Aerosol Jet Printed 3D Interconnects Enable Millimeter Wave Applications over 100GHz

OPTOMEC®
Production Grade 3D Printers... with a Material Difference

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Open Materials Platforms, Over 40 Suppliers Qualified

Over 500 Global Installs

Global Distribution Network

INTELLECTUAL PROPERTY

50+ Patents Issued
50+ Pending

125+ Employees

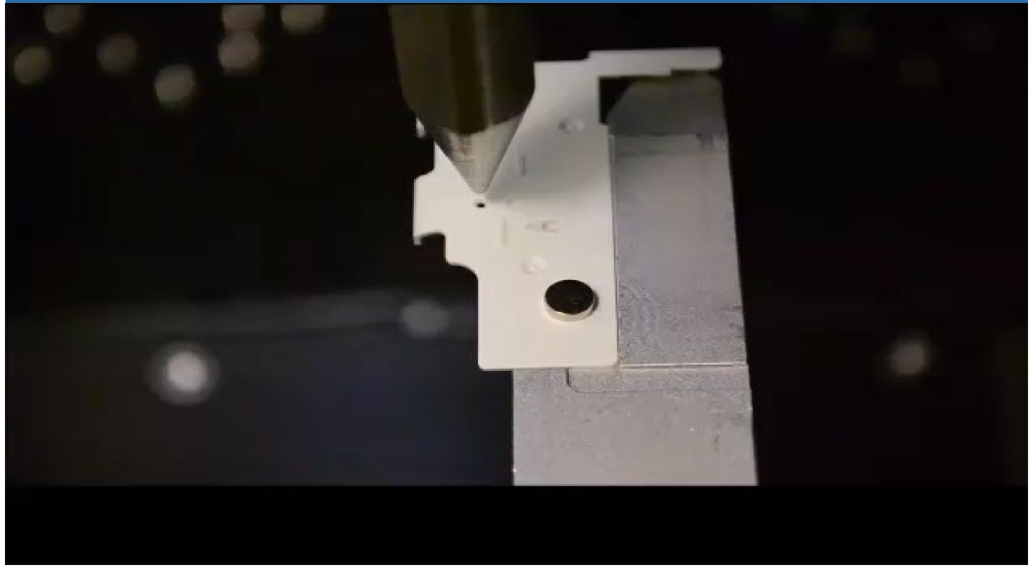
CONFIDENTIAL

Privately Held & Profitable

Key Technologies

Aerosol Jet®

- Functional materials digital printing (conductors, dielectrics, adhesives, ceramics, etc.)
- Printed feature size capability from microns to mm's
- Key capabilities in printed electronics



LENS®

- Structural metals printing (steel, stainless steel, titanium, copper-Brass, nickel super alloys)
- Printed feature size capability mm's to meters
- Key capabilities in part turbine blade repair, 3D printing, & general cladding applications

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Aerosol Jet Overview

INPUT

Low Viscosity nanoparticle and particle free inks

- Conductors, Insulators, Semiconductors

OUTPUT

Printed features as small as 10µm in width & as thin as 100 nanometers in open atmosphere

- High stand off from part (up to 5 mm)
- 2D / 3D conformal surface printing

COST & FUNCTIONAL ADVANTAGES

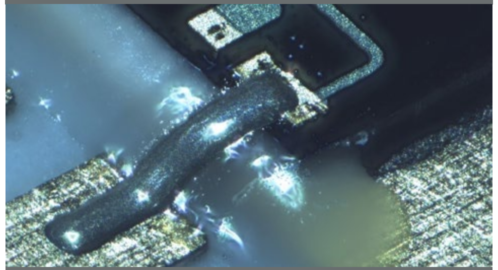
- Lower material and process costs
- Increased design freedom
- Performance advantage for RF devices

HIGHLY CAPABLE MACHINE PLATFORMS

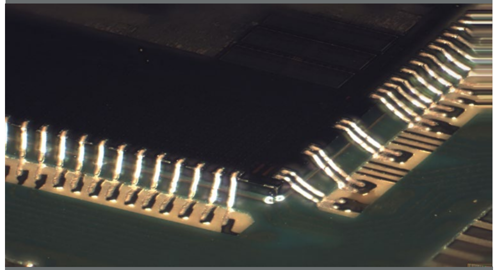
- Flexible for R&D use
- Low to medium volume production
- OEM print modules for integration

Contactless, Fine Feature Digital Printing Process

Printed Conformal Antenna

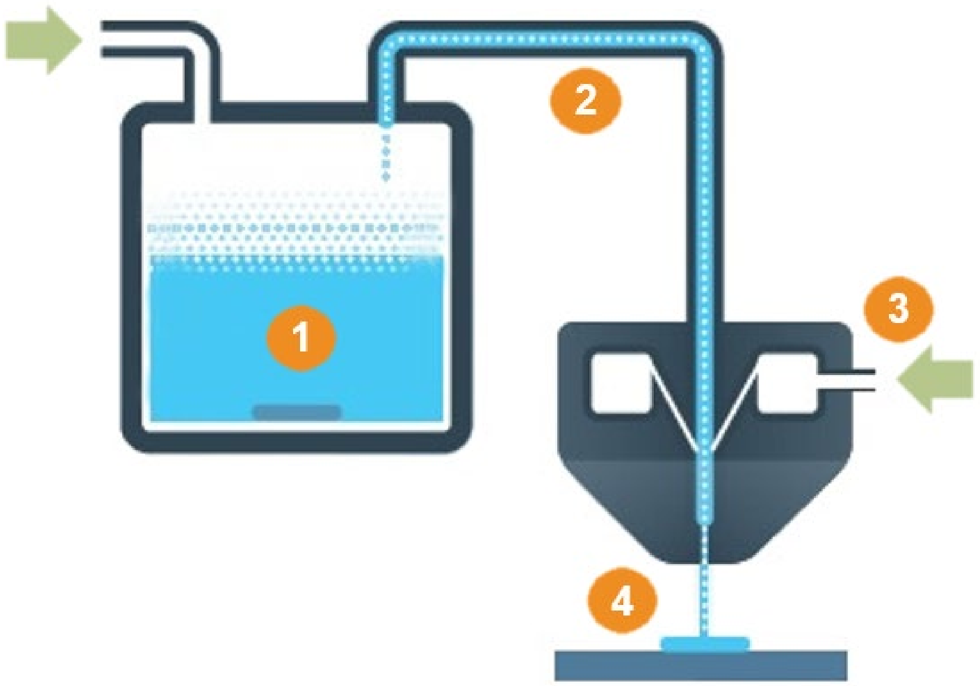


Hi Frequency Interconnects



Bond Wire Replacements

Aerosol Jet Technology Basics

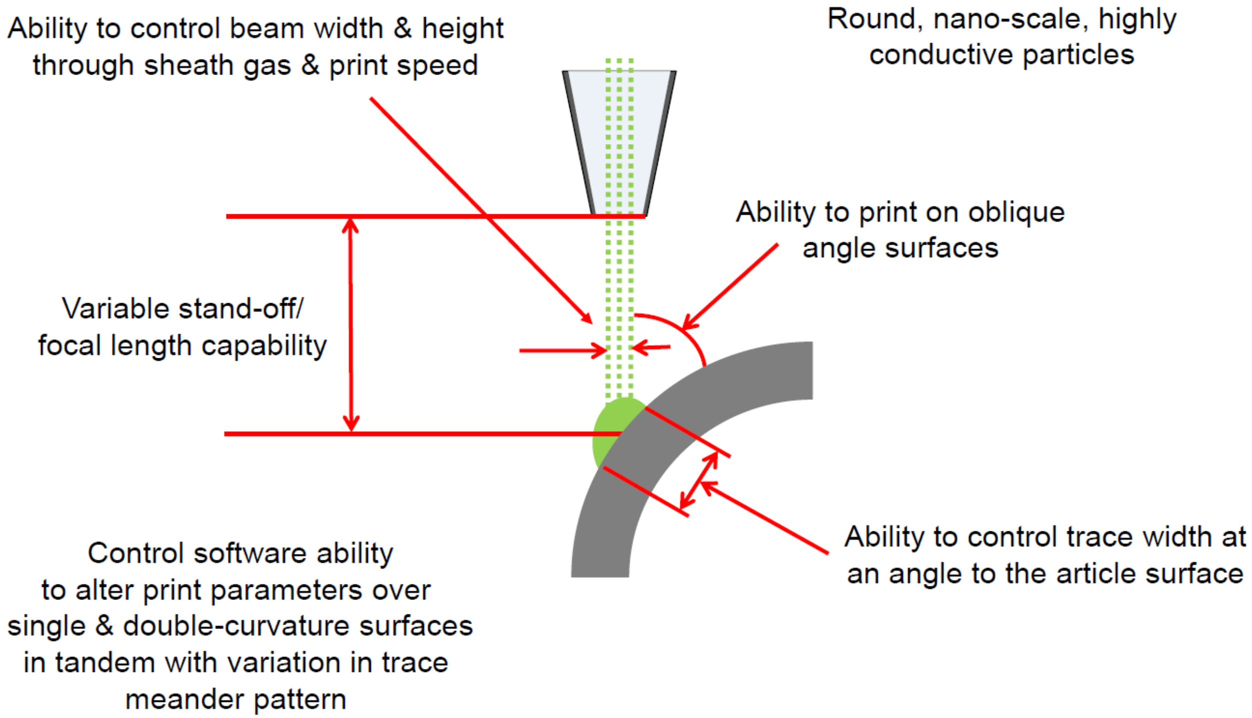


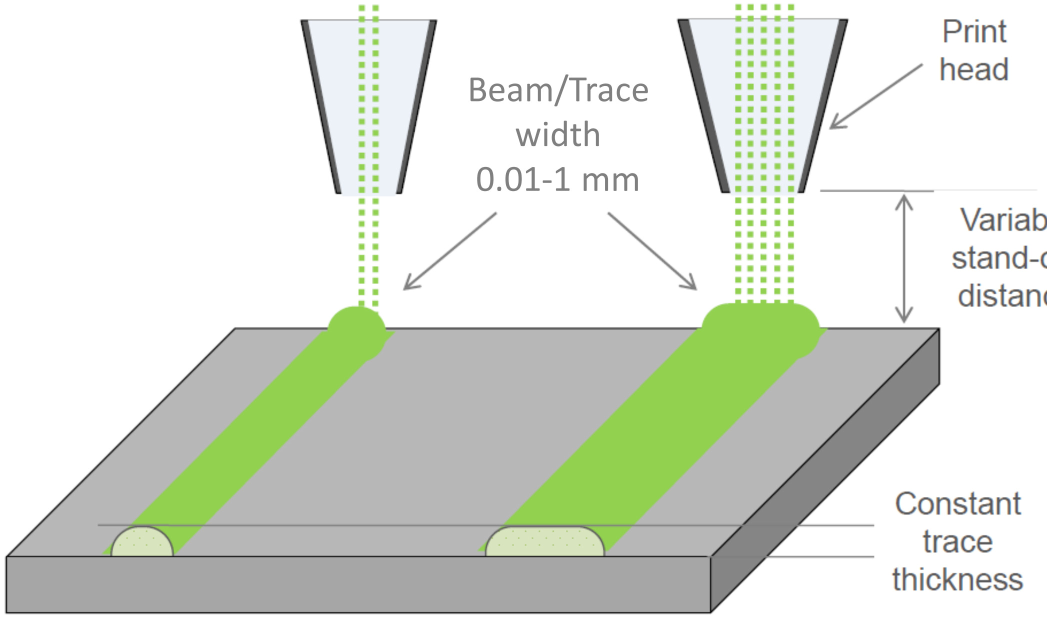
Planar

Non-Planar

1. Nanoparticle & particle free inks from 1-500cP are atomized into a mist of 2-5 µm droplets
2. Mist is carried from the atomizer to the print head using high purity nitrogen at low flows.
3. Mist enters print head where a sheath of nitrogen collimates & accelerates the mist through a converging nozzle orifice.
4. The mist beam, traveling at >50m/s, impacts both planar & non-planar substrates continuously, enabling a high stand off distance of up to 5 mm. The mist beam can be shuttered quickly to create discrete features.

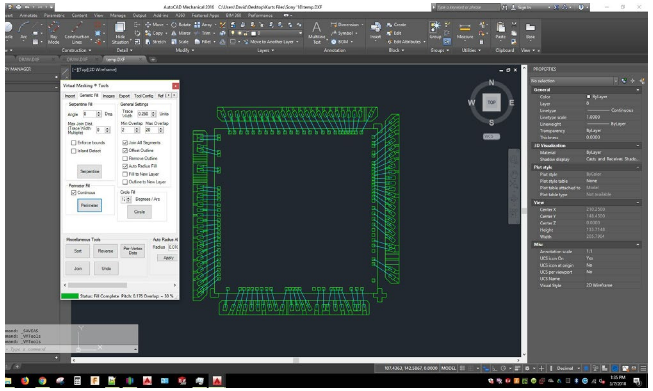
Aerosol Jet: Process Key Enablers





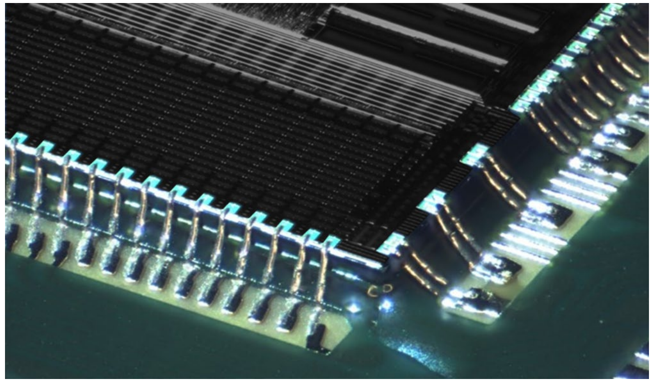
Printed Interconnect Design Process

Design



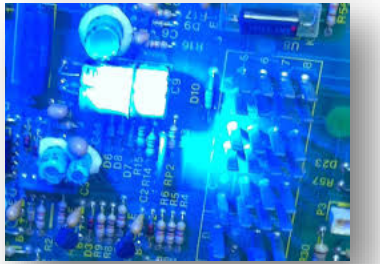
- Start with a .DXF (2D) or 3D CAD model
- Convert patterns and geometry to printing paths
- Toolpaths generated with AutoCAD plugin

Print



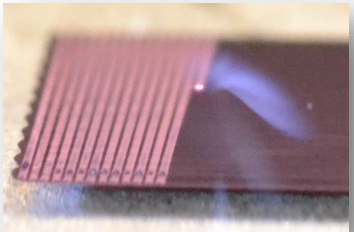
- Vision based alignment for micron accuracy & Repeatability
- Print part!

Post -Process



- UV cure polymers

- Laser sintering of metal inks



- Oven sintering & curing of metals and polymers

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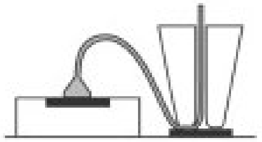
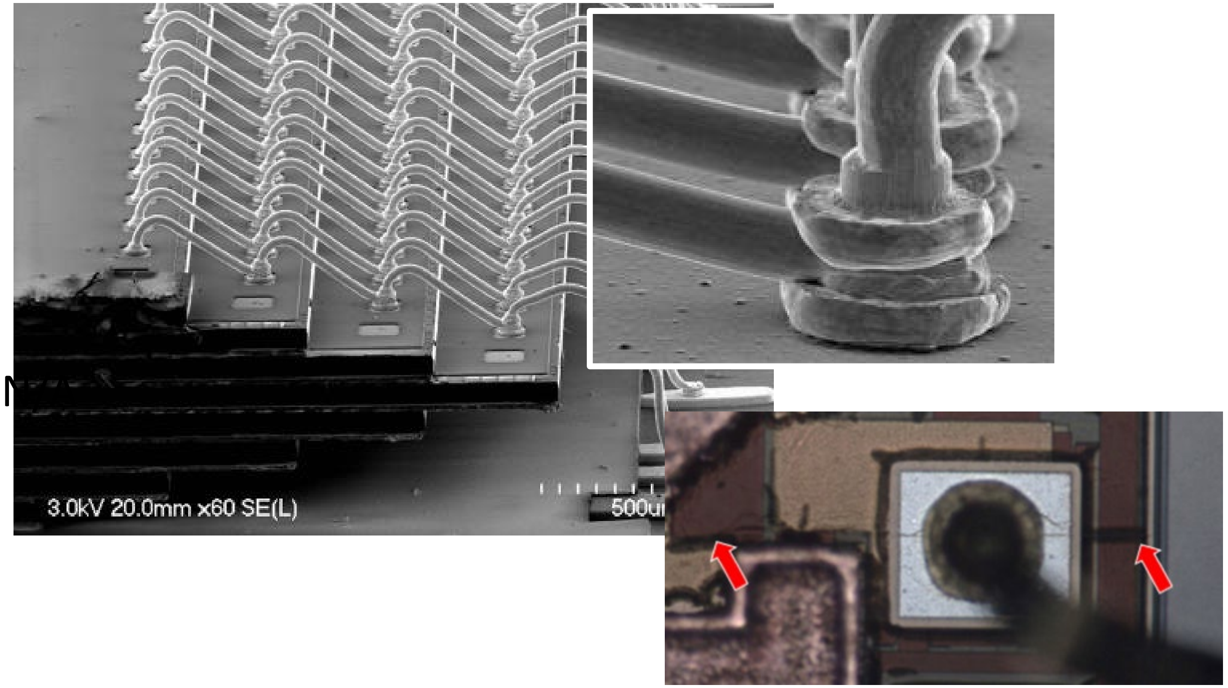
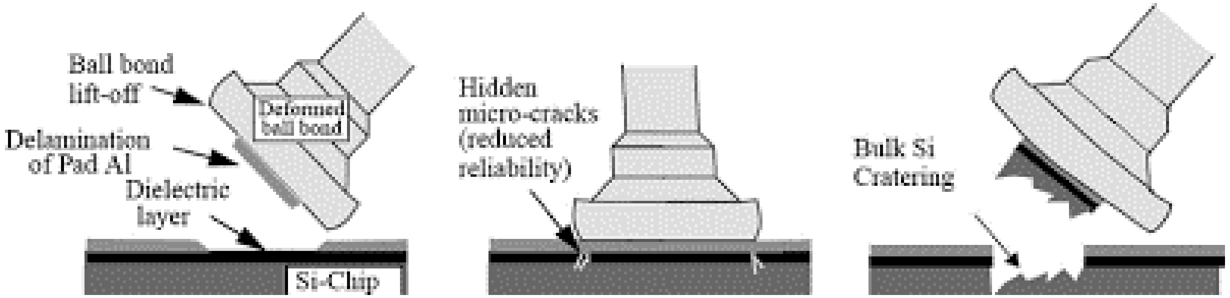
Aerosol Jet: Potential to Address Limits of Wire Bond

- Design Issues:
  - Excessive Loop Height
  - Lateral space claim
  - Reduced Active Area in Silicon

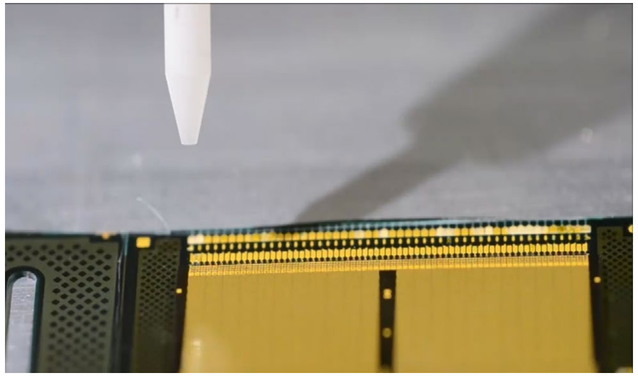


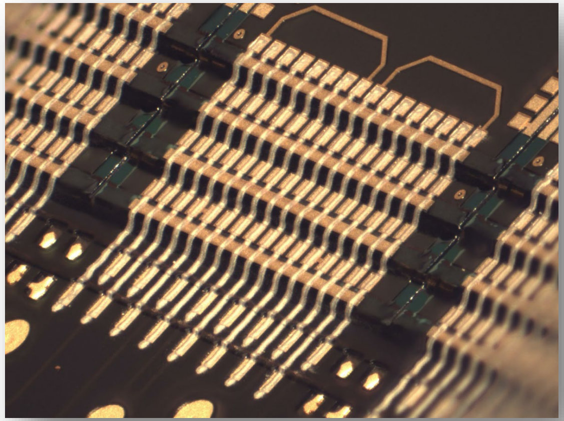
- Manufacturing Issues:
  - Impact Cracking of thin die
  - Multi-Step Bonding Process for Die Stacks
- Reliability Issues:
  - Mechanical Robustness
  - Corrosion leads to delamination at bond
- Operational Issues:
  - Cross Talk
  - Wire Inductance and tuning required for wide band high frequency applications





Aerosol Jet: Printed Interconnect Solution





Benefits Include:

- ✓ Zero bonding force, Zero loop height
- ✓ Maximize use of active silicon by reducing pad area
- ✓ Shorter, conformal wires for lower inductance
- ✓ Smaller, thinner packages

- Non-contact, room temperature process
- Optomec qualified commercial inks & pastes
- Scalable printed wire widths from 10um* to >1mm
- Print conformal to non-planar topologies & 3D surfaces
- 8 Hour MTTR for consistent production yield

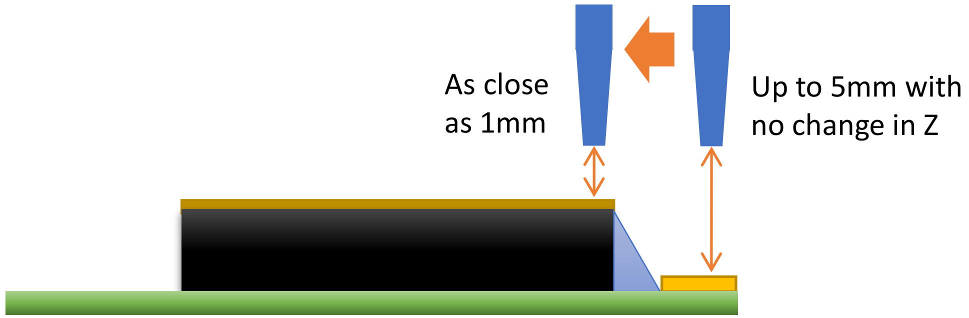
Jettable Inks & Compatible Substrates

Conductors	Dielectrics	Substrates
Silver (Primary)	UV Acrylics	**Glass**
Copper	Adhesives	**Polyimide**
Gold	Polyimides	**Silicon, GaAs**

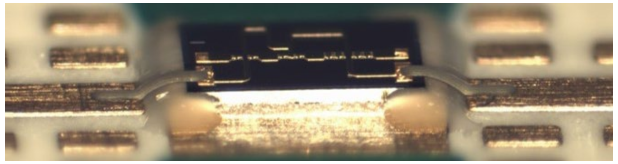
* Minimum feature size is Ink rheology dependent and not possible with all feature sizes. 20um is achievable with >90% of materials offered.

Capability: Interconnect Geometry

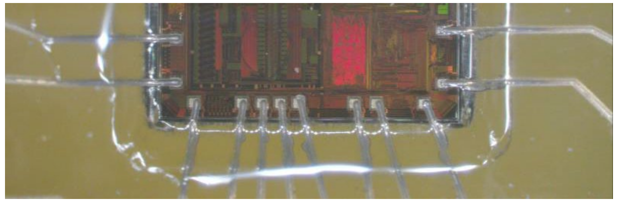
Interconnect thickness:	<1um to >10um
Interconnect length:	>10um to any
Interconnect Conductivity:	>2.9e-8 Ω*m
Printed Materials:	Ag, Cu, Au
Bond Pad Required:	ENIG, ENIPG, Cu



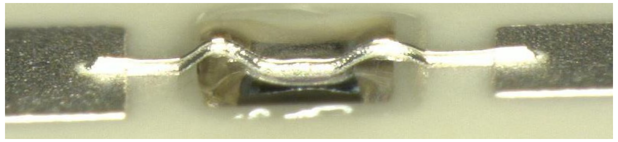
- Thick Die



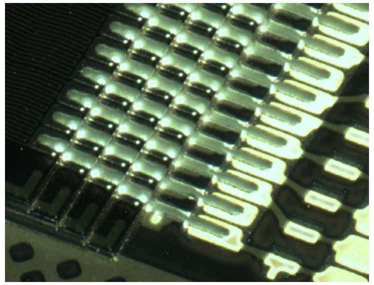
- Thin Die

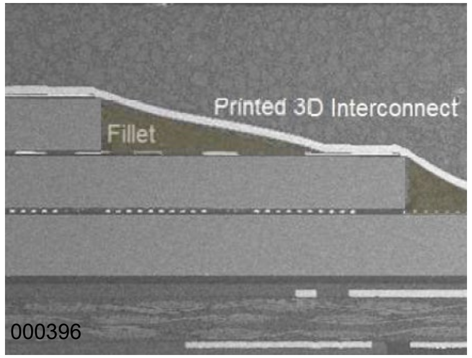


- Die in Trench



- Stacked Die



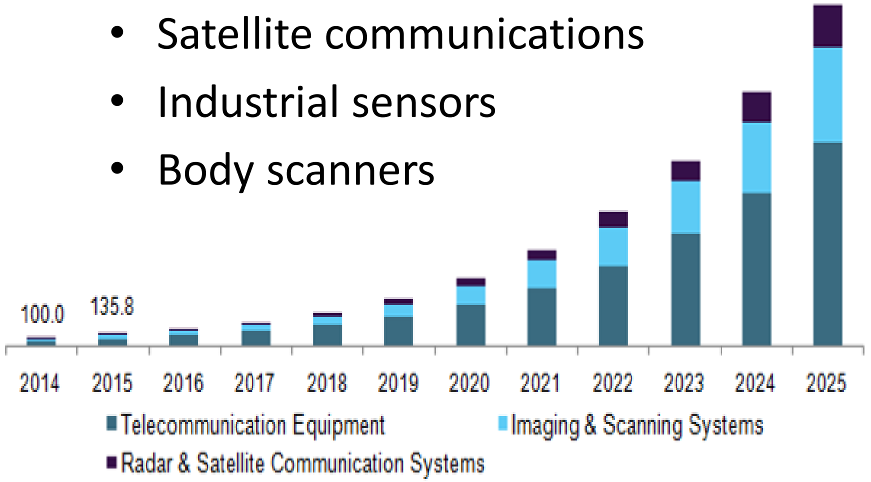


Interconnects can be printed over non planar substrates with 2D motion

Value for Emerging mm-Wave Applications

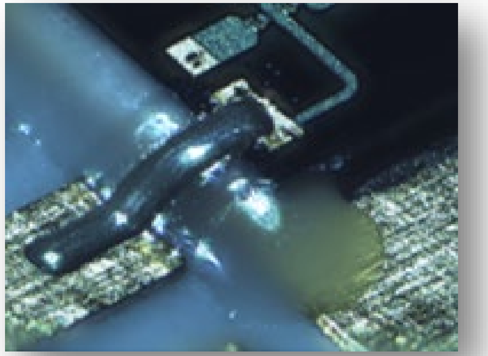
mm-Wave Applications Growing at >30%:

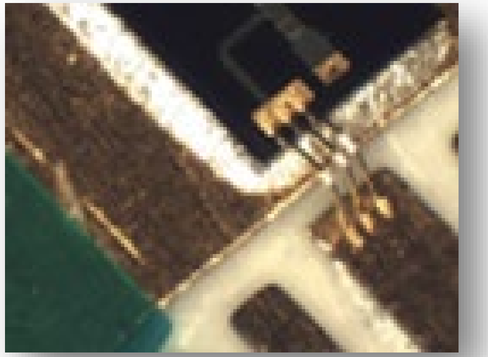
- 5G wireless communications
- IoT
- Automotive radar
- Military applications
- Medical devices
- Satellite communications
- Industrial sensors
- Body scanners



Aerosol Jet Advantages for mm-Wave:

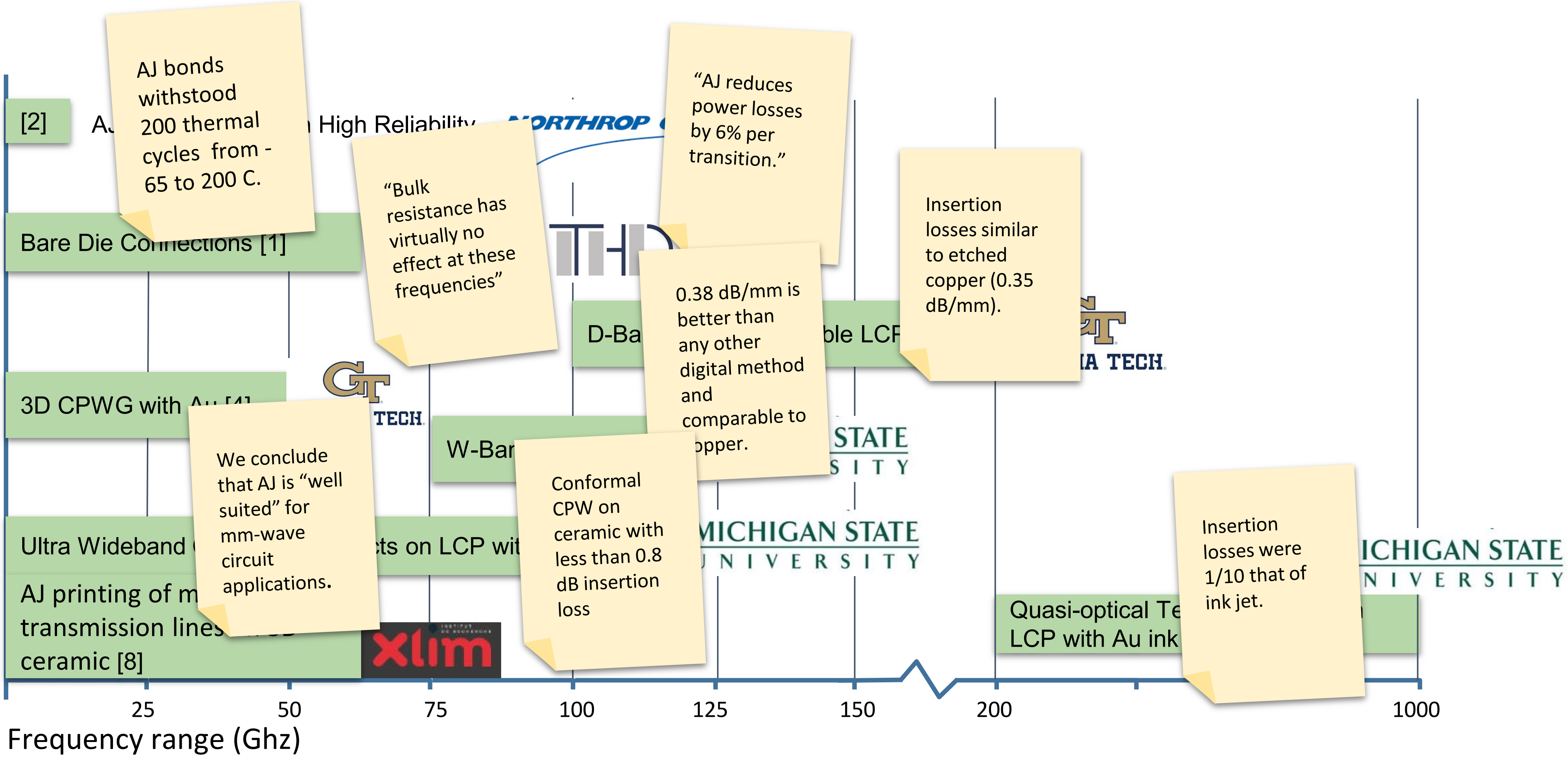
- Lower inductance for Lower Insertion Loss
- Lower Parasitics
- Lower cost bond pads vs. ENIPG
- Better RF stability over temperature than flip chip packages
- Single bond/pad vs. Multiple with Wires





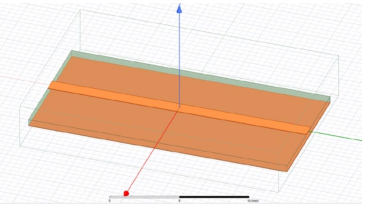
Power limiter with large AJ interconnect vs. Multiple Wires

Current Research with mm-Wave Interconnects

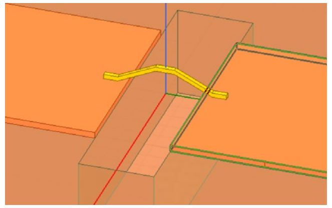


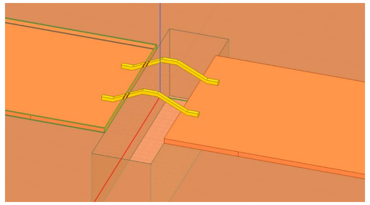
HFSS Simulation of Printed Interconnects vs Wire Bonds

½ oz. Copper reference line

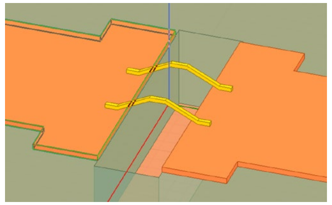


Single 1-mil gold bond wire



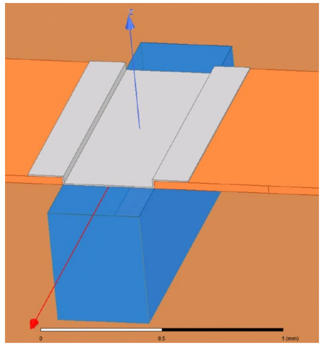


Dual 1-mil gold bond wire

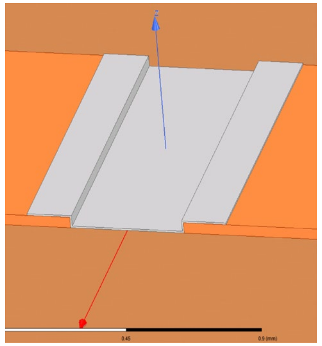


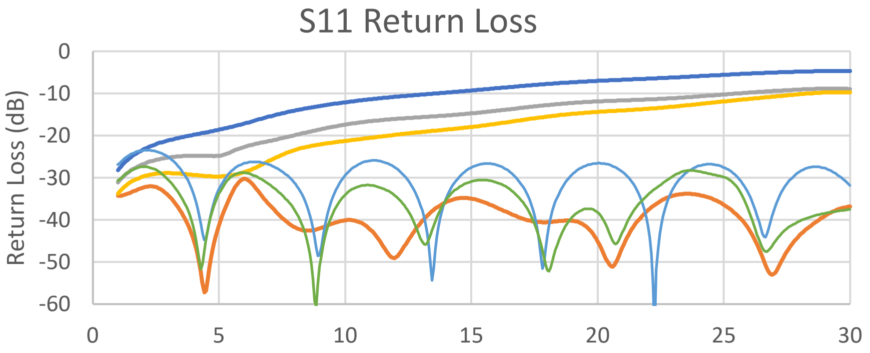
Dual Bond Compensated (minimal optimization)

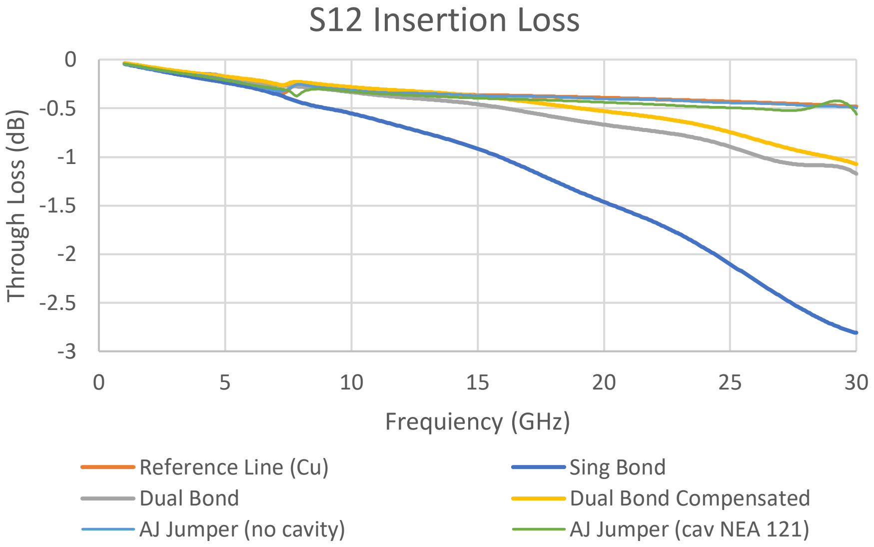
Printed Interconnect to fill break in microstrip over a dielectric filled trench



Printed Interconnect to fill break in microstrip







Printed Interconnects improved signal reflection & insertion loss for two different scenarios

No noticeable Insertion or return loss as frequency increases

Insertion loss closely matches that of ½ oz copper reference line

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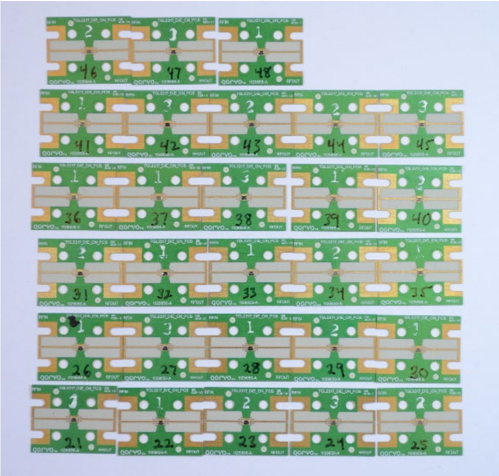
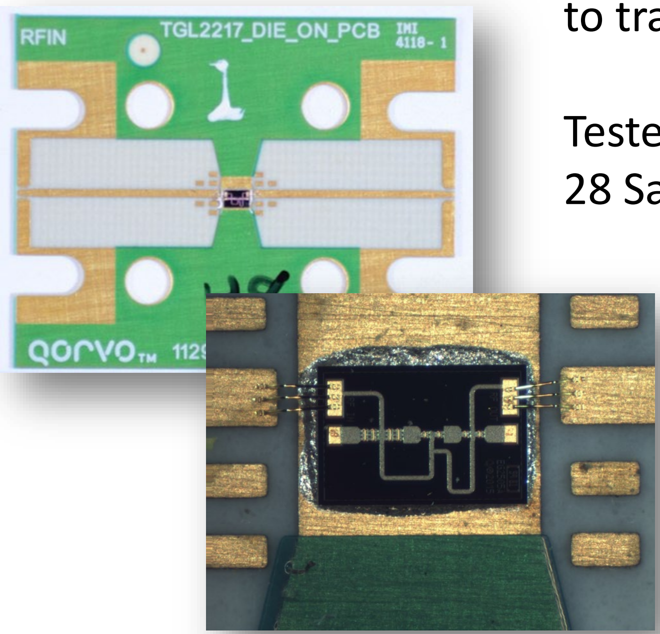
Measured Performance up to 20 GHz

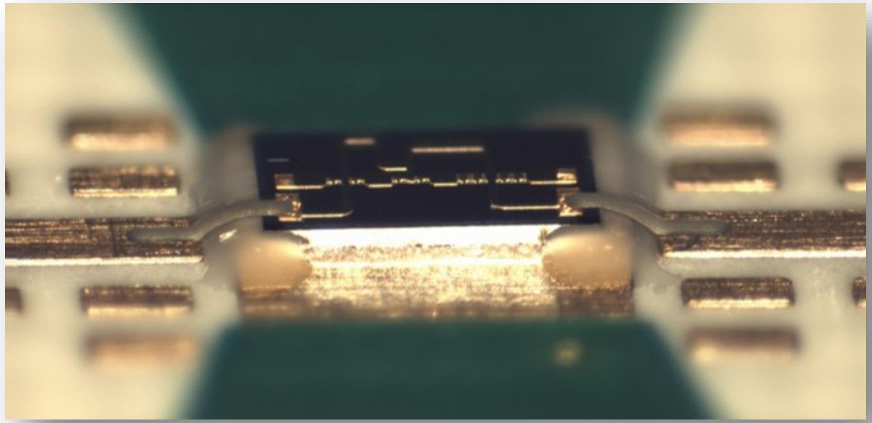
TriQuint Qorvo TGL2217 VPIN Limiter
0.1-20 GHz 10 Watt

Printed Interconnects directly compared to traditional wire bond techniques

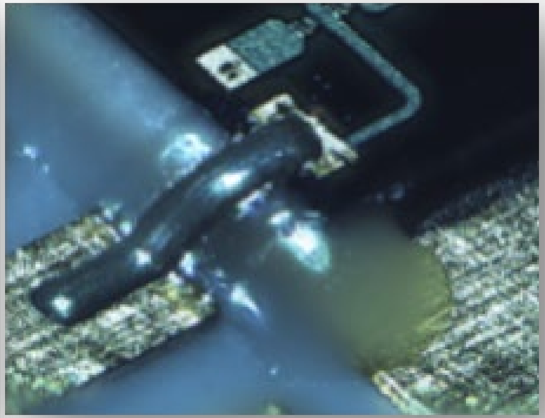
Tested up to 20 GHz
28 Samples



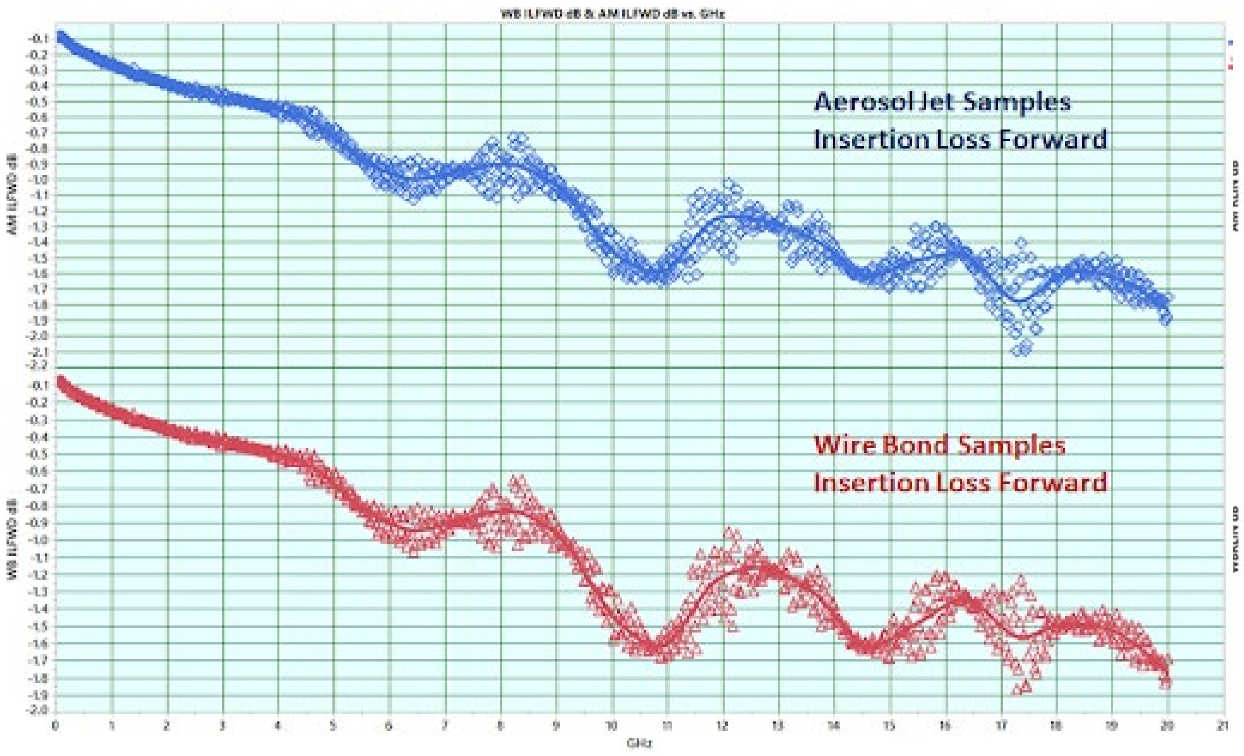


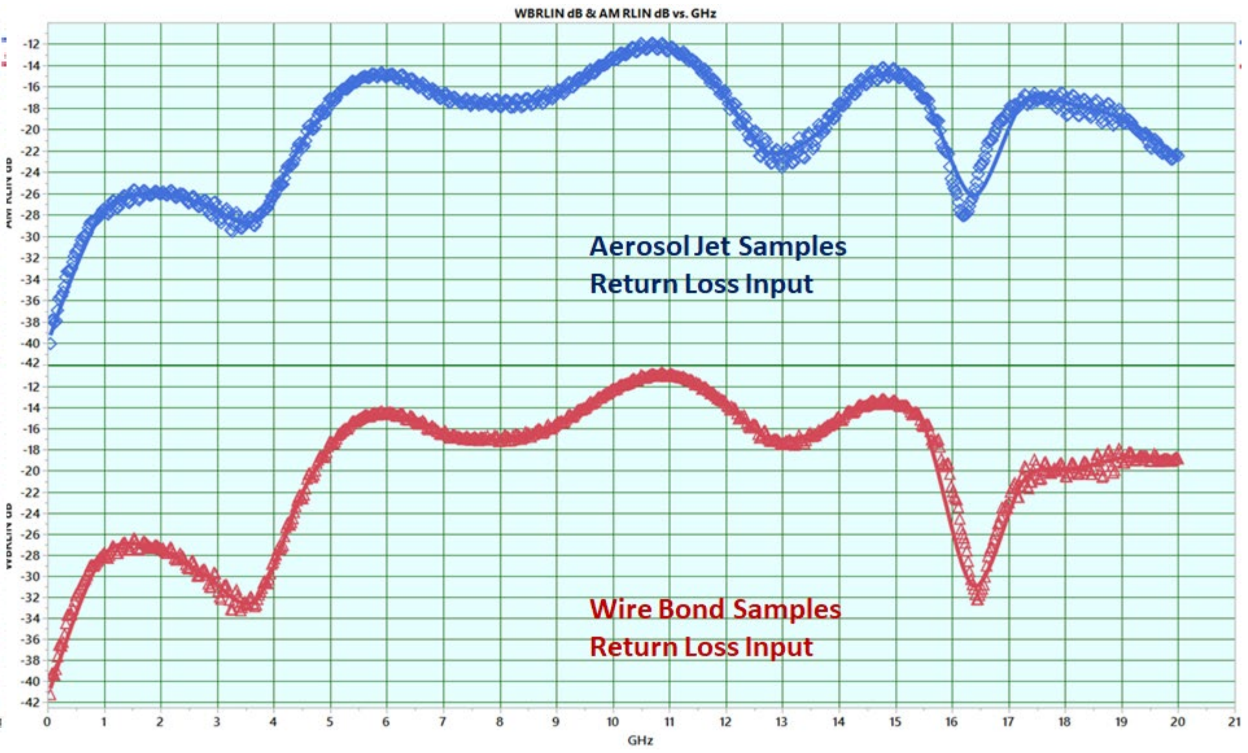


Aerosol Jet Printed Silver Interconnect over adhesive Fillet



Measured Performance up to 20 GHz

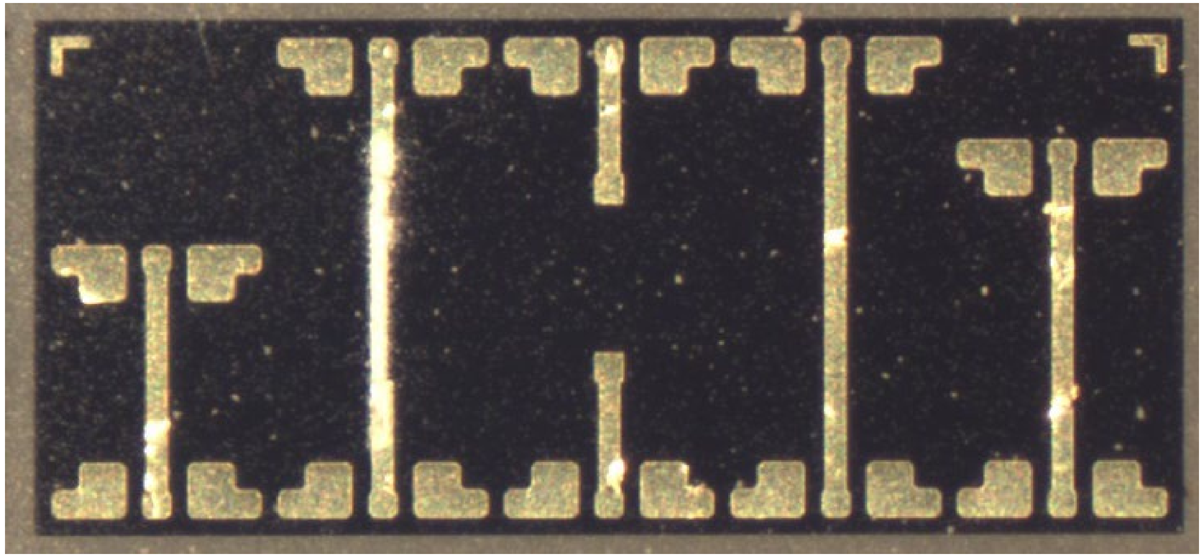




Network analyzer data collected from 0 to 20 GHz at 25 MHz Steps

Goal of test was equivalency to existing wire bond process

AJ Printed Transmission Lines Vs. Wire bonds.



A gap is printed over with a AJ printed line matching the width of the transmission line

Compare to:

- Wire bond over same gap
- A through line with no change
- Simulation

Aerosol Jet Printed lines were made with Henkel Loctite ECI-1011 Silver Ink.

A Frequency sweep from 0 to 110 GHz was done to measure S11, S21 loss performance

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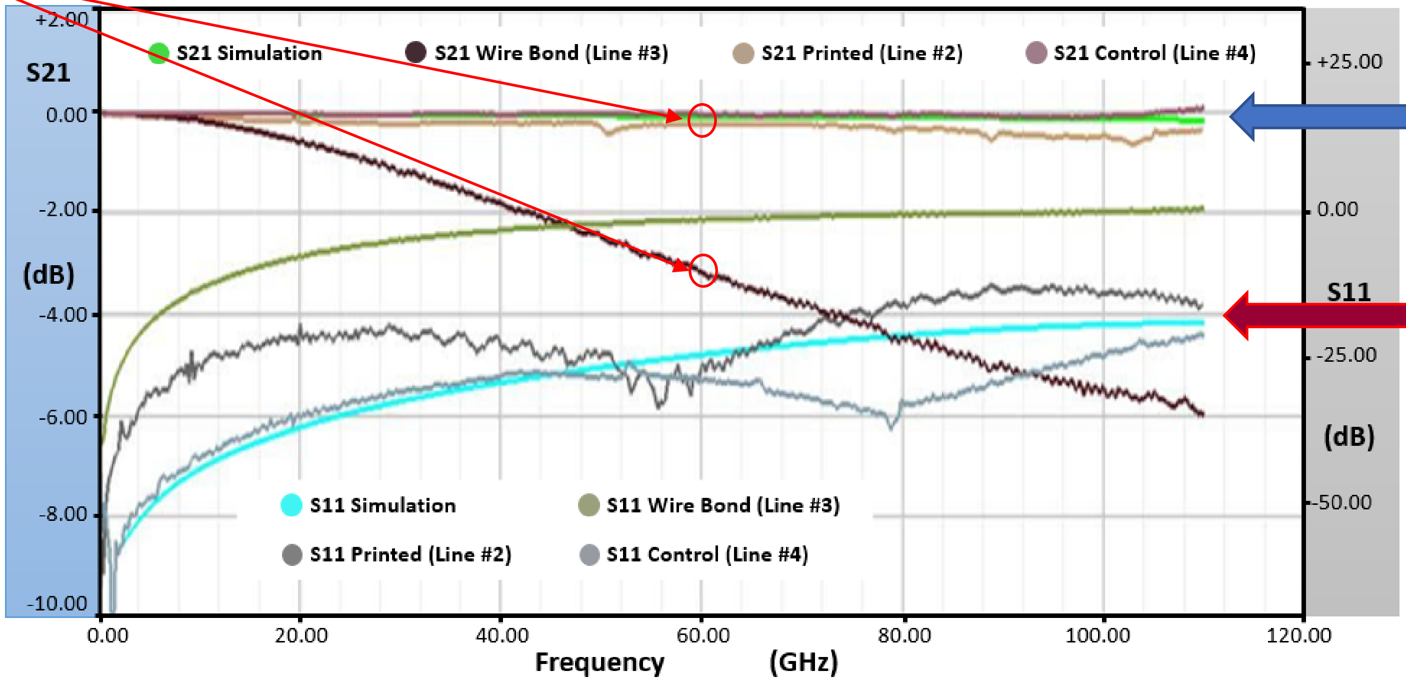
Measured Performance up to 110GHz

Micro Strip & Printed Interconnect
~3 dB lower S21
than Wire bond at 60 GHz

S21
"Return Loss"



S11
"Through Loss"

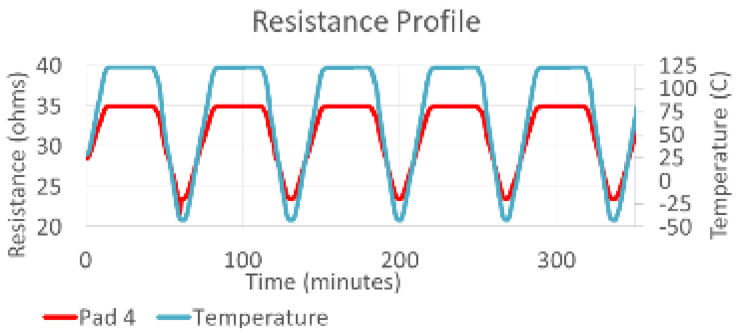
Printed Interconnect matches simulation & micro strip ("Near Zero Loss")

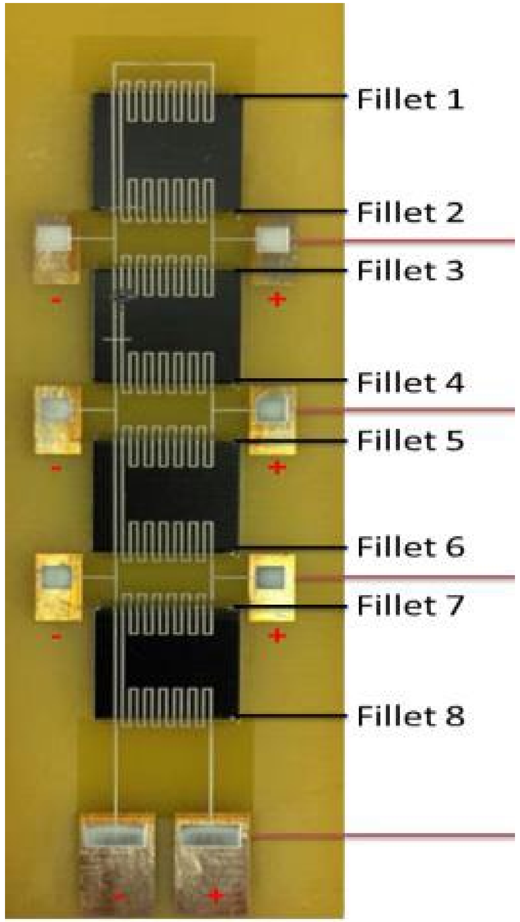
Wire Bond shows 6dB S21 loss up to 110 GHz vs <0.5dB loss with Interconnect

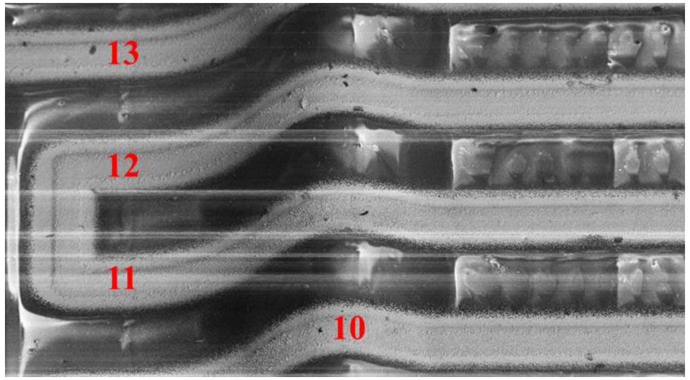
Thermal Cycling of Filleted nAg-Ink Traces over Silicon Die

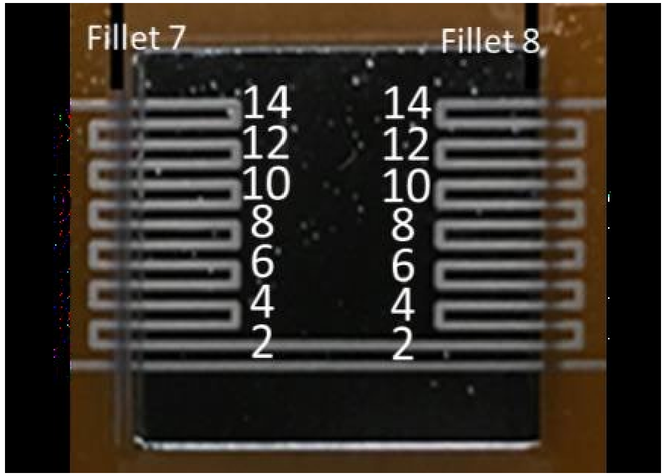
Thermal Cycle Test Results:

- A test sample consisting of blank Silicon die with UV Curable fillets (NEA-121) and printed nAg lines in a serpentine pattern overlapping onto the die.
- 200 Cycles (-40 to 125°C) with zero failures
- Follow up testing with different inks exceeded 1000 cycles with zero failures.



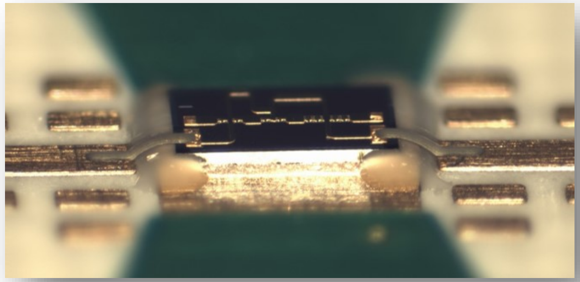


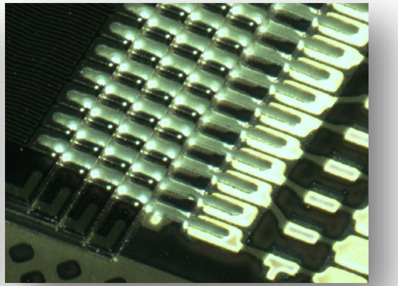




Key Take-Aways for Aerosol Jet for Printed Interconnects

- Reduce size, power & weight of devices with printed 3D Interconnects
- Capability for dramatically improved performance of interconnects with signal loss performance approaching copper clad transmission lines
- Printed 3D interconnects are proving reliable for a wide variety of applications.
- Optomec's printed interconnect solution and machine platforms are well suited for low to high volume production of packaged devices





Thank You for Your Time & Attention!

Bryan Germann

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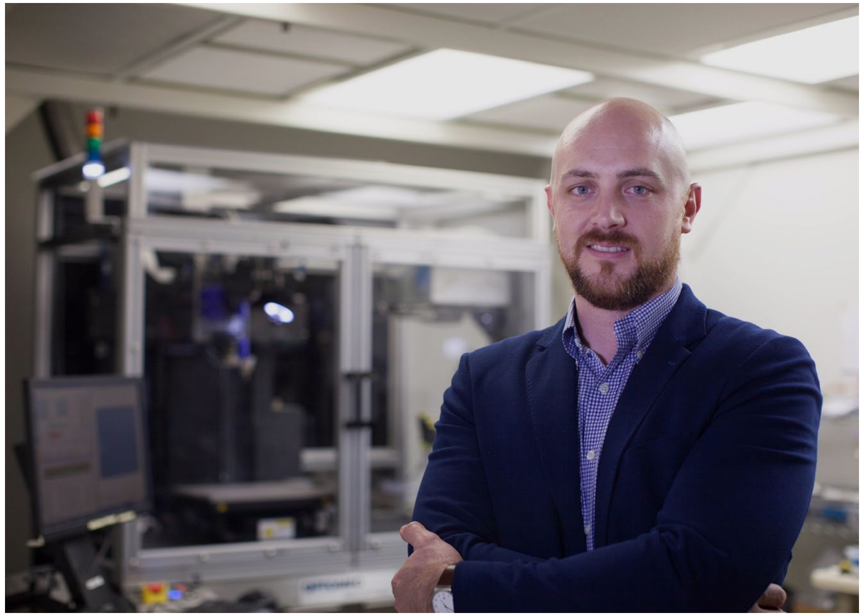
Find me on Linked IN!



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References

[1] Franz Xaver Rohrl et al, Technische Hochschule Deggendorf, “Bare Die Connections via Aerosol Jet Technology for Millimeter Wave Applications”

[2] X. Lan et al, Northrup Grumman Corp., “AJ Printed Functional Nanoinks with High Reliability and Reconfigurability”, 2017.

[3] Fan Cai et al, “High Resolution Aerosol Jet Printing of D-Band Printed Transmission Lines on Flexible LCP Substrate, Georgia Institute of Technology”

[4] Fan Cai et al, “3D Printing for Multilayer Passive Microwave Circuitry, Georgia Institute of Technology”

[5] Michael Craton et al, “Realization of Fully Printed W-Band Bandpass Filters using Aerosol Jet Printing Technology”, Michigan State, AGH University, Krakow, Poland.

[6] Jubad Abdul Qayyum et al, “Ultra Wideband 3D Interconnects using Aerosol Jet Printing up to 110 GHz, Michigan State”.

[7] Christopher Oakly et al, “Aerosol Jet Printed Quasi-Optical Terahertz Filters”, 2017.

[8] Anthony Delage et al, “Aerosol Jet printing of millimeter wave transmission lines on 3D ceramic substrates made by additive manufacturing”, Limoges, France. IEEE, 2018.

[9] Xing Lan et al, “Direct On-chip 3D Aerosol Jet Printing with High Reliability” IEEE Transactions on Components, Packaging & Manufacturing Technology, Vol 7, NO. 8, August 2017.