Additive Manufacturing Packaging Applications and Growth Needs for Heterogeneous Integration Impact

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Research Manager, Materials Development

Feb 2024

Meta

Agenda

1. Additive Manufactured Electronics (AME) & Heterogenous Integration (HI)
2. AME Benefits
3. AME for XR
4. AME Manufacturing & Materials
5. AME Advances & Applications towards Future Electronics & HI
6. AME Growth Needs

Large collaborative team for creating full content!

Finalizing as a Chapter within HIR 2024

Technical Working Group Contributing Members

HIR
HETEROGENEOUS INTEGRATION ROADMAP

Kris Erickson
(Meta)

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(Intel)

Alex Cook
(Nextflex)

Jeroen van den Brand
(Holst Center)

Mike Newton
(Sciperio)

Annette Teng
(Promex)

David Bowen
(Laboratory for Physical Sciences)

Mark Poliks
(Binghamton U)

Girish Wable
(Jabil)

Martin Hedges
(Neotech AMT)

Dean Turnbaugh
(NTV)

David Weins
(Siemens)

Richard Neill
(ADVPES)

David Rosenfeld
(Celanese)

Markus Scheibel
(Heraeus)

Additively Manufactured Electronics (AME)

AME = Printed Conductor + (Printed/Existing) Dielectric + (optional) Additional Processes

AME Deposition
Dot Deposition
Line Deposition
Area Deposition

Direct-write & Conformal**

Dispensing & Extrusion Print

Non-contact Jetting Methods

Inkjet Print
Aerosol Print
Electrohydrodynamic Print
Piezo-Valve Jetting
Laser Induced Forward Transfer (LIFT)

*** can deposition on 2D or 3D substrate*

3D Print Methods

Fused Deposition Modeling
SLA (Stereolithography)
2-photon SLA
Digital Light Processing (DLP)
Powder Bed Fusion

Contact 2D Print Methods*

Screen/Stencil Print
Gravure Print
Flexographic Print

** 2D only substrate*

Additively Manufactured Electronics (AME)

Structural Electronics

Pick & Place
Laser Direct Structuring (LDS)
Electroplating

In-Mold Electronics

Pick & Place
Thermoforming

Flexible Hybrid Electronics (FHE)

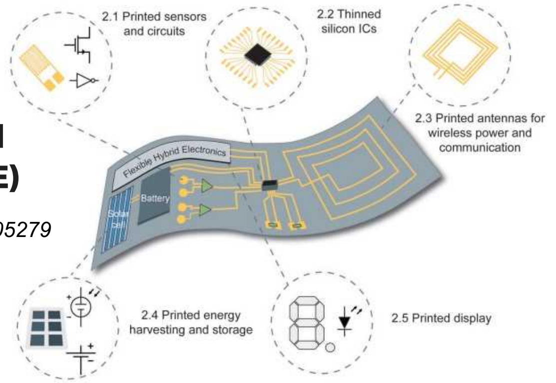
Pick & Place Solder Deposition
Lithographically Defined Features
Over-molding

Additional Supporting Processes

Pick & Place (Si, passives, etc.)
Curing/Sintering
3D Scanning
Metrology
Subtractive (Laser, Milling)

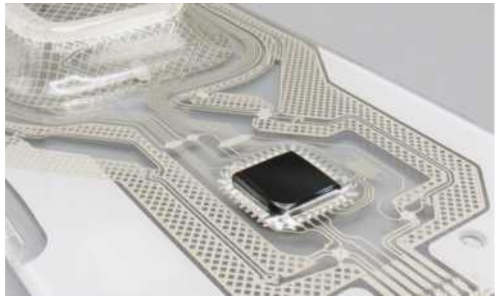
Flexible Hybrid Electronics (FHE)

DOI: 10.1002/adma.201905279



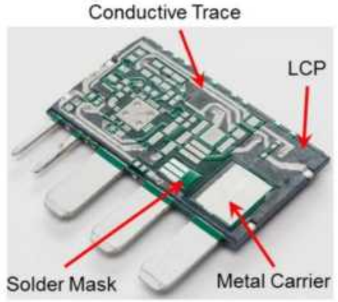
In-Mold Electronics

Project "*Origami*", 02/2018 - 01/2021,
Innovations with Organic 3D Electronics.
#thanks & with permissions from
@Christine Kallmayer and Fraunhofer IZM

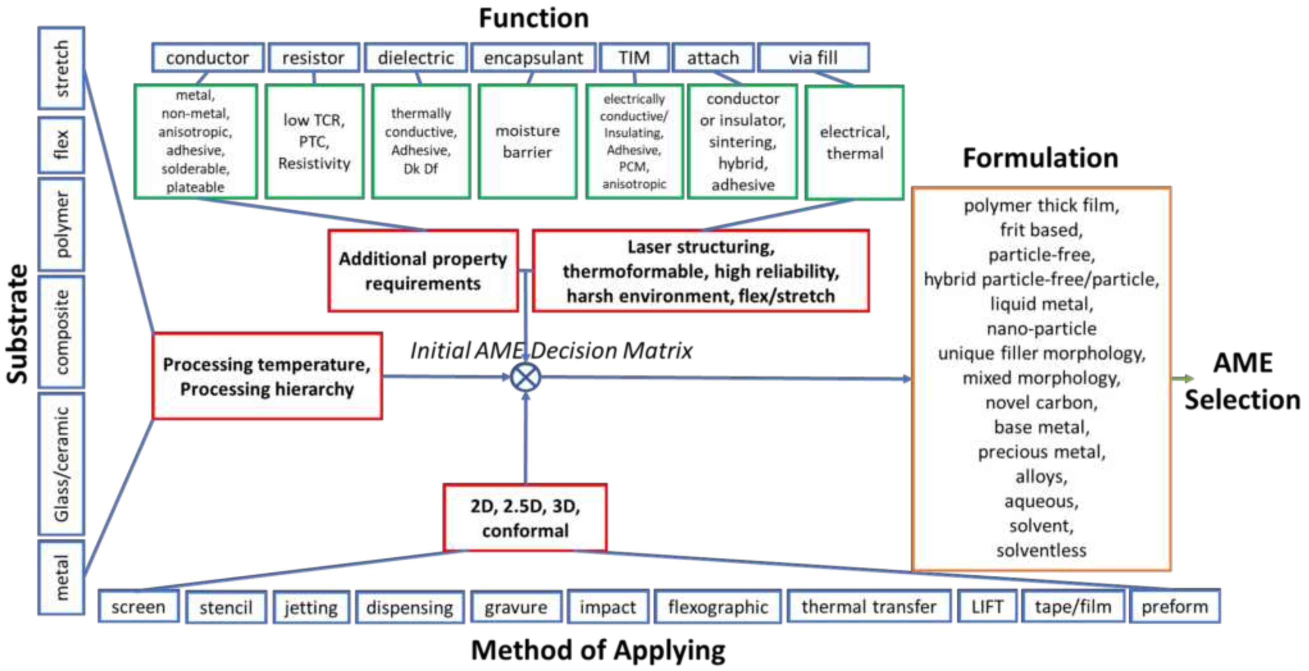


Structural Electronics

DOI: 10.1109/MID50463.2021.9361621

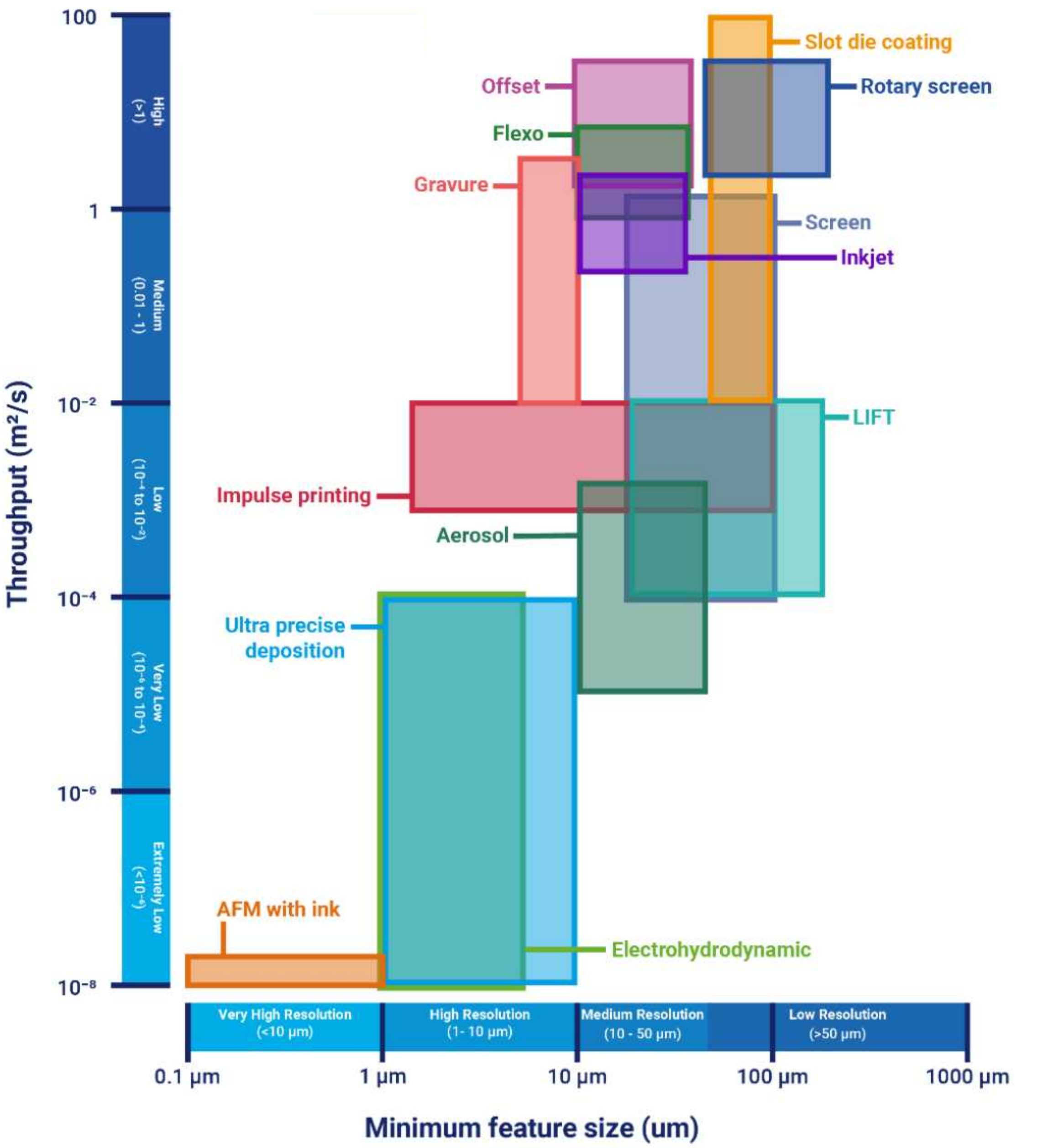


AME Considerations

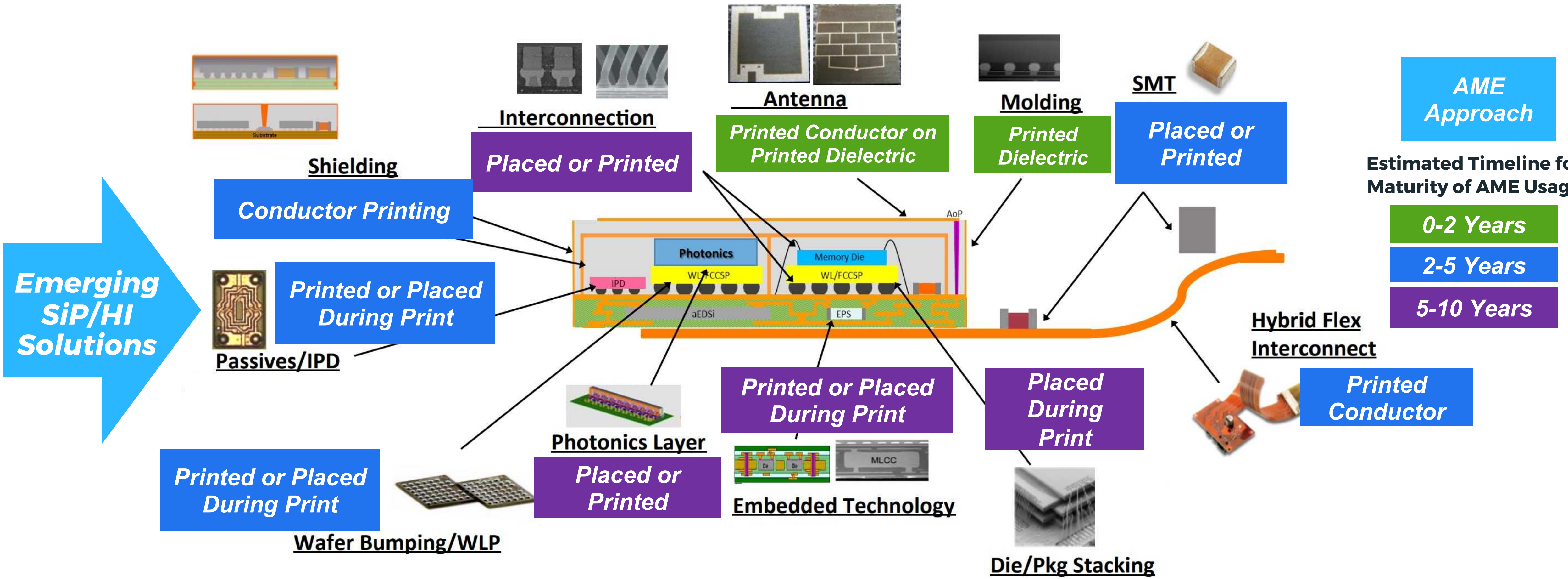


#thanks to Dave Rosenfeld, Celanese, and AME for HIR group

#thanks and with permissions from Max DePhillips, IDTechEx



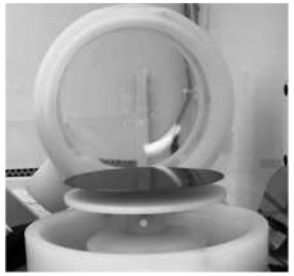
AME for Heterogenous Integration (HI)



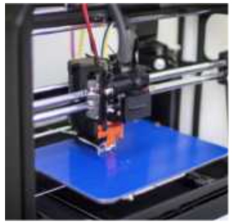
[HIR 2021 version (eps.ieee.org/hir), Ch. 8, Single and Multichip Integration]
***In-progress** 2024 on HIR Chapter on AME*

AME Benefits

Material efficiency



VS.

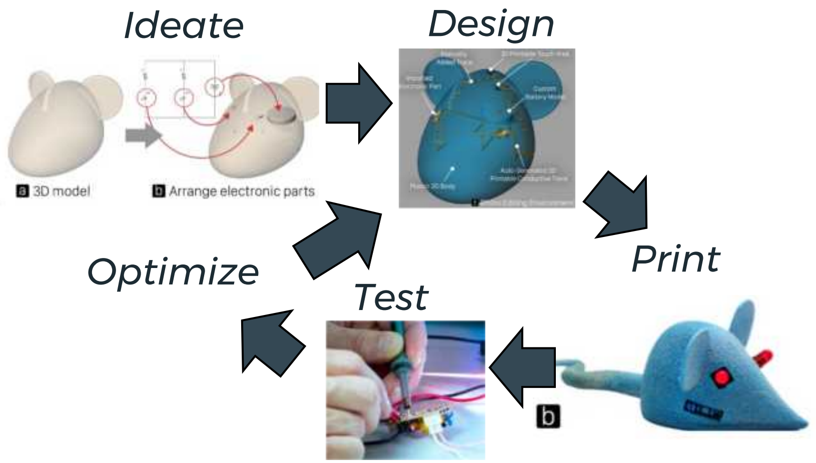


+

[https://https://commons.wikimedia.org/wiki]

[https://commons.wikimedia.org/wiki]

Design Freedom & Rapid Prototyping

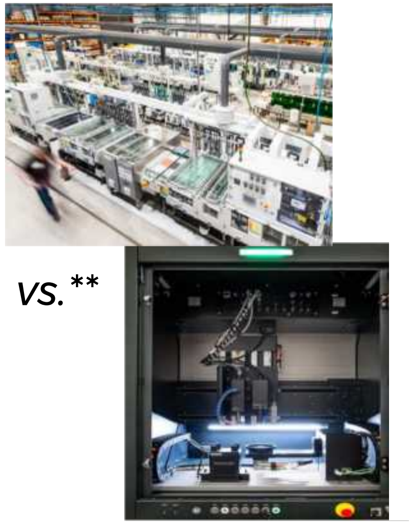


[ModElec: A Design Tool for Prototyping Physical Computing Devices Using Conductive 3D Printing, L He, et al - Proceedings of the ACM on Interactive, 2021]

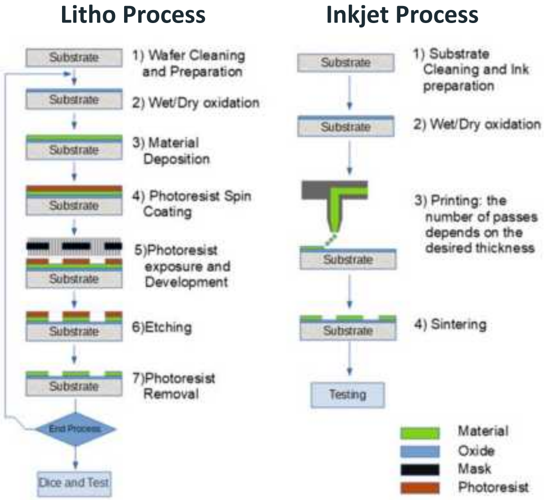
Novel Form Factors

DOI: 10.29026/oea.2018.170004

Simplified Manufacturing



VS.**



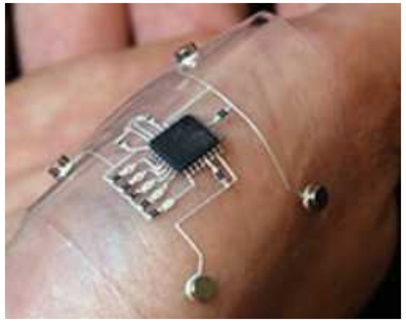
#thanks and with permissions from @Martin Hedges (Neotech AMT)

https://doi.org/10.1002/adem.202000679

Low-volume/ Individualized Designs

DOI 10.1186/s13104-015-0971-9

Flex/Wearable Devices



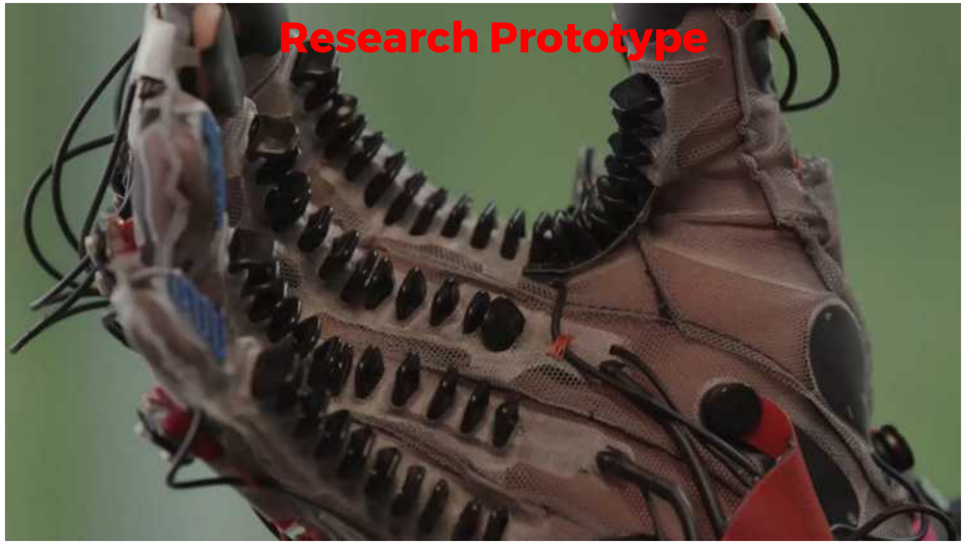
https://doi.org/10.1002/adma.201703817

AME for Extended Reality (XR)

EMG Wristband

https://tech.facebook.com/reality-labs/2021/3/inside-facebook-reality-labs-wrist-based-interaction-for-the-next-computing-platform/

Haptic Glove



https://about.fb.com/news/2021/11/reality-labs-haptic-gloves-research/

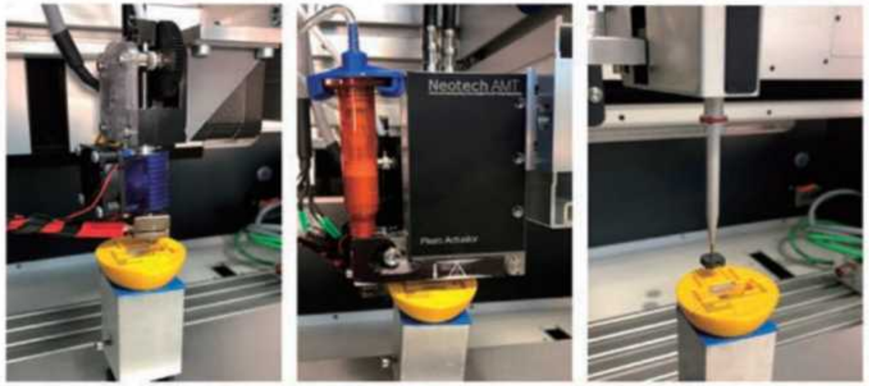
Fused Deposition Modeling for AME

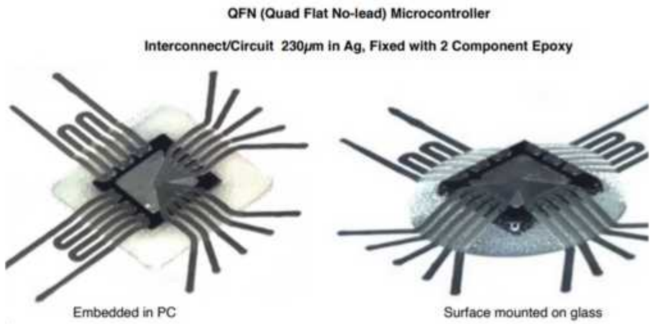
Down to ~100 micron features (~250 w/o micromachining), alternative conductor deposition methods typical, creating full 3D structures

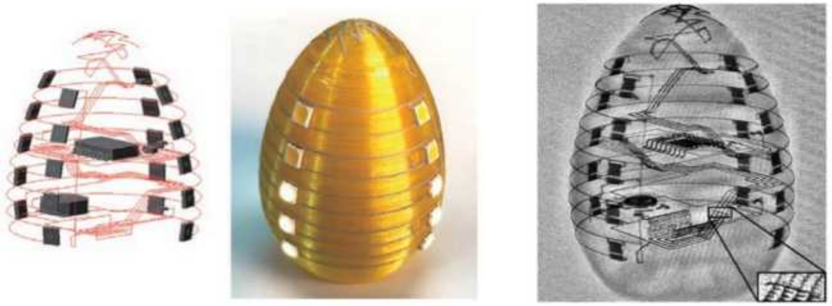
Neotech AMT

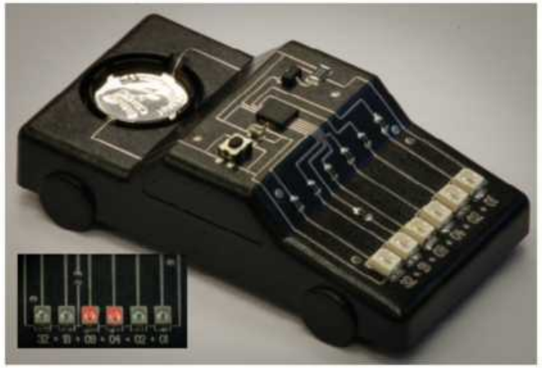
Combined, hybrid system
- FDM printing
- Direct write/Syringe
- 5-axis, Conformal Inkjet
- 5-axis, Conformal Aerosol Jet
- Laser sintering

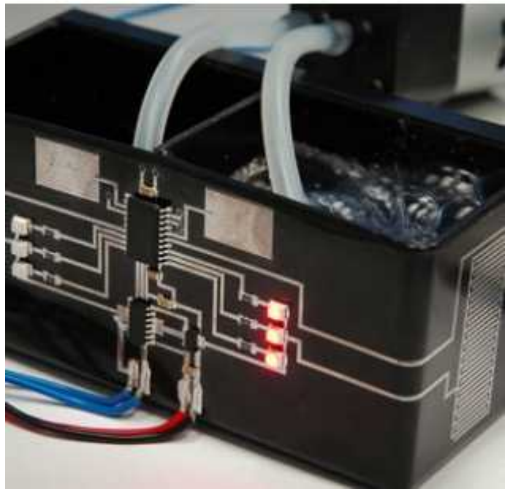
FDM **Piezo-Valve Jet** **P&P**











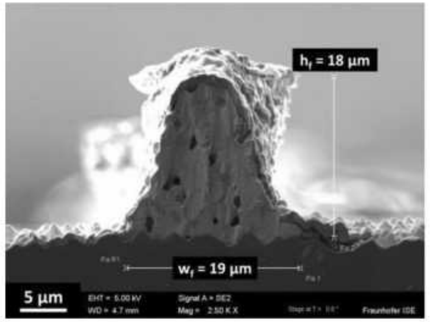
[M. Ankenbrand, et al. 2019 International Conference on Electronics Packaging (ICEP), 2019, pp. 273-278]

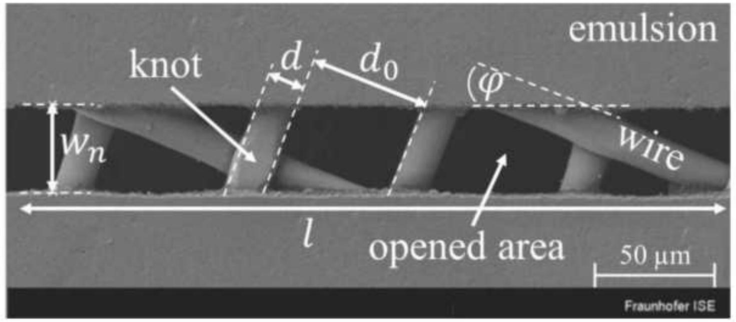
DOI: 10.29026/oea.2018.170004

Screen Print for AME

High speed, panel processing, typically to 50 micron features

Pushing Resolution for High Throughput Screen Print





https://doi.org/10.1038/s41598-021-83275-0

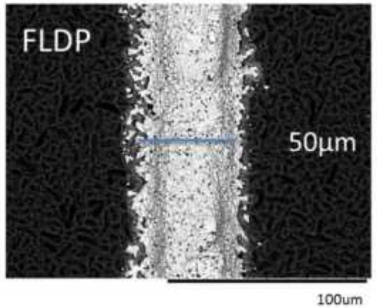
<= 20 micron feature demonstrations
Fraunhofer ISE, Asada Mesh

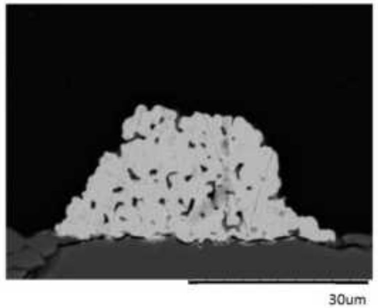
Continued Scaling for High Throughput

e.g. Applied Materials – Tempo Presto PE Screen Printer

High productivity 8,000 wafers/hr
High Repeatability +/- 5 micron
3 Continuous line Modules – Load, Print, Unload/Dry/Clean
Integrated: Profilometry, Alignment, Electrical Inspection

Solar Cell Metallization Applications



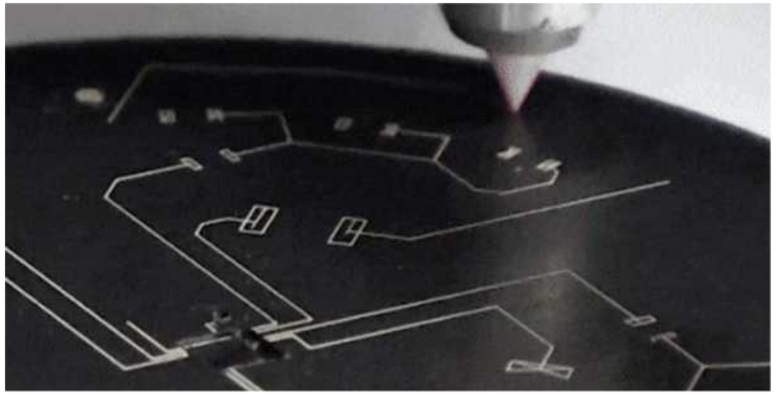


doi: 10.1016/j.egypro.2015.07.074

Direct Write Dispense for AME

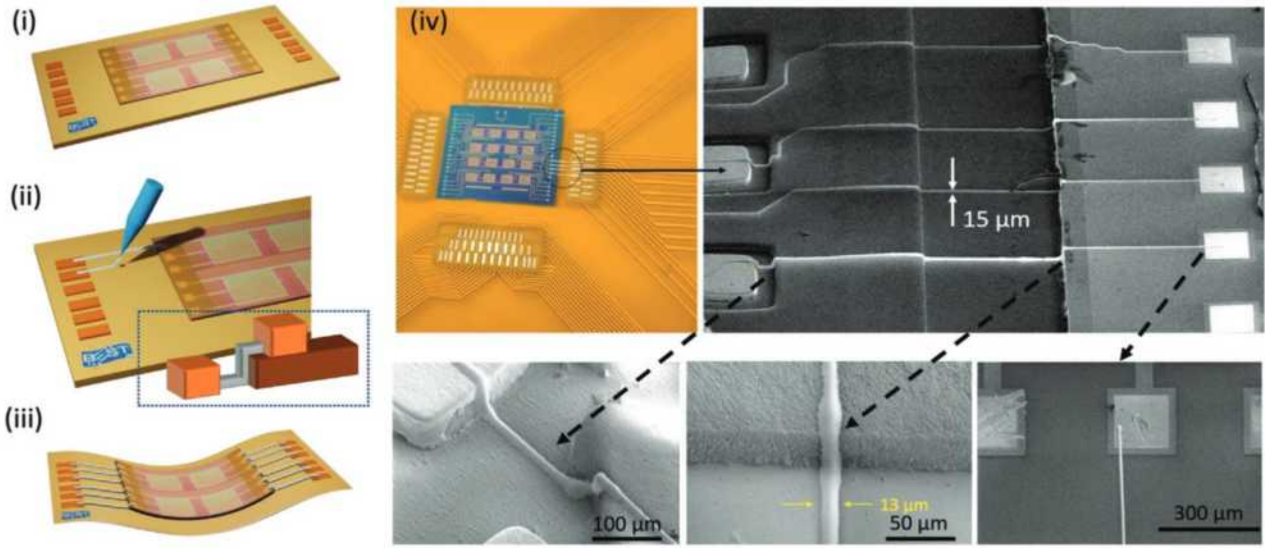
Down to ~15 micron features, high viscosity inks, patterning over topologies

nScrypt



[https://www.nscrypt.com/]
#thanks and with permissions from Mike Newton, nScrypt

XTPL



Traces over substrate & chip steps
Wire-bond alternative

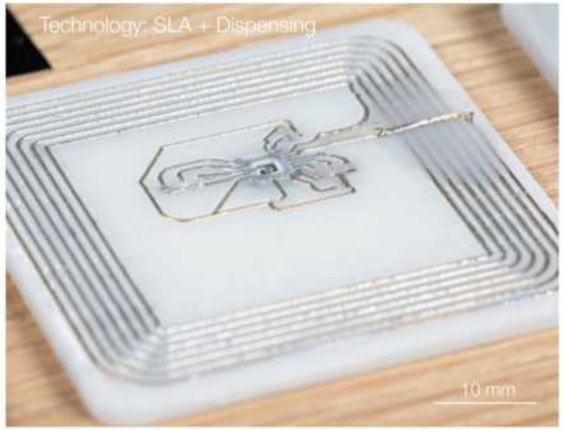
DOI: 10.1002/aelm.202101029

Stereolithography (SLA) for AME

Down to ~100 micron features, alternative conductor deposition methods, creating full 3D structures

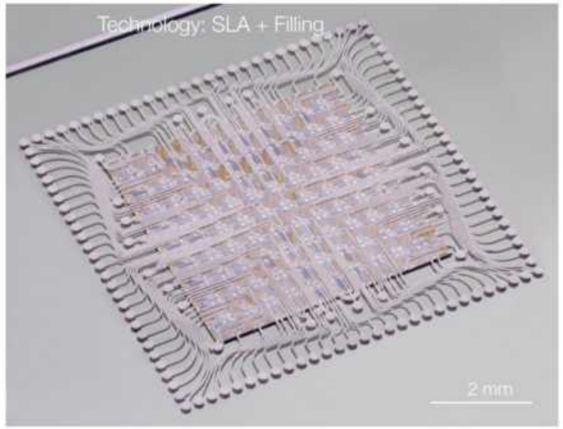
TNO Holst

SLA + Dispense



Self-harvesting NFC tag with temperature sensor

Modified SLA-Rake Process



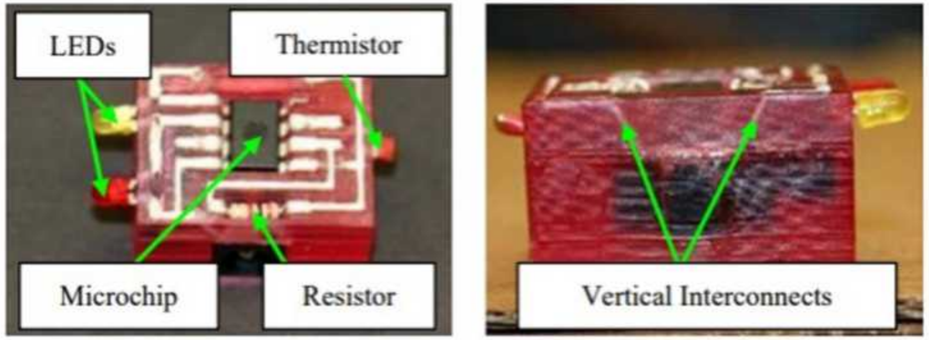
Fanout structure with 220 interconnects

[https://executivereport.holstcentre.com/innovation-updates/enabling-technologies/3d-printed-electronics/]
#thanks and with permissions from Jeroen van den Brand and Holst Center

UT – El Paso

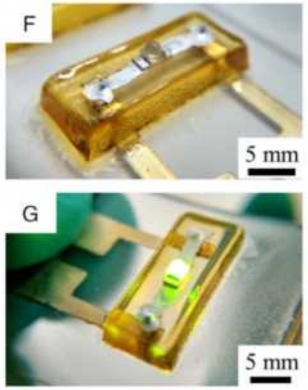
MacDonald Group – Keck Center

SLA, DW + Pick and Place Components



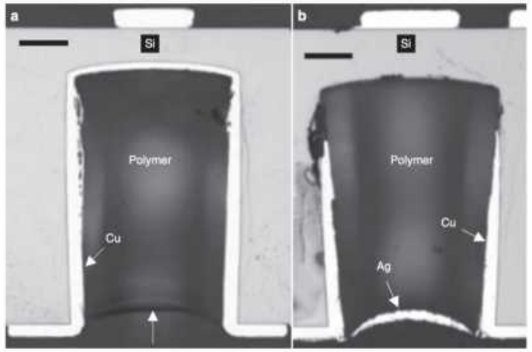
*[D. Espalin, E. MacDonald. Int J Adv Manuf Technol **72**, 963–978 (2014)]*

Inkjet for AME



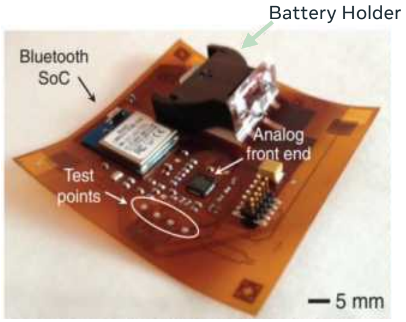
Inkjet Vertical Interconnects

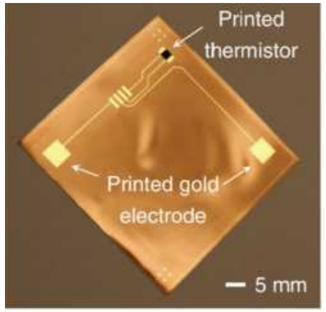
DOI: 10.1002/adem.201900568



Inkjet filled & planarized TSV → increase I/O Density

doi.org/10.1038/micronano.2017.2





Wearable Health Monitoring – electrodes, thermistors

https://doi.org/10.1002/adfm.201603763

Example Application Areas

- *Multilayer PCB-board applications*
- *Selective Solder masks for PCB*
- *Panel etching mask*
- *Encapsulation layers*
- *Dielectric, Conductor, Adhesive, and/or Mask Resist for Semiconductor Back-End Packaging*
- *Integratable with P&P methods*
- *Antenna Printing*

Commercial Examples

NanoDimension

Dragonfly

Down to 75 micron features, 150 micron interconnects, min layer thickness 3 micron, multi-layer PCB builds

ChemCubed

ElectroJet

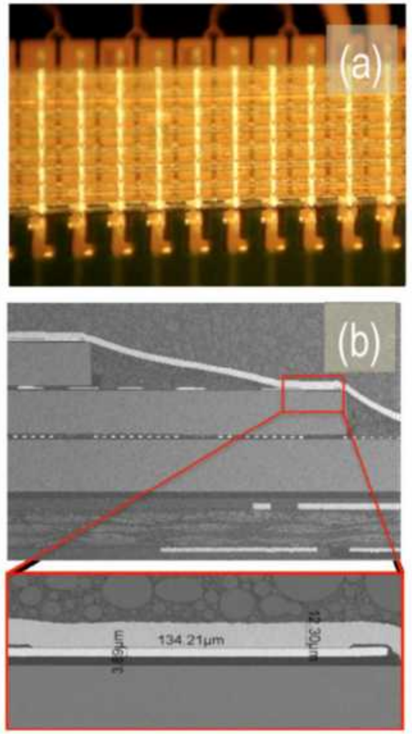
Suss PiXDRO

Down to 20 micron features

- Multiple commercial printheads
- In-line curing
- Precision substrate manipulation
- Automated Print Optimizations
- Gerber files → Inkjet Bitmap
- Material efficiency vs. standard coat + etch
- Up to 1200 wafers/hr (Jetx-P) or 80 panels/hr (Jetx-M)

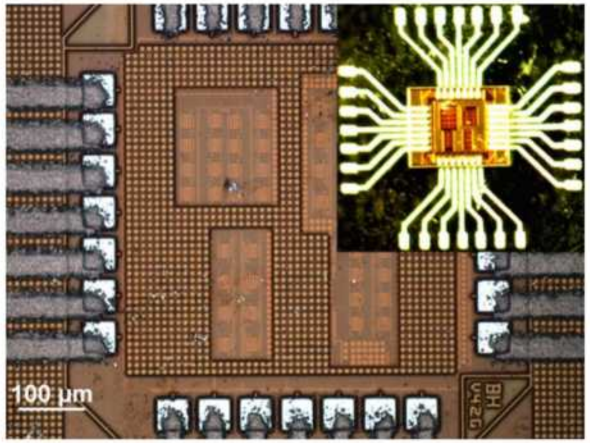
Aerosol Printing for AME

To 20 micron features, multi-materials, printing over topologies



Wire-bond Replacement

Hedges, Martin, and Aaron Borras Marin. "3D aerosol jet printing-adding electronics functionality to RP/RM." DDMC 2012 conference. 2012.



Print on un-Packaged Bare-die

Additional Applications

- High Frequency RF Interconnects
- Printed RDLs
- Package-level Shielding
- Printed Antennas

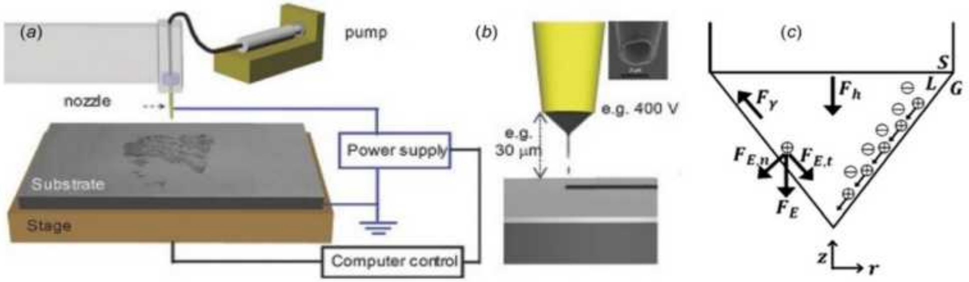
Commercial Examples

Optomec
Aerosol Jet 5X 3D Printer

IDS
NanoJet Systems

Electrohydrodynamic Jet for AME

High Resolution (at or below 1 micron features), wide ink viscosity range

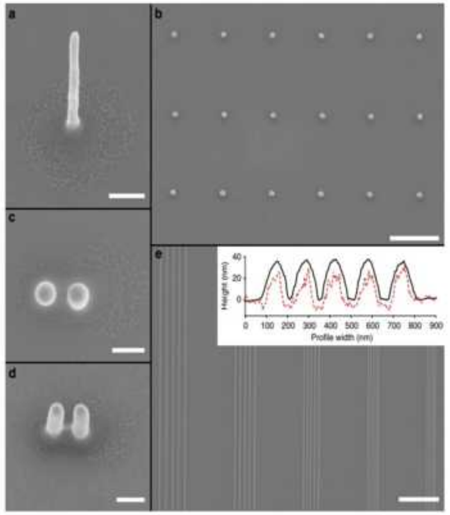


DOI: 10.1115/1.4041934

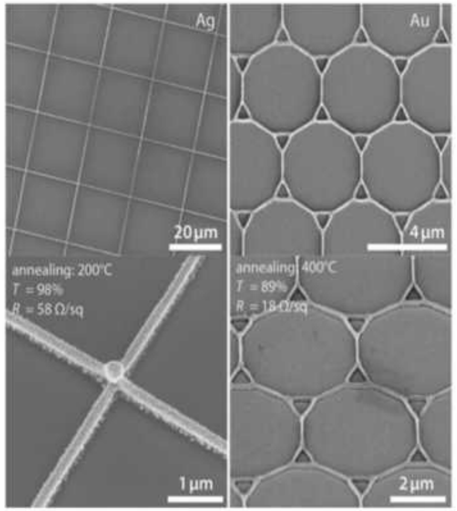
Commercial Examples

Super InkJet
1 micron line/space

Scrona
Multi-Nozzle, Annular Anode, down to 500 nm features, up to 10K cP inks

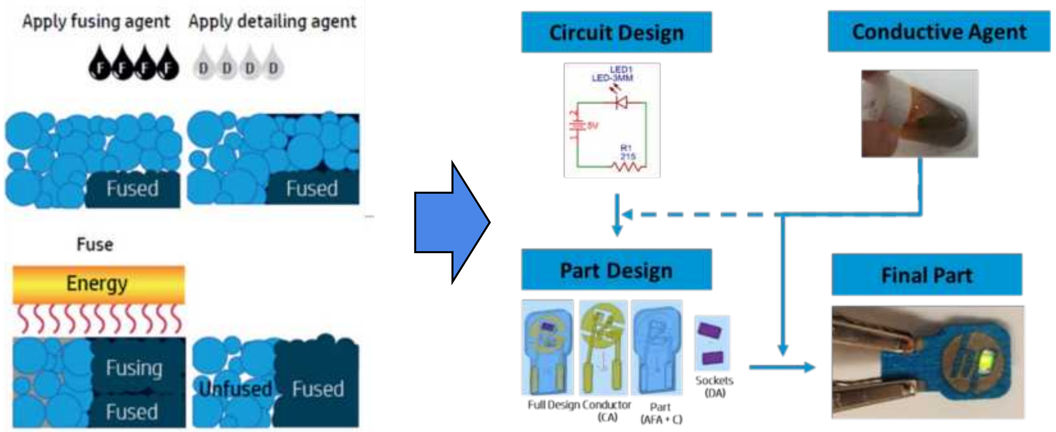


DOI: 10.1038/ncomms1891

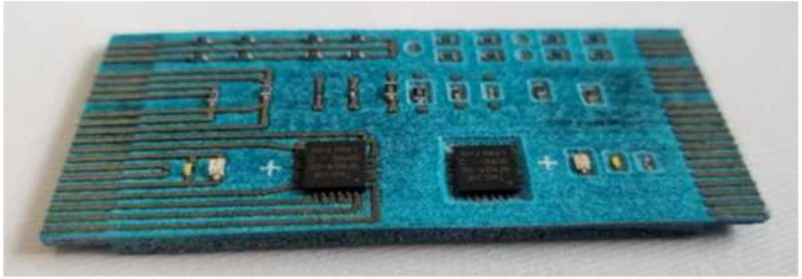


https://doi.org/10.1515/ntrev-2021-0073

Powder Bed Fusion for AME



*[Techblick.com: **HP | 3D Printing of Electronics using Multi Jet Fusion]***
#thanks and with permissions from Jarrid Wittkopf, HP Inc.



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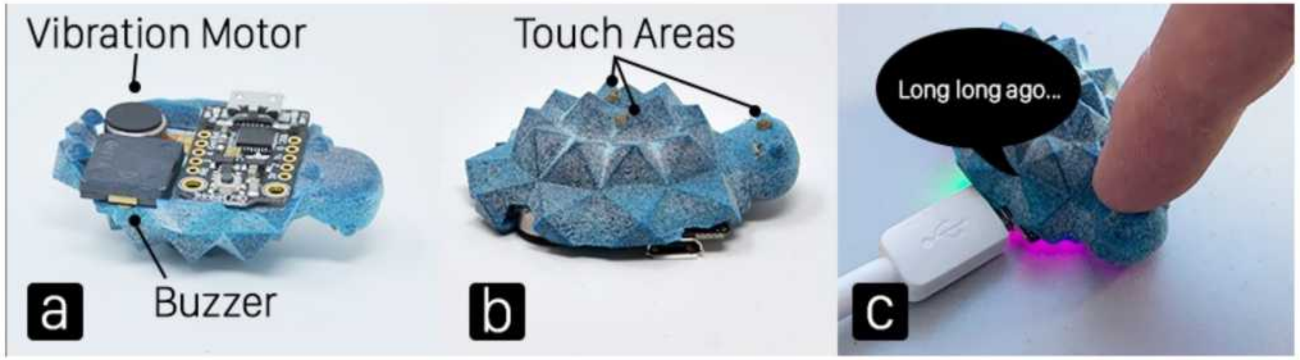


[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

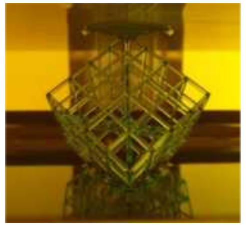
AME Advances Materials

FORM

Highly tailored per manufacturing approach

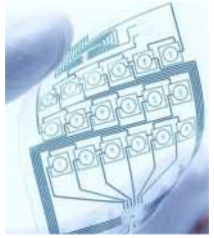
[https://www.shutterstock.com/]

Filaments
FDM



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

Photo-resins
SLA, DLP



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

Films/Sheets
Screen, Stencil, Gravure, Flexo

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

Powders
Powder Bed Fusion

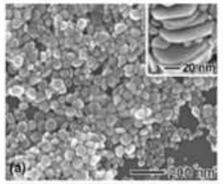
Inks
Inkjet, Aerosol, EHD

Pastes
Dispense, Screen, Stencil, Gravure, Flexo, Piezo-Valve

FUNCTION

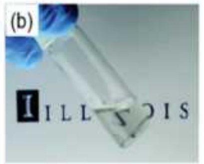
Conductors
Traces, Interconnects, Vias, Antenna

Silver-based



DOI: 10.1007/s11665-014-1166-6

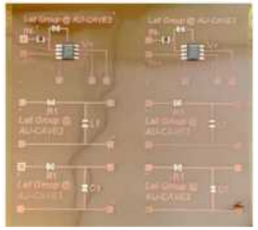
Nano/Micro-particle



DOI: 10.1039/c9tc05463d

Metal Salt

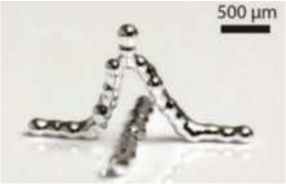
Copper-based



***DOI**:10.1109/iTherm5 4085.2022.9899673*

Flex-Stretch

Micron-Ag + Elastomer



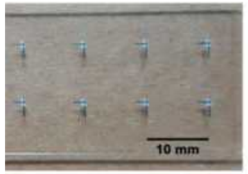
doi.org/10.1002/admt.202000070

Liquid-Metal based

Dielectrics
Substrate, Packaging, Shielding, Capacitors

Flex/Stretch Substrates
PET, TPUs, Silicones, Beyolux, etc.

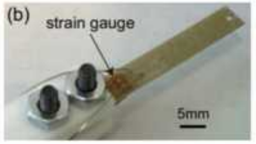
[https://www.shutterstock.com/]



doi:10.1021/acsnano.8b06464

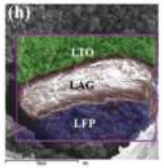
Cross-over & High-K Dielectrics
For multiple trace layers or capacitors

Specialized
Sensors, Resistive, Batteries, Optical, etc.



doi:10.1109/jsen.2020.2976508

Force Sensors



https://doi.org/10.1002/adfm.201906244

Batteries

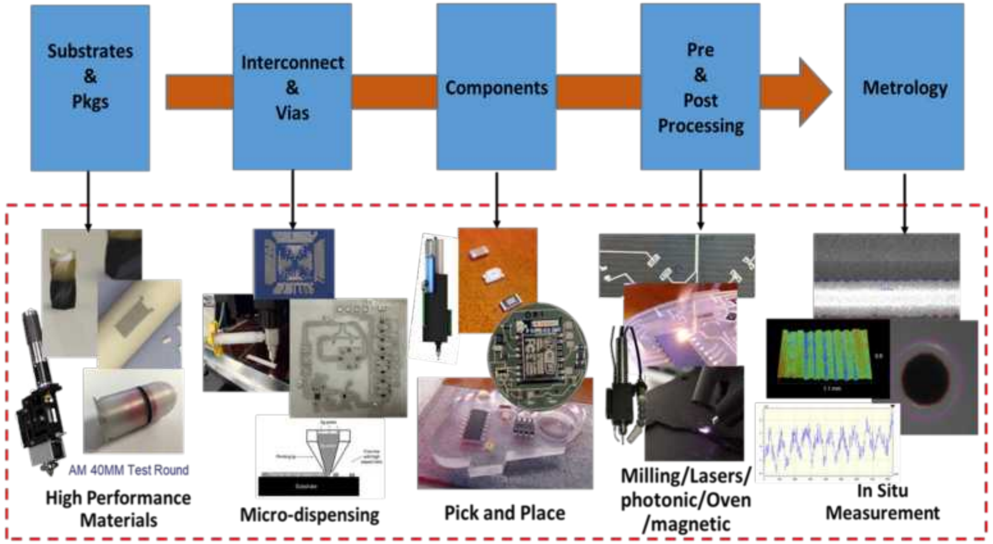
AME Advances Manufacturing Integration & Productivity

Manufacturing Integration

Fraunhofer IPA – Next Factory
IJ + Cure/Sinter + Planarize + P&P/Assembly + Measurement/Inspect
100X100X50 mm build area; 10 micron layers, 150/250 micron l/s

[https://doi.org/10.1016/j.microrel.2018.04.008]

nScrypt
FDM + DW + P&P + Milling + Curing + Measurement



#thanks & with permissions from Mike Newton & nScrypt

Integration & Productivity

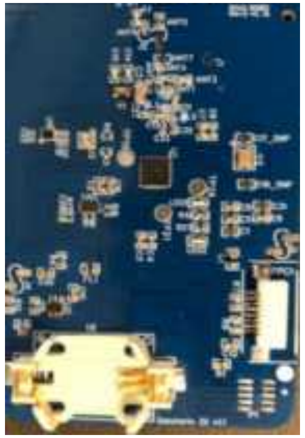
Screen Print
Up to 8K Wafers/hr Tempo Presto PE Screen Printer
Integrated Profilometry, Alignment, Electrical Inspection, Wafer Load/Unload/Clean

Inkjet Print
Up to 1.2K Wafers/hr Suss PiXDRO
Integrated Curing, Alignment

AME HI Applications Flex Use-case

#thanks and with permissions from Girish Wable, Jabil

RIGID PCBA



Board: Rigid FR4

Subtractive process

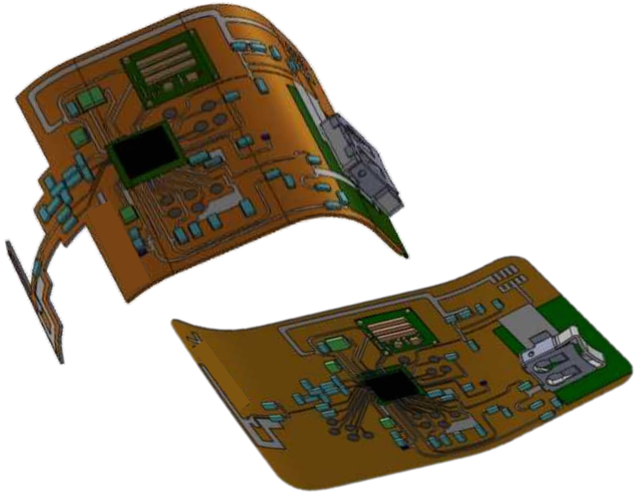
Copper traces

Weight (board): 17 grams

Assembly Temperature – 220 – 250 deg c

Cost: Baseline
PCF - Baseline

RIGID-FLEX or FLEX PCBA



Flexible Polyimide Substrate

Subtractive process

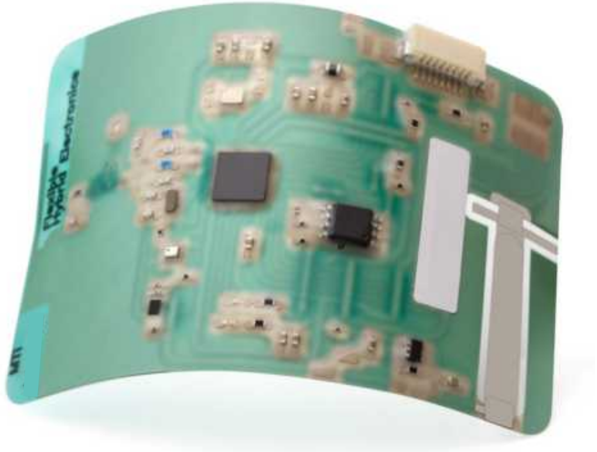
Copper traces

Weight: 6 grams

Assembly Temperature – 220 – 250 deg c

Cost: Higher
PCF - Baseline

FLEXIBLE HYBRID ELECTRONICS



Flexible Plastic Substrates

Printing (additive) process

Silver/Copper traces, Sensors

Weight: 2 grams

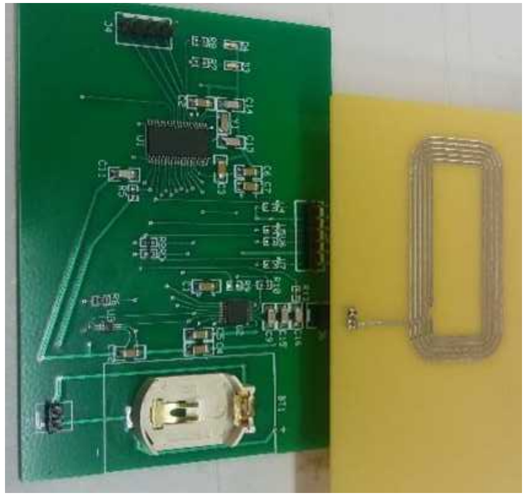
Assembly Temperature – 120 deg c

Cost*
Lower compared to Rigid Flex or Flex
PCF – Significantly Better*

*** - more data needed**

Benefits Leveraging **Weight** **Temperature** **Cost** **Flexible**

AME HI Applications Wearable Use-case



VALUE TRANSFORMATION

FLEXIBLE BENDABLE CONFORMAL

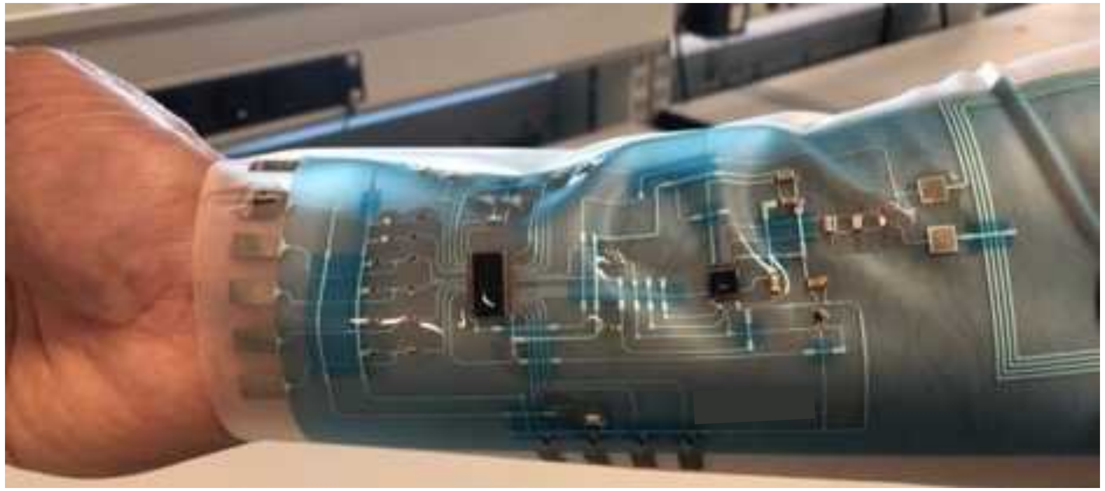
STRETCHABLE LIGHT TWISTABLE

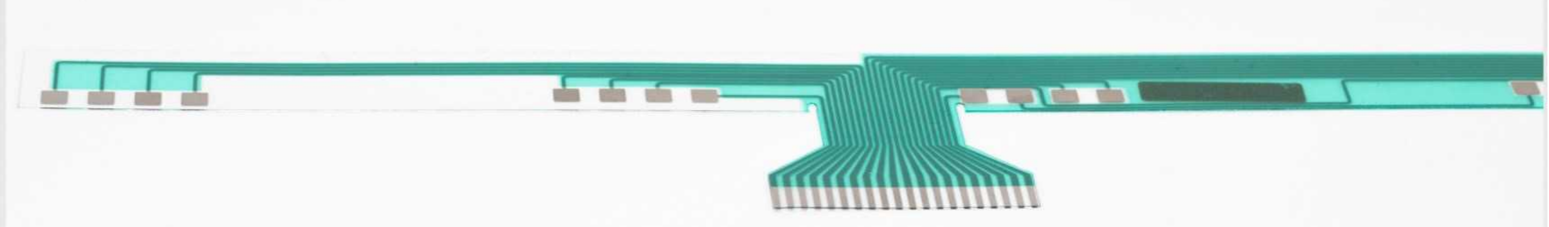
THIN DIRECT-DEPOSITED 3D

COST BENEFITS

BOM CONSOLIDATION

ASSEMBLY INTEGRATION

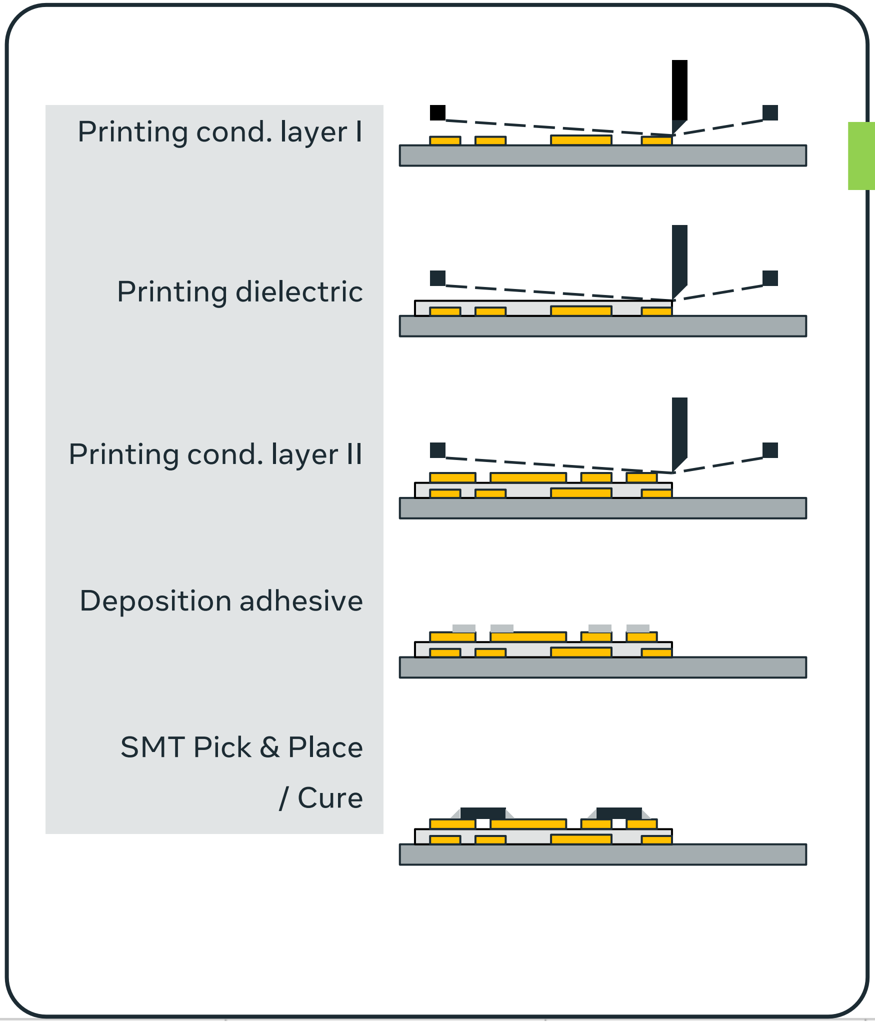


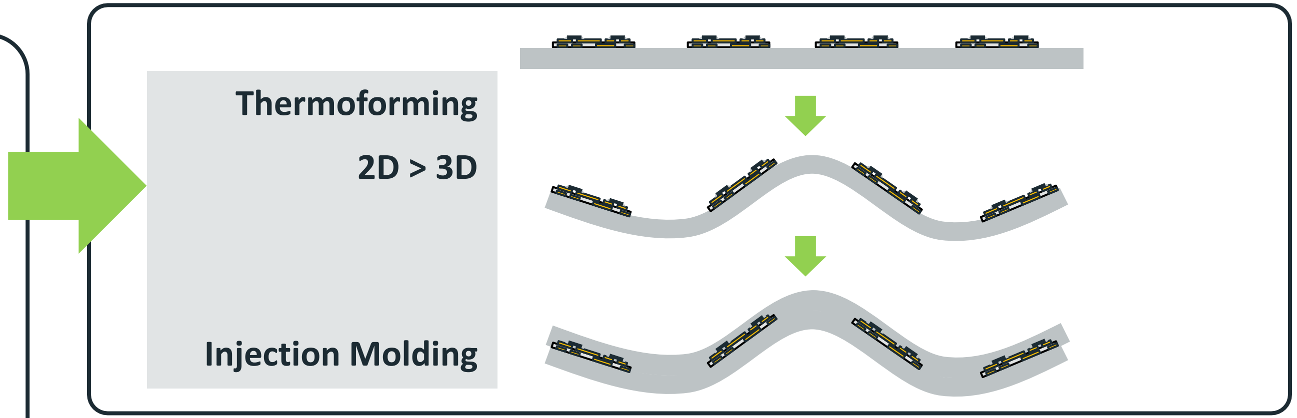


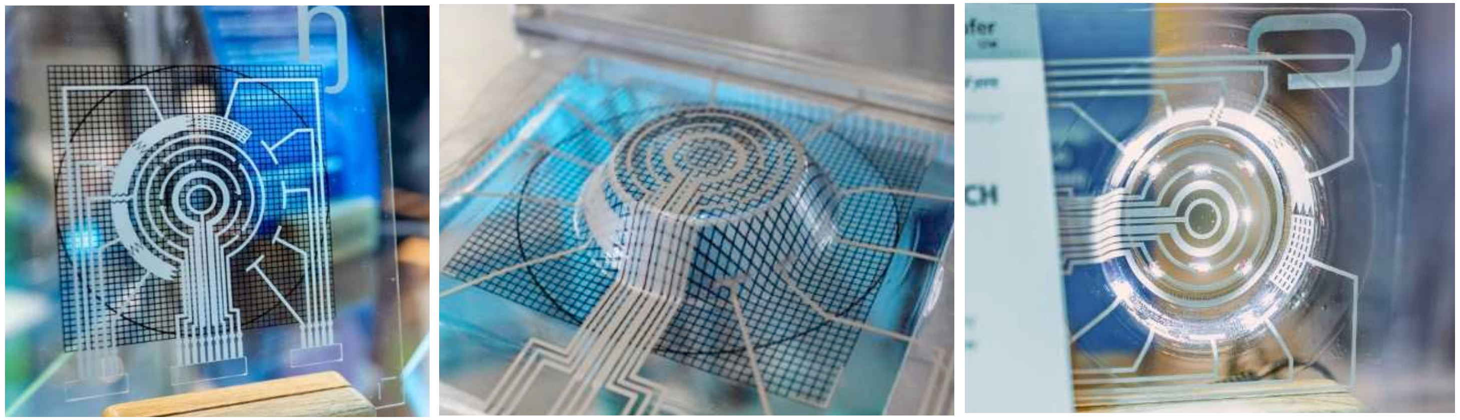
#thanks and with permissions from Girish Wable, Jabil

Benefits Leveraging **Wearability** **Integration** **Cost**

AME HI Applications Structural Electronics



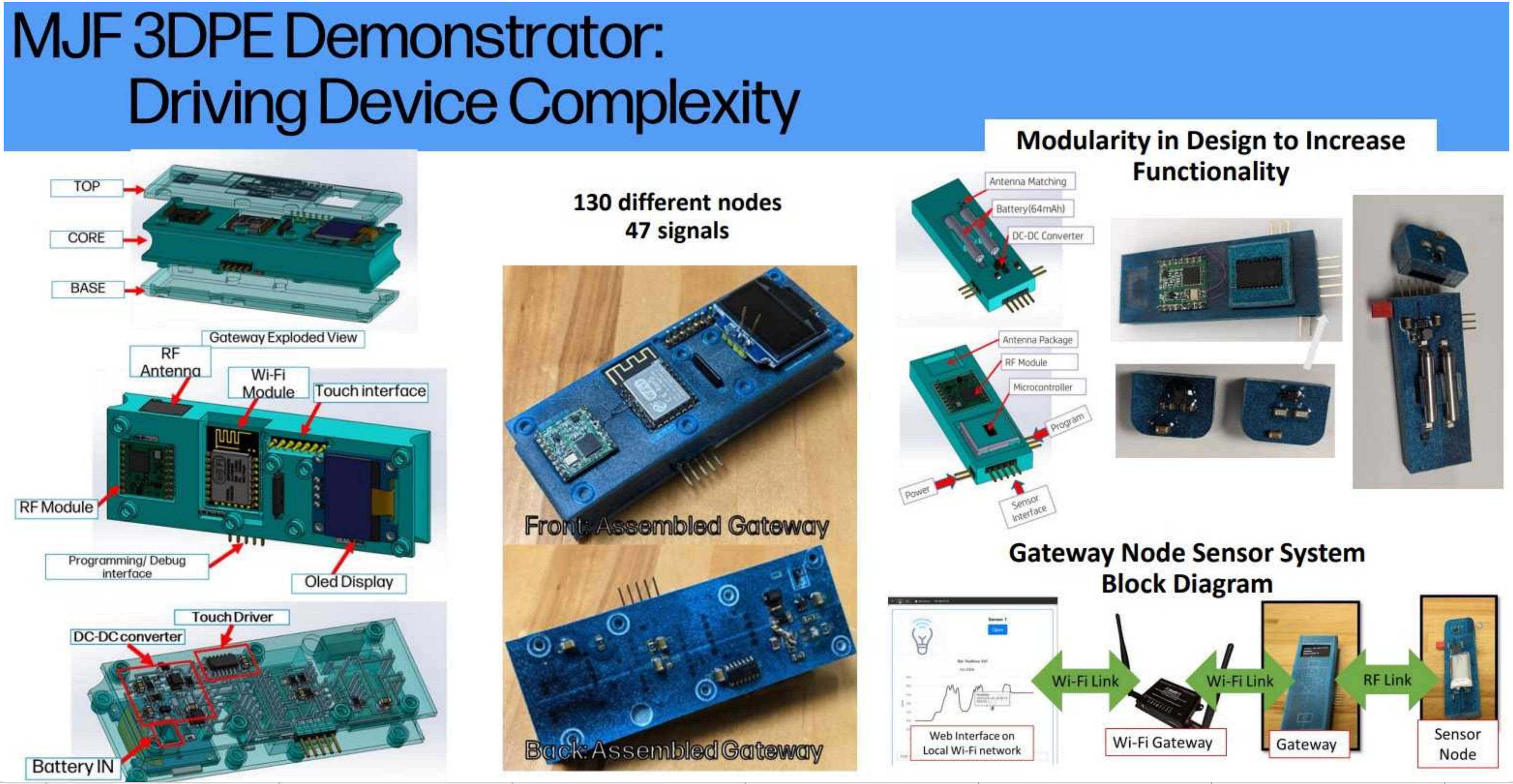




Demo of thermoformed PC foil with printed Ag-conductors and LEDs
Project "*Origami*", 02/2018 - 01/2021, *Innovations with Organic 3D Electronics.*
Funded by BMBF, Germany
#thanks & with permissions from @Christine Kallmayer and Fraunhofer IZM

Benefits Leveraging **Design Freedom**

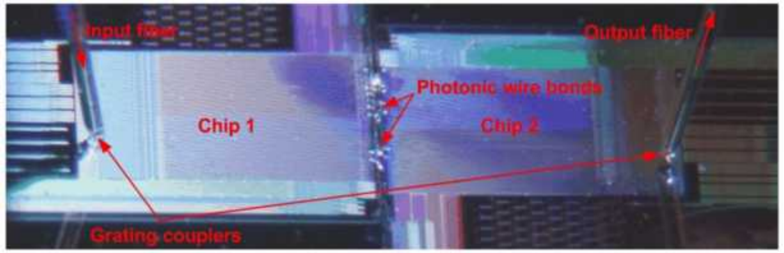
AME HI Applications 3DPE Demonstrator



Benefits Leveraging **3D Integration**

AME HI Applications Optical Wirebond

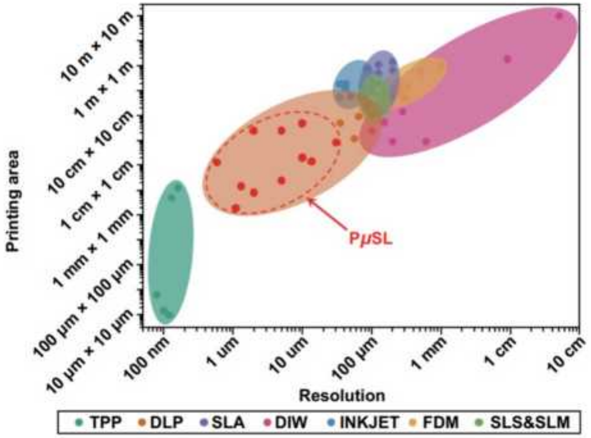
Specific Unmet HI Need
Interconnection Between Optical Chips & Output Fibers



DOI *10.1364/OE.20.017667*

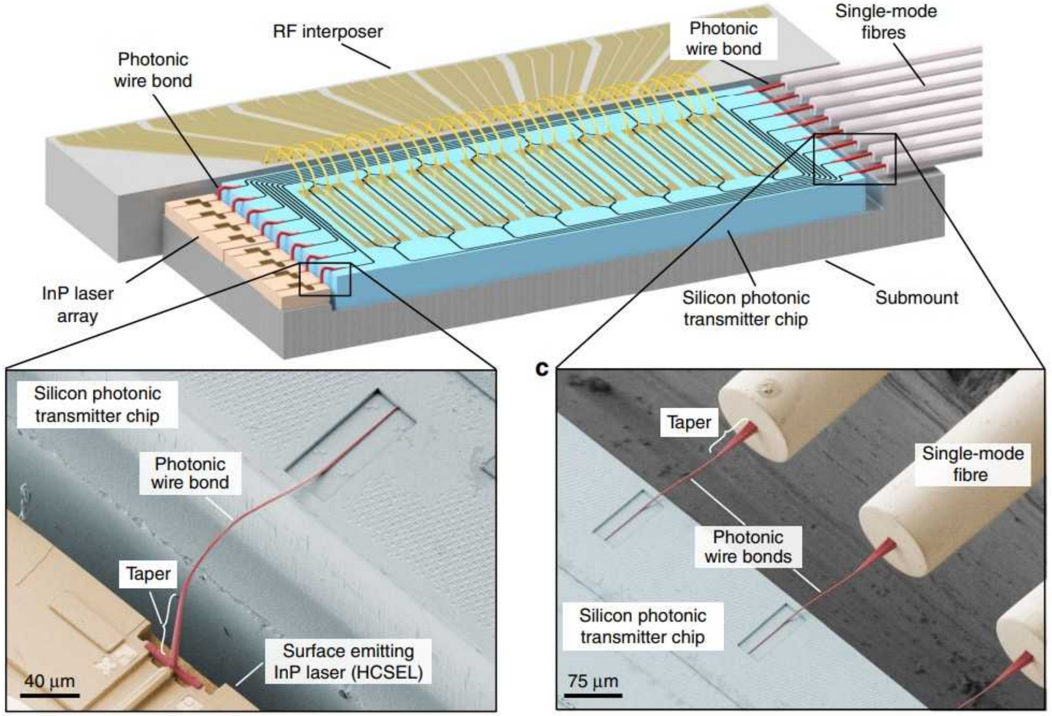
Ultra-high Resolution 2-photon AME
TPP - Two-Photon Polymerization

DOI *10.1088/2631-7990/ab8d9a*



Unique Solution Space

Index Matched Photo-resin
Automated Fabrication, Low losses, Passing Reliability Testing
400-700 GB/s Data Rate Demonstrations

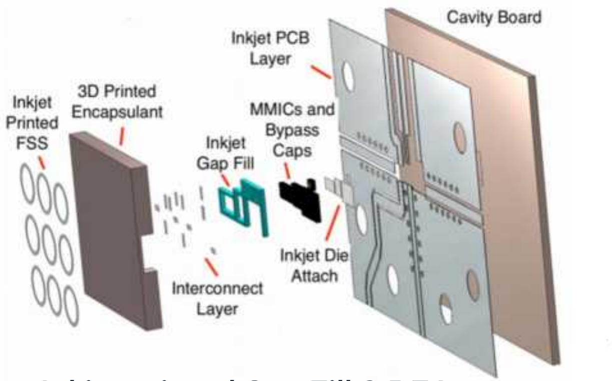


Photonic Wire-bond *doi.org/10.1038/s41377-020-0272-5*

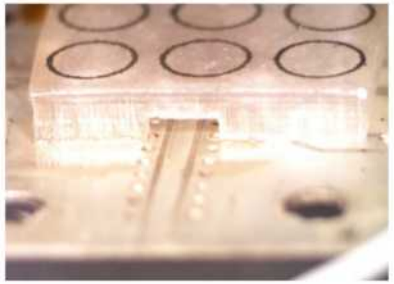
Benefits Leveraging **Unique Need + Unique Solution**

AME HI Applications RF Structures

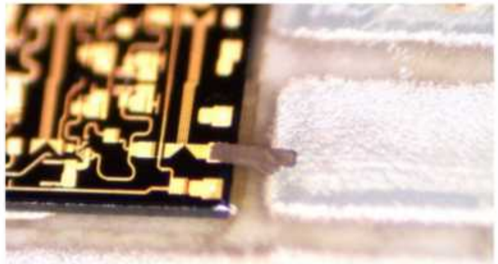
High performance monolithic microwave integrated circuit

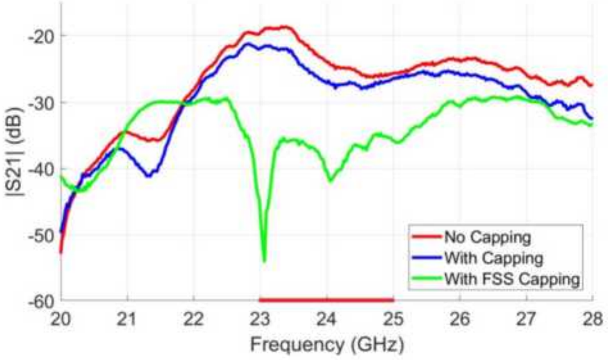


Inkjet printed FSS & SLA Printed Encapsulant



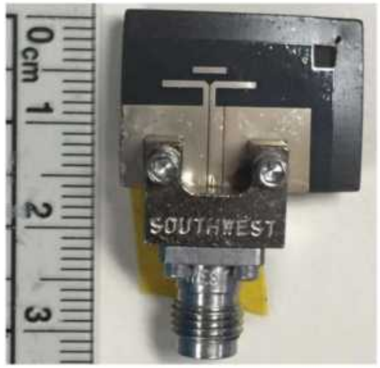
Inkjet printed Gap Fill & RF Interconnect

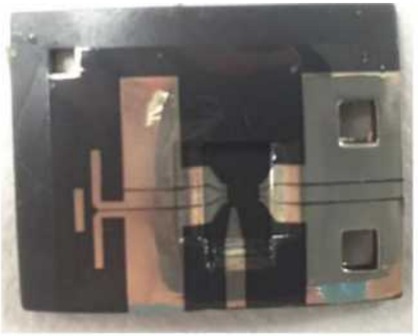




[M. Tentzeris, et al. IEEE Trans Microwave Theory Tech., **2020**, 68, 2716-2724]

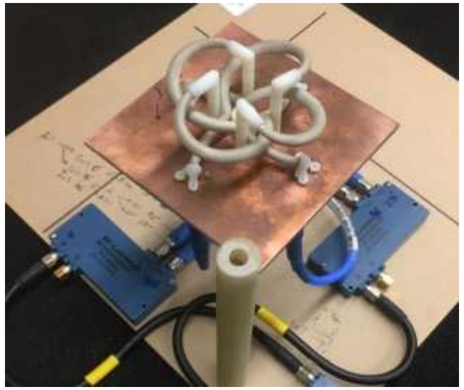
Inkjet & 3D Printed Broadband on-package Antenna





DOI 10.1109/ECTC.2018.00041

Fully 3D Antenna Geometries



DOI: 10.1109/ACCESS.2022.3202536

Benefits Leveraging **Unique Geometrics**

AME HI Applications Thermal

Air Cooled Heat Sinks

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

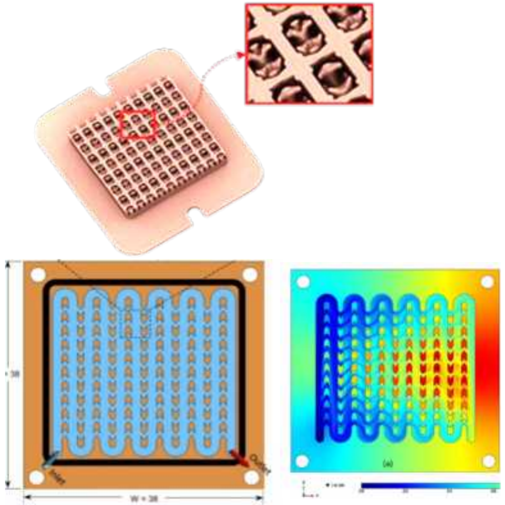
Current

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

AM Thermal

Liquid Cooled Heat Sinks

Current



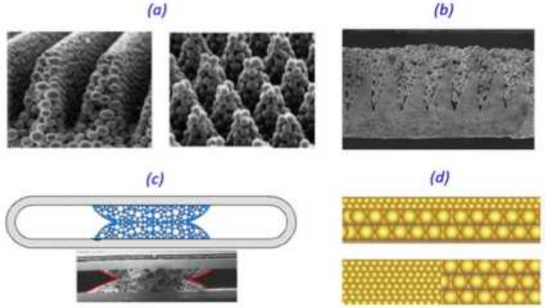
AM Thermal

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

Two Phase Convective Cooling

Current

[DOI: 10.1109/ITHERM.2006.1645335]



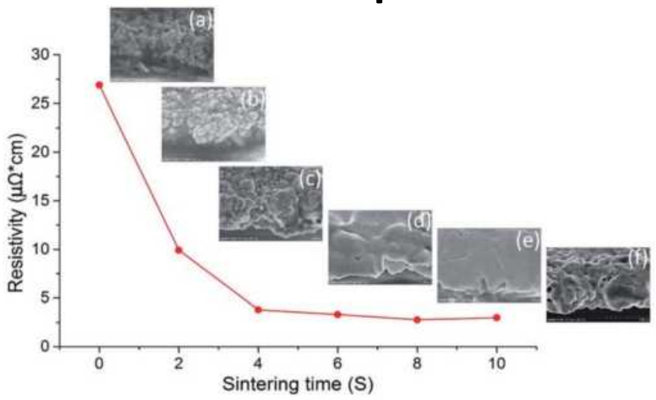
AM Thermal

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

Benefits Leveraging **3D & Design Freedom**

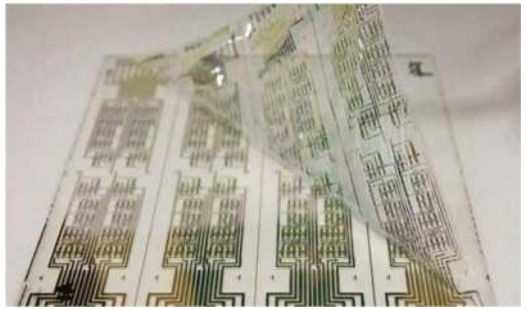
AME Growth Needs

Material Properties



[W. Gu, W.Yuan, et al. **RSC Adv.**, 2018,**8**, 30215-30222]

Productivity & Yield

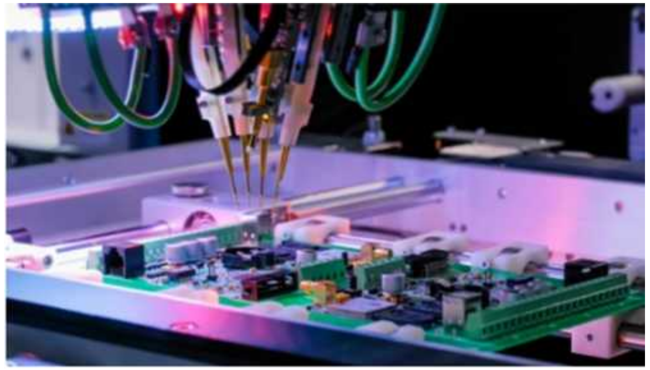


[https://commons.wikimedia.org/wiki]

Product-Level Reliability

[https://commons.wikimedia.org/wiki]

Automated Inspection & Correction



[https://www.shutterstock.com/image-photo]

Design Tools

[https://www.shutterstock.com/image-photo]

Integrated Manufacturing

Leveraging CapEx Investment & Adaptability to Current tooling

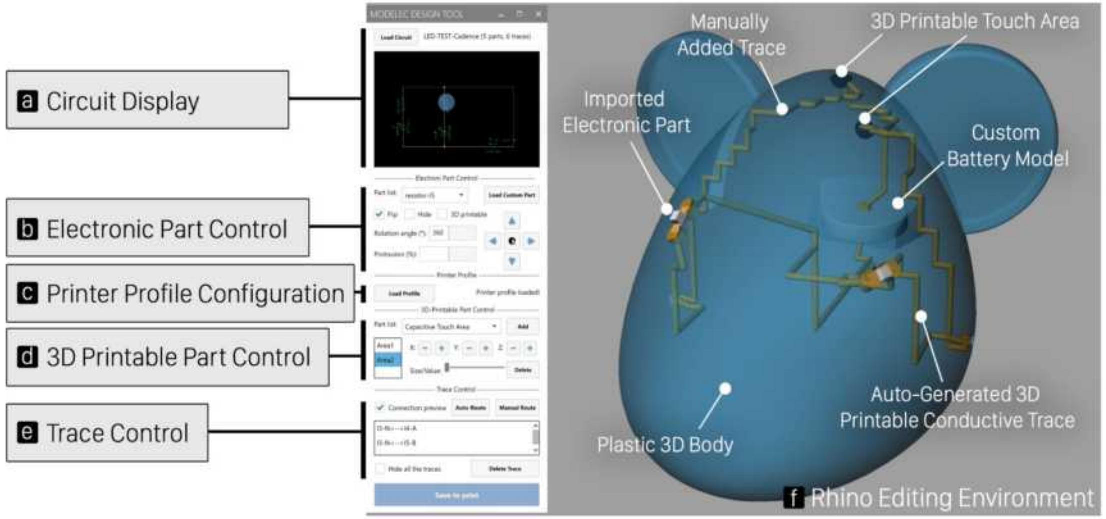
- Panel Sizes
- Planarity
- Alignment
- Form Factor
- Thermal Processes

[https://www.microwavejournal.com/articles/31986]

AME Growth Needs Design & Layout

Merging of EDA & CAD

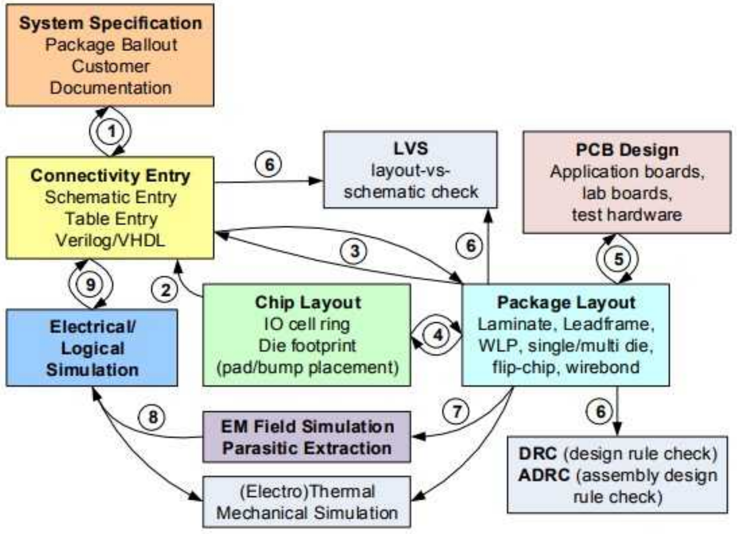
ModElec

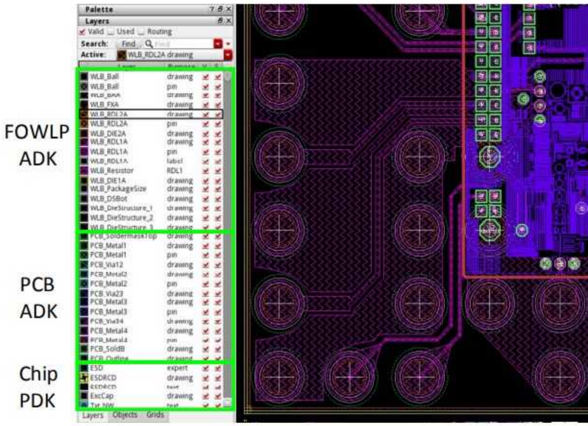


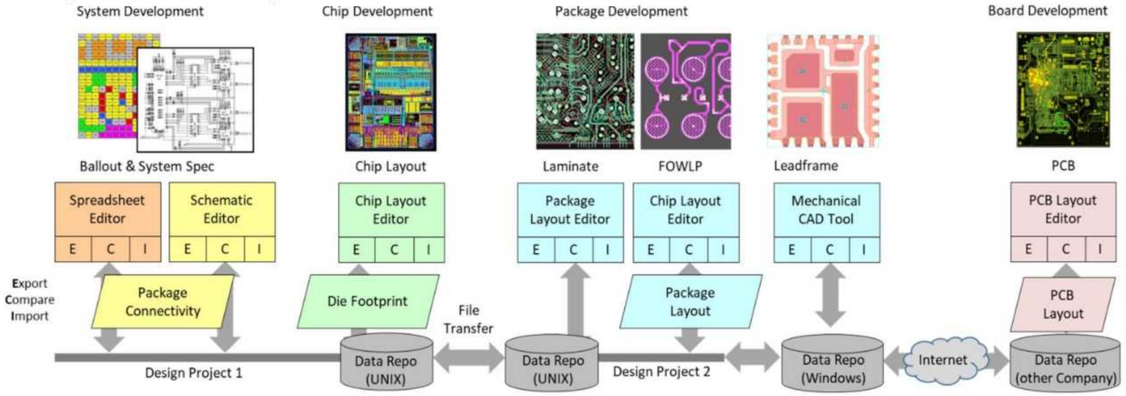
[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

Integrated Co-Design Workflows

Example of Chip/Package/Board Co-design flow







DOI: 10.1109/ECTC32862.2020.00269

AME Growth Needs Reliability

Product Testing Considerations

Thermal Cycling
Typical Tested Operating Temperature Ranges
Military -55°C to 125°C
Automotive -40°C to 125°C
Industrial -40°C to 85°C
AEC-Q100 Lvl 2 -40°C to 105°C

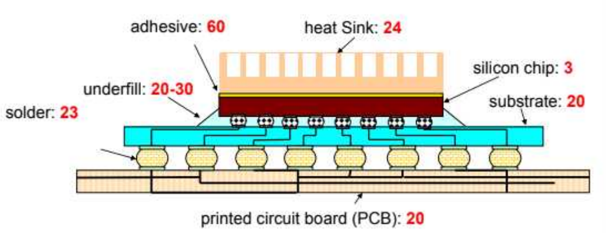
High Temp/High Humidity
Level 1 - 85°C/85%RH – 1000 hrs

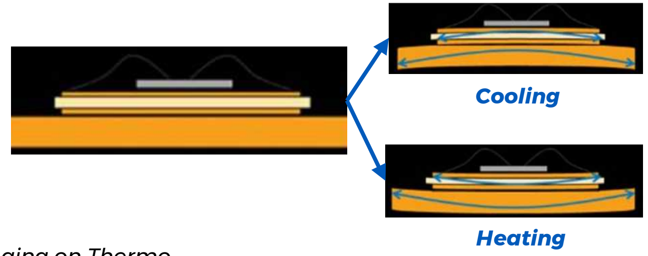
Drop Analysis
Per JESD22-B111A (2016)

Electromigration
Void & Hillock generation

Material CTE Considerations

CTE for Standard Packaging Materials ppm/°C

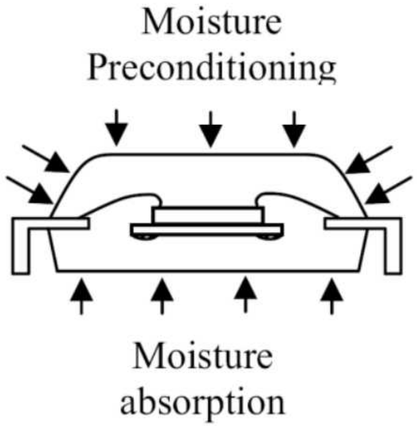




Ramdas, et al. (2019). Impact of Accelerated Thermal Aging on Thermo-Mechanical Properties of Oil-Immersed FR-4 Printed Circuit Boards.

Moisture Effects

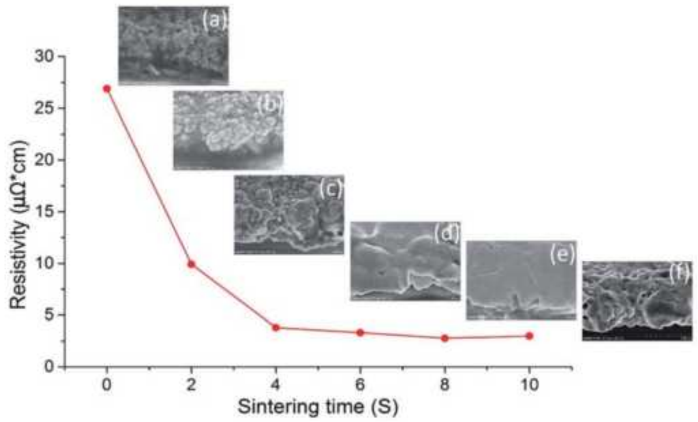
Humid Environment Effects
Material Swelling & Expansion
Moisture Density enhancement
Moisture Vaporization at Reflow
Corrosion



https://doi.org/10.4233/uuid:9141f50e-5362-4b01-b06f-f1cc3acd6543

AME Growth Needs Material Properties

Conductor Properties



[W. Gu, W.Yuan, et al. ***RSC Adv.***, 2018,**8**, 30215-30222*]*

Ink Type	Ink Composition	Conductivity
Carbon conductive ink	Carbon CNT	1.8×10^3 S/m $(5.03 \pm 0.05) \times 10^3$ S/m
Polymer conductive ink	PEDOT:PSS	8.25×10^3 S/m
Nano-silver ink	Ag-DDA Ag-PVP	3.45×10^7 S/m 6.25×10^6 S/m
Liquid metal ink	EGaIn $Bi_{35}In_{48.6}Sn_{16}Zn_{0.4}$	3.4×10^6 S/m 7.3×10^6 S/m

doi:10.3390/mi7120206

Ag bulk conductivity *6.3E7 S/m*
Cu bulk conductivity *6.0E7 S/m*

Dielectric Material Properties

Example - RDL Material Property Considerations

Characteristic	Ideal Properties	Polymer Family							
		Epoxy		BCB	Polyimide	Polybenz-oxozole (PBO)	Fluro-polymer	Hydro-carbon	Metal Oxide
		Non PID	PID						
Electrical	Low loss Low D_k								
Physical	Ultra thin dry film (2-5 μm) Planar								
Thermal	Low-CTE Withstand 260 ºC solder reflow								
Mechanical	High Elongation Low modulus								
Chemical	Resistance to chemicals Good adhesion								
Cost	Low Material and Processing Cost								
Reliability	Low Stress Low moisture absorption								

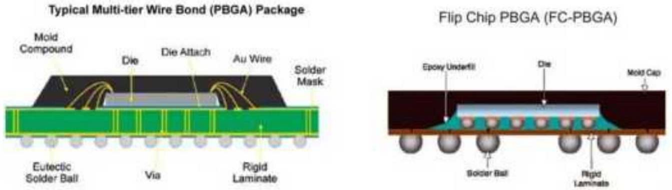
DOI 10.1109/ECTC32862.2020.00182

Both especially important for high-speed and high-frequency Applications!

AME Growth Needs Application Targets

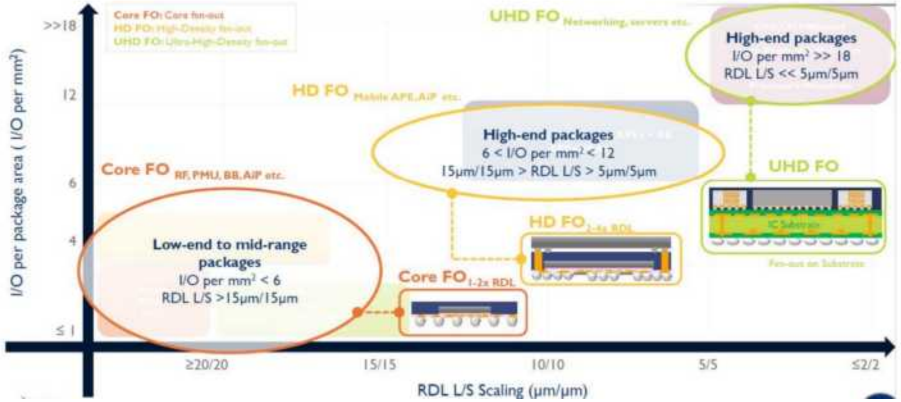
Advanced Packaging Targets

Interconnects



Bonding Method	C4 FC (Contolled Collapse Chip Connect)	C2 FC (Chip Connect)	TC/LR (Local Reflow) FC	TC FC
Schematic Diagram				
Major Bump Pitch Range at Application	> 130 um	140 um ~ 60 um	80 um ~ 20 um	< 30 um

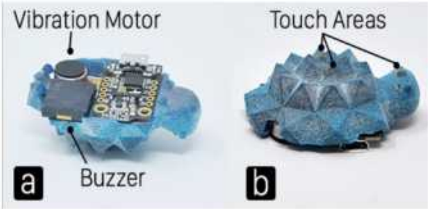
Redistribution Layers (RDL)



	2019	2023	2027
Link speed (Gbps)_Serial Speeds [4]	50	100	200
BU dielectrics loss, Df	0.007	0.004	0.002
BU dielectric roughness (Rq)	300~400 nm	150~200 nm	100~150 nm
Cu roughness (Rq)	350~400 nm	200~250 nm	50~100 nm

[HIR 2021 version (eps.ieee.org/hir), Ch. 8 & Ch. 23]

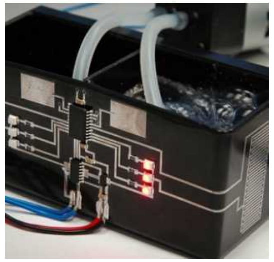
Application Targets Leveraging Unique AME Capabilities



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

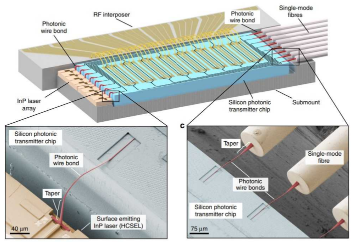
DOI 10.1186/s13104-015-0971-9

Individualized Designs



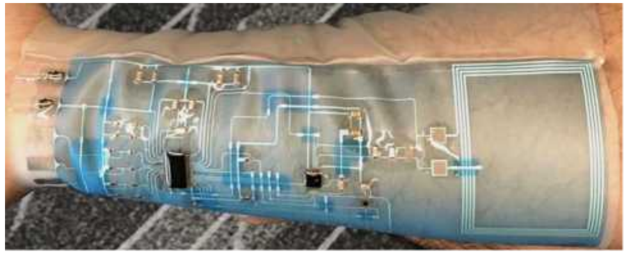
DOI: 10.29026/oea.2018.170004

3D Form Factors

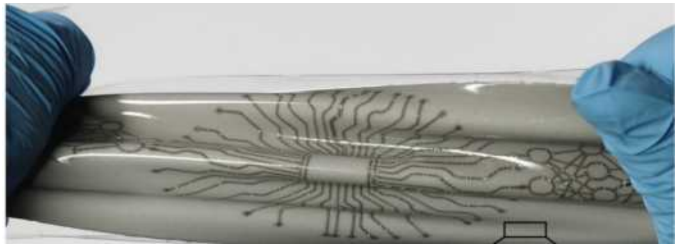


doi.org/10.1038/s41377-020-0272-5

Meeting Unique Needs



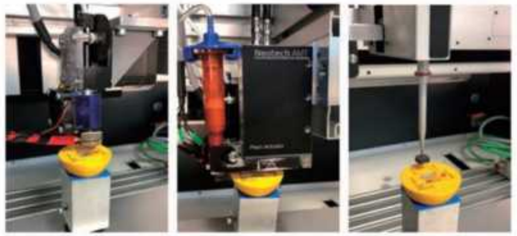
[https://www.jabil.com/blog/flexible-electronics.html]



https://doi. org/10.1038/s41563-018-0084-7

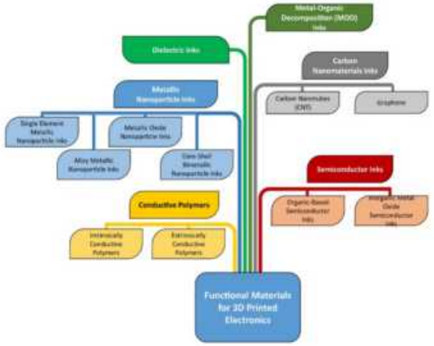
Flex/Stretch Electronics

AME for Packaging & HI Impact



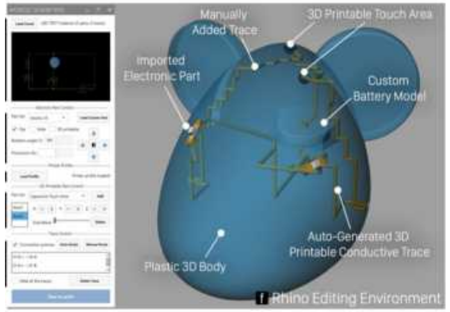
[M. Ankenbrand, M. Hedges. 2019 International Conference on Electronics Packaging (ICEP), 2019, pp. 273-278]

Manufacturing Methods & Integration **+**



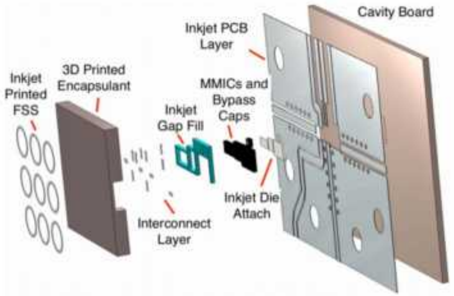
[H. Tan, C. Chua. Progress in Materials Science 127 (2022) 100945]

Materials **+**



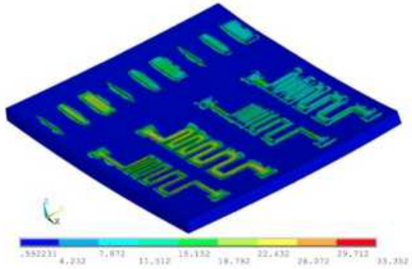
[L. He, J. Wittkopf. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., Vol.5, No.4, Article159]

Design Tools **+**



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

Application Development **+**



[https://doi.org/10.1016/j.microrel.2018.04.008]

System Reliability

Needing Concerted Advances from all for Adoption & Market Success