Aerosol Jet Printing for Three Dimensional Interconnects

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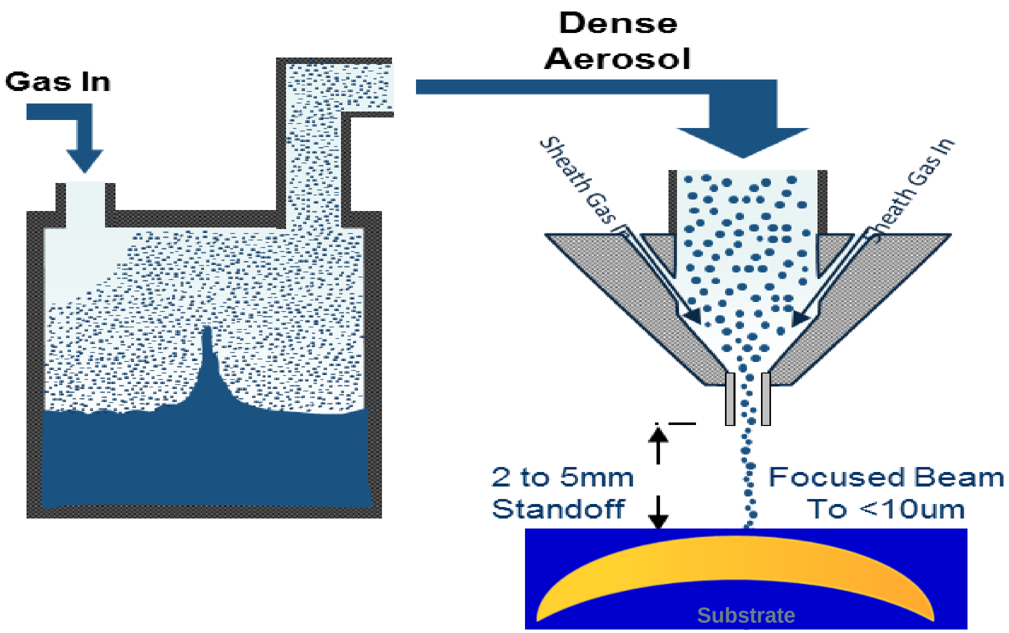
Optomec, Inc

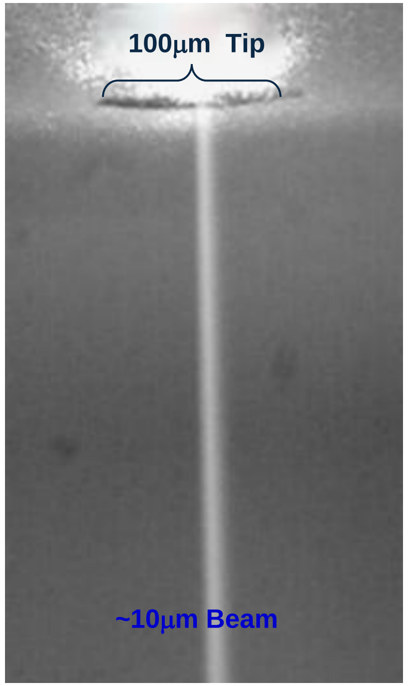
March 6, 2024

Outline

- **Introduction to Aerosol Jet Printing**
- **Materials Compatibility**
- **Characteristics of Printed gold**
- **Role of Dielectric Support Materials**
- **3D Interconnect Printing**
- **Wirebonding on Printed Gold**

Aerosol Jet Process (Ultrasonics)





1. Atomize Liquid Electronic Material: conductive inks, dielectric, (1-12 cP)
2. Mist of 2 to 5 um Ø highly dense, highly loaded droplets
3. Sheath gas surrounds and focuses particle beam
4. Continuous Flow Exits at 50m/s remains collimated for up to 5 mm
5. Print on planar and non planar substrates

Common applications:

- Fine features with high density (10um/10um L/S)
- Thin films (50nm)
- Aqueous 'inks': acids, bases, CNTs, Graphine
- On-the-fly UV curing and laser sintering

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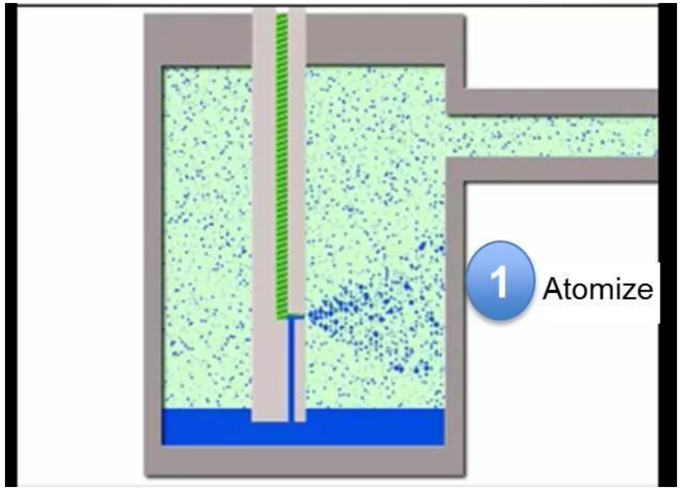
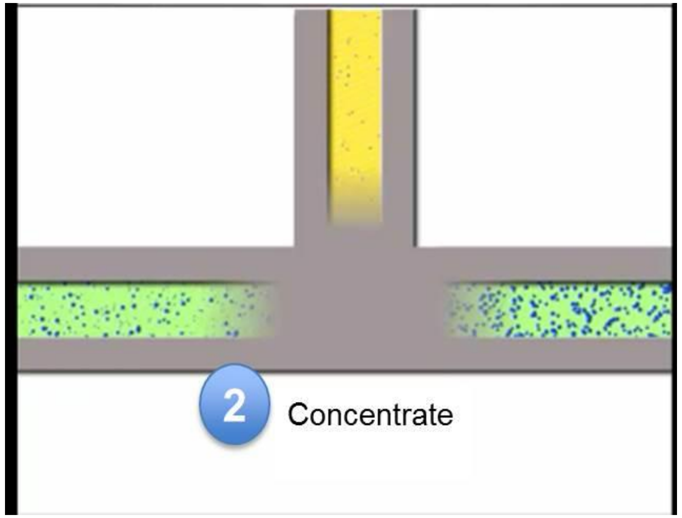
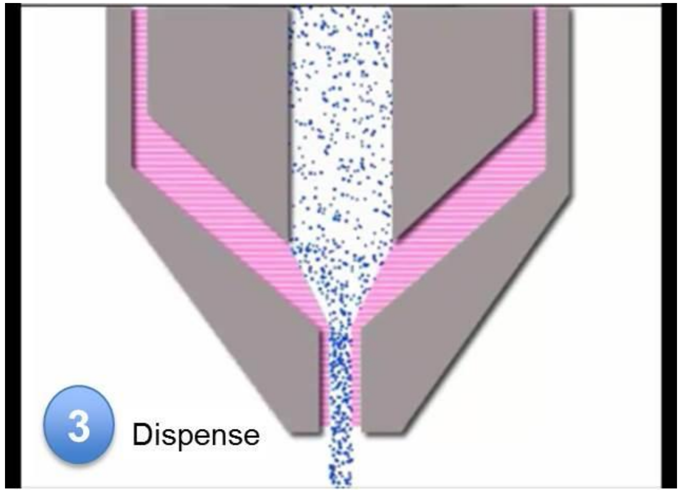
3D Interconnect Printing

Aerosol Jet Process (Pneumatics)







(1) Pneumatical atomize ink
- Small droplets 2 to 5 microns in diameter
- Supports many materials w/high solids loading
- 60wt% dispersions, all solids UV polymers
- Viscosity 1000+ cP

(2) Concentrate aerosol w/virtual impaction
- Remove excess gas
- Partially dry the droplets

(3) Dispense aerosol
- Focus aerosol with sheath gas
- Prevents clogging
- High exit velocity 50 m/s
- Print on 2D and 3D surfaces

Enables printing of conventional screen print pastes

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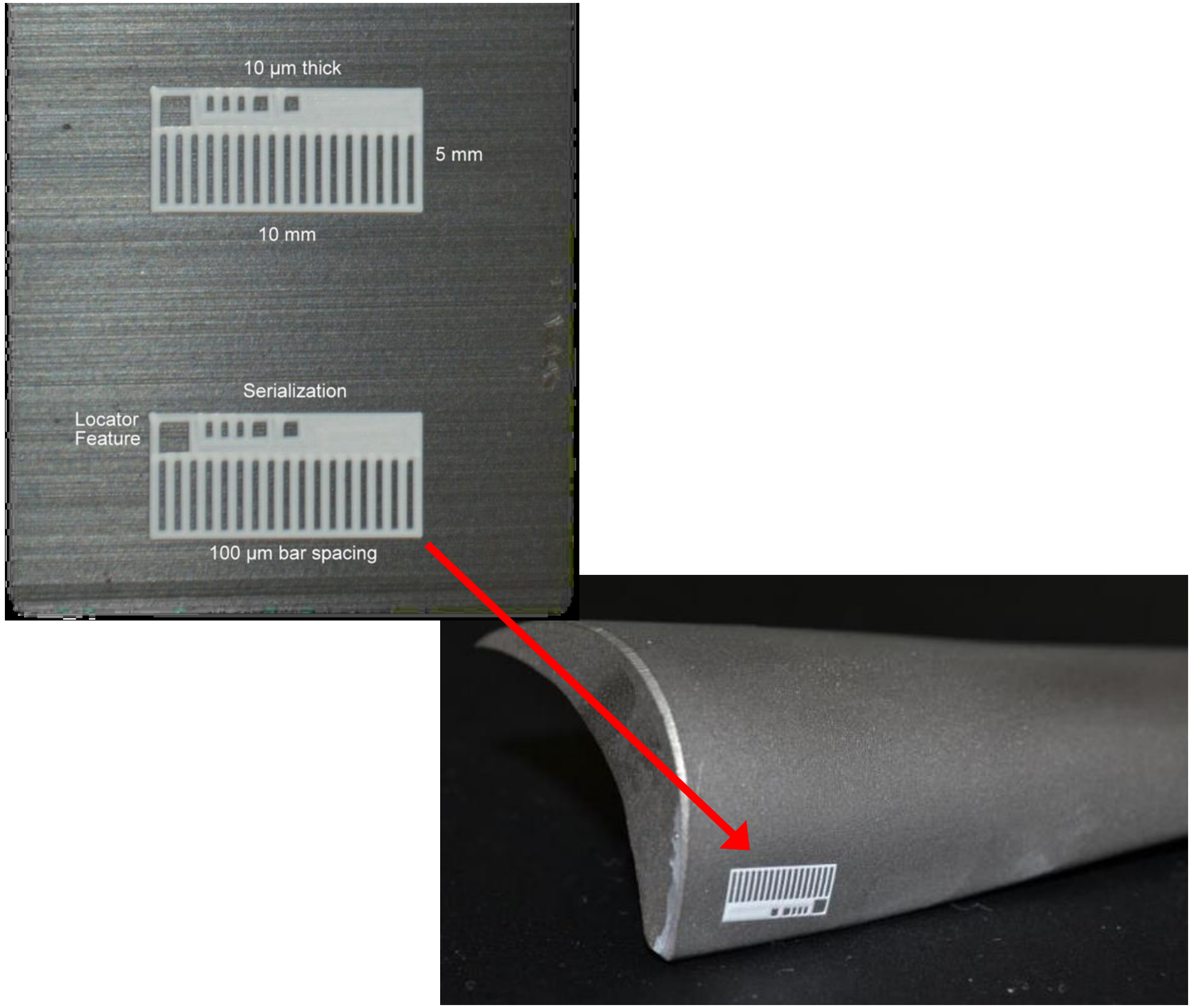
Enabled by Pneumatics: Creep Sensor for Predictive Maintenance

- **Health Monitoring for High-Value Components**
- **High Temp (>1800°F) In-Situ Creep Sensors**
  - **Optical sensors detects fatigue and creep**
  - **Unique serialization for each gage**
- **Enabled by Aerosol Jet Printing**
  - **3D Conformal Printing directly onto parts.**
  - **Digital input enables Serialization**
  - **Supports High Temp YSZ Ceramic Ink**



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Wide Range of Commercial Materials

Metal Inks	Resistor Inks	Non-Metallic Conductors
Electron Inks (Ag, Au)	Acheson (carbon)	Brewer Science (SWCNTs)
Applied Nanotech (Ag, Ni, In, Cu/Ni)	Asahi (carbon)	Heraeus (PEDOT:PSS)
Advanced Nano Products (Ag)	DuPont (carbon and ruthenate)	NanoIntegris (SW & MW CNTs)
DuPont (Au)	Lord (carbon)	Chasm (SW & MW CNTs)
Henkel (Ag)	Novacentrix (carbon)	**Semiconductors**
PV Nanocell (Ag, Cu)	**Dielectrics and Adhesives**	Aldrich (organic semiconductors)
Novacentrix (Ag, Au, Cu)	**HD Microsystems (polyimide)**	Alfa (organic semiconductors)
Paru (Ag)	Microchem (SU8)	Merck (organic semiconductors)
Creative Materials (AgE)	DuPont (fluoropolymers)	NanoIntegris (SWCNTs)
Dycotec (Ag, Cu)	Namics (epoxy)	**Reactive Chemistries**
UTDots (Ag, Au, Pt)	Loctite (adhesives)	Shipley (photo and etch resists)
Xerox (Ag)	Dow (silicones)	Aldrich (acid, bases, etc.)

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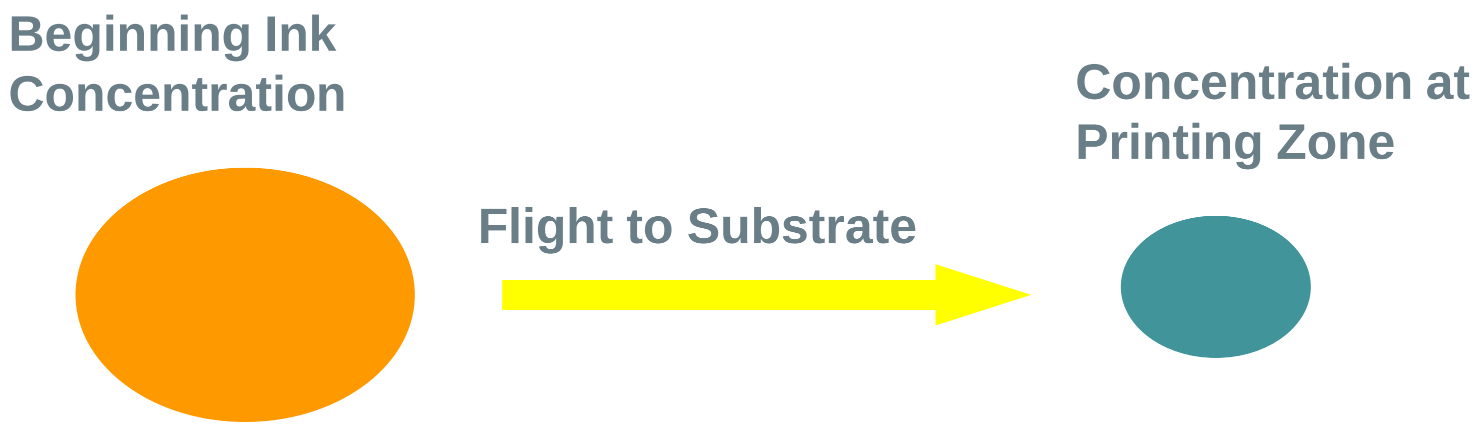
Why Gold Inks for Printed Electronics

- **Corrosion resistance with high operation temperature**
- **Low resistivity(2.2 x10^{-8} Ω-m)**
- **Reduced electrochemical migration at high interconnect density**
- **Wire bondable and solderable**
- **High cost but low waste with digital printing ($0.0003/mm)**
- **High work function for active devices.**
- **Biocompatibility**

Formulating Inks: Co-solvent Method

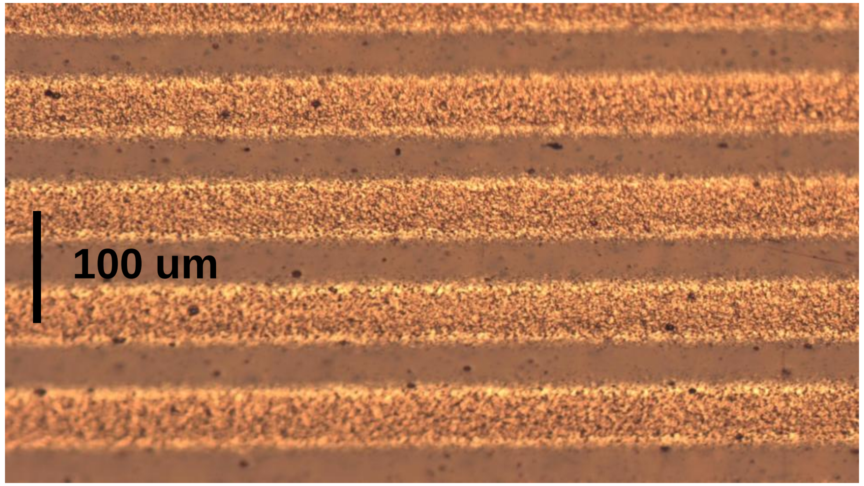


- Gold ink 40wt%, 10vol%
- Xylenes 80vol% (fast dry)
- Terpineol 10vol% (slow dry)

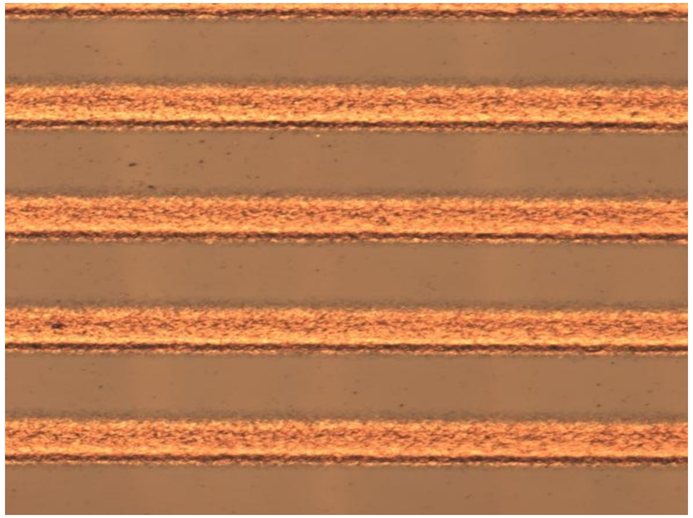
- Gold ink 90 wt%, 50vol%
- Xylenes ~trace %
- Terpineol 50vol% (slow dry for dense packing)

Optimal ink allows printing of high aspect ratio features with low spreading

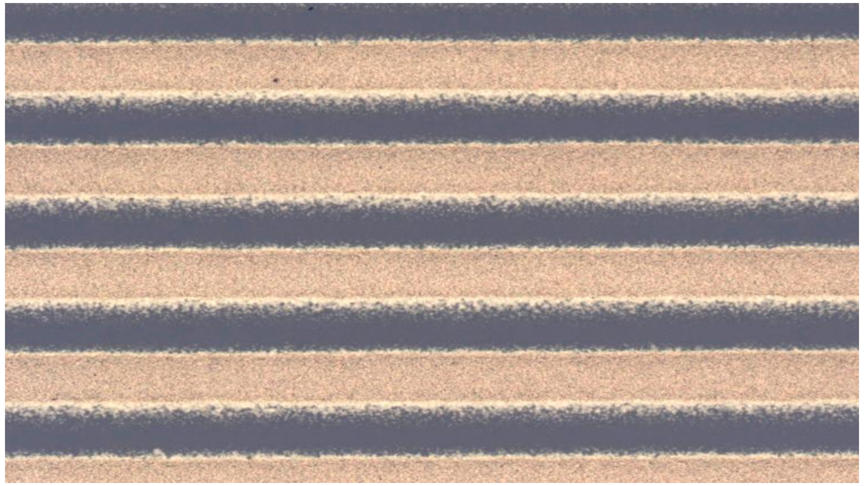
Summary of Three Gold Ink Formulations



JG-014UA on Kapton (50%w/w)
Thickness 2-3 um



JG-024UA on Glass(40%w/w)
Thickness 1.0 um



JG-023UA on Glass(25%w/w)
Thickness 0.4 um

- **All samples sintered at 200C overnight and printed at 5 mm/s.**
- **JG-014 significantly rougher, higher porosity, and lower conductivity. Not stable in the system.**
- **JG-023 is denser with better conductivity. But more overspray and ink spreading**
- **JG-024 appears to be a good compromise -- stable, good output, good conductivity, good line shape.**

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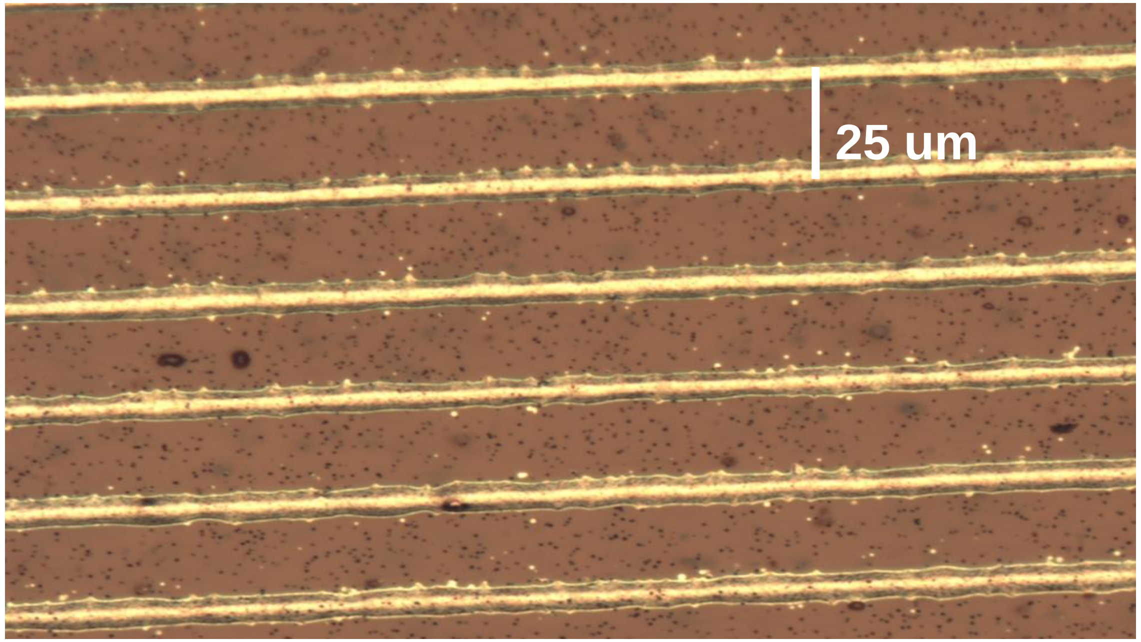
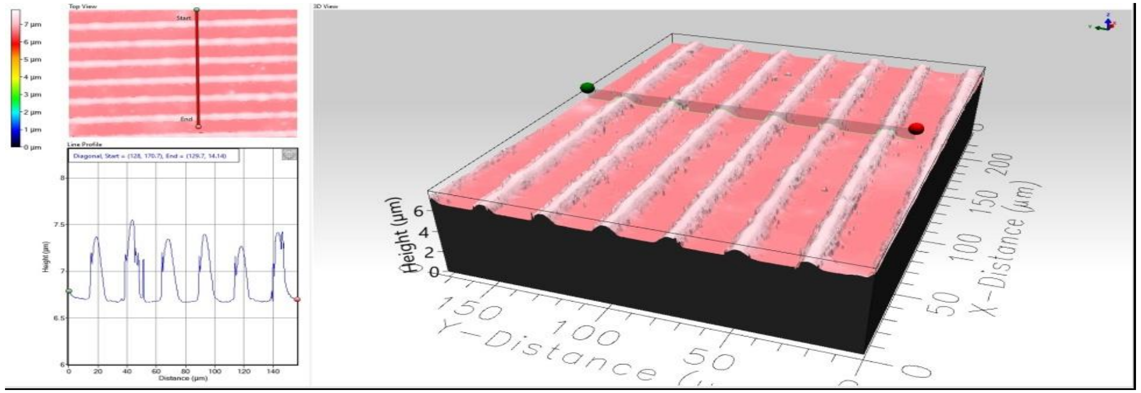
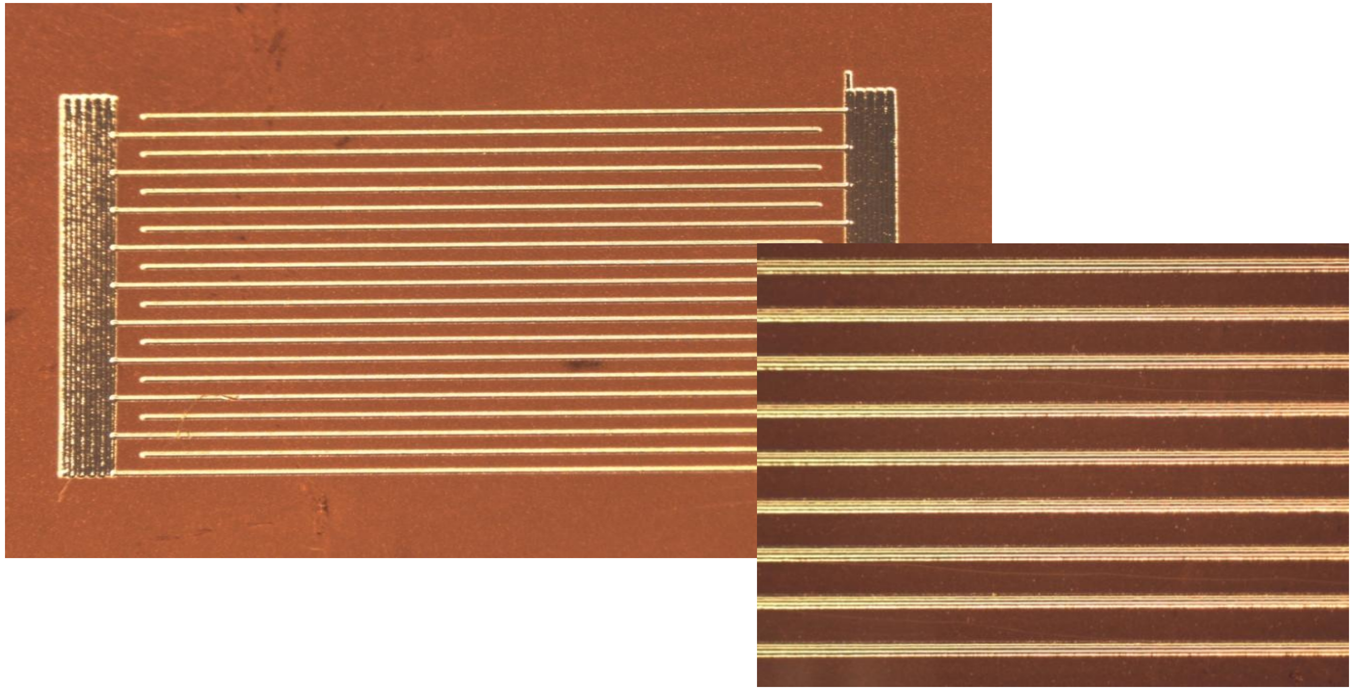
Feature Size Scaling

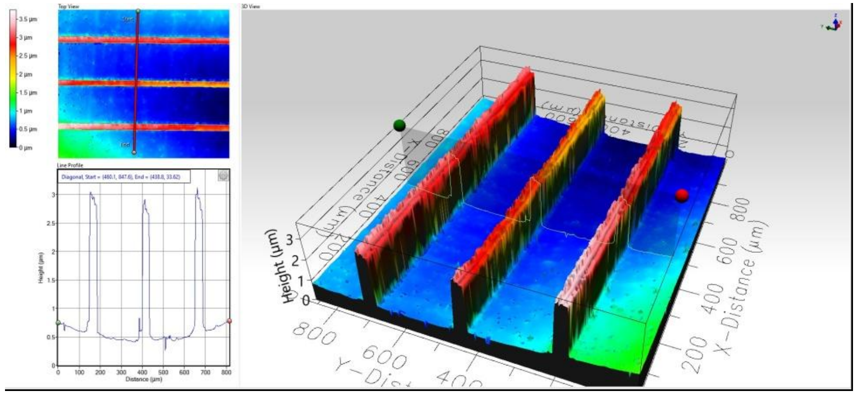




Feature sizes can be below 10 um.

Test Coupon for Line Isolation Testing (> 10 GΩ target)



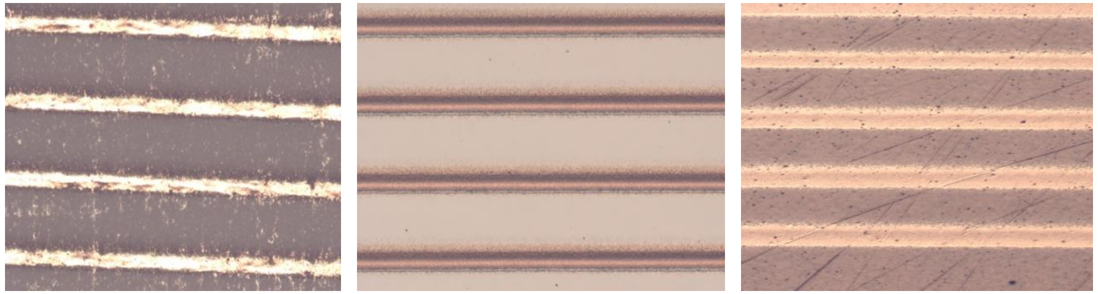


200um spacing

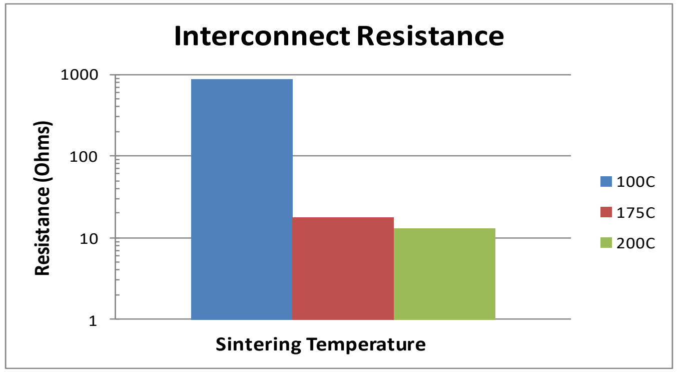
- **Novacentrix JG-014 gold.**
- **Interdigital Electrodes as test coupon for visual overspray detection and isolation measurement.**
- **Ink drying rate controlled by ink additives and solvent vapor in air stream.**
- **Line isolation meets spec until width and space are about equal.**

Sintering Strategies for Gold

Laser (832 nm)



Substrate	Laser Power (W)	Translation Speed (mm/s)	Resistivity (Ω-m)
Kapton	0.5	5	1.7×10^{-7}
Silicon	5	5	9.0×10^{-8}
Alumina	5	5	9.0×10^{-8}



Oven sintering (2 hrs)

- **Laser sintering roughly equivalent to sintering in oven at 250C for 2 hrs)**
- **Laser sintering highly dependent on thermal conductivity of substrate**
- **Sintering on heterogeneous substrate requires rapid power modulation to prevent substrate damage**

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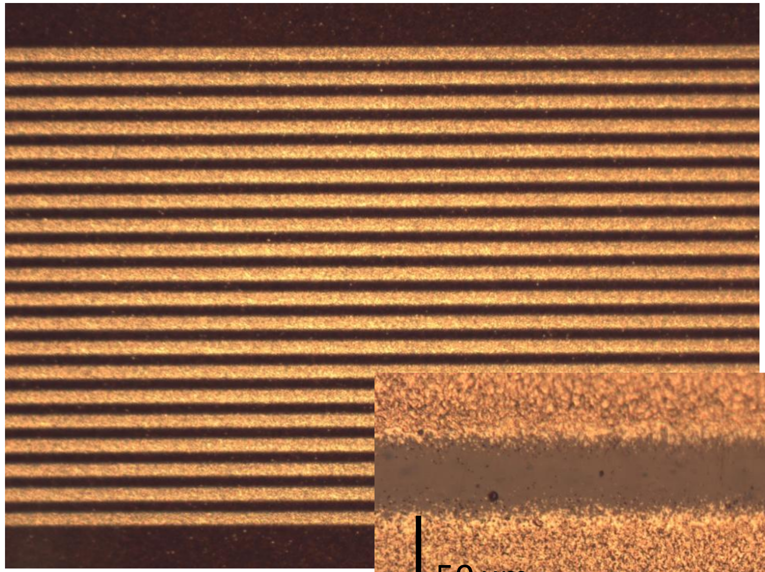
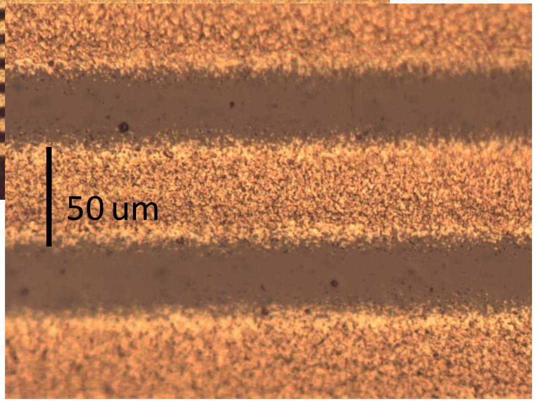
Thermal Stability

Line resistivity (Ohms/mm) and thermal reliability for 7mm long, 50 µm/50 µm L/S gold lines on Kapton.

			TC -40 to +85C	
Line	R_L	R_R	R_L	R_R
1	250	239	241	222
2	250	241	244	234
3	252	242	243	236
4	252	242	247	235
5	251	242	249	234
6	252	242	246	237
7	250	244	242	237
8	253	246	241	238
9	254	244	245	239
10	251	245	232	238
Ave	251.5	242.7	243	235
STDEV	1.4	2.1	4.7	4.9

50 cycles





2 um thickness
Sintering 2hrs@250C

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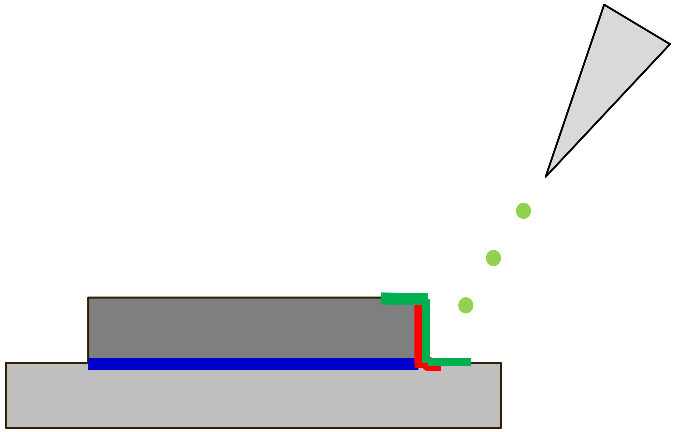
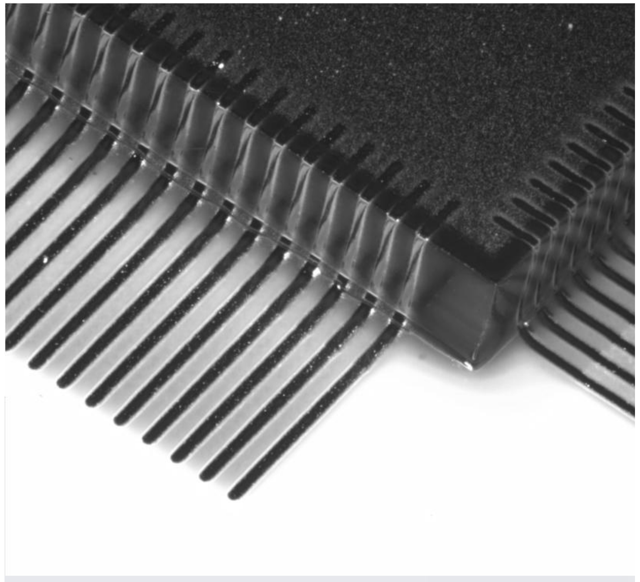
Applications to 3D Interconnects



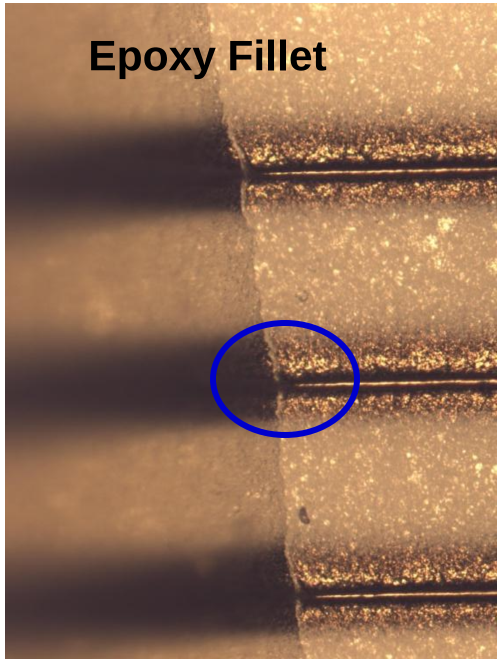


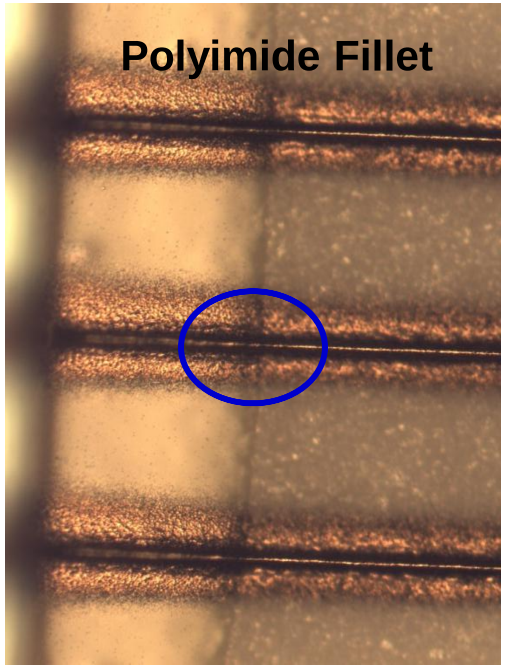
Line #	Resistance(Ω)
1	5.8
2	5.5
3	5.5
4	5.2
5	5.2
6	5.4
7	5.4
8	5.0
9	4.9
10	5.2
11	5.3
12	5.1
Ave	5.3
STDEV	0.25

- Epoxy die attach
- Polyimide sidewall coating
- Gold nanoparticle ink
- Thermal curing and sintering at 250C for 1 hr.

Advantages:
- **Reduced package Z-height**
- **Higher speeds by eliminating parasitic inductive loop**
- **Improved reliability**
- **Higher interconnect density (below 50 um pitch)**
- **Multilevel crossovers possible**

Importance of Fillet Material





Lines break during sintering due to thermal expansion mismatch

Epoxy:
Tg 45C, CTE = 211 ppm/C
Polyimide:
Tg 300, CTE 40 ppm/C

Silicon: CTE = 2.6 ppm/C,
Alumina: CTE = 7.2 ppm/C

Lower CTE Polyimide is a more stable support material

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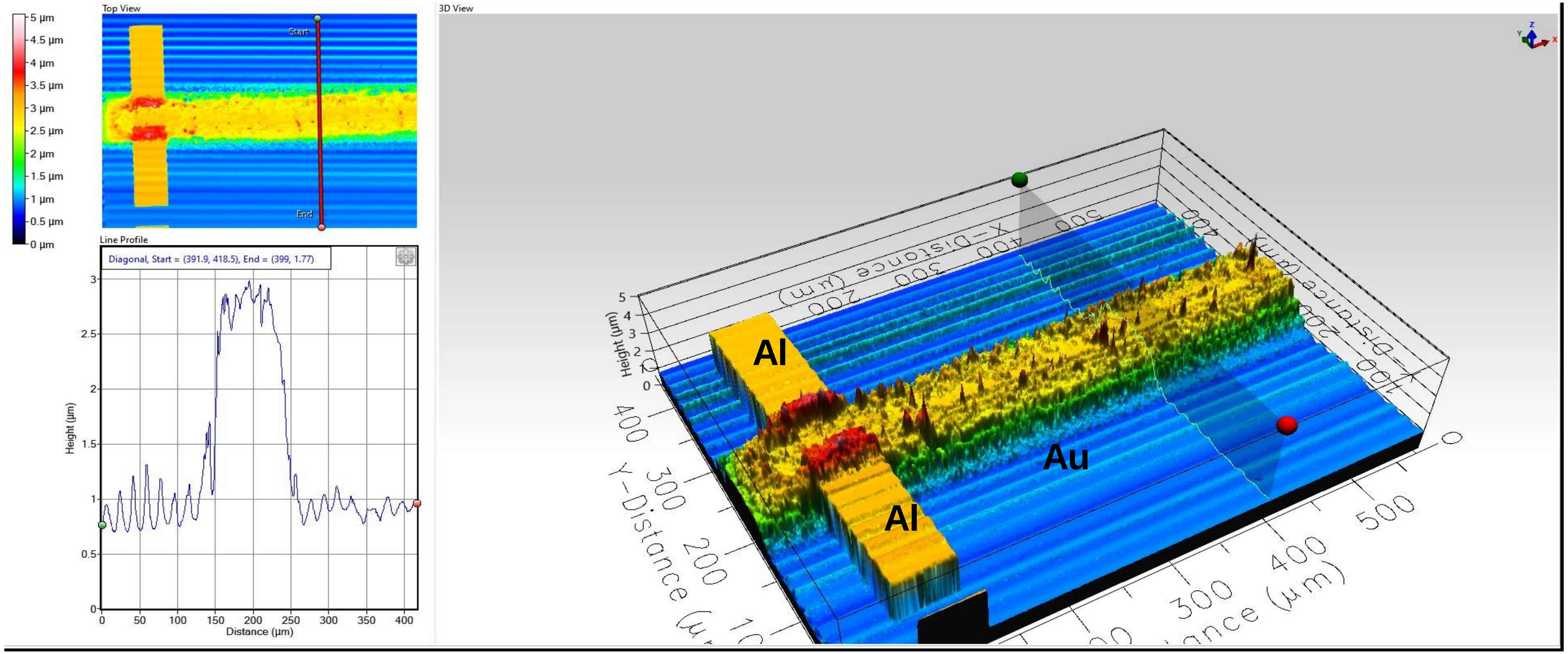
Connecting to Al Bond Pads: Contact Resistance



- Native oxide on aluminum causes contact resistance
- Ammonium Hydroxide can be added to ink (25%) to etch/clean the aluminum pads
- Other reducing agents may be possible by printing separately or adding agent to ink

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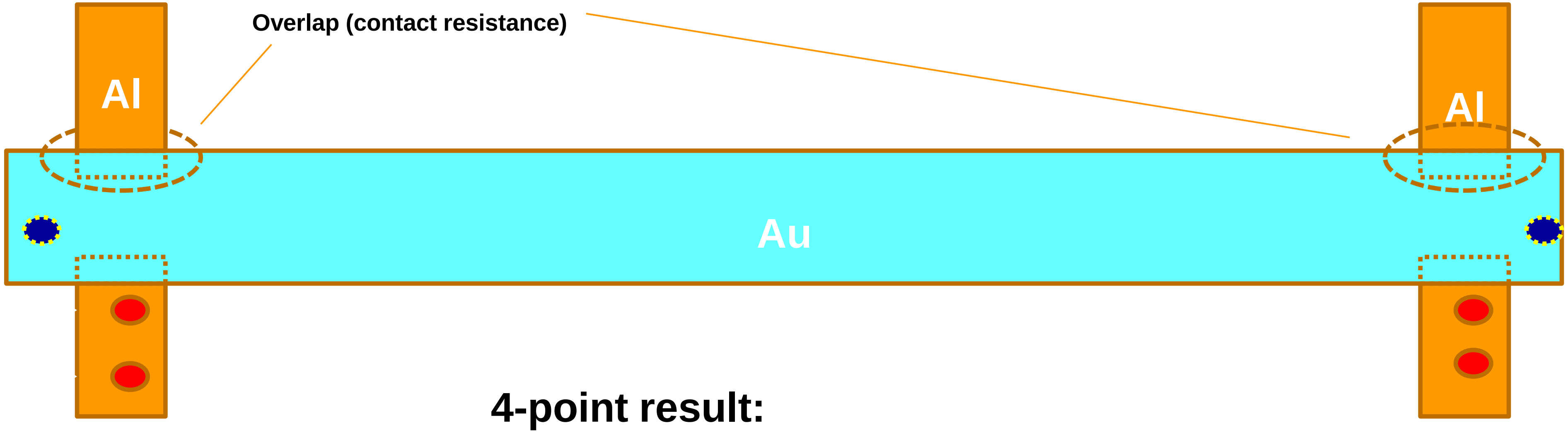
4- Point Test for Contact Resistance

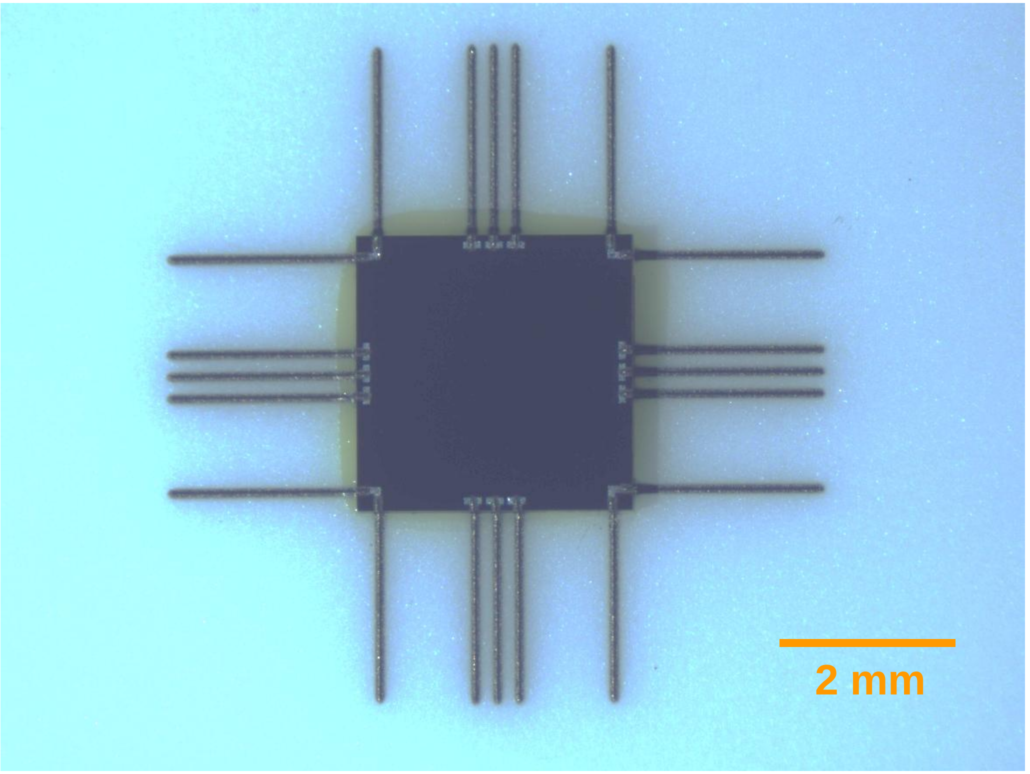


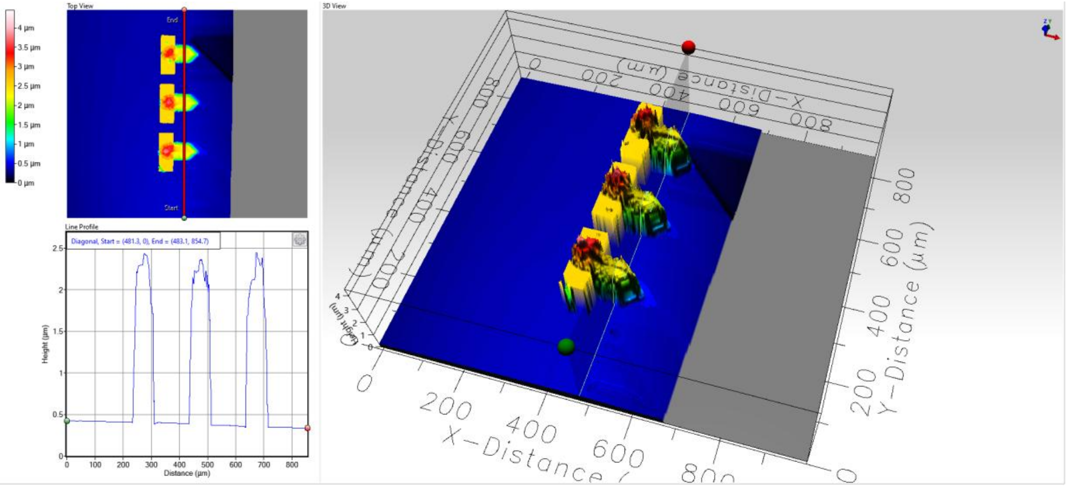
4-point result:

Line Resistance = 5.5 Ω
Contact Resistance = 2.2 Ω
Total Resistance = 9.9 Ω

Contact resistance is comparable to line resistance

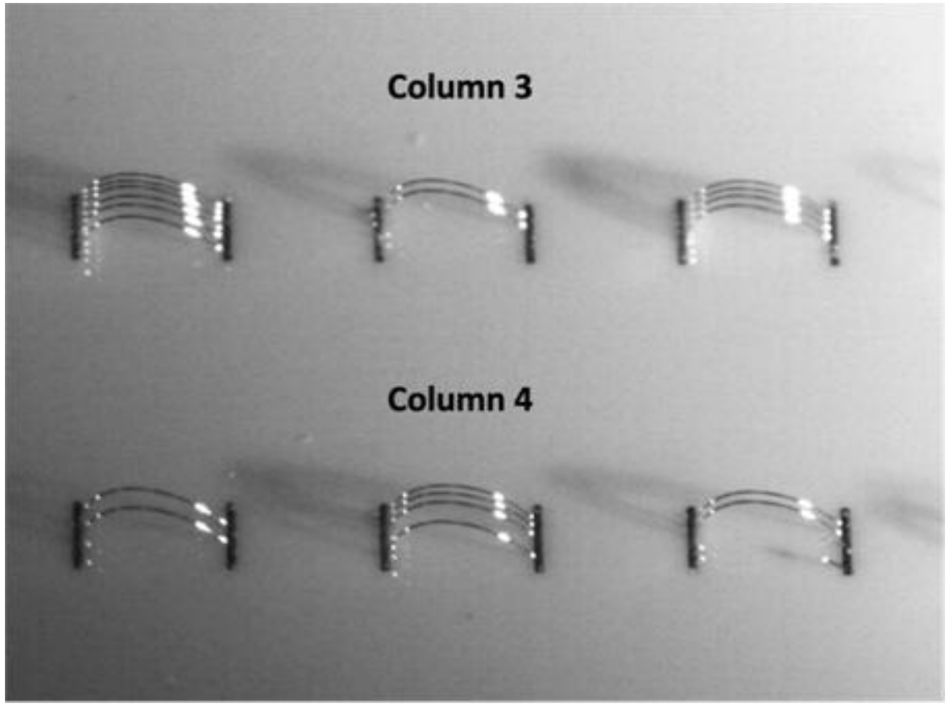
3D Connects to Aluminum Pads

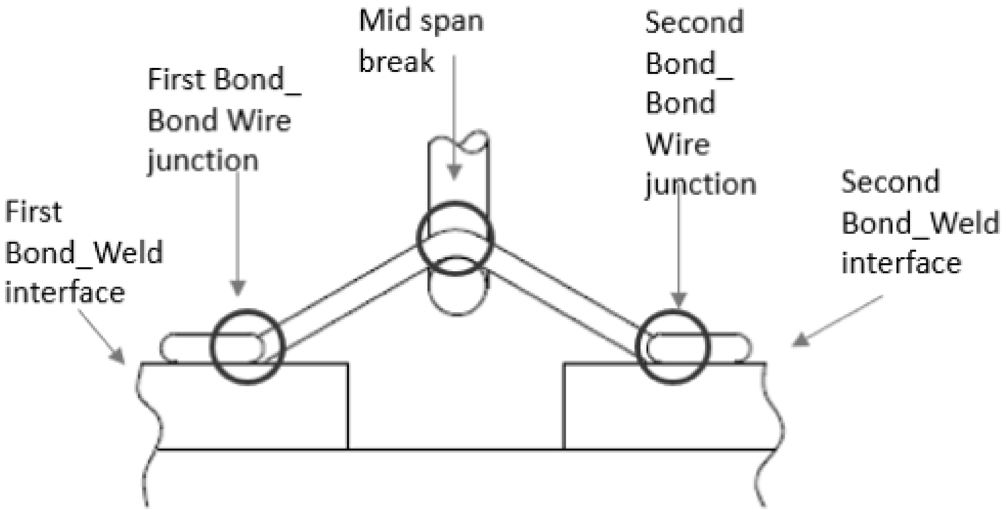




Total resistance = 5 Ohms
Contact resistance = 2 Ohms

Wirebonding to Gold





	Test No.	Force		Min. Accept Force	Grade Code	Grade Description	Result
33-37 A 1	1	5.194 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
33-37 B 1	2	6.002 gf		2.500 gf	4	Failure in bond at substrate, package post, or other than die.	Pass
33-37 C 1	3	5.296 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
35-39 A 1	4	5.150 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
35-39 B 1	5	4.328 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
41-45 E 1	6	3.088 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
41-45 F 1	7	2.770 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass
41-45 G 1	8	4.086 gf		2.500 gf	9	Break in wire at neckdown on the substrate or package post.	Pass

- **Gold ink (Dupont QR150) printed on alumina and high fired (850C, 30 mins)**
- **Aluminum ribbon bonds to gold pads**
- **Pull test to determine bond strength and failure mode.**

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Conclusions

- **Commercial Gold ink formulations optimized for Aerosol Jet.**
- **Feature sizes down to 10 um. 3D features to 25 um.**
- **Matching dielectric for mechanical support and insulation.**
- **Contact resistance to aluminum reduced by alkali clean**
- **Wire bonding to printed gold demonstrated**

Acknowledgement: NASA SBIR funding

Optomec System