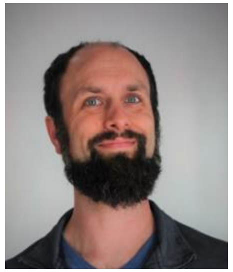
Heterogeneous Integration Roadmap Symposium 2023

Additively Manufactured Electronics (AME) for Heterogenous Integration

Kris Erickson

Meta

Feb 23, 2023



Kris Erickson
(Meta)

Eric Dede
(Toyota Research Institution of North America)

HIR
HETEROGENEOUS INTEGRATION ROADMAP

Jarrid Wittkopf
(HP Labs)

Dishit Parekh
(Intel)

Alex Cook
(Nextflex)

Jeroen van den Brand
(Holst Center)

Annette Teng
(Promex)

David Bowen
(Laboratory for Physical Sciences)

Mark Poliks
(Binghamton U)

Martin Hedges
(Neotech AMT)

Benson Chan
(Binghamton U)

William Chen (ASE)

IEEE | IEEE photonics Society | semi | IEEE ELECTRONICS PACKAGING SOCIETY | ASME | ELECTRON DEVICES SOCIETY

Topics

Additively Manufactured Electronics (AME) for Heterogenous Integration (HI)

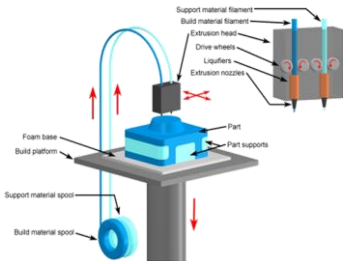
{Comparison to previous content as part of Ch. 8 – Single Chip & Multi Chip Integration}

1. AME for HI – Overview *{expanding scope}*
2. AME Manufacturing Methods *{expanding methods}*
3. AME Materials *{expanding coverage & comparisons}*
4. AME Applications *{covering - Photonics; Antenna; Thermal; Flex/Stretch}*
5. AME Design Tools *{adding}*
6. Target Metrics & Roadmap *{expanding metrics; adding roadmap}*
7. Cross-TWIG Collaboration *{adding – Medical, Health; Thermal; Photonics; more!}*

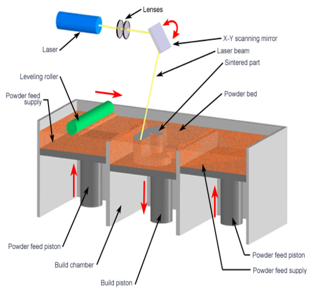
HIR
HETEROGENEOUS INTEGRATION ROADMAP

Additive Manufacturing Methods

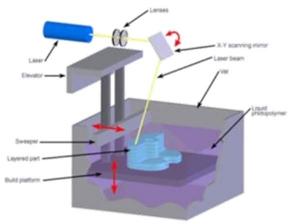
Fused Deposition Modeling (FDM)



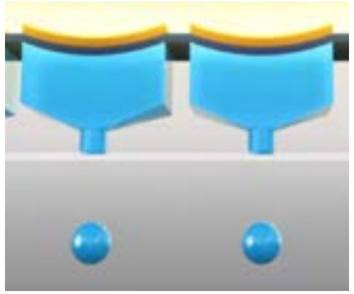
Powder Bed Fusion



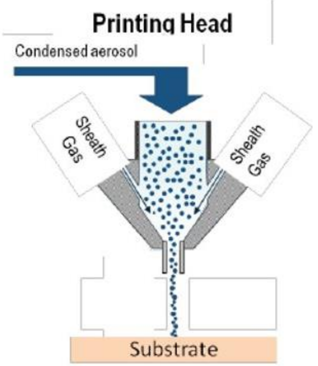
Stereolithography



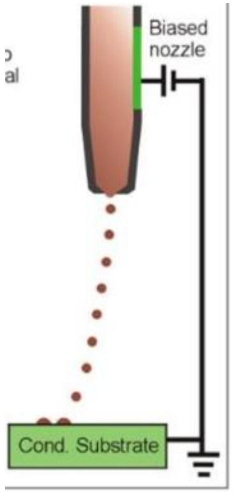
Inkjet Printing



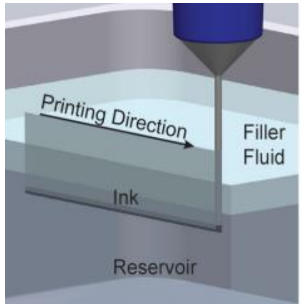
Aerosol Jet Printing



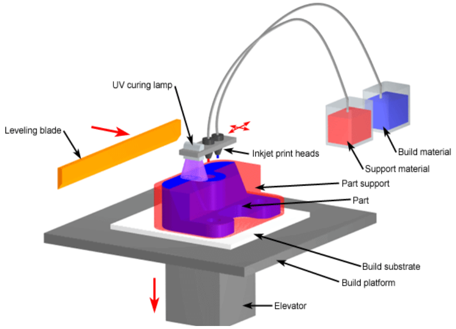
Electro-hydrodynamic Printing



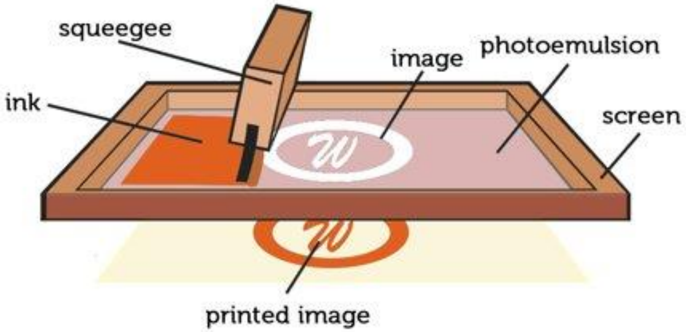
Direct Write (DW)



Resin Jetting



Screen printing



[HIR 2021 version (eps.ieee.org/hir), Ch. 8, Single and Multichip Integration]

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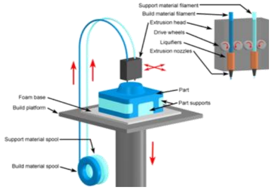
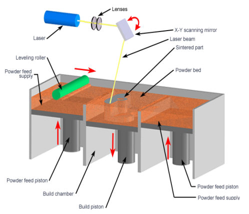
Additively Manufactured Electronics (AME) for Heterogenous Integration

Additive Manufacturing Methods

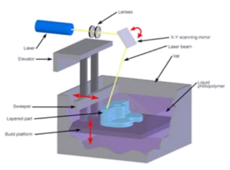
Fused Deposition Modeling (FDM)



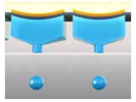
Powder Bed Fusion



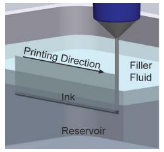
Stereolithography



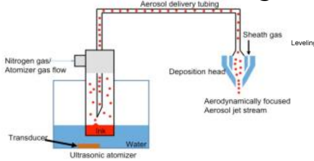
Inkjet Printing



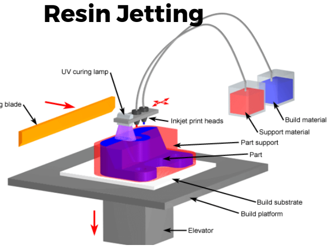
Direct Write (DW)



Aerosol Jet Printing



Resin Jetting



[HIR 2021 version (eps.ieee.org/hir), Ch. 8, Single and Multichip Integration]

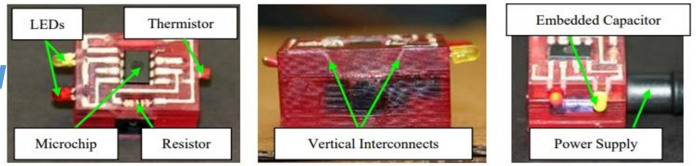
Combine Multiple

Plus additional processes, i.e. Pick & Place

Additive Electronics Methods

Examples

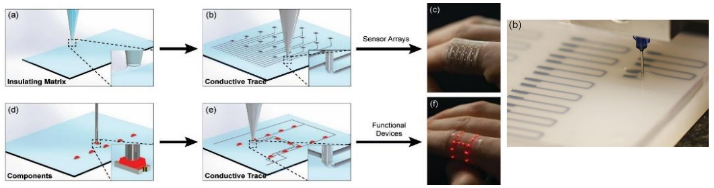
MacDonald Group



SLA + Pick and Place Components ***And*** *FDM + Machining + DW + P&P*

[D. Espalin, E. MacDonald. Int J Adv Manuf Technol ***72****, 963–978 (2014)]*

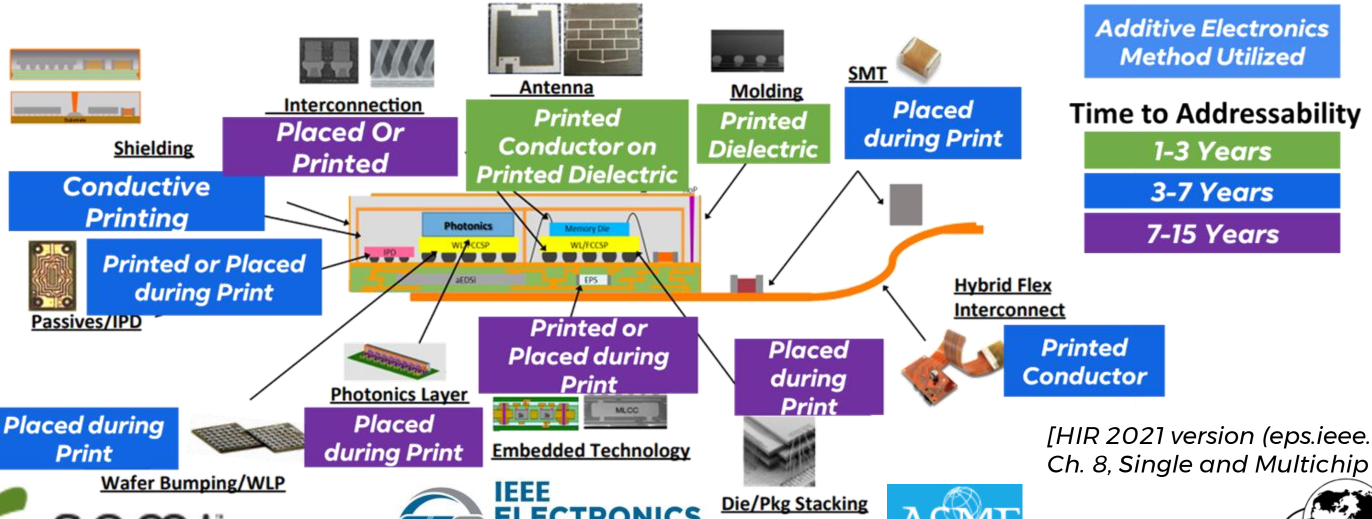
Jen Lewis Group



Curable Elastomer Resin + DW Ag + P&P

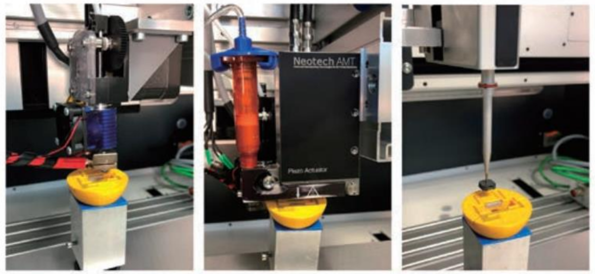
[J. Muth, J. Lewis. Adv. Mater. 2014, 26, 6307–6312]

Emerging SiP/HI Solutions



[HIR 2021 version (eps.ieee.org/hir), Ch. 8, Single and Multichip Integration]

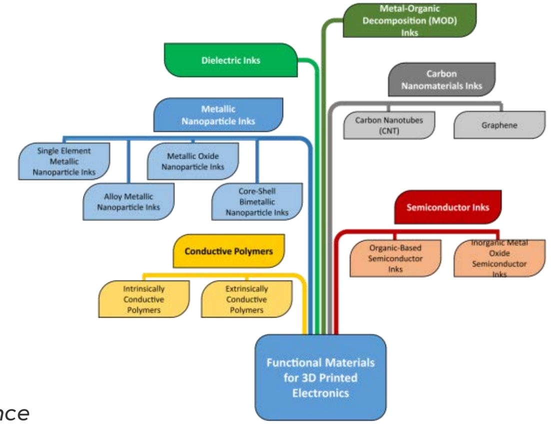
AME need for HI impact -
Concerted Advances from all for Market Success



[M. Ankenbrand, M. Hedges. 2019 International Conference on Electronics Packaging (ICEP), 2019, pp. 273-278]

Manufacturing Methods

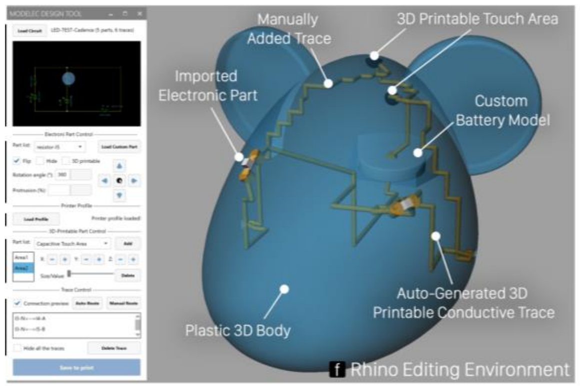
+



[H. Tan, C. Chua. Progress in Materials Science 127 (2022) 100945]

Materials

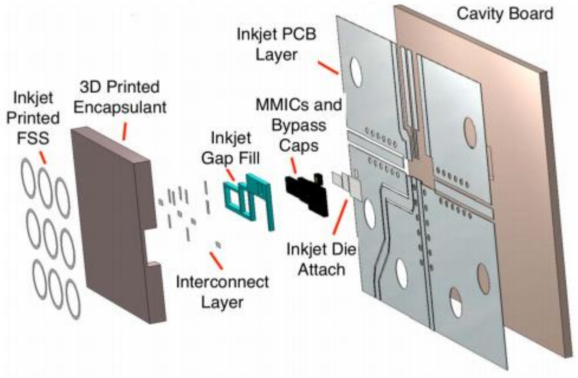
+



[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

Design Tools

+



[M. Tentzeris, et al. IEEE Trans Microwave Theory Tech., **2020**, 68, 2716-2724]

Application Development

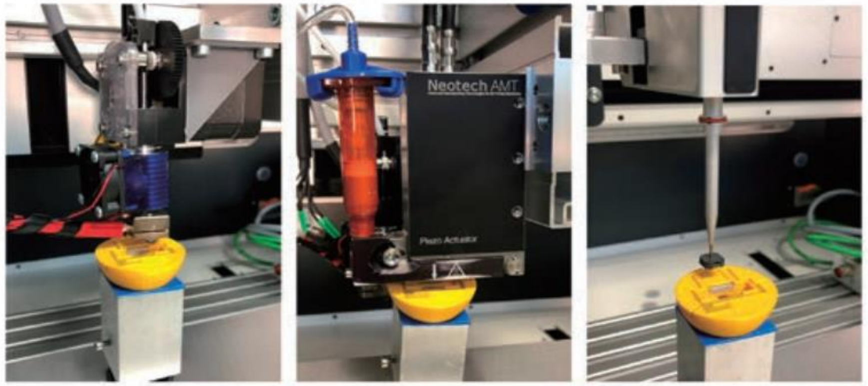
Fused Deposition Modeling (FDM) – based AME

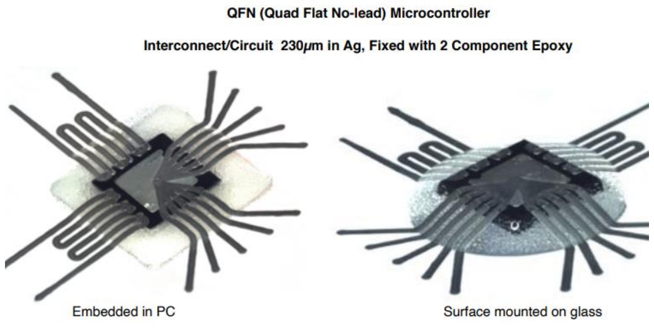
Neotech AMT

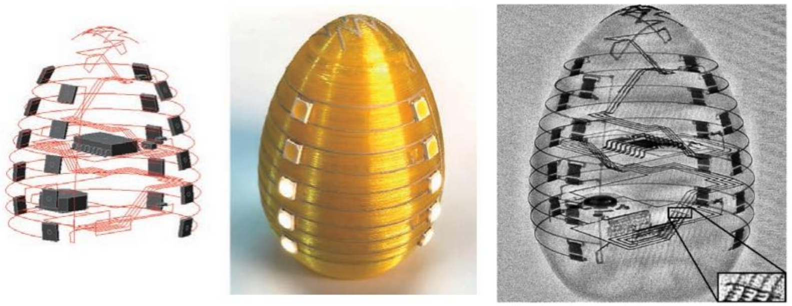
Combined, hybrid system

- FDM printing
- Direct write/Syringe
- 5-axis, Conformal Inkjet
- 5-axis, Conformal Aerosol Jet
- Laser sintering

FDM Inkjet P&P



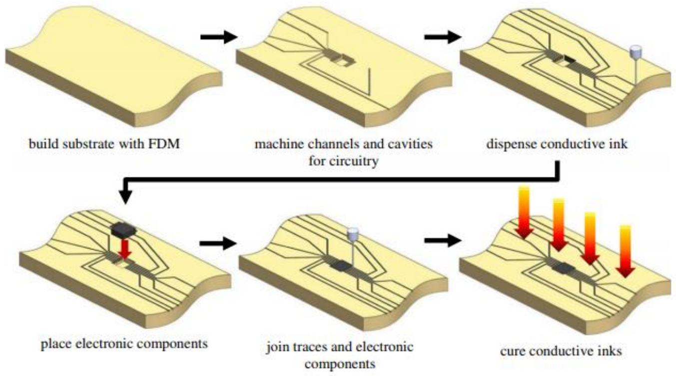


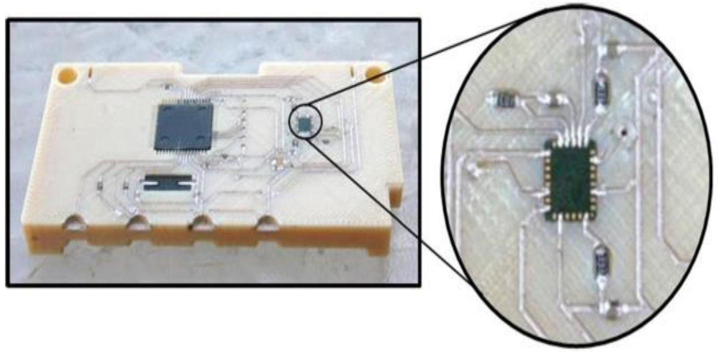


[M. Ankenbrand, et al. 2019 International Conference on Electronics Packaging (ICEP), 2019, pp. 273-278]

UT – El Paso

MacDonald Group



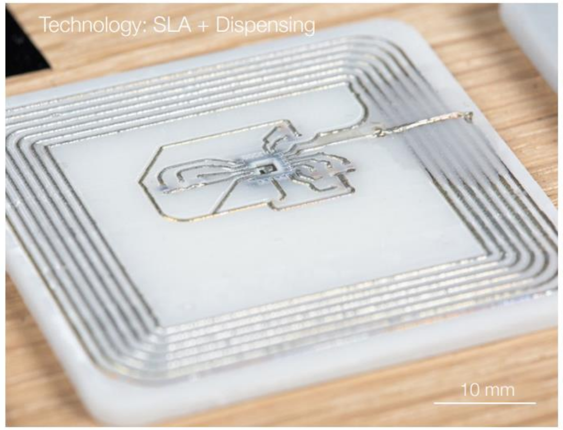


*[D. Espalin, E. MacDonald. Int J Adv Manuf Technol **72**, 963–978 (2014)]*

Stereolithography (SLA) – based AME

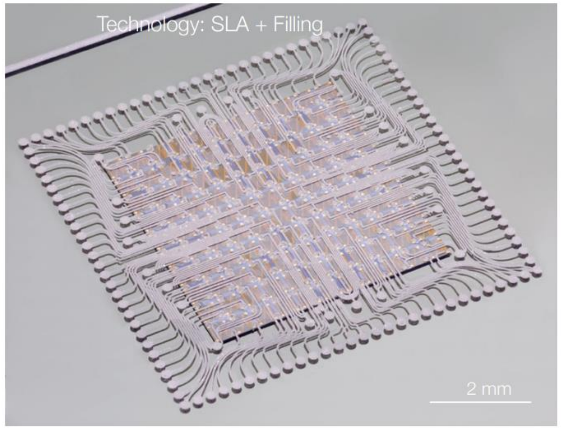
TNO Holst

SLA + Dispense



Self-harvesting NFC tag with temperature sensor

Modified SLA-Rake Process



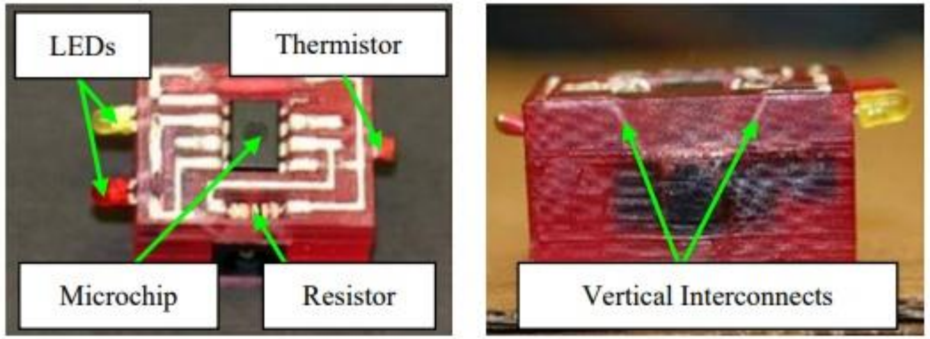
Fanout structure with 220 interconnects

[https://executivereport.holstcentre.com/innovation-updates/enabling-technologies/3d-printed-electronics/]

UT – El Paso

MacDonald Group – Keck Center

SLA, DW + Pick and Place Components

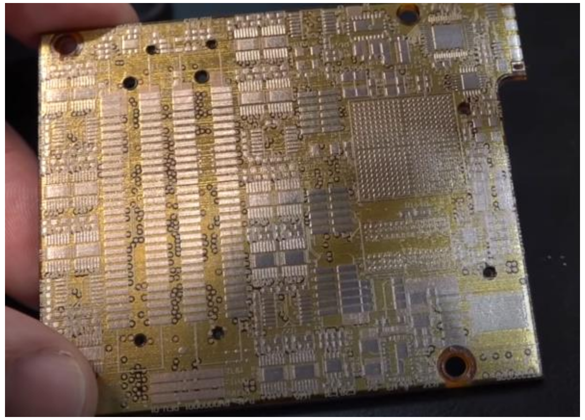


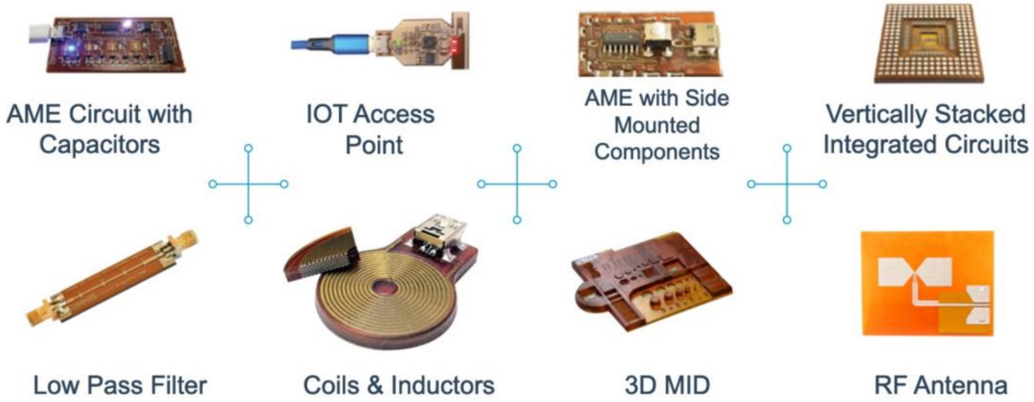
*[D. Espalin, E. MacDonald. Int J Adv Manuf Technol **72**, 963–978 (2014)]*

Inkjet-based AME

HETEROGENEOUS INTEGRATION ROADMAP

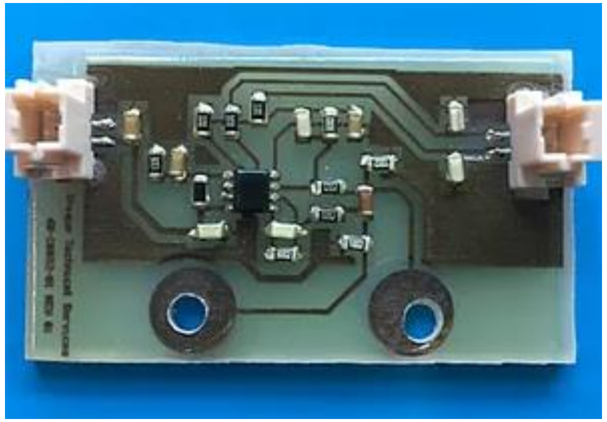
NanoDimension
Dragonfly

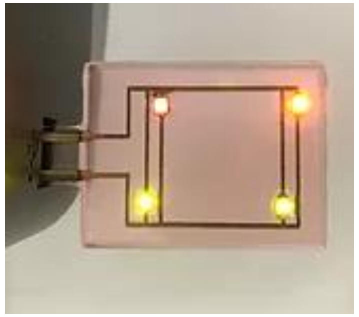




[https://www.nano-di.com/dragonfly-iv]

ChemCubed
ElectroJet





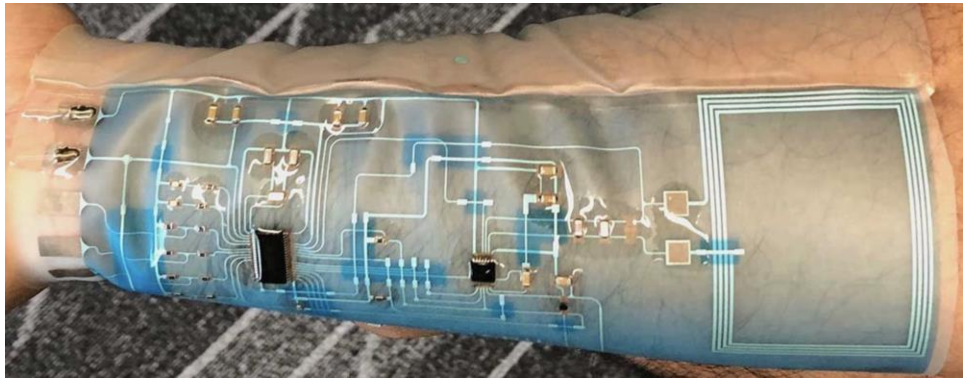
[https://www.chemcubed.com/electrojet]

Screen Print-based AME

HETEROGENEOUS INTEGRATION ROADMAP

Jabil

[https://www.jabil.com/blog/flexible-electronics.html]



Applied Materials

Tempo Presto PE Screen Printer

Screen Print Manufacturing System Developments

Leveraging Wafer Handling Expertise

- ***3 continuous line modules***
- ***High throughput***
- ***Printing repeatability of ±5 µm***
- ***Solar cell metallization (application)***

Loader
Slide Cassette Loader

Printer
Roto-centering Device & QR Code Reader
Alignment Cameras
Printhead
Electrical Integrity Check
Automated Optical Inspection
Profilometery

Unloader
Drying Unit
HMI
Slide Cassette Unloader
Screen Cleaning

[https://www.appliedmaterials.com/il/en/product-library/applied-tempo-presto.html#carousel-984c50e963-item-e546ca9ea7-tabpanel]

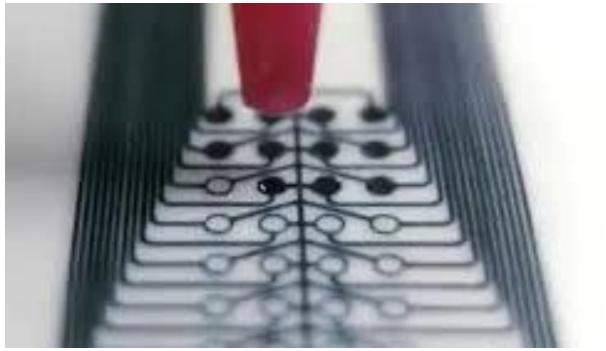
Aerosol Jet-based AME

HETEROGENEOUS INTEGRATION ROADMAP

Optomec
Aerosol Jet 5X 3D Printer

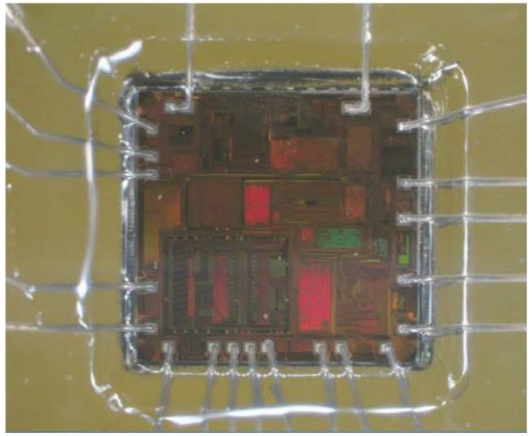
[https://optomec.com/resources/3d-printing-application-videos]

IDS
NanoJet Systems



[https://www.idsnm.com]

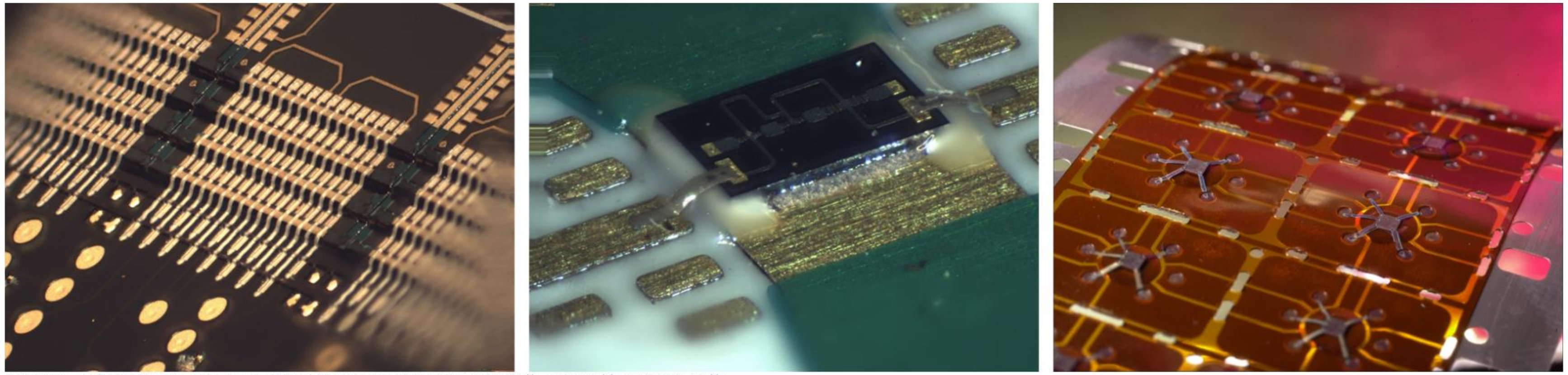
Print on un-Packaged Bare-die



Printed Interconnects and traces connecting a bare micro-controller die

[https://optomec.com/printed-electronics/aerosol-jet-technology]

3D Interconnects: Stacked Die, mmWave, & Flex Circuits

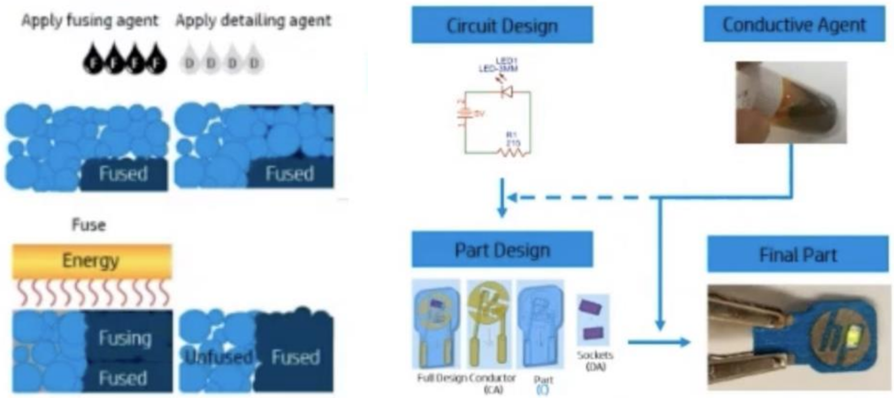


Semiconductor Packaging examples showing Printed 3D Interconnects for 3D stacked die (l), mmWave (c), and flex circuit (r).

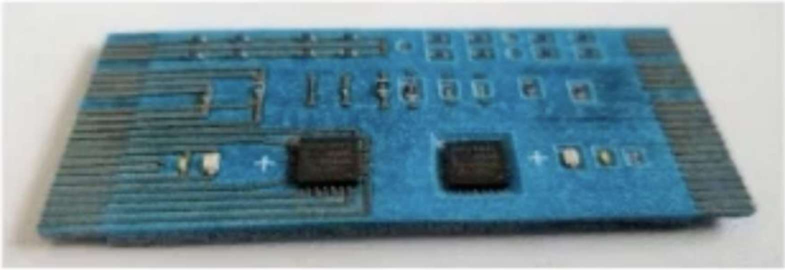
[https://optomec.com/optomec-receives-2-million-order-for-6-production-3d-electronics-printers/]

Power-bed Fusion-based AME

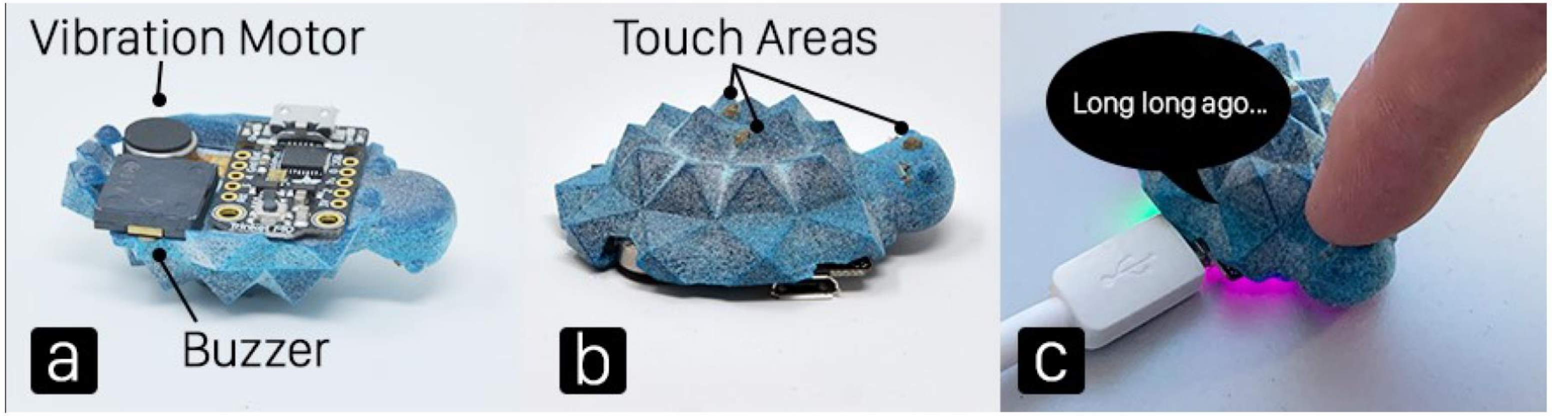
HP, MultiJet Fusion



*[Techblick.com: **HP | 3D Printing of Electronics using Multi Jet Fusion]***



*[Techblick.com: **HP | 3D Printing of Electronics using Multi Jet Fusion]***



[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

High Resolution Direct Write

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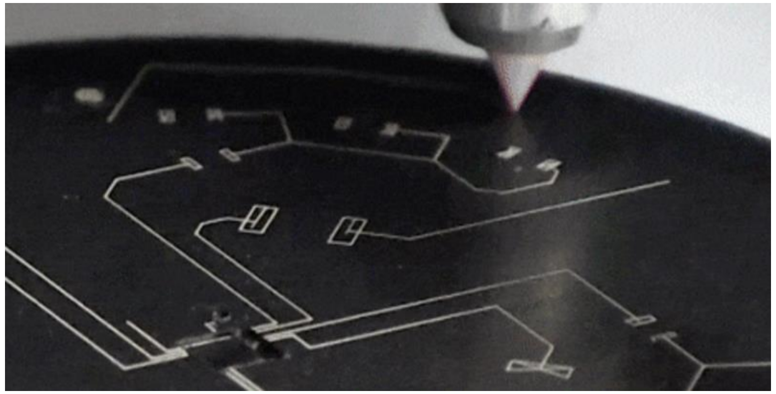
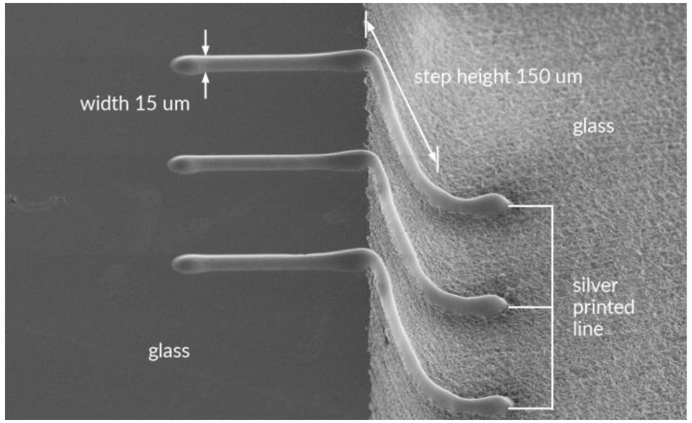
nScrypt

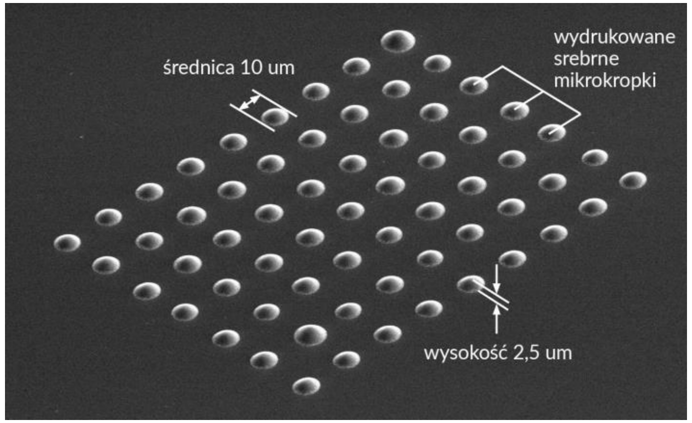


[https://www.nscrypt.com/]

XTPL

[https://xtpl.com/]





[Techblick.com: ***XTPL | High-Resolution 3D-Printed Conductive Features In Single Micron Scale***]

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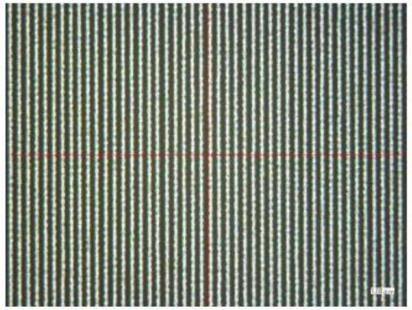
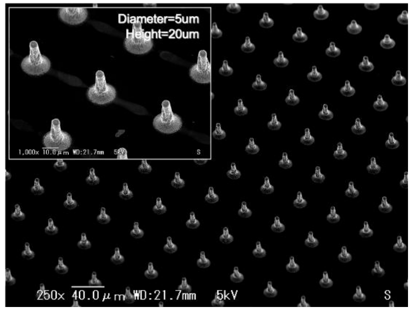
Electrohydrodynamic Printing

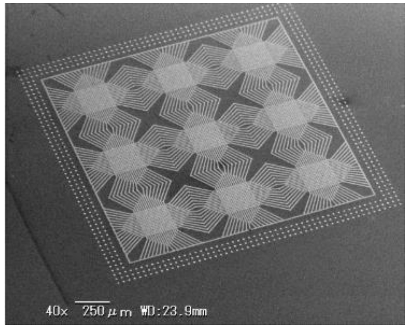
High Resolution, down to 500 nm features, wide viscosity range

Super InkJet



Silver ink, L/S=1 μm

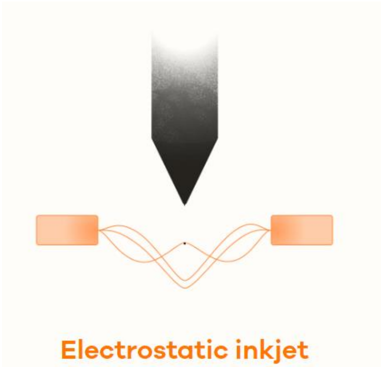




[https://sijtechnology.com/en/products/]

Scrona

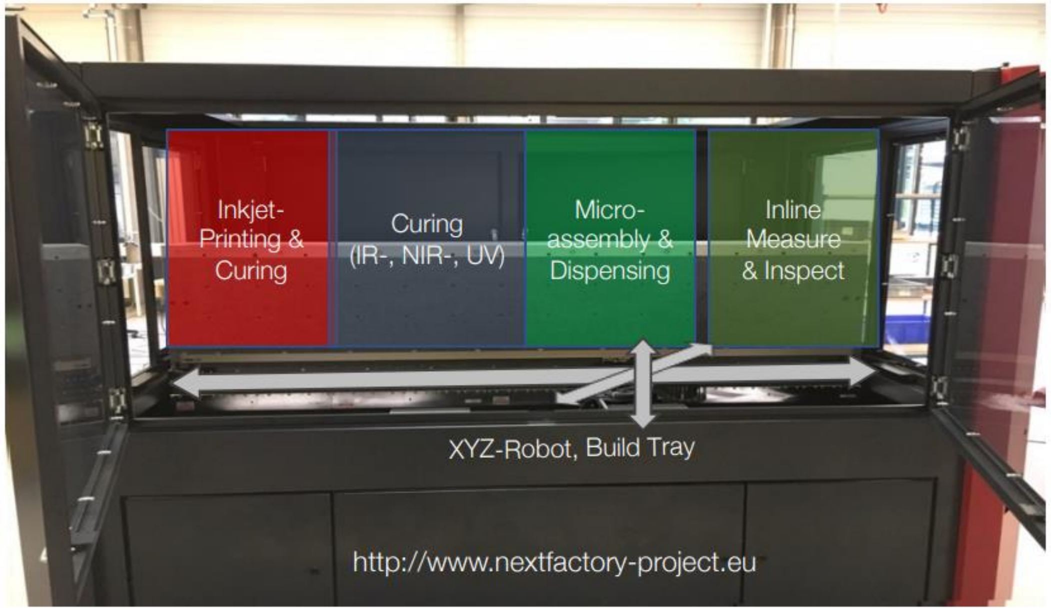
Multi-Nozzle, Annular Anode



[https://www.scrona.com/]

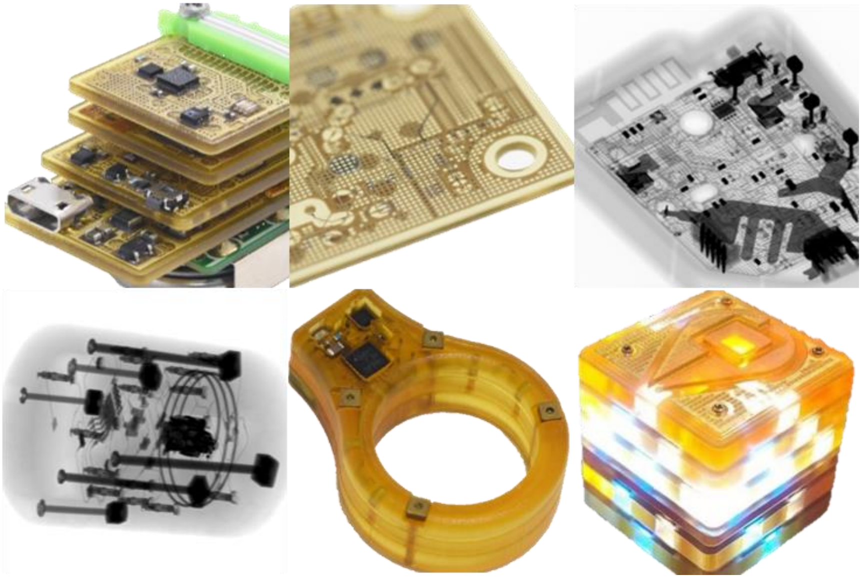
Hybrid Research Systems

Fraunhofer IPA – Next Factory
IJ + Cure/Sinter + P&P/Assembly + Measurement/Inspect



[https://www.ipa.fraunhofer.de/en/expertise/ultraclean-technology-and-micromanufacturing/precision-assembly-and-application-technologies/hybrid-manufacturing.html]

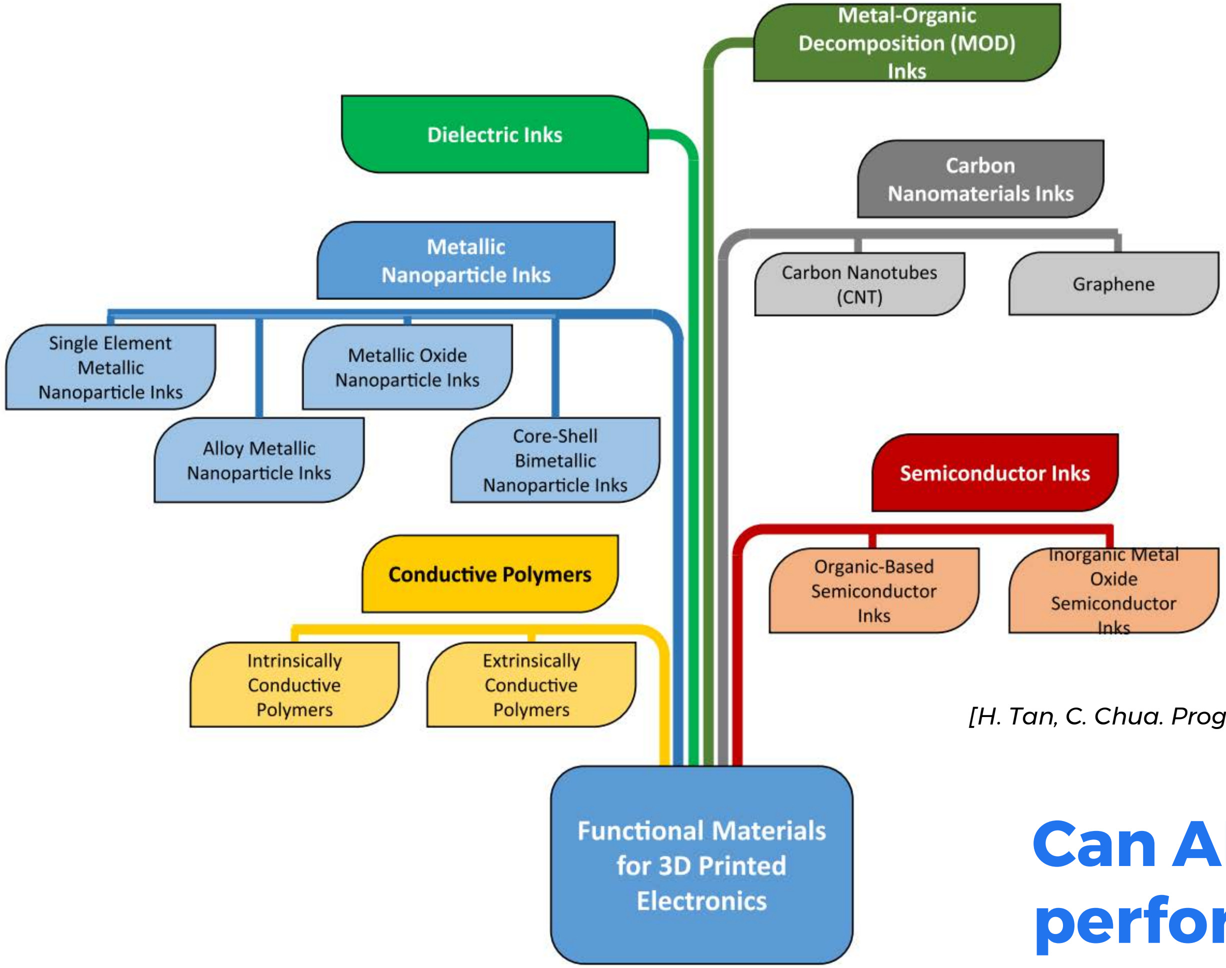
Fuji FPM Trinity System
IJ + Paste Deposition + P&P/Assembly + Measurement/Inspect

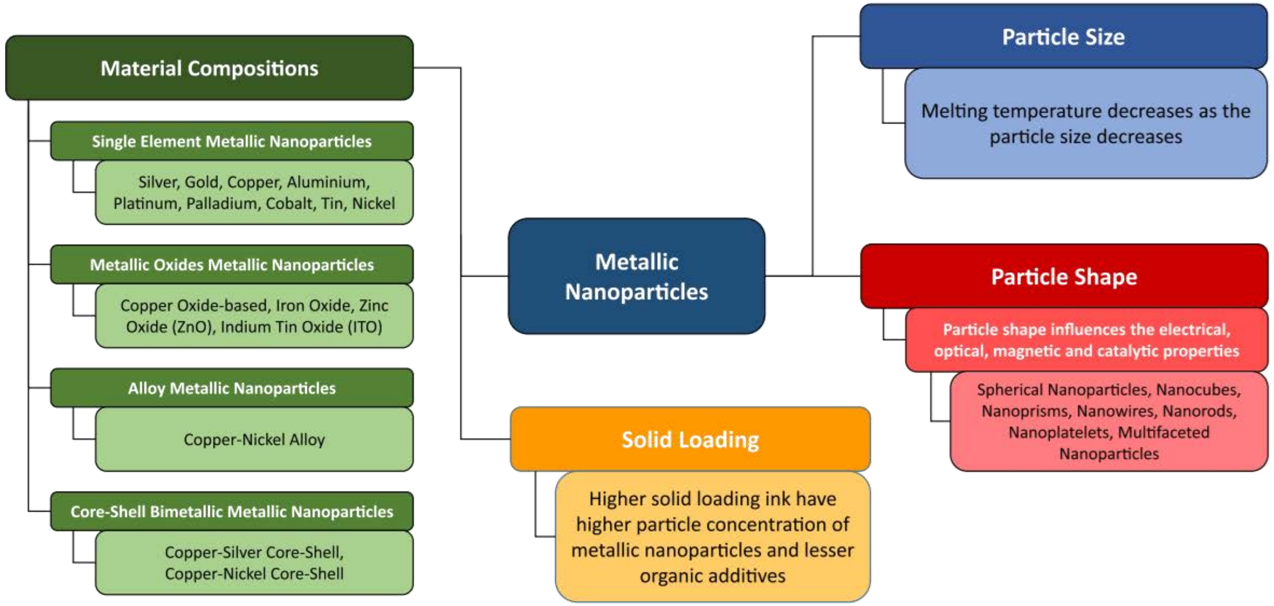


[https://www.fuji.co.jp/en/about/fpm-trinity/]

AME Materials

HETEROGENEOUS INTEGRATION ROADMAP





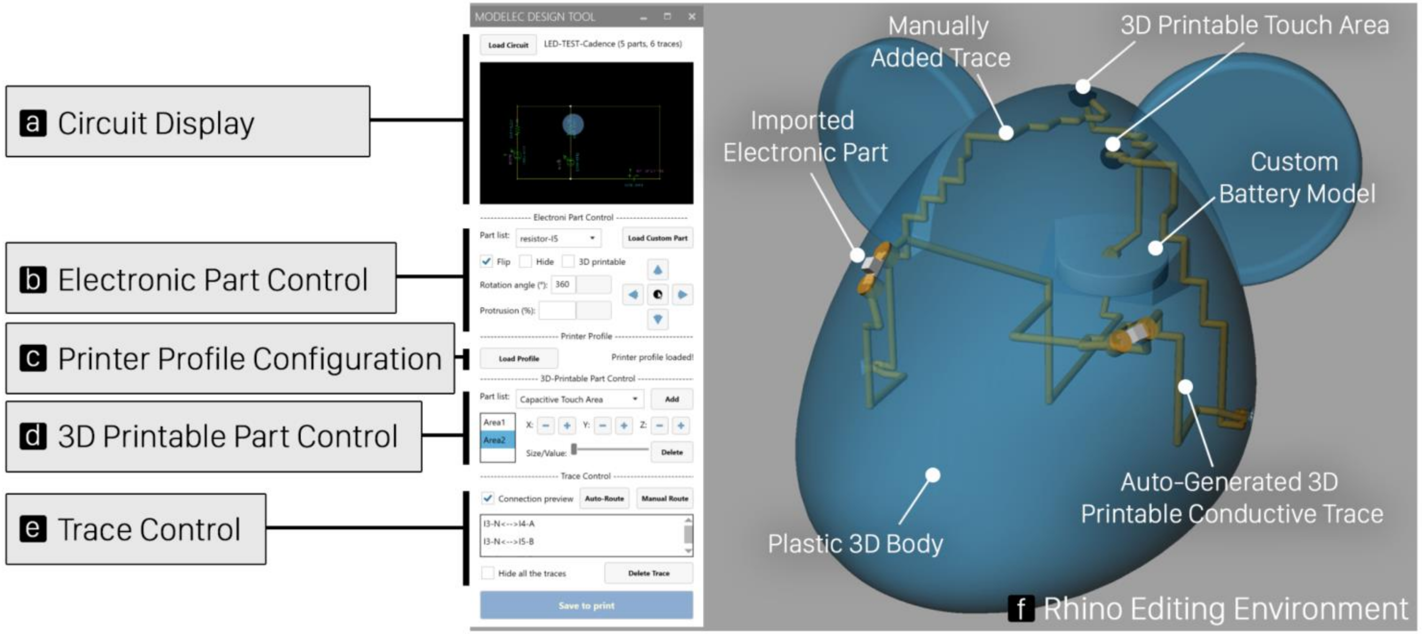
[H. Tan, C. Chua. Progress in Materials Science 127 (2022) 100945]

Can AME materials be adapted to hit CE performance specs and reliability needs?

AME Design – Merging EDA & CAD

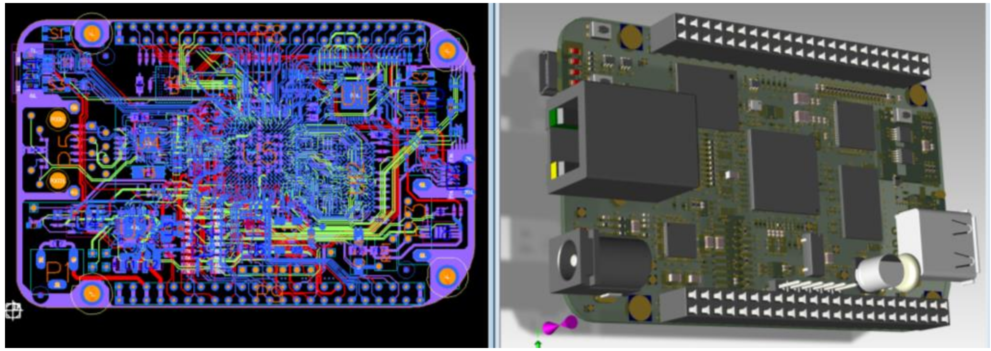
HETEROGENEOUS INTEGRATION ROADMAP

ModElec



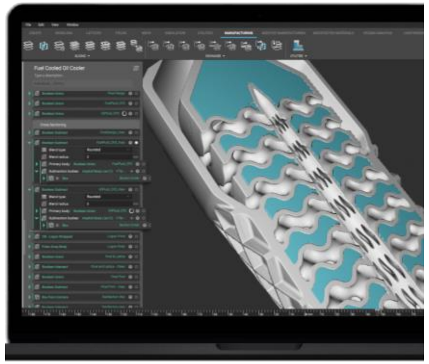
[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

Siemens – Mentor Graphics



[https://eda.sw.siemens.com/en-US/]

nToplogy



[www.ntopology.com]

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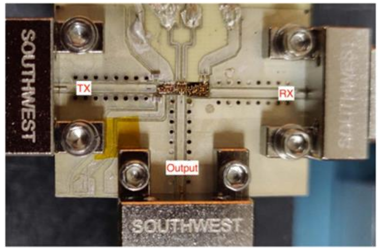
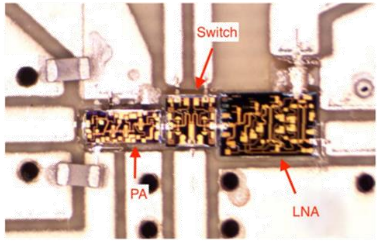
AME Applications - Antennas

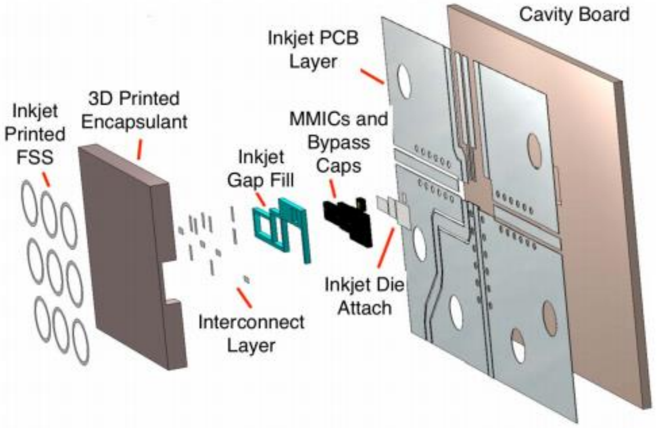
Frequency Selective Surface
RF & DC interconnects through inkjet – ribbon bond replace
Gap fill & adhesives inkjet printed
SLA printed Encapsulant
Inkjet Printed Frequency Selective Surface
→ High performance monolithic microwave integrated circuit

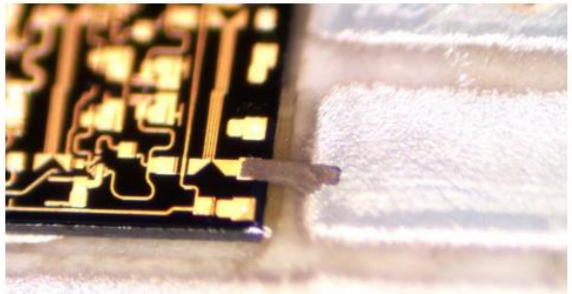


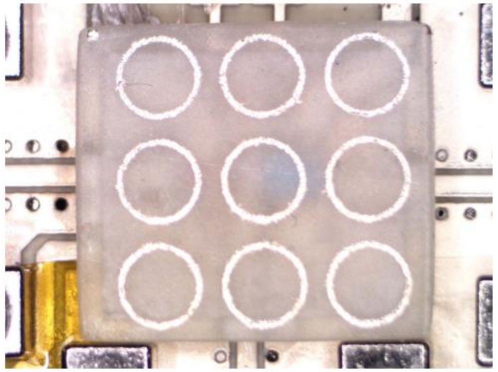
(a)

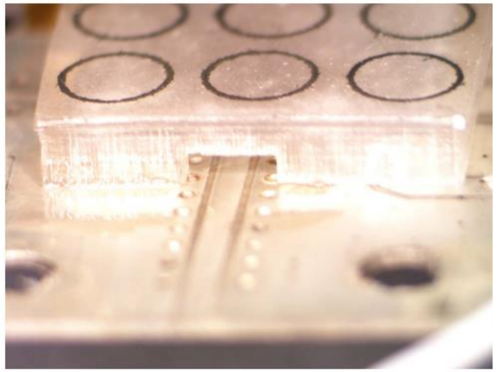


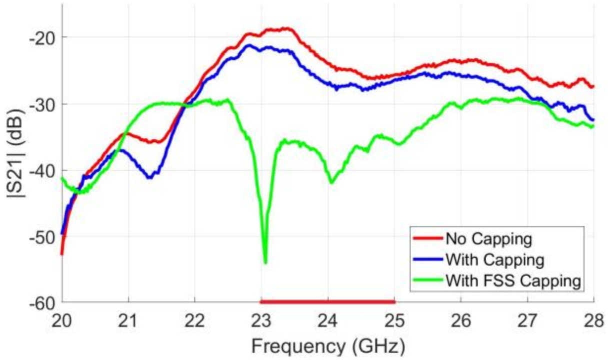
(b)





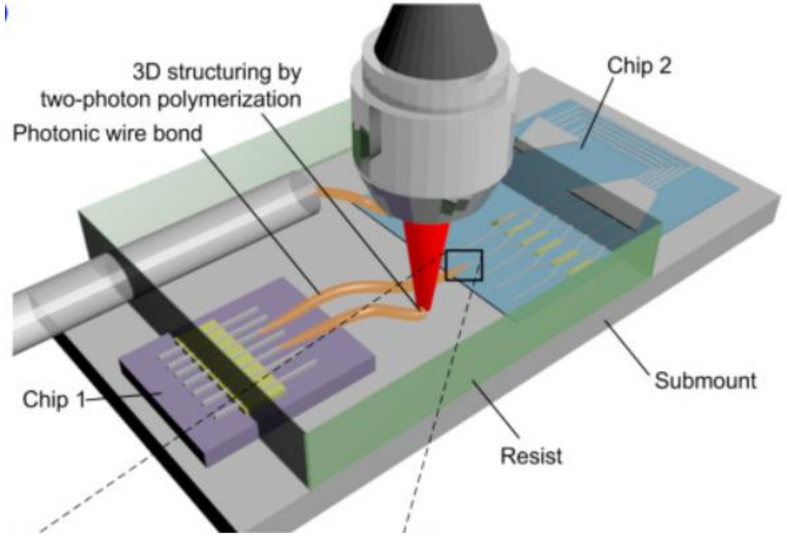




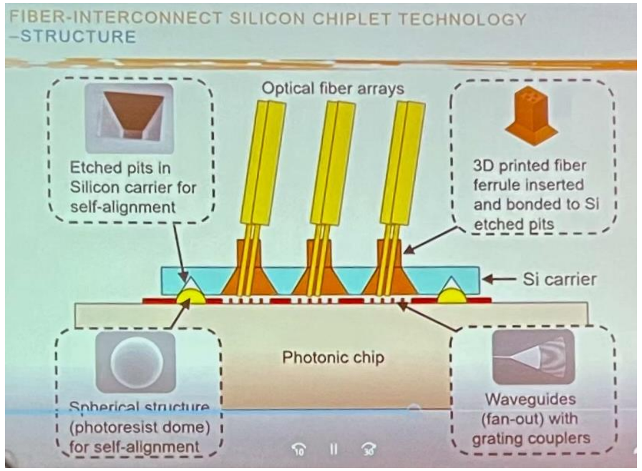


[M. Tentzeris, et al. IEEE Trans Microwave Theory Tech., **2020**, 68, 2716-2724]

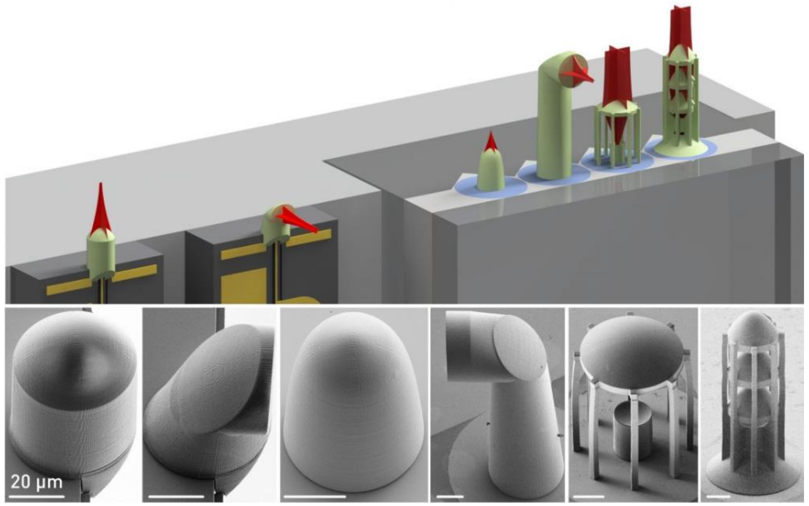
AME Applications - Photonics



[Blaicher, M., Kemal, J. et al. Light Sci Appl **9**, 71 (2020)]



[www.vanguard-automation.com/photonic-wire-bonding-2/]



[www.kit.edu/kit/english/pi_2018_032_3D-nanoprinting-facilitates-communication-with-light.php]

Printed Photonic Wires - connect Photonic IC & fiber.

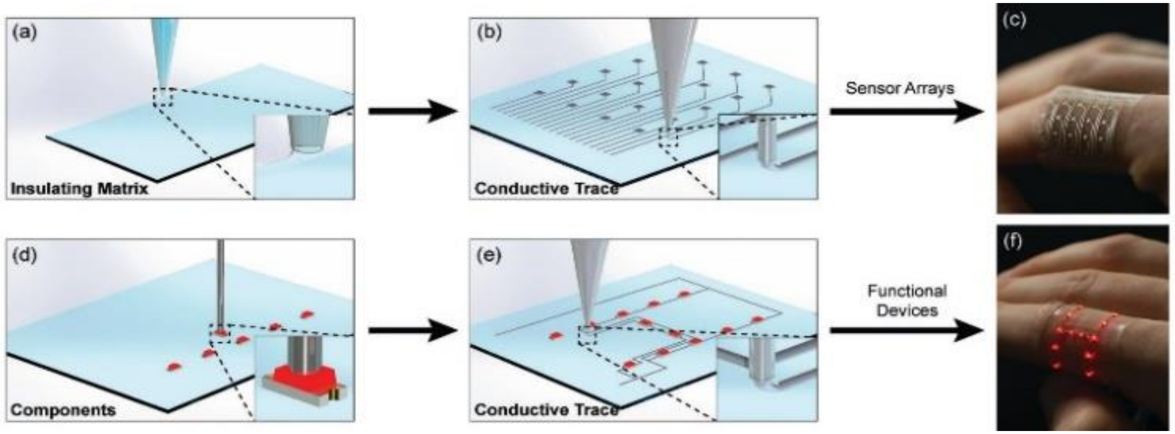
- Very fine diameters of ~2um
- Very low db loss <1dB
- Very high speed ~ 1 Tb /s

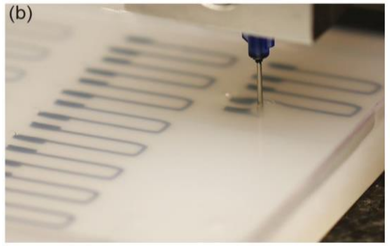
Printing of ferrules on silicon Photonic IC to as “sockets” for fibers avoiding active alignment.

Printing of microlenses and beam-shaping elements direct on chip.

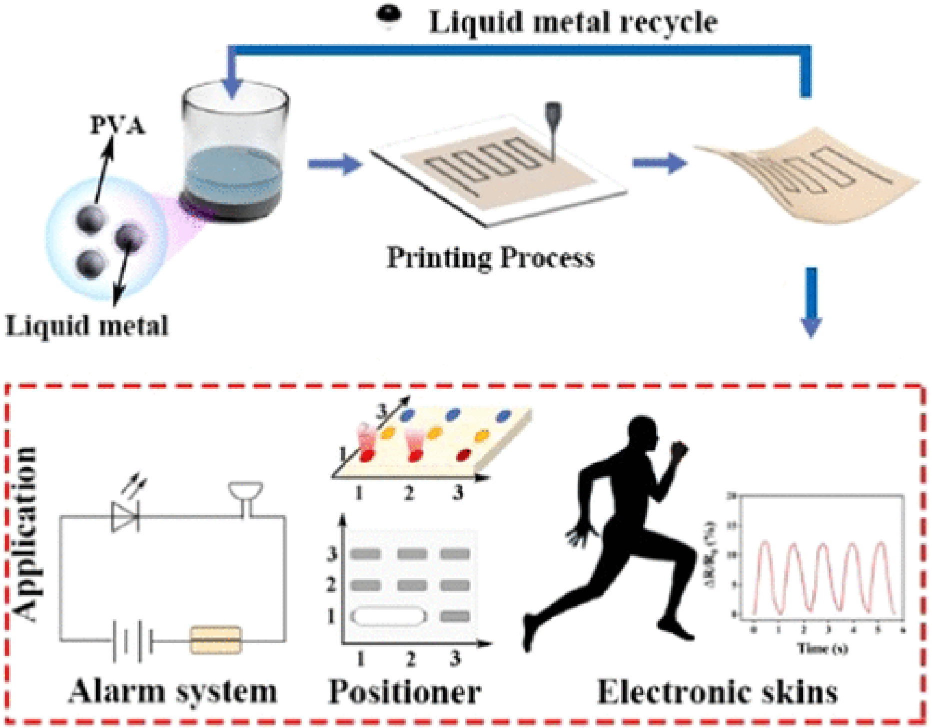
#thanks @Annette Teng

AME Applications – Flex/Stretch Electronics





[J. Muth, J. Lewis. Adv. Mater. 2014, 26, 6307–6312]



[J. Xu, G. Sun, et al. ACS Applied Materials & Interfaces 2021 13 (6), 7443-7452]

AME Applications - Thermal

HETEROGENEOUS INTEGRATION ROADMAP

Air Cooled Heat Sinks

[www.arrow.com/en/research-and-events/articles/understanding-heat-sinks-functions-types-and-more]

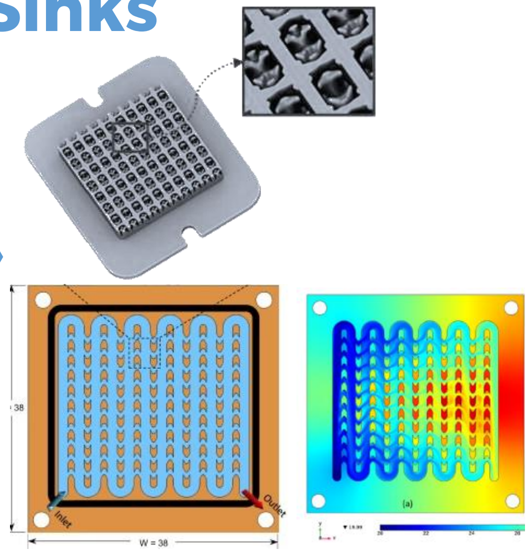
Current

[Lazarov BS, Alexandersen J. Appl Energy. 2018;226(February): 330-339]

AM Thermal

Liquid Cooled Heat Sinks

Current

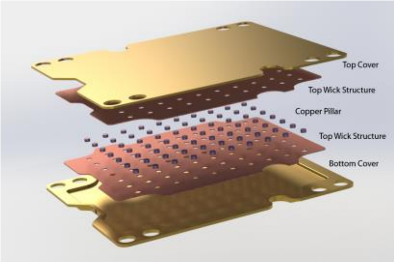


AM Thermal

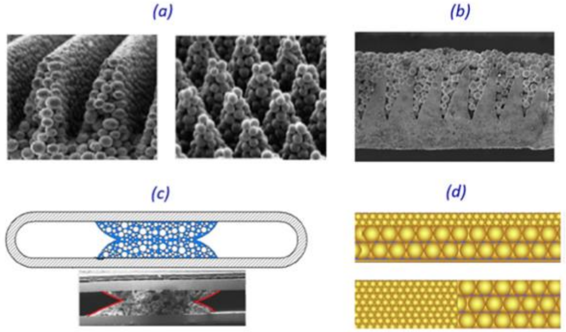
[Al-Neama AF, Thompson HM. Int J Heat Mass Transf. 2018;120:1213-1228]

Two Phase Convective Cooling

Current



[cofan-usa.com/products/vapor-chambers]



AM Thermal

[Jafari D, Wits. Renew Sustain Energy Rev. 2018; 91(April 2017):420-442]

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AME Status & Roadmap

HETEROGENEOUS INTEGRATION ROADMAP

Development Area	Current Best State	AE Approach for Current Best	Desired State (Depends upon Use Case)	Developmental Challenges Requiring Innovation (Depends upon Use Case)
Printing Attributes				
Line Width	>40 µm	Resin Jetting, Inkjet Printing	≤40 µm	Making robust to all print conditions and geometries. DW not at inkjet levels. Higher resolution inkjet incorporated into AE to push below 40 µm line.
Space Width	>100 µm	Resin Jetting, Inkjet Printing	≤150 µm	Making robust to all print conditions and geometries. DW not at inkjet levels. Higher resolution inkjet incorporated into AE to push below 150 µm space.
Trace Conductivity	12E-8 Ωm	DW, Aerosol Jet	≤10E-8 Ωm	Making robust to all print conditions and geometries and at above width and pitch. Resin jet and Inkjet + PBF need conductivity improvement.
Build Speed, Parts per Build	>15 mm/hr, multiple parts	Inkjet + PBF	Maximize for optimal utility	Improvements to build-speed and number of parts per build. Multiple nozzles or printheads incorporated into printer, improved and quicker mechanics of printer, additional energy sources for sintering conductor, optimized support removal when required (FDM, SLA).
Multiple Electronic Type Printing	Resistive, insulation, semiconductive	Inkjet	High functionality printed components	Ability to print additional components during AE printing may help drive utility, but tolerances on printed components must be tight, especially if P&P already integration option. Higher resolution of printheads to be preferable to a P&P solution. Also different electronic property ink developments.
Substrate Attributes				
Dielectric Strength	~10 kV/mm	FDM	>15 kV/mm	High dielectric strength materials available, but changes to build material can cause significant printing challenges and must still be developed for AE
HDT	189 ℃	FDM (PPSF)	>220 ℃	High temperature polymer available, but need development for AE. High temp stability of substrate required for part life-cycle and stress testing. Also needed for possible reflow for joining processes post-printing
Tensile Strength	70 MPa	FDM (ULTEM)	Unknown	Highly rigid polymers available for AE, need to be adapted into optimal AE solution.
Additional Process Integration				
Component Attachment	Amenable to P&P	FDM, SLA, Resin Jet	Optimized with P&P	Processes incorporating P&P into AE not optimized: speed, interconnect formation, in-situ testing, resumption of printing processes, etc.
Print Pausing/Resume	Amenable to P/R	SLA, FDM	Optimized with P/R	Processes incorporating P/R into AE not optimized: system integration, workflow optimization, mechanical integrity of interface once print resumes, etc.

[HIR 2021 version (eps.ieee.org/hir), Ch. 8, Single and Multichip Integration]

Expanding from starting point (shown here) to roadmap with 5, 10, and 15 year targets

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TWIG Collaboration Help!

HETEROGENEOUS INTEGRATION ROADMAP

- Single & Multi-Chip Integration
- Aerospace & Defense
- Medical, Health
- Thermal
- Photonics

Eager for Collaborations with other TWIGs!