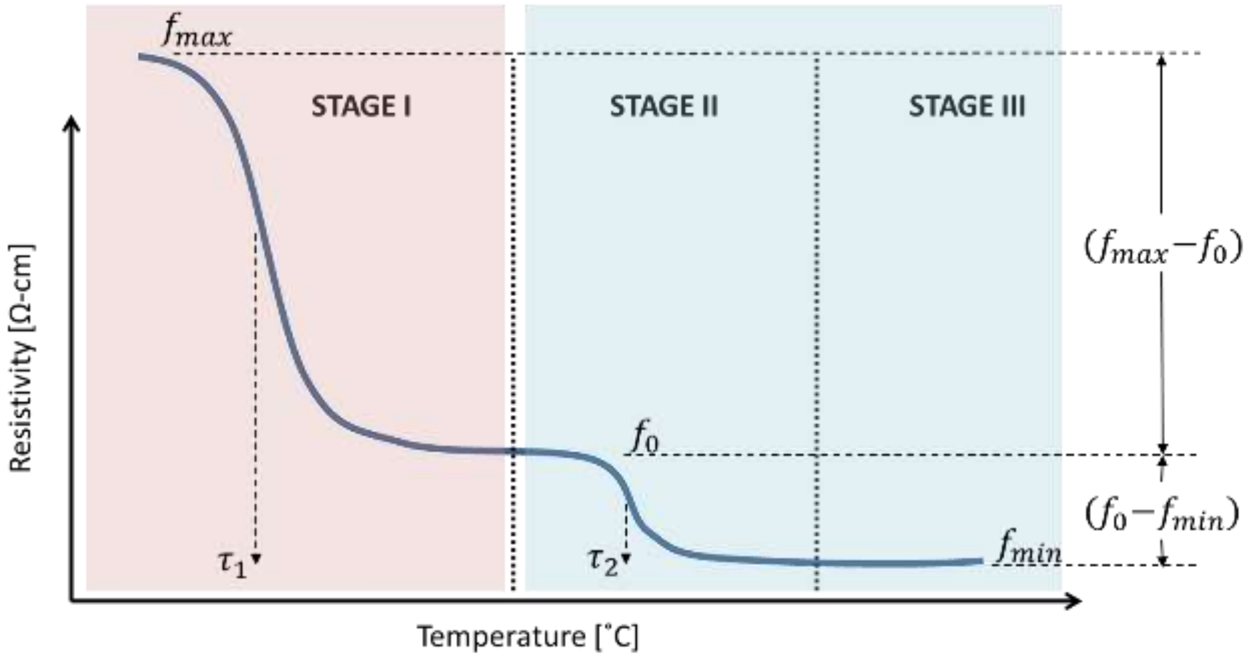
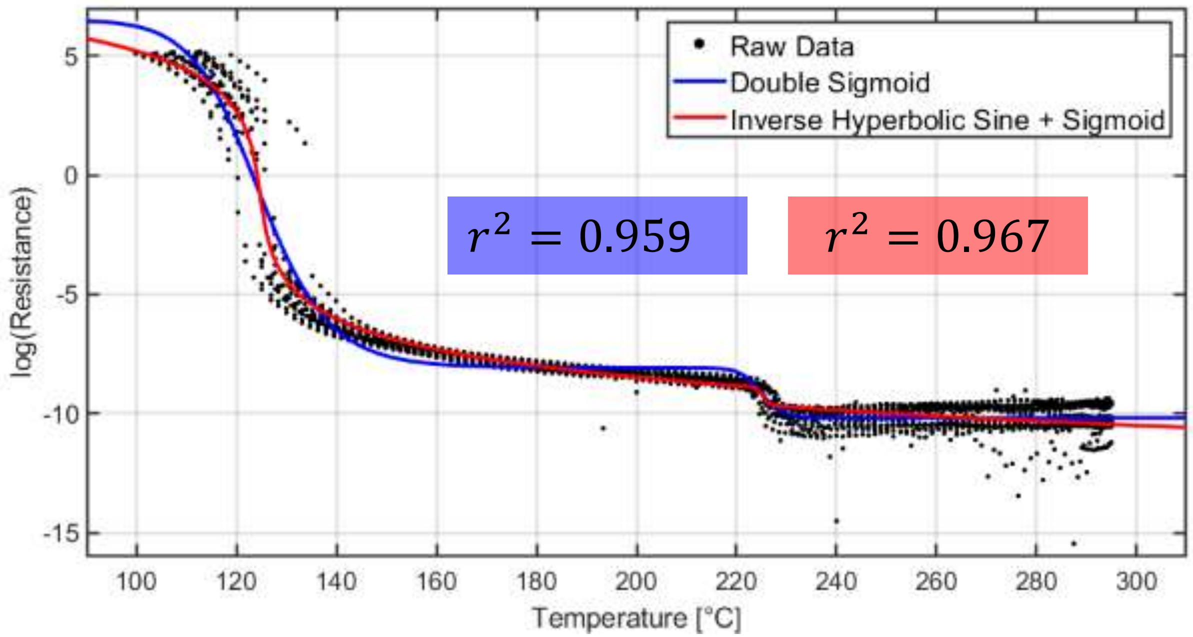
DRT: Regression Model, Double Sigmoid Function

$$\rho(T, A(T)) = \exp\left\{\frac{\log(R)A(T)}{L}\left[\frac{f_{max}-f_0}{1+\left(\frac{T}{\tau_1}\right)^{n_1}} + \frac{f_0-f_{min}}{1+\left(\frac{T}{\tau_2}\right)^{n_2}} + f_{min}\right]\right\}$$

- T: *Temperature* [°C]
- R: *Measured resistance* [Ω]
- $A(T)$: *Measured Cross Section*
- L: *Constant length*
- f_{max}: *Start of percolation network*
- f_0: *Max. squeeze of percolation network*
- f_{min}: *Value after LMP action*
- $\tau_{1,2}$: *Time of maximum drop intensity*
- $n_{1,2}$: *Slope – related at* $\tau_{1,2}$





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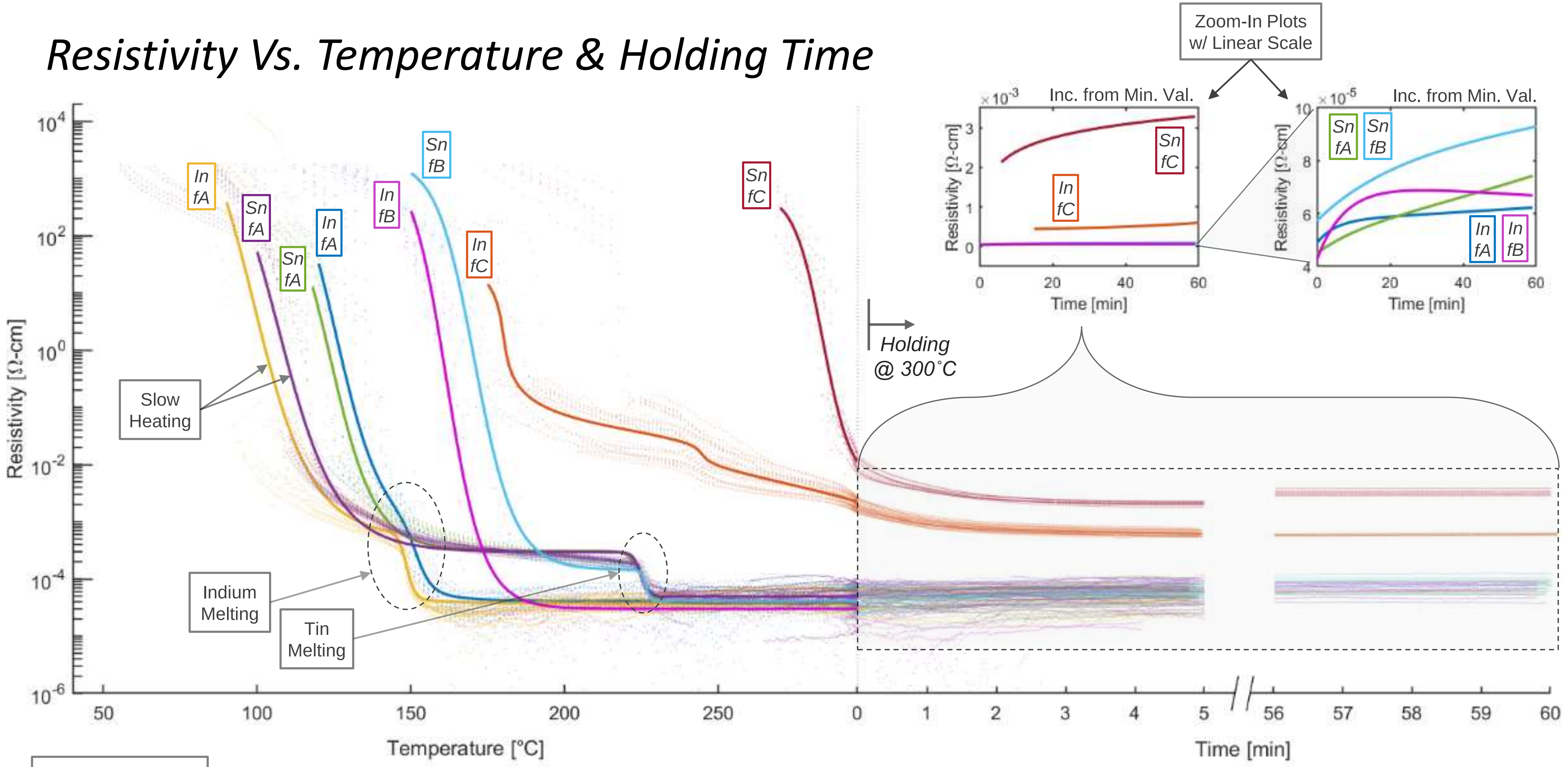
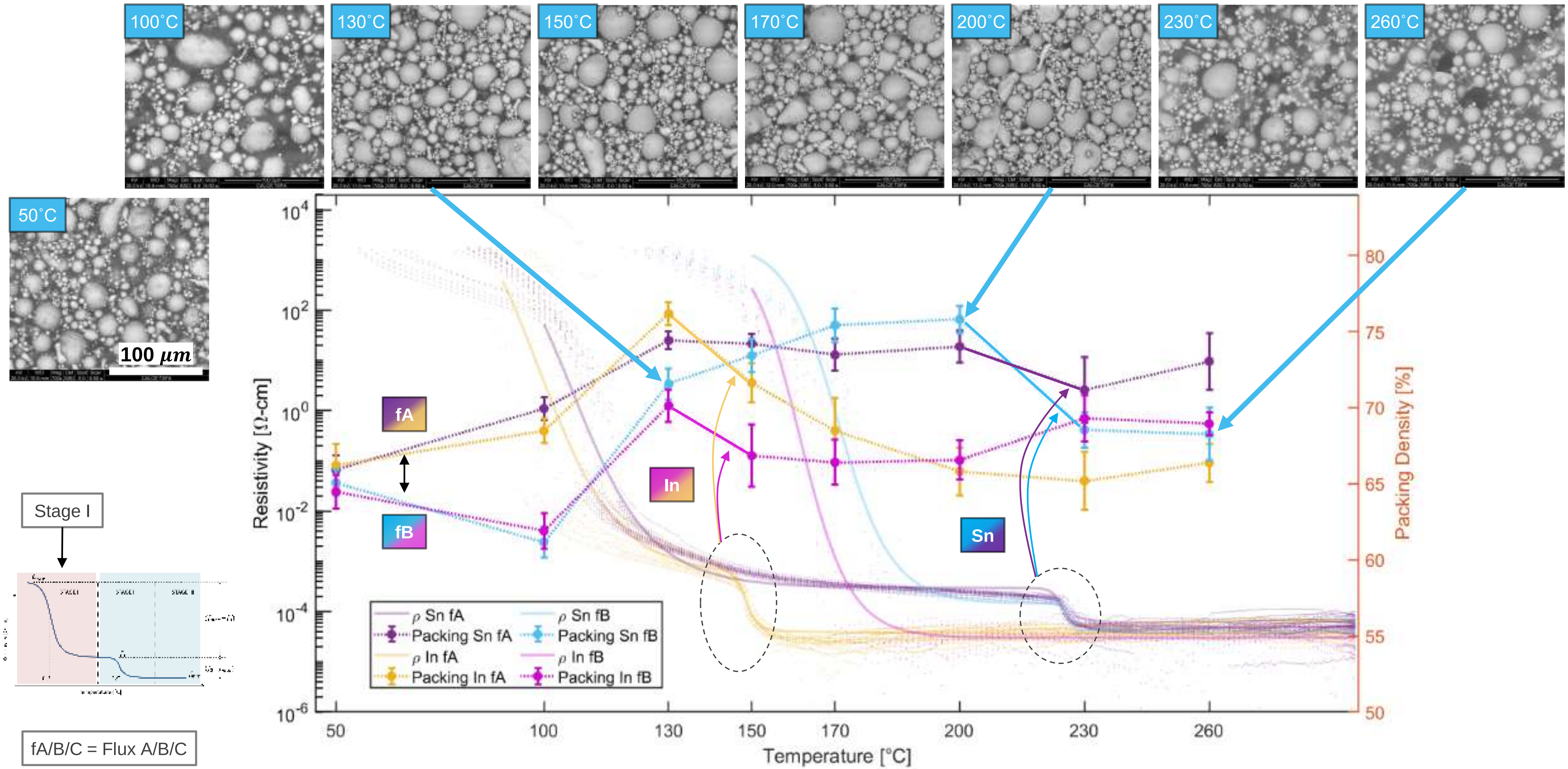
Experimental Data and Results

Resistivity Vs. Temperature & Holding Time



fA/B/C = Flux A/B/C

Stage-I Correlation to Packing Density



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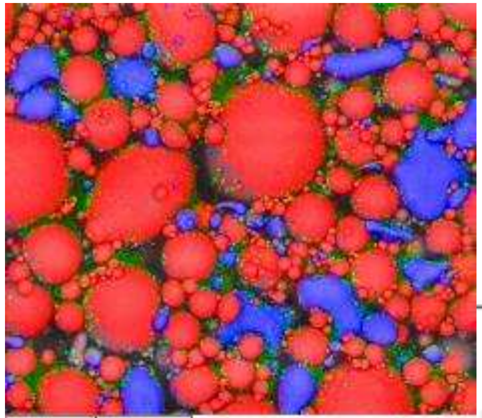
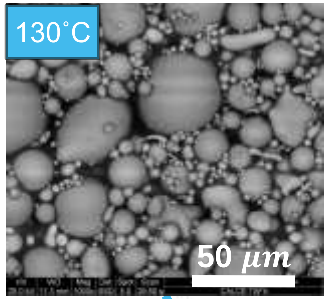
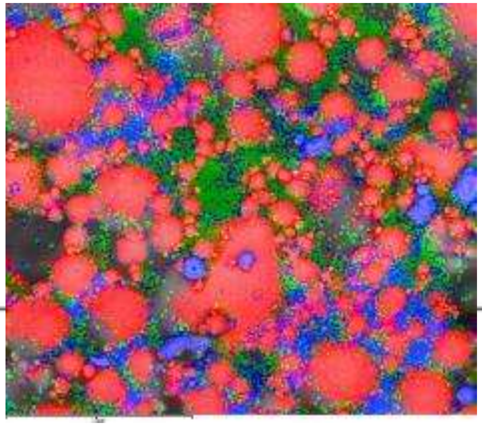
Stage-I Correlation to Packing Density and Flux Evaporation

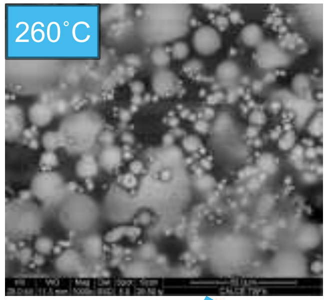
Ag
Sn
C

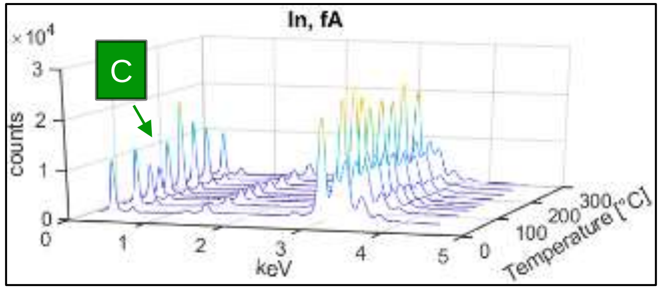
EDS Data

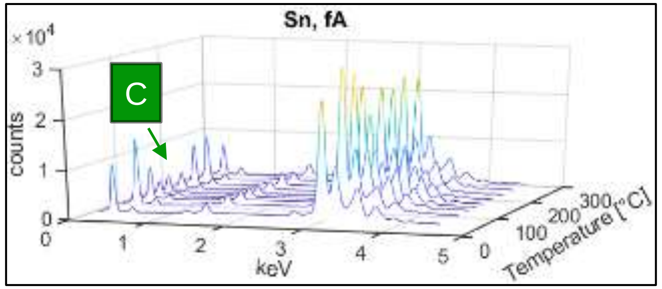


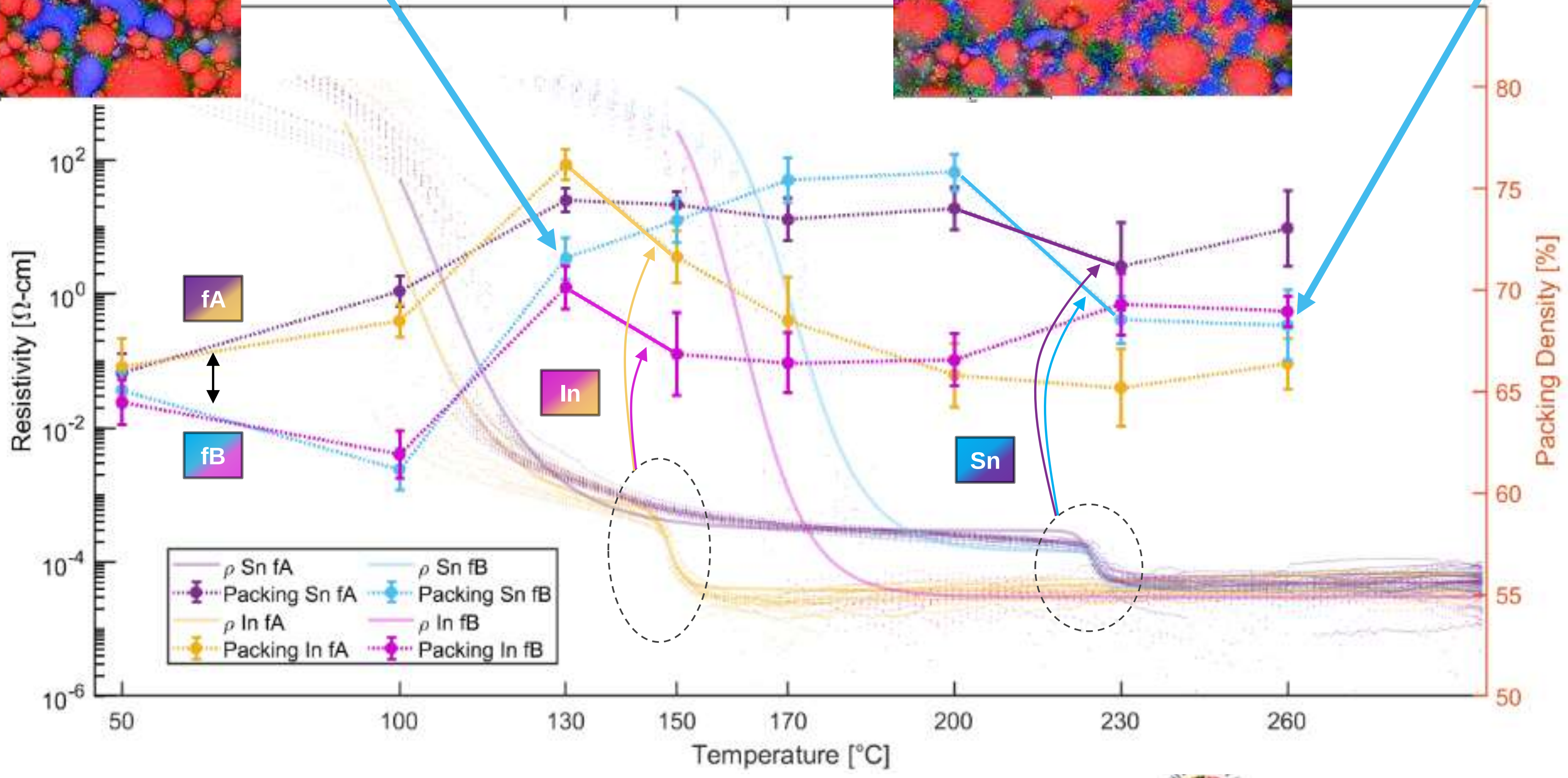






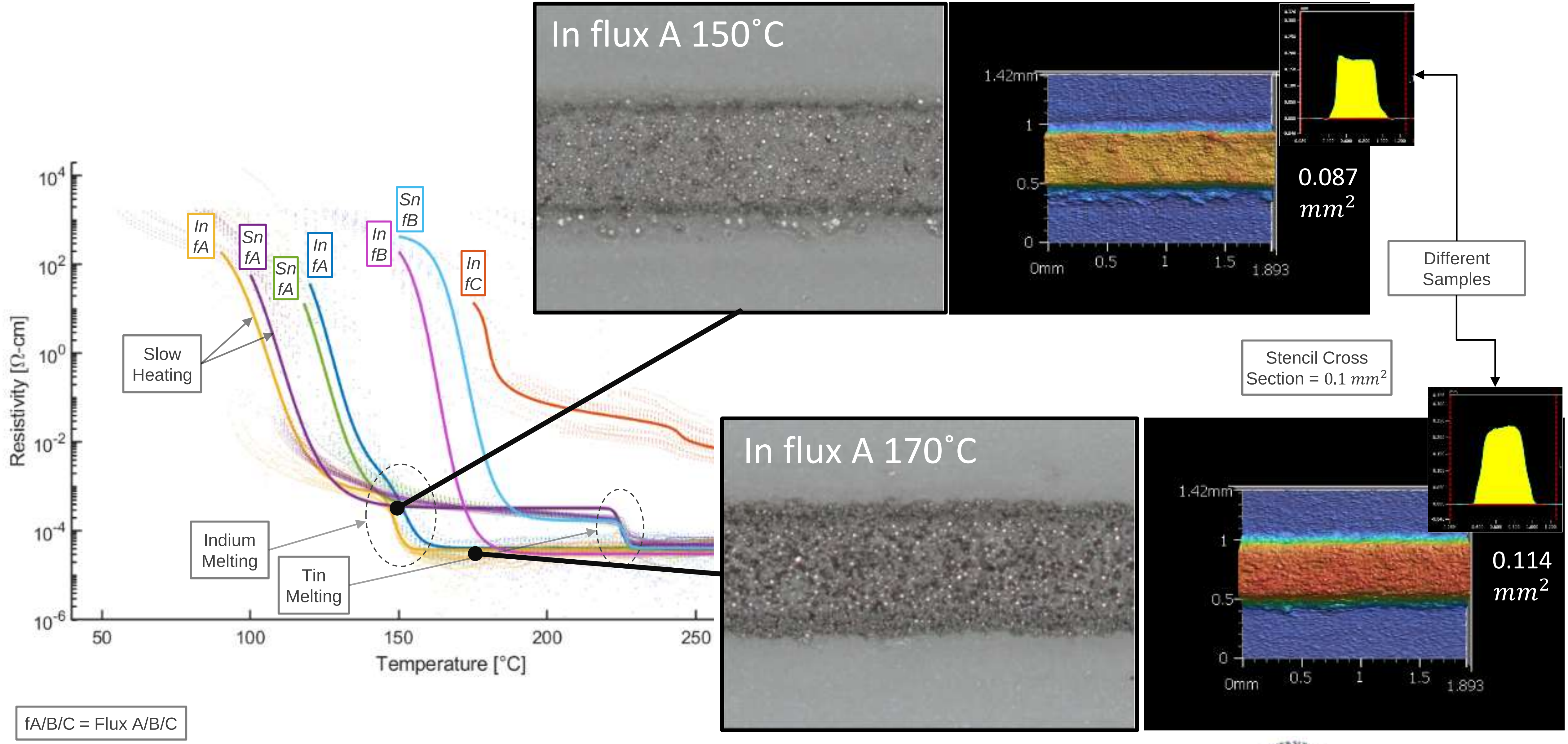




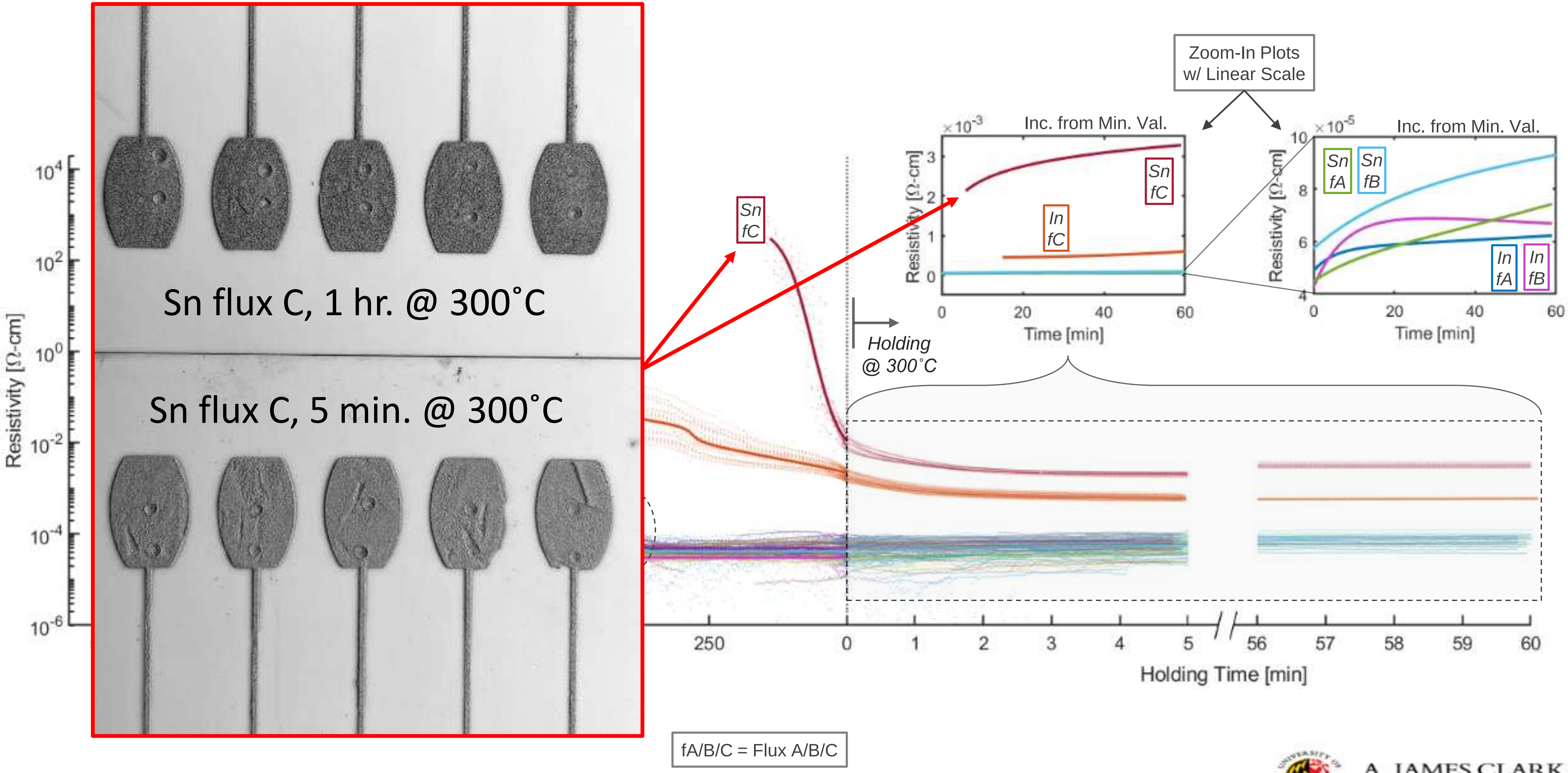


fA/B/C = Flux A/B/C

No Observed Significant Change in Overall Cross-Section



Increase in Resistivity due to Oxidation



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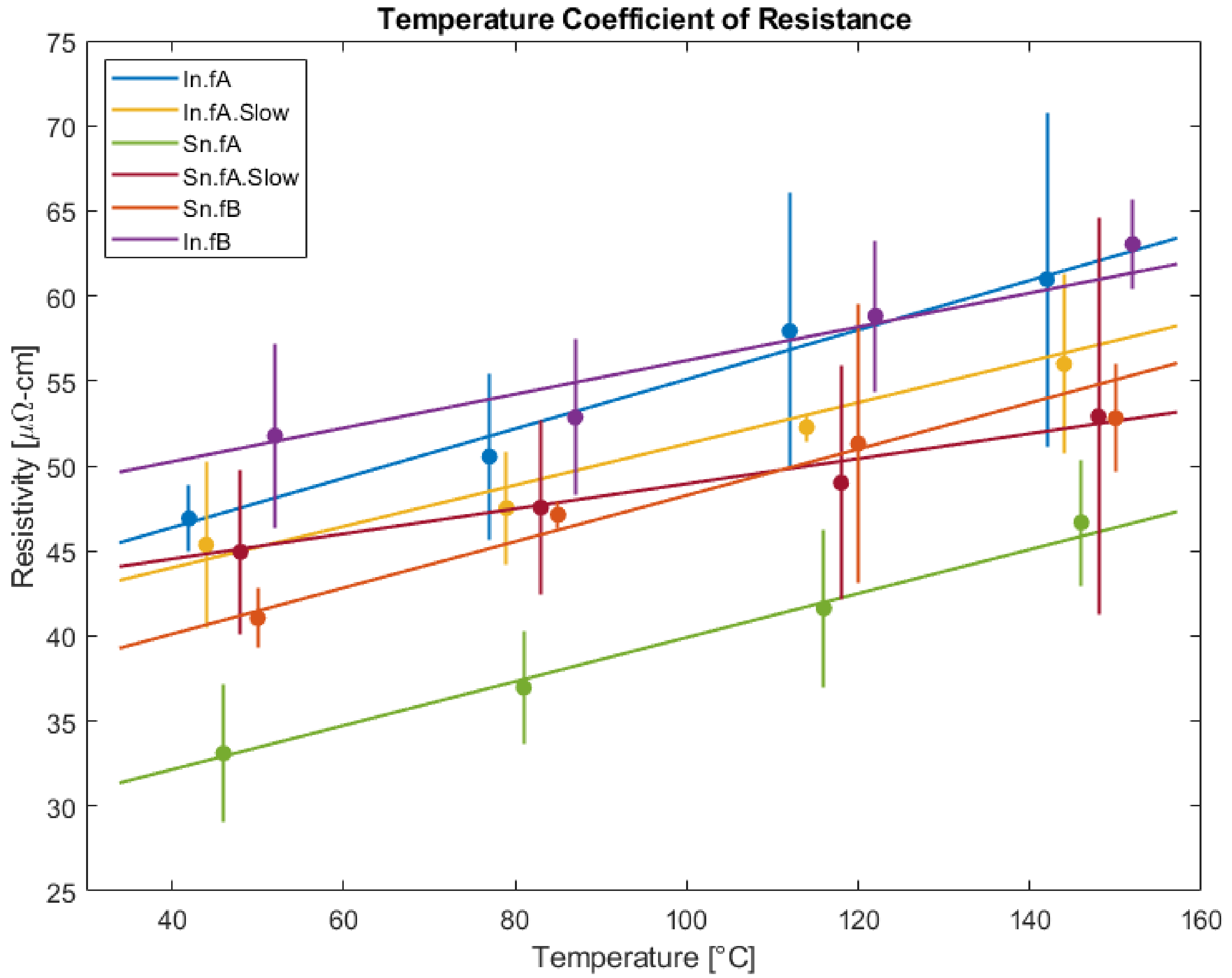
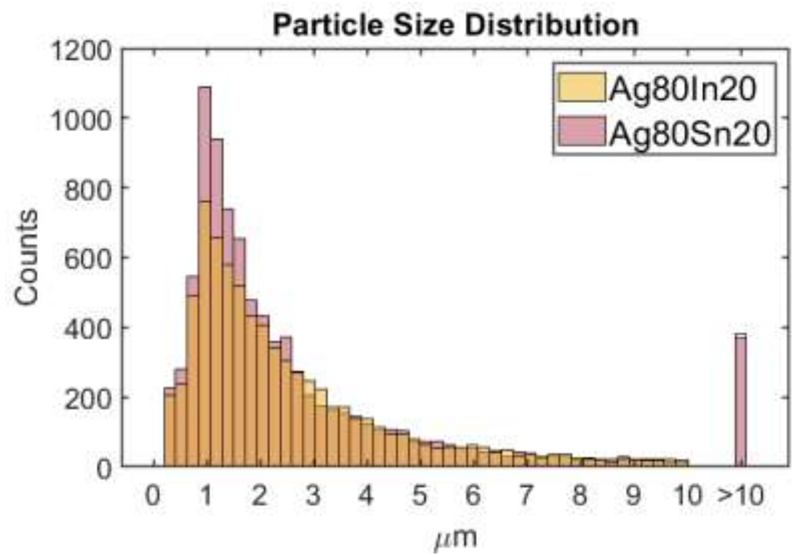
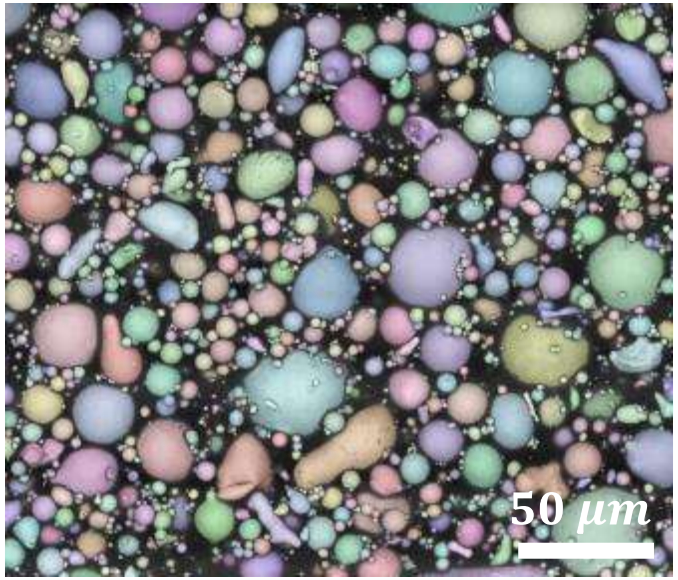
Experimental Control and Results







fA/B/C = Flux A/B/C

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Conclusions

- The resistivity curve evolution of TLPS pasts was established and mathematically modeled.
- The main contributors to the electrical resistivity of the TLPS material are:
  - Pre-sintering packing density, and percolation
  - Evaporation of the organics
  - Melting of the LMP, their liquid-state diffusion, and attracting capillary forces
- The rapid development of electrical conductivity was demonstrated.
- Flux selection has a major effect over the curve evolution and the final resistivity of the TLPS material.
- In-based TLPS systems show better resistance to oxidations over long sintering times than Sn-based TLPS systems.
- This study contributes to the optimization effort of using TLPS materials in AM application in remote locations, and power electronic applications.

Acknowledgments

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- The University of Maryland, College Park
- **CALCE**: Center For Advanced Life Cycle Engineering
- **NCMS**: National Center for Manufacturing Sciences
- **AMMP**: Advanced Manufacturing, Materials, and Processes

Thank You!

Any Questions?