On-demand Micro and Nanoelectronics Using a Fab in a Box Micro Factory

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And
CTO
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www.nanomanufacturing.us, www.nano-ops.us

Use One Deposition Process for Several Conductors, Semiconductors, and Dielectrics Using the Fab in a Box Platform

- On-demand chips, interposers, or packages in a few hours
- Multi-material, monolithic, quick turnaround, low cost fab
- No etching, chemical reactions, or vacuum
- Faster than conventional fabrication
- Faster than 3D printing (one circuit layer per minute)
- 25 nm to 1000 microns feature size demonstrated
- Modular, automated ~10 m^2 system footprint
- Up to a 1000 times reduction in materials use
- Carbon footprint is 10 times smaller

Semiconductor Foundry in a Box

Patented new technology, directed assembly-based printing for printing circuits at the nano and microscale funded by NSF and DoD.

What inorganic and organic materials have been demonstrated?

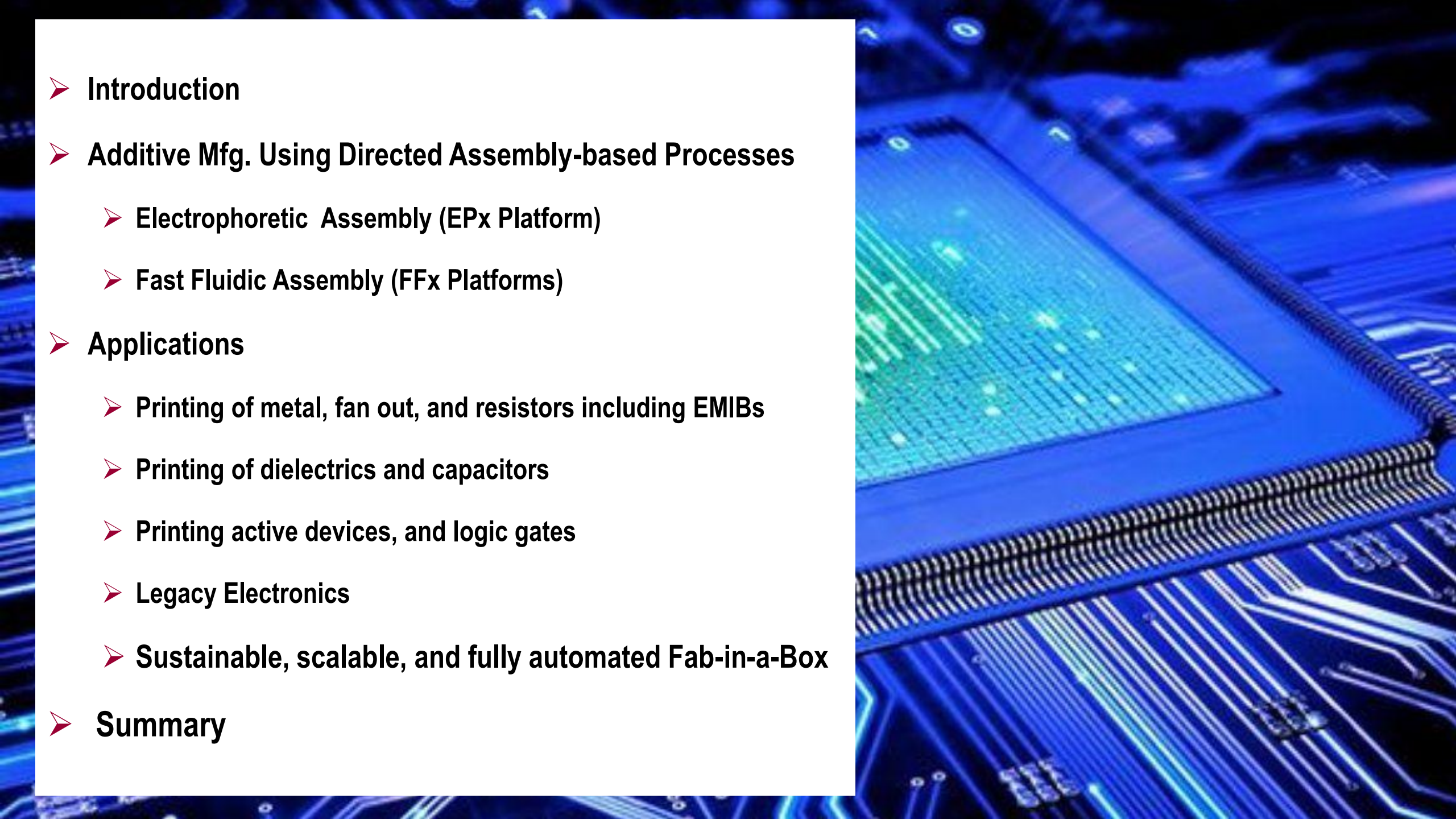
Material Type	Material	Made nano & micro structures	Sintered at room temp	Sintered at High temp	Devices made & tested
Conductor	silver	yes	yes	yes	passive & active
	copper	yes	yes	yes	passive & active
	gold	yes	yes	yes	passive & active
	platnium	yes	no	yes	passive
	alumnium	yes	yes	no	no
	Tungesten	yes	yes	no	no
Semiconductor	Silicon	yes	yes	yes	active
	ZnO	yes	no	yes	active
	ZnSe	yes	yes	yes	active
	InP	yes	no	yes	no
	GaAs	yes	no	no	no
	GaN	yes	no	no	no
	In2O3	yes	no	yes	active
Dielectric	SiO2	yes	yes	yes	passive & active
	Alumina	yes	yes	yes	passive & active
	HfO2	yes	yes	yes	passive & active
dopants	B+	yes	no	yes	passive & active
	P-	yes	no	yes	passive & active

Inorganic Materials

Room-temperature sintering for inorganic materials, yielding single-crystal or polycrystalline structures, requires the assembly of nanoparticles of 5-20 nm.

Material Type	Material	Made nano & micro structures	Devices made & tested
Conductor	MSWNT	yes	passive & active
	PANI	yes	passive & active
	Graphene	yes	passive & active
Semiconductor	SWNT	yes	passive & active
	C8 BTBT	yes	passive & active
	MoS2	yes	passive & active
Dielectric	up to eight different materials	yes	passive & active

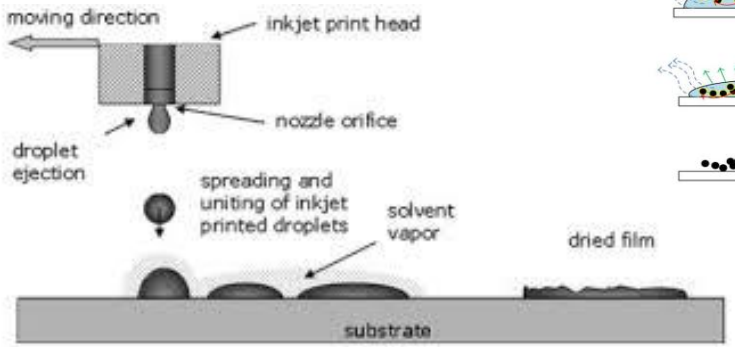
Organic Materials

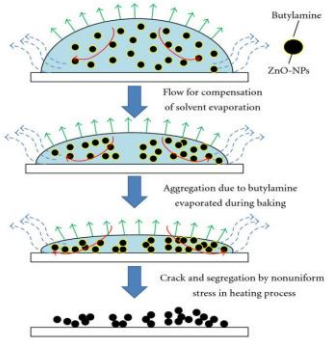


- Introduction
- Additive Mfg. Using Directed Assembly-based Processes
  - Electrophoretic Assembly (EPx Platform)
  - Fast Fluidic Assembly (FFx Platforms)
- Applications
  - Printing of metal, fan out, and resistors including EMIBs
  - Printing of dielectrics and capacitors
  - Printing active devices, and logic gates
  - Legacy Electronics
  - Sustainable, scalable, and fully automated Fab-in-a-Box
- Summary

How does directed assembly-based printing work?

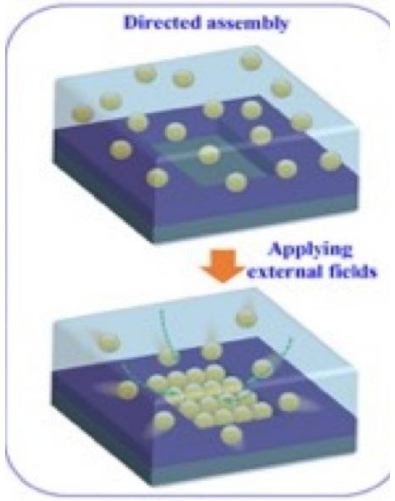
Inkjet printing

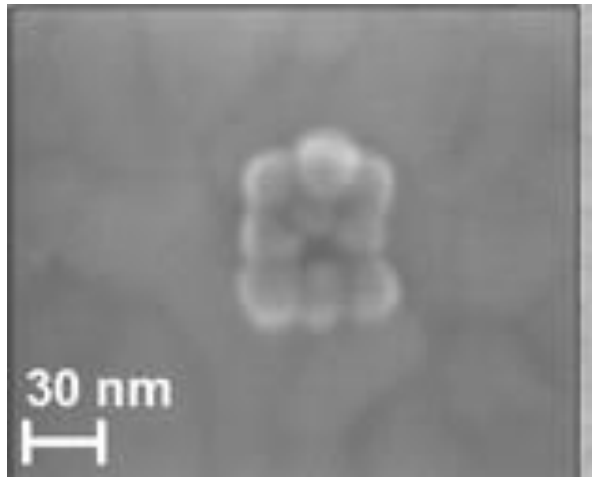




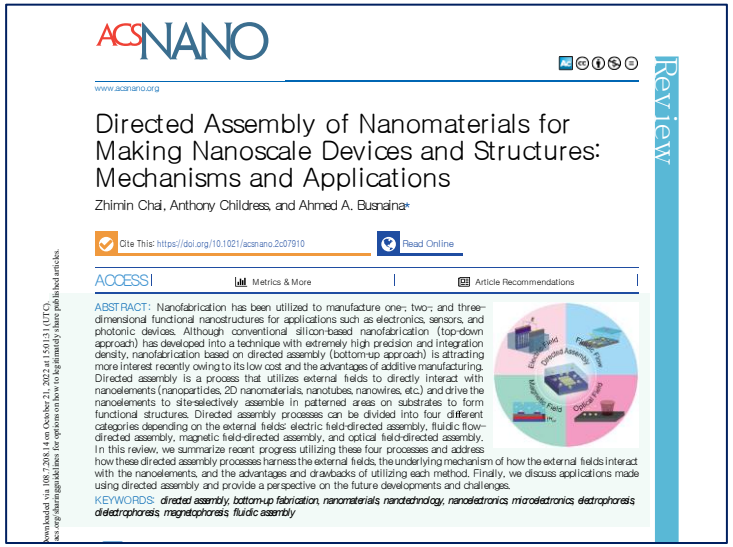
- **Directs a droplet** toward a substrate to form a pattern using many (dots) limiting pattern resolution and fidelity.
- Inherently relies on mechanical accuracy.
- Materials limited to organics and metals

Directed assembly-based printing





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


ACSNANO
www.acsnano.org
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 Read Online

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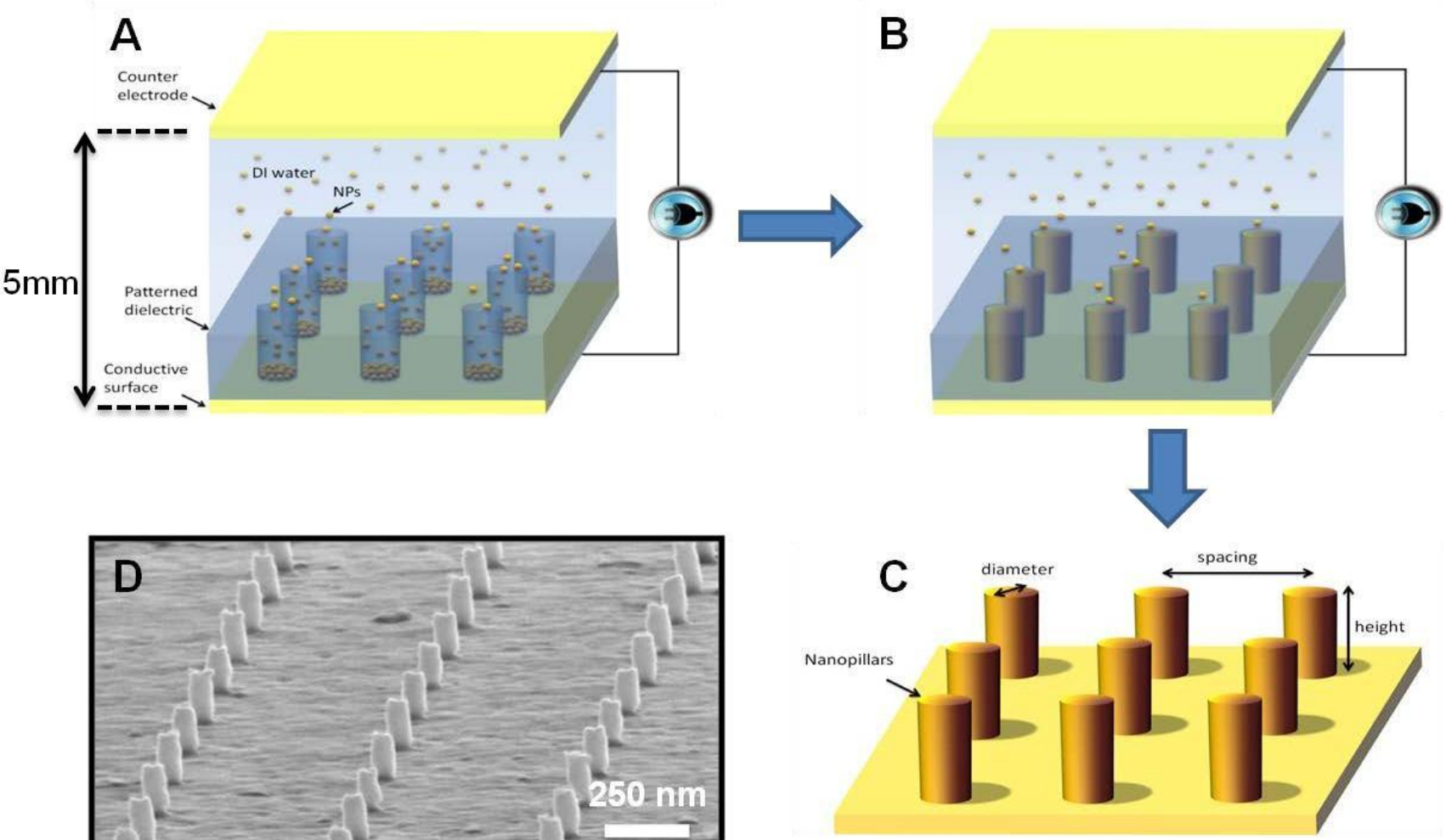
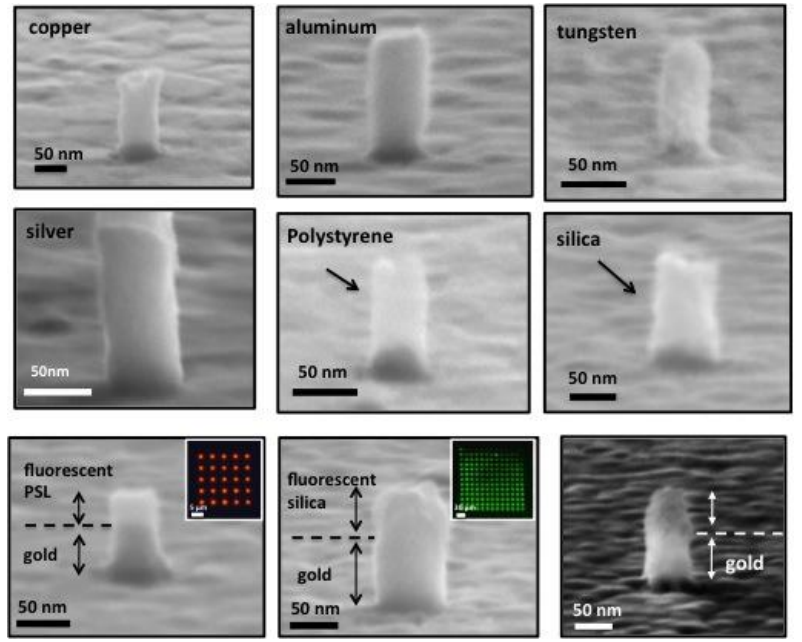
ABSTRACT: Nanofabrication has been utilized to manufacture one-, two-, and three-dimensional functional nanostructures for applications such as electronics, sensors, and photonic devices. Although conventional silicon-based nanofabrication (top-down approach) has developed into a technique with extremely 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

Electrophoretic Directed Assembly– EPx Platform

Assembled Interconnects

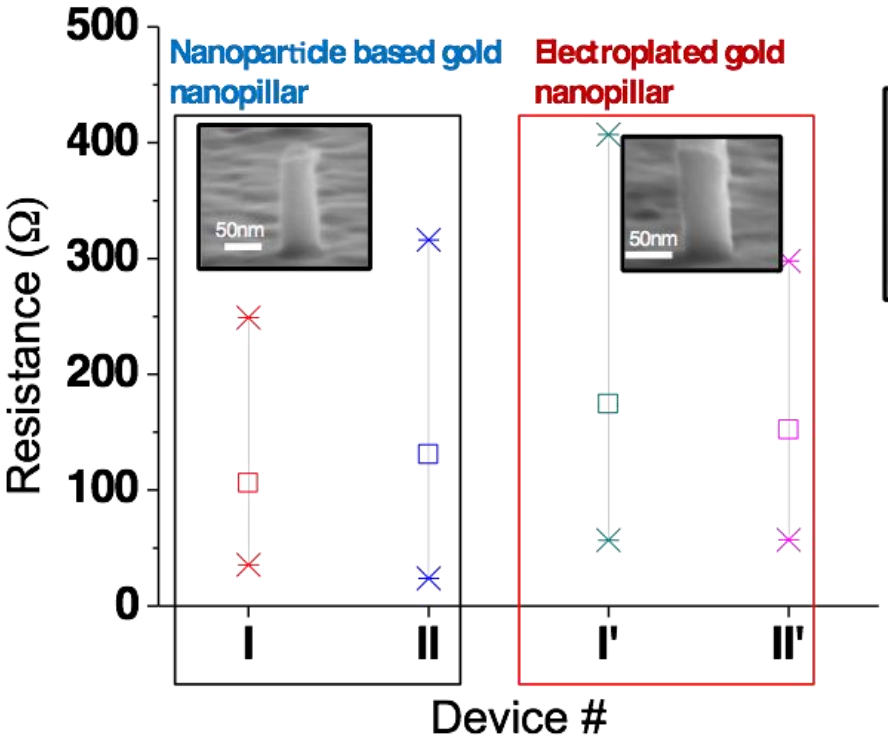


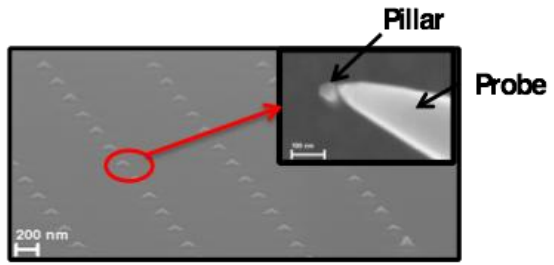


All assembled Nanoparticles are completely fused insitu.

ACS Nano, 8 (5), 2014.

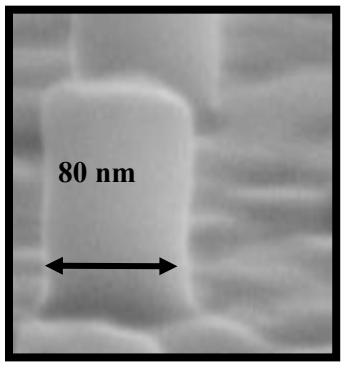
Interconnects Properties

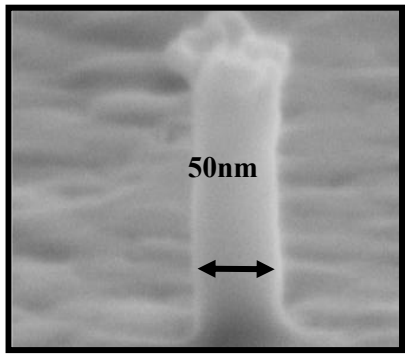


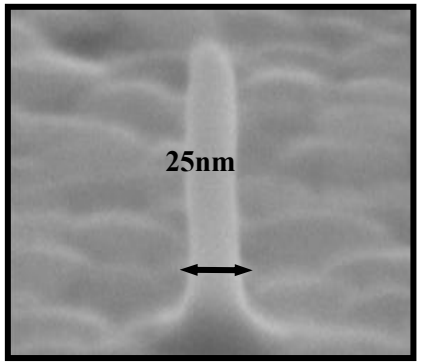


Resistance of assembled interconnects is the same as bulk (electroplated interconnects).

Crystalline Au Pillars



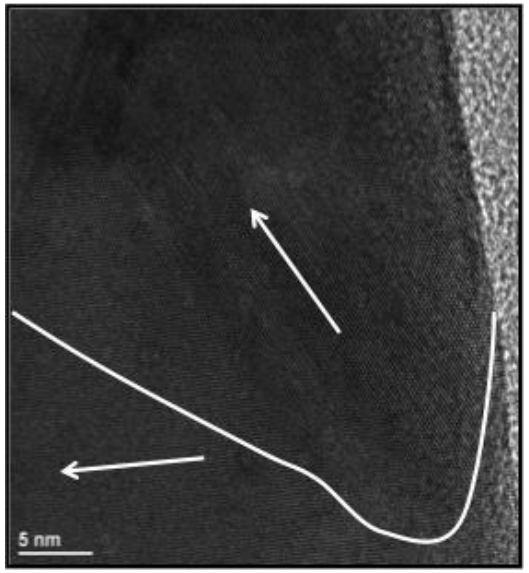




Directly assembled structures properties are equivalent to electroplating, CVD and PVD fabrication.

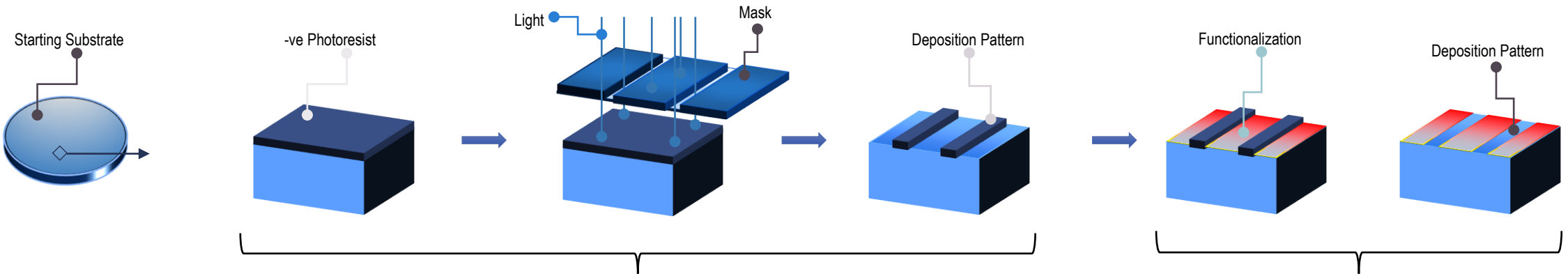
Directly assembled metallic structures (Cu, Ag, Al, Au, and W, etc.) in addition to semiconductors and dielectrics were demonstrated.

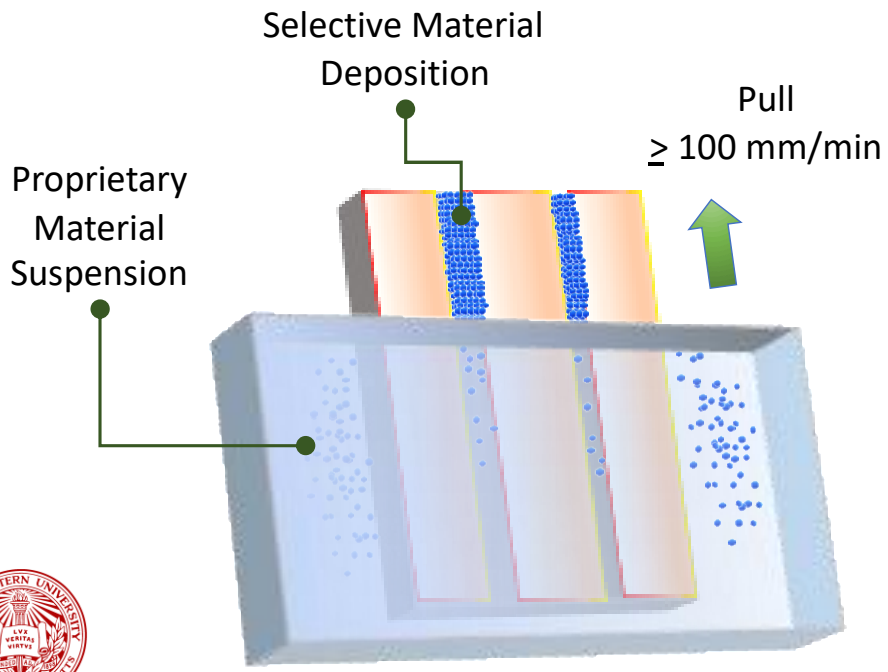
- TEM shows that NPs completely fuse without any voids at room temperature.
- Nanopillars have polycrystalline nature.



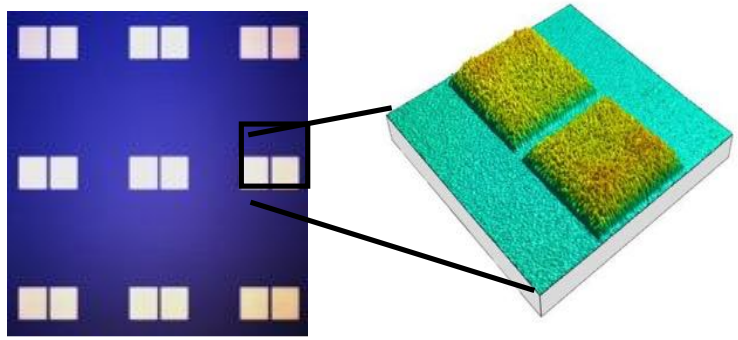
ACS Nano, 8 (5), 2014.

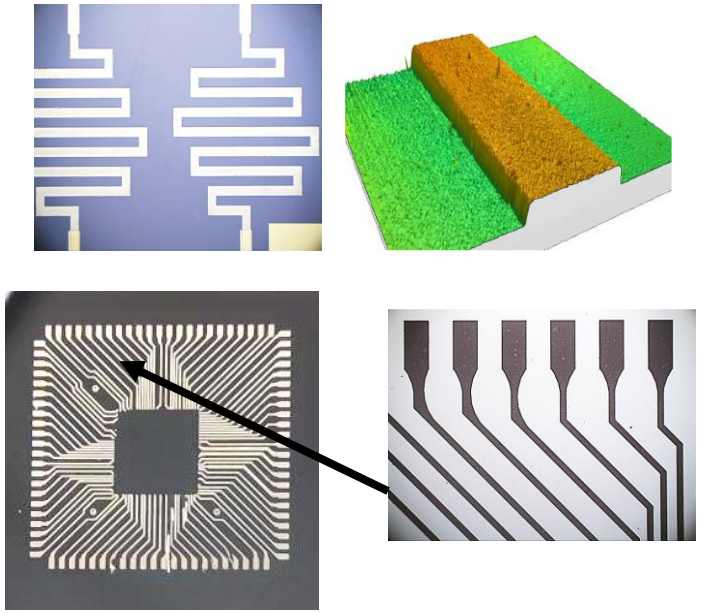
Fast Fluidic Assembly Process– FFx Platform





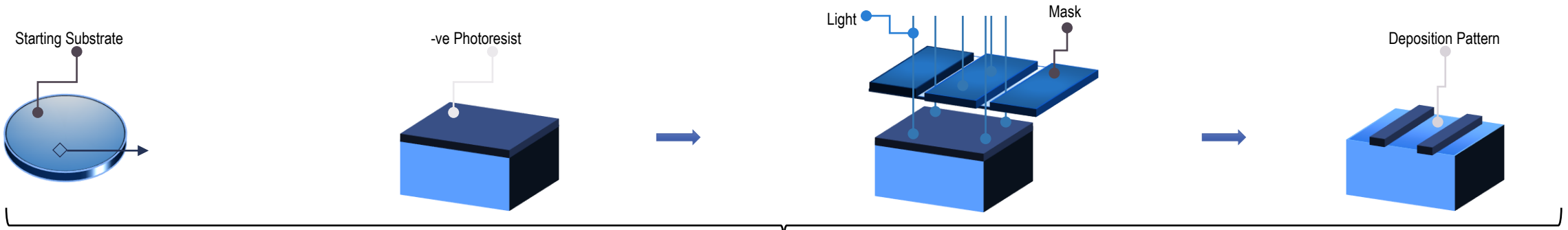
SiO_2 substrate – 10 µm spacing



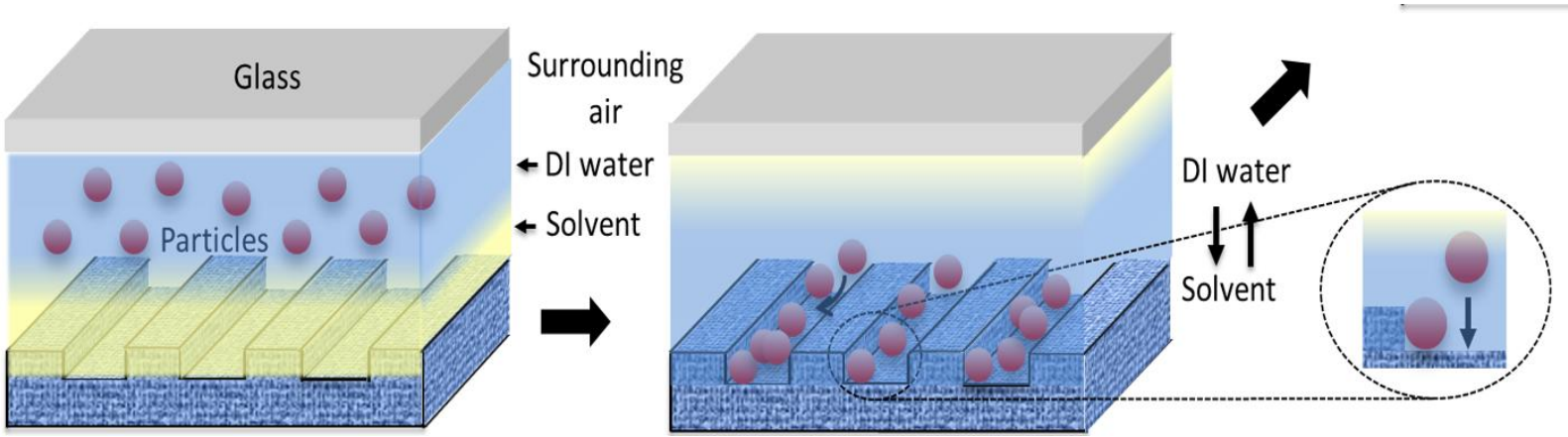


Fast Fluidic Assembly Process

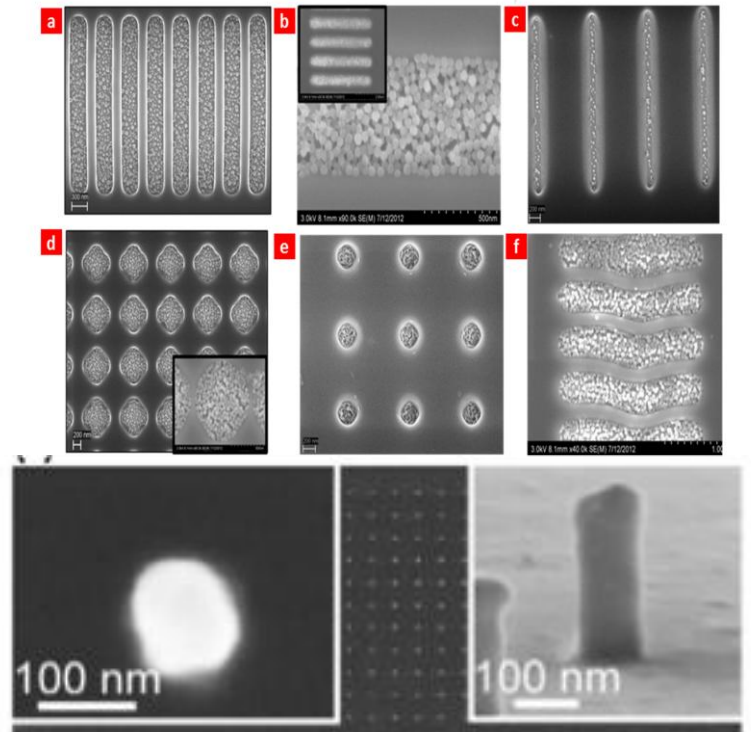
Convective Interfacial Assembly Process– CIx Platform



Patterning - Lithography



Convective Interfacial Process

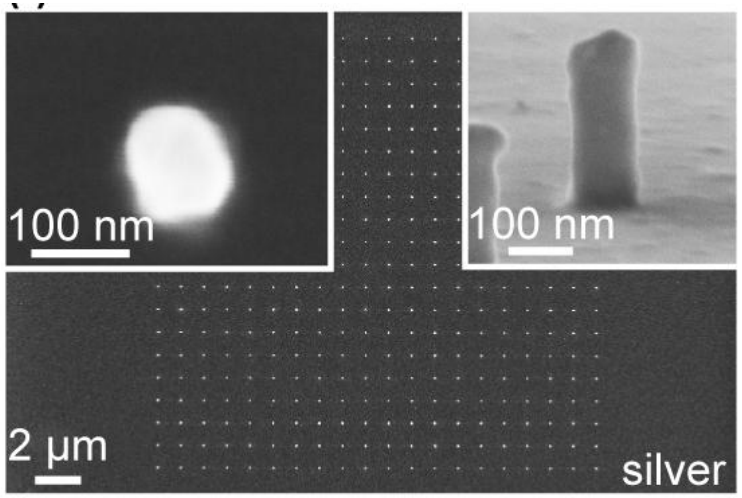


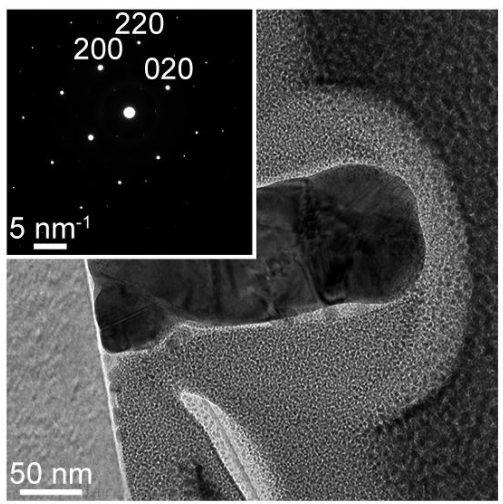
Various applications and Geometries

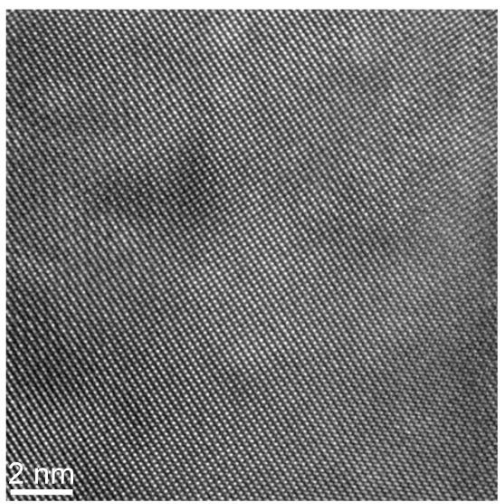
Advanced Materials, 2000747, 2020.

Wafer-scale Additively Manufacturing Single Crystal Semiconductor and Metal

Interfacial convective directed assembly





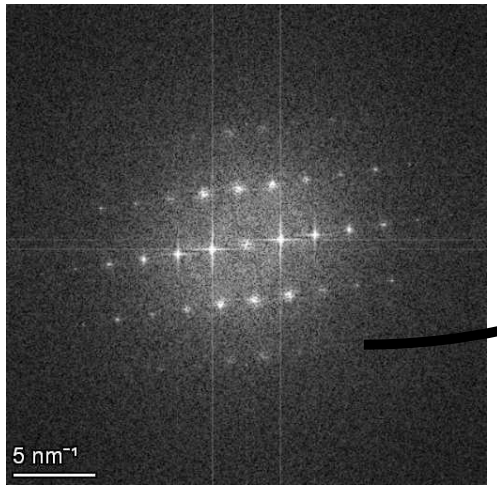


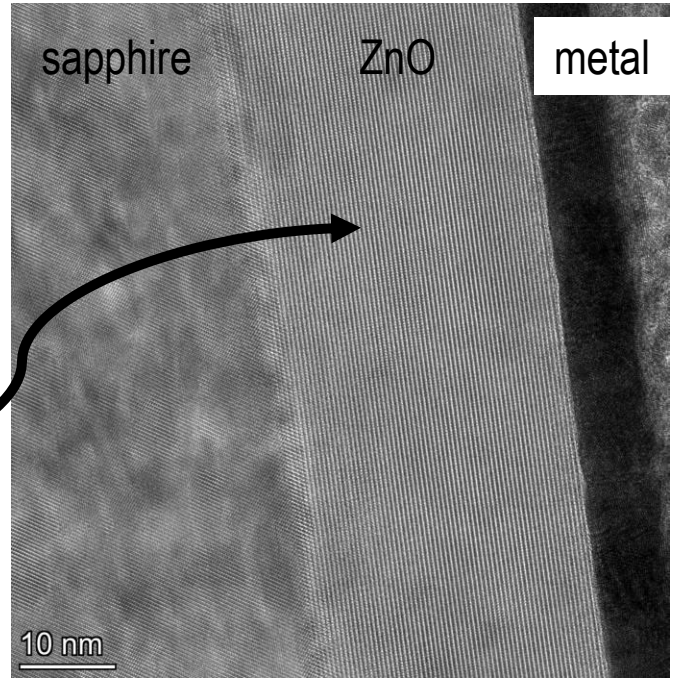
Advanced Materials, 2020.

Room temperature Directed assembly of Ag nanoparticles (5-10 nm) yields single-crystal metal (Ag) nanopillars

Large area Single Crystal ZnO after sintering of the ZnO nanoparticles

Fast Fluidic directed assembly

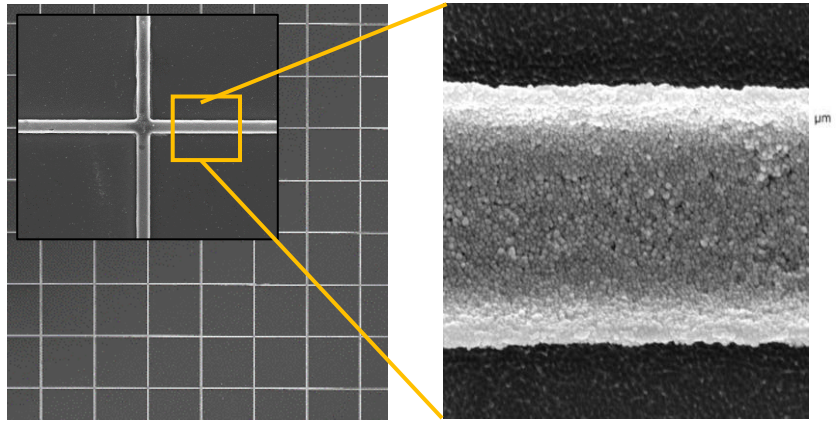




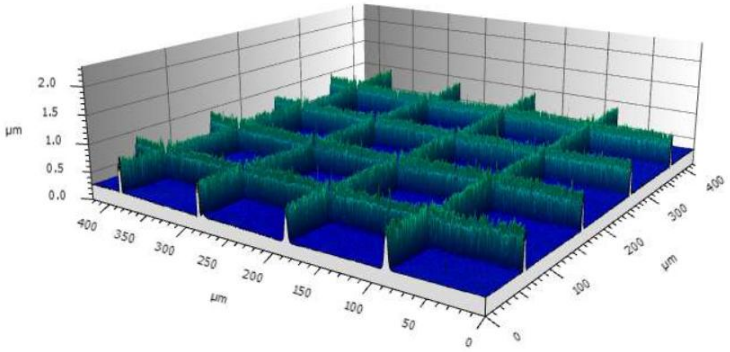
RTP sintering (1000 C for 2 min) of II-VI nanoparticles (50-100 nm) on sapphire yields a single crystal structure throughout.

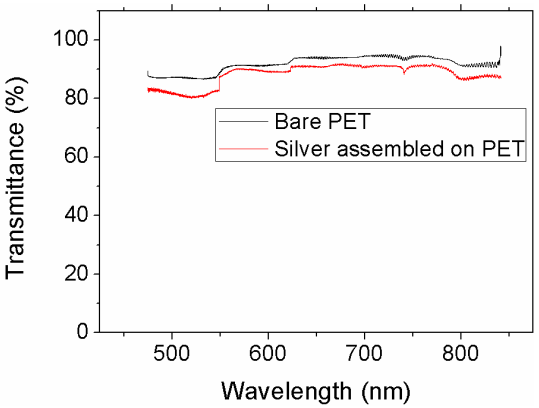
Additively Manufactured Touch Display at the Micro and Nanoscale

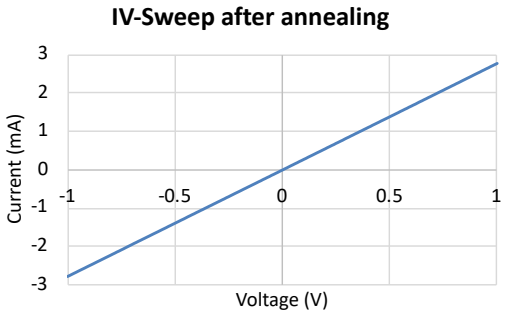
Ag grids for touch display applications

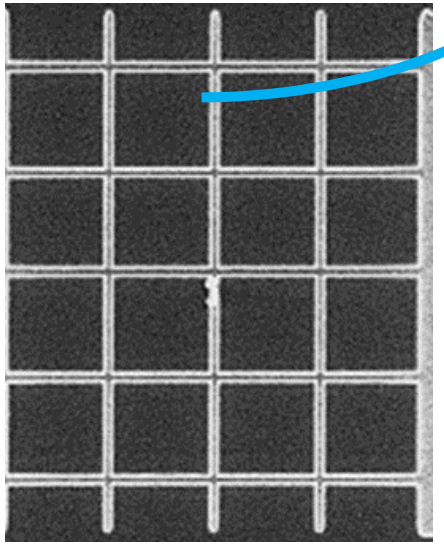


Line width 2 um

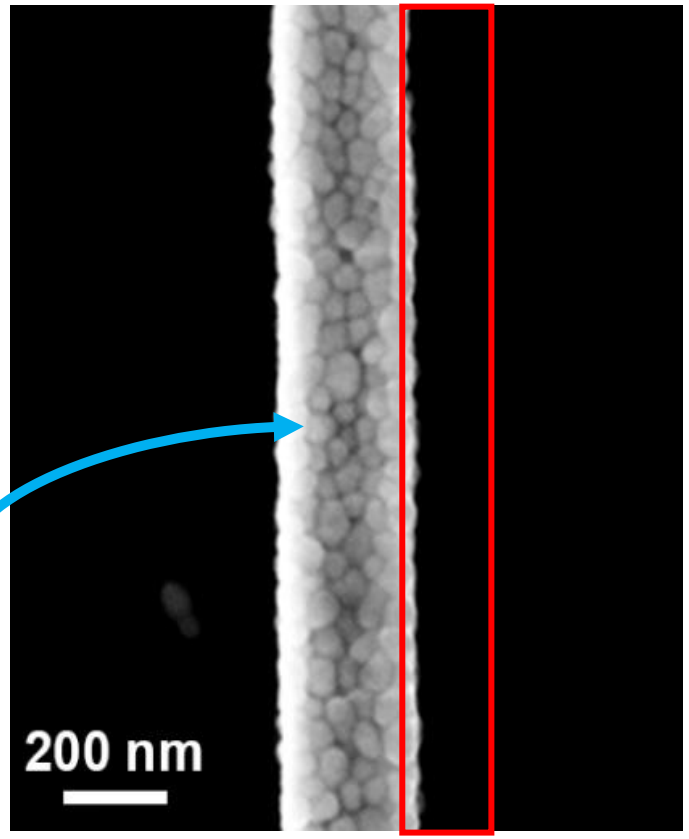








Line width 300 nm



Excellent Line edge roughness
3.7 nm
Using large nanoparticles

COMMUNICATION

Transparent Electrodes

ADVANCED MATERIALS INTERFACES

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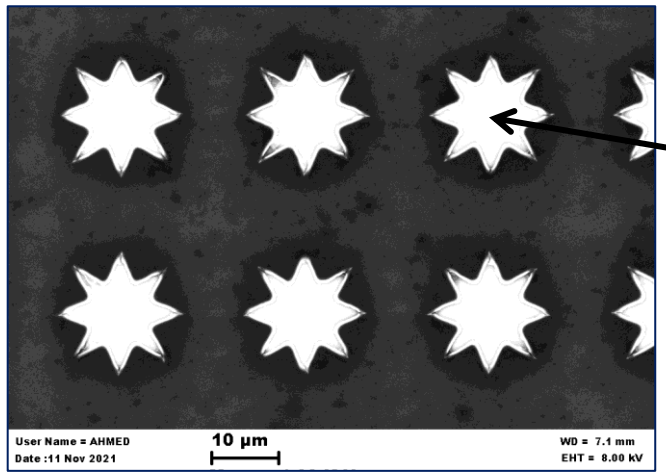
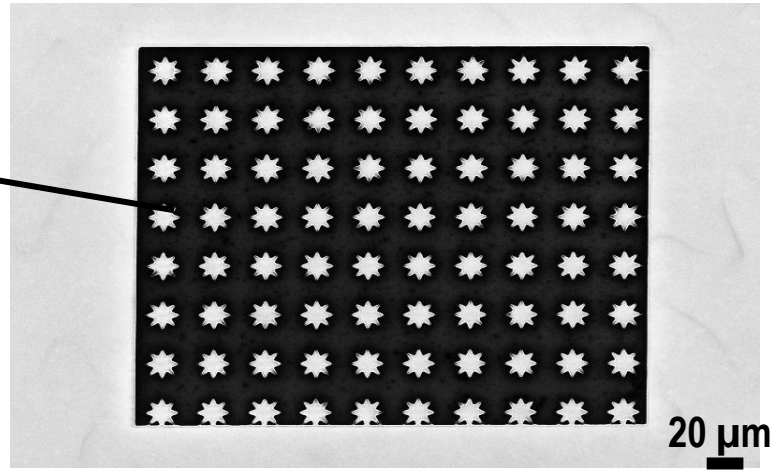
Scalable Printing of High-Resolution Flexible Transparent Grid Electrodes Using Directed Assembly of Silver Nanoparticles

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

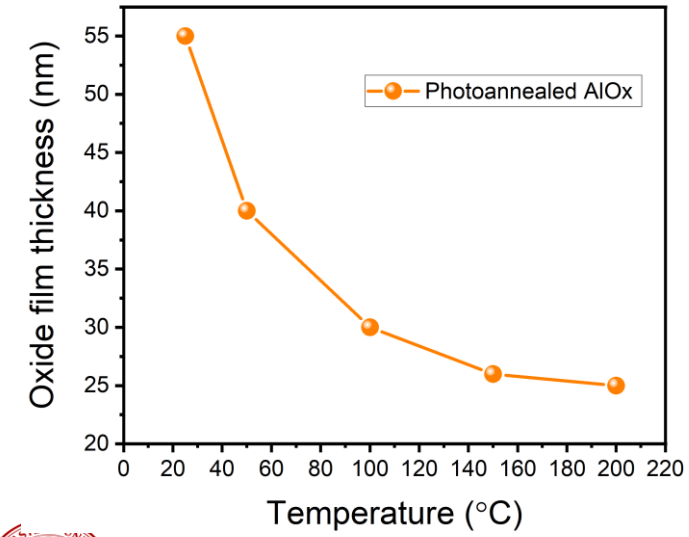
Additively Manufactured Dielectrics

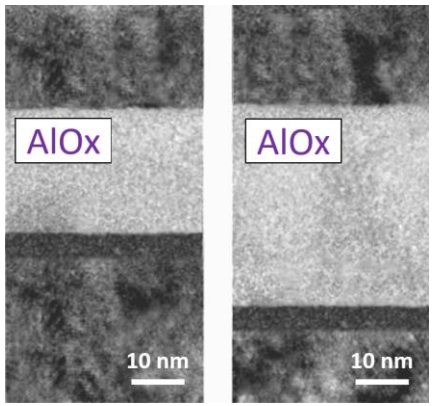
The SEM images below shows Al_2O_3 micropatterns prepared by directed fluidic assembly with a dielectric constant that matches that obtained by CVD or ALD ($\varepsilon_d = 7.2$).

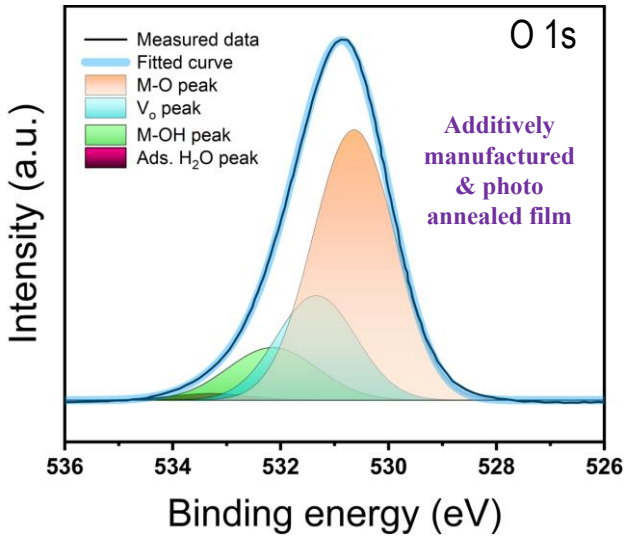


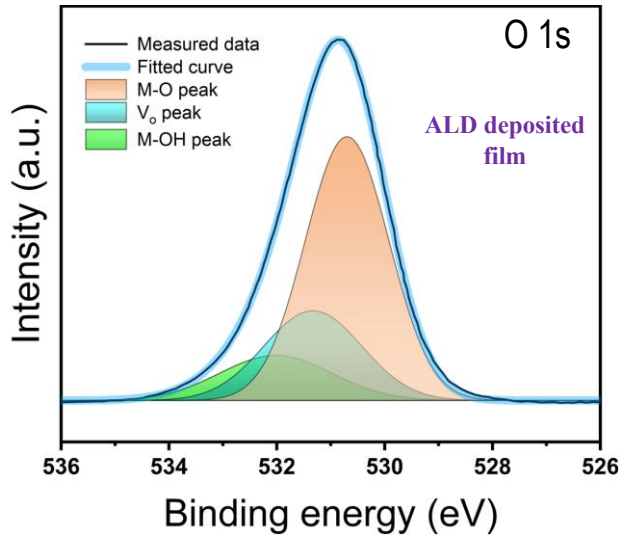


X-ray Photoelectron Spectroscopy (XPS) characterization of the Dielectric Layer shows agreement in between ALD and printed films in terms of peak intensities and composition ratios.







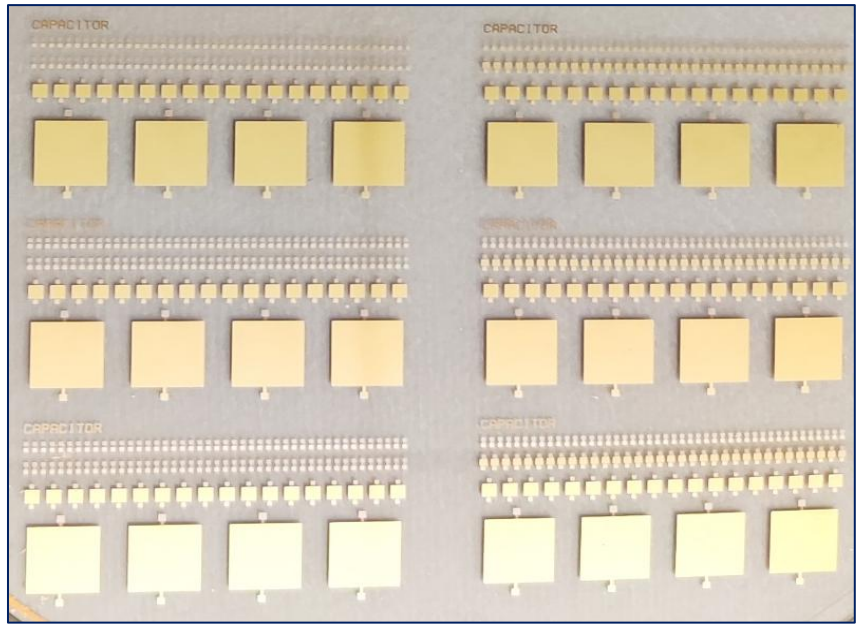


- Higher temperature densification and better dielectric properties for the film.
- Cross-sectional shows the oxide film thickness variation between 50 °C and 200 °C annealing.

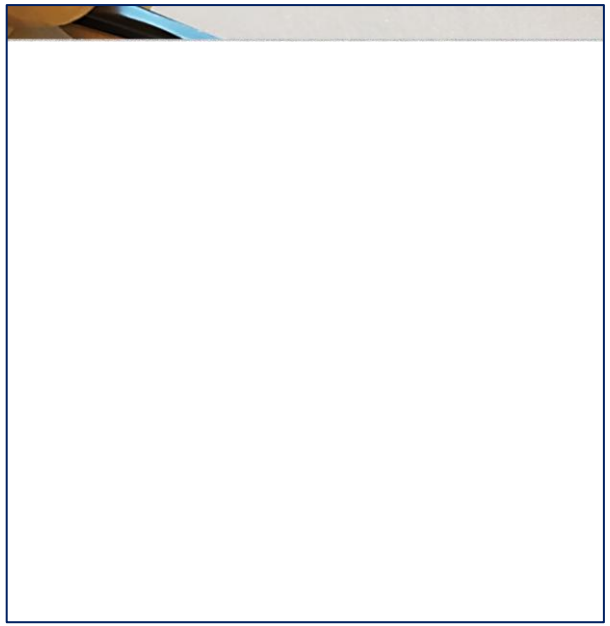
Additively Manufactured Capacitors on Rigid and Flexible Substrates

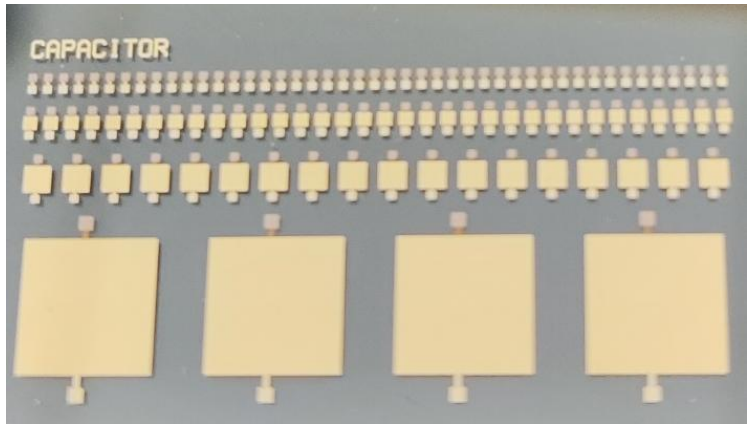
- Large-scale fabricated capacitors with a dielectric layer onto sapphire or polymer substrates.
- Each substrate has 640 capacitors with different surface areas of side lengths 20, 50, 100, 500, 1000, and 5000 µm.
- Metal: **Silver**
- Dielectrics: **Al_2O_3, SiO_2, HfO_2**

Capacitors on a sapphire substrate

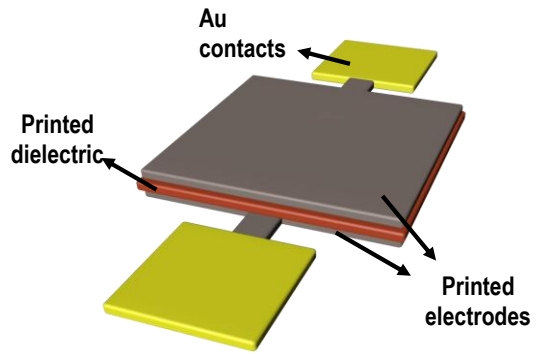


Capacitors on a polymer



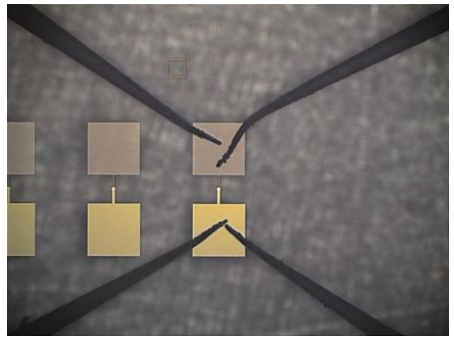


Capacitors on silicon



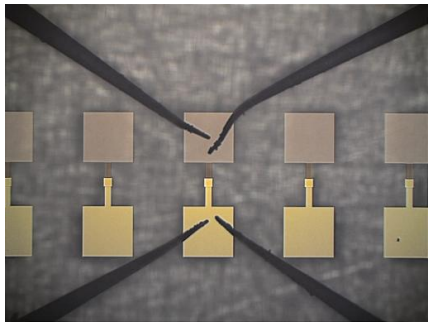
Characterization of Additively Manufactured Capacitors

- For high-frequency applications, the capacitors need to show reliable performance under high frequency.
- The curve shows the capacitance variation versus different frequencies up to 1 MHz.



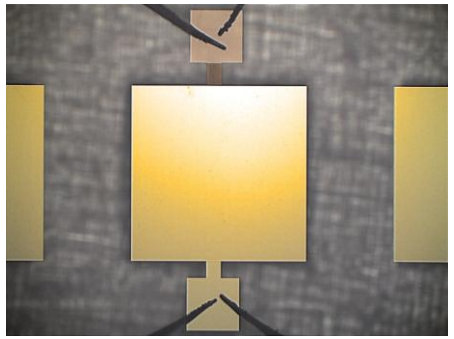
20x20 µm

C= 857 fF



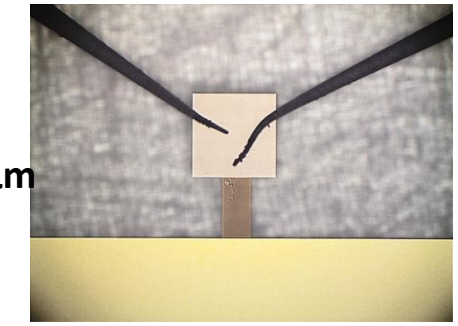
50x50 µm

C= 4.3 pF



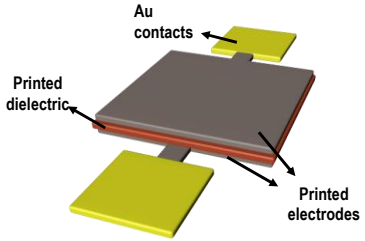
1000x1000 µm

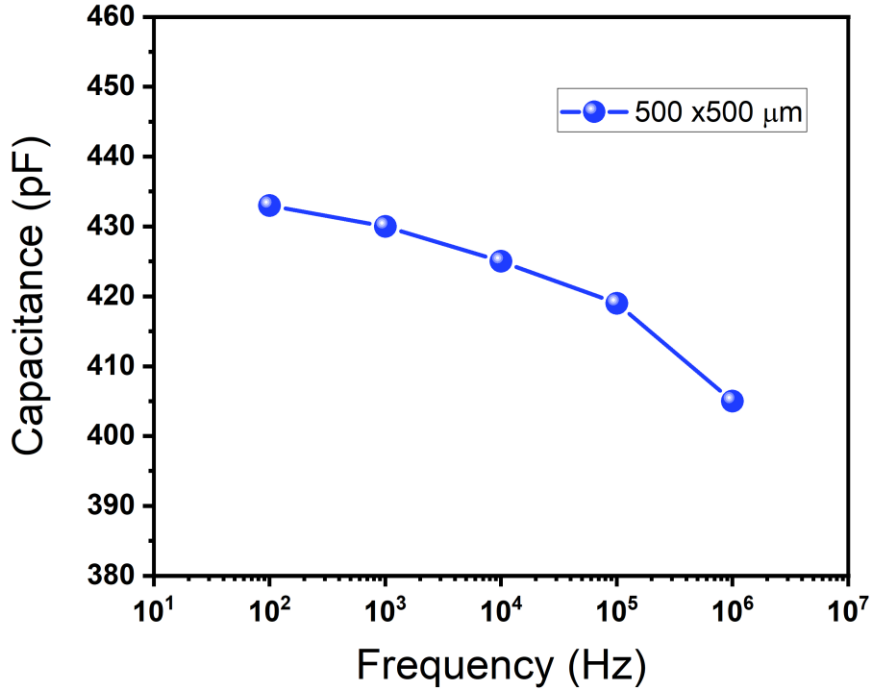
C= 1.6 nF

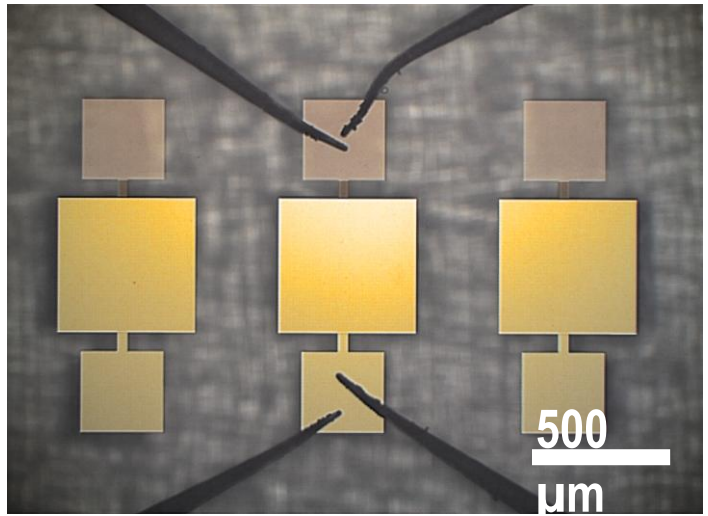


5000x5000 µm

C= 5.68 nF

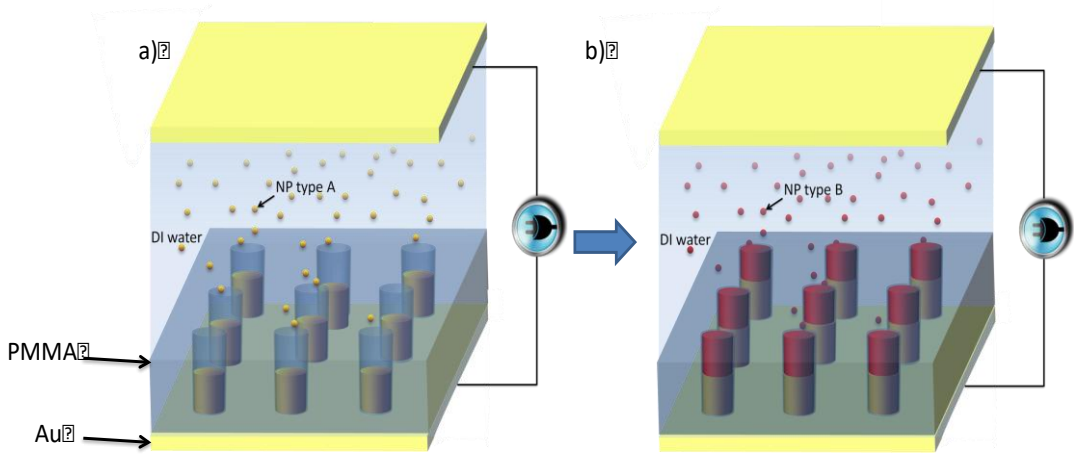


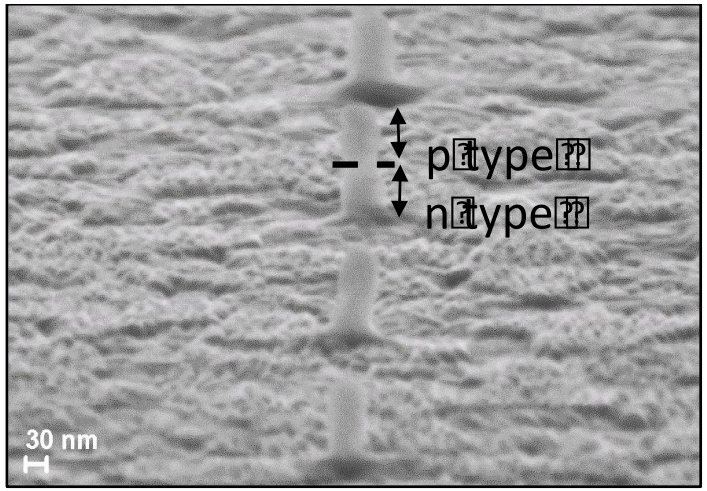


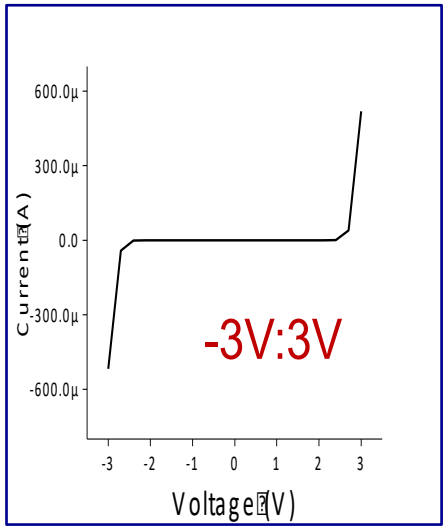


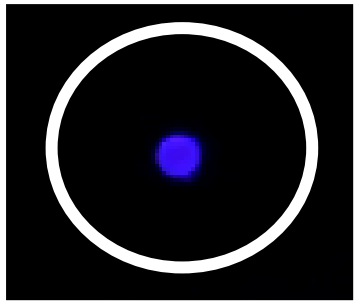
Printed Nano LEDs

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





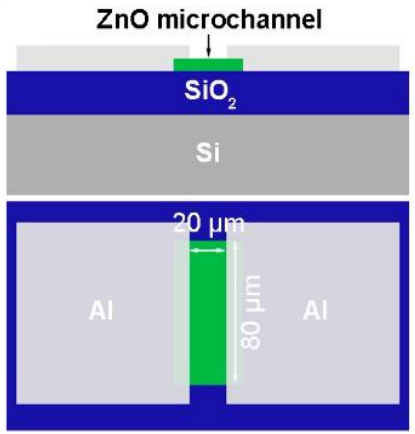


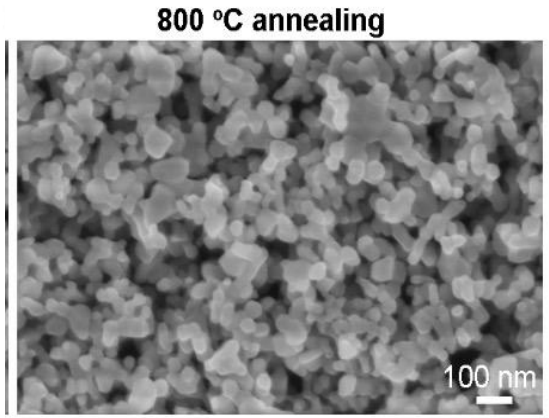


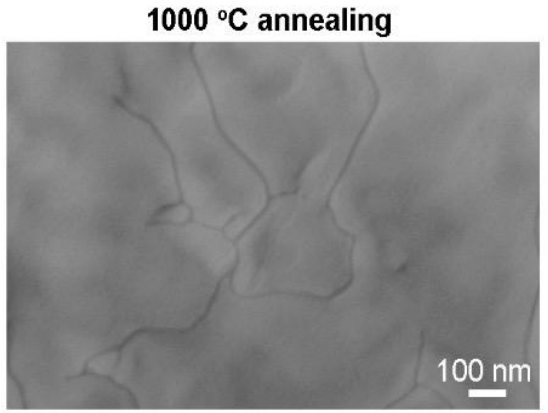
Printing N-doped and P-doped II-VI semiconducting particles that are self annealed insitu during the directed assembly-printing process to yield printed blue LEDs.

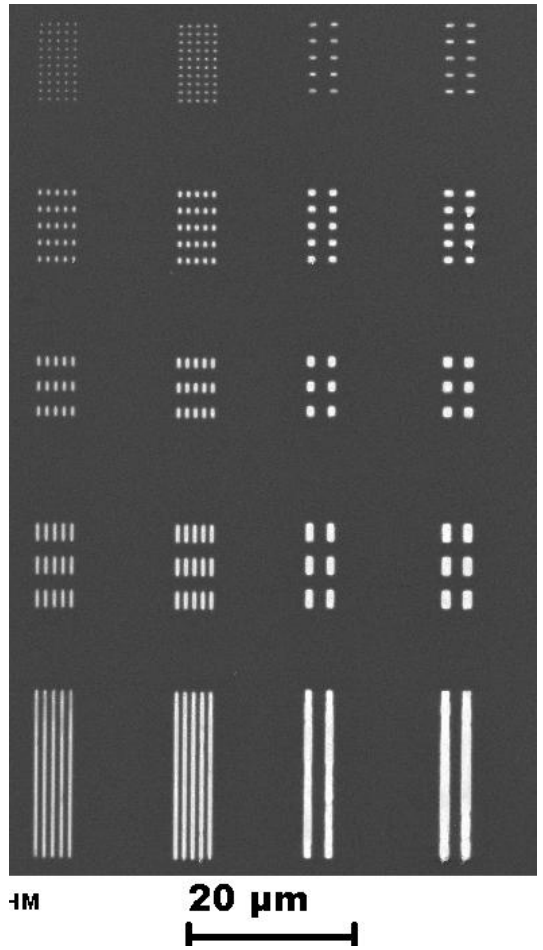
Color	Wavelength (nm)	Voltage (ΔV)
Blue	450 < λ < 500	2.48 < ΔV < 3.7

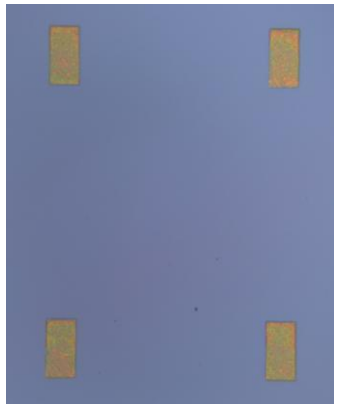
Field Effect Transistor (FET) Using II-VI Semiconductors (NMOS)



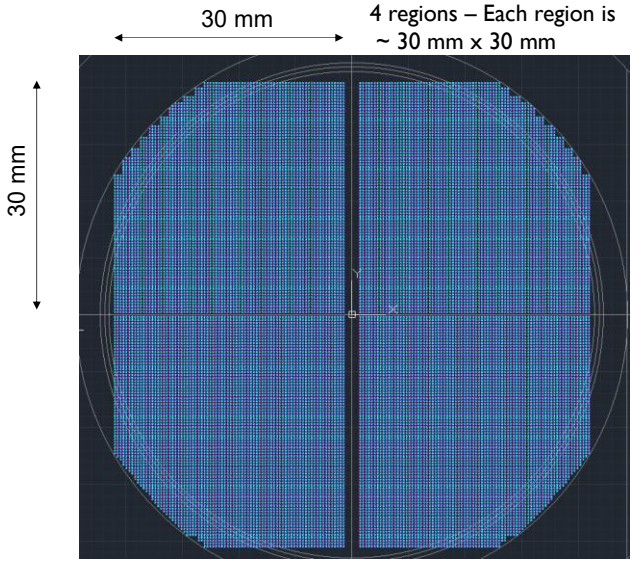


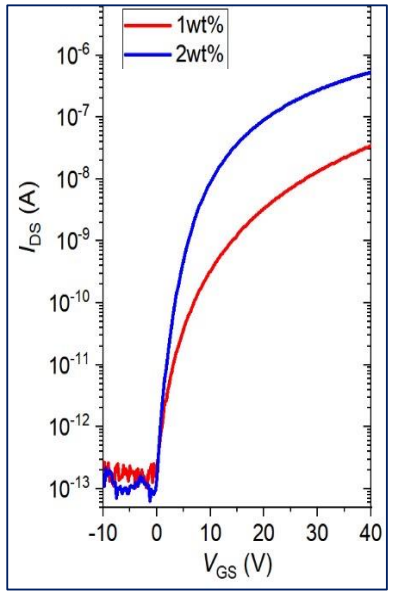






Channel width varied from 100 nm to 2 um, length varied from 100 nm to 20 um

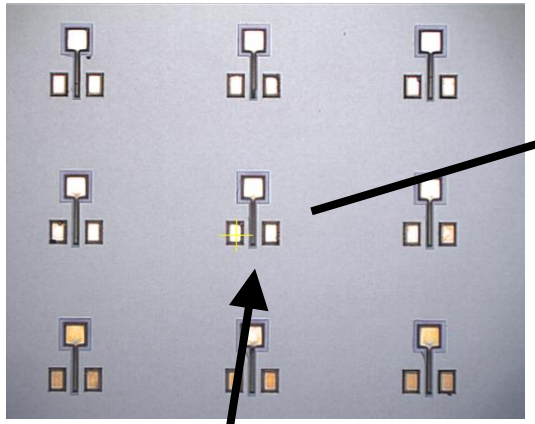


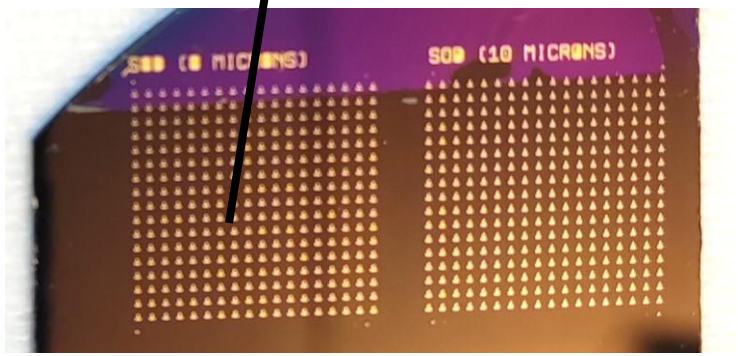


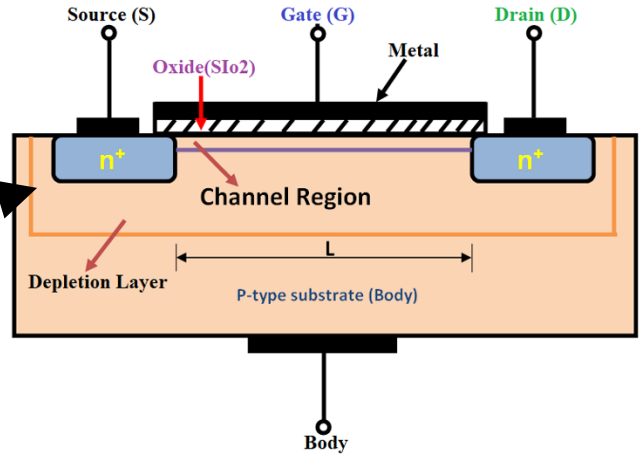
Wafer-level manufacturing of 37,000 transistors exhibiting an on/off ratio higher than 10^6 after annealing.

ACS Applied Electronic Materials, 2023

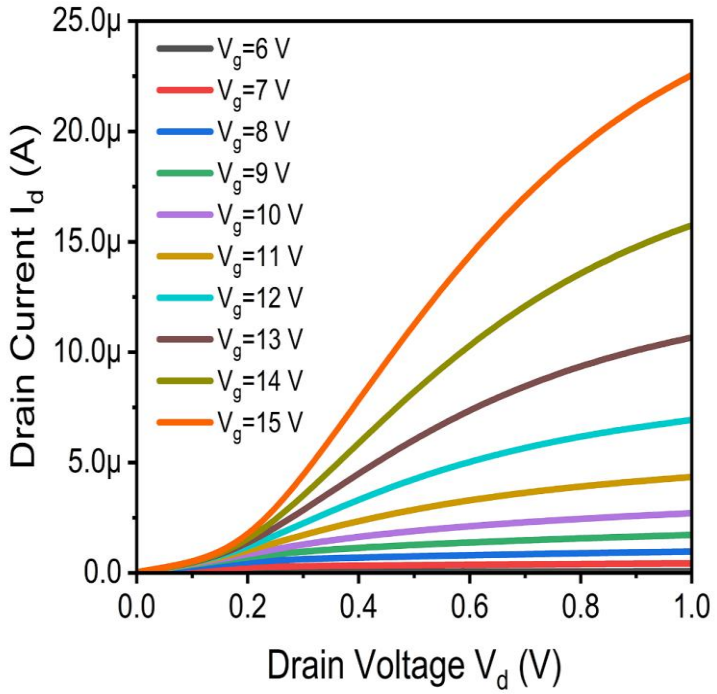
Additively Manufactured Silicon Transistors (MOSFETs)

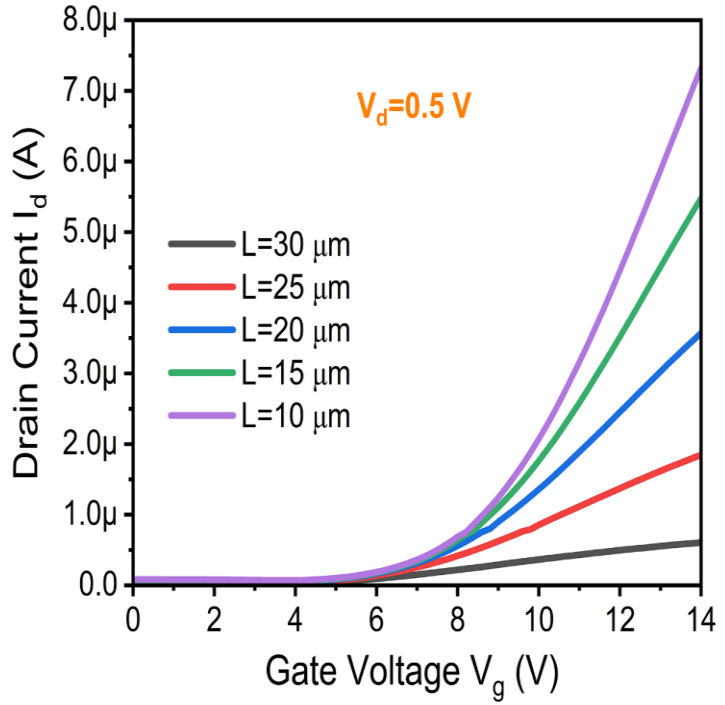






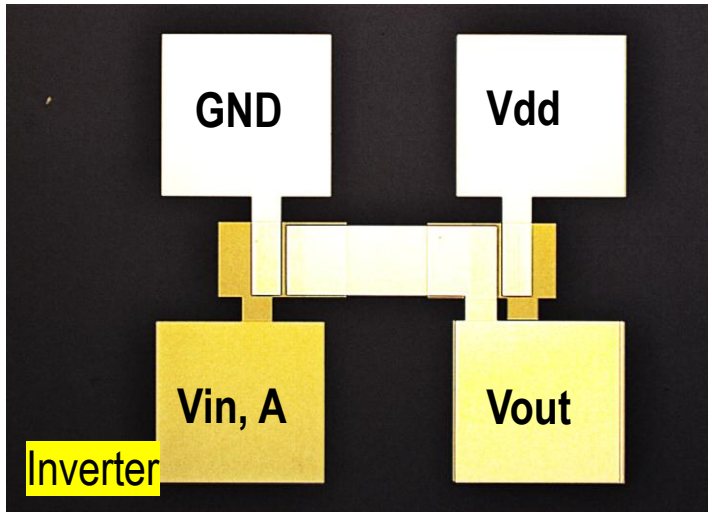
A fully additive liquid-based process process to manufacture MOSFETs using dopants inks to make NMOS.

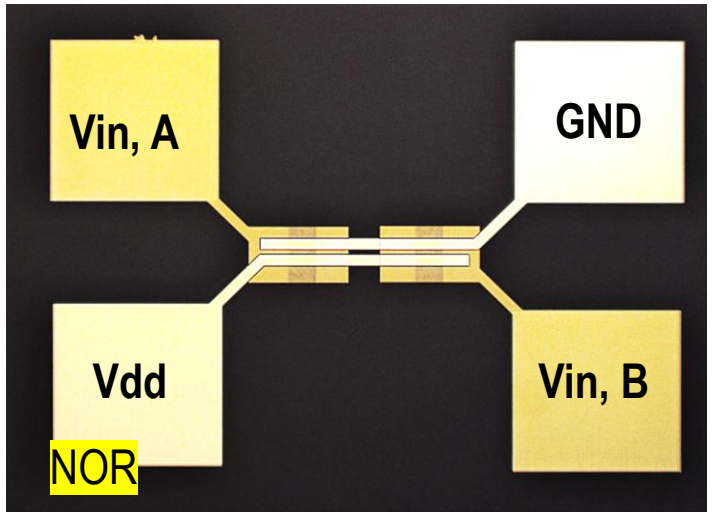


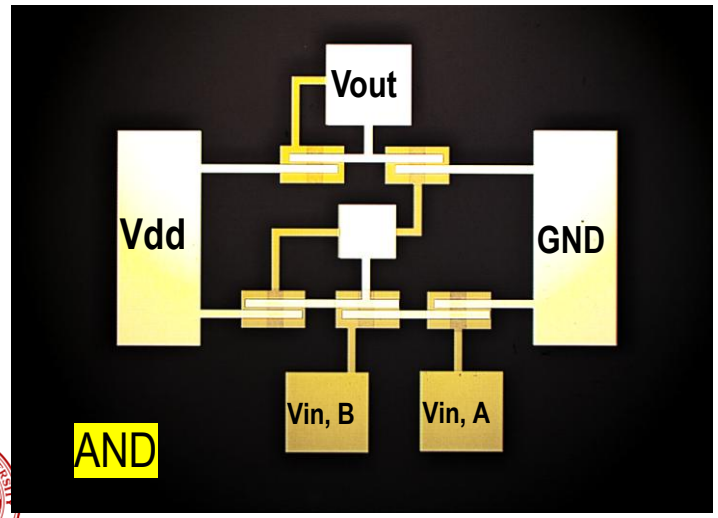


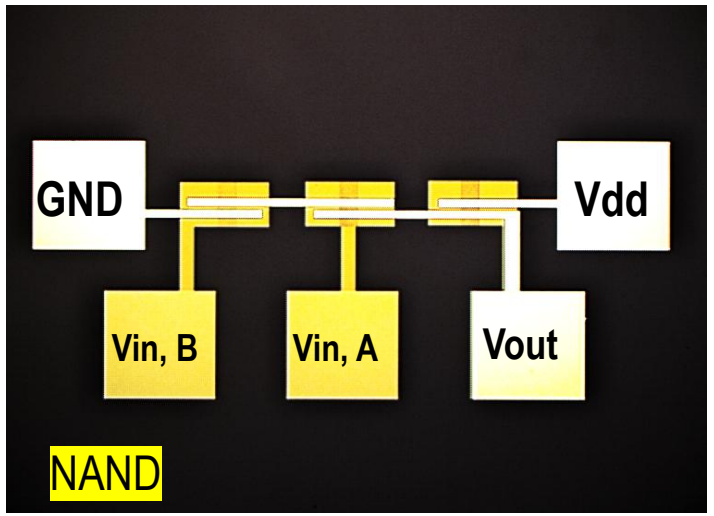
Additively Manufactured Logic Gate Electronics

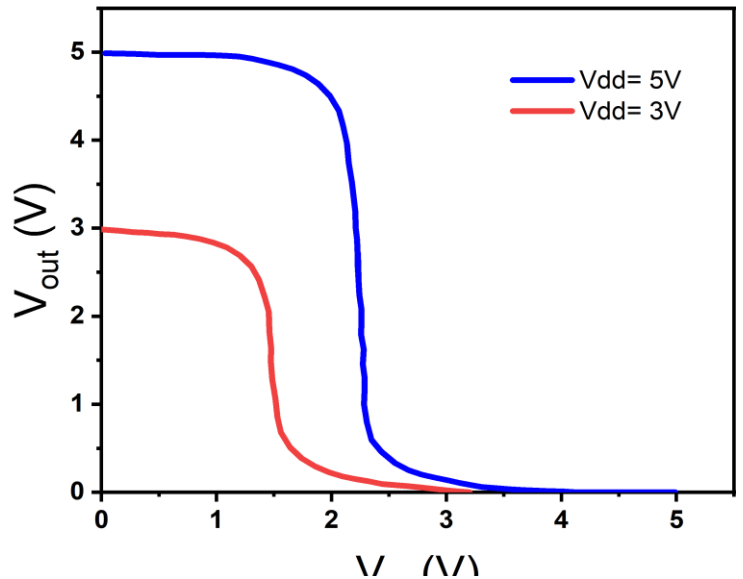
- Logic gates such as Inverters, AND, NAND, and NOR were printed
- The figures below show the fabricated logic circuits (using PMOS)

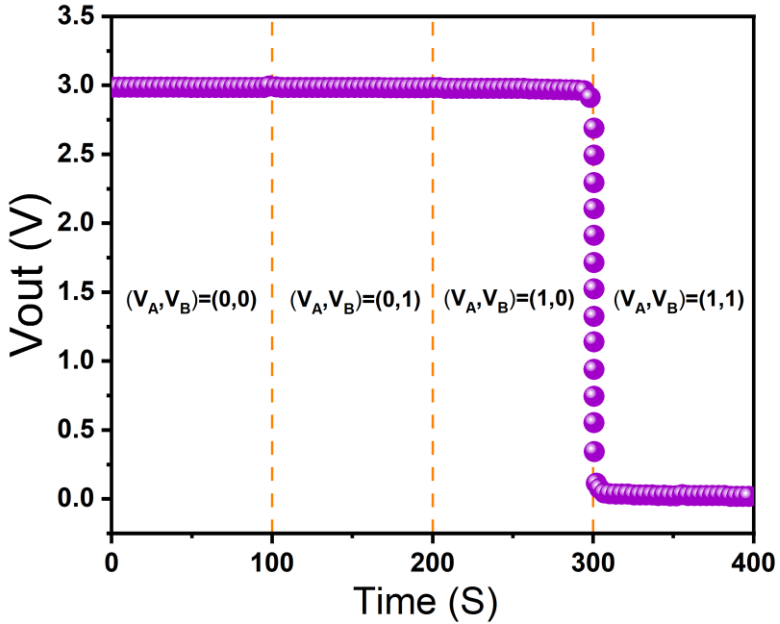




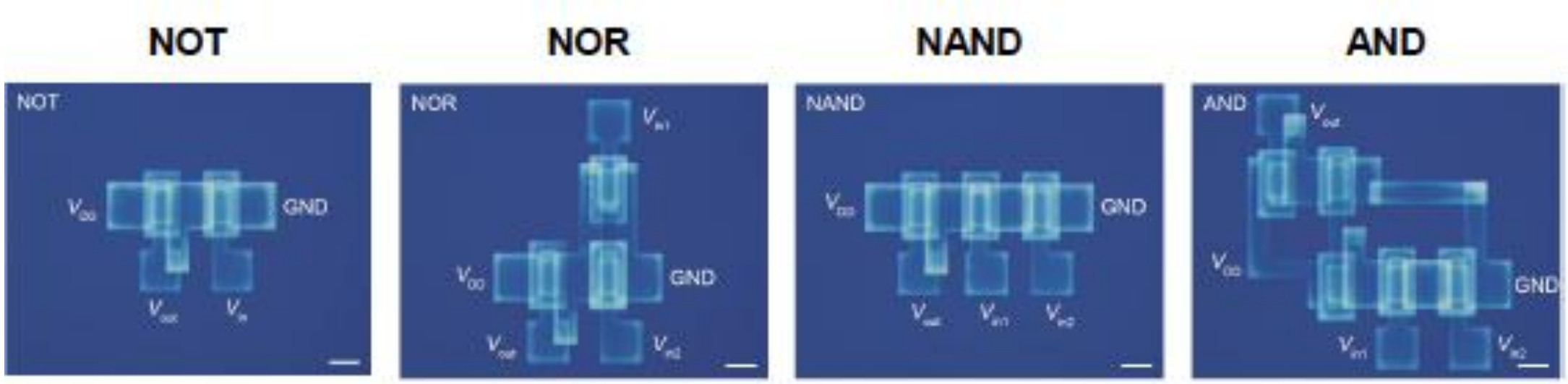


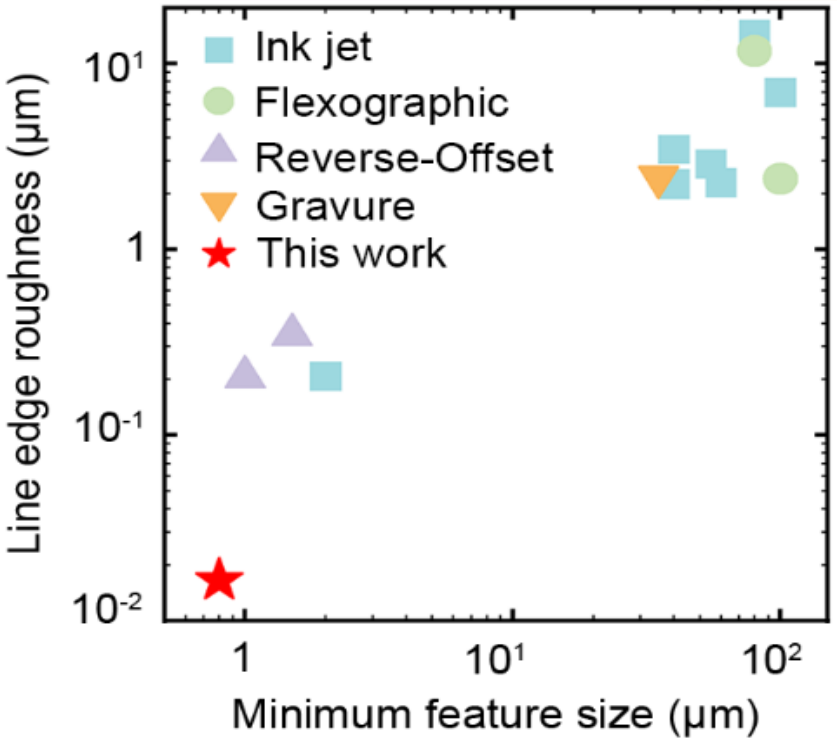


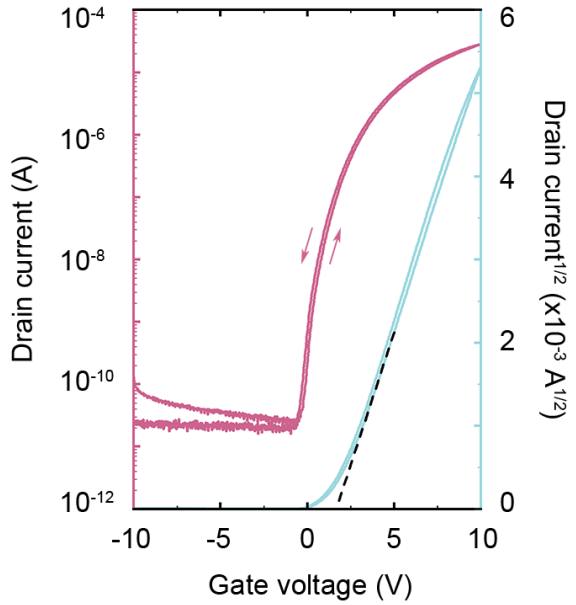


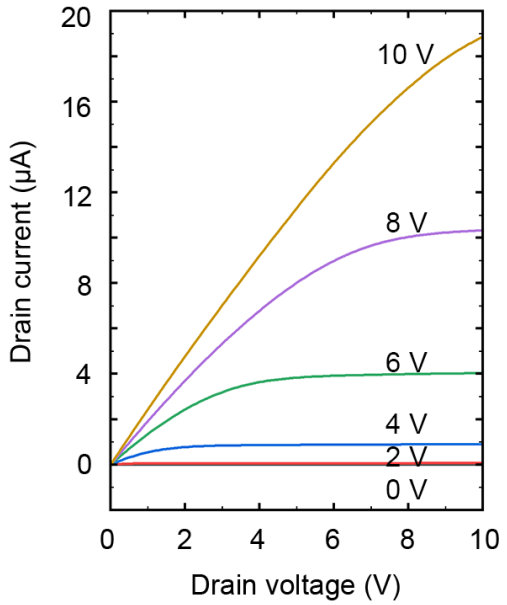


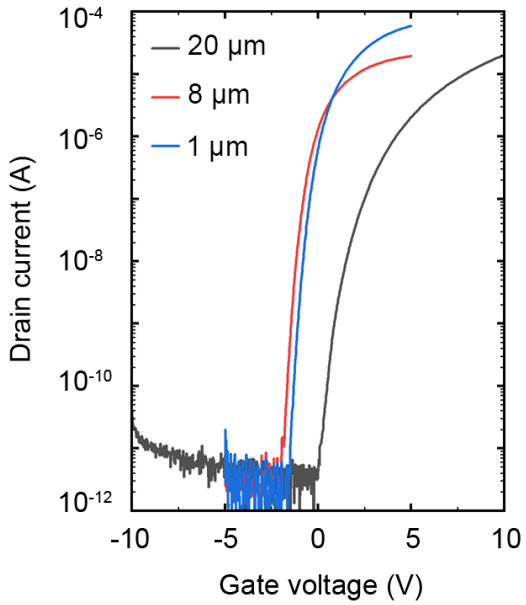
Additively Manufactured Logic Gate Electronics using Indium Oxide (NMOS)





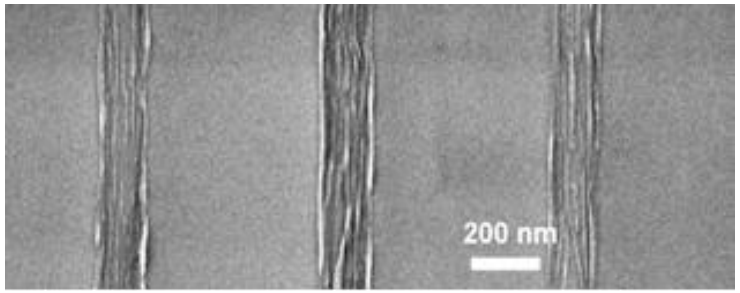


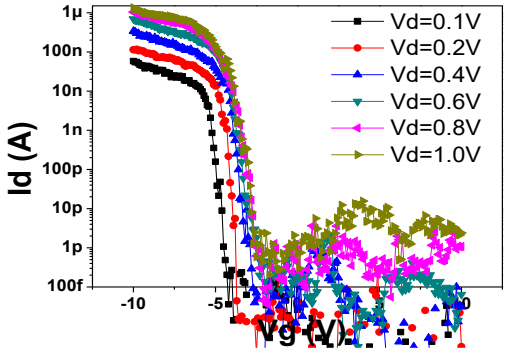




ACS nano, Vol. 18, 2024.

Printed Organic, CNT, and 2D Materials Electronics

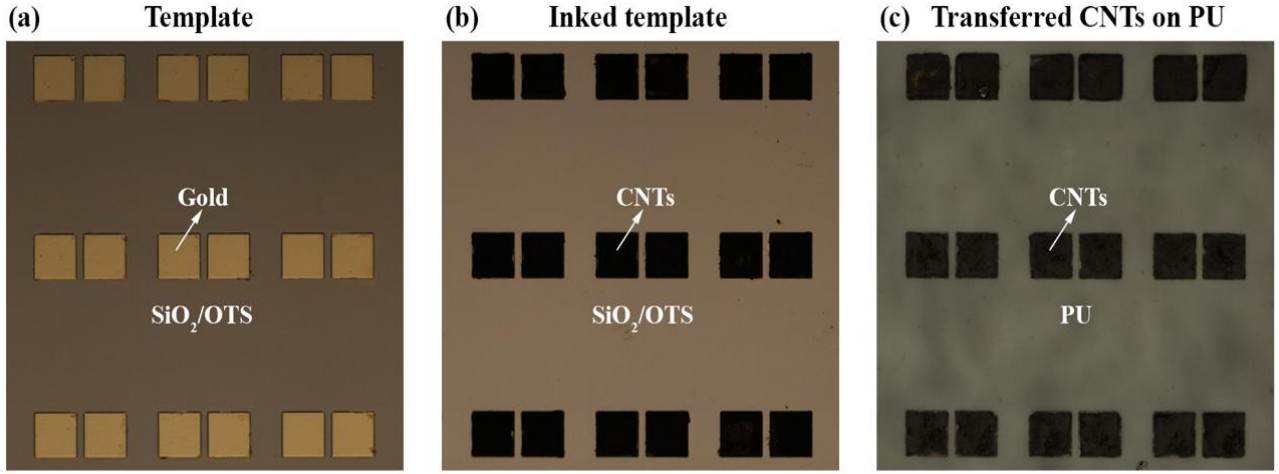




200nm wide carbon nanotubes transistors

with up to $I_{on/off} > 10^6$

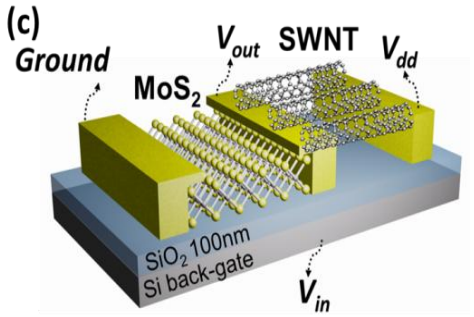
Appl. Phys. Lett. 97, 1 2010

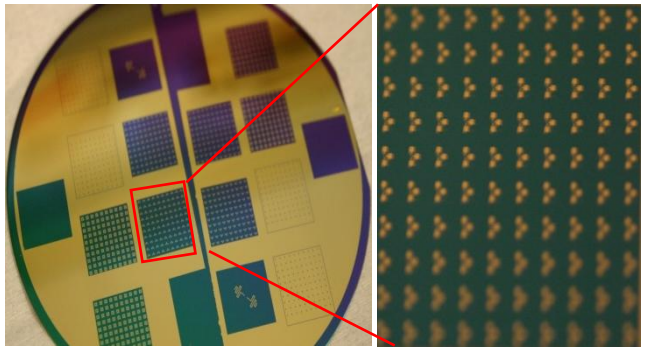


Printed all CNT (all carbon-based) flexible transistors with on/off ratio > 10^5

Appl. Phys. Lett. 117 (13), 133101, 2020.

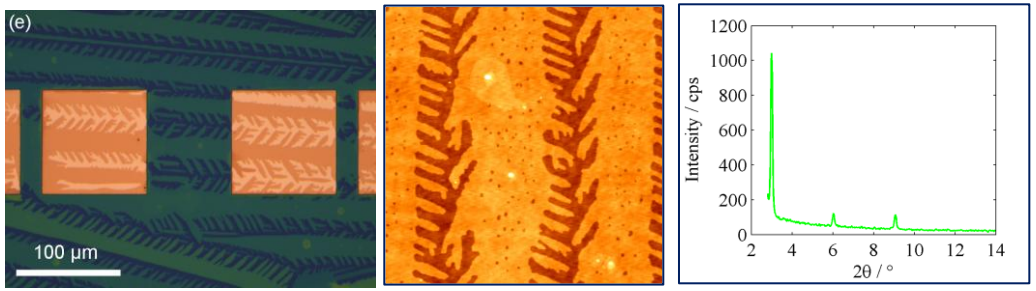
Making devices using 1D and 2D materials: Heterogeneous SWNTs and MoS_2 complimentary invertors





Nanotechnology, Vol. 23, (2012).

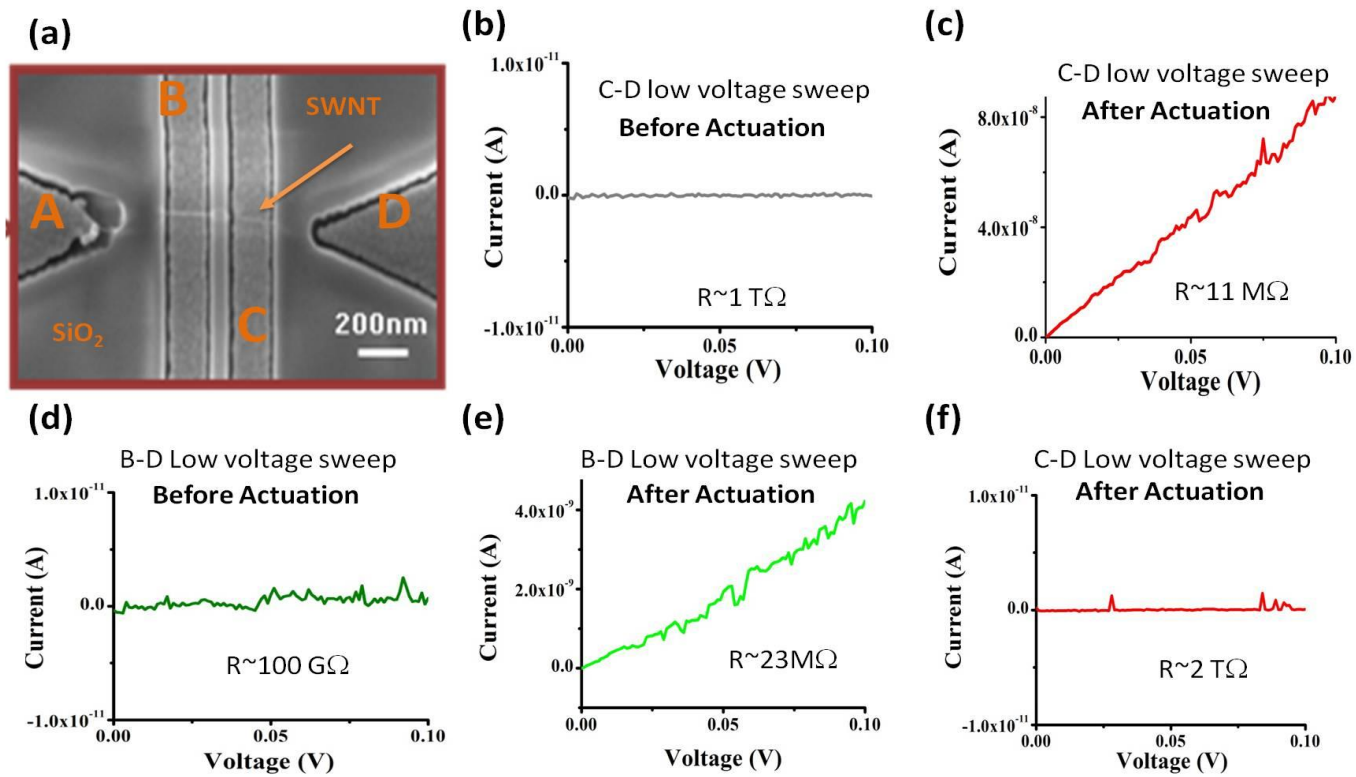
OFET with assembled single crystal C8-BTBT



On/off ratio > 10^4 and mobility up to 4.0 $cm^2 v^{-1} s^{-1}$

ACS Appl. Mat. Interfaces, 2018, 10 (21).

SWNT NEMS Bi-stable Switch



(b) continuity testing before actuation of the first trench, showing open circuit **(c)** continuity testing after actuation of the first trench, showing closed circuit **(d)** continuity testing before actuation of the second trench, showing open circuit **(e)** continuity testing after actuation of the second trench, showing closed circuit **(f)** continuity testing of the first trench after actuation of the second trench, showing open circuit.

Journal of Physics D, Volume 53, Number 23, 2020.

The Future of Electronics Manufacturing

Any Material
Any Substrate

Minimum Feature Size
20 nm

High throughput
10 – 100x Faster

Cheaper 10 – 100x

Submit your GDS or DXF files, load ink, wafers, substrates and Print devices.

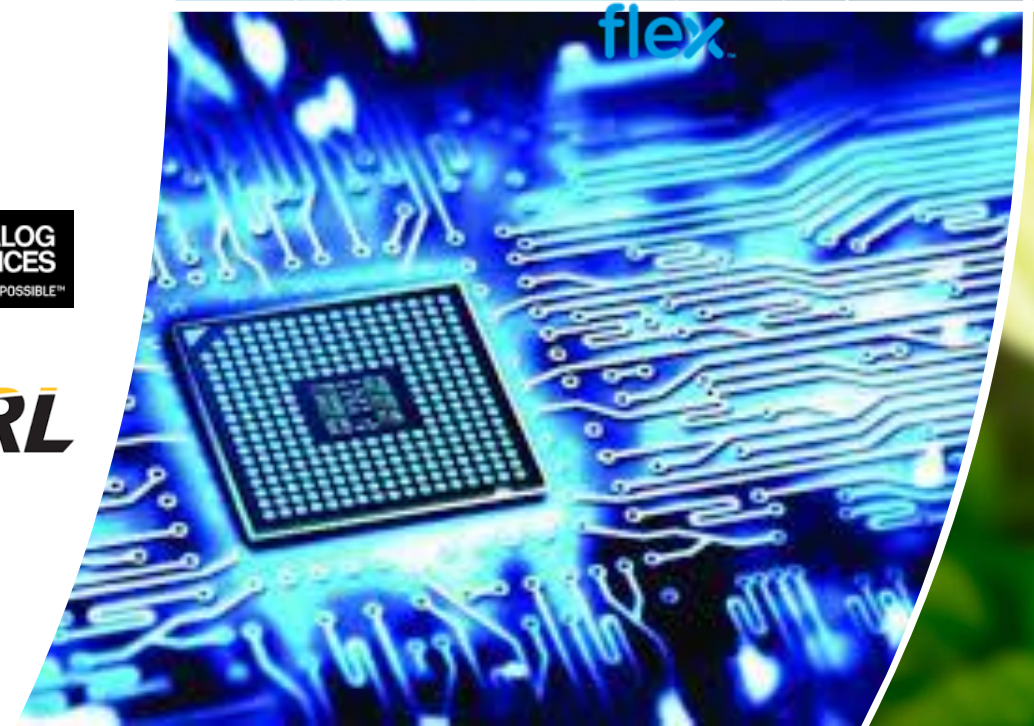
Fab-in-a-Tool: A Fully Automated Nanoscale Electronics Manufacturing Platform

https://www.youtube.com/watch?v=QpbDfAJzXDU&t=7s

www.nano-ops.us

Technological Impact

- Adv. Packaging on demand
- Passive and Active components on demand
- Fast prototyping and development cycle
- Security
- Sustainable
- Material innovation



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