36th Symposium on “Printed Electronics – Prospects of Additive Manufacturing in Pakistan ”

The Pakistan Academy of Engineering.

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PRINTED ELECTRONICS LAB, FME, GIKI

Self-Introduction

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Address:

G-01, Faculty of Mechanical Engineering (Since 2012)

Ghulam Ishaq Khan Institute of Engineering Sciences and Technology

Work Experience:

- Professor - Faculty of Mechanical Engineering at Ghulam Ishaq Khan Institute of Engineering Sciences and Technology.
- Senior Scientist - Ubiquitous Sensing (USE) Lab, Klagenfurt University and Silicon Austria Labs, Austria (from July 2023 till January 2024)

- 7 years of industrial experience

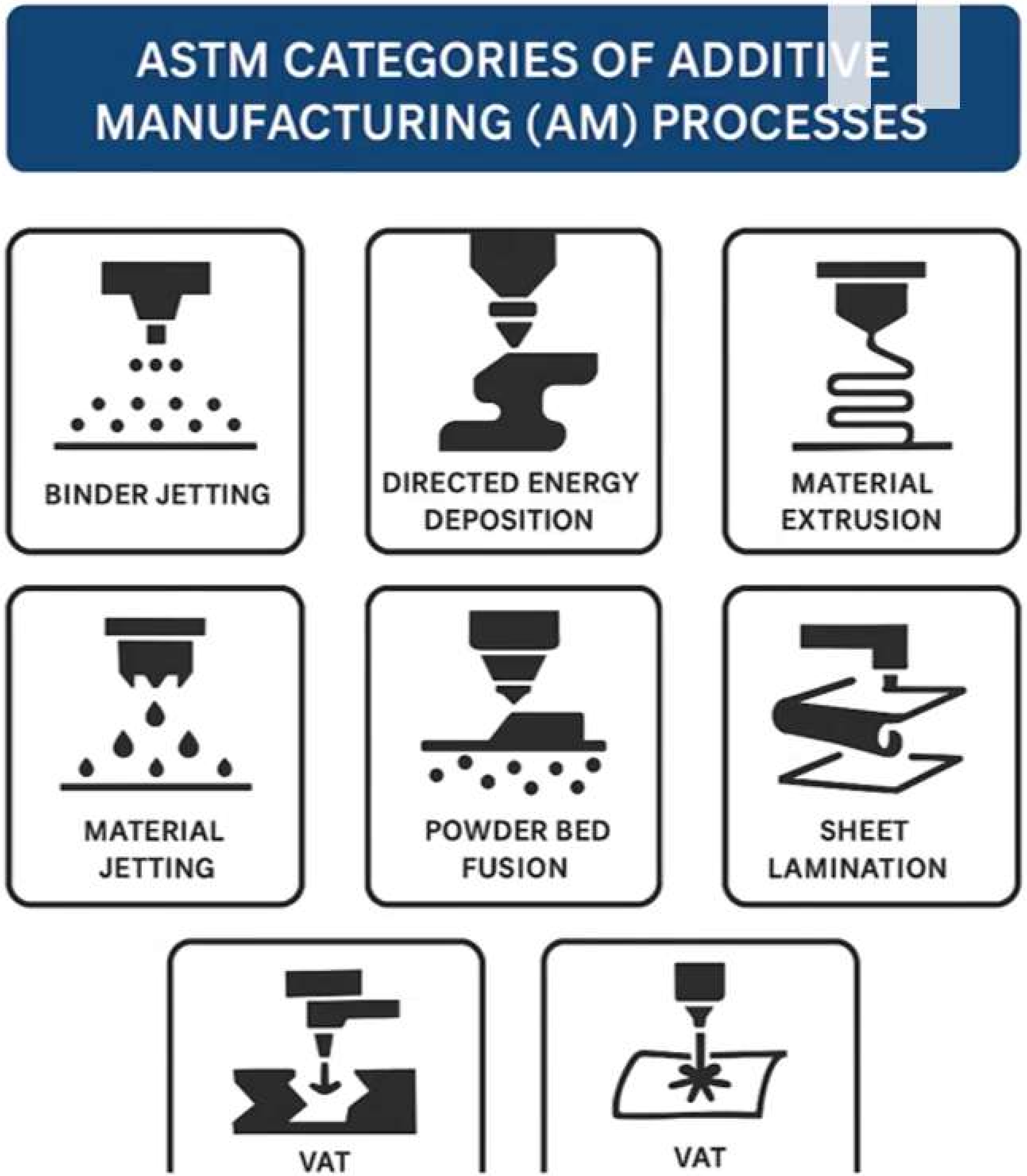
Research Interests:

- Electrohydrodynamic Inkjet Printing, Direct Write Technology, Printed Electronics, ANSYS (linear and nonlinear Structural Analysis)

Additive Manufacturing

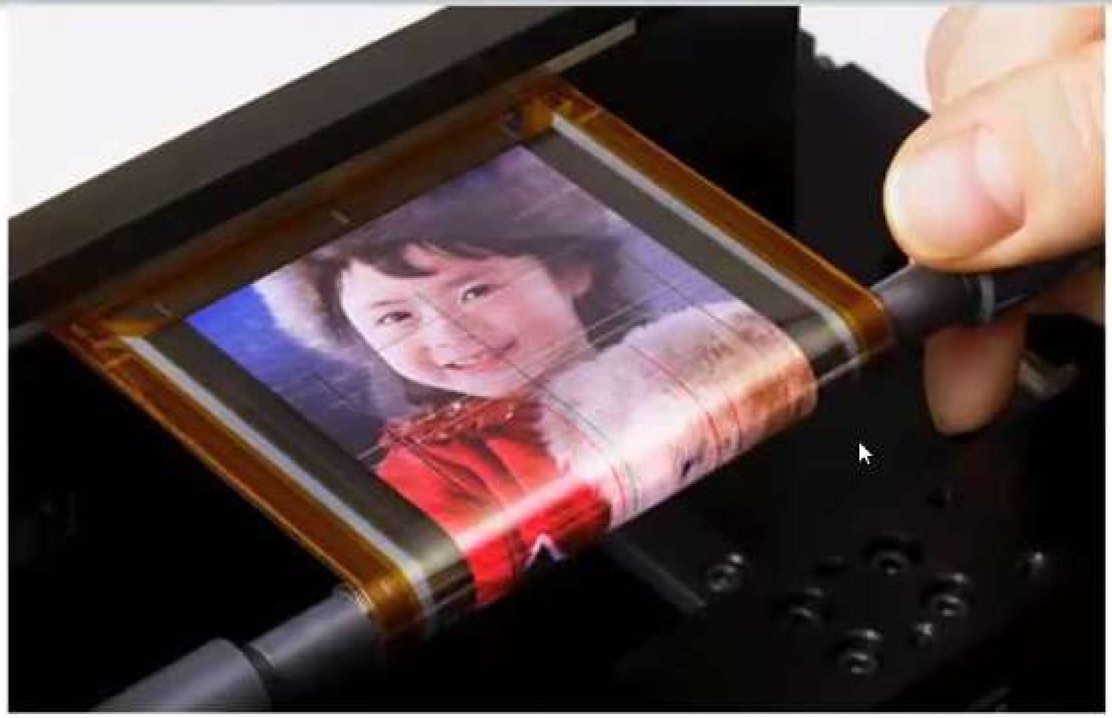
"Additive Manufacturing is the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"

ASTM F2792

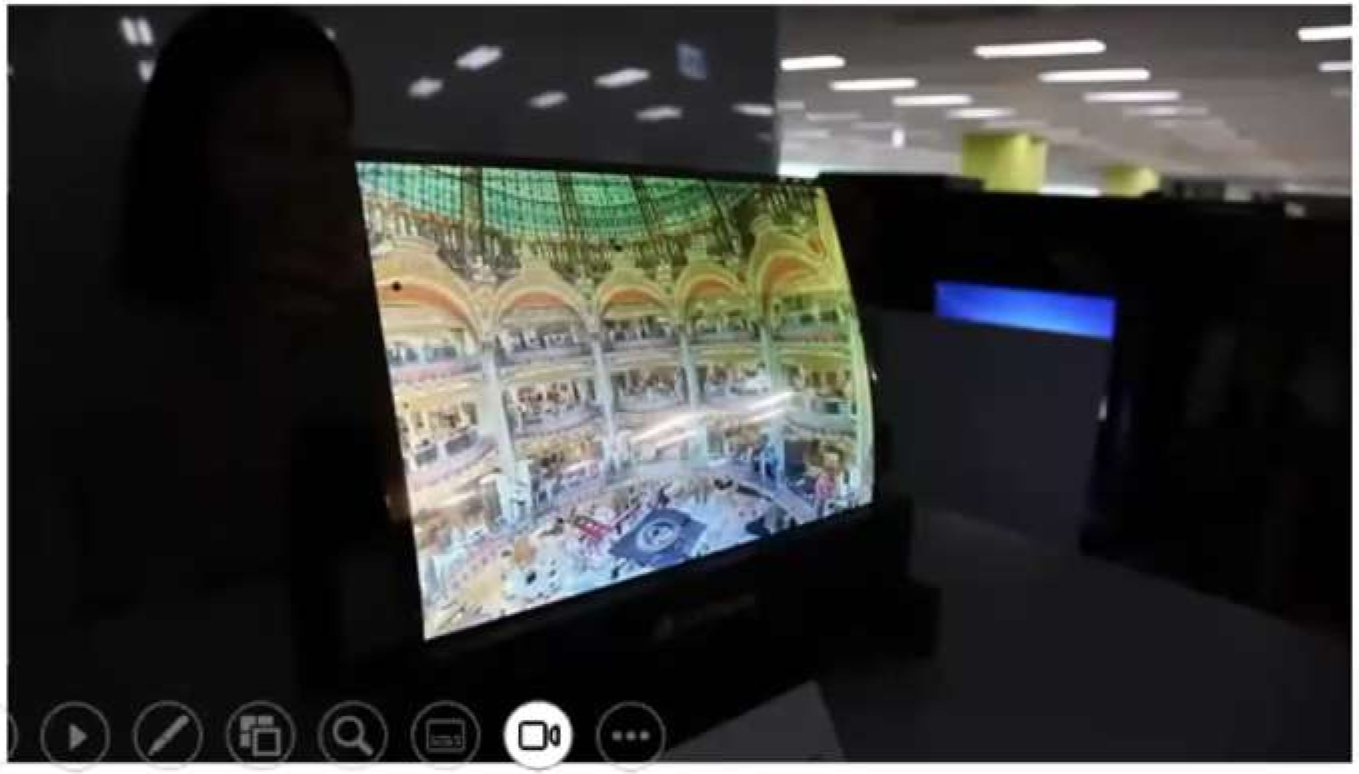


Future Electronics

Minority Report 2002



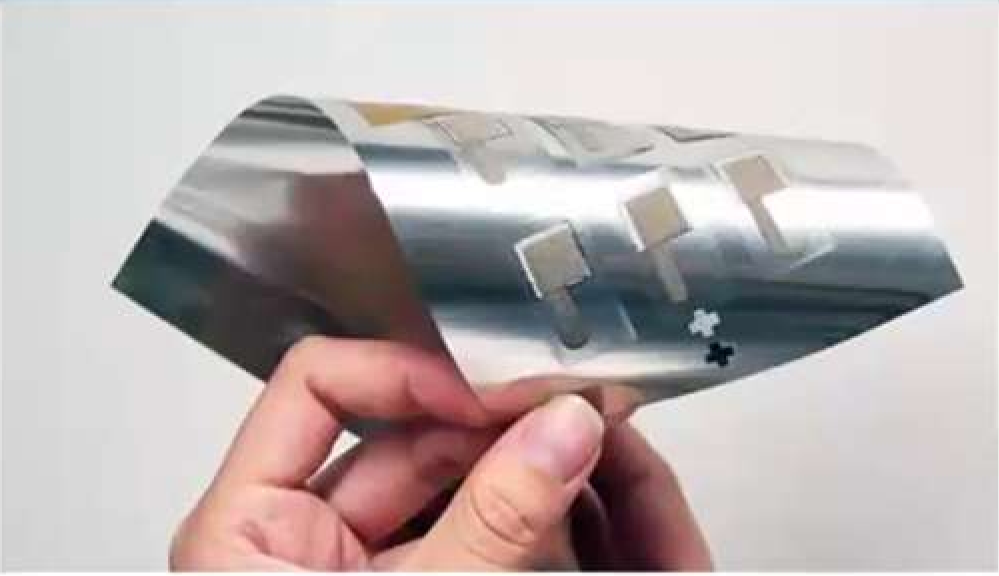
Sony 2007

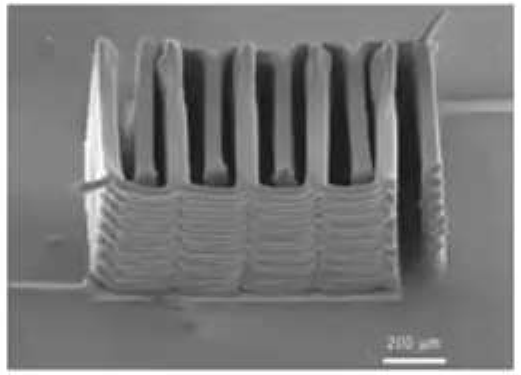


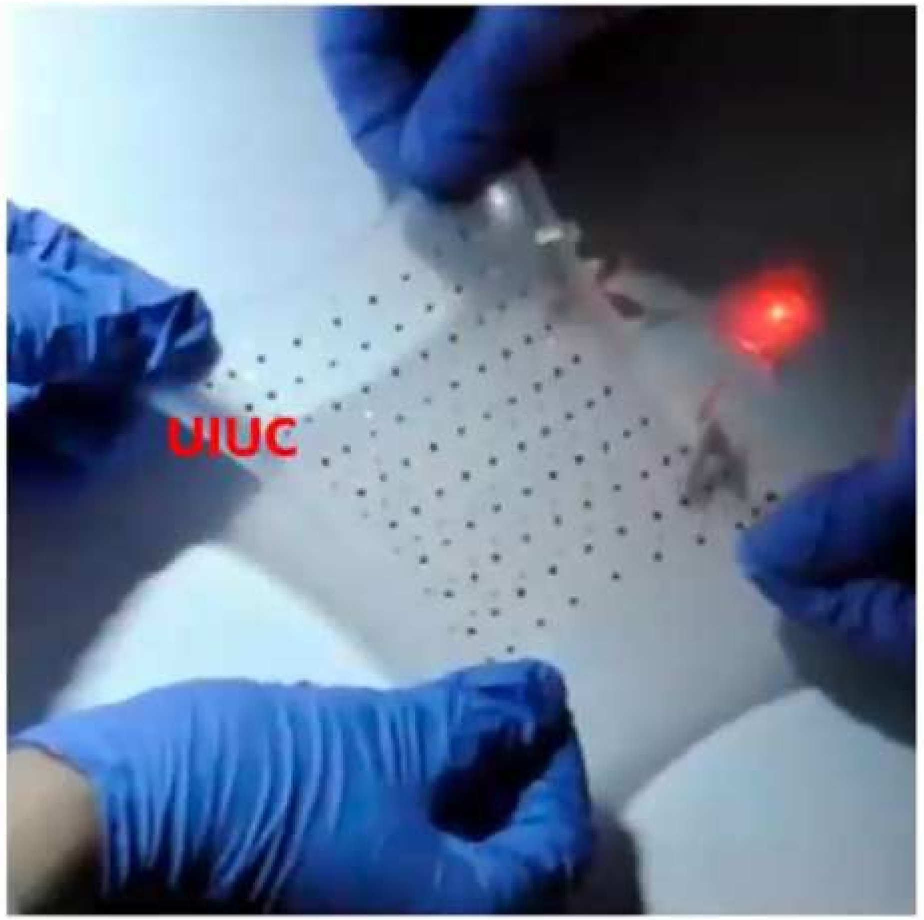
LG 2015

Samsung 2019

Future Electronics



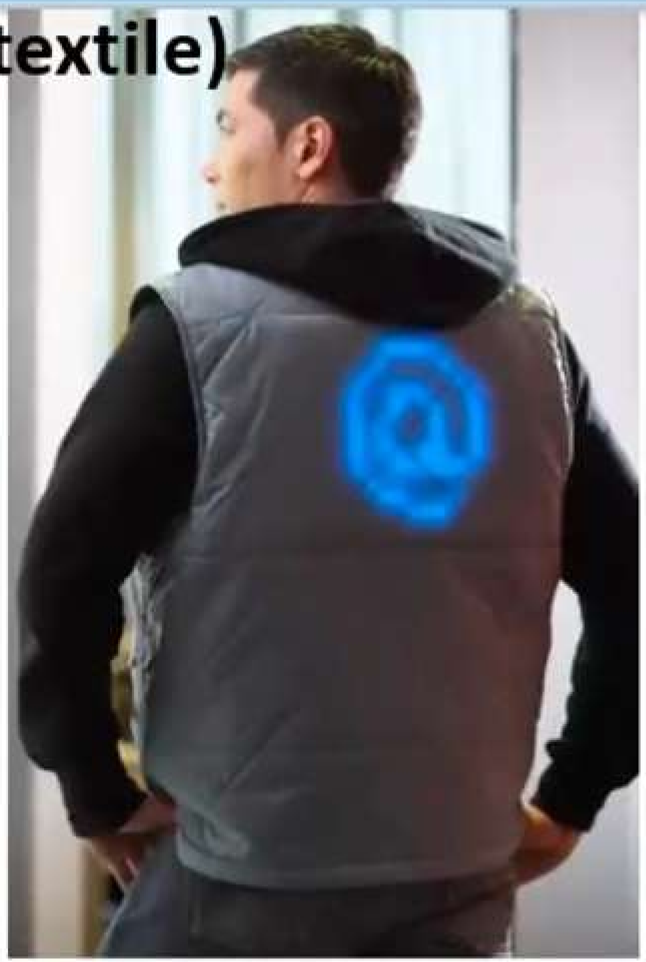


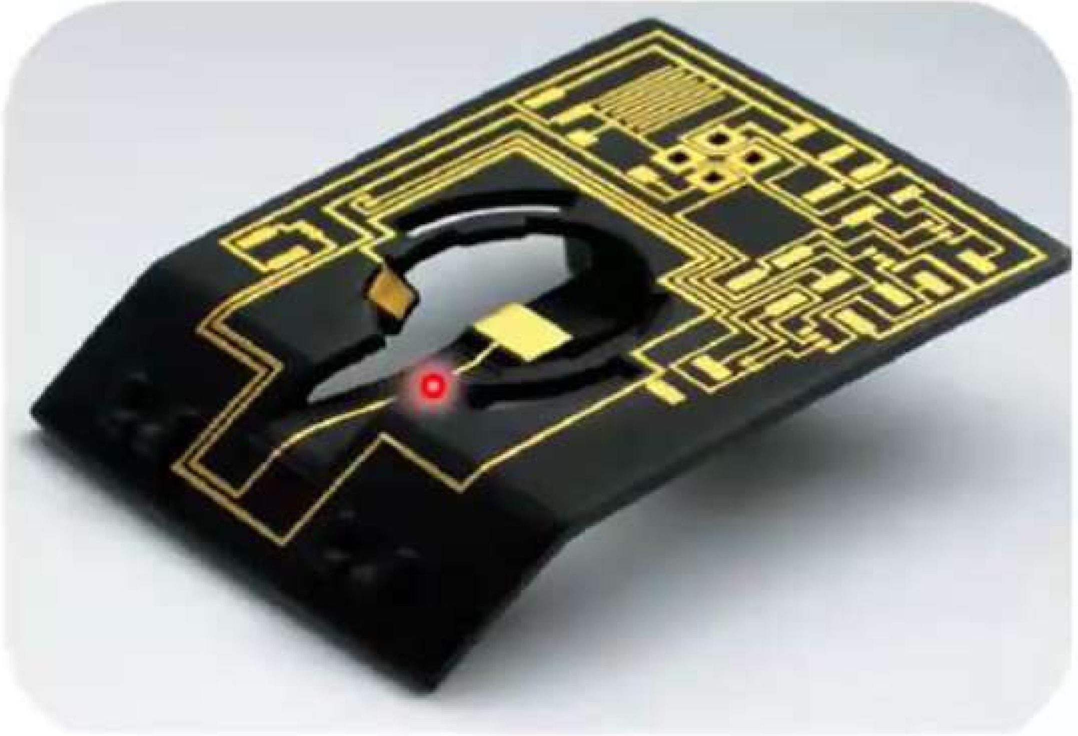


Wirelessly powered flexible electronics

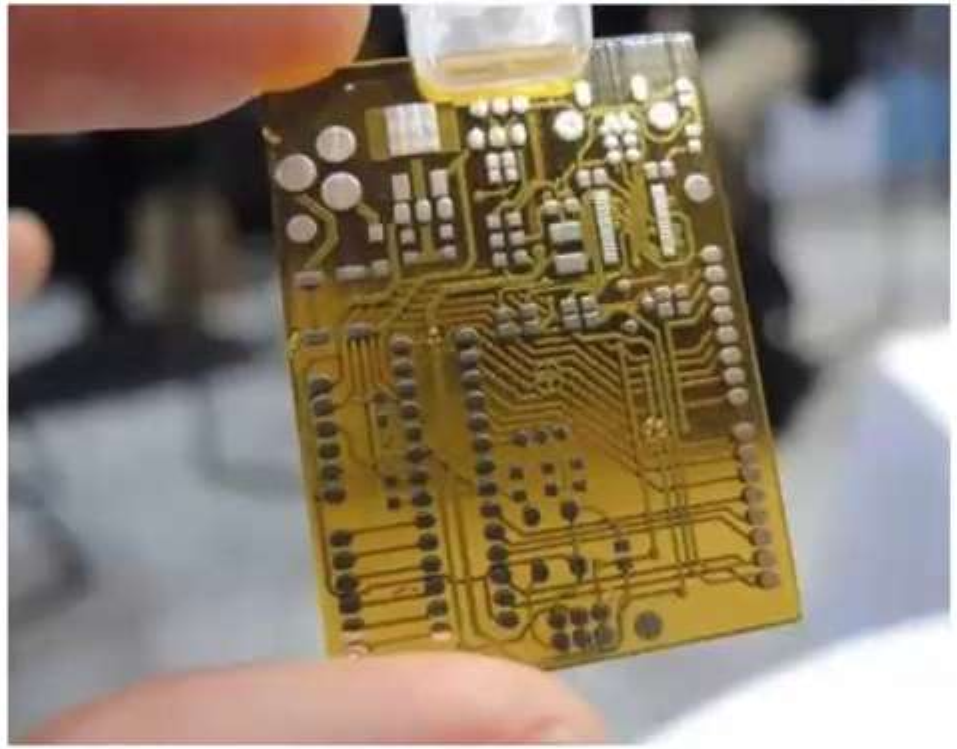
Future Electronics

Smart Textile (e-textile)



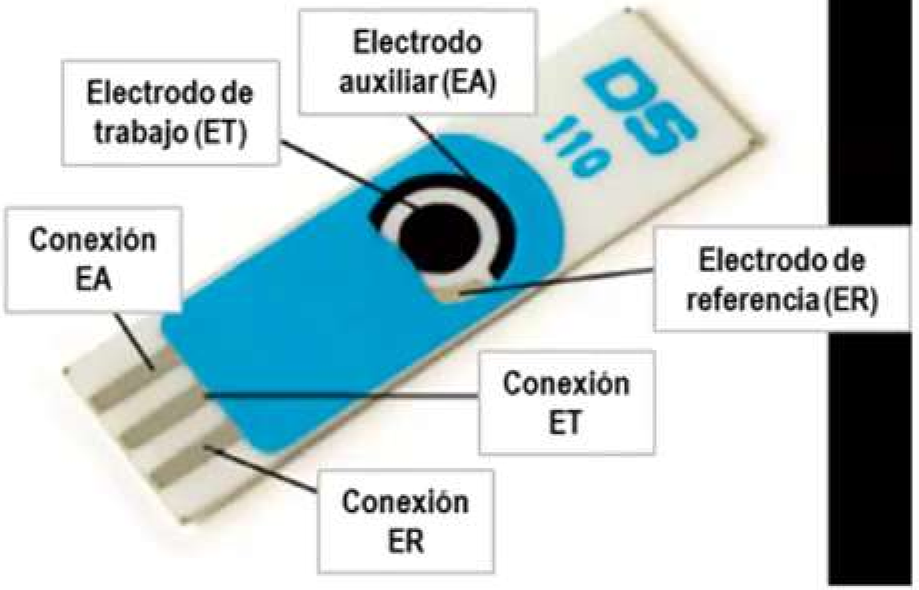


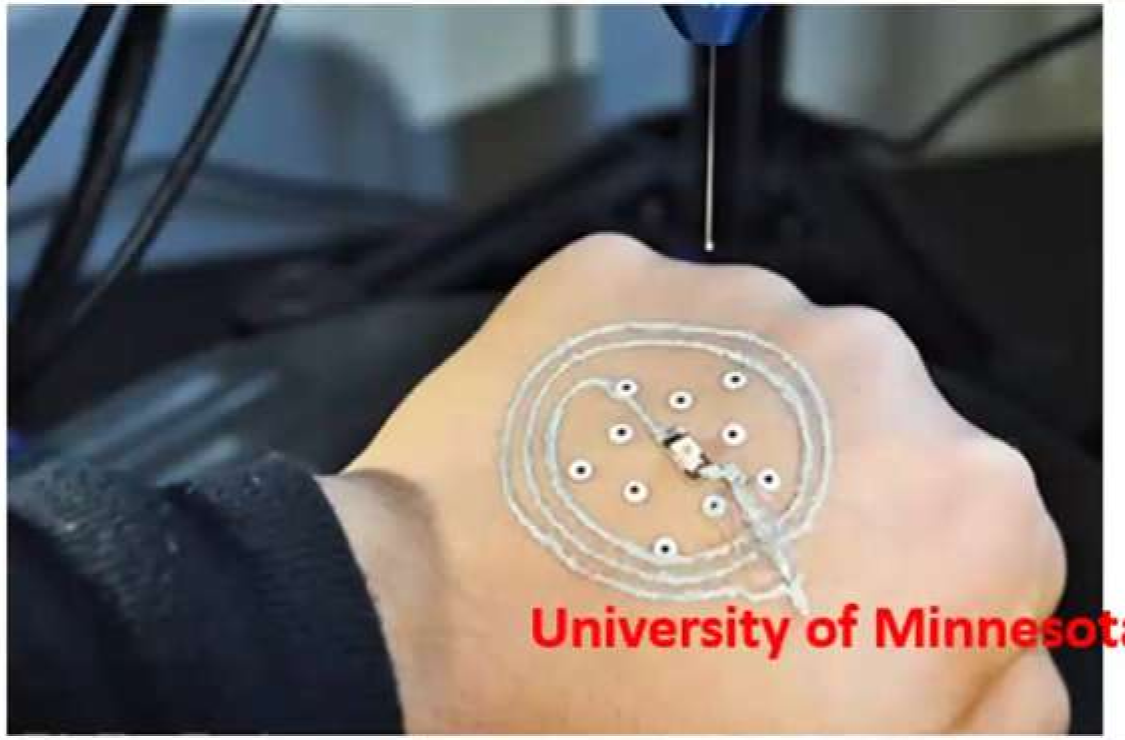
Molded interconnect devices

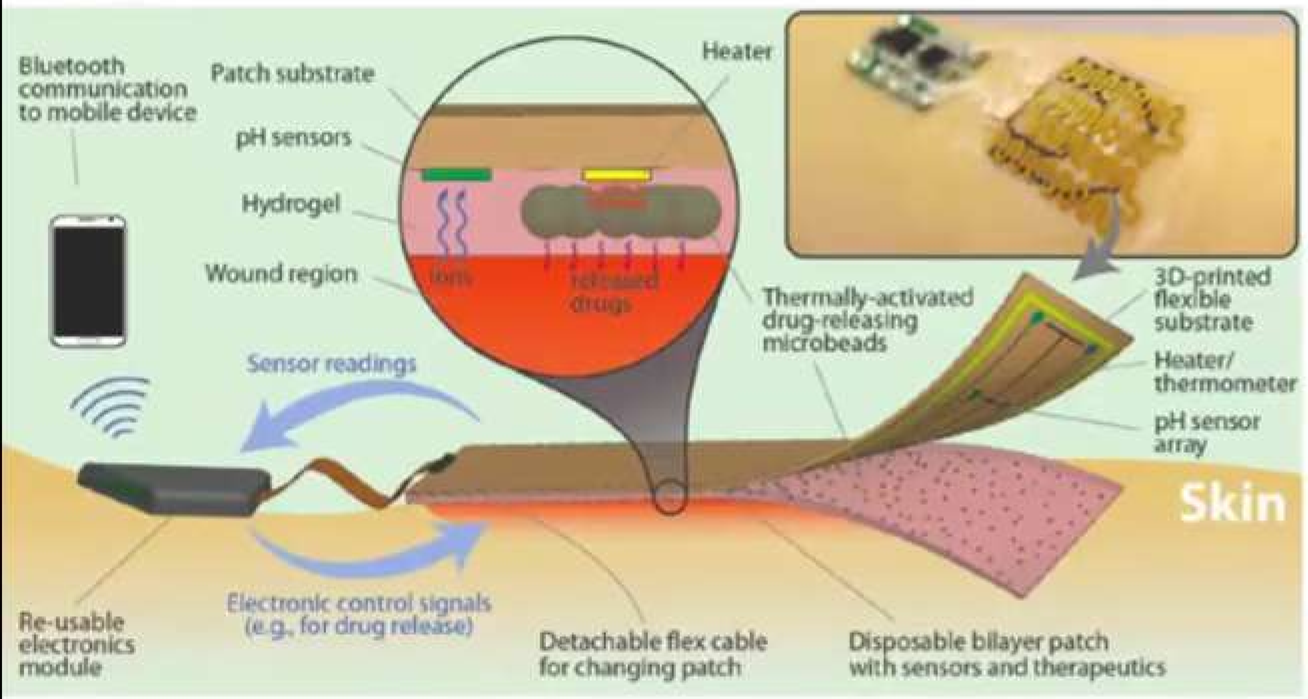


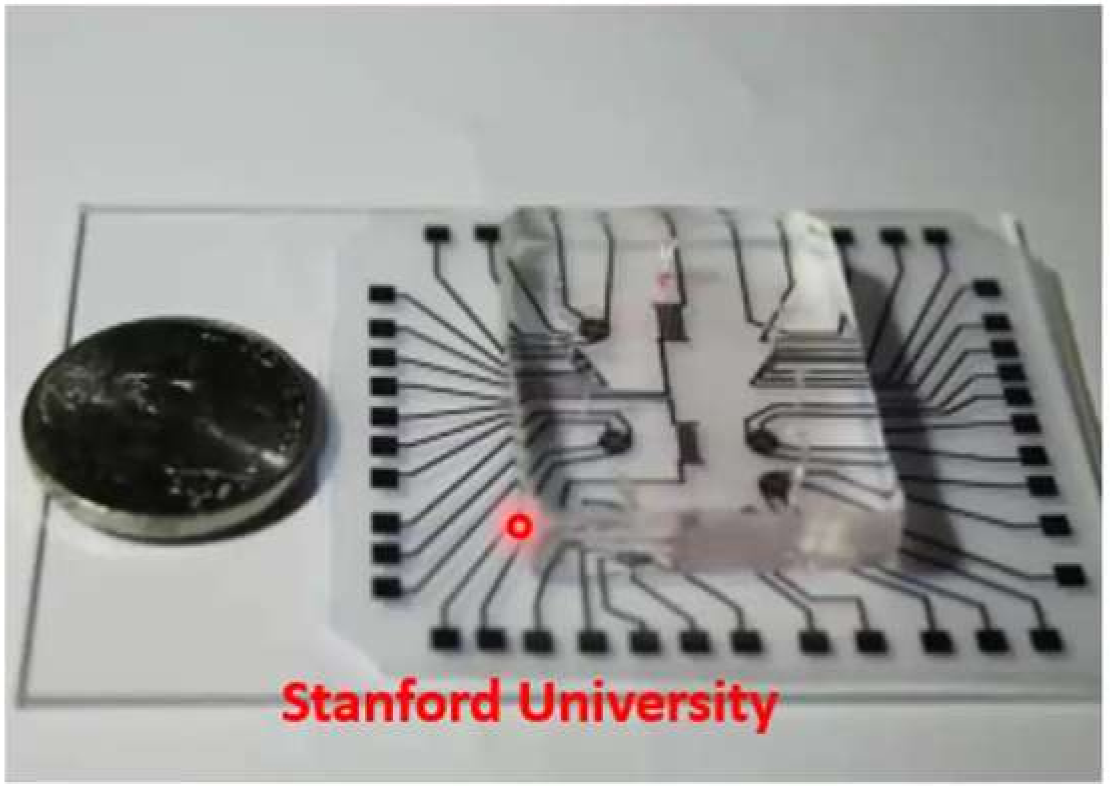
3D Printed Structural Electronics

Future Electronics



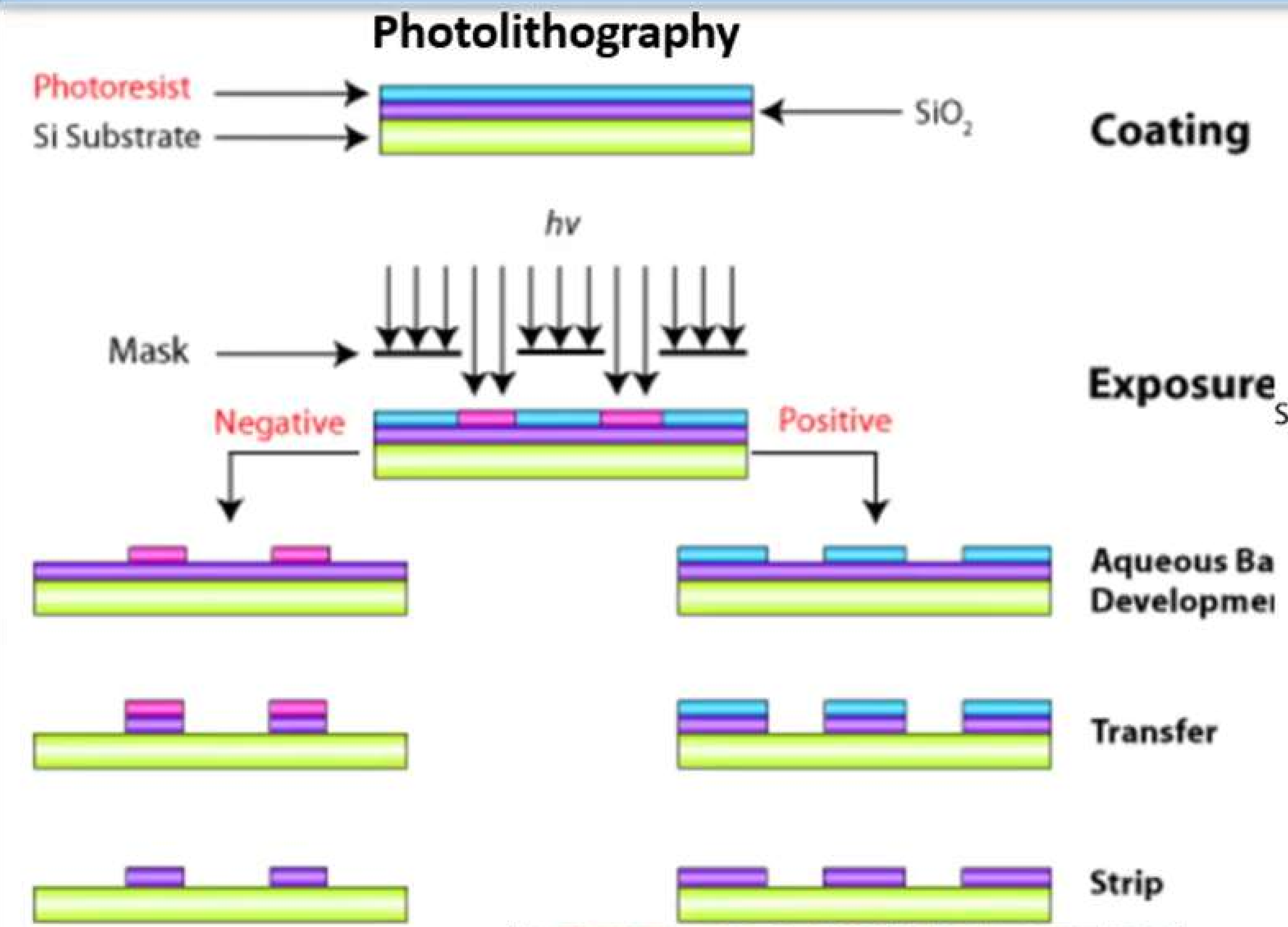


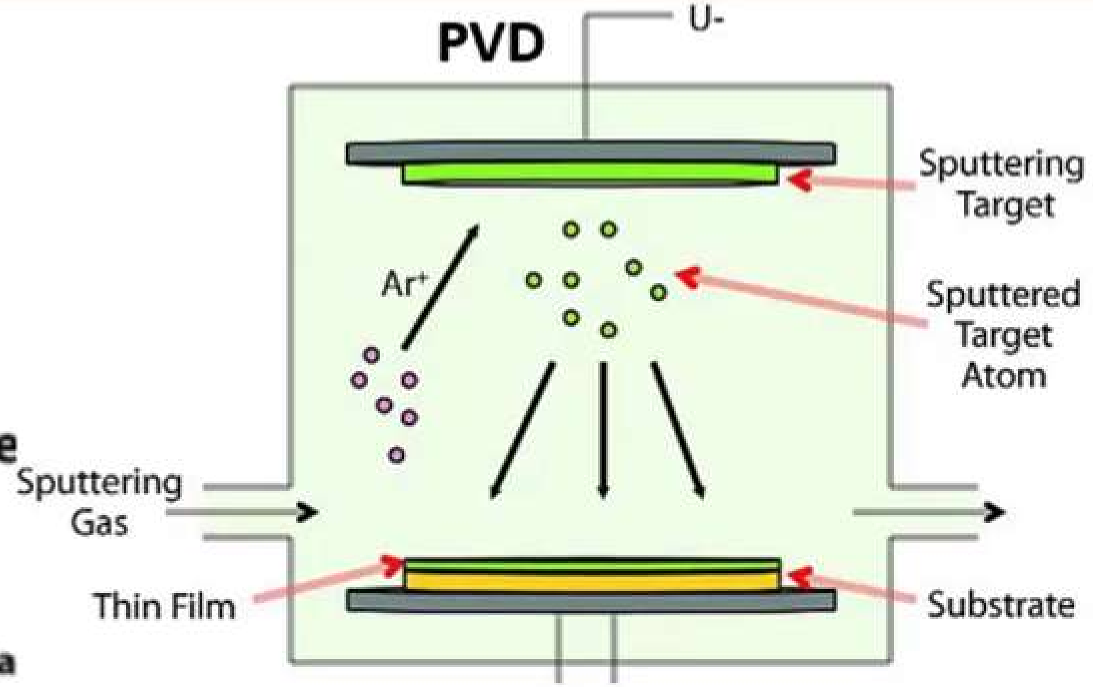


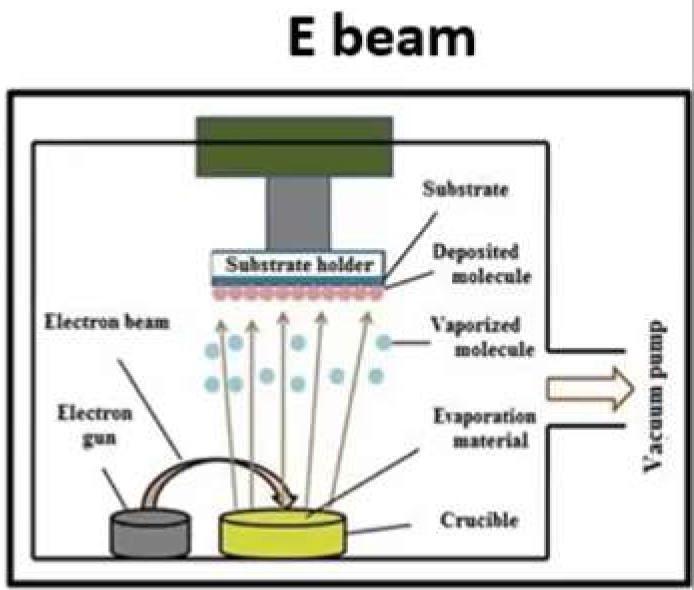


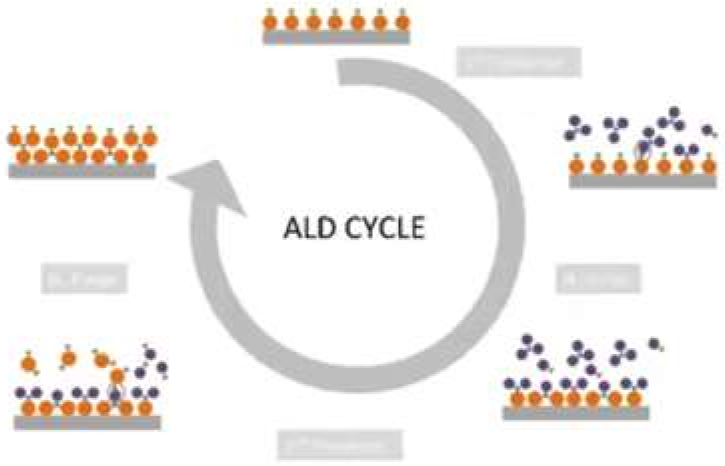
"Flexible" "Stretchable" "Bendable" "Wearable" "Disposable"

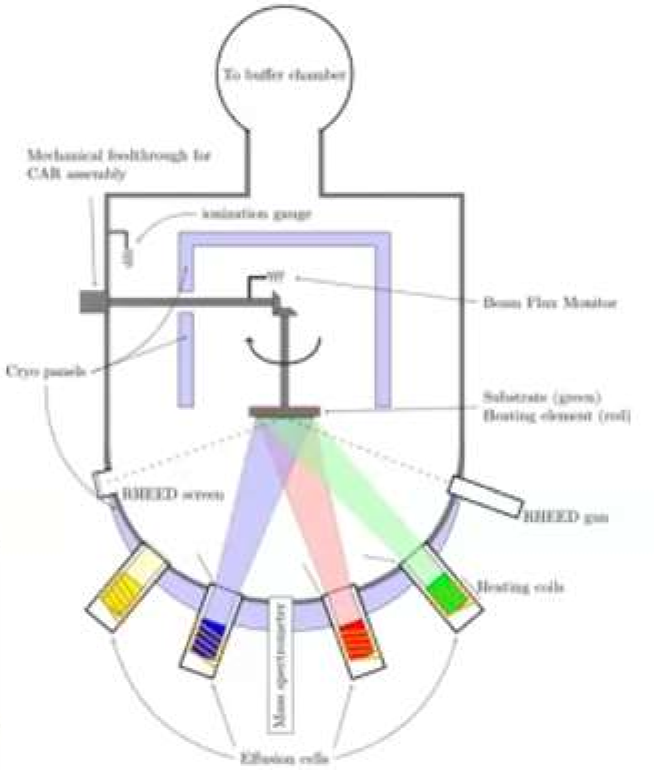
Electronics Fabrication



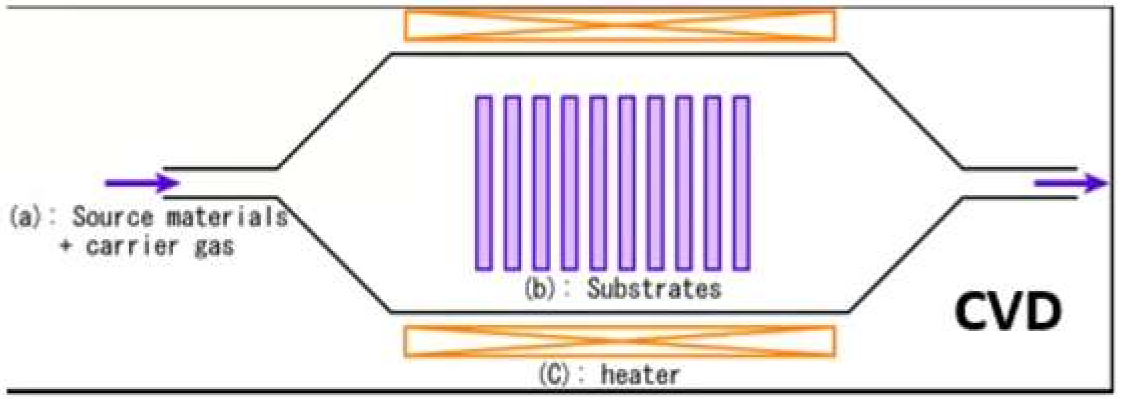




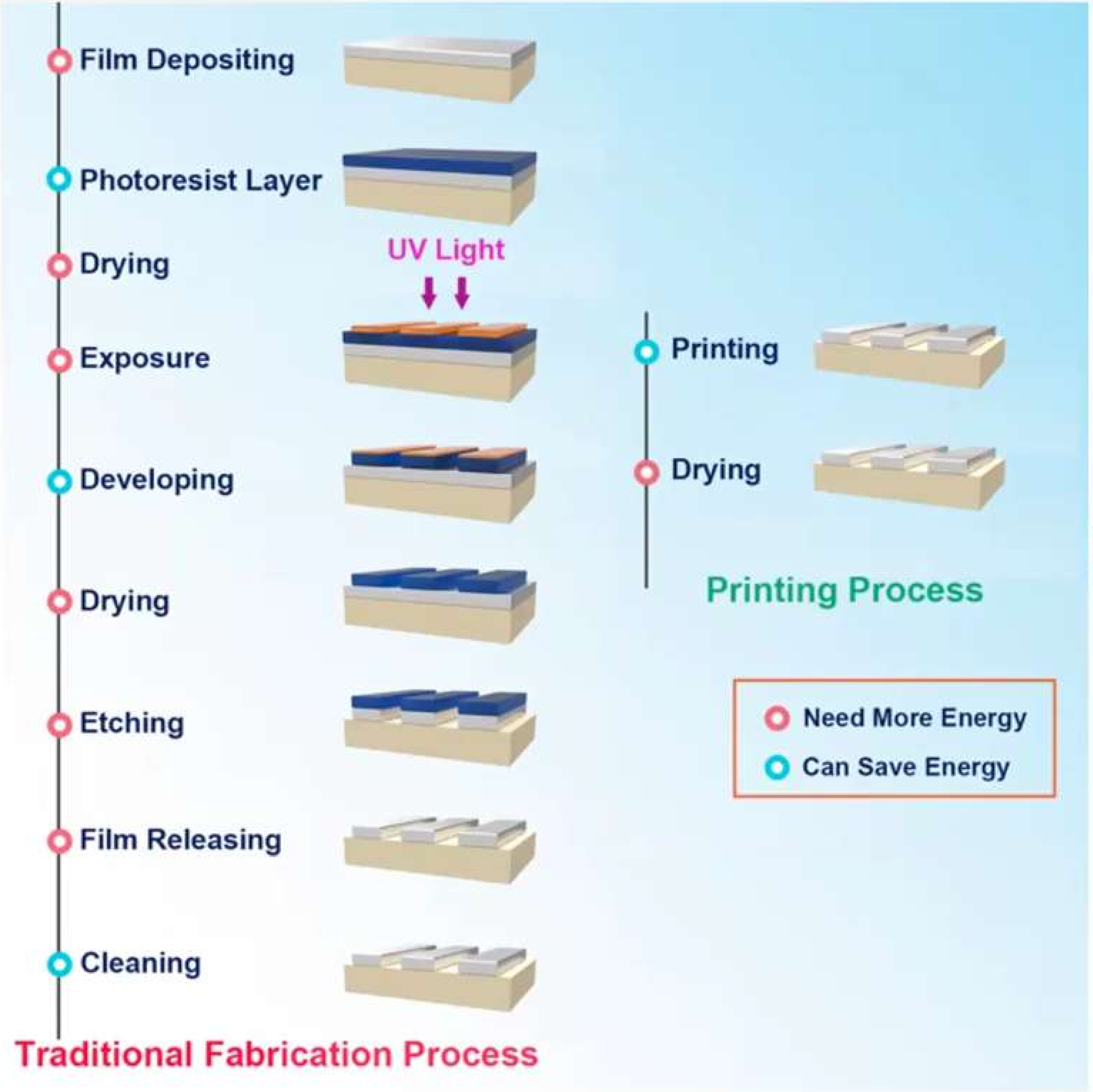


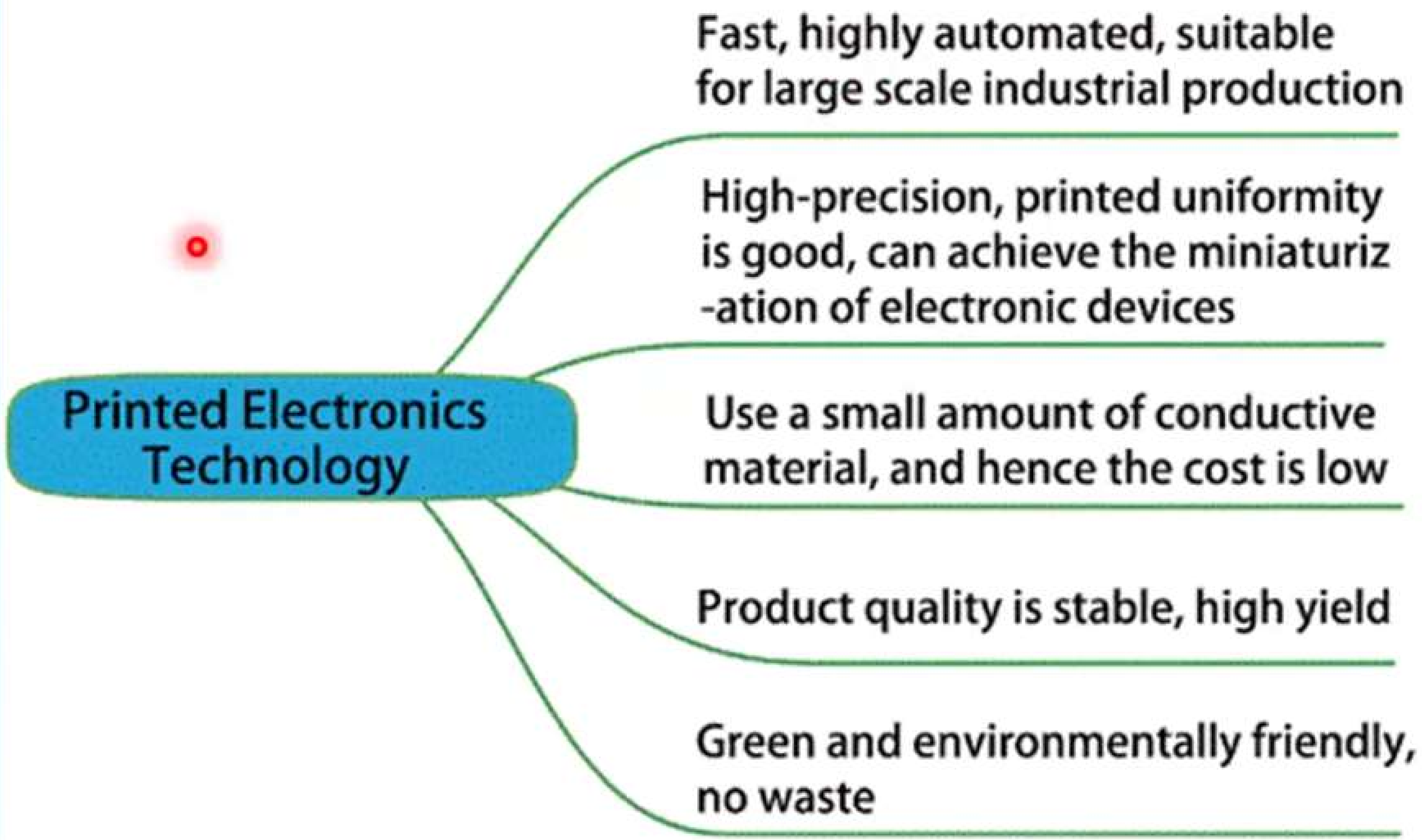


Subtractive Process



Electronics Device Fabrication

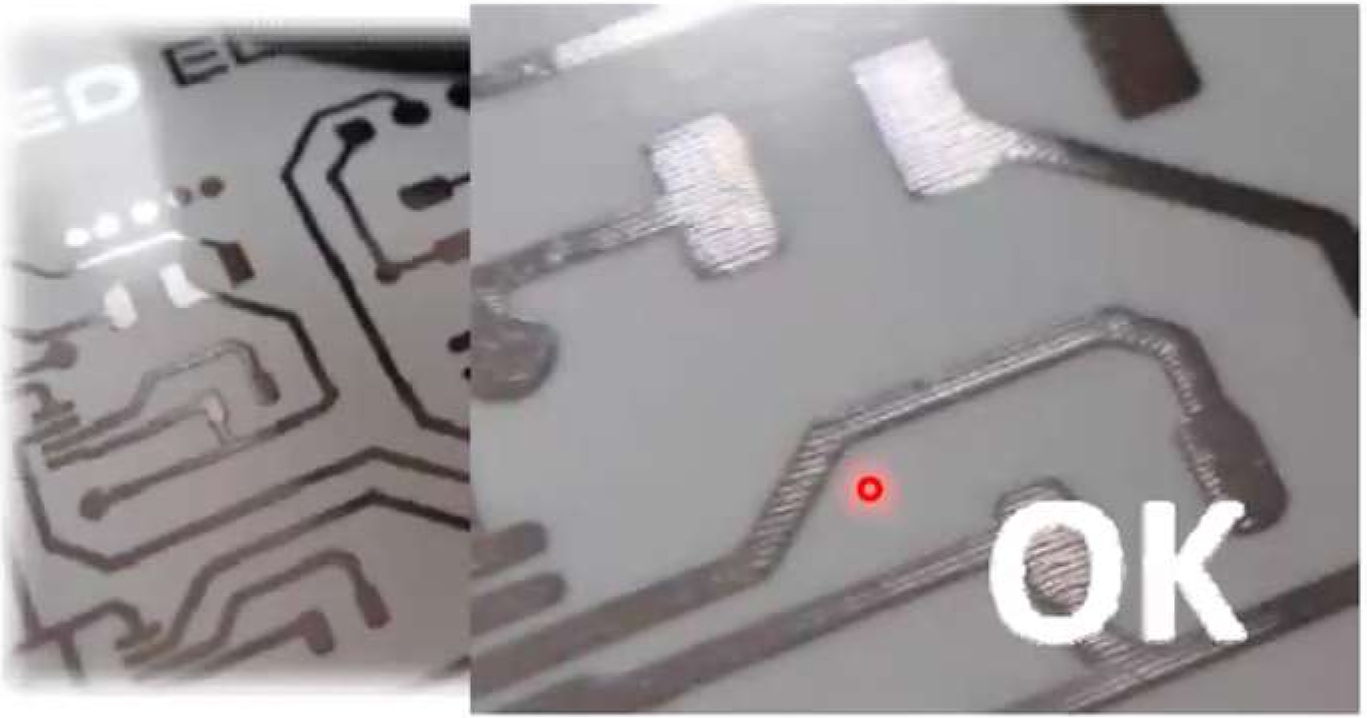


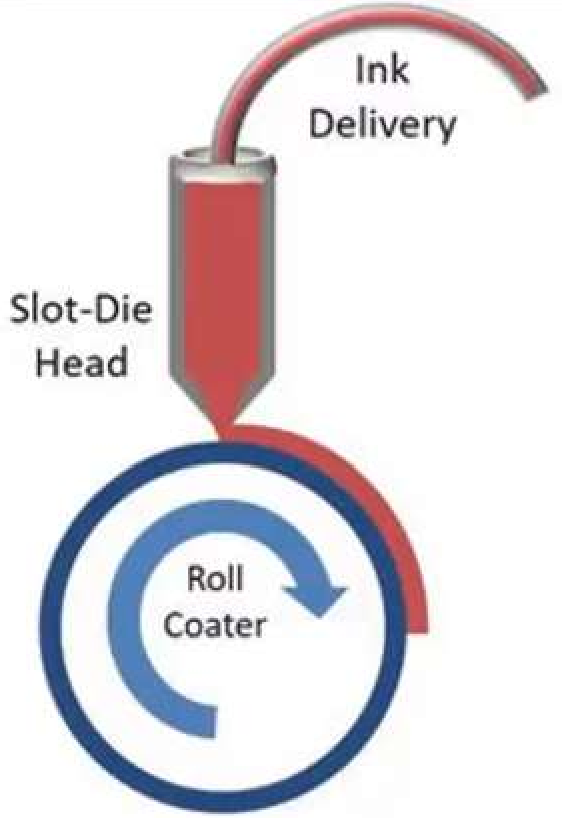


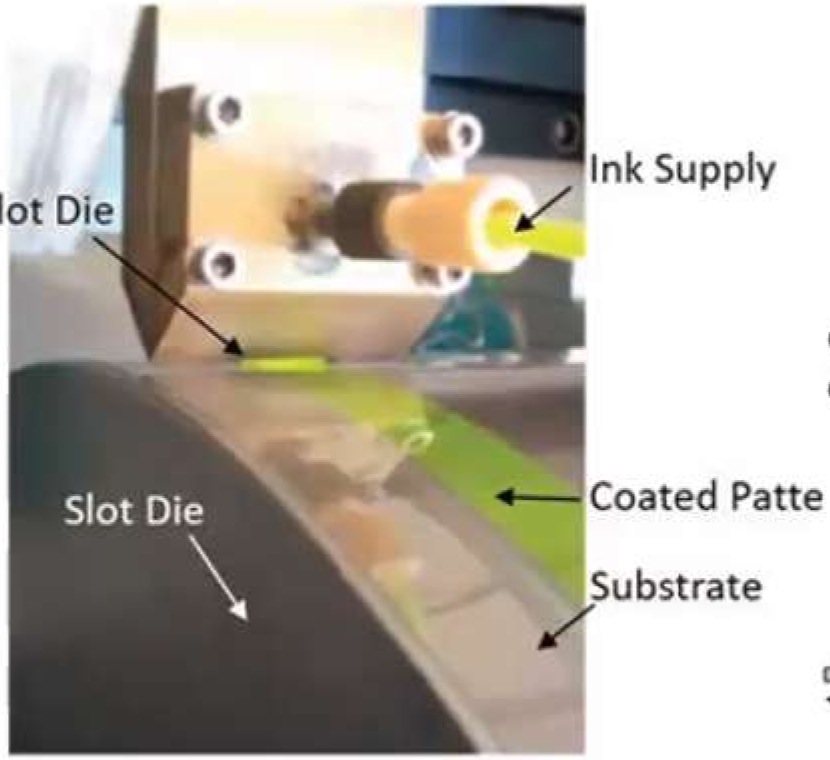
Printed Electronics as Additive Manufacturing

Printed electronics is a subset of additive manufacturing that involves the layer-by-layer deposition of functional materials—such as conductive, semiconductive, and dielectric inks—onto various substrates using printing techniques (e.g., inkjet, screen, aerosol jet).

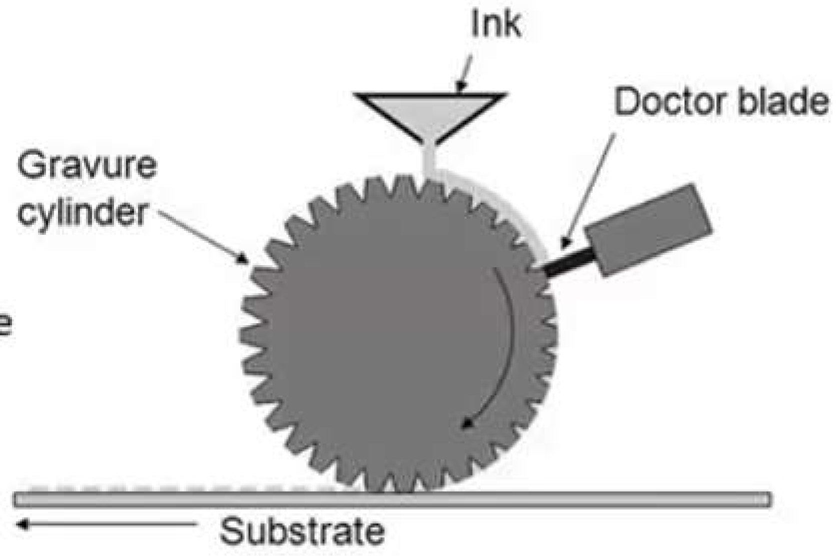
Printing Beyond Color



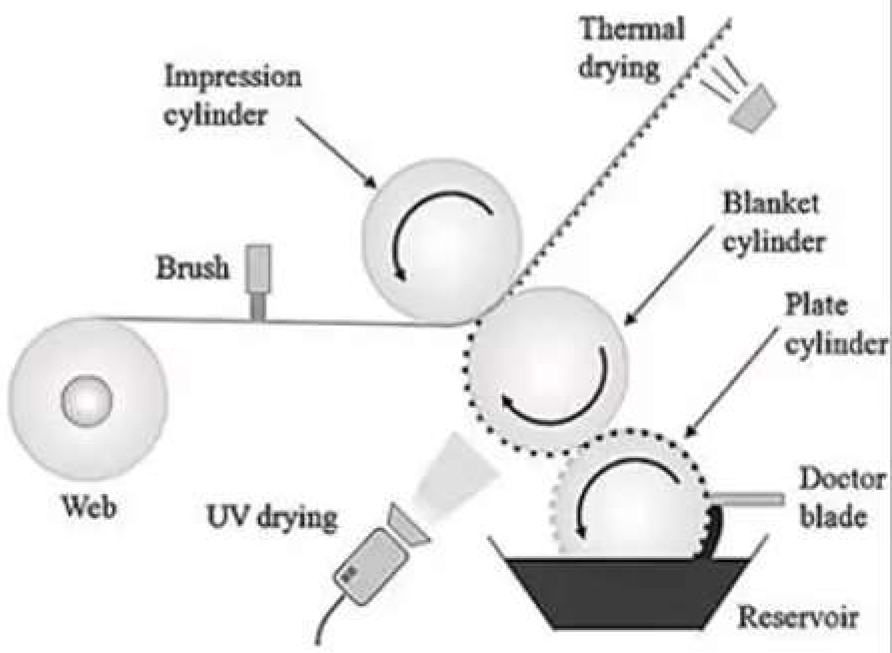




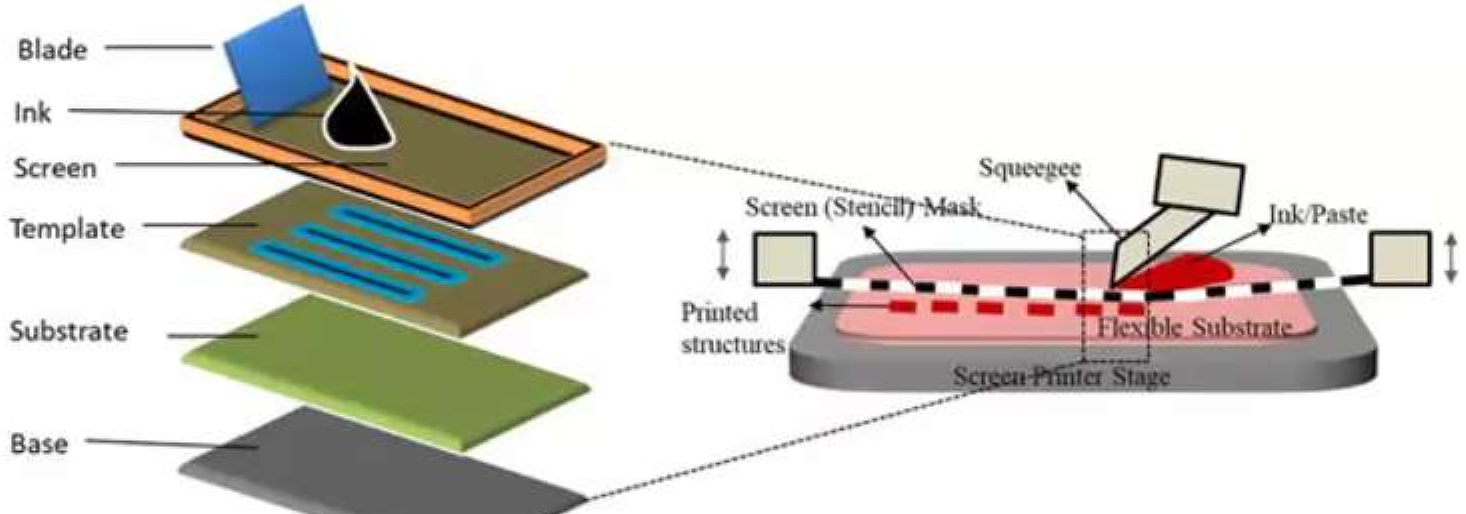
Standard gravure system

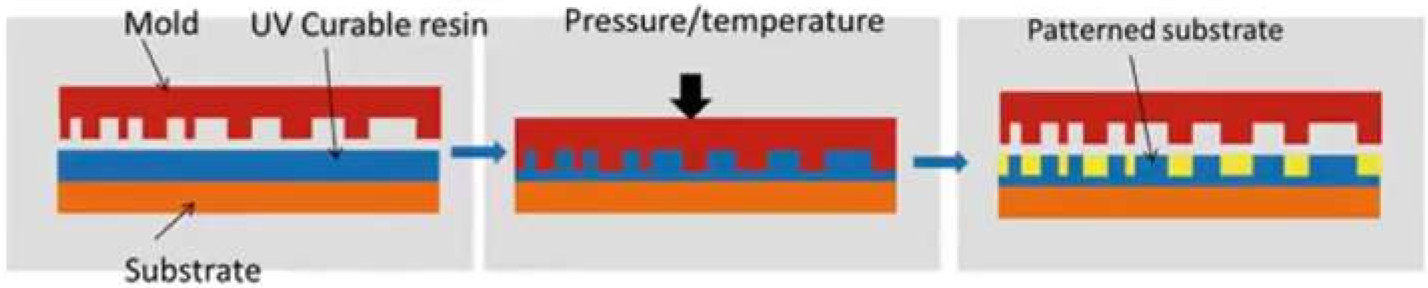


Micro-gravure-offset- system

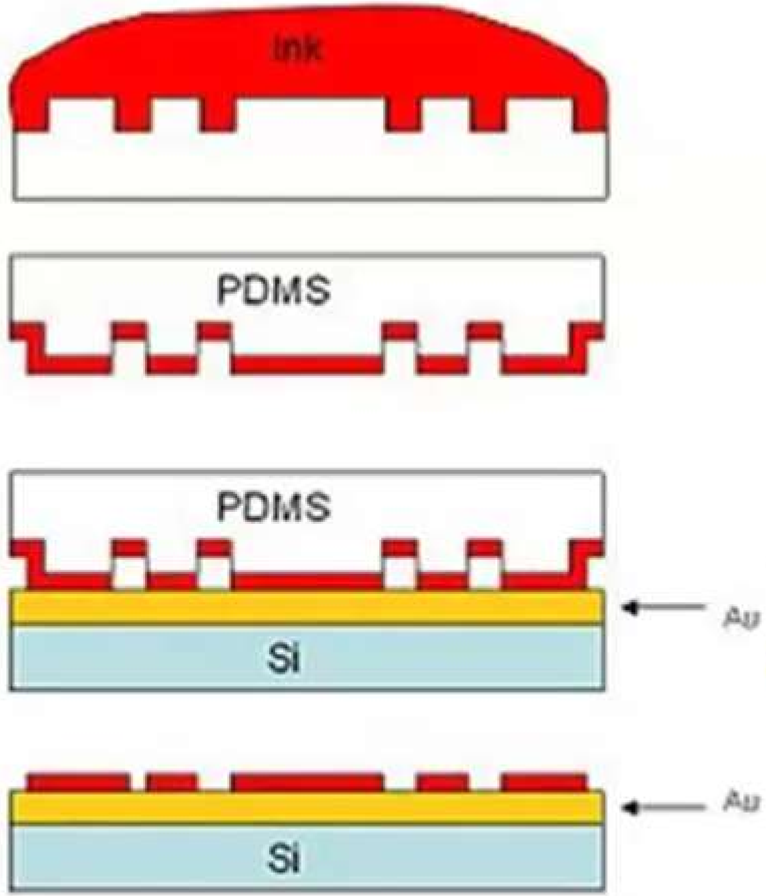


Screen printing system

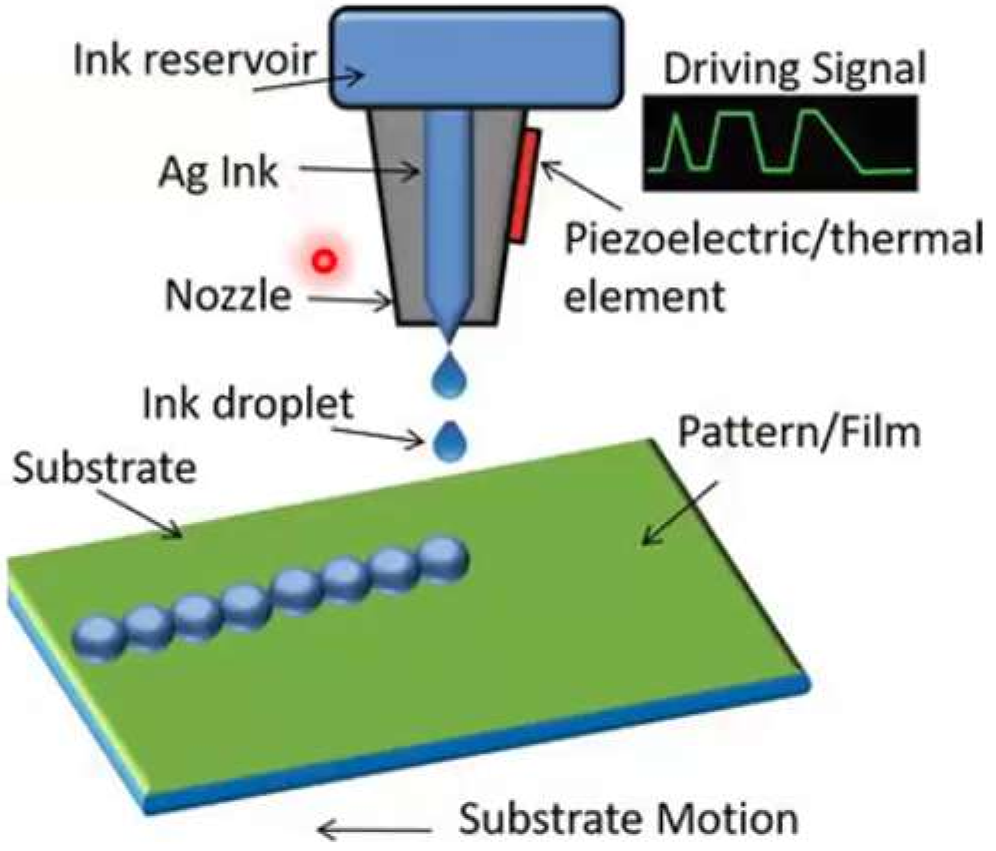




Nanoimprint

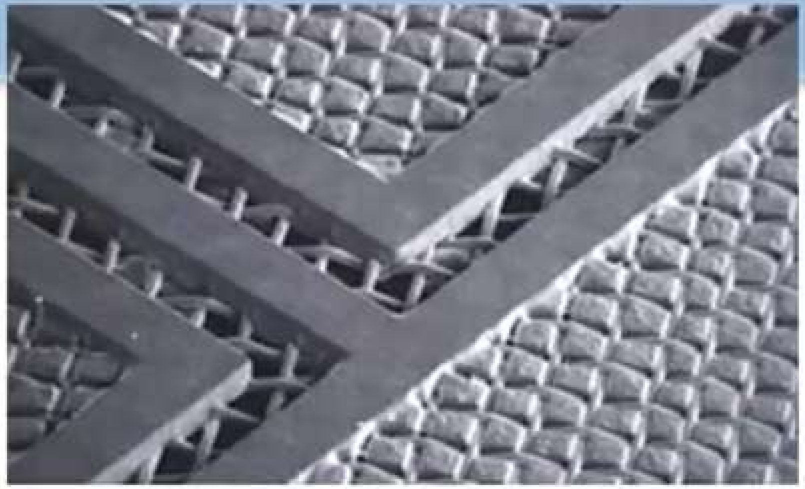


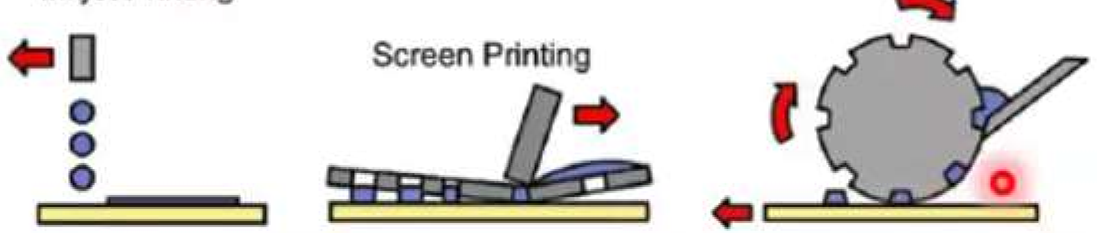
Stamping/micro-contact printing



Printed Electronics

- Printing Techniques
  - Contact printing
    - Flexographic printing
    - Gravure printing
    - Offset printing
    - Screen-printing
  - Non-contact printing
    - Inkjet printing
    - Aerosol-Jet printing
    - Organic Vapor-Jet printing (OVJP)





Printing properties	Inkjet Printing	Screen Printing	Gravure Printing
Ink viscosity	5 – 50 cP	500 – 5000 cP	10 – 1000 cP
Critical linewidth	30 – 70 μm	50 – 150 μm	5 – 100 μm
Film thickness	0.1 – 1 μm	5 – 100 μm	0.1 – 1 μm
Film roughness	Low	High	Low
Printing speed	0.01 – 0.1 m s^{-1}	0.1 – 1 m s^{-1}	0.1 – 10 m s^{-1}
2D patterning	Yes	Yes	Yes
Large-area scalability	Limited	Yes	Yes
Design flexibility	High	Low	Low

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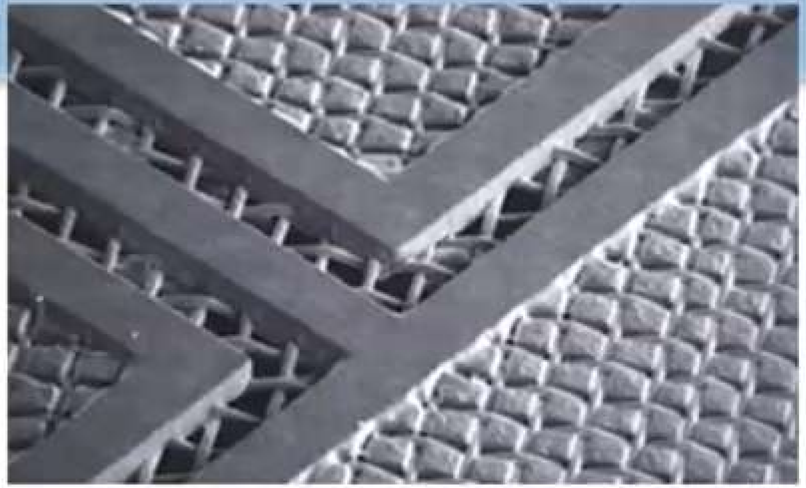
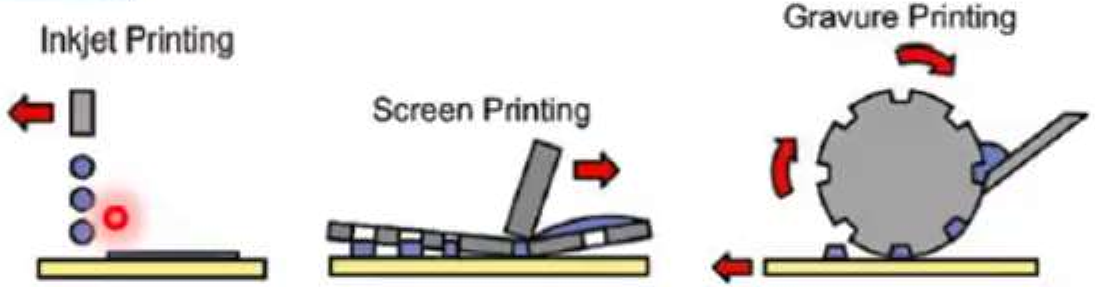
Advantages:

- Cost effective
- Easy operation and flexibility
- Non-contact
- Material directly applied to substrate





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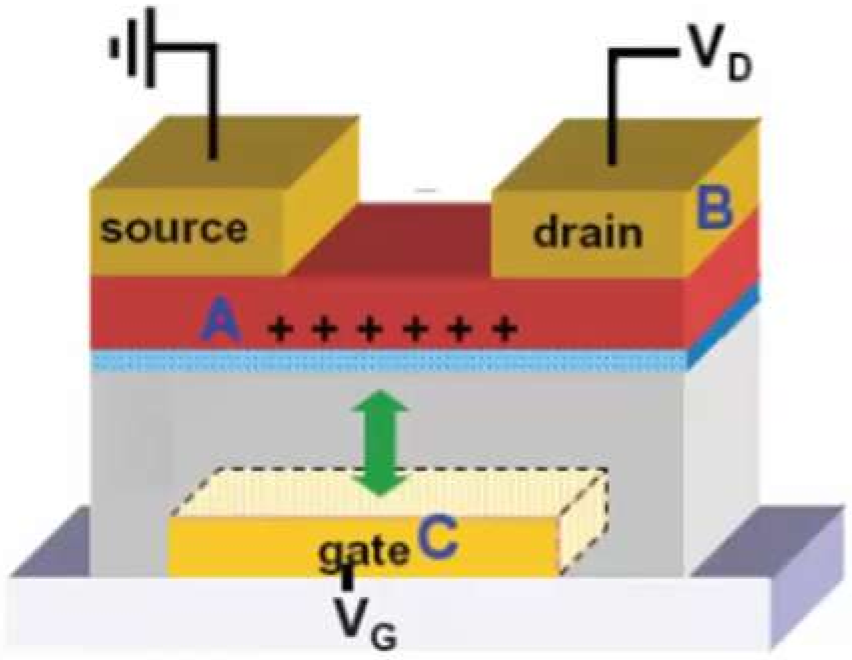
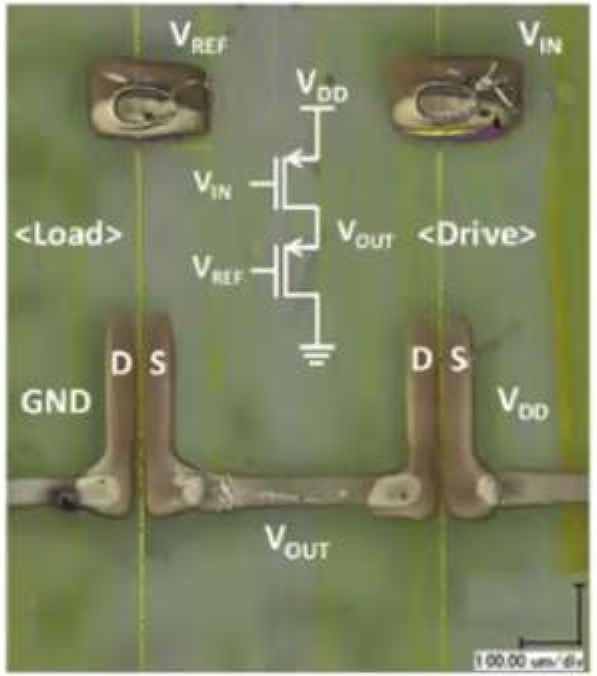
Printed Electronics



Thin film Transistor (TFT)



Conductor

Carbon, silver, aluminum flakes, Polypyrrole, polyacetylene, thiophenes (PEDOT:PSS), Metal nanoparticles (Ag, Au, Cu, Ni), Carbon nanotubes, metal nanowires, Graphene

Insulator

Oxides, nitrides, Polymer dielectrics (PVP, PMMA, …)

Semi Conductors

Organic semiconductors (small molecule, polymer), Oxide Semiconductors (ZnO, InGaZnO), CNT, Nanowires, nanoribbons (Si, GaAs), Nanoparticles (Si, CdSe, ZnSe)

Printed Electronics

- **Traditional Electronics**

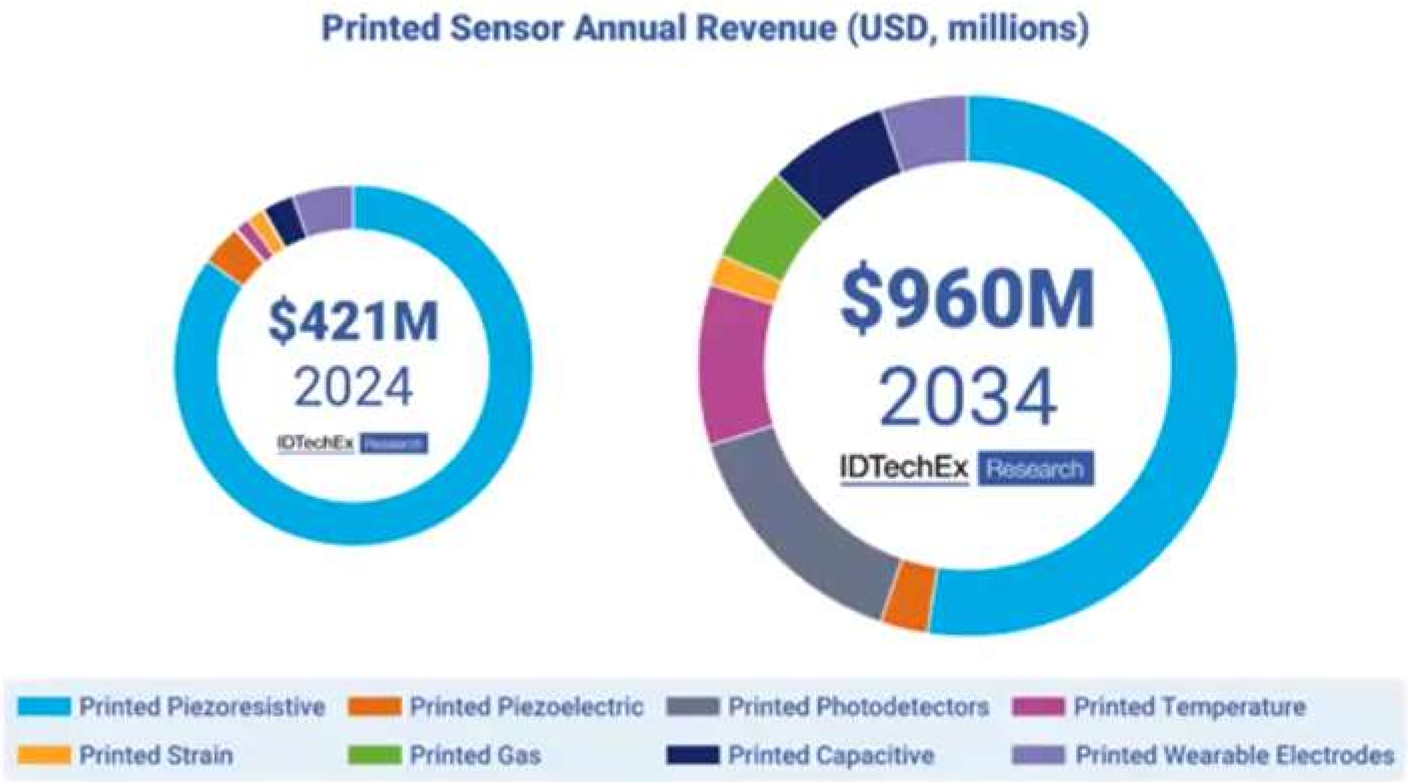
- Made in batches on wafers in cleanroom
- Devices run fast
- Layers added in furnace, vacuum or crystal growth
- High resolution
- Expensive processing
- Rigid silicon wafers or glass
- Devices are small
- Not transparent
- Established
- A cohesive industry

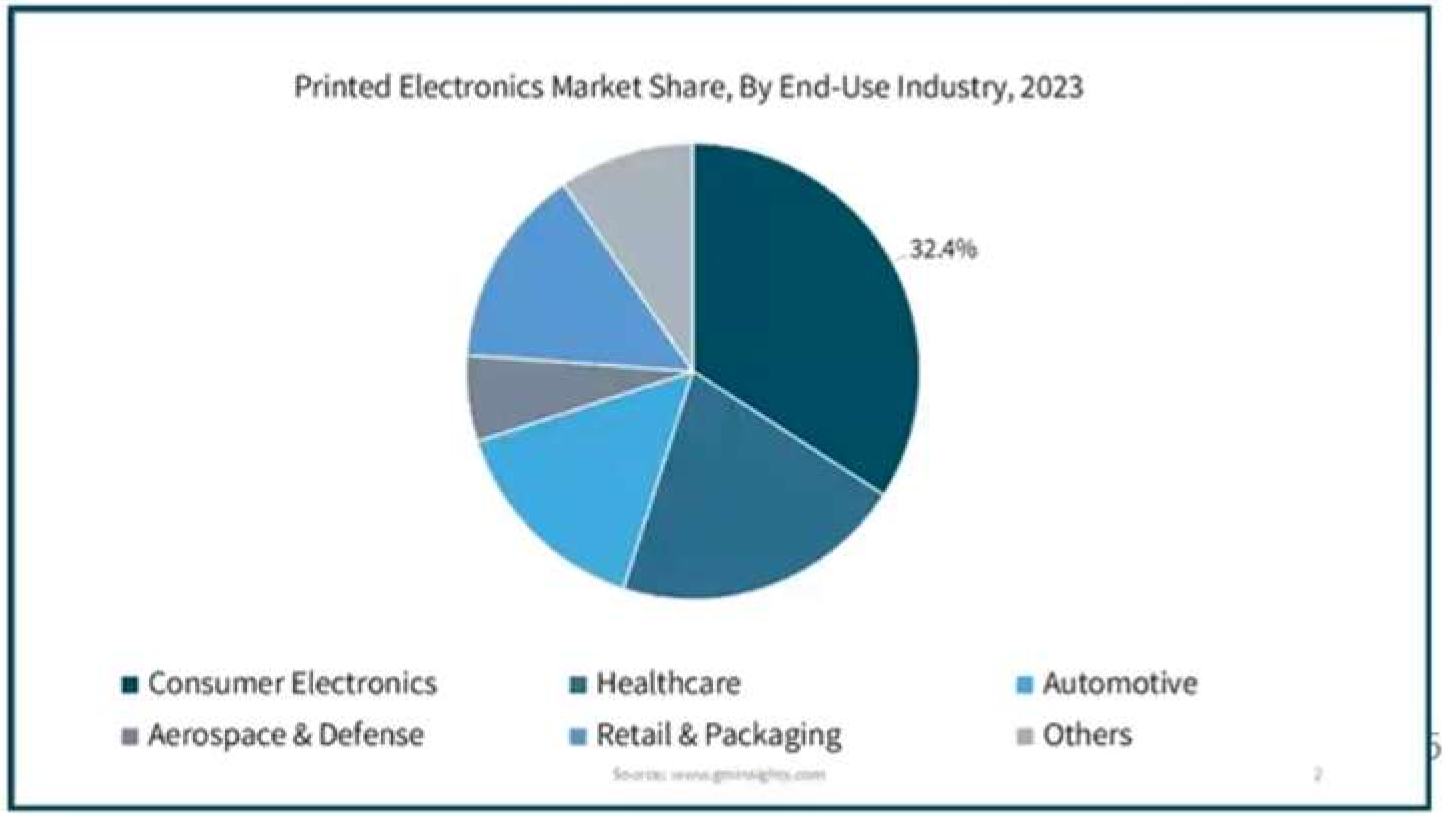
- **Printed Electronics**

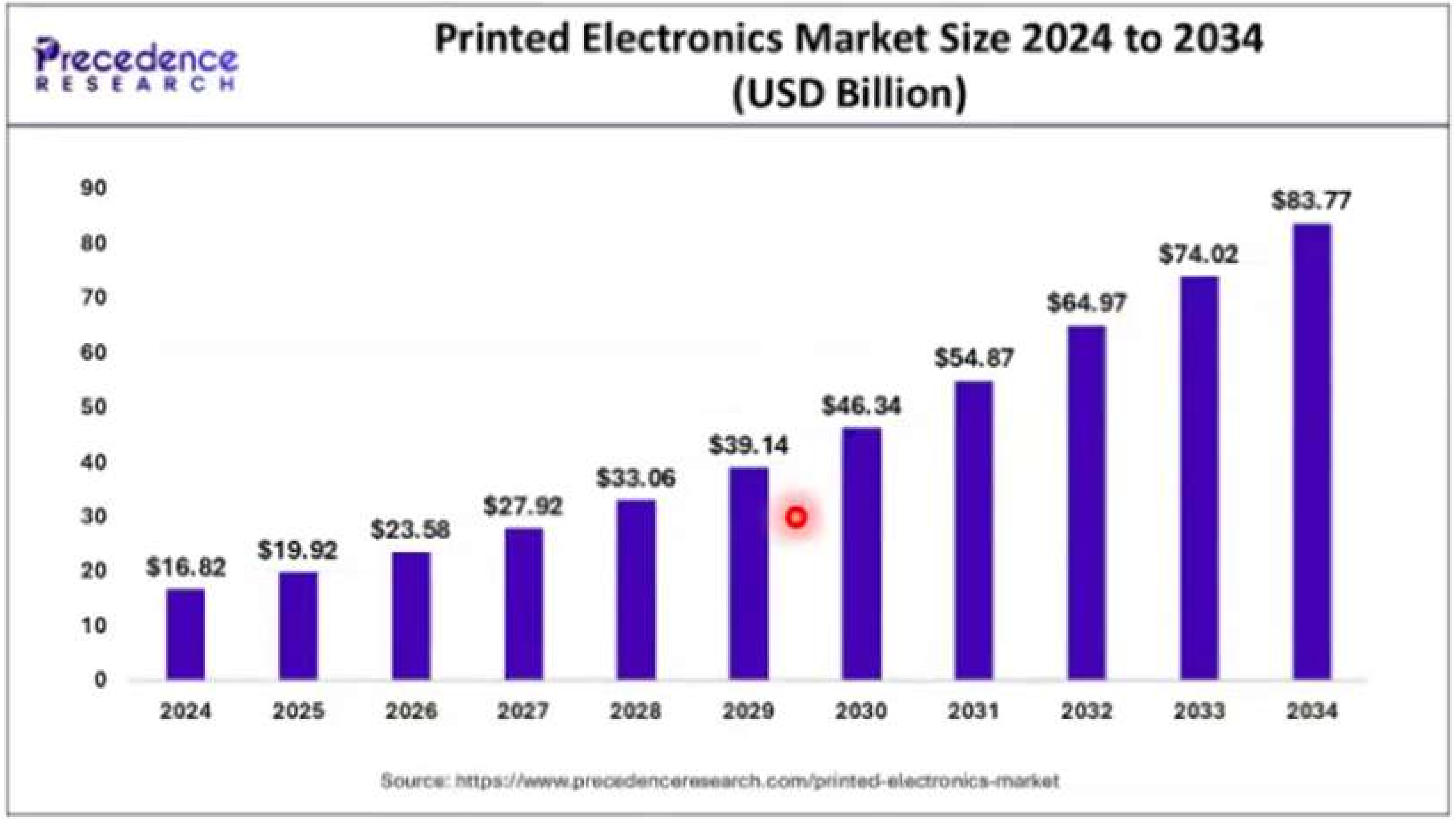
- Can be printed on a roll (or batch processed) non-cleanroom
- Devices run slowly (no plastic Pentium)
- Layers added by printing (or vacuum)
- Lower resolution
- Cheap processing
- Flexible films –paper plastic, or rigid (glass)
- Devices small or large
- Can be transparent
- Early-Stage Technology
- Diverse industry


Printed Electronics
Display & Lighting
Sensors & Devices
Conduct Lines & Electrodes
Energy Store & Harvestors
Lighting
Sensors
Printed TFTs
Supercapacitors
Solar Cells
RFID Tags
Transparent Electrodes
Flexible Displays

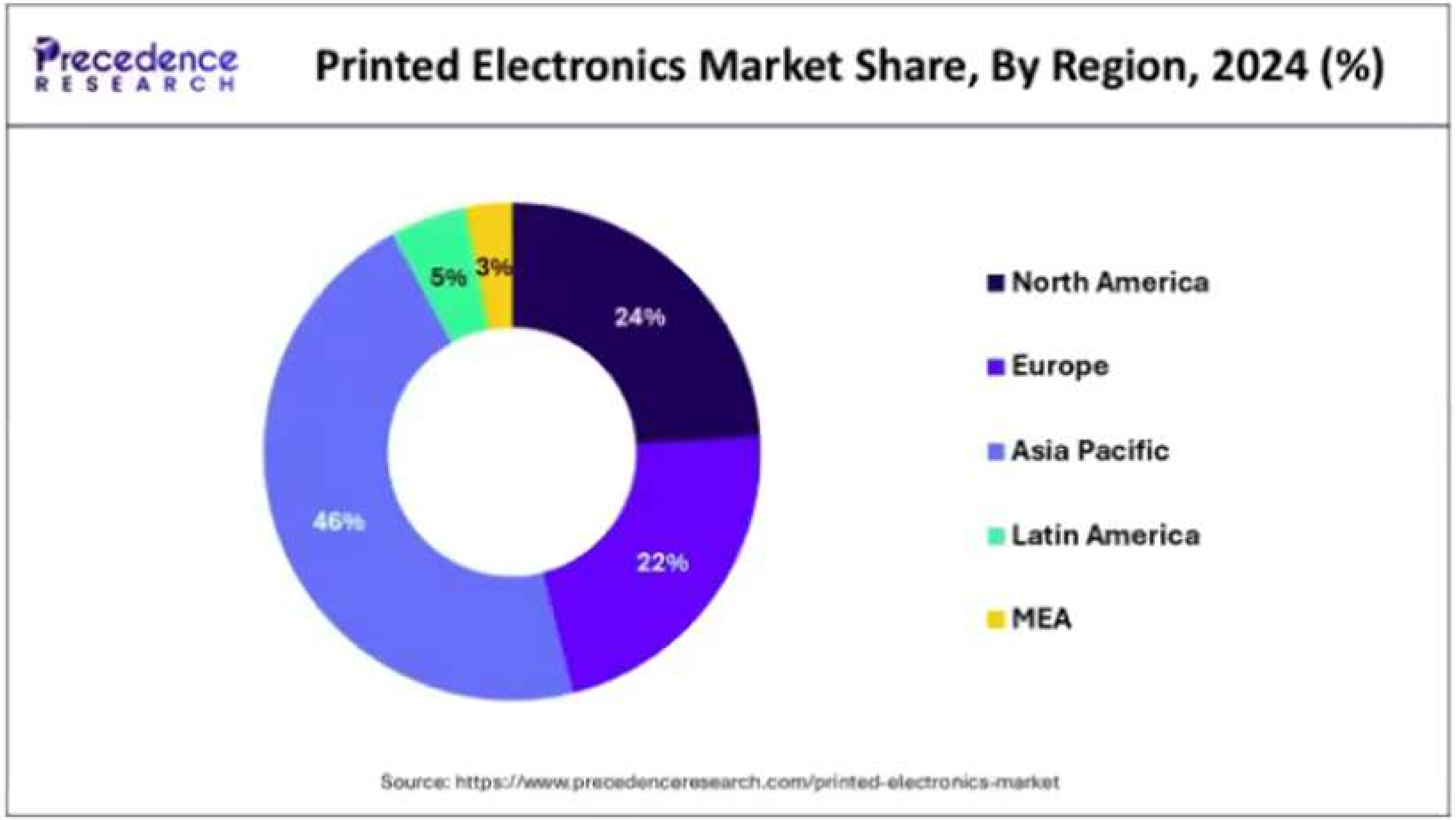

Printed Electronics Market
GLOBAL FORECAST (2024 – 2032)
MARKET STATISTICS
Market Value (2023)
$9.2 BN
Market Value (2032)
>$48 BN
CAGR (2024-2032)
>20%
SEGMENT STATISTICS
Inks segment
Market Size (2032) >$21 BN
Healthcare segment
CAGR (2024-2032) >22%
REGIONAL STATISTICS
North America
Market Share (2023)
>35%


Printed Sensor Annual Revenue (USD, millions)
$421M
2024
IDTechEx Research
$960M
2034
IDTechEx Research
Printed Piezoresistive
Printed Piezoelectric
Printed Photodetectors
Printed Temperature
Printed Strain
Printed Gas
Printed Capacitive
Printed Wearable Electrodes

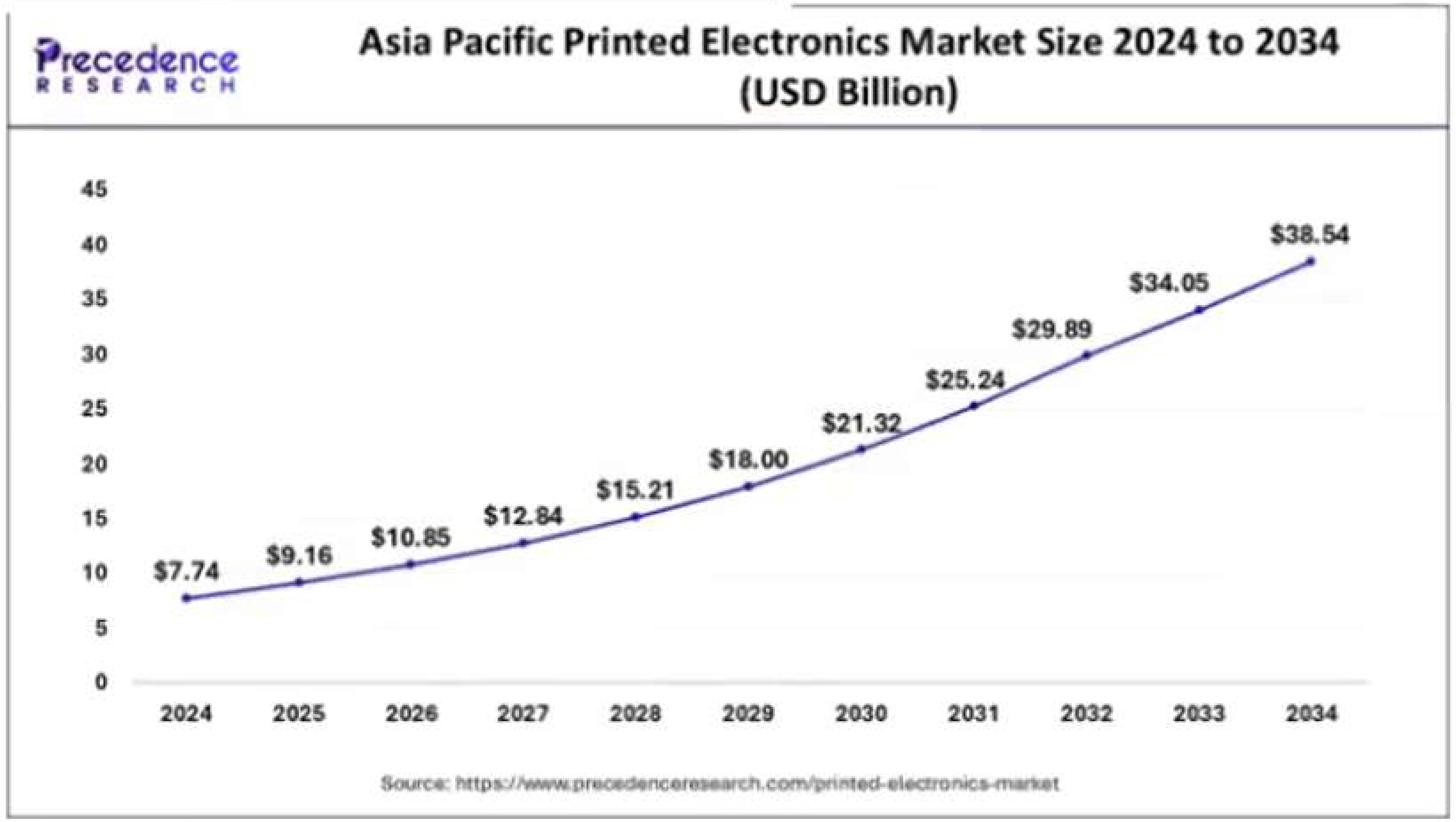

Printed Electronics Market Share, By End-Use Industry, 2023
32.4%
Consumer Electronics
Healthcare
Automotive
Aerospace & Defense
Retail & Packaging
Others



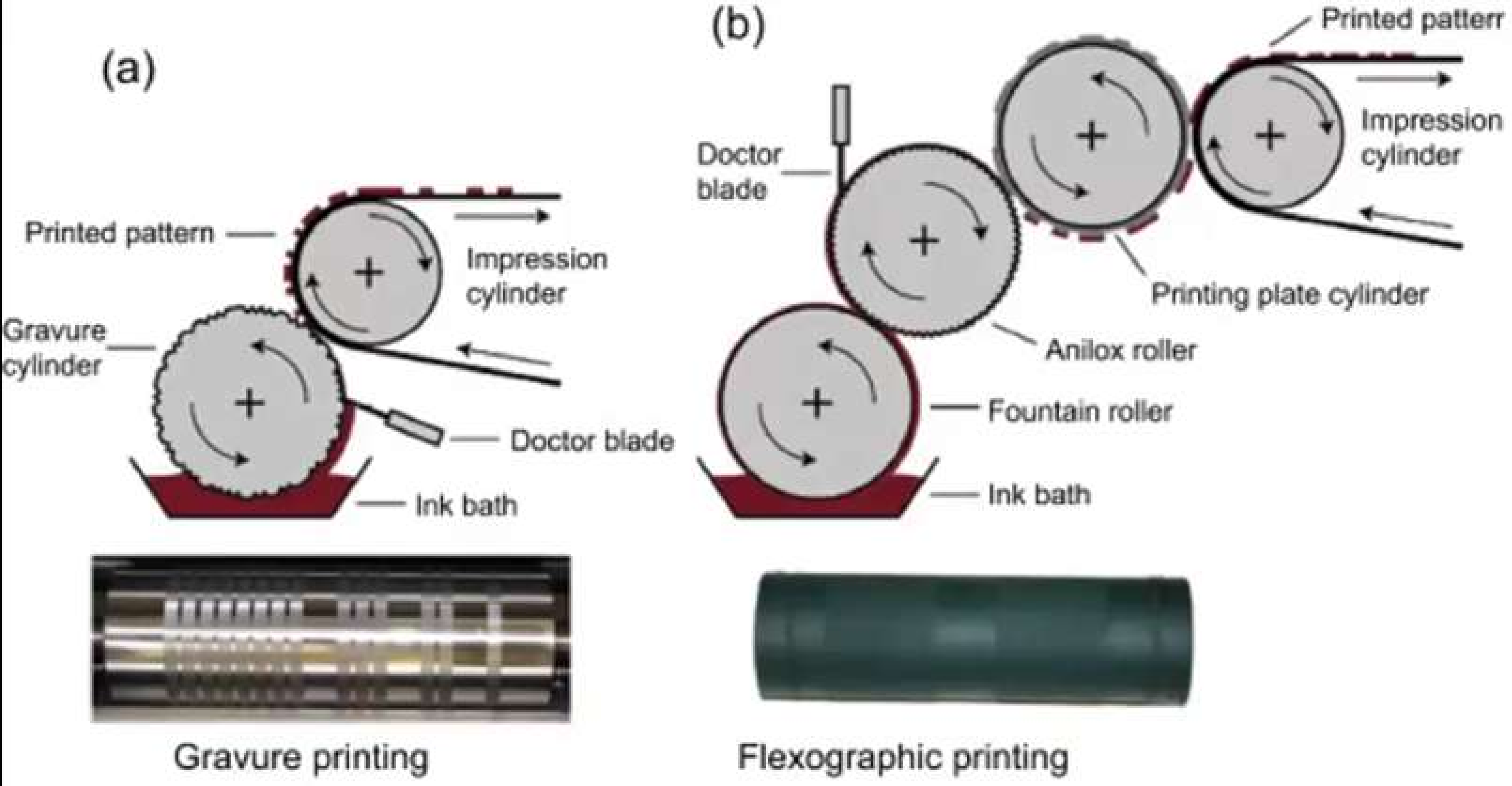
Precedence RESEARCH
Printed Electronics Market Size 2024 to 2034 (USD Billion)
90
80
70
60
50
40
30
20
10
0
$16.82
$19.92
$23.58
$27.92
$33.06
$39.14
$46.34
$54.87
$64.97
$74.02
$83.77
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
Source: https://www.precedenceresearch.com/printed-electronics-market



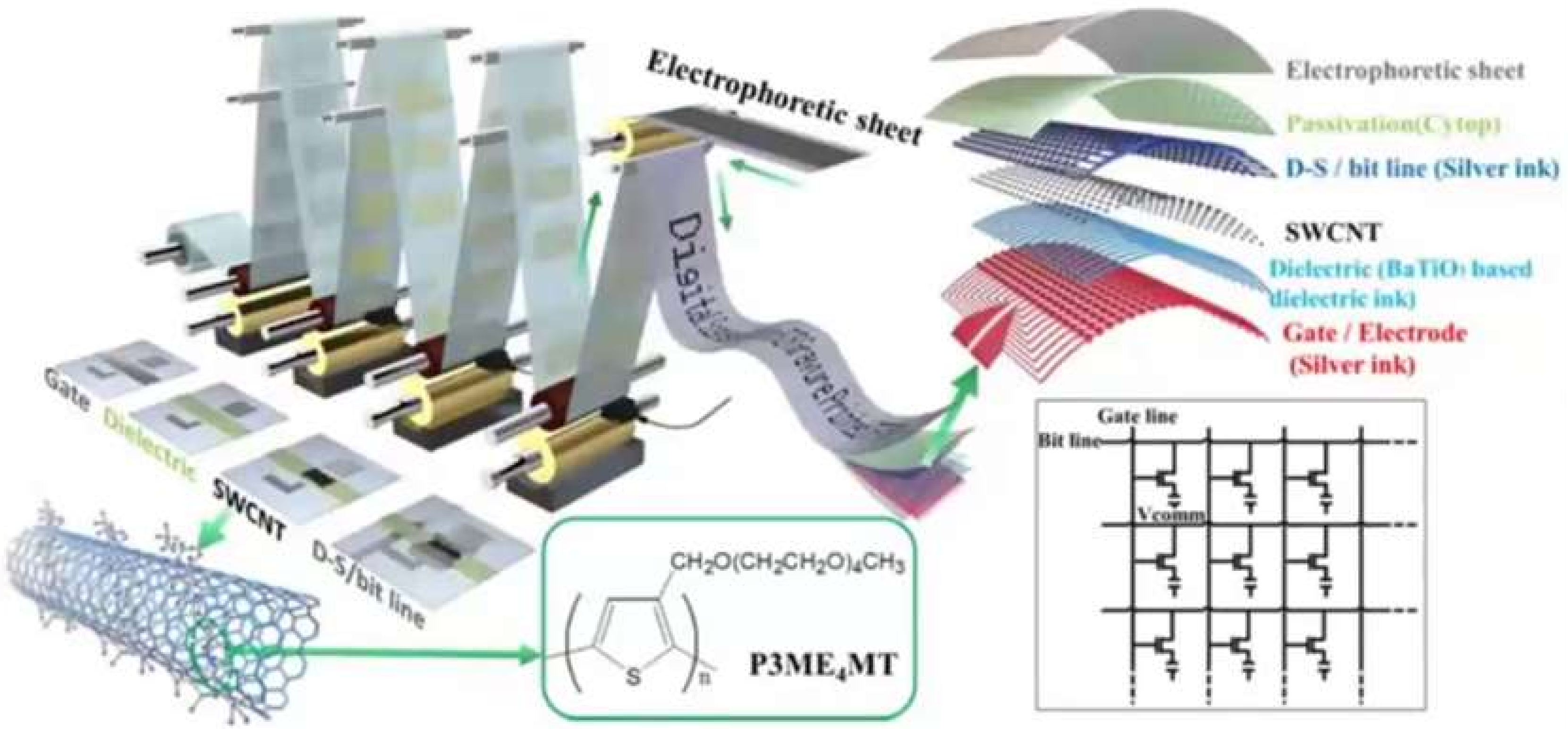
Precedence RESEARCH
Printed Electronics Market Share, By Region, 2024 (%)
24%
22%
46%
5%
3%
North America
Europe
Asia Pacific
Latin America
MEA
Source: https://www.precedenceresearch.com/printed-electronics-market



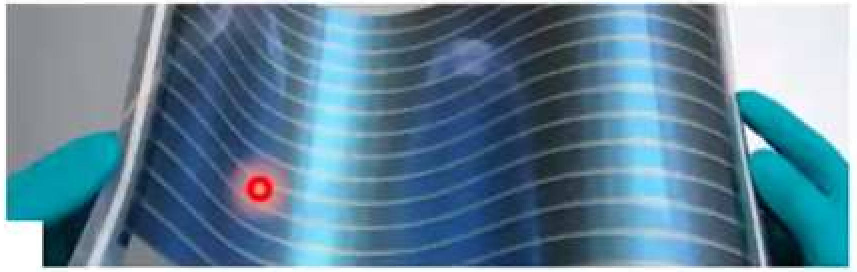
Precedence RESEARCH
Asia Pacific Printed Electronics Market Size 2024 to 2034 (USD Billion)
45
40
35
30
25
20
15
10
5
0
$7.74
$9.16
$10.85
$12.84
$15.21
$18.00
$21.32
$25.24
$29.89
$34.05
$38.54
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
Source: https://www.precedenceresearch.com/printed-electronics-market

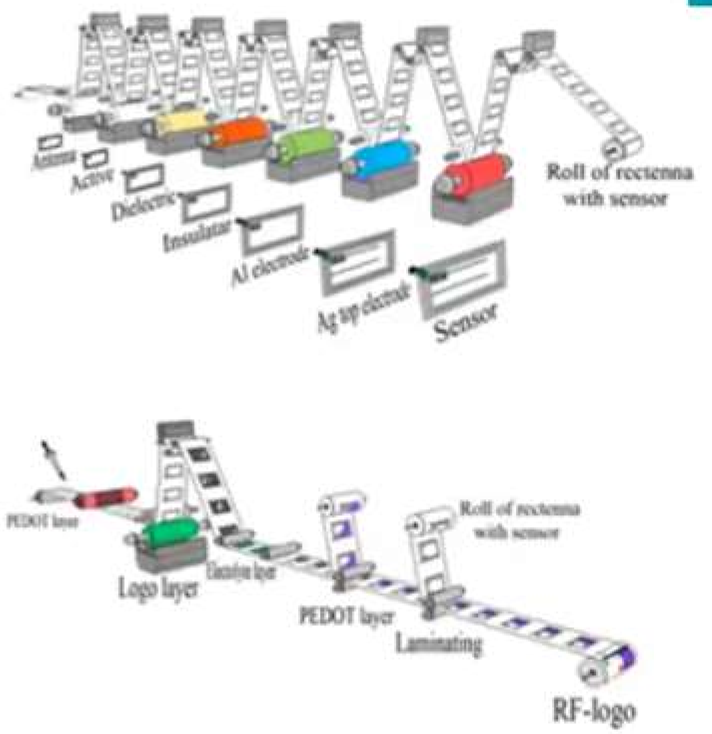


(a)
Printed pattern
Impression cylinder
Gravure cylinder
Doctor blade
Ink bath
Gravure printing
(b)
Printed pattern
Doctor blade
Impression cylinder
Printing plate cylinder
Anilox roller
Fountain roller
Ink bath
Flexographic printing

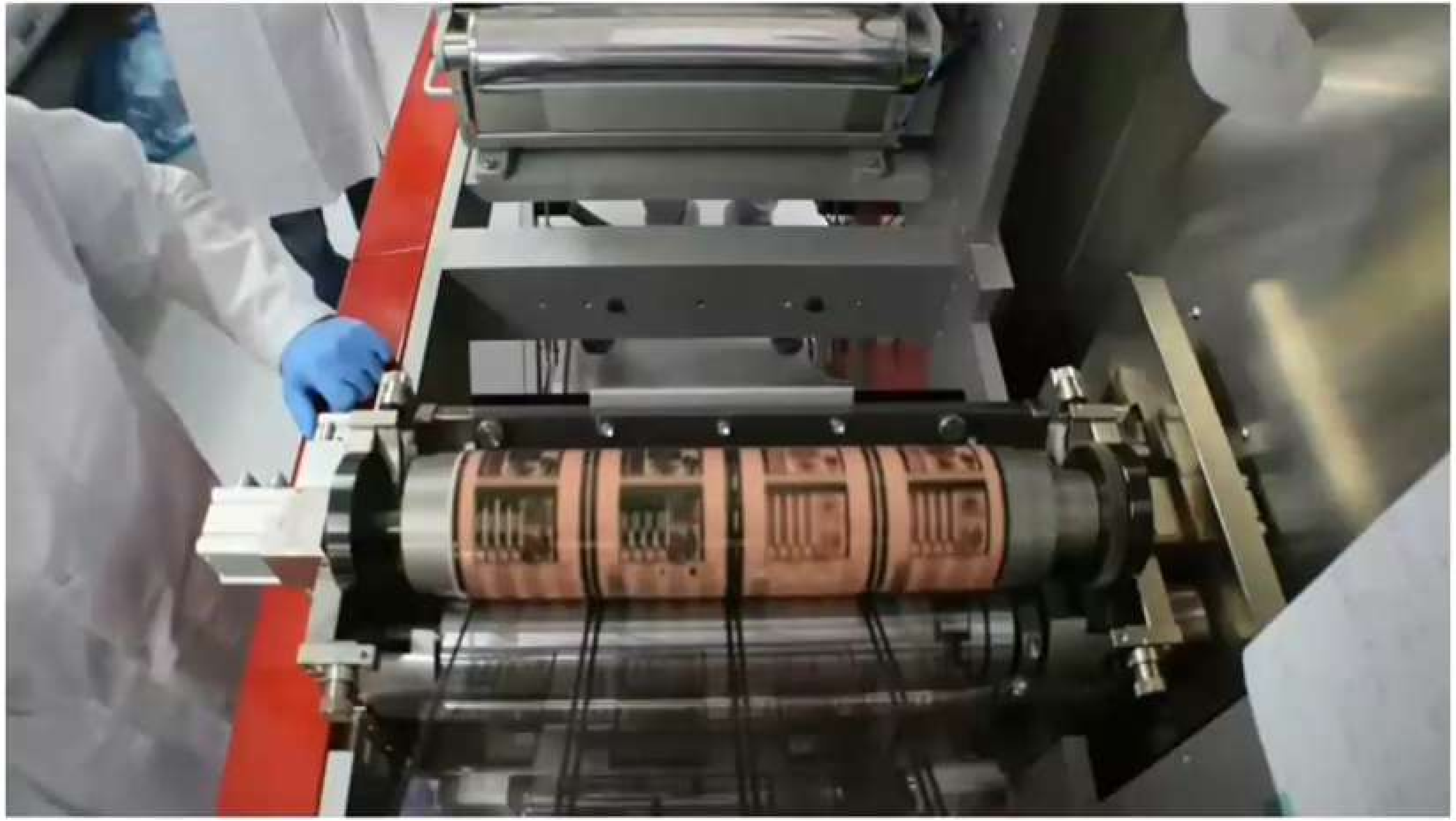


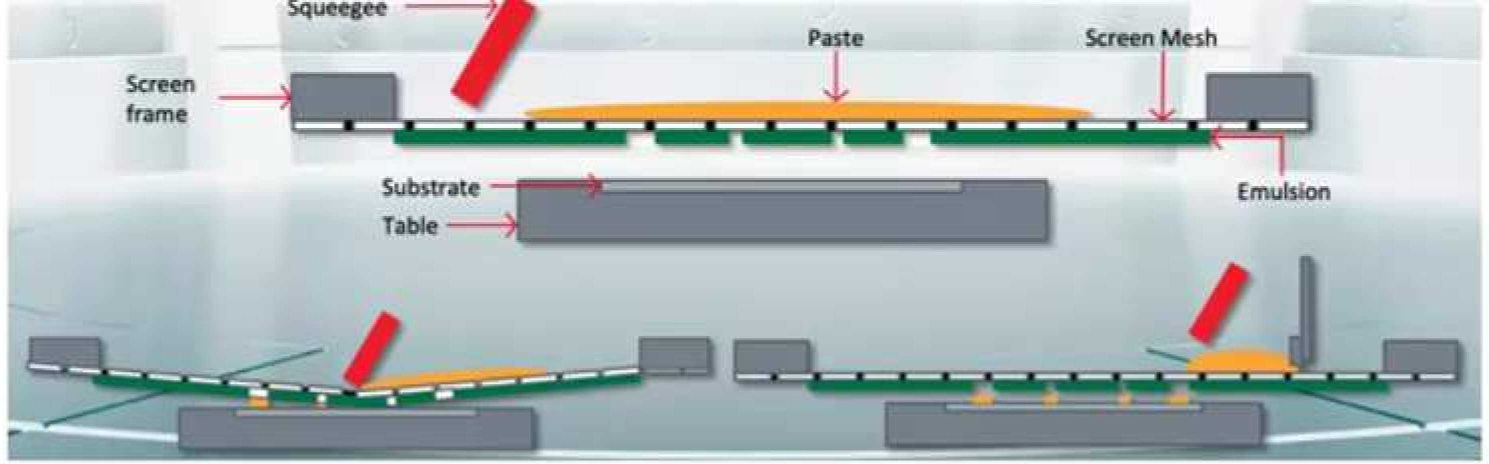
Electrophoretic sheet
Gate
Dielectric
SWCNT
D-S/bit line
$CH_2O(CH_2CH_2O)_4CH_3$
P3ME$_4$MT
Electrophoretic sheet
Passivation(Cytop)
D-S / bit line (Silver ink)
SWCNT
Dielectric (BaTiO$_3$ based dielectric ink)
Gate / Electrode (Silver ink)
Gate line
Bit line
Vcomm

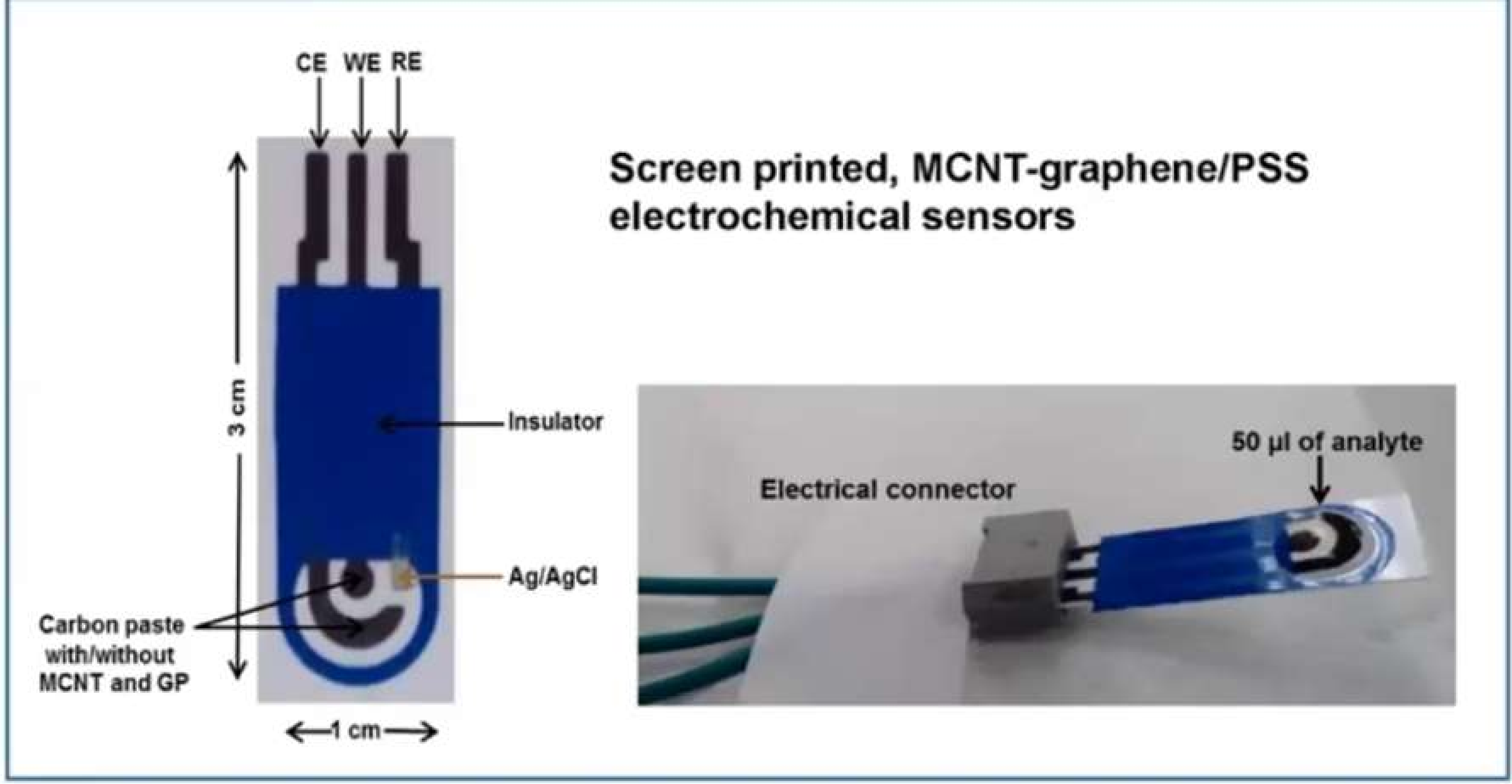


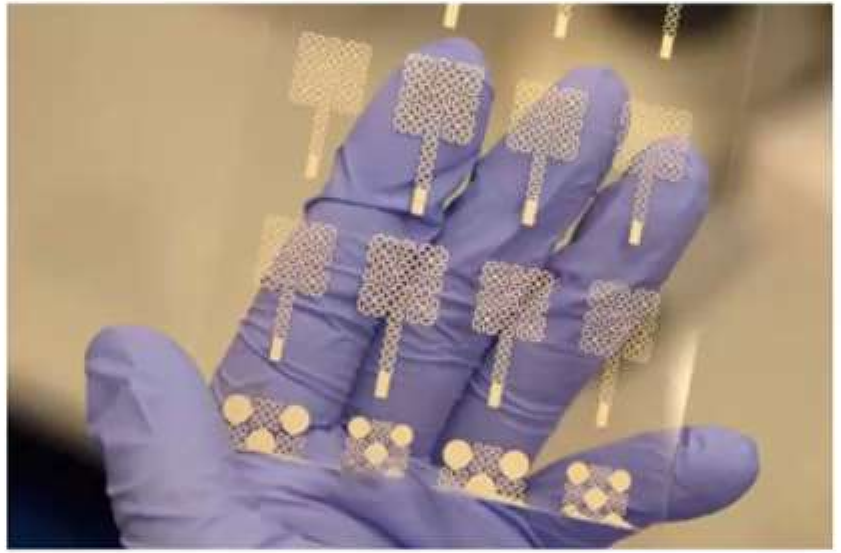


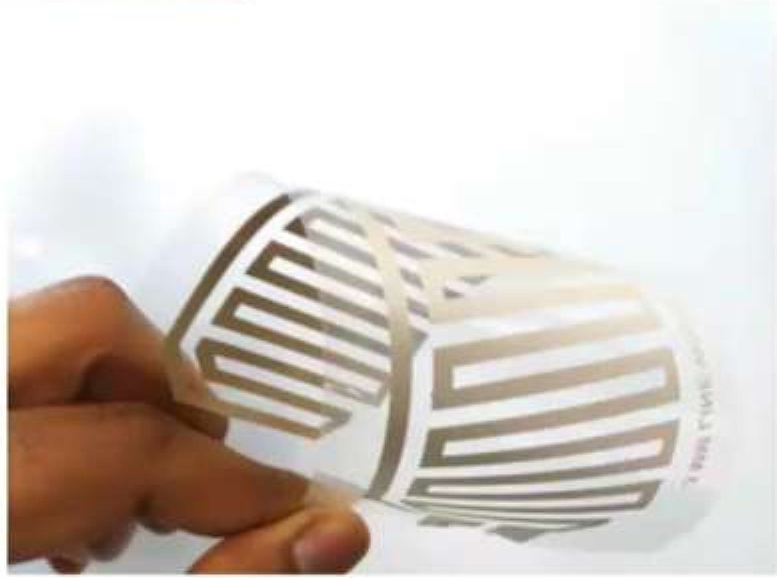
Antenna
Active
Dielectric
Insulator
Al electrode
Ag top electrode
Sensor
Roll of rectenna with sensor
PEDOT layer
Logo layer
PEDOT layer
Laminating
Roll of rectenna with sensor
RF-logo




Squeegee
Paste
Screen Mesh
Screen frame
Substrate
Table
Emulsion


CE WE RE
Screen printed, MCNT-graphene/PSS electrochemical sensors
3 cm
Insulator
Ag/AgCl
Carbon paste with/without MCNT and GP
1 cm
Electrical connector
50 µl of analyte



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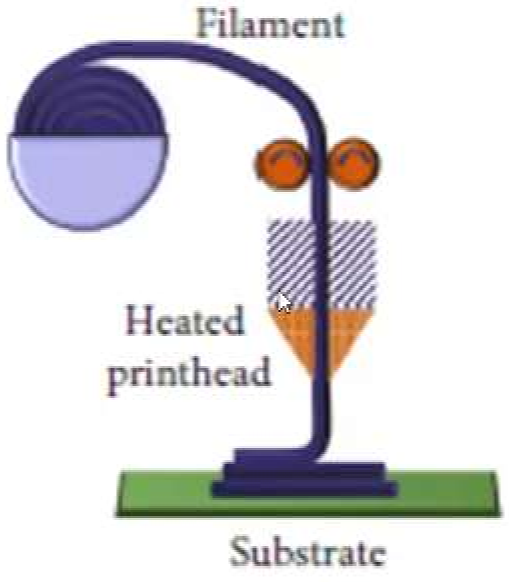
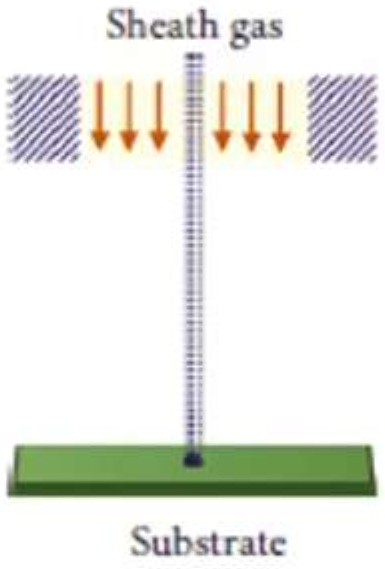
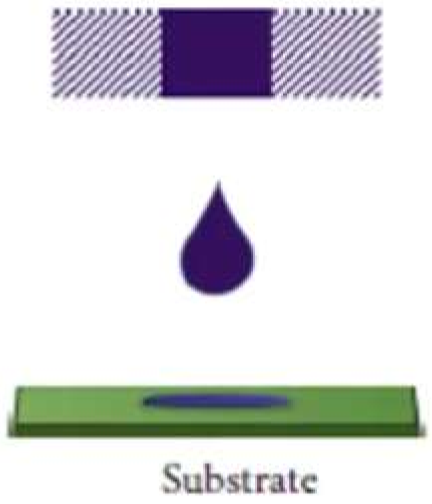
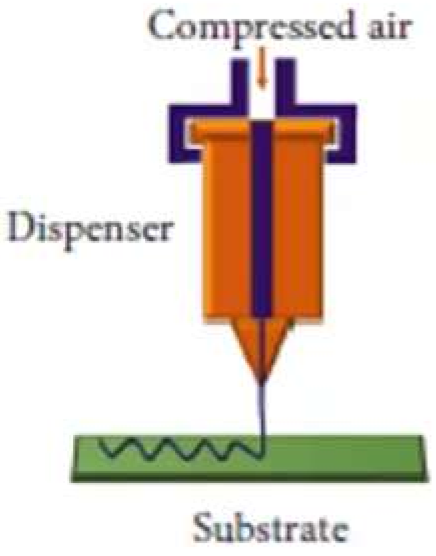
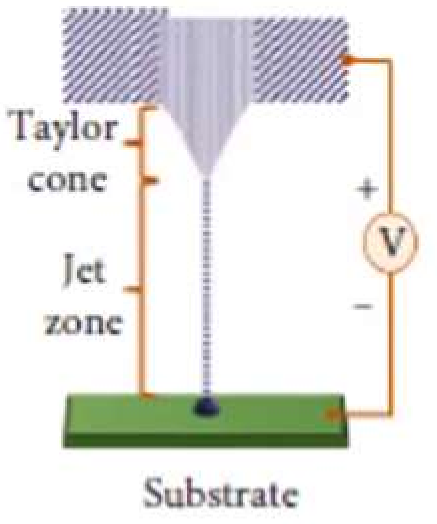
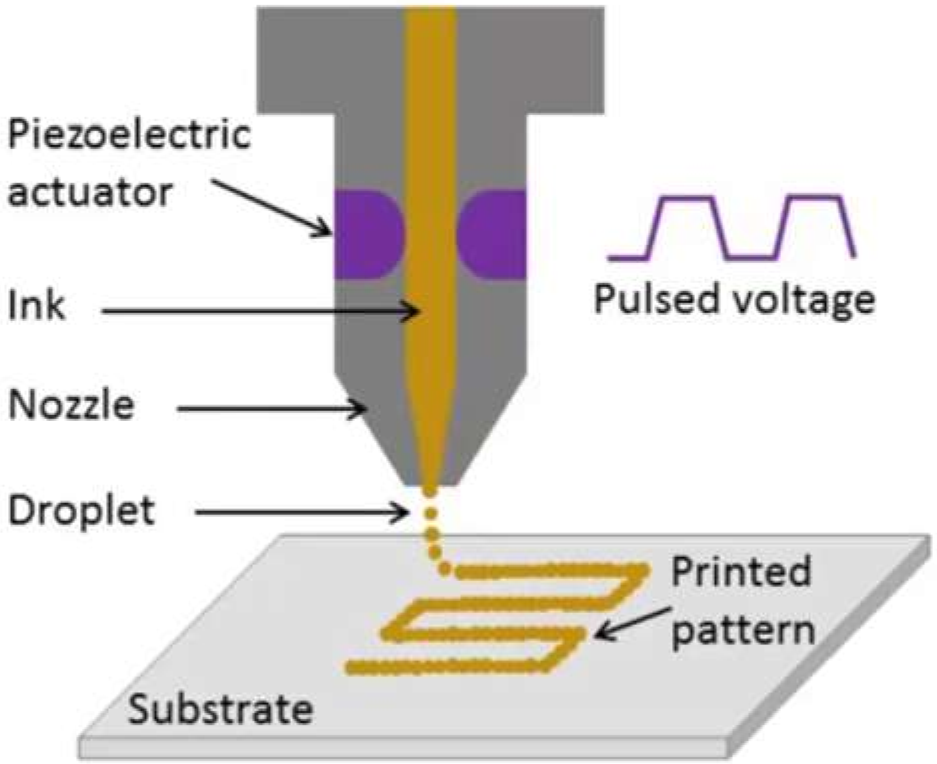
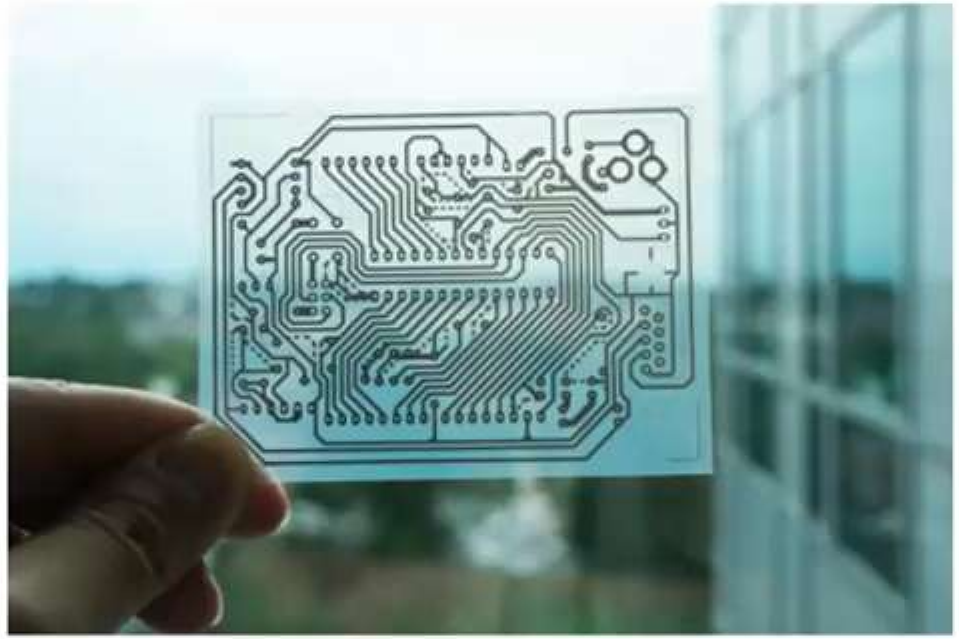
TECHNOLOGICAL
INSTITUTE

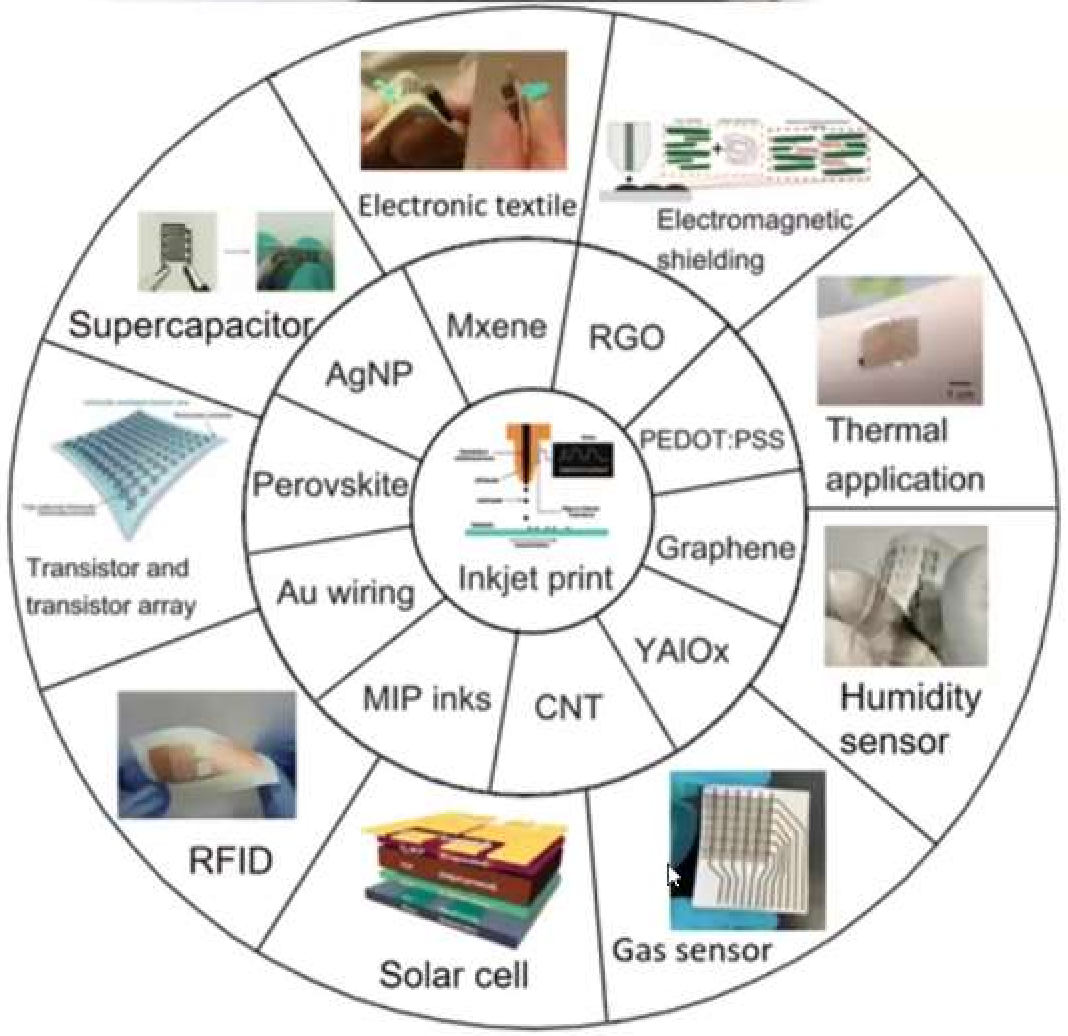
Non-Contact Printing Technologies

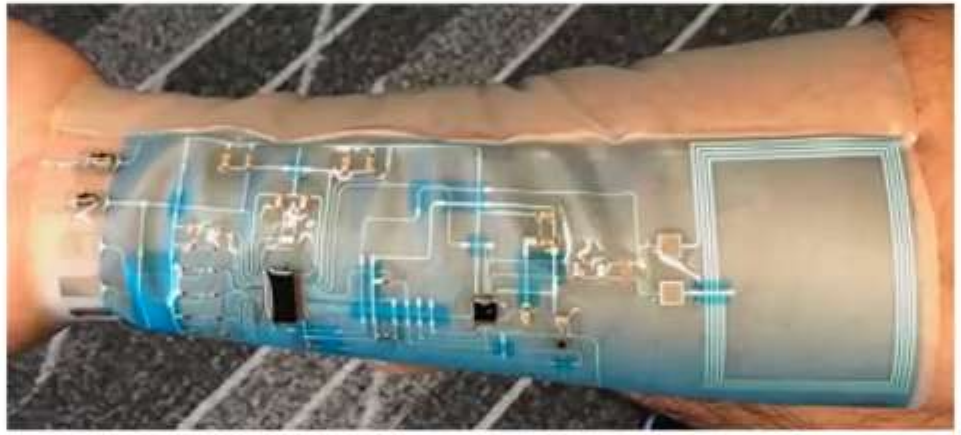
Fused filament fabrication (FFF) [18, 233]	Aerosol jet printing	Inkjet printing [33]	Direct ink writing (DIW)	Electrohydrodynamic printing (E-jet) [44, 234, 235]
				
Technology				
Heated nozzle by thermal energy	Aerodynamic focussing	Thermal or piezoelectric	Pneumatic or syringe nozzle	Driven by electric field
Flexibility of printed element				
★★★☆☆	★★★★☆	★★★★☆	★★★★★	★★★★★
Stretchability of printed element				
★★☆☆☆	★★★★☆	★★★☆☆	★★★★★	★★★★★
Flexible/stretchable element (FSE) material				
Thermoplastic, composites made into filaments	Conductive inks, dielectrics of viscosity (1–1000 cP)	Any low viscosity inks (1–20 cP)	Any type of flowable ink	Polymer, nanoparticle inks
Dimensional accuracy				
50–500 μm	10–250 μm	20-100 μm	250 nm–100 μm	Few hundred nm-μm

Inkjet Printing





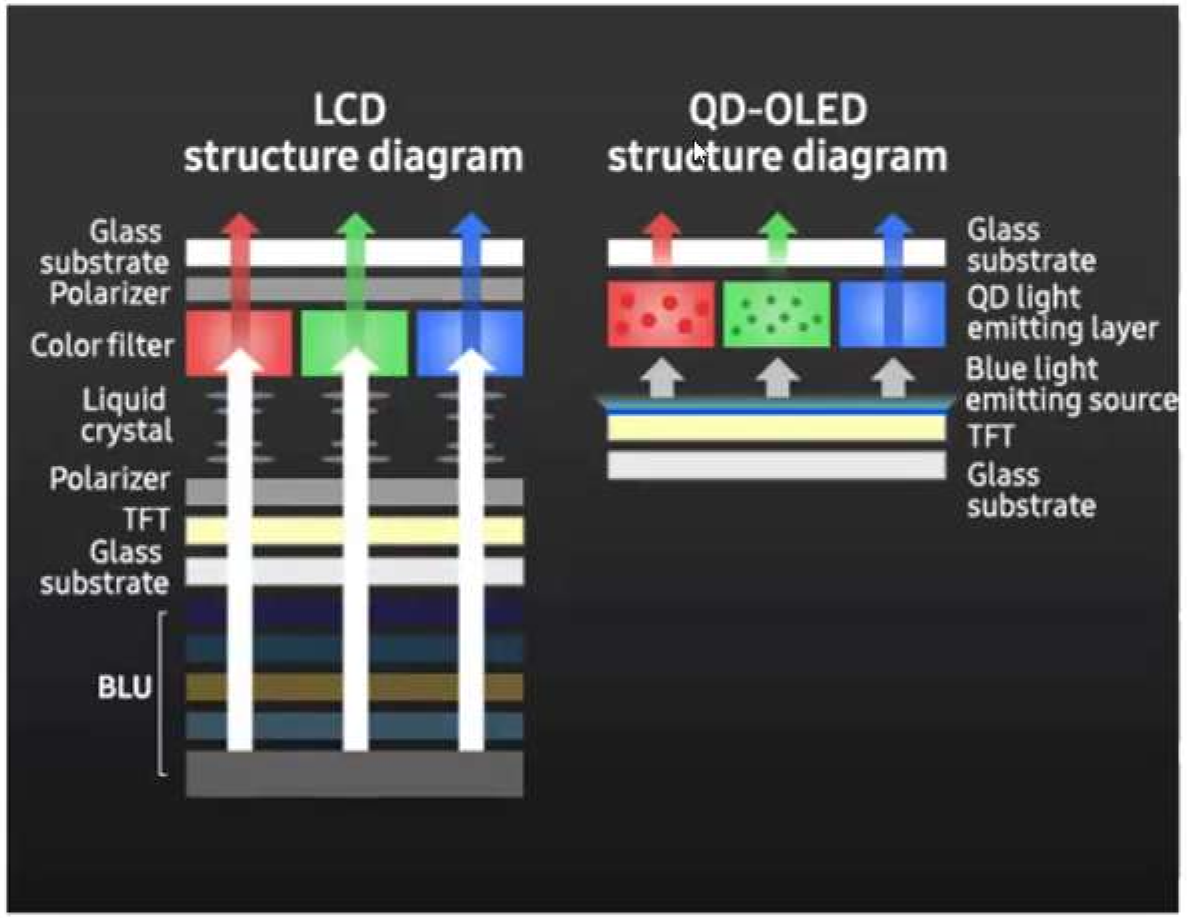




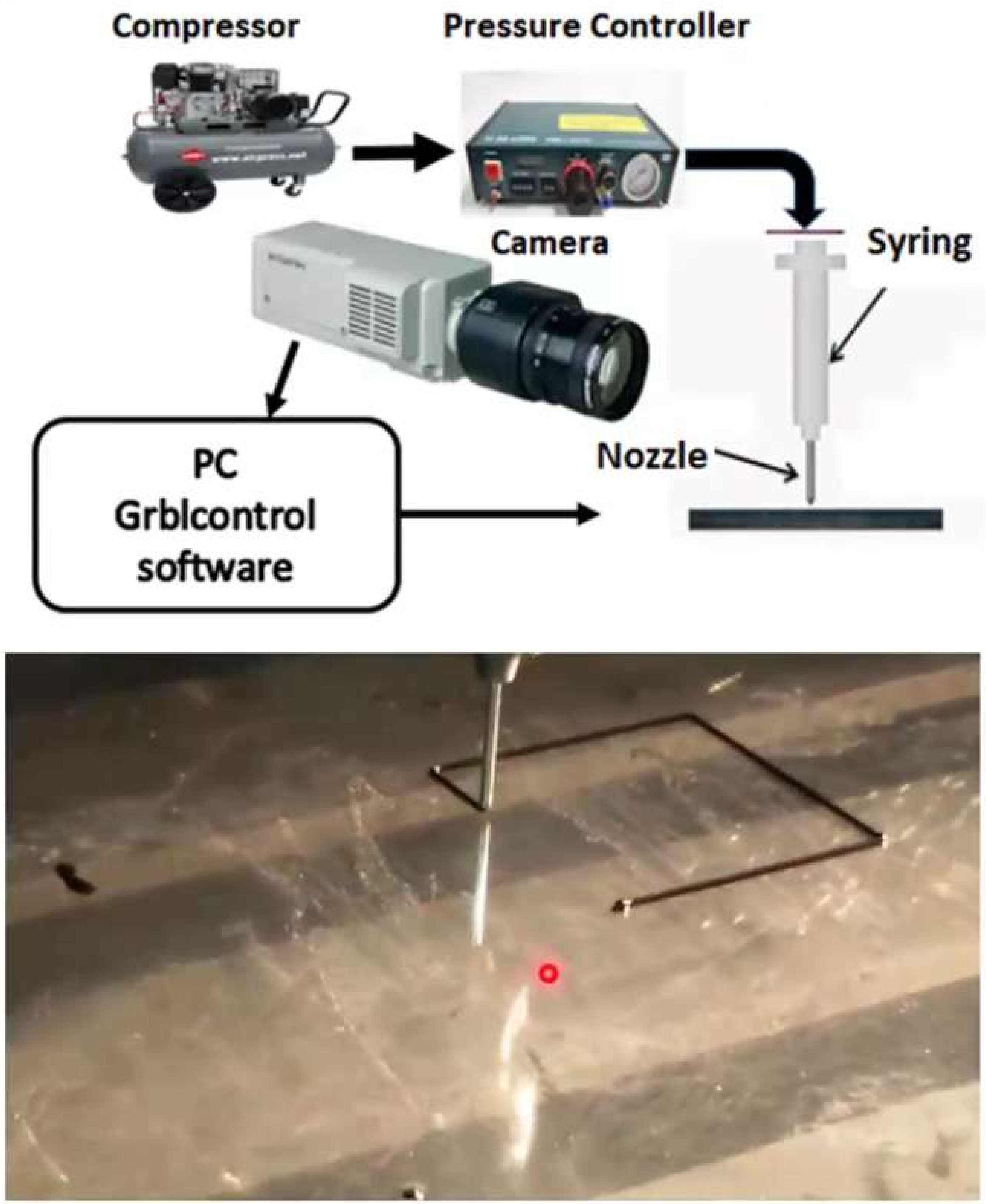
Process	normal 4 Mask	Printed TFT 1st stage	Printed TFT 2nd state
Photo	4	2	0
CVD	2	0	0
Sputter	3	2	0
Cleaning	5	6	6
Wet etch	4	1	0
Strip	4	2	0
Dry etch	3	1	0
Printing	-	4	6
Total	25	18	12
Step reduce	-	28%	52%

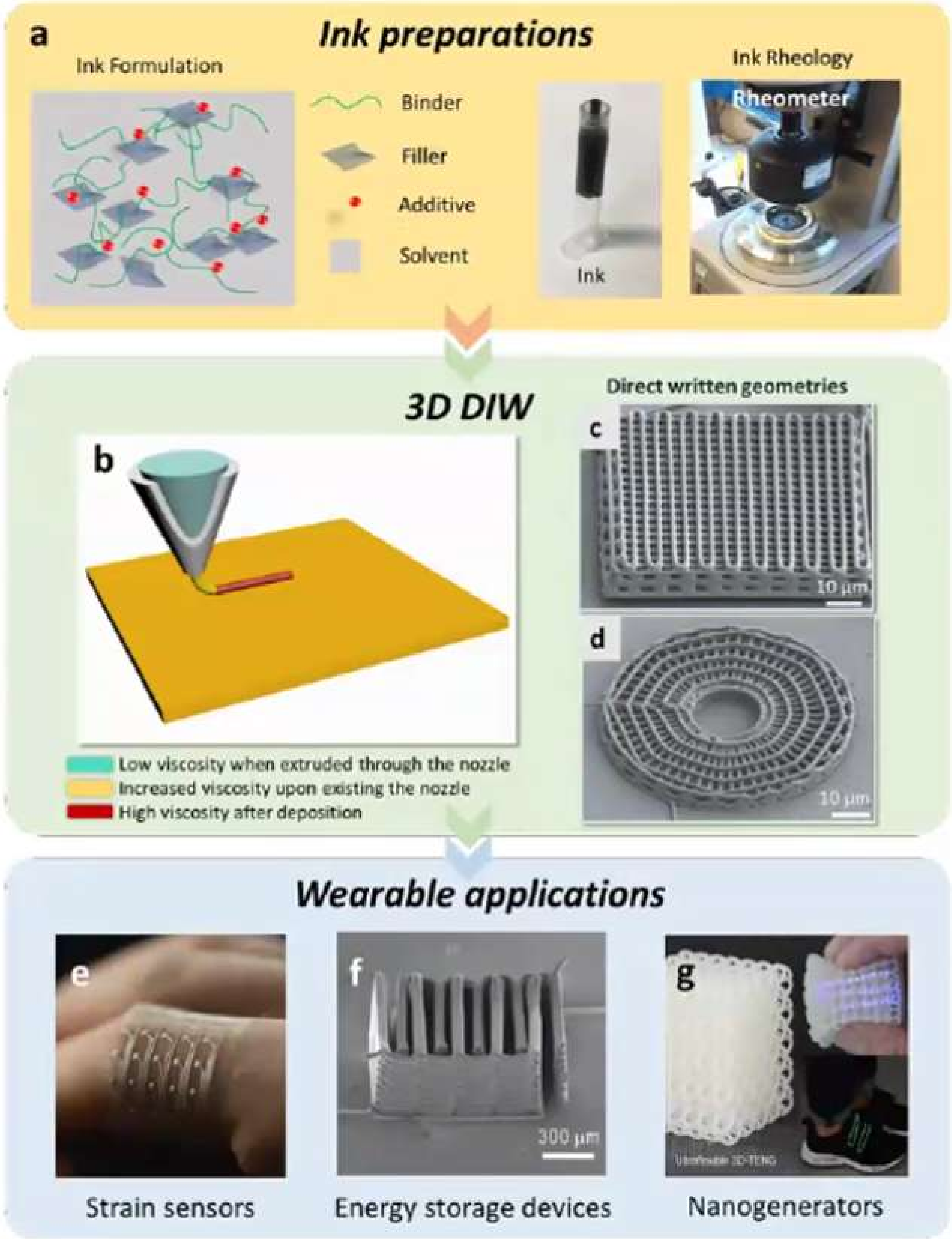
1st stage : Gate, Active, Passi. → Printing
2nd stage : all TFT Layer Printing.

8.5-Gen Inkjet Printer for Display Manufacturing

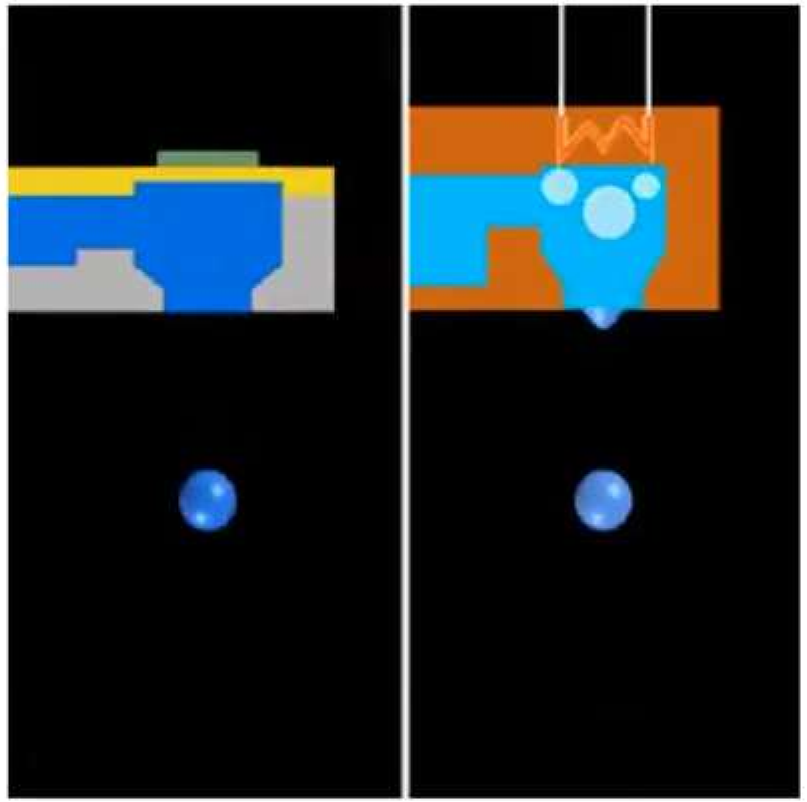


Micro Extrusion DIW Printing

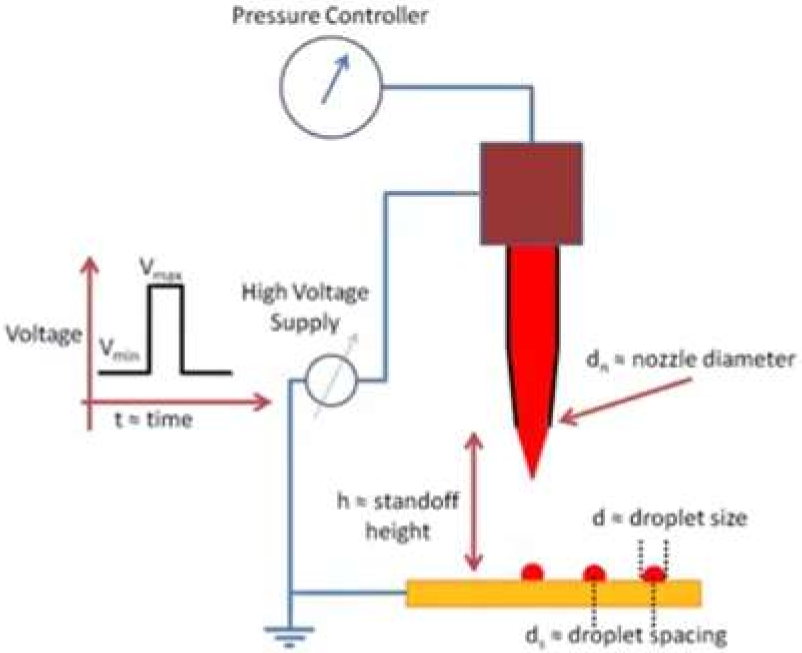


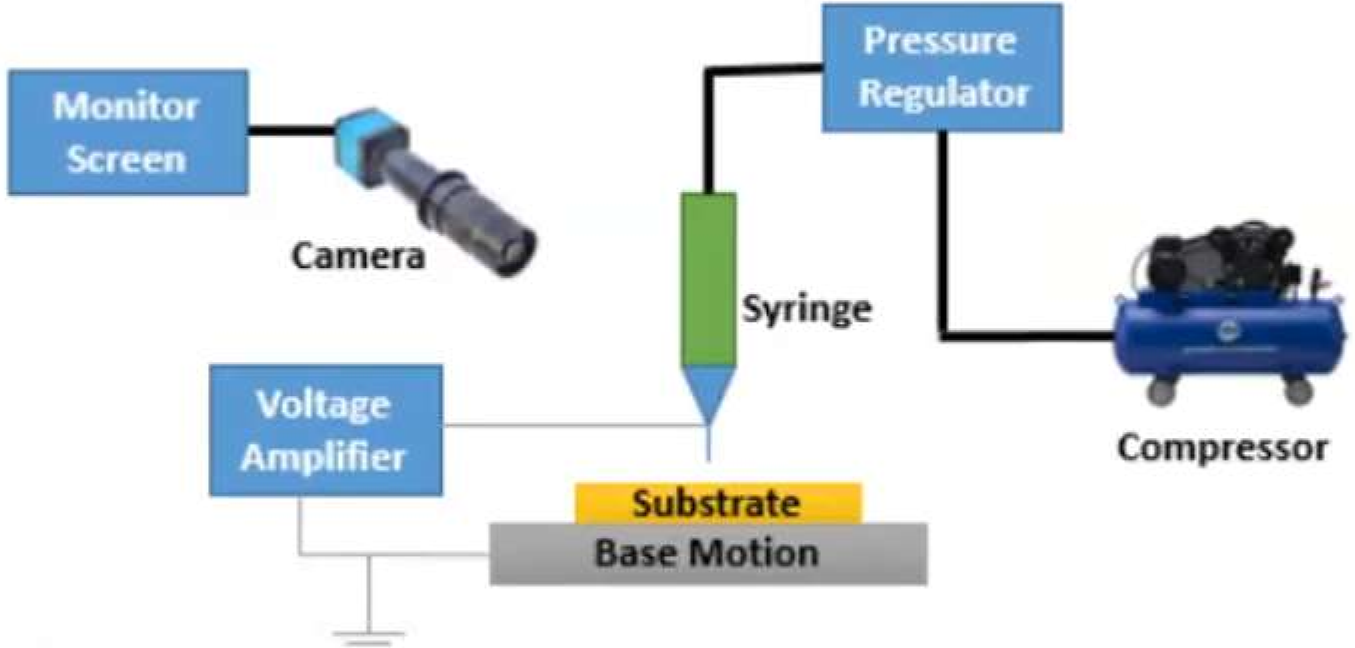


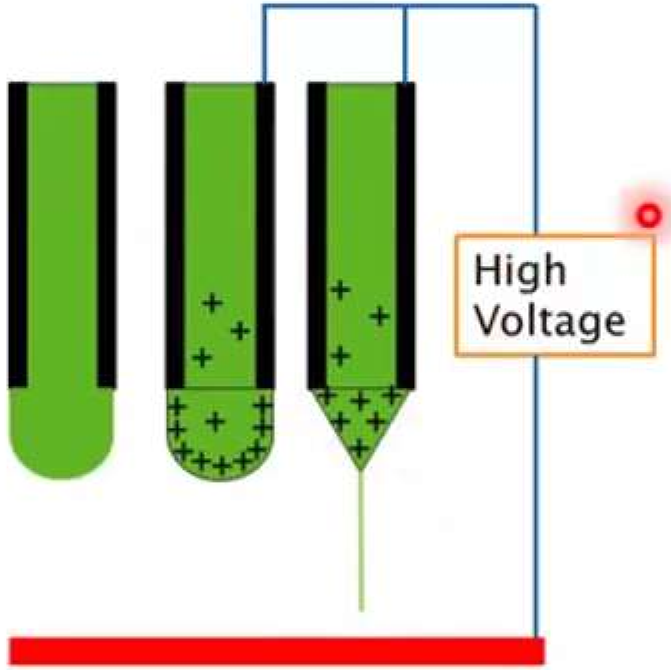
Electrohydrodynamic (EHD) Printing

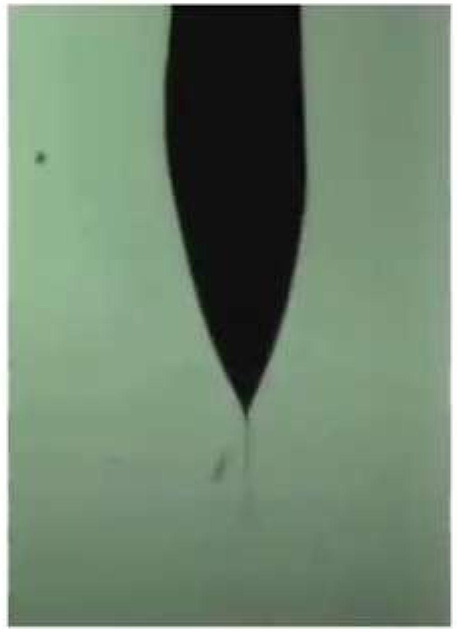


Piezoelectric Thermal









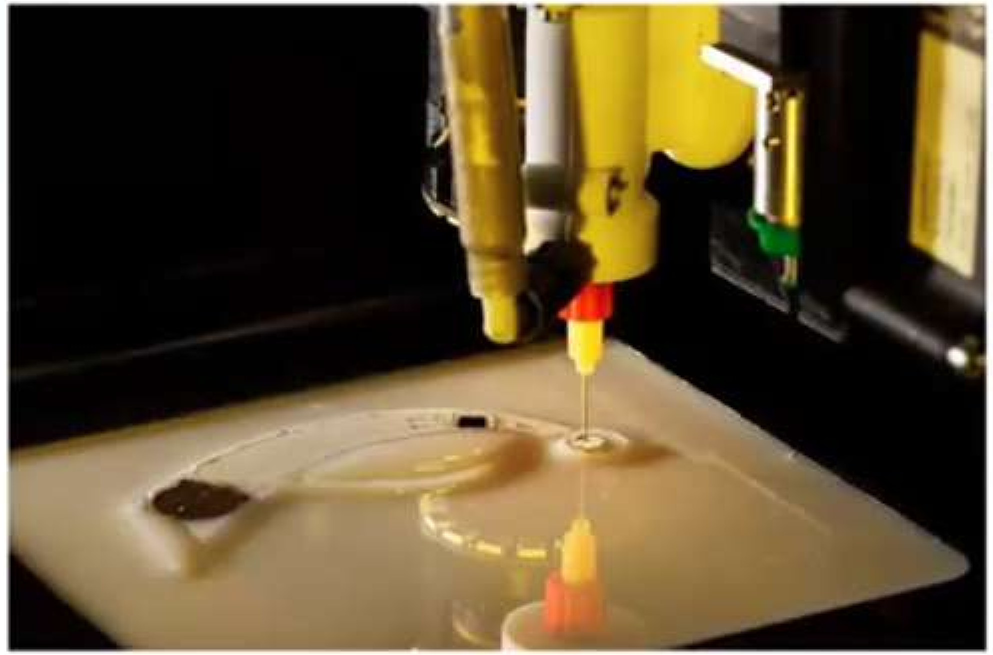
Continuous EHD

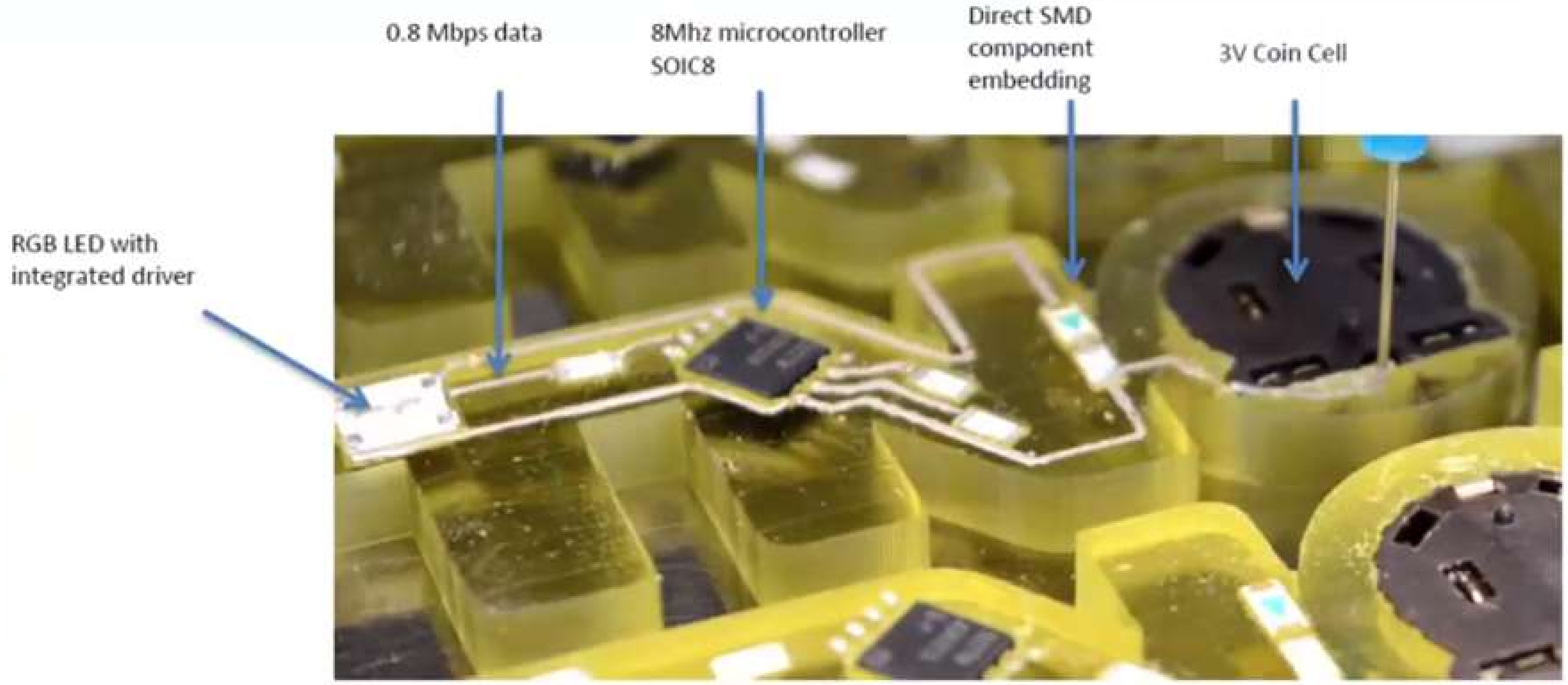
On-Demand EHD

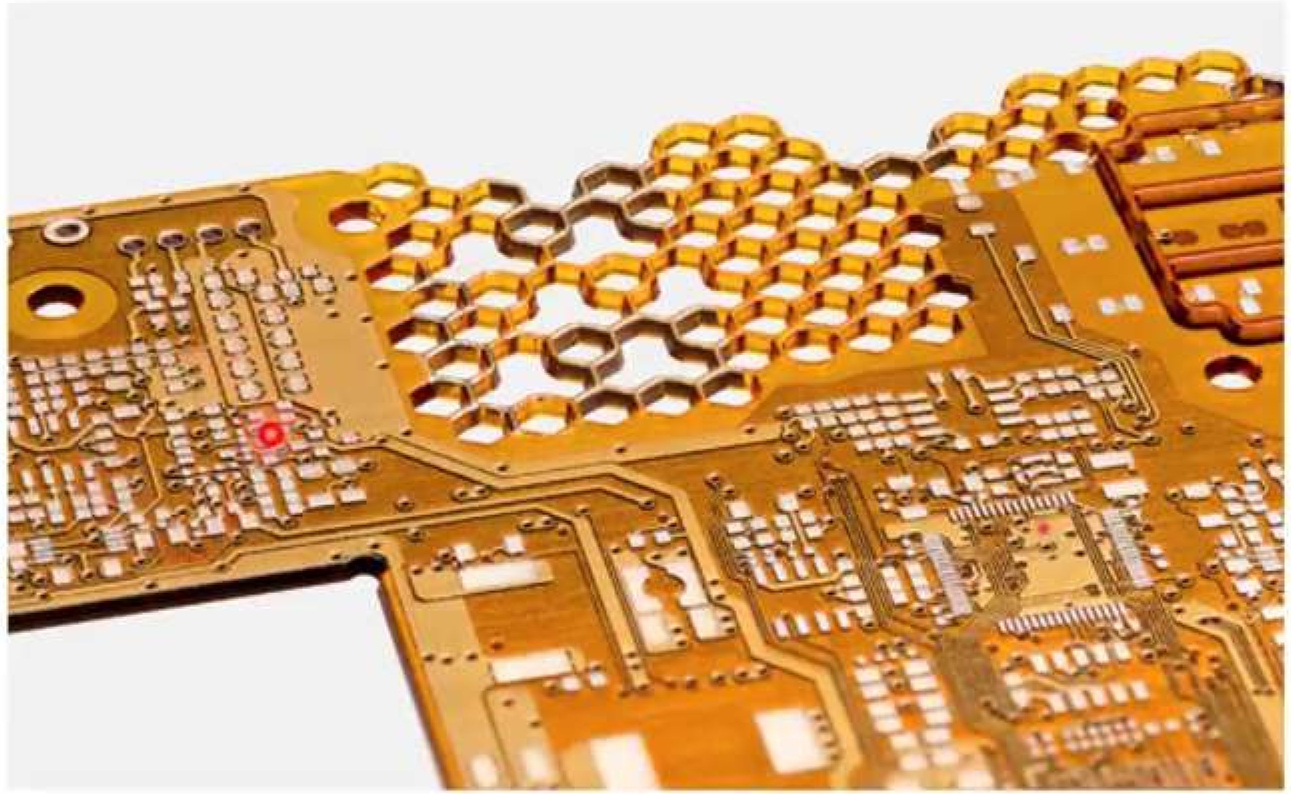
Benefits:

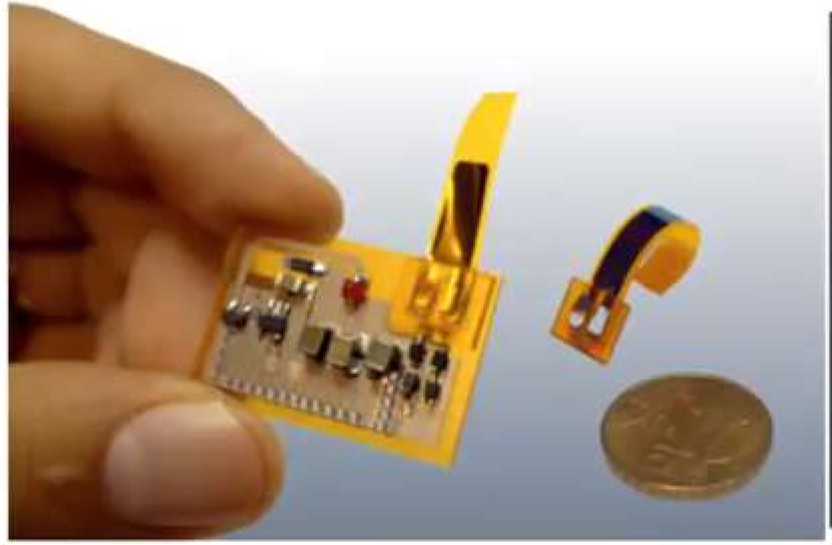
1. Liquid is pulled out from the nozzle
2. No mechanical parts (electric field)
3. High viscosity inks
4. Continuous and DOD mode
5. Patterns resolution less than10 µm
6. Thin film deposition (electrospray)

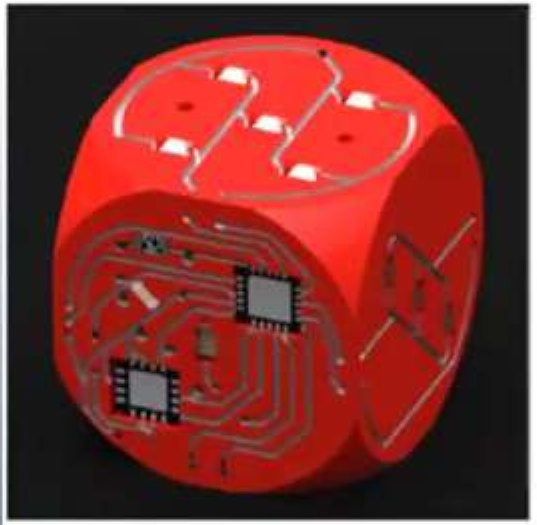
3D Printed Structural Electronics



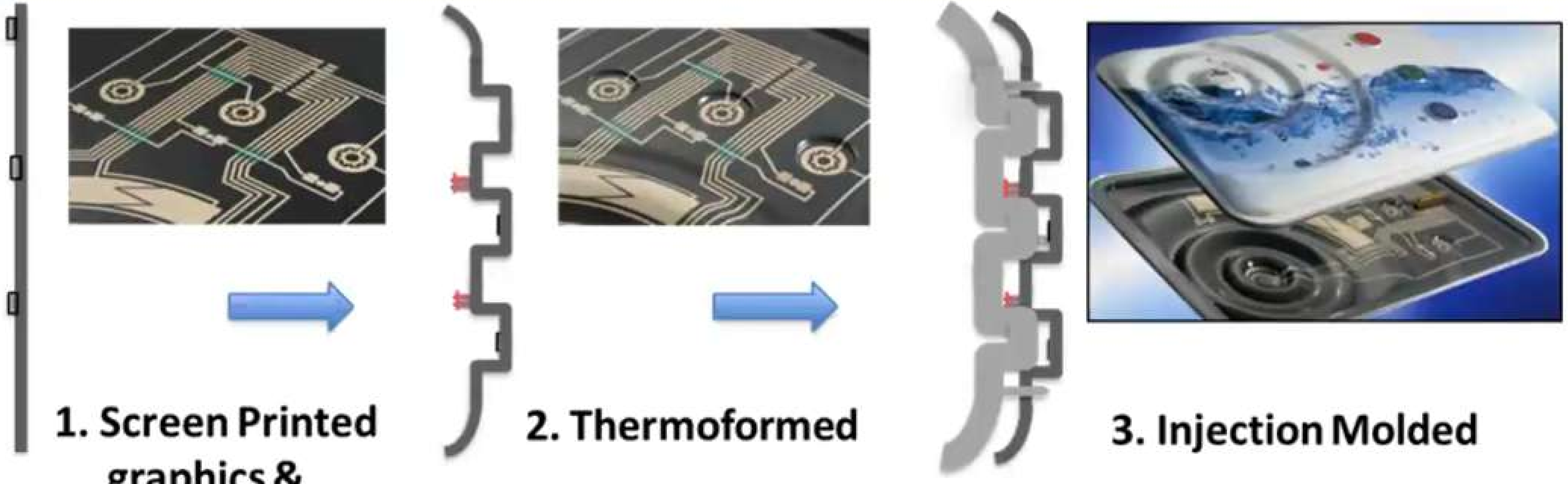








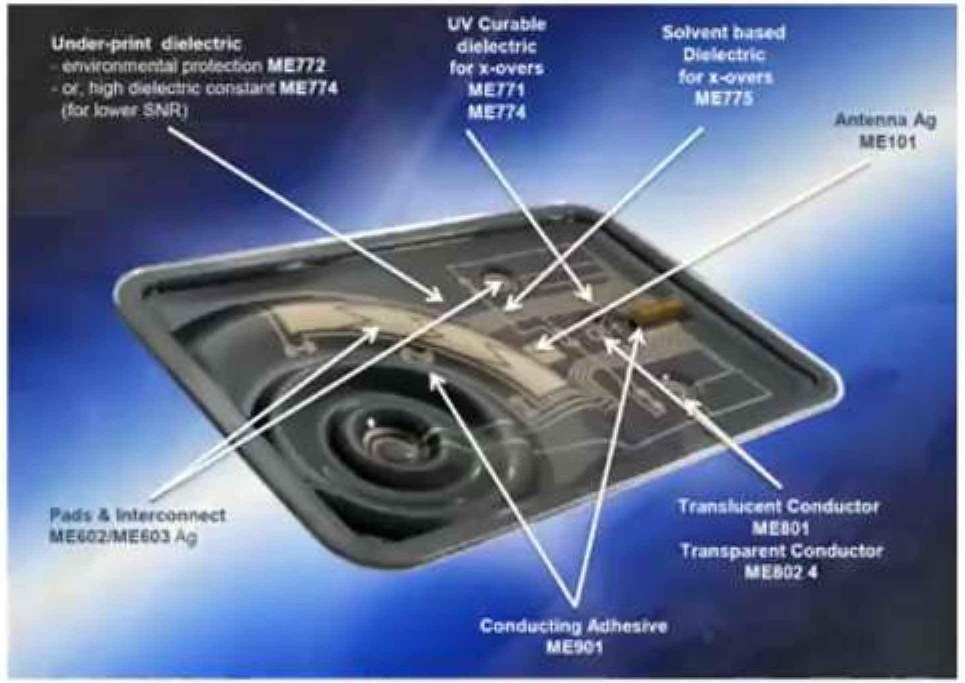
In-Mold Electronics



1. Screen Printed graphics & functional inks

2. Thermoformed

3. Injection Molded



A Traditional Control Panel Tear-Down

578 g
Depth **60** mm
> **25** tools
> **60** assemblies

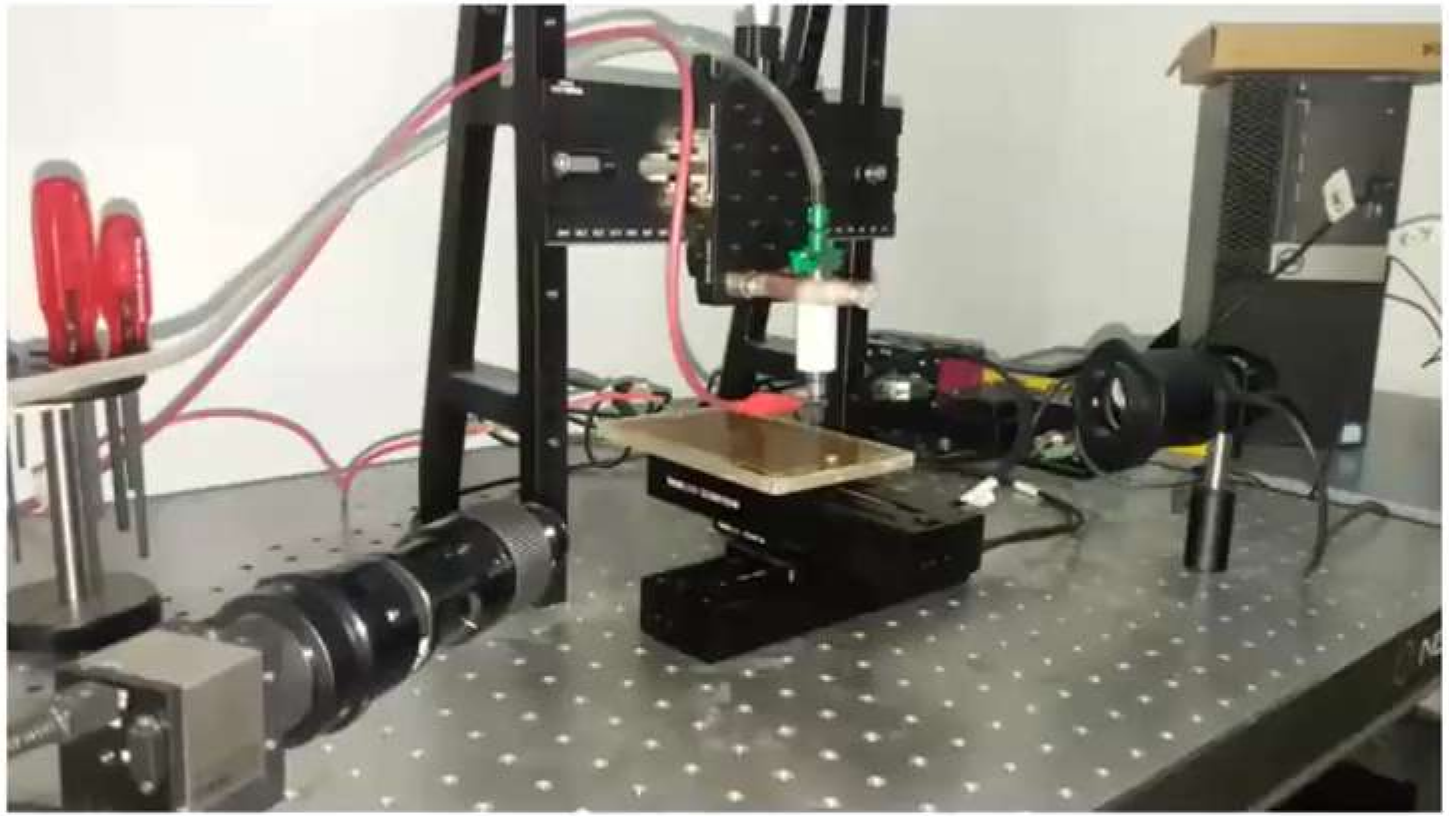
Structural Electronics Control Panel Tear-Down

160 g
Depth **3** mm
2 tools
1 part

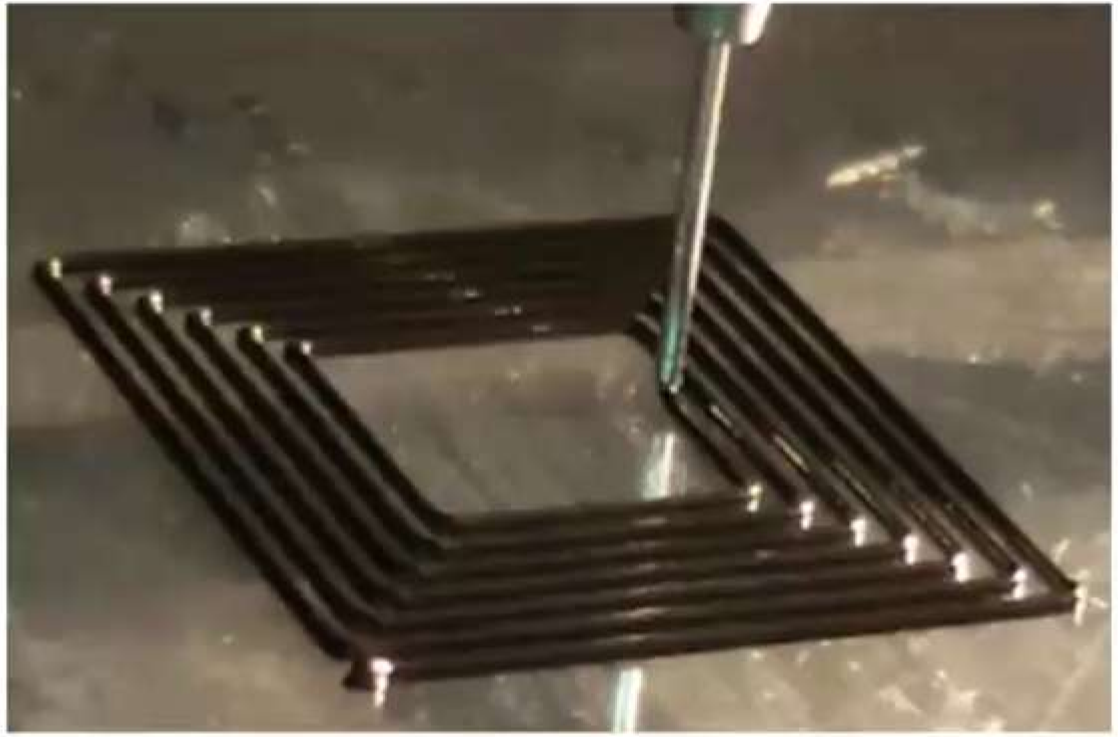
Research at GIK Institute

Printed Sensors

- Printed Strain gauge
- Printed Flex sensor
- Printed Humidity sensor
- Printed Temperature sensor
- Printed thermocouple/TEG
- Printed Micro-heaters



*Sensors were printed at **Printed Electronics Lab**, Faculty of Mechanical, Ghulam Ishaq Khan Institute of Science and Technology, Topi-Swabi, Pakistan.*



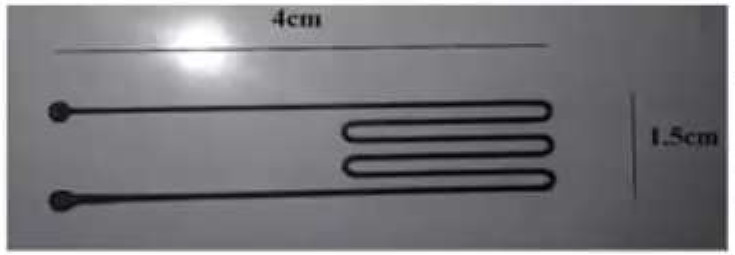
Printed Flex Sensor

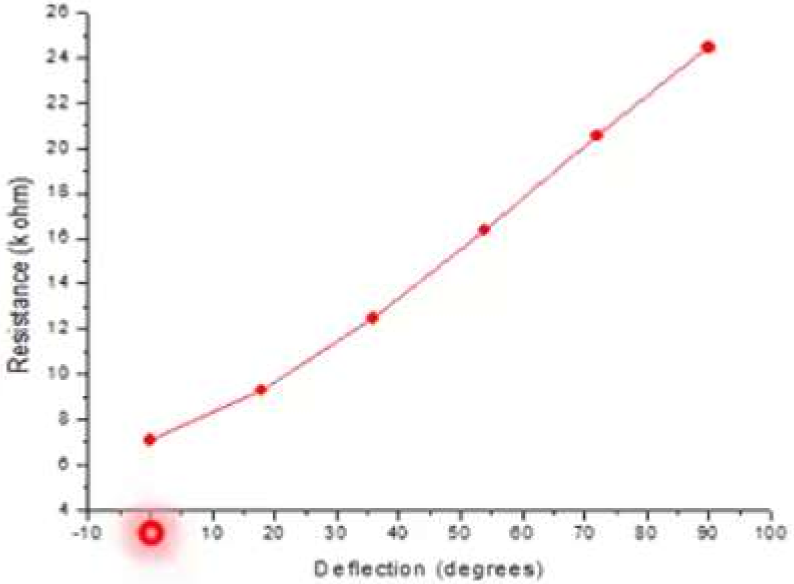
Fabrication of flex sensors through direct ink write technique and its electrical characterization: ***Applied Physics A [20]***

Material:
- Carbon

Substrate:
- PET

Dimension:
- 4 X 1.5 cm

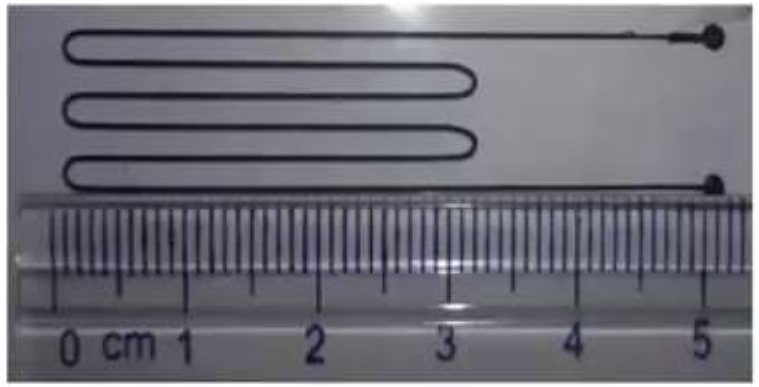


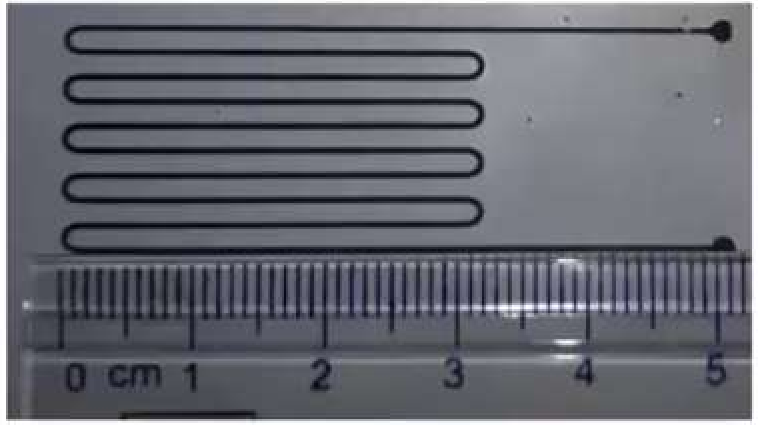


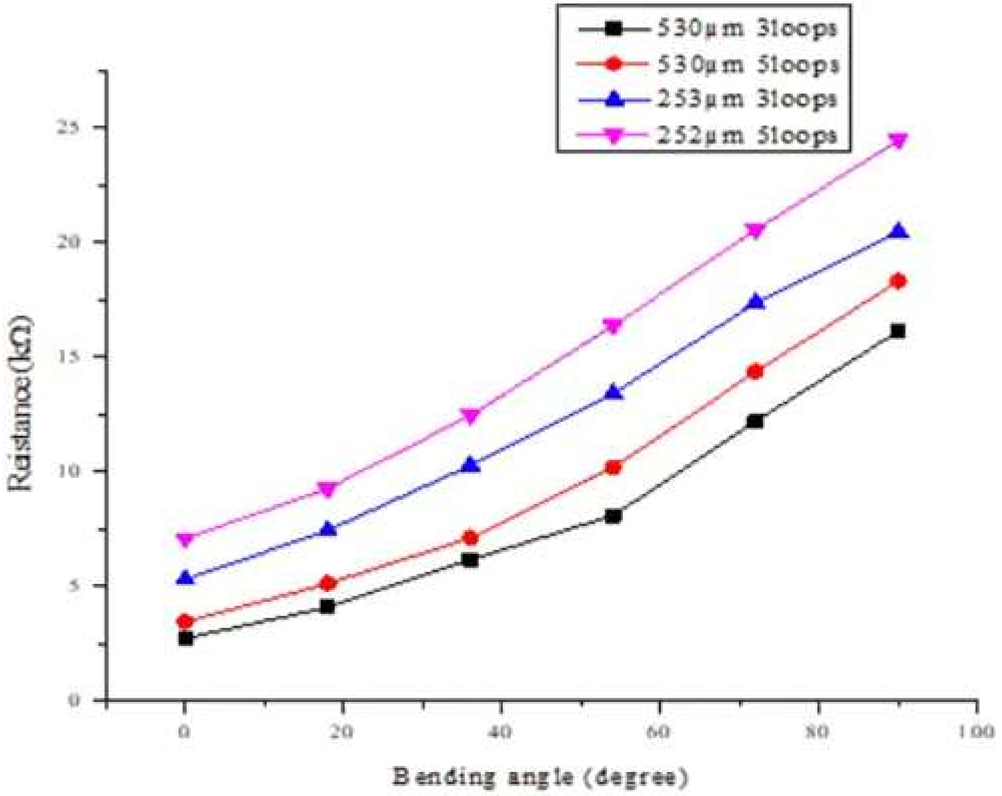
Controlling Parameters:
- Pressure
- Feed rate
- Stand-off distance

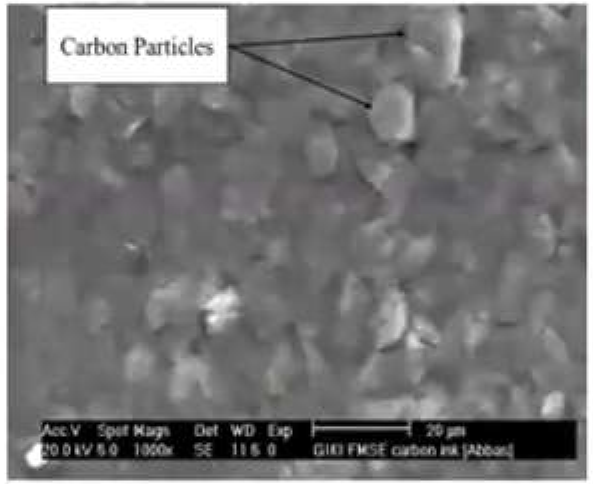
200µm nozzle
- Pressure 84 psi
- feed rate 1.2mm/s
- standoff distance 0.4mm

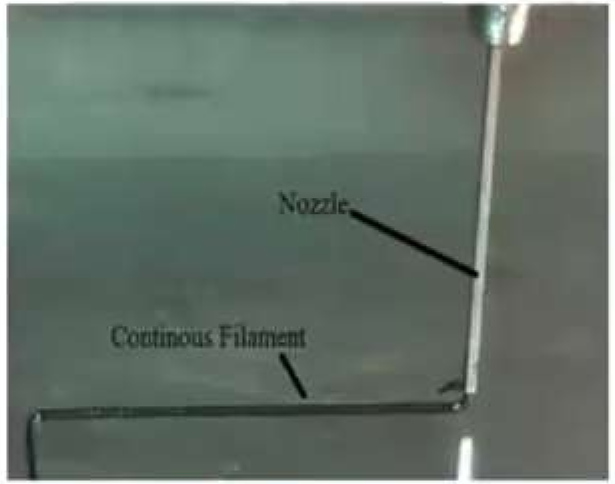
Printed width:
- 253 µm











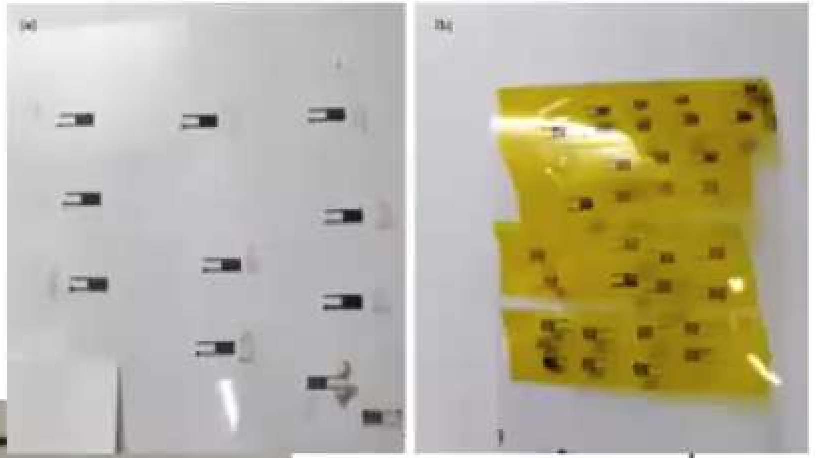
Printed Strain Gauge

Fabrication of cost effective and high sensitivity resistive strain gauge using DIW. ***Sensors and Actuators A: Physical [21]***

Material:
- Carbon Paste

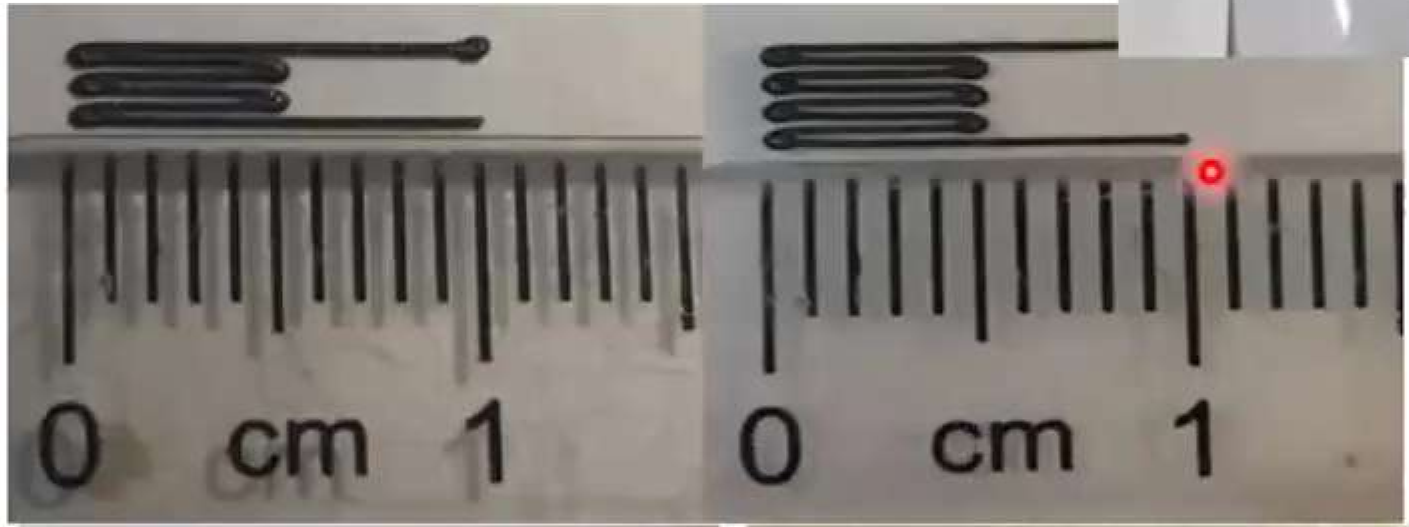
Substrate:
- PET

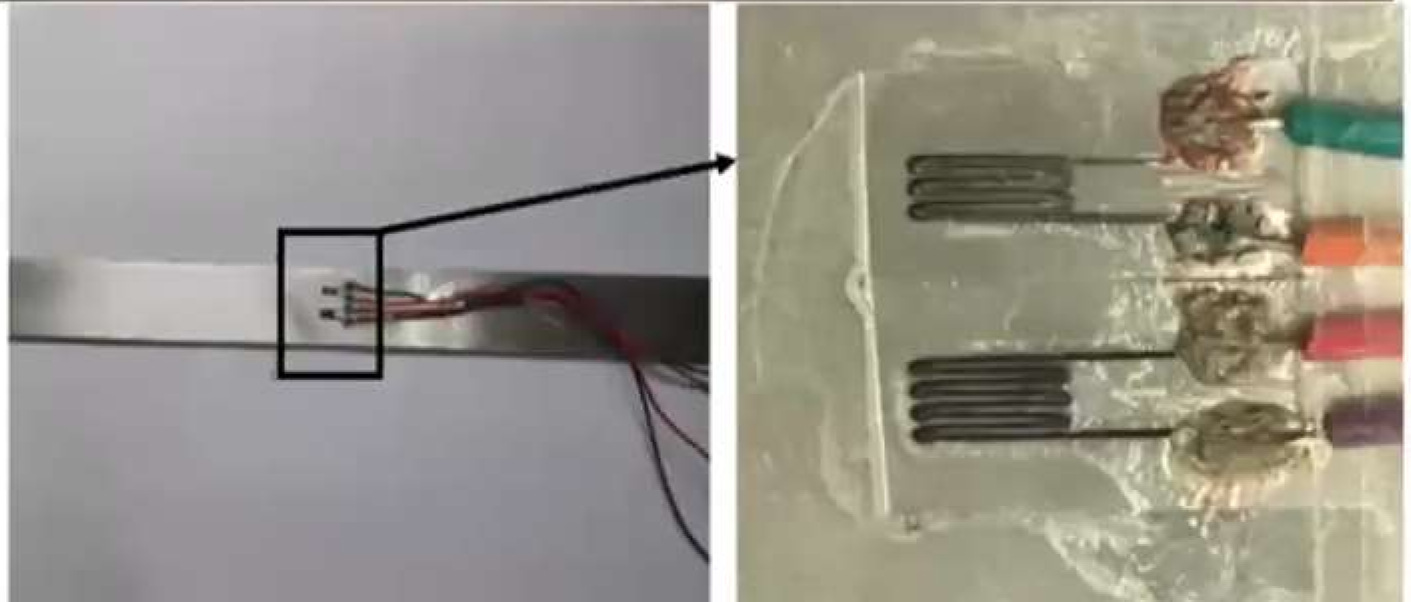
Printed width:
- Less than 250 µm

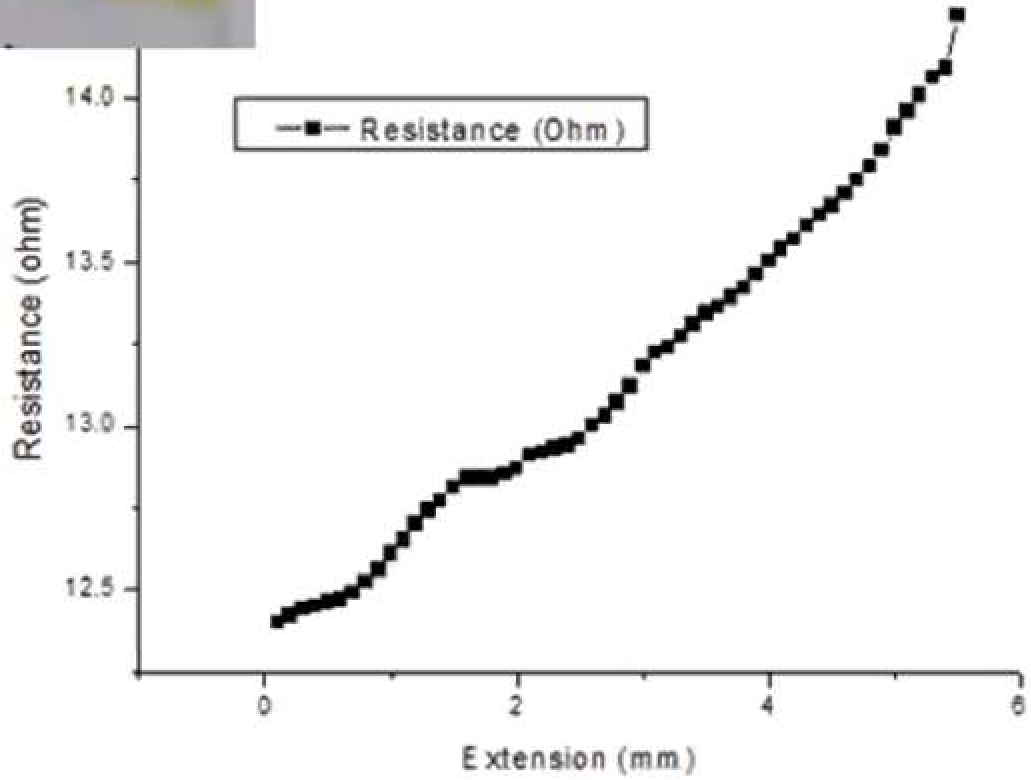


Controlling Parameters:
- Pressure
- Feed rate
- Stand-off distance

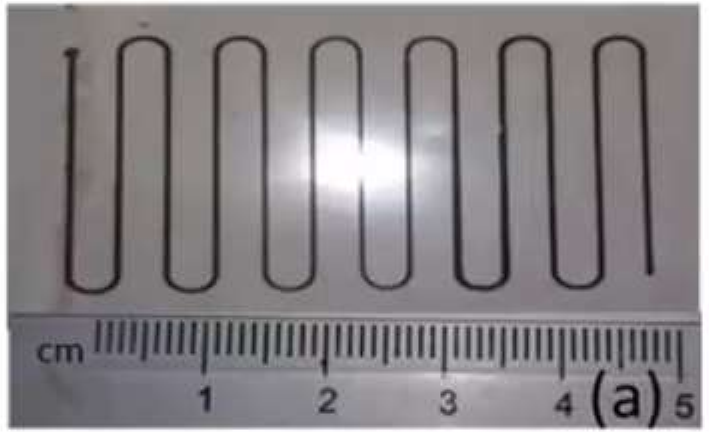
200µm nozzle
- Pressure 50 psi
- feed rate 1mm/s
- standoff distance 0.1mm



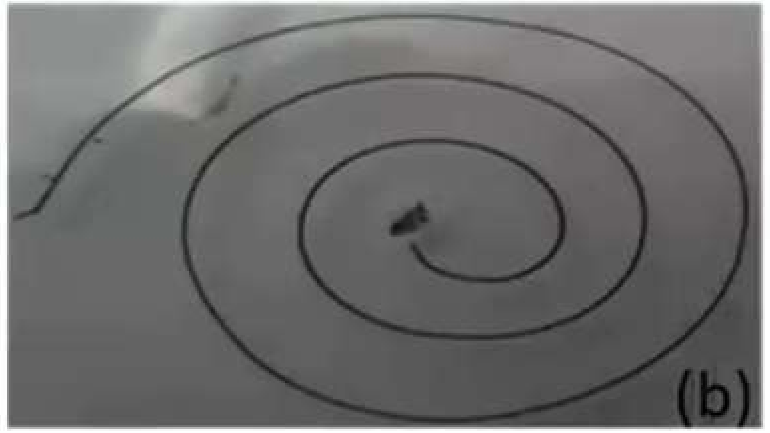




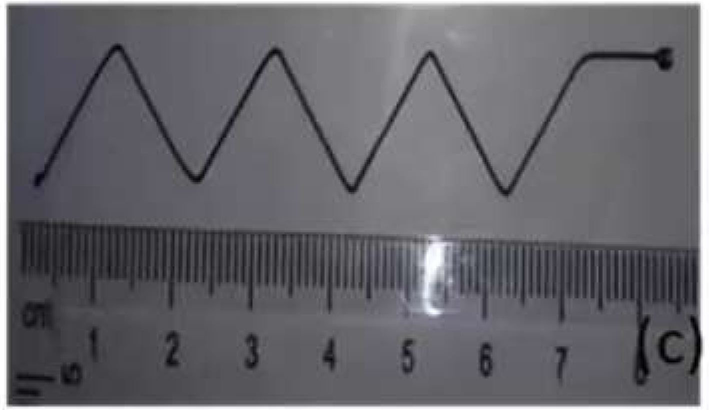
Patterns Deposition



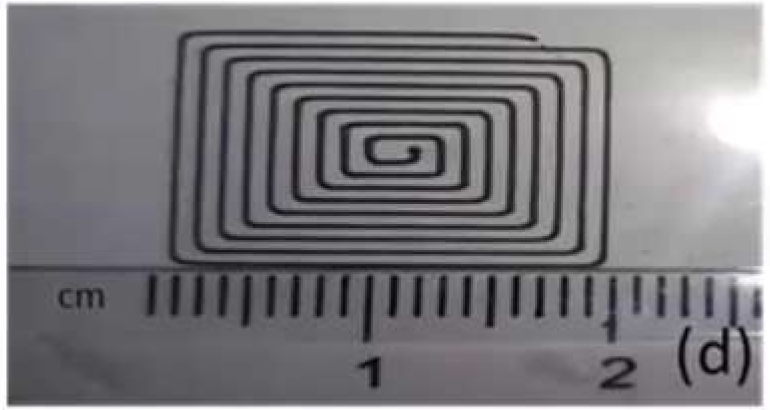
535µm average width



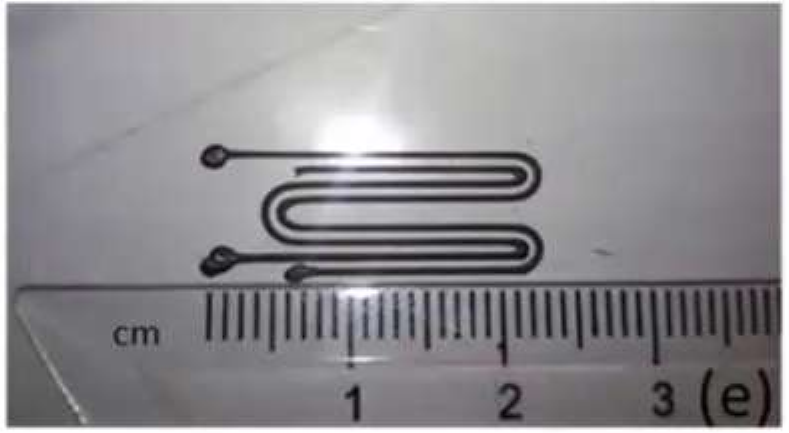
255µm average width



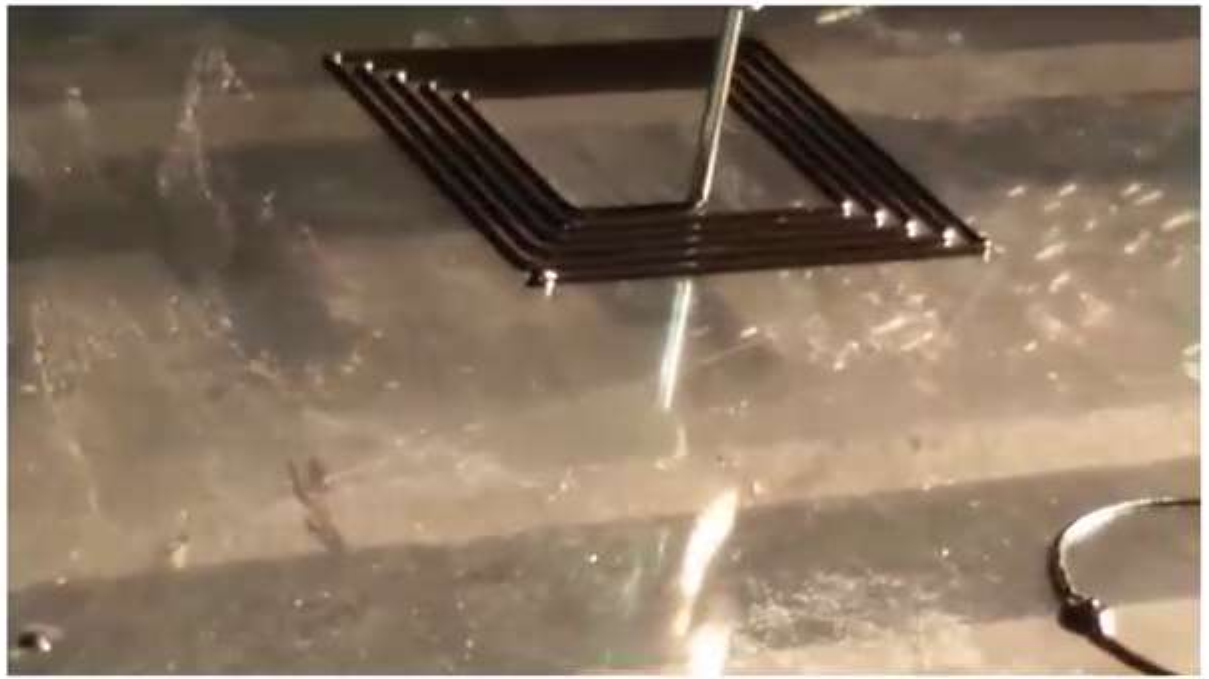
532µm average width

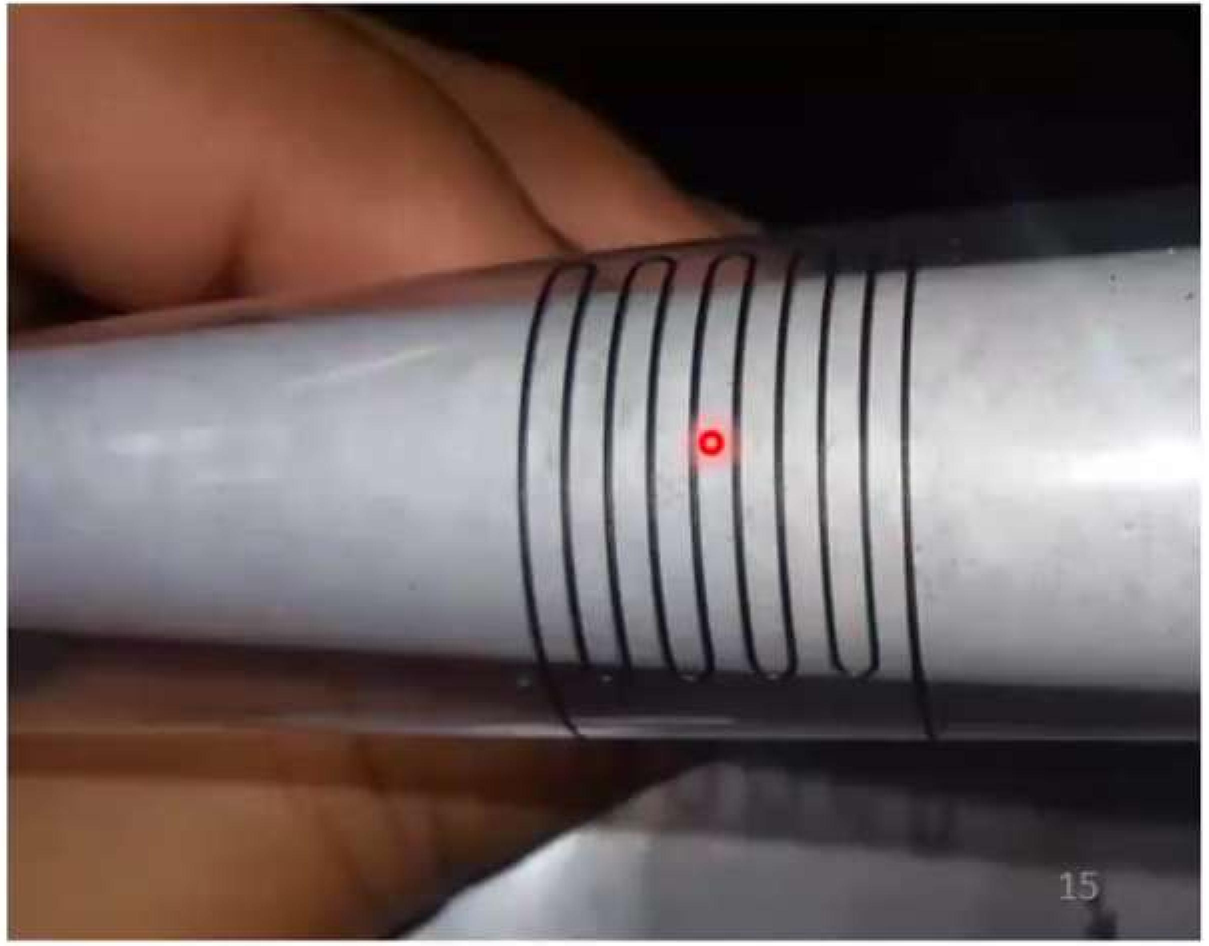


250µm average width



Patterns on Flexible substrate

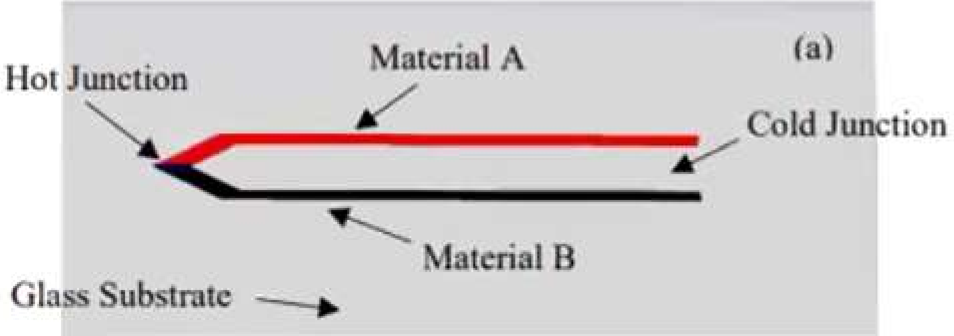




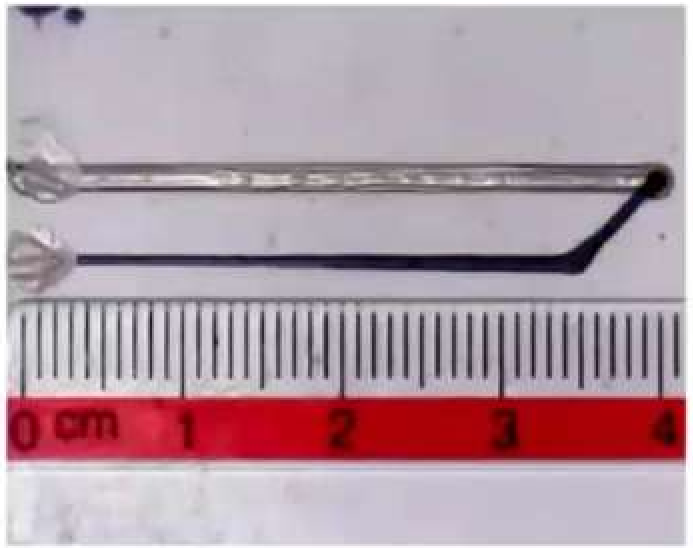
Printed Thermocouple

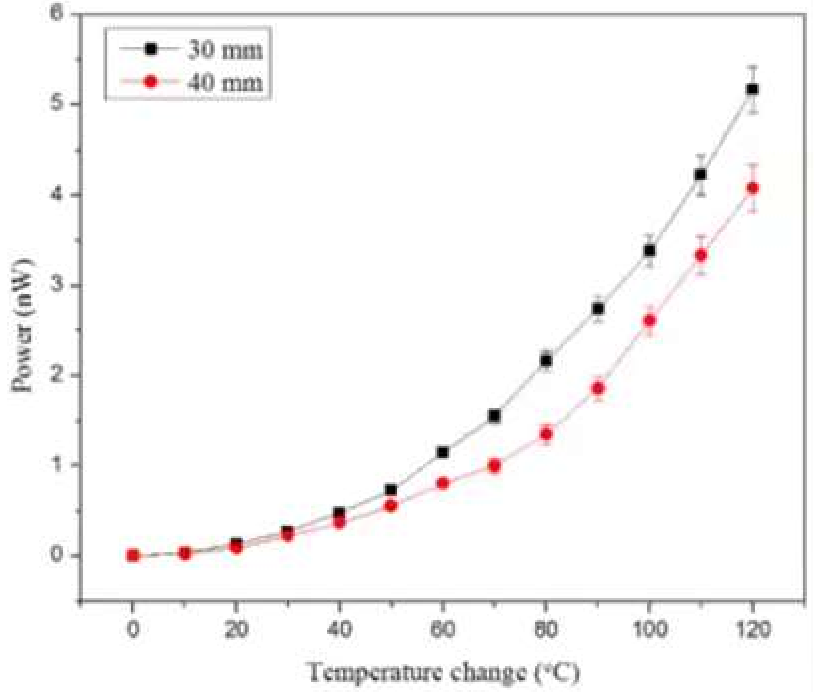
<u>A Weldless Approach for Thermocouple Fabrication Through Direct Ink Writing Technique: **IEEE sensors [22]**</u>

<u>A low-cost printed organic thermoelectric generator for low-temperature energy harvesting: **Renewable Energy [23]**</u>

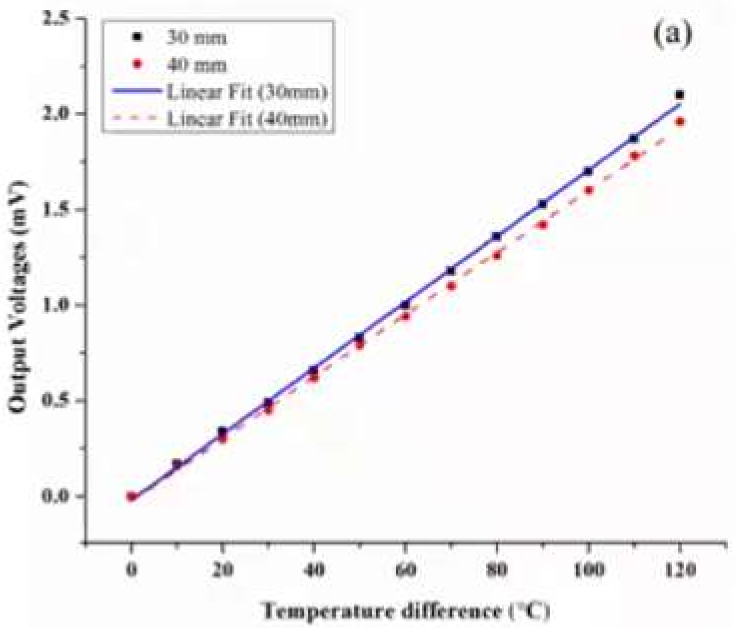


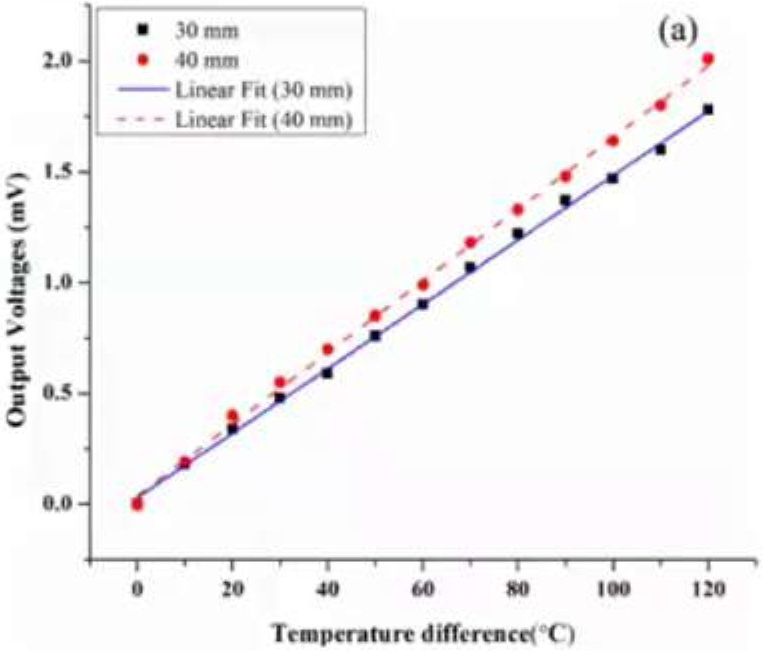
Materials
- Silver paste
- PEDOT:PSS/Carbon





Temperature difference vs Power generated

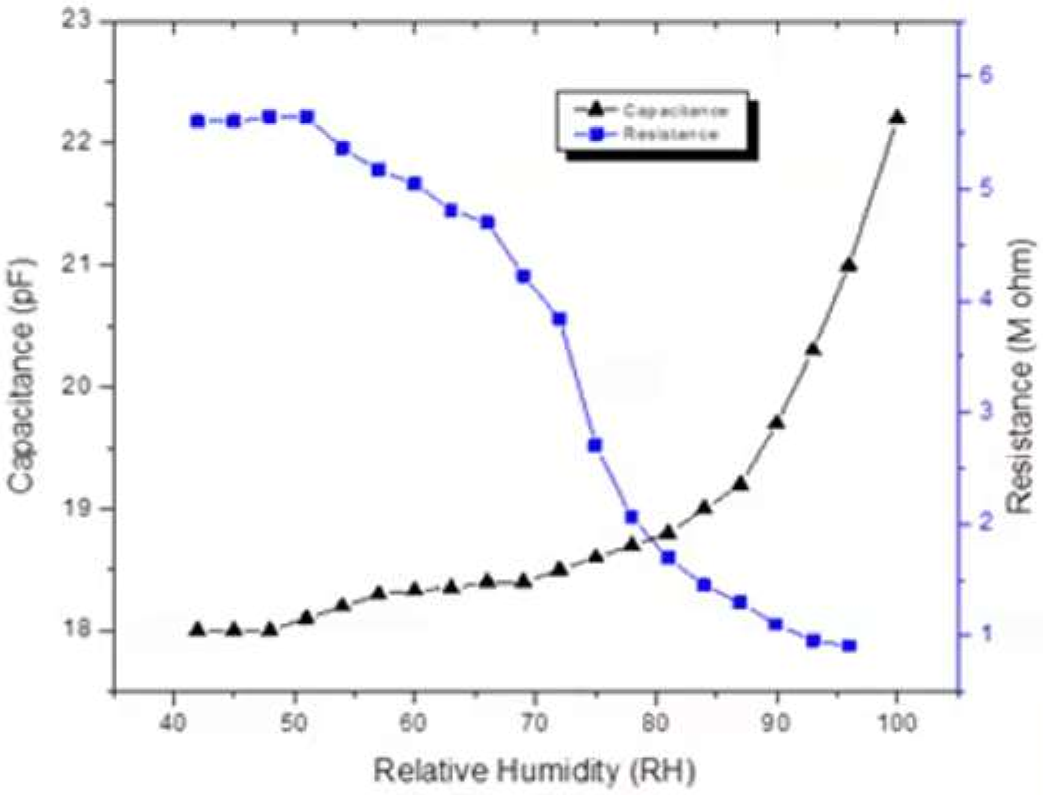




Temperature difference vs Output voltage

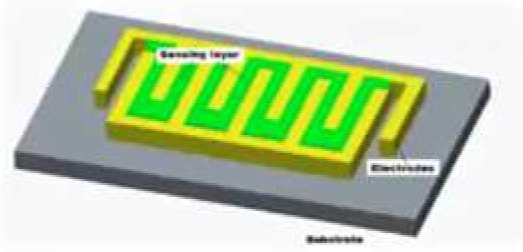
Printed Humidity Sensor

A low-cost printed humidity sensor on cellulose substrate by EHD printing: **Journal of Materials Research [24]**

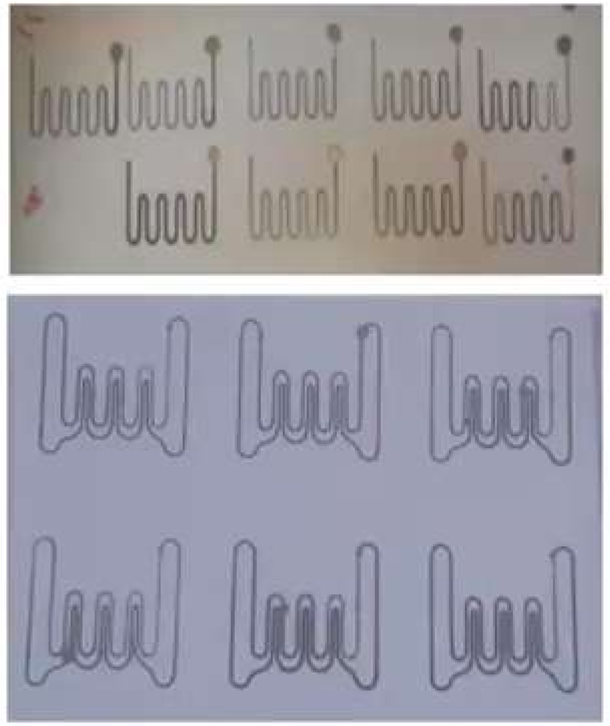


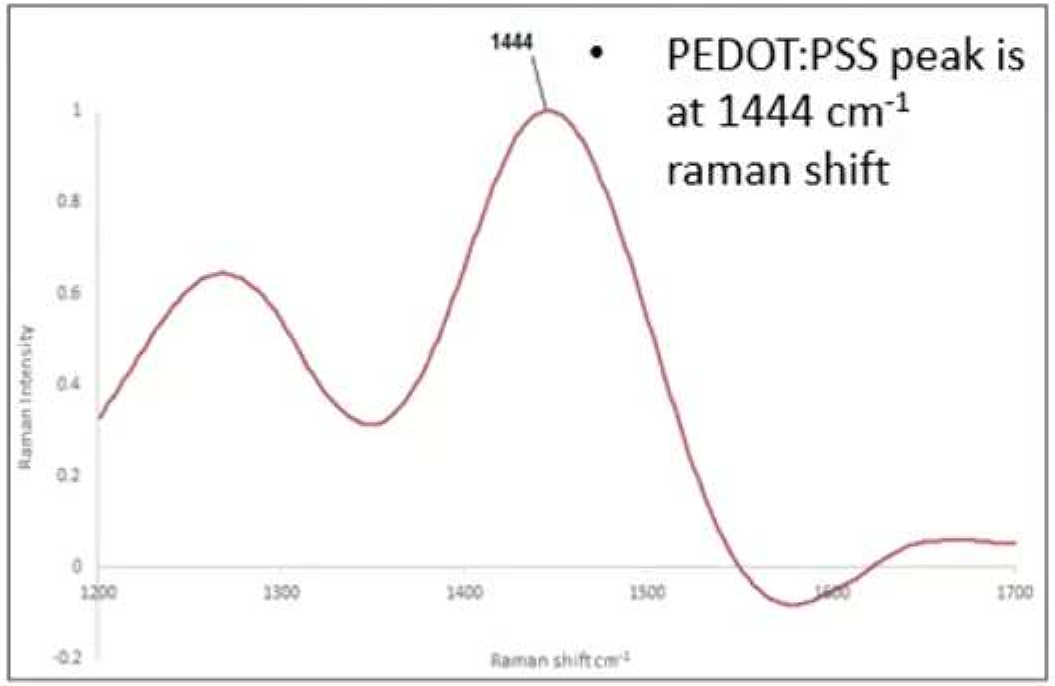
EHD parameters

- 70% Ag. ink
- Pressure = 3.2 kPa
- Voltage = 1.63 kV
- Substrate speed = 2000 mm/min
- Strand off distance = 1mm

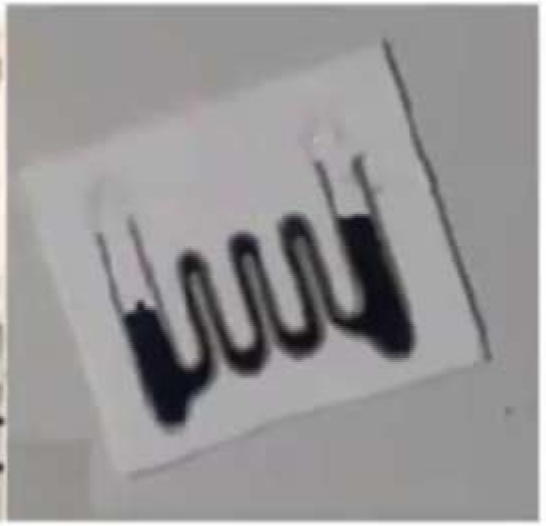


EHD printed humidity sensor on paper





- PEDOT:PSS peak is at 1444 cm^{-1} raman shift



Printed Width

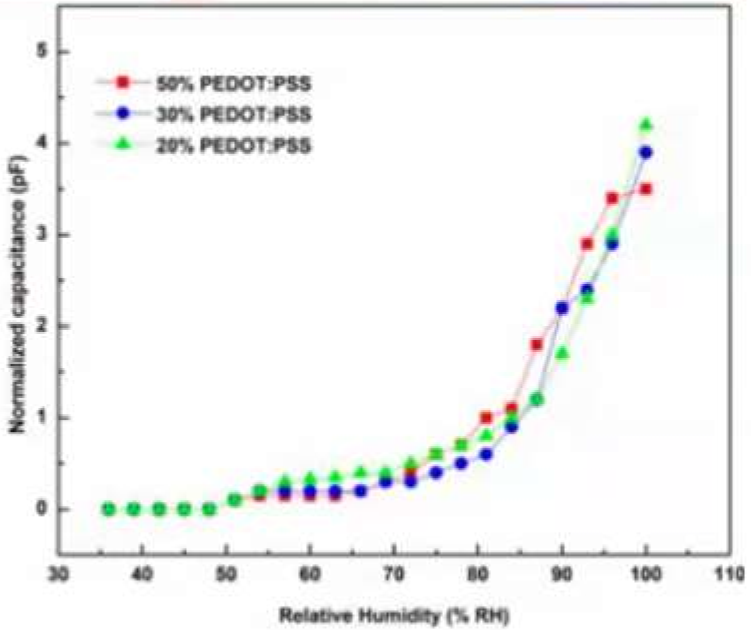


Figure :Raman spectroscopy of PEDOT.PSS

Printed Temperature Sensor

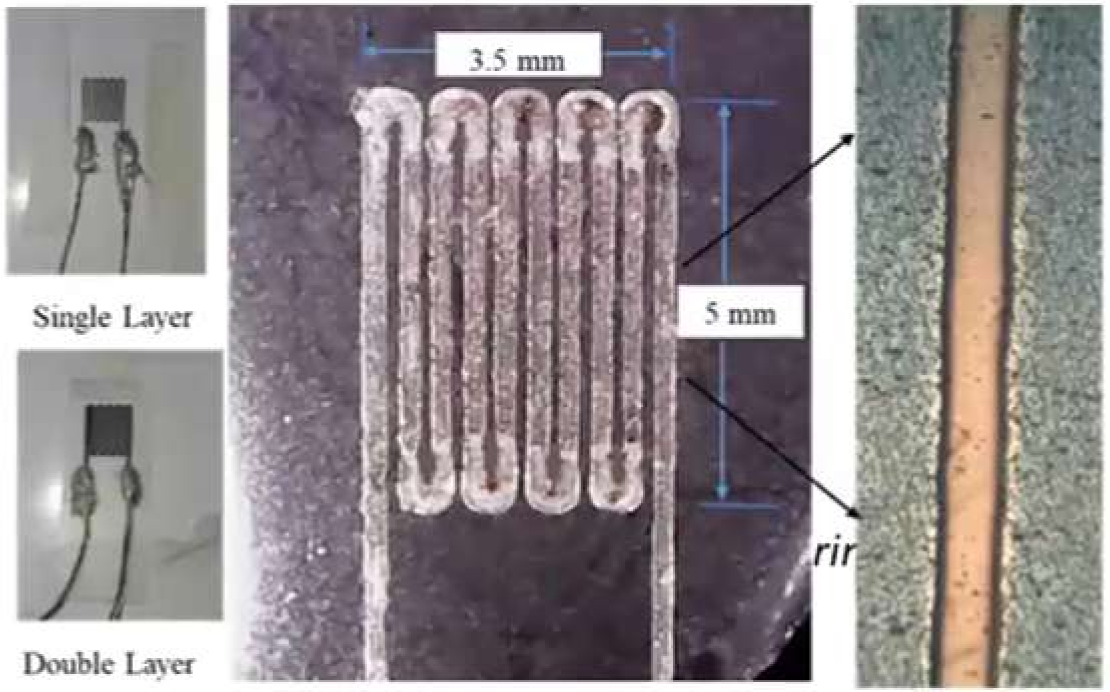
Fabrication of flexible temperature sensor through DOD EHD on PET substrate

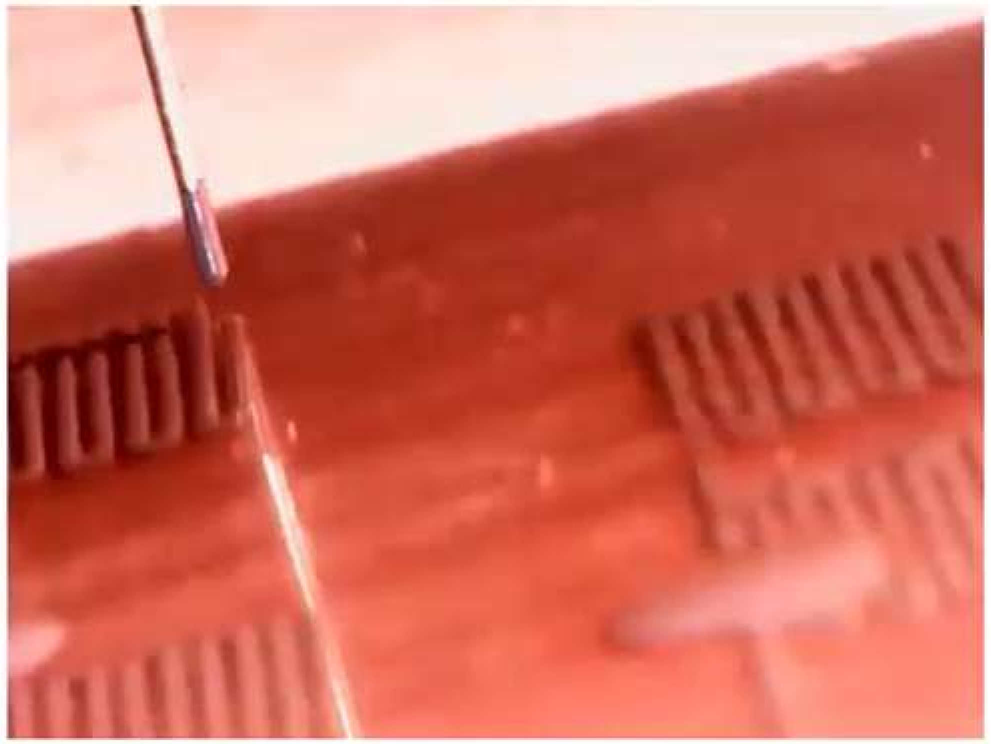
Material:
- Silver nano particles

Substrate:
- PET

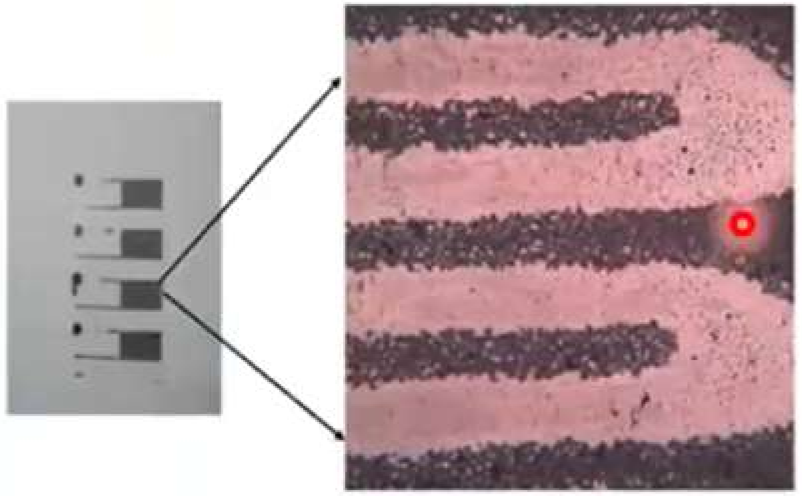
Printed width:
- 100 µm

Controlling Parameters:
- Nozzle diameter
- Base voltage
- Pulse voltage
- Duty cycle
- Pressure
- Feed rate
- Stand-off distance

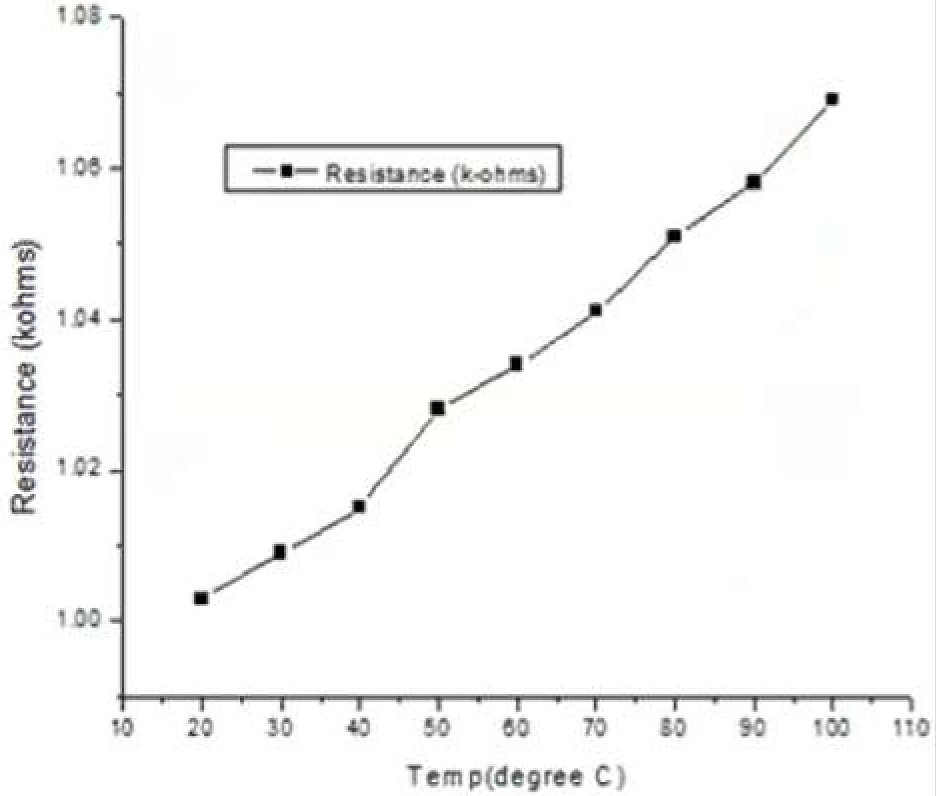




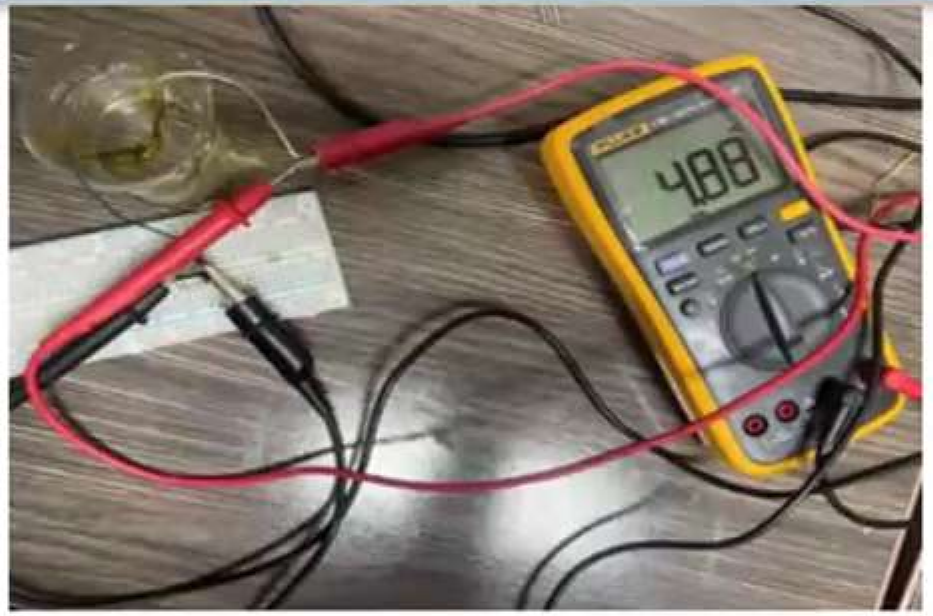
EHD Parameters	Values
Base voltage	2 kV
Pulse voltage	2.6 kV
Feed rate	1200(mm/min)
Stand-off distance	< 1 mm
Pressure	< 0.5 kPa

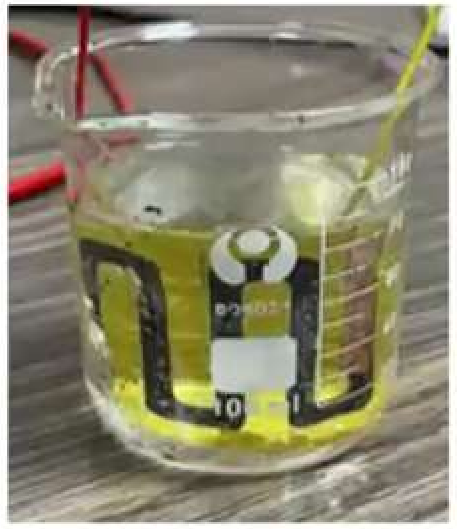


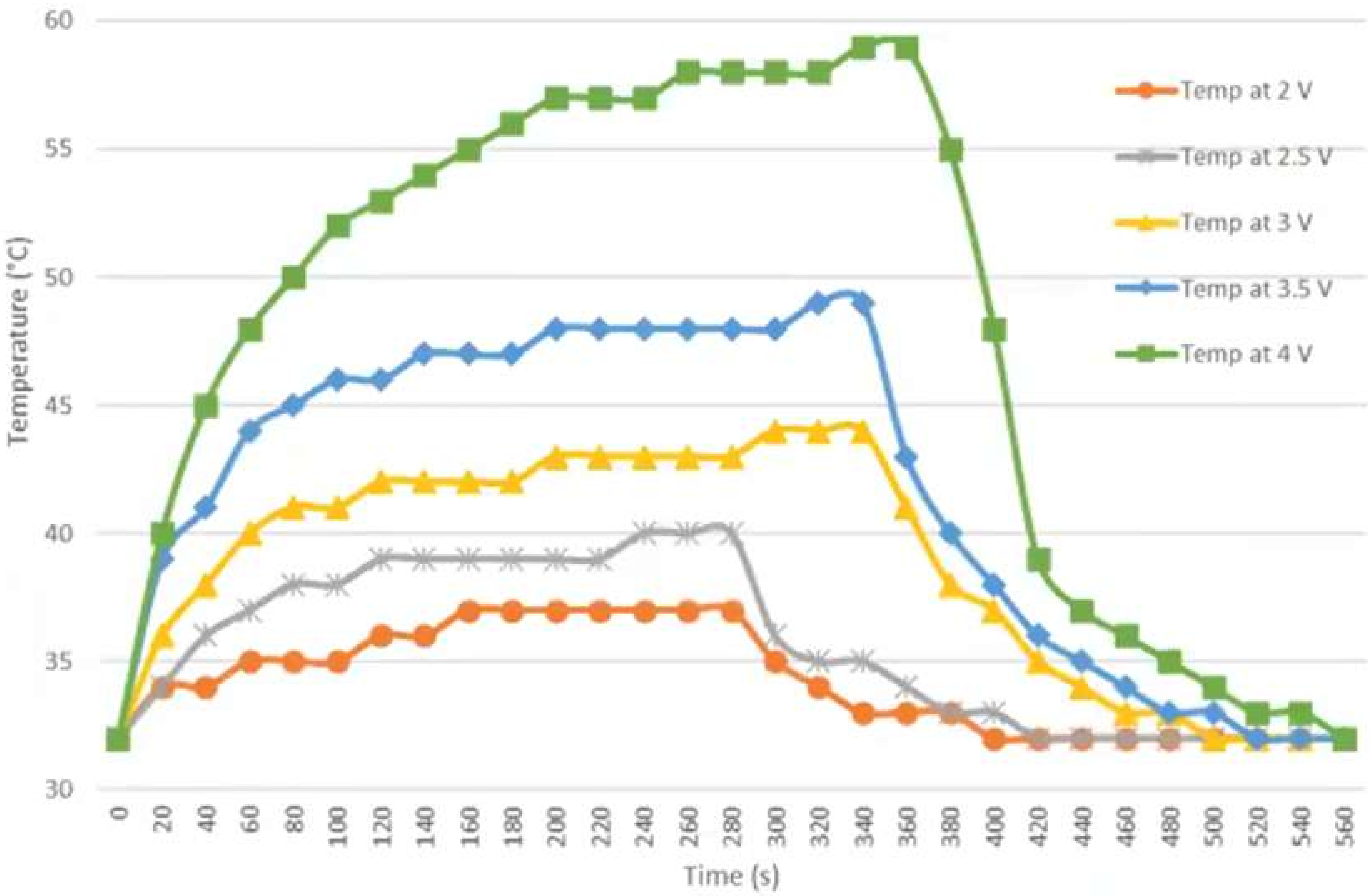
EHD printed temperature sensor on paper



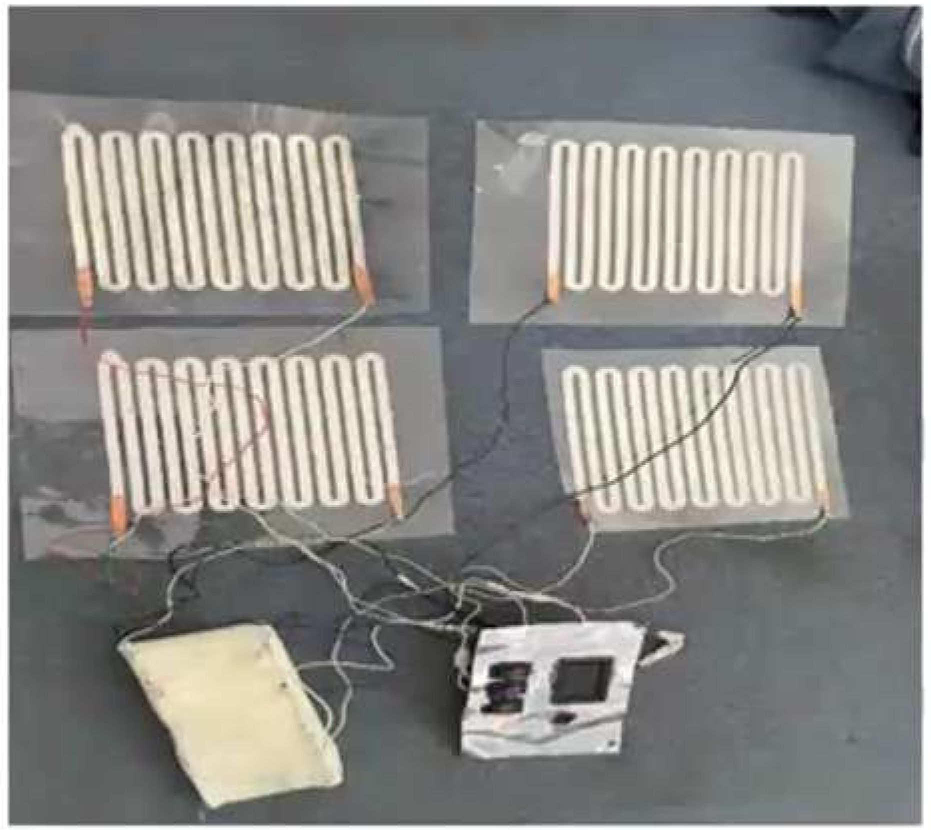
Printed Heater for Wearable Applications

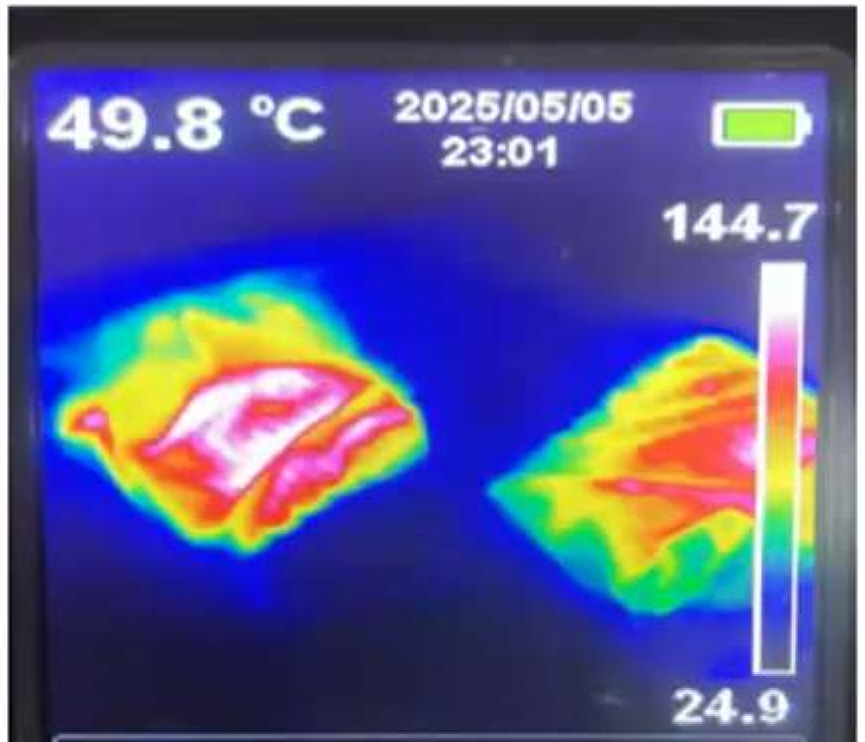


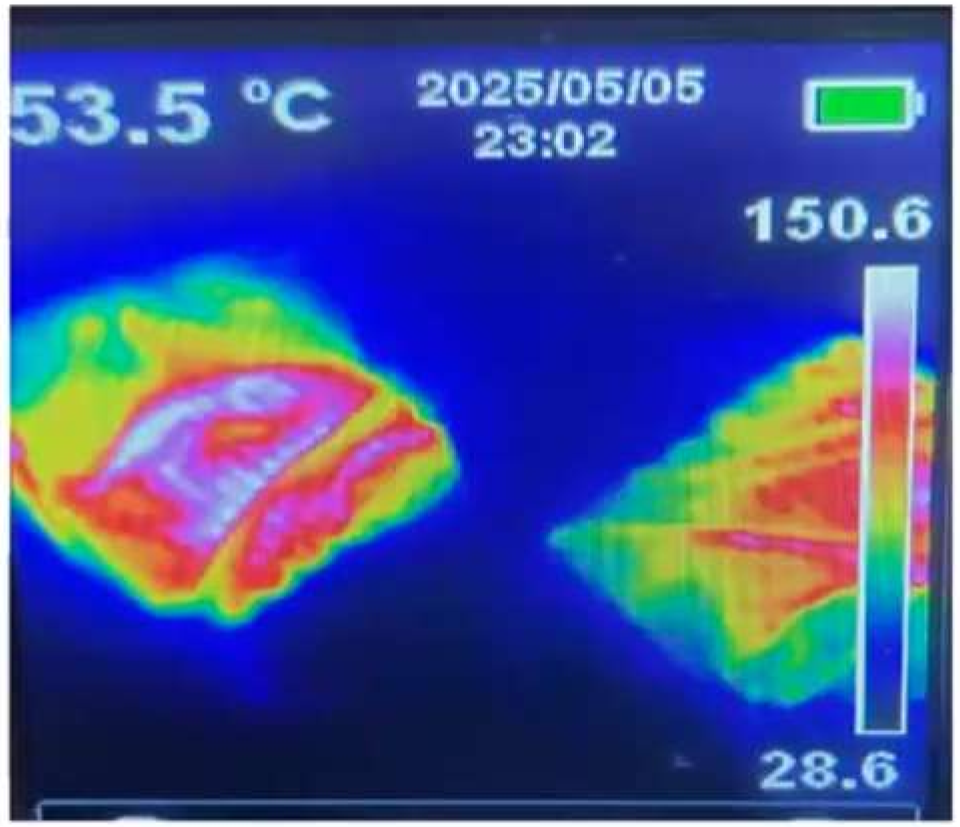




Printed Heater for Wearable Applications



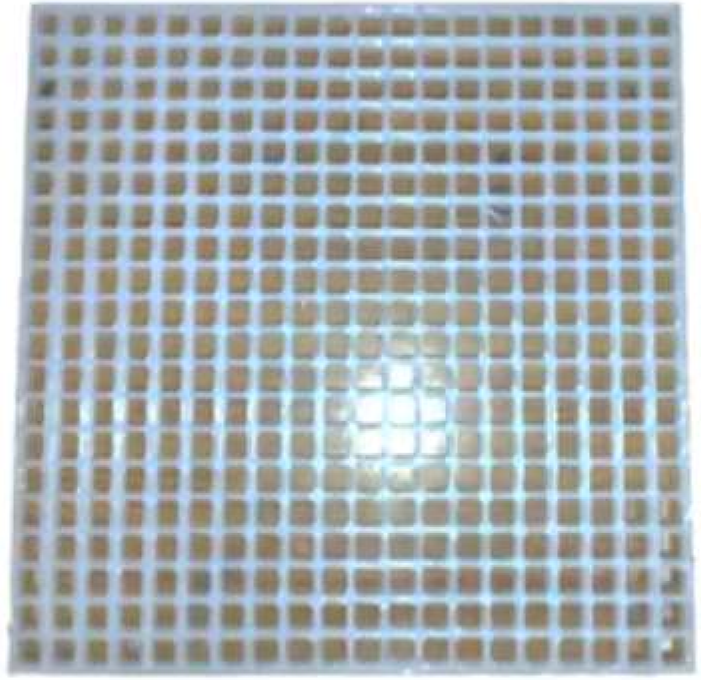


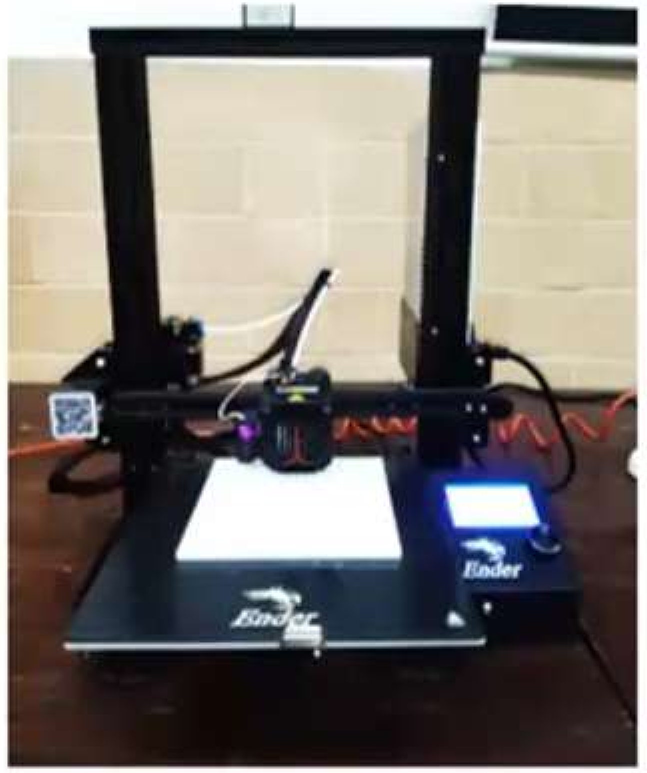


Fabrication of Absorber for Screen Printed Metasurface

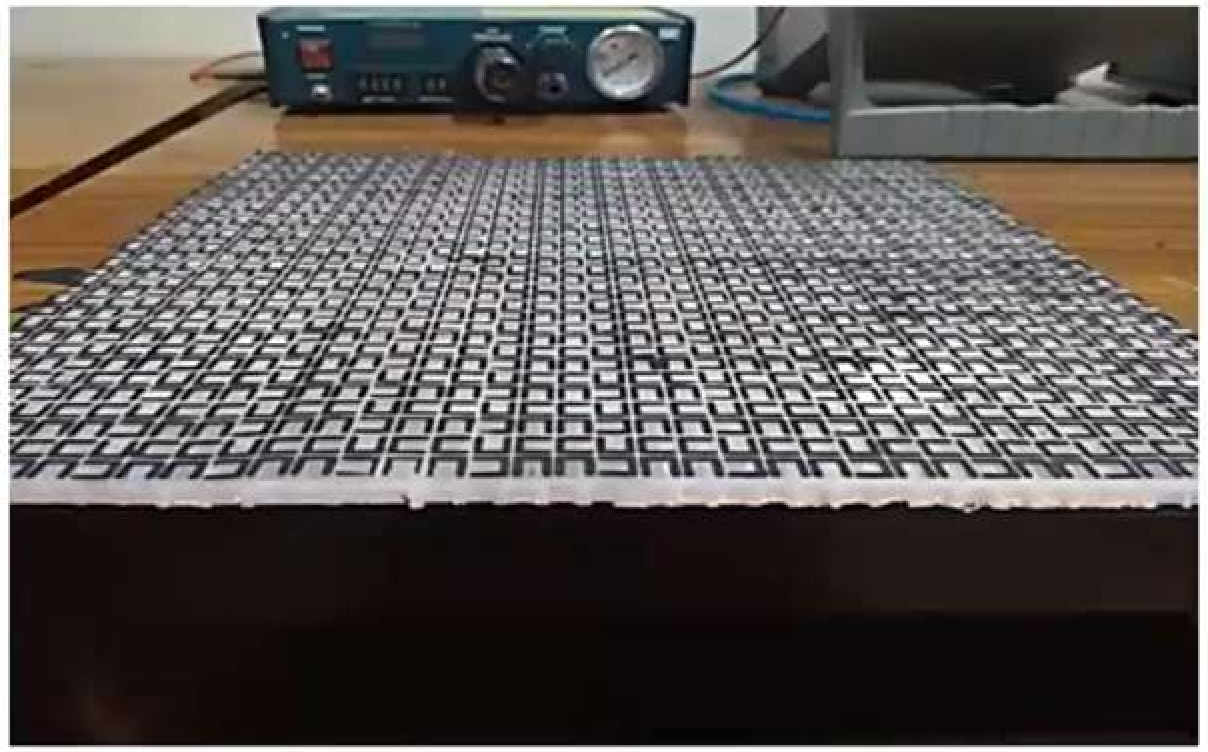
Metasurface

TPU Dielectric



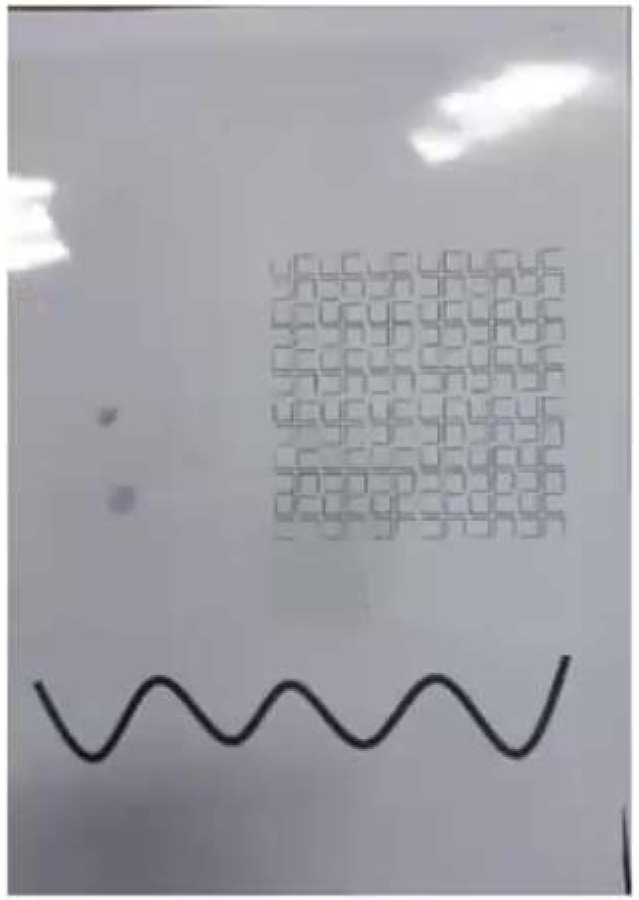


Fabricated Absorber Structure

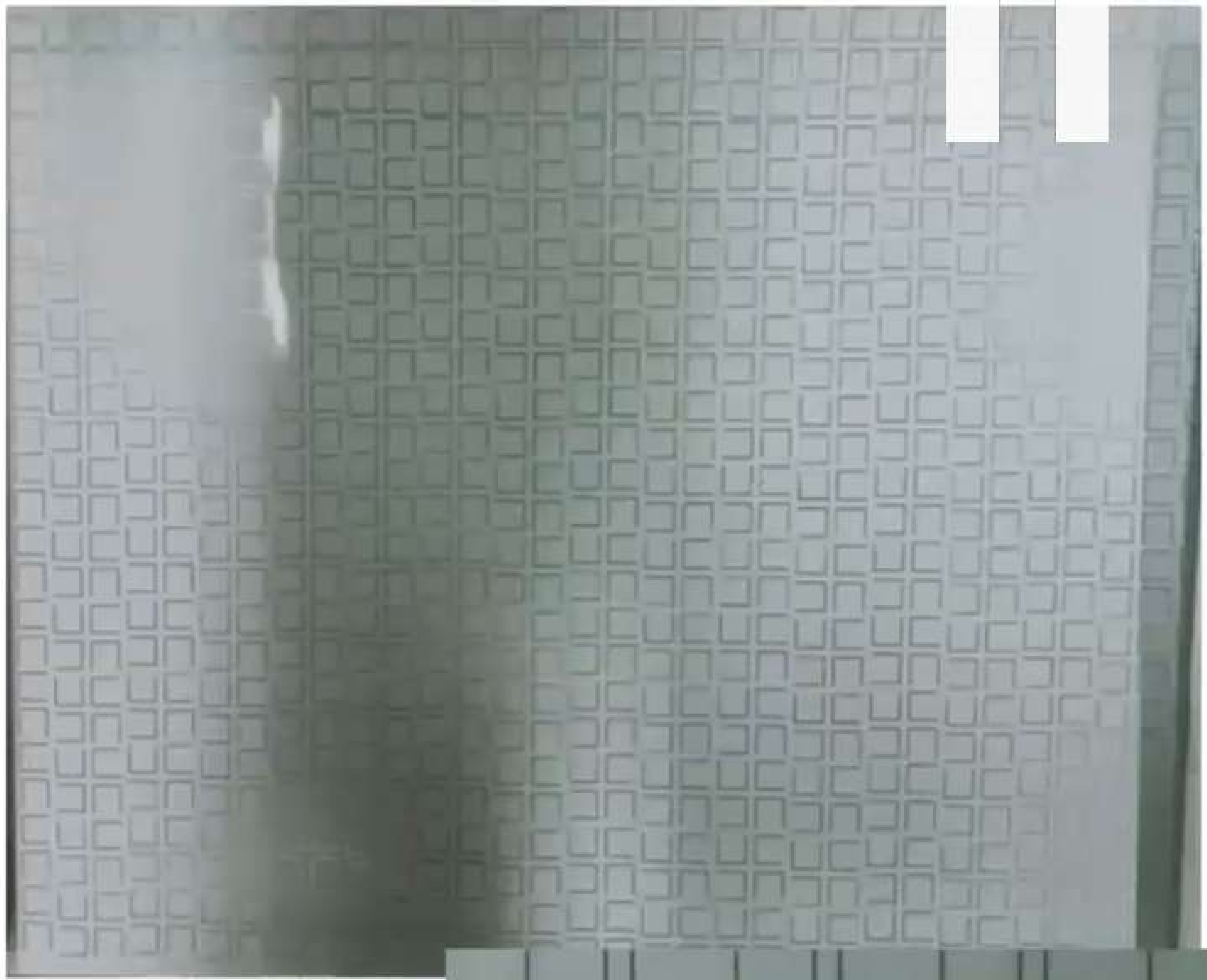


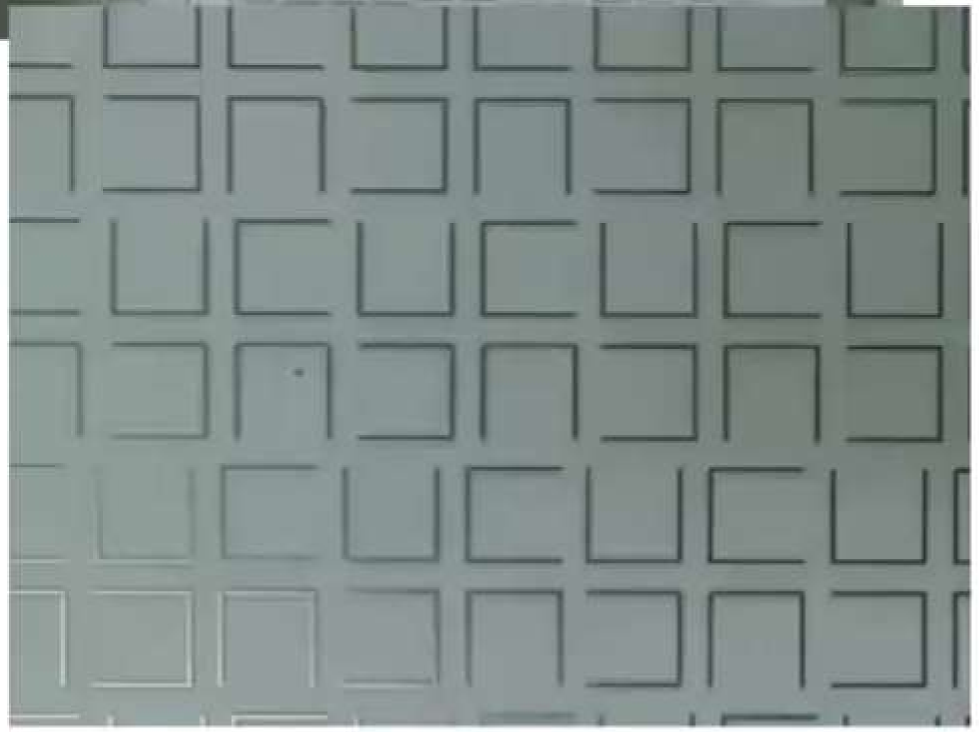
Inkjet Printed Metasurface

Inkjet Printer (single ink)



Carbon Ink





Silver Ink

- Carbon printed structure – high resistance
- Silver printed structure – low resistance

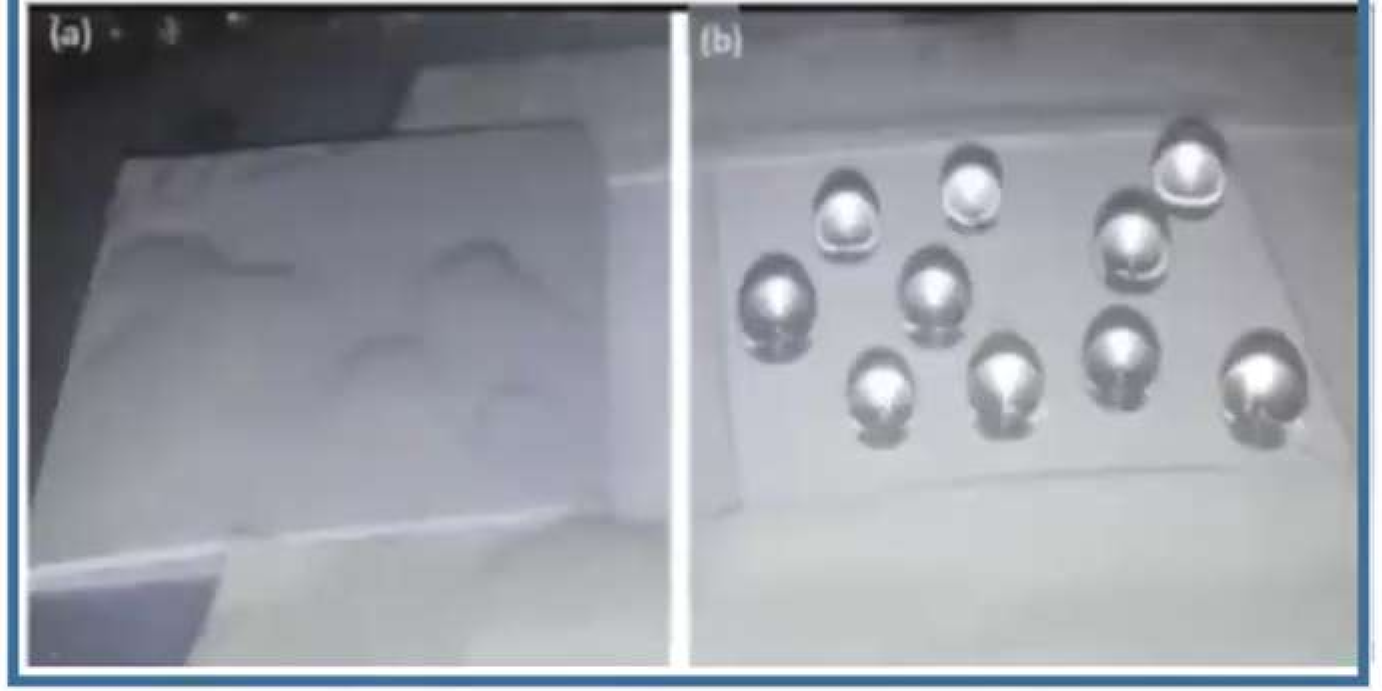
Inkjet Printer (multimaterial inks)

Printed Electronics Lab

Facilities Available

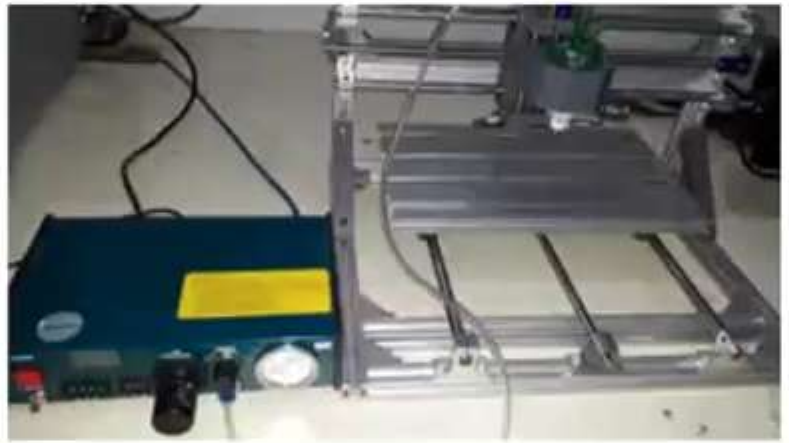
- EHD printing
- Direct Ink Writing technique
- Spray coating through EHD (electrospray and spray gun)
- Sample sintering/curing
- Characterization of printed samples
- Ink preparation apparatus

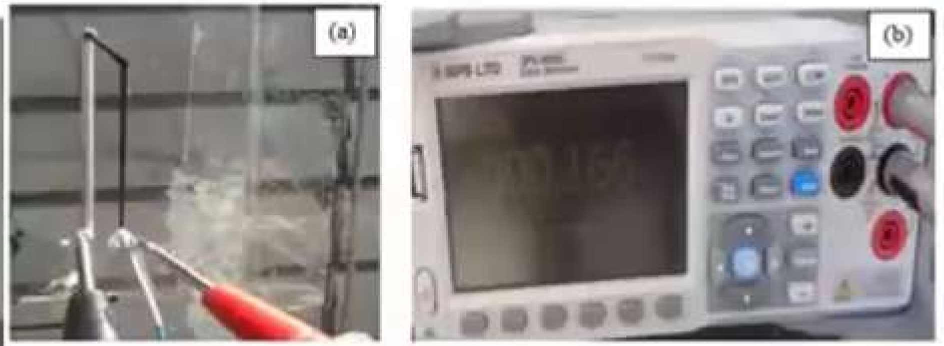
Coating (ZnO/PMMA)



Research in-progress

- EHD printing resolution
- Printed Thermocouples
- Printed sensors
- Printed TEGs
- Spray coatings





Limitations and Challenges

- Ink formulation (adjusted viscosity, surface tension, evaporation rat)
- Ink stability (e.g. particle agglomeration, settling,...)
- Substrate quality (surface energy, roughness control)
- Layer to layer registration (self-alignment)
- Jetting-reliability (monitoring, redundancy)
- Process/solvent compatibility
- Device performance
- Resolution

Prospects of Printed Electronics for Pakistan

- **Low-Cost, Scalable Manufacturing**
  - PE uses inexpensive materials (e.g. carbon-based inks, silver nanoparticles) and simple printing techniques.
  - Ideal for resource-limited environments where affordability is crucial.
- **Enabling Technologies for Local Challenges**
  - Healthcare: Printed biosensors for diagnostics in rural areas.
  - Agriculture: Smart packaging and environmental sensors.
  - Energy: Printed solar cells and thermoelectric harvesters for off-grid regions.
  - Education: Low-cost educational electronics and lab kits.
- **Industrial Potential**
  - Opportunity to build local supply chains for inks, substrates, and printed components.
  - Integration with existing textile, paper, and packaging industries.
  - Possibility of attracting foreign direct investment (FDI) in flexible electronics and IoT manufacturing.

Prospects of Printed Electronics for Pakistan

- **Academic and R&D Growth**
  - Pakistan's universities and research centers can develop expertise in: Materials science (nano-inks, substrates)
  - Printable energy devices
  - Sensor design International collaboration can boost technology transfer and training.
- **Sustainability and Energy Efficiency**
  - PE supports green manufacturing: low material waste, energy-efficient processes.
  - Printable solar panels and energy-harvesting devices support sustainable development goals (SDGs).

Recommendations for Pakistan

- Launch national R&D initiatives focused on printed electronics.
- Encourage public-private partnerships for prototyping and scaling.
- Provide funding and policy incentives for startups and tech incubators.
- Foster international collaboration for capacity building.

Thank You!