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
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 and inkjet as a non-contact method have more design flexibility compared to other contact methods.
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.
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: polyvinylpyrrolidone + ethylene glycol + AgNO₃

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: TiO₂, BTO, ITO
- Additives/solvents free, No post-treatment process

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:

![TiO2 target](image)

![2 µm TiO2](image)
![1 µm ITO](image)
![1 µm Ag](image)
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.
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.
• Effect of the laser beam energy on the crystallization of TiO$_2$ nanoparticles

  • In-situ generated nanoparticles
    o 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$^{-2}$,
    o 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$_2$. 

![Raman Spectroscopy Study of TiO$_2$](image)
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\(^{-2}\))

Increasing gas flow rate $\rightarrow$ increasing deposition thicknesses.

Increasing repetition rate $\rightarrow$ increasing deposition thicknesses

With ANM technique, thickness is controllable.
Conductivity of printed ANM Ag and ITO as a function of different parameters:

- 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.
\[
\frac{\Delta R}{R_0} \text{ (\%)} = \frac{R_s - R_0}{R_0} \times 100 \quad (1)
\]

\[
\text{Strain (\%)} = \frac{t_{\text{substrate}}}{2R_{\text{bend}}} \times 100 \quad (2)
\]

- 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.

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

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

Additive Nanomanufacturing on Flexible and Rigid Substrate

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

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

- Mounted SMD IC and LEDs on the circuit.

Applications

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

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

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.
References


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Q & A

Thanks for the attention
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