HETEROGENEOUS INTEGRATION ROADMAP

2024 Edition

Chapter 25: Additive Manufacturing & Additive Electronics for Heterogeneous Integration

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Chapter 25: Additive Manufacturing & Additive Electronics for Heterogeneous Integration

1. Introduction

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1.1. Executive Summary

The focus of this chapter within the Heterogeneous Integration Roadmap is on Additive Manufacturing methods as applied towards advanced electronics packaging needs, generally termed Additively Manufactured Electronics (AME), with a growing number of additive manufacturing or printing (2D print and 3D print) methods which have begun to find use for advanced electronics fabrication and heterogeneous integration.

Additive methods are varied, so the introductory material defines which methods are discussed by providing an overall taxonomy for the full chapter. This is followed by comparison metrics between the different additive methods which are relevant to advanced electronics packaging and then a discussion on how additive methods can be utilized by and be beneficial for heterogeneous integration.

The rest of the chapter is then split into sections covering specific additive manufacturing methods, AME design tools, AME materials and finally AME application areas (including printed passives, thermal, optics/photonics, wearables, and printed sensors).

This chapter aims to provide sufficient rationale for why additively manufactured electronics is a compelling, complimentary direction for future electronics manufacturing, to speak to the benefits and drawbacks of additive manufacturing approaches, to highlight key growth areas needed for further adoption and to provide examples of where additive methods are already finding in-roads into future electronic device fabrication.

Briefly, some major opportunities that are covered for AME as applied towards HI include:

- **Environmental considerations** – less material waste and fewer process chemical
- **Reduced Manufacturing steps and parts** – for BOM reduction, process flow simplicity and reduced manufacturing infrastructure
- **Scalability and manufacturing flexibility** – quicker possible fabrication times and adaptability of design (digital manufacturing) for broad SKU's or even individualized designs
- **Design Freedom and 3-dimensionality** – broader design possibilities, especially allowing for creation of complex, 3-dimensional form-factors

Some drawbacks of AME which need further development before broader adoption by electronics manufacturers include:

- **Final conductivity of traces** – typically less than bulk metals
- **Resolution and edge quality** – for high productivity AME methods, typically below the resolution of standard PCB technologies
- **Reliability**- early-stage usage of AME methods within production environments means that many reliability issues (i.e. material properties/performance under accelerated life-testing) have not yet been fully optimized or proven through full product life-cycles
- **Design environments** – design tools for AME methods are less developed compared to their PCB counterparts

The authors intend for this broad coverage of AME as it applies to advanced packaged electronics and heterogenous integration to both provide a sufficient overview of these technologies to inform the electronics community about the growing importance of this field, as well as to highlight to those active in additively manufactured electronics to understand what opportunities exist and what growth is needed to best develop towards robust solutions which can accompany or replace current electronics manufacturing approaches.

Section and lead authors for the different sections are found below:

Number	Section	Sub-Section	Write-up Lead
1.1	**Introduction**	Executive Summary	Kris Erickson
1.2		Overview	Kris Erickson - *Meta*
1.3		AME Benefits & Drawbacks	Jeroen van den Brand - *TNO Holst Center* Rich Neill - *ADVPES*
2.1	**AME Fabrication Methods**	FFF/FDM	Martin Hedges - *NeoTech AMT*
2.2		Powder Bed-based	Jarrid Wittkopf - *HP*
2.3		SLA/DLP	Kris Erickson - *Meta*
2.4		Screen Print	Girish Wable - *Jabil*
2.5		Additive + Subtractive	Alex Cook - *Nextflex*
2.6		Aerosol Printing	Martin Hedges - *NeoTech AMT* Rich Neill - *ADVPES* Mark Poliks - *Binghamton University*
2.7		Electrohydrodynamic Jetting	Dean Turnbaugh - *NTV USA*
2.8		Thermoforming/MID	Christine Kallmayer - *Fraunhofer - IZM*
2.9		Piezo Valve	Martin Hedges - *NeoTech AMT*
2.10		Inkjet	Kris Erickson - *Meta*
2.11		Laser Direct Structuring	David Bowen - *University of Maryland - College Park*
3	**AME Design Tools**	Design Tools - 2D, 3D	David Weins - *Siemens* Martin Hedges - *NeoTech AMT*
4.1	**AME Materials**	Conductive Materials	Markus Scheibel - *Heraeus*
4.2		Printed Thick Film	Dave Rosenfeld - *Celanese*
5.1	**AME Applications**	Printed Passives	David Bowen - *University of Maryland - College Park*
5.2		Thermal	Ercan M. Dede - *Toyota Research Institute of North America*
5.3		Optical/Photonics	Annette Teng - *Promex*
5.4		AME for Wearables	Dishit Parekh - *Intel*
5.5		Printed Sensors	Christine Kallmayer - *Fraunhofer - IZM*

1.2. Overview

Additively Manufactured Electronics (AME) is defined within this chapter as being a manufacturing process which has a printed conductor material combined with a printed or non-printed dielectric material, with optional additional supporting processes (see Figure 1.2.1). This is further broken down into 4 different categories of:

1. **Direct-write and conformal, contact methods, i.e.:**
   a) *Dispense and Extrusion*
2. **Direct-write and conformal, non-contact methods. i.e.:**
   b) *Inkjet Print (Section 2.10)*
   c) *Aerosol Print (Section 2.6)*
   d) *Electro-hydrodynamic Print (Section 2.7)*
   e) *Piezo-valve Print (Section 2.9)*
   f) *Laser Induced Forward Transfer (LIFT)*
3. **3D Print Methods, i.e.:**
   g) *Free-Form Fabrication (FFF or FDM, Section 2.1)*
   h) *Stereolithography (SLA, Section 2.3)*
   i) *2-photon SLA (Section 2.3)*
   j) *Digital Light Processing (DLP, Section 2.3)*
   k) *Powder Bed Fusion (PBF, Section 2.2)*
4. **Contact 2D Print Methods, i.e.:**
   l) *Screen print (Section 2.4)*
   m) *Gravure Print*
   n) *Flexographic Print*

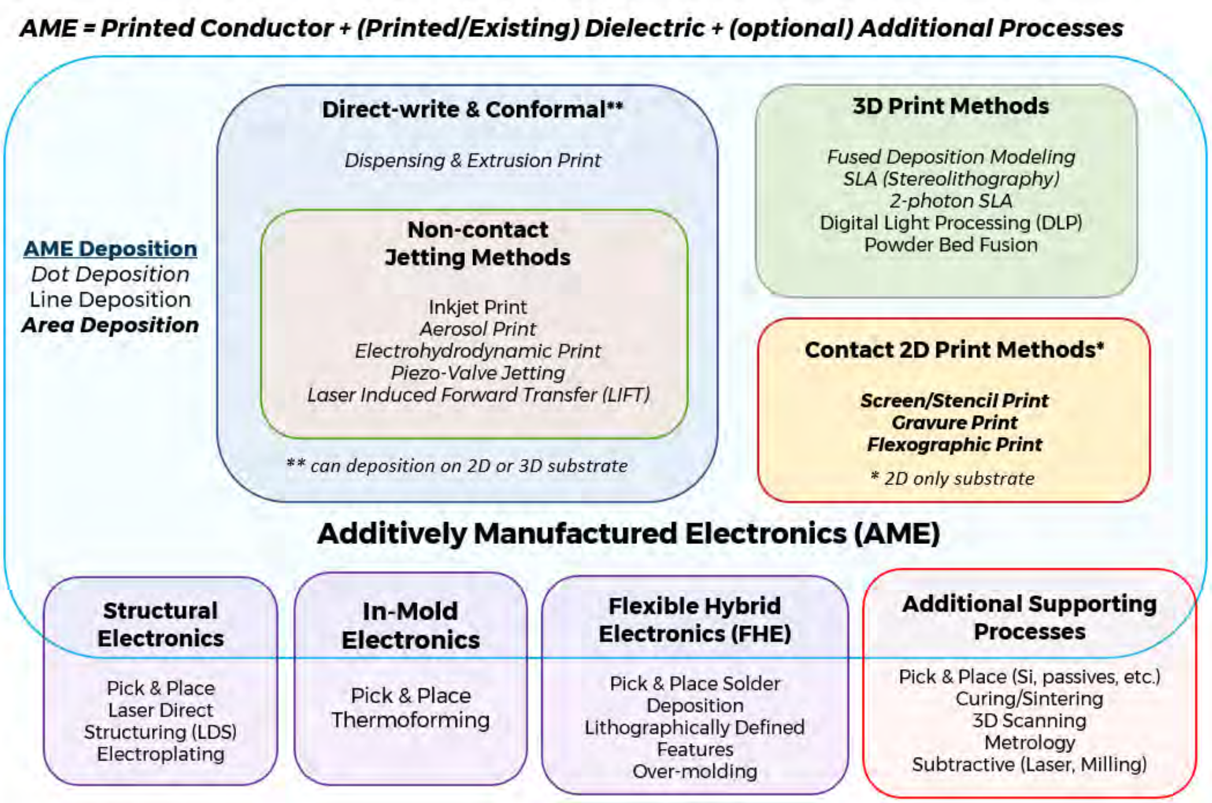


Figure 1.2.1 *- Additively Manufactured Electronics Taxonomy*

The few times where this chapter will deviate from this definition is when speaking to additive manufacturing for thermal applications (Section 5.2), wherein a single thermal materials is 3D printed, and when discussion Laser Direct Structuring methods (LDS, Section 2.9), shown above as a structural electronics process. These deviations were deemed necessary in order to still cover these important areas which are not otherwise covered within the Heterogenous Integration Roadmap effort.

Figure 1.2.1 also provides further details around if these methods are either Dot/Line/Area deposition processes and the types of dielectric substrates which are conducive for features being printed upon (either 2D or 3D substrates, as indicated). AME methods which are covered more in-depth within this chapter were selected given the prevalence of their use within a manufacturing context as well as the understanding of their potential for intersecting with heterogenous integration.

For additional supporting processes, the main one for AME methods is Pick and Place, wherein pasives, components, and/or silicone die can be placed upon a substrate during AME manufacturing, with printed traces being interconnected to contact pads. Other supporting processes worth mentioning include curing or sintering (elevated temperature for drying solvents and/or sintering nanoparticles within printed inks), in-line scanning or other metrology (for active or passive process feedback), and subtractive processes (i.e. laser ablation for finer resolution, Section 2.11).

The overlap of AME methods with other manufacturing methods is also highlighted **Figure 1.2.1**, differentiating between AME and Structural Electronics (wherein LDS and electroplating are used), In-mold electronics (wherein thermoforming is used), and Flexible Hybrid Electronics (wherein either printed or semi-additive conductive features are fabricated, over-molding may be used, and the overall device becomes flexible which may include thinned Si dies). Taxonomy within this space is highly inconsistent within literature and industry, so these definitions are largely intended for reference within this chapter, although they are generally aligned with many references to these manufacturing methods.

Another framing for AME is provided in **Figure 1.2.2** which highlights the variety of additive manufacturing methods covered within AME, the variety of starting substrates and the variety of intended applications. This framing also highlights how intentions of dimensionality (2D, 2.5D, 3D) and limitations around processing temperatures or reliability needs all go into a decisions matrix of sorts to inform the AME materials sets which are then needed for a final AME selection to be successful towards the intended application.

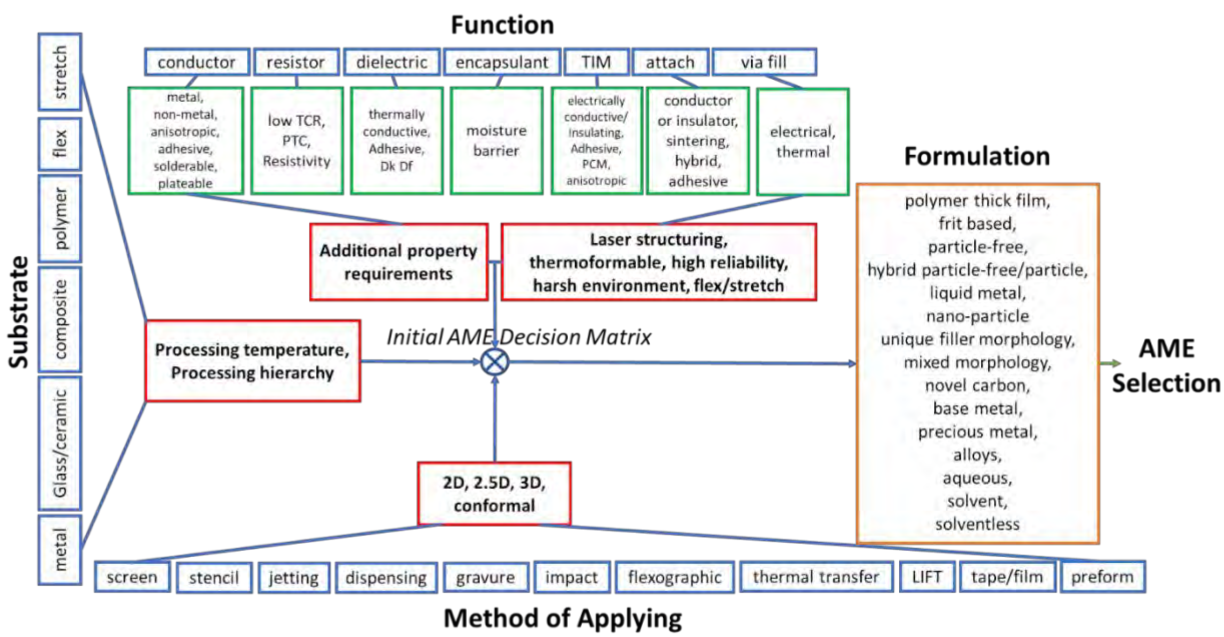


***Figure 1.2.2 -** Additively Manufactured Electronics Considerations*

Although this decision matrix is not a full and accurate decision tree to define a fully successful AME approach towards an intended application, which is beyond the scope of this chapter, it is meant to demonstrate the breadth of the AME space, with the following sections elaborating upon different portions of this AME decision matrix, speaking towards Materials, Methods, and functions or applications.

As applied towards manufacturing of electronics, two metrics in particular are useful to distinguish different AME methods:

1) Minimum feature size - *typically for a printed conductive trace*
2) Throughput - *for distinguishing manufacturing speeds and potential for scalability*

The manufacturing methods discussed within this chapter as well as some additional manufacturing methods are represented in **Figure 1.2.3**, with multiple orders of magnitude in both feature size and throughput being seen for different AME methods.

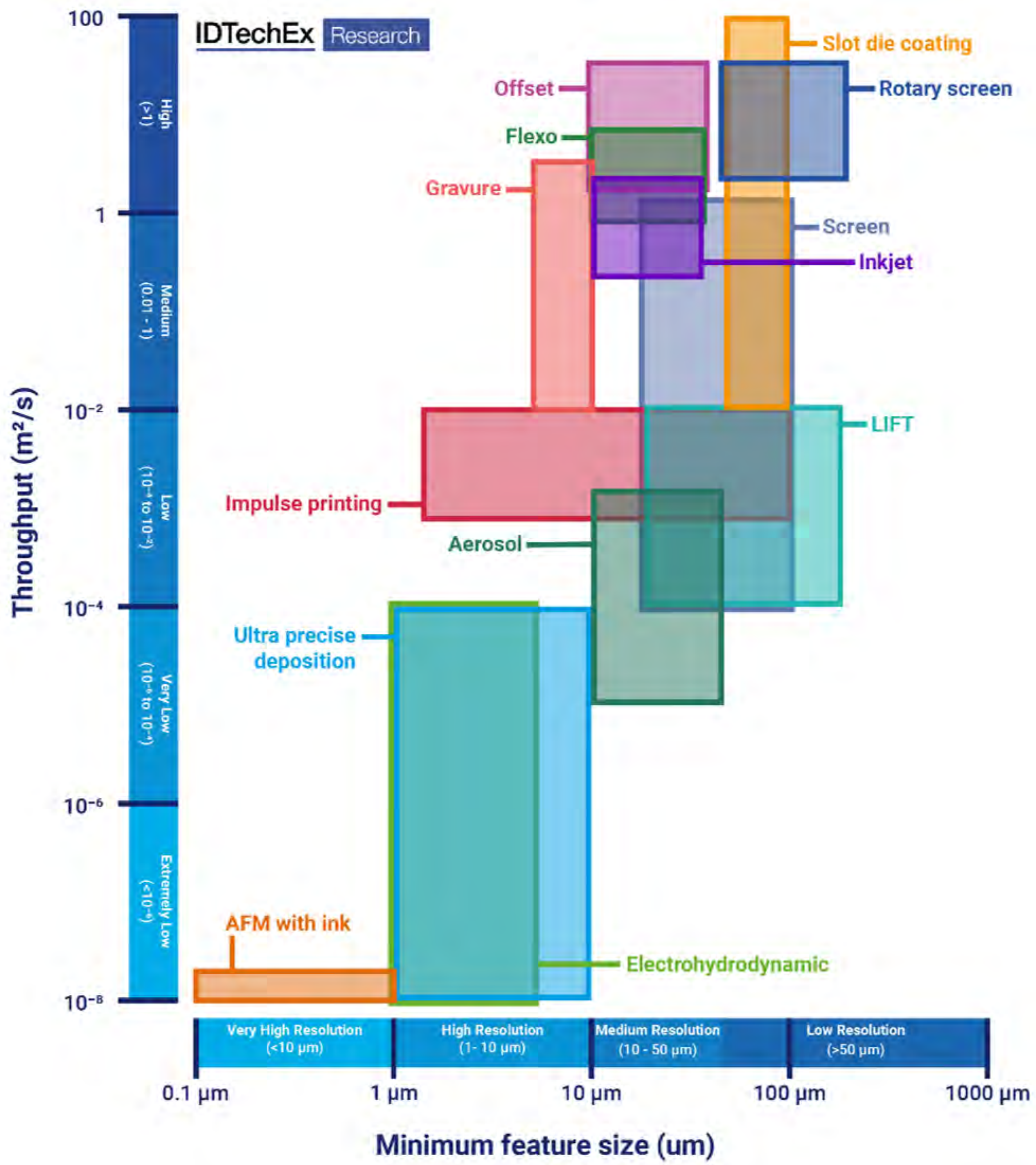


Figure 1.2.3 *- Print Speed vs Feature Size, #thanks to Max DePhillips, IDTechEx*

Although applications for electronics manufacturing vary greatly depending on the fabricated features, resolution at or below ~50 micron are often needed to achieve required features sizes (i.e. conductive traces and vias). Throughput targets for AME methods vary greatly, but generally to motivate usage of printing methods, which can have higher throughput than conventional electronics manufacturing processes, throughput of 0.01 m2/s or greater is typically targeted.

Before getting into the benefits of AME, a framing of where AME methods could be applied within heterogeneous integration is provided within **Figure 1.2.4**.

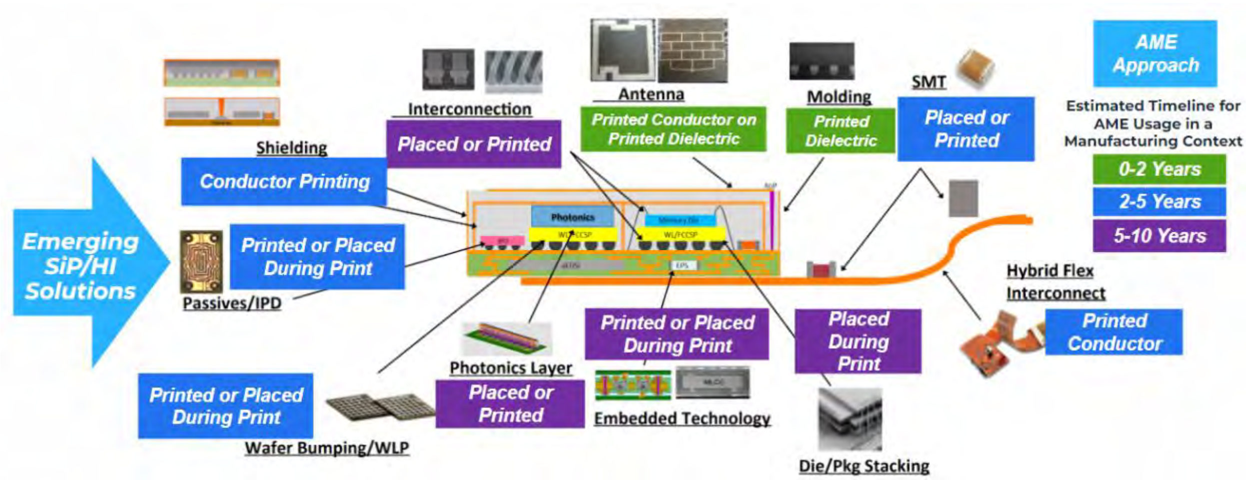


Figure 1.2.4 *AME usage within Heterogeneous Integration*

Therein, the various portions of an advanced electronic package are highlighted (i.e. antenna, shielding, SMTs, molding, interconnects, etc.), with an overlay of how each of these portions of the package can either be printed directly or could be placed during a printing process for incorporation within a heterogeneously integrated package. Examples of where AME has been used already for these different functions are provided throughout the rest of the chapter, with estimates of how long these uses will need for maturity of use within a manufacturing context indicated by the color coding.

Finally, the various AME methods and the important comparison parameters are brought together for comparison within Table 1.2.1.

		Feature Created				Resolution				Material Properties			Manufacturing Properties		
Type	**Process**	**Conductive**	**Dielectric**	**Conformality**	**Structural**	**Resolution X,Y (micron)**	**Resolution Z (micron)**	**Features sizes (Line/Space[L/S]; dielectric[E]) (micron);**	**Vias possible**	**Deposited Materials Forms**	**Multi-Material ?**	**Max Bulk Conductivity**	**Build Height per pass (micron)**	**Deposition Speed (m2/s - areal; mm/s - linear)**	**Build Dimensionality (0D,1D, 2D, 3D)**
Direct Write & Conformal	*Inkjet Printing*	X	X	X	X	20	17	L/S,E - 40/40	X	*inks, photo-resin*	*Y*	2.7E7 S/m	17	0.1-1 m2/s	1D
	Aerosol Printing	X	X	X	O	10	2	L/S - 20	X	*inks, photo-resin*	*Y*	2.7E7 S/m	*0.5-5*	5-30 mm/s	*0D*
	Electrohydrodynamic Jetting	X	X	X	O	0.5	0.5	L/S - 0.5	X	*Inks, pastes, photo-resin*	*Y*	2.7E7 S/m	*0.25-1*	50 mm/min	*0D, 1D**
	Dispensing/ Extrusion Printing	X	X	X	O	100	100	L/S - 100	X	*Inks, pastes*	*Y*	2.7E7 S/m	*1-50*	50-500 mm/s	*0D*
	Piezo/Valve Jetting	X	X	X	O	320	5-25	L/S - 320/200	X	*ink, pastes*	*Y*	2.7E7 S/m	*15-25*	15-50mm/s	*0D*
3D Printing	*Powder Bed Fusion*	O	X	-	X	100	80	E - 100	O	*powders*	*Y*	2E6 S/m	80-150	**3D -** 25 mm/hr	*0D, 1D*

	Stereolithography (SLA)	-	X	-	X	50-100	50-100	E - 150		*photo-resin*	*N*		20-100	20-700 mm/s	0D
	2-photon SLA	-	X	-	X	0.1-1	0.1-1	E - 1		*photo-resin*	*N*		0.1-10	30-100 mm/s	0D
	Digital Light Processing (DLP)	-	X	-	X	50-100	50-100	E - 150		*photo-resin*	*N*		20-100	**3D -** 10-300 mm/hr	2D
	Fused Form Fabrication (FFF/FDM)	O	O	O	X	150	50	E - 150	O	*filament, granulate*	Y		20-100	50-150 mm/s	0D
Thermally conductive 3D Print	*SLM*					50-250	50-250	200-400		*metal powder*	N	*thermal -* Cu** 400 W/mK	30-100	0.5-3.0 m/s	0D
	Binder Jet					100	80	150		*metal powder*	N	*thermal -* Cu** 400 W/mK	80-150	**3D -** 25 mm/hr	1D
	ECAM					30	30	60		*metal electro-deposition*	N	*thermal -* Cu 400 W/mK	10-50	**3D** 1-2 mm/hr	2D
Planar 2D Print	*Screen Printing*	X	X	-	O	10-50	25-40	L/S, E - 50/50	X	*pastes*	Y	2.7E7 S/m	1-50	0.01-1 m2/s	2D
Hybrid & Structural Electronics	*Laser Direct Structuring*** *	X	O	X	O	1	1	L/S - 25/25	X			3.48E7 S/m			0D
	Additive + Subtractive	X	X	X	X	10		L/S - 15/15	X					1,000 mm/s **OD** 1E-6 m2/s **2D**	0D

Table 1.2.1 *- Comparison Matrix for AME Methods.*

Legend: X *Typical;* ***O*** *Case-dependent;* ***-*** *Not typical;* ***Greyed cell*** *- Not applicable*

Table 1.1 highlights many different comparators, including:

1) **Features Created:**
   a) Conductive - *if typical conductive features like traces can be fabricated*
   b) Dielectric - *if dielectric features can be fabricated, typically substrate material*
   c) Conformality- *if features can be deposited conformally onto a substrate which has some level of 3-dimensionality*
   d) Structural- *if fabricated material can be a mechanically active feature, wherein additional material is build upon it or mechanical loads can be applied*
2) **Resolution:**
   a) Resolution - *in the x/y build-plane, and in z-axis or perpendicular to the build-plane*
   b) Feature sizes - *for line and space of printed traces (L/S), dielectric features (E) and vias*
3) **Material Properties:**
   a) Deposited material forms - *inks (<1,000 cP), pastes (>1,000 cP), powders, photoresins, filaments, etc.*
   b) Multi-Material - *if multiple types of materials can be co-fabricated*
   c) Max Bulk Conductivity - *fully optimized process (may include multiple print passes, substrate optimizations, etc.) for printed trace material. Typical values have a broader range, usually below the max indicated. Details further within the materials (conductor) section*
4) **Manufacturing Properties**
   a) Build-height per print pass
   b) Deposition Speed
   c) Build Dimensionality - *0D (point deposition); 1D (line deposition); 2D (area deposition)*

Sections throughout the chapter will elaborate upon these manufacturing methods as well as the values indicated within Table 1.2.1.

1.3. AME Benefits

Lead: Jeroen B.
Contributors/Editors: Rich N., Christine K.

1.3.1. Introduction

Traditional electronics heavily relies on standard, mostly rigid PCB technology, which requires many individual and often environmentally unfriendly processing steps. Next to this, because of the extended supply chains, the time between initial electronic design idea and final product can be quite long.

In contrast to existing approaches, the emergence of AME has introduced several advantages and new capabilities to designers and fabricators as well as manufacturing approaches enabling sustainability and reusability for a greener environment. Starting with the design and development approach, AME benefits from the ability to; accelerate (or reduce) design-to-fabrication time, enabling quick prototypes, greater design space freedom, all while offering the ability to support different functionalization scenarios coupled to 3-dimensional package geometries. From a sustainability perspective, emerging AME methods and innovations are paving the way towards material recapture and automated repair techniques that reduce waste and offer opportunities for product recycling. Consequently, AME is being actively investigated with a view to adoption across a wide range of industries including medical devices, automotive, signal electronics and wearables to name a few.1. Figure 1 below gives a nice illustrative example of how for an automotive interior application, a part can be simplified using AME technologies. On the left side, the original part is shown, which consists of many different elements that need to be assembled into the final part. On the right-hand side, the AME-optimized part is shown. Significant improvements could be achieved on space, weight and ease of assembly.

<table>
<tr><td></td><td></td></tr>
<tr><td>Traditional part:
● 64 parts + PCBA
● Costly assembly
● 45 mm assembly depth
● 650 grams</td><td>IME-based part:
● 1 molded part + small PCBA
● Fewer parts to design, minimal assembly
● 3 mm molded material thickness
● 150 grams</td></tr>
<tr><td colspan="2">Figure 1.3.1. Comparison between traditional automotive part (left) and AME-enabled part (right). Source: TactoTek.</td></tr>
</table>

The following sections expand on specific AME benefits and drawbacks and concludes with two sample illustrative use-cases.

1.3.2. Benefits of AME from a manufacturing perspective

From a manufacturing point of view, additive manufacturing brings advantages in several aspects. In general, AME-based products can be designed and fabricated in a more integrated lifecycle leading to greater efficiencies in design-to fabrication product lifecycle. CAD tools for AME are being developed to support concurrent schematic and electronic design alongside mechanical design. This includes tool-pathing, material selection, and multi-material deposition, enabling designers to perform design tasks, followed by fabrication, significantly reduced the product development lifecycle.

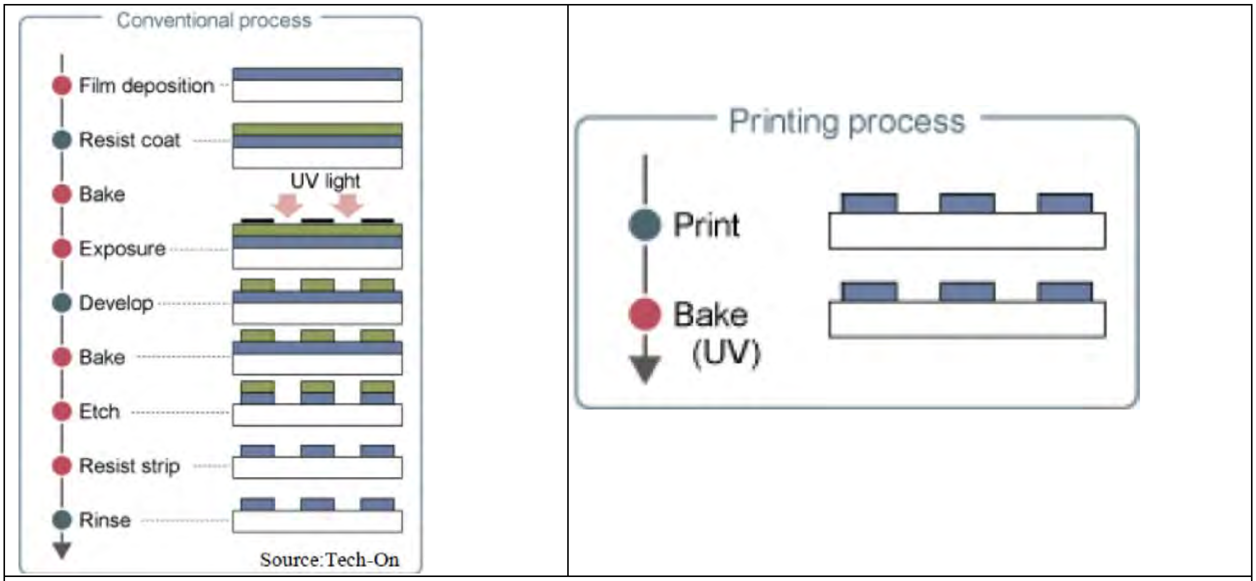


Figure 1.3.2. Comparison of process flows for conventional PCB manufacturing (top) and for AME (bottom).

1.3.3. Process flow simplicity

A clear advantage of AME is that the overall manufacturing of the circuits is greatly simplified as compared to standard PCB manufacturing. See Figure 2. Traditional PCB's are made through a (large) number of individual processing steps. For multilayered circuits, these processing steps need to be repeated. AME-based manufacturing process has less steps: typically just a printing step of a liquid functional ink and then a curing step (UV or thermal) to remove solvents and to dry and/or cure the polymer. Multilayer circuits are made by repeating these printing/curing steps.

1.3.4. Volume scalability and flexibility

A second advantage of AME-based manufacturing can be found in the volume scalability of the technology: the full range from single piece manufacturing up to volume manufacturing is achievable. For small volumes, digital printing technologies like inkjet or dispensing can be used to - with minimum effort - produce a first part or a small series of products. This allows to quickly iterate designs and to produce one-of-a-kind products (including personal, individualized designs, if needed) or first prototypes. In what used to take weeks if not months for design/fabricating PCBs, can now be completed in hours or days. For medium-sized volumes, typically screen printing technologies are available to be used, see Section 2.4 - Screen Print. For really large volumes, R2R printing technologies are available to be used, which is not covered in the HIR chapter, but other references can be found for this level of scale.

Since AME design and manufacturing can be based on digital technologies, product configuration becomes possible at manufacturing time. Indeed, such programmatic and dynamically configurable manufacturing processes underlies one of the single largest benefits of AME based product manufacturing and the promise of Industry 4.0.

Moreover, because of this inherent flexibility with respect to volumes, AME technologies can excellently serve to simplify the long supply chains that currently exist for electronics manufacturing.

1.3.5. Substrate and material flexibility

AME technologies typically work by 'adding' a functional ink in a structured fashion to an existing substrate or structure. These inks are then either thermally or photonically (e.g. UV) cured to give the final properties. Because of this, AME has a much greater flexibility with respect to substrate material than conventional PCB technologies. Only some basic requirements with respect to dimensional stability and some thermal stability requirements need to be met. In the figure below, some illustrative examples are shown in which AME has been deployed on different substrate types.

Figure 1.3.3 *- .Some examples of AME deployed on different substrate types. Bottom left: NFC tag on a silicone substrate, Top left: moisture sensor on paper for smart envelope application, Top right: Printed circuit on textile. (Source: Holst Centre).*

1.3.3. Benefits of AME from a product perspective

Also from a product perspective, the deployment of AME technologies can bring clear benefits.

1.3.3.1. Limiting and optimizing the space needed for electronics

In the traditional way of making electronics, electronic circuits are built on a rigid/flexible PCB, which has a typical thicknesses in the mm-range. Integrating these often big and bulky PCB's into the final product (for example an appliance) consumes quite a lot of space and their presence needs to be taken into account during product design stage. With AME technologies, adding electronic functionality becomes considerably more simple. The circuits themselves are very thin, up to a maximum of some 10's of micrometers thick.

These circuits can be built on very thin and flexible films or even directly on the materials of the final product. In this way, the space usage of the electronic functionality is greatly reduced. This can either be used for miniaturization of products or it can be used to use the space for other purposes.

This relative simplicity of adding electronics brings also other benefits. It allows to easily electronically functionalize the surface of a product. This is for example highly relevant for HMI (human machine interfaces) to integrate touch or lighting functionality inside the surface instead of behind it. Functionalizing surfaces can be done by either thermoforming of thin films with AME circuits (also often called IME – in-mold-electronics), *see Section 2.8 - Thermoforming/MID*, or "freeform" by mounting digital printing technologies on 5+axes range of motion (x-y-z linear motion + A/B rotation) systems, see *Section 2.1 - FFF/FDM*.

More recent developments even allow utilization of 3rd dimension for electronics integration. 3D printed electronics is beginning to emerge in which 3D printing technologies are combined with AME technologies to yield full 3D electronically functionalized products, see *Section 2.2 - Powder Bed-based*.

1.3.3.2. Reduced environmental impact

Traditional PCB's are made with subtractive technologies, in which full area copper films are etched to give the final circuit. These metal layers are typically This results in a lot of 'waste' and uses environmentally unfriendly processes and chemicals. AME technologies do not have these problems. Material is only added where it is really needed in the final circuit and moreover, environmentally unfriendly chemicals like typical semiconductor manufacturing etchants, solvents, and process gasses can be eliminated from manufacturing work-flows, allowing for lessened regulatory hurdles for AME-based manufacturing and less environmental concerns and waste.

1.3.4. Drawbacks of AME

Of course, every (new) technology also has some drawbacks. Before deploying AME technologies, it is good to be aware of these.

1.3.4.1. Drawbacks on the technology

One drawback of AME technologies is originating from the fact that the conductive circuits are often made with low temperature curing conductive inks. These inks are typically solvents/polymeric binders filled with nano- or micron-sized conductive (typically Ag or Cu) particles, see *Section 4.1 - Conductive Materials*. For most of the inks and for most of the applications, these particles remain present also after curing/drying. Because of the interfaces between these particles, the conductivity of the final circuit will be less than that of bulk metal. Typical values that can be achieved are 20-40% of bulk copper for the Ag or Cu-based inks, see *Section 4.1 - Conductive Materials*. Because of this, in case low temperature curing conductive inks are being used for the circuits, are not suitable for power-intensive application (e.g. LEDs, power electronics). In case the application can withstand higher curing temperature, e.g. for LTCC applications, it is possible to use inks in which the particles sinter together, thereby achieving closer to bulk metal conductivity. An additional work-around to improve on conductivity, is to realize pure metal circuits using AME technologies. This can for example be done using LDS or a combination of printing of a seed layer and subsequent Cu plating, see *Section 2.11 - Laser Direct Structuring*. Another limitation on the materials for AME can be the development of the materials supply-chain, especially for developmental materials that have not yet been scaled to commercial volumes. Given this, batch-to-batch consistency and shelf-life issues may occur for lower-volume, developmental materials, with more scaled formulations typically having solved issues like these.

A second drawback of AME technology is that it is currently not routinely possible to achieve the circuit resolutions/circuit edge quality that is possible with standard PCB technologies. This makes the technology less suitable for demanding RF/high frequency (e.g. above 1 GHz) applications.

Then, a final drawback is related to the achievable reliability. As AME and the underlying technologies and materials are relatively new and largely still under development, one cannot always and automatically expect the reliability that is achievable with standard PCB technologies. The latter has been optimized for reliability for decades, with materials and manufacturing which have been optimized for reliability testing of various types, including thermal cycling, damp heat exposure and electromigration. Optimizations for reliability of final products based upon AME processes is still largely nascent, which affects some adoption of these technologies for scaled-up final products.

1.3.4.2. Drawback on designing in AME

The use of AME technologies requires partially different design concepts and design rules than standard PCB technologies. On one hand because the circuits are realized in a different way, for example with respect to how vias are realized. On the other hand also because typically AME needs to be designed much closer and integral to the final product. This implies that product and electronic circuit need to be co-designed.

Though AME design tools are under development and partially available, see *Section 3 - Design Tools*, they are not as established as conventional PCB design tooling. This means that the threshold for moving from conventional PCB technologies towards IME does require some careful consideration at this point in time.

1.3.4.3. Example Case-Study 1: UAV Payload Expansion

One example that highlights the benefits of AME is illustrated in figure 1, a UAV (drone) payload expansion assembly. The original product design included a similar shaped geometry conforming to the UAV shape; however, a separate planar PCB and attachment hardware is required to complete the package assembly. One of the goals of the project was to reduce the weight and profile height of the expansion unit to increase the UAV flying time (longer battery life) and reduce its size to facilitate flight into smaller spaces. With AME this was achieved as the expansion PCB and mounting hardware was eliminated, reducing the weight by 30%. The unit height was also reduced enabling a meaningful reduction in UAV height. The circuit implementation shown in figure 1 utilizes 5 electrical layers, comprising 3 conductive (Ag ink) at 200um trace width/gap and 2 insulating (PI) layers fabricated over an FFF printed structural body within a Neotech AMT 15XSA system. The conductive circuitry was jetted through a piezo-based dispensing tool. The AME-based payload expansion shown is a step towards a fully additive approach to UAV customization and manufacturing with further integration of UAV flight control electronics as the next step for additional integration, weight/size reduction, and battery life extension. Leveraging the AME approach, an added benefit for quick design iteration was also realized. Multiple payload module functionalities are easily accommodated and in a rapid iterative manner, thanks largely to an integrated design-to-process chain as well as fabrication within a single AME manufacturing system.

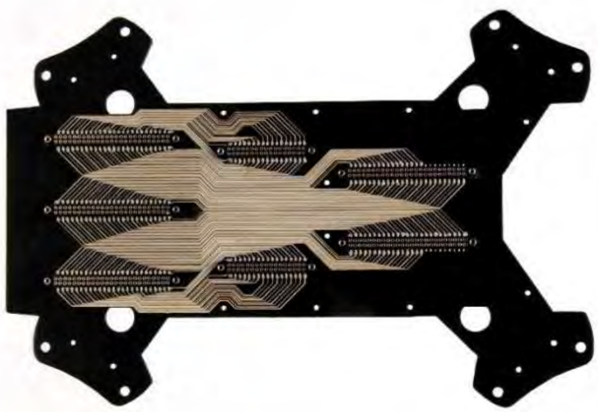


Figure 1.3.4. AME-based UAV Payload Expansion
Courtesy Advanced Printed Electronic Solutions

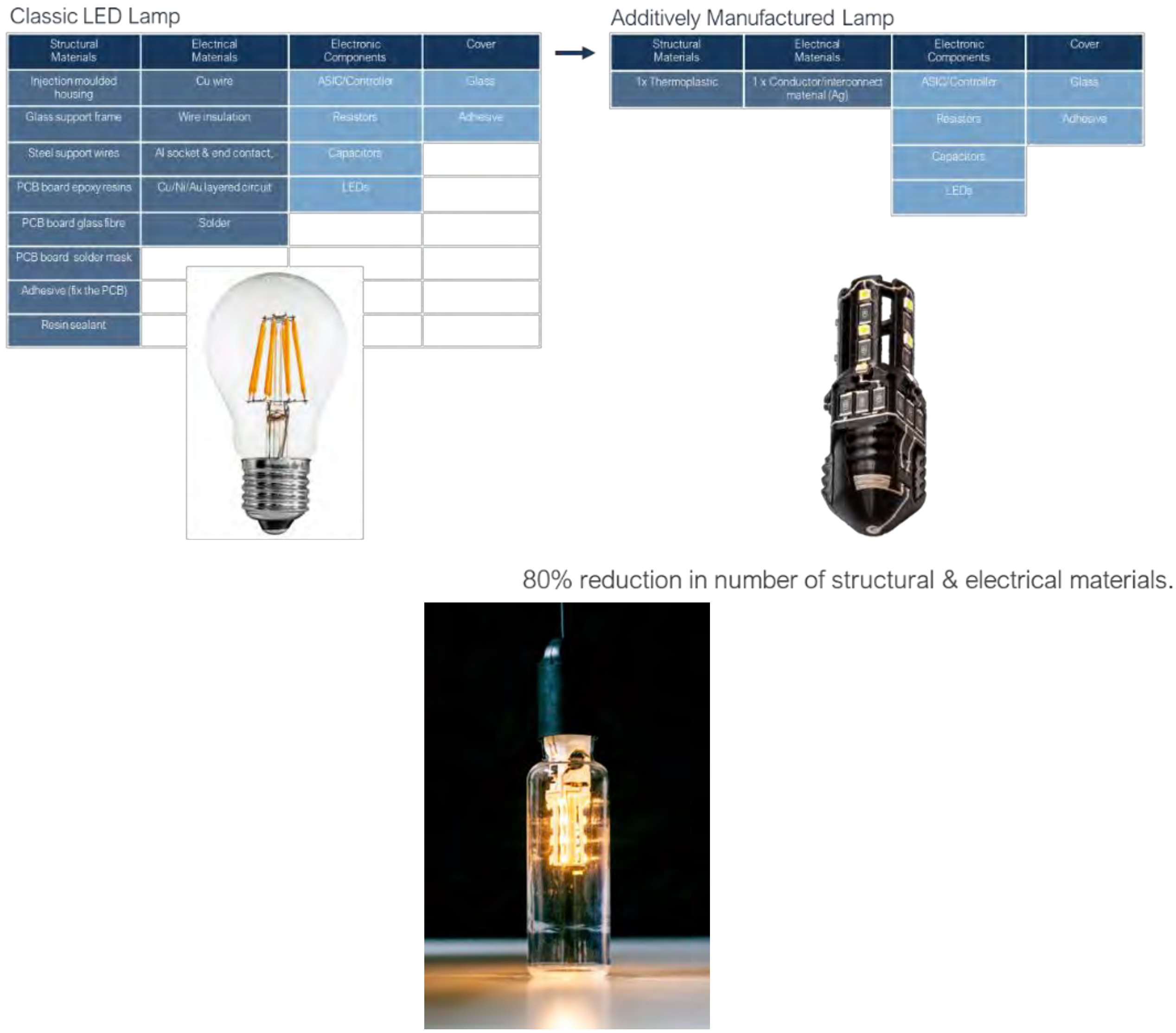


Figure *1.3.5*. AME-based Lighting[1]
Courtesy Neotech AMT

1.3.4.4. Example Case-Study 2: AME Lighting

Figure 2 illustrates a proof-of-concept AME-based Luminaire or 3D Printed Lamp that functions as a complete lighting device. A table provides a comparative between classical LED lamps and the AME-based lamp in terms of number of materials and components required to fabricate a complete functional lamp. Referring to the table, it is evident that there is a significant reduction in the number of materials (over 80%) required for the AME-based lamp. This includes a single thermoplastic and conductive ink or paste used for the electrical circuitry. In comparison, the classical standard LED lamp is composed of a complex mix of many different materials[1] as enumerated in the table of figure 2. In addition to material efficiencies, the AME-based process enables a product architecture that is significantly simplified in comparison. Figure 3 below illustrates this comparison, where the top of figure 3 depicts a typical PCB-based lamp manufacturing work flow comprising over 20 process steps requiring multiple systems. In contrast, the AME-based LED lamp approach can be completed in as little as 5 process steps and completed within a single AME system that integrates all required tools and materials.

To summarize, the AME-based LED lamp can be efficiently manufactured using available AME systems, leading to a sustainable lamp that can be essentially refurbished and upgraded (e.g. LEDs replaced with more energy efficient ones as the technology improves) multiple times extending the lamp product lifetime many years[1].

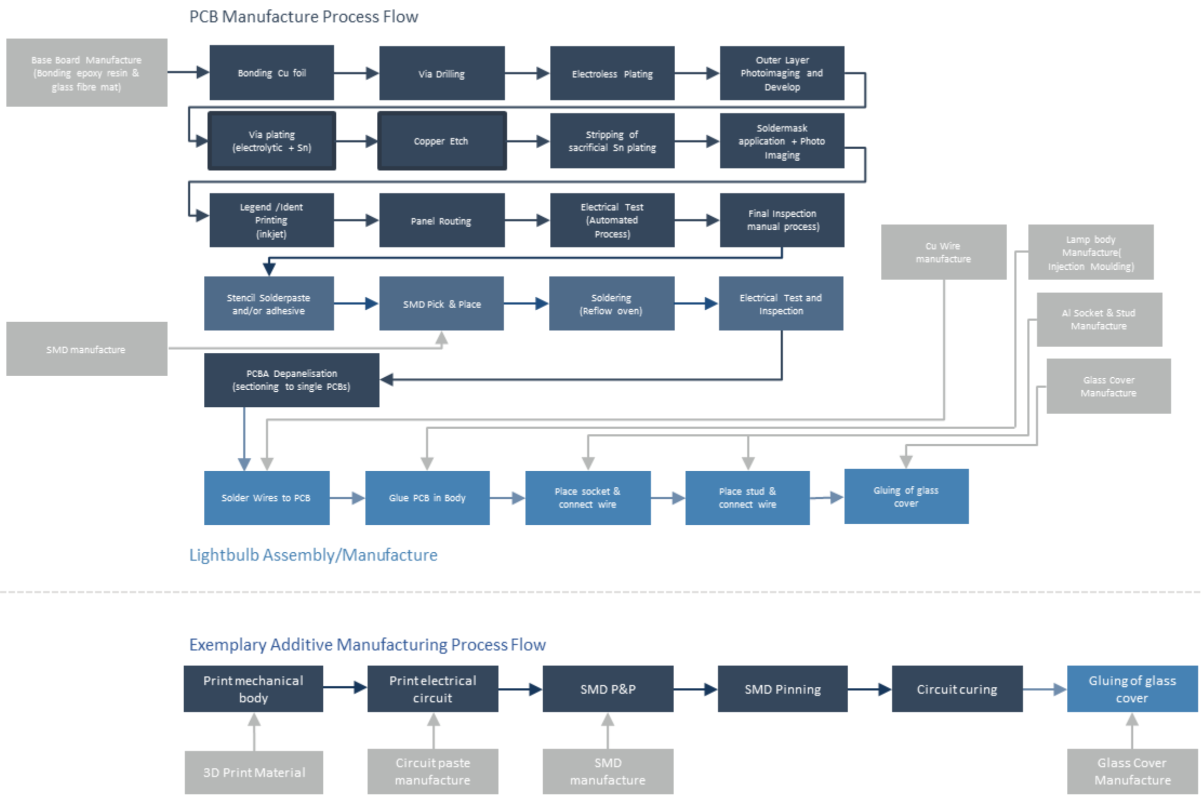


Figure *1.3.6.* LED Lamp Manufacturing Flows[1]
Courtesy Neotech AMT

[1] "Current Status on Additive Manufactured Luminaires". M. Hedges, F. Gohlke, C. Hedges, and K. Hedges. SPIE Conference 3D Printing for Lighting, San Diego, 23.Augost 2023. ©Neotech AMT, 2023.

2. AME Manufacturing Methods

2.1. Fused Filament Fabrication (FFF)

Lead: Martin H.
Contributors/Editors: Rich N.

Fused Filament Fabrication is one of the oldest structural AM technologies. It was invented and patented 1998 by Stratasys Inc. who also trademarked the acronym FDM of the alternative process name of Fused Deposition Modeling. Since the expiration of the patents in 2009 it has become the most common AM process for building mechanical structures.

The process uses a continuous filament of a thermoplastic polymer resin material, fed from a large spool through a heated printer extruder head, Fig. 2.1.1.[1] The head is manipulated in 3D space using a variety of CNC or robotic motion systems (3-, 5- or 6- axis) to build the mechanical structure line-by-line, layer-by-layer. Multiple heads are commonly used to enable multi-material printing.

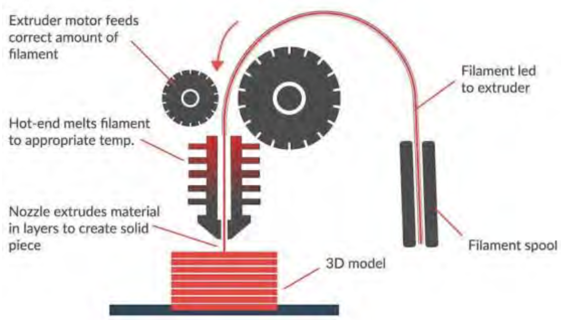


Fig. 2.1.1. Schematic of the FFF Process.

One strength of the FFF process is the availability of a wide variety of filament[2] materials such as polylactic acid (PLA), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU) and aliphatic polyamides (Nylon). Specialist high temperature materials such as PEEK are also available but due to cost and processing complexity are less commonly used. Composite materials consisting of continuous and short Carbon fiber filled reins are also used commercially for high strength structural applications. Other composite materials that are under development include filled (Cu and/or boron nitride) resins for use as thermally conductive heat sinks[3] and ferrite, $M(Fe_xO_y)$ electrical filters[4] and inductive SMDs.

Some basic electronic features can be built with FFF print materials where the resin is filled with electrically conductive particulate (for example metals, graphene or Carbon black). However, these are not generally considered in HI applications due to low electrical conductivity and low resolution (>>100um generally).

As with all AM techniques, process speed is strongly linked to resolution. The finer the resolution the slower the speed. The most common standard nozzle sizes are in the range the 0.35mm-0.4mm giving an approximately similar minimum feature size/resolution in X-Y direction. Printed layer height (Z) can be reduced to to ca. 0.1mm or less giving higher Z direction resolution but longer print times. The smallest Z height is reported to be sub 20 microns[5]. Finer diameter nozzles increase resolution of the print in X & Y; however, this also constrains material throughput which results in longer print cycle times. For example, reducing the nozzle diameter from 0.4mm or 0.2mm reduces the material deposition rate by a factor of 4x. A

[1] https://www.3dprintaj.com/wp-content/uploads/2020/12/FDM-manufacturing-process-2.jpg

[2] https://en.wikipedia.org/wiki/Fused_filament_fabrication

[3] EU Penta Penta Project AMPERE: “Additive Manufacturing based Production of Embedded Robust Electronics”

[4] BMBF Project: MEPPOFERRI: „Hybride Metall-Polymer-Filamente für die generative Fertigung von Ferritkernen mit integrierten Spulen“

5

further disadvantage of reducing nozzle diameter is the ability to build overhangs (relative to the Z axis) is also reduced.

The filament print quality becomes more critical the higher the resolution. For example only a small agglomeration of particulates of other defects will result in the clogging of a 0.1mm diameter nozzle.

For producing parts at scale (number of parts) it is also possible to use a pellet extruder that uses pellet or granulated feedstock much lower cost, ca. 10x lower cost compared to filament.

The resolution of the print process currently limits the use in HI to more macro scale (mm+ sized) sized devices for "packaging" electronics components into a mechatronic system, Fig. 2.1.2.

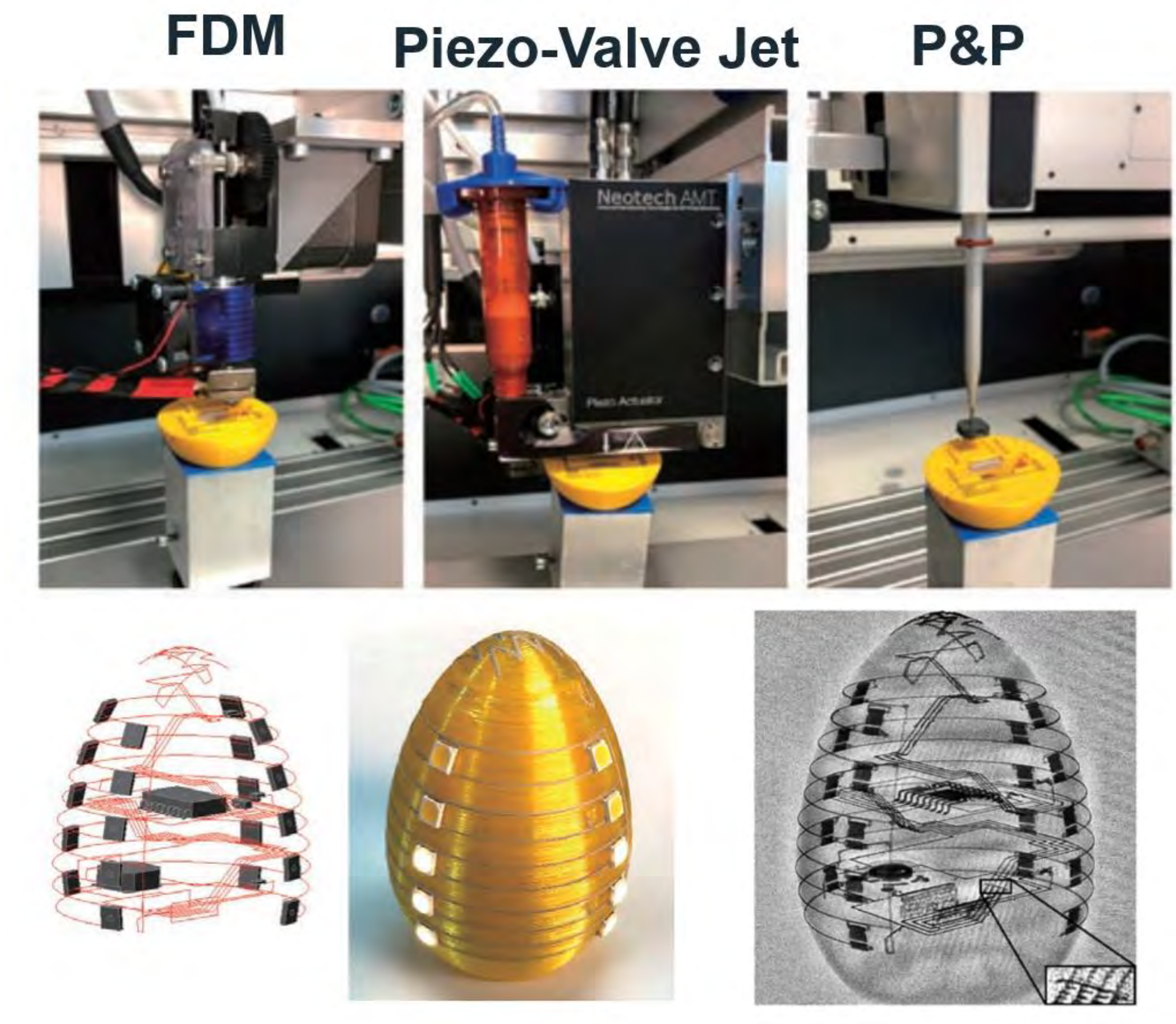


Figure 2.1.2 - FDM-based AME, courtesy of Neotech AMT

A further limiting factor for FFF use in HI relates to the surface texture inherent in the process. This unevenness affects the quality/resolution of printed circuits and interconnects that are added. This can be mitigated by applying surface smoothing via laser or CNC machining processes.

Benefits

- Lowest cost structural AM method
- Wide range of standard materials available with known properties.
- Little to no post-processing required
- Simple Operation

Drawbacks

- Resolution (ca. 100um in Z height)
- Surface Texture
- Anisotropic mechanical properties (X-Y direction stronger than Z)

Glossary

CNC – Computer Numerical Control
SMD – Surface Mount Devices.

2.2. Powder Bed Methods

Lead: Jarrid W.
Contributors/Editors: David B., Kris E.

2.2.1. Method Overview

Powder bed fusion (PBF) is an additive manufacturing (AM) process that has the potential to be utilized to fabricate elements for additive electronics (AE) applications. The core process in PBF technology is achieved through spreading a thin layer of powdered polymeric material over a build area and selectively melting a predefined region of the spread powder layer to form a slice of the CAD geometry. The melting of the polymer can be achieved through various methods such as a laser selectively melting the specified region or through the deposition of an energy absorbing agent (fusing agent) combined with an appropriate energy source (Figure 1). [1, 2] These set of operations in the PBF process are repeated until the build is complete. This technology benefits from high mechanical properties, high build rates (>25 mm/hr), moderate resolution (~100 microns), no need for supports, and the printing of multiple parts with diverse shapes and orientations at a time.

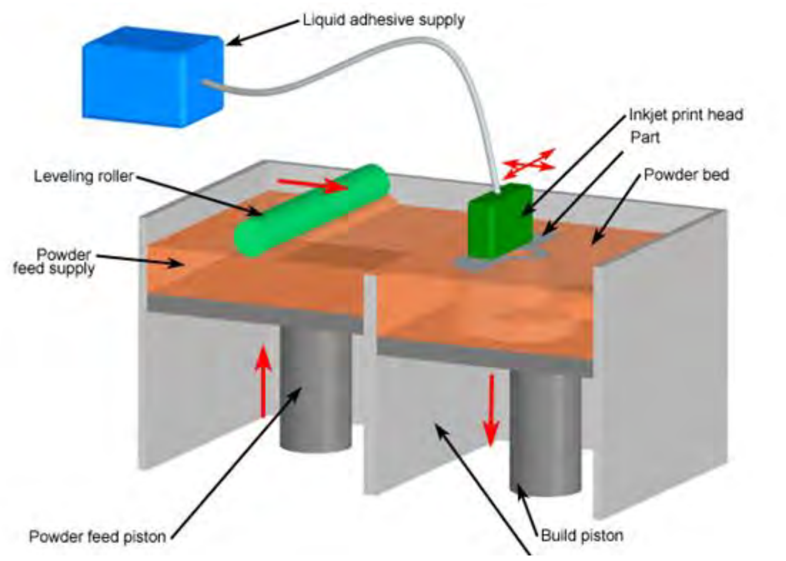


Figure 2.2.1 Depicts powder bed fusion (PBF) AM process. [3]

PBF printed parts, like many other additive and conventional manufacturing technologies, can enable AE through post process multi-axis direct write and component placement. However, PBF, especially those who utilize deposition methods like inkjet printing can demonstrate voxel, or volumetric pixel, manipulation by depositing material in addition to the fusing agent (FA) to further manipulate the material properties. Utilizing electronic agents with multi-material voxel manipulation enables the production of additive electronics and enables addressing electronic functionality throughout the volume of 3D printed geometries thus enabling true 3D printed electronics (3DPE). These electronic agents include a core conductive agent (CA) as well as peripheral electronic modifying agents such as a dielectric agent, magnetic agent, and/or resistive agent to create and manipulate the electronic properties of the 3D geometry.

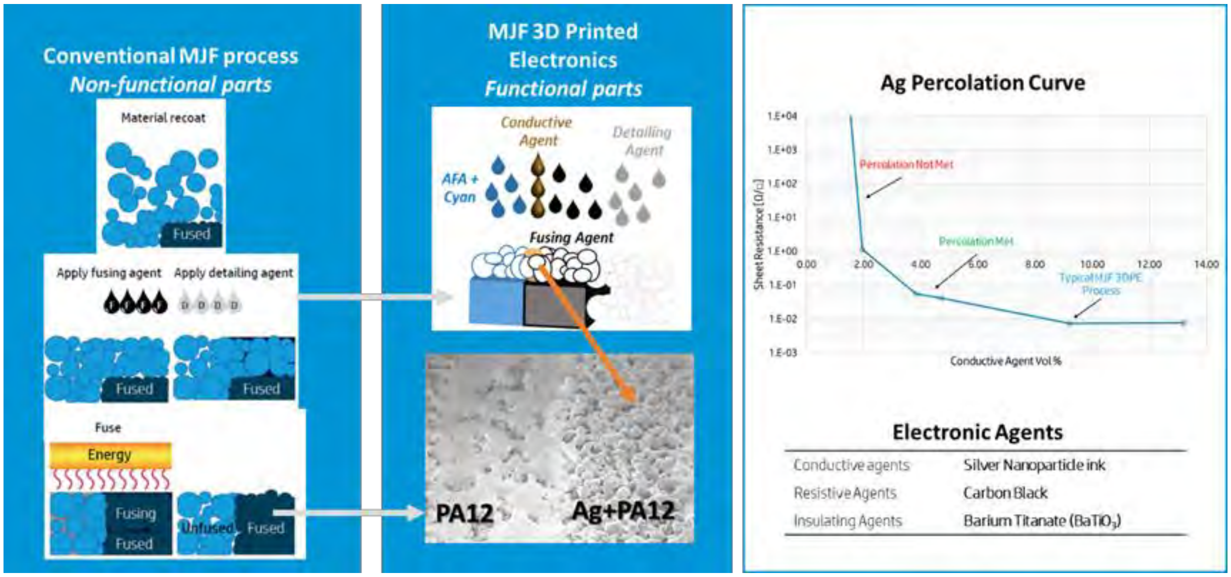


Figure 2.2.2: *Mechanism of MJF and MJF-3DPE processes. Additionally, a percolation curve demonstrating the volume percent of CA to achieve stable conductive networks in the composite. Also shown are additional electronics agents that have been utilized in the process*

HP has presented a pre-commercial, research-level PBF + inkjet technology based on its commercial Multi Jet Fusion (MJF) technology [4]. MJF is a PBF technology that uses a FA and a detailing agent to melt and coalesce the polymer particles and better control the process and define the geometry. The enabled AE process built on the PBF + inkjet capabilities with MJF is referred to as MJF-3DPE and it can produce highly conductive traces with high levels of geometry freedom within a dielectric polymer material. [5,6] The basic concept behind MJF-3DPE is to use a CA in conjunction with the other process agents to selectively impart conductivity wherever it is designed within a 3D printed part (see Figure 2). This enables the creation of traces, vias, and pads anywhere within or on the surface of a part.

For MJF-3DPE current CA is a metal nanoparticle dispersion that has been formulated to work with thermal inkjet (TIJ) pens. To ensure conductivity throughout the printed composite MJF-3DPE structure, a percolation of the conductive network is required. The plot on the right side of Figure 2 shows the sheet resistance as a function of the conductive agent volume ratio. It can be observed that the percolation point happens at ~4 vol. % for the CA content. The typical MJF-3DPE process operates between 8 – 10 vol % to ensure repeatable electrical performance in the conductive regions of a part. Other electronic agents have been demonstrated for the MJF-3DPE process aside from the CA. These include a resistive agent which consists of carbon black, and a dielectric (or insulating agent) consisting of a suspension of barium titanate nanoparticles.

2.2.2. Heterogeneous Integration Uses

Two case studies highlighting PBF with inkjet technology for uses of interest to heterogeneous integration have been published and highlights from that work will show below. Both studies were from HP's MJF 3DPE and focus on printed passives and component attach. [5,6]

As discussed earlier, PBF with inkjet is capable of depositing CA into voxels to create electronic circuits throughout the volume of a 3D printed part. By modifying the recipe of agents that are added to the voxel to impart conductivity and adding an additional resistive agent an internally printed resistor can be formed. More specifically, to form the resistive structures a blend of the conductive metal nanoparticle-based agent and carbon black resistive agent is deposited into the voxels assigned to the resistor design. By varying the ratio and amount of the two inks as well as the geometry at which these blends are allocated different resistive lines can be generated. (Figure 3) The figure showing the difference in appearance of resistors with higher resistance (more carbon loading, black appearance) and lower resistance (less carbon, silverish appearance).

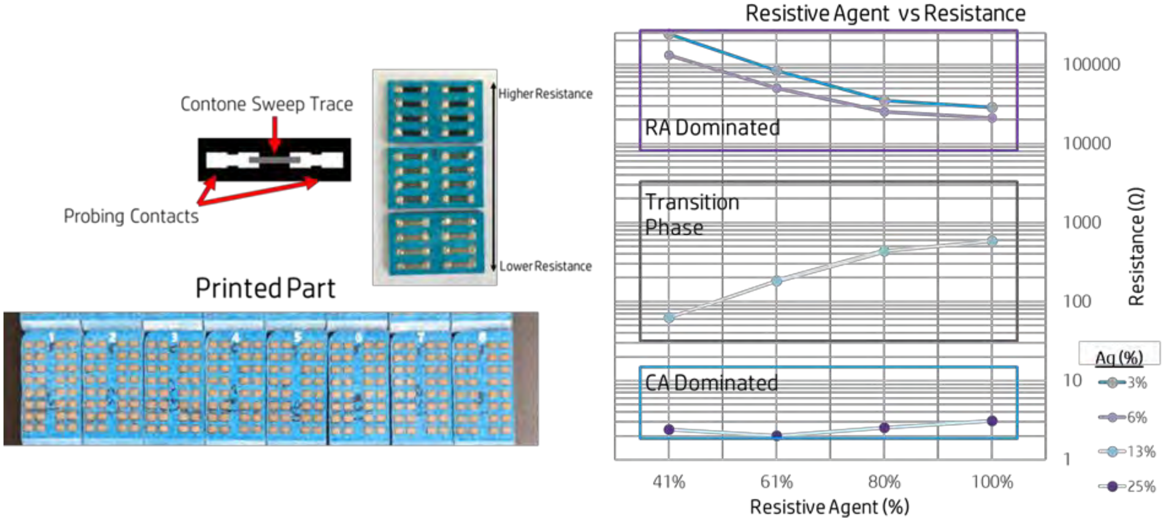


Figure 2.2.3: *Design and prints of 3DPE MJF printed resistors with resistance results from various conductive and resistive agent loadings*

This plot in Figure 2.2.3 highlights various resistive and conductive agent loadings and their corresponding resistance. The amounts of ink are correlated to the percent of the conductive agent used in our standard MJF 3DPE trace recipe (resistive agent or ink amount of 80 % correlates to 80 % of the amount of silver agent that would be jetted into the region if a standard trace was being formed). For the sweep of resistive agent's various amounts of silver agent was also blended (3 % total conductive agent up to 25 % of conductive agent). In the data analysis we identified 3 regions of resistor properties. The first being a conductive agent dominated recipes. These recipes have 25 % of the conductive agent used in the resistor blend and the resistance values do not change much in the varying of the resistive agent's loading. The second category is the transition phase which has conductive agent loadings of 13 % total silver used in the standard process. This region demonstrates a wide range of resistances measured in the test parts. Additionally, increasing the resistive agent amount increases the resistance of the printed resistor. The final region of performance is the resistive agent dominated resistors. These resistors have low conductive agent loadings between 3 – 6 % conductive agent. For these resistors increasing the resistive agent loading decreases the resistance of the resistor. This is due to the carbon being the main conductor in these structures.

2.2.3. Component Attach Study

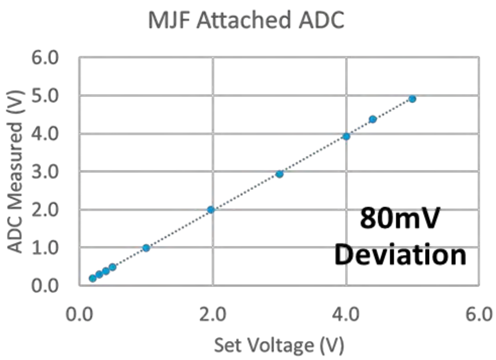
SOT-23 Attached on MJF-3DPE

Resistance Validation

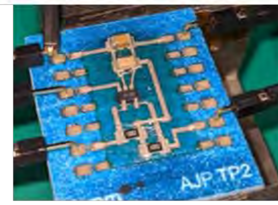
IC PIN	Resistance Ohms	PASS/Fail (R<3 Ohms)
1	0.8060	PASS
2	0.7442	PASS
3	1.0280	PASS
4	1.1120	PASS
5	1.0160	PASS

Voltage Validation

IC PIN	Voltage (V)	Expected Voltage (V)	PASS/Fail
1	5.0240	5.0000	NA
2	0.0000	0.0000	NA
3	0.2010	Input(0-5V)	NA
4	4.9971	~5.000	PASS
5	4.9972	~5.000	NA



SOT-23 Attached on AJP-MJF



Resistance Validation

IC PIN	Resistance Ohms	PASS/Fail (R< 3 Ohms)
1	2.3610	PASS
2	2.7780	PASS
3	1.0920	PASS
4	2.2580	PASS
5	2.4070	PASS

Voltage Validation

IC PIN	Voltage (V)	Expected Voltage (V)	PASS/Fail
1	5.0330	5.0000	NA
2	0.0000	0.0000	NA
3	2.4570	Input(0-5V)	NA
4	5.0247	~5.000	PASS
5	5.0244	~5.000	NA

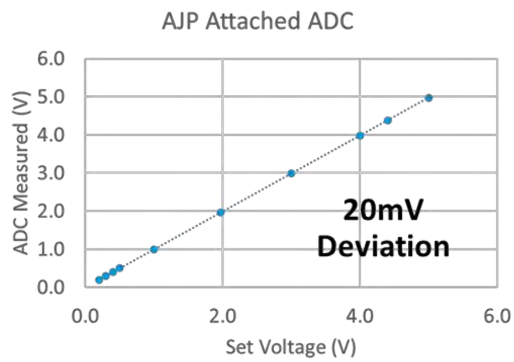


Figure 2.2.4: *Results for the assembled SOT-23 package containing ADC onto MJF-3DPE substrate. Results for the assembled SOT-23 package containing ADC onto AJP fan in from MJF-3DPE substrate.*

The next study focused on comparing the performance of components placed on MJF-3DPE contact points with components assembled on aerosol jet printed (AJP) traces on the surface of MJF printed parts. To perform the study two designs for attaching an SOT-23 package containing a 5 pin ADC were made. One design used the MJF-3DPE process directly, and the other demonstrated the integration capabilities of the AJP post process on MJF. The resistance and operational voltage measurements were done to show that the component is attached properly to both substrates (Figure 4). The operational testing was then performed on each of the Serial ADC in the SOT-23 packages. The I2C signal out of both ADCs was measured at 400 kHz and the rise and fall time were measured as 330 ns and 102 ns respectively for the MJF-3DPE and 709 ns and 10 ns respectively for the AJP on MJF attached component. The performance of the ADC was further determined by feeding voltage values and corelating it to the ADC’s output. The error in the ADC’s output was 80 mV for the MJF-3DPE attached and 20 mV for the AJP on MJF attached component. Overall, the AJP trace on the MJF assembled ADC and the MJF-3DPE assembled ADC performed well. The ADC assembled on the AJP on MJF showed a higher line resistance than that of the MJF-3DPE printed trace, however, the AJP version was easier to assemble with our P&P procedure which may lead to a higher yield in component attach for scalable production.

2.2.4. Benefits and Drawbacks

PBF coupled with Inkjet printing has numerous benefits which have been driving some of these applications, with major ones including:

- **Efficient use of material:** Additive process that enables build material recycling as well as depositing electrical agents only when needed.
- **Design Freedom:** Addressable conductive features throughout the volume of a 3D printed geometry as apposed to only enabling surface functionalization or 2.5 D addressable build space due to build rate limitations.
- **Digital Design:** Application designs can be updated and adapted for personalized or customized performance. This can enable designs that can adapt and evolve along with the manufacturing lifecycle of a product.
- **Build speeds:** PBF processes are inherently fast compared to other AM processes and the electronic functionalization with the voxel can in some print modes be accomplished in a comparable time frame. This enables 3D electronic production at production build rates.
- **Enable further post-processing with other AE processes:** 3DPE parts generated from PBF /w inkjet can be further functionalized to meet the hybrid electronic needs. This can be further direct write processes to achieve finer resolutions or hybrid assembly techniques to integrate conventional or flexible electronics onto the printed device.

However, many drawbacks still exist for PBF with inkjet, which often limits its current use and applications, including:

- **Material Diversity:** Build material development for PBF is more involved than other AM processes and requires certain polymer characteristics to be met to enable the processability. This can limit the development of a wide variety of build materials that could be of interest to AE applications.
- **Design tools:** Design tools that integrate the mechanical and electrical components allowing for efficient workflows to design 3DPE geometries do not exist and would need to be developed for the technology to be fully commercialized.
- **Electronic Agent Stability:** High loading functional inks that are needed for the electronic agents are difficult to formulate and can increase the total cost of the manufacturing process making it prohibitive for certain application spaces.
- **Reliability and Repeatability:** The complexity of PBF w/ inkjet process requires close process control to enable repeatable performance. Coupling this with the complexity and variability in designs that the process would have to control around would be a challenge to implement in a cost effective technology.

2.2.5. Growth Areas and Roadmap

Multiple companies exist for the different technical aspects of inkjet, including for printheads, printers, and inks. Each of these are pushing for improvement areas, with major developmental directions including:

Printer Manufacturers:

- **Resolution:** Enhanced by improvements to the hardware of the printers as well as the particle size of the polymer build material and inkjet drop size
- **Build Volume:** Printers that can efficiently manufacture 3DPE parts at needed sizes with highly controlled build volumes tailored to application needs

Material Vendors:

- Diversity of build materials: better representing electronic materials with low Dk/Df, low CTE and other tuned properties
- Higher conductivity and higher loadings: for improved printed trace properties
- Copper inks: Lower cost conductive materials like copper would reduce cost of production.
- Stretchable inks: enabling use-cases of wearable electronics and other required flex/stretch applications.

Design Tools:

- EDA-CAD and MCAD combined tool:
- Simulation and property prediction
- Design libraries that can be inputted into designs based on the intent of the designer or the application needs

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2.3. Stereolithography and DLP-printing

Lead: Kris E.
Contributors/Editors: David B.

2.3.1. Method Overview & Print Modes

Stereolithography (SLA) is the oldest form of additive manufacturing, dating back to the 1970's, wherein a light source (initially a laser) is used to cure a photo-resin selectively within a layer, with subsequent layers being built-up to create a 3-dimensional object.[1] Many adaptations have been made from this initial approach. Two notable ones including the use of a DLP-projector, often combined with a method for inhibiting adhesion to the transparent window (for example CLIP[2]), which enabled going from 0D/point-wise patterning to 2D/areal patterning with significant increases in production speeds, going from laser-write speeds of ~30 mm/s (0D patterning) to full volume fabrication speeds of 10-300 mm/hr (2D patterning), also known as Continuous Stereolithography.[1] The second notable adaptation was a 2-photon approach (TPP), utilizing multiple lasers from different orientations to enable significantly higher resolution, near the diffraction limit of the light source, going from resolutions of ~20-100 microns to ~0.2-1 microns.[3]

Adapting these methods for use in AME has taken a few different routes. Early SLA-based AME efforts revolved around sequential materials deposition, driven by work at the UT-El Paso Keck center, with conductive features being direct-write extruded into voids patterned in using a previous SLA printing process.[4] This method was successfully used for fabricating multiple mid-complexity devices, with pick-and-placed components, interconnect formation, vias, and multi-layers or traces (Figure 2.4.1A). This approach allowed for the deposition of highly loaded silver-based inks for high conductivity traces, but was limited by fabrication time limitations, as parts needed to be removed from the resin vat and brought over to an alternative apparatus for direct-write steps.

Another adaptation was developed at TNO-Holst which involved a "rake-and-scrape" method, wherein a SLA-printed part had patterned voids filled through a "scraping" step where a squeegee filled the voids with conductive pastes.[5] This method provided some level of increased manufacturing speed, and was used to fabricate applications like a fan-out structure with >200 interconnects (Figure 2.4.1B), forming a redistribution layer connecting directly to an underlying Si-die.

Both these adaptations still have the limitation of needing multiple material sets and multiple manufacturing steps for the dielectric and conductor materials, so have inherent manufacturing speed limitations. Recent approaches which look to improve one or multiple of these restrictions include an approach wherein photo-reducable Ag-based metal salts are dissolved within the photo-resin, with different laser-sources which can selectively either photo-cure the underlying resin or photo-decompose the dissolved metal-salt, for selective deposition of traces.[6] Although this effort is still in its early stages, printed 3D-traces have been demonstrated with this method (Figure 2.4.1C). Other adaptations which work from a composite resin + filler material have been developed, which allows for the formation of higher strength composites, like those which utilize a continuous kinetic mixing module.[7]

A final relevant adaptation of stereolithography has been the use of multiple laser light sources, which allows for patterning at or below the diffraction limit of the patterning photons being used, for instance using TPP.[8,9] This significantly improves the resolution of the printing process, with resolution down to 80 nm and features sizes of 160 nm being typical with some commercial systems. and features sizes of 160 nm being typical with some commercial systems.[10] Although this approach is only amendable for the fabrication of dielectric materials, it can be used for optical signaling structures, with applications in optical compute including the formation of optical wire-bonds (see Section 5.3).

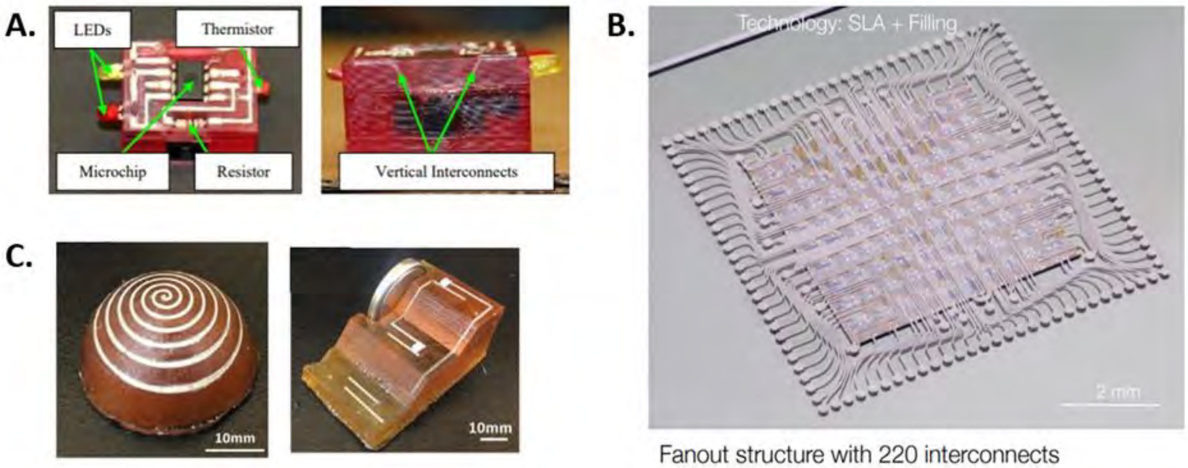

Figure 2.4.1 Stereolithography-based methods for fabrication of AME structures

2.3.2. Materials

Stereolithography-based applications, like with all AME methods, are limited by the material sets conducive with the manufacturing process. Thankfully for SLA-based methods, photo-resins which have been adapted for traditional semi-conductor manufacturing processes can be somewhat adapted into 3D printable resins, with examples of polyimide-based photo-resins[11] as well as other methacrylate-based, multi-functional acrylates,[12] and elastomeric materials, like PDMS-based resins.[13] Although modifications to the resins systems must be made to allow for appropriate photo-polymerization, rheological properties and other requisite materials properties for the specific printing process employed, final material properties often match the standard polymeric systems, and follow-up photocuring of the entire printed part can be done to get to final mechanical properties.

2.3.3. Heterogeneous Integration Uses

Stereolithography-based processes have begun to find some applications within advanced electronics packaging, with advanced packaging and heterogenous integration[4] uses including:

- **Optical Features** Optical wire-bonds,[14] Micro beam-forming element[15]
- **Redistribution Layers** Fan-out structure interconnected to bare-die[5]
- **3D Devices** Motion sensing example 3D device[4], Pyramid example device[16]
- **Antenna/RF Structures** FSS surfaces,[17] 3D Antenna[18], low loss dielectric substrates[19]

2.3.4. Benefits and Drawbacks

Stereolithography-based Methods have some benefits including:

- High fabrication speed, especially for DLP-based methods
- High resolution, especially for 2-photon based methods
- Materials can often be near traditional semiconductor organic materials
- Very low surface roughness compared to other 3D print methods (FDM, power-bed)
- Largely isotropic material properties (especially for DLP-based methods)

Drawbacks of SLA-based methods include:

- Follow-up processes required for conductive feature fabrication (typically only producing dielectric structures) with minimal opportunity for in-situ pick-and-place or other multi-material processes
- Base resin material need significant tuning to allow for material properties required for manufacturing (especially rheological and photo-absorption)
- Post-process step of further photo-curing to get to final material properties

2.3.5. Growth Areas and Current properties

One key growth area for SLA-based methods in order to be applicable towards broader advanced packaging needs would be to enable simultaneous deposition of both dielectric and conductive materials, or enabling this through facile follow-up processing methods. Beyond that key enabler, further improvements in resolution and print speed would also provide benefits.

For the 3 different methods described within this section (SLA, DLP and 2-photon SLA), typical resolution and manufacturing properties are provided below.

Printing Method	Resolution X,Y (micron)	Resolution Z (micron)	Feature sizes (dielectric[E]) (micron);	Build Height per pass (micron)	Deposition Speed (m2/s)	Build Dimensionality
SLA	50-100	50-100	[E] - 150	20-100	**1D** 20-700 mm/s	0D
DLP	50-100	50-100	[E] - 150	20-100	**3D** 10-300 mm/hr	2D
2-Photon SLA	0.1-1	0.1-1	[E] - 1	0.1-10	**1D** 30-100 mm/s	0D

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Screen Print

Lead: Girish W.
Contributors/Editors: Jeroen van den Brand

Screen printing is a printing technique that uses a woven mesh to support an ink-blocking stencil to receive a desired image. The attached stencil forms open areas of mesh that transfer ink or other printable materials which can be pressed through the mesh as a sharp-edged image onto a substrate. A fill blade or squeegee is moved across the screen stencil, forcing or pumping ink into the mesh openings for transfer by capillary action during the squeegee stroke. Screen printing is also a stencil method of print making in which a design is imposed on a screen of polyester or other fine mesh, with blank areas coated with an impermeable substance. Ink is forced into the mesh openings by the fill blade or squeegee and onto the printing surface during the squeegee stroke. It is also known as silkscreen, serigraphy, and serigraph printing.

Key Characteristic	Parameter
Ink film layer thickness	10-100+ µm (typically 25-40 um)
Registration tolerance	50-250 µm
Minimum feature size (i.e. trace width)	>20-30 µm, Manufacturing, >10 µm, Lab
Minimum trace spacing	>50 µm, Manufacturing, >25 µm, Lab

State of Art for Screen Printing *(IDTechEX and other sources)*

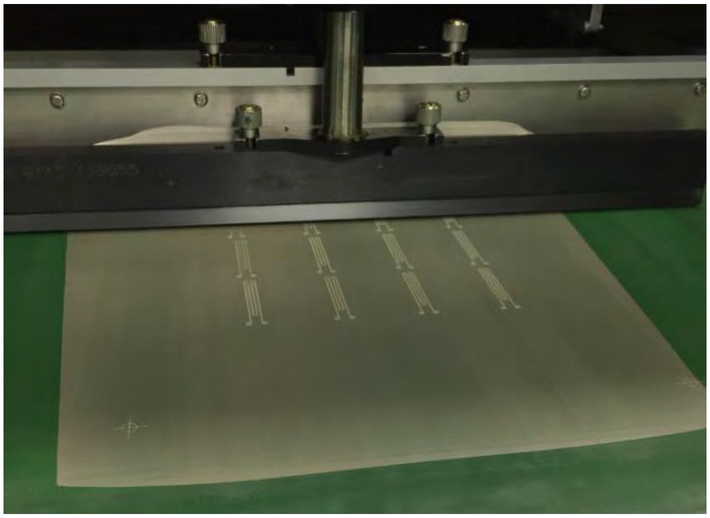

Figure 2.4.1: *Screen Print Process*

Printed electronics use different types of inks depending on what properties and application are needed. Some common inks used in printed electronics are conductive inks, dielectric inks, and resistive inks. Conductive inks make conductive traces and can be from different materials like silver, copper, and carbon. Dielectric inks make insulating layers and can be from materials like polyimide and silicone. Resistive inks make resistive elements and can be from materials like carbon and some polymers. There are also new high-temperature inks being made for power electronics and other high-temperature uses. Conductive inks, like those from copper, silver, or carbon, can make generic traces that can stretch, bend, and be injection molded. These inks can have different forms, such as flakes, nanoparticles, nanowires, silver salt, conductive polymers, graphene, and carbon nanotubes. Dielectric inks can also be used, which can be cured with UV or heat. These inks can be used as generic PTF insulators or as stretchable dielectrics. Inks can also be organic, inorganic, or a mix of both, and can be used for semiconductors, OLEDs, sensors, and more. Early users of 3D surface inks may use silver or copper to make conductive traces, heaters, or capacitive sensors.

Thermoforming is a process where thermoplastic sheets are heated, deformed by shaping force into a mold, and allowed to set in the new shape during cooling. There are three main stages in the thermoforming process: heating, forming, and cooling. Conductive inks are used in the thermoforming process to create 3D-shaped electronics, specifically In-Mold-Electronics (IME). IME is the process of developing and producing embedded circuitry in 3D shaped electronics by means of thermoforming and/or molding processes. This new emerging market of IME and 3D-shaped electronics requires inks, specifically developed to address the technical challenges of this market. Technical challenges to be addressed by IME-compatible conductive inks include high elongation, thermoformability, adhesion, fine line printability, and high conductivity. These properties should enable the printing of electronic circuitry on a 2D substrate prior to converting it into a functional 3D electronics circuit.

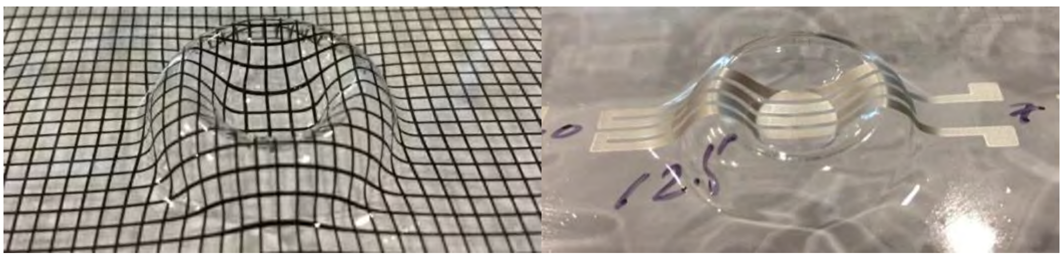

Figure 2.4.2: *Examples of thermo-formed screen print graphic and conductive inks*

For thermoforming of printed silver inks, highly formable conductive silver and dielectric inks are needed. These inks are designed for thermoforming applications employing Polycarbonate (PC) film and PET substrates. The dielectric ink should provide uniform, pin-hole free, thin insulating or encapsulation films, enable a variety of crossover structures for low voltage circuits, have excellent adhesion and compatibility with PC & PET substrates, various emulsion coatings and decorative (graphic) inks, and have excellent electrical insulation after thermoforming and injection molding. The silver ink should have excellent electrical conductivity after thermoforming, excellent adhesion and compatibility with PC substrates, dielectric inks, various emulsion coatings & decorative (graphic) inks, be capable of forming deep draw configurations, and be injection molding capable (Ink-wash off resistance). Thermoforming of silver inks for 3D surfaces has several advantages. It enables a variety of crossover structures for low voltage circuits and has excellent adhesion and compatibility with PC and PET substrates, various emulsion coatings, and decorative inks. Thermoforming of silver inks also provides excellent electrical conductivity after the process and can form deep draw configurations. It is also injection molding capable, meaning that the ink can withstand the wash-off resistance of the process. It is also important to consider the protection techniques for printed electronics such as dispensing or laminating barrier materials.

Several approaches and combinations of process steps need to be considered, based on each specific location that needs to be formed, and within cost, time to market and performance constraints. Print formable graphic and conductive inks that provide acceptable and adequate conductivity and visual requirements on a variety substrate. It is necessary to optimize the material stack up, design of the overlapping patterns, thickness of the prints, print methods, and curing profiles to name a few. It is also important to consider the subsequent assembly steps during the selection of the materials so they can survive harsh assembly temperatures or strains due to handling. In some cases barrier materials will be dispensed and cured, while in others films may be laminated to protect the circuit traces. In some applications graphic layers may not be necessary simplifying the material stack up constraints. In most common applications, conductive traces act as capacitive touch sensors, pads for LED or connector attachment as well as the main circuit. In some cases additional components such as integrated circuits are also added. In one approach, conductive materials are dispensed on appropriate locations, followed by pick and place of components at locations that are determined to be acceptable for component attachment and then curing, right after printing. The thermoforming step follows, giving the desired 3D shape, followed by trimming. In another approach, thermoforming follows the printing process and then trimming. In this case custom automation and/or special tools and fixtures may be necessary to orient the part for material dispensing and component attach. There are different approaches such as mechanical integration into the final product or injection molding (in-mold electronics) of the 3D surface based on the product strategy. In-mold electronics (IME) is a process of integrating printed electronic circuitry into 3D injection molded plastics. This technology enables the creation of innovative and functional products by combining printed electronics with 3D forming and molding. IME can be used to create thinner, lighter, and more cost-effective products with increased design freedom. Some of the benefits of IME include reducing assembly steps, reducing the bill of materials (BOM), and reducing the size of the control circuit (printed circuit board (PCB)) due to standardization. The impact of molding process on material stack up as well as the topology of the materials and its ability to allow molding material to flow has to be considered.

Visual inspection and functional tests are performed along the way. In an alternate approach, components can be added to the circuit traces after the injection molding process after steps are taken to first protect and then to prepare the circuit traces to attach components. Components could also be attached using mechanical approaches during any of these steps. All combinations require application specific development and industrialization.

Consumers demand for novel form factors needs to be matched by their ability to value the benefits such as low-profile, lightweight devices. Applications that have been considered for these approaches include human machine interfaces (touch control, illumination) for consumer, medical, automotive, industrial, and aerospace industries. In some cases, antennas may be integrated to provide the ability to operate or wake up the device. Several EDA suppliers have included these approaches in their design tools making it feasible for designers to envision and create products leveraging them.

Examples of High volume production possibilities (i.e. solar cell metallization layers) are included in figure 2.4.3 (Courtesy IDTechEx).

High volume production possibilities (i.e. solar cell metallization layers)

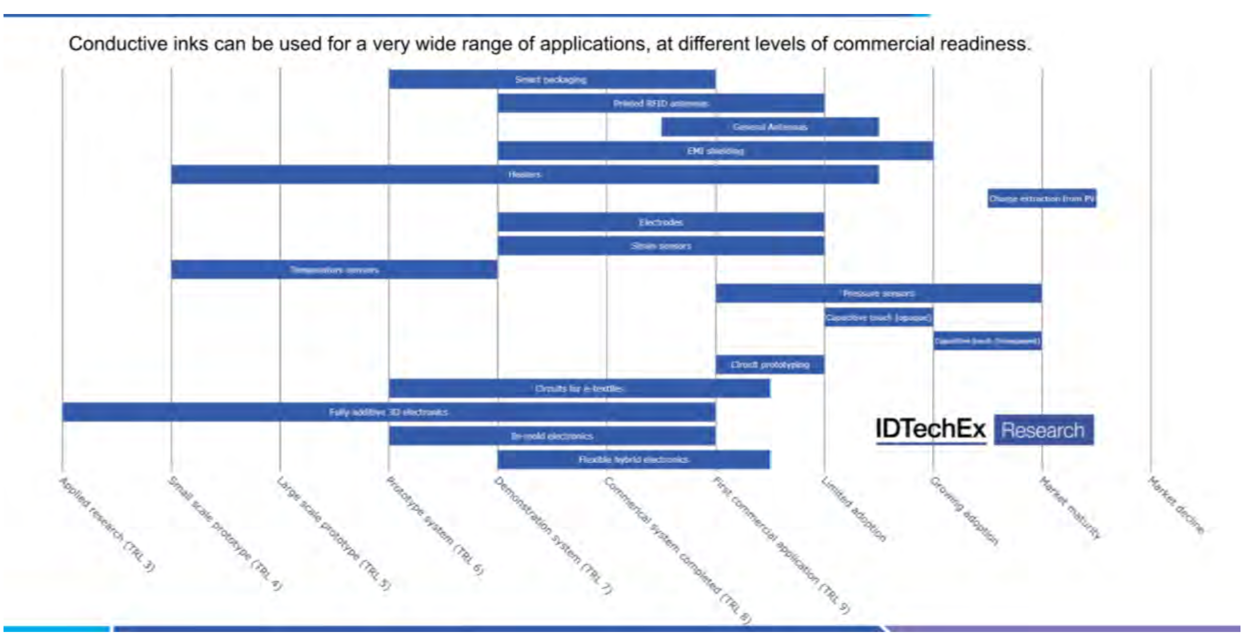

Figure 2.4.3: *Examples of High volume production possibilities (i.e. solar cell metallization layers).*
#thanks and with permissions from IDTechEx

Screen-print inks have been made with various materials, for more see Section 4.2 - Printed Thick Film, with a subset of conductive inks and their typical conductivity values show below in Figure 2.4.4.

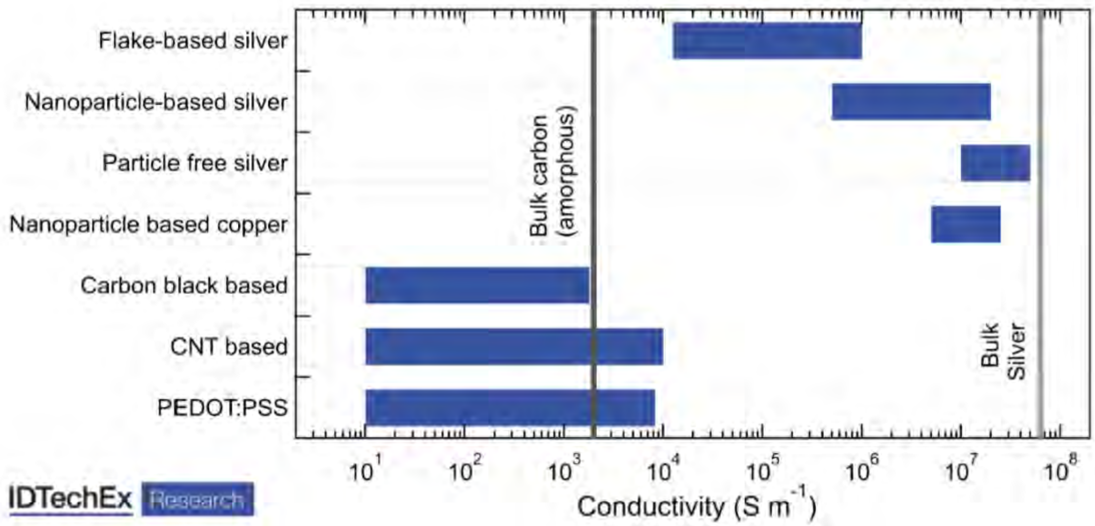

Figure 2.4.3: Examples of types of conductive inks and their conductivity.
#thanks and with permissions from IDTechEx

Several of these features produced with screen printing such as circuit traces for in-mold electronics, capacitive sensors, EMI shielding, micro heaters and flexible hybrid electronics will find applications in AME either by sequentially creating layers on top of each other or doing so and then thermoforming. In applications such as Lab on Chip devices, screen printing can be used to deposit materials that create micro channels for fluids as well as electronic circuits such as micro heaters and sensors.

One consideration while selecting any of these approaches would be to explore the impact on product carbon footprint as it will have an influence on the recovery, separation, and disposal of these products. However, by replacing multiple parts and driving higher level integration maybe some ways to explore reduction in the product carbon footprint. In the example shown in Figure 2.4.5, screen printed ag ag/cl electrodes are deposited on flexible substrates and the electronics is assembled on the same flexible substrates. In some cases, additional sensors or components can also be printed or deposited on the same substrates. While the accuracy of the device depends on many different factors, for several use cases, this transition helps reduce the number of parts, size and assembly steps for such a monitoring device.

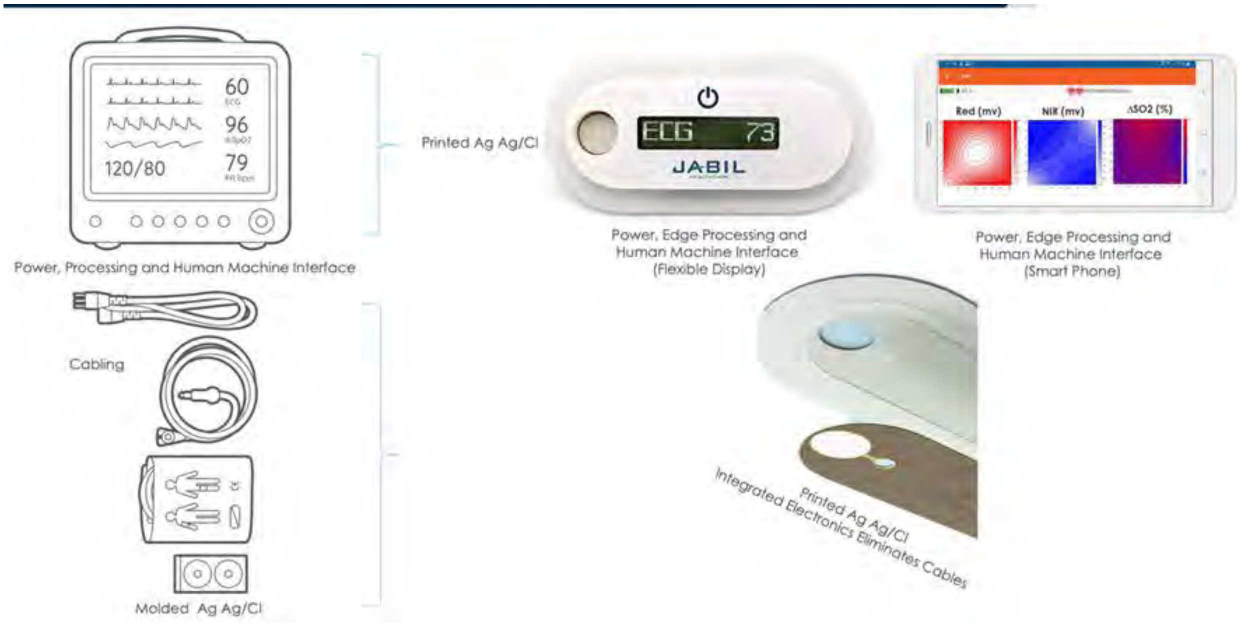

Figure 2.4.5: *Smart Wearables enabled by reduction in parts, size, weight and assembly steps offering a potential option for vitals monitoring.*

2.4. Additive + Subtractive

Lead: Alex C.
Contributors/Editors: David B.

2.4.1. Introduction

While additive techniques boast benefits including reduced processing steps, higher process throughput, and reduced cost, subtractive techniques or semi-additive techniques can still provide additional benefits when used in conjunction with additive techniques. This section will focus on selective subtractive patterning which augments but does not replace additive techniques. An example includes screen printing a layer of ink then laser-ablating a small section of the ink to achieve an area with smaller line width and pitch. Semi-additive processes such as LDS are considered in other sections of the chapter (Section 2.11). Semi-additive processes such as mSAP are considered out of scope as they rely entirely upon lithography and may be covered in other chapters of this roadmap.

2.4.2. Subtractive Techniques

Subtractive techniques can be broadly broken down into chemical and physical techniques. Additively deposited features can be resistant to chemical etching as the inks when finished processing often are chemically resistant cross-linked polymers or sintered metals. The 3D nature of additive techniques can be difficult for photolithographic techniques as well. Finally, the chemicals needed for chemical lithography are increasingly a concern for health and environmental reasons. For these reasons, the focus is largely on physical removal methods such as mechanical milling and laser ablation processes.

2.4.2.1. Milling

Additively printed conductors and insulators can be patterned using a mill. Mills for machining metals and plastics are ubiquitous, but are usually designed for larger scale parts than electronics. Some printers (such as the nScrypt) may include milling heads for use on 3D printed parts. Using subtractive milling to an additively printed part can smooth surfaces, drill vias, and improve line width and thickness tolerance, however, improvements in resolution are limited by the comparatively large size of end mills and drill bits. End mills are commercially available down to 1 mil (25.4 micron diameters at the time of writing). Mills can typically cut up to a few tens of mm/s with a depth of cut less than one half the end mill diameter. Milling additively printed mechanical parts and electronic substrates is of particular interest as mills can improve surface flatness and tolerance on complex 3D surfaces.

2.4.2.2. Laser Drilling or Ablation

There are two modes of laser patterning, a positive or forward mode in which the laser sinters or catalyzes material before washing untreated areas, or a negative method in which the laser ablates undesired materials. The former is closely related to additive methods such as selective laser sintering or stereolithography. The latter ablative method is considered here.

Ablative laser processes are much like milling in that material can be removed from a surface to increase the tolerance of a printed feature or form the feature entirely from a blanket printed area. Laser processes can achieve higher resolution and speed with laser spot sizes down to 10 microns and speeds up to 1000 mm/s. Such laser tools are commonly available in PCB lines and are commonly used for via drilling and cutting applications. Unlike milling, laser ablation cannot smooth a surface, but will remove a more consistent volume of material from the surface.

2.4.3. Compatible Additive Techniques

Additive techniques most compatible with subtractive techniques make use of the subtractive technique's higher resolution by selecting a faster but less accurate additive technique. These may include screen print, inkjet print, or extrusion printing. As these methods are physically removing material, they are somewhat agnostic to the time of material being removed.

2.4.4. Applications

1. Microchannel cutting
2. Higher Resolution
3. Tailored resistance (e.g. high precision resistors)
4. Kirigami
5. Laser-sintering or laser formulation of materials

2.4.5. Potential for Heterogeneous Integration

Subtractive techniques are common in semiconductor and PCB manufacturing, making this a useful approach while additive technique improve in quality and throughput. Laser patterning in-particular can achieve resolutions capable of forming interconnection traces and pads between dice. Use of these technique can also create microchannels for cooling or sensing functions.

2.4.6. Benefits & Drawbacks

Benefits

1. Can improve the resolution of a high-speed additive process
2. More vertical trace edges for coplanar waveguides
3. Compatible with 3D surfaces
4. Utilizes common tools & processes
5. Improved tolerance
6. Improved surface finish (milling)

Drawbacks

1. Substrate damage
2. Creates debris
3. Laser tools can be expensive

2.4.7. Alternatives

The primary alternative to utilizing subtractive techniques is to pair a low resolution additive technique with a high resolution additive technique. An example can include printing die interconnections with an Aerosol Jet tool, but printing board-level circuitization with a screen printer. Compatible processes are discussed at length in other sections of the chapter. A secondary emerging alternative is to choose a printing technique capable of high resolution and sufficient speed to be faster than the combination of additive printing and subtractive patterning.

2.4.8. Future

This technique is primarily improving as the subtractive techniques improve. Laser tools can achieve smaller spot sizes by utilizing improved optics, as seen in laser mask cutting tools, but such improvements may not be practical. However, further improvements in the additive techniques which these approaches accompany could make obsolete the need for the additional subtractive step.

2.5. Aerosol Printing

Lead: Martin H..

Contributors/Editors: Rich N.

Aerosol Printing was originally developed in the early-to-late 1990's in the US Defense Advanced Research Projects Agency (DARPA) program "Mesoscale Integrated Conformal Electronics (MICE)". It was developed to fill a neglected middle ground in microelectronic fabrication. At that time electronics manufacturing techniques created very small electronic features (<1µm), for example by vapour deposition, and relatively large ones for example by screen printing (>100 µm). No technology was capable for satisfactorily creating crucial mesoscale-sized (1-100µm) production of interconnects, components, and devices.

The process starts with the functional ink being placed in the atomizer chamber. The atomizer uses either ultrasonic or pneumatic methods to create an aerosol. In the pneumatic atomization method, a high-pressure flow of an inert gas (such as nitrogen) is fed into the atomizer chamber through the top, resulting polydisperse microdroplets of various sizes. Large, high-inertia microdroplets are impacted on the side wall of the atomizer chamber and descend into the ink chamber while lower inertia microdroplets are transported with a carrier gas to the printing nozzle where a secondary gas flow (sheath gas) constrains it in an annular ring and compresses it as it flows thought the nozzle orifice. On the other hand, ultrasonic atomization is simply based on an ultrasonic transducer that is immersed in coupling medium. The pressure waves coupled through, typically a water, bath propagates to the ink vial which is suspended above the transducer. This causes local shear resulting in small microdroplets being ejected from the ink in which then traveled through the carrier gas to the printing nozzle. The choice of the atomization method mainly depends on the ink characteristic including ink viscosity, main solvent, and solid content size and percentage [1-4].

AJP uses aerodynamic focusing approach to direct and focus the aerosol stream onto the substrate. Focusing ratios of up to 10:1 (nozzle diameter to focused aerosol beam diameter) means that very fine print resolution of down to 10 µm from 100µm nozzle diameter can be obtained. The focused aerosol is projected on to the substrate, moving relative to the substrate, to create the printed feature. Unlike Piezo Jet or Ink Jet printing the aerosol print process is a continuous flow process. Therefore, shuttering mechanisms, either inside the print head or externally, interrupt the aerosol based on the applied machine code to enabled clean starts and stops of the printing on the substrate surface. Fig 1 shows a schematic diagram of AJP process, based on: (a) pneumatic and (b) ultrasonic atomization.

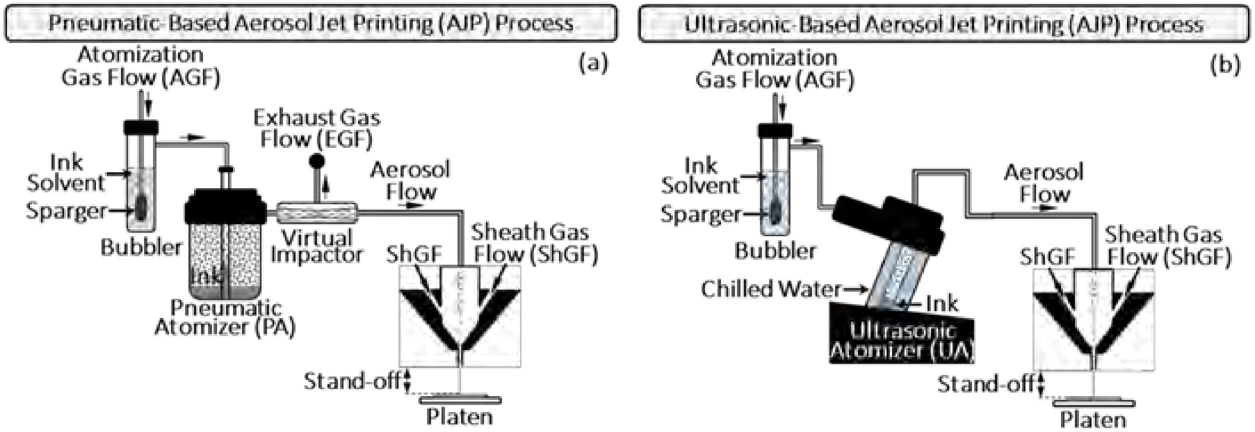

Figure 2.6.1: AJP process schematic illustration [3]

Pneumatic atomization has the advantage of being able to process inks with higher viscosity (1000cP), making it possible to print relatively thick polymer inks. However, there is a limit for the uniformity and the stability of the aerosol stream and the high shear forces involved can “work” the ink to negative effect. On the other hand, ultrasonic produces highly uniform aerosol but it is limited to inks with low solid content, smaller particles size, and smaller window of ink viscosity (1-20cP). Aerosol Printing systems need extraction and filter systems (Active Carbon and HEPA filters) to operate safely since small amounts of the aerosols, that can contain nano-particles, can stay airborne during the printing process.

AM using AJP has been reported extensively in the literature, relating to AJP-based device fabrication, demonstrating the scope and potential areas, engendered by AJP technology. Devices such as interconnects, sensors, transistors, optical waveguides, electromechanical and chemical devices, solid oxide fuel cell, RF elements, quantum dot devices, flexible and wearable devices, optoelectronics, photodetectors and photo switches, solar cells and photovoltaic devices, and high temperature electronics have been demonstrated [1,5-7]. The AJP process is capable of printing a range of organic and inorganic materials, including metal (single metal, metallic oxide, metallic alloys, and core-shell bimetallic), polymer, carbon-based inks, insulators, biological materials, magnetic materials, and adhesives, provided that the specified ink is suitable for atomization. These materials can be printed on a wide array of surfaces, including polymers, metals, ceramics, silicon, glass, and biomaterials. In addition, the performance of the such material can be enhanced through various postprocesses, such as thermal sintering, laser, microwaves, photonic, chemical and electrical sintering [8].

Two commercial aerosol printing processes are currently commercially available – Aerosol Jet™ from Optomec Inc. and NanoJet™ from IDS Inc. Aerosol Jet was developed under the DARPA program and patented in 2003, US Patent 7045015 “Apparatuses and method for maskless mesoscale material deposition.”. The NanoJet process is based on Sandia National Laboratories U.S. Patent 6,348,687, ”Aerodynamic Beam Generator for Large Particles.” from 1999.

The main difference between the processes is that the Aerosol Jet process has a single aerodynamic focusing step and Nano Jet has two focusing stages, Fig. 2.6.1:

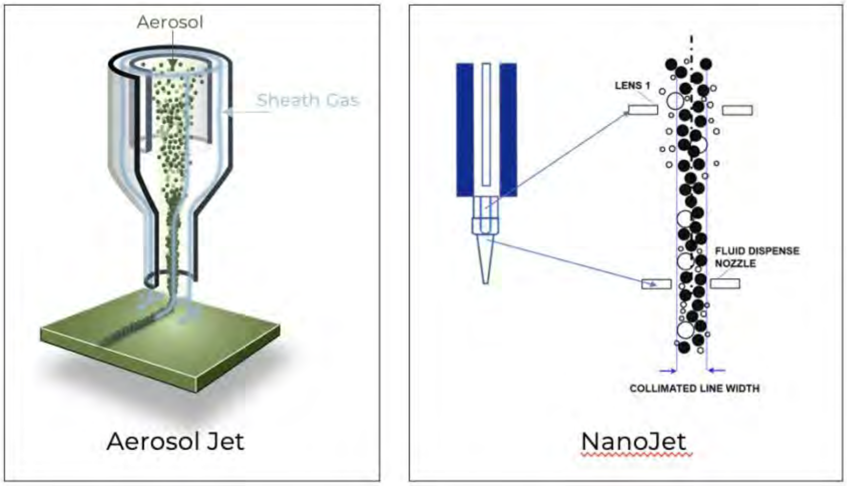

Fig. 2.6.1. Schematic view of the aerosol focusing steps in Aerosol Jet (1 focusing step) and NanoJet (2 focusing stages).

Both processes can create the aerosol by ultrasonic atomization. The ink is placed in a vial above an ultrasonic transducer that transfers the ultrasonic energy via a water "bath" to the ink, Fig. 2.6.2.

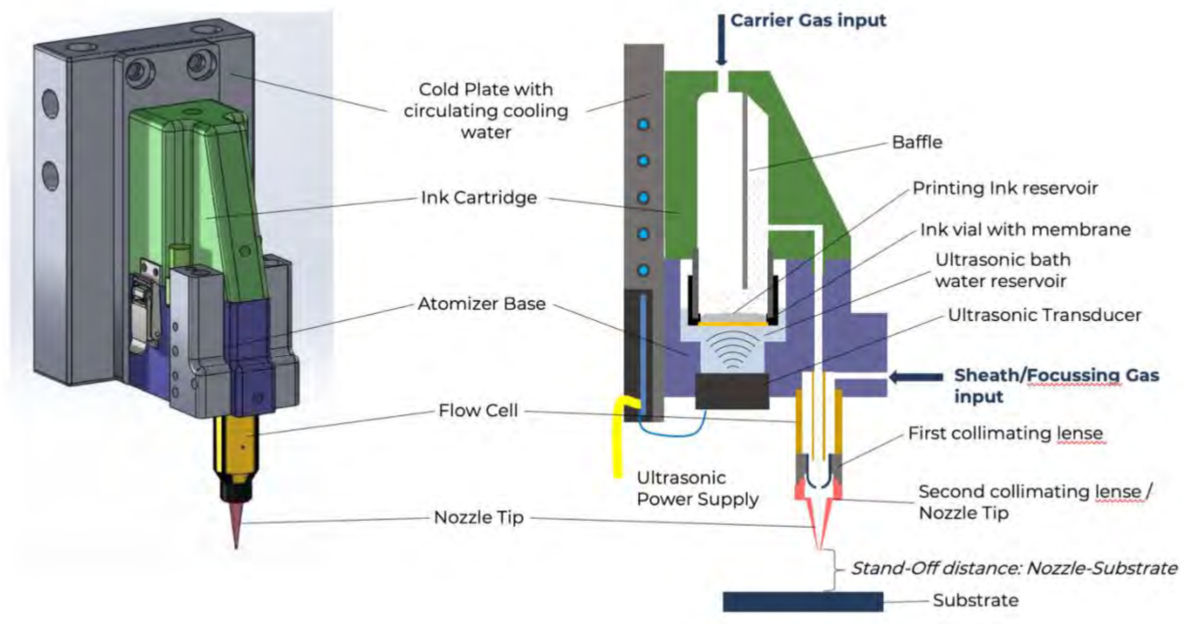

***Fig. 2.6.2. Schematic of the NanoJet process (Ultrasonic Atomization*).** Courtesy Neotech AMT GmbH

This breaks down the surface tension in the ink to create the aerosol mist. In the case of Aerosol Jet atomization can also be done pneumatically. In this case an atomizing gas (typically N2) flows above a venturi tube which draws up the ink and shears it off into a stream the impacts the atomizers walls. Large droplets flow down the atomizer wall or drop form the aerosol by gravity leaving a fine mist of airborne femtolitre droplets. This aerosol is then further processed to remove excess atomizing gas and ultrafine droplets that will not deposit properly in the printing. Pneumatic atomization has the advantage of being able to process inks with higher viscosity (to ca. 1,000mPas) then the ultrasonic method (max. Ca. 20mPas), but is more difficult to do in a stable way and the high shear forces involved can “work” the ink to negative effect.

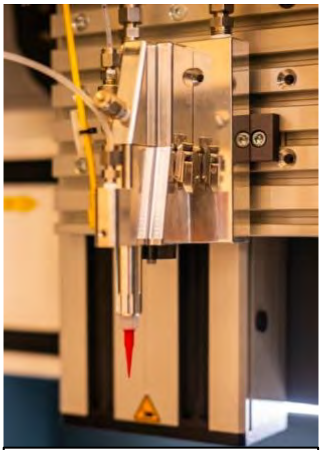

Fig. 2.6.3. Photo of the NanoJet print head

Aerosol Printing systems need extraction and filter systems (Active Carbon and HEPA filters) to operate safely since small amounts of the aerosols, that can contain nano-particles, can stay airborne during the printing process.

Both the Nano Jet and Aerosol Jet process delver an aerosol with a long focal distance (>1mm) and the print heads have long, narrow nozzle, Fig x., means that aerosol printing is ideally suited to working in 3D. Figure x. shows an example of two printed antenna on the inside of a molded PC body that is the housing for an IoT Device. The structure on the base of the box is an NFC antenna for writing and reading data to and from the device motherboard. The antenna on the walls are combined LoRa (Long Range Wide Area Network) and NB-IoT (Narrowband Internet of Things) antenna for communicating with gateways.

Fig. 2.6.4. *Ag nanoparticle antenna Aerosol Jet printed inside an injection molded PC body.*
Courtesy University Erlangen Nuremberg - FAPS Institute

As well as excellent 3D capability, the ability to print to fine resolution making Aerosol Printing is ideal for miniaturized 3D HI. Figure x. shows a miniaturized ultrasound camera for use in pacemaker lead extraction tool that is being developed in the current EU Penta project "Additive Manufacturing based Production of Embedded Robust Electronics (AMPERE)":

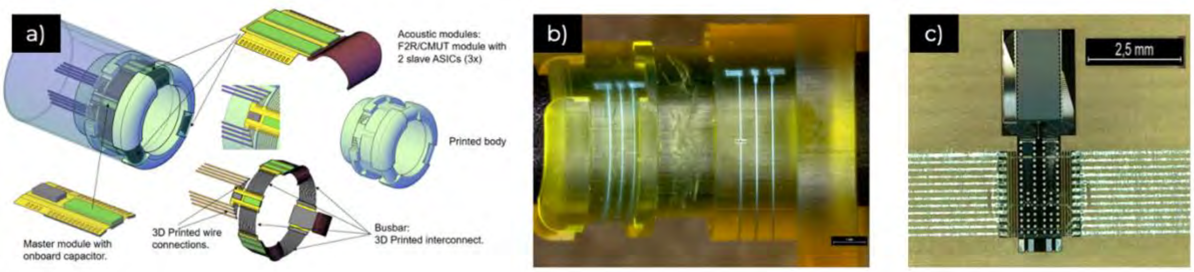

Fig. 2.6.5. *Miniaturized ultrasound camera device being developed in the APERE project.*

a) Schematic of final camera design.
b) Initial print tests with 40µm wide NanoJet printed Ag circuits on micro-SLA printed resin.
c) 2D test for connecting the Acoustic module to the printed Ag circuit.

Courtesy Phillips Medical N.V./Neotech AMT GmbH.

The ability to print fine conducive structures on a 3D printed body and electrically connect the placed SMDs are key capabilities in this application. Print speeds for the aerosol processes are strongly dependent on the resolution required. For example, printing at 20 µm would be at lower speed (a few mmm/s) than printing at 200 µm (ca. 30mm/s). Additionally, printed line thickness varies dependent on feature size, print speed and material used but is typically in the range from 0.2µm to 5um per pass.

Relating to HI 3D, AJP promotes the ability to print high resolution and well-defined conductive traces, pads, blind and through vias to interconnect components within the same substrates in planner or 3D fashion. With that, AJP AM technology can be of great use for printed redistribution layers (RDL) and interposer directly on the package or in the substrate. RDL and interposers through AJP AM is in fact great step in the integration of semiconductor components. Simply AJP with functional inks is used to print multilayers or crossed interconnects directly on the chips which allow stacking components such as memory in 3D fashion. In addition, such 3D integration offers process flexibility, short time-to-market as several materials (conductors and cross over insulator) can be printed simultaneously, customization, and low materials cost, waste, and usage.

AJP is an attractive technology to facilitate heterogeneous integration in comparison to the traditional processes such as flip chip technology that are often costly and limited in the scope of device geometries that may be worked with. Wire bonding interconnecting process is another process that possess some limitation despite its use. These limitations include mechanical reliability, associated parasitic inductance and capacitance, and induced stress due to the bonding process. On the other hand, utilizing AM such as AJP can mitigate that resulting in low profile conformal interconnection (no loops), smaller footprint, lower inductance and mechanically more robust. This of course introduces AJP as emerging approach for heterogeneous integration of mm-Wave circuits. The chips are embedded, flip chipped, or surface interconnected to variety of substrates and then AJP is used to interconnect chips to the substrates. As examples of such integration is utilizing AJP to fabricate GCPW transmission lines interconnect interfacing a GaAs MMIC with an LTCC packaging substrate using silver-based nanoparticles ink [10]. AJP was also, utilized to fabricate on-chip gold interconnects over printed polyimide onto GaAs MMICs to connect a gate pad and a ground pad of the MMICs [11]. A 2.5 D interconnection method for electro-photonic integration was demonstrated where a four-channel VCSEL transmitter was successfully demonstrated at high-speed of 50 Gb/s. The printed interconnects showed no failure or degradation even after performing a standard 85 °C/85 RH test over 700 hours [11]. Figure 2.6.6 shows examples of AJP in HI.

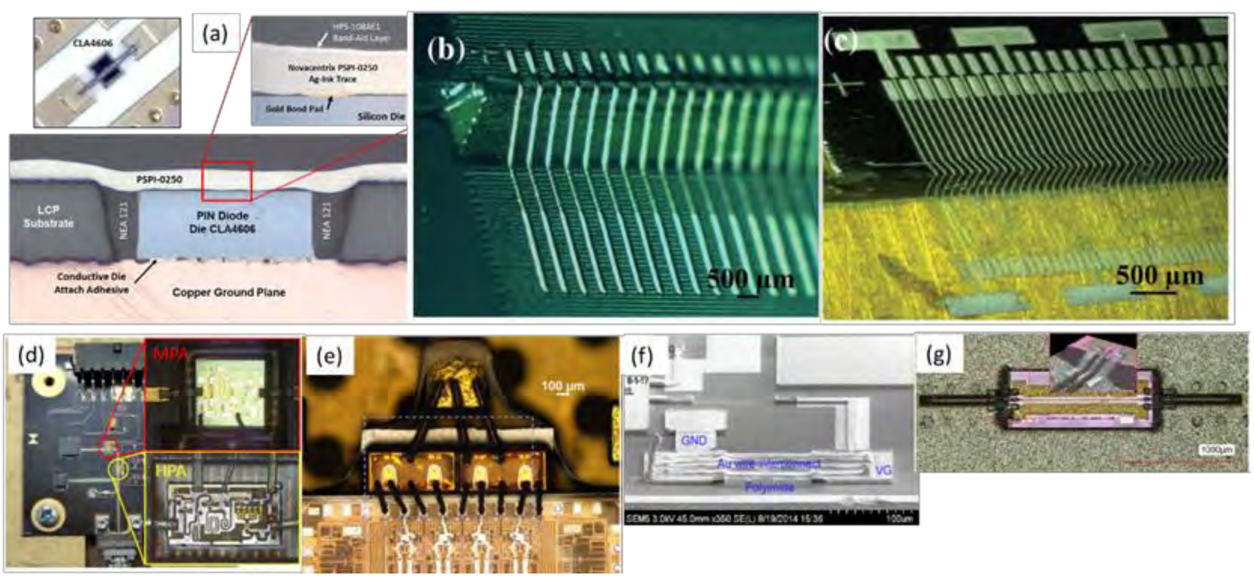

Figure 2.6.6: a) Embedded PIN-Diode Die Interconnections with Aerosol-Jet (Binghamton University), b,c) AJP Ag lines printed over 1 mm and 0.375 mm printed fillet [13], d) An RF transceiver module with AJP materials interconnecting [14], e) Assembly of 4-channel driver IC and 4 single-mode VCSELs using AJP [11], f) AJP printed Au over PI to connect gate and ground in MMICs [12], and g) AJP interconnect to GaAs-MMIC on LTCC [10].

The successful optimization and inline process monitoring and control has allowed to print electronics components with high quality, good repeatability for a long printing time. The introduction of new inks, innovation in design, and new sintering techniques that enable near bulk conductivity are all key to pushing such technology further. Another important key measure for building successful heterogeneous systems is the adhesion of such printed patterns onto the substrates, chips and conventional metallizations. Despite such feasibility studies, still there are plenty of room to mature and advance AJP for HI 3D. Challenges associated with AJP for HI 3D include materials, resolution capacity, electrical performance, throughput in the production, reliability (tolerating thermomechanical stress, handling current, electromigration), design tools, and production scaling.

Benefits

- Excellent 3D Capability – focal length of aerosol greater than 1 mm, long narrow nozzle.
- Fine print resolution down to 10um line width.

Drawbacks

- Print speed relatively slow (1-20mm/s)
- Highed investment cost – patented process.
- Viscosity range of materials limited to sub 20mPaS for ultrasonic and sub 1000mPas for Pneumatic atomization.
- Limited to particle free and nano-particle inks (<200nm preferred, 300-500nm max.)

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2.6. Electrohydrodynamic Printing

Lead: Dean T.

2.6.1. Introduction

The principle of electrohydrodynamics (EHD) has been known for over 100 years and is used a variety of applications to move fluids including micropumps, micro fluidics, micro-batteries [8] food dehydration and relatively recently, fine line printing for R&D and industrial applications.

This additive manufacturing method enables the printing of line widths as small as 0.5mm with typical use in the 1- 50um range.

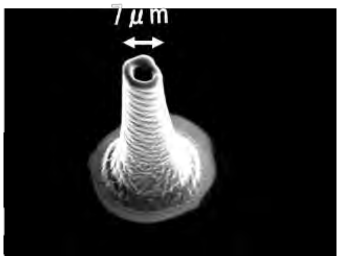
EHD printing is a non-contact print technology and can be used on rigid or flexible substrates, typically 2D substrates but with some capability to print on 3D topographies with limited range. Some systems have developed applications to print simple and small 3D structures such as micro-pillars. A wide variety of inks and other materials can be printed with EHD spanning a wide viscosity range and a wide range of material characteristics.

A small number of companies offer commercially available EHD printing systems and some individual organizations have made their own one-off tools typically for use in a lab or university environment.

General EHD Characteristics

- Femtoliter droplets
- Line width from 0.5um and up
- Multiple nozzle sizes for multiple applications and materials
- Disposable nozzles
- Multi-nozzle heads (up to thousands of nozzles)
- Autofocus to control working distance and print over 3D topography
- Monitoring cameras to watch the drop delivery process and line quality
- Range of printing parameter and waveform controls drive the wide viscosity range capability
- Controllable working distance for line integrity control [3]
- Print area up to 350mm x 350mm (compatible with 300 mm wafers) or larger
- Digital file inputs from a variety of sources and design tools
- Printing standoff distances 10-50 um, dependent on resultant drop size target [4][6]

Typical EHD Printing System



21 x 7 *u*m Pillars

5 *u*m Line Widths

Fig. 2.7.1. EHD Printer and printed features. *Images Courtesy SuperInkJet Technologies (2021)*

2.6.2. EHD Benefits

The prominent advantage that drives the selection of EHD printing for an application is the requirement of small line widths. Line widths down to 0.5um have been achieved with typical application in the 1 to 10um range which extends capability of digital inkjet below 20 um. Although some gravure printers are attempting to reach 3um, EHD provides the added advantage of printing digital patterns and no need for gravure plate engraving, reducing cost and set up times and making modifying the next iteration of design much quicker at a lower cost.

The second key feature driving EHD selection is the requirement to print with unique materials and/or materials with non-traditional jetting viscosities. Some applications with even larger dimensions can also drive EHD use especially if a more viscous material is required and cannot be printed with an inkjet or aerojet technologies. Typically digital jetting requires viscosities in the 3 to 20 cps range.

The EHD delivery mechanism allows the use of a wide range of materials and a much wider range of viscosities unable to be applied by other digital printers such as piezo inkjet or aerosol jet as shown below.

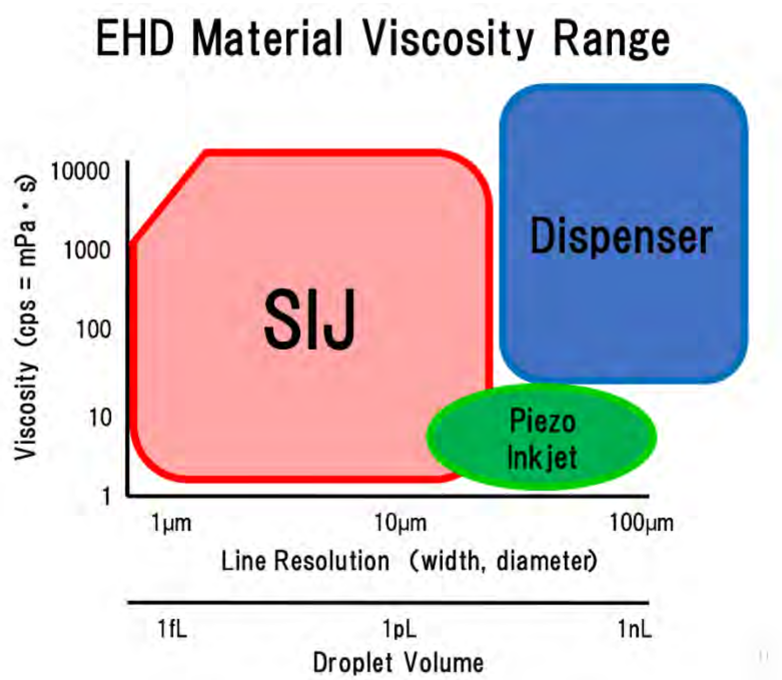


Fig. 2.7.2. Materials viscosity and resolution tradeoffs. *Images Courtesy SuperInkJet Technologies (2021)*

The third deciding advantage of common EHD printers is the ability to print accurately over topography such as over the first layer of a printed transistor [(5)] or printing a connection onto a component such as a resistor, capacitor or IC die. [(4).] If an application requires printing to a small patterned target with a precise location and/or to a target site with Z height, such as a repair application, EHD may be your only choice for an additive approach.

2.6.3. EHD Drawbacks

The most notable limitation for high volume applications of EHD is the print speed. The application of femtoliter drops to achieve fine line prints, by definition, drives the slow speeds of printing long lines or dense patterns.

The second limitation to consider for your application is the restriction of printing “same patterns” in the parallel multi nozzle systems. Where the typical multi nozzle inkjet systems can print using 1000s of independently fired nozzles, standard single nozzle EHD systems cannot do this.

However, this speed limitation can be significantly enhanced by using a relatively new advancement of Multi-Nozzle EHD heads. Multi-Nozzle EHD can be used to mitigate the speed limitation if your application has repeating patterns. Multi-nozzle EHD printers to date are limited to print a pattern such as 100 parallel identical 1um lines. Multiple nozzles in EHD cannot today be fired independently like a piezo inkjet head with a digital pattern. For repeating patterns or lines such as 100 parallel 1um lines, printing an array of micro-lenses or any identical repeating pattern, custom nozzles can be provided to dramatically increase the speed of these applications versus a single nozzle approach.

2.6.4. Material Considerations

There is a myth associated with EHD technology that says due to the electrostatic principle used to deliver the ink droplets there is a restrictive requirement that limits EHD printing only on conductive materials. This is a consideration but practically not correct with the currently available printing systems. EHD requires such a small conductive path that with an especially thick or insulative substrate, a mere increase in humidity in the system may be able to provide the necessary path. Some systems are supplied with a humidifier for this reason.

2.6.4.1. Material Compatibility

There is a wide range of material types and viscosities, which extends beyond traditional inks and beyond the normal digital jetting systems compatible inks, that can be used for EHD printing applications, examples include:

Conductive Inks

- Ag, Pt, Ni, C, Pt, Au, W, Ni, Cu, Nb, Co, Fe, Zn, In, Al_20_3
- Copper inks [7]
- Any metal ink type available with particle sizes compatible with the selected nozzle diameter
- Ag & C nanowire inks are also possible depending on nanowire size relative to nozzle size
- Thermal inks ($BiTe_3$)
- Formulations for stretchable, flexible or transparent inks are all EHD compatible

Other Inks and Fluids

- Dissolved Polymers; Adhesives; Fluorescent inks; Graphics Inks; Dielectrics; Ceramic inks; Quantum Inks

Substrate Types

- Many types of substrates have been successfully printed using EHD. The list includes most popular rigid and flexible substrates.
- PET; TPU; Metals; Polyimide; Silicone; Other polymers including thermoplastics; Glass

Heterogeneous Integration Specific Applications

- Uses of EHD within a heterogeneous integration context have begun to develop, including use for:
- Interconnect on rigid or flexible substrates [4]

- Redistribution layer [4]
- Fill small cavities, trenches, Through Silicon Vias, Through Glass Vias [6]
- Repair connections
- Print micro devices-Capacitors, resistors, etc
- Multi-layer circuits
- LEDs, Micro-LEDs, OLEDs
- Micro-lenses
- Micro sensors
- Thin film transistors [5]
- Antennas

2.6.5. 3D Features

Whereas the EHD printers available today are not 3D printers as traditionally defined, they do have some capability to print over 3D topography[4] or print limited small dimension 3D structures such as micro-bumps, micro-lenses or micro-pillars. [3]

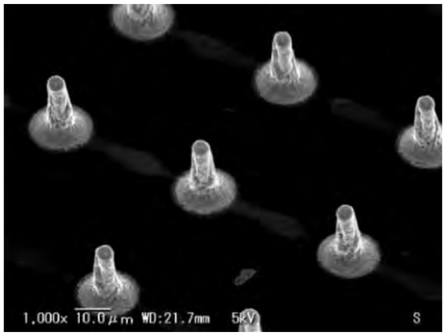


Fig. 2.7.3. *3D EHD Features- Height 20um, Diameter 5 um. Courtesy SuperInkJet Technology (2020)*

2.6.6. Future of EHD Printing

A large percentage of the potential EHD users are still unaware of the capabilities of EHD. As more users discover EHD, new applications will grow and EHD will be required by the general drive to make smaller and smaller devices and products. Other existing applications now done with subtractive methods requiring processes such as lithography and etching will continue to be displaced by additive methods at the smaller dimension applications. EHD will be used to address these advanced applications. An example is the growing interest within heterogeneous integration in the use of printing fine conductive lines, with an emphasis on interconnect and filling small vias and trenches. More applications will be implemented as the FHE and Additive Communities push the edge of the available technology to smaller and smaller dimensions. As more unique applications appear and require unique printing materials, formulations will be developed for more materials to be compatible with EHD.

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2.7. In-mold and Thermoformed Electronics

Lead: Christine K.
Contributors/Editors: David B.

2.7.1. Overview

In-Mold Electronics (IME) is often used as an umbrella term describing processes combining printed electronics with conventional components using 3D forming and molding to create 3D objects/surfaces with embedded electronics. The innovation lies in the combination of the fabrication of electronic modules with thermoforming and traditional injection molding processes. This emerging field has gained significant attention in recent years due to its potential to revolutionize the way electronic devices are designed and manufactured. IME allows for the seamless integration of electronic functionality into 3D-shaped surfaces, enabling new products.

IME enables the creation of complex, 3D-shaped electronic devices. It has been shown to reduced weight and size as the integration of electronic components directly into the substrate eliminates the need for additional housing or enclosures. IME can reduce the number of assembly steps and materials required, leading to cost savings in production together with higher yield. It also simplifies logistics by reducing the number of components that need to be sourced and assembled. By embedding electronics within the substrate, they are less susceptible to environmental factors like moisture and dust, enhancing robustness and reliability of the final product. IME allows for mass customization of products, catering to individual preferences and specific applications. This is particularly appealing in the fashion and automotive industries. The reduction in materials and improved energy efficiency during production can lead to a smaller environmental footprint, aligning with sustainability goals.

On the other hand the technology also comes with some challenges. The number of materials (substrates, conductors, interconnects) that can withstand the molding process (>150C) while maintaining electronic functionality is limited. Ensuring the quality and reliability of IME products is complex, as defects or failures in the molding process can affect the electronic components' performance. IME requires a high level of manufacturing expertise as technologies and materials from two different fields have to be merged. While feasibility has been shown for years the transitioning from prototyping to mass production can be challenging, as maintaining consistent quality and precision at scale is a complex task. The IME field still lacks widely accepted industry standards, making it difficult for manufacturers to develop products. The initial setup costs for IME is high, and therefore the technology may not be cost-effective for all applications, particularly those with simpler designs. Integrating IME components with existing electronic systems and interfaces can be a complex task, requiring careful planning and engineering as well as a new form of co-design of electronics and product.

2.7.2. Equipment & Methods

IME is based on the process flow for printed electronics on polymer foils. After the Modules are assembled the 3D forming is done in 1 or 2 steps.[1] Thermoforming alone can be sufficient for certain applications and simple circuits can be deformed and over-molded in one step without damage. The general process flow is shown in Figure 2.8.1. The most important advantage is the use of conventional equipment for printed electronics manufacturing in the first two process steps. For thermoforming, especially high-pressure thermoforming, has been demonstrated as it allows lower processing temperatures while maintaining very accurate geometries.

Besides printed electronics also electronics with meandered copper tracks can be used for IME.

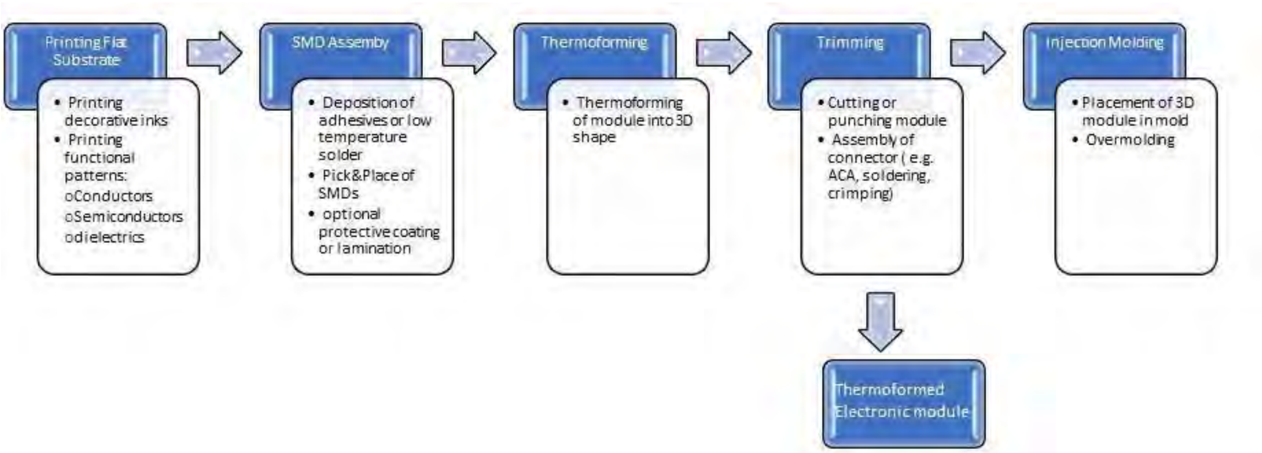

Figure 2.8.1: *Process Flow In-Mold Electronics*

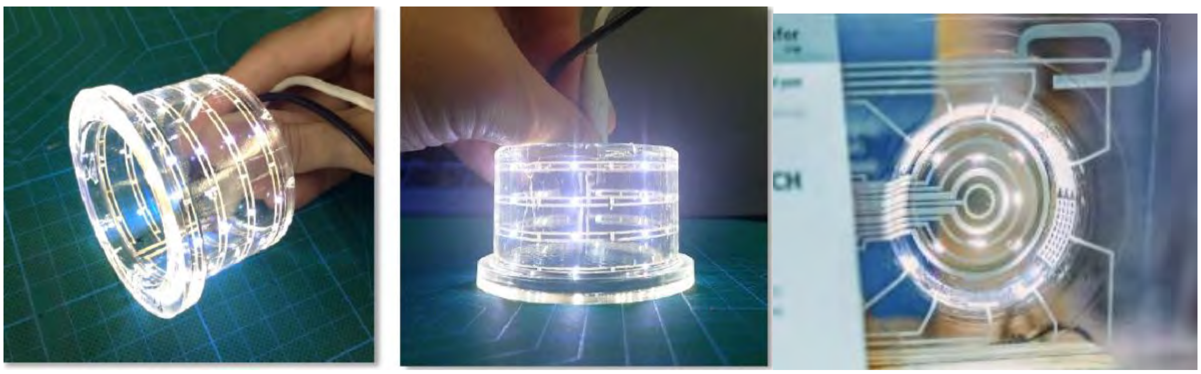

Figure 2.8.2: *Examples for typical IME demonstrators*

2.7.3. Materials

The basis for IME are flexible hybrid electronic (FHE) modules. The materials are therefore those typical for FHE - but with restrictions. The deformation requires a stretchability of min. 30 % (> 60% desirable) for substrates, conductors and printed components. The most important criterion for the materials used for the microelectronic modules before the thermoforming and injection molding step is their stability at the process parameters during these steps. Depending on the materials used, up to 350°C may occur (150-250C typical). Besides thermoplastic materials, thermoset materials like Polyimide can also be used with a suitable layout. An overview of materials used for the different components / layers is shown in Figure 2.8.3. The material properties for some common substrate materials for IME are given in Table 2.8.1.

As the processes involve softening or even melting of materials the investigation of the material compatibility, e.g. adhesion properties, is very important for the realization of robust modules.

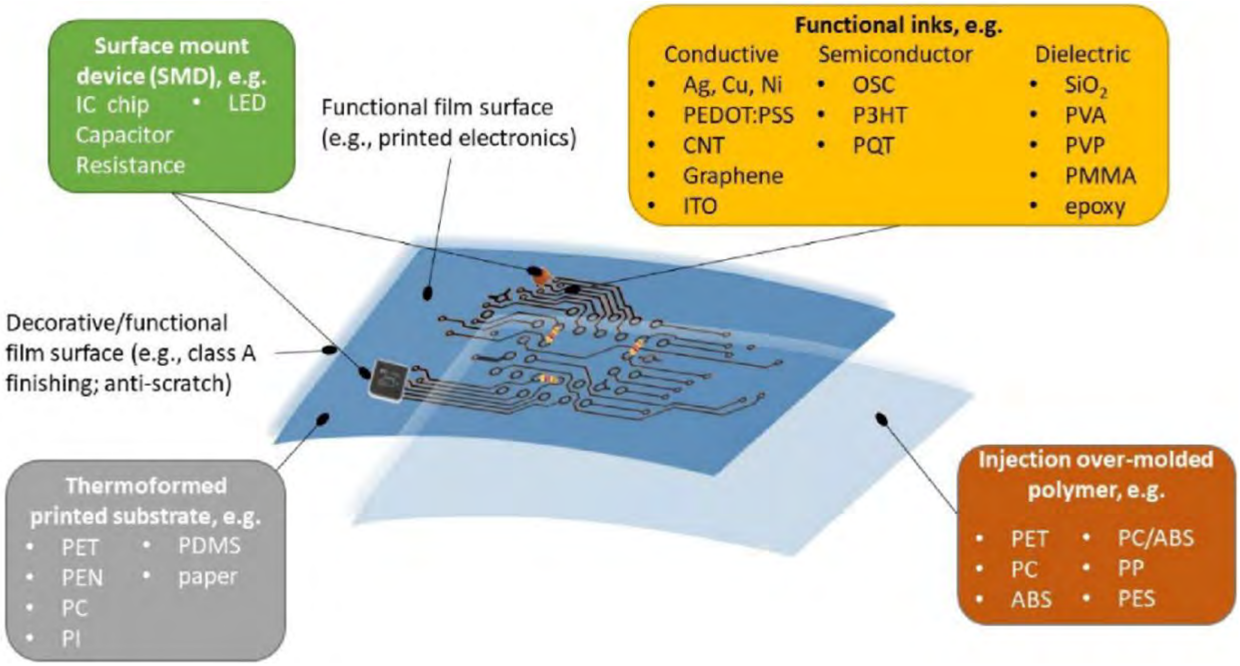

Figure 2.8.3: *Material overview for the different IME components*

Material	Tg/ Tmelt (°C)	Tensile Strength (MPa)	CTE (ppm/°C)	Elogation @Break (%) @298°C
TPU	155-170	55	200	>300
PC	220-230	70	70	115
PET	80	25	45	88
PEN	120-140			
LCP	300-350	30	45	
PI	410	100	13-20	44

Table 2.8.1: *Material properties for IME substrates*[6]

The components found in IME are typically various SMD components, flip-chips, sensors (printed and conventional), printed resistors.

Besides the currently available materials, it can be expected that a need for higher deformation rates will lead to the use of liquid metals as conductors within IME. Higher complexity of application can be realized using printed semiconductors. Sustainability aspects will lead to the investigation of biopolymers for IME.

6

2.7.4. Applications

The design freedom of IME is particularly valuable in industries like automotive and aircraft interior, consumer electronics, and wearables, where aesthetic and ergonomic considerations are crucial. But also robotic applications (collaborative robots, soft robotics) are a major opportunity.

In general, the technology allows smart surfaces – especially for human-machine interfaces and smart structures. The surfaces usually comprise sensor functionalities as well as direct feedback (actuators, LEDs, sound) or data processing and wireless interfaces.

After a false start with a focus in Europe, the market, material selection and manufacturing capabilities have continued to grow worldwide.

2.7.5. Outlook

- To enable the implementation of the technology in production there is still a need to improve modelling and simulation of thermoforming and injection molding of complex multi-material build-ups.
- The complexity and also the 3D design freedom can be increased by controlled high resolution temperature distribution for thermoforming.
- There is still a need for conductive Inks / pastes for higher deformation rates – even after prior thermal process steps like adhesive curing.
- Methodologies for co-Design of product (housing) and electronics taking into account the IME process limitations will have to be established.
- The challenge of sustainability and recyclability with increased level of integration / embedding will have to be solved – especially for automotive and aircraft applications.
- IME will show its full potential combined with other technologies – e.g. 3D printing – to overcome intrinsic limitations (e.g. undercuts).

BELTRÃO, Mariana, et al. A review on in-mold electronics technology. *Polymer Engineering & Science*, 2022, 62. Jg., Nr. 4, S. 967-990.

[2] IDTechEx report In-Mold Electronics 2023-2033

2.8. Piezo-Valve Jetting

Lead: Martin H.
Contributors/Editors: Rich N.

The Piezo-Jet process was initially developed to meet the assembly demands, consumer electronics (mobile devices, LEDs) and medical devices using adhesives, sealants and other polymeric materials. It has found use in the last 5 years in emerging printed electronics applications where conductive inks and pastes are deposited.

In the piezo-jet process, the ink or paste to be dispensed is pneumatically delivered through a fluid assembly to the jet nozzle. A ceramic tappet (piston) that is connected to a piezoelectric actuator, is moved according to a pre-programmed waveform, which opens and closes the nozzle orifice. This oscillating motion imparts significant kinetic energy into the ink/paste which is then ejected from the nozzle, under controlled pressure, forming precise volumes of material on the substrate.

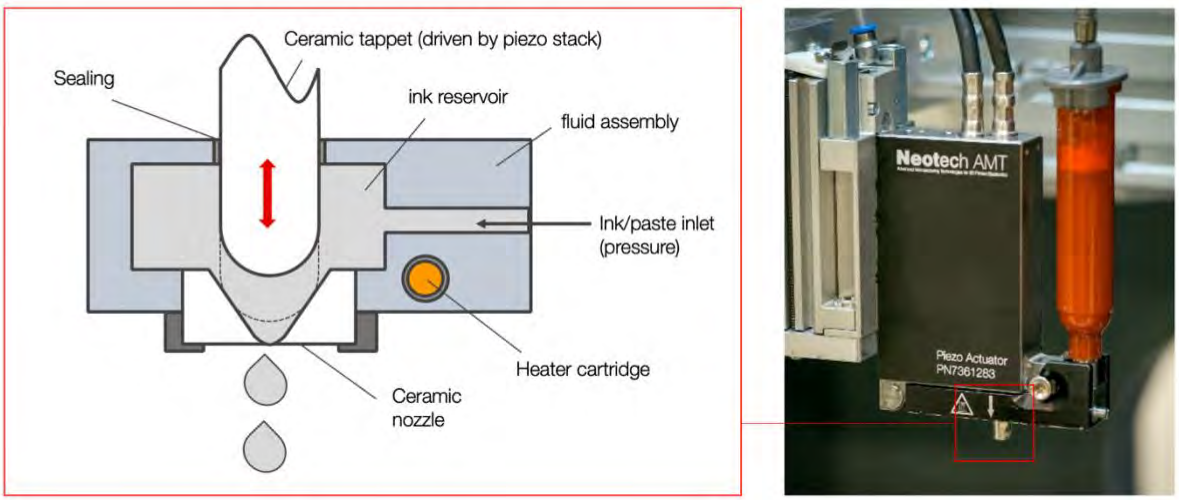

Fig. 2.2.1. *Schematic diagram of the Piezo-Jet process.*

The frequency of operation varies dependent on the material processed. In printing conductive material systems such as metallic inks and pastes frequencies in the range of 80Hz to 200Hz are typical. This relates to line print speeds of 15-50mm/s. Printing of easier to process materials (for example single component adhesives or resins) higher frequencies, in excess of 1,000Hz can be used.

Material volume per droplet is in the pico-litre range. For example when using PiezoJet to deposit relatively viscous (>10,000+mPas) conductive Ag pastes individual droplets can be ca. 300-350um diameter and 20+um peak thickness. With more fluid materials, for example with Ag-nano-paricle inks (10s-100s of mPas) cross sections tend to be wider and thinner due to material spread as it hits the surface, Fig.2.2.2.

One significant advantage of the piezo jet process is its ability to accurately deliver material on substrates with irregular heights, or where there are hard-to-reach areas. Throw distance (the distance that the droplets can travel to produce a trace with clean edges) varies dependent on the ink/paste used, nozzle diameter and process settings but is typically in excess of 1-2mm and can reach 5+mm in certain cases. The print head

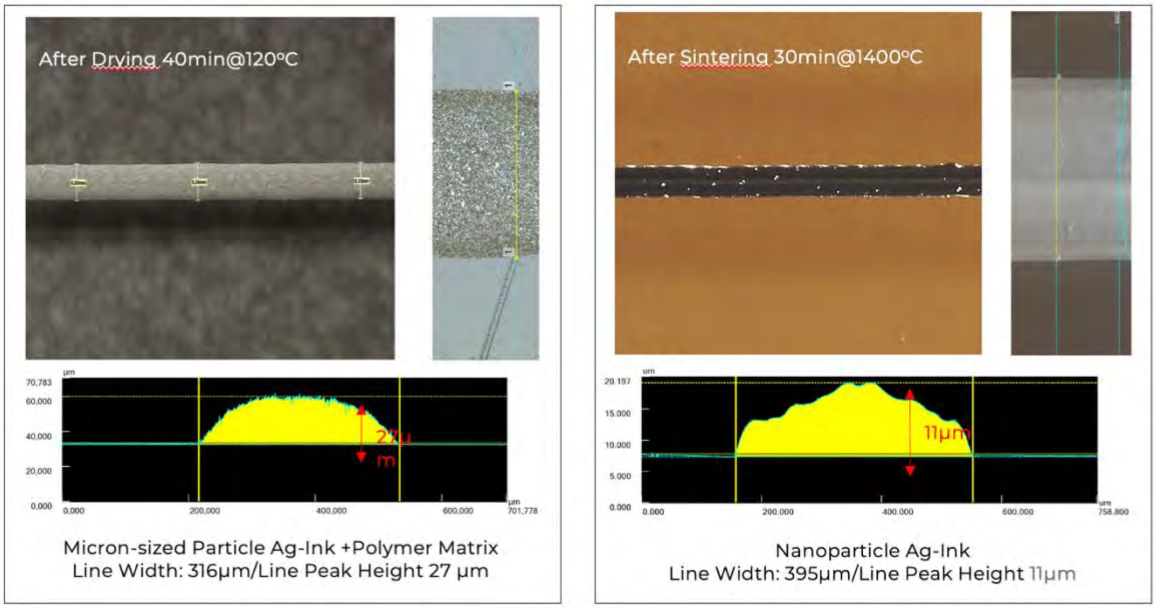

Fig. 2.2.2. *Images and Cross Sections of Piezo-Jet printed Ag.*

geometry does somewhat limit access to recessed areas compared to Aerosol Based processes. The head can be angled relative to the substrate to reach the side walls of recesses several mm deep.

Benefits

- Low investment cost
- Can handle a wide range of viscosities and particulate sizes.

Drawbacks

- Well industrialized within semiconductor adhesives/coatings, developmental for AME
- Resolution (ca. 300um minimum line width)
- Head access to narrow, deeply recessed areas (>5mm deep)

2.9. Inkjet Printing

Lead: Kris E.
Contributors/Editors: Jarrid W.

2.9.1. Method Overview & Print Modes

Inkjet printing is an additive manufacturing method which leverages inkjet print heads (typically piezo-inkjet or thermal-inkjet with multiple print nozzles) to deposit material in the form of droplets onto a target substrate. Inkjet printing is a digital process, meaning that each pixel can either be turned on or off during each printing pass such that unique patterns can be printed for each pass or layer. Various companies have commercially available printheads1,2 with varied ink properties (conductors, insulators, dielectrics, resistive, etc.), resolutions (typically 150-1200 dpi, or 170-21 micron), number of nozzles (up to multiple thousands per printhead), and firing frequencies (up to tens of kHz), droplet sizes (typically from 1.5-150 pL) which can then be selected per specific intended use-cases. Integrators often take multiple printheads and incorporate them into a single printer, with numbers of inkjet nozzles within a single system being upwards to 1 million nozzles2 with print carriage speeds of tens of centimeters per second and the ability to utilize multiple ink reservoirs for simultaneous multi-color (or multi-material) printing. This relatively high resolution combined with high build rates (up to multiple meters-squared per second) and variability of deposited materials has poised inkjet as a promising manufacturing approach for use with heterogeneous integration and advanced packaging applications.

Since inkjet is a non-contact method (with drops being ejected at multiple meters/second towards substrates with up to 1-2 mm stand-off distances), inkjet can be used either on planar or non-planar surfaces, being categorized within this context as a “non-contact jetting method”. Given this, applications of inkjet include printing onto planar substrates (like Si-wafers, glass-wafers, or polymeric sheets), topologic pseudo-planar substrates (like on wafers with attached dies or other placed components) or conformally onto 3D structures (like 3D printed or injection molded polymers). Furthermore, given the multi-material printing capabilities and high build rates, some examples of utilizing inkjet for building up entire 3D structures exists, like that from NanoDimension3, wherein 3D structures are built-up layer-by-layer with dielectric and conductor materials. Single parts or multiple parts can be printed at the same time, depending upon the part size and print platen size.

2.9.1. Heterogeneous Integration Uses

Inkjet has seen significant recent uses within the advanced packaging and heterogenous integration space,4 including printing of materials for use as:

- Conductive Traces - Silver-based,[5] Copper-based[6], and others
- Via formulation - within dielectric polymers [7,8] and as Through-Silicon-Vias[7]
- Interconnects - Solder ball and solder paste jetting technology or solder bump replacement,[9],[10] Interconnect to bare die[11]
- Interlayer Dielectric (ILD) Materials - BCB,[12] SU-8,[13] Polyimide [5,14]
- Encapsulants and Stretchable Substrates - PDMS,[5,14]
- Multi-layer PCBs[15],[11] and Redistribution Layers[16]
- RF structures - Antennas [17],[18] Frequency Selective Surfaces[19]
- Micro-optics - OLEDs, Micro-lenses [20]

- Sensors - thermal [21,22], pressure[23], proximity[21] and others
- Selective Oxide Etching [24]

Of the above applications, some of the most common uses of inkjet within commercialized applications to-date include for OLED printing, RF-structures, and printed conductive traces.

2.9.3. Benefits and Drawbacks

Inkjet printing has numerous benefits which have been driving some of these applications, with major ones including:

- Efficient use of material: selective placement of materials enables highly efficient material use, greatly reducing the number of steps required compared to additive plus subtractive approaches
- Digital Design: unlike some other printing processes, each printed pattern or layer can be different such that no re-tooling is required.
- Non-contact: topologies on substrates can be tolerated (up to ~1-2 mm), such that printing onto thinned die or other structures can be done.
- Relatively High Resolution: features down to 20 microns are possible, with typical features being ~50-100 microns.
- Material Versatility - numerous types of materials can be made into inkjet inks
- Build speeds - multiple factors play into inkjet being a high build-speed printing technique included volume of deposited material (with droplets upwards of 100 pL being possible, but ~10 pL being standard) with numerous nozzles firing near-simultaneously (thousands per print-head, up to millions per printer) at high nozzle firing speed (up to tens of kHz) and high printhead and/or platen movement speeds (up to tens of inches per second), placing it near the highest throughput printing system as seen in *Figure 3*.
- Co-integration: inkjet printheads are relatively small in form-factor, so co-integration within broader systems is relatively straightforward, with demonstrations of systems which include additional equipment such as: pick and place, in-situ inspection, curing, micro-dispense,[25] and in combination with additional printing technologies. Suss has also demonstrated systems integrating together inkjet and high throughput wafer-handling.[26]

However, many drawbacks still exist for inkjet, which often limits its current use and applications, including:

- Material Properties: since materials need to be formulated into inks, the resultant properties of deposited materials can often be inferior compared to their bulk counterparts. This is largely true for printed conductor materials based upon metal nanoparticles, with properties around 30-50% with-respect-to-bulk being considered “high-conductivity”. This limits some applications which may need better performance of patterned features
- Sintering Equipment: for conductive traces, often sintering of nanoparticles requires additional high-energy density light source equipment to be included
- Ink formulation: since inkjet requires an ink to deposit material, ink formulations for all materials to be deposited must be formulated. This requires significant in-lab effort and specialized materials expertise, which can limit the development cycle for inkjet printing applications, especially

considering all the fine-tuning required to make a suitable ink operating within the printable regime[20].

- Reliability: although copper inks are now becoming available for inkjet, a reliance upon silver has limited some applications, especially owing to the environmental stability of deposited conductors under reliability testing like biased HAST and concerns over electromigration.

2.9.4. Inkjet Materials

The key materials for inkjet include the printed inks and the target substrate. Substrate materials vary widely, but commonly are either 2D planar substrates (commonly Si-wafer, glass-wafer, PET, TPU) or 3D objects (commonly 3D printed or injections molded polymers). Inks are much more varied and depend largely upon if the deposited material is desired to be conductive (typically using silver, gold or copper nanoparticles), resistive (typically carbonaceous nanomaterials), insulative (low-K polymeric dielectrics like polyimide and SU-8 or high-K polymeric dielectrics like barium titanate or titania), stretchable (PDMS) or other materials.

Categories of inks can be classified as either dispersed or dissolved, with dispersed ink systems having a dispersed solid (typically referred to as a pigment) or liquid phase dispersed within a carrier fluid. A common example for these use cases is a conductive nanoparticles, which must be stabilized within a carrier fluid which consists of the majority of the ink volume. Dissolved systems can either consist of a solubilized molecule (like a polymer or a metal-organic material) or polymeric precursor materials (like polyimide monomers or oligomers), with polymeric precursor materials allowing for 100% “solids-loading” inks, wherein a post-process curing step (i.e. with UV-light) enables the full ink volume to be used as build material.

All inks must have tailored material properties to allow for proper formation of an inkjet droplet, which also vary depending upon the inkjet printhead being used. Typical properties include viscosities between 2-20 cP, surface tension between 10-40 dyne/cm, dispersion phase particle size less than 200 nm (to enable ejection from the nozzle), with other common ink components of humectants (low vapor pressure solvents which keep the nozzle wet), pH stabilizers and others. Different printheads also have different needs around solvent systems (typically aqueous and/or solvent-based) and droplet sizes (typically from 2-150 pL).

2.9.5. Growth Areas and Roadmap

Multiple companies exist for the different technical aspects of inkjet, including for printheads, printers, and inks. Each of these are pushing for improvement areas, with major developmental directions including:

Printhead Manufacturers:

- Micro-recirculation: improving the fluid flow near the firing nozzle to enable a broader viscosity range (up to 100 cP) and higher solids loading
- Resolution: new, higher resolution printhead nodes continue to be developed, pushing towards 1600 dpi (16 micron) and eventually likely 2400 dpi (11 micron)
- Multiple drop sizes: enabling printing with either a small or larger drop from each nozzle

Printer Manufacturers:

- Improved accuracy and drop placement: through finer precision tuning of print systems and closer stand-off distances
- More Printheads: improving build speeds as well as further enabling multi-material printing

- Further Co-integration: including with pick-and-place equipment, integrated inspection, and optimized curing

Ink Vendors:

- Stretchable inks: enabling use-cases of wearable electronics and other required flex/stretch applications
- Copper inks: for more straightforward replacement of copper traces and for improved reliability
- Higher conductivity and higher loadings: for improved printed trace properties
- Improved Dielectrics: better representing ILD materials with low Dk/Df, low CTE and other tuned properties

Given these trends, the following are projections of some of the key properties of inkjet, both highlighting resolution, material properties and build speeds:

Retro- and Prospective Properties	Resolution				Material Properties	Build Speed	
	Resolution X,Y (micron)	Resolution Z (micron)	Via Size (micron)	Feature sizes (Line/Space[L/S]; dielectric[E]) (micron);	Max Bulk Conductivity	Build Height per pass (micron)	Deposition Speed (m2/s)
2017	40	17	200	[L/S] - 100/100 [E] - 100	1.5E7 S/m	17	1
2020	40	17	200	[L/S] - 100/100 [E] - 100	2.2E7 S/m	17	1
2023 (present)	20	17	150	[L/S] - 75/75 [E] - 75	2.2E7 S/m	17	1
2026	*20*	*17*	*150*	[L/S] - 40/40 [E] - 40	*2.2E7 S/m*	*17*	*3*
2029	*15*	*17*	*100*	[L/S] - 30/30 [E] - 30	*3.5E7 S/m*	*20*	*7*

Table 2.10.1: Inkjet printing retro- and pro-spective properties

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2.10. Laser Direct Structuring

Lead: David B.

Contributors/Editors: Alex C., Kris E.

2.10.1. Structural Electronics

Structural electronics is a field of electronics focused on integrating electronic circuits in/on parts that serve a structural/mechanical purpose (e. g. device cases, connectors, antenna structures, automobile interiors, etc.). Historically, the parts are such that the mechanical function made it challenging to integrate electronics. The industry was born from research in the late 1970's and 1980's, focused on novel electrical connectors, known commonly by the name "molded interconnect device" or "mechatronic integrated device" (*MID)*.[1] 3D MIDs have resurged in the past 20 years due to advances in both additive manufacturing and conductor integration methods. Currently, the largest markets are automotive and mobile communications, with 3DI semiconductor packaging / heterogeneous integration interconnects an emerging market. Structural electronics are expected to co-develop with IoT, smart consumer products, and biomimetics in the coming years.[2,3]

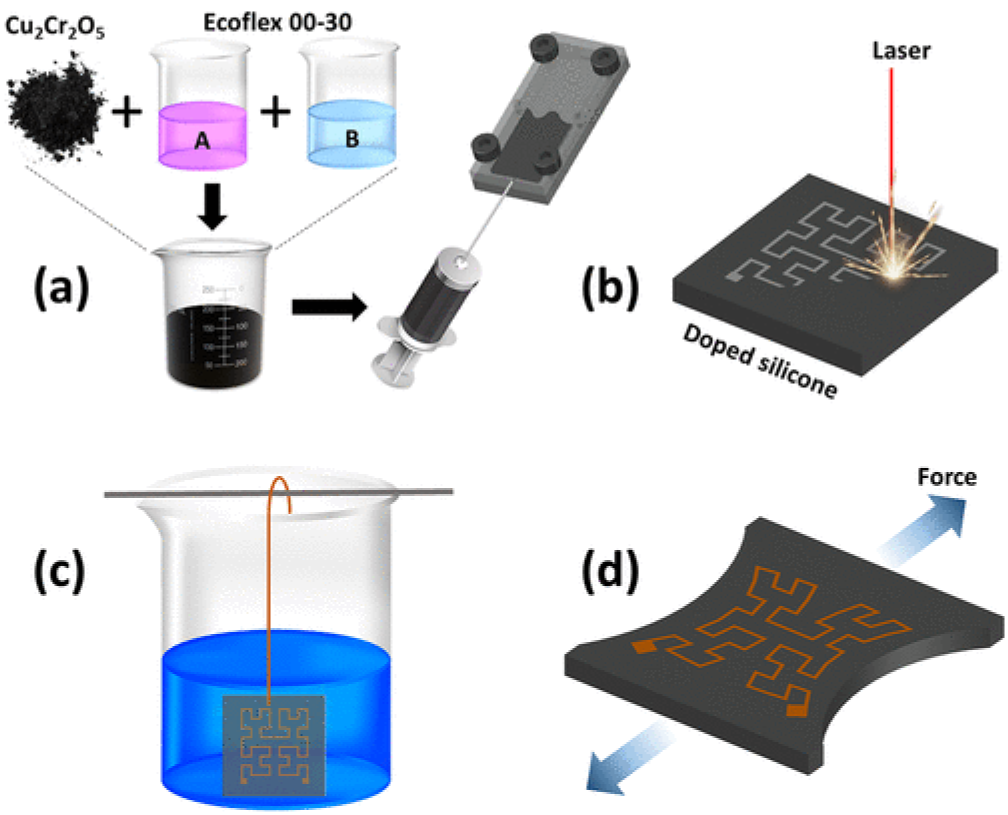

Figure 2.11.1. *The general LDS process. (a) Polymer material is doped with an LDS additive and cast or printed into a shape (b) The desired circuit pattern is laser written on the part (c) the part is non-galvanic copper plated (d) the part can be deformed [4]*

2.10.2. Laser Direct Structuring

Laser direct structuring (LDS) is the common name given to the circuit fabrication process of using a laser to thermally decompose additives in a material at the surface, selectively catalyzing it for subsequent non-galvanic metal plating (Figure 2.11.1). The additives are metal oxides or salts: Copper Chromite $Cu_2Cr_2O_5$, metal oxides/organic salts of Al, Sb, Cu, Pb, Ni, Fe, Sn, Cr, Mn, Ag, Au and Co.[5,6] Pico to nanosecond-pulse laser ablation reduces the additives to pure metal seeds, localized to the surface of the material; the laser exposed regions remain insulating, but are effectively catalyzed for single-beaker wet-chemical metal plating. By use of 3D laser scanning heads (XY scanning mirrors with a dynamic focusing unit for Z control), LDS can be conducted on arbitrary 3D contoured parts. In practice, the LDS additive can be mixed with the bulk material, or the additive can be mixed with a thin coating material (like a paint) and applied to the surface of the 3D object. LPKF Laser and Electronics is currently the sole commercial vendor of the entire LDS process, with the 3D laser scanning systems and companion tool-pathing software being the key enabling tools.

Other similar process technologies to LDS exist, currently with lower commercial success, but with technological merit. The laser structuring chemical activation (LSCA) process, developed by Sunway with little published information, does not require material doping but requires a post structuring chemical activation that selectively activates the laser regions. The “selective surface activation induced by a laser” (SSAIL) process is nominally the same, where a 3D laser is used to micro-roughen traces on the surface of a polymer, which make those regions selective for the adsorption of a silver nitrate catalyst. The catalyzed traces were then copper plated in non-galvanic plating solution.[7] 3D laser systems supporting SSAIL are being produced by Akoneer. The advantages of these alternative processes is that they do not require an additive be mixed into the substrate material, which opens possibilities for more substrate materials in their native state (transparent, low loss, etc). A wet chemical processing step is added to the SSAIL process, but all of the processing required to mix LDS additive into the substrate or coat the substrate in LDS additive is removed.

LDS is not strictly an additive technique, as the process does not directly deposit material, but LDS is still strongly associated with 3D MIDs and additive structural electronics for three reasons: low processing temperature (45°C - 60°C) compatible with injection molded thermoplastics, solderable bulk-resistivity copper circuits, and fast processing speed acceptable for medium volume production. The laser pattern writing has a long standoff distance (>200mm) on a stationary part, for a fast, low vibration exposure. The non-contact, high precision features of this process make it a good candidate for use in semiconductor packaging and heterogeneous integration.

2.10.3. Additive manufacturing and LDS

The low temperature of the LDS process is a distinct advantage over other methods of conductor deposition on thermoplastics, ranging from 45oC to 60oC depending on the plating chemistry and the desired plating rate. These temperatures are below the glass transition temperature for thermoplastics, avoiding deformation during processing. LDS has been demonstrated on all three main additive methods of fabricating plastic parts: stereolithography8, powder bed fusion9, and fused filament fabrication.10 Performance plastics (PPA, PEEK, LCP) are common for LDS parts to withstand lead-free soldering.11-13

The LDS process is practically limited to materials which can be doped with LDS additives. However, depending on the constraints of the application, non-LDS bulk materials can always be thinly conformally coated with an LDS-doped coating material. Further blurring the definition of LDS, alternative additive processes such as inkjet or aerosol jet can also be used to deposit tracks of catalysts for subsequent plating.14 This latter approach would not require high temperature sintering as with most direct ink writing methods for conductive ink, but would still face challenges of adhesion.

2.10.4. Potential for heterogeneous integration

A feature of the LDS process is the use of organic polymer substrates. Organic polymer substrates, unlike silicon or common printed circuit board materials, can be deposited using additive technologies in precise ways. Another feature of LDS is the ability to toggle between a lower-power circuit writing mode to a higher-power laser milling mode to create vias (a previous underlayer of copper functions to precisely stop the laser milling). The process concept for LDS in heterogeneous integration is to use an LDS-active epoxy mold compound (EMC) for semiconductor packaging, and deposit, by compression molding or liquid dispensing[15], thin layers of the EMC. Each layer of EMC will encapsulate the circuit components of the previous layer, and planarize the surface of the current layer. This process concept is in a broad commercial development phase, being marketed as the Active Mold Packaging (AMP)[16] process, as a partnership between LPKF Laser and Electronics, Sumitomo Bakelite, Shin-Etsu, Henkel Loctite, and others. Attempts are underway to create embedded circuit cubes with contacts on all six faces with this process. Recent commercial availability of liquid LDS EMC enables low encapsulation stress on a substrate integrating diverse processing technologies (heterogeneous integration), and freeform printing of encapsulation materials.

In the near term, planar heterogeneous integration using LDS/AMP is being demonstrated for more and more complex interconnections. Unique packaging capabilities of LDS/AMP include copper thermal management layers, copper 3D EMI shielding covers, reduced volume flat/solid interconnects, and antennas on package (AOP).[16] With development, the future vision would be to perform high-precision microelectronic heterogeneous integration into a larger 3D structural component.

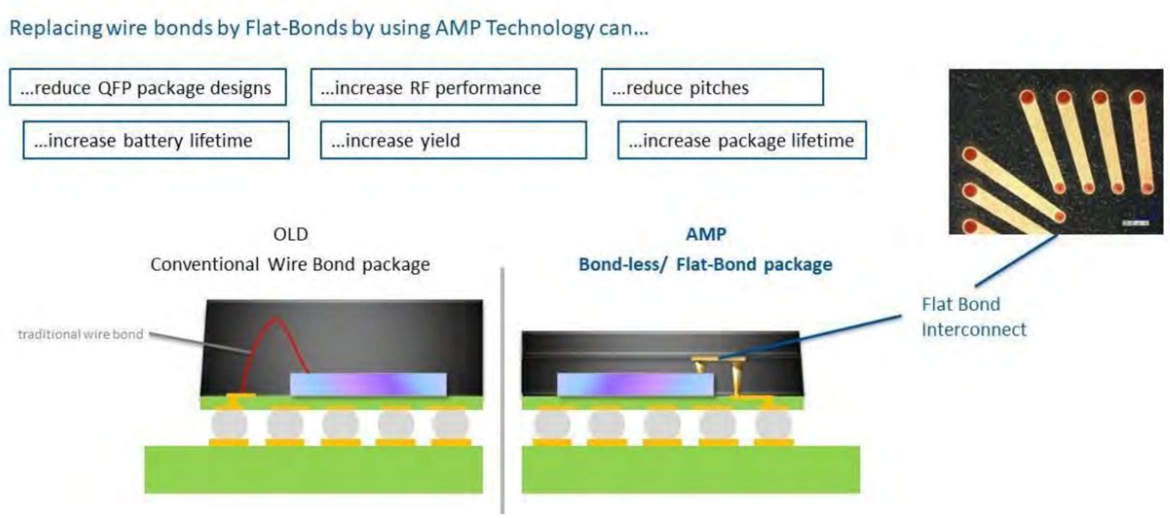

Figure 2.11.2. *Active mold packaging (AMP) of semiconductors, showing package thickness reduction with the unique AMP flat-bond interconnects (Image courtesy of LPKF Laser and Electronics [15]).*

2.10.5. Benefits & Drawbacks

Benefits

- High precision (claimed 25µm line/space, limited mostly by laser spot size), low-vibration, non-contact circuit writing
- Low-temperature process (45°C - 60°C), compatible with thermoplastics
- Low resistivity, solderable resulting copper circuits
- Laser writing is overhead/non-contact, compatible to be integrated with many AM processes, and very fast (~1 m/s scan speed).

- Process is robust and reliable; process variability is minimal once developed for a specific material.

Drawbacks

- Short-pulse laser systems / 3D laser scanners are large and expensive; it has not been demonstrated to integrate LDS laser writing on a still part within a 3D printing platform, though laser milling is common.
- Requires wet-chemical metal plating to grow the circuits, which is difficult to interleave with other AM processes for hybrid printing.
- Materials are limited; currently it is a copper-only process, but it could only ever be used for conductor deposition.

2.10.6. Growth Areas and Roadmap

Market / material availability

- Similar to other industries, the plating solution specifically used for the LDS process is produced in Asia and Europe nearer to the largest customer base. As such, it is much easier to procure in those parts of the world. Growth of the US customer base will justify to the plating chemistry producers (MacDermid Alpha, Dow Chemical, DuPont) to make the plating chemistry available globally.

Laser systems / Resolution

- LDS minimum line/space will approach the diffraction limit when writing with an infrared laser. Initial offerings of laser systems targeting 2.5D semiconductor packaging are 355nm ultraviolet with ps pulses. The LDS process should continue to be developed for higher resolution using alternative beam writing techniques, such as deep UV laser systems or switching to alternatives like e-beam or X-ray. The precision of the entire LDS process doesn't *entirely* rely on the laser system precision, but it mostly does.

Substrates

- Currently, LDS is most commonly used on mass-produced thermoplastics. Ensinger is producing and marketing wafers of LDS-active PEEK[17], as a replacement for silicon on which LDS can be used for semiconductor assembly. Only recently is LDS being performed on thermosetting printable photoresins and epoxy mold compounds for semiconductor packaging. However, with small modifications to the process parameters, LDS can be performed on RF-grade ceramic substrates, either planar or 3D, without additives or organic coatings. This has been demonstrated in research[18] for moderate feature sizes but is not in broad use. Green-laser LDS directly on ceramics would be akin to an LTCC process, with the advantage of high thermal-dissipation capability. The process should be further developed for finer features suitable for HI. When combined with alternative laser wavelengths, it may be possible to perform LDS on Sapphire substrates; excimer lasers have also been shown to create conductive tracks in aluminum nitride without non-galvanic plating.[19]

General active mold packaging (AMP) development

- The AMP process is significantly different from current methods of semiconductor packaging, system-in-package, and system-on-chip integration. The AMP process with liquid mold compound (LMC) needs to be developed and demonstrated at increasing levels of circuit complexity that can be achieved with this approach. Eventually, the added freedom of this approach will push beyond what is possible with traditional integration and packaging methods, with or without surpassing the resolution of the current technology.

Retro- and Prospective Properties	**Resolution**				**Material Properties**	**Build Speed**
	Resolution X,Y (micron)	Resolution Z (micron)	Via Size (micron)	Feature sizes (Line/Space[L/S]; dielectric[E]) (micron);	Max Bulk Conductivity	
2017	25	1	100	[L/S] - 50/50	5.8E7 S/m	~1 m/s scan speed
2020	25	1	100	[L/S] - 50/50	5.8E7 S/m	~1 m/s scan speed
2023 (present)	15	1	50	[L/S] -25/25	5.8E7 S/m	~1 m/s scan speed
2026	*9*	*0.5*	*40*	[L/S] - 15/15	5.8E7 S/m	~1 m/s scan speed
2029	*5*	*0.1*	*25*	[L/S] – 9/9	5.8E7 S/m	~1 m/s scan speed

Table 2.11.1: *LDS retro- and pro-spective properties*

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3. Design Tools

Leads: David W., Martin H.

3.1. Optimizing the tool-chain from Design Manufacturing

Achieving an optimized tool chain first requires a definition of what's being built. There are many different manufacturing processes being applied for additive manufacturing of electronics, each with a different impact on the tool chain.

An optimized tool chain for is shown in Figure 3.1. Of course, depending on the process there are differences that we'll explore in this chapter. An 'optimized tool chain' is defined as one in which the data flows seamlessly from one stage to the next, with full intelligence maintained. No data re-entry is necessary to transition through design and into manufacturing. There are also no work-arounds required to adapt existing tools to the desired process.

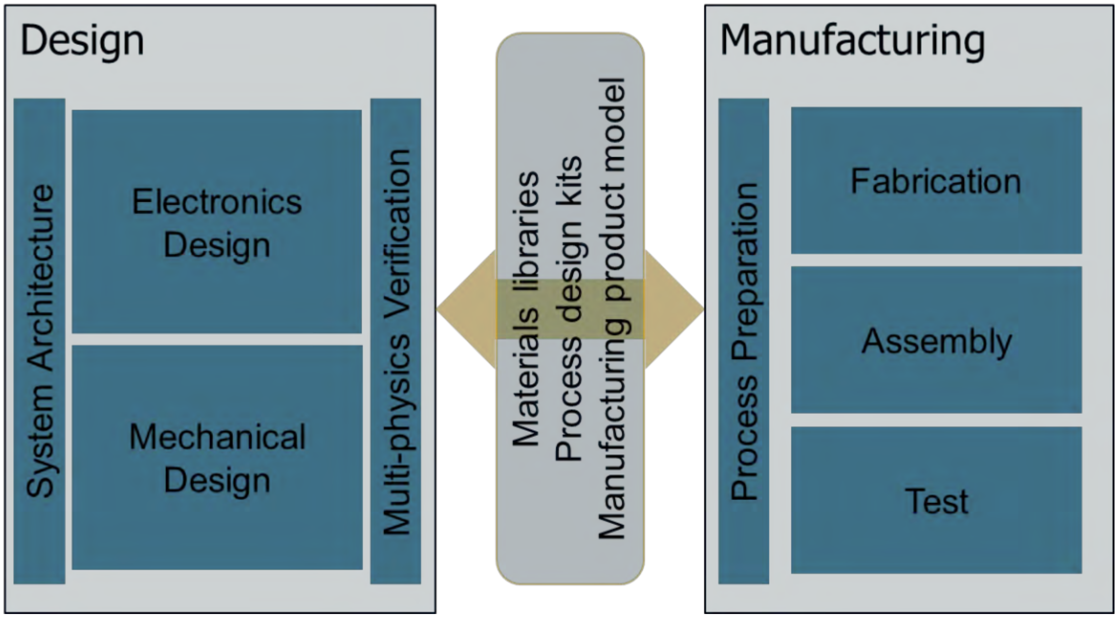

Figure 3.1: *An optimized digital thread through design/verification and manufacturing*

To simplify this, we can loosely divide what's being built into planar and non-planar electronics. Each have their unique challenges, requirements and opportunities.

3.2. Planar electronic structures:

These structures are designed and manufactured flat, similar to PCBs, with multiple material layers. Examples include FHE (flexible hybrid electronics), that are built on a flat substrate, but can be 100% flexible. FHE circuits can also be conformed to many 3D surfaces. MID's (molded interconnect devices) are also built flat, then thermo-formed into their final shape.

3.2.1. Design challenges

Design of planar AME's is possible today, typically leveraging PCB design tools, but workarounds may be required based on the following:

- **Circuit flexibility:** Need to consider flex regions and associated constraints that dictate component placement, curved traces, etc. Must also consider 100% flex circuits that can flex on multiple axes.

- **Embedded actives:** Bare die can be placed on internal layers, with connections printed to the die pins.
- **Embedded passives:** Printed resistors, capacitors and inductors can be added to any layer.
- **Materials library:** Because of the number of available options, need a vendor-supplied library of materials, with associated design constraints (e.g. thickness, surface roughness, clearance, material compatibility, resistivity, dielectric constant, etc.). Cost and availability would be a bonus.
- **Localized dielectrics and cavities:** Because it's an additive process, materials can be applied just where they're needed, rather than uniformly across a space.
- **Verification:** Need to verify circuits for performance and form/fit in their final, bent state, not their planar designed state. Possible verification criteria vary depending on the complexity of the circuit, but could include signal integrity, power integrity, thermal, EMI, stress, vibration, stretch, moisture, impact and manufacturability (see next section).

3.2.2. Manufacturing challenges

- **Process design kits (i.e. DFM rule decks):** Given the variability of materials and manufacturing processes, need to design/verify designs according to rules defined for those specific variables. Ideally, manufacturers would create these, but given that multiple machines and materials are involved it would be more complex.
- **Product data model:** The data models derived for PCB design (e.g. Gerber, ODB++, IPC-2581) largely work here, but some of the new design elements noted above may not be included, depending on the format.
- **Process preparation:** Design data must be converted to machine instructions (e.g. tool pathing for printers, coordinates for pick/place). Must consider intermixed fabrication and assembly (e.g. adding bare die mid-print).

3.3. Non-planar electronic structures:

These structures are designed and manufactured either by one of two methodologies: stacking 2D layers in the Z direction (x-y-z linear motion) or "freeform" by using 5+axes range of motion (x-y-z linear motion + A/B rotation).

Design of non-planar AME's is possible today but generally rely on proprietary CAD/CAM Software from the machine tool manufacturer. Workarounds may be required based on the following:

3.3.1. Design Challenges – Stacked 2D

- **3D Circuit :** The 3D circuit relates very much to the current topology of a classical multi-layer PCB: i.e. a combination of multiple 2D planes connected by vertical vias.
- **Embedded actives:** Bare or already packaged dies can be placed on internal 2D layers or the top surface. Electrical connection can be created by:
    a. directly printed to the die contact pads
    b. soldering or
    c. conductive adhesives
- **Embedded passives:** Resistors, capacitors and inductors can be either printed or added to any 2D layer or the top surface during the build process.

- **Materials library:** No standardized materials library exists at this time. There are many available options that are limited mainly by the print process used to build the structure (e.g inkjet, FFF, Dispensing, see Materials section 4.1). Long term a vendor-supplied library of materials, with associated design constraints (e.g. thickness, surface roughness, clearance, material compatibility, resistivity, dielectric constant, etc.) would be beneficial. Cost and availability would be a bonus.
- **Localized dielectrics and cavities:** Because it's an additive process, materials can be applied just where they're needed, rather than uniformly across a space.
- **Verification:** Verification of circuits for dimension and integrity is complicated due to the fact that they can be embedded/hidden. Electrical performance can be checked post manufacture. Additional verification criteria vary depending on the complexity of the circuit, but could include signal integrity, power integrity, thermal, EMI, stress, vibration, stretch, moisture, impact and manufacturability (see next section).

3.3.2. Manufacturing challenges

- **Process design kits (i.e. DFM rule decks):** Given the variability of materials and manufacturing processes, need to design/verify designs according to rules defined for those specific variables. Ideally, manufacturers would create these, but given that multiple machines and materials are involved it would be more complex.
- **Product data model:** The data models derived for PCB design (e.g. Gerber, ODB++, IPC-2581) largely work here for the electrical layout , but some of the new design elements noted above may not be included, depending on the format.
- **Process preparation:** Design data must be converted to machine instructions (e.g. structural build, electrical build, SMD pick & place, post processing operations). The exact method of the CAM operations depends on the individual processing steps used in manufacture: e.g stacked bit map images for driving Ink jet or vector based tool-paths for continuous flow processes (aerosol, dispensing, piezo-.jetting…).

3.3.3. Design Challenges – Freeform 3D

- **3D Circuit :** The 3D circuit has a higher degree of freedom than stacked 2D since the additional rotary axes allow printing and or placement of passives/actives on any 3D surface. Consequently there is a greater design freedom but also complexity in the design methodology and design rules.
- **Materials library:** As with stacked 2D, no standardized materials library exists at this time.
- **Localized dielectrics and cavities:** Because it's an additive process, materials can be applied just where they're needed, rather than uniformly across a space.
- **Verification:** Verification of circuits for dimension and integrity is complicated due to the fact that they can be embedded/hidden. Some development of AI driven QA and automated repair has been completed (Ref. BMBF ZIM Project: KAM-EL).
- Electrical performance can be checked post manufacture. Additional verification criteria vary depending on the complexity of the circuit, but could include signal integrity, power integrity, thermal, EMI, stress, vibration, stretch, moisture, impact and manufacturability (see next section).

3.3.4. Manufacturing challenges

- **Process design kits (i.e. DFM rule decks):** Given the variability of materials and manufacturing processes Process design kits are not currently available.
- **Product data model:** Freeform 3D enables radically different designs to be created. The data models are generally split onto two domains: structural (M-CAD) and electrical (E-CAD). For structural features standard M-CAD systems and formats can be used. For E-CAD some for PCB formats can be used, e.g. .dxf, that are imported and modified into to 3D features (sectioning, projection and/or wrapping onto 3D bodies):

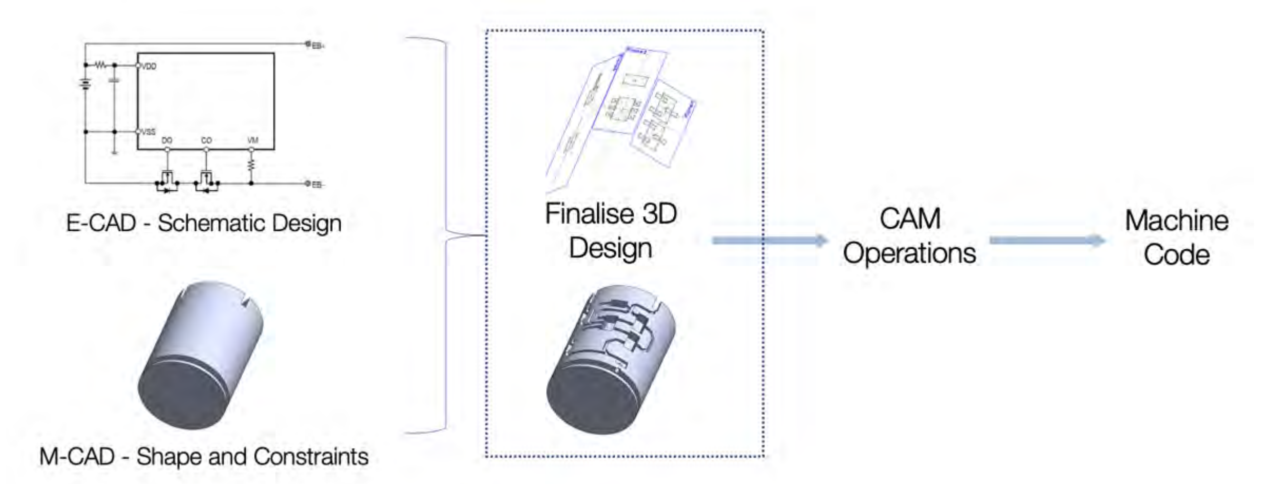

Fig. 3.2. *Exemplary design process flow for Freeform 3D AME.*

In some limited cases proprietary software specifically for AME can enable the complete design for be modelled. In this case the electrical circuit routing is created manually:

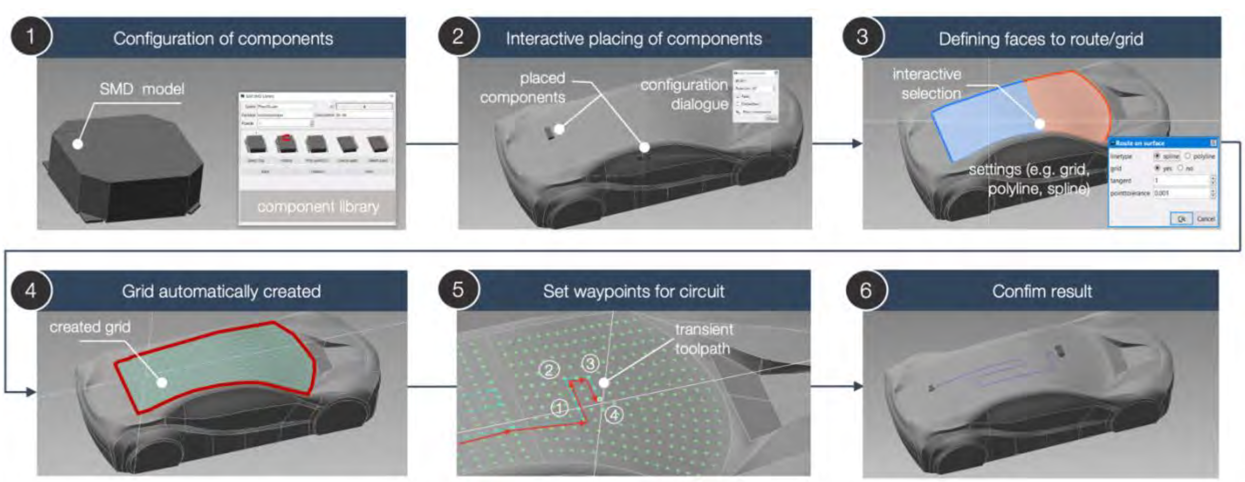

Fig. 3.3. *Process flow for circuit routing for Freeform 3D AME. Source: Neotech AMT GmbH*

- **Process preparation:** Design data must be converted to machine instructions (e.g. tool pathing for printers, coordinates for pick/place). This in generally done on standard CNC type CAD/CAM systems or specially developed proprietary SW from the machine tool manufacturer, for examples Neotech AMTs Motion 3D CAD/CAM software.

4. AME Materials

Introduction

AME materials covers such a broad range of material types, forms, and functions that a full representation is beyond the scope of this chapter. Instead of comprehensive coverage, we aim to briefly outline the different forms of materials sets used within AME (*AME Materials - Introduction*), describe the critical conductive materials which are used within AME (*AME Materials - Conductor Materials*), and outline the most developed materials space within AME, that which has been developed for screen print and related manufacturing methods (AME Materials - Printed Thick Films).

The different material forms found within AME is summarized in Table 4.1, outlining the form of build-material, AME manufacturing techniques which utilized these forms, the thickness of features which are created within one manufacturing layer of the AME techniques, and highlighting typical materials (*non-compressive*) which are used for these different material forms.

Form	Techniques	Feature Thickness (microns)	Common Materials
Filament	FFF/FDM	100-300	**Dielectrics** ABS, PLA, Nylon
Photo-Resin	SLA, DLP, 2-photon SLA	20-100 (1-10 for 2-photon)	**Dielectrics** PI-like, acrylates, elastomers
Films/Sheets/ Tapes	*Substrates for:* Screen, Stencil, Gravure, Flexo	2-100	**Dielectrics** PI, TPU, PET
Powders	Powder bed fusion	30-150	**Dielectrics** Nylon, TPU
Inks <1K cP	Inkjet, Aerosol, EHD	0.1-10	**Dielectrics** PI-like, SU-8-like **Conductors** Ag or Cu Nanoparticles; MOD
Paste >1K cP	Dispense, Screen, Stencil, Gravure, Flexo, Piezo-Valve, EHD	5-50	**Dielectrics** low or high K-dielectric polymers or ceramics **Conductive** Micronized Ag or Cu, optional elastomeric fillers

Table 4.1 *Forms of Materials used within AME*

4.1. Conductor Materials

Lead: Markus S.

Contributors/Editors: Kris E.

Printed conductors are the key component of AME methods which differentiate them from other Additive Manufacturing methods which product objects with only one material type. Table 4.1.1. outlines the different types of printed conductor materials which are utilized within AME, and compares them along many vectors, with definitions of these vectors described in the following text.

Technology	Thickness [µm]	Curing Temperature	Conductivity [%AgBulk]	Open time	Equipment costs	Design change	Layer purity	ESG	Typical applications	Function	Available elements
Nano-ink	2 – 10	120 – 180 °C	40%	0.5 h	+	+++	0	-	R&D	Signal transmission, conductivity	Ag
MOD ink	0.2 – 2	130 – 220 °C	20-50%	28 d	+	+++	+	+++	EMI shielding/ signal transmission	Signal transmission, conductivity	Ag, Au, Pt, Ir, Ni, Ti, Pd, Cu, …
Reactive inkjet	1	20 – 80 °C	20%	28 d	--	+++	---	--	R&D	Signal transmission, conductivity	Ag
Paste	5 – 50	230 °C	40%	8 h	0	+	0	++	TIM, die attach, joints	Power and thermal transmission	Ag, Cu
CVD	0.1 – 10	150 – 180 °C	100%	-	---	--	+++	--	EMI shielding, semi front end	Conformal coating	Ag, Au, Pt, Ir, Ni, Ti, Pd, Cr, Cu, …
Plating	0.5 – 5	25 – 40 °C	100%	-	---	---	-	---	Functional surface,	Conformal coating	Ni, Ag, Au, Cu, Sn, …

Table 4.1.1: *Overview on different material precursor systems, their respective application and performance regime.*

Thickness

The coating thicknesses for various additive manufacturing technologies depend on the limits of the application method. Inkjet printing, chemical plating baths, and CVD processes allow for thin application thicknesses due to the high dissolution degree of the metal precursor in low viscosity inks and gas mixtures. Metal powder filled pastes are limited by the particle diameters and printing screens.

Curing temperature

The curing temperature is determined by the diffusive nature and reactivity of the metal precursor. Small nano particles can be sintered at low temperatures due to their high surface energies. Coating agents ensure a stable system and are removed thermally at the beginning of the curing process. In the case of metal organic decomposition (MOD) inks, the curing temperature is limited by the decomposition temperature of the metal precursor.

Conductivity

The final metal conductivity is an important property for determining the suitability of a technology. It is influenced by curing conditions such as time, temperature, and pressure. The desired conductivity is limited by application requirements, such as thermal robustness, and the acceptable processing times.

Open time

The open time is a crucial factor for estimating process stability and maintenance intensity. Nano inks may have suitable rheological properties for inkjet printing, but fast nozzle clogging limits their broad application. Screen printing is preferable in such cases.

Equipment costs

Economic considerations are crucial for the industrial acceptance of new application technologies. Screen printing equipment, with its comparatively low costs, is widely used in many industries. The same equipment can be used for lab-scale, prototype, and mass production, making it cost-effective.

Design changes

The ability to implement design changes distinguishes between additive and full digital additive solutions. Digital technologies such as inkjet printing offer design flexibility, avoiding the need for physical aids like screens to establish desired printing layouts. Conformal coating technologies like plating or CVD, on the other hand, require costly masking technologies to achieve selective deposition patterns.

ESG

Environmental, social, and governance (ESG) factors are increasingly important decision criteria for printing technologies. Additive technologies offer advantages in terms of CO_2 emission reduction, material yield, and avoidance of high energy steps. Chemical hazards, such as plating chemistry, face stricter regulations in terms of governmental permissions for production processes and sites.

Typical applications/Function

Applications can be categorized as signal transmission or grounding for thin conductive metal layers, and mechanical or current transmission for thick layers.

Available elements

The precursor properties, particularly their basic reactivity, determine the availability for extending to different metals. Silver has high mobility via sintering, allowing for low-temperature sintering with condensed nanoparticles. Less mobile metals, such as Nickel, require higher sintering temperatures and are preferably applied using mechanisms like CVD or plating at ambient to moderate temperatures. MOD mechanisms also enable metal layer application at moderate temperatures based on the thermodynamic stability of the metal precursor rather than metal atom mobility.

	Inkjet	Aerosol Jet	Screen Printing
MOD Ink	+	+	0
Nano Ink	0	0	+
Paste	/	/	+

Table 2: *Correlation of metal ink and application technologies.*

4.1.1. General Materials Cluster

Formation of metal layers by additive methods requires a processable/liquid metal precursor, i.e. dispersed or dissolved in a solvent system, that can be applied selectively on a substrate and then transformed into the final metal layer. These initial processable products are well-tailored to their respective application processes, to fit the respective requirements with regards to the needed visco-elastic properties reflected in the material nature of a paste or an ink.

These products apply adjusted metal precursors, which consist of small metal powders for paste products, metal nano-powders to form nano-inks or dissolved metal salts as one or two component reactive systems (particle free) or a mixture of thereof. After application on the substrate, the applied material needs to undergo a transformation process, that turns a liquid/paste material into a solid conductive metal layer, typically named as the curing process.

For particle containing systems, the curing step consists of a sintering of the particles, which typically comprises the desorption of molecular binders on the particle surface and adjacent sintering. The latter is typically thermally driven and defined by the nature of the metal (230 °C for Ag), however can be facilitated by external pressure or – manly used by nano-inks – by the increase in surface energy with decreasing particle size. Accordingly, small particles typically cure at significantly lower temperatures as compared with the sintering temperature of the respective metal. Additionally, hybrid materials composed of polymers and metal particles only require a drying of the solvent for curing, and the paste shrinkage leads to percolation, yielding in a conductive metal layer with high stretchability at low temperatures. However, significantly high bulk metal conductivities are not achievable using such technologies.

For particle free systems, the main curing mechanism is initiated by reduction of the metal precursor, that can be initiated by a metal organic decomposition (MOD) via intramolecular electron transfer, by addition of a second component comprising a (dissolved) reducing agent (reactive systems) , or by physical methods such as plasma processes. Metal atoms as the initial reduction product will instantaneously cluster to form highly reactive nanoparticles and undergo immediate sintering. Accordingly, the curing temperatures of these systems are highly dependent on the decomposition temperatures for MOD precursor, or on the condFormation of metal layers by additive methods requires a processable/liquid metal precursor, i.e. dispersed or dissolved in a solvent system, that can be applied selectively on a substrate and then transformed into the final metal layer. These initial processable products are well-tailored to their respective application processes, to fit the respective requirements with regards to the needed visco-elastic properties reflected in the material nature of a paste or an ink. (1)

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For particle free systems, the main curing mechanism is initiated by reduction of the metal precursor, that can be initiated by a metal organic decomposition (MOD, s. Figure 1 left) (3; 4) via intramolecular electron transfer, by addition of a second component comprising a (dissolved) reducing agent (reactive systems), (5) or by physical methods such as plasma processes. (6; 7) Metal atoms as the initial reduction product will instantaneously cluster to form highly reactive nanoparticles (s. Figure 1 center) and undergo immediate sintering (s. Figure 1 right). Accordingly, the curing temperatures of these systems are highly dependent on the decomposition temperatures for MOD precursor, or on the conditions of chemical or physical processes, which can come down to room temperature. Also, physical methods such as UV excitation can further support lower temperature sintering as compared with particle based systems of the same metal. (1)

4.1.2. Material difference

The central difference for the suitability of various material technologies derive from the final application requirements, and finally from the best suited application method. Thin layers (< 5 µm) are best applied selectively via inkjet printing, and thicker stacks preferably by screen printing methods. Accordingly, the inks (inkjet) or pastes (screen) for printing specify different ink/paste requirements to guarantee process stability (open time, screen live), or particle loading and thixotropy. Particle free systems are superior for inkjet processes, and particle containing systems for screen printing. A further restriction is given by the thermal robustness of the substrate, and thus set upper limitations for curing temperatures. (8)

Paste products typically contain metal particles in spherical or flake-shape to ensure ideal sintering behavior under acceptable curing temperatures, pressures, and times. Nano-based inks and paste increasingly penetrate the market, which offer the advantage of lower particle size distributions, leading to higher particle surface energies, that reduce the sintering temperatures from bare metal (e.g. 230 °C for silver particles) down to 120 °C for silver composites. These advantages however are on cost of the metal loading from 85% for pastes down to typically 40% of nano-inks, and shorter curing at low temperature further limits the addressable bulk metal conductivity. (9)

Even lower metal loadings are found for particle free MOD inks, facing limits in addressable layer thicknesses, however enabling full digital selective coatings via inkjet printing, which prevents the needs for any physical stencils, masks or other tooling. Although also nano inks can be applied by lab scale inkjet printers, only particle free systems are foreseen to enable process stability und full continuous production environment, caused by the absence of nozzle clogging issues. Furthermore, functional inkjet printing allows to move from the lab to production on the same platform technology, as affordable printers are available for lab scale, sample production and full continuous production needs. In contrast to the thermodynamic background of nano-inks, the curing temperature of MOD ins is mainly driven by the decomposition temperature of the metal precursor at a first glance, and the sinter kinetics of metal itself.

Besides that, further innovative activities are observable in the fields of reactive inkjet system that allow room temperature curing by printing two salt components together on a single substrate, plasma curing inks that print and cure in one single step at a plasma torch equipped with an ink nozzle and high precision capillary inkjet printing for very tinny structures in ultra-high resolution.

4.1.3. Application Processing for materials

The most striking rationalism to decide for the appropriate technology is given by the basic function of the metal layer (Current vs. signal transmission, appearance, EMI shielding, …), the throughput needs (conformal coating in the semiconductor industry vs. fine line printing for medical applications), the feature resolution requirements and the thermal robustness of the substrate (PET films vs. ceramics). There are plenty of application methods for additive processes for the many different requirement bundles, that finally suggest for an appropriate material of choice.

Some methods like screen printing allow for coverage a wide range of throughput demands, from initial laboratory hand samples to small scale samples and full series productions. The availability for scaling is one of the major items to define the success of an additive manufacturing technology, and gaps for low-cost sample production or availability for robust full series production represent one major hurdle that prevents certain additive technologies to penetrate the market.

Particle based systems are ideal for high layer thickness and applied via screen printing, facing the drawback of a non-digital additive technology, and physical screens are needed for each design and for different throughput requirements. Nano particle-based inks and paste address medium thickness requirements and allow for low temperature curing. Further unique technical features like high stretchability can be achieved with nano based composites. Application methods are also based on non-digital methods like screen printing or spraying technology, however without the possibility of selective coatings. Particle free systems like Plasma-Curing, MOD or reactive inkjet are beneficial for very thin layers, as they can be selectively applied by fully digital methods, e.g. inkjet printing.

4.1.4. Outlook

Further trends of materials for conductors address for a broader portfolio of different metals then silver, and roadmaps offer development trends towards Cu, Au, Pd, Pt, Ni and more. Also alloy formation offers flexibility that is challenging to achieve with alternative conformal coating technologies, such as sputtering or plating. (10)

The trends for reworkable process to increase production yields in combination with selective material applications for a large variety of new products offer new economic aspects to decentralize operation facilities and bring the production close to the customer. Such trends show high potential for energy savings (transportation costs) and shorten down complex value chains.

In contrast, high volume productions will face new challenges connected with high CO2 emissions caused by high energy demanding processes (e.g. sputtering), or material waste for non-selective application methods (e.g. spray) and EHS concerns for new lines of reactive chemistry (e.g. plating).

These markets pull factors will be further accelerated by trends towards bridging technology for all kinds of sample volume, to facilitate technology evaluation in the lab and introduction of new methods for mass manufacturing on the same platform technology.

Last but not least, the development of transferable application equipment to cover the full range from lab trials over prototype to mass manufacturing is the next puzzle piece to facilitate the success of full digital additive manufacturing technologies.

Figure 4.1.2: *Upscaling of inkjet printing equipment to realize the upscale from lab based prototyping to mass production equipment suited for semiconductor industry (Heraeus Prexonics System solution). (3)*

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4.2. Printed Thick Films

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Contributors/Editors: Girish W.

Printing, in its various methods, has been used for centuries as a low-cost, high-volume means of reproducing text and graphics. In 1925, Charles Ducas was awarded U. S. patent 1,563,731 describing production of electrical circuit boards in an additive, printing process. A conductive ink was stencil printed onto a dielectric substrate. Electroplating over the ink thickened the metallization and produced a practical conductive circuit trace. Thomas Edison may have had the earliest additive process of painting an adhesive resin and sprinkling with graphite, but it was not a printed solution. About the time of Ducas's invention, a variety of patents arose describing etching processes. The exigencies of the Second World War placed the subtractive method of etched copper using a printed resist into large scale production of radios and proximity fuses. This made it the volume leader for production of reliable electronic devices to this day.

But that is not to say that efficient high-volume production cannot be achieved through additive manufacturing. Screen printing is the manufacturing method of choice in highly productive fabrication of solar cell contact structures, capable of processing up to 8000 wafers per hour. Modern production of electronic circuits through additive, printing of conductive pastes or inks on both rigid and flexible substrates was developed for production of membrane touch switches in the 1970's and gained significant consumer acceptance in the 1980's and beyond with introduction of metal domes. Originally screen printed on polycarbonate, A spacer separated a conductor on the substrate from a conductor above it. A finger press made contact between the two. Metal domes added tactile feedback and with a change to polyester film, greatly extended the life of the switch.

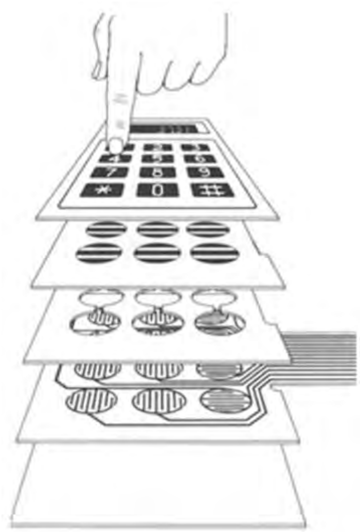

Figure 4.2.1. *A membrane touch switch.*

The conductive pastes used to print the membrane switch circuits onto the flexible polyester substrate were a mixture of a medium, consisting of a solvent and a polymer resin, and a conductive filler. These pastes were typically screen printed with a dried thickness of 5 to 10 microns. They came to be known as Polymer Thick Films (PTF) to distinguish them from the thin films created by sputtering or plating. PTF pastes are commonly applied by screen or stencil printing, then dried to evaporate the solvent and consolidate the mixture of resin and conductive filler, the former acting as a binder. In some formulations a curing step is needed, such as UV crosslinking, and would take the place of drying in a solventless formulation.

Applications for PTF pastes have expanded into a wide variety of applications. Low temperature processing pastes have allowed them to be used on low melting substrates such as polyethylene. Polyimide binder systems have expanded their use temperature to over 300C when used on compatible substrates, both flexible and rigid. They can be broadly classified into conductors, resistors and dielectrics. They are typically used to create and encapsulate circuits, analogous to the copper traces, resistors and coverlays found on FR4 PCBs. They are sometimes used as electrically conductive adhesives for mounting discrete components, like LEDs or packaged ICs, replacing solder. Some can function as die attach pastes where they are usually sintered to form high-reliability, high-thermal conductivity bonds between a die and a substrate. Some find use as Thermal Interface Materials (TIM), forming bonds between two surfaces that improve the flow of heat across the interface.

PTF pastes have been applied using virtually every method used for printing graphic inks. Screen and stencil printing are quite popular for high volume production. High volume auto parts and consumer electronics components are produced through additive manufacturing by screen printing PTF pastes on flexible substrates. Billions of blood glucose test strips are produced each year by screen printing PTF pastes onto disposable substrates. Gravure or flexographic printing are possibilities with modification of paste rheology. However, the resulting print is often very thin and while the volume conductivity of the printed paste may be quite high, the actual conductivity of such thin print layers might be very poor. This is a caveat that needs to be considered with any additive application for conductors. What matters is how much conductivity you can lay down on the substrate. A high volume-conductivity paste that prints too thin will require multiple print passes to build up a useful conductive trace. This may not be practical or desirable. Inkjet printing is another method that lays down very little material per pass. Four or more print passes are required to produce a fully dense, smooth, conductive trace. In some cases, the extra time to print multiple passes is justified by the benefits of being able to customize the circuit with nothing more than a software change (e.g., prototyping). Aerosol jetting and dispensing are the other common methods for depositing PTF material. They can both be adapted to conformal applications and can lay down suitably thick layers of paste to achieve practical component conductivity in a single pass. Jetting and micro-dispensing can also allow printing of smaller features than the ~30µm lower limit for screen printing. PTF pastes made for screen printing can sometimes be adapted to jetting and dispensing with appropriate adjustment of the paste rheology. Screen printing requires some shear thinning. The paste should thin and flow under the shear of the squeegee and when passing through the screen mesh, then thicken on the substrate and not flow out to preserve size and sharpness of the feature as defined by the screen artwork. Dispensing needs similar behavior to prevent tailing when dispensing pressure is stopped. Jetting often needs to be limited to mono-disperse filler systems to prevent self-selection of a single size range that might occur when jetting a filler with a broad particle size distribution.

4.2.1. Screen Printing

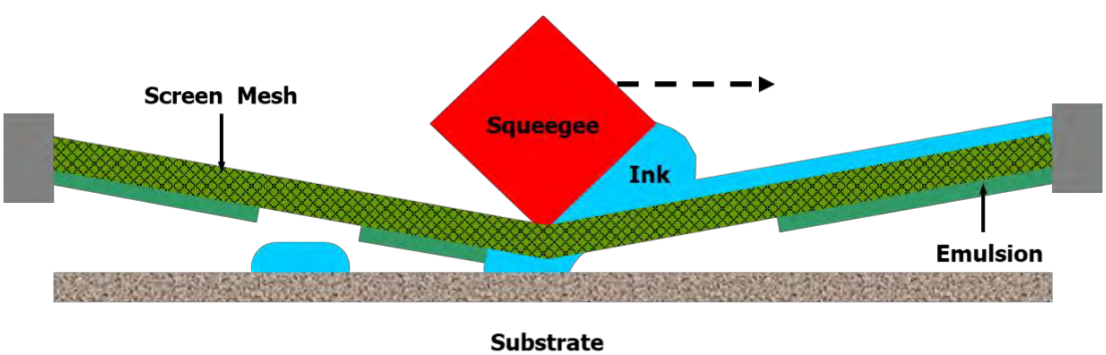

Figure 4.2.1. *Screen printing elements.*

A complete primer on screen printing is beyond the scope of this document. Here we introduce the basic elements and concepts. A mesh screen is coated with a photo-imageable emulsion. A drawing of the desired printed circuit is applied, and the emulsion is exposed to light. This renders the exposed areas insoluble in water. The screen is then washed, and emulsion is removed where the paste or ink must flow through to form the circuit. The screen can be stainless steel or polyester and a wide variety of wire/thread sizes and mesh openings are available. The combination of mesh thickness, open area in the mesh and emulsion thickness controls the wet print thickness as the squeegee is drawn across the screen. Squeegee attack angle and durometer also play a role in determining print wet thickness. Dried thickness then becomes a matter of the solids volume fraction of the paste.

Thick, highly conductive dried prints require high solids loads in the paste. This is where particle size of the solids can become an important factor. Viscosity increases as solids increase. The rise in viscosity can be especially severe with nano-scale filler particles that are well dispersed. Managing viscosity to have a paste that can flow under squeegee pressure and keeping solids content high for dried print thickness is essential to good performance. For this reason, micron sized filler particles are frequently preferred.

Squeegees come in a range of hardness. Lower durometer, softer squeegees will produce thicker prints, especially at lower attack angles, they can also conform to the substrate over which they are drawn. A skilled operator can quickly dial in print parameters to achieve the required electrical characteristics of the printed circuit. Attention must also be paid to the alignment of circuit features relative to the squeegee direction to avoid thickness variations in the print. Likewise, good design practices will keep the openings in the emulsion small to allow it to control thickness and avoid thick and thin spots in the print as the squeegee pushed down on the screen mesh. The volume capability of screen printing can be extended through roll-to-roll printing and rotary screen printing.

PTF pastes for screen printing can also be used to produce through hole via connections to allow circuits to pass from one side of a substrate to the other or create a multi-layer design.

4.2.2. Conductor Pastes

PTF pastes processed at temperatures which are compatible with film substrates like PET will see little or no sintering of metal filler particles when they are dried at 120-130C. Conduction is through a percolating network of particle-particle contacts. As a conductive filler is added to a polymer matrix the change in volume resistivity of the composite paste will depend on filler shape and size, as well as the intrinsic conductivity of the filler particles themselves. Little change in resistivity will be seen until the level of filler loading approaches a critical level where a continuous network of connected particles is formed. This level is called the percolation threshold. The volume fraction at which percolation is achieved will be lower when particle size is small. It also increases with dimensionality. 1D rods and wires will percolate at lower loadings than will 2D plates which in turn require less loading than 3D spheres. Conduction by percolation also requires that the surfaces of the filler particles remain conductive. For this reason, silver dominates in use for high conductivity PTF pastes. The oxide is conductive, so it can be processed in air and remains conductive even in the absence of sintering. Gold is also a good choice due to its resistance to oxidation, but the cost is high. Sometimes alloys of silver with palladium are used to reduce the potential for silver to migrate under high voltage gradients in moist conditions. Base metals, like copper, are frequently seen as attractive based on cost, but the effort that is required to process them and keep them oxide free, and ultimately sinter them to provide a permanent conductor often more than offsets the cost savings of the metal itself. Still, much effort is being put forth to realize practical copper pastes and reliable low temperature sintering of same. These will be discussed elsewhere. Commercial PTF conductor pastes based on micron and submicron silver fillers can achieve volume resistivity as low as 3-5mΩ/□/mil (8-13μΩ-cm) with print thickness per pass ranging from 5μm to 12μm, resulting in practical conductor traces of 10-15mΩ/□.

4.2.3. Resistor Pastes

Most PTF resistor pastes are based on carbon fillers. Carbon black and graphite are common. Novel forms of carbon (e.g., graphene, CNT) also find use on their own, or as additions to a conventional carbon filler. Selection of filler type(s) and loading can lead to a wide range of volume resistivity. Single digit Ω/□/mil through MΩ/□/mil examples are found. Blend end members can be provided, allowing for custom adjustment to meet application requirements. Dried print thickness depends on solids content. Pastes based solely on nano-particle carbon will tend to be low solids and will print thin, resulting in high as printed resistance. Some carbon PTF pastes feature very high volume percent loading and will print very thick, often more than 20µm in a single pass. These materials will typically have a temperature coefficient of resistance (TCR) that is positive. Values of 10-100ppm/K are not uncommon, but can be much larger depending on filler morphology, loading and the polymer matrix they are in. These factors are sometimes exploited to create pastes with very large positive temperature coefficients of resistance at and above a specific temperature. These so-called PTC pastes can be used to create self-regulating heater circuits that reduce power when a desired operating temperature is reached.

4.2.4. Dielectric Pastes

Dielectric PTF pastes find a number of applications. Among the most common is as an encapsulant to insulate a conductive or resistive element from contact. This also serves to provide protection against wear, abrasion and, in the case of electronics in apparel, wash resistance. As a dielectric, they can be used with conductor pastes to form capacitors. Then can also be used to produce crossovers where one printed conductor must pass over another without making electrical contact. While the polymer resins used as binders are themselves good insulators, most PTF dielectric pastes add a solid filler to raise viscosity or build printed thickness, or to change the dielectric properties (e.g., dielectric constant, loss tangent). The resulting heterogeneous film will often suffer from poor breakdown voltage performance compared to the BDV of its component parts. Crossovers must always be applied in at least two print passes to ensure any pinhole defects in the first layer are covered by the second. Insulating films requiring high BDV (>1kV) will sometime require 3 or more print layers for reliable, safe operation. Another consideration is that many of the binders used are not good moisture barriers. In a humid environment, moisture can cause mobile silver ions to form, which easily pass through most dielectric films and can create short-circuit conditions. This is especially true for crossovers separating conductors with a significant voltage difference. The moisture barrier properties of the dielectric and the propensity for the designed circuit to encourage silver migration need to be considered, or a more migration resistant conductor must be employed.

As suggested, fillers can be functional beyond just film building. Boron nitride (cubic or hexagonal) and alumina are often selected when good thermal conductivity is desired in an electrically insulating paste. Ferroelectrics like BaTiO3 and other titanates, or relaxor ferroelectrics like lead magnesium niobate might be selected for high k dielectrics, especially when used to form capacitors. Mica and graphene oxide have been added to increase dielectric constant in low loss dielectric formulations[i]. Core-shell structures of carbon and silicon have been used to that purpose as well [ii]. Porous fillers of silica, silicon and other inorganics may be employed where low dielectric constants are desired. Titania can be readily dispersed in polymer/solvent media and can improve mechanical and thermal performance. Many other examples can be found in the literature. These are among the most commercially relevant.

The demands on high performance dielectrics within electronic devices can be very stringent, with a host of multiple properties needing simultaneous optimization, especially when considering applications including high speed signaling and RF, and for performance under harsh manufacturing and reliability testing conditions. Table 4.2.1 shows a qualitative representation of different dielectric materials, different property categories, ideal properties, and their qualitative performance (with an RDL application in-mind), showing the difficulty in meeting all of these properties simultaneously. The last row also shows AME methods which can either utilize these materials as a substrate (screen), ink (Inkjet), photo-resin (SLA/DLP) or filament (FFF/FDM).

Category	Ideal Properties	Polymer Family					
		Epoxy	Benzocyclo butene (BCB)	Polyimide	Polybenz-oxozole (PBO)	Fluoro-polymer	Hydro-carbon
Electrical	Low Loss Low Dk, Df						
Physical	Ultra-thin, planar films						
Thermal	Low-CTE Stable at 260C for reflow						
Mechanical	High Elongation Low Modulus						
Chemical	High Chemical Resistance Good Adhesion						
Cost	Low Material & Process Costs						
Reliability	Low Stress Low Moisture Absorption						
Applicable AME Methods		SLA/DLP; Inkjet; Screen	Inkjet; Screen	SLA/DLP; Inkjet; Screen		FFF/FDM; Screen	Inkjet; Screen

Table 4.2.1 *Dielectric material types, required materials properties for high-speed electronics applications, and applicable AME methods*

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5. AME Applications

5.1. Printed Passives

Lead: David B.

5.1.1. Passive Components AME Opportunities

Passive electronic components (resistors, inductors, and capacitors) are ubiquitous in electronic devices. From power conversion and RF filtering, to sensors and smart phones, passive components exist in every electronic circuit. Passive components are defined *passive* as they consume no additional power beyond that supplied by the circuit into which they are inserted; i. e. they possess no amplifying transistor components. Inductors, resistors, and capacitors (*passives)* are distinguished by the relationship of their voltage to their current; inductors are composed of conductors and often magnetic materials, while capacitors are made from conductors and often high-permittivity or large microstructure surface area dielectric materials. Resistors are made from a variety of resistive materials, to create the required resistance in the desired form factor with the desired level of power dissipation, and can possess parasitic inductance or capacitance.

The range of values and form factors for commercially available passives is broad, but discrete. Electronics designers must always use values of passive components that can be commercially procured in the required shape, which may be near, but not exactly, the optimal value. This is a constant challenge for designers, being restricted to commercially-available components. The ability to tailor the values and form factors of passive components to the requirements of the circuit, rather than the other way around, will remove these restrictions to the circuit designer and improve products, both electrically and structurally.

5.1.2. Advantages

Additively manufactured passive components offer key advantages and opportunities. First, it is possible to implement a digital warehouse concept for electronic components; specific values of components can be printed on demand, eliminating the need to maintain a diverse stock or abide procurement delays. It would also be possible to print passive components with an arbitrary value in a desired shape. As discussed in the preceding paragraph, this would give circuit designers significantly more freedom in their designs.

Second, additively manufactured passive components would fit within the overall process of additively manufactured electronic assemblies. This would enable lights-out additive manufacturing (LOAM), where a circuit assembly printer could be left to run without human intervention from start to finish. It would not be necessary for humans to stock, load, and change reels of passive components for subsequent pick and place, when the printer can simply fabricate the component within the overall printing process.

Third, most traditional passive components have a form factor compatible with the target assembly method; surface mounting components are flat lead rectangular prisms, through-hole mounting components are cylindrical, and in-line components are large and tend to have the same shape as through-hole components. Additive manufacturing would enable truly free-form fabrication of components, to match custom form-factors within structural electronics or contoured parts.

5.1.3. Examples of AME Passives

5.1.3.1. Resistors

The general approach to AM resistors is to deposit a material of a predictable *final* resistivity in a specific shape, abiding the equation

$$R = \rho \frac{l}{A} \quad (1)$$

where *l* is the length in the direction of current flow, *A* is the conductor area in the plane normal to current flow, and ρ is the effective resistivity of the material. The length, thickness, and width of the deposition determine the resistance. The challenge becomes precise deposition of the geometry to achieve small manufacturing tolerances, but also selecting or engineering a resistive or conductive material to achieve the resistance. Referencing equation 1, lower resistivity material is less sensitive to imprecision in geometry, but requires longer geometries to achieve the same resistance.

Resistive materials can and have been deposited with many different AM methods. Syringe extrusion (*robocasting*) of resistive inks and pastes has been demonstrated,[1] producing flexible carbon ink resistors with widths down to 400µm. It is generally more difficult in any print method to precisely control extruded thickness rather than XY dimensions; Poulin et al[1] deposited by syringe extrusion an average thickness of 60.9µm with a standard deviation of 4.8µm. DuPont[2], among other companies, produce graphite-based pastes and thinners that can be mixed in proper proportions to achieve the desired material resistivity, from which printed geometry will determine the final resistance. An active mixing extruder (such as from Preeflow[3]) would be capable of setting the mix ratio of conductor paste and thinner on demand, and set the material resistivity to achieve the desired resistance with the same geometry. However, to this author's knowledge, this has not been demonstrated.

Other methods to print resistors have been demonstrated. Fused filament fabrication (FFF) using a thermoplastic filament, loaded with conductive particles to create a finite resistivity material, was capable of printing the same geometry with multiple different resistances by controlling the number of layers[4] printed or line width[5]. FFF is generally low precision, with the conductor-loaded thermoplastic having a high resistivity requiring large-area structures to achieve low resistance values. Resistors have also been inkjet printed; Inkjet has been used to deposit transparent PEDOT:PSS in varying layer thickness to achieve resistances from 25Ω to 650Ω.[6] Another example used inkjet to deposit a conductive material and a resistive material in multiple layers with different proportions over a powderbed, resulting in a range of resistances with the same geometry.[7] The slower but high precision print method of aerosol jet printing has also been used to print resistors from a low viscosity carbon particle loaded ink, printing 1cm long lines with resistances from ~80Ω to ~640Ω in multiple printed layers at different feed rates.

5.1.3.2. Capacitors

Capacitors store energy in an electric field, with current that leads the component voltage. Similar to resistors, there is a general and simple guiding equation for capacitor design based on a parallel plate structure.

$$C = \epsilon \frac{A}{d} \quad (2)$$

where ε is the permittivity of the dielectric material separating the plates, *A* is the overlapping area of the plates, and *d* is the distance between the plates. Capacitance can be controlled through the permittivity of the dielectric material, or by changing the overlapping area (*geometry*) or the effective distance between the electrodes. Capacitance is increased in electrolytic capacitors on a microstructure level by etching the surface of the electrodes and then using a thin oxide layer as the dielectric.

Capacitance can be maximized by either increasing the permittivity of the dielectric layer, increasing the effective electrode area, or reducing the electrode separation. Simple printed overlapping parallel plate capacitors have been fabricated using FFF9 and inkjet,10 achieving capacitance densities on the order of 0.2 pF/mm2 and 46.5pF/mm2 respectively. With additively manufactured capacitors, effective area is usually increased by some manner of interleaved (interdigitated) electrodes. Aerosol jet printing was used to print co-planar interdigitated electrodes and then oversprayed with high permittivity barium titanate in different concentrations.11 This method achieved capacitance densities around 2pF/mm2. Very high capacitance and capacitance densities have been achieved with interdigitated parallel plane capacitor stackups, both using FFF4 (~1.6pF/mm2) and inkjet printing (~48pF/mm2).12 Another inkjet-based method achieved high capacitance with a small overlapping area of graphene electrodes, using a 3µm thin higher-permittivity hexagonal boron nitride (hBN) dielectric (20pF/mm2);13 another similar approach used silver electrodes, with 1.2µm thick hBN (estimated 87pF/mm2).14

Printed electrolytic capacitors have also been demonstrated. A pseudo-printed example achieved a capacitance density of 10,000 pF/mm2 with an oxide dielectric 49nm thick; this was pseudo printed because the bottom electrode of etched aluminum was not printed, and the electrolytic gel PEDOT:PSS was screen printed. Only the top graphene electrode was syringe printed. In a final example of AM printed capacitors, an electrostatic double layer capacitor (EDLC) has been printed using a hybrid of FFF and syringe extrusion.15 The electrodes were 100µm thick, but the reported electrode capacitance was 5mF/mm2. What is apparent is that the incorporation of electrolyte and thin oxide dielectrics significantly boosts capacitance, which generally creates more freedom of shape design by allowing smaller components. Trade-offs do exist, however, and other performance metrics will be discussed in a later section.

5.1.3.3. Inductors

Inductors are passive components which momentarily store energy in magnetic flux, relying on Faraday's law as the governing equation. Faraday's law states that the terminal voltage on an inductive component is related to the magnetic flux *linking* the circuit of the component by the time derivative of that flux. The flux is created by current flowing in the component circuit, and the most general equation relating inductance to physical device parameters is as follows.

$$L = \frac{\mu N^2 A}{l} \quad (3)$$

where µ is the core material's magnetic permeability, *N* is the number of winding turns of the component circuit, *A* is the cross-section area perpendicular to magnetic flux, and *l* is the length of the flux path. Miniaturizing magnetic components has long been the most challenging, for reasons apparent in eq. 3. High magnetic core material permeability is difficult to achieve with in-situ fabrication. Unlike capacitors, which can boost capacitance by increasing effective electrode area in a straightforward way, increasing the number of turns of an inductor circuit is limited by microelectronic fabrication. This poses an additional challenge of adding long lengths of fine conductor traces (the winding turns) without adding significant winding resistance when compared with the inductive reactance (low quality factor devices).

Additive manufacturing methods are certainly capable of printing the most basic and broadest band inductors without core materials (*air-core*). The inclusion of magnetic core materials serves to significantly boost inductance but over a limited bandwidth. Without magnetic core materials, inductors are just wire loops with geometries such that the flux created by winding currents links the winding turns, e. g. planar spirals with substrate-perpendicular flux, or square solenoids with substrate-parallel flux. Many examples of

AM air-core inductors exist. Air-core inductors have been printed with silver inkjet (25 turns square spiral[15] with 27.65nH/mm^2, and 3.5 turn circular spiral[17] with 2.36 nH/mm^2), FFF[4] (9 turn circular spiral, 1.22 nH/mm^2), and SLA cavities post-filled with liquid eutectic gallium indium (4-turn circular spiral[18] with 1.3 nH/mm^2, and 6-turn solenoid[20] with 100pH / mm^3). Laser direct structuring (LDS) has even been used on elastomeric silicone for high-Q fractal and meander planar inductors (Hilbert fractal : 0.28 nH/mm^2, Meander : 0.40nH/mm^2).[19]

To boost the inductance density, magnetic material can be included. Similar to printed conductors, printed magnetics have the highest effective permeability when the magnetic fraction of the deposited paste or ink or resin is high such that the magnetic particles are in contact in a large volume fraction (percolation threshold and above). The magnetic permeability of magnetic materials is comparably not as high as the conductivity of conductor materials, so it is more difficult to achieve a high effective permeability with a binder-diluted printed magnetic composite material. Binders can be removed by sintering, but the sintering temperatures prevent including these magnetic materials with other materials in a hybrid printed assembly; the magnetic cores in this case must be printed and sintered separately and placed during an electronics assembly. It is possible to 3D print a freeform magnetic part, and then sinter it to achieve higher permeability. However, comparing to the similar ferrite manufacturing process, there is no die-pressing of the magnetic powder material to achieve high mechanical density before sintering, so the resulting 3D printed freeform cores are not expected to achieve as high a permeability as those made with traditional manufacturing.

Despite expecting myriad challenges and tradeoffs, magnetic materials have been incorporated into many 3D printed transformers and inductors. Commercial-off-the-shelf ferrites have been included in FFF/DIW-printed helical winding transformers, achieving inductance densities of 276nH/mm^3, but lower quality factors in the 1 – 30 range.[21] Another case of using additive techniques with a COTS magnetic core was when laser direct structuring (LDS) was used to fabricate helical transformer windings directly on the surface of toroidal ferrite cores, achieving inductance densities of 1027 nH/mm^3 with a quality factor of around 2500.[22] Another example used magnetite ferrofluid, injected into an SLA-printed cavity, within injected eutectic gallium indium liquid windings, achieving 0.7nH/mm^3 and a quality factor of 46.7.[18] Integration of DIW printing of the magnetic core material and DIW printing of the silver inductor windings has also been demonstrated.[23] This sort of integration is a challenge as typical magnetic core paste materials require temperatures above 1000°C to achieve densification and high permeability, but the authors of [23] developed a moderate permeability magnetic (Permalloy and Metglas) feedstock that sinters at 250°C, a temperature compatible with DIW silver ink. That process produced an example toroidal inductor with an inductance density of 0.89 nH/mm^3.

In all of the previously discussed examples, the inductor as a circuit component was completed through an entirely additive process, with COTS or in-situ magnetic core and windings. However, there is significant value in the use of additive manufacturing to fabricate custom shaped magnetic cores ex-situ, without co-deposition with dielectrics or conductive ink. By removing the compatibility requirement with hybrid plastic or DIW ink printing, there exists many methods to additively manufacture custom cores ex-situ, that can later be inserted into an additive process to complete the inductor windings. Binder jetting has been used with Fe-6%Si powder, vacuum sintered up to 1300°C, to achieve relative permeabilities around 10,000.[25] Laser powder bed fusion has produced magnetic rings of pure iron with relative permeabilities around 500 without additional processing, or around 1100 with spark plasma sintering.[24] Recently, electron beam powder bed fusion (under vacuum) has demonstrated the printing of FeSi parts with as-printed relative permeabilities of 4244.[27] Magnetic cores have also been produced using FFF with a NiFe loaded polyethylene composite filament without sintering; the relative permeability of the printed parts were measured to be at most 2.7.[26]

5.1.4. Key challenges

A main challenge to electronic component fabrication, in general, is miniaturization. Making components smaller requires achieving the same electronic values of resistance, capacitance, or inductance in a smaller volume, while requiring much higher manufacturing precision to maintain acceptable value tolerances. Additively manufactured electronics are no different with regard to the challenge of miniaturization; additional challenges can be divided by time scale.

5.1.4.1. Immediate

Process temperature incompatibilities restrict the passive component value densities (value per unit area or volume) that can be practically realized. The compatibility of sintering temperature for conductive inks with organic polymers is a well known problem, with resistive inks facing the same challenge. Capacitors and inductors can boost value density by inclusion of high-permittivity ferroelectrics or high permeability magnetic materials, the direct writing of which requires a high temperature sinter to achieve those material properties. What is becoming apparent is the necessity for a holistic approach to optimize electronic passives printing ability, where the temperature limits of all materials incorporated in the process are considered. This will be discussed as a mid-term goal, but the immediate focus should be to achieve the highest passive value densities within an acceptable temperature range of the entire AME process, while maintaining a reasonable level of value control.

5.1.4.2. Mid-term

Considering the long term goal of the commercial transition of an AME process that includes printed passives, it is necessary to forecast that transition pathway with regard to what is practical. Would a viable process include a possible pick&place step to include ex-situ capacitive or inductive core materials that can't be fabricated in-situ? Would a pick&place step destroy the advantage of the AME process? Would the 3D and on-demand advantages of AME redeem the loss of passive value density? It is necessary to envision the use cases and applications for AME with printed passives and the range of passive values that are realizable now and in the near future with some development. Once the commercial transition path is decided or, at least, reduced to fewer possibilities, long term development can begin.

5.1.4.3. Long-term

The long term challenge of AM passive components is reducing the value tolerance and increasing the manufacturing repeatability. XY geometry in AM process can be made very high, but the Z-dimension (material thickness) is often more difficult to precisely control, especially if the material contains a solvent or binder that is removed in subsequent processing. In-situ monitoring of deposited material thickness may need to be integrated into the process to ensure a precise deposition thickness when applicable. The lower the tolerance of AM passive components, the more consistent an on-demand passive value printing process would be.

5.1.5. Key Metrics needing improvement

Table 5.1.1. Passive component performance metrics. Primary (more important) and secondary metrics

Component	Primary Metrics	Secondary metrics
Resistor	Value density, Power handling, Reliability	Frequency and Temperature stability, tolerance
Capacitor	Value density, Breakdown voltage, Reliability	Bandwidth, Temperature stability, tolerance
Inductor	Value density, Quality factor, Reliability	Bandwidth, Temperature stability, tolerance

For all three passive components, the metrics for additively manufactured components are the same as for traditional fabrication. The primary metrics that are significantly different for additive components when compared with traditional fabrication is the value density, quality factor, and reliability. The need to increase the value density has already been discussed in the previous section. Regarding the quality factor, compared with alternative conductor fabrication methods, parasitic resistance tends to be higher and reduces Q; this is mostly an issue with inductors where the length of conductor is significant. Reliability, similar to traditional fabrication methods, is very process dependent, and will need to be determined empirically. However, common failure mechanisms should be considered in the process design, including thermal cycling and CTE mismatch, oxidation from environmental exposure, and mechanical shock. Additive processes, in general, rely on the deposition and adhesion of many polymer or polymer/conductor composite layers, which has made additive components susceptible to delamination during thermal cycling.

In the survey of research discussed in the preceding sections, the value densities, power handling, and quality factor vary significantly with the fabrication method. It is most prudent to compare with values currently achievable with SMD components fabricated with traditional industry methods (Table 2).

Table 5.1.2. *Approximate maximum values for 0201 size SMD passive components available (2023)*

SMD Component	**Value Density (max value in an 0201 footprint)**	**Power handling / Quality Factor / Rated voltage**	**Demonstrated additively manufactured value Density**
Resistor	283.1MΩ/mm^3 (55.6MΩ/mm^2)	Rated Power = 0.05W (1% value tolerance)	650 Ω / mm^2
Capacitor	79.1 µF/ mm^3 (26.1 µF/ mm^2)	Rated voltage = 6.3V (20% value tolerance)	10 nF/mm^2
Inductor	162.7 µH / mm^3 (45.5 µH / mm^2)	Q = 8 (2% value tolerance)	1.027 µH / mm^3 (10.29 nH / mm^2)

Currently, demonstrations of additive passives in research are not matching SMD value densities. The highest AM inductor value density is more than a factor of 100 smaller than commercial SMD inductors. The best demonstrated AM capacitor, ignoring the dubious AM EDLC value of 5mF/mm^2, are still about a factor of 2000 smaller in value density than commercial products. AM resistors, currently demonstrated in literature, are four orders of magnitude below the resistance density of SMD counterparts. However, it was most likely not the intention of the researchers to create a very large resistor, so this comparison is not the best representation of the state of the art.

An important endeavor to the commercial transition of AM passive components, that was not found in the literature, is a manufacturing tolerance and lifetime reliability study. Plenty of examples exist in research literature showing that passives can be printed in a certain way using a certain process, but never have the authors pushed further and established or worked to improve the tolerance of on-demand printability of specific component values on a large set of printed components. The onus of such an endeavor would most likely be on an industry adopter, rather than a researcher, or perhaps a collaboration between the two. Establishing and improving tolerance for a print method is certainly required on the path to commercial transition.

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5.2. Thermal Applications

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5.2.1. Introduction and Scope

This section addresses applications and considerations for additive manufacturing (AM) of thermal solutions for heterogeneous integration of electronics. A primary thermal application of additive manufacturing for electronics (AME) is the rapidly expanding area of heat sink, cold plate, or heat exchanger fabrication. Extensive recent surveys have been published examining common metal printing methods, post-processing, heat transfer effects, and heat transfer augmentation approaches [1]. Select relevant methods are outlined below for metal AM. However, AM of additional (i.e., polymer and ceramic) materials is covered herein with an eye towards integration of comprehensive cooling solutions for electronics. Beyond this surveyed range of additive methods, recent design approaches for heat sinks and cold plates for electronics are also briefly examined. Here, design of heat exchangers for AM is another adjacent, rapidly growing, and impactful research field [2], where three-dimensional printing unlocks new design freedom for thermal management of devices. Overall, since this section is focused on existing state-of-the-art fabrication methods and design techniques, the research and development of new material sets and processes is only briefly covered. Nonetheless, the section concludes with a discussion of key opportunities and growth areas for thermal applications based on current fabrication and material limitations. Important heterogenous integration packaging challenges for electronics are also identified as areas for future work in the field over the next decade.

5.2.2. Methods & Heterogeneous Integration Use Cases

Below we provide a concise categorized review of metal, ceramic, and polymer AM processes aimed towards thermal management applications for electronics. The role of each of these different material fabrication processes for heterogeneous integration of electronics in terms of thermal-fluid performance benefits is highlighted in the following subsections, and key process characteristics are summarized in Table 1.

5.2.2.1. Metals

Due to high thermal conductivity, k (W/m-K), metals including aluminum (Al, k ~ 130-190 W/m-K) and copper (Cu, k ~ 350-400 W/m-K), plus associated alloys, are commonly used for fabrication of air-cooled heat sinks plus single and two-phase liquid-cooled cold plates for electronics. Metals have the benefit of higher temperature range operation when compared to polymers. The following different metal AM processes enable the realization of various complex heat exchanger internal geometries with different materials at various structural feature length scales.

5.2.2.2. Selective Laser Melting (SLM)

Selective laser melting (SLM) of metals is a process whereby powder metal that is distributed in a layer is selectively melted using a laser, and the part is built up layer-by-layer. As reviewed in [3], this process is now commonly used to fabricate heat sinks, and an example air-cooled heat sink for electronics is shown on the furthest left versus a range of conventionally machined heat sinks to the right in Fig. 1 [4]. The SLM process can achieve feature sizes as small as 200-400 µm with tolerances on the order of 50-250 µm [5]; see Table 1. Example materials for use in this additive process include tool steels, stainless steels, AlSi10Mg, AlSi12, Inconel, Ti64, tungsten, molybdenum, and copper, to name a few. Key considerations for this well-established process include finished part material porosity and surface roughness which are important aspects in thermal-fluid applications since they relate to material thermo-physical properties, disruption of thermal boundary layers, and flow resistance within a heat sink or cold plate (i.e., heat transfer vs. pressure drop tradeoffs) [1, 4]. Leftover powder removal can also be a post-processing issue for complex internal channel geometries and appropriate design considerations are required. As for the final part, the most common approach to integrating a heat sink manufactured using SLM into an electronics package is to utilize a separate conventional thermal interface material (TIM) such as a grease or compliant gap pad between the heat sink and device or package.

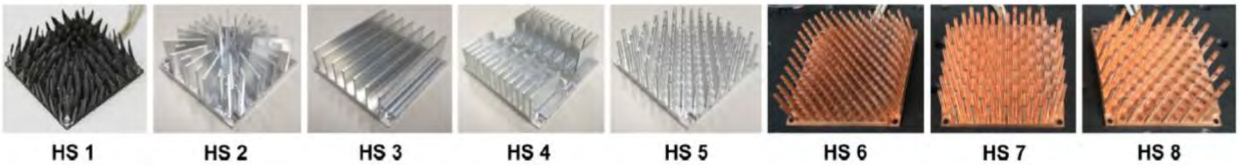

Fig. 5.2.1: An air-cooled additively manufacturing AlSi12 heat sink for electronics cooling (HS1 furthest left) versus a range of conventionally machined 7075 Al (HS2-HS5) and Cu (HS6-HS8) heat sinks; Reprinted from [4], Copyright (2015), with permission from ASME.

Table 5.2.1: Summary of important characteristics of AM processes for heterogenous integration of thermal management solutions for electronics.

Process Name	Feature Size	Tolerances	Materials	Finished Part Package Integration Approach
SLM	200-400 µm	50-250 µm	Tool steel, stainless steel (SS), AlSi10Mg, AlSi12, Inconel, Ti64, tungsten, molybdenum, Cu	• Discrete metal parts with possible post-process powder removal for internal channel geometries • TIM (e.g., grease or gap pad) for package attachment
Binder Jet	150 µm to mm range	-	SS, free sintering low alloy (FSLA) steel, Cu, possible polymer materials	• Discrete or package-integrated metal parts with post-process sintering • TIM (e.g., grease or gap pad) for package attachment • Possible heterogenous integration of thermal solutions for multi-material builds depending on sintering and active devices§
BPE	85-170 µm	-	17-4PH SS, A2 and D2 tool steel, Inconel 625, Cu	• Discrete metal parts with post-process sintering • TIM (e.g., grease or gap pad) for package attachment
ECAM	60 µm	30 µm	Cu	• Discrete or package-integrated metal parts without post-process treatment • Range of Cu, FR-4, silicon, or alumina substrates§
SLA-assisted IC	mm-scale depending on design	100's of microns	Broad array of castable metals	• Discrete metal parts with post-process treatment for demolding • TIM (e.g., grease or gap pad) for package attachment

FDM	mm-scale depending on design	sub-mm-scale depending on material and printer	Broady array of high temperature (e.g., PEEK, PEKK) and low temperature polymers including high thermal conductivity materials (e.g., nylon, etc.)	• Discrete plastic fluid manifold or heat sink parts with possible post-process treatment for fluidic sealing • TIM (e.g., grease or gap pad) for heat sink to package attachment • Snap-fit or mechanical fastener with gasket or O-ring for manifold to cold plate attachment • Enables multi-material cooler assemblies[§]
LCM	50-200 µm	50-75 µm	Aluminum Oxide (Alumina), Aluminum Nitride (AlN)	• Discrete ceramic fluid manifold parts with post-process sintering • Mechanical fastener with press contact, gasket, or O-ring for manifold to cold plate attachment

Notes:
[§]Indication of unique integration capability

5.2.2.1.2. Binder Jet

The binder jet process [6] for fabrication of metal heat sinks or cold plates is somewhat analogous to the SLM process above, where metal powder is bound by a binder. One of the key limitations of SLM process is the metal weldability, and binder jetting since no melting and solidification involved, it opens the opportunities to a wide variety of metals and alloys Here, metal powder is first prepared and loaded for printing. The powder is then spread into a layer and a binding agent is selectively jetted over the powder layer. This process is repeated layer-by-layer until a green part is formed. The powder bed is then heated for evaporation of liquid binder components and curing of the binder and resulting in a high strength green part. De-powdering and cleaning then follow, and the green part is ready for debinding and sintering treatments. Sintering treatment causes the green part to reduce porosity and increase in density. The sintered part is typically ready for application, however, depending on the application, in some cases is subjected to post processing treatments like HIP for further densifying the part close to its theoretical density. TIM may be used for integration of a discrete metal heat sink, Fig. 2 (left image), or cold plate into an electronics package, Table 1.

However, a uniqueness of this process is that it may be adapted and extended to multi-material builds, Fig. 2, for possible heterogeneous integration of thermal management components into an electronics package, although post-process sintering is a key consideration/limitation for possible active devices integrated into the package.

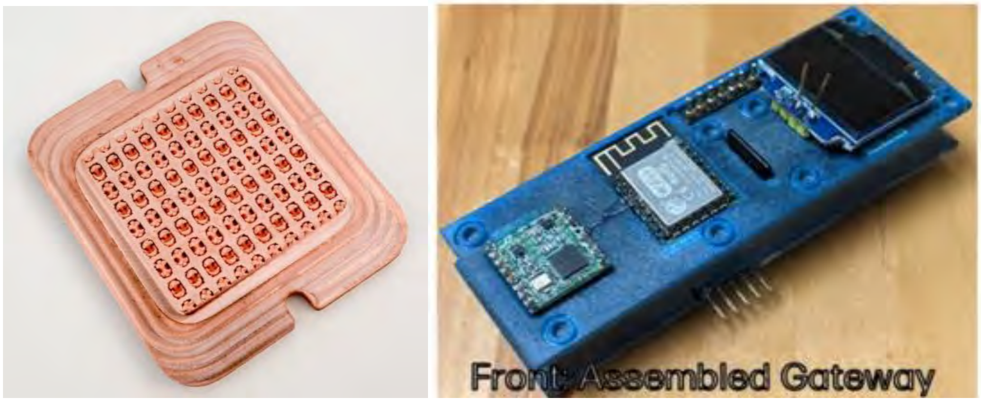

Fig. 5.2.2: A representative Cu prototype AM manifold microchannel (MMC) heat sink part printed using a binder jet process (left image). Metal jet 3D printed electronics (3DPE) demonstrator including metal and non-metal materials highlighting possibility of integrating thermal management solutions (right image).

5.2.2.1.3. Bound Powder Extrusion (BPE)

The BPE process is a combination of metal injection molding (MIM) and fused deposition modeling (FDM), whereby metal powder is bound in a plastic matrix filament and then printed in a similar fashion as a pure polymer filament [7]. Thus, there is no loose powder or lasers used in the printing process. After printing, the metal part is washed to debind and then sintered to achieve the final functional part. Common materials and example post-sinter feature sizes are reported in Table 1. Once more, a standard TIM may be used for integration of a discrete metal heat sink or cold plate into an electronics package.

5.2.2.1.4. Electro-Chemical Additive Manufacturing (ECAM)

The ECAM process is a layer-by-layer additive approach based on the electrodeposition of metal. Typical ECAM process is shown in the top portion of Fig. 3 [8]. Given a part geometry, a water-based feedstock flows across a printhead followed by micro-electrode printhead activation to form the print material on a vertically translating stage. The part is then printed upside down through precise pixel activation that drives a focused electric field to precisely deposit metal onto a base substrate. Part heights on the order of 10 mm are possible to print on a range of substrate materials including Cu, silicon, alumina, and FR-4 (see Table 1) opening a range of potential electronics integration approaches for novel microscale thermal management structures [8]. This additive process can facilitate intricate geometries, Fig. 3 (lower image), and further exploits the complexity of topology optimized channels, fins, and/or porous structures that can benefit single and two-phase heat transfer at microscales for power dense applications.

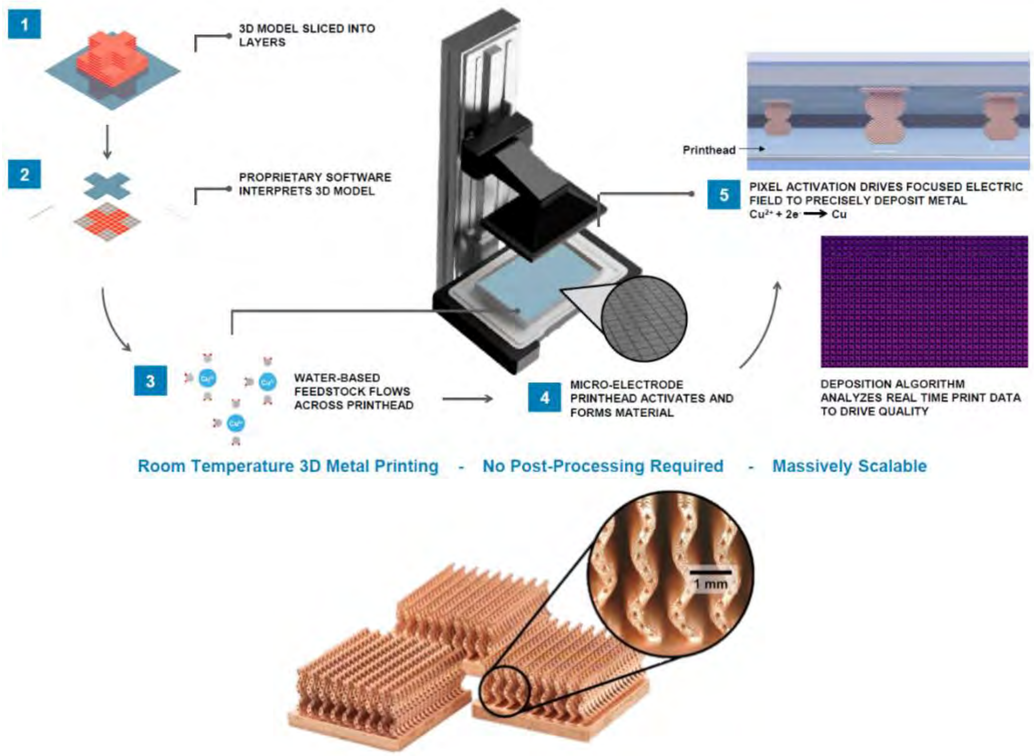

Fig. 5.2.3: Electro-chemical additive manufacturing process overview (top) and a representative Cu structure fabricated on a Cu substrate (bottom) [8]. Images used with permission from Fabric8Labs.

5.2.2.1.5. Stereolithography (SLA)-Assisted Investment Casting (IC)

Investment casting has been uniquely coupled with SLA-assisted additive processes for fabrication of positive part resin patterns to produce eventual plaster casting negative molds then used to realize cast metal heat sink parts, as illustrated in Fig. 4. In [9], this workflow enabled the fabrication of complex heat sink designs for light emitting diodes (LEDs). The designs in [9] were determined using topology optimization for natural convection in air, where like [4], non-standard heat sink fin geometries for enhanced thermal-fluid performance become available through a novel manufacturing process. As indicated in Table 1, a limitation of the SLA-assisted IC method might include minimum feature size, although tight fabrication tolerances using a broad array of metals is likely accessible.

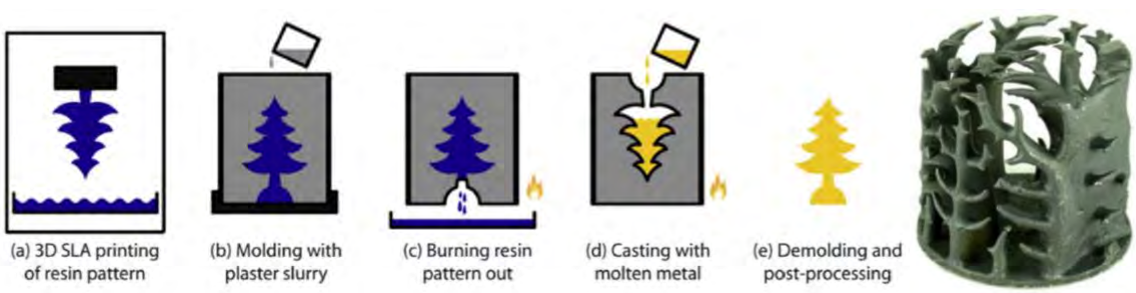

Fig. 5.2.4: SLA-assisted investment casting process (left) with a representative finished heat sink part for LED cooling (right); images Reprinted from [9], Copyright (2018), with permission from Elsevier.

5.2.2.2. Polymers

The use of polymers in AM of thermal management solutions for electronics is somewhat limited due to the low thermal conductivity (k ~ 0.2 W/m-K) of most base polymers and also a generally lower temperature range of operation. Fluid compatibility for coolants in contact with polymers additionally needs to be considered if one is not working with air. Regarding thermal conductivity, investigations have been performed on the AM of polymers with fillers for thermal conductivity enhancement in heat sink parts as outlined below. Fused deposition modeling (FDM) is a main approach to fabricating parts.

5.2.2.2.1. Fused Deposition Modeling (FDM)

FDM is a logical choice for the AM of polymer manifolds that can provide an engineered flow path for liquid or air delivery to an electronics cold plate or active device. As explained in [10], this design approach may provide an integration opportunity for cooling solution modularity, lightweighting, and multi-material assembly that enables the retention of high thermal conductivity parts in locations of greatest thermal importance (e.g., closest to the electronics package); see Fig. 5. In terms of electronics package integration, polymers also allow for the design of unique (e.g., snap fit) connections that further eliminate weight associated with mechanical fasteners. More recently, FDM has been used for additive fabrication of polymer heat sinks using Ice9 Rigid Nylon from TCpoly [11], where the material thermal conductivity is reported to be anisotropic with different printed in-layer, k ~ 3.23 W/m-K, and cross-layer, k ~ 0.88 W/m-K, values. Further advancements in the thermal conductivity of the base polymer material itself may offer future advantages for high performance and lightweight heat sinks for electronics.

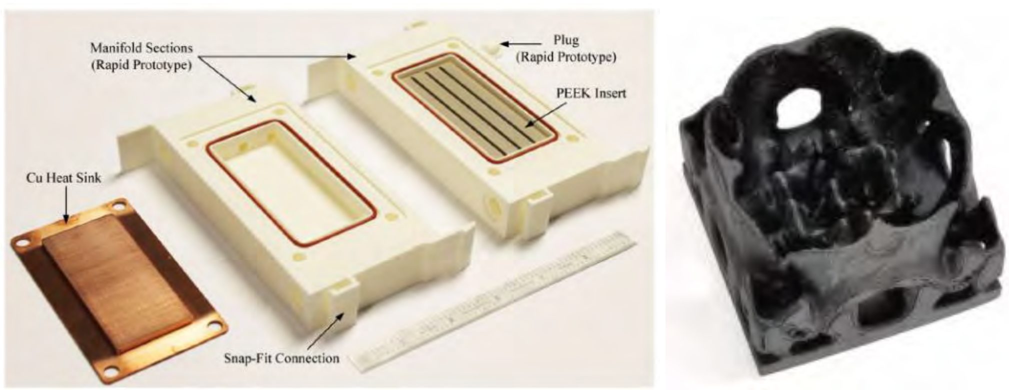

Fig. 5: Lightweight, modular, and multi-material cold plate assembly enabled by an additively manufactured FDM polymer manifold (left); left image Reprinted from [10], Copyright (2016), with permission from ASME. Heat sink FDM printed using Ice9 Rigid Nylon from TCpoly (right); right image adapted from [11] CC-BY.

5.2.2.3. Ceramics

Like polymers, ceramics can be employed for fluid delivery structures in electronics cooling solutions. Advantages of ceramics relate to weight reduction, corrosion resistance (depending on the selected ceramic and coolant), and favorable thermal-mechanical properties such as a coefficient of thermal expansion (CTE) that is more closely matched to semiconductor device materials such as silicon or silicon carbide. However, ceramics can be brittle, and care needs to be taken regarding mechanical strength in applications where a part may be pressurized by a working fluid with the ceramic material loaded in tension.

5.2.2.3.1. Lithography-Based Ceramic Manufacturing (LCM)

Somewhat analogous to metal AM processes that use MIM powder in a slurry with an optical printer (e.g., see [12]), LCM is a fabrication method that involves a ceramic-loaded liquid slurry into which a movable build platform is dipped from above [13]. This platform is selectively exposed from below to a layered image in visible blue light via a projection system. The process is repeated layer by layer to create a 3D green ceramic part that is thermally post-processed and sintered resulting in a fully dense part. This procedure allows macroscale porous lattice structures to be fabricated out of materials such as aluminum oxide (alumina) or aluminum nitride with micron-scale struts and features, Table 1. These lattices can have complex designs in 3D similar to concepts in [14], where the lattice serves as a wick-like structure, Fig. 6 right side image, that may be integrated into electronics cooling solutions for possible capillary fluid delivery to a cold plate.

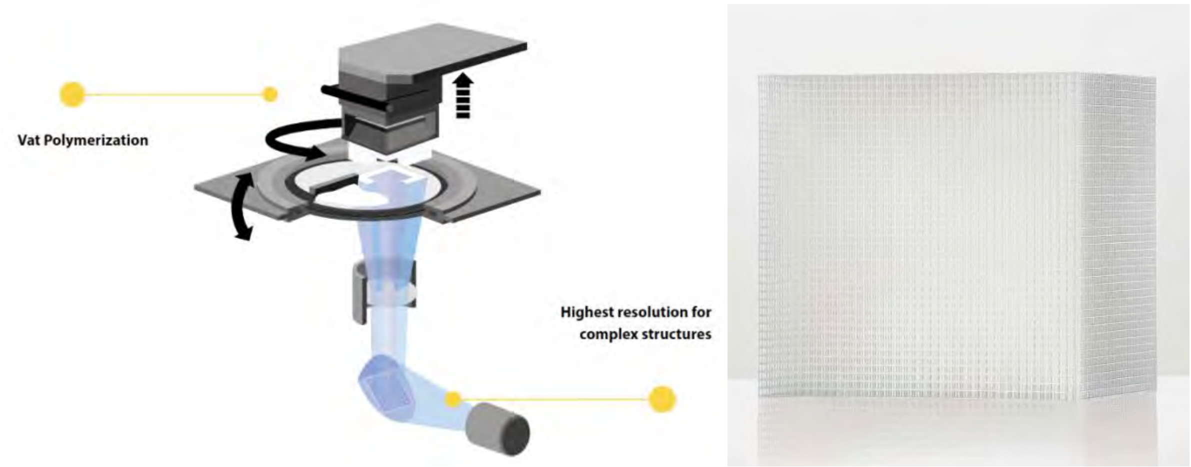

Fig. 5.2.6: Overview diagram of LCM process (left), and representative alumina lattice fabricated using the LCM process (right) [13]. Images used with permission from Lithoz.

5.2.3. Design Methods

Numerous advances in understanding of design for additive manufacturing of heat exchangers is covered in a range of recent reviews [1-3, 15, 16], and inverse design (e.g., topology optimization) techniques for the optimization of heat sink fin and cold plate channel geometry is being widely studied [2, 15]. As shown in these reviews, the field of design optimization for AM of heat sinks and cold plates has advanced rapidly over the last 15 years with may numerical investigations and some experimental examples involving AM available in the academic literature; in particular, the reader is referred to Table 5 in [2] for a comprehensive summary related to topology optimization. A topology optimized design of a manifold microchannel (MMC) heat sink from [17] plus an image of a representative AM prototype part for a power electronics module cold plate is shown in Fig. 7, for reference. Here, we see that topology optimization enables unique, non-intuitive fin designs that may perform better than traditional structures. Beyond the range of examples found in the literature, some commercial software companies have also been formed recently [18, 19] looking to capitalize on the trend in this field and bring the technology to bear in the market. These tools complement other existing commercial software resources that are well established for design optimization [20, 21].

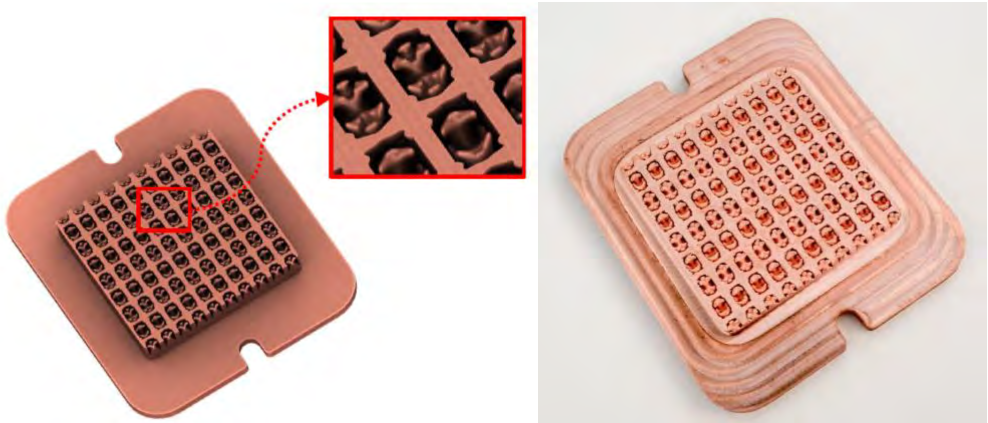

Fig. 5.2.7: Topology optimized MMC heat sink (left) [17]; © [2020] IEEE. Reprinted, with permission, from [17]. A representative Cu prototype MetalJet part (right).

5.2.4. Challenges & Growth Areas

Based on the above review, growth areas and challenges for integration of additively manufactured thermal management solutions for electronics can be separated into two categories including the manufacturing itself and design for AM. Regarding manufacturing, major challenges include the following:

1. Material porosity as it relates to thermal, mechanical, and fluidic sealing properties,
2. Realization of reliable interfaces for dissimilar materials,
3. Thermal-mechanical (i.e., thermal stress, CTE) considerations for dissimilar material interfaces,
4. Development of thermally conductive polymers,
5. Development of metal AM processes that can achieve feature resolution in the range of 1-5 µm.

Controlling material porosity in the AM process is a challenge and depending on the application (e.g., cold plate versus fluid/air flow manifold), the requirement for a water-tight design is different. Nonetheless, many porous material heat transfer applications exist, and porous materials may be well-used in air, single-phase (liquid), and two-phase (liquid-vapor) cooling solutions. Thus, being able to specify and control porosity in the near term (1-3 years) is a major manufacturing opportunity. As for printing dissimilar materials, multi-material printing should further evolve in the mid-term (3-6 years) to realize low conductive thermal resistance interfaces and/or composite TIMs. Here, optimal strategies are needed to mate materials (e.g., Cu to FR-4, or similar) to realize continuous and high conductance thermal interfaces that are reliable. Thermal stress from the manufacturing process itself, in addition to actual use, should be considered which may require engineering of a thermal composite material CTE or interfacial properties. The end goal is to ensure a mechanically robust and reliable interface between an electronics platform and heat sink or cold plate. In the mid-to-long term (6-9 years) further research into reducing the minimum feature size for metal AM parts is needed in order to fully connect to the requirements for wick structures found in advanced two-phase (e.g., vapor chamber or capillary cooling) heat transfer applications for electronics.

Major design method challenges for AM of heat sinks and cold plates include how to account for the following items in the design technique itself:

1. Build orientation effects [1, 11, 22] in terms of mechanical strength and thermal conductivity variations,
2. Material porosity [1, 4, 5],
3. Finished part surface roughness effects [1, 23],
4. Constraints on overhanging features [24],
5. Composite material representations.

Additionally, from a computational perspective, major challenges also exist in relation to the design optimization for multiphysics thermal-fluid systems in 3D at the global heat exchanger scale. As described in [17], a periodic local unit cell approach may be employed to support a design problem that is computationally tractable. Alternatively, a homogenization approach may be exploited to optimize fluid flow or heat sink channel structures at the global scale using effective porous media material properties on a relatively coarse mesh with eventual dehomogenization of an explicit microstructure based on a range of numerical techniques [25, 26]. The inverse design strategy using the homogenization method has the added built-in benefit of being able to effectively utilize AM material porosity effects for the design of new heat exchanger topologies [26], and utilization of the approach is expected to grow as an opportunity in the near term (1-3 years). Topology optimization for turbulent flow [27, 28] and considering heat transfer [29] then adds additional complexity to the above discussion points given the range of different flow models available in the literature. Here, in the mid-term (3-6 years), there may be opportunity to leverage physics-based machine learning methods (in the forward problem solution) to probe the intersection of heat exchanger AM and design for large-scale conjugate heat transfer under turbulent flow. Finally, design optimization for heterogeneous integration of embedded thermal solutions into power conversion and compute electronics packages considering both electrical and thermal functions simultaneously is an enormous area of future research opportunity. Embedded structures related to near-junction cooling [30, 31] and thermal metamaterials for heat flow control within the package [32, 33] for ultra-compact heterogenous integration might be realized in the mid-to-long term (6-9 years). Here, functionally-graded thermal design using AM for local hotspot mitigation becomes a possibility. However, these ideas require further development and maturity of multi-material/composite (i.e., metal plus polymer plus ceramic) AM processes plus associated electronic design automation (EDA) and optimization tools, where high performance cooling, continuous thermal interfaces and TIMs, routing for heat flow control, and fluidic design aspects are more holistically addressed.

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5.3. Photonics Packaging

Lead: Annette T.

Contributors/Editors: Ercan D.

5.3.1. Introduction

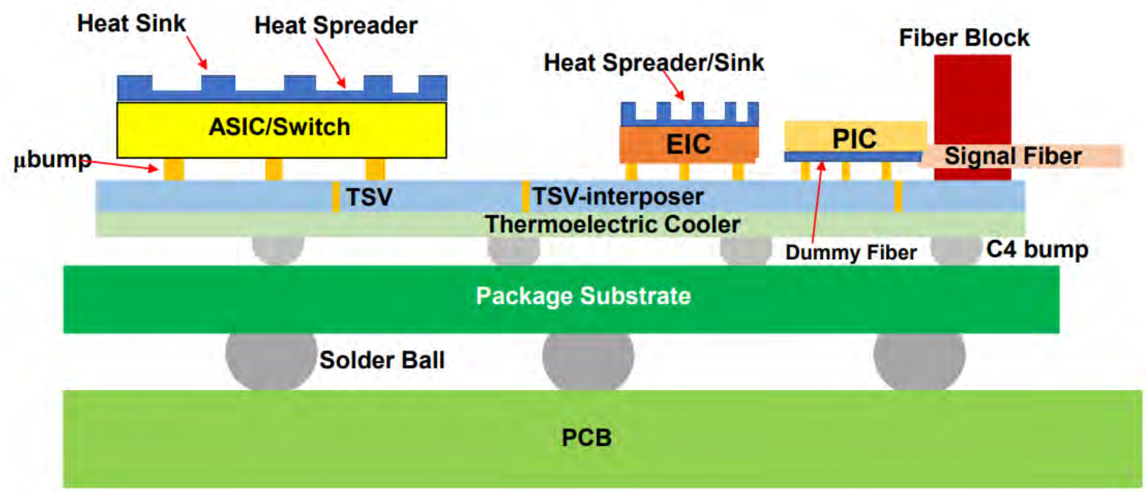


***Figure 5.3.1** – Photonic Package*

Photonic packaging is semiconductor packaging with added integration of optical components including optical fibers, waveguides and lasers. Coupling these components, especially the long fibers, to the chips with ultra-high precision has driven the cost of assembling optoelectronic packages to as high as 90% of the total cost of the product. The current demand for high speed, low power consumption and low cost is driving the need for reduced geometry while increasing heterogeneous integration. Research labs are exploring additive manufacturing as a solution to these challenges.

The 2 main areas of photonic packaging challenge are 1) Fiber/chip/light source coupling and 2) Interconnects between chips or package (Figure 5.3.1). Both require extreme submicron level precision of alignment to achieve negligible coupling loss. Additionally, the coupling must be mechanically robust and withstand thermal excursions or warpage. Achieving good strength during fabrication usually involves high temp processing, which is a challenge in heterogeneous integration due to the variety of materials and their unique properties. 3D printing is beneficial in solving some of these issues where high temperature processing must be avoided or isolated to very specific areas. This section describes some of the interesting use of Additive Printing in photonic packaging including 1.Fiber to Chip coupling. 2. Polymer waveguide 3. Bump interconnect.

5.3.2. Fiber to Chip coupling

Conventional fiber to chip coupling is the placement of the fiber at the precise desired location next to the waveguide and dispense index-matching epoxy and strain relief epoxy. Immediately after dispense, the 2 epoxies are cured by UV source. If this is done actively with a set of testing equipment to measure light signal loss, it is slow and costly. The cost is lowered if performed passively without testing and measurement, however, the alignment may not be optimal resulting in costly yield loss. Photonic wire bond is a potential solution where the placement of components is not optimal or within 5 micron of target. A fiber is subsequently additively printed between the chip and the fiber using Two Photon Polymerization. This

Stereolithography equipment made by Vanguard Automation is able to smartly attach the photonic wire bond at the exit of the chip waveguide and couple it to the center of the fiber.

Photonic wirebond process flow is shown in Figure 5.3.2. Components are placed using standard pick and place machine. A drop of photoresist is dispensed between the waveguide and fiber followed by laser beam which targets at the facet by machine vision and information from stored library of chip designs. The beam can create a wire diameter as small as 2 um as well as tapering of the photonic wire to improve optical performance as shown in Figure 5.3.3.

Figure 5.3.2 shows the process flow of photonic wirebonding (Lukas Chrostowski, Dream Photonics, UBC.)

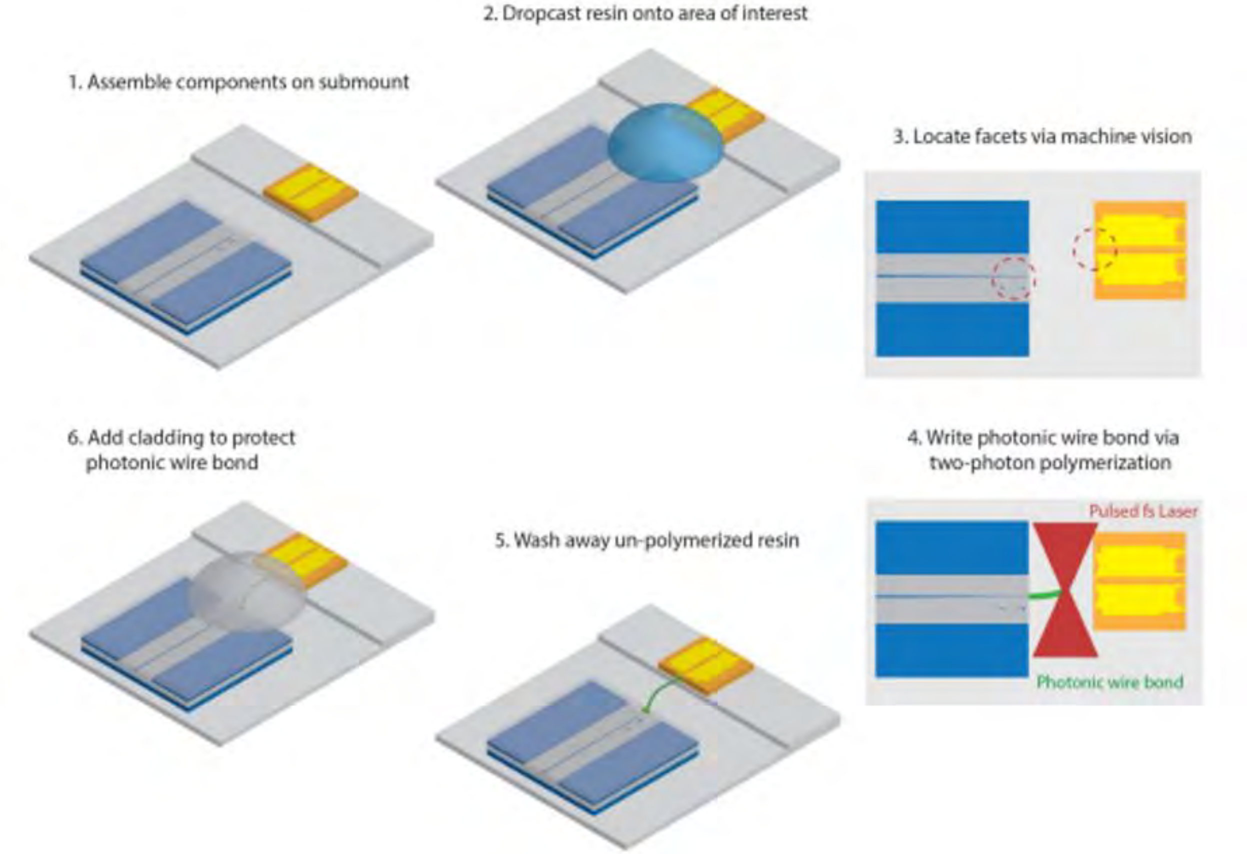


Figure 5.3.2. A row of photonic wires printed between fiber array and PIC die. (#thanks & permission from Stefan Preble, Rochester Institute of Technology)

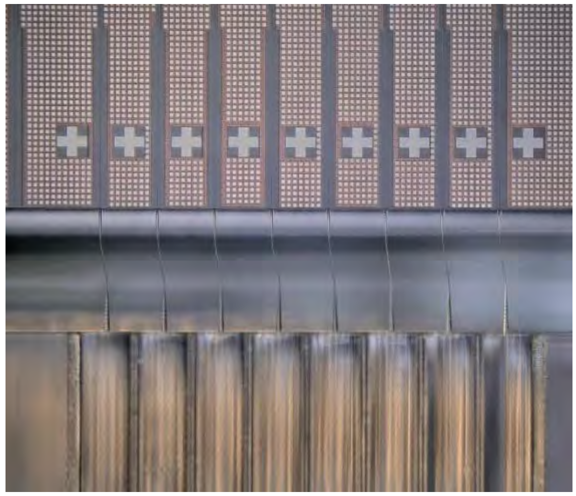
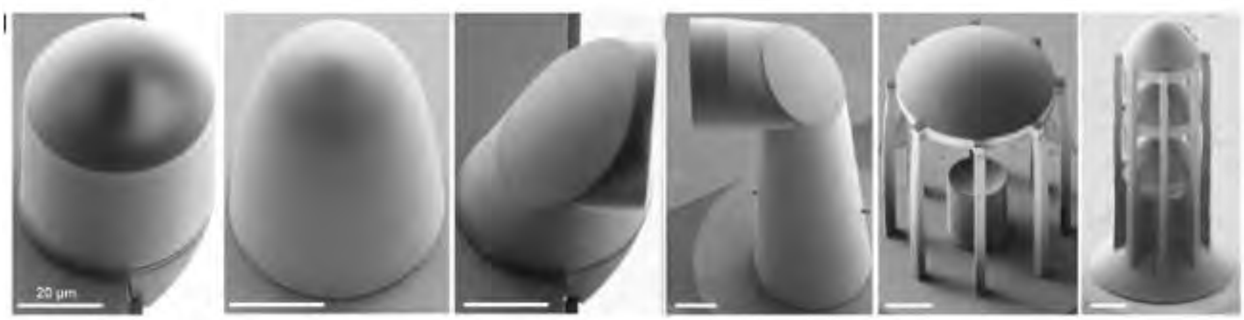


Figure 5.3.3

Additive printing using this stereolithography technique is very useful from printing microlenses (Figure 4) to mirrors and all shapes of light routing components. It is compatible to wafer level packaging, hence the possibilities of additive printing is quite limitless in this area.

Figure 5.3.4. various complex shapes for light routing can be additively printed for photonic packaging.



https://doi.org/10.1002/adfm.202214211

5.3.3. Printed Polymer Waveguides

3D Printing of Polymer Waveguides on flat substrate is available commercially as there are many suppliers of polymer waveguide material. Groups from Keio University and Dresden University have demonstrated low transmission losses.

In summary, various organic light transmission components can be printed with ultra fine geometry control and ultrahigh precision with acceptable loss in coupling or transmission. As with photonic wire-bonding, these additively printed waveguides are beneficial for rapid prototyping. Whether it can compete with thermocompression molding in volume manufacturing and production remains to be seen.

5.3.4. Printed Interconnects

The technology of additive printed interconnect applies not only to photonic packaging but to all semiconductor packaging. Materials used for additively manufacturable interconnects are 1) Conductive Ink that is curable or sinterable, and 2) Solders which are reflowable. Inks have inferior strength unless they are sintered at very high temperatures. Solders are preferred as they can be reflowed at relatively low temperatures. Low temperature bismuth tertiary solders are potential solutions to warpage problems during manufacturing of photonic packages . Solder is a more robust interconnect between layers or between components. However, additively manufacturable solders have yet to come in nano particle sizes. Hereaus and Alphametals are making Type 7 solder where the max solder particle size is 11um (Figure 5.3.5). Microbumps as small as 40um can be additively printed with Type 7 solder paste using special dispense heads made by nScrypt and NSW Automation. Sources for even smaller size solder paste of >Type 7 is limited or under development to get microbumps smaller than 40um.

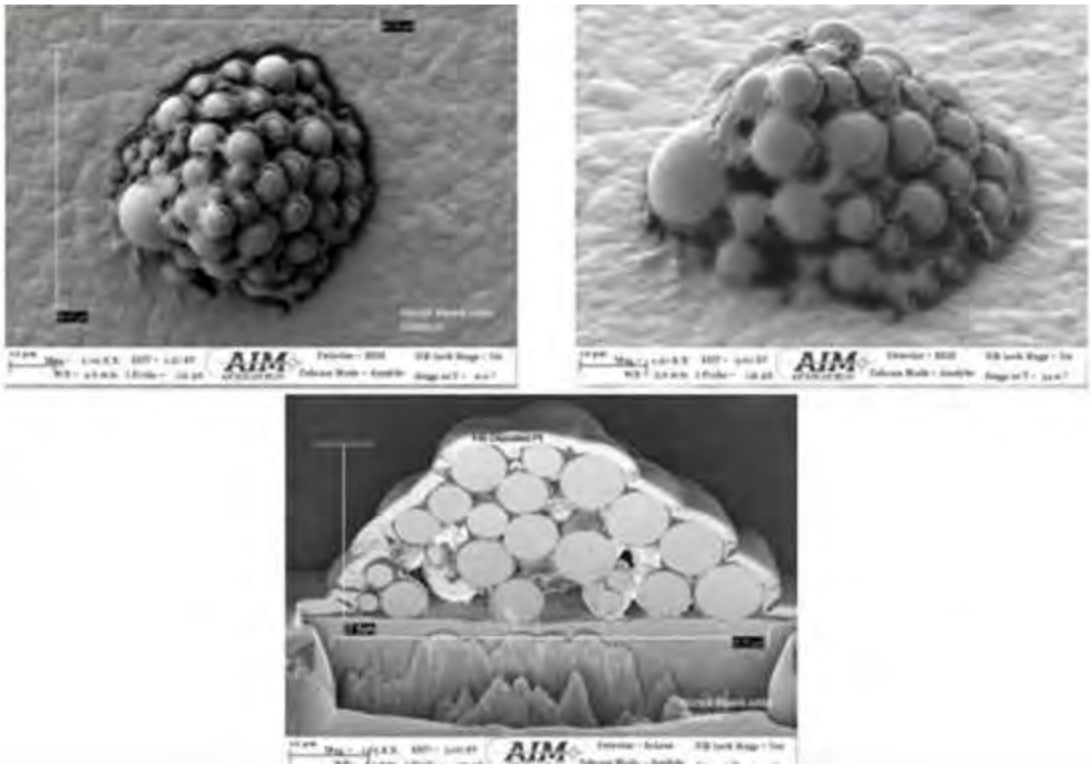
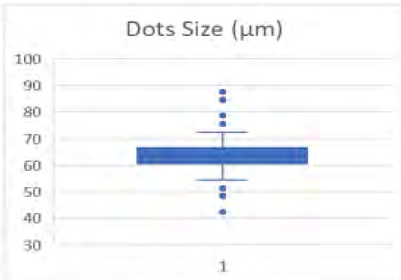


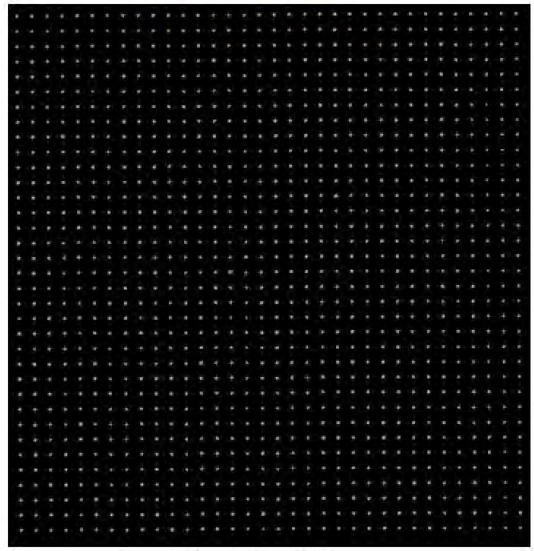
Figure 5.3.5. A 60um diameter printed dot using Heraeus Type VII SAC 305 paste dispensed by nScrypt.

Special dispenser heads are needed to control small solder paste dot size. Companies have integrated special dispense heads to achieve small consistent solder dots includes nScrypt and NSW Automation. nScrypt smart pump features 100 Picoliter Volumetric Control with Wide Range of Viscosity/Materials Choice and a Nozzle Orifice as small as 25 µ. NSW Automation has a patented solder paste dispensing valve with special ceramic nozzle to achieve 60um diameter solder dots or solder lines.

Before 1 hour					
Range Between(µm)			QTY	%	
30	to	40	0	0.00	
40	to	50	6	0.50	
50	to	60	265	22.27	
60	to	70	867	72.86	
70	to	80	49	4.12	
80	to	90	3	0.25	
90	to	100	0	0.00	
		total unit	1190	100.00	total %



Dot size 60 µm



Column: 34 units Row: 35units
Total unit: 1190

Use ALPHA solder paste (OM-234HF SAC305 75.5-7-M05),

total dispense 1190 units on bare wafer, 1181 units (99.25%) concentrated in 50 to 80 µm.

Figure 5.3.6. Additively printed solder dots to use as bump interconnects for flip-chip interconnects

Figure 5.3.7. Printer and special dispense head from NSW Automation for solder paste micro-printing.

Microbump dispense of solder paste requires reflow in a separate oven and must be followed by flux removal. This additional process step and equipment is eliminated by Pactech's solder ball jetter (Figure 5.3.8) using laser attach.

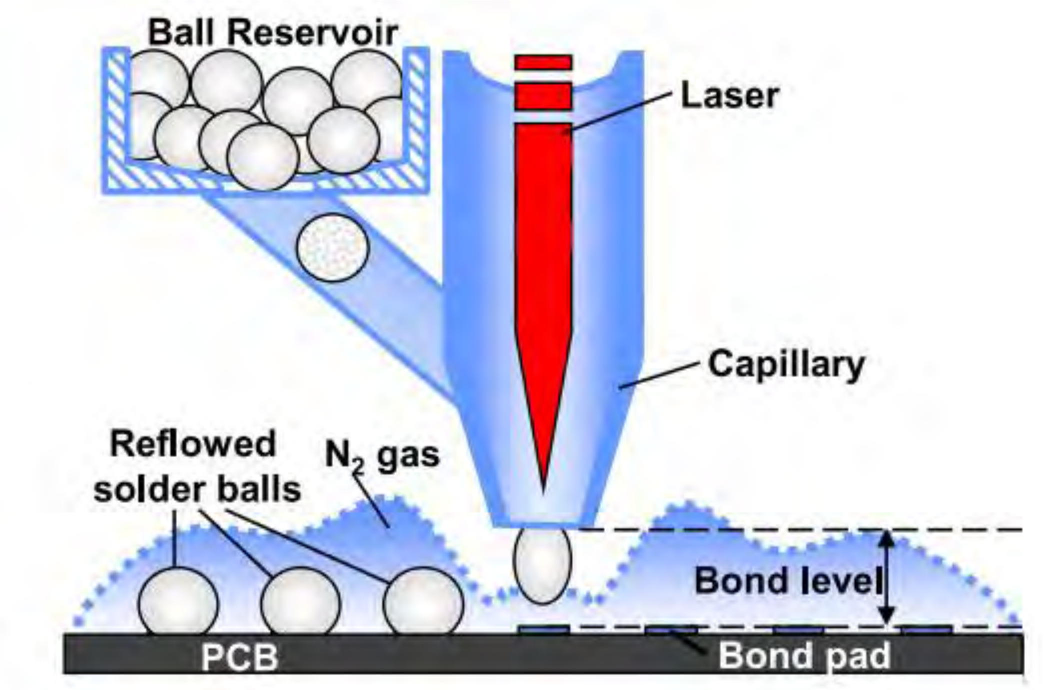


Figure 5.3.8. Drawing on the theory behind the solder ball jetter.

The solder ball bumper is an additive printer that prints balls invented by Elke Zakel of Pactech. As many as 2000 of these have been sold in the last 30 years. Although this technique has not been marketed as part of additive printing, solder ball bumping by laser is definitively an additive printing and computer aided manufacturing technique. Solder ball bumping is possible with the availability of solder balls as small as 40um from suppliers like Nippon MicroMetals. This ball printing technique is fluxless and does not require separate reflow nor require stencils. Entire 300mm wafers can be bumped with this ball printing method especially for lower volume flipchips. For higher volume manufacturing, solder ball bumping is replaced by batch processes such as plating, solder paste stenciling and ball drop with stencils.

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5.4. Wearables

Lead: Dishit P.

Contributors/Editors: Christine K., Kris E., Girish W.

1. Introduction

The world of electronics and wearables has witnessed a remarkable transformation in recent years. Traditional manufacturing methods for electronics often involve rigid, flat circuit boards and assembly processes that are inherently limited in terms of design flexibility. This limitation has impeded the seamless integration of electronics into wearable devices, which require adaptability, comfort, and aesthetics. Historically, wearables faced constraints imposed by conventional manufacturing techniques, these constraints include, (a) Design Limitations, (b) Bulkiness and Rigidity, (c) Cost and Scalability, (d) Environmental Impact. The motivation to explore additive manufacturing of electronics (AME) for wearables arises from its transformative potential. Additive manufacturing (AM), with its design freedom, flexibility to rapidly prototype, and customization capabilities, offers a solution to these challenges. It enables the creation of lightweight, flexible, and intricately designed wearables, responding to the growing market demand for personalized, environmentally sustainable, and user-friendly wearable technology.

While using AM for fabrication of wearables, various established & emerging semiconductor packaging techniques and materials need to be employed to encapsulate and protect electronic components. These include 3D printing and microfabrication, flexible substrates, Chip-on-Board (COB) and Chip-on-Flex (COF), encapsulation materials, conductive and dielectric inks, and flip-chip bonding, amongst other packaging technologies. The choice of packaging technique depends on the specific requirements of the wearable device, including factors, such as, form factor, flexibility, and the environment in which it will be used. AM allows for a high degree of customization and adaptability in semiconductor packaging for wearables. As wearables continue to impact various industries, from healthcare & fitness to fashion & communication, Additively Manufactured Electronics (AME) is poised to play a pivotal role in shaping the future of this technology. The overall wearable technology market is expected to grow at a compound annual growth rate (CAGR) of 13.60 % from 2023 to 2032. [1] The global AME for wearables market size is projected to surpass USD 4.2 Billion in 2023 and is likely to attain a valuation of USD 9.3 Billion by 2033. The AME for wearables industry share is expected to rise at an astounding CAGR of 8.3% from 2024 to 2033 as seen in the **Figure 1** below. [2]

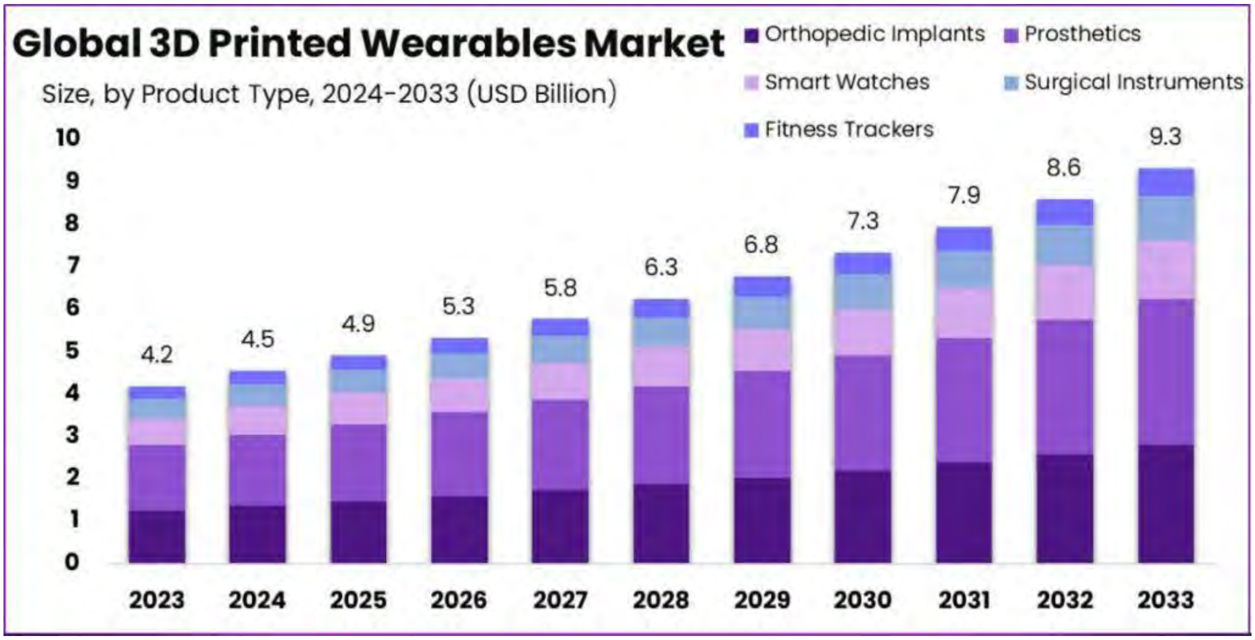

Figure 1. *Market share and size of the global 3D printed wearables market segmented by product type. [2]*

With the ability to produce complex three-dimensional (3D) structures, AME opens possibilities for innovative designs, enabling personalized and ergonomic wearables tailored to individual needs. This roadmap chapter is focused on understanding the multiple dimensions of AME for Wearables, namely,

- The need of AME for wearables
- AME technologies and materials available today for wearables fabrication
- Applications of AME-fabricated wearables in academia and industry
- Integration challenges & design opportunities for AME in Wearables

The purpose of this chapter is to educate the readers on the latest developments in the field of AME for Wearables, the scope for which is fairly wide, and hence we will employ the usage of literature sources wherever needed, and cross-referencing the other chapters written as a part of the prior year editions of Heterogenous Integration Roadmap (HIR), including, but not limited to, Chapter 4: Medical, Health and Wearables. [3]

2. Need for AME in Wearables

Conventionally, integrated circuits (ICs) consist of conductors, resistors, insulators, and semiconductors integrated and patterned spatially into complex circuits and devices on a planar substrate. The techniques to build these devices are inherently 2D and involve several expensive and energy-intensive process steps such as deposition (e.g., physical vapor deposition, sputtering), removal (e.g., etching), patterning (e.g., lithography), and modification (e.g., ion implantation for doping) of electronic materials. [4], [5], [6], [7], [8], [9], [10], [11] There is a need for alternative processes and toolsets to print electronic materials directly and inexpensively in 3D by eliminating the masking and etching steps. The ability to additively print electronics reduces the material waste, energy consumption, and processing time and steps relative to IC processing. [12], [13]

In addition, product customization has been a challenge for traditional manufacturers, typically due to the high costs in fabricating the mold, especially for small-scale productions of custom-tailored products. On the other hand, Additive Manufacturing (AM) can print small quantities of customized products in plastic (in 3D) with extremely low costs compared to traditional mold-based productions. This is specifically useful in wearables, whereby unique personalized / customized products are required.

Additive Manufacturing (AM) technologies such as 3D printing are poised to reshape the entire field of electronic manufacturing. Printing technologies open exciting new ways of scaling electronics “Beyond Moore,” through the integration of micro and macro, creating new form factors, complex shapes, conformal devices, and distributed systems. Printed, hybrid electronics systems will enable new classes of sensor systems, structural electronics and wearable devices, where the “system is the package”. [14]

3. AME Technologies & Materials for Wearables

Additive Manufacturing (AM) offers many advantages with respect to traditional manufacturing, including an improved versatility, less waste, more freedom in design, a low-cost fabrication, high-automation, and short fabrication cycle time. [15] Due to these advantages, several AM technologies have been employed for prototyping wearables. More common methods used are Fused Deposition Modeling (FDM), Inkjet 3D Printing, Screen Print and Stereolithography (SLA), amongst others, where significant progress has been made to enable the fabrication of wearable devices. These techniques and many other relevant methods have been reviewed extensively and discussed in detail in the earlier sections of this chapter and hence the readers are guided to the corresponding sections for the respective methods for additive manufacturing.

The growing need to shrink not only the footprint of an electronic system, but also to limit its thickness has led to increased interest in flexible circuits. For maximum miniaturization, flexible polymeric substrates combined with ultrathin IC´s have become a pivotal technology for demanding systems. [16], [17] Soft electronics are devices that can be bent, folded, stretched, or conformed regardless of their material composition, without losing the electronic functionality. One of the subsets of soft electronic devices is flexible electronics that embeds conductors in thin form factors inside a polymer matrix and retain their function while being bent. Intrinsically stiff materials, such as copper, can be rendered flexible by making them sufficiently thin. Examples of such wearable electronics include fully integrated and sensor arrays for in situ perspiration analysis, and transparent, lightweight electronics that can be transferred on another object, surface, or biological tissues, i.e., human skin. One of the drawbacks of these wearables devices is that they are not inherently stretchable as the conductors and the off-the-shelf electronic components used in the fabrication process are rigid and brittle by nature. While flexible wearables can be bent, stretchable wearables can be elongated. Thus, stretchable wearables can be used in a wider application space while providing increased durability. [18], [19]

To build a stretchable wearable, in addition to having the backbone of a soft polymer matrix, it is required to pattern interconnects that are intrinsically stretchable. Additive manufacturing and molding techniques make it possible to realize complex 3D structures with a variety of soft materials and allow the integration of different materials to generate unique functionality and material properties. For example, Polygerinos et al. [20] realized a soft robotic glove for rehabilitation and training as seen in **Figure 2**. They used fiber-reinforced rubber to create a pressurized bending actuator, which was composed of a molded elastomer main body and strain limiting layers.

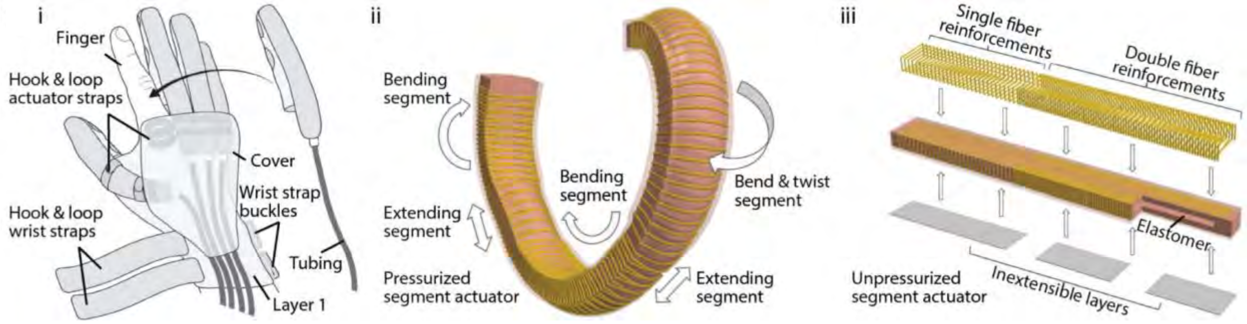

Figure 2. *Example of a functional soft and wearable robotic device realized using various stretchable elastomeric materials and AM methods. [20] (i) Schematic of the soft robotic glove design. (ii) Pressurized soft actuator showing a combination of motions including bending, extending, and twisting. (iii) Exploded view showing inextensible layers, elastomer, and fiber reinforcements.*

Polymeric substrates are widely used in building flexible circuits. Recent developments to realize such high density flexible circuits for wearables have demonstrated the capability to improve production volume, cost, and reliability significantly. Especially with the material of main interest, polyimide, substantial improvements in the production of high-density circuits have been achieved. Although polyimide is regarded as a highly versatile, robust, and capable material, flex circuit realization is not limited to this. Niche materials like Parylene, silicone, PC (polycarbonate) or LCP (liquid crystal polymers) have been sided with materials targeting volume markets e.g., PU (polyurethanes), or PET (polyethylene terephthalate). Especially thermoplastic polyurethanes (TPU) have come to the attention of the industry, as processing of these results not only in flexible, but highly pliable and stretchable products if applied with a suitable structuring technology for the conductive tracks. In combination with thermosetting or thermoformable backings [21], [22], these stretchable properties even allow to build wearable electronic systems conforming to complex 3D surfaces. A summary of these materials and their corresponding AME techniques with pros and cons are provide in the **Table 1** below.

Table 1. The materials, benefits, and limitations of the three 3D printing methods commonly suitable for fabrication of wearable electronics such as microfluidics. [23] (*Reproduced with permission from Padash et. al., Microfluidics by Additive Manufacturing for Wearable Biosensors: A Review; published by MDPI, 2020*)

3D Printing Methods	Materials	Benefits	Drawbacks
Fused deposition modelling (FDM)	Polyethylene terephthalate (PET) Polystyrene (PS) Polycarbonate (PC) Acrylonitrile butadiene styrene (ABS) Polycaprolactone (PCL) Poly-lactic acid (PLA) Polybutylene terephthalate (PBT) Polyglycolic acid (PGA) Polypropylene(pp)	Low cost High speed Simplicity Low-cost Manufacturing of centimeter-sized prototypes Using inexpensive biocompatible polymers	Weak mechanical properties Limited materials (only thermoplastics) Layer-by-layer finish Leakage due to filament bonding Difficulty of removal of support structure for complex internal features Inter-layer distortion
Inkjet printing (i3Dp)	Soft elastomers Liquid metals (i.e., EGaIn) Wax-based inks Liquid suspensions Acrylonitrile butadiene styrene (ABS), Polystyrene (PS), Polypropylene (PP), Polymethylmethacrylate (PMMA), Polycarbonate (PC) Ethylene propylene diene monomer (EPDM) High-impact polystyrene (HIPS)	Layer-by-layer fine structures Fast High resolution smooth surface Low cost Ability to easily print highly complex devices without using lithography Precise control Realizing microfluidics directly on other systems without any bonding steps Absence of sticking agents in between layers	Difficulty in removing the support material Layer-by-layer finish
Stereolithography (SLA)	Epoxy Hybrid resins Acrylate based resin Clear acrylic polymer Elastomers and ceramics Composites of photopolymers Hybrid polymer-ceramics	High quality Smooth surface Use flexible resin Fine resolution (a nometer scale) custom low-cost resins No need for external alignment Ability to directly print the channels Manufacturing complex nanocomposites Making a monolithic structure without the need for bonding	Slow printing Sometimes expensive chemicals Low biochemical adaptability of the resist Limited choice of the materials

4. Applications of AME-fabricated Wearables

The range of wearable devices enabled by AM of flexible and stretchable electronics ranges from wristbands over smart textiles to soft robotic exoskeletons. AM technologies allow the integration of electronics functionalities in dynamically deforming devices molded to the shape of the human body.

Physical assistance and rehabilitation using additive manufacturing of soft robotics are among the most actively researched biomedical application areas for wearables. Assistive devices are designed to restore the body's capacities for performing physical tasks or movements that are affected by injury, disease, or congenital effects. Polygerinos et al. [20] 3D printed a robotic glove for stroke patients, employing soft fiber-reinforced silicone-based actuators that can enact a variety of motions under fluid pressurization as shown in **Figure 3 (a)**. Mohammadi et al. designed a 3D printable soft robotic prosthetic hand that has multi-articulating capabilities for daily grasping tasks [24] as shown in **Figure 3 (b)**. Many robotic supernumerary (supplemental) devices have been designed to be modular, comprising arrays of moving segments that can produce substantial motion. Some integrate multiple actuators that increase the size of the kinematic workspace of the limb. Examples include supernumerary limbs based on wearable fabric actuators [25] as shown in **Figure 3 (c)**.

The properties of the skin and associated ergonomic requirements are motivating many researchers to investigate soft technologies for wearable haptics. Several researchers have already printed wearable, soft interfaces for haptic applications to allow users to experience touching and interacting with virtual objects whose properties are simulated haptically. These include devices for providing tactile feedback to a hand or finger as seen in **Figure 3 (d)** in virtual reality. [26] Originally envisioned in science fiction, one category of size-adaptive garments is that of self-lacing shoes. Many other self-fitting garments have been proposed, such as the 3D printed sleeves that are actuated by nickel-titanium (NiTi)-based shape memory alloys (SMA) materials as shown in **Figure 3 (e)** by Granberry et al. [27]

Esthetics, art, and personal expression have also informed many developments in soft, wearables for fashion and art. Many design researchers have also investigated the opportunities that such technologies, including sensors and actuators, can provide for interaction with a wearer's environment or others within it. Drawing inspiration from human emotion and social behaviors, Farahi [28] designed expressive, gaze-actuated garments actuated via SMA as seen in **Figure 3 (f)**

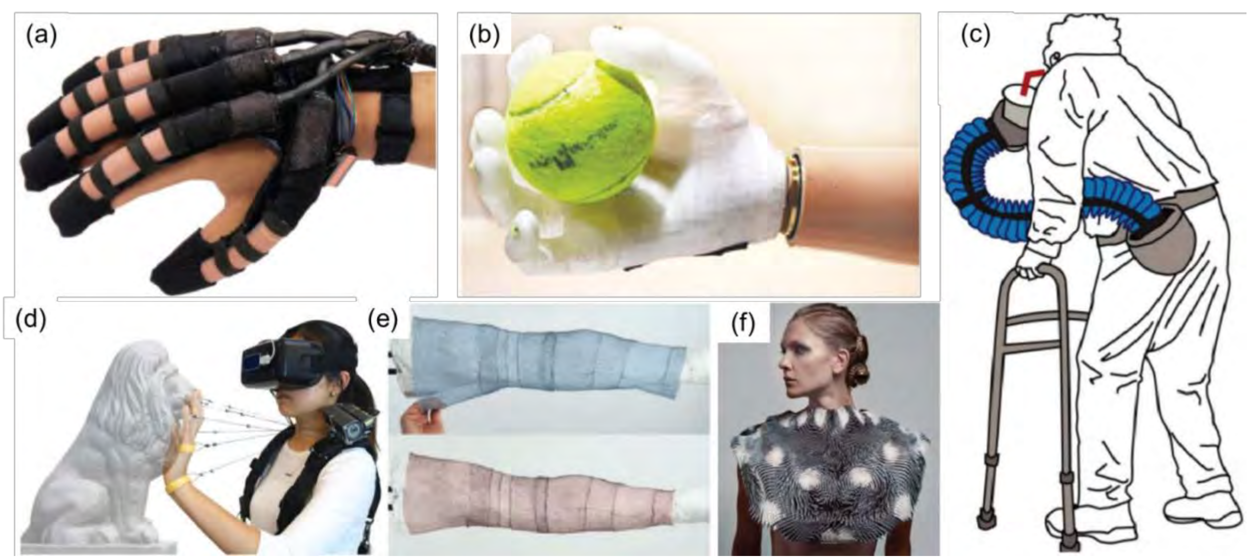

Figure 3. *Examples of soft wearable devices fabricated using AME in diverse application areas. (a) 3D printed pneumatic glove for hand rehabilitation. [20] (b) Cable-driven soft prosthetic hand. [24] (c) Supernumerary pneumatic arm for aiding activities of daily living. [25] (d) String-based wearable haptic interface for virtual reality.*

[26] (e) Leggings knit from SMA that can contract to match the limb shape. [27] (f) Expressive soft robotic garment actuated by SMAs responds to the gaze of others. [28]

The techniques and materials for AME discussed in this chapter also provide the opportunity for using multi-material to improve the function and the quality of the final printed product. For wearable electronics such as microfluidics, three substrate interfaces are typically used, including fabric, polymer, and silicone such as an elastomer/rubber as seen in **Figure 4**. [23], [29] These kinds of substrates are chosen since they are biocompatible and, therefore, they are particularly suitable for the biosensing systems used in wearable applications. Fabric may be soft, absorbent, and breathable. Several different polymers are possible with properties of flexibility, robustness, and a strong resistance to chemicals. Silicone elastomers are stretchable and conformable, with properties of long-term durability, and present an excellent chemical resistance and viscoelasticity.

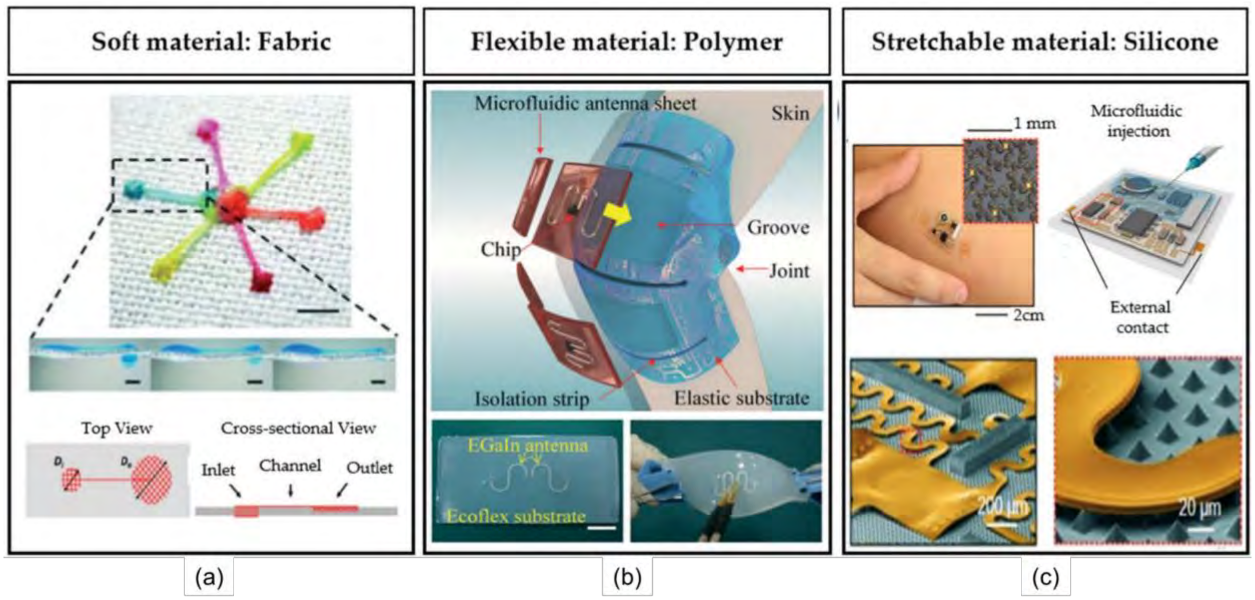

Figure 4. *Wearable microfluidic systems realized with multi-material methods: (a) Interfacial microfluidic transport principle to drive three-dimensional liquid flows on a micropatterned superhydrophobic textile, [30] (b) Triboelectric pressure sensor integrated with an antenna for data transmission, [31] (c) Stretchable skin-patch with integrated electronics. [32] (Reproduced with permission from Padash et. al., Microfluidics by Additive Manufacturing for Wearable Biosensors: A Review; published by MDPI, 2020)*

There are several other examples of wearables fabricated using AME, utilized in the field of medical applications, the scope for which is fairly wide, and hence we will like to guide the reader to Chapter 4: Medical, Health and Wearables [3] written as a part of the prior year editions of Heterogenous Integration Roadmap (HIR).

5. Integration Challenges & Design Opportunities for AME in Wearables

Personalized Prototyping vs Mass Manufacturing: Current embodiments of AME technologies are suitable for fabrication of products that have customized features, low-volume production, and / or increased geometric complexity. [33] Typically, the cost for achieving economies of scale via batch fabrication of standardized part geometry using AME is significantly larger than via traditional patterning techniques such as lithography and molding due to the discrepancy in cycle time.

Material Heterogeneity, Design, and Reliability: Wearable electronic products that are manufactured, even while using state-of-the-art AME systems, suffer from anisotropic mechanical and electrical properties due to interlayer bonding deficiencies leading to short-term and long-term reliability issues. [34] Additionally, a large majority of AME systems process only a single material at a time. While multi-material AME systems that enable functionally-graded materials are emerging in both dielectric [35] and conductor [36] contexts, the adoption of these systems is limited due to uncertain behavior at the material interfaces [37] and a lack of design for manufacturing (DfM) software support.

Leveraging the ability to embed resistive, inductive, and conductive components into 3D printed parts, many researchers have combined AM and Direct-Write (DW) technologies such as Inkjet printing to enable fabrication of wearables. When integrated into an AM process flow, DW can be leveraged to physically realize electronic signal routing, embedded sensors, and integrated power systems in additively manufactured structures.

While embedding of a diverse collection of foreign elements, circuits, and sensors has been demonstrated for multiple AM processes, there remains significant need for computer-aided design (CAD) software that is able to support the mechanical modeling and electrical analysis of these heterogeneous assemblies and their multi-functionality (*see Section 3 for more detail*). More specifically, existing commercially-available software packages do not enable a designer to easily model or analyze multiple material geometries and their accompanying anisotropy and reliability of the final product.

Re-thinking Efficient Design Exploration: As we know, AME is now pushing the frontier of new breeds of design approaches and tools to fabricate wearables. The new areas that are open for such explorations include topologies and geometries that take advantage of AM. For example, envisioning new types of mechanisms, materials, and structures with multi-scale and multi-resolution, for 4D programmable matters, [38] cellular materials, [39] deployable structures, [40] and biomimetic materials. [41]

6. Conclusions

This section provided a holistic review of the latest AME developments, highlighting its transformative impact in this rapidly evolving field of wearables. The advancements in AME have revolutionized the way we design, prototype, and manufacture wearables, offering unprecedented levels of customization, efficiency, and material utilization. It becomes evident that each AME technique contributes to the diverse range of applications and possibilities in manufacturing. Moreover, the integration of diverse electronic materials, has expanded the capabilities of AME, allowing to rapidly prototype end-use products with enhanced mechanical, electrical properties, and increased reliability. Additionally, the development of multi-material printing systems has opened avenues for creating with intricate material compositions, introducing a new level of functionality and performance.

The continuous progress in materials, technologies, and software tools paves the way for a future where AME becomes an integral part of various industries, including wearables. As researchers and industry professionals continue to push the boundaries of AME, we can anticipate even more remarkable developments and its widespread adoption in the years to come. In the future, AME processes are expected to witness remarkable breakthroughs, with continuous improvements in speed and accuracy driven by innovative materials, enhanced printing techniques, and sophisticated control systems including AI.

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5.5. Printed Sensors

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5.5.1. Overview

In the world of sensing technology, printed sensors have emerged as an approach to developing cost-effective, flexible, and customizable sensing solutions. These sensors are created through various printing techniques, allowing for the deposition of functional materials on flexible or stretchable substrates. Due to the cost advantage and potentially sustainable materials, printed sensors can be disposable. The processes and materials allow new form factors (e.g. large area, bendable and stretchable). Printed sensors find applications across diverse industries, from healthcare and environmental monitoring to automotive and consumer electronics.

5.5.2. Principles of Printed Sensors

Printed sensors rely on the fundamental principles of sensor technology to detect and quantify specific physical, chemical, or biological properties. The key principles governing printed sensors are summarized in Table 1. Printed sensors employ various transduction mechanisms to convert a target property into a measurable signal. These mechanisms can include changes in resistance, capacitance, inductance, optical properties, piezoelectric effects or electrochemical reactions.

The output signals from printed sensors are typically analog in nature. Signal conditioning and processing electronics are used to convert these signals into meaningful data, which can be further analyzed or displayed.

Table 5.3.1: Printed sensor principles

	Electrochemical	Capacitive	Piezoresistive	Piezoelectric	Resistance / Impedance	Photoelectric	Inductivity
Biosensor	X						
Humidity					X		
Gas	X						
Temperature					X		
Pressure		X	X	X	X		X
Strain		X		X			X
Touch		X					
Light						X	

5.5.3. Materials

The basis of any printed sensor is the selection of appropriate functional materials. Conductive inks, organic polymers, nanoparticles, and other materials are chosen based on their sensitivity to the target property. For example, conductive inks containing carbon nanotubes or graphene may be used for strain sensors, while chemical-sensitive inks can be employed for gas sensors.

5.5.4. Equipment

Printing techniques like screen printing, inkjet printing, flexographic printing, and gravure printing are used to deposit functional materials onto a substrate in precise patterns. These techniques enable the fabrication of sensors with varying levels of complexity and resolution.

5.5.5. Applications of Printed Sensors

The versatility and adaptability of printed sensors make them suitable for an extensive range of applications.

Table 5.5.2: *Overview printed sensor applications*

Application	Sensor devices
Healthcare	Wearables, POC, disposable biosensors
Environmental monitoring	Air quality, water quality, soil condition
Automotive	Airbags, tire pressure, fuel level, tank integrity
Consumer	human-machine interfaces
Industrial	Process condition monitoring
Smart Packaging	Data logging
Agriculture	Soil and environmental conditions
Security	Tampering, intrusion, biometric identification

5.5.6. Advantages and Challenges

Printed sensors are highly scalable and cost-effective, making mass production of sensors more affordable. They can be fabricated on flexible substrates, making them suitable for curved surfaces and wearable applications. They are also lightweight. The design of printed sensors can be easily customized to meet specific requirements, allowing for rapid prototyping and adaptation to different applications. Many printed sensors are designed to operate with low power, making them ideal for battery-powered and energy-efficient devices. Printing technology allows for the creation of sensors with large area coverage, which is advantageous in some applications like environmental monitoring. The simplicity of printing processes facilitates rapid prototyping and iterative design improvements.

Printed sensors also face several challenges and limitations. They may have lower sensitivity compared to traditional sensors – e.g. due to drift, hysteresis and cross sensitivity, which can be a limiting factor in applications requiring high precision. The materials used in printed sensors may be less durable than those used in conventional sensors, affecting their longevity in harsh conditions. The complexity of certain sensor types, such as imaging sensors, may be challenging to achieve with printing techniques.

The lack of standardized manufacturing processes and materials can hinder the widespread adoption of printed sensors. The disposal of printed sensors, particularly those with specialized materials, may raise environmental concerns if not properly managed. Integrating printed sensors with existing systems and electronics can be challenging, especially in highly regulated industries.

5.5.7. Future Outlook

The field of printed sensors continues to evolve, driven by ongoing research and development efforts. Advancements in materials science will lead to the development of more sensitive and durable materials for printed sensors. The combination with emerging technologies like machine learning and IoT will enable more sophisticated data analysis and sensor fusion and overcome the intrinsic weaknesses (sensitivity, cross sensitivity, drift). Efforts to establish industry standards for printed sensor manufacturing will promote consistency and reliability. There is a major drive to explore eco-friendly materials and manufacturing processes to address environmental concerns. As printed sensor technology matures (higher resolution, sensitivity, robustness), it will find new applications in fields such as augmented reality, robotics, and smart textiles. Especially the development of biocompatible printed sensors for healthcare applications, including implantable devices, holds significant promise.