Low temperature processing for high temperature conductors: transformational inks

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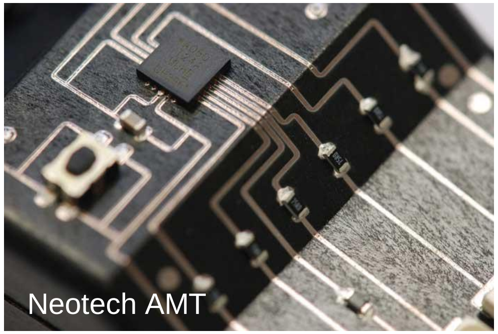
IMAPS New England, May 1, 2018

Outline

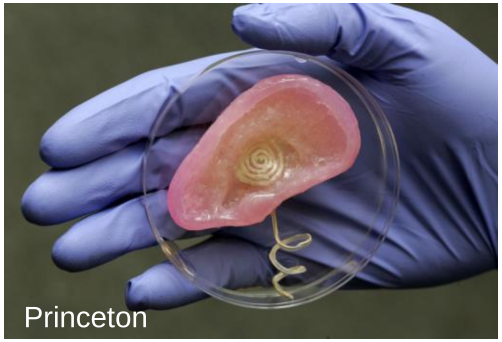
- Current printed conductor: silver
- Transformational printed conductor: High temperature conductor from low temperature inks
- Transformational Materials
  - *Multicomponent particles*
  - *Simultaneous phase transformation and interparticle sintering during flash anneal*
- For Printed Electronics
  - *Printability & ink formulations*
  - *Low temperature substrates during flash anneal*
  - *Electrical performance*

The Promise of 3D Printed Electronics

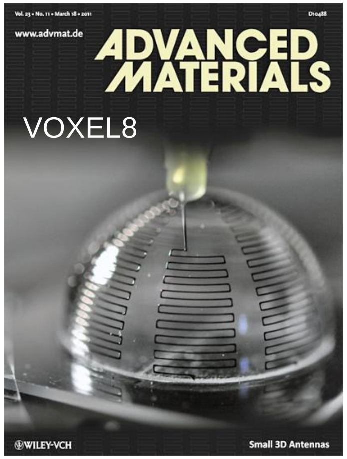
- 3D Printing of electronics will change the way we build, repair, integrate, and recycle electronics.



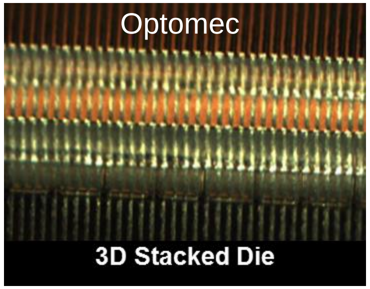
Custom 3D Interconnects



Human-Machine Interfaces,
Personalized Medicine

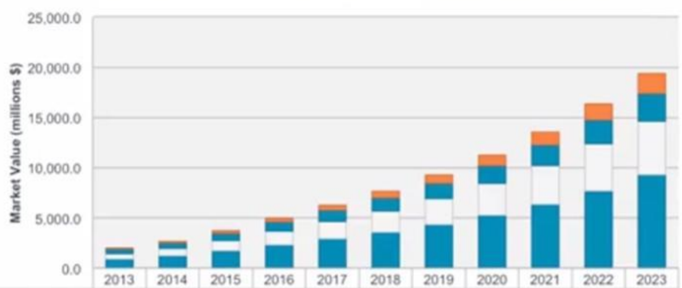


Conformal Electronics



High Density Die Integration

Total Market For 3DP Related Goods and Services



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Total Software (millions $)	102.8	161.2	236.5	352.3	496.4	669.0	834.2	1,038.9	1,286.4	1,596.9	1,982.7
Total Services (millions $)	465.0	545.4	733.8	931.5	1,121.0	1,303.1	1,514.1	1,760.0	2,041.1	2,369.9	2,754.6
Total Materials (millions $)	525.6	718.2	1,010.3	1,355.3	1,717.7	2,111.9	2,588.4	3,169.6	3,857.2	4,696.1	5,318.8
Total Equipment (millions $)	916.9	1,250.1	1,743.6	2,321.8	2,936.2	3,574.0	4,342.9	5,272.5	6,359.5	7,691.9	9,307.5

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Total Market (millions $)	2010.3	2674.9	3724.3	4960.9	6271.3	7658.1	9279.5	11241.0	13544.1	16354.7	19363.6
CAGR		33.1%	39.2%	33.2%	26.4%	22.1%	21.2%	21.1%	20.5%	20.8%	18.4%

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Market for 3D Print Materials to double every 3-4 years with per 2016 Wolhers Report
Conductive Materials fastest growing segment per IDtechEx 2016-2026 Forecast

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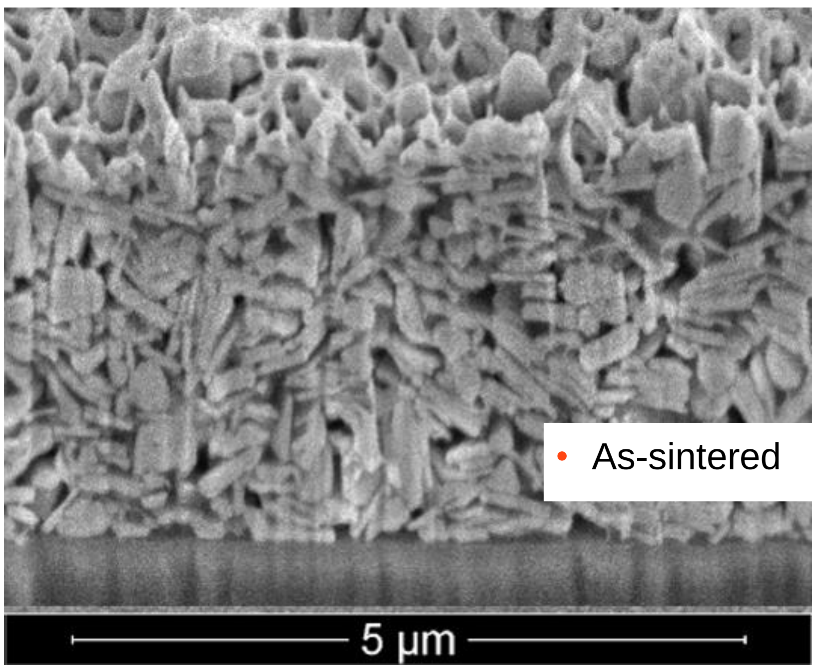
Workhorse: printed silver

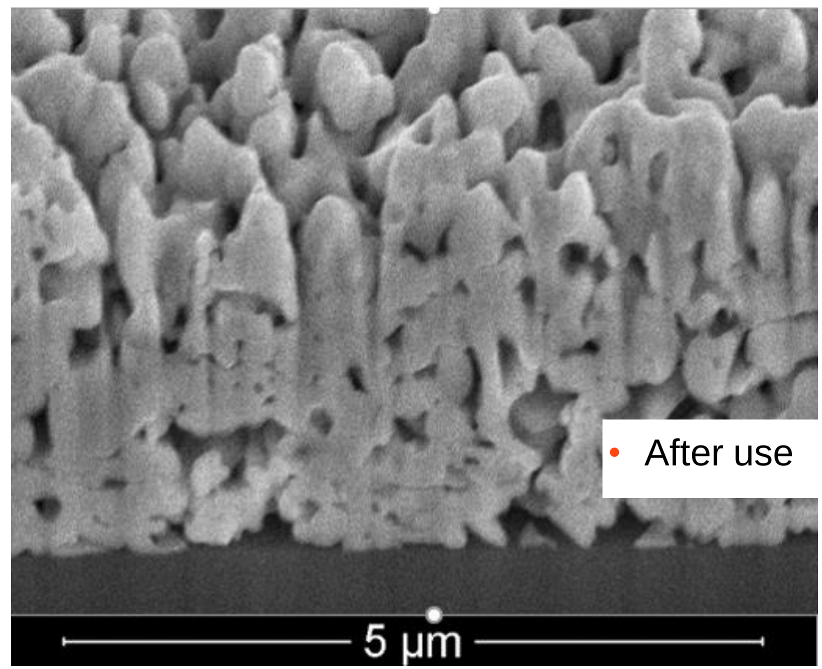
- Nanoparticle silver ink – first commercialized because it can be sintered at low temperatures to high conductivity.
  - *High surface diffusivity aids in sintering*
  - *Still dynamic at operational currents, times, temperatures.*

Cross-section

Nanoparticle Ag ink annealed at 200°C for 1 hour



Nanoparticle Ag ink after ~0.4 MA/cm^2 for 6 weeks



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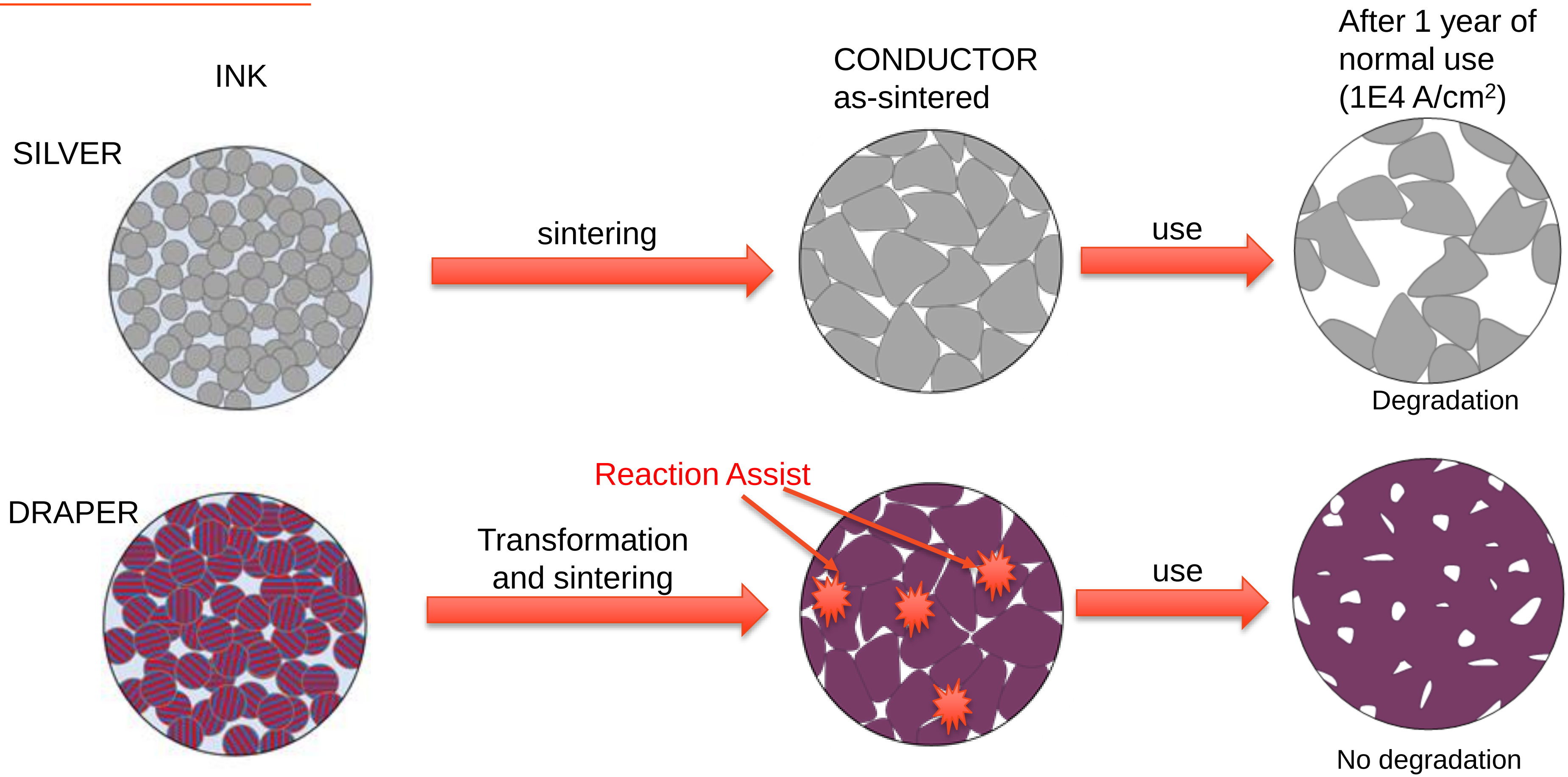
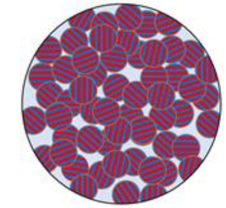
Exothermic Transformation to High T phase



Metastable INK transforms to a stable CONDUCTOR during sintering.

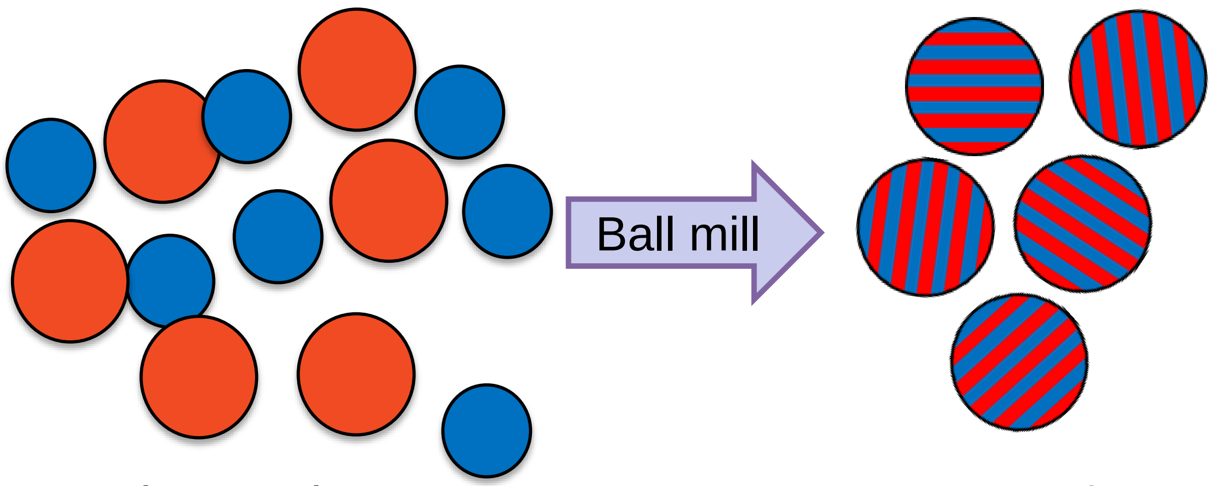
Transformation to High Temperature Conductor

How to make multi-component particles



Ball milled particles

- Competition between fragmenting and cold welding



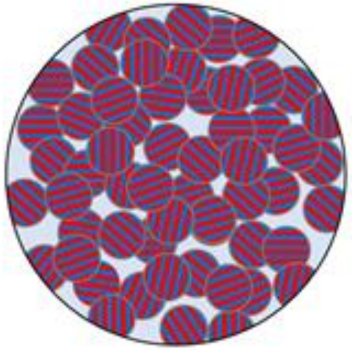
Elemental particles

Composite particles ready to be "inked"

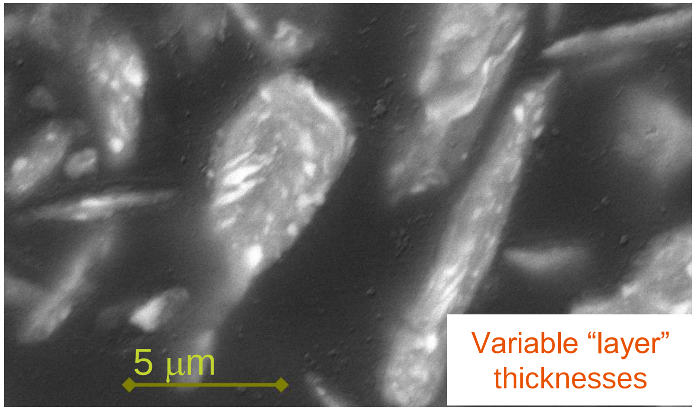
Balls and powder in vial

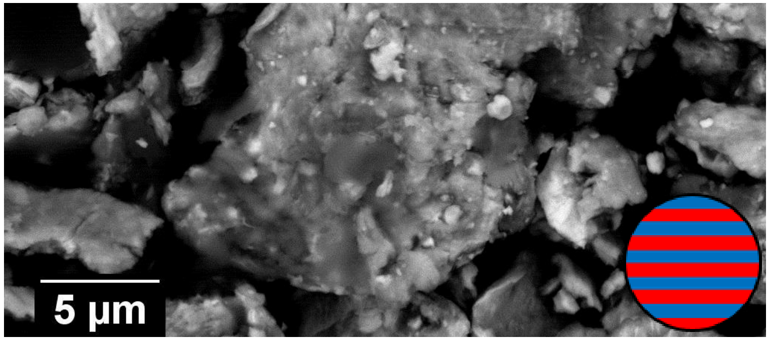
Batch size = 60 g

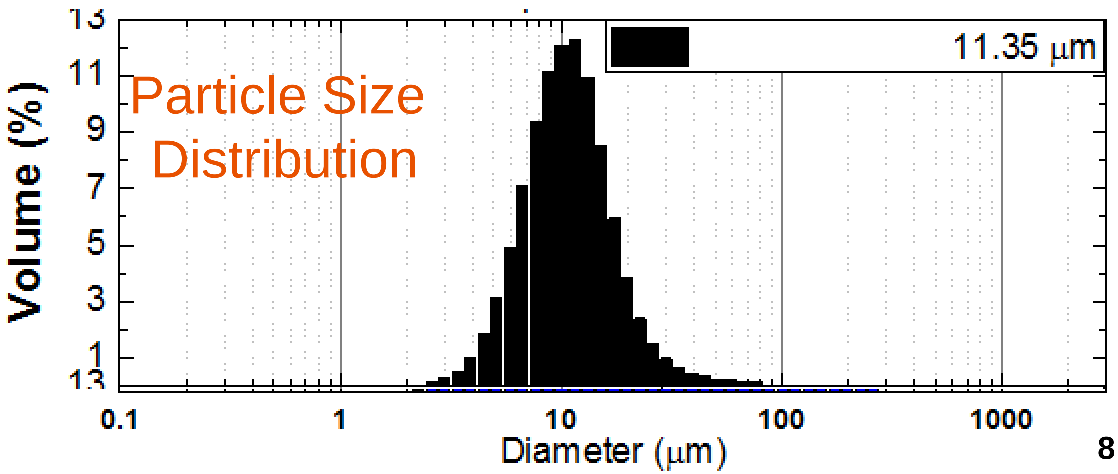
Our multi-component particles



Layers of Constituents that will later transform into Conductor



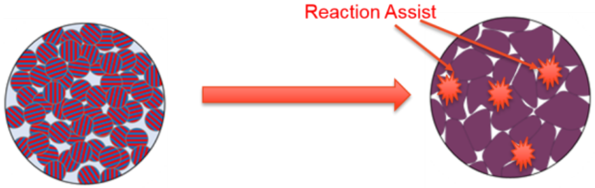




Transformation to High Temperature Conductor: Sintering in Pulsed Lamp

- Intense Pulsed Light (IPL) – Xenon lamp
- NovaCentrix PulseForge 1200
  - *Also used to sinter nanoparticle silver ink*
- Conditions
  - *Short Exposure to Lamp Light ~ 1-100 ms*

Transformational Materials



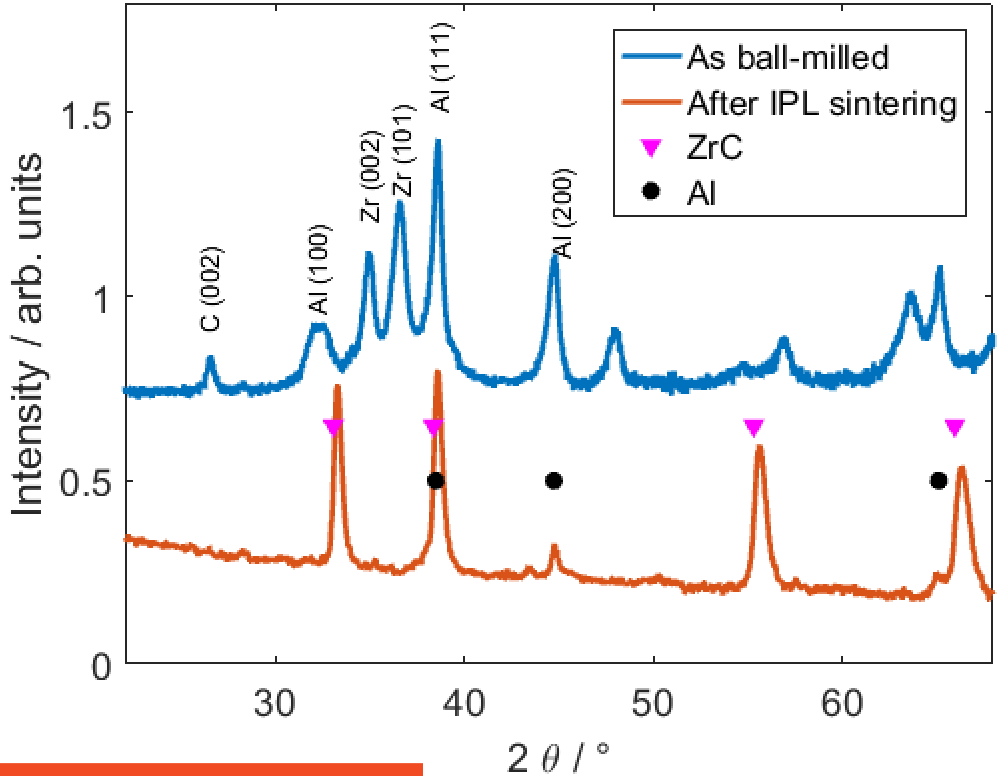
The Al, Zr, C composition is a representative example

Other formulations are developed as well

- ***During IPL, a phase transformation occurs.***

$$Al + Zr + C \xrightarrow{IPL} ZrC + Al$$

(Unbalanced)



	Crystalline phases (XRD)
Ink particles as printed	Al, Zr, C
Conductor as sintered	ZrC, Al

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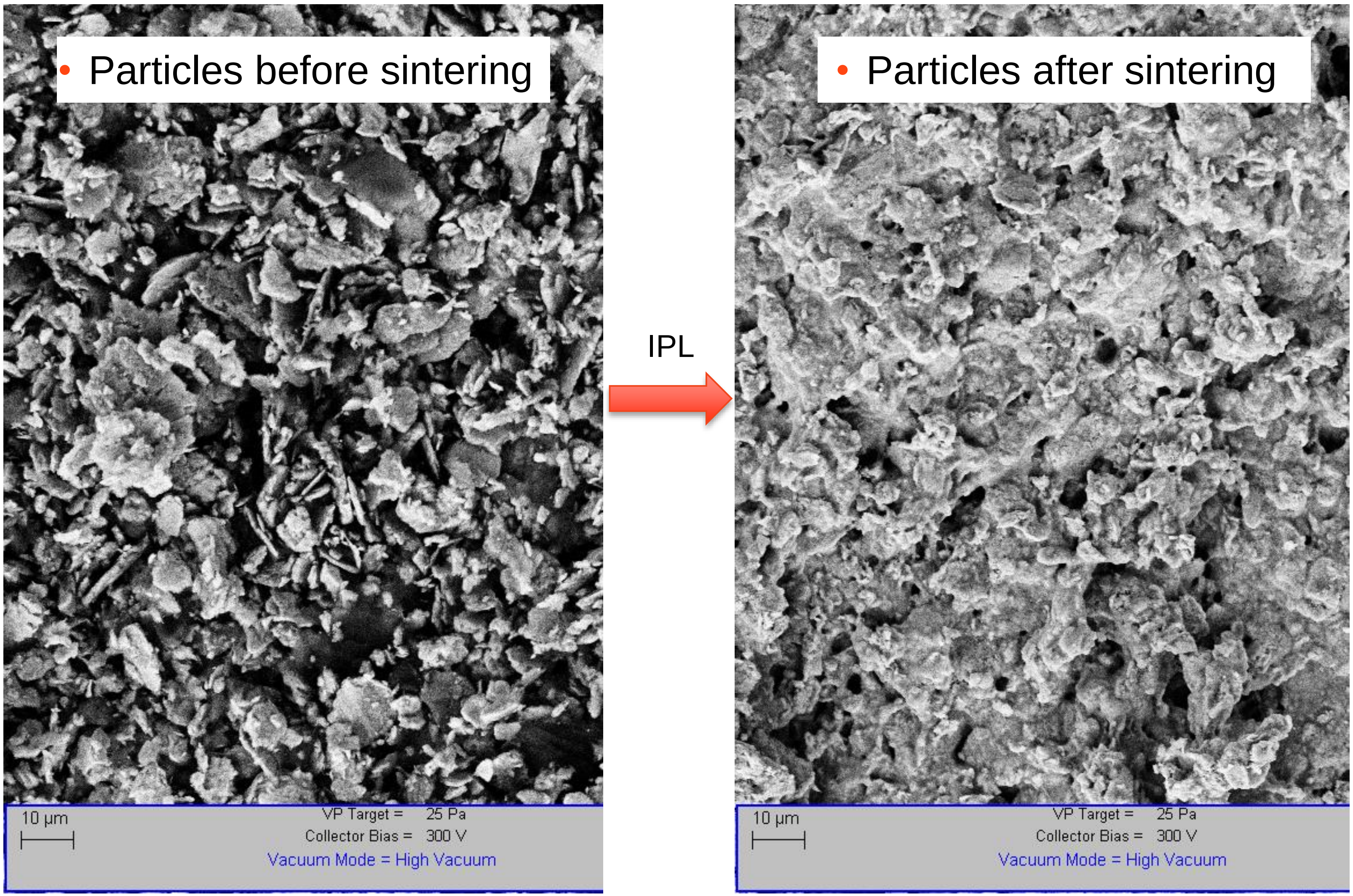
Particle sintering during transformation

- Sintering = particles coalescing into a solid form during heat treatment



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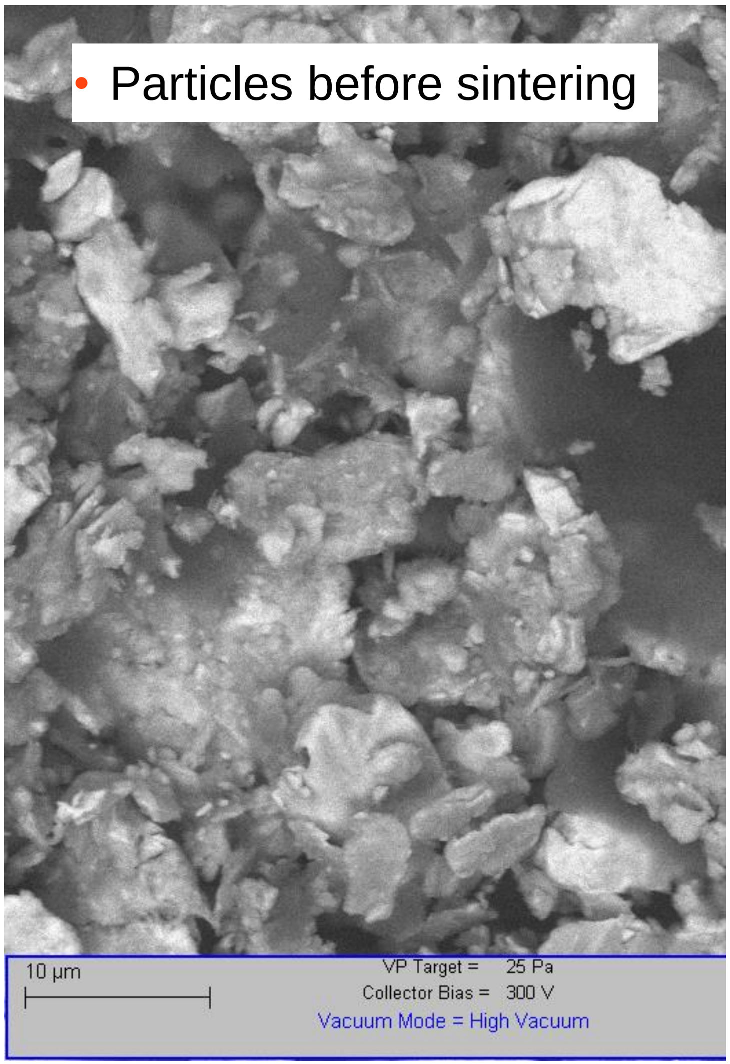
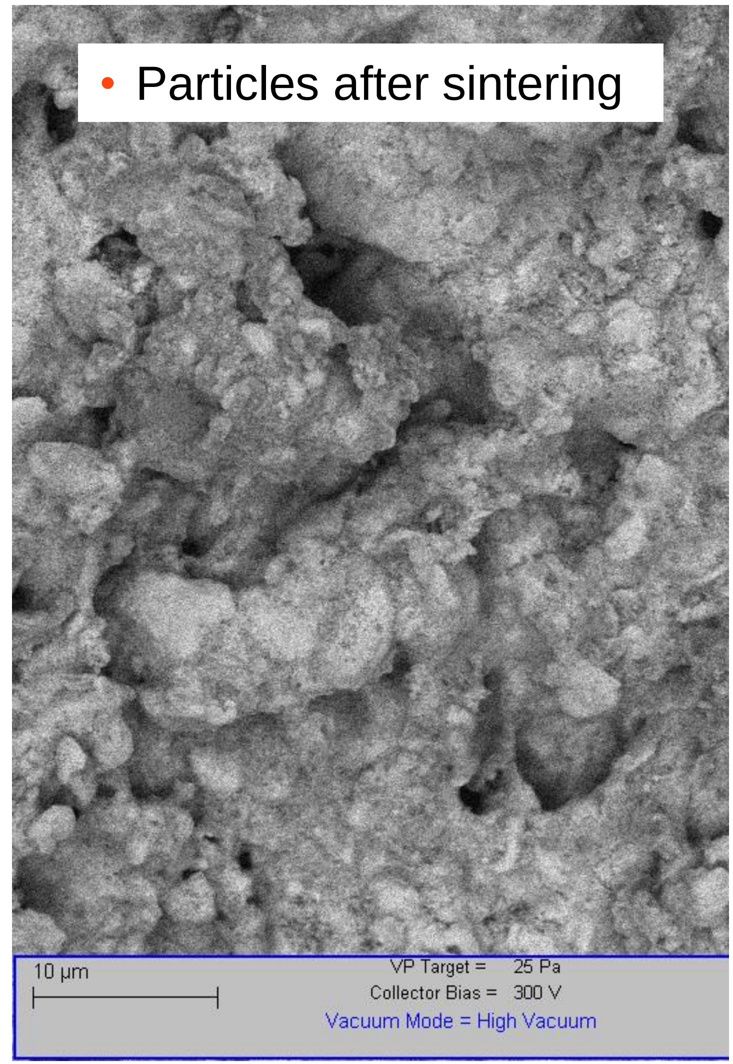
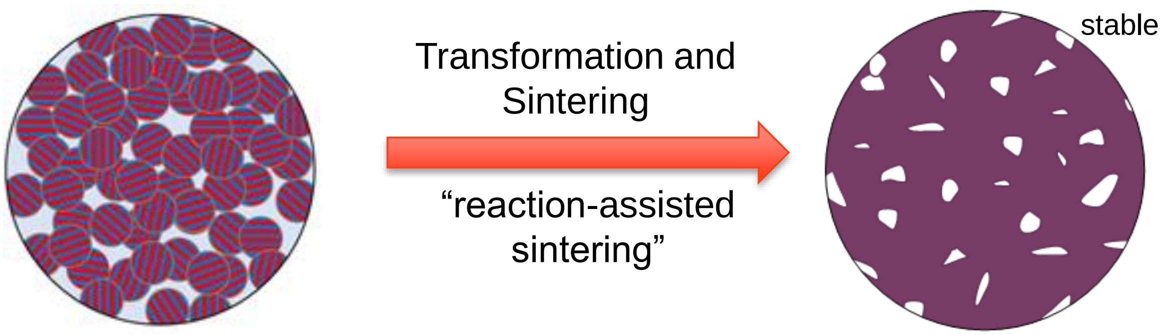


IPL

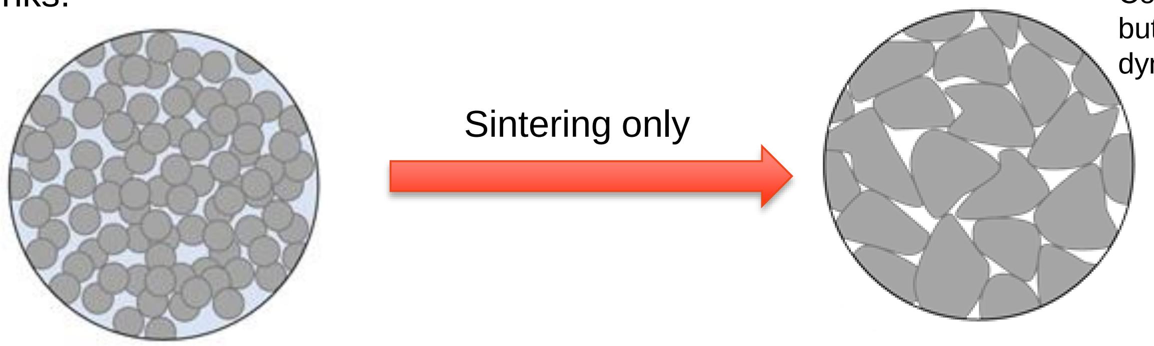


Transformational Material



Continuous, porous matrix. Now a high temperature-stable phase.

Compare to silver inks:



Continuous, porous matrix, but still silver & hence dynamic under use

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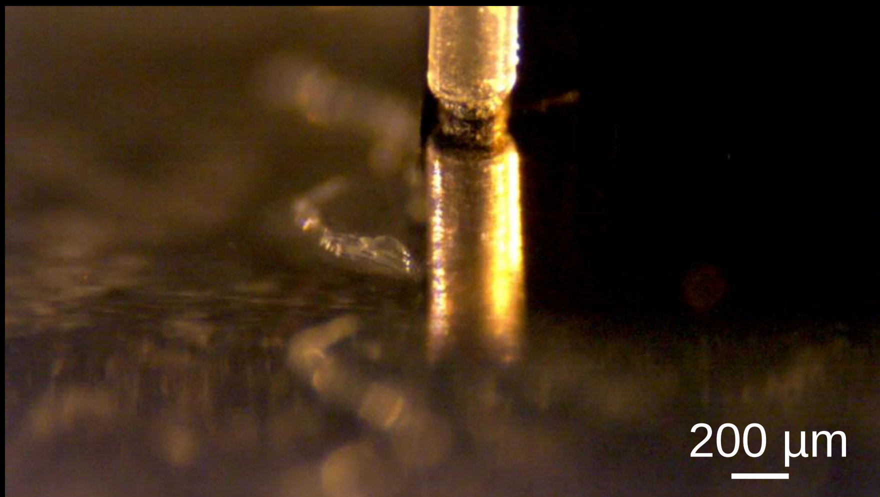
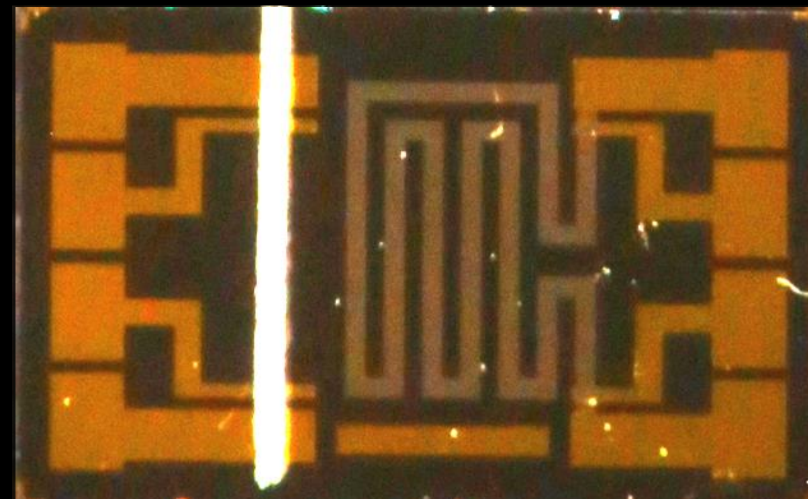
Printing and Performance

Printing RAIL 3D shear thinning ink

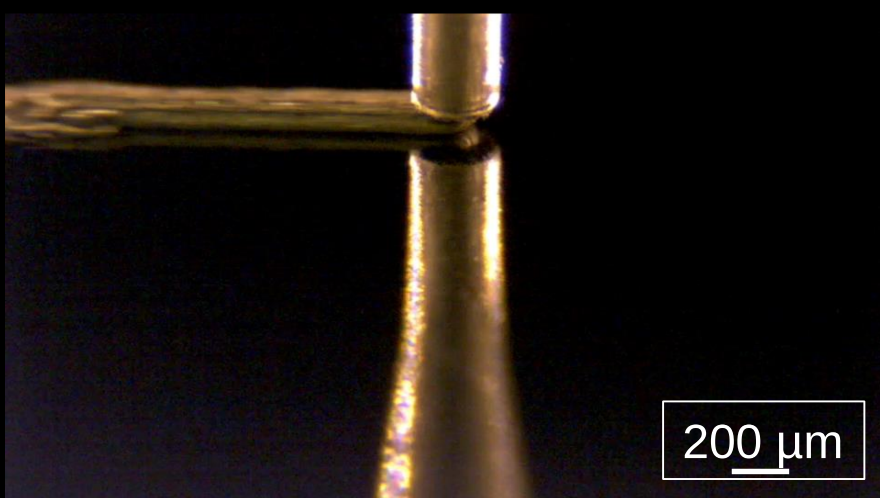
4 Probe Array (real time)



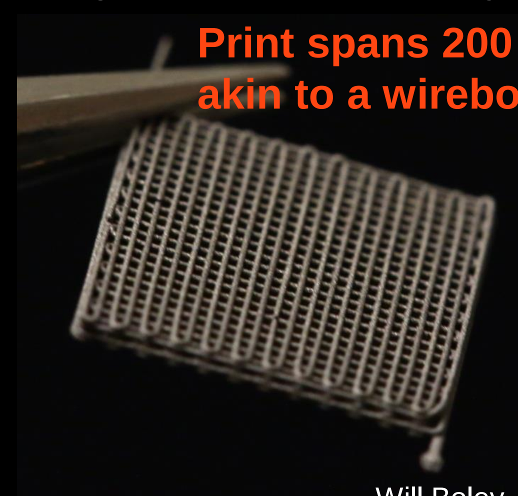
~200 µm Trace on a Probe Device



5 Layer Square Lattice (sped up 8x)



Free standing 1 cm X 1 cm 5 layer lattice

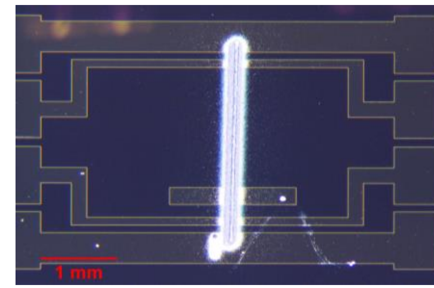


Print spans 200 µm gaps akin to a wirebond

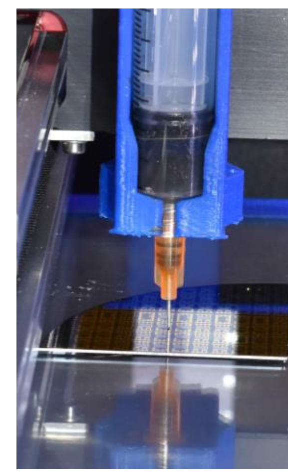
Will Boley, Jennifer Lewis

Printability in different tools

- We have printed our inks with a range of COTS printers without modification
  - ***Optomec aerosol-jet printer***
    - Can write ink from a stand off distance (up to cm)
    - Difficult to write at tight pitch due to overspray
  - ***HyRel syringe printer***
    - Uniform deposition of low viscosity inks
    - Limited by size (0.5 mm)
  - ***Screen Printers***
    - Simple, well-known technique
    - Limited by size (0.5 mm) and must be on planar surface (can later be flexed)
  - ***Voxel8 shear thinning type printer***
    - Can write tight pitch (~10 um)
    - Must be in contact with print surface & must be high viscosity ink



300 μm wide, 5 μm thick
Draper Ink printed by Optomec



Draper Ink in HyRel syringe printer

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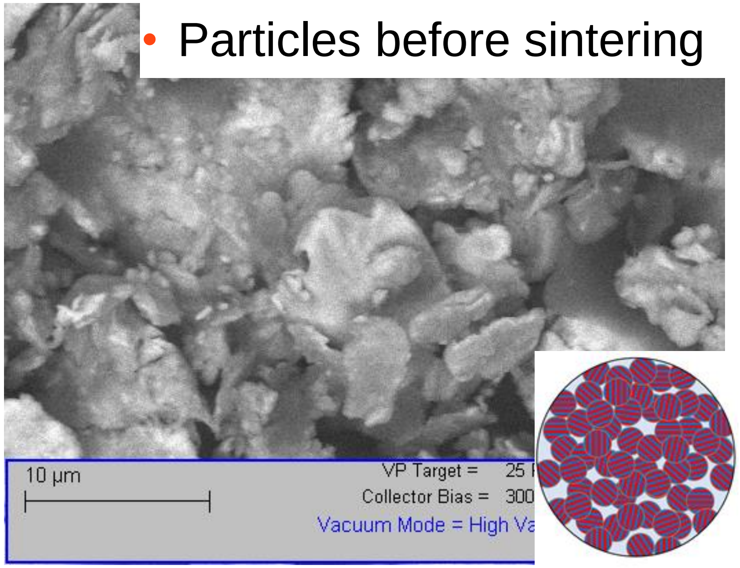
Transformation to High Temperature Conductor: Sintering in Pulsed Lamp

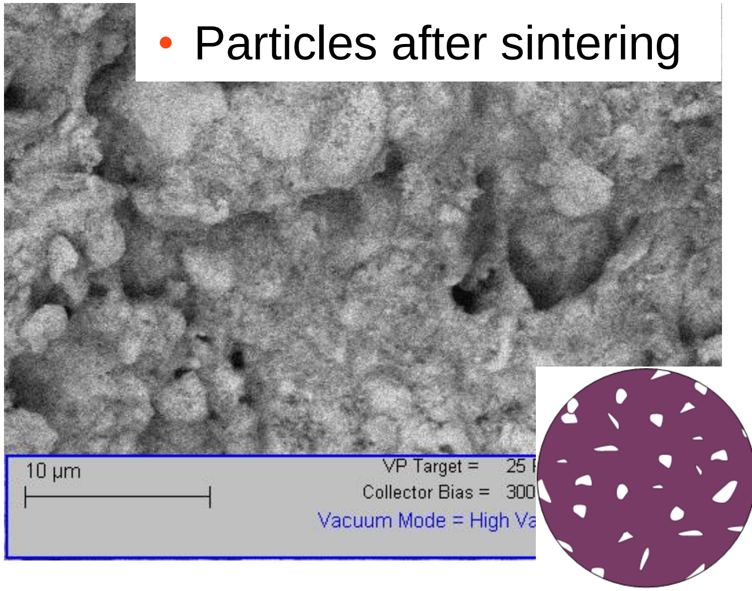
- Intense Pulsed Light (IPL) – Xenon lamp
- NovaCentrix PulseForge 1200
  - *Also used to sinter nanoparticle silver ink*

- Particles before sintering



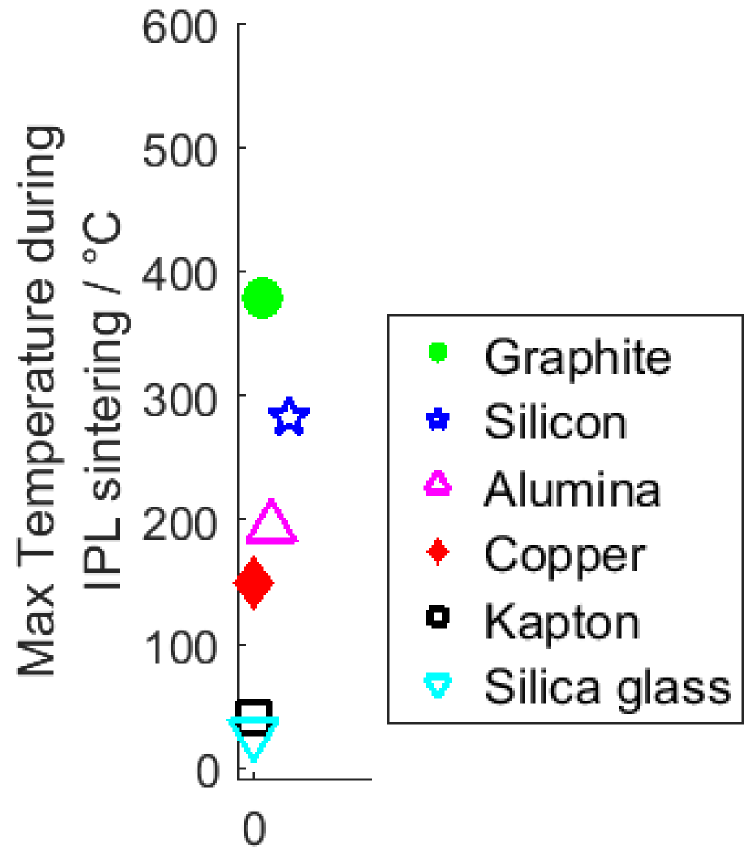
IPL sintering

- Particles after sintering



Temperature of substrate during IPL

- Substrates stay cool during IPL sintering because they have low absorption of xenon spectrum.



Max temperature of substrate during IPL anneal
- Short Exposure Time
- Substrate cools to < 100°C in < 6 s

Compare to:

Oven anneals at 200 °C for hours

We've printed on Kapton, glass, FR4, silicon.

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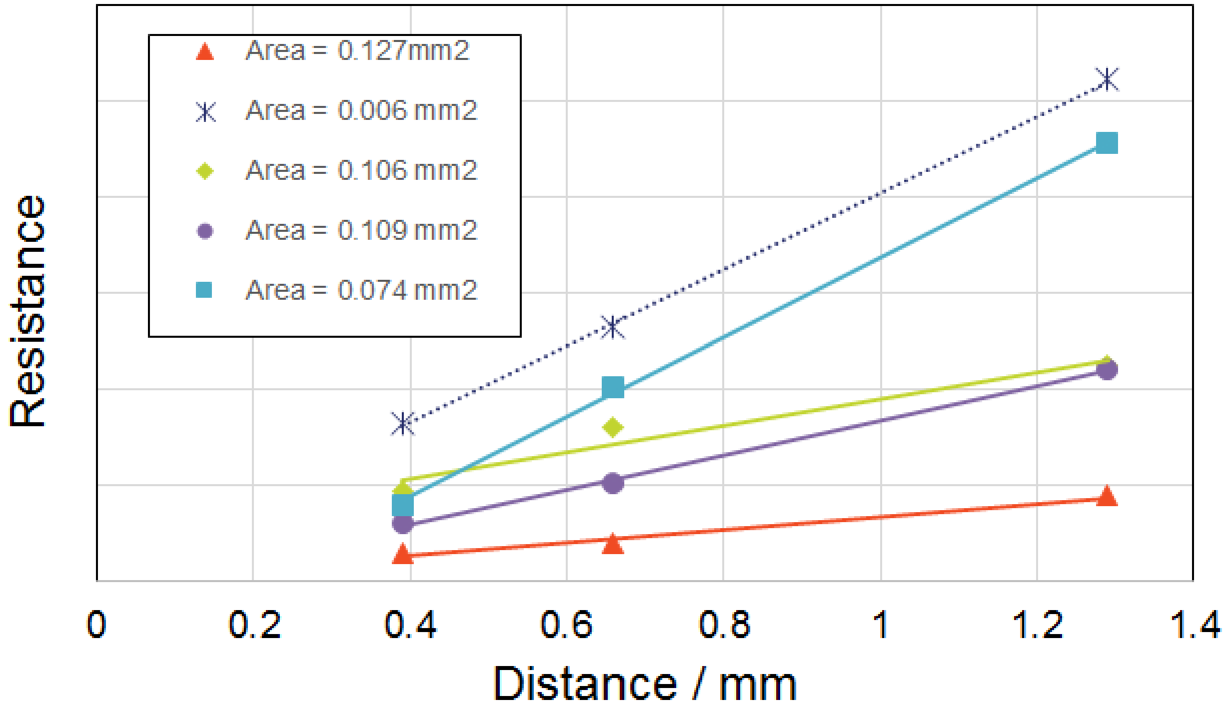
Performance – Resistance per length

- Our printed lines have Resistance per Length < **10 mΩ/mm**
  - *Cross-sectional areas = 0.006 to 0.130 mm²*



Line with 1 mm² cross-sectional area

Aspect ratios of up to 1:1 can be printed in single pass & sintered in single IPL event

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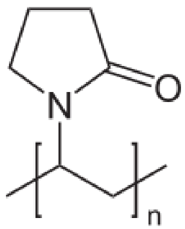
Designing the ink formulation

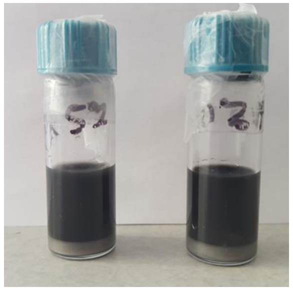
Different printers require different ink formulations

Surfactants (1-10 wt. %)

- Functionalize particles' surface to prevent clogging and promote adhesion to substrate

Example: Polyvinylpyrrolidone (PVP)

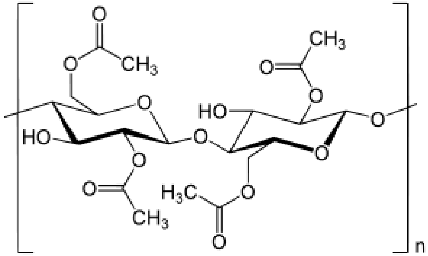




Thickening Agents (~0-20 wt. %)

- 3D printing (spanning gaps)
- Printing small (~10 µm) features

Example: Cellulose Acetate



Solvents (~10-40 wt. %)

- Suspend the metal particles during printing. Evaporates during curing.

Example: Isopropanol, DMF, hexane, ethanol

How do these additives interact with transformational materials?

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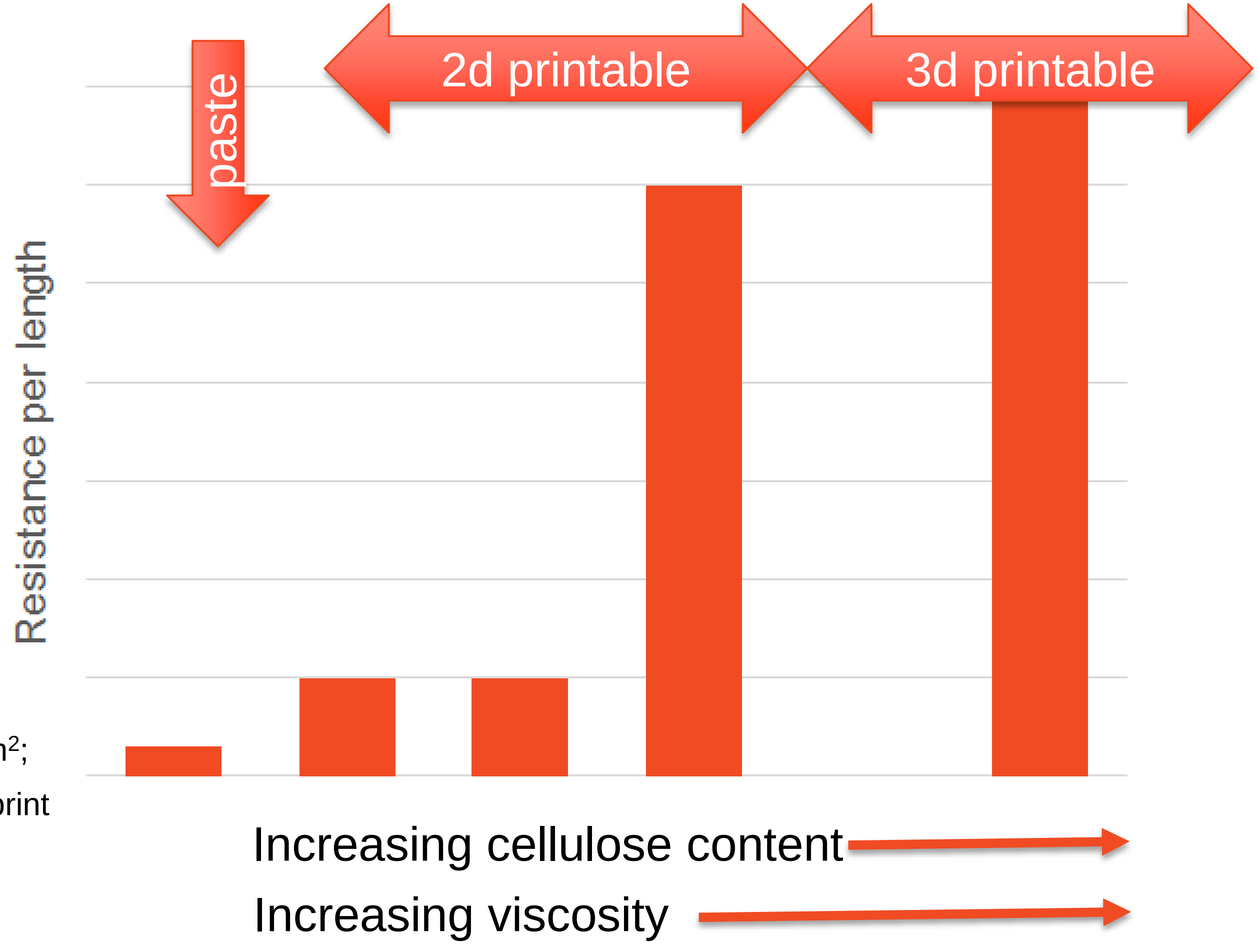
Trade-off: Printability vs Low Resistance

- Cellulose interferes with transformation to high temperature/low conductivity phase & increases resistance.



Cross-sectional areas ~ 1 mm^2;

1:1 aspect ratios, in a single print pass & single IPL event

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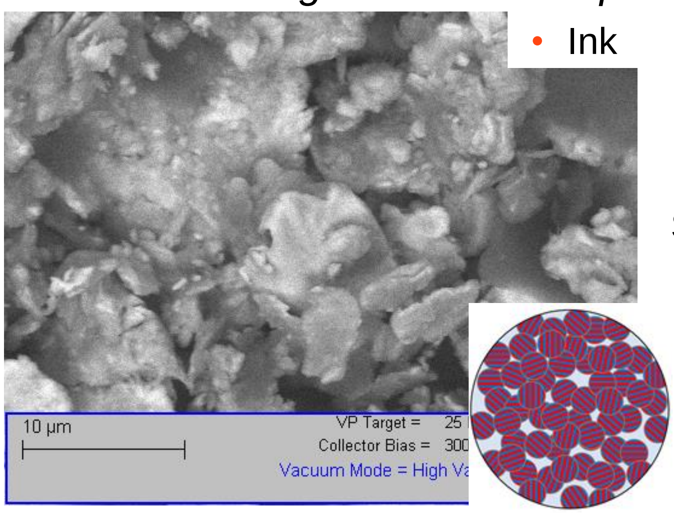
Summary

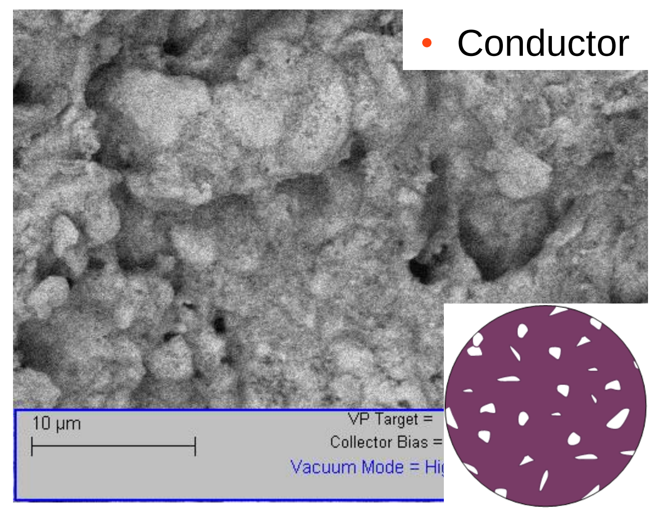
- Transformational material
  - *An ink containing: Composite particles*
  - *Transformation during IPL sinter:*
  - *A conductor: Sintered conductive line of high temperature phase*
- For printed electronics
  - *Printable at high aspect ratios.*
  - *Sinterable to low Resistance per length (<10 mΩ/mm).*
  - *Sintering ok for low temperature substrates*

- Ink



Transformation and Sintering during IPL

- Conductor



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