Additive Manufacturing of Electronics at the Nano and Microscale for Making Trace, Interconnects, Passive and Active Components

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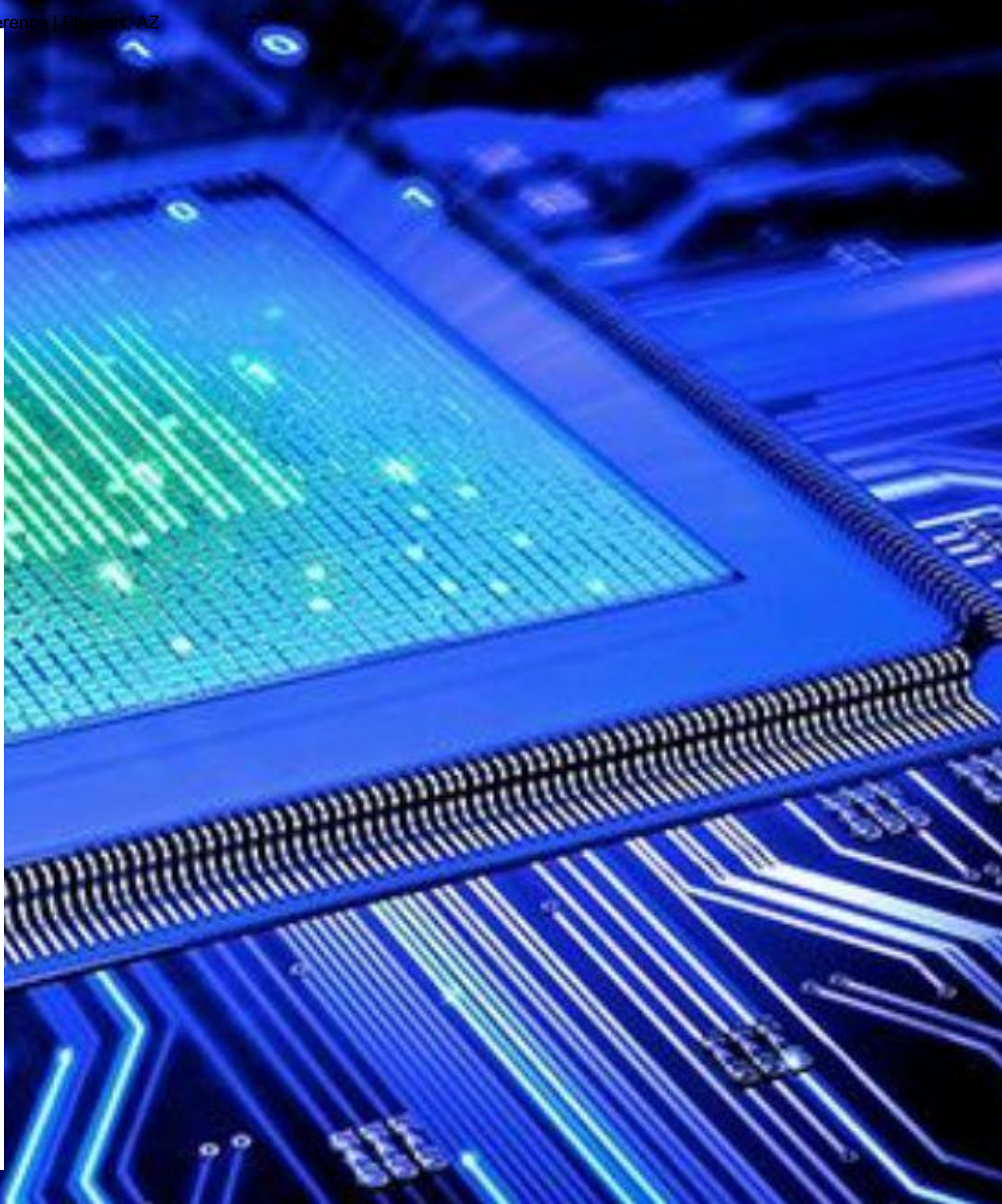
- Introduction
- How does it work?
- Nanoscale Directed Assembly-based Processes
  - Electrophoretic Assembly (EPx Platform)
  - Fast fluidic Assembly (FFx Platforms)
- Printing of Organic electronics
- Printing of crystalline and single crystal of metals and inorganic semiconductors
- Applications (transistors, diodes, display, etc.)
- Scalable and fully automated Fab-in-a-Box
- Summary



A Semiconductor Foundry in a Box

- On demand chips in a few hours
- No etching, chemical reactions, or vacuum
- Secure (trusted) foundry (from zero to full trust).
- 100 times less cost
- 100 times faster than conventional fabrication
- 1000 times reduction in materials use
- 1000 times faster than 3D printing
- 25 nm to 1000 microns feature size demonstrated
- eliminating 100s of process steps

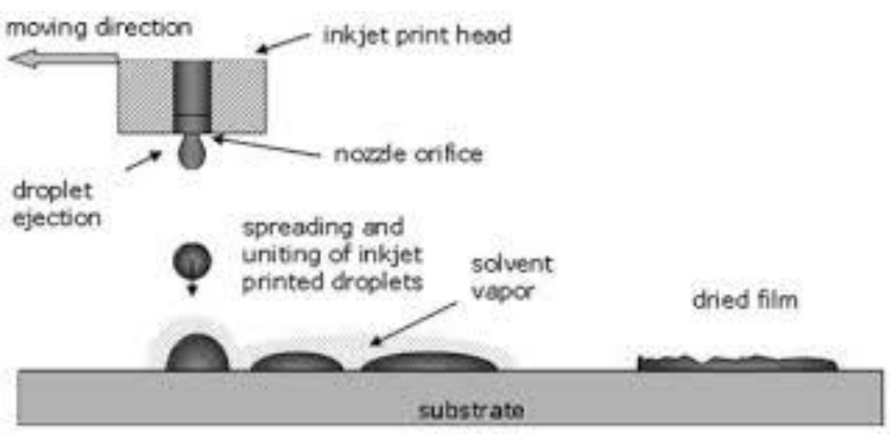
Semiconductor Foundry in a Box

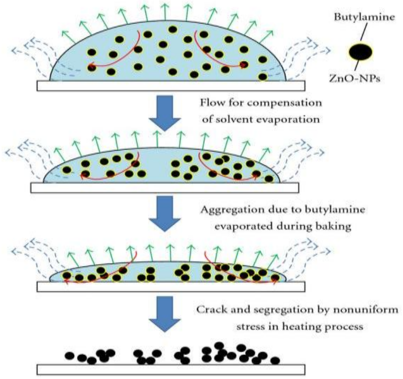
Nano PS

Patented new technology (directed assembly-based printing) to print circuits at the nano and microscale funded by NSF and DoD.

Directed Assembly versus Inkjet Printing?

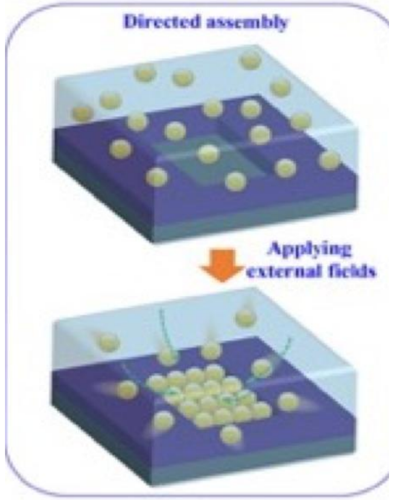
Inkjet printing

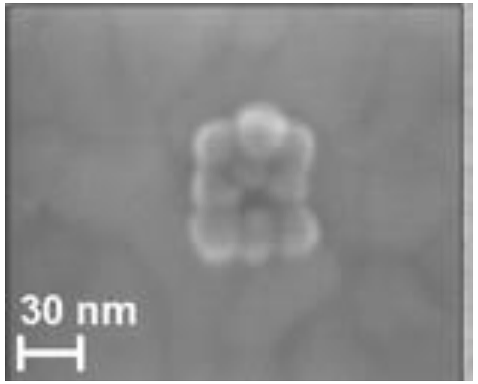




- **Directs a droplet** toward a substrate to form a pattern using many (dots) limiting pattern resolution and fidelity.
- Inherently relies on mechanical accuracy.
- Materials limited to organics and metals

Directed assembly-based printing

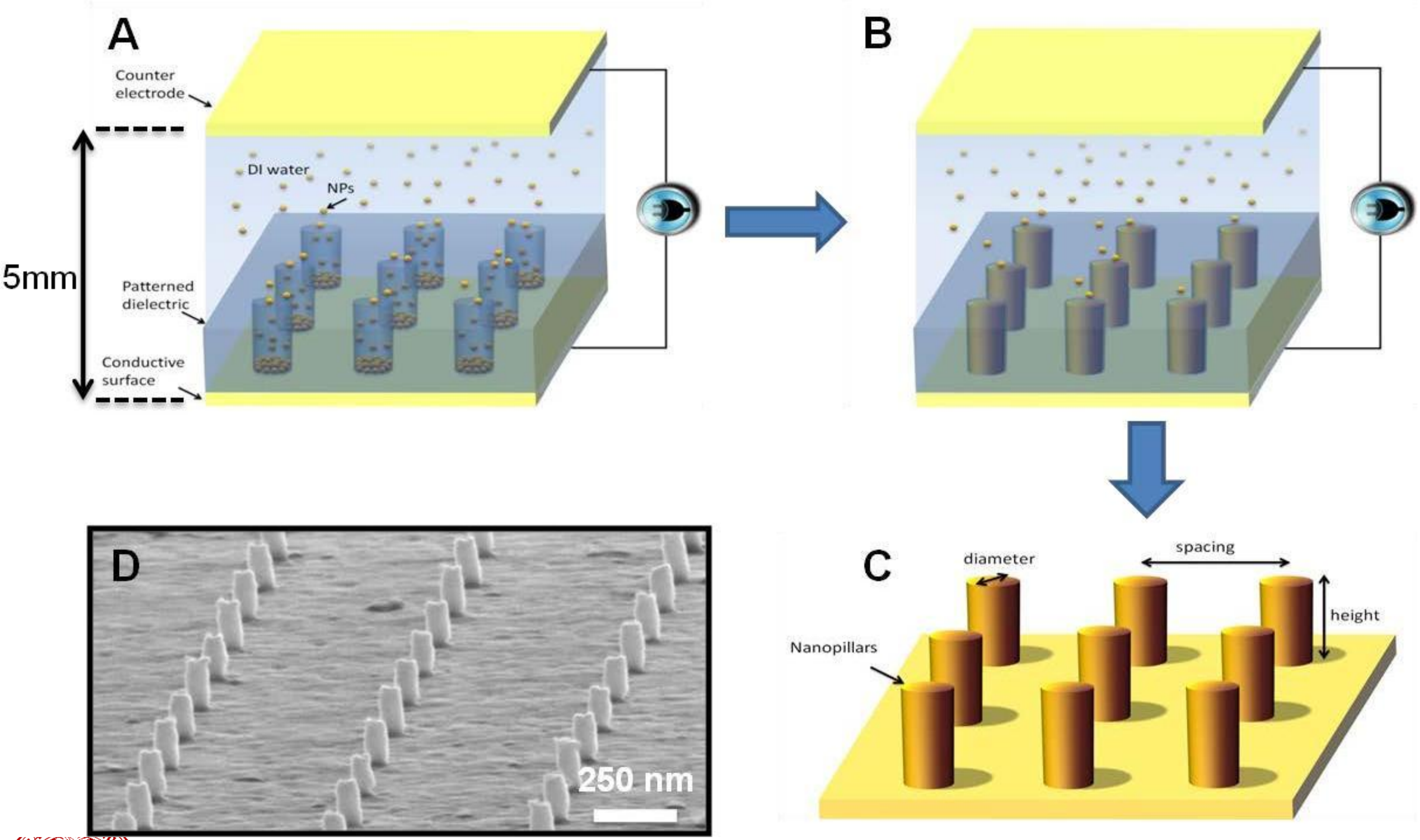


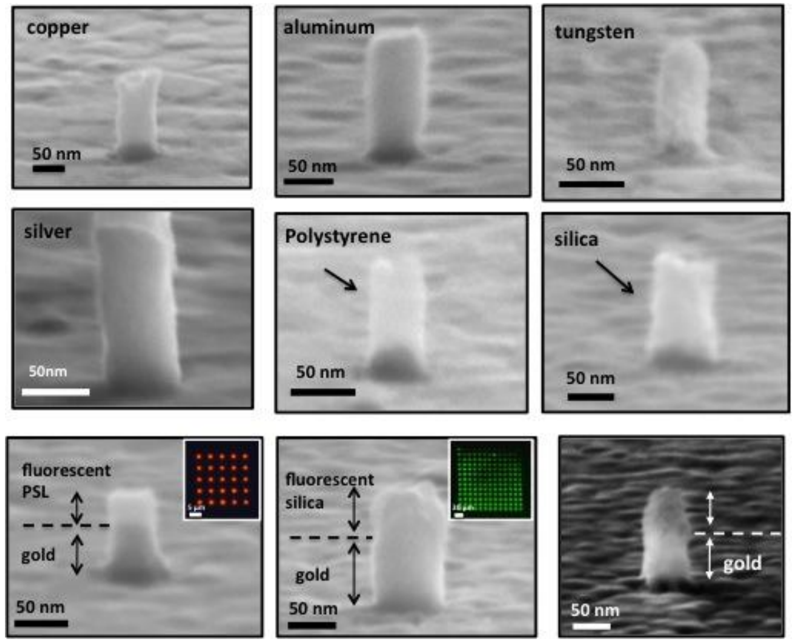


- ➢ **Directs each nanoparticle** (down to 3nm in size) toward a substrate to form a nanopattern.
- ➢ Prints 1000 times faster & smaller patterns than inkjets
- ➢ Prints one circuit layer per minute

Electrophoretic Directed Assembly– EPx Platform

Assembled Interconnects

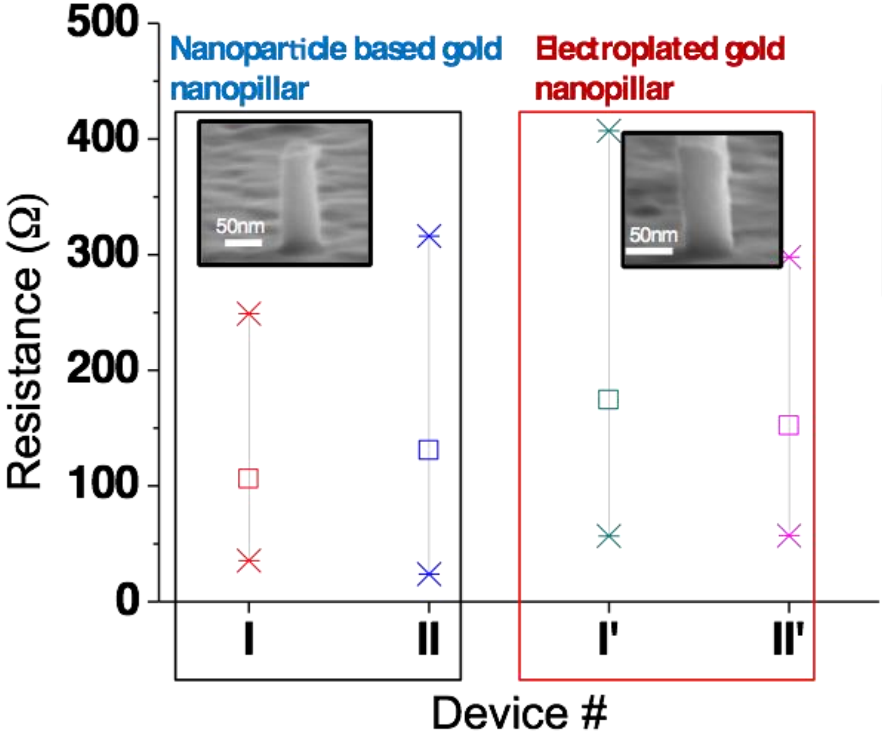


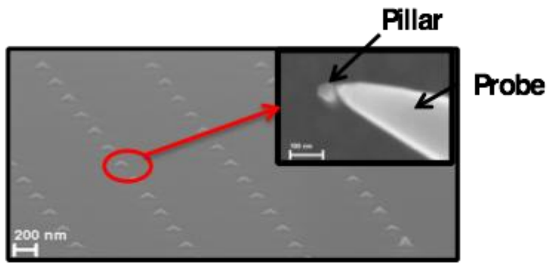


All assembled Nanoparticles are completely fused insitu.

ACS Nano, 8 (5), 2014.

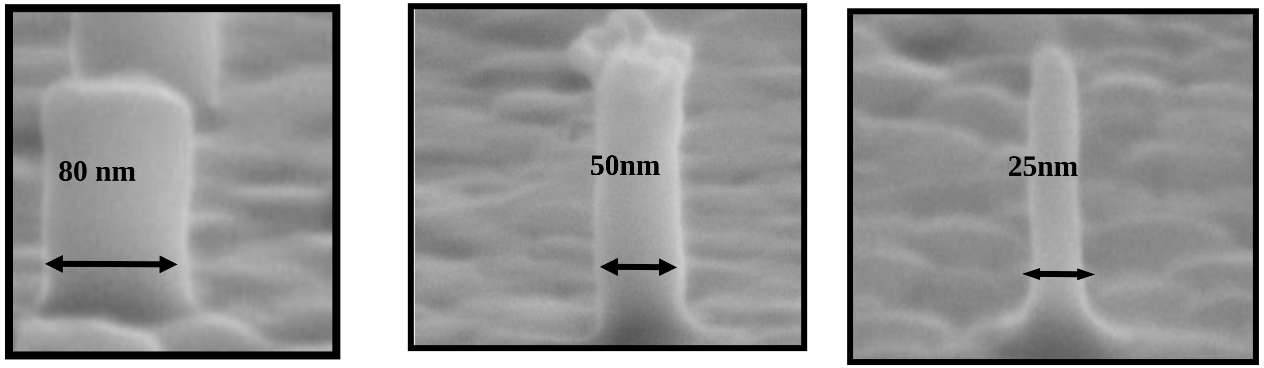
Interconnects Properties





Resistance of assembled interconnects is the same as bulk (electroplated interconnects).

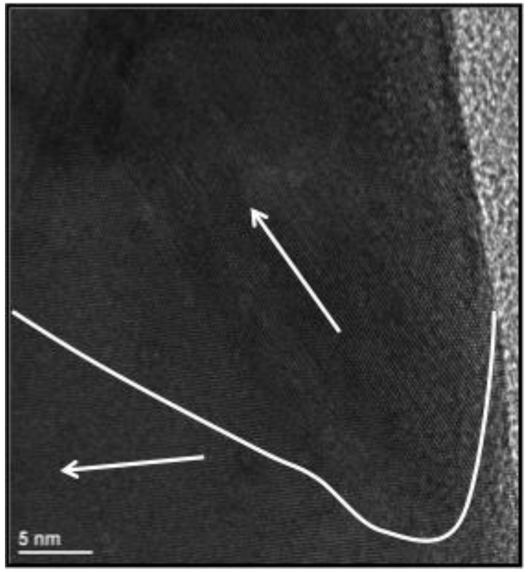
Crystalline Au Pillars



Directly assembled structures properties are equivalent to electroplating, CVD and PVD fabrication.

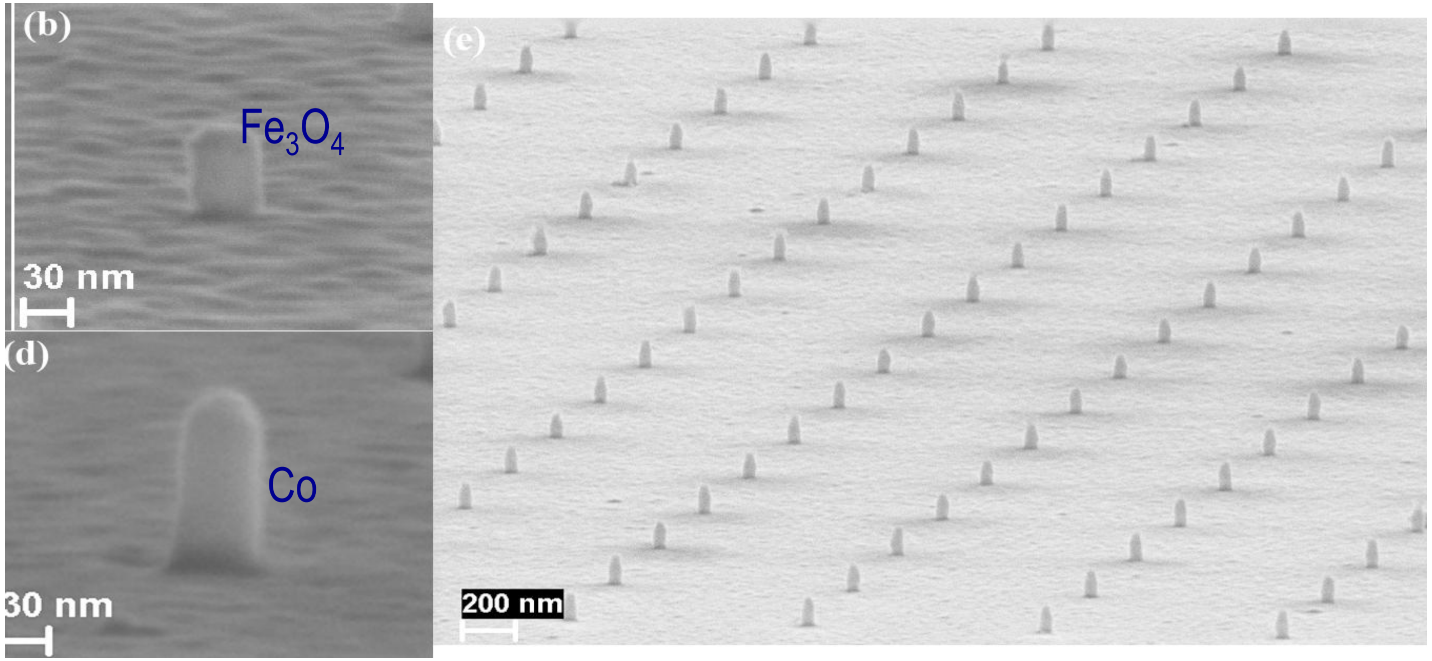
Directly assembled metallic structures (Cu, Ag, Al, Au, and W, etc.) in addition to semiconductors and dielectrics were demonstrated.

- ➢ TEM shows that NPs completely fuse without any voids at room temperature.
- ➢ Nanopillars have polycrystalline nature.

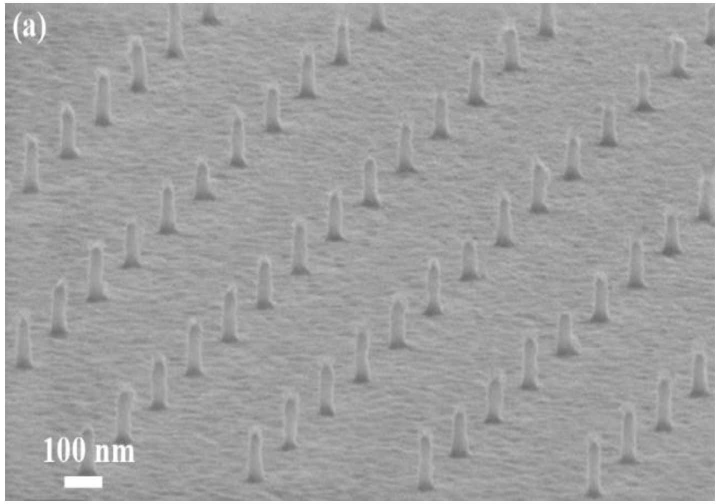


ACS Nano, 8 (5), 2014.

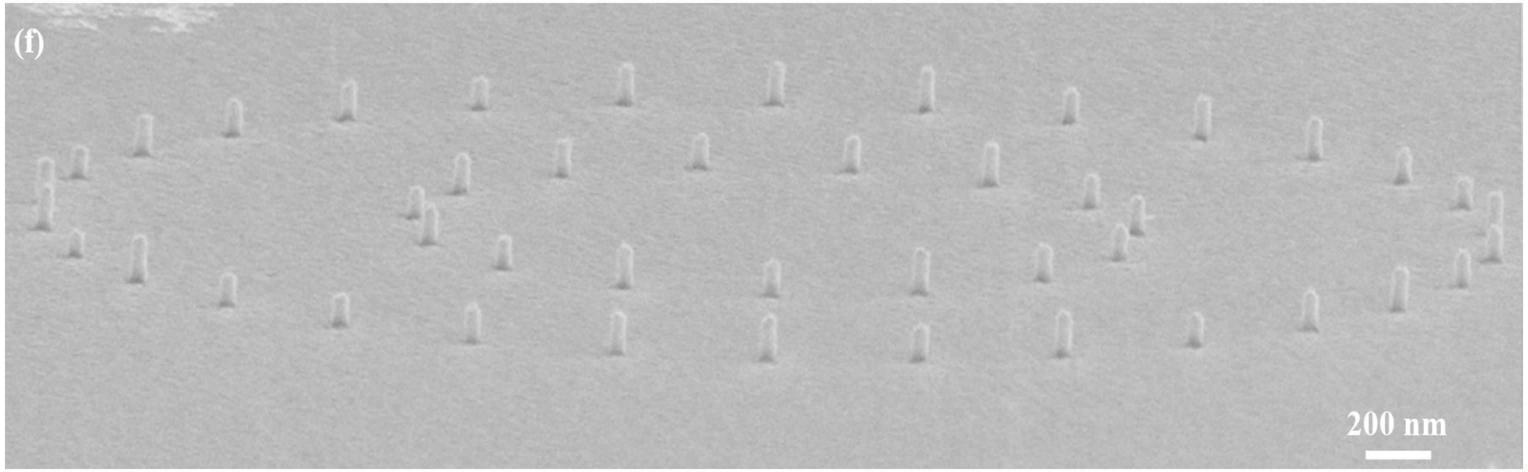
Printing Nano Structures (EPx)



Magnetic memory
(MRAM) applications

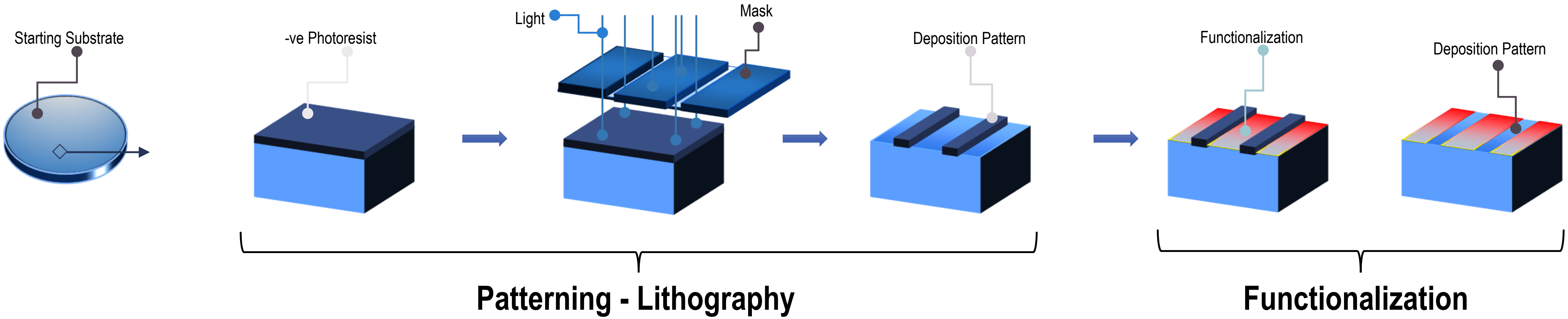


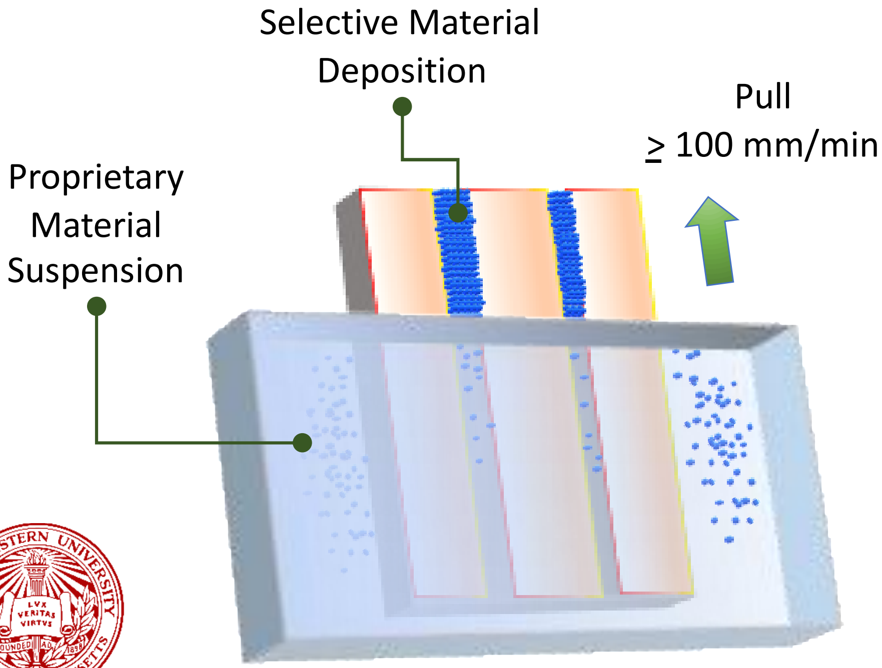
Printed nano rods using 20 nm particles



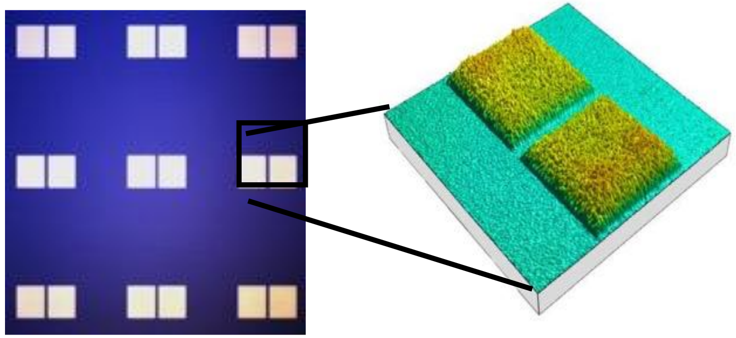
Nanotechnology, Volume 28, Number 47, November 2017.

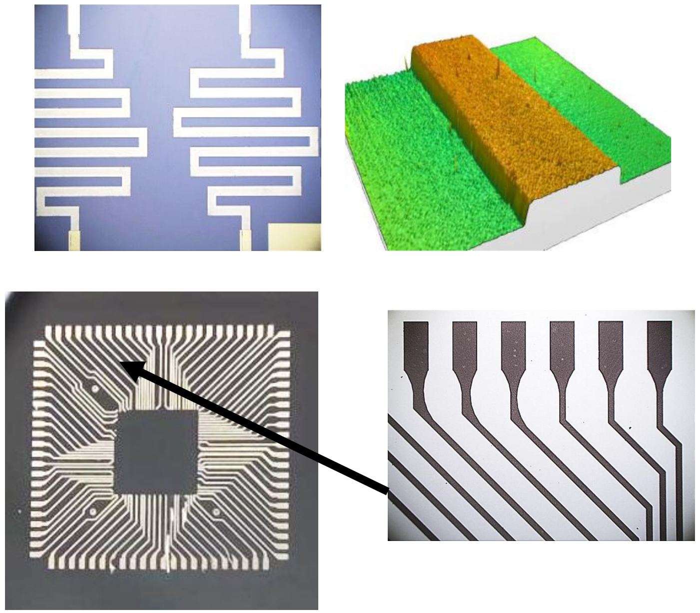
Fast Fluidic Assembly Process– FFx Platform





SiO_2 substrate – 10 µm spacing

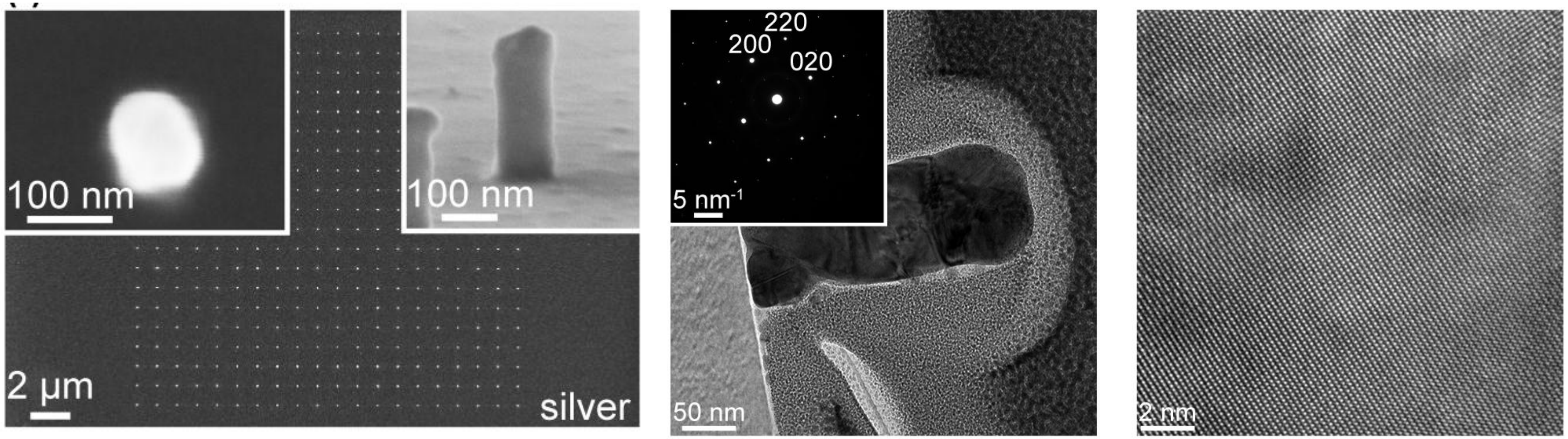




ACS Nano, 16 (11), 2022.

Additively Manufacturing Single Crystal Semiconductor and Metal

Interfacial convective directed assembly

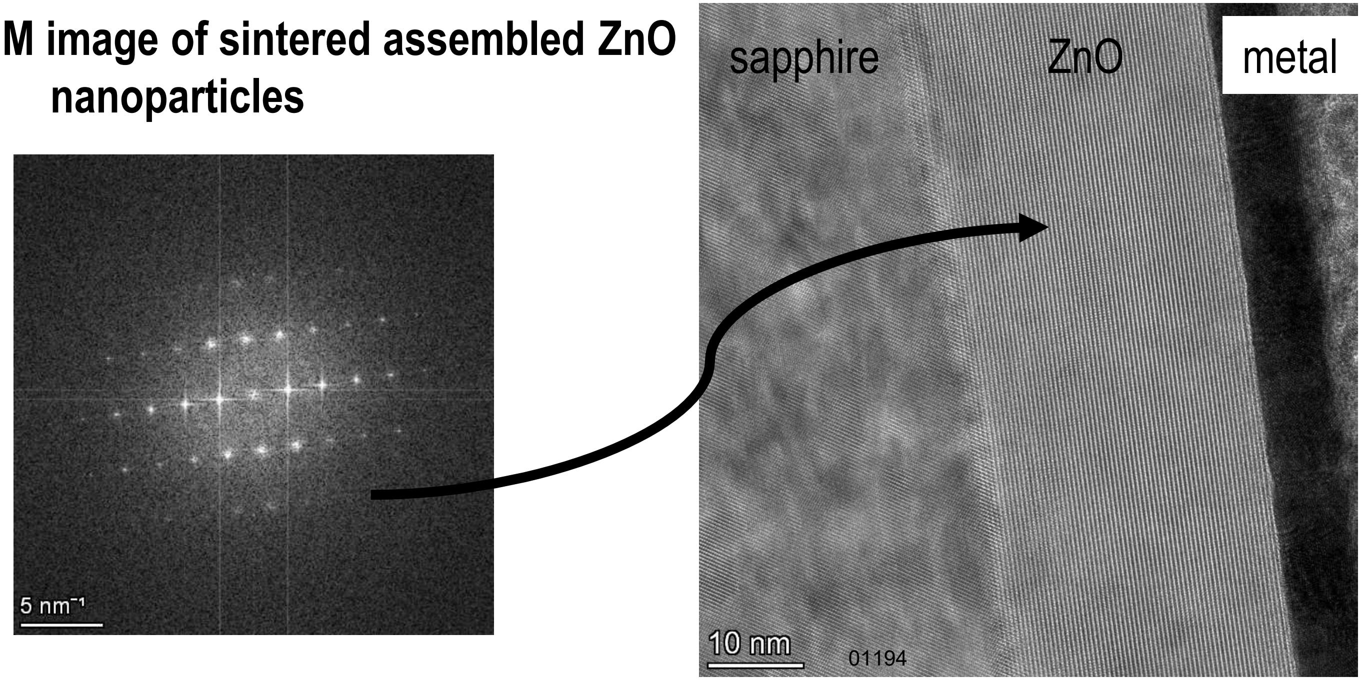


Advanced Materials, 2020.

Room temperature Printing & sintering to make wafer scale single crystal metal (Ag) nanostructures

Single Crystal TEM image of sintered assembled ZnO nanoparticles

Fast Fluidic directed assembly



RTP sintering of II-VI nanoparticles (1000 c for 2 min) on sapphire yields gives a single crystal structure throughout.

Directed Assembly for Nanoscale Devices Review Articles

ACS NANO
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Review

Directed Assembly of Nanomaterials for Making Nanoscale Devices and Structures: Mechanisms and Applications

Zhimin Chai, Anthony Childress, and Ahmed A. Busnaina*

Cite This: https://doi.org/10.1021/acsnano.2c07910

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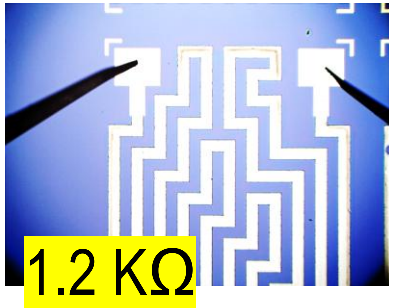
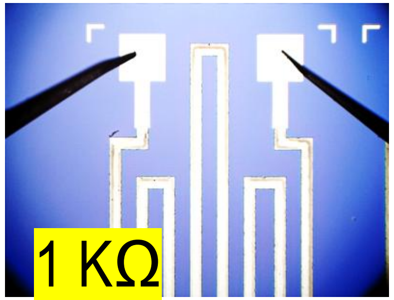
ABSTRACT: Nanofabrication has been utilized to manufacture one-, two-, and three-dimensional functional nanostructures for applications such as electronics, sensors, and photonic devices. Although conventional silicon-based nanofabrication (top-down approach) has developed into a technique with extremely high precision and integration density, nanofabrication based on directed assembly (bottom-up approach) is attracting more interest recently owing to its low cost and the advantages of additive manufacturing. Directed assembly is a process that utilizes external fields to directly interact with nanoelements (nanoparticles, 2D nanomaterials, nanotubes, nanowires, etc.) and drive the nanoelements to site-selectively assemble in patterned areas on substrates to form functional structures. Directed assembly processes can be divided into four different categories depending on the external fields: electric field-directed assembly, fluidic flow-directed assembly, magnetic field-directed assembly, and optical field-directed assembly. In this review, we summarize recent progress utilizing these four processes and address how these directed assembly processes harness the external fields, the underlying mechanism of how the external fields interact with the nanoelements, and the advantages and drawbacks of utilizing each method. Finally, we discuss applications made using directed assembly and provide a perspective on the future developments and challenges.

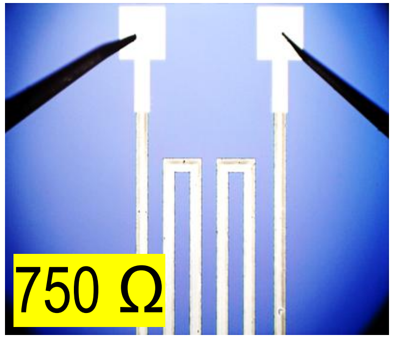
KEYWORDS: *directed assembly, bottom-up fabrication, nanomaterials, nanotechnology, nanoelectronics, microelectronics, electrophoresis, dielectrophoresis, magnetophoresis, fluidic assembly*

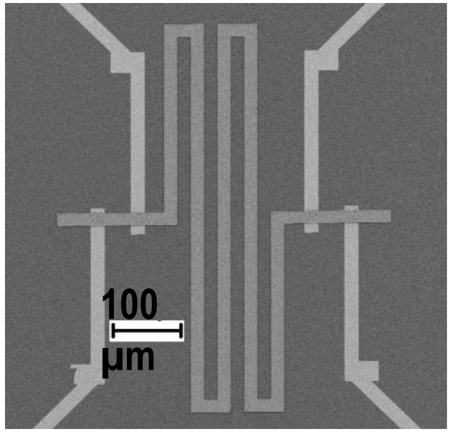
Additively Manufactured Metals Fan out Patterns and Resistors

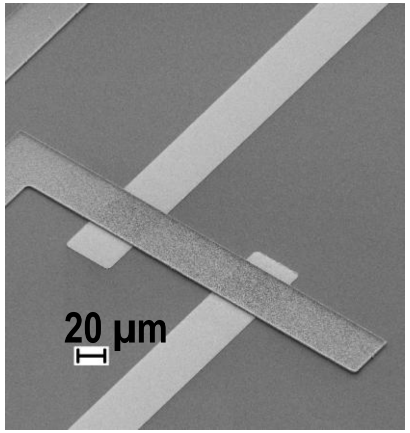
Additively Manufactured Components: Resistors

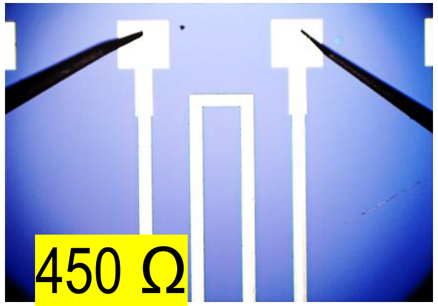


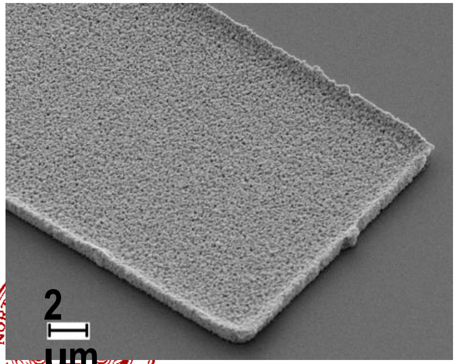


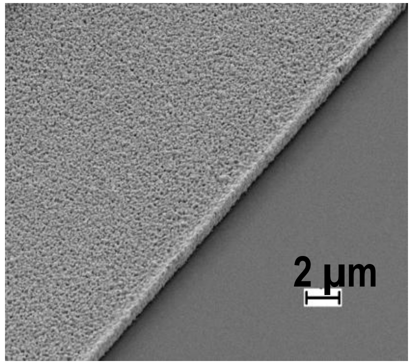


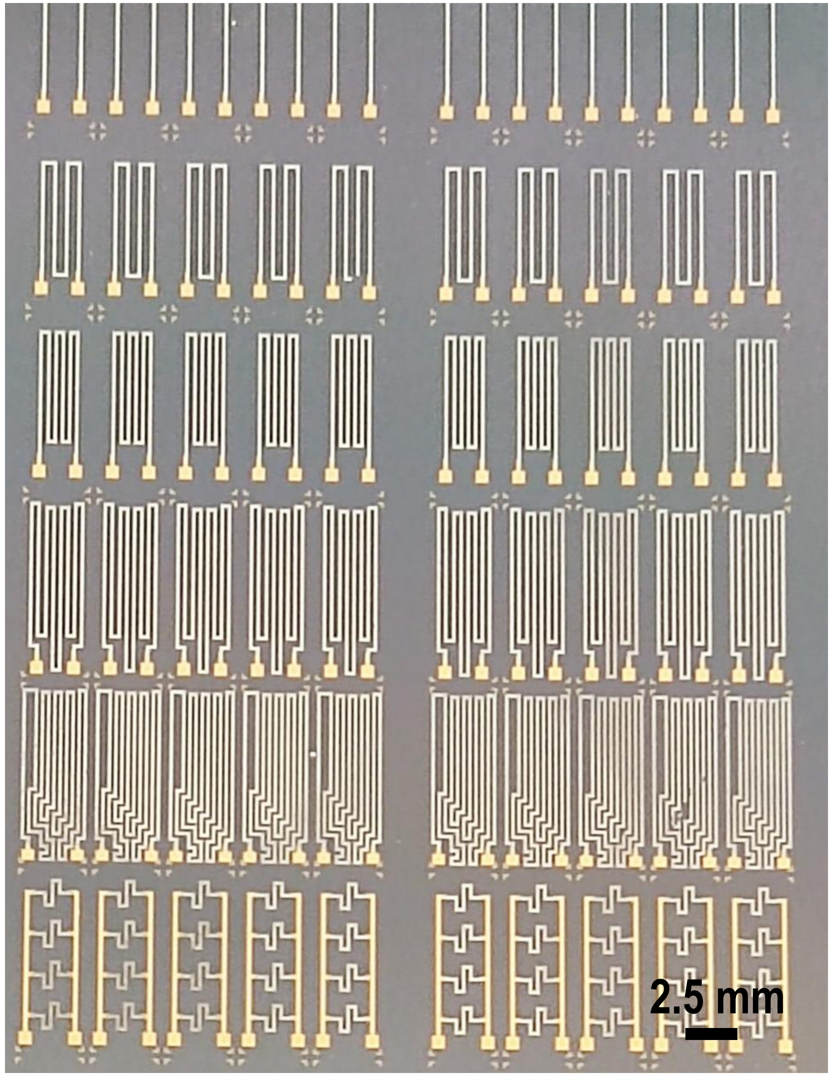












50 Ω

100 Ω

250 Ω

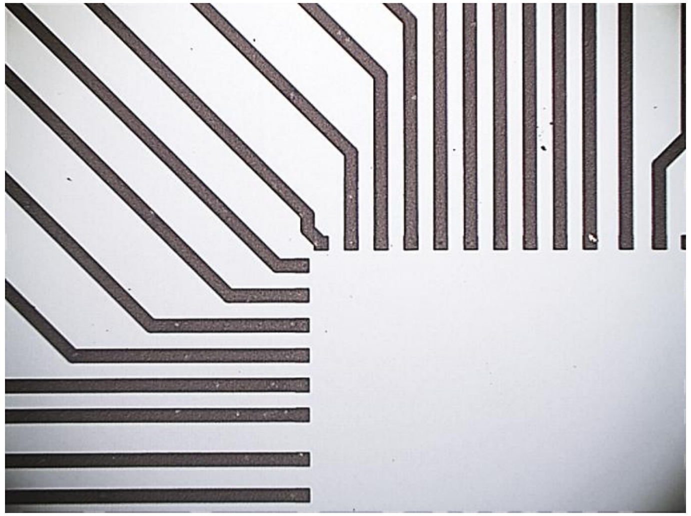
550 Ω

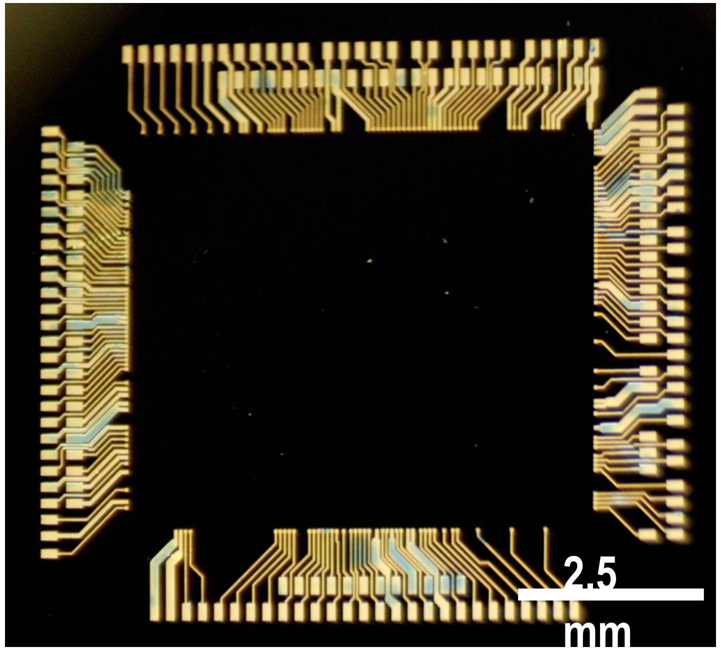
800 Ω

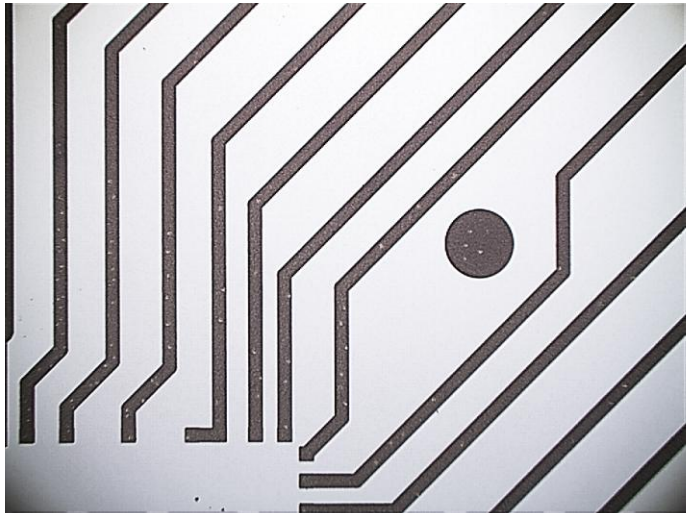
30 Ω

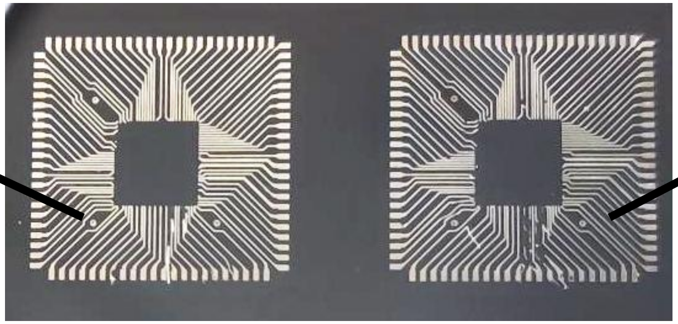
Thin metal film resistors

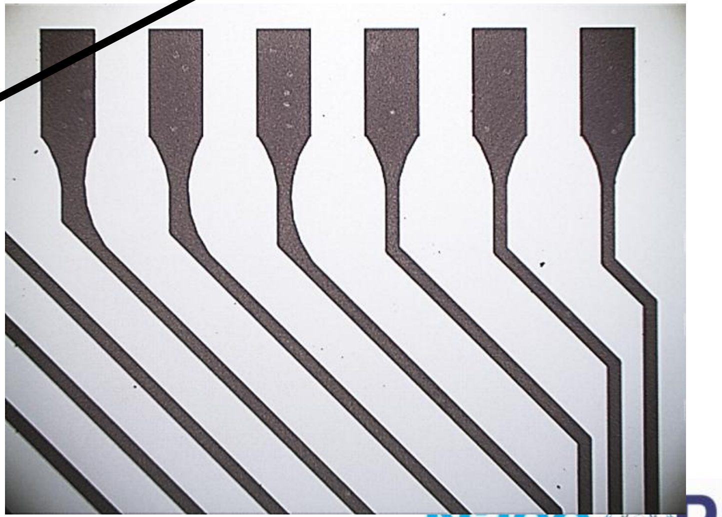
Additively Manufactured Fan Out Patterns











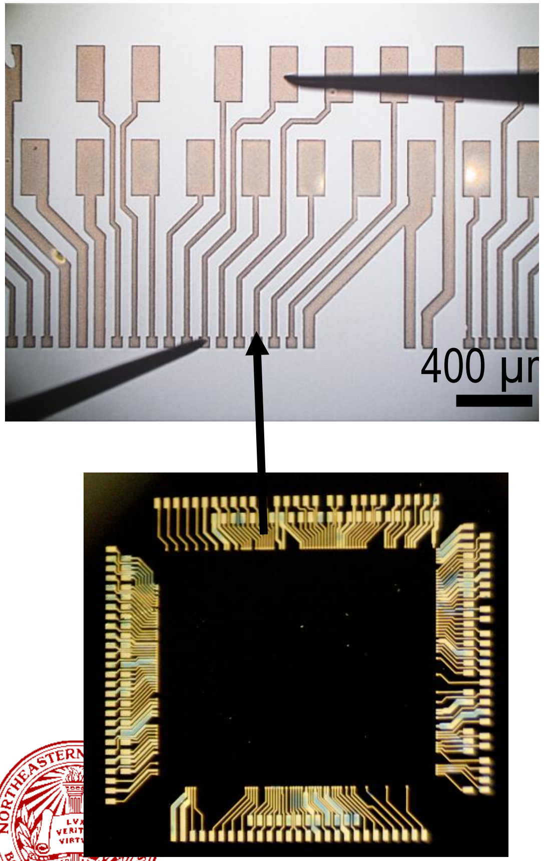
Printed Silver Flip Chip Fan Out Patterns

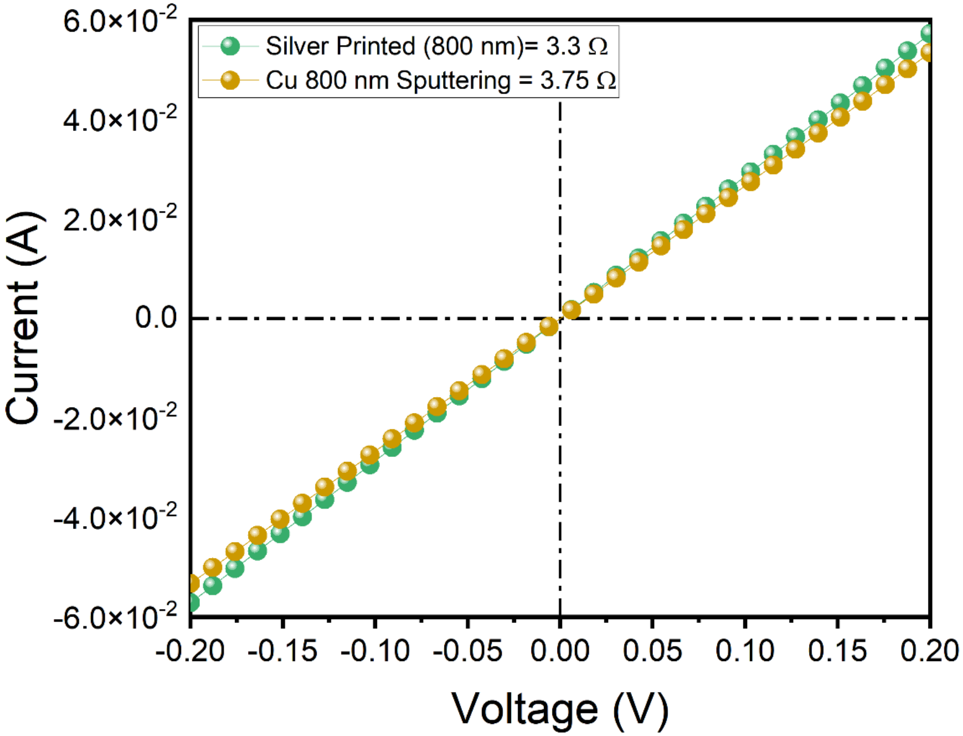
Additively Manufactured Metals Line

Silver vs Sputtered Copper

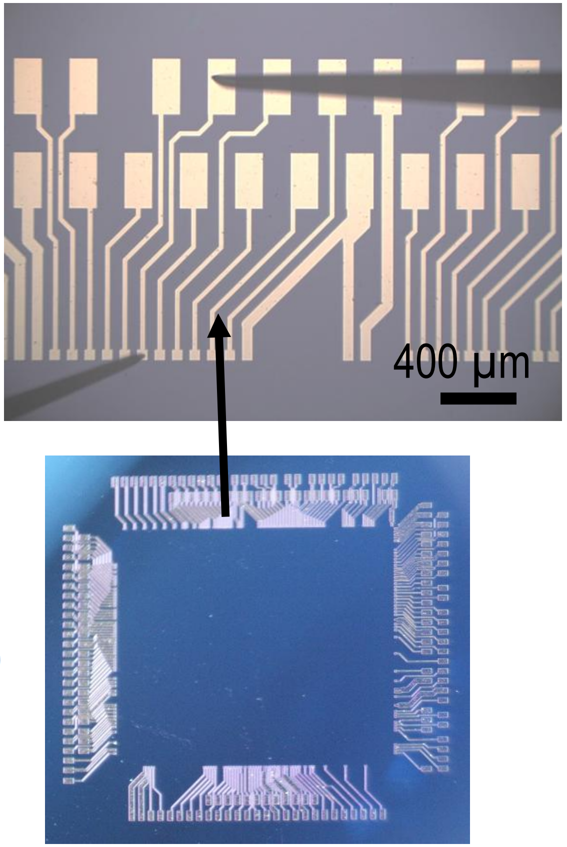
- ➢ Fan out Flip chip pattern was made using silver (internal pads < 40 microns)
- ➢ The trace's conductivity is equivalent to sputtered copper at the same thickness.

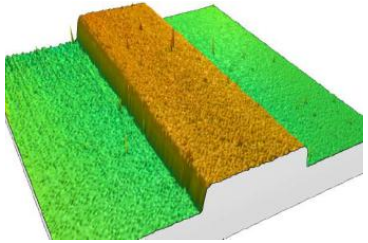
Silver

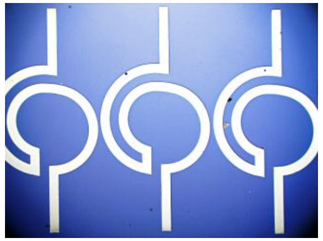




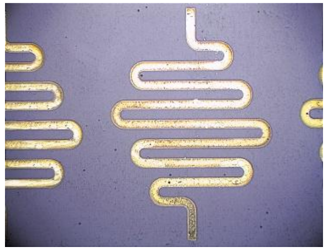
Copper (sputtered)



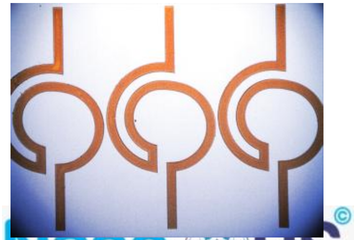




Platinum



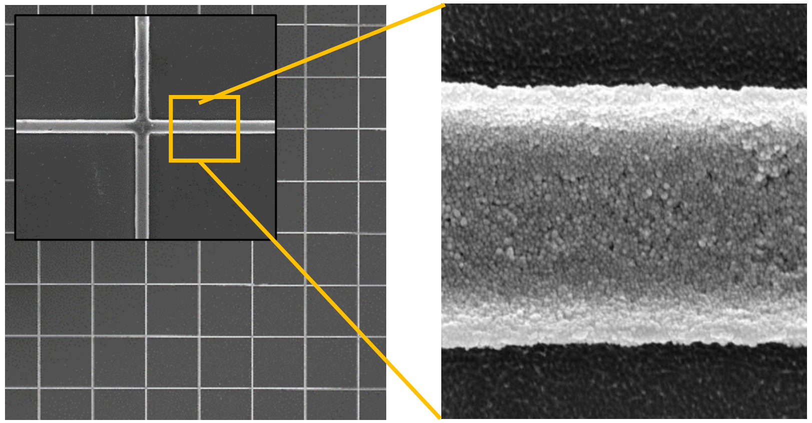
Gold



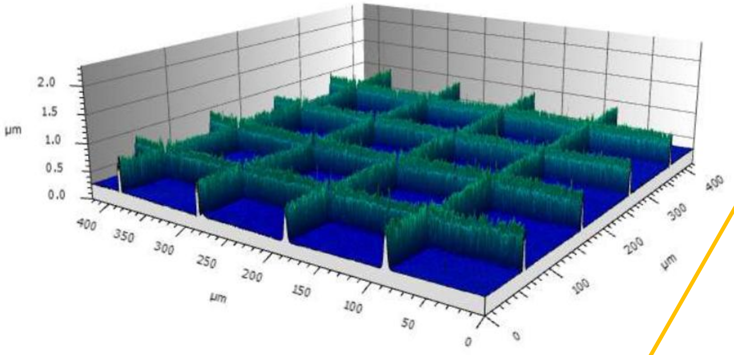
Copper

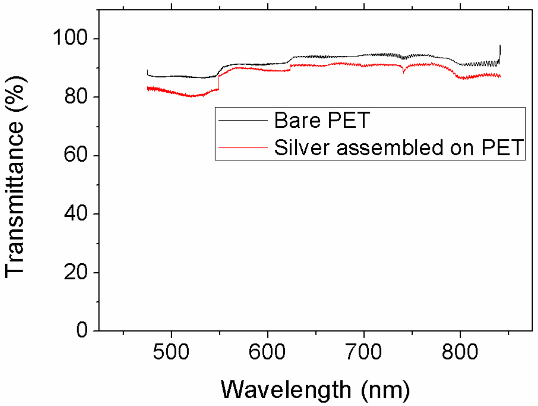
Additively Manufactured Touch Display at the Micro and Nanoscale

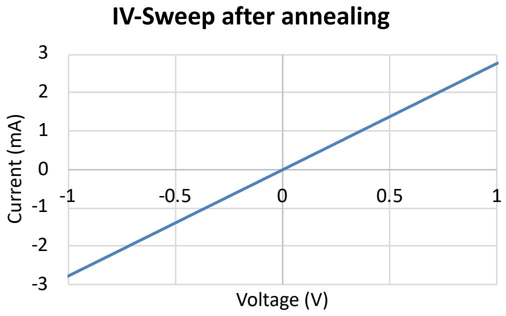
Ag grids for touch display applications



Line width 2 um







COMMUNICATION

Transparent Electrodes

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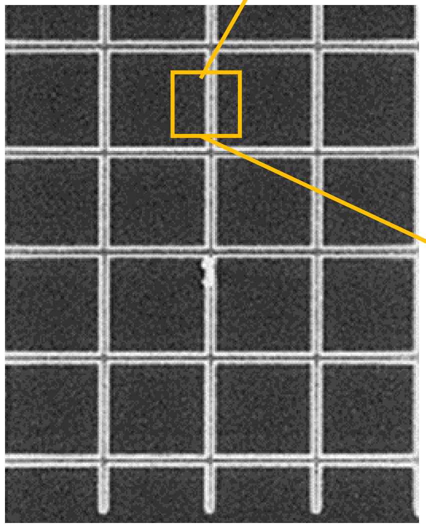
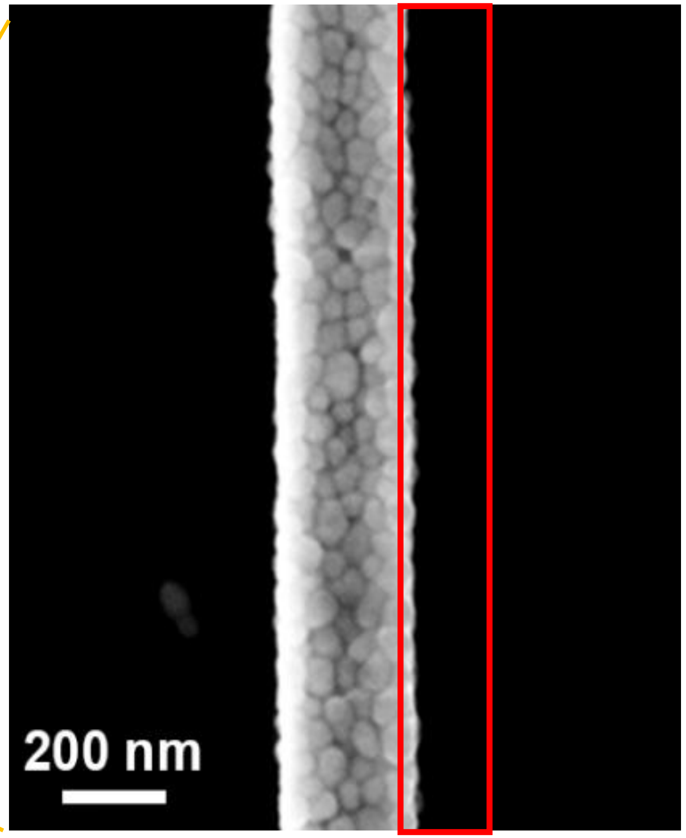
Scalable Printing of High-Resolution Flexible Transparent Grid Electrodes Using Directed Assembly of Silver Nanoparticles

*Salman A. Abbasi, Zhimin Chai, and Ahmed Busnaina**



Line width 300 nm

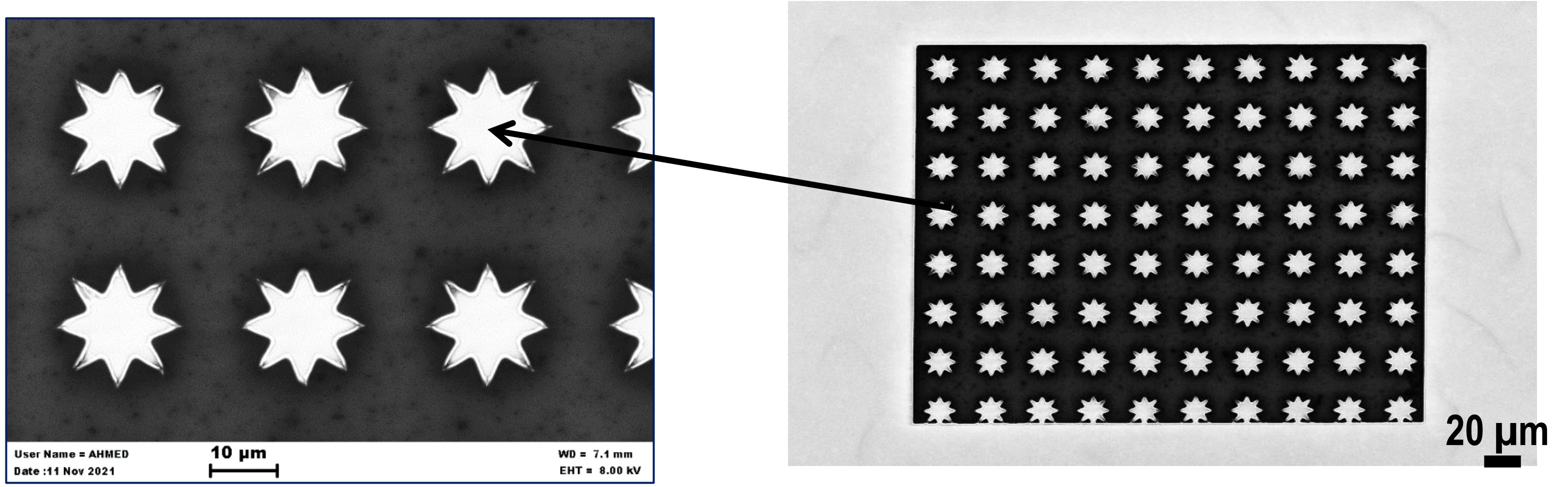


Excellent Line edge roughness
3.7 nm
Using large nanoparticles

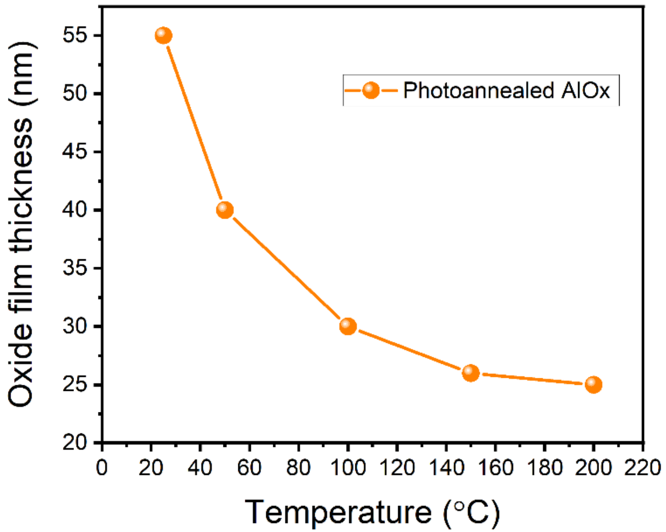
Additively Manufactured Dielectrics and Capacitors

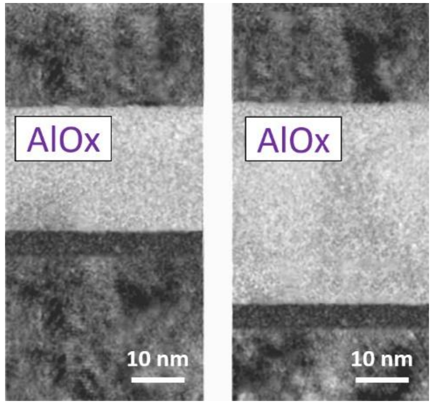
Additively Manufactured Dielectrics

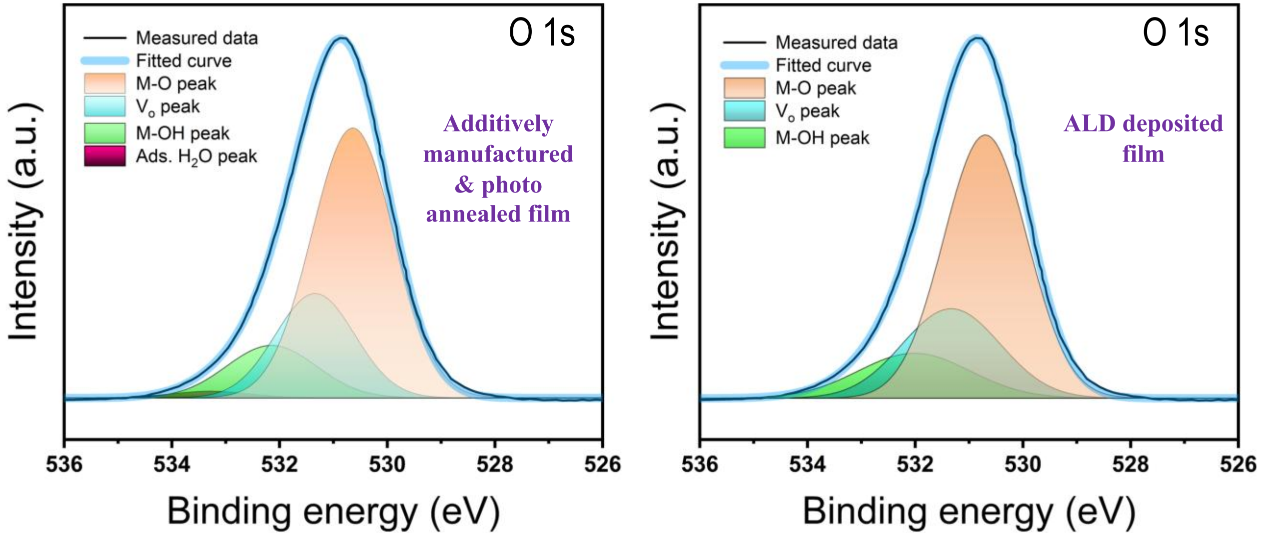
The SEM images below shows Al_2O_3 micropatterns prepared by directed fluidic assembly with a dielectric constant that matches that obtained by CVD or ALD ($\varepsilon_d = 7.2$).



X-ray Photoelectron Spectroscopy (XPS) characterization of the Dielectric Layer shows agreement in between ALD and printed films in terms of peak intensities and composition ratios.





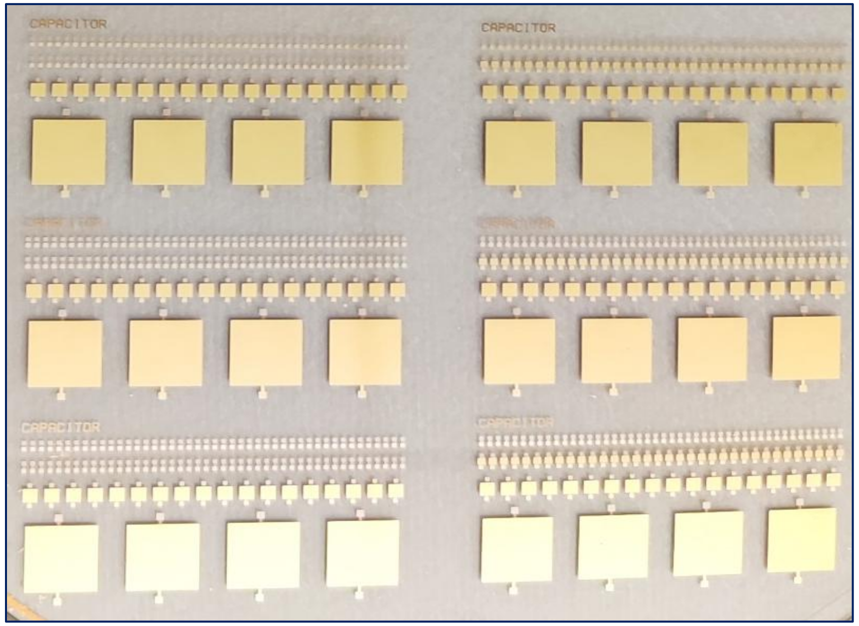


- ➢ Higher temperature densification and better dielectric properties for the film.
- ➢ Cross-sectional shows the oxide film thickness variation between 50 °C and 200 °C annealing.

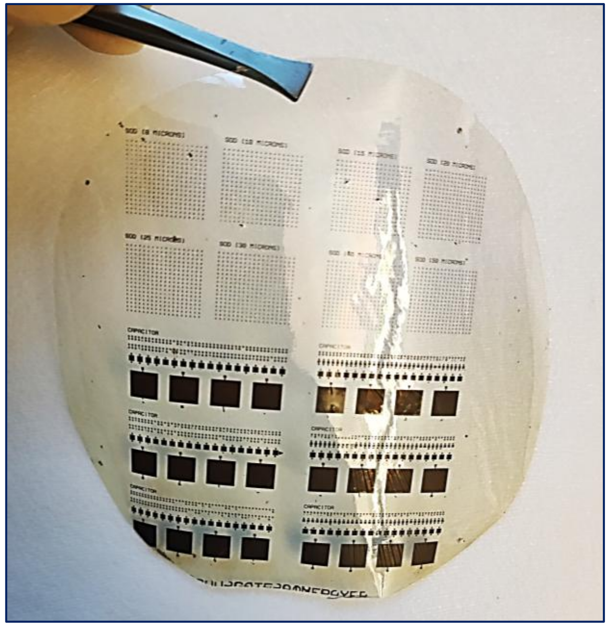
Additively Manufactured Capacitors on Rigid and Flexible Substrates

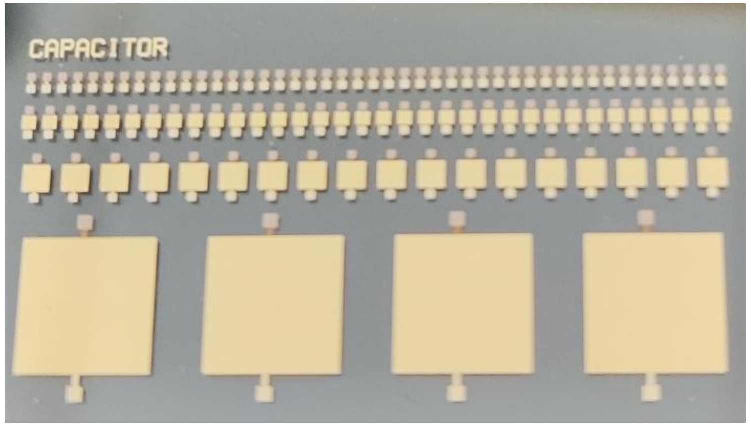
- Large-scale fabricated capacitors with a dielectric layer onto sapphire or polymer substrates.
- Each substrate has 640 capacitors with different surface areas of side lengths 20, 50, 100, 500, 1000, and 5000 µm.
- Metal: **Silver**
- Dielectrics: **Al_2O_3, SiO_2, HfO_2**

Capacitors on a sapphire substrate

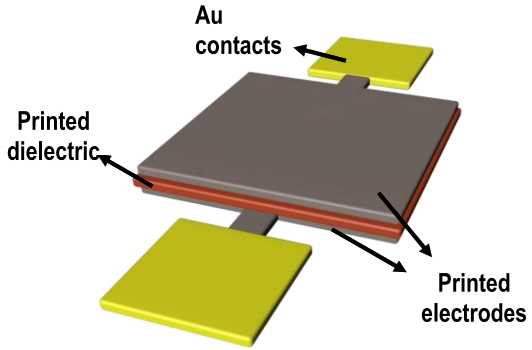


Capacitors on a polymer



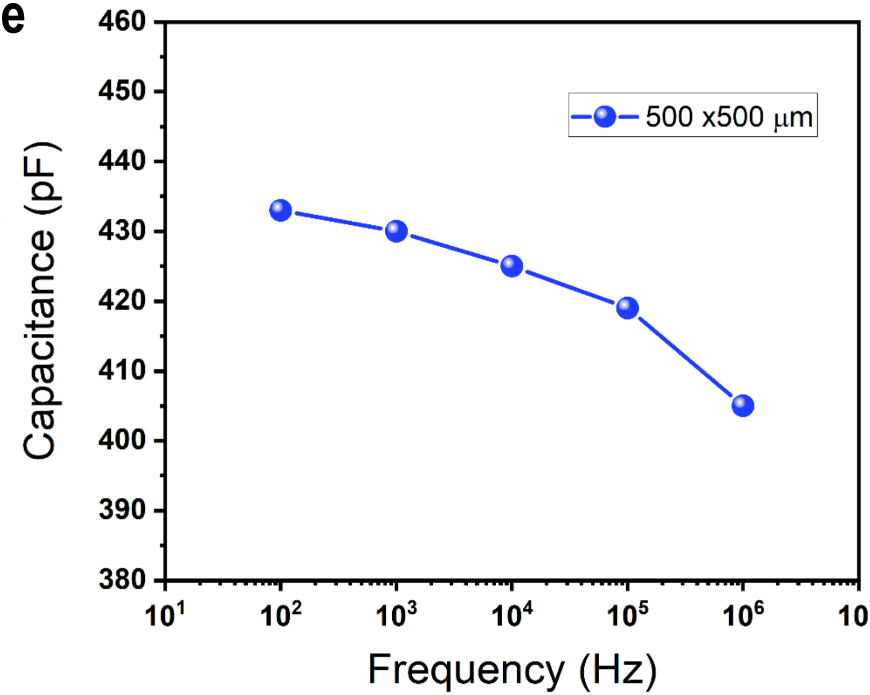


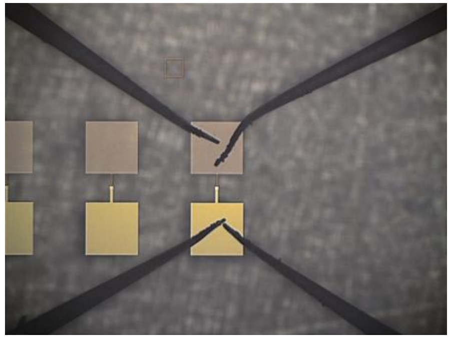
Capacitors on silicon



Characterization of Additively Manufactured Capacitors

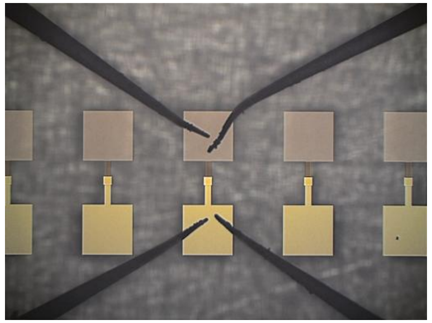
- **For high-frequency applications, the capacitors need to show reliable performance under high frequency.**
- **The figure shows the capacitance decreases with frequency up to to 1 MHz.**





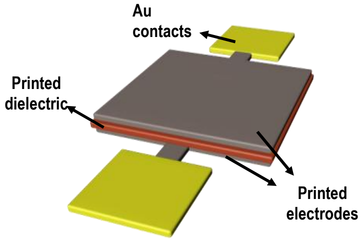
20x20 µm

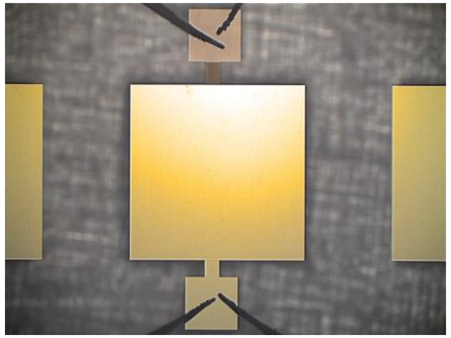
C= 857 fF



50x50 µm

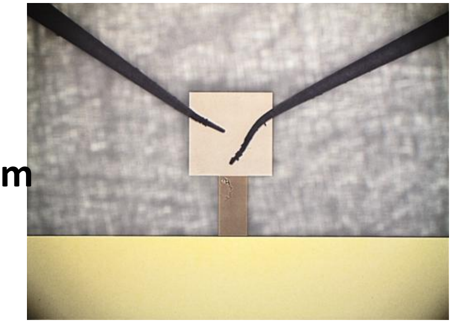
C= 4.3 pF





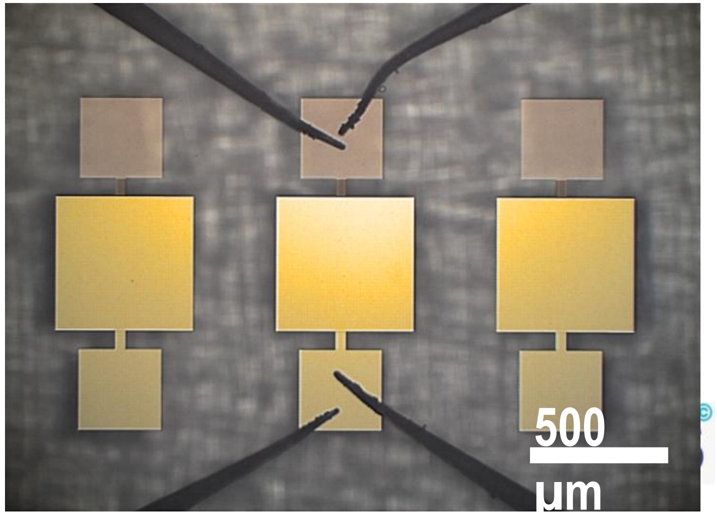
1000x1000 µm

C= 1.6 nF



5000x5000 µm

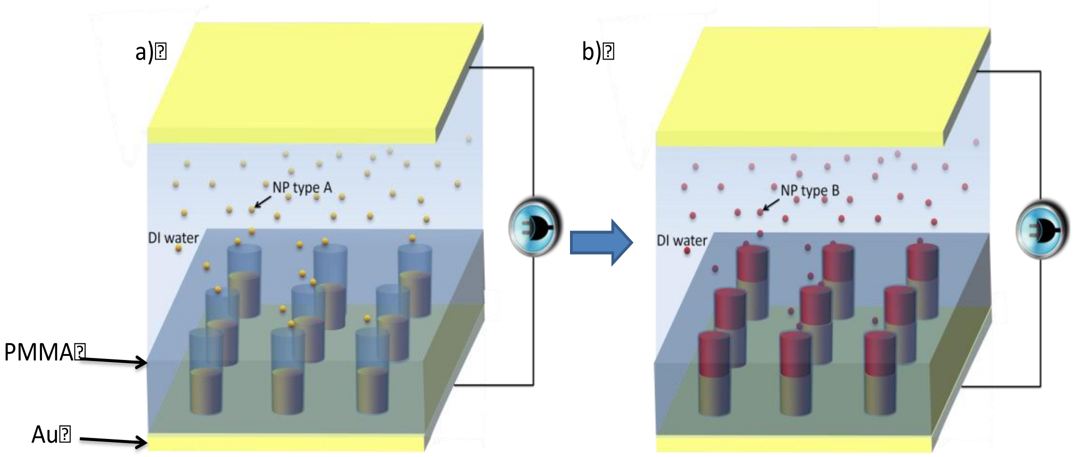
C= 5.68 nF



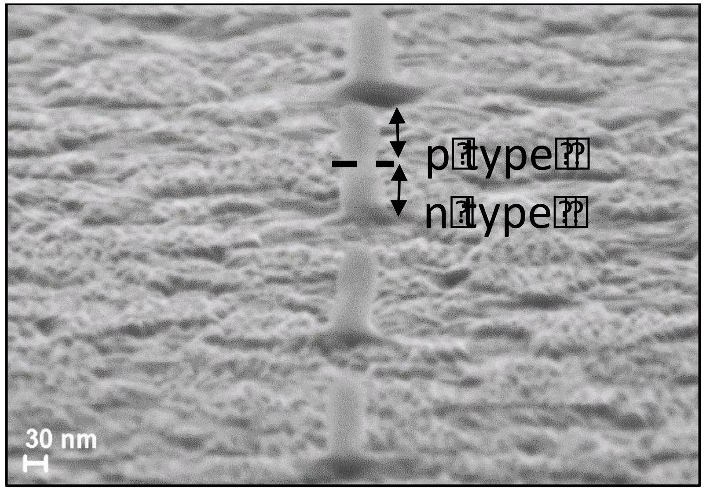
Could Active Components be Additively Manufactured?

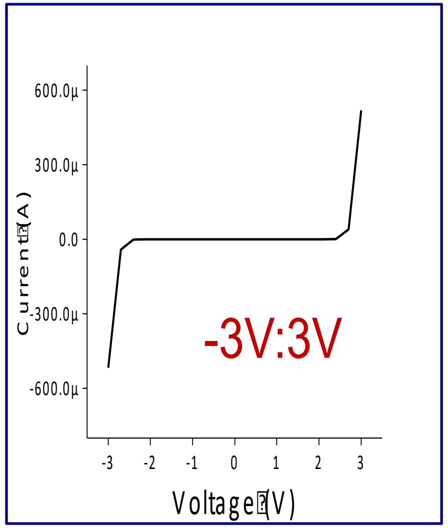
Printed Nano LEDs

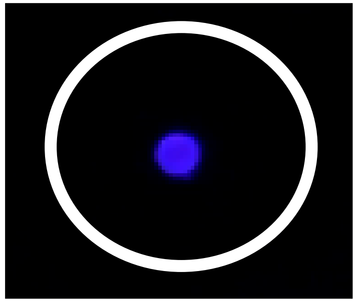
Printed 50 nm diodes (P-N junctions) using directed assembly-based printing



Printing N-doped and P-doped II-VI semiconducting particles that are self annealed insitu during the directed assembly-printing process to yield printed blue LEDs.

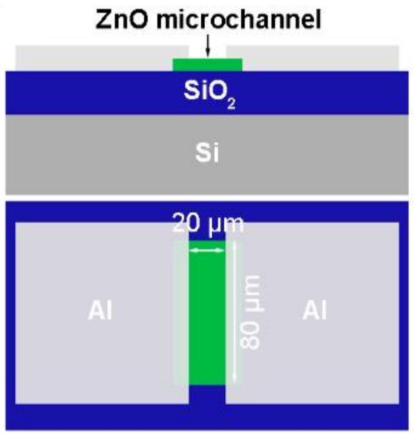


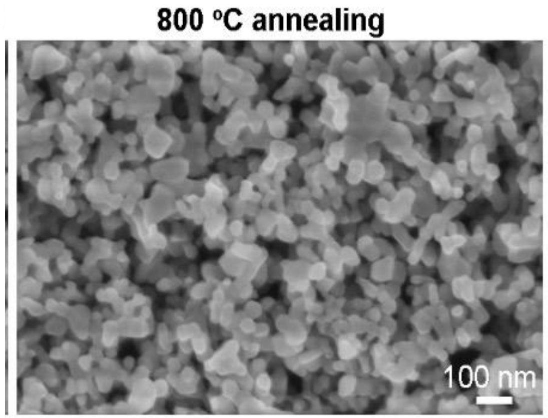


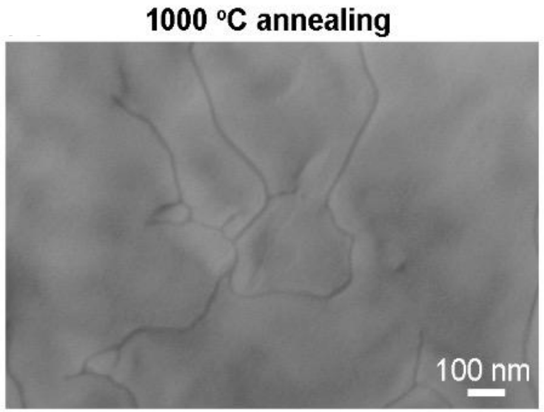


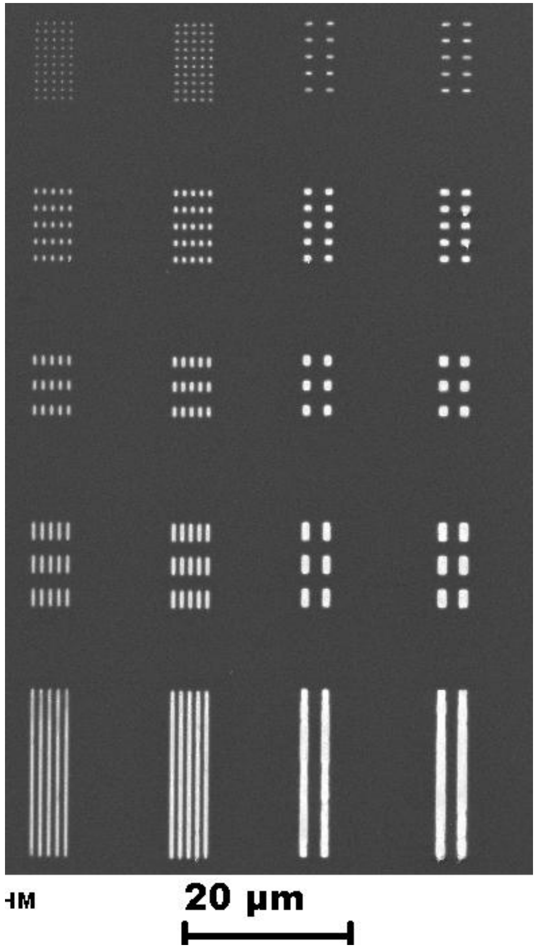
Color	Wavelength (nm)	Voltage (ΔV)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$

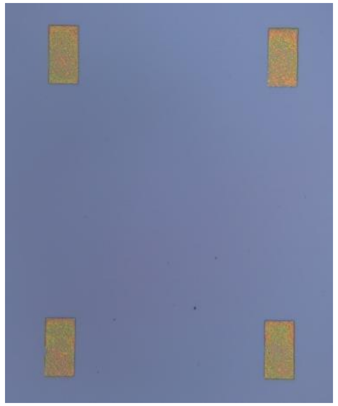
Field Effect Transistor (FET) Using II-VI Semiconductors



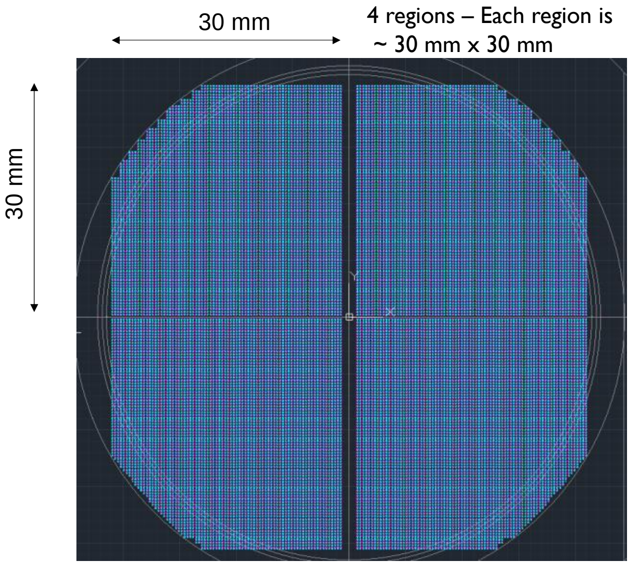


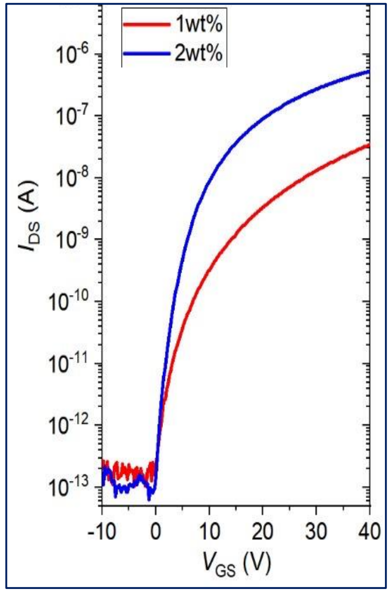






Channel width varied from 100 nm to 2 um, length varied from 100 nm to 20 um





Wafer-level manufacturing of 37,000 transistors exhibiting an on/off ratio higher than 10^6 after annealing.

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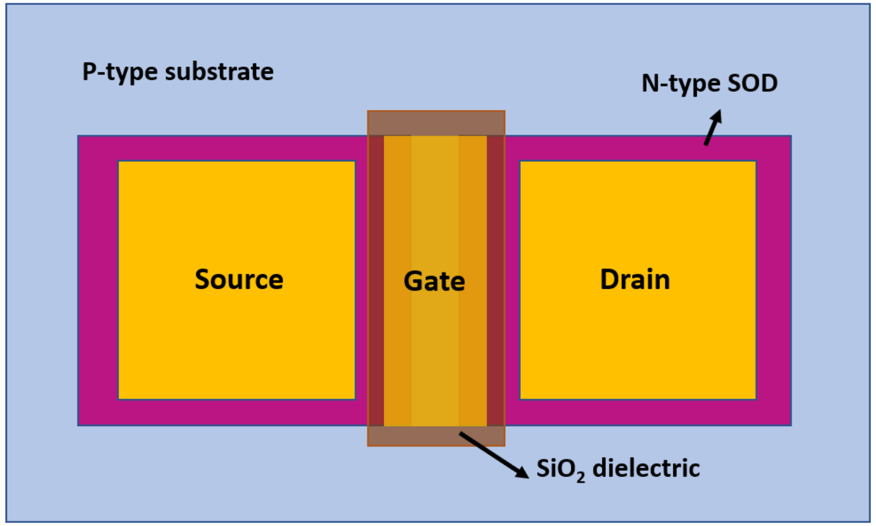
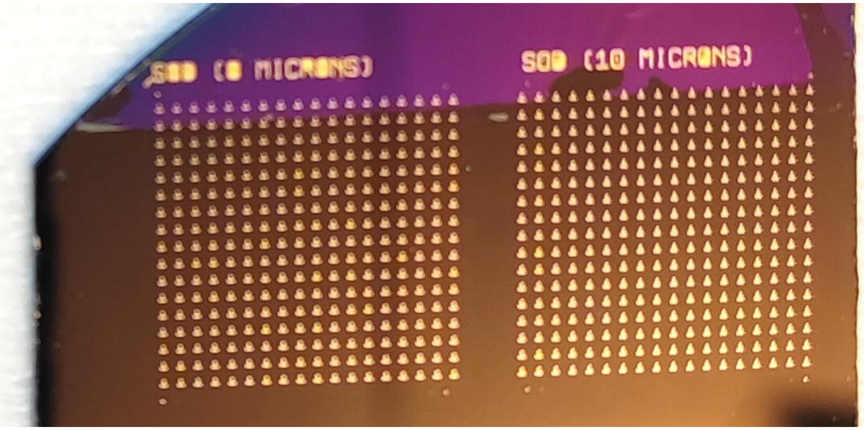
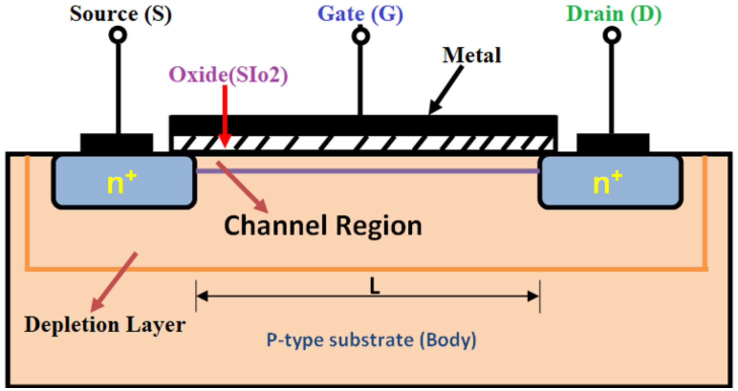
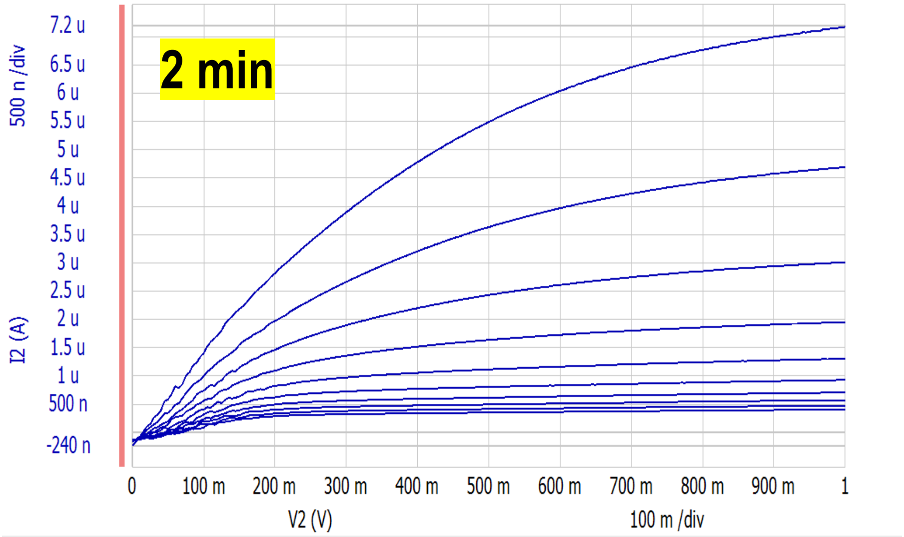
Additively Manufactured Silicon Transistors (MOSFETs)

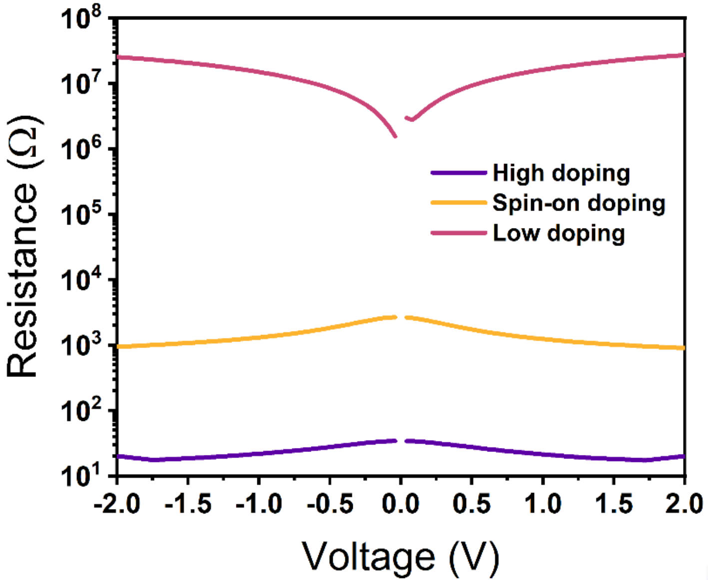


A fully additive liquid-based process process to manufacture MOSFETs using dopants inks.



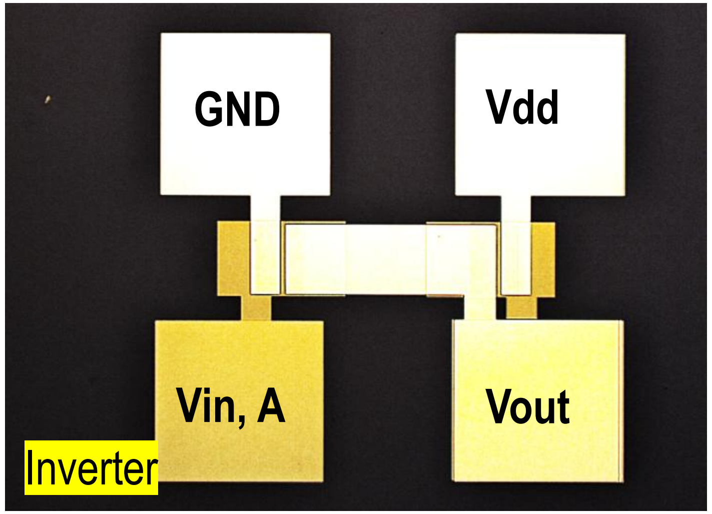


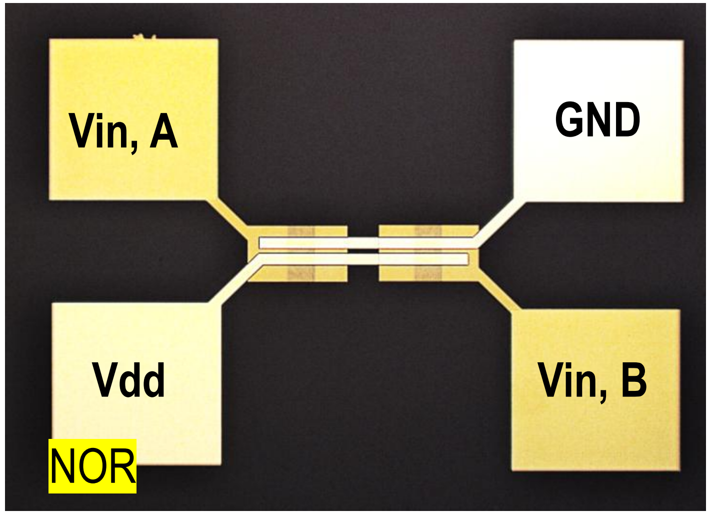


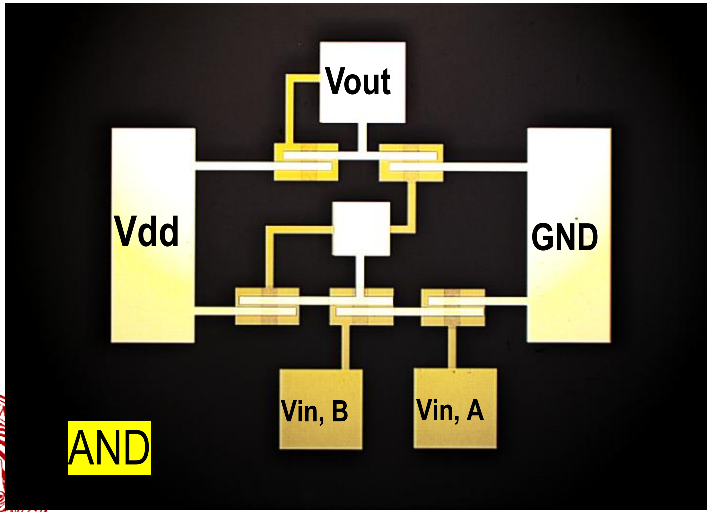


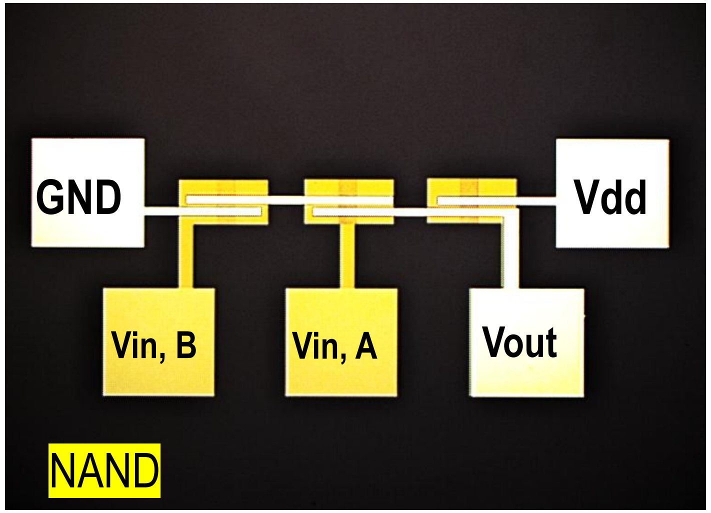
Additively Manufactured Logic Gate Electronics

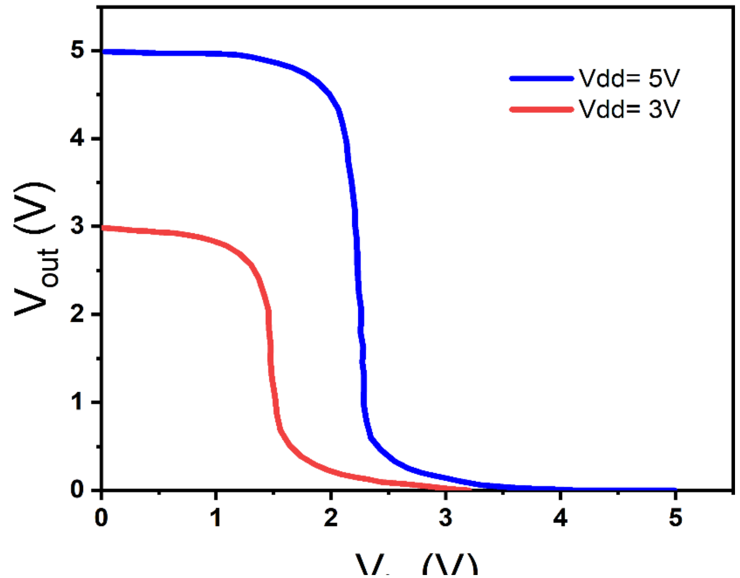
- Logic gates such as Inverters, AND, NAND, and NOR were printed
- The figures below show the fabricated logic circuits

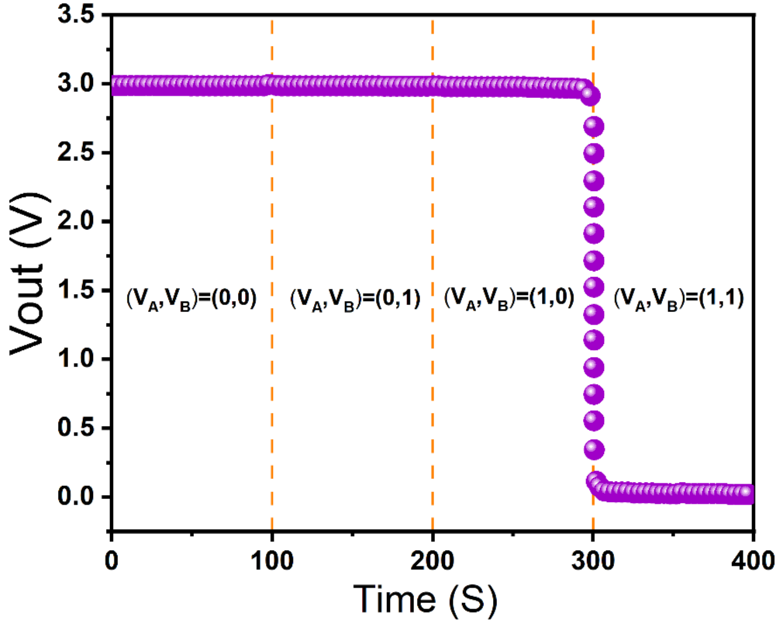




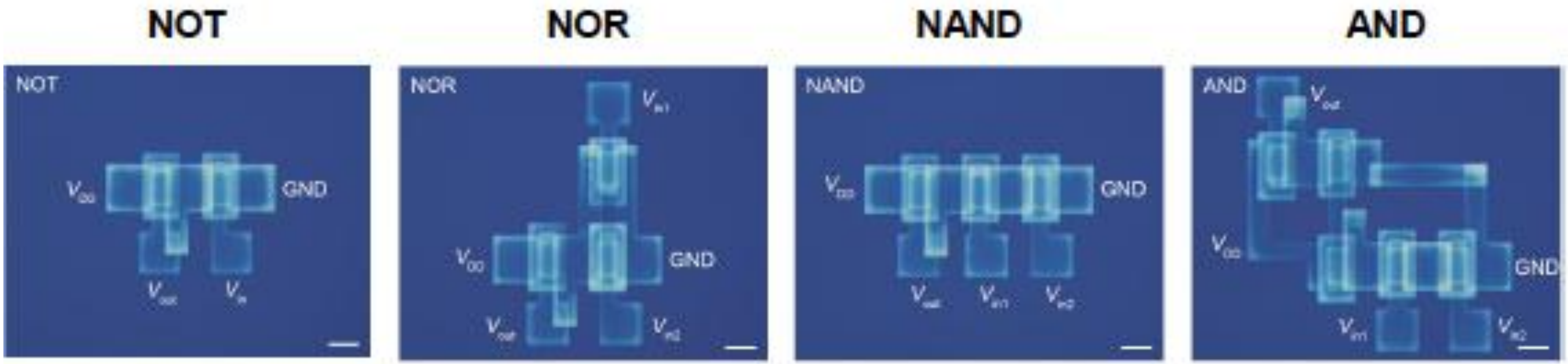


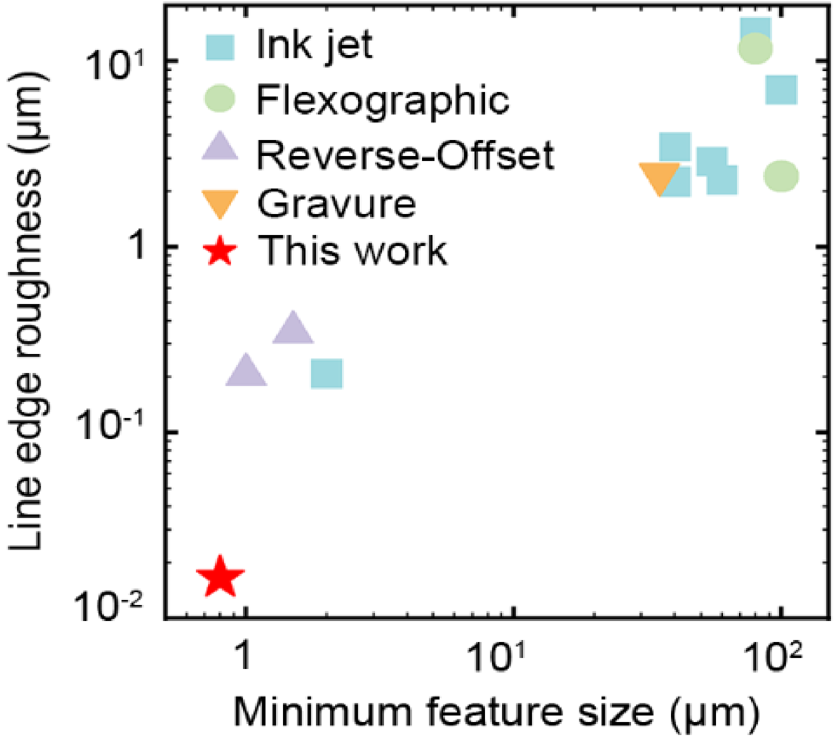


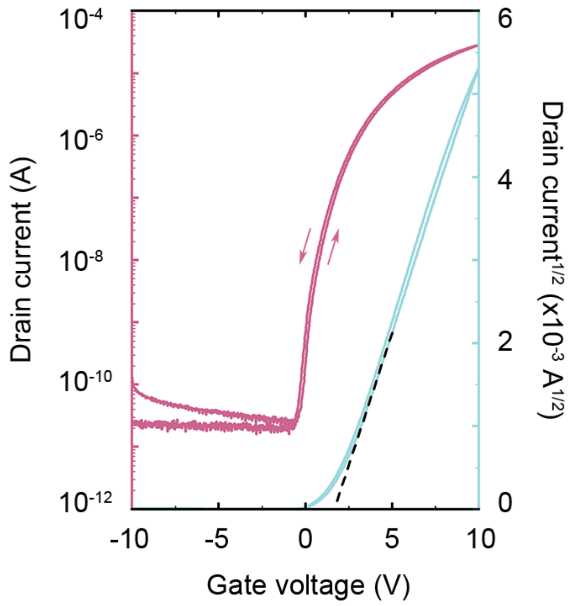


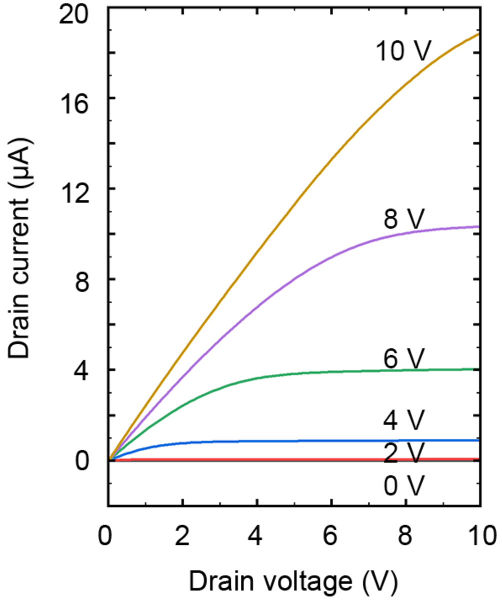


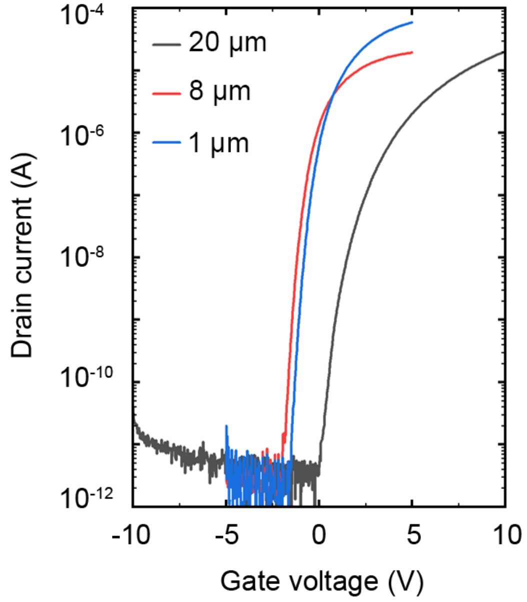
Fast Fluidic Assembly Process– FFx Platform (In_2O_3)



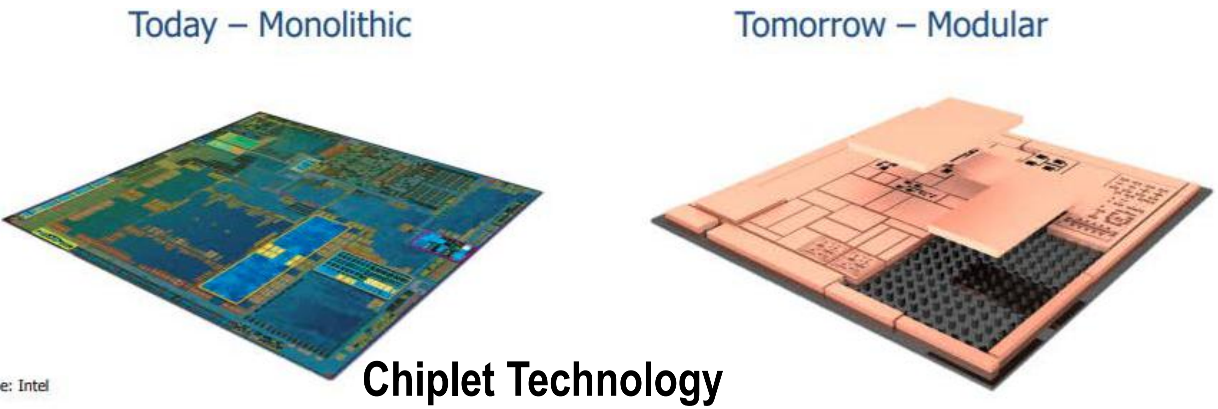








Advanced Packaging for Heterogeneous Integration for chiplet technology for integrating multiple dies in a package or system



Chiplet Technology

- Conventional packaging approaches can not meet the resolution and density requirements.
- It can only be done at conventional fabs now.

Fully automated and cyber enabled system

- Submit DXF or GDS files and load ink, wafers, etc.
- Additively Manufacture:
  - micro and submicron interconnects.
  - passive components
  - onto silicon, glass or organic substrates (interposers)

A Semiconductor Foundry in a Box for advanced Packaging

Electronics Manufacturing Landscape

Microscale

- ✓ Low end & low throughput
- ✓ Low cost

Micro & Nanoscale

- ✓ High end & high throughput
- ✓ Low cost

Micro & Nanoscale

- ✓ high-end & high throughput
- ✓ High cost

Nano OPS, Inc.

The Future of Electronics Manufacturing

Any Material
Any Substrate

Minimum Feature Size
20 nm

High throughput
10 – 100x Faster

Cheaper 10 – 100x

Fab-in-a-Tool: A Fully Automated Nanoscale Electronics Manufacturing Platform

www.nano-ops.us

The Future of Electronics Manufacturing

Fab-in-a-Box Platform Advantage:

- **Successfully demonstrated the capability to print capacitors and resistors using metals, inorganic high K dielectrics (HfO2, Al_2O_3), and low K dielectrics (Sio2).**
- **Successfully demonstrated print diodes, MOSFET, and Logic gates.**

✓ Minimum feature down to 25 nm demonstrated

✓ 5 – 10x reduction in capital equipment cost as compared to current fabs;

✓ 10 – 100x reduction in cost compared to conventional fabrication;

✓ 1000 times faster than inkjet or 3D printing;

✓ 1000 times reduction in materials use compared to current technology ;

✓ Crystalline metal and semiconducting structures at room temperatures.

✓ Expanding material choices for specific design needs.

Technological Impact

- Chips on demand
- Supply chain
- Hardware security
- Thermal Management
- Sustainable
- Material innovation

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www.nanomanufacturing.us, and www.nano-ops.net

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