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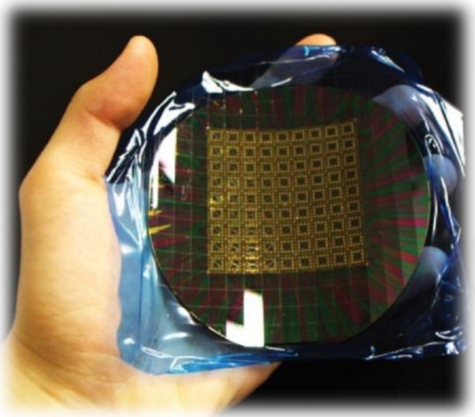

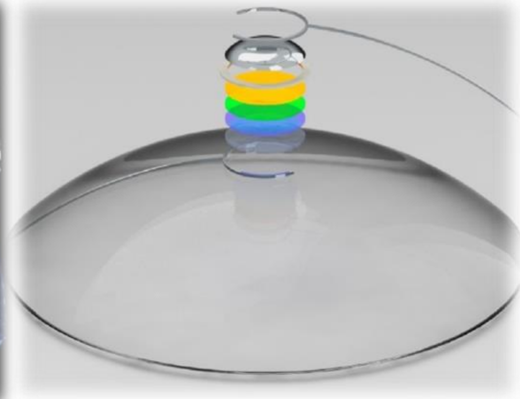

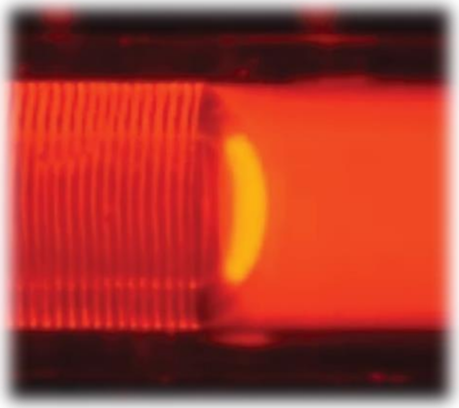

Multiscale additive manufacturing of active electronics

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ADDITIVE MANUFACTURING LABORATORY

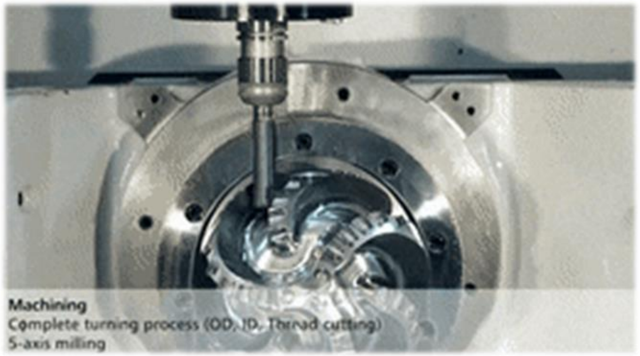
Additive manufacturing

Additive manufacturing (AM),
n—process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing.

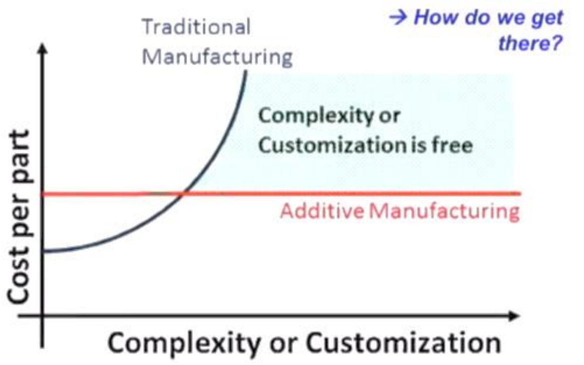
- **Subtractive shaping:** The desired shape is acquired by selective removal of material, examples: milling, turning, drilling, EDM etc, micromachining (lithography)

- **Formative shaping***:* The desired shape is acquired by application of pressure to a body of raw material, examples: forging, bending, casting, injection molding, the compaction of green bodies in conventional powder metallurgy or ceramic processing etc.

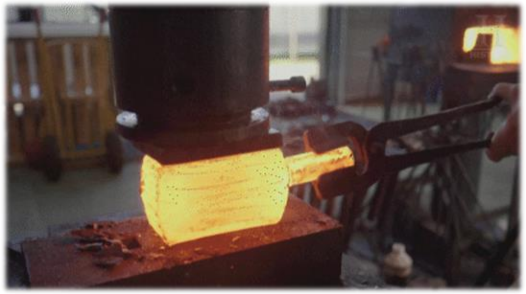
Additive manufacturing



Subtractive manufacturing



Conner et al. *Additive Manufacturing*, 2014

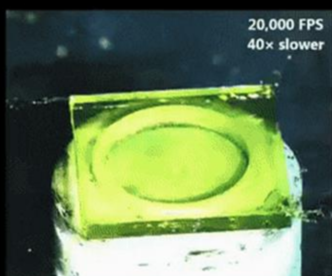


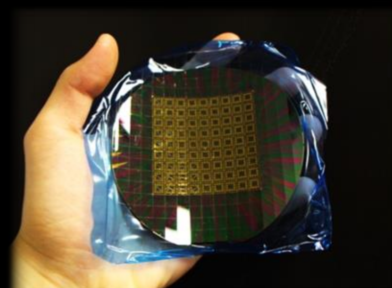
Formative manufacturing

The integration of devices with a 3D construct is inherently challenging:

→ Geometrical, mechanical and material dichotomies

→ Conventional device manufacturing



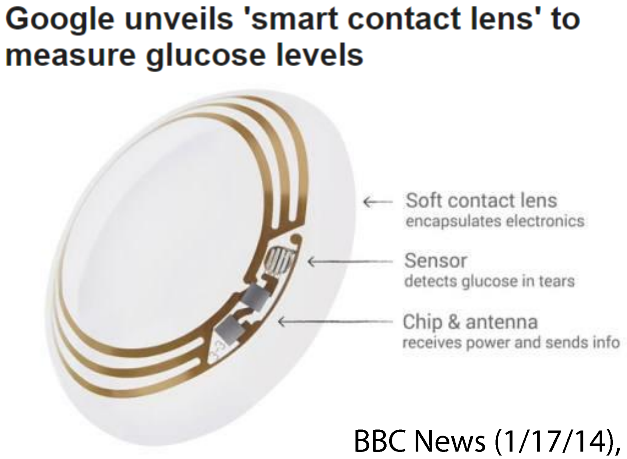


- Tailored for mass production
  - Top-down process
  - Require assembly - limited functionality
- Waste of materials (*e.g., subtractive manufacturing*)
- Limited control of properties
  - 2D , planar, rigid(*e.g., electronics*)

→ Naturally grown biological system

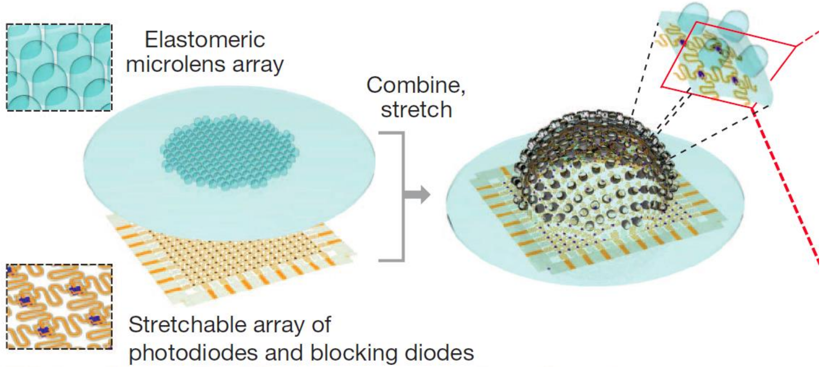
- 3D, multifunctional complex system
  - Uniquely grown
  - Bottom-up processes
  - Physiological conditions
- Materials are sourced from the environment.
- Exceptional control of local properties
  - 3D, property gradient

Incorporation of electronics with a 3D constructs is challenging



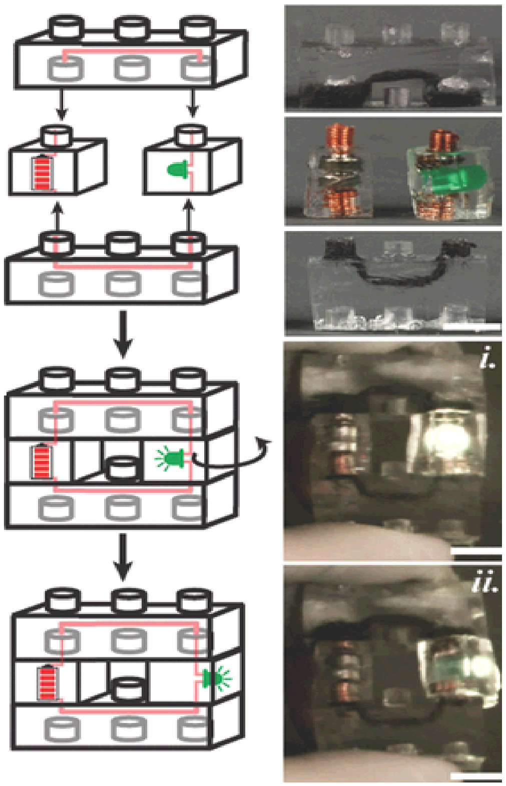
BBC News (1/17/14), Designed by Dr. Babak Parviz and Dr. Brian Otis.

The conformal integration of electronics onto the 3D surfaces requires various complicated device design as well as a meticulously performed transfer procedure.



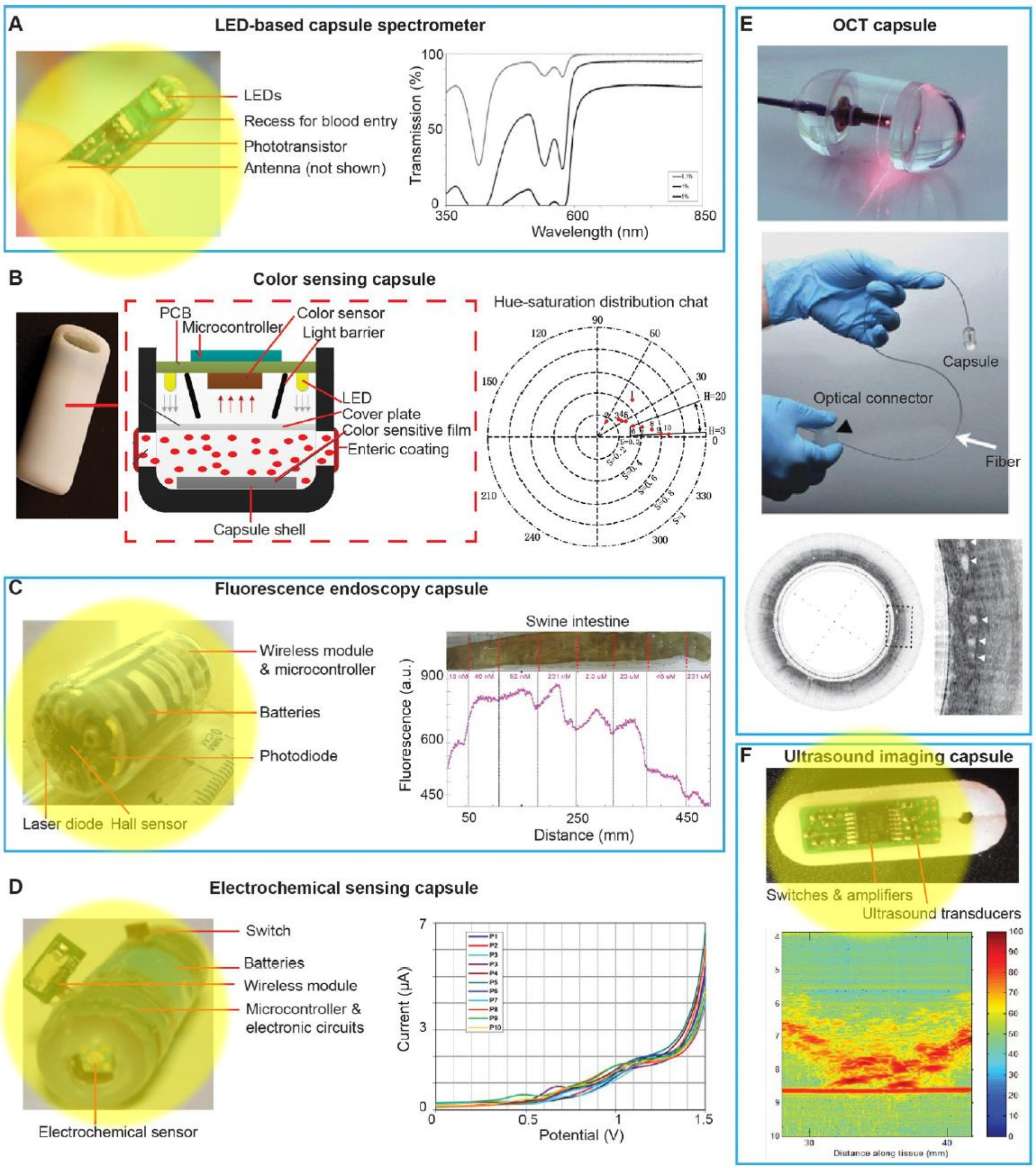
Song, Young Min, and Rogers, John A., et al. "Digital cameras with designs inspired by the arthropod eye." *Nature* 497.7447 (2013): 95-99.

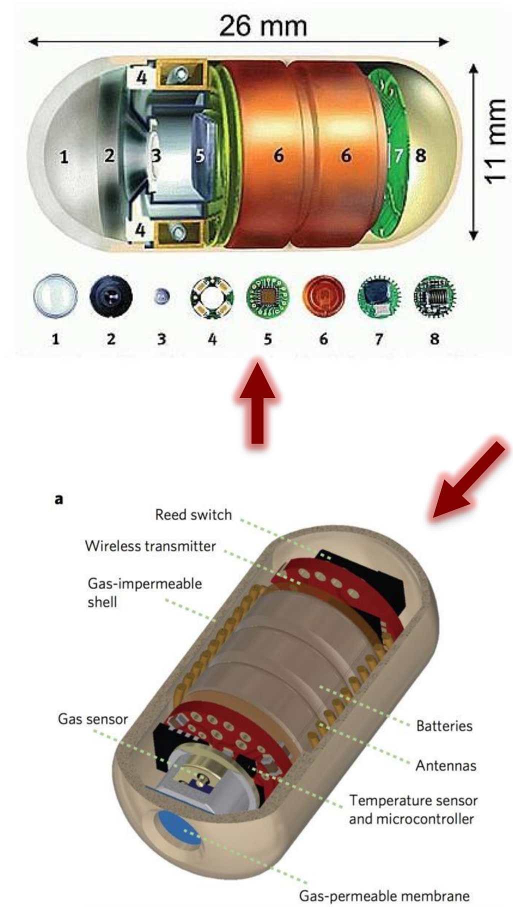
The integration of electronics into a 3D constructs is achieved through a separate assembly process of a prefabricated electronics into the structure.



Morin, Stephen A., and Whitesides, George M., et al. "Using "Click-e-Bricks" to Make 3D Elastomeric Structures." *Advanced Materials* 26.34 (2014): 5991-5999.

Smart Pills





Kalantar-Zadeh, Kourosh, et al. "Ingestible sensors." *ACS sensors* 2.4 (2017): 468-483.

Kalantar-Zadeh, K., Berean, K.J., Ha, N. *et al.* A human pilot trial of ingestible electronic capsules capable of sensing different gases in the gut. *Nat Electron* **1,** 79–87 (2018).

Creating 3D biomedical electronics

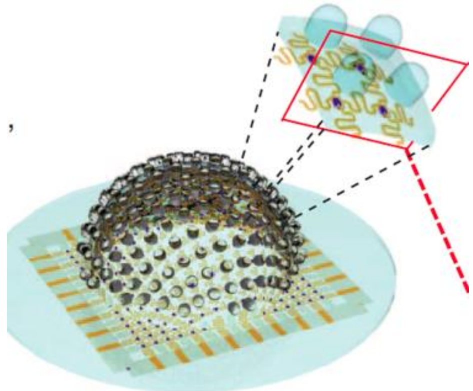
The conformal integration of electronics onto the 3D surfaces requires various complicated device design as well as a meticulously performed transfer procedure.

The integration of electronics into a 3D constructs is achieved through a separate assembly process of a prefabricated electronics into the structure.

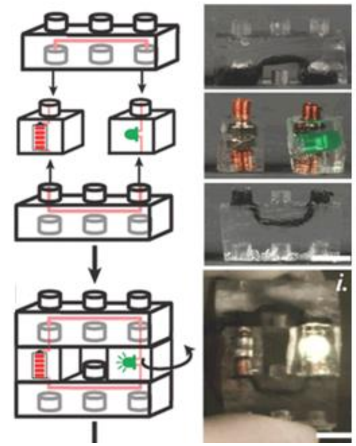
Prefabricated Electronics in 2D

Device design

Transfer to a 3D surfaces



Song, Young Min, and Rogers, John A., et al. "Digital cameras with designs inspired by the arthropod eye." *Nature* 497.7447 (2013): 95-99.



Morin, Stephen A., and Whitesides, George M., et al. "Using "Click-e-Bricks" to Make 3D Elastomeric Structures." *Advanced Materials* 26.34 (2014): 5991-5999.

Prefabricated Electronics in 2D

Creation of unit cell

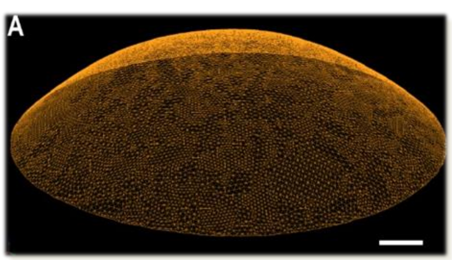
Assemble into a 3D construct

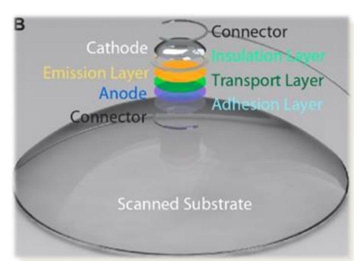
?

Direct 3D fabrication of electronics

[1] on a 3D surfaces

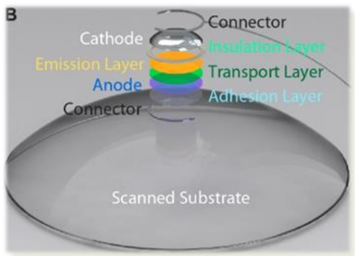
[2] in a 3D construct



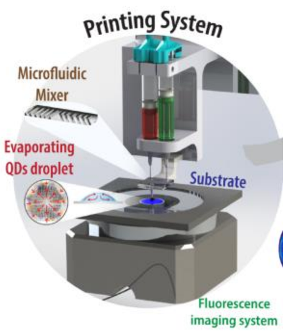


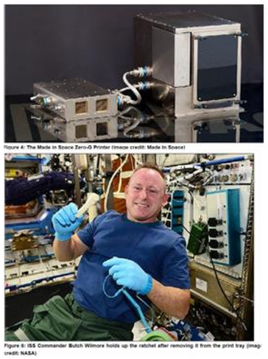
Advantages of entirely 3D printed electronics

3D printing (**3DP**) can complement conventional electronics manufacturing (**CM**) in several aspects:

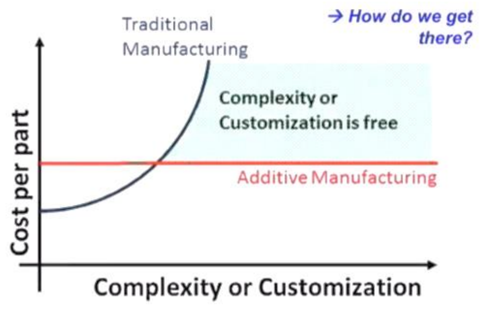


1. **3D integration:**
   - CM: *fundamentally limited by its planarity and rigidity constraint.*
   - 3DP: seamlessly integrate with a broad range of three-dimensional constructs to impart active functionalities.
2. **Remote fabrication:**
   - *CM: relies on complex equipment and facilities.*
   - 3DP: immune to supply chain disruption or constraints (e.g., chip shortage); or availability in austere, remote environments and future space missions.



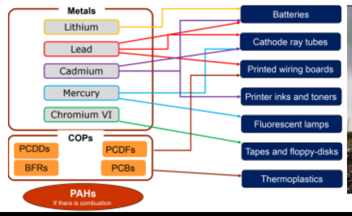


3. **Economy of customization:**
   - *CM: mass production of identical devices to achieve economy of scale.*
   - 3DP: the cost per part of 3D printed electronics remains relatively constant with the increase of customization. Providing an economically feasible approach to:
     - optimize device properties for a target application.
     - Introducing variations – e.g. ,cyber security (unclonable)



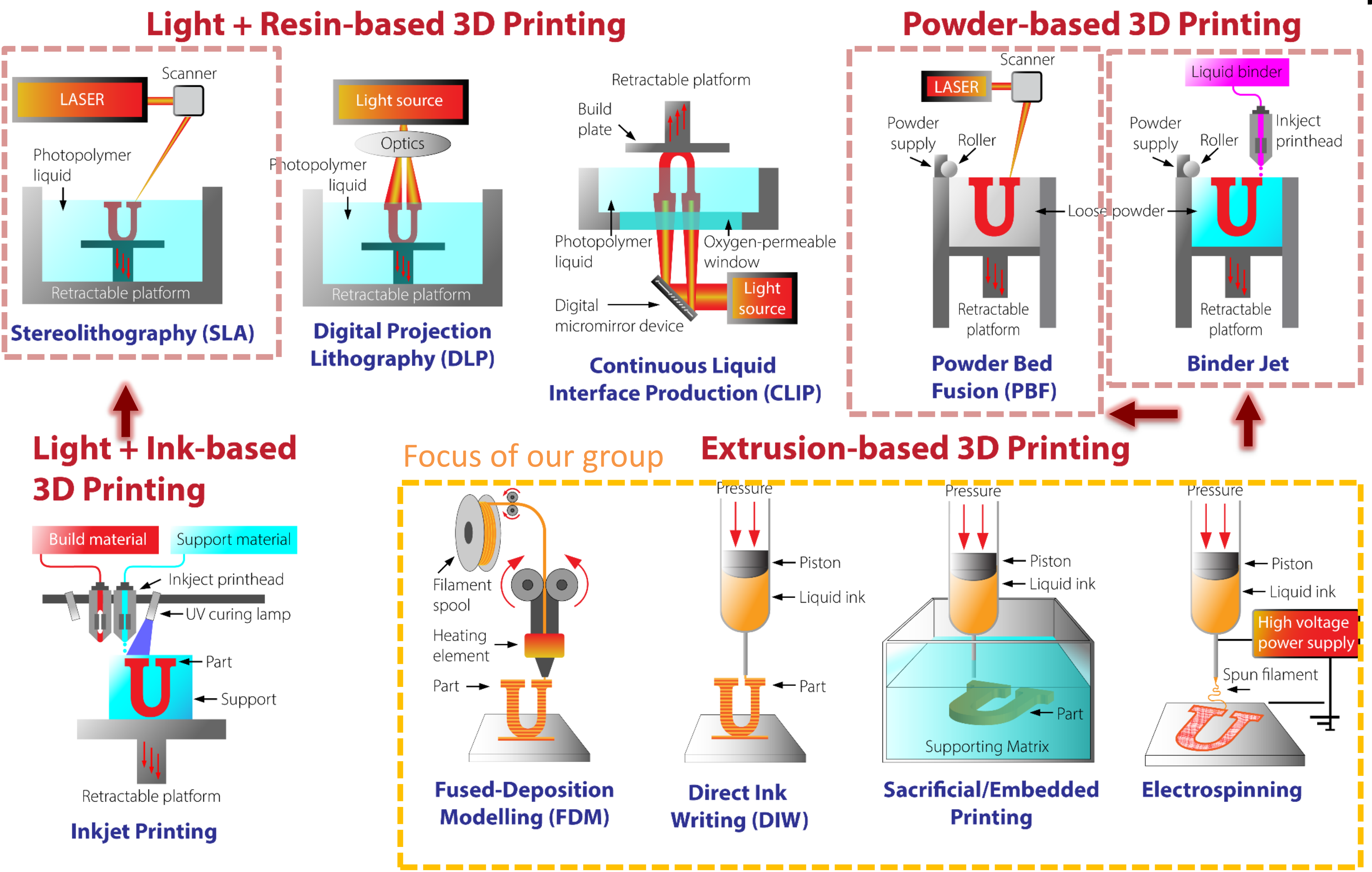
Conner et al. *Additive Manufacturing*, 2014

4. **Sustainable manufacturing:**
   - *CM: mass production – wasteful approach – pollution.*
   - 3DP: reduce waste of materials, cost of inventory, minimize electronics waste & pollution.



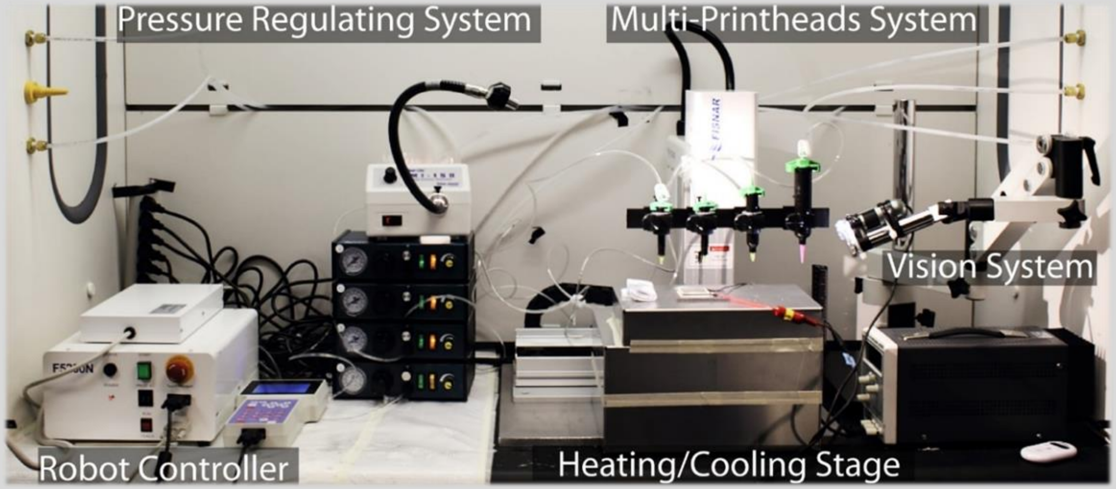
WHO

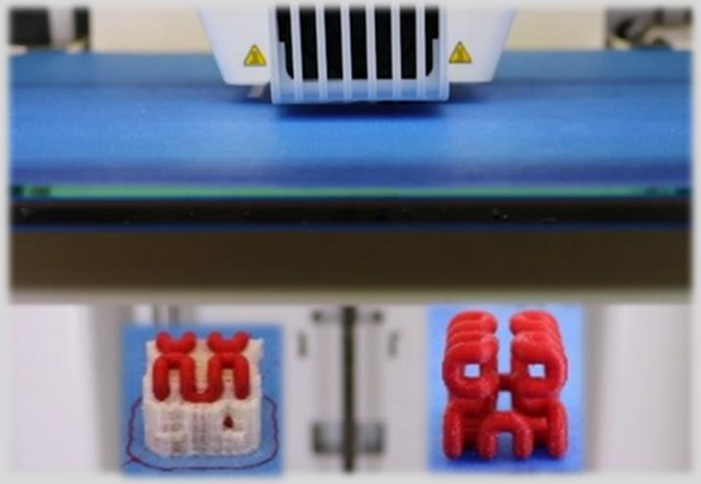
Additive manufacturing (a.k.a 3D printing) is a broad class of manufacturing technology
Overview of University of Utah AM capabilities



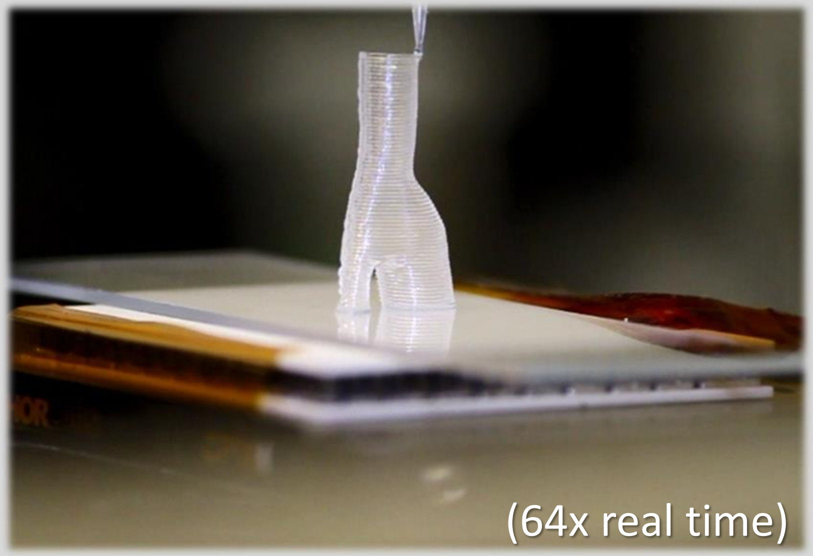
B. Elder, R. Neupane, E. Tokita, U. Ghosh, S. Hales, **Y. L. Kong*** *Advanced Materials* 1907142 (2020)

Extrusion-based 3D printer

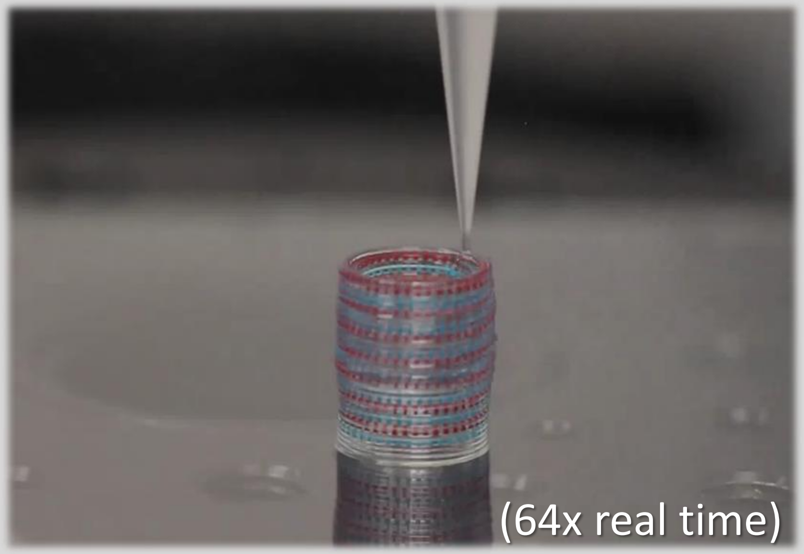




Compatibility with a wide range of materials



Multi-component printing capability

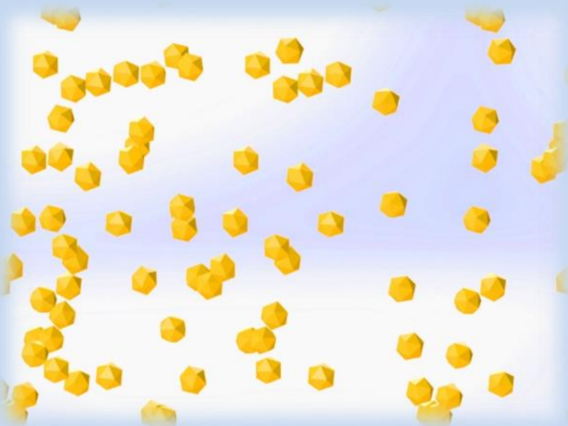


Multi-scale 3D printing of bioelectronics

Impart
tunable +
functional properties

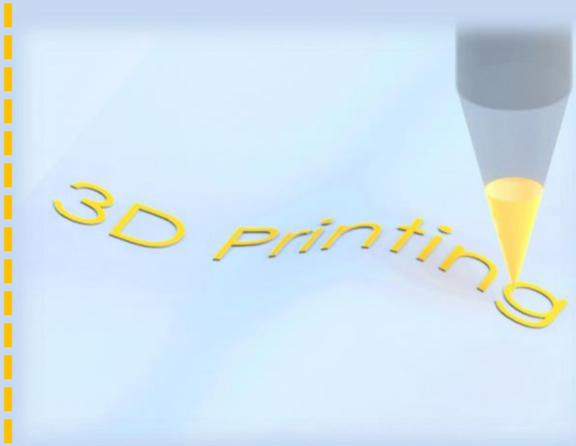
Our research focus

Nanomaterials Inks



+

Microscale Patterning



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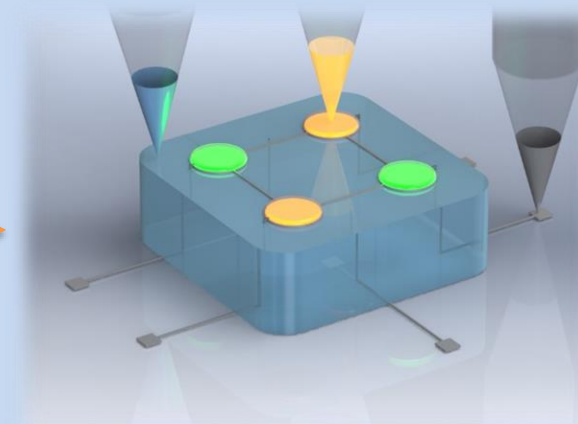
Macroscale Device Fabrication

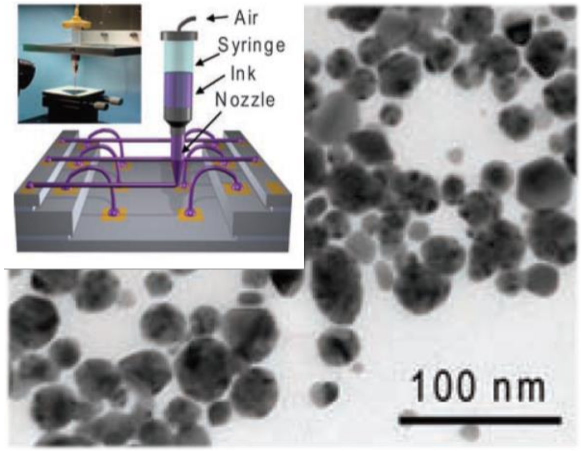


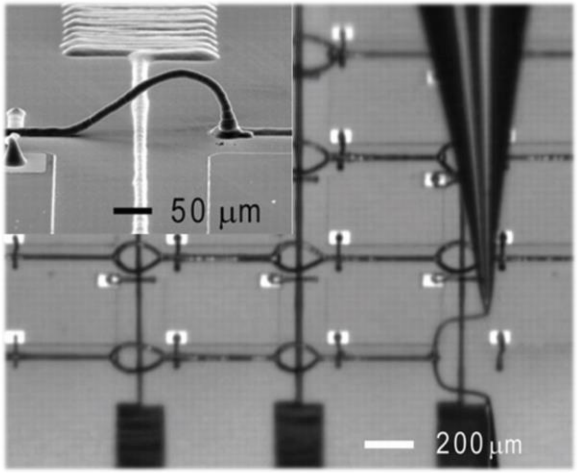
Functional nanomaterials can be dispersed in solvents to form solution-processable **inks,** which can be integrated into coating or **printing** processes to create functional **electronics** that can better interface with the 3D construct.

Y. L. Kong*, M. K. Gupta, B. N. Johnson, and M. C. McAlpine*. "3D printed bionic nanodevices." *Nano Today* 11, no. 3 (2016): 330-350.

Previous work: extrusion printing of nanomaterials as conductors

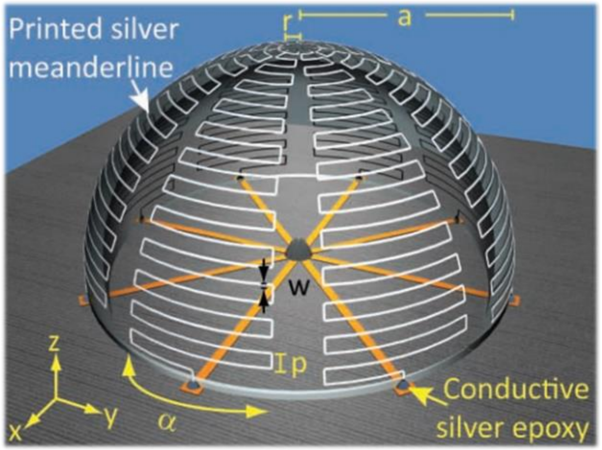
Silver interconnects

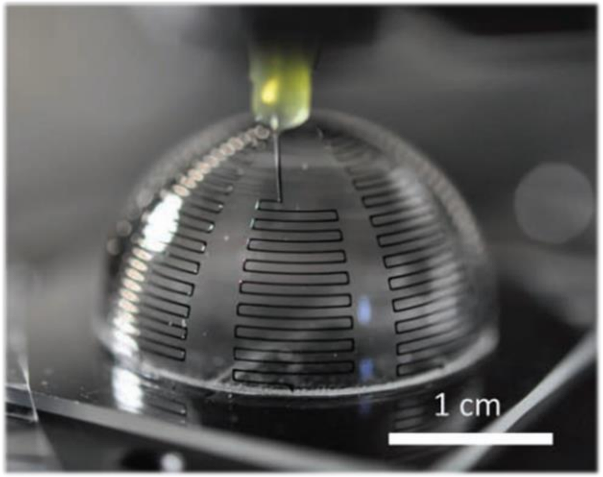




Ahn, Bok Y., and Lewis, Jennifer .A. et al. "Omnidirectional printing of flexible, stretchable, and spanning silver microelectrodes." *Science* 323.5921 (2009): 1590-1593.

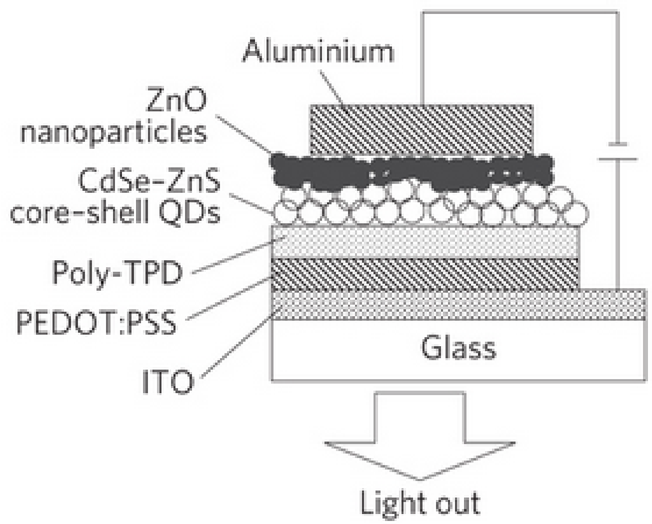
Antenna on a 3D constructs



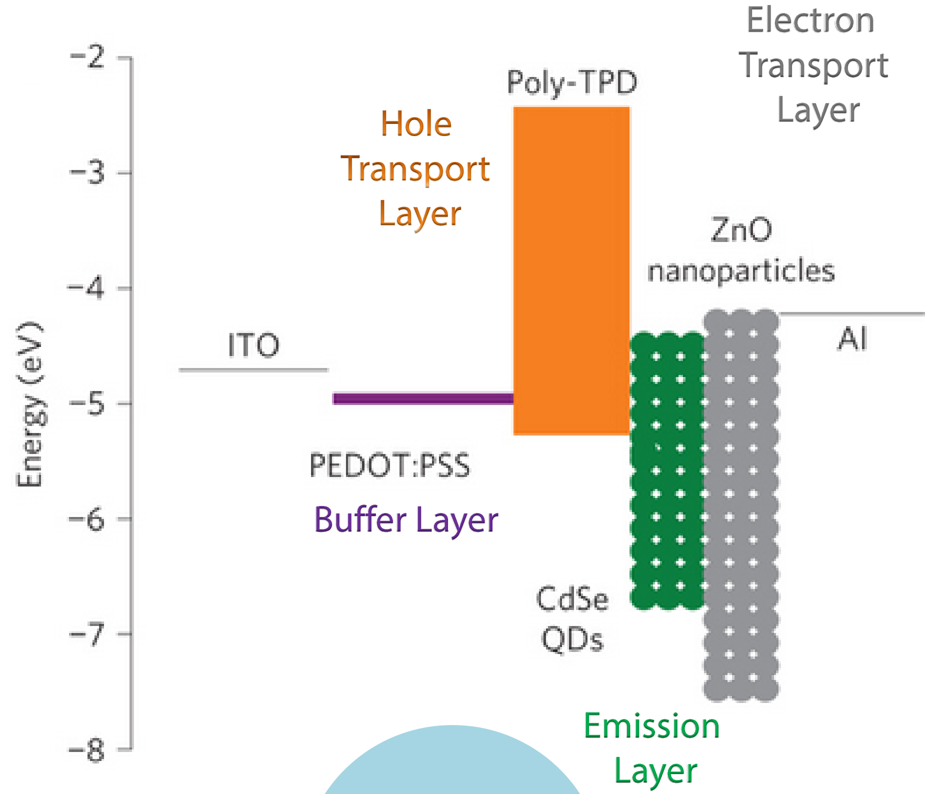


Adams, Jacob J., and Lewis, Jennifer .A et al. "Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces." *Advanced Materials* 23.11 (2011): 1335-1340.

3D printing of an active electronics?

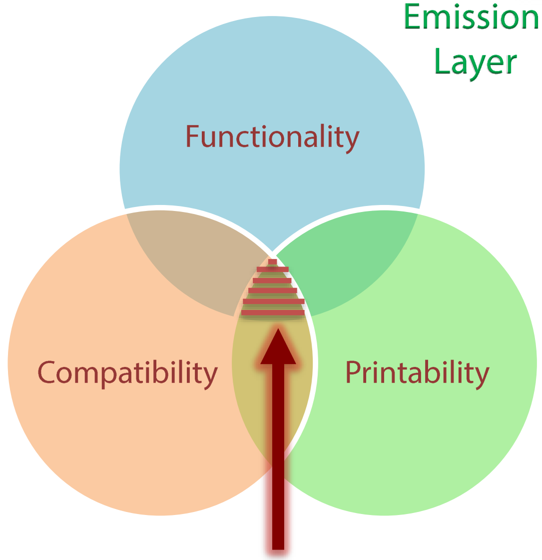


Qian, Lei, et al. "Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures." *Nature Photonics* 5.9 (2011): 543-548.

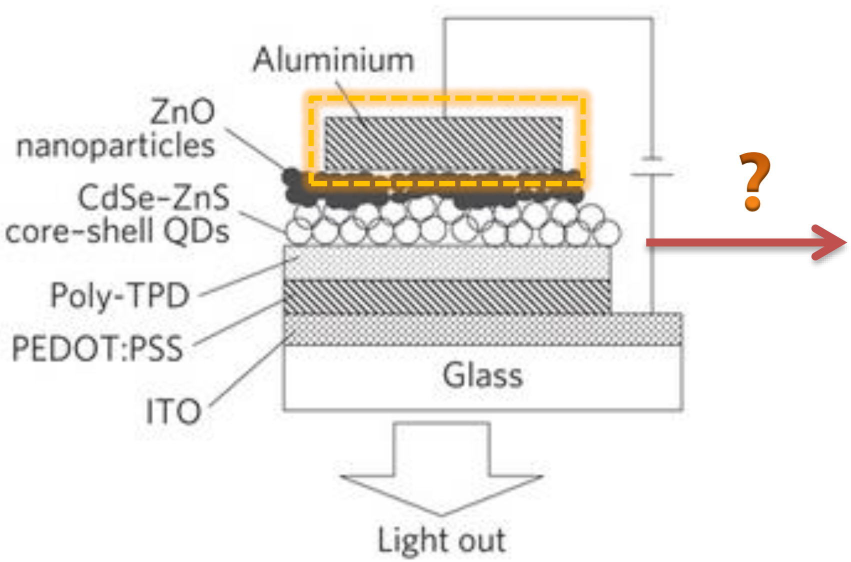


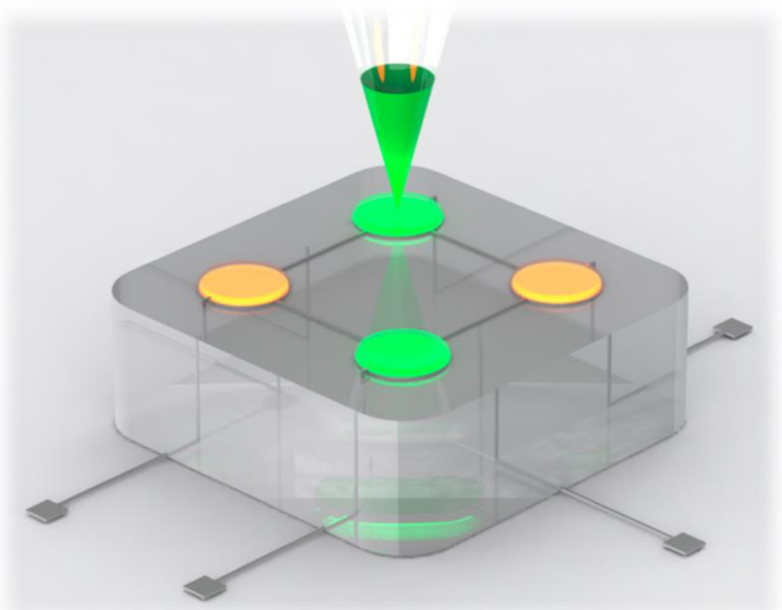
Identify electrodes, semiconductors, and polymers that possess

- desired functionalities
- printable formats
- chemically compatible



3D printing a Quantum Dots LED?

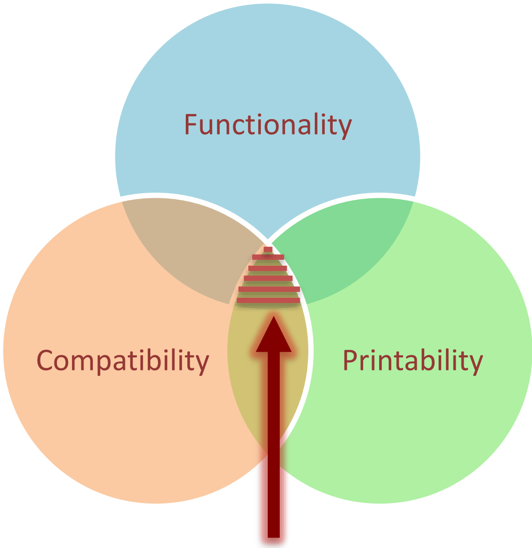




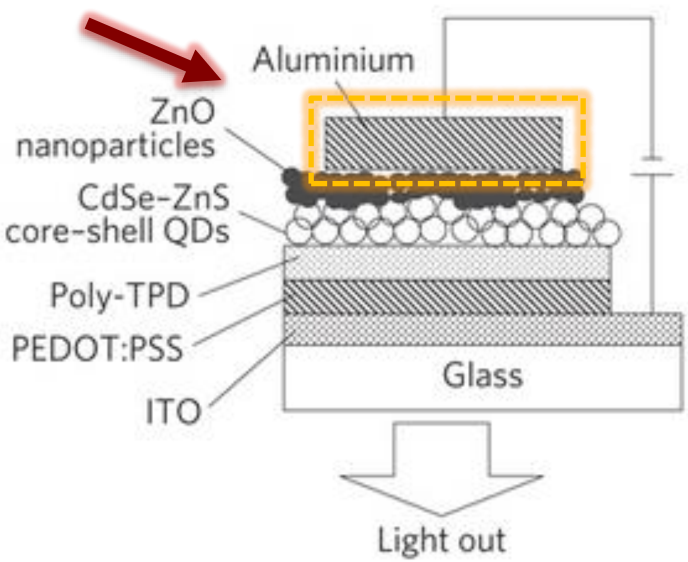
Qian, Lei, et al. "Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures." *Nature Photonics* 5.9 (2011): 543-548.

Strategies to overcome printing challenges:

1. **Printing materials: e.g. *printing of cathode with liquid metal***
2. **Soft matter physics: *printing of emissive nanoparticles with co-solvent***

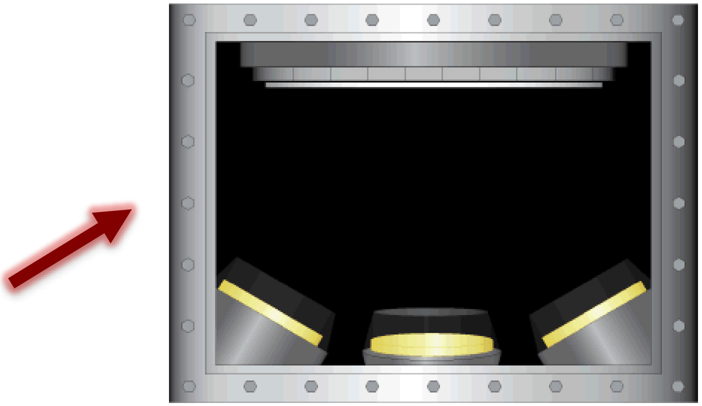


Materials challenge: cathode



Qian, Lei, et al. "Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures." *Nature Photonics* 5.9 (2011): 543-548.

- Cathode is usually material that is highly reactive, especially in printable format
- Involves processes such as evaporation or sputtering in a vacuum chamber



Confocal sputtering system by *AJA International Inc.*

Strategies to overcome printing challenges:

1. **Printing materials: e.g. *printing of cathode with liquid metal***
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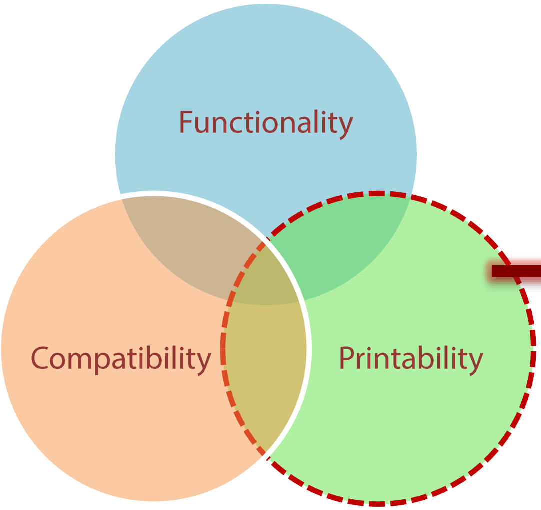
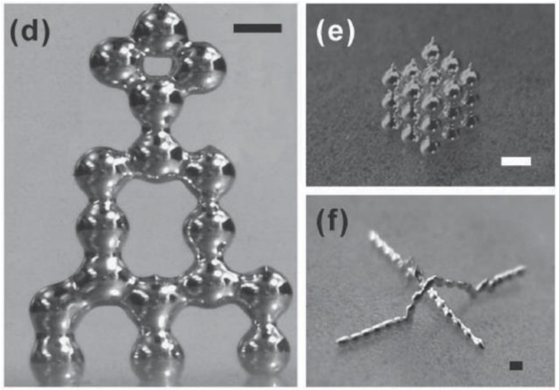
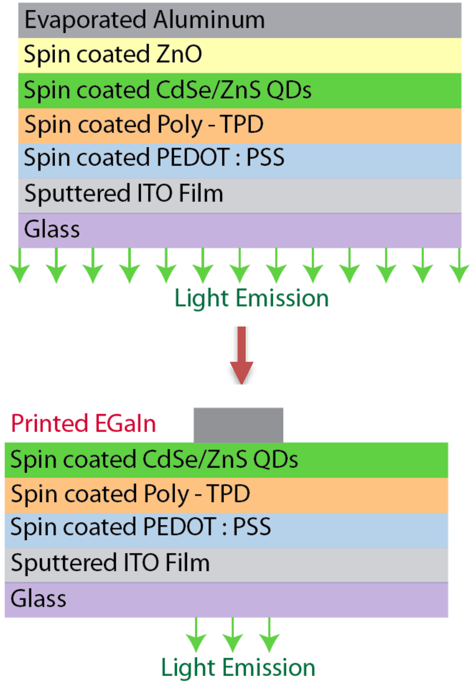
Eutectic gallium indium alloy is 3D printable

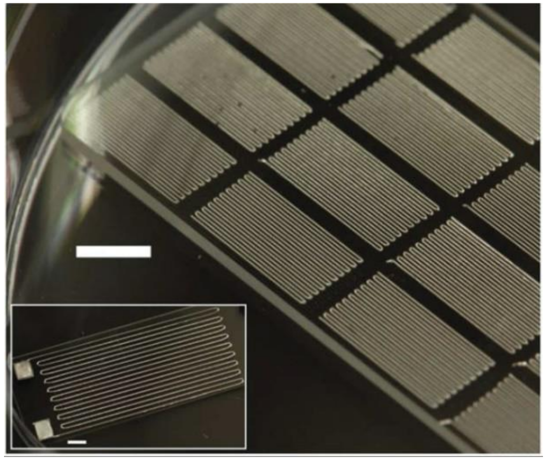


- Viscosity ≈ 2.4 mPa s
- Thin oxide layer maintain structure stability (surface tension ≈ 0.6 N m^{-1})
- **No heat treatment needed**

Ladd, C., So, J.-H., Muth, J. & Dickey, M. D. 3D Printing of Free Standing Liquid Metal Microstructures. Advanced Materials 25, 5081-5085 (2013).

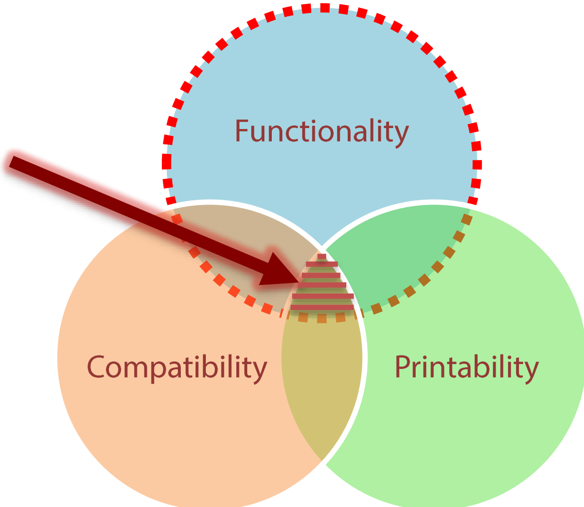




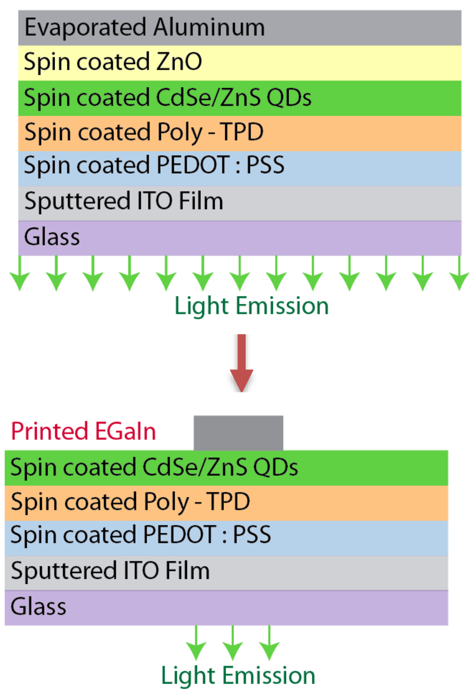


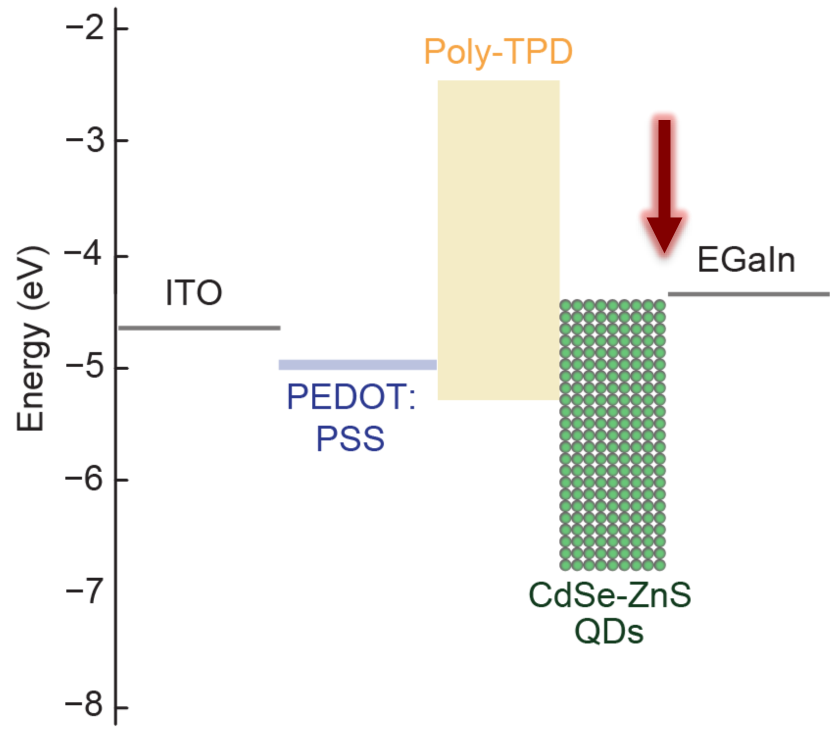
Boley, J. W., White, E. L., Chiu, G. T. C. & Kramer, R. K. Direct Writing of Gallium-Indium Alloy for Stretchable Electronics. Advanced Functional Materials (2014).

Eutectic gallium indium alloy as cathode

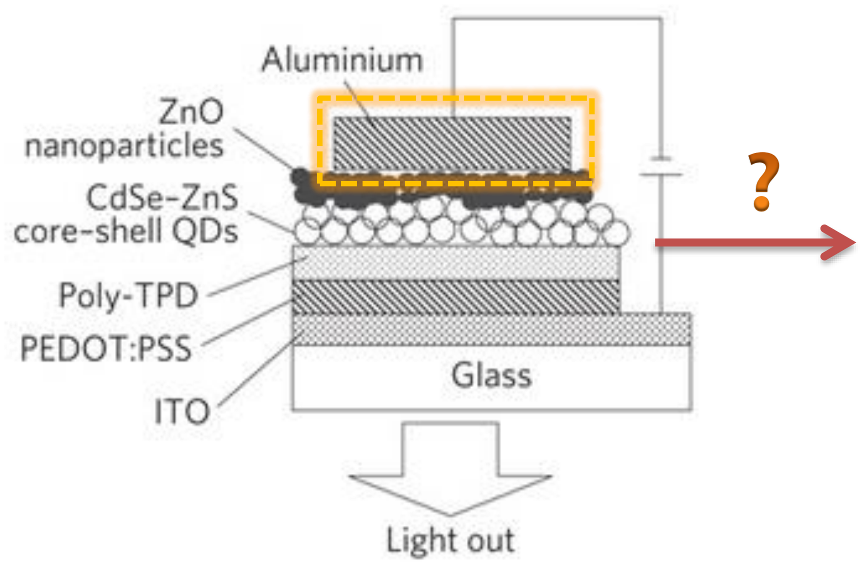


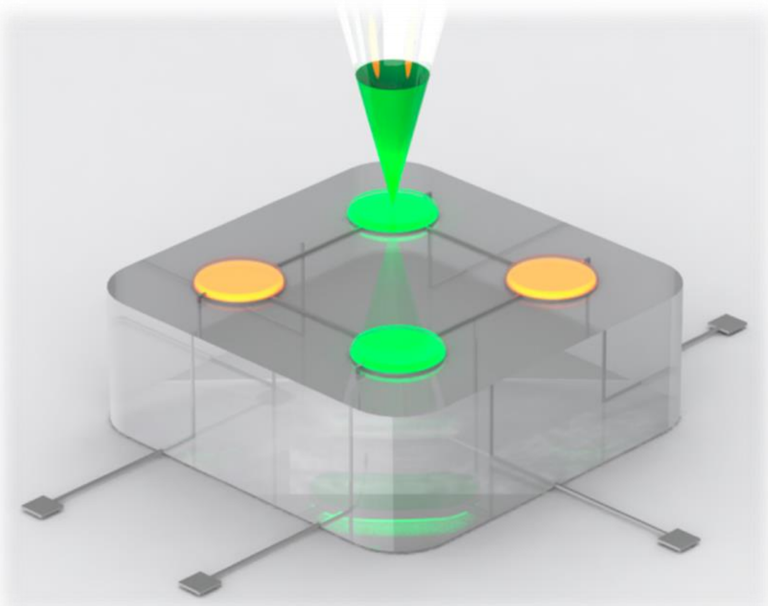
- Highly conductive (3.4×10^4 S cm^{-1})
- Work function of –4.3 eV





3D printing a Quantum Dots LED?





Qian, Lei, et al. "Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures." *Nature Photonics* 5.9 (2011): 543-548.

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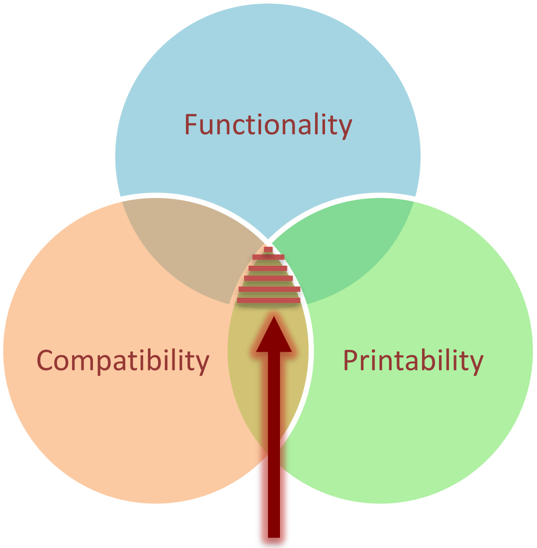
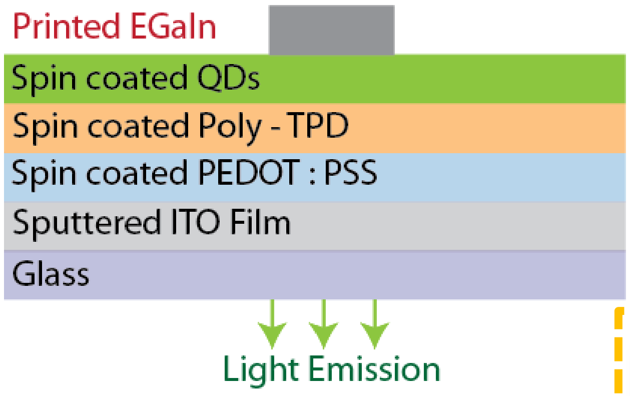


How to generate film without spin coating?



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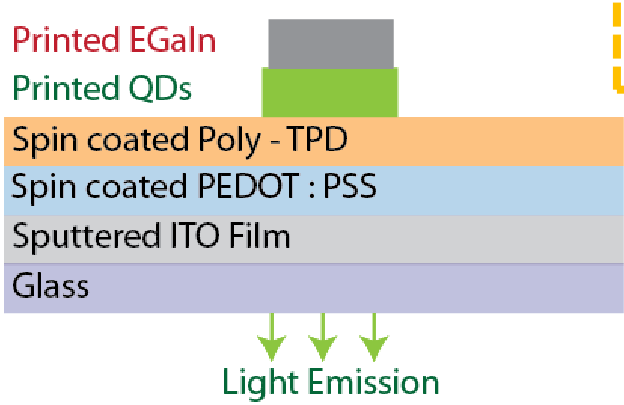

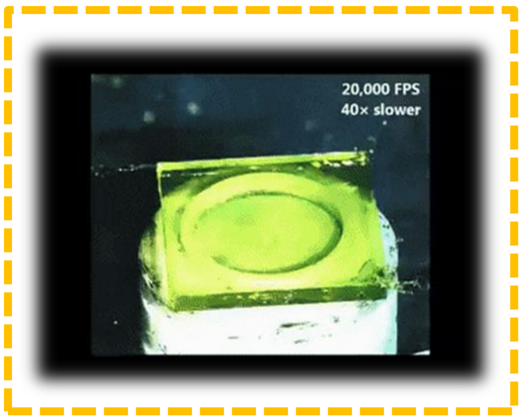

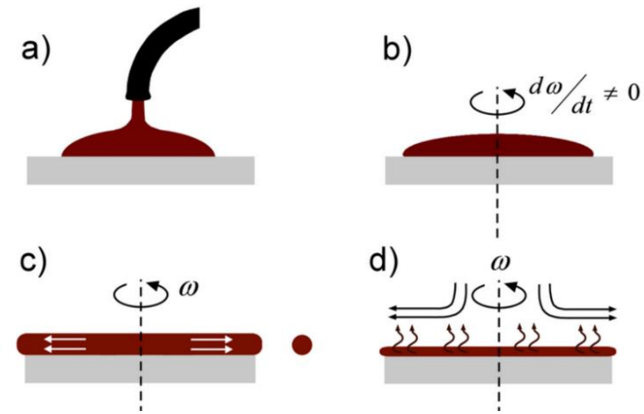

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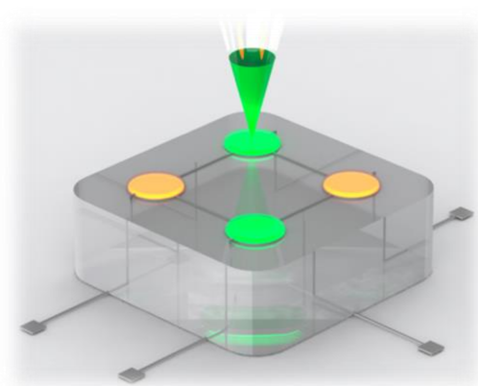
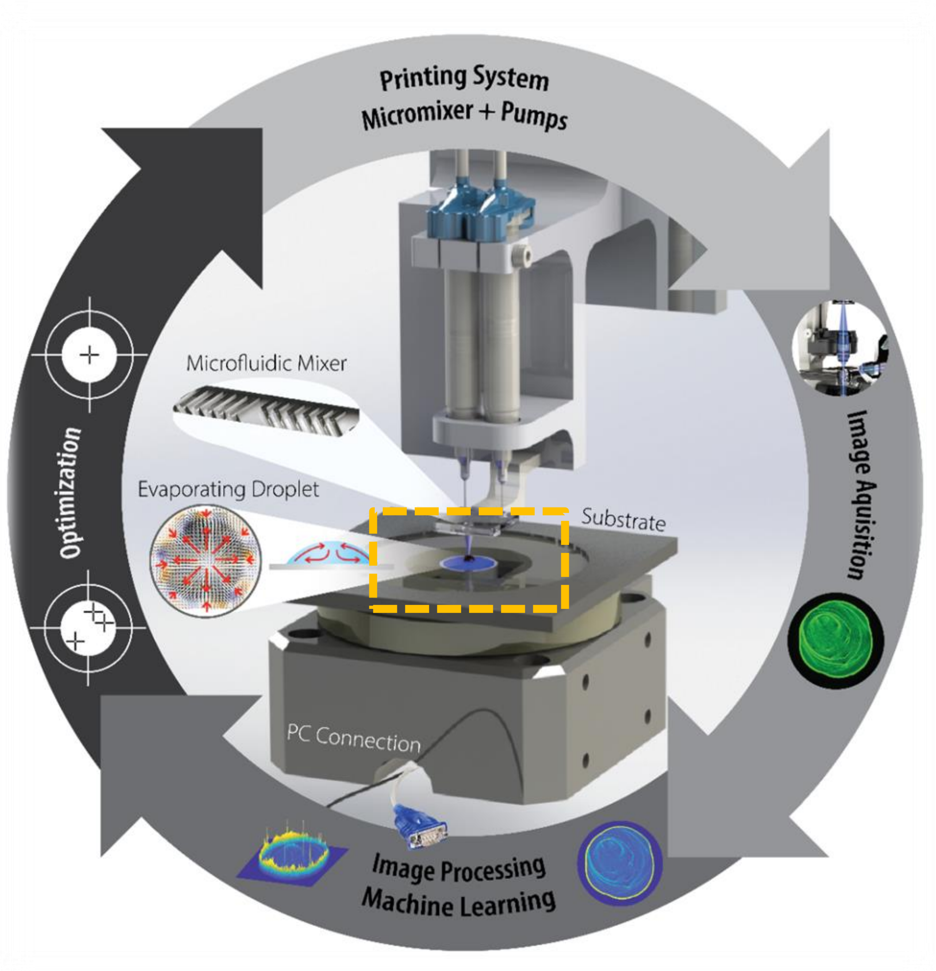
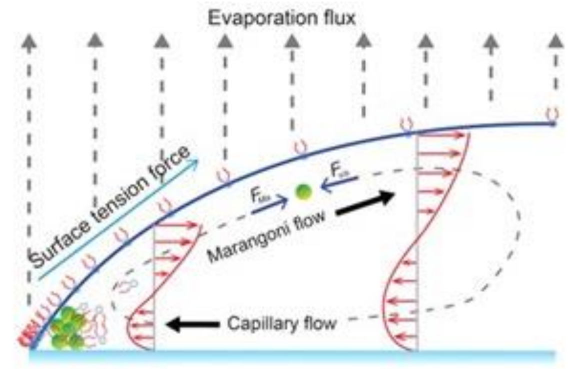


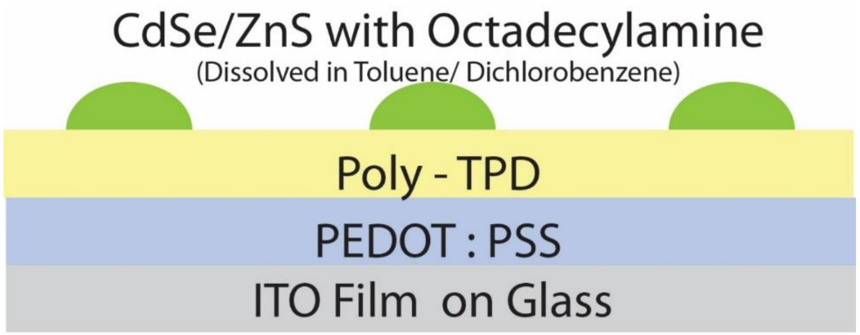
Printing of quantum dots



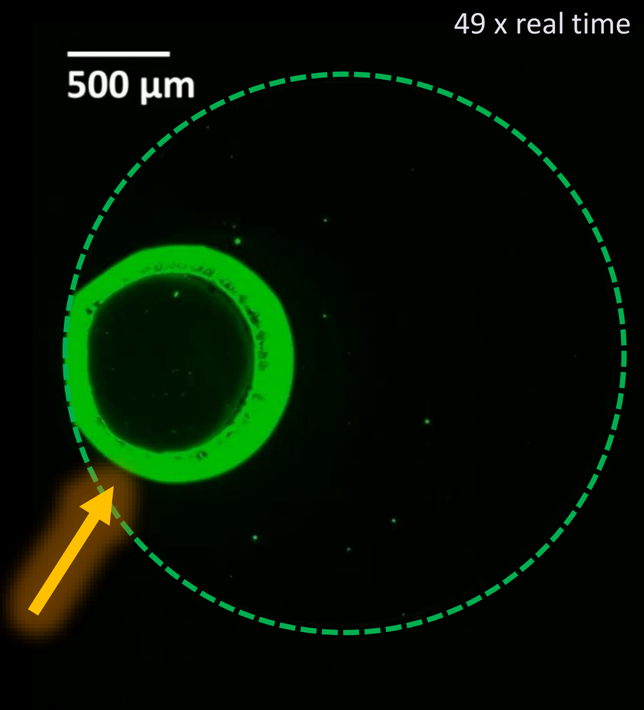
Inverted fluorescence microscope



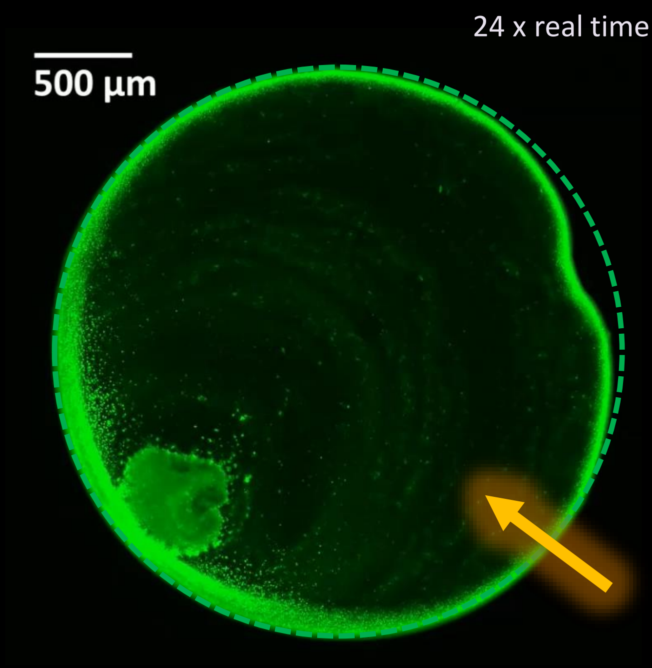
https://rdcu.be/b9tIE



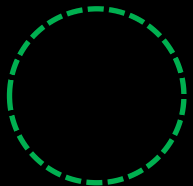
Single solvent and binary solvents



100% Toluene

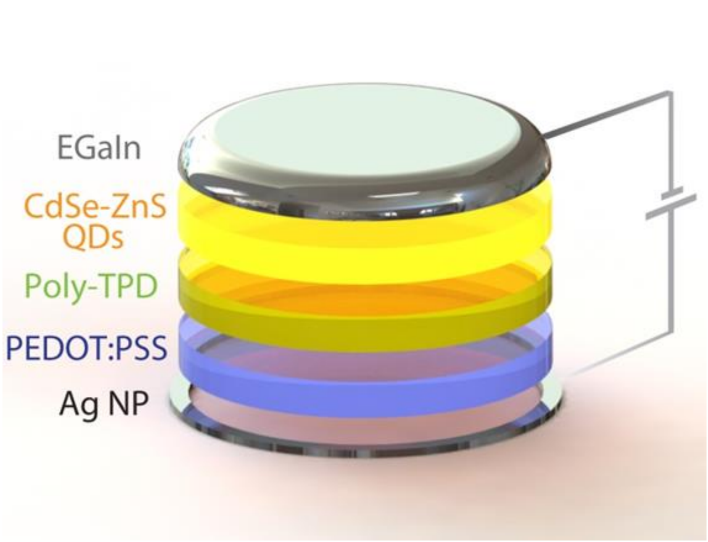


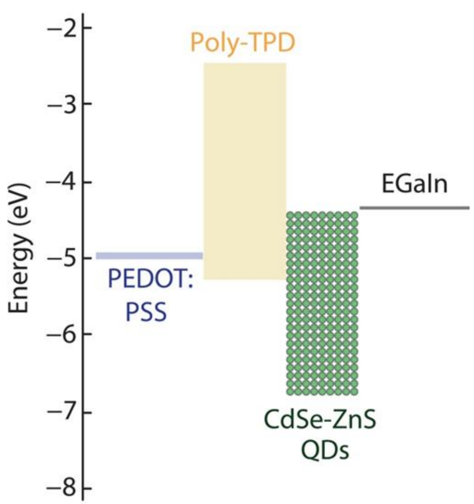
80% Toluene
20% Dichlorobenzene

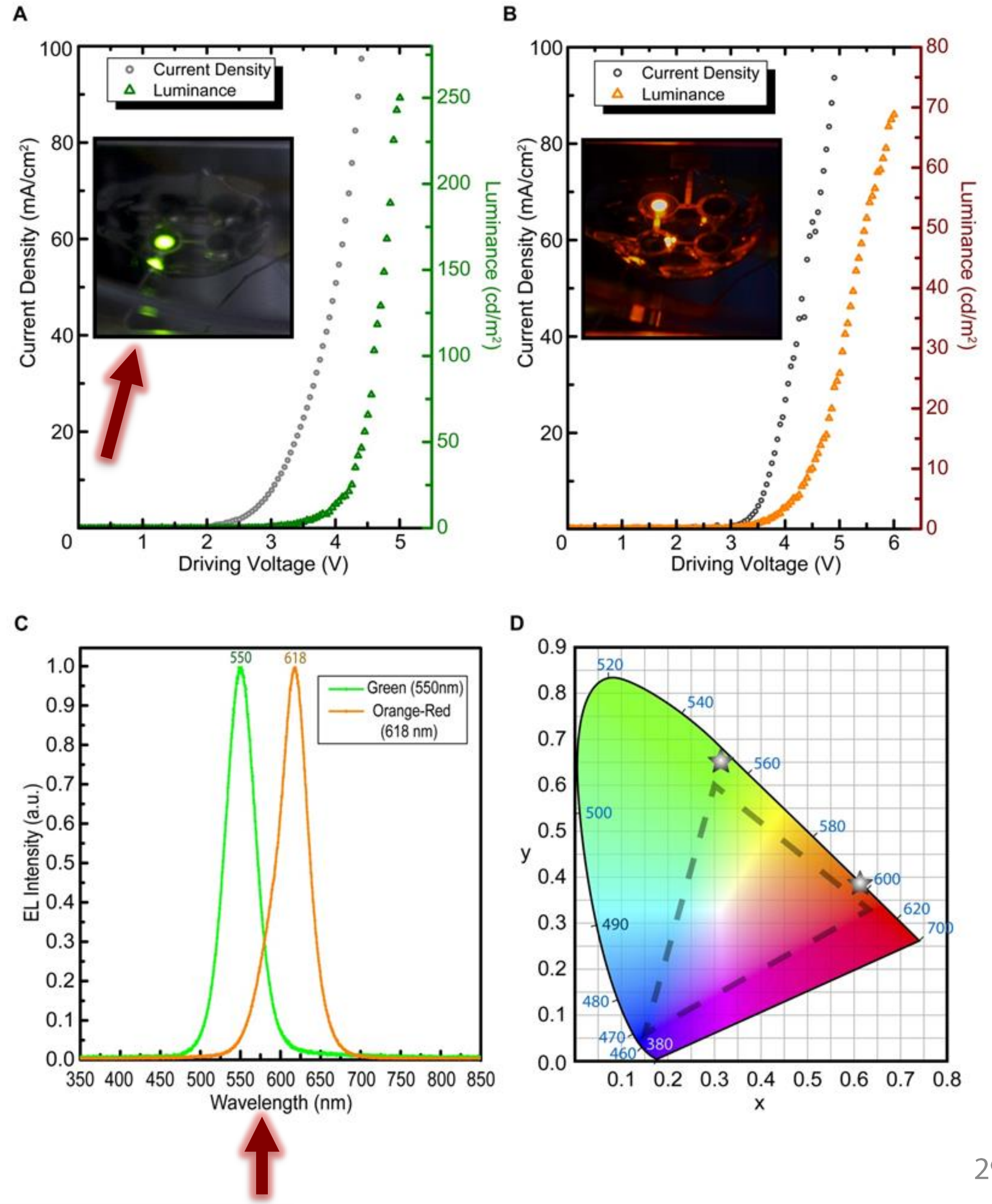


Initial print area

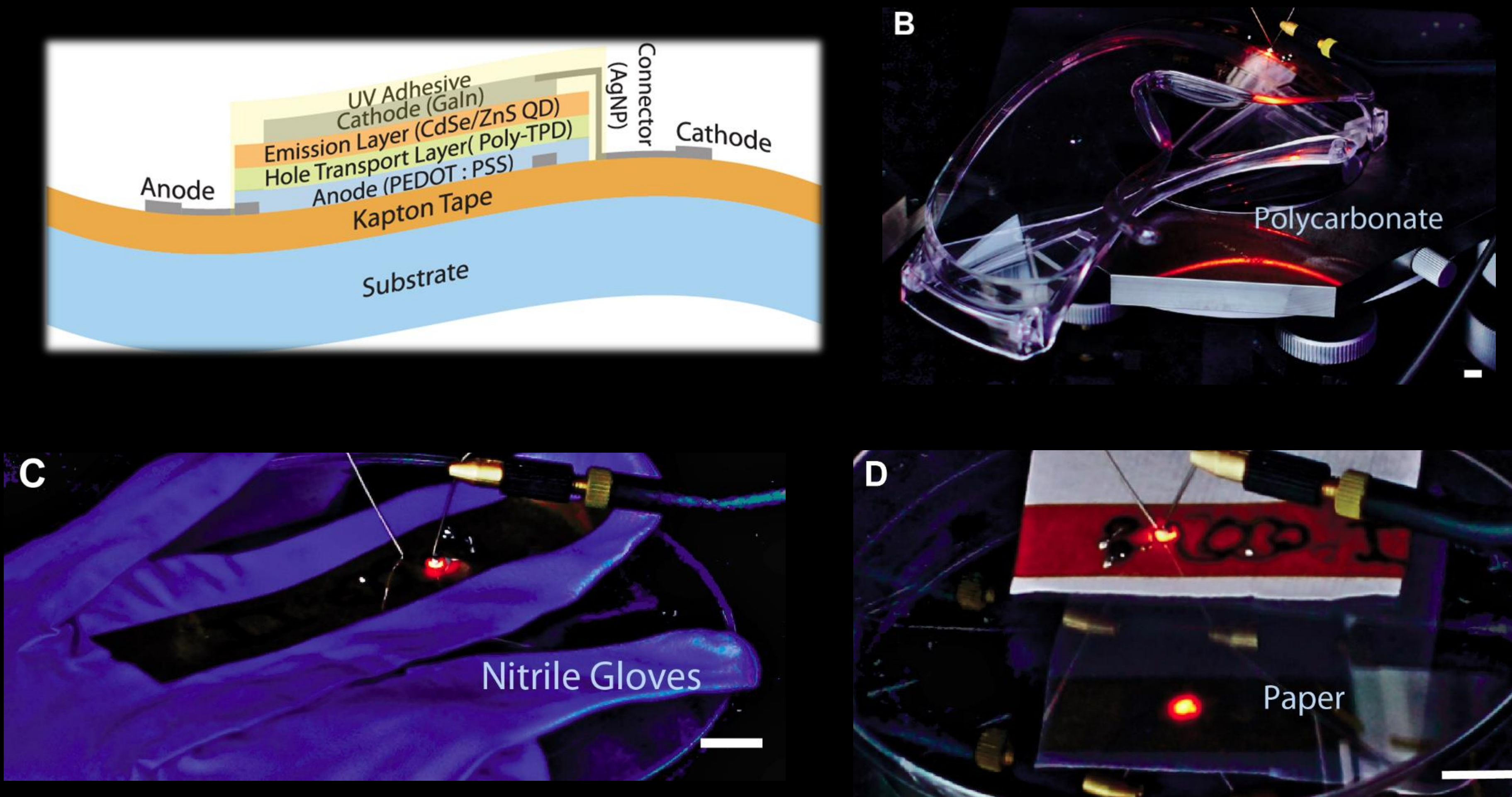
Device design and performances



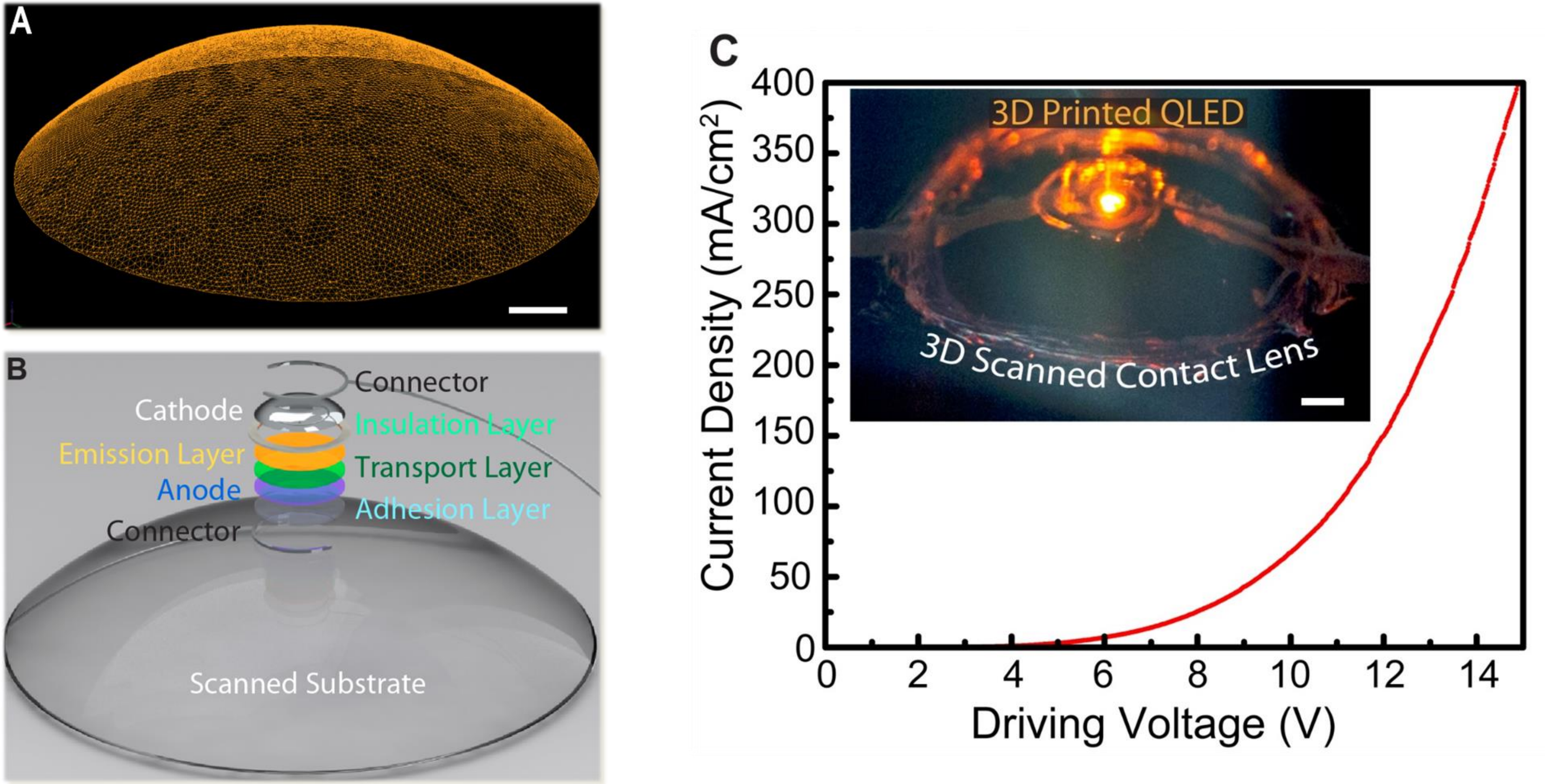




Printing on polyimide substrate

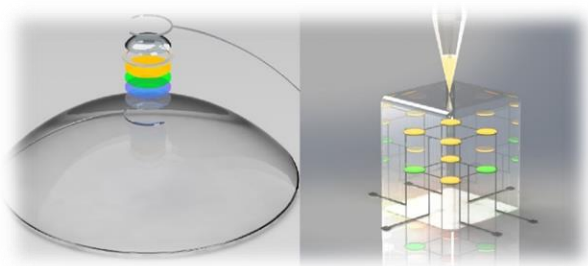


Conformal printing on a contact lens



"3D Printed Active Electronic Materials and Devices." U.S. Patent 9,887,356 (issued February 6, 2018).

3D Printed Quantum Dots LED



Computing

3-D-Printing Bio-Electronic Parts

With new "inks" containing semiconductors, researchers have been able to print LEDs for the first time.

by Katherine Bourzac December 1, 2014

3-D printing allows many things to be custom-made, but its usefulness is limited by the range of compatible materials and the available techniques for fabrication.

A 3-D printer can already make a prototype or spare part out of metal or polymer. Researchers at Princeton University have now taken an important step toward expanding the technology's potential by developing a way to print functioning electronic circuitry out of semiconductors and other materials. They are also refining ways to combine electronics with biocompatible materials and even living tissue, which could pave the way for exotic new implants.

"3-D-Printing Bio-Electronic Parts." *Technology Review, December 2014*

DEVICE FABRICATION

Three-dimensional printed electronics

Can three-dimensional printing enable the mass customization of electronic devices? A study that exploits this method to create light-emitting diodes based on 'quantum dots' provides a step towards this goal.

JENNIFER A. LEWIS & BOK Y. AHN

The ability to rapidly print three-dimensional (3D) electronic devices would enable myriad applications, including displays, solid-state lighting, wearable electronics and biomedical devices with embedded circuitry. Writing in *Nano Letters*, Kong *et al.*[1] report an intriguing route to this goal by creating fully 3D-printed light-emitting diodes (LEDs) based on quantum dots. Quan- nearly three decades ago, 3D-printing methods have been used to build myriad objects, primarily prototypes, in a sequential, layer-by-layer fashion.

To create 3D objects of arbitrary form and specific function, a broad palette of materials and multi-material printing platforms are required. One promising approach is 3D extrusion printing[5], in which functional inks are deposited through fine cylindrical nozzles under an applied pressure at ambient

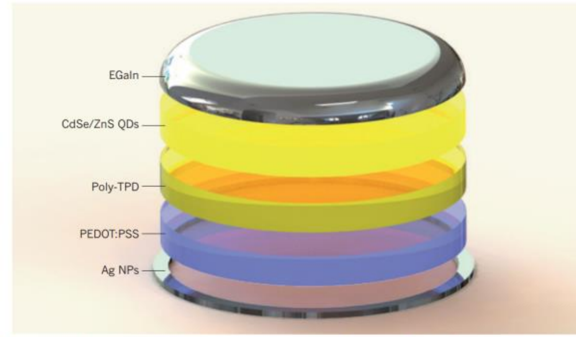


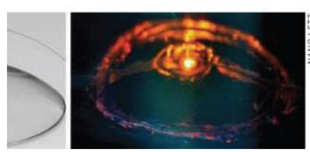
Figure 1 | Fully 3D-printed quantum-dot-based light-emitting diodes (QD-LEDs). The QD-LEDs reported by Kong and colleagues[1] consist of five layers: a conductive ring of silver nanoparticles (Ag NPs) that surrounds a transparent anode layer composed of poly(ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS); a hole-transport layer made of poly[*N,N*′-bis(4-butylphenyl)-*N,N*′-bis(phenyl) benzidine) (poly-TPD); a light-emitting layer composed of cadmium selenide/zinc sulfide quantum dots (CdSe/ZnS QDs); and a cathode layer composed of eutectic gallium indium (EGaIn). The diameter of the printed QD-LEDs is approximately 2 mm. (Figure adapted from ref. 1.)

The printed devices exhibit brightness, an essential metric of device performance, that is 10- to 100-fold below that of the best solution-processed QD-LEDs[3,8]. However, substantial improvements in device performance are must be designed for rapidly and accurately patterning materials over a broad range of compositions and ink-flow behaviour. As these advances are realized, it may be possible to print customized 3D electronic devices in

"Device fabrication: Three-dimensional printed electronics." *Nature* **518**, 42-43 (2015).

EXTENDING THE REACH OF 3-D PRINTING

Researchers led by Michael C. McAlpine of Princeton University have fabricated the first quantum dot light-emitting diodes (LEDs) built using only a three-dimensional printer (*Nano Lett.* 2014, DOI: 10.1021/nl5033292). Most 3-D printers are used to pattern plastics, metallic inks, and some biological materials, McAlpine says, but not fully printed semiconductor devices. To print an entire LED, the Princeton researchers had to make careful materials decisions. They created a suspension of CdSe-ZnS core-shell quantum dots using a mixture of toluene and dichlorobenzene as the solvent. Their formulation allowed the dots to settle more uniformly as the ink dried, instead of pinning the nanostructures near droplet



NANO LETT.

"Extending the reach of 3-D Printing", C&EN News

MATERIALS

Diodes printed in three dimensions

Researchers have created a light-emitting diode (LED) by three-dimensional (3D) printing of five different materials — expanding the number and type of material

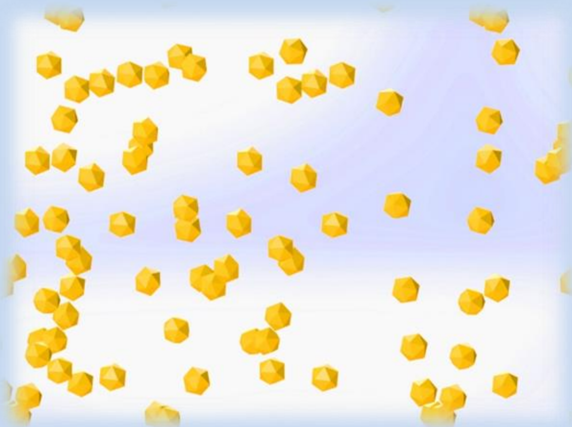
"Materials: Diodes printed in three dimensions." *Nature* **515**, 468 (2014).

Y. L. Kong, I. A. Tamargo, H. Kim, B. N. Johnson, M. K. Gupta, T.-W. Koh, H.-A. Chin, D. A. Steingart, B. P. Rand, M. C. McAlpine. "3D Printed Quantum Dot Light-Emitting Diodes." *Nano Lett.* **14**, 7017-7023 (2014).

- Featured: "Materials: Diodes printed in three dimensions." *Nature* **515**, 468 (2014).
- Highlighted: "Device fabrication: Three-dimensional printed electronics." *Nature* **518**, 42-43 (2015).

Nanomaterials as Functional Building Blocks for a Device

Nanoscale Inks



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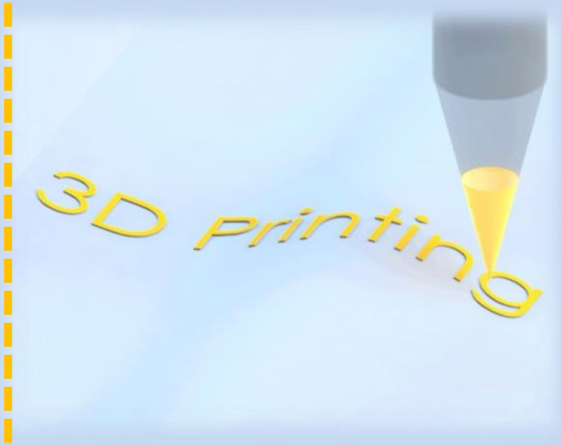
Microscale Patterning



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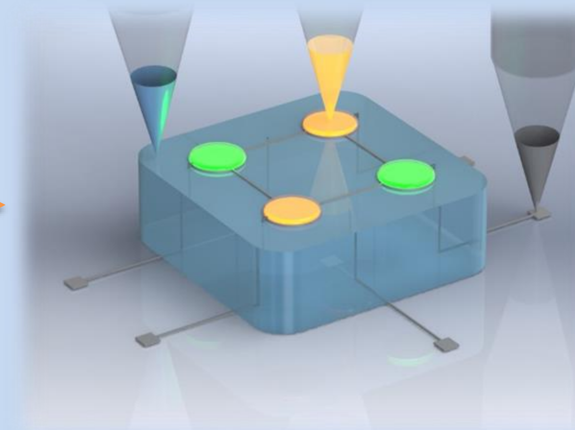
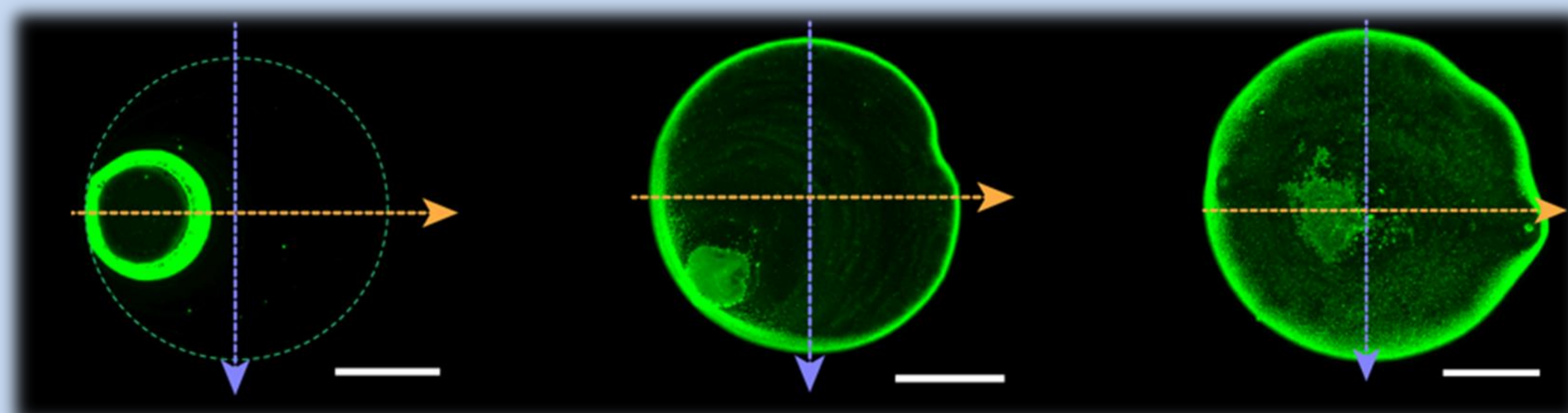
Macroscale Device Fabrication

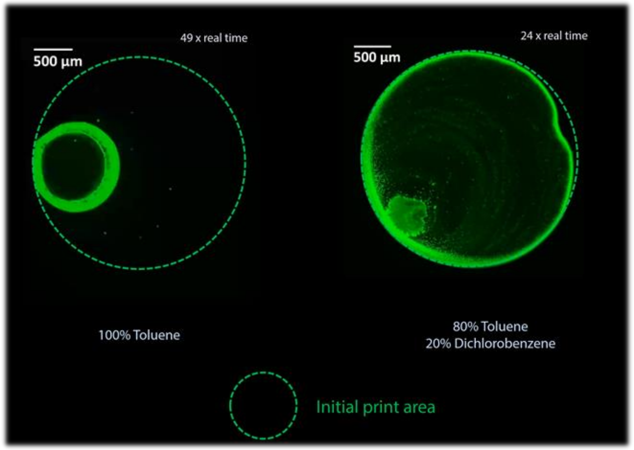


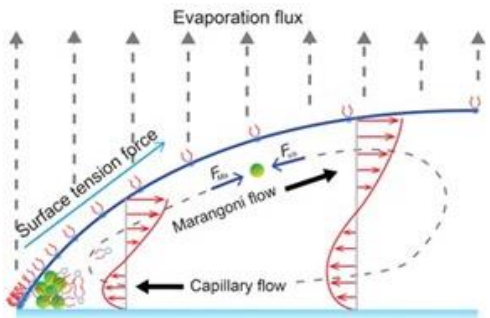
Functional nanomaterials can be dispersed in solvents to form solution-processable **inks**, which can be integrated into coating or **printing** processes to create functional **devices**.



Y. L. Kong*, M. K. Gupta, B. N. Johnson, and M. C. McAlpine*. "3D printed bionic nanodevices." *Nano Today* 11, no. 3 (2016): 330-350.

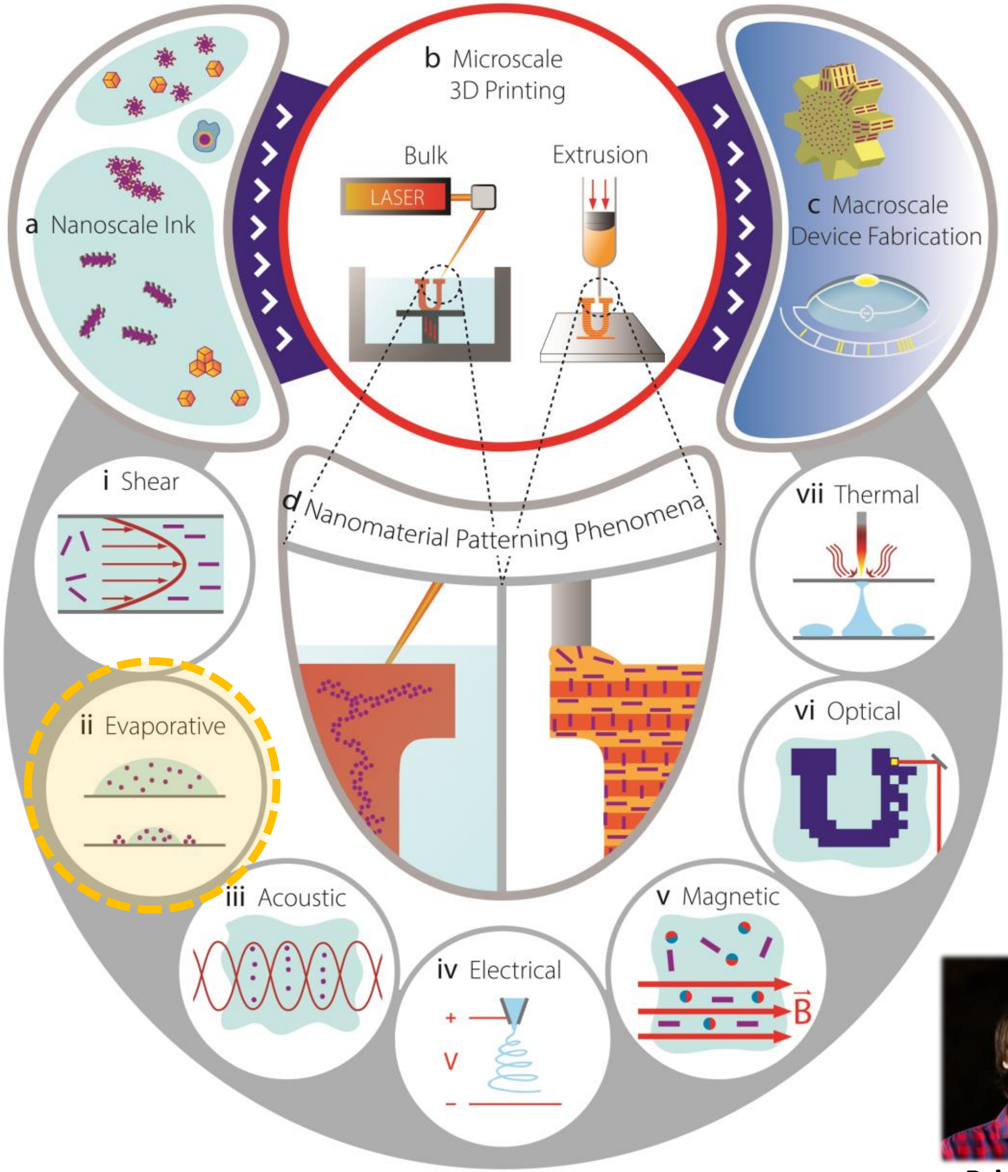
Review paper: *"Nanomaterial Patterning in 3D Printing"*





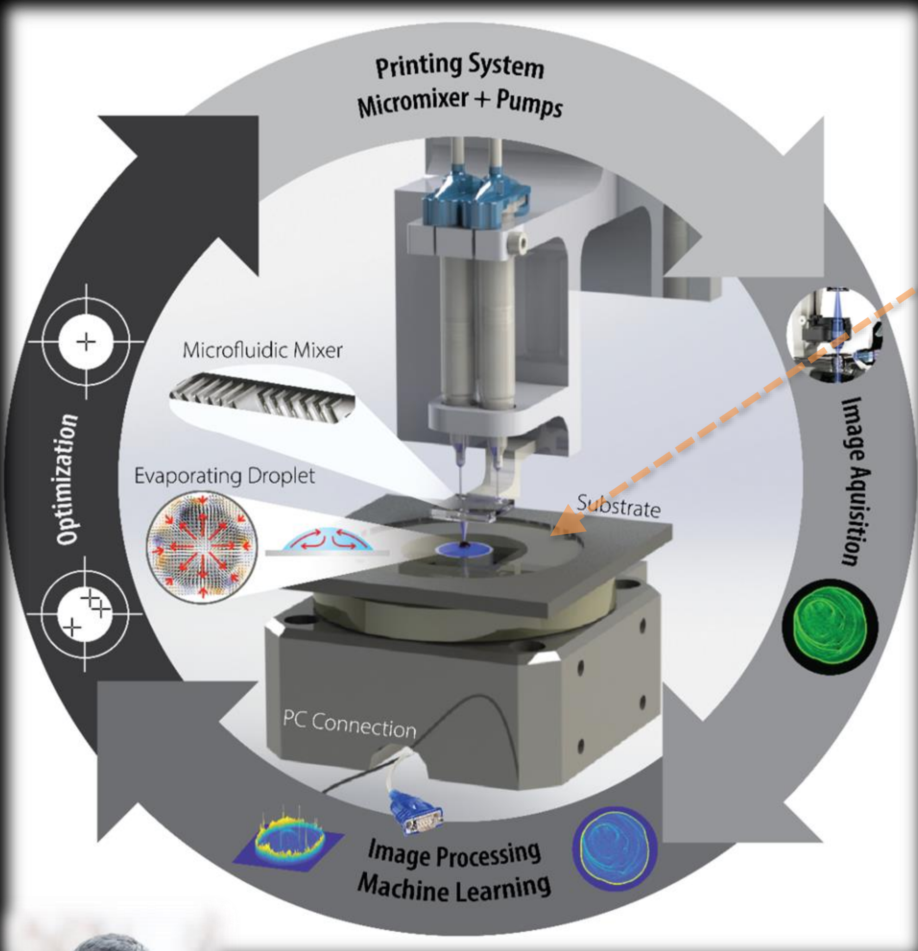
https://rdcu.be/b9tIE

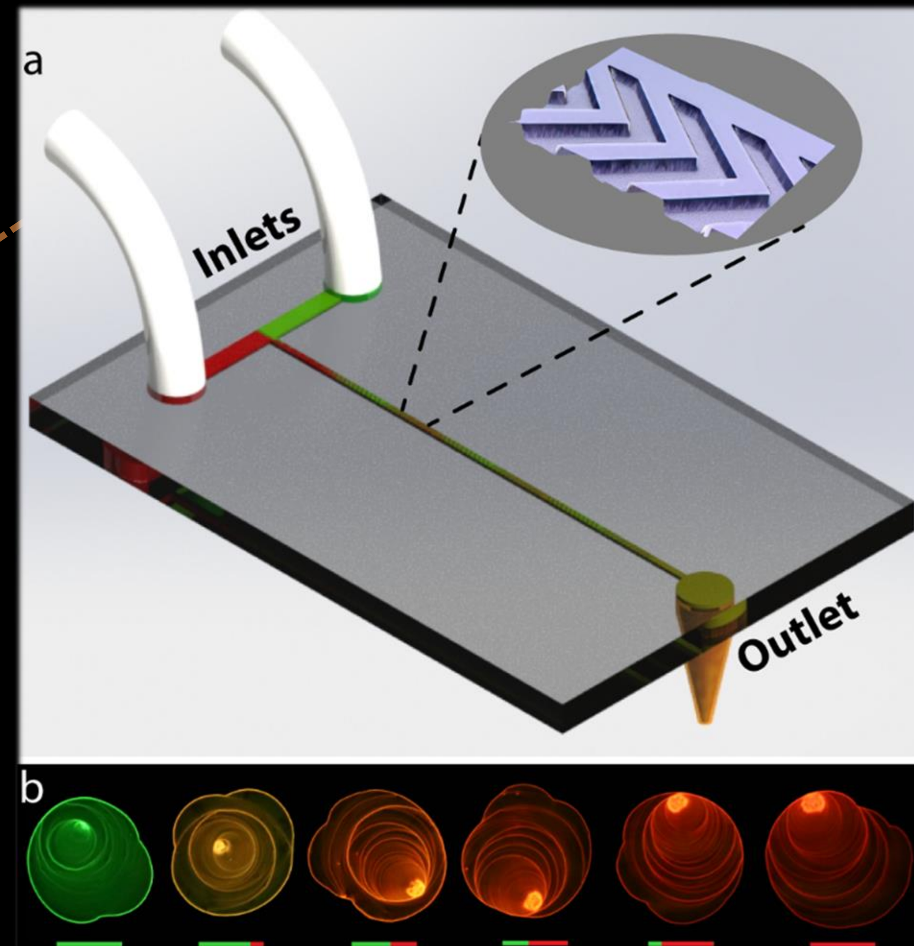
B. Elder, R. Neupane, E. Tokita, U. Ghosh, S. Hales, **Y. L. Kong***. *Advanced Materials* 1907142 (2020).



Brian Elder

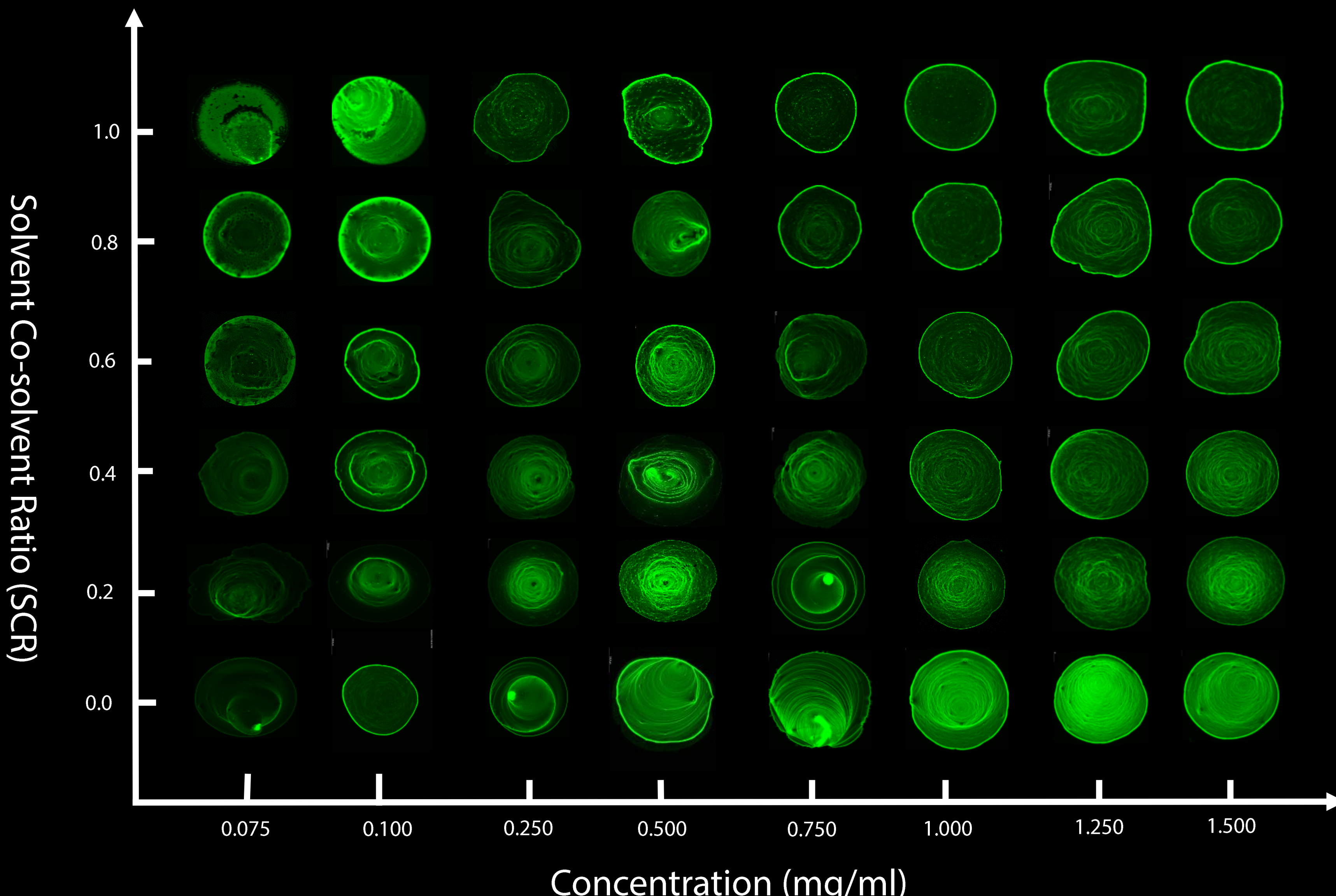
Automated mixing printing system



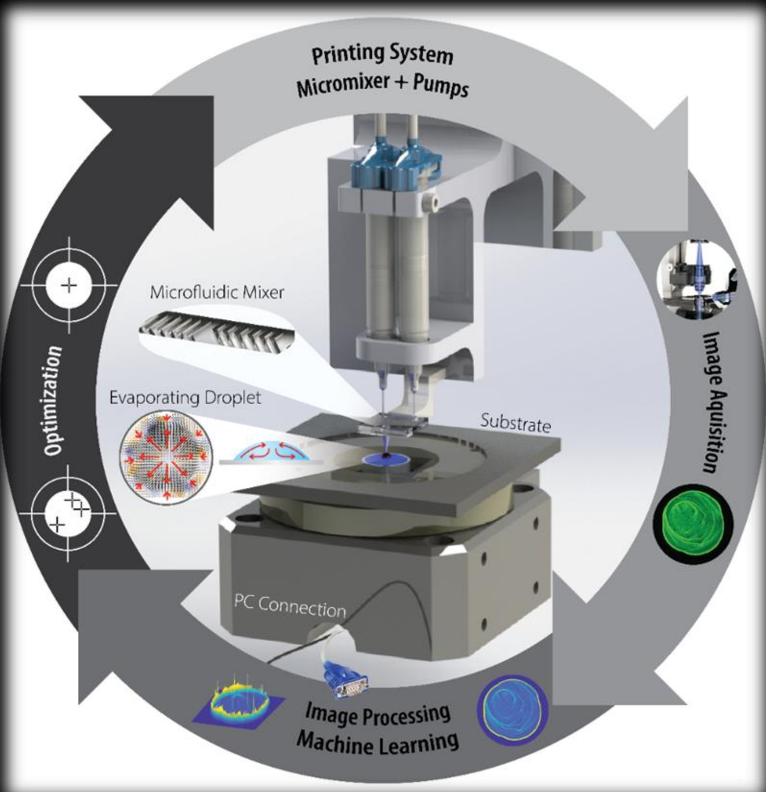


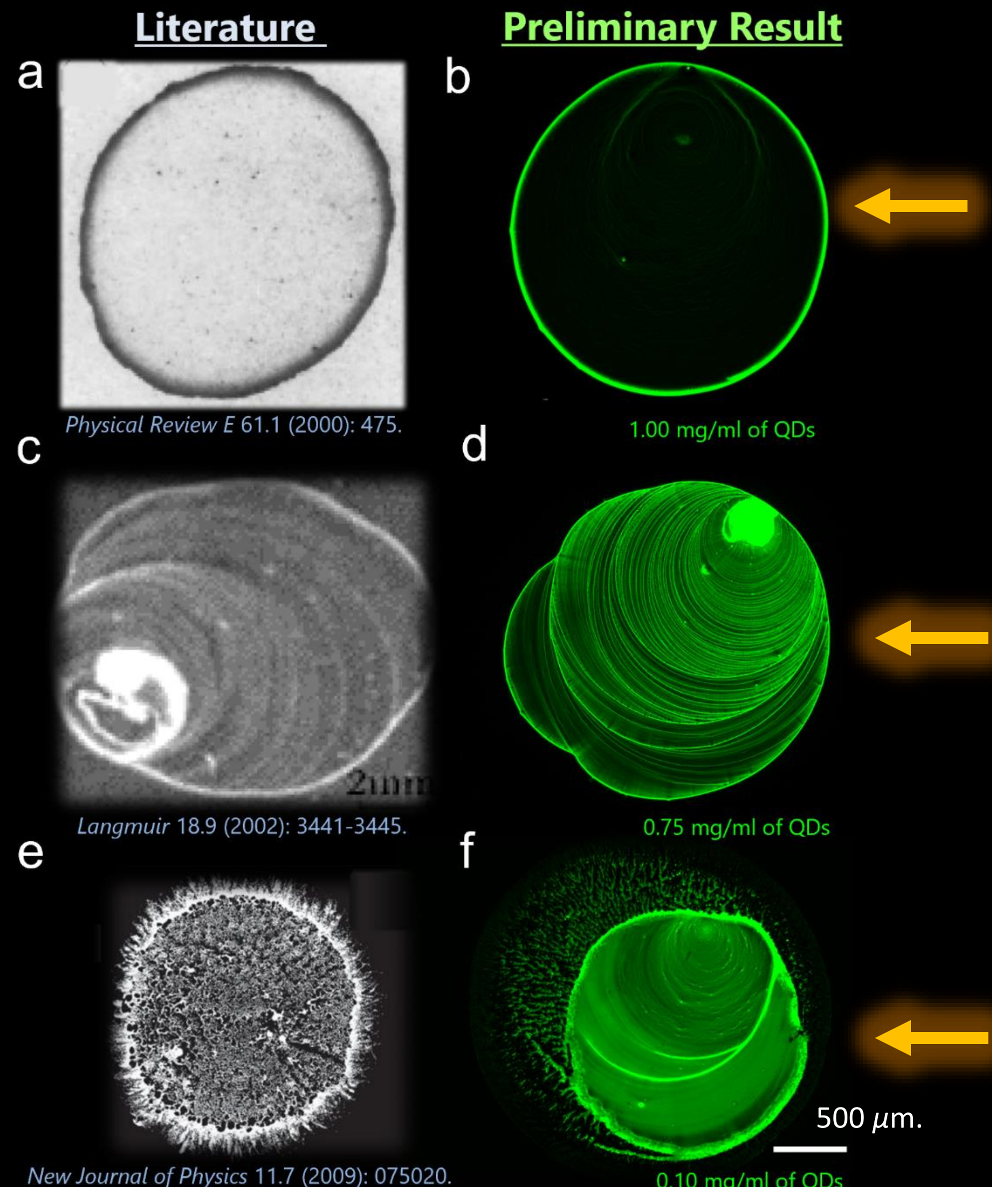
Samannoy Ghosh

Evaporative driven printing is a highly sensitive process

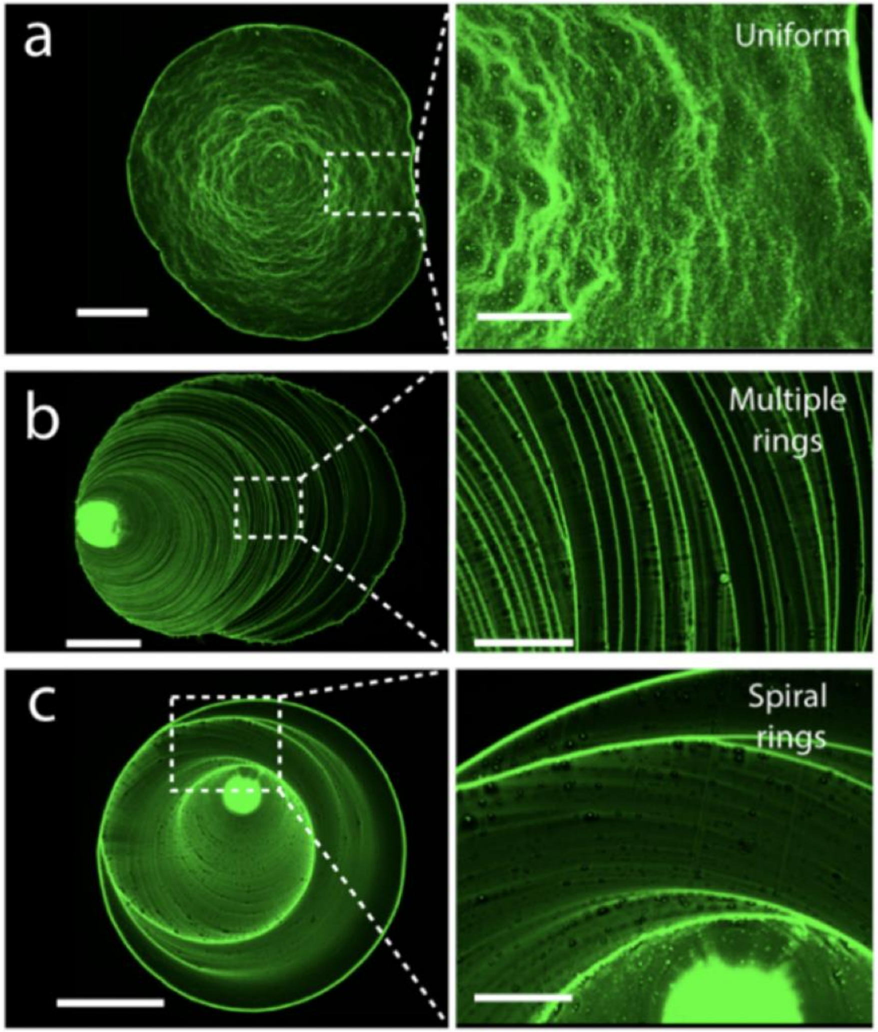


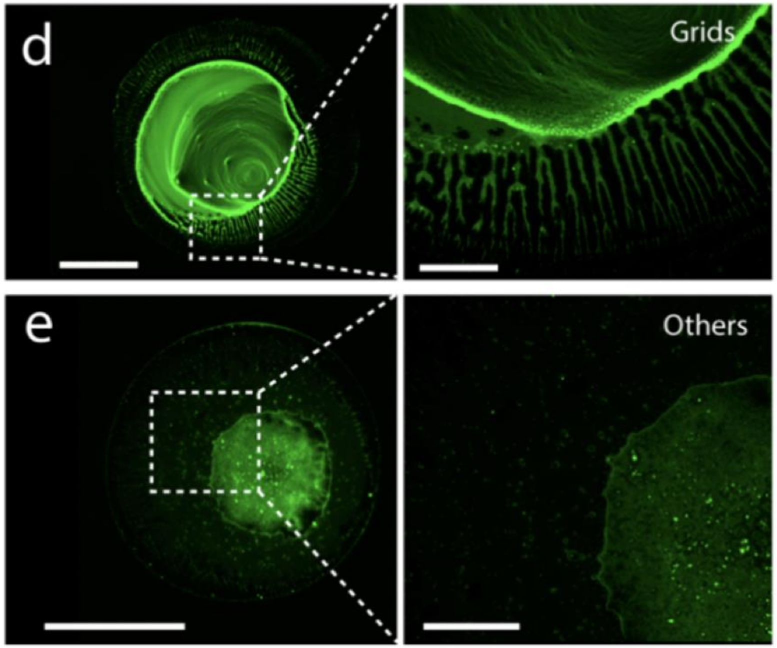
Evaporative driven printing is a highly sensitive process





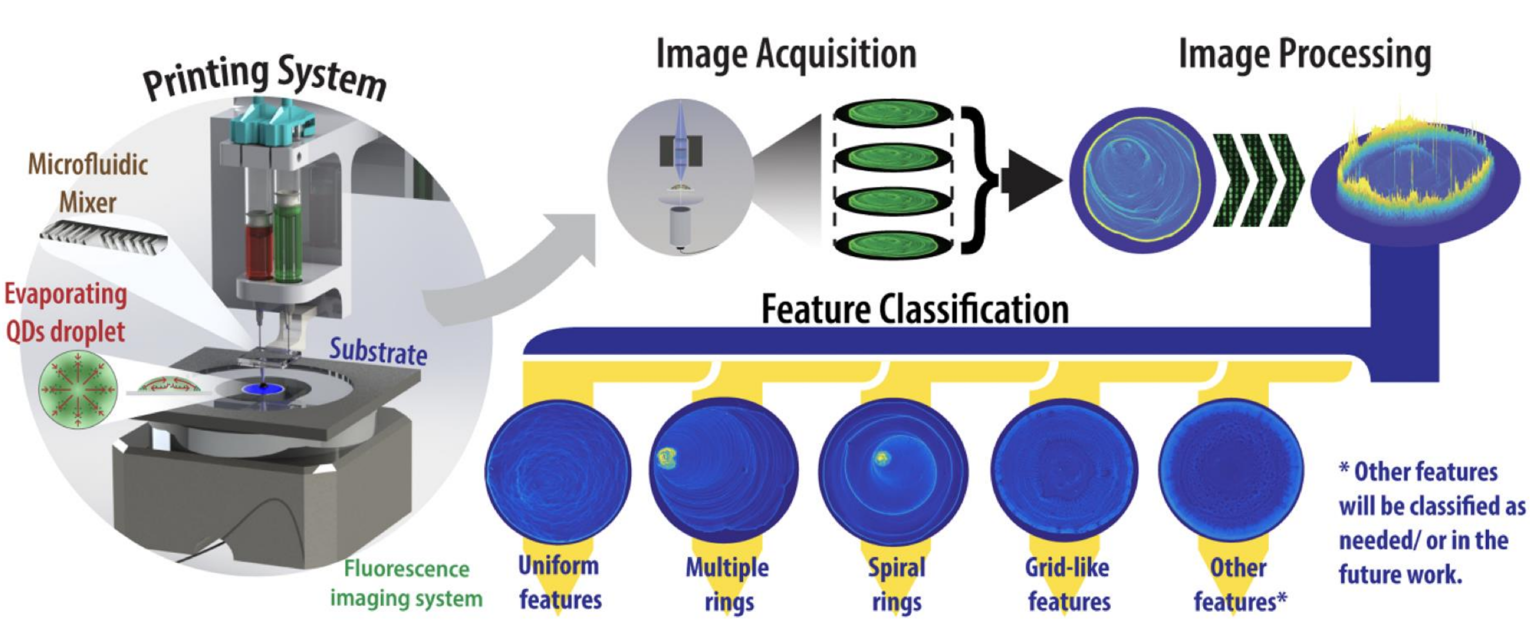
Features from evaporative driven assembly

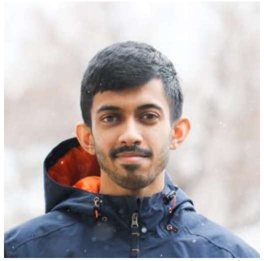




Machine Learning-enabled Feature Classification of Evaporation-driven Multi-scale 3D Printing
S. Ghosh, M. V. Johnson, R. Neupane, J. Hardin, J. D. Berrigan, S. R. Kalidindi, **Y. L. Kong***.
Flexible and Printed Electronics **7**, 014011 (2022).ç

Machine learning-enabled feature classification




Samannoy Ghosh


Marshall Johnson

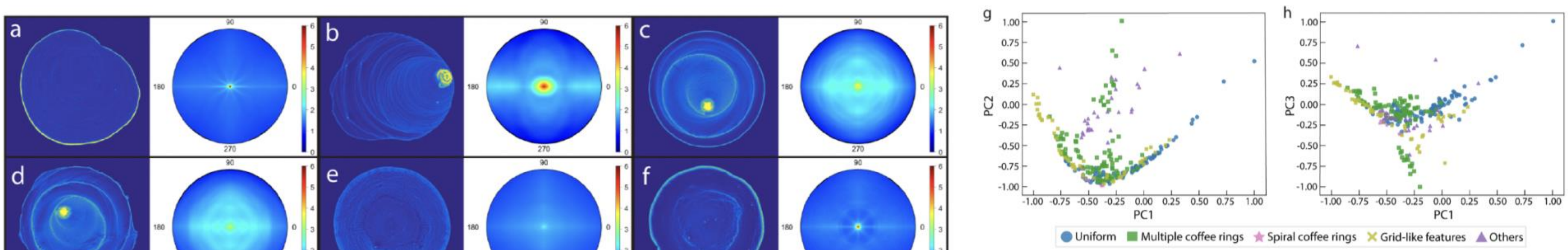


Figure 6. Example deposition density plots and corresponding rotationally invariant feature maps for the different classes of printed drops studied in this work: (a) uniform, (b) multiple coffee rings, (c–d) spiral coffee rings, (e) grid-like features, and (f) others. (g–h) Selected principal component (PC) projections of the rotationally invariant autocorrelations of the normalized deposition rate maps for all samples included in this study.

Machine Learning-enabled Feature Classification of Evaporation-driven Multi-scale 3D Printing
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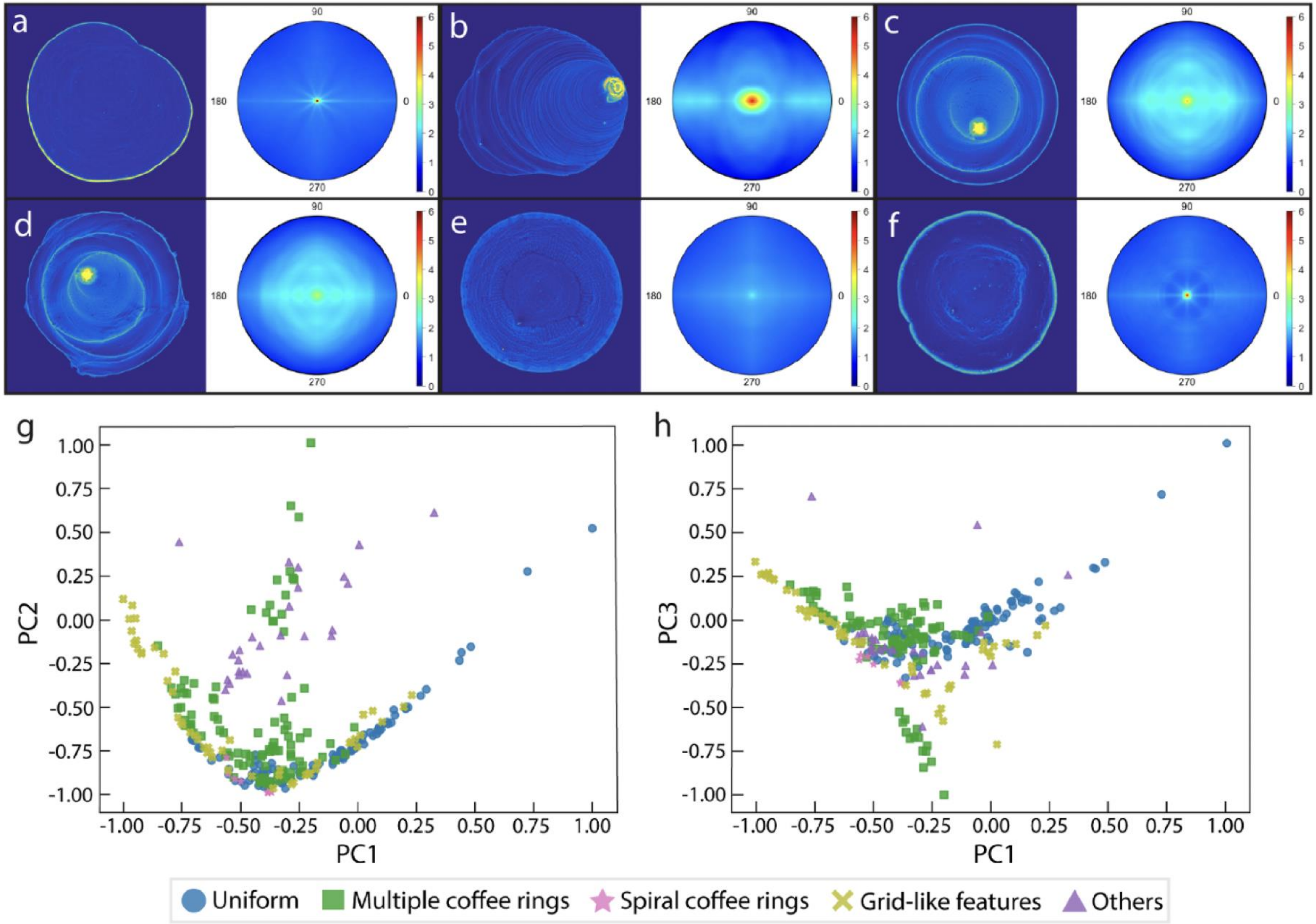

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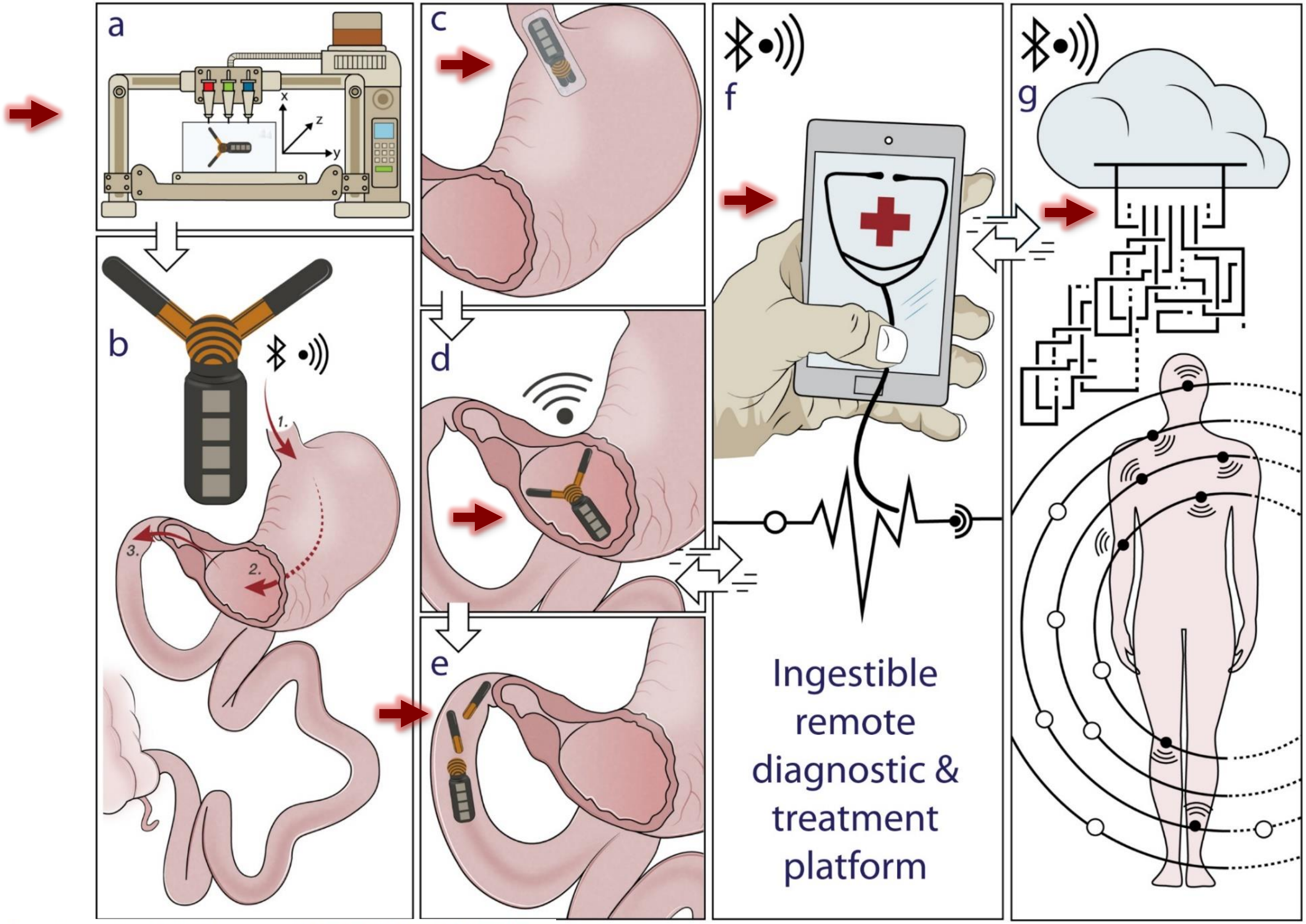
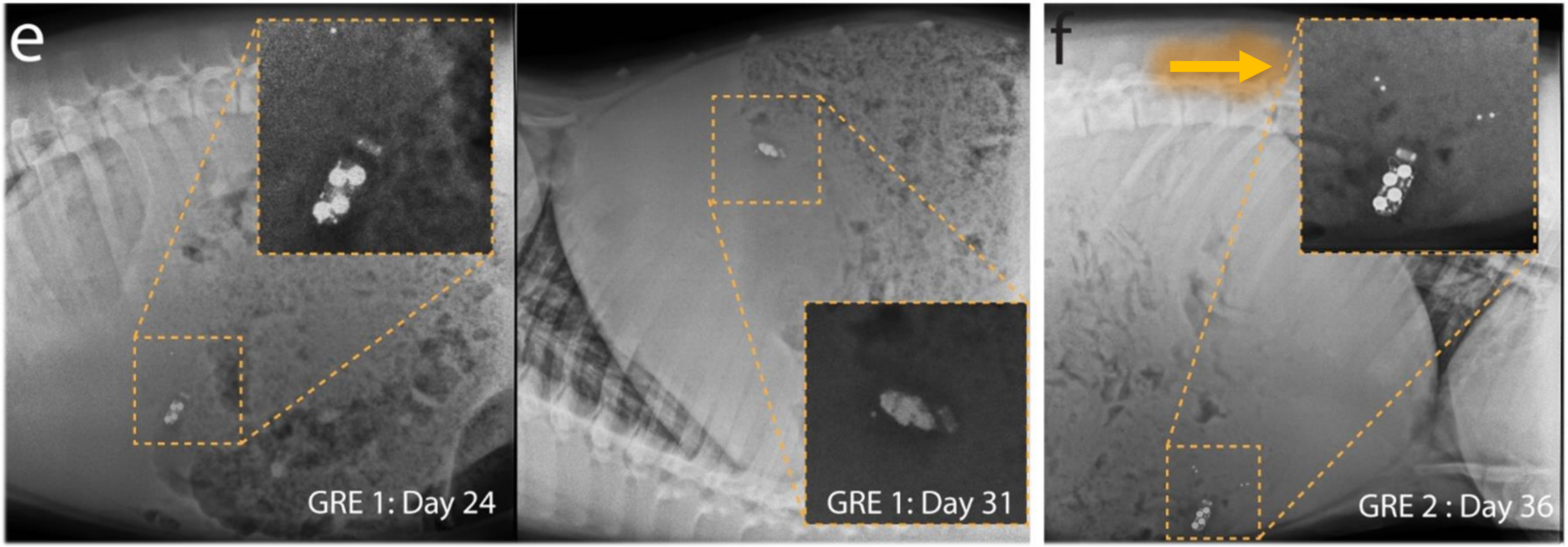
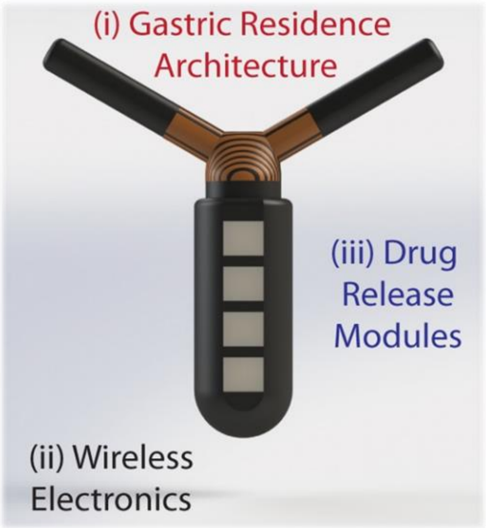
Overview of Gastric Resident Electronics

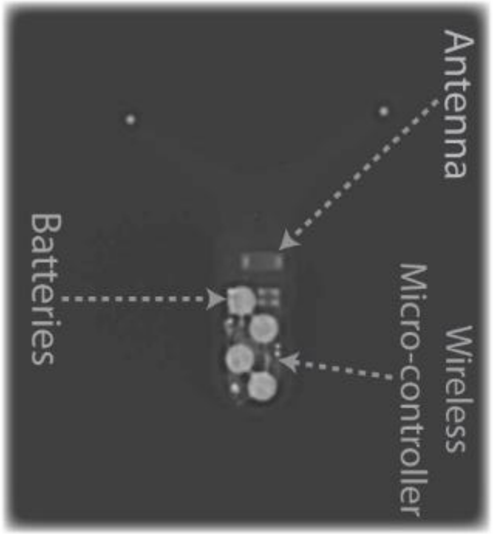


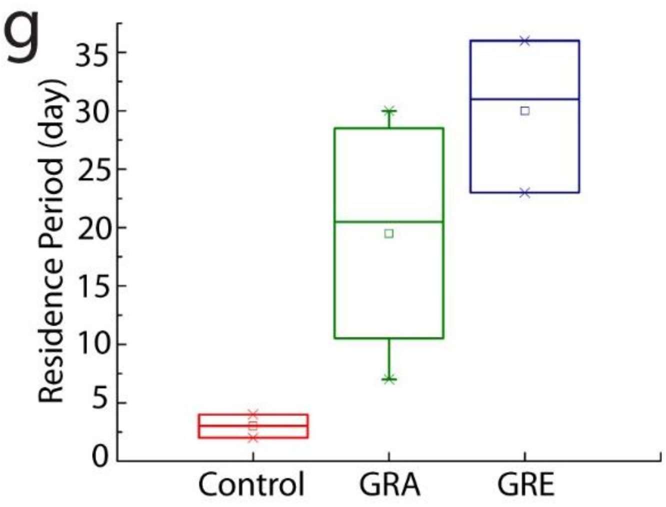
"3D Printed Gastric Resident Electronics." *Advanced Materials Technologies*, 1800490 (2018).

Gastric Resident Electronics



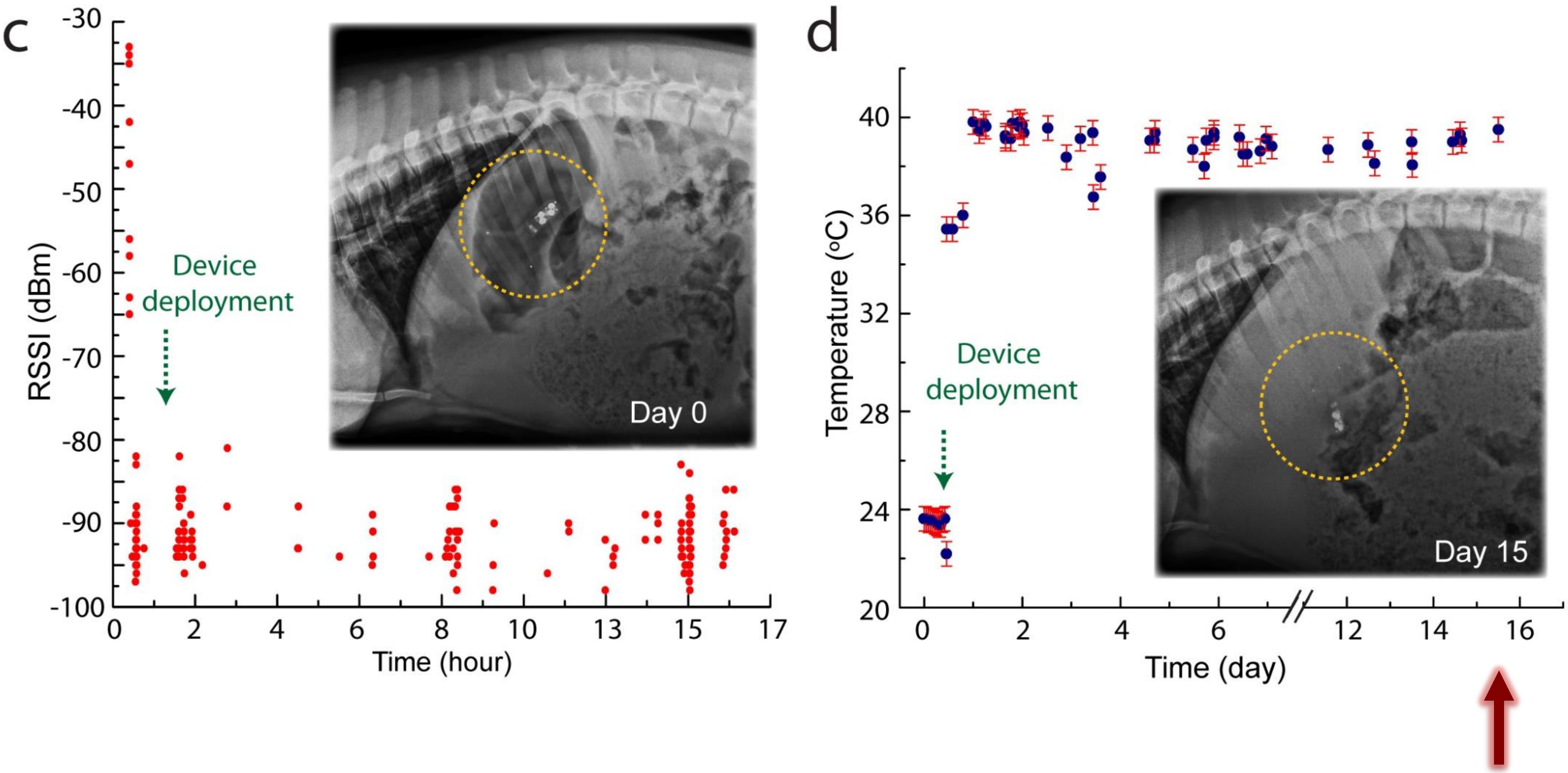






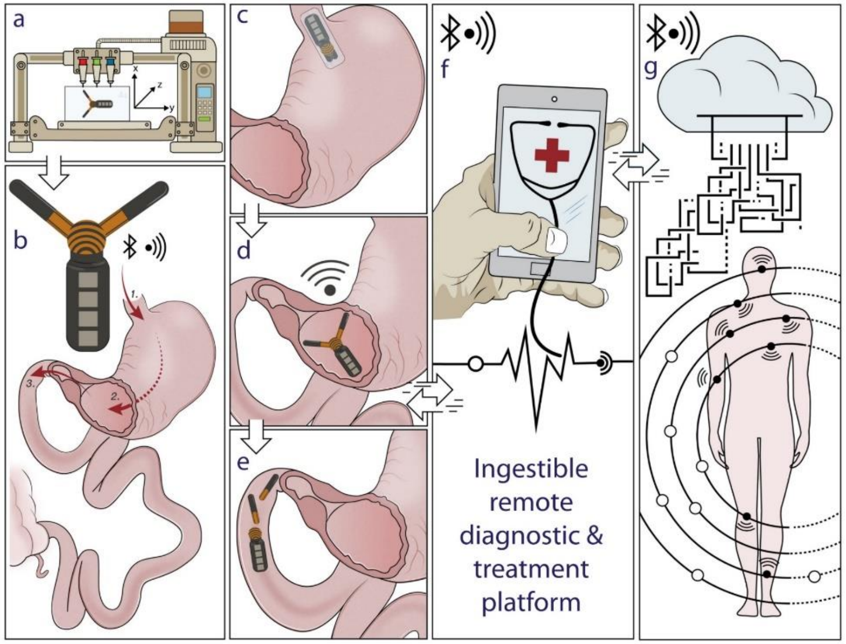
"3D Printed Gastric Resident Electronics." *Advanced Materials Technologies*, 1800490 (2018).

In vivo electronics study



"3D Printed Gastric Resident Electronics." *Advanced Materials Technologies* , 1800490 (2018).

Multi-materials 3D printing of ingestible gastric resident electronics



We are developing wireless ingestible biomedical electronics platform as the next generation remote monitoring, diagnosis and treatment platform. The surgical-free biomedical electronics integration with the human body can revolutionize telemedicine by enabling a real-time diagnosis and delivery of therapeutic agents. Towards this aim, we create functional materials, design unique architectures and develop a hybrid fabrication approach to enable the creation of highly-functional and safe ingestible biomedical electronics.

1. **"3D Printed Gastric Resident Electronics."** *Advanced Materials Technologies* , 1800490 (2018).
2. **"Prolonged Energy Harvesting for Ingestible Devices."** *Nature Biomedical Engineering* **1**, 0022 (2017).
   1. Featured in "**Bioelectronic devices: Gut-powered ingestible biosensors."** *Nature Biomedical Engineering* **1**, 0050 (2017).
3. **"Ingestible Power Harvesting Device, and Related Applications."** *U.S. Patent Application 15/498,268.*

Y. L. Kong* *Journal of the Homeland Defense & Security Information Analysis Center (HDIAC)*, **6**, 34 - 38 (2019)

NSF EFRI C3 SoRo: Magneto-electroactive Soft, Continuum, Compliant, Configurable (MESo-C3) Robots for Medical Applications Across Scales, $2,015,910, 4 years

Jake J. Abbott (PI),
Yong Lin Kong (Co-PI),
Kam K. Leang (Co-PI),
University of Utah

On Shun Pak (Co-PI)
Santa Clara University

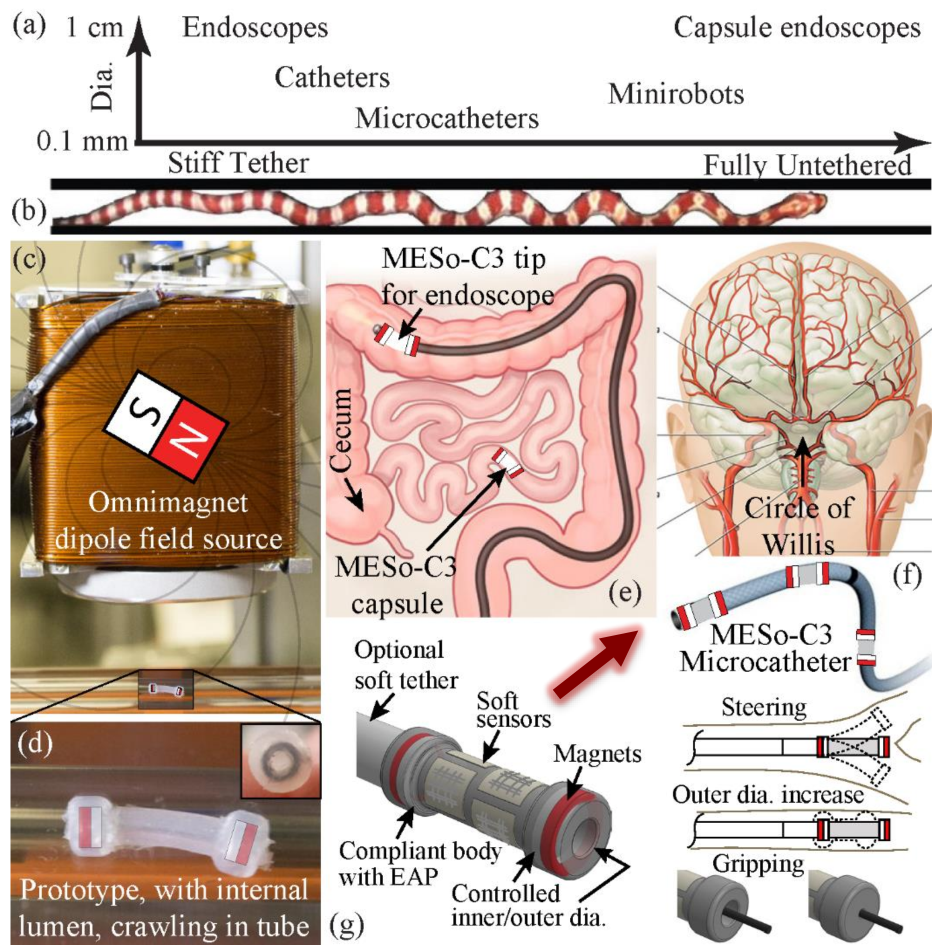
Rajesh Rajamani (Co-PI)
University of Minnesota

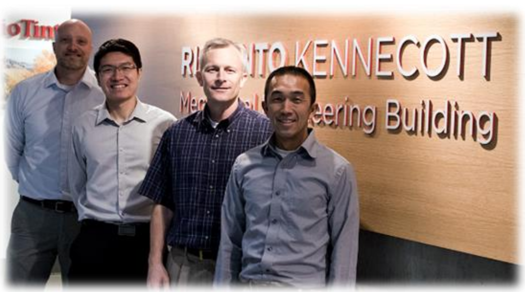
The **vision** is to enable minimally invasive access to locations in the human body that are currently difficult or impossible to reach, using a new class of magneto-electroactive soft, continuum, compliant, and configurable (MESo-C3) mesoscale robotic devices that will travel along the natural pathways of the human body for a wide range of diagnostic and therapeutic applications.

Our **goal** is to understand the kinematics, dynamics, sensing, control, and fabrication of MESo-C3, which will enable bio-inspired propulsion reminiscent of concertina locomotion of a snake in a tube, with a simplicity that enables application across scales.

MESo-C3 will explore four integrated thrusts:

1. compliant cylindrical structures with wireless high-bandwidth propulsion using rotating magnetic dipole fields,
2. low-bandwidth large-deformation electroactive polymer (EAP) actuators for morphology control,
3. ultra-sensitive soft super-capacitance-based strain, force, and moduli-of-elasticity sensors,
4. additive manufacturing techniques to fabricate integrated robots across scales.

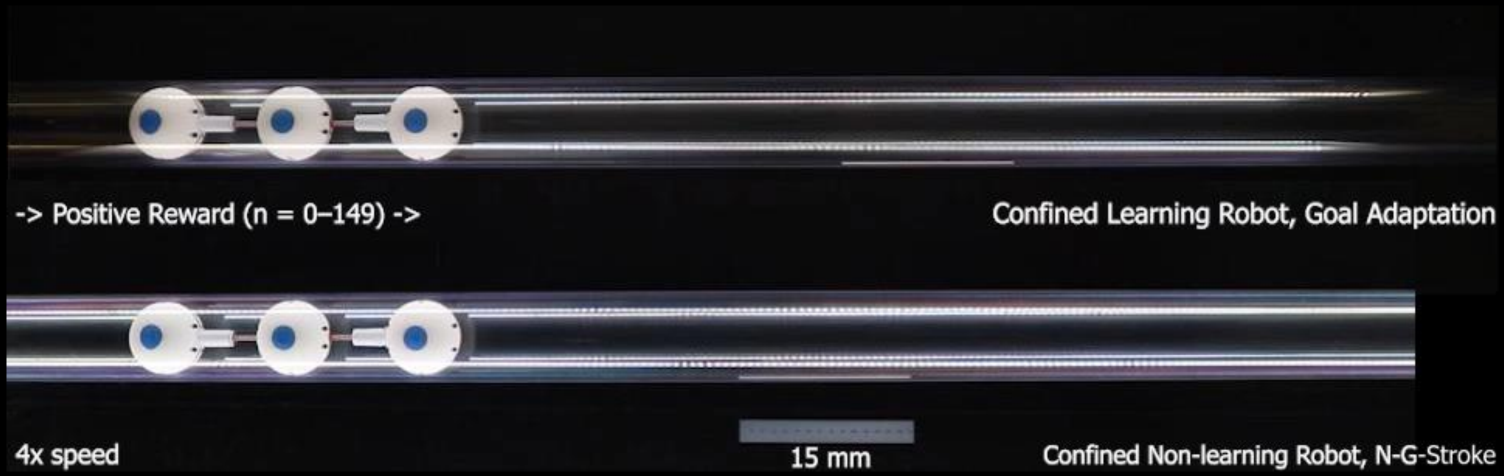




Prof. On Shun Pak

Prof. Rajesh Rajamani

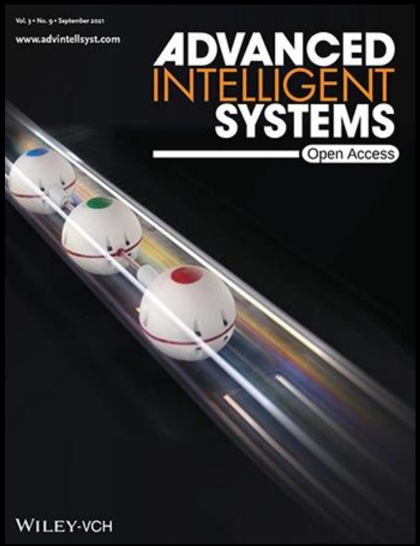
Adaptive gait in a complex & dynamic confined system

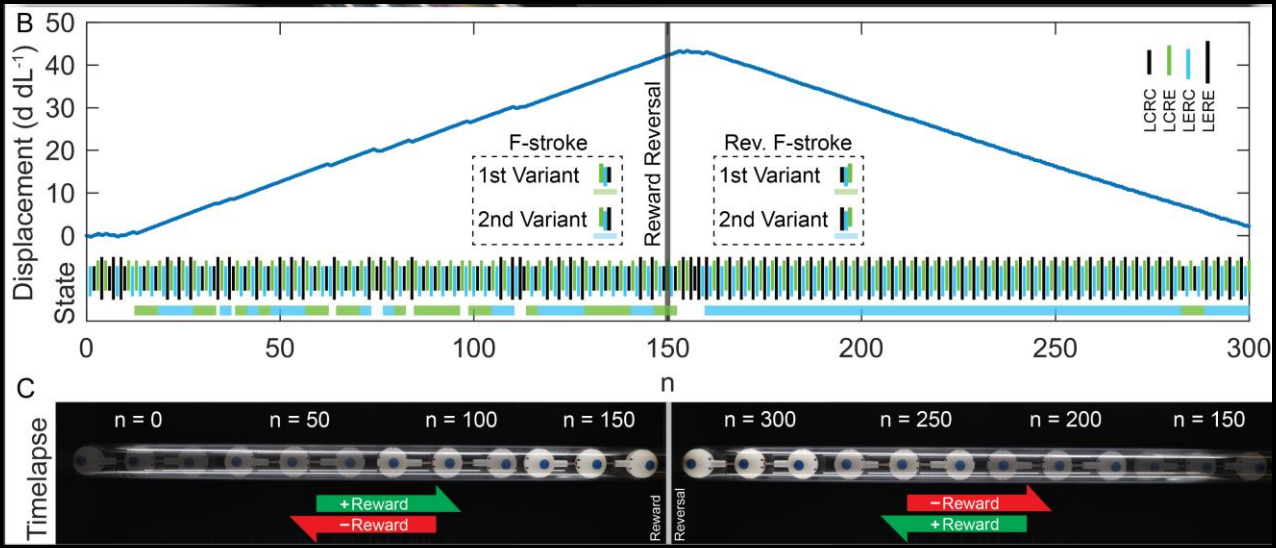


Brian Elder

In collaboration with Prof. **On Shun Pak**, Santa Clara University

20x speed



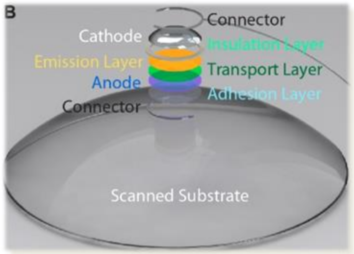


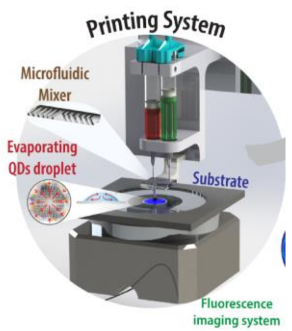
Elder, B. Zonghao, Z., Ghosh, S., Silverberg, O., Greenwood, T., Demir, E., Su, V.S-E., Pak, O.S., & **Kong, Y.L.***, *A 3D printed self-learning three-linked sphere robot for autonomous confined space navigation.* Advanced Intelligent Systems 2170064 (2021).

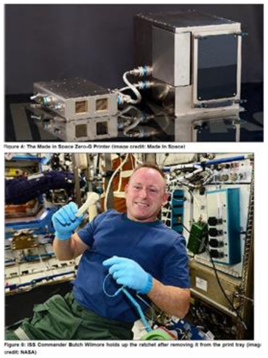
Advantages of entirely 3D printed electronics

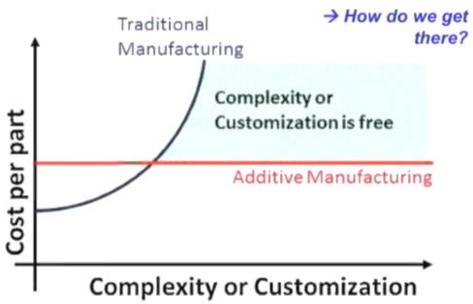
3D printing (**3DP**) can complement conventional electronics manufacturing (**CM**) in several aspects:

1. **3D integration:**
   - CM: *fundamentally limited by its planarity and rigidity constraint.*
   - 3DP: seamlessly integrate with a broad range of three-dimensional constructs to impart active functionalities.
2. **Remote fabrication:**
   - *CM: relies on complex equipment and facilities.*
   - 3DP: immune to supply chain disruption or constraints (e.g., chip shortage); or availability in austere, remote environments and future space missions.
3. **Economy of customization:**
   - *CM: mass production of identical devices to achieve economy of scale.*
   - 3DP: the cost per part of 3D printed electronics remains relatively constant with the increase of customization. Providing an economically feasible approach to:
     - optimize device properties for a target application.
     - Introducing variations – e.g. ,cyber security (unclonable)
4. **Sustainable manufacturing:**
   - *CM: mass production – wasteful approach – pollution.*
   - 3DP: reduce waste of materials, cost of inventory, minimize electronics waste & pollution.

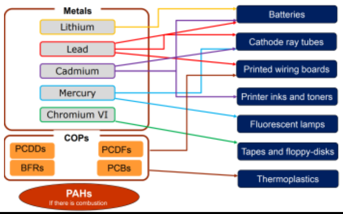








Conner et al. *Additive Manufacturing*, 2014



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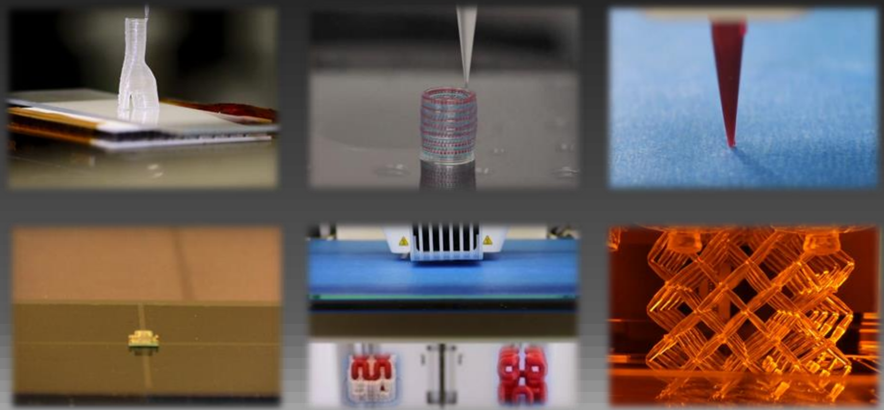

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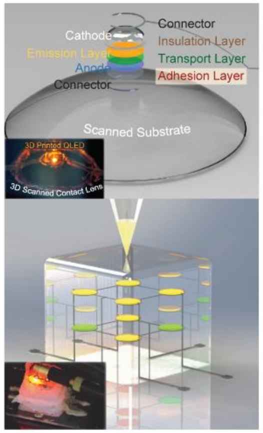
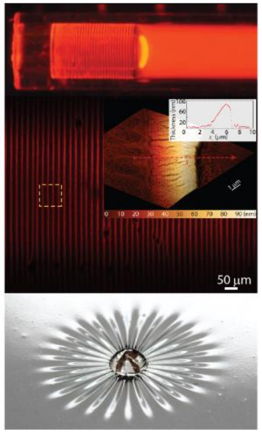
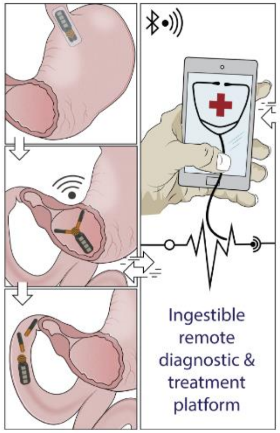


3D printed nanomaterials-based electronics



Multi-scale printing & soft matter physics



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Nanomaterials | Soft matter physics | Additive manufacturing | Ingestible electronics | Soft robotics

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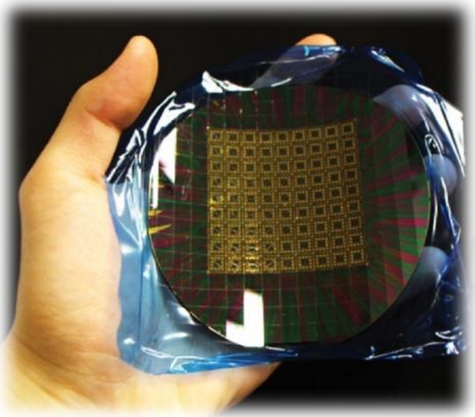
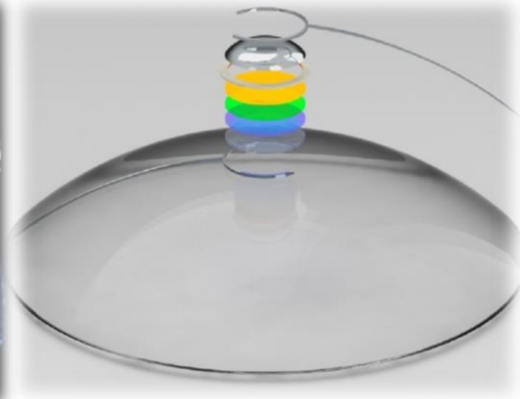
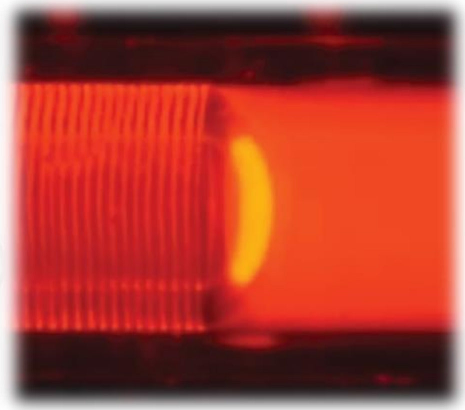


Multiscale additive manufacturing of active electronics

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