M.Tech
Digital Manufacturing

BITS Pilani
Pilani Campus

Jayakrishnan J
Guest Faculty

innovate achieve lead

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DMZG521- Design for Additive Manufacturing
Session 8 & Lecture 15-16

Functional Complexity

- AM process can able to fabricate some operational mechanisms by ensuring the clearances between links.
- A wide variety of kinematic joints has been fabricated directly in VP, ME, and PBF technologies, including vertical and horizontal prismatic, revolute, cylindrical, spherical, and Hooke joints

Courtesy: Ian Gibson

Functional Integration

- Functional integration means implementing as many technical functions as possible into as few parts as possible.
- New washing rotor consists of 3 instead of 32 assembly parts, two of which are produced by Hettich using AM
- Improved product functionality
- Tools are no longer required
- No more costly deburring
- Much faster assembly
- lower logistics costs

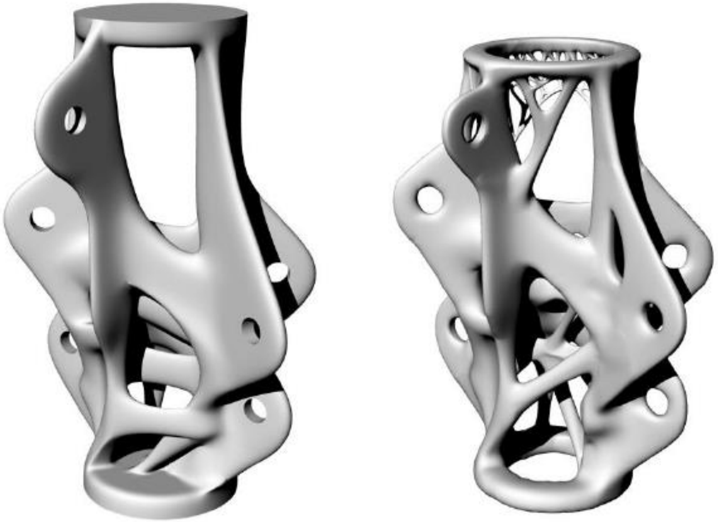
Courtesy: Eos Functional integration

What are the drivers for multifunctional design

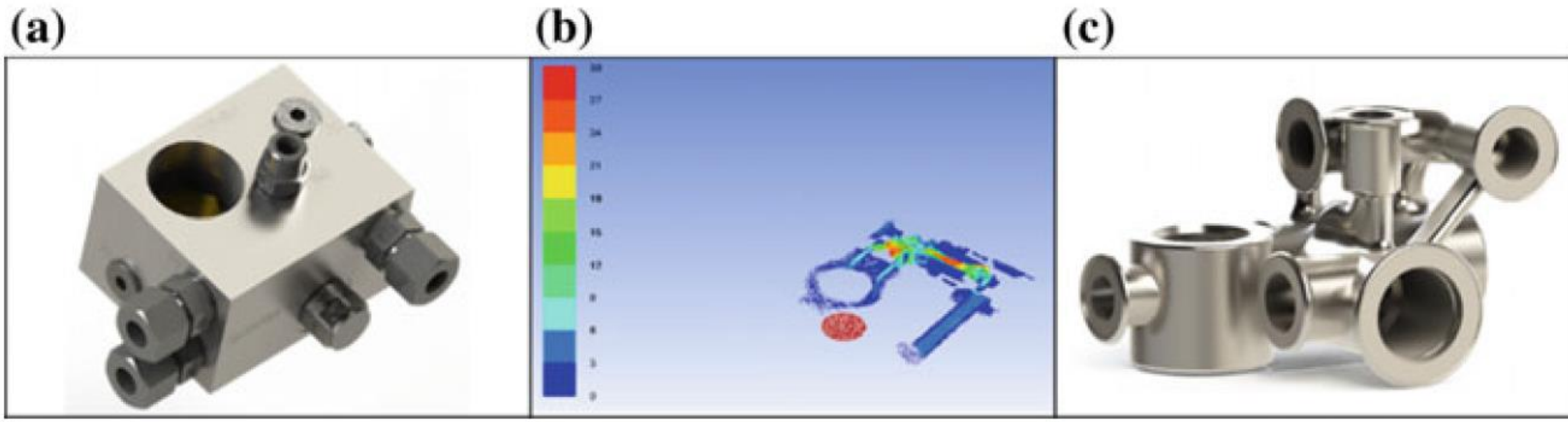
- Multi-material AM
- Layer-by-Layer manufacturing
- Shape complexity
- Hybrid AM
- Smart material Printing

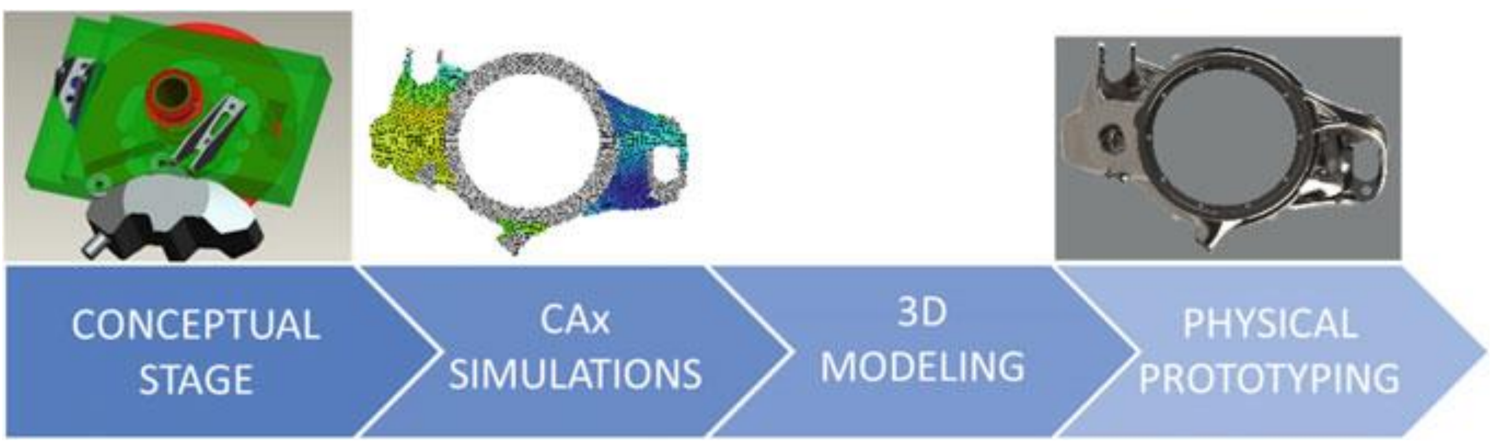
Function- Form

- Function drives form or Form drives function?
- In AM Function can drive form
- Topology Optimization
- Generative Design



Functional Optimization



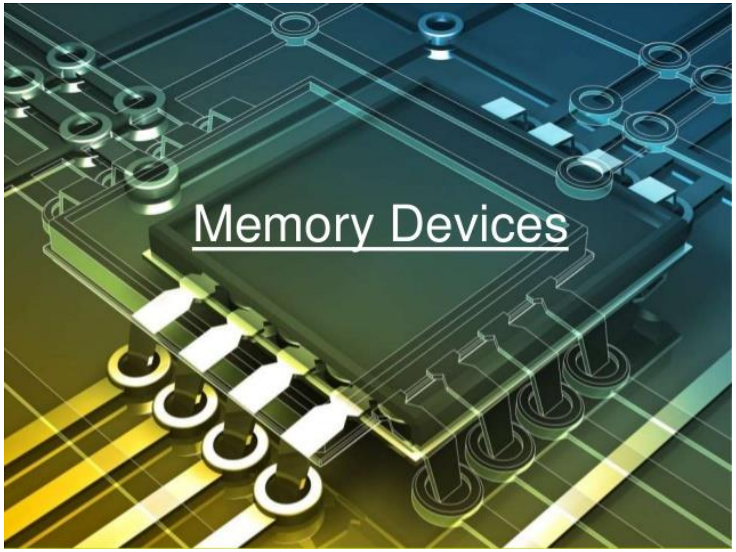


Application of Functional Integration

- Electronics
- Electro-mechanical
- Automotive
- Medical
- Mould making industry

Electronic Industry

- Communications
- Sensing
- Computation
- Memory



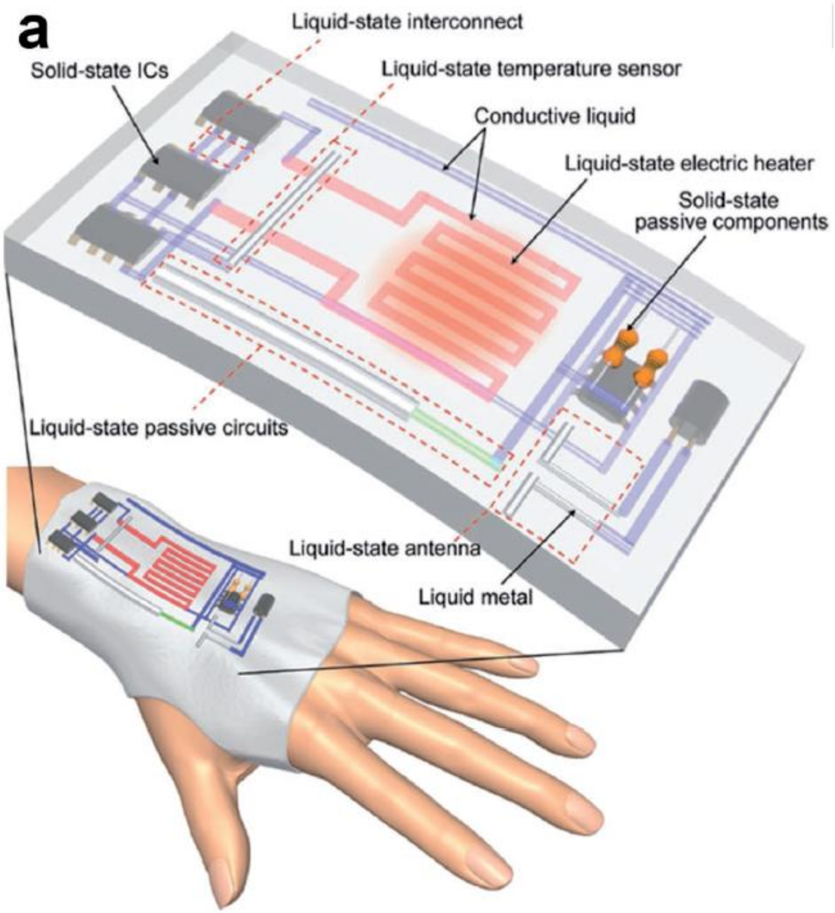
Electronic Components

- Passive circuit elements
- Conductors
- Insulators,transistors, sensors
- Microelectromechanical systems
- Flexible electronics

Flexible electronics

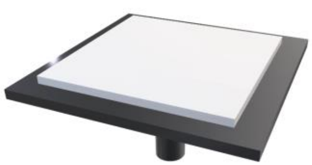
- It is a technology for assembling electronic circuits by mounting electronics device on flexible plastic substrates
- Substrates are PEEK, Polyamide
- It can be used to monitor the health information of human body due to the improved ability to interface with human skin

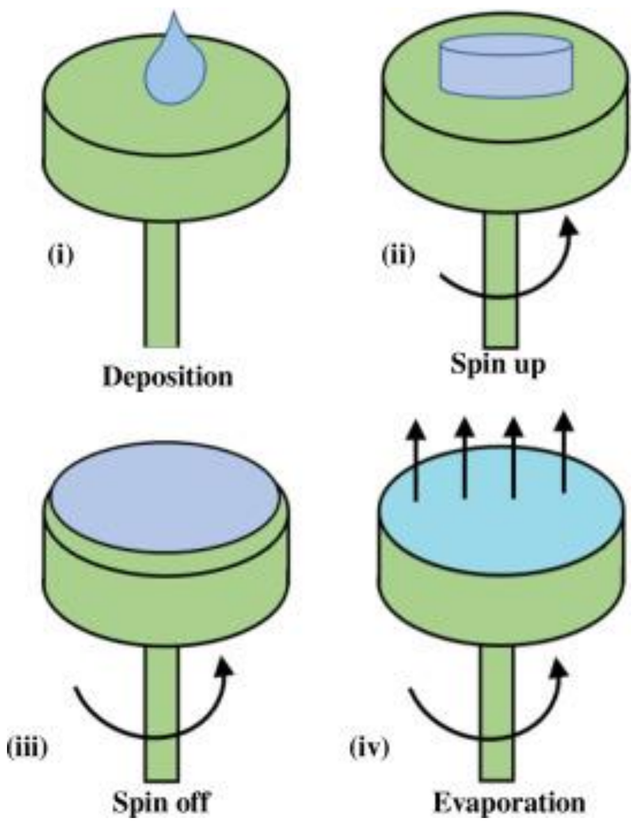
3D flexible electronics



Flexible electronics manufacturing

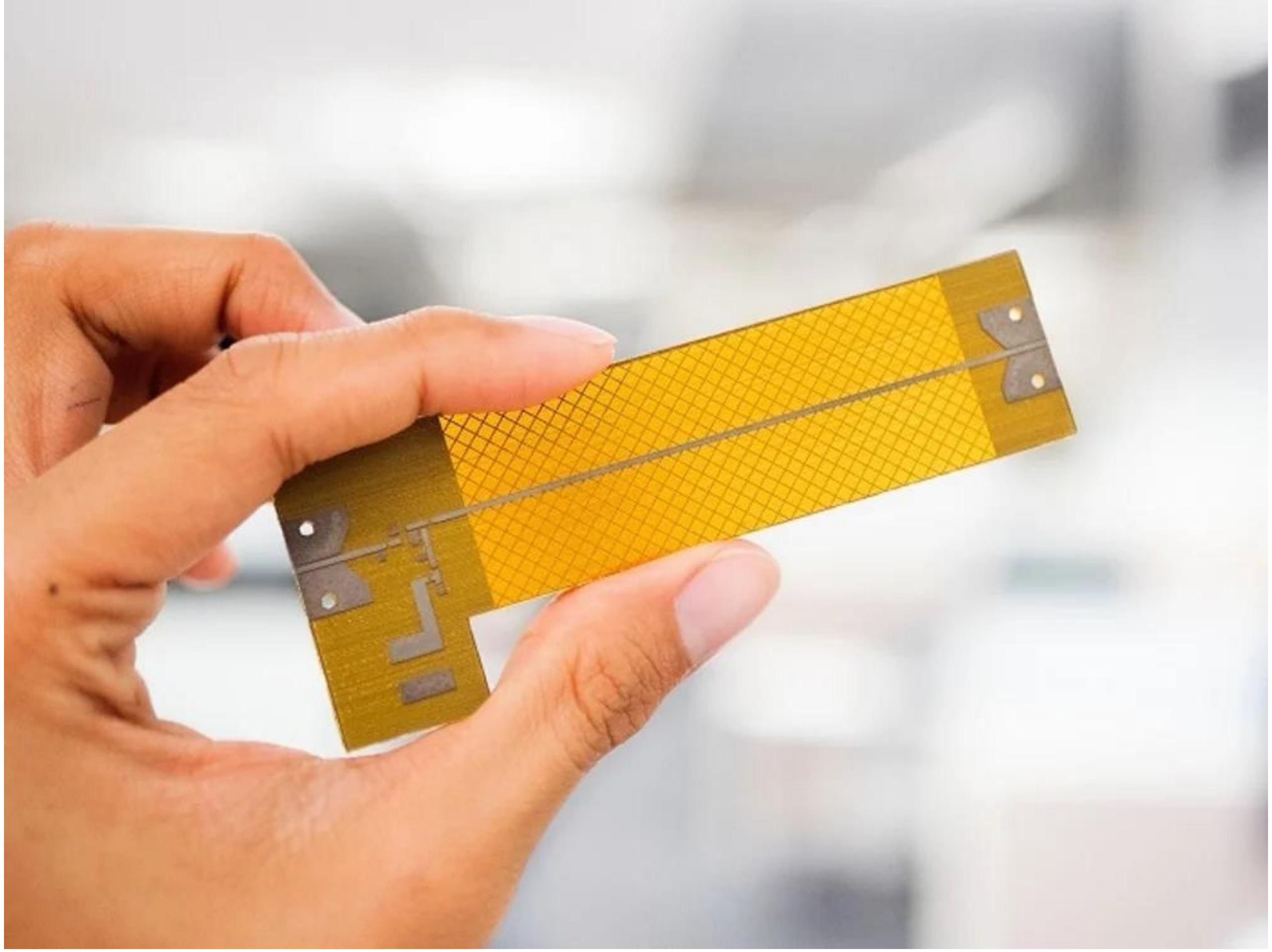
- Spin coating
- Casting
- Extrusion





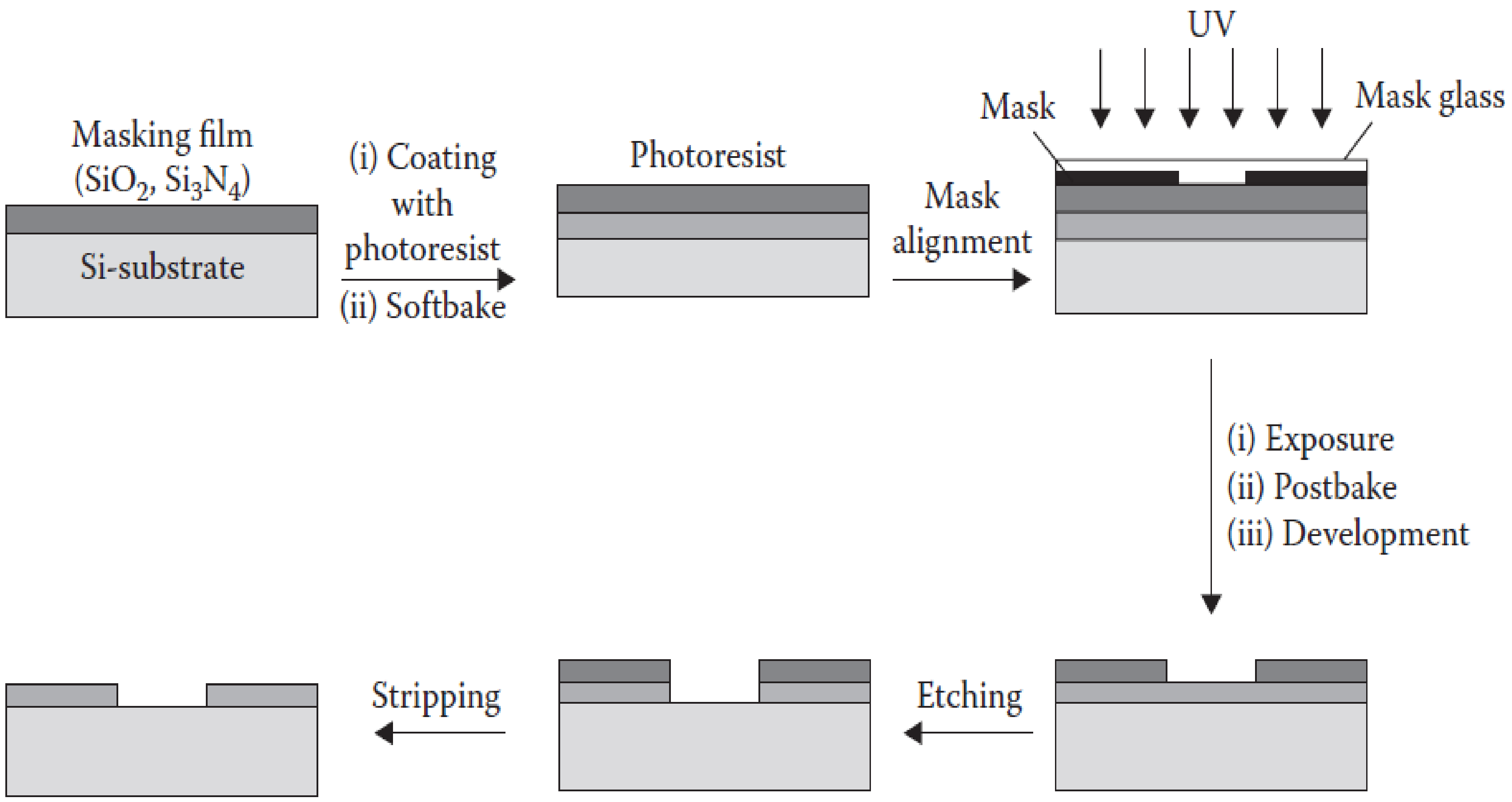
Source: ossila enabling material science

3D printed PCB's

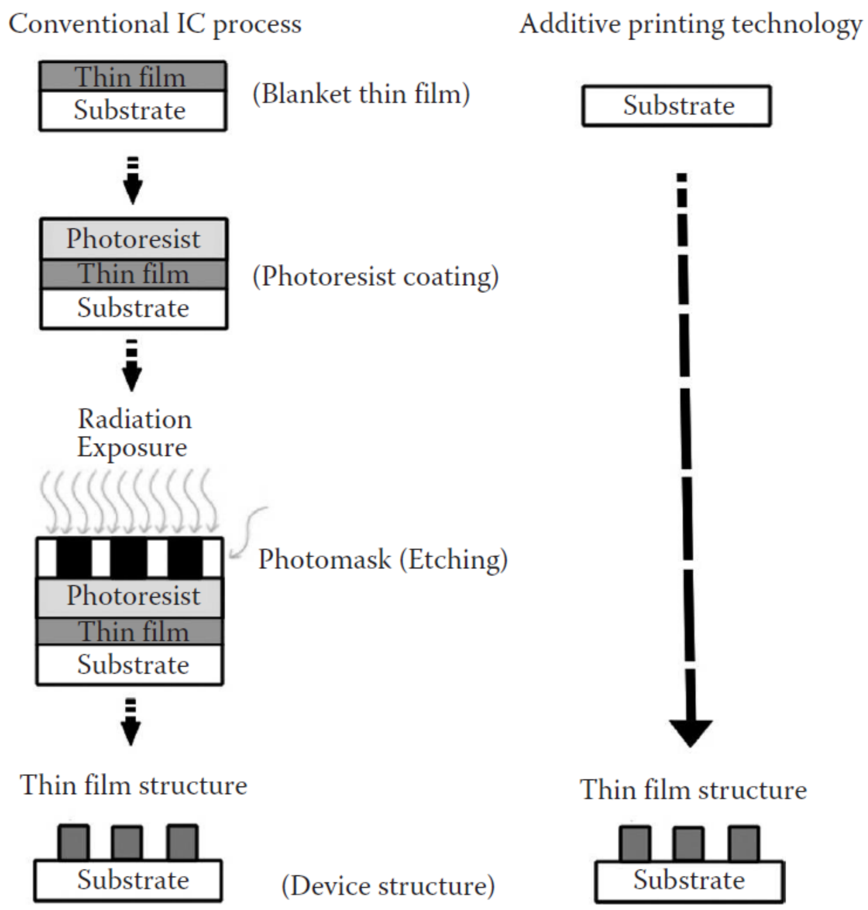


A 3D printed circuit board for an RF amplifier. Source: thefabricator.com

Conventional Manufacturing



Subtractive IC processing and additive printing



Materials in electronics 3D printing

- Carbon Materials
- Metal nanomaterials and polymers
- Metal oxides

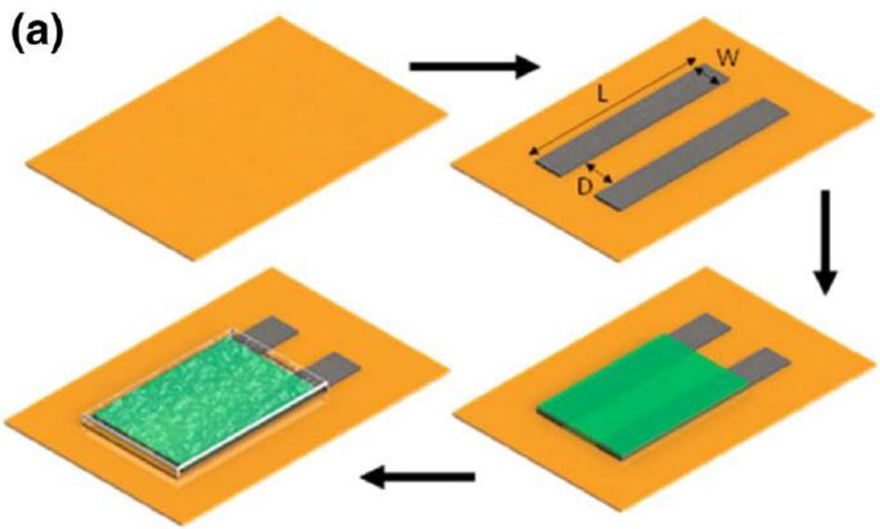
Carbon materials

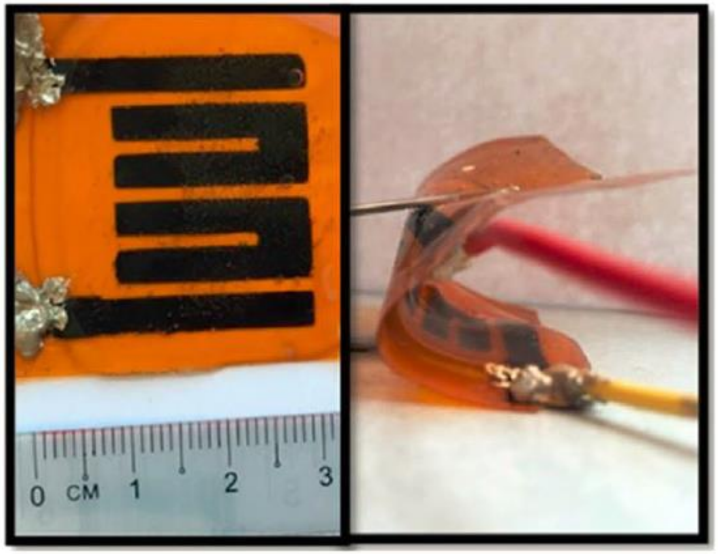
- The high-feature viscosity and shear-thinning rheological behavior are critical for the ink printability
- These materials are used in 3D printed components and functional devices for energy and environmental application

Carbon nanotubes and blacks

- Device manufactured are supercapacitors, batteries and sensors
- The superiorities of DIW combining the excellent properties of carbon nanotubes have great advantages such as low cost, rapid, mask-free, which provide helpful guidance for integration of supercapacitors and otherelectronics

Carbon nanotubes and blacks

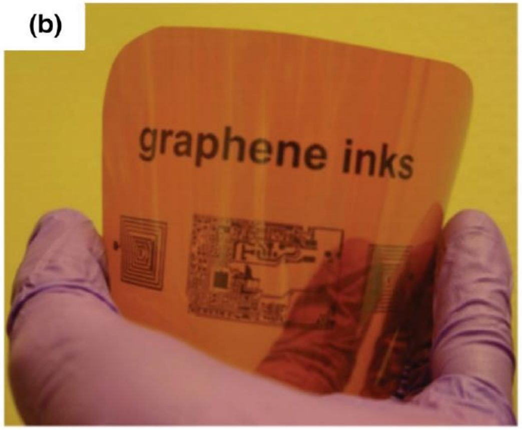




Graphene oxide

- GO exhibits good printing capabilities with unique viscoelastic properties in the aqueous solution
- The high concentration GO solution exhibits a gel-like behavior with a high modulus that can be used for ink-jet printing
- Applications are electrochemical storage, electronics, sensors

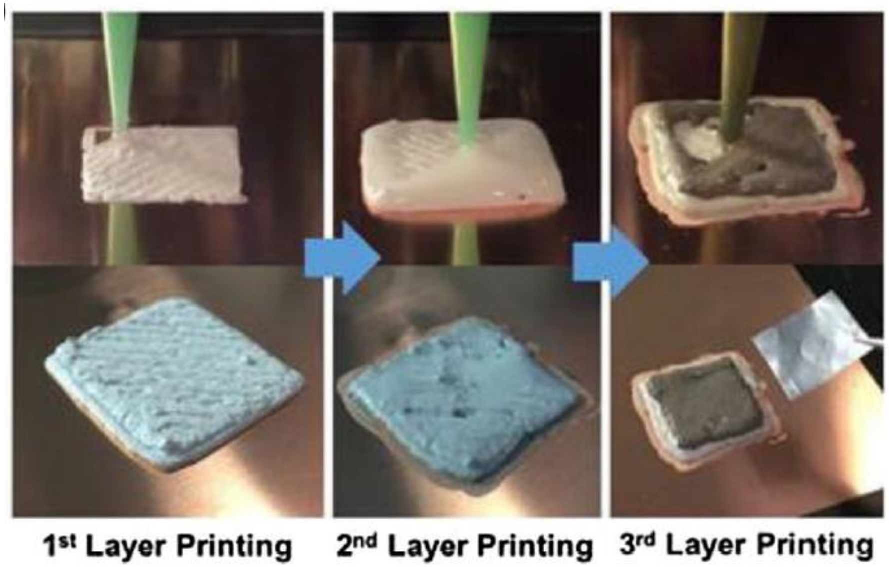
(b)

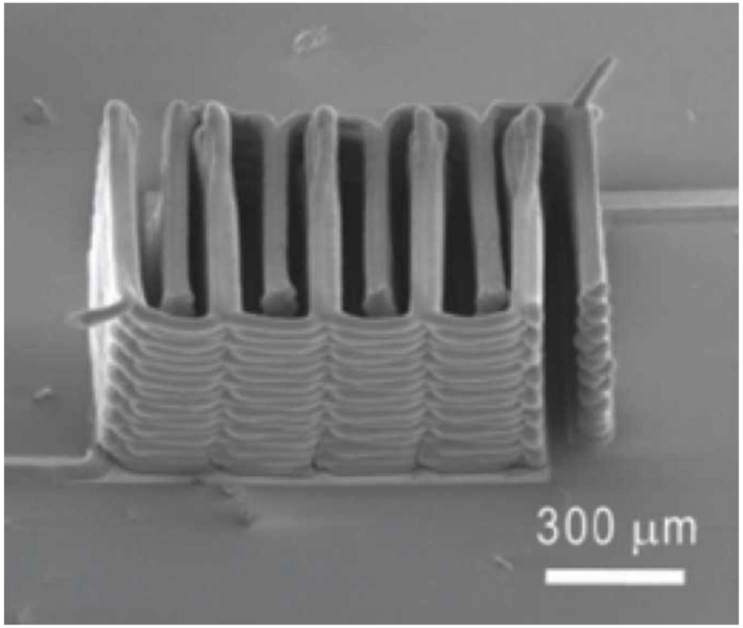


Metal nanomaterials and polymers

- Electronically conductive silver nanowires (AgNWs) has the excellent fillers for the application of conductive nano composition
- Conductive nano particles are mixed with the inks whose having good rheological properties
- Sodium carboxymethyl cellulose (CMC) is commonly introduced as an additive material
- Poly vinylidene fluoride (PVDF)

For Battery printing

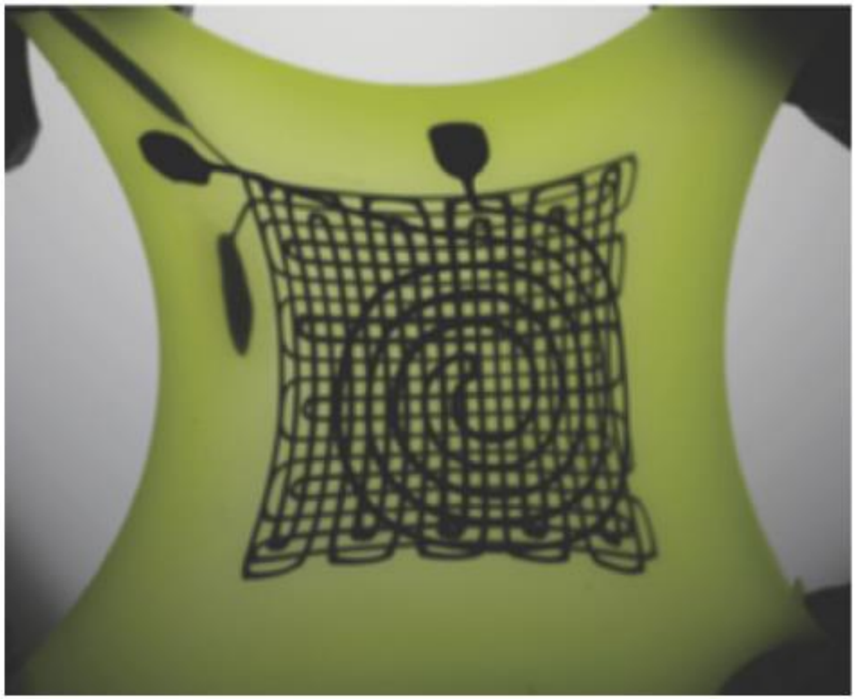




a three-layered battery was fabricated by DIW, in which, the first layer is anode (CMC + Li4Ti5O12 + AgNW), second layer is separator layer (PEO + LiClO4 + TiO2) and the third layer is cathode layer (CMC + LiFePO4 + AgNW). The voltage measurement of 3D printed battery is shown in Fig. 5h. The battery has an open circuit voltage of 0.32 V and full cell potential is about 1.8 V
Carboxy Methyl Cellulose-CMC

Sensors

A



B

A stretchable touch sensor B capacitive touch sensor

Example Parts

a pneumatically controlled prosthetic hand fabricated in titanium by using a powder bed fusion 3D printing technology known as electron beam melting (4). [Photo courtesy of
Oak Ridge National Laboratory

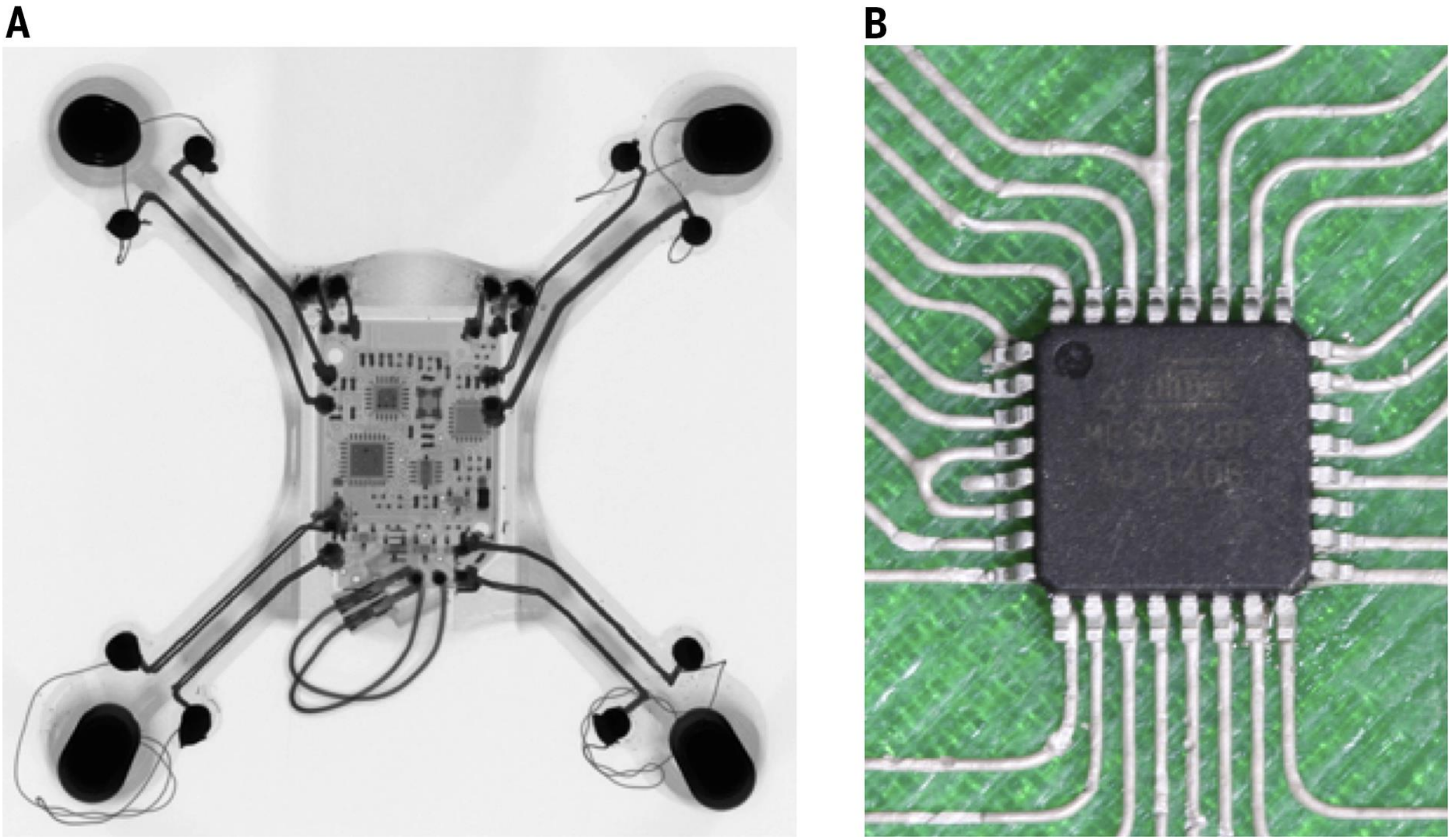
Example Parts

A

B

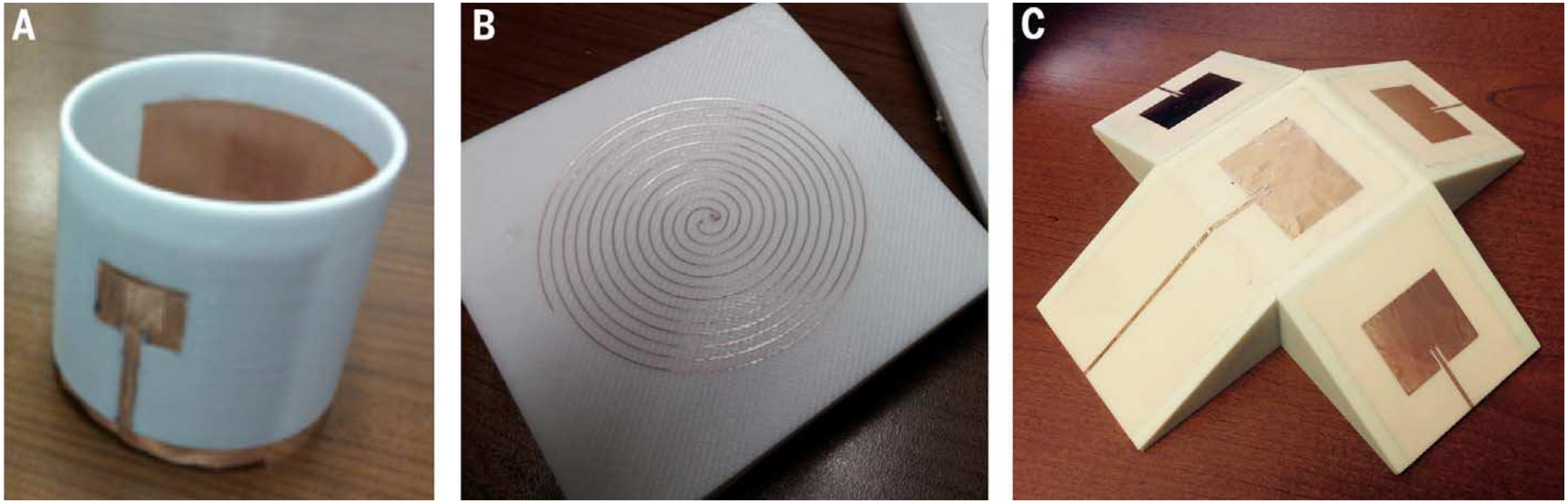
(A) A gaming die with an embedded processor and accelerometer. [From (7)] (B) A 3D periodic spiral antenna. [Image courtesy of Draper Labs]

Example Parts



Examples of printed structures from Voxel8. (A) X-ray micrograph of a quad copter drone. (B) Printed electrical interconnection. [Photos courtesy of Voxel8]

Example Parts



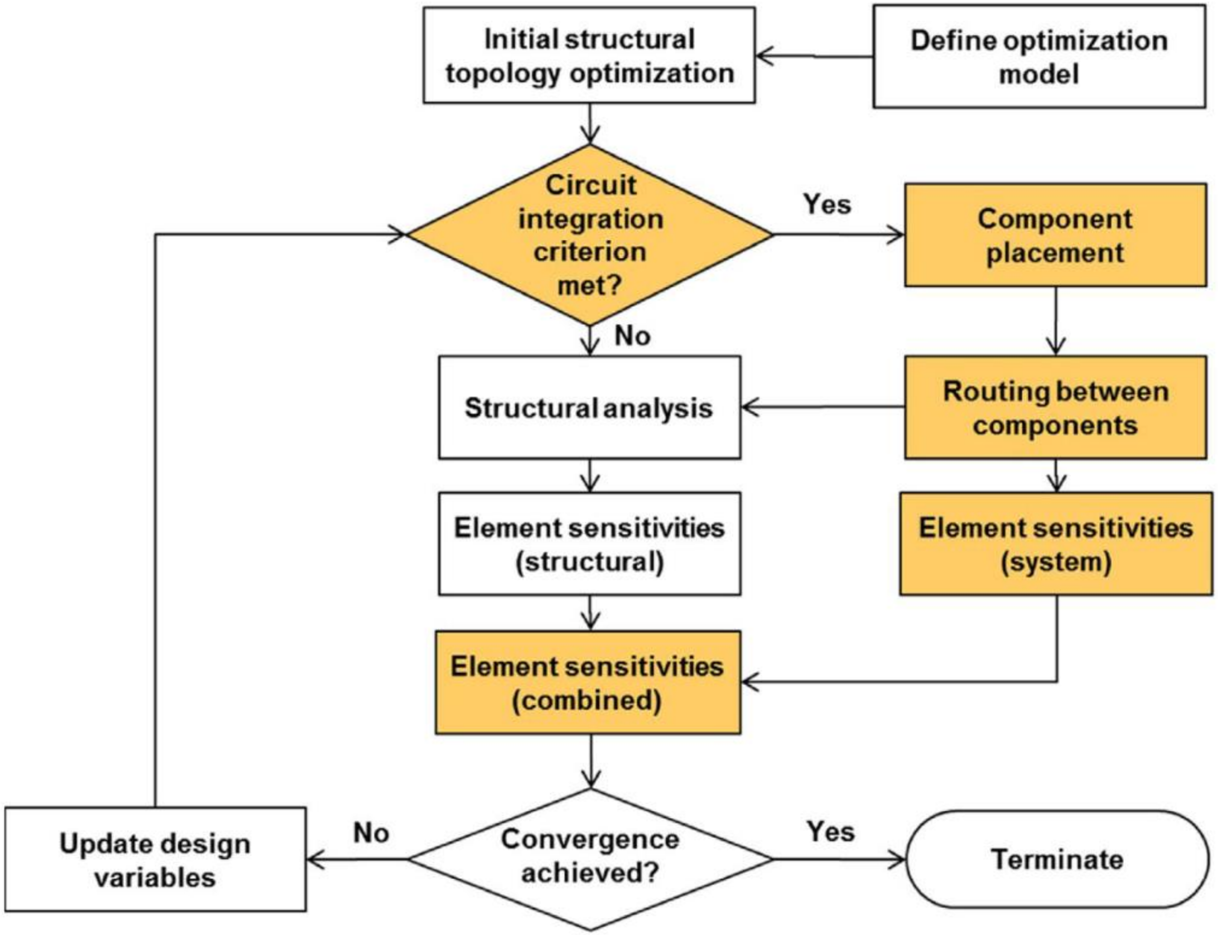
3D-printed antenna structures. (A) A cylindrical patch antenna, (B) an Archimedes antenna, (C) and a multiplane patch antenna

Future of 3D printing electronics

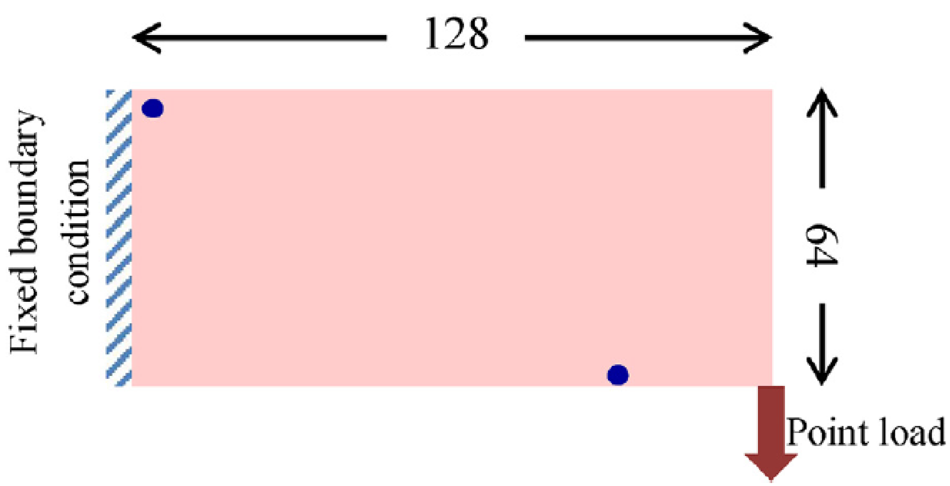
Harris to Test 3-D Printed RF Systems in Space

International Space Station, Credit: NASA/Roscosmos

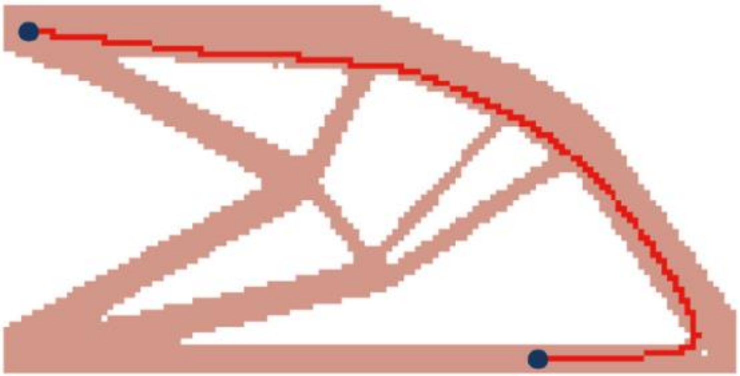
Functional Integration along with optimization



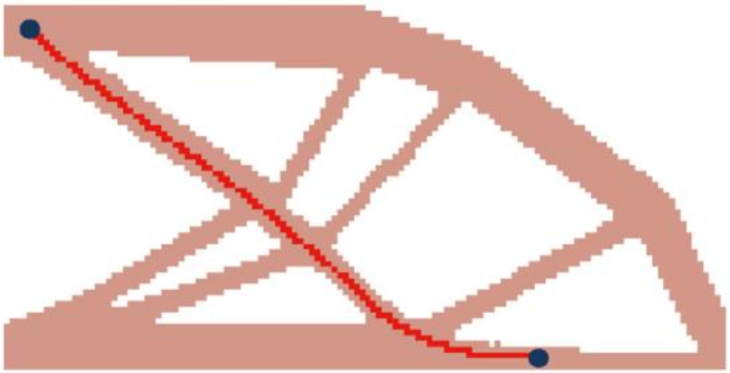
Comparison of results



a)

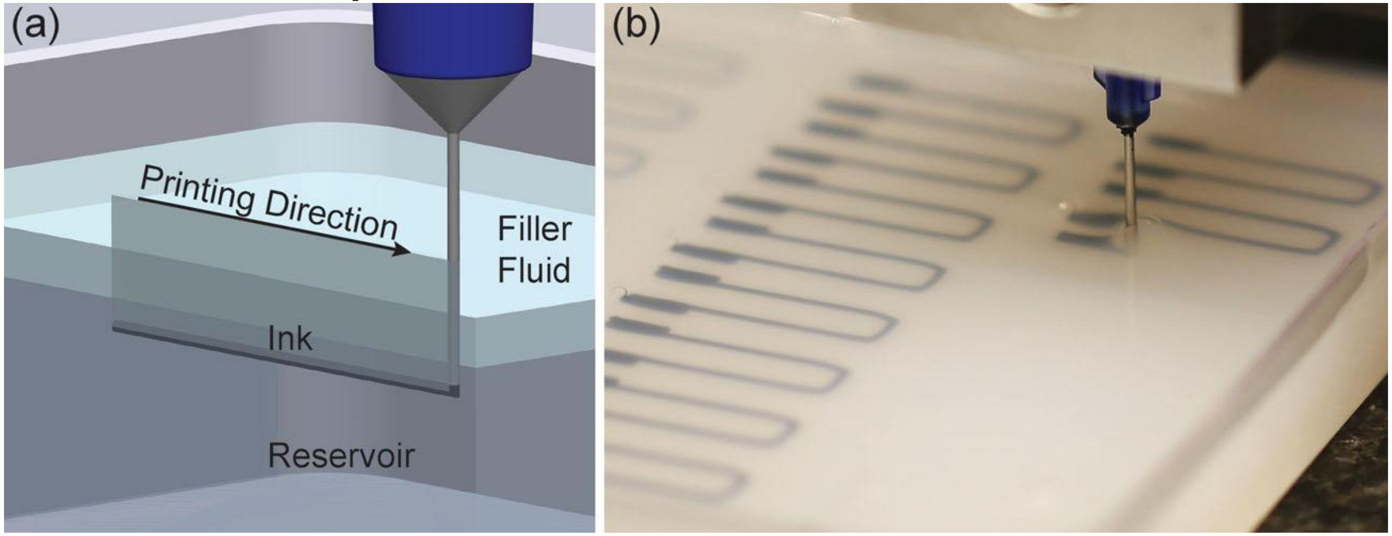


b)



Direct Writing

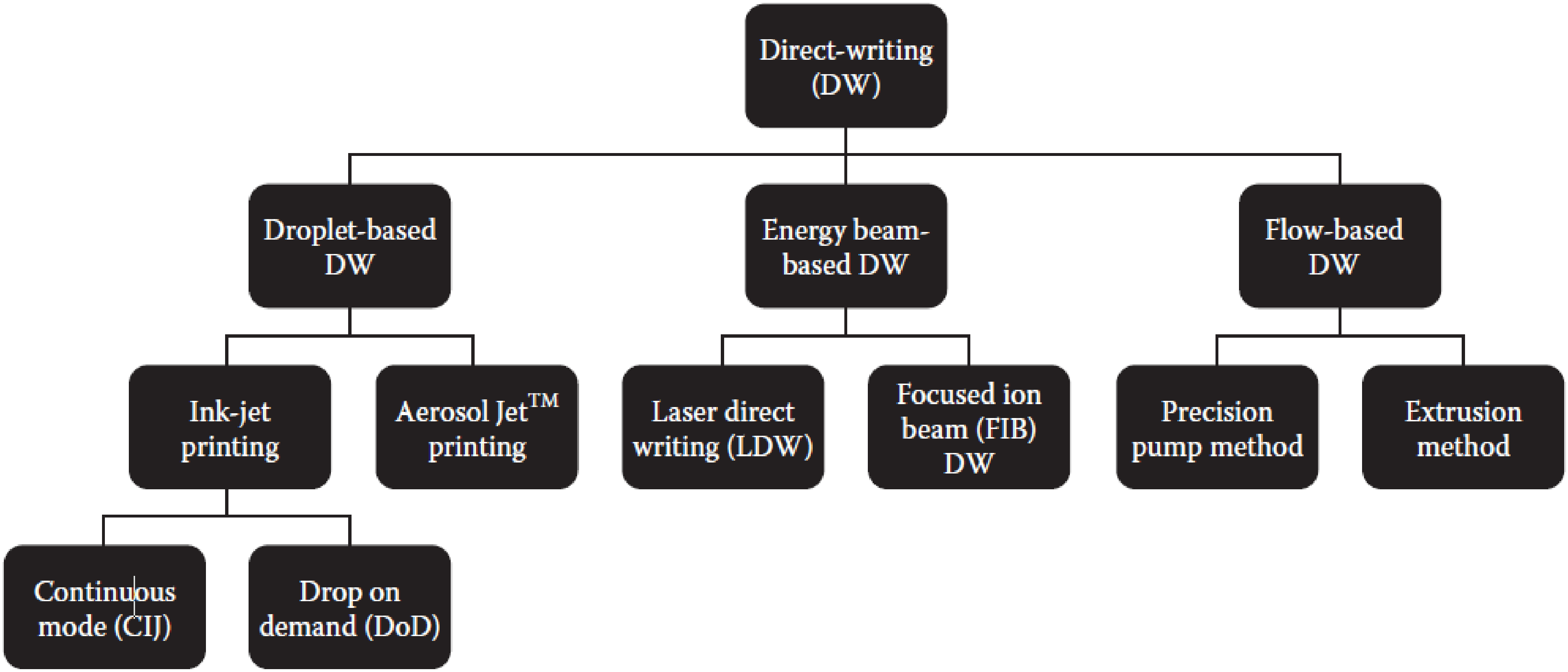
- Technology helps to create two- or three-dimensional functional structures directly onto flat or conformal surfaces in complex shapes, without any tooling or masks
- Also known as Robocasting
- Extrusion based process



Direct Writing

- The resolution of the features printed by DW ranges from ~250 to 0.1 μm
- DW uses varies classes of materials including metals, ceramics, polymers, and biological materials such as cells. These materials can be used as powders, slurries, or suspensions depending on the technique employed for printing.

Classification of DW



Droplet based DW

- Two techniques (1) Ink-jet printing (2) Aerosol Jetting
- In ink-jet printing four stages
- Ink-jet systems usually work best with low viscosity materials (up to 100 mPa-s) that have low interfacial tension (~20 dynes/cm)

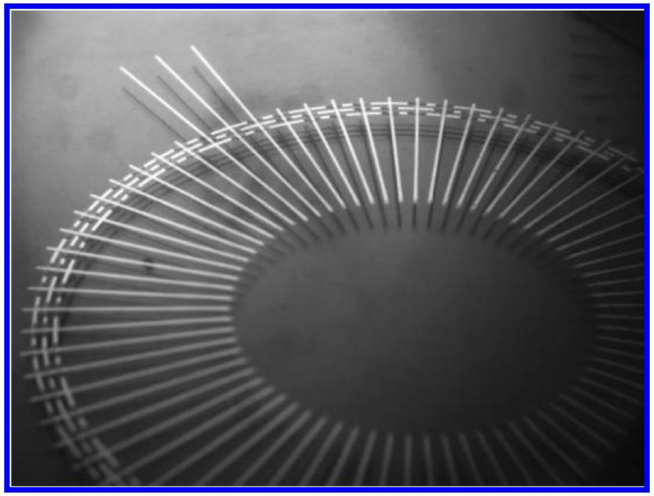
Materials Compatible with Inkjet

- Metal particles (gold/silver/copper/aluminium)
- Ceramic particle suspension
- Electronic/optical materials such as epoxies, solders and organometallics
- It's a non contact printing method so compatible with all substrates

Single nozzle is typically on the order of 0.3 mm3/s (DoD) and 60 mm3/s (CIJ), which can be increased by using an array of nozzles.
The resolution of ink-jet-based DW is measured in terms of the droplet size that can range from ~20 μm to 1 mm for CIJ printing and ~15 to 200 μm for DoD printing.

Application

- Printed electronics
- Solar cells, transistors, OLEDs,RFIDs,MEMS



Optical micrograph of an ink-jet printed electrostatic rotary motor

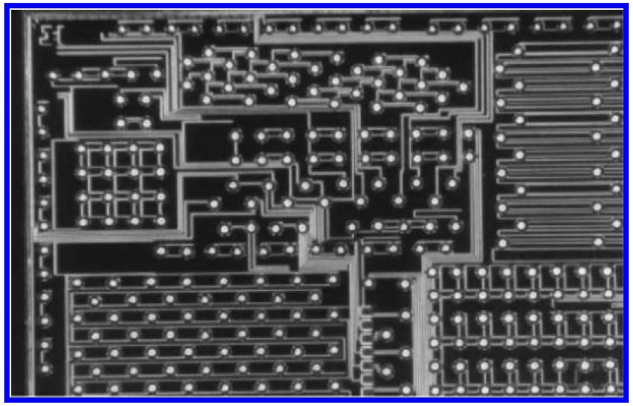
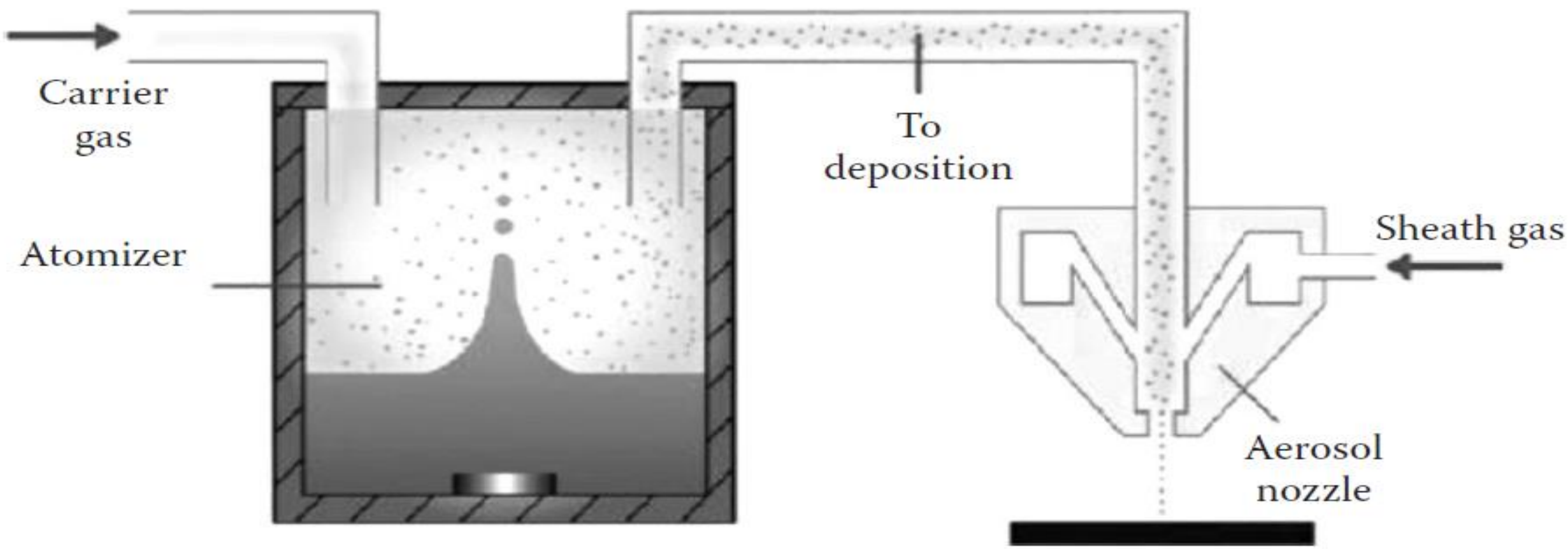


Image showing solder bumps (70 µm diameter) deposited by DoD ink-jet printing onto an IC test substrate.

Aerosol Jetting

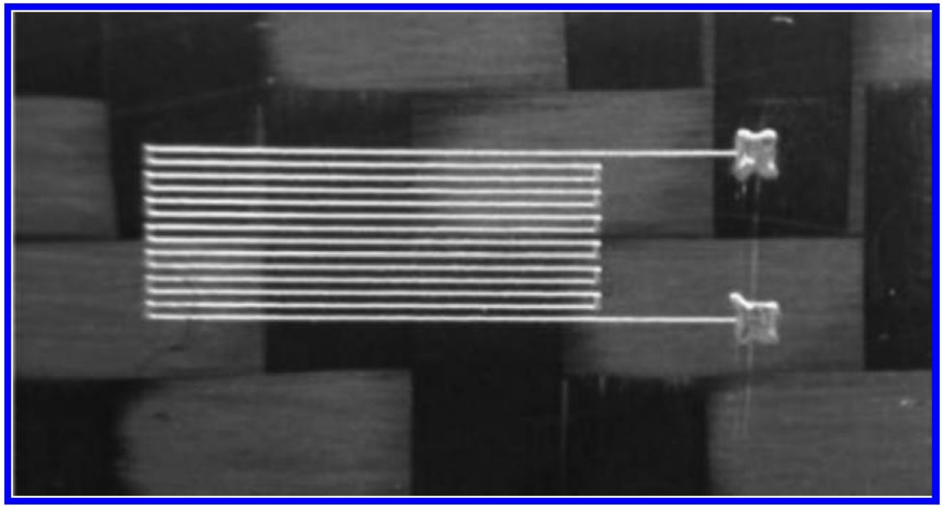


it is possible to obtain fine feature definition as the aerosol consists of a high density of micro-droplets that are aerodynamically focused to produce lines as narrow as ~10 μm.

Materials, Speed and Resolution

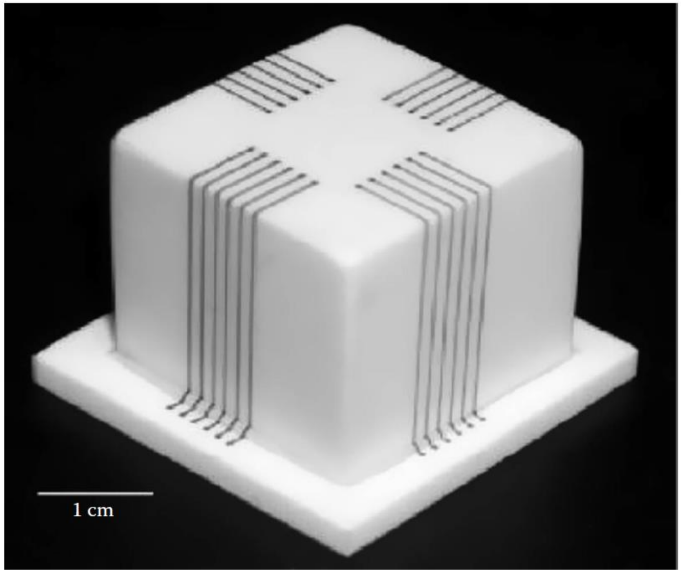
- Metals, polymers, adhesives, organic electronics
- Deposition rate 0.25 mm^3/s
- Resolution is measured in terms of width range and thickness range

Application



aerosol jet printed silver strain gauge on carbon fibre composite.

3D silver interconnects (150 µm line width) written over an alumina cube



Challenges

- Ink which forms aerosols only suitable
- Substrate with high coefficient of thermal expansion
- Surface roughness issues

For substrates with high coefficient of thermal expansion, thermal mismatch between the ink and substrate material can lead to cracking or delamination of the printed metallic circuit material, although this is a challenge of all multifunctional printing processes. Rough and porous surfaces can severely affect the behavior of the deposited ink as such surfaces have relatively high surface energy, which makes it difficult to form a clean and uniform deposit. This effect is aggravated when the surface roughness is much larger than the ink thickness as it affects the quality of the printed lines. This issue can be avoided by pre-machining the rough areas where the Electrical circuit is to be printed, although that adds extra processing steps.

Energy Beam-Based DW

- Uses high power laser/ion/electron beam as a mode of deposition
- Laser DW
- Focused ion beam DW
- Not used in electronic 3D printing

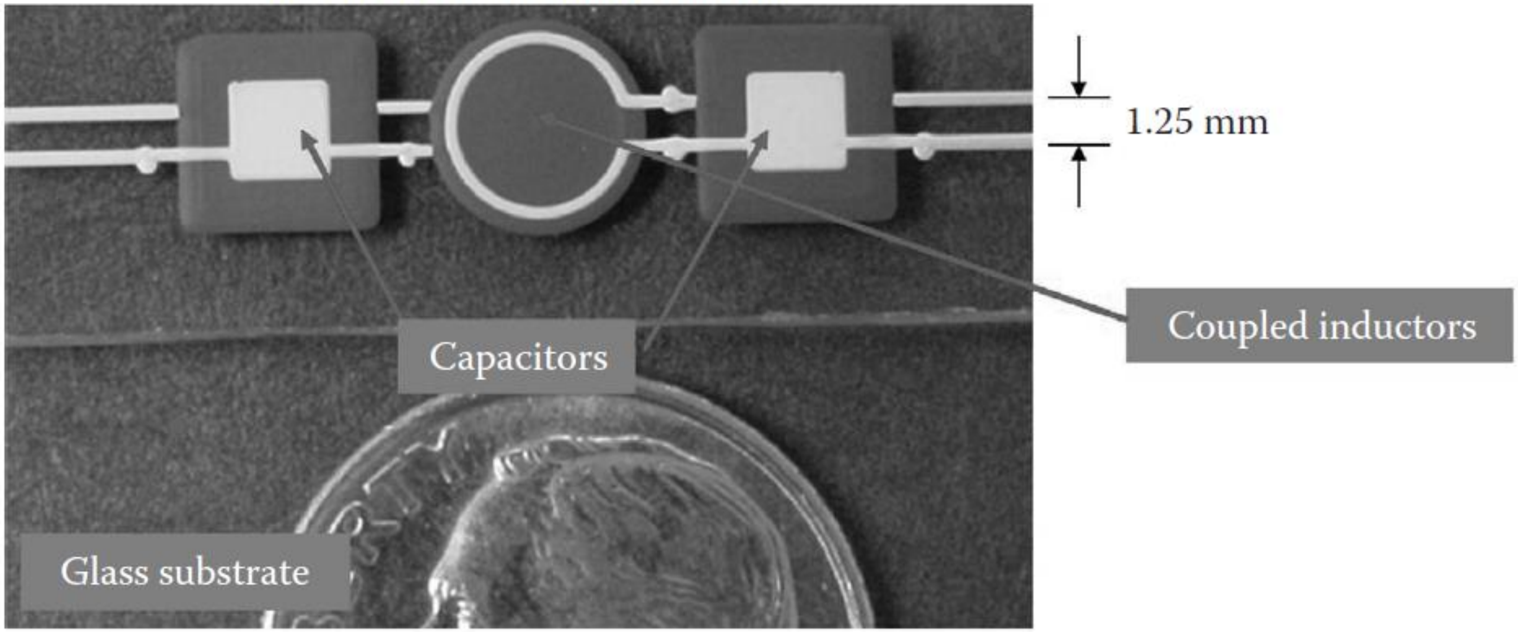
These sources precisely heat local regions of the substrate to high temperatures for sintering and curing while taking care to avoid melting of the substrate. The feature sizes are of the order of 25 μm due to the small spot size and high energy made possible by commercial laser systems. There are many different varieties of these techniques, but almost none of them have been used for electronics in 3D objects. These methods have not been used for integrating electronics due to large processing temperatures involved which can easily affect any surrounding electronic circuitry

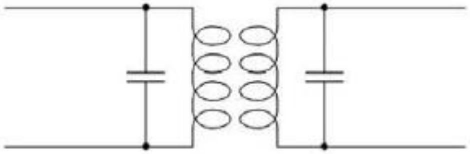
Flow based DW

- These uses syringe tip to deposit material in the substrate
- Two process (1) precision pump method, and (2) extrusion method.

Application

400 MHz tuned RF transformer





Equivalent circuit

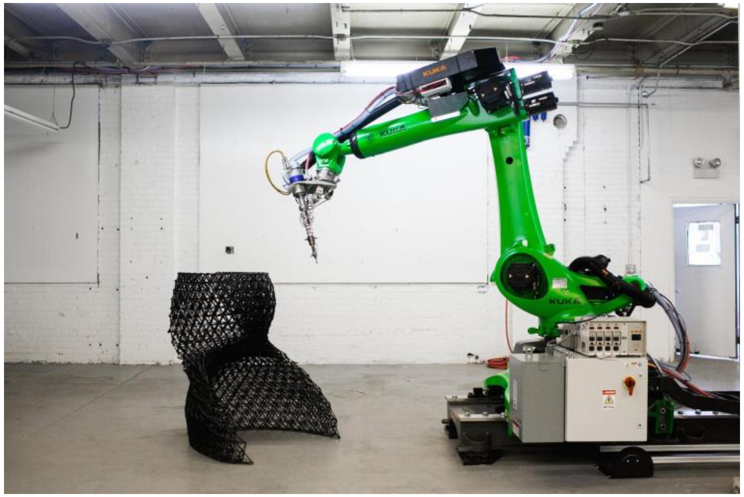
Capacitors and coupled inductors dispensed on an uneven surface by the precision pump method to fabricate a printed RF device

Challenges

- Line width is 10 times the particle size
- Depends on the nozzle diameter
- Flow rate is depends in the dispensing height

Extrusion method

- Material will be in the form of liquid particulate slurry, or molten polymer filament.
- Depending on the material robotic deposition, FDM, micro pen writing

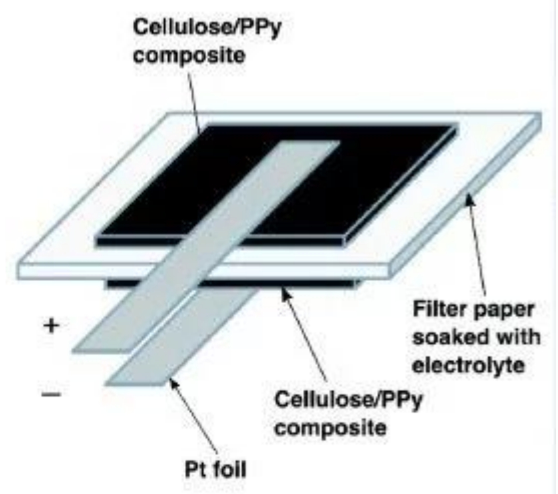


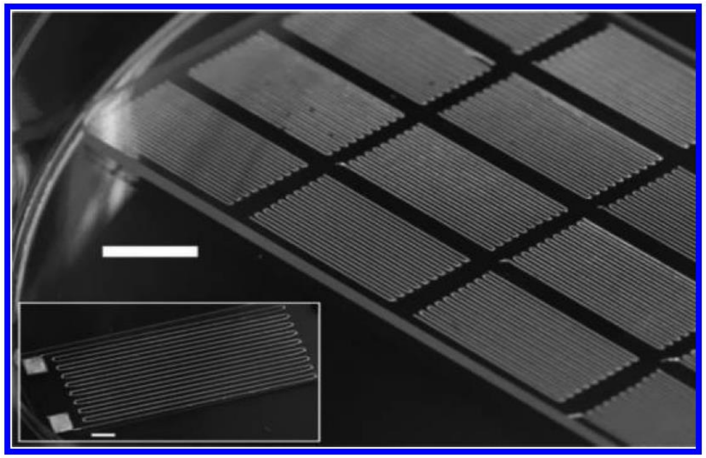
Materials, Speed, Resolution

- The extrusion systems can dispense fluidized materials with viscosities up to 5000 Pa-s
- Metals gold ,silver are commonly used
- Carbon based inks
- Speed is 300 mm/s
- resolution 50 μm to 2.5 mm

Application

RFID tags, cellulose based batteries

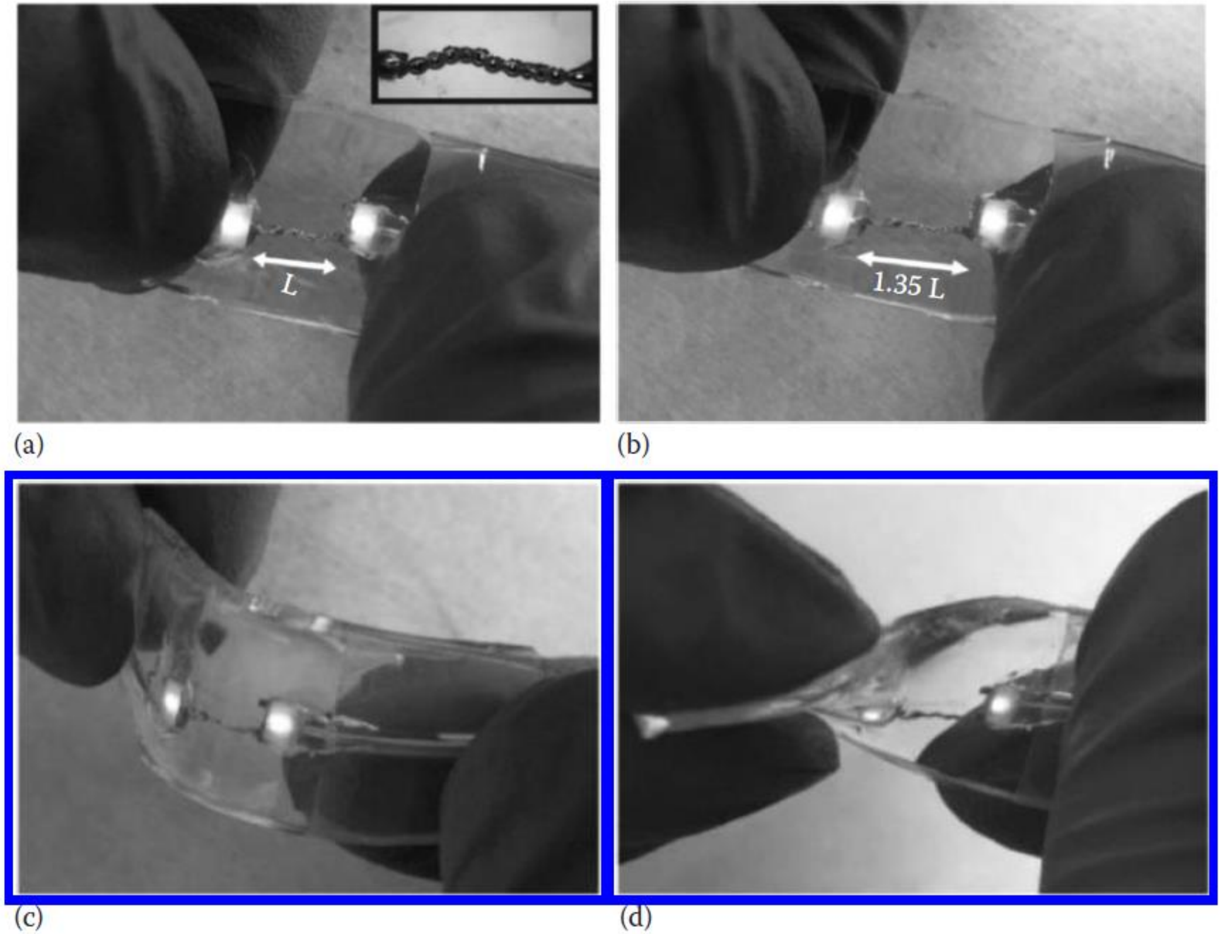




Liquid Metal Printing

- It is possible to direct write a low viscosity liquid metal (e.g., gallium and its alloys, such as eutectic gallium–indium alloy)
- Metal filament, droplets, injecting through microchannels
- Curing is because of oxidation of the outer skin

Application

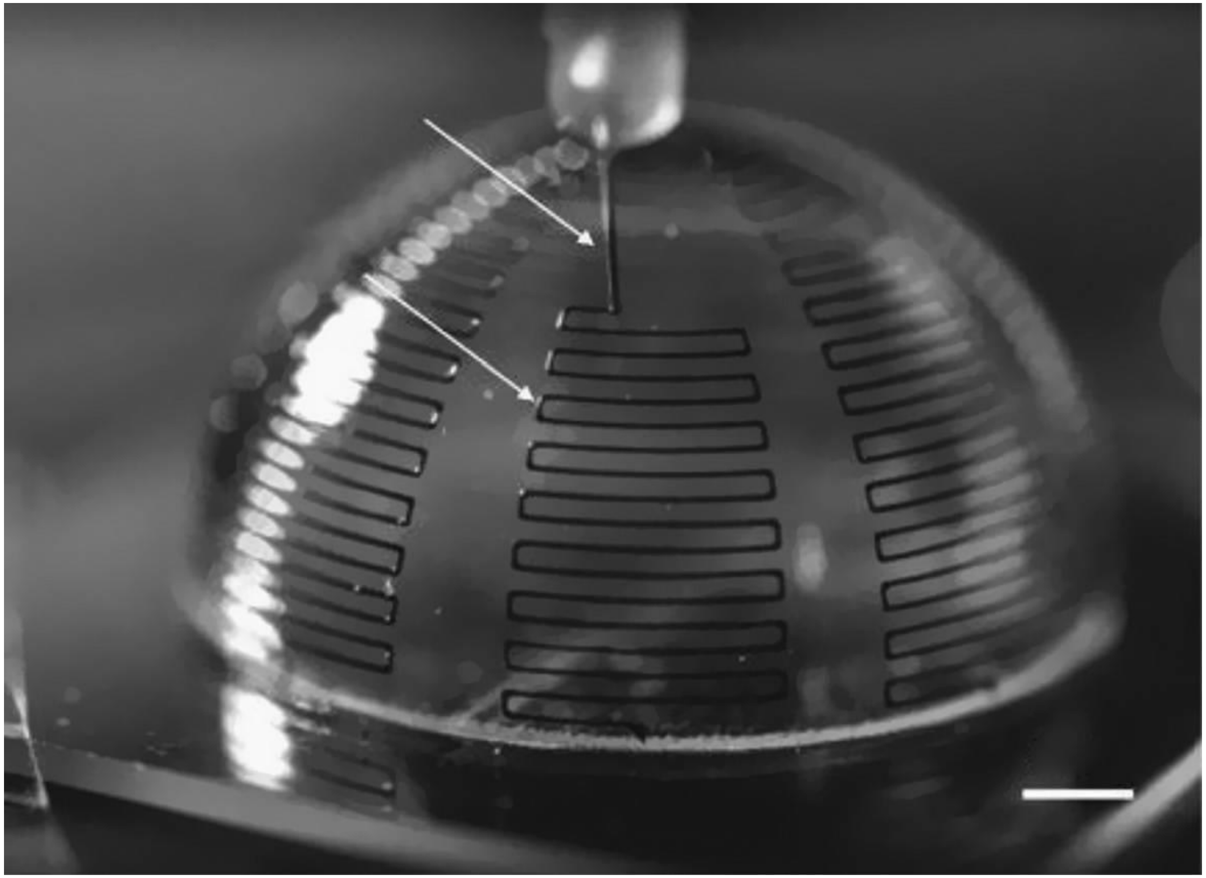


Focused Ion beam DW

- FIB DW, a low energy ion beam (10–50 keV) generated from a liquid gallium source is used
- Process is done in a vacuum environment.

The deposition rate is lower than the LDW methods but it offers higher resolution with the minimum feature that can be produced being of the order of 80 nm.

Conformal Printing



Summary

Comparison of All the Approaches Used for Integrating Electronics into 3D Parts Excluding Laser Direct-Write Techniques

Approach	Deposition Method	Mechanism for Integration	Deposition Rate/ Writing Speed	Materials and Viscosity (μ)	Resolution or Minimum Feature Size	3D Periodic Structures
Hybrid chip insertion (Category 1)	Ultrasonic Consolidation (UC)	Deposition of metallic foils using ultrasonic energy	To 50 mm/s	Metals and alloys like Ni, Fe, Cu, brass, and steel	Foil thickness ~0.1 mm	N/A
	Transfer printing	Transfer patterns from TS to DS via differential adhesion	To 10 cm/s	Metallo-organics and conductive polymers	Pattern size ~12 μm	N/A
Surface DW (Category 2)	Ink-jet printing (CIJ)	Deposition of liquid droplets by break-up of continuous jet	To 60 mm^3/s with a single nozzle	Liquid with μ ~2 to 10 mPa-s; can contain small particles	Droplet size ~20 μm to 1 mm (typically 150 μm)	No
	Ink-jet printing (DoD)	Deposition of individual liquid droplets when required	To 0.3 mm^3/s with a single nozzle	Liquid with μ ~10 to 100 mPa-s; can contain small particles	Droplet size ~15 to 200 μm	No
	Aerosol jet printing	Kinetic bombardment of atomized droplets	To 0.25 mm^3/s with a single nozzle	Materials with μ < 2.5 mPa-s that can be atomized	Line width ~10 to 150 μm, thickness ~10 nm to 5 μm	Yes
	Precision pump	Precision micro-dispensing pump with suck-back action	Typically 50 mm/s (up to 300 mm/s)	Liquid, paste and slurry materials with μ up to 1000 Pa-s	Line width ~25 μm to 3 mm	Yes
	Extrusion	Deposition of materials via syringe-based flow	Typically 25 mm/s	Liquid, paste and slurry materials with μ up to 500 Pa-s	Line width ~50 μm to 2.5 mm	Yes
Freeform multi-material 3D printing (Category 3)	Omnidirectional printing	Extrusion of concentrated inks through fine cylindrical nozzles	Typically 6 mm/s	Liquid, paste, and slurry materials with μ up to 500 Pa-s	0.1 to 250 μm	Yes
	Liquid metal printing	Deposition of microstructures via extrusion of liquid metals at room temperature	Not yet known	Gallium-based alloys with μ up to 2 mPa-s	~10 μm	Yes
	Focused ion beam (FIB) DW	Ion-induced deposition of precursor gas molecules	Typically 0.05 $\mu m^3/s$	Metals and insulators	Line width ~80 nm to 20 μm	Yes

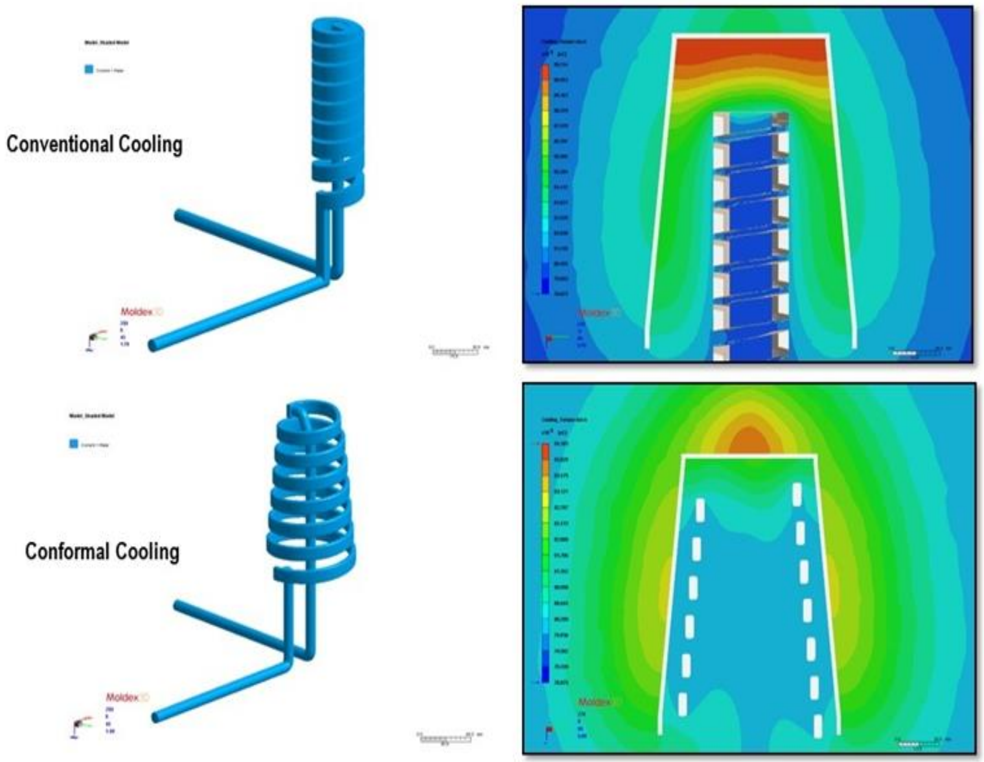
Summary Cont.

Comparison of All Laser Direct-Write Techniques

Deposition Method	Mechanism	Deposition Rate/ Writing Speed	Materials and Viscosity (μ)	Resolution or Minimum Feature Size	3D Periodic Structures
Thin film consolidation	Melting, fusion onto substrates	10 to 2000 μm/s	Metals/ceramics on metal/ ceramic substrates	10 to 50 μm	No
LIFT and MAPLE DW	Transfer of material by kinetic energy of vaporizing organic binders	Typically 3 to 50 mm/s (up to 500 mm/s)	Metals, ceramics, semiconductors, polymers, composites	10 to 100 μm	No
LEEP	Thermal decomposition of the liquid	0.1 to 80 μm/s	Metals and ceramics on inorganic substrates	2 to 12 μm	No
Laser-activated electroplating	Accelerated chemical reaction by local high temperatures	Typically 0.1 to 10 m/s (up to 2.5 m/s)	Metals on metallic substrates	0.1 to 300 μm	No
LCVD	Decomposition of gases after vaporization and condensation takes place	Typically 50 to 100 μm/s (up to 5 mm/s)	Metals, semiconductors and ceramic such as Al, W, Si, Al_2O_3, WC	1 to 20 μm	Yes
LIBT	Physical vapor/liquid deposition after laser irradiation through transparent medium	10 to 100 mm/s	Metals and ceramics on transparent substrates	5 to 200 μm	No
LGDW	Laser-assisted deposition of generated aerosol using optical forces	To 1 m/s	Non-absorbent droplets and solid particulates with $\mu < 2.5$ mPa-s	2 μm	No
FGDW	Gas flow-assisted deposition of generated aerosol using hydrodynamic forces	To 0.25 mm³/s	Atomizable fluids and colloids with $\mu < 2.5$ mPa-s	25 μm	No
TPP	Photopolymerization of UV-curable resin at laser focus within matrix	To 100 μm/s	Photo-sensitive acrylate polymers	≤100 nm	Yes
SLS	Locally sinters and binds the powder bed	To 35 mm/h	Polymers, metals, alloy mixtures and composites in powder form	100 μm	No

Conformal cooling channels

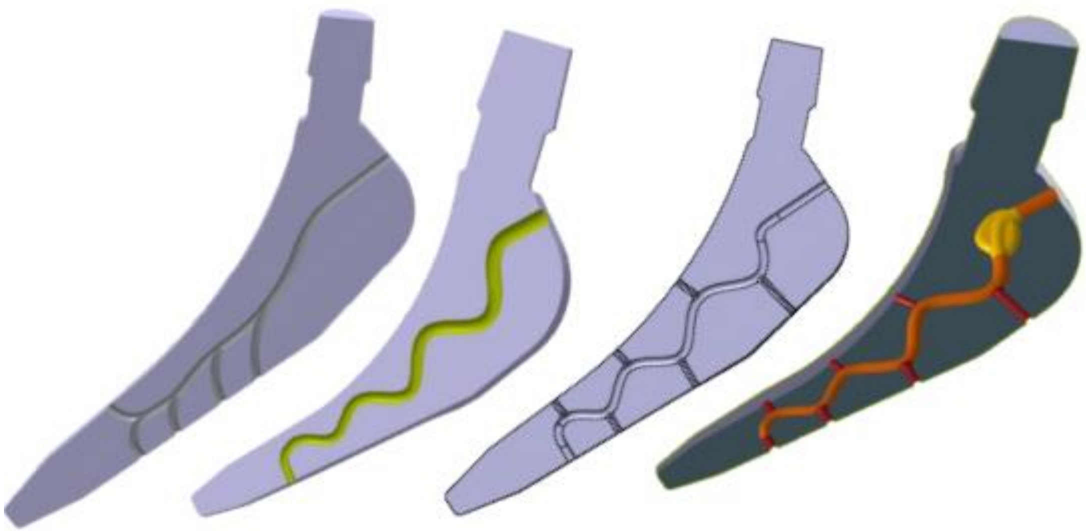
- Conformal cooling is an analysis to establish the most effective uniform cooling of the injection molded parts.
- Conformal cooling offers much greater flexibility in the design of cooling for the mold.

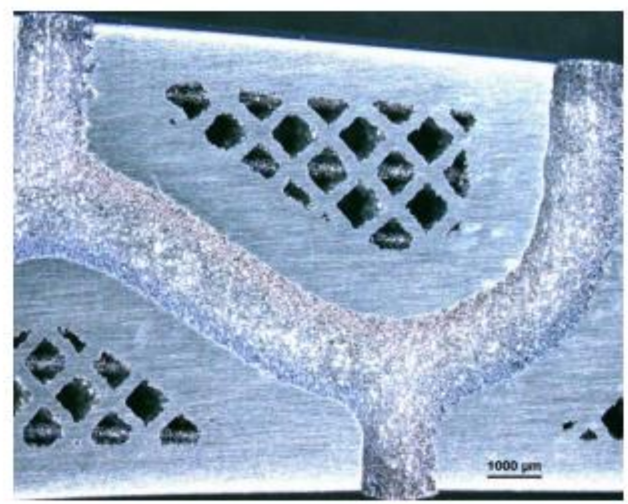


https://www.moldex3d.com/en/blog/top-story/conformal-cooling-vs-standard-cooling/

Biomedical Application

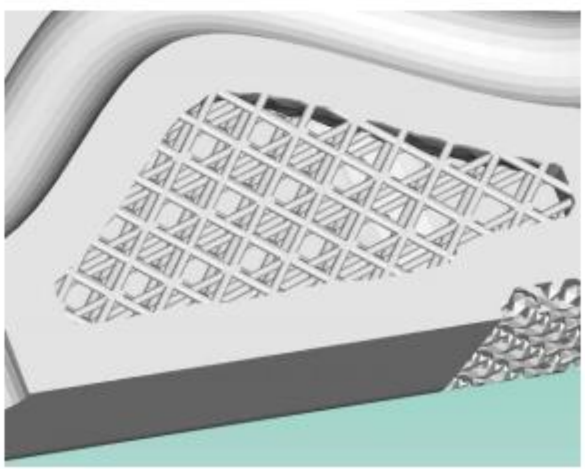
- Inner functional channels and cavities
- virtually unlimited freedom of design in shaping the channels and cavities, depending on desired function
- High material and structural quality assure strength and stiffness of implant despite weakened cross section

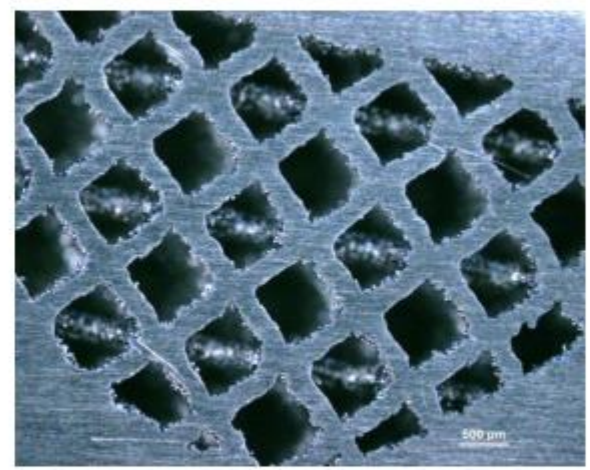




Inner lattice structure

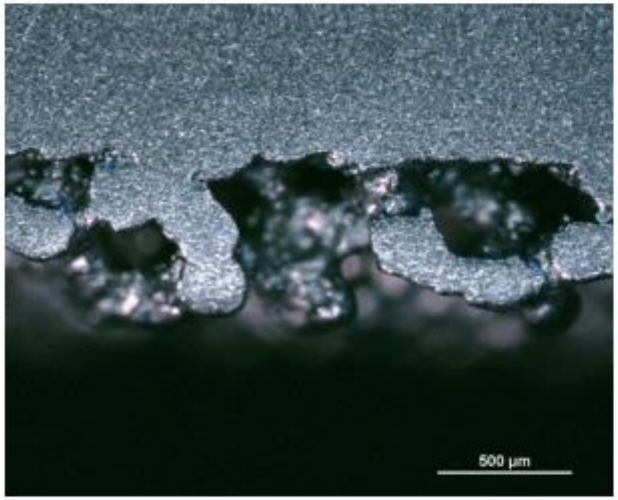
- Creation of periodic lattice structures in different shape and size
- Stiffness adaption to the bone
- Reduction of dead weight





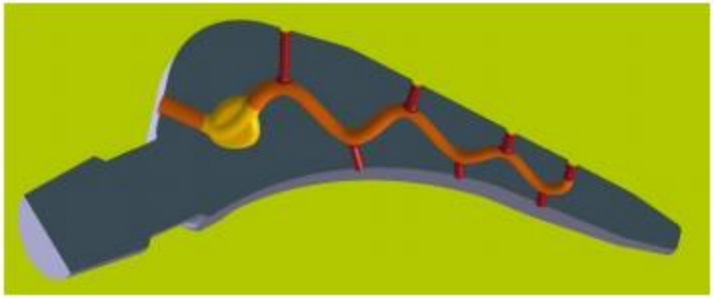
Macro-porous surface structure

- Design of any desired surface structure
- Creation of structures partially or on whole part
- Depth/thickness of structure can be defined as desired
- Better ingrowth

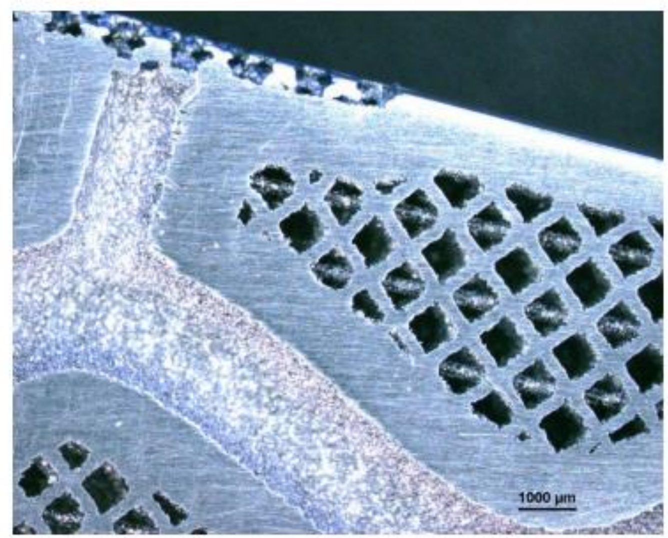
Drug depot inside the implant

- Supply & distribution of bio-resorbable filler or bone cement
- Post-surgery medical treatment of patient:
  - improving wound healing
  - promoting ingrowth
  - pain relief
  - preventing infections



Other potential functions

- Post-surgery drainage of blood and wound ooze through the implant‘s body
- Support of revision surgery by feeding a medium for local dissolution of implant-bone joining for easier and faster explanation with less damage in sound bone structure



innovate achieve lead

BITS Pilani
Pilani Campus

End of Session - 8