Laser-Based Additive Nanomanufacturing: Rigid to Flexible Substrates

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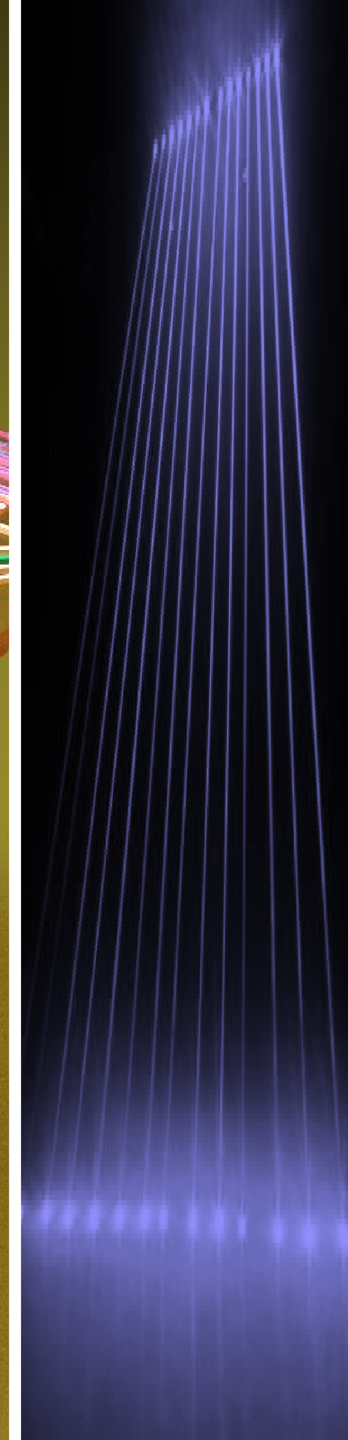

Outline

- Printed Electronics
- Applications of Printed Electronics
- Laser-Based Additive Nanomanufacturing (ANM)
- Examples of ANM-Printed Devices
- Conclusion
- References
- Acknowledgment

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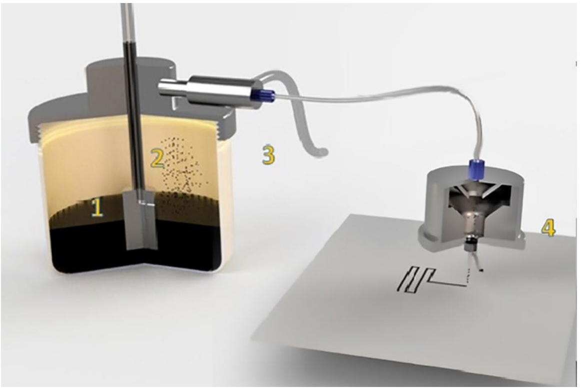
Printed Electronics

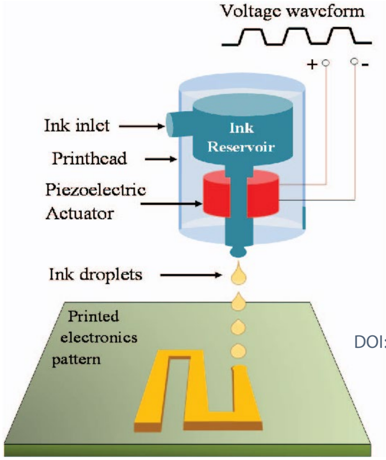
- Printed electronics:
  - A set of printing methods used to create electrical devices on different substrates.

- Main printed electronic techniques are:
  - **Aerosol jet and inkjet printing**, screen printing, gravure, offset lithography.

Aerosol jet printing



https://www.led-professional.com/

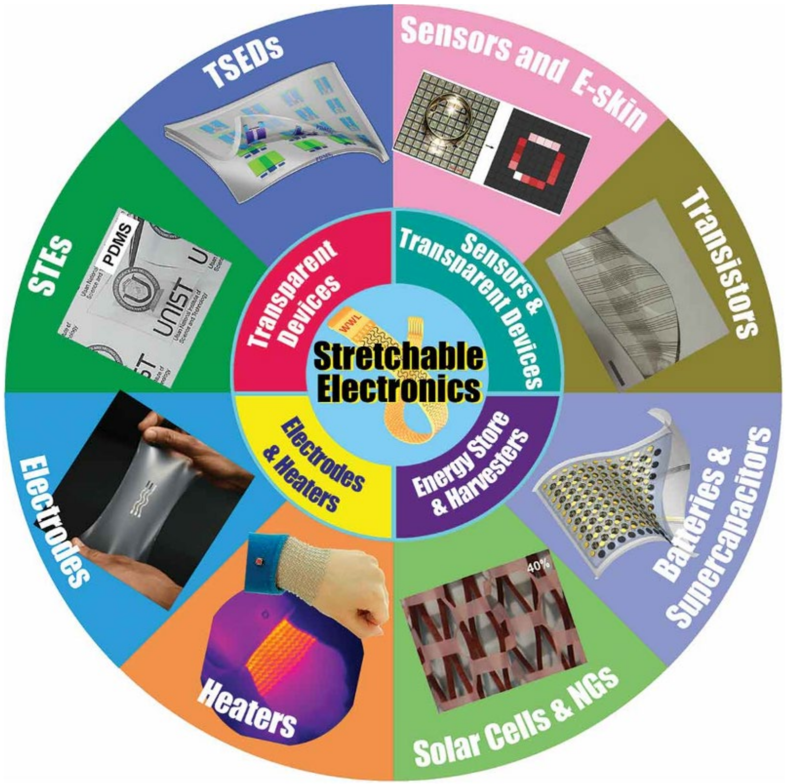


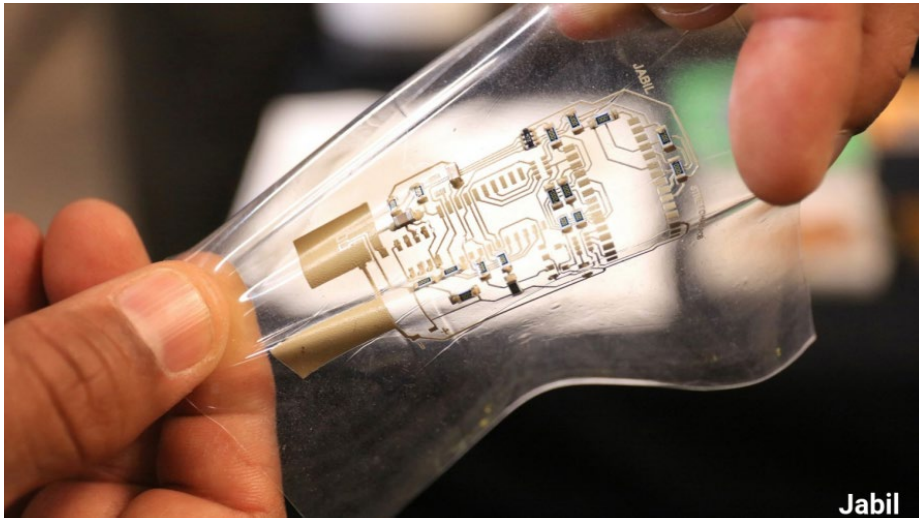
Inkjet printing

DOI:10.1109/PANPACIFIC.2016.7428385

- ❑ Aerosol jet and inkjet as a non-contact method have more design flexibility compared to other contact methods.

Applications of Printed Electronics





https://www.semi.org/en/communities/flextech/what-are-flexible-electronics

Advantages: product shape, weight, and durability

Flex circuits are printed on ultra-thin substrates, such as plastic, which impart them the foldable, rollable, and bendable characteristics without affecting the functionality.

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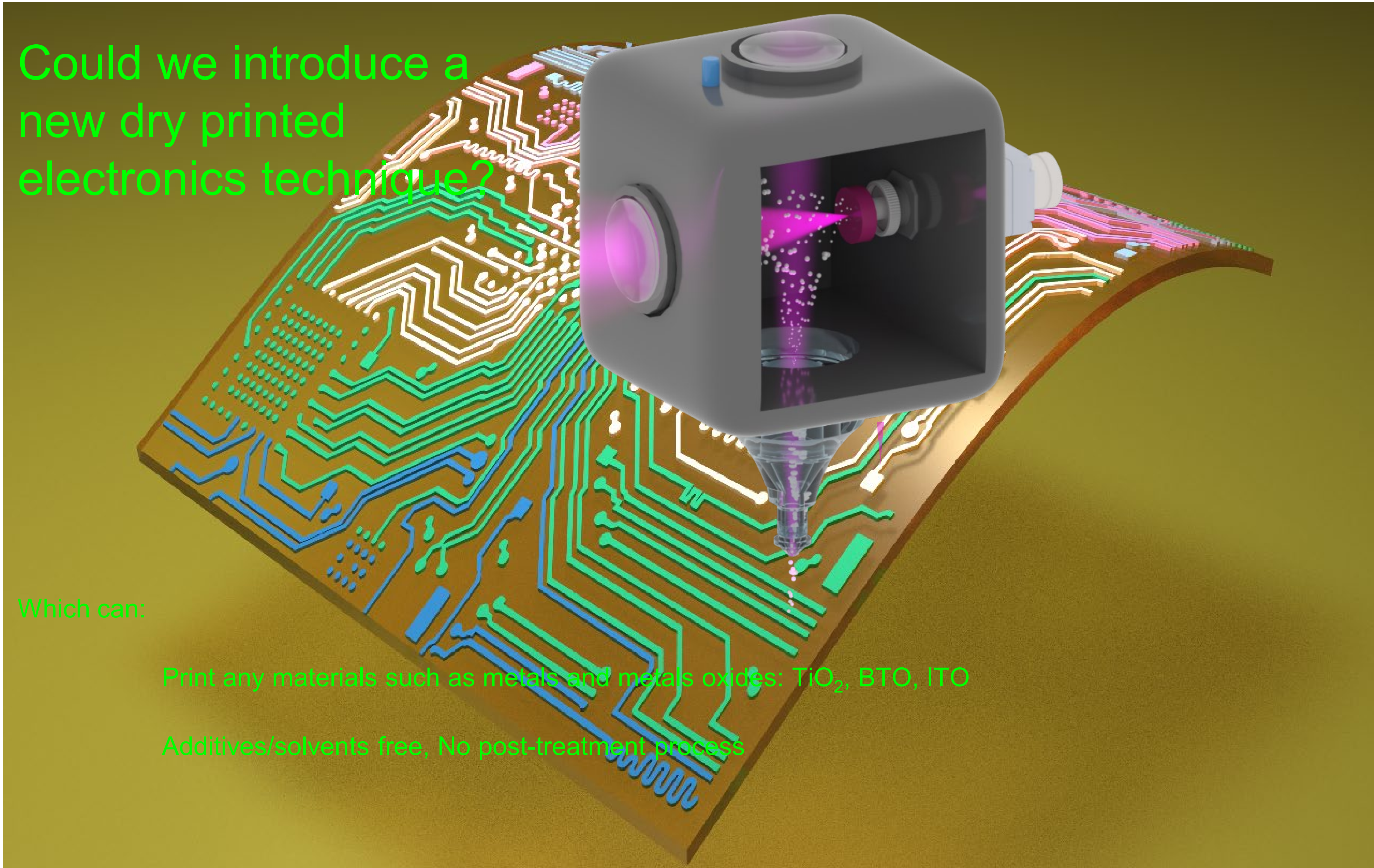
Challenges of Inkjet and Aerosol Jet

- Solvents/additives are used in ink formulations: most inks are not pure liquids but have a very complex composition, containing multiple liquids with different material properties
  - As an example, for Ag ink: polyvindone+ethylene glycol+ $AgNO_3$
- Limited source of materials
- Additional post annealing step for removing additives/solvents
- Due to the liquid-nature of ink, it is not best option for paper-based printing
- Ink maintenance
  - Settle and need to shake



Could we introduce a new dry printed electronics technique?

Which can:

- Print any materials such as metals and metals oxides: TiO_2, BTO, ITO
- Additives/solvents free, No post-treatment process

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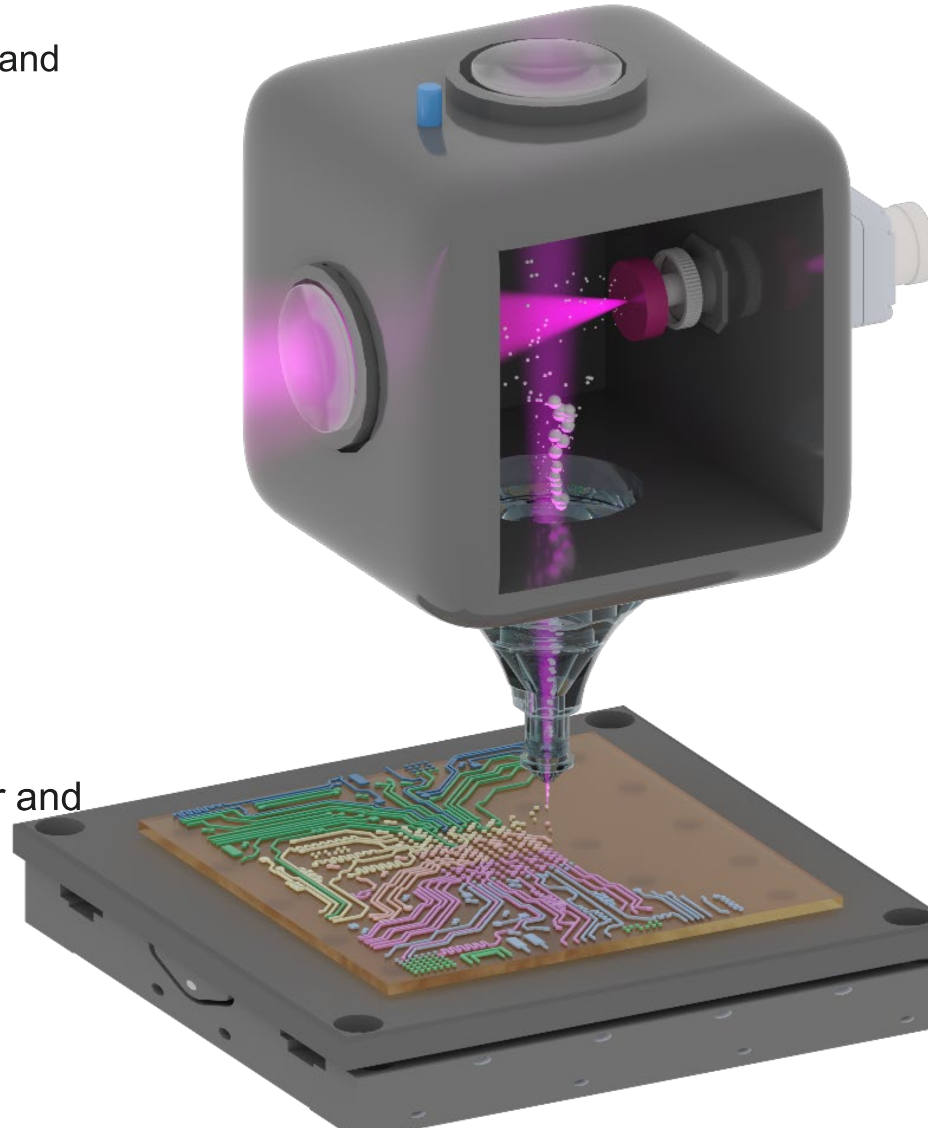
Laser-Based Additive Nanomanufacturing (ANM)

Process Steps:

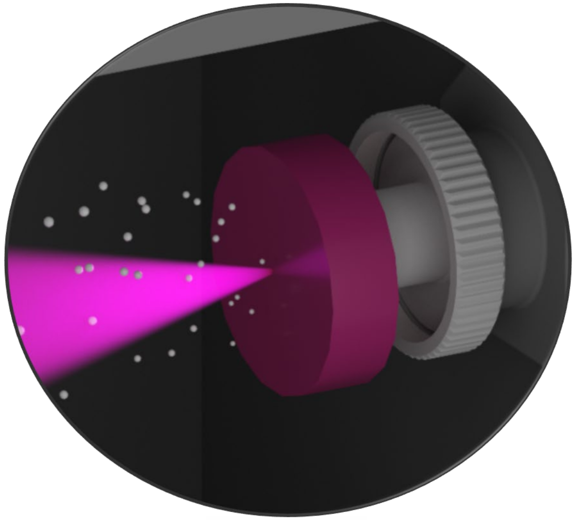
- Splitting pulsed excimer laser beam for sintering and ablation.
- Generating amorphous nanoparticles
- Delivery of nanoparticles
- Sintering of pure amorphous nanoparticles
- Scanning of stage



Key features of ANM system

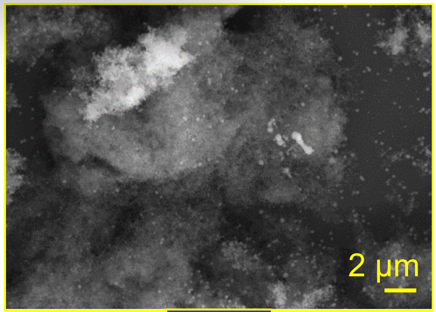
- Generates dry and pure nanoparticles
- Compatible with rigid and flexible substrates
- Suitable for metals, semiconducting, insulator and metal oxides.
- Capable of patterning different shapes
- Non-contact process/ Room temperature and atmospheric pressure

Ablated Nanoparticles-ANM process

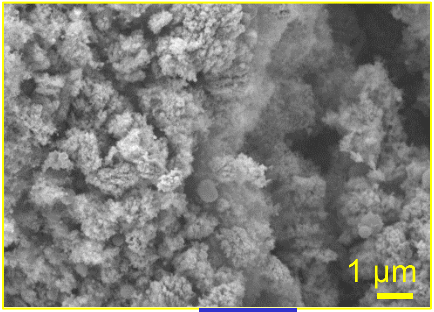


- Notes:
  - 248 nm excimer laser ablated the solid targets.
  - Nanoparticles generate during this interaction.

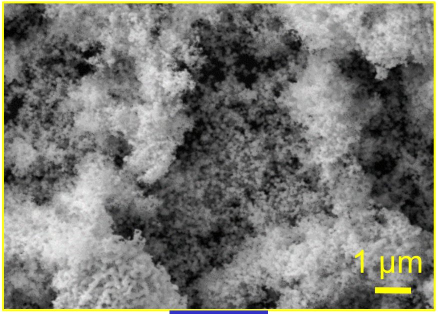
- Scanning Electronic Microscopy (SEM) images of produced nanoparticles:



TiO_2



ITO

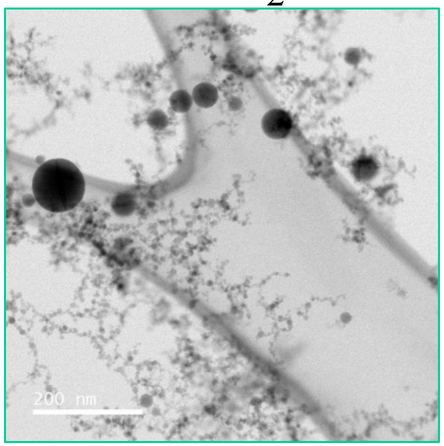


Ag

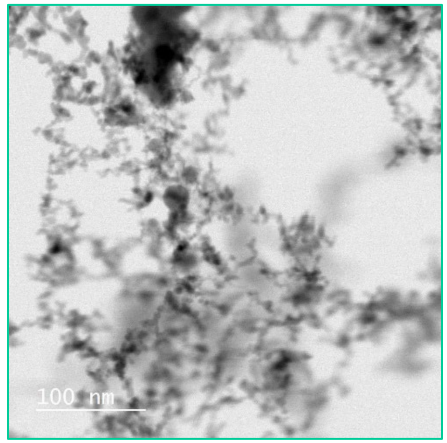
Ablated Nanoparticles- ANM process

Scanning Transmission Electron Microscopy (STEM)

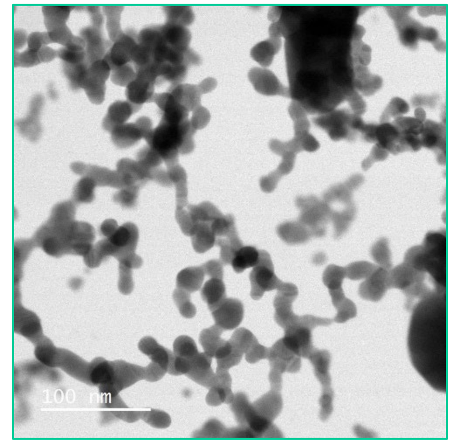
- TiO_2



- ITO



- Ag



The nanoparticle size is ~3 to 10 nm.

Comparison:

- Nanoparticles size in inkjet and aerosol jet printing ~ range of >10 nm, depending on the material.

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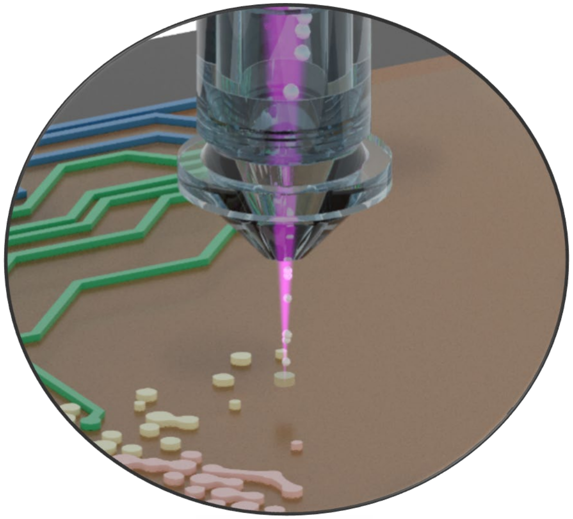
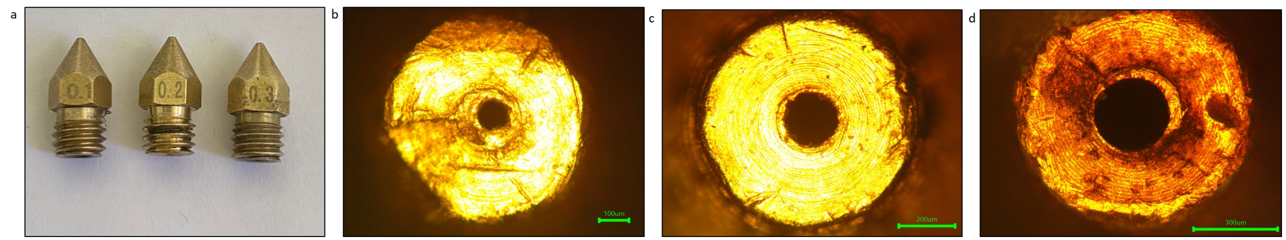
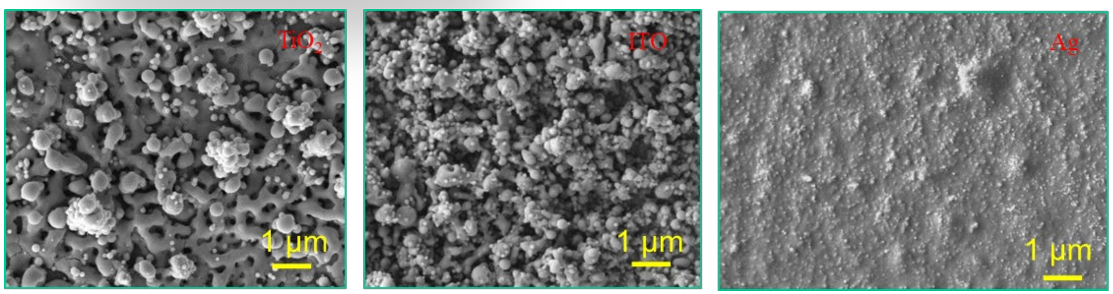
Laser Sintering and Crystallization of Nanoparticles



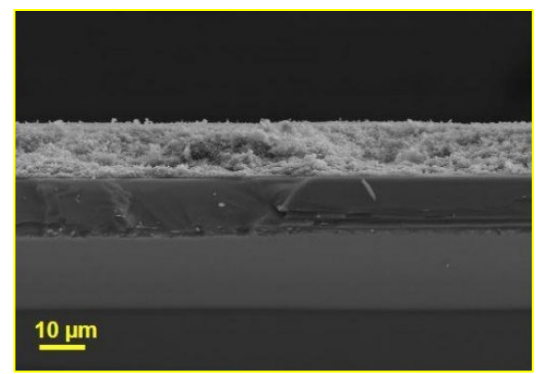
- Nanoparticles guided via carrier gas through the nozzle to the surface of the substrate.
- 248 nm excimer laser sinters and crystallizes the nanoparticles on the substrates.



- SEM images of sintered/crystallized nanoparticles:



Nanoparticles fused together during laser sintering/crystallization.



Cross-sectional SEM images showing the sintered ITO on SiO_2 substrate by the ANM process

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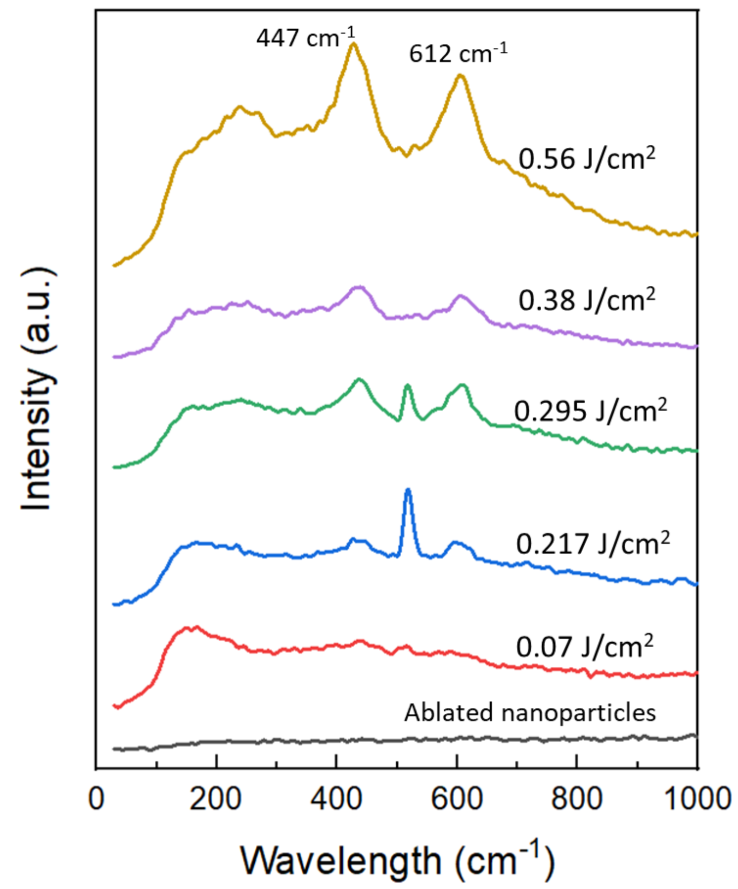
Raman Spectroscopy Study of TiO_2

- Effect of the laser beam energy on the crystallization of TiO_2 nanoparticles
  - In-situ generated nanoparticles
    - no peaks suggesting that the generated TiO_2 nanoparticles are primarily amorphous-TiO_2.
  - Using crystallization energy from 0.07 to 0.56 J cm^{-2},
    - Generated a-TiO_2 nanoparticles starts to sinter and crystallize (according to the appearance of new Raman peaks.
- The Raman lines at 447 cm^{-1} and 612 cm^{-1} are assigned to the Eg, A_{1g} modes of the rutile TiO_2 phase.
- Note:
  - Sintering and crystallization of anatase phase is possible by changing the carrier gas from Ar to O_2.



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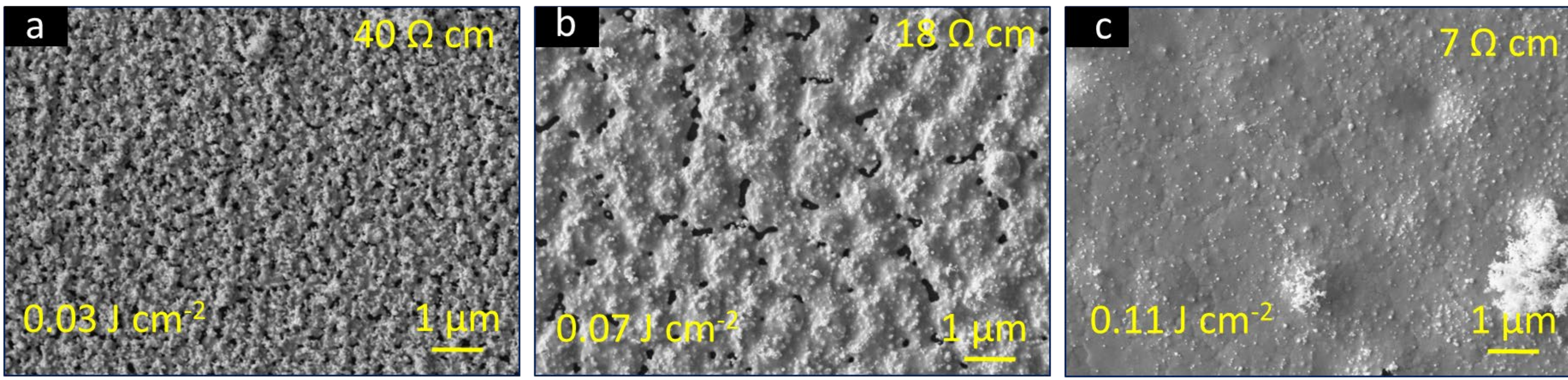
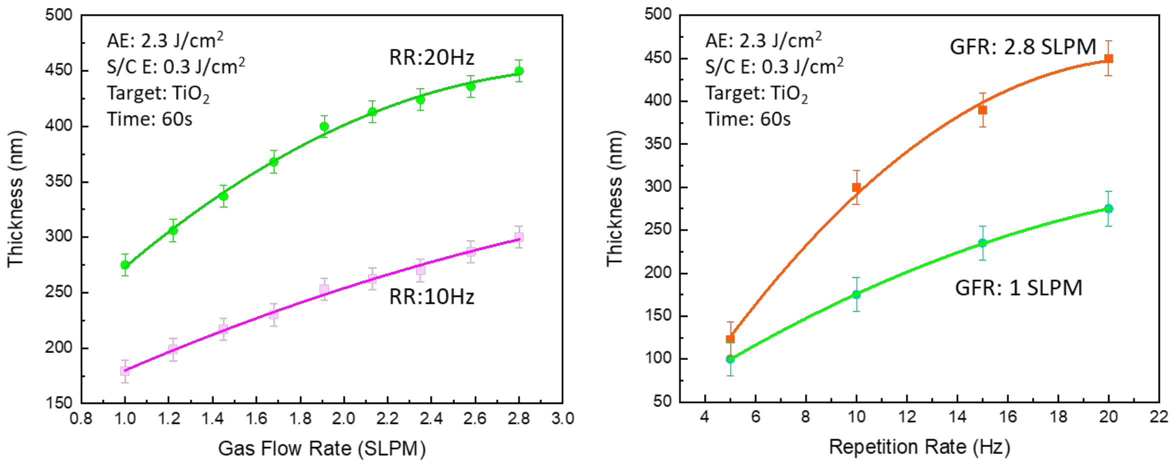
Morphological Evolution of Printed Ag Lines

- By increasing the sintering energy, the nanoparticles start to fuse together.
- The highest porosity was seen at the lower sintering energy (~0.03 J cm^{-2})
- The lowest porosity was achieved at the higher laser sintering energy (~0.11 J cm^{-2})



Thickness vs. ANM-parameters



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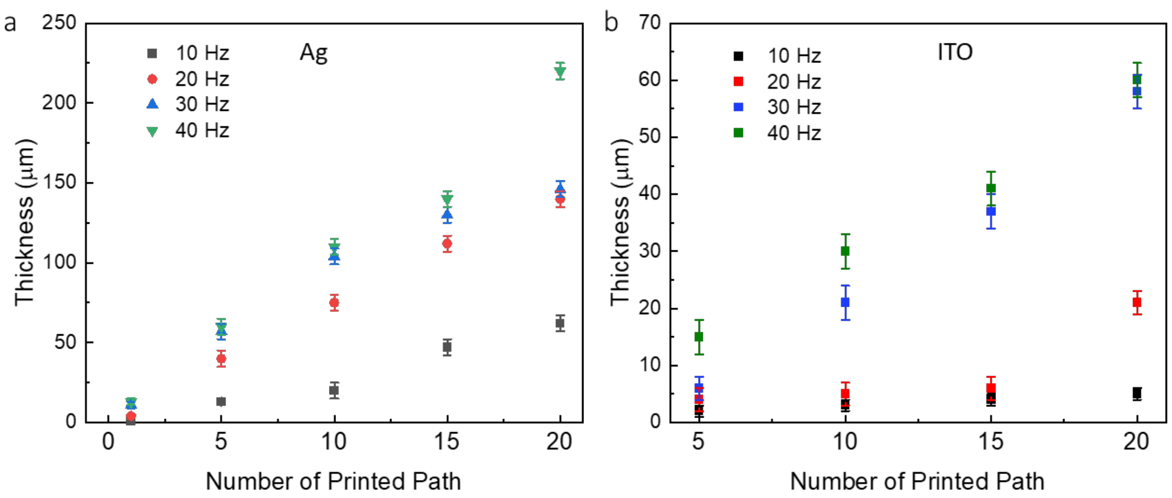
- Increasing gas flow rate → increasing deposition thicknesses.
- Increasing repetition rate → increasing deposition thicknesses



- With ANM technique, thickness is controllable.

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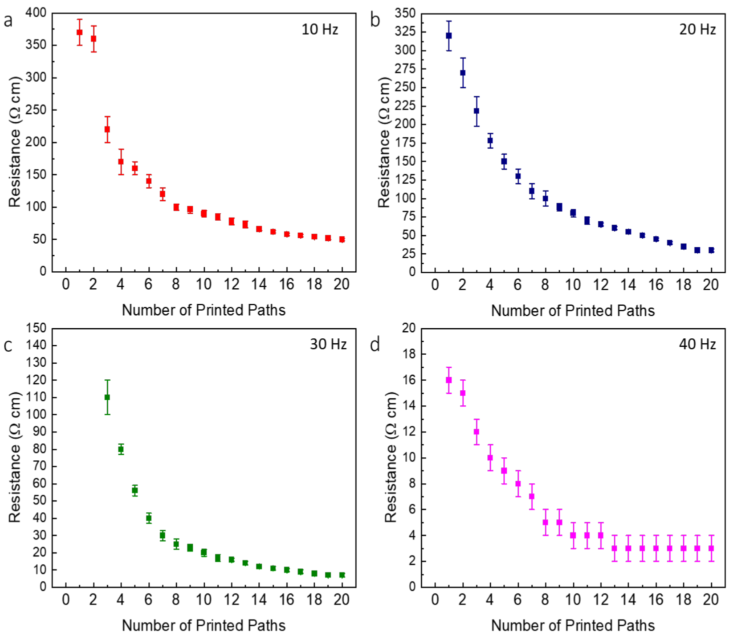
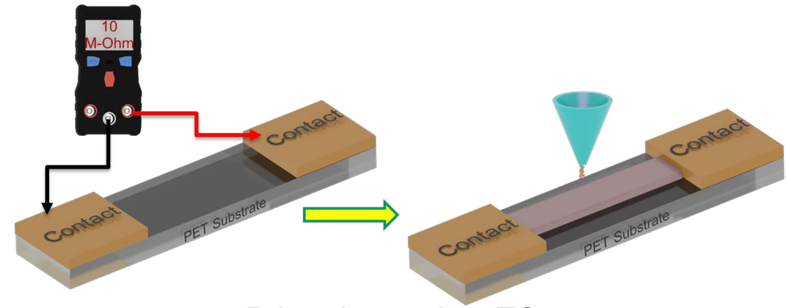
Resistance vs. Number of Printed Paths

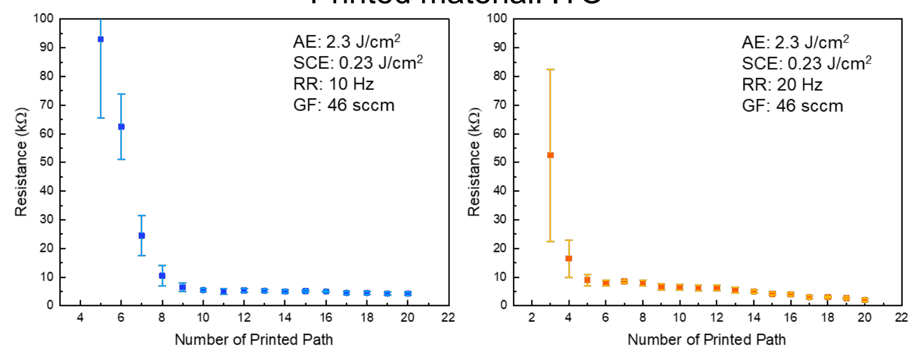
Conductivity of printed ANM Ag and ITO as a function of different parameters:

Printed material: Ag

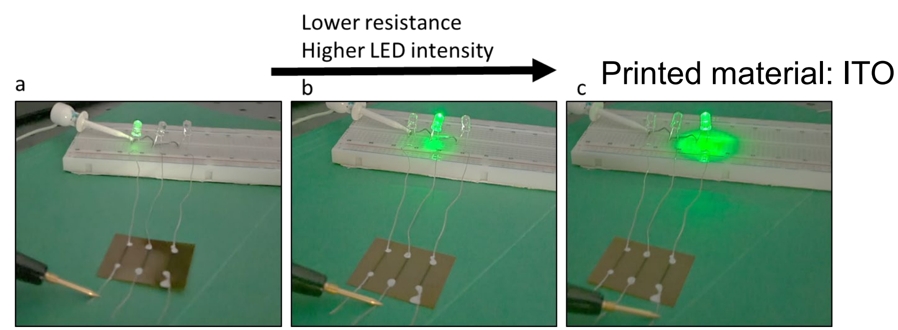




Printed material: ITO



- The electrical resistivity has proportional relationship with number of printed paths.
- Increasing the repetition rate will result in increasing the line thickness and hence conductivity improvement.



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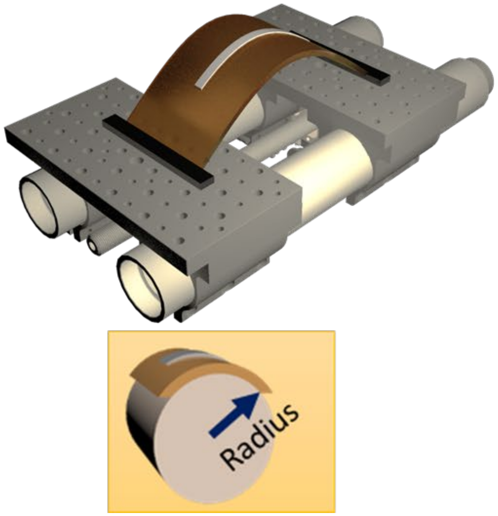
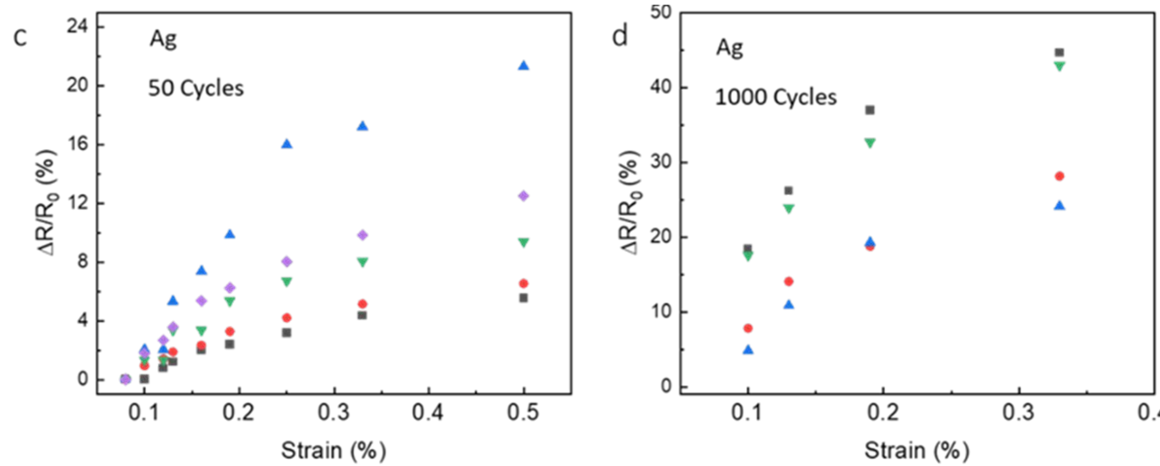
Reliability Test on ANM-Printed Ag





$$\frac{\Delta R}{R_0}(\%) = \frac{R_s - R_0}{R_0} \times 100 \qquad (1)$$

$$Strain\,(\%) = \frac{t_{substrate}}{2R_{bend}} \times 100 \qquad (2)$$

R_0, R_s, $t_{substrate}$, R_{bend} are initial resistance, under-stress resistance, substrate thickness, and bending radius, respectively.

- The resistance increased more at higher bending strains (lower bending radius)
- According to the results:
  - tolerate a large strain with a slight increase in their electrical resistance.

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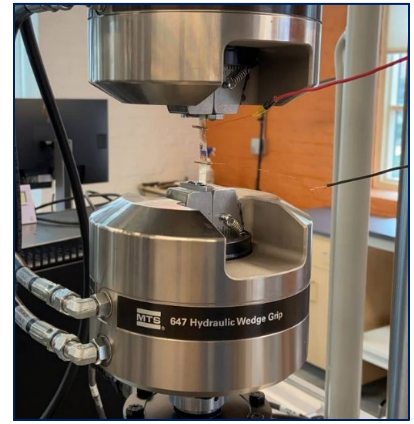
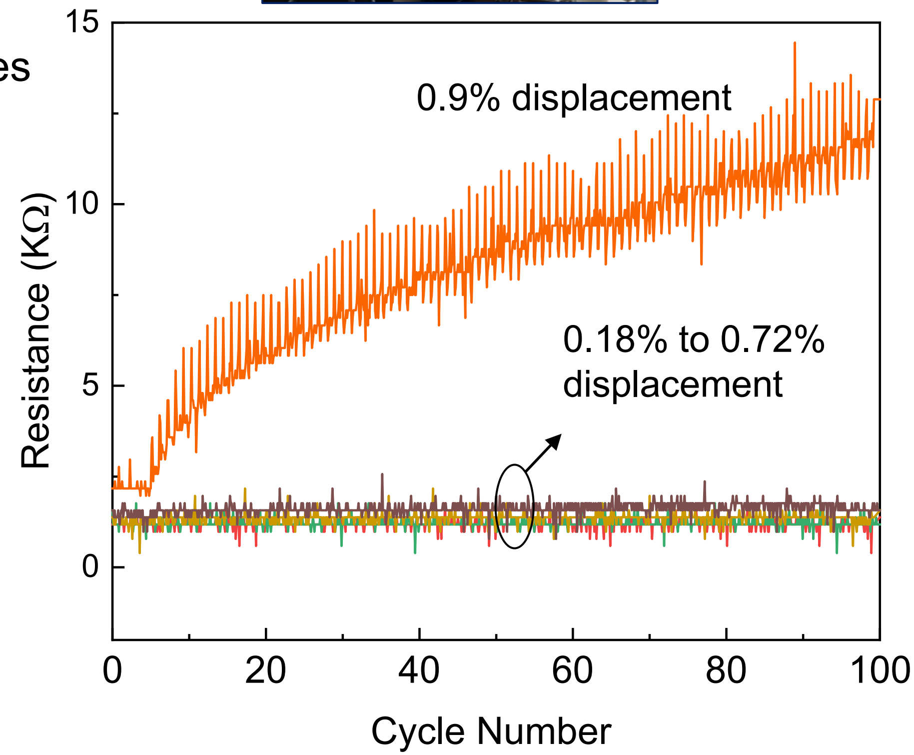
Stretching Tests on ANM-Printed ITO

- Hydraulic fatigue machine used for stretching tests



- ITO lines were printed onto the PET substrates (55 mm×5 mm×0.175 mm)
- Stretch from 0.18% to 0.9% displacement for 100 cycles
- Above 0.9% displacement, permanent substrate plastic deformation was observed, resulting in resistance overload



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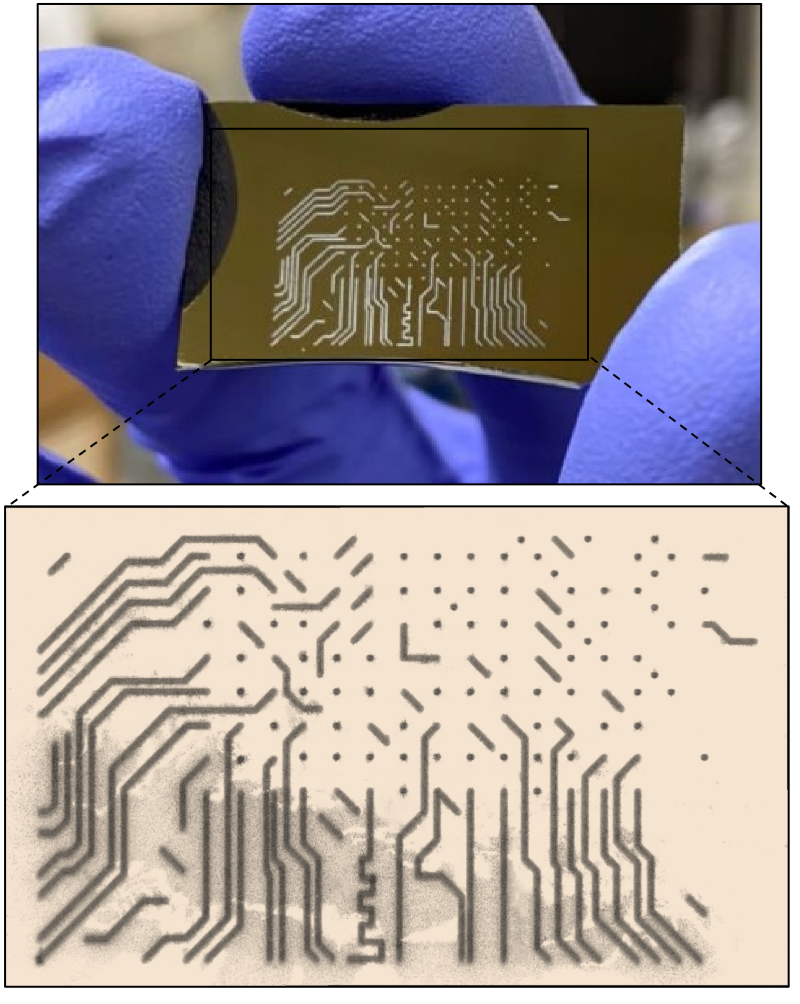
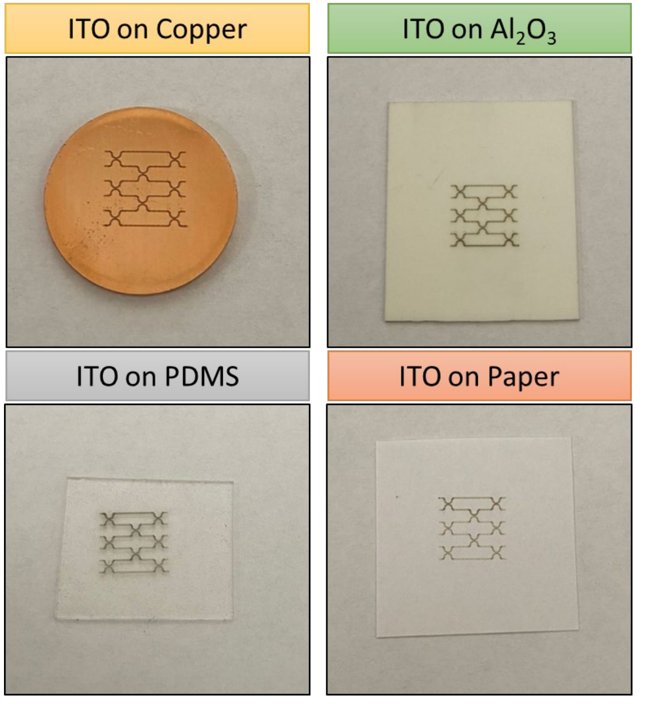
Applications

Additive Nanomanufacturing on Flexible and Rigid Substrate





- Printing on numerous substrates, including flexible substrates, paper, metals, glass, and ceramics.

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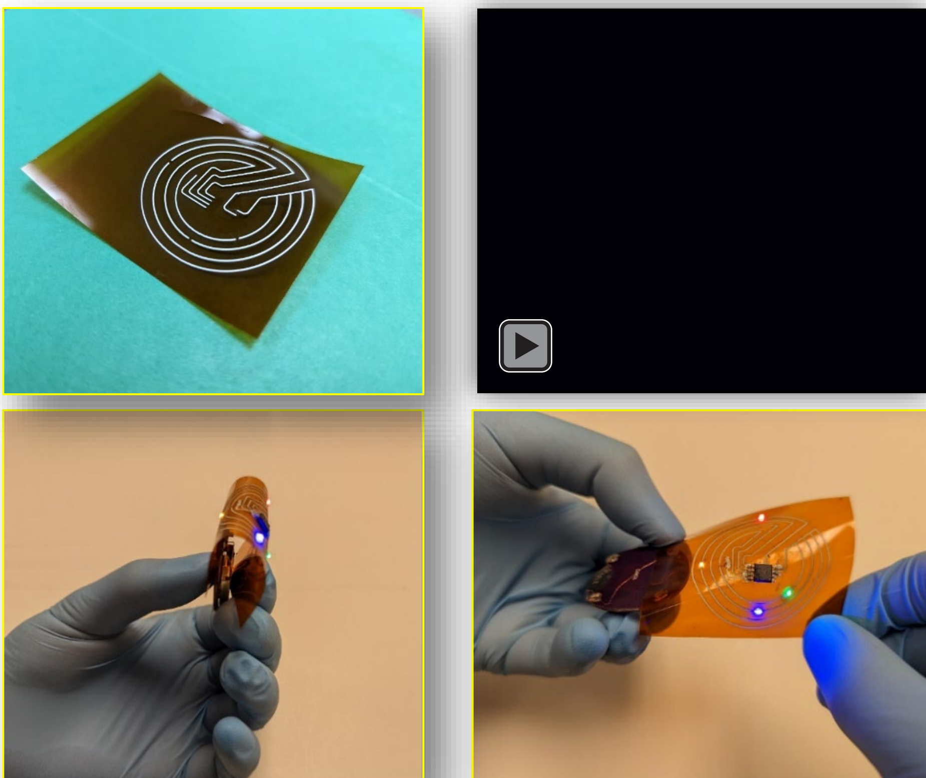
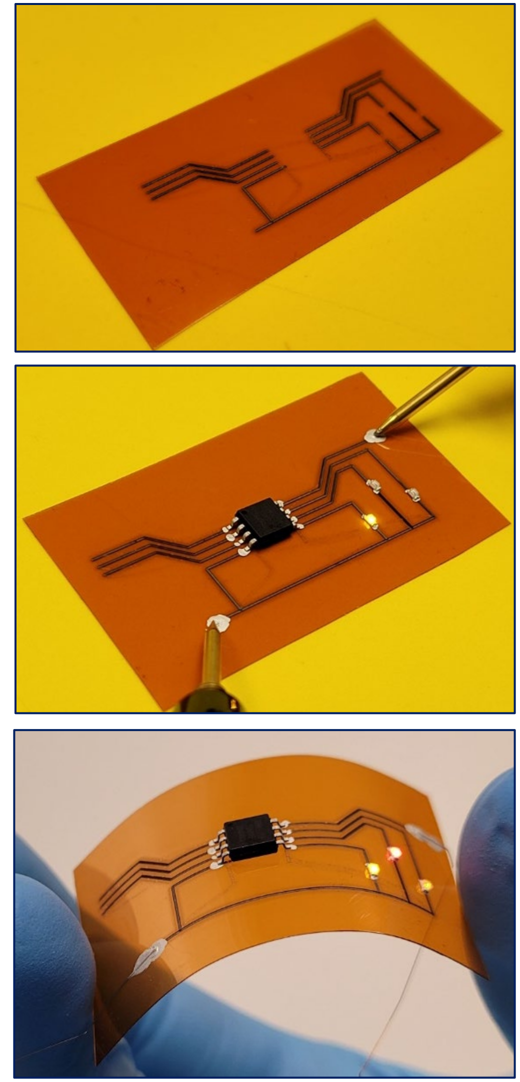
Applications

- Conductive electronics circuit and pattern of Ag printed by ANM process on polyimide substrate.

- Mounted SMD IC and LEDs on the circuit.





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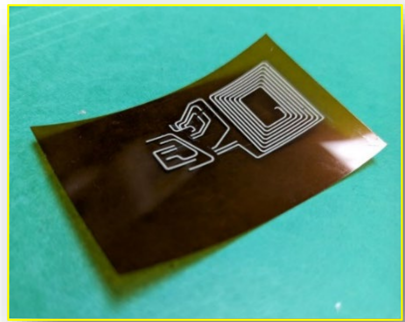
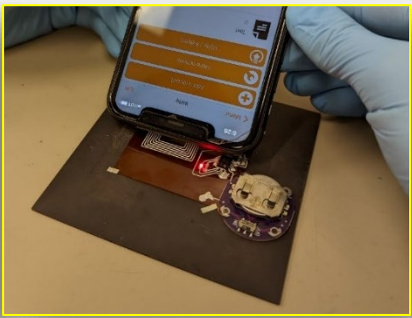
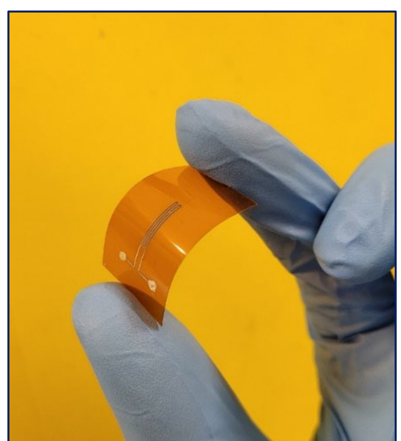
Applications

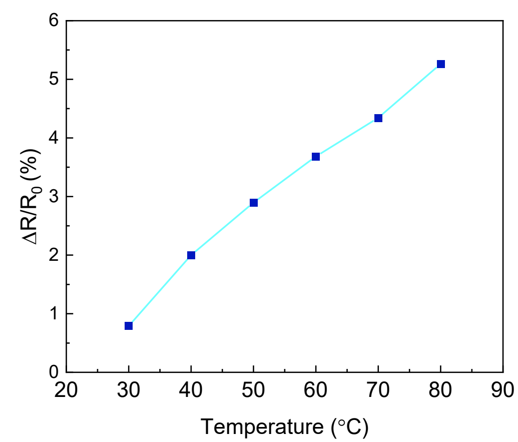
- Flexible Ag passive near field communication (NFC) tag for LED's controlling
  - SMD LED, 2-3V
  - ATtiny 85 IC programed with Arduino
  - Silver paste





- Temperature sensor
  - The sample on hotplate
  - Temperature measurement range
  - from 30 °C to 80 °C with 10 °C temperature increment.





The percentage of resistance change at different temperatures

Conclusion

- Inkjet and aerosol jet printing techniques have some disadvantages such as:
  - Solvents and additives used in ink
  - Limitation in materials selection
- We introduced a novel technique, Additive Nanomanufacturing (ANM) printing technique capable of:
  - Dry and solution-free printing (No additives or solvent)
  - Suitable for a wide range of materials including metals and metal-oxides
  - Compatible with variety range of rigid and flexible substrates
- Wide range of devices and applications can be printed by ANM-technique.

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- Alabama Micro/Nano Science and Technology Center (AMNSTC)

Q & A

Thanks for the attention

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