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Printed Sensors for System State of Health Monitoring

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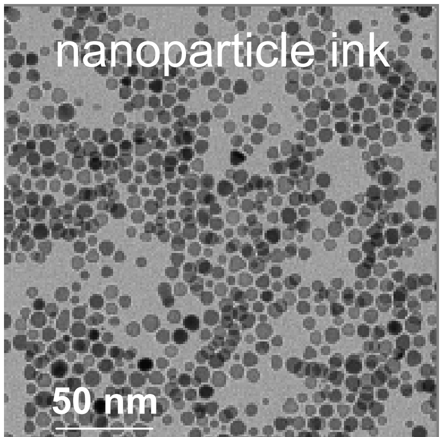
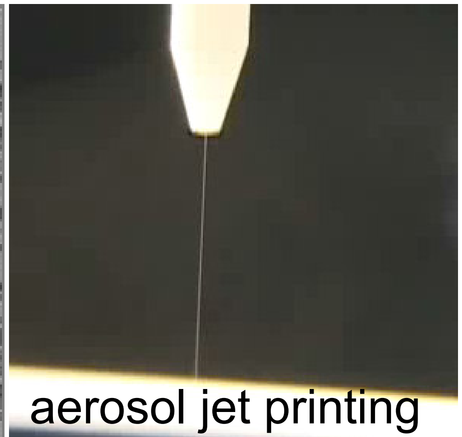
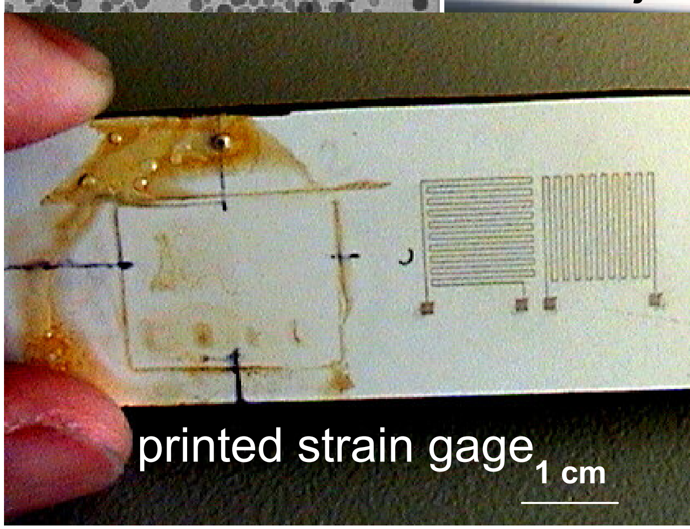




Printed electronic materials:

1) metals nanoparticle inks for
   - antennas
   - strain gages
   - thermocouples
2) printed lithium batteries



DARPA MICE mesoscopic integrated conformal electronics

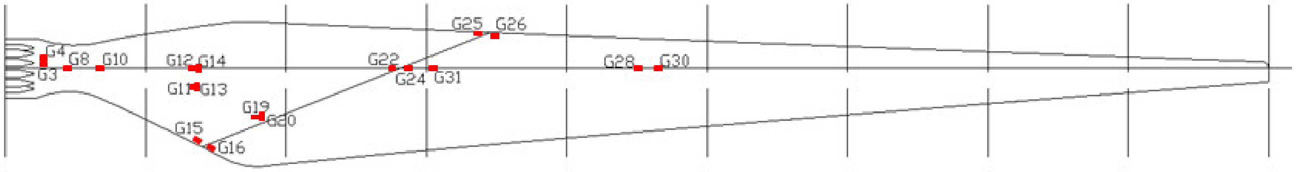
Sandia National Laboratories Sciperio A Science Revelation OPTOMEC Directed Material Deposition™ Solutions DARPA

GE 1.5 MW turbines, Fort Sumner, NM

45 m blade test NREL/NWTC, CO

Motivation for printed turbine sensors

Current technologies:



"Experimental Results of Structural Health Monitoring of Wind Turbine Blades," M.A. Rumsey et al. AIAA 2008

<u>Strain</u>

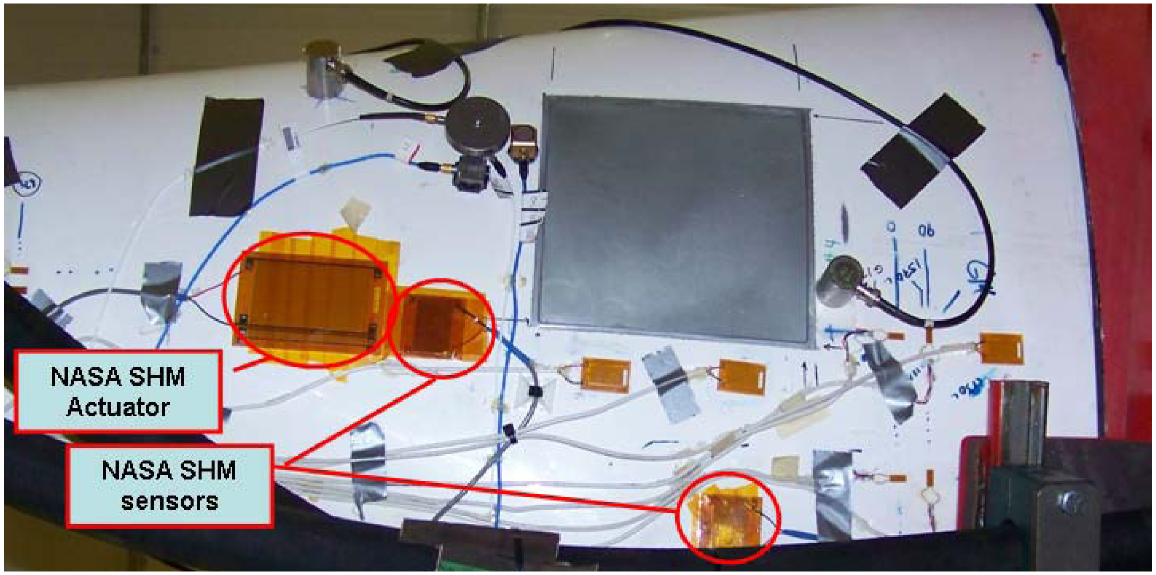
- metal foil strain gages
- Bragg grating fiber optic gages
- piezoelectric actuators/sensors

<u>Pressure/wind speed</u>

- Pitot sensors
- hotfilm

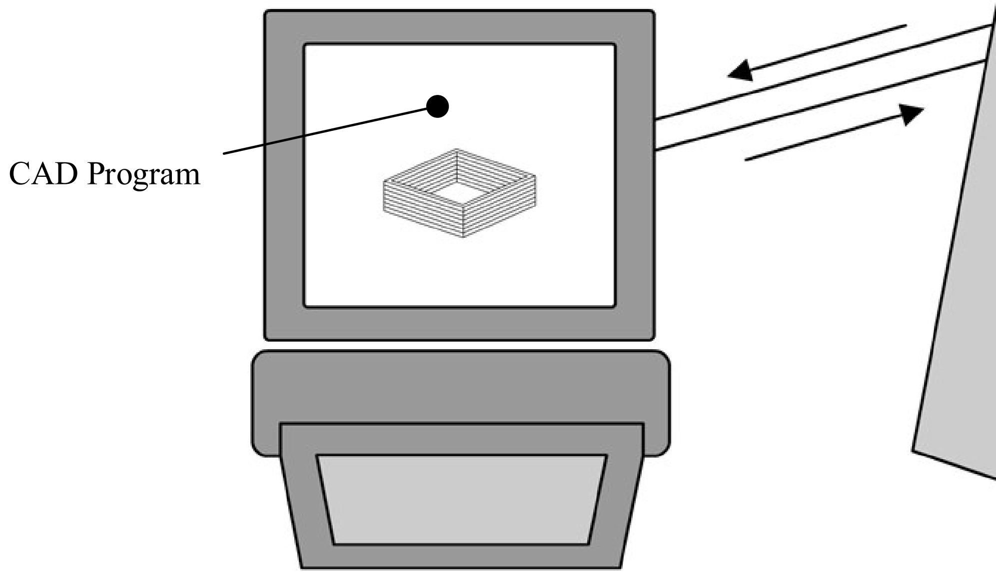
<u>Issues:</u>

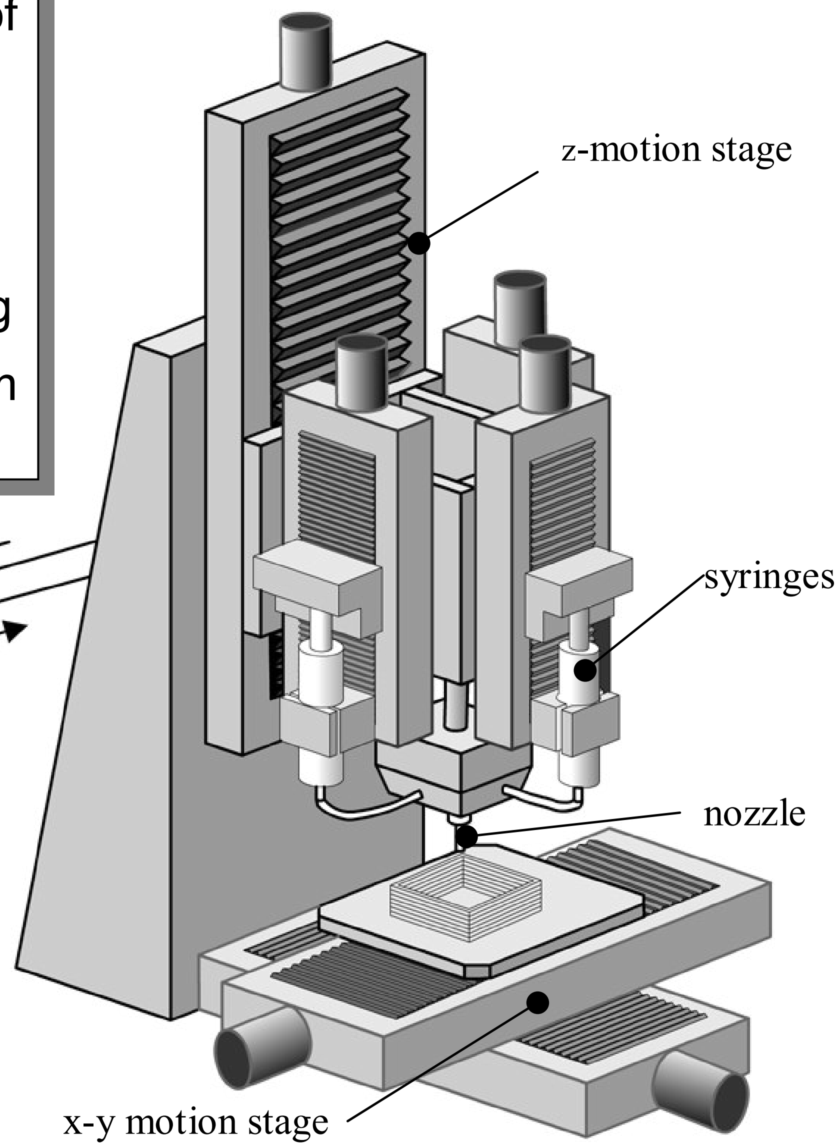
- adhesion/reliability
- cabling/lightning
- real world data output



Sandia direct-write printing platform

- •Robotically controlled deposition of nanoparticles and inks
- • metals, ceramics, polymers
- •3-D parts are built up layer-by-layer
- •3-axis (x,y,z) or 5-axis (x,y,z,θ,ϕ) printing
- •Syringe or aerosol spray deposition from 15 μm - 2 mm linewidths





*J. Cesarano III and P. Calvert,
"Freeforming Objects with Low-Binder Slurry"
US *Patent No.* 6,027,326.

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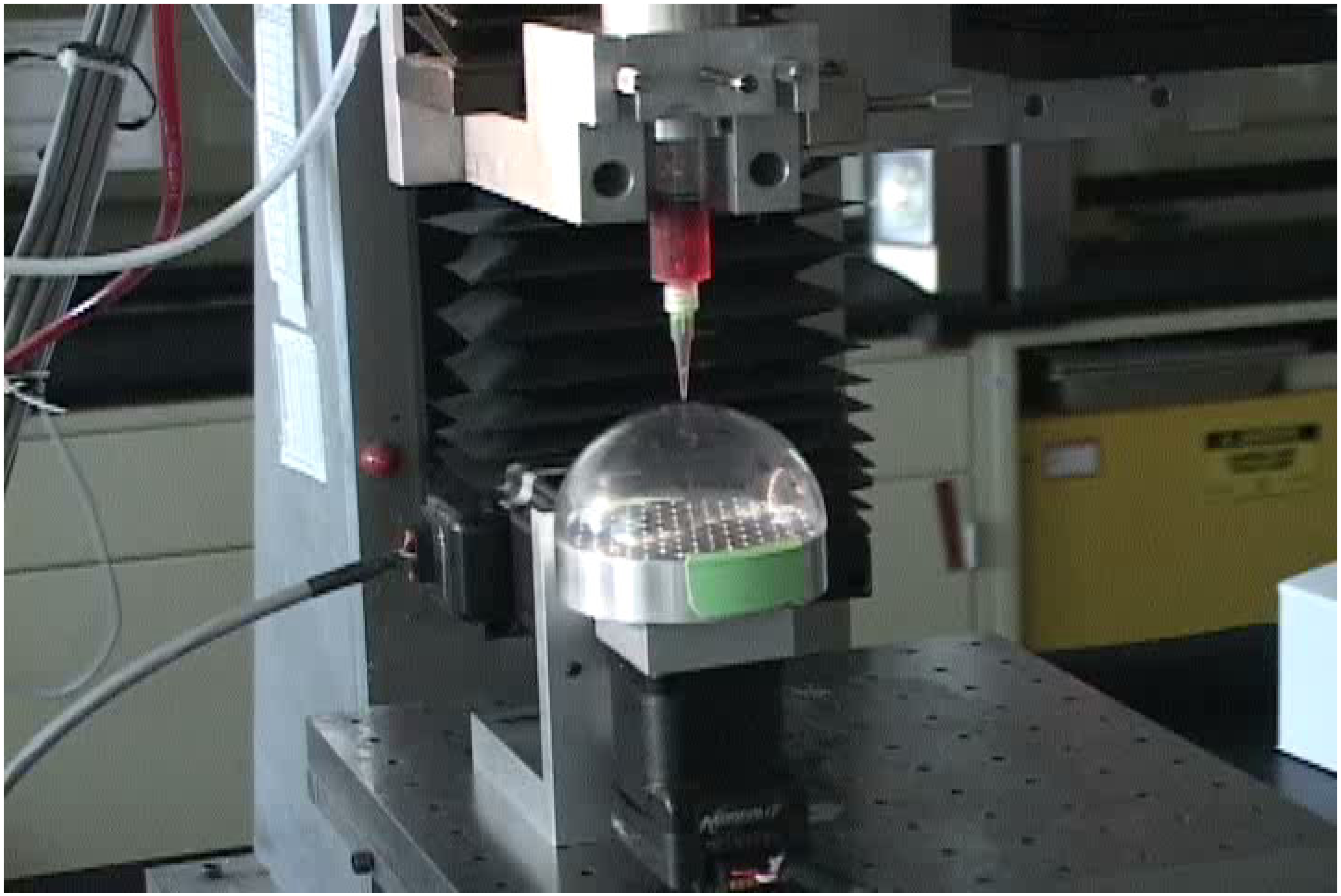
Robocast/pen-dispense 5 axis printing



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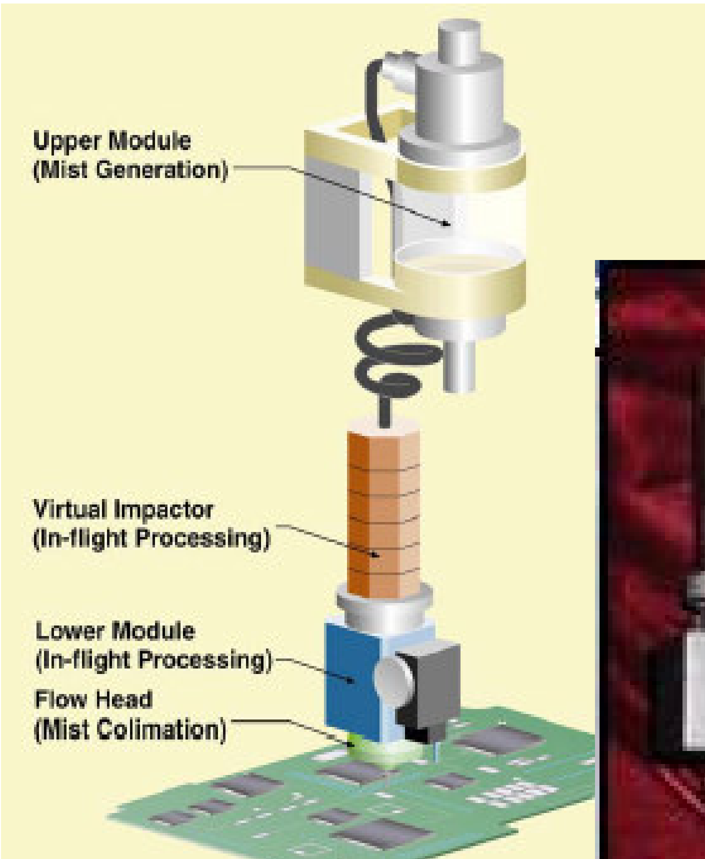
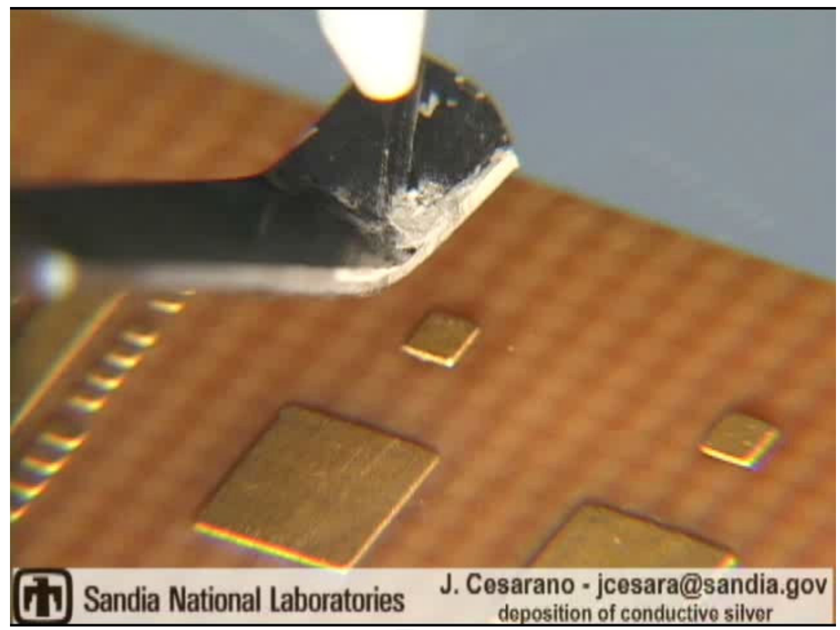
Aerosol Jet direct write method
(Optomec M^{3}D/collimated microspray)



Microspray head
(10-25 μm lines)

Process Steps:

- Mist Generation - 2-5 μm droplets
- Mist Collimation – air sheath compresses stream to 10-25 μm
- Deposition - focused mist stream prints pattern from AutoCAD file
- Final Cure - treatment to cure deposit (heating, laser, UV etc.)



OPTOMEC™
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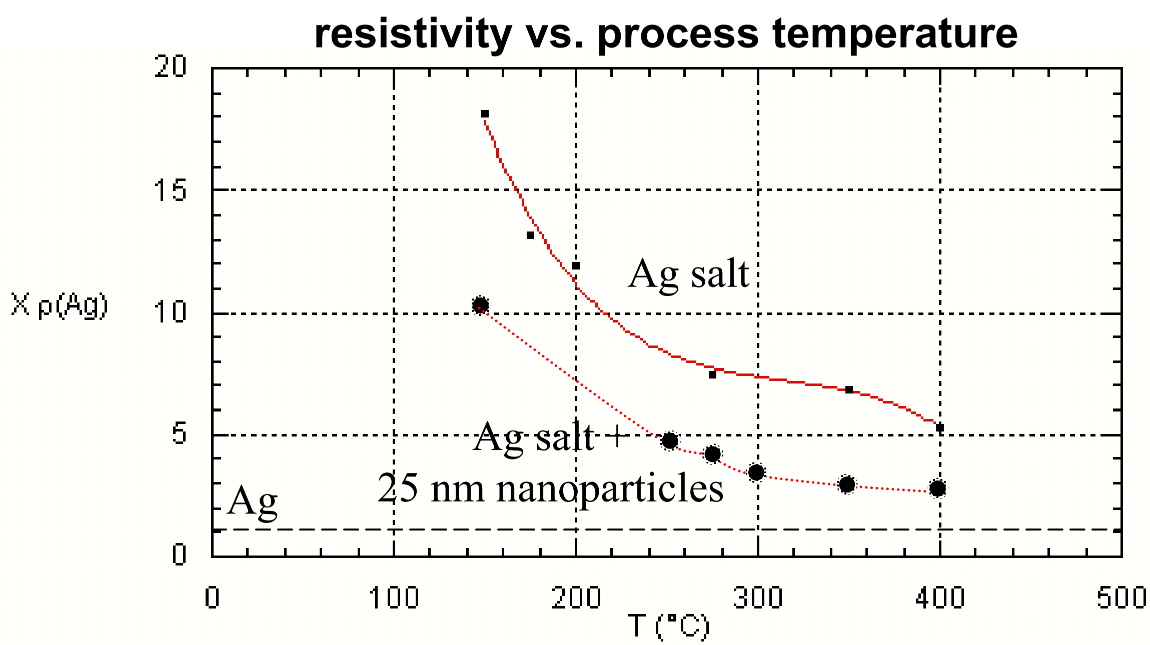
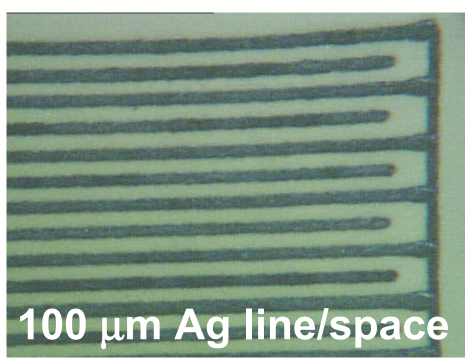
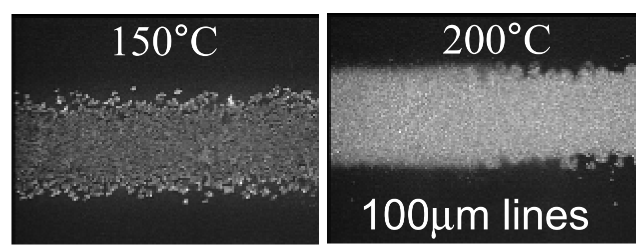
Silver nitrate precursor ink for 150°C stereolithography polymer integration

Silver nitrate dissolved in solution, converted to a metal at 150°C

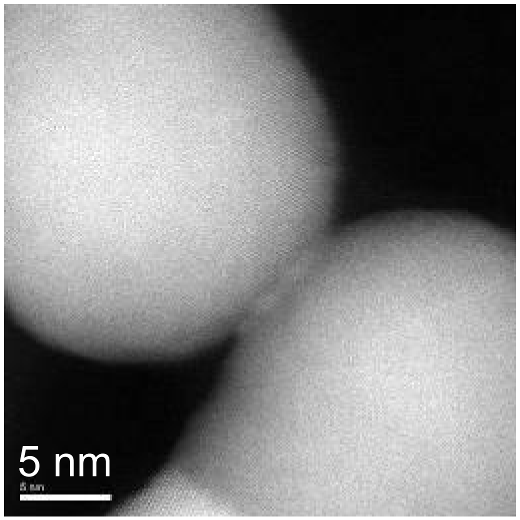




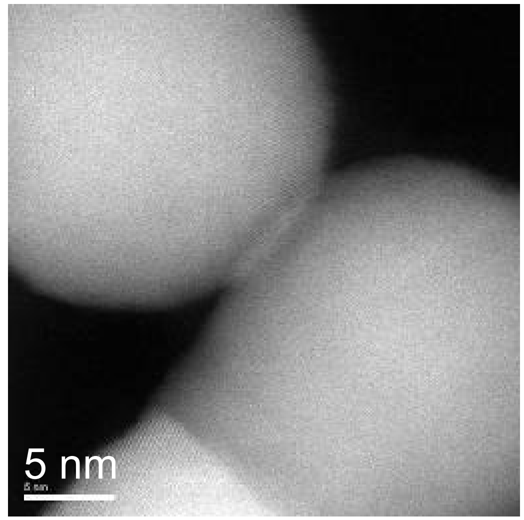


Silver nanoparticle (25 nm) inks:
in situ TEM annealing (25-300°C)

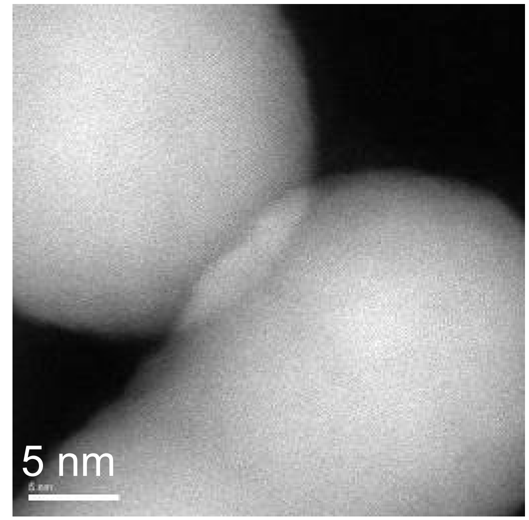
50°C



100°C

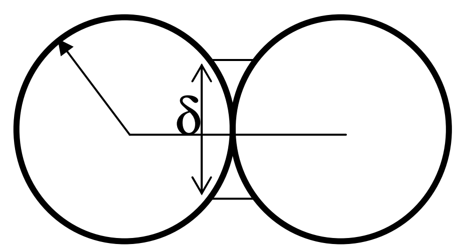


170°C



25 nm silver nanoparticles display necking beginning at 100°C

$$\sigma = A\sqrt{\delta}\ (\phi-\phi_c)^{\tau}$$

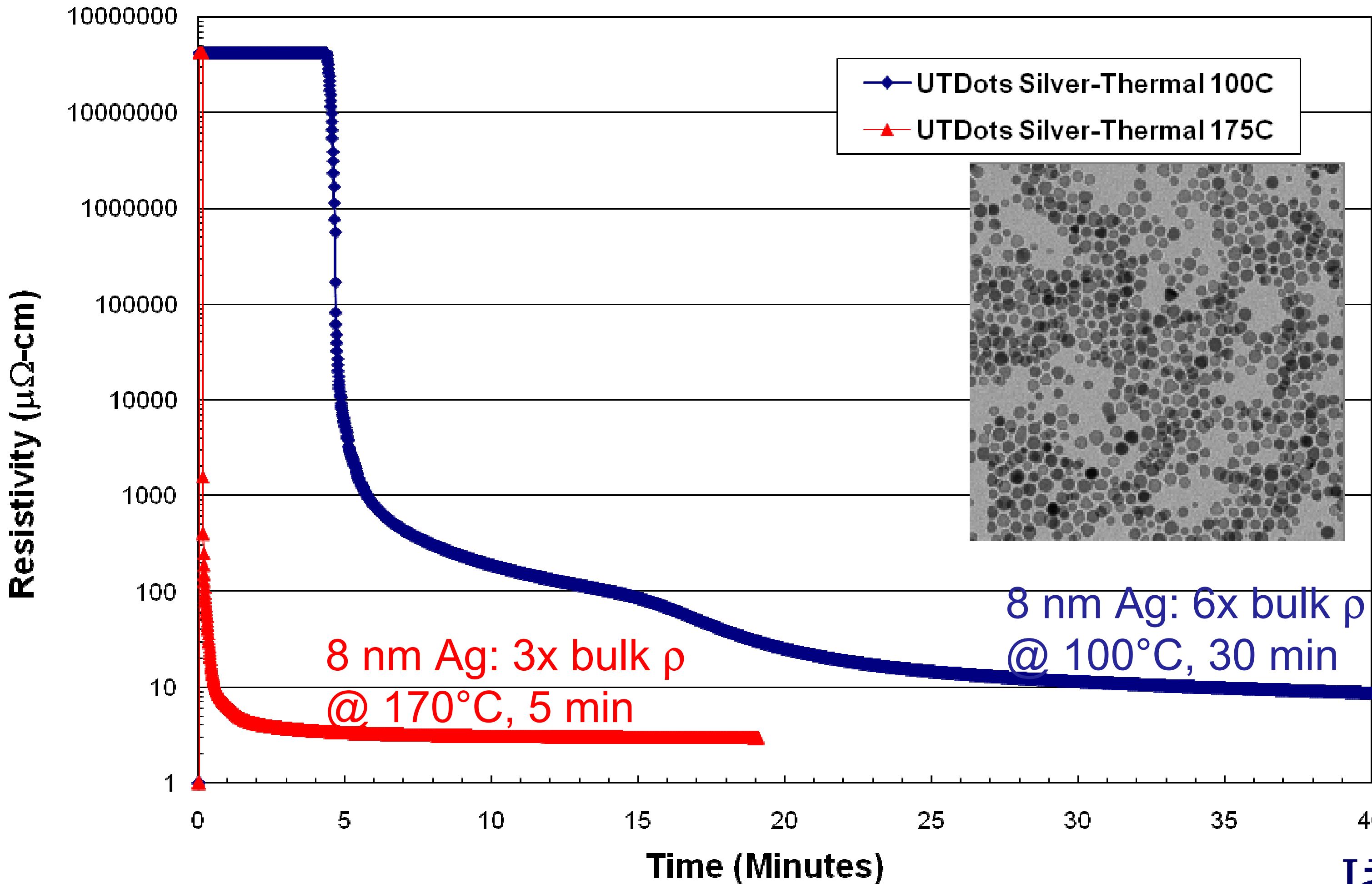


High surface mobilities and grain boundary curvatures present in nanoparticles appear to drive low temperature coarsening

STEM Images: Prof. D. Kovar, Prof. P. Ferreira, Univ. of Texas

8 nm silver nanoparticle UT Dots ink

ultralow T processing (100-170°C)



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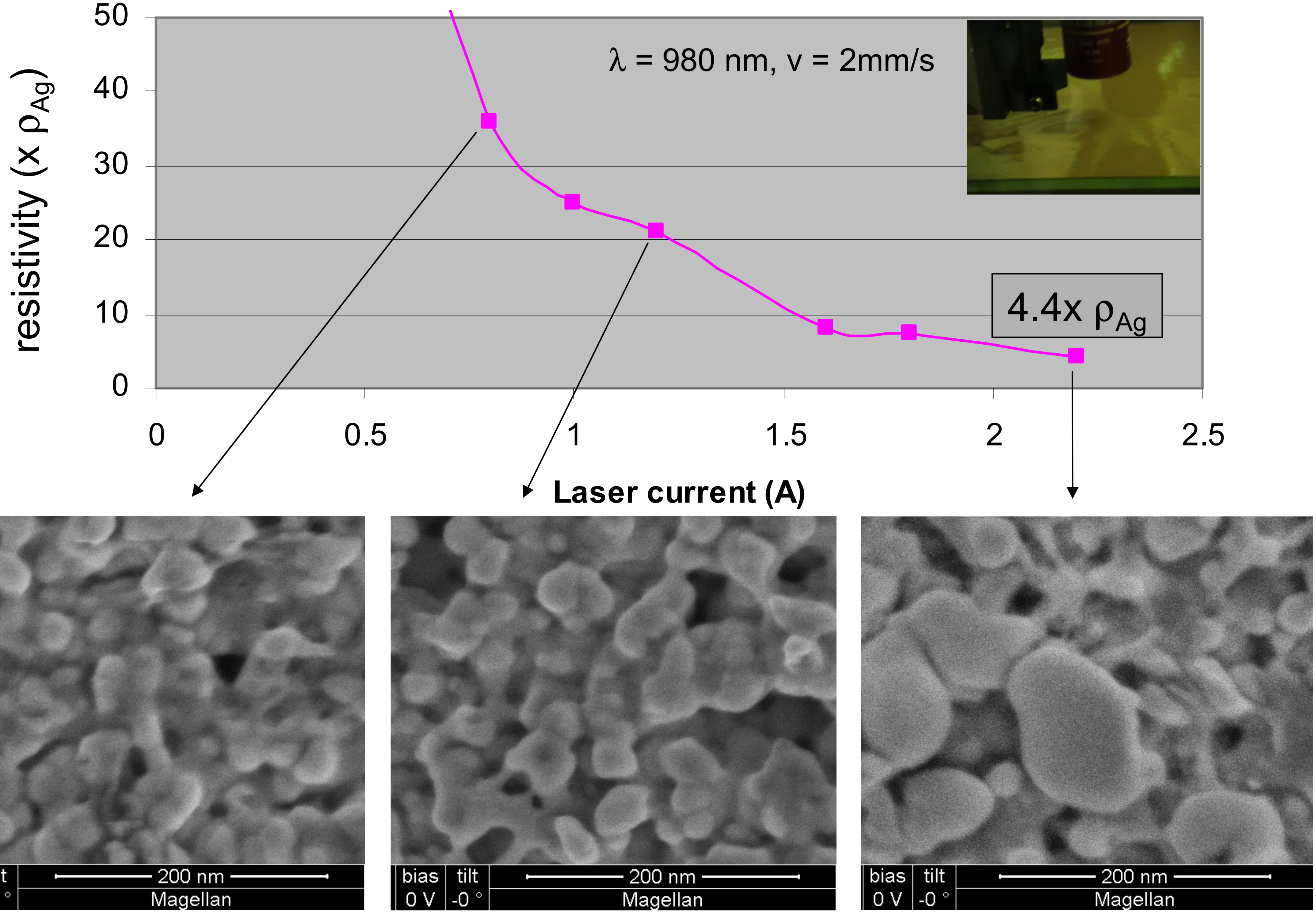
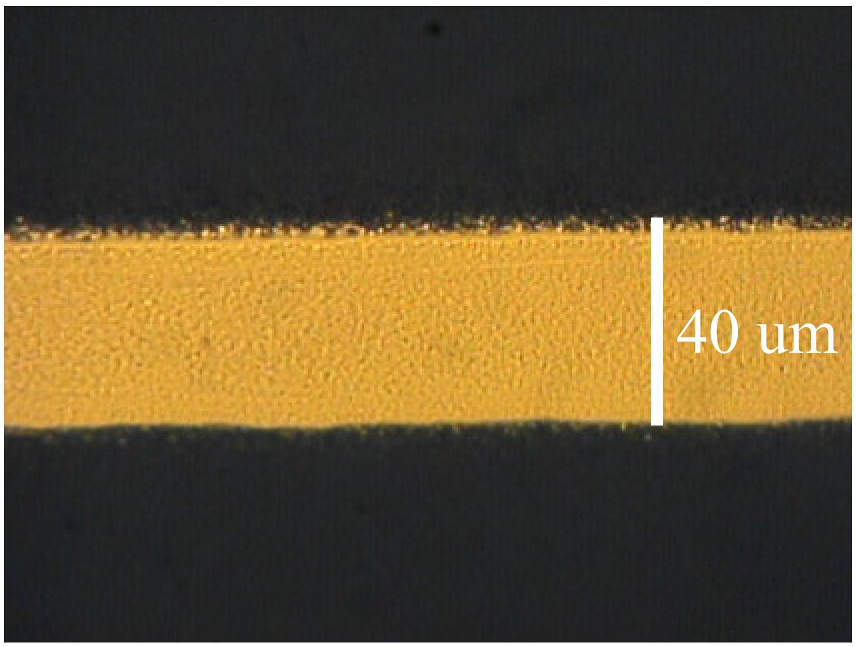
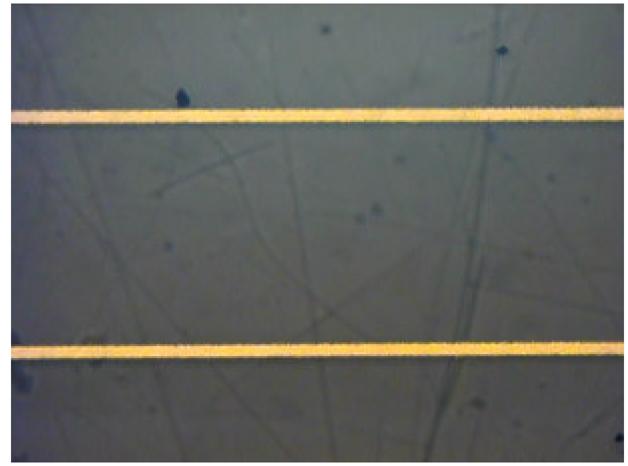
Laser sintering of 8 nm silver nanoparticle UT Dots ink

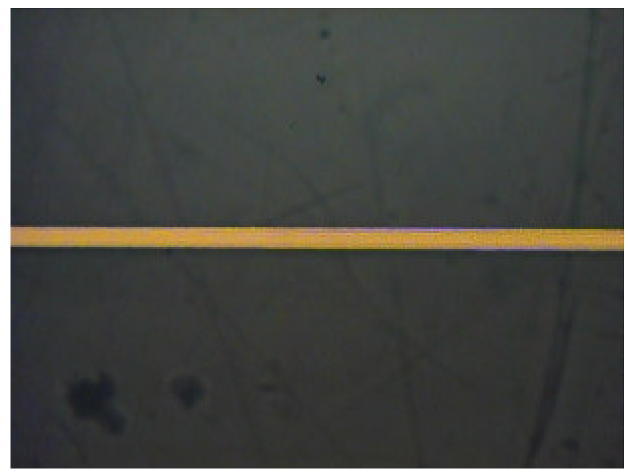
sample ambient temperature processing (25°C)



Gold nanoparticle ink traces (40 µm, 1.6 mil)







Low cure temperature (200°C)

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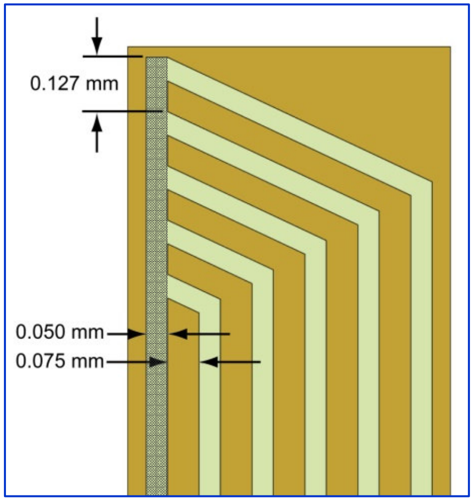
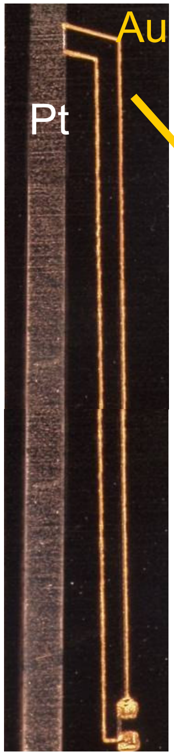
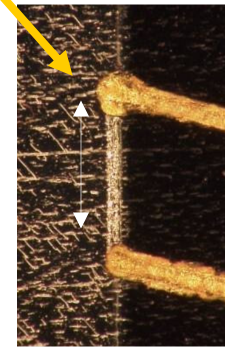
Printed Au/Pt thermocouples

- Pt/Au bimetal junction thermocouples with two temperature sensing junctions were printed.
  - Common Pt ground
  - Printed Au to form junctions
    - 8-nm Au nanoparticles in solvent
    - laser-cured after printing.

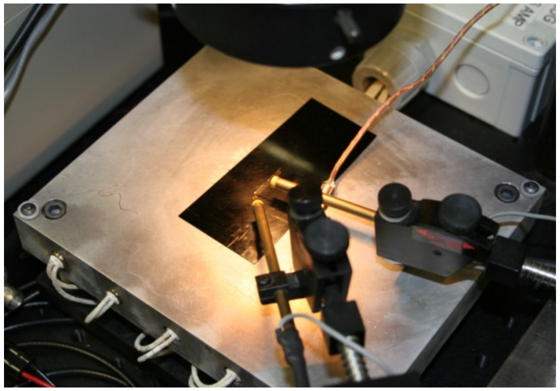


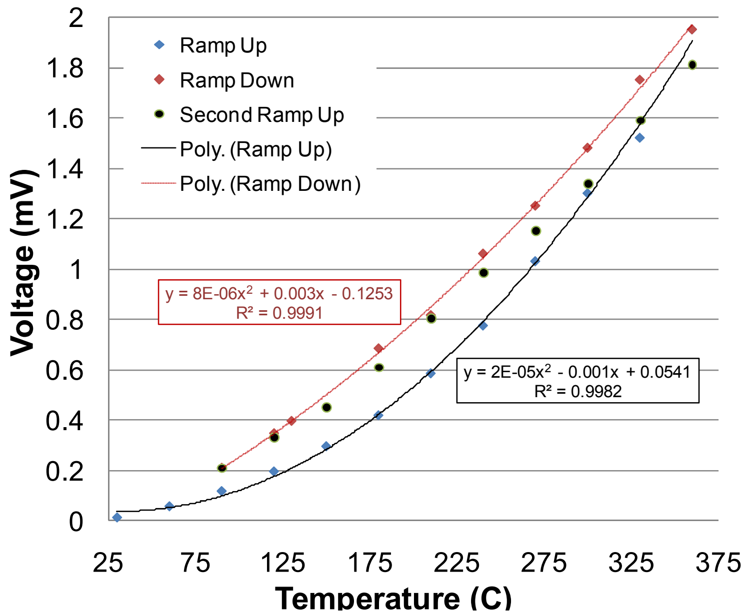
Prototype TC Probe
with 5 junctions
(1 mm separation)





Printed Au
(~80 μm)

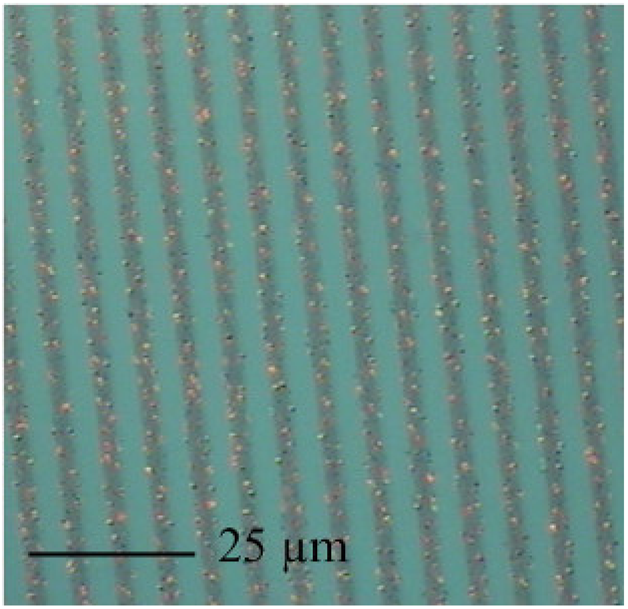


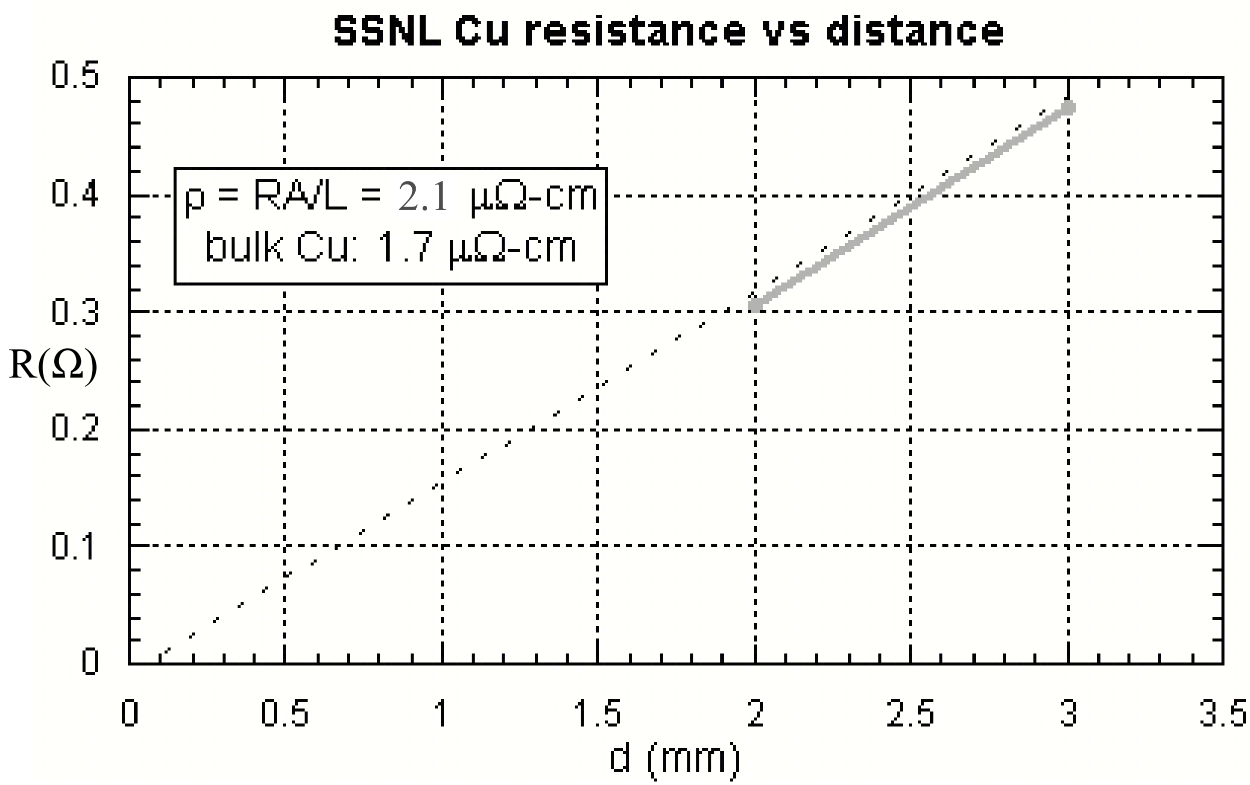


Printed 5 μm copper: 80% bulk Cu conductivity

Copper processing:

1) Cu ink decomposed in air
2) CuO reduced to Cu metal in H_2/N_2 at 250°C





N.A. Chang, J. Richardson, P.G. Clem, and J.W.P. Hsu, "Additive patterning of conductors and superconductors by solution stamping nanolithography," Small, 2(1), 75-59 (2006).

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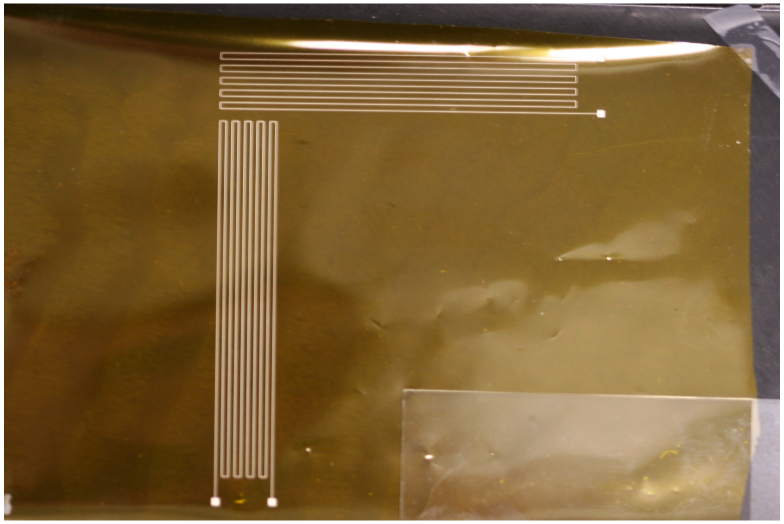
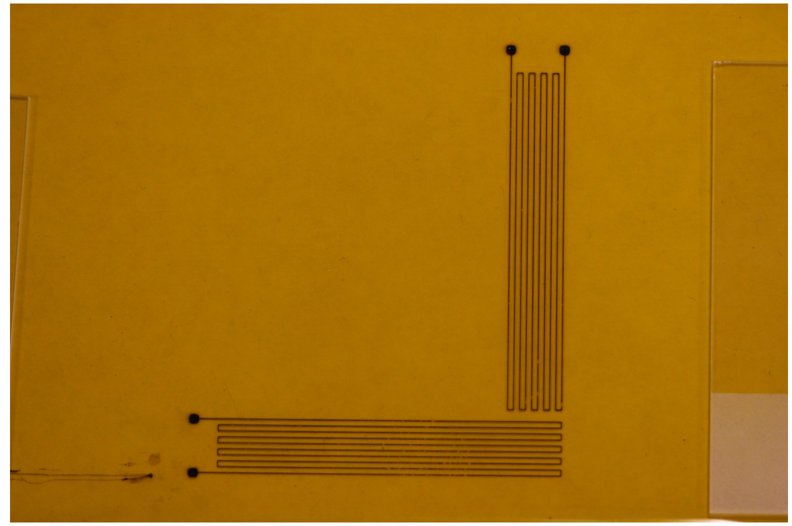
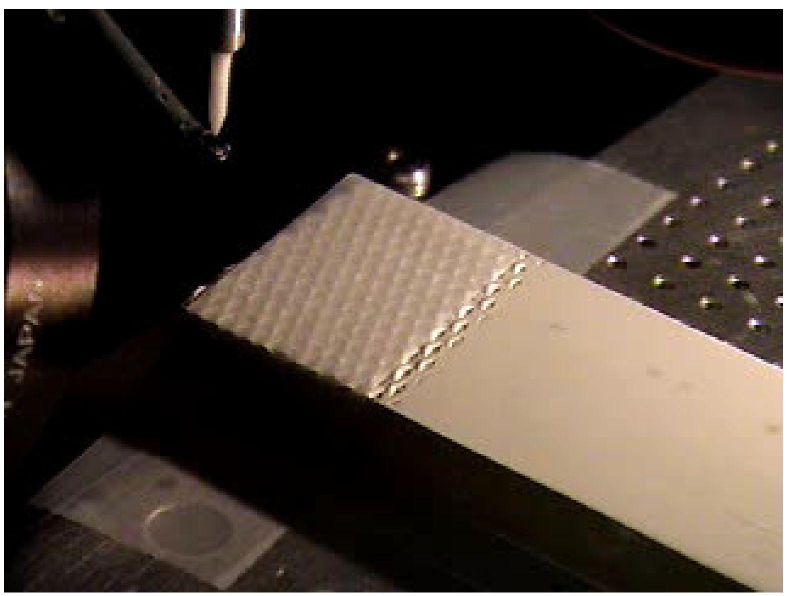
Printed silver and constantan strain gages



silver on Kapton



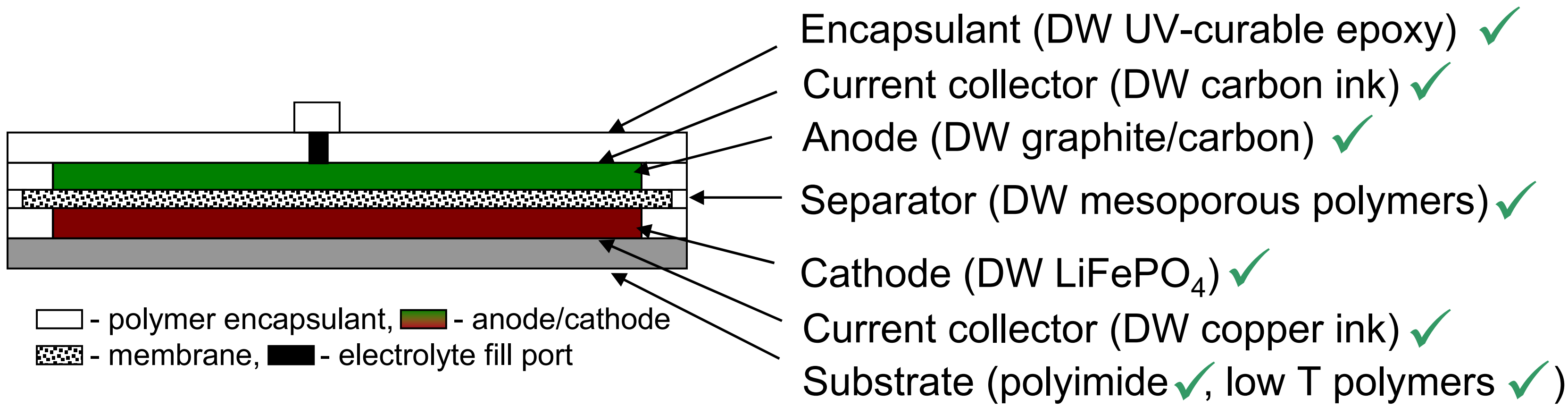
constantan on Kapton

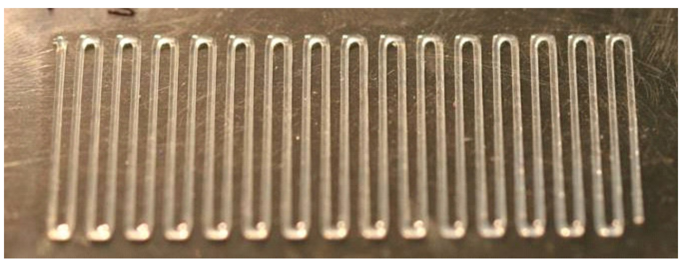


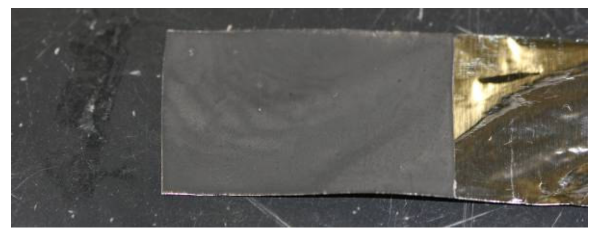
silver on turbine blade segment

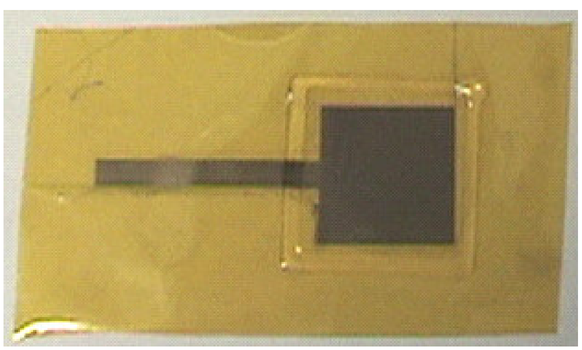
constantan on turbine blade

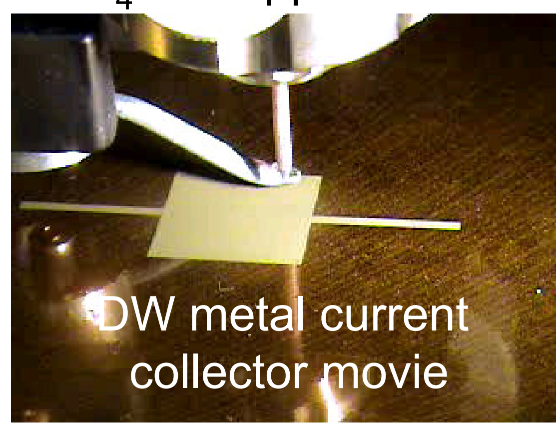
Direct Written $LiFePO_4$ Battery Anatomy




Direct written epoxy encapsulant


DW $LiFePO_4$ on copper current collector

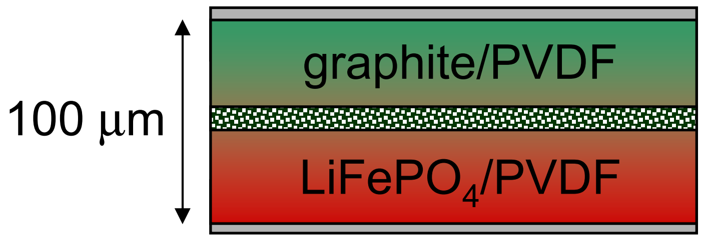

DW cathode + encapsulant on Kapton



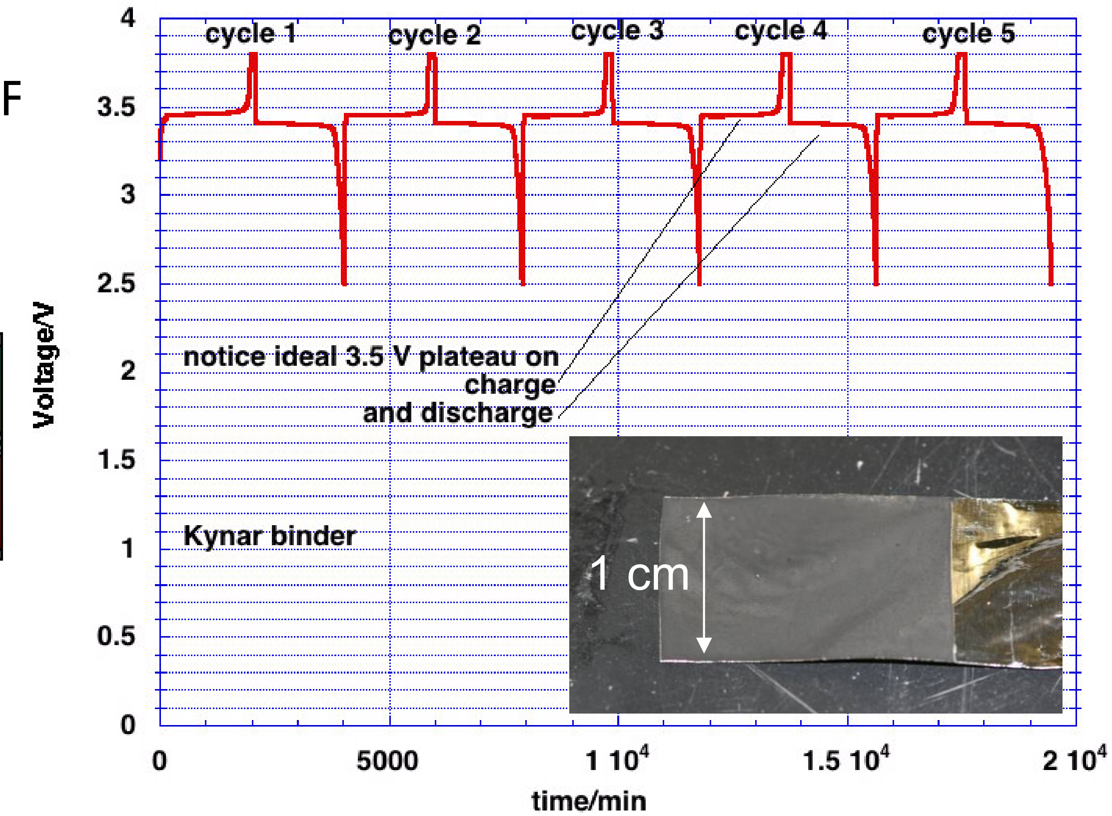
Printed 2D lithium ion battery

<u>Printing topology:</u>

•$LiFePO_4$/graphite/PVDF
•porous separator
•graphite/PVDF
•$LiPF_6$ liquid electrolyte



107 mA-h/g, 1.5 mA-h printed $LiFePO_4$ cell



• cell energy density is 76% of theoretical capacity (140 mA-h/g)

• no electrochemically active materials (0-4 V) may be used in cell printing

Conclusions and Future Work

- Sensor capabilities: strain gages, thermocouples, antennas
  - Ag & constantan strain gages on composite blade sections under test
- Metal sensors sintered at 100-200°C, or laser sintered at 25°C – is this compatible with composite blade fabrication?
  - Apply sensors to buried layers & ply drops
  - Develop pressure sensors, crack sensors…
  - Portable printing of sensors
- Wireless state of health data transfer?
  - Power: printed lithium batteries
  - Antennas successfully printed
  - Wireless sensors in development
- Seeking other ideas/applications