Microplasma Sputtering for 3D Printing of Metallic Microstructures

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MIT Lincoln Laboratory

MIT Lincoln Laboratory is a Department of Defense (DoD) federally funded research and development center (FFRDC) working on problems critical to national security.

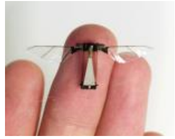
Core Competencies

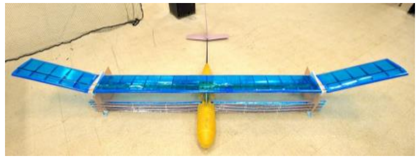
- Sensors
- Signal processing
  Embedded computing
- Communications
- Advanced electronics
- Integrated sensing
- Cybersecurity
- Decision support

Motivation: Agile Production of 3D Microsystems

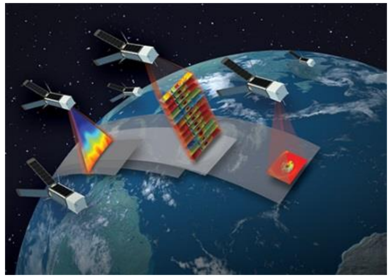
Bioengineered Systems

Micro UAVs



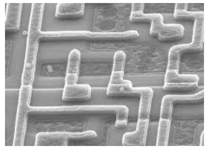


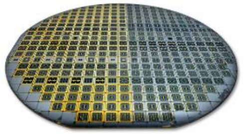
Small Satellites



Small UUVs

Rework and Tuning





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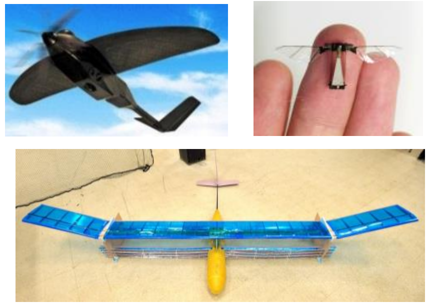

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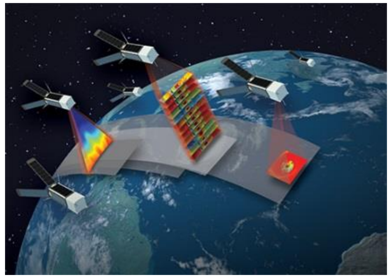

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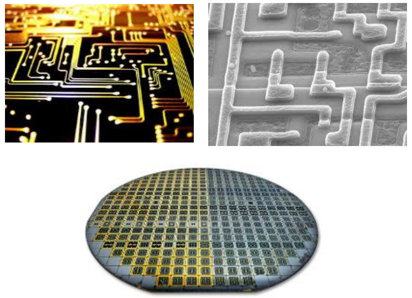


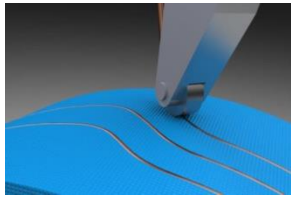
Microsystems Fabrication

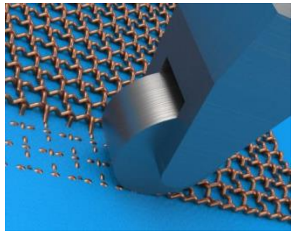
Waferscale IC Fabrication | **Additive Manufacturing**

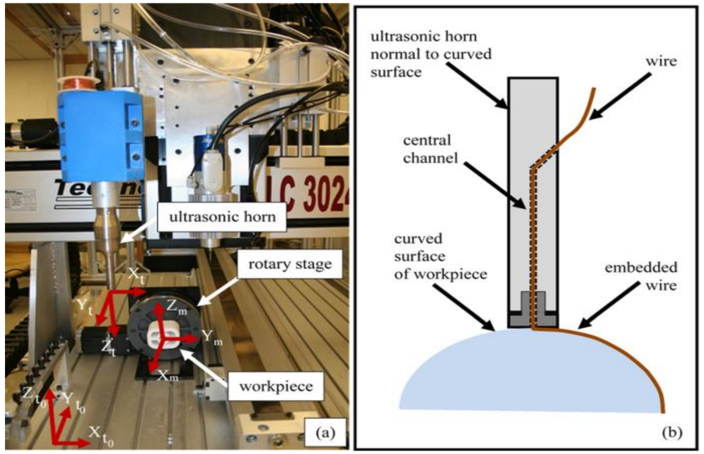
Key capability → Printing high-quality functional materials (electrical, optical, magnetic)

3D Printed Interconnect: Current Technologies

Wire embedding (Keck Center, U.Texas)







Extruded pastes (Stratasys)

Laser induced transfer (Orbotech)

Scientific Reports | 5:17265 | DOI:10.1038/srep17265

Ag nanoparticles (Voxel8, Lewis Group at Harvard)

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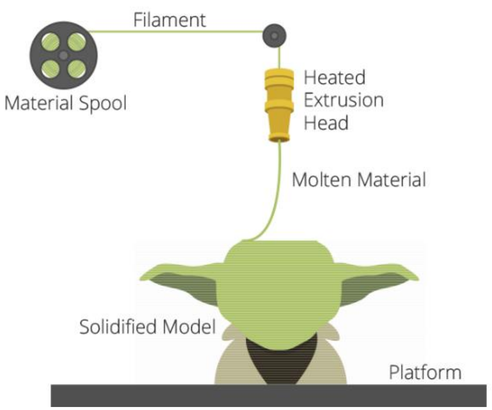

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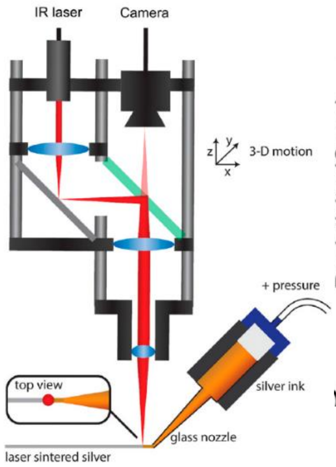

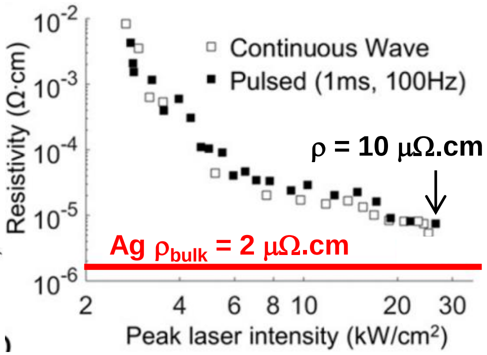

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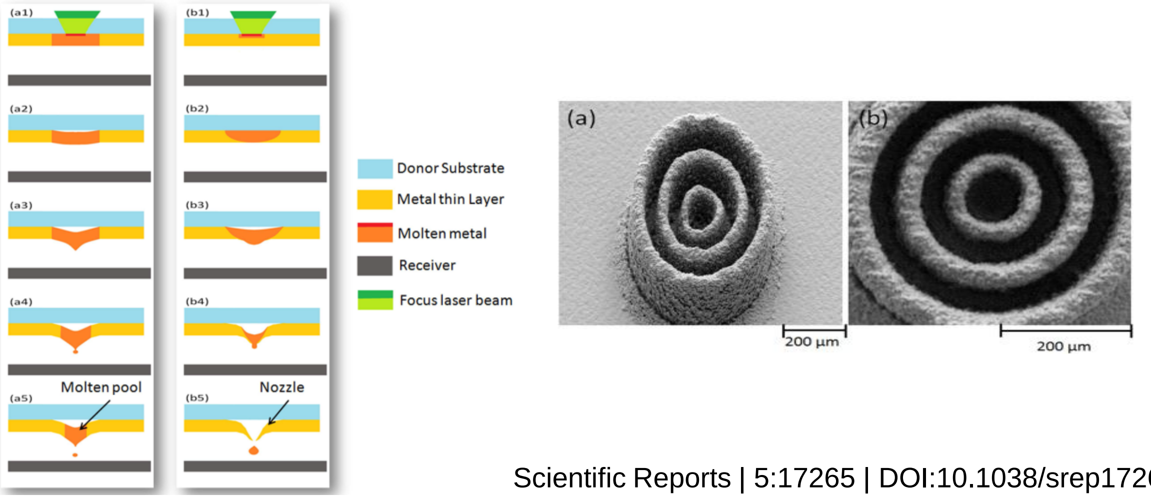

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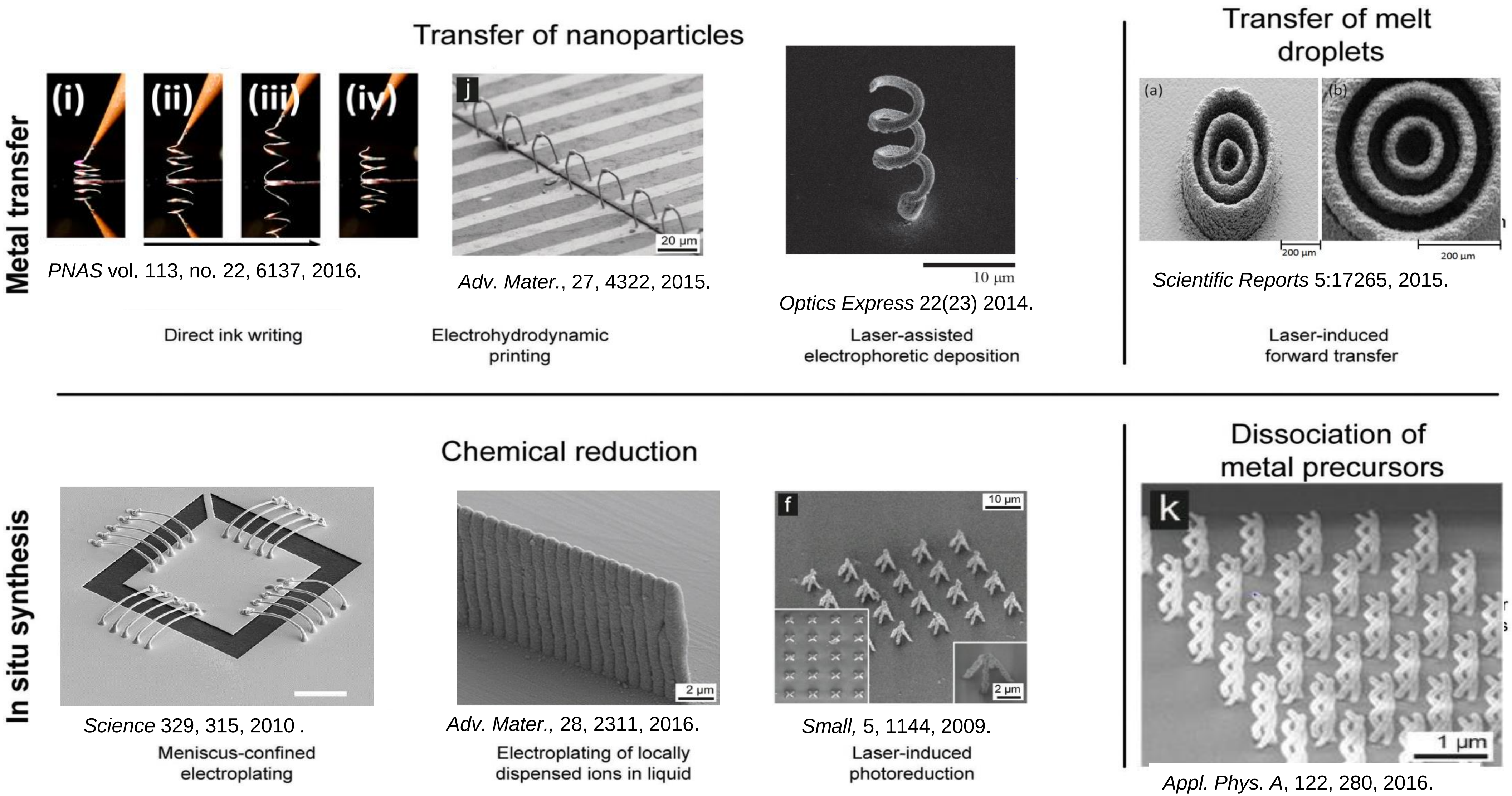
State of the Art in
Additive Manufacturing of Conductors



PNAS vol. 113, no. 22, 6137, 2016.

Adv. Mater., 27, 4322, 2015.

Optics Express 22(23) 2014.

Scientific Reports 5:17265, 2015.

Science 329, 315, 2010 .

Adv. Mater., 28, 2311, 2016.

Small, 5, 1144, 2009.

Appl. Phys. A, 122, 280, 2016.

Hirt, Reiser, Spolenak, Zambelli, Adv. Mater. 2017, 1604211

State of the Art in Additive Manufacturing of Conductors and Semiconductors

Technique	Conductivity	Materials Demonstrated	Minimum feature size	Substrate	Post processing	Commercial example
Direct ink write DIW	~10x bulk with anneal	Ag	10s μm	No constraints	Laser anneal	Harvard/ Voxel8
Electrohydrodynamic printing	~10x bulk with anneal	Au, Ag, Cu	10s μm	Conductive	Thermal anneal	
Laser assisted electrophoresis	~100x bulk	Au	~10 μm	Conductive	Thermal anneal	
Laser induced forward transfer LIFT	~10x bulk	Many metals	~10s μm	No constraints	None	Orbotech
Meniscus confined electroplating	~10x bulk	Cu, Pt	<10 μm	Conductive	None	
Laser induced photoreduction	~100x bulk	Ag	<10 μm	Transparent	None	
Focused ion beam induced deposition	~10x bulk with anneal	Many metals	<10 μm	Conductive	Thermal anneal	
Extruded pastes	1e2-1e5 bulk	Ag, Au	100s μm	High temp	High temp compatible	Stratasys

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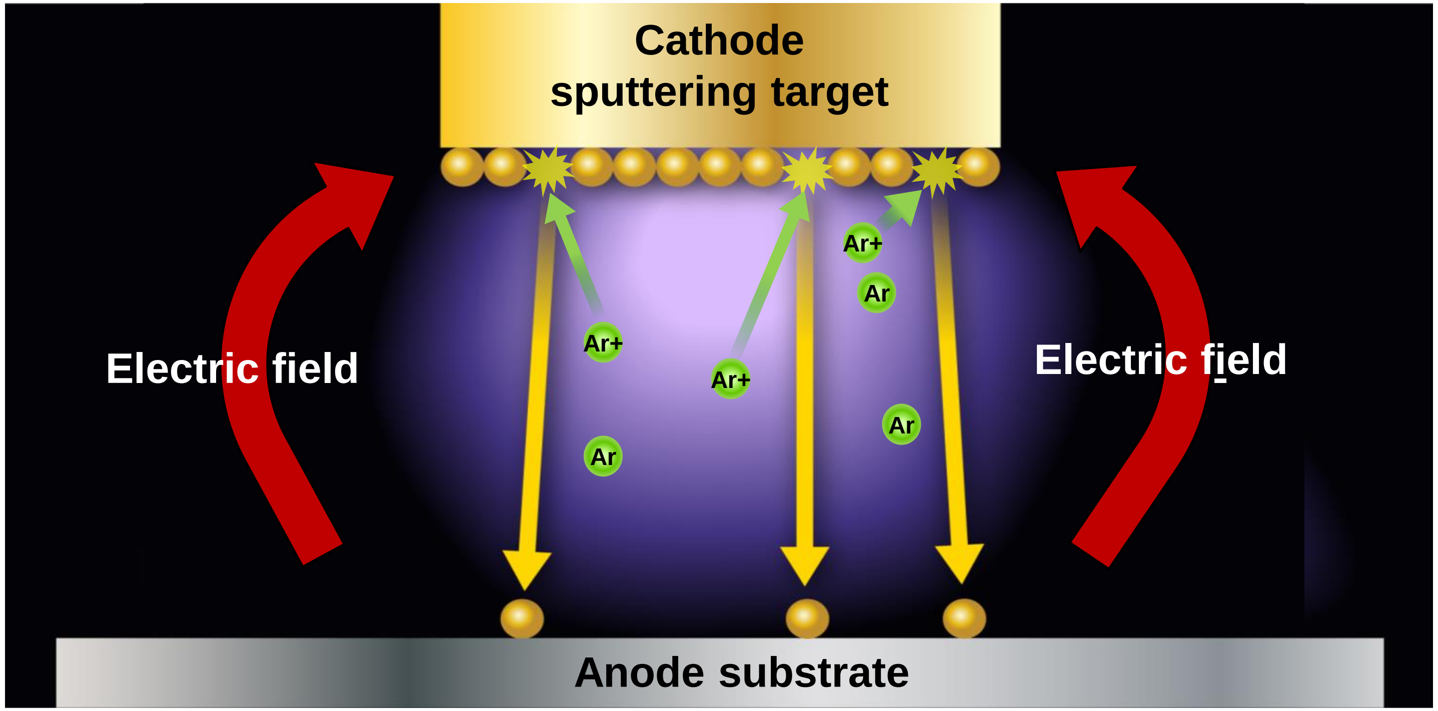
Microplasma deposition	**Thin film material**	**Any sputtered material**	**<10 μm**	**No constraints**	**None**	

Atmospheric Microplasma Sputtering



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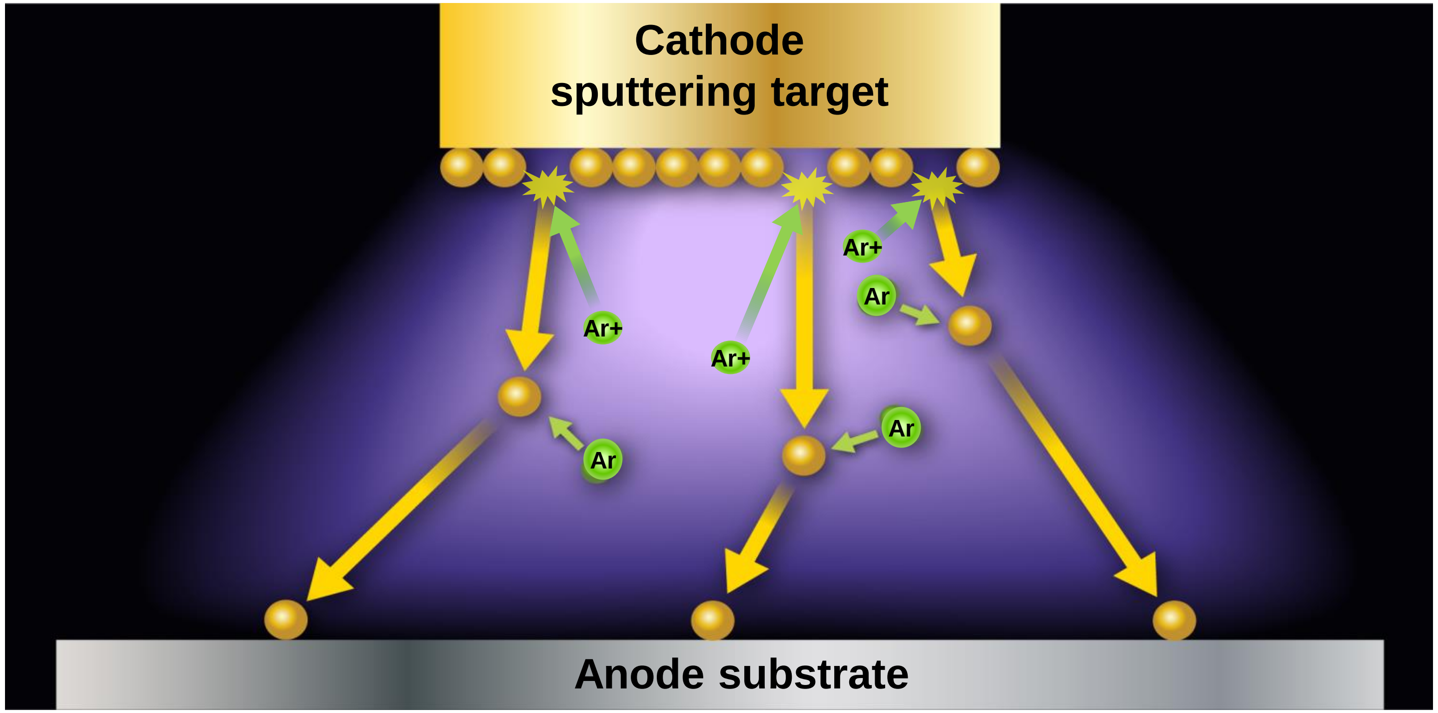

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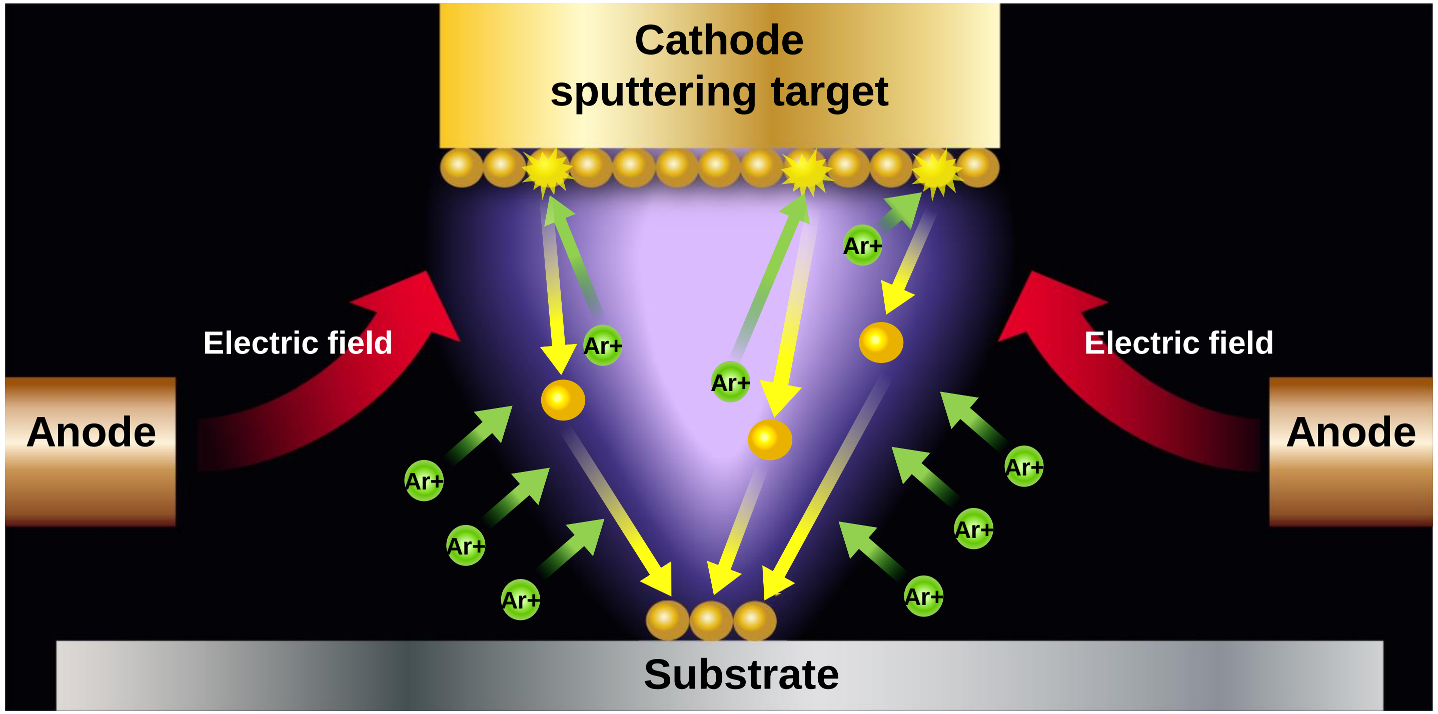

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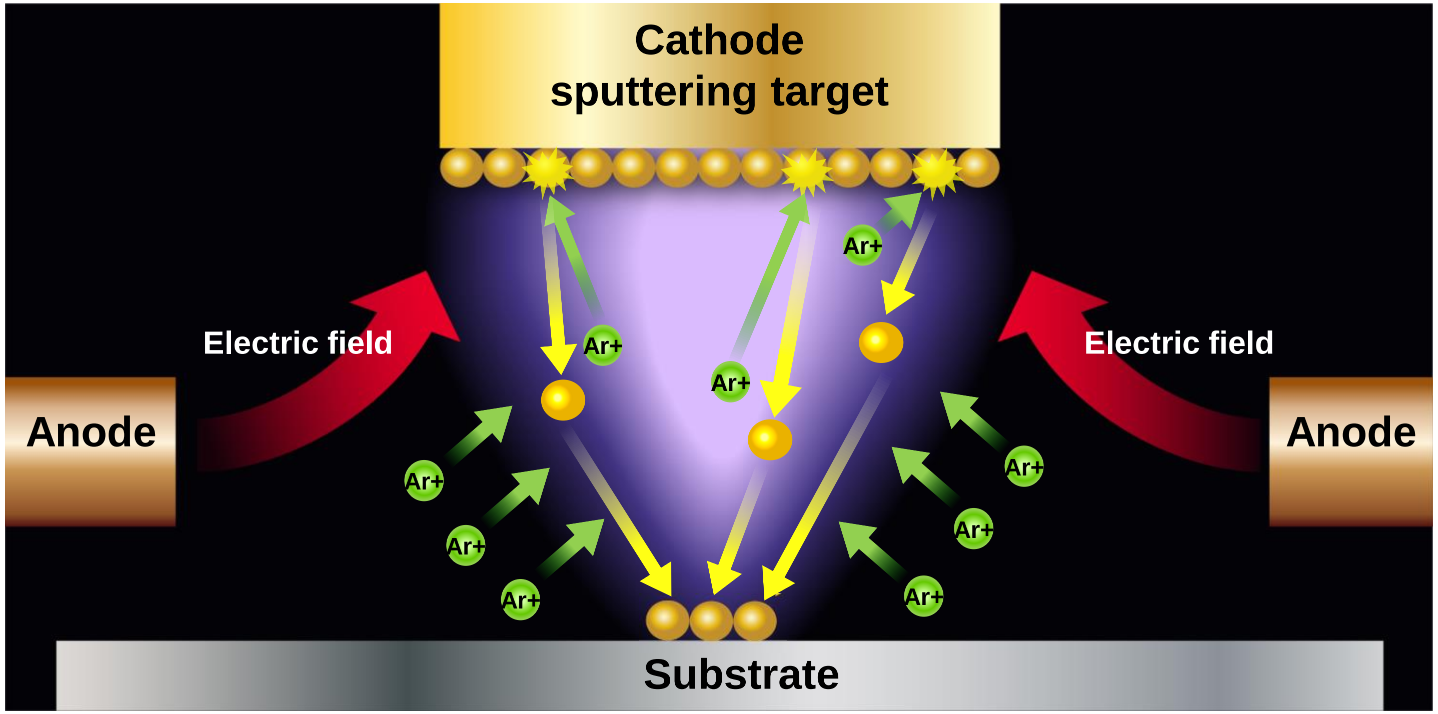
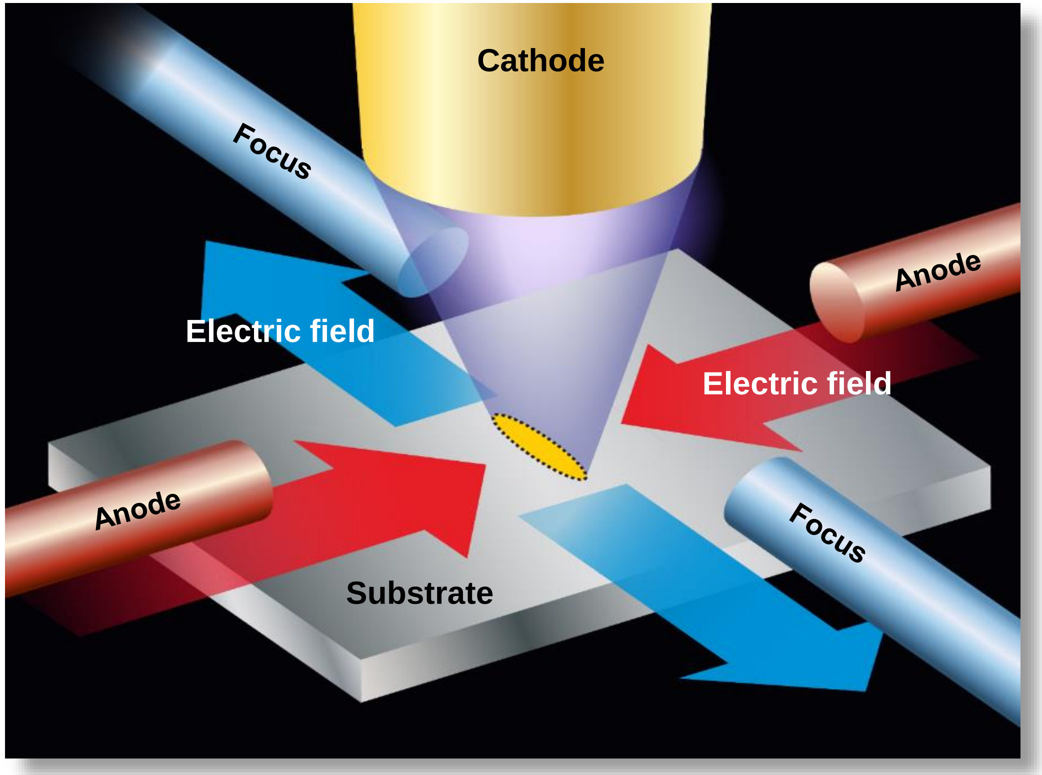


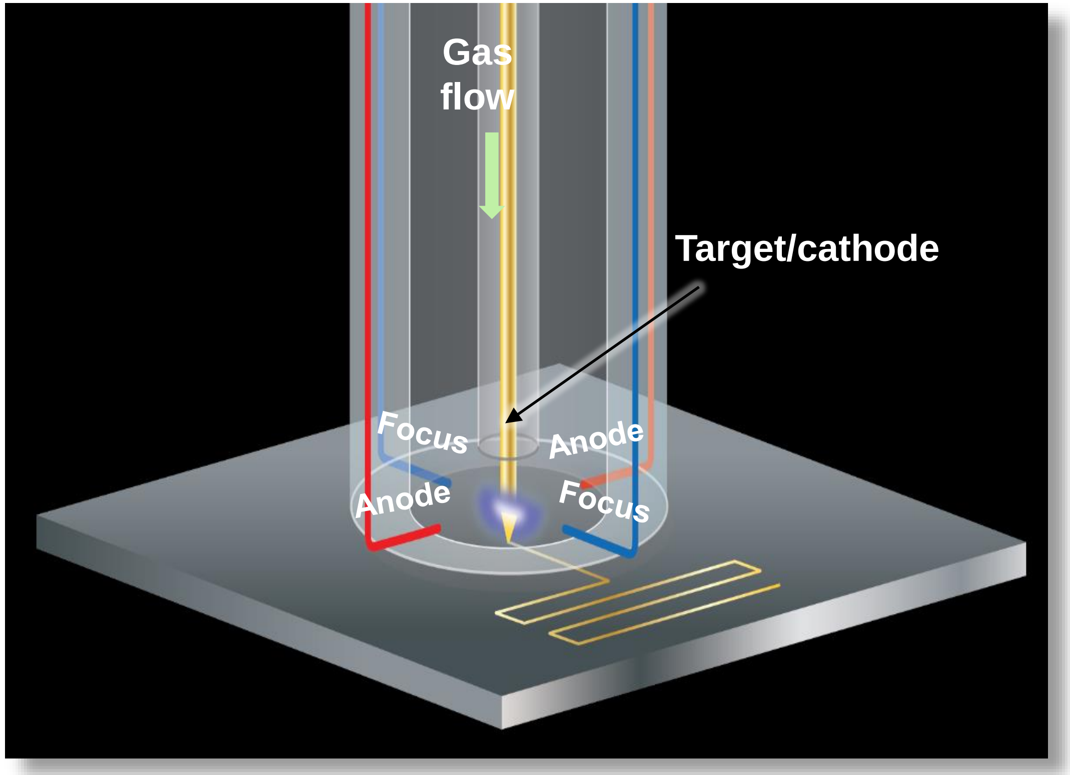
Leapfrog technology has potential for:

- High quality, smooth deposits
- Many materials – conductors, semiconductors, dielectrics
- Maskless feature definition
- No substrate limitations
- No post-processing
- Scalability, compatibility with 3D printers

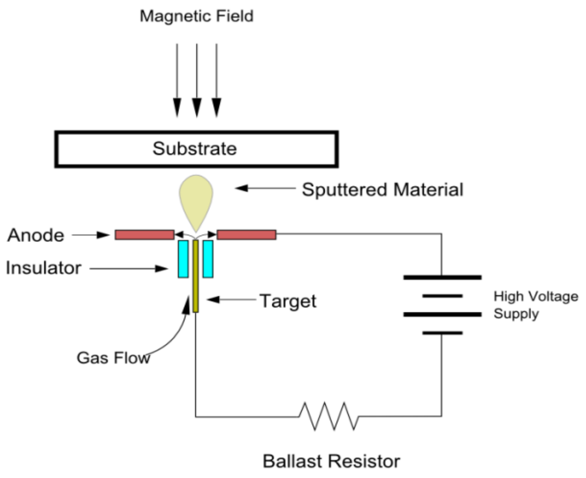
Achieving Focused Depositions

- In atmospheric plasma, collisions spread sputtered material
- Electric fields used to focus plasma, but ion drag focusing generates pressure which forces defocusing
- <u>Innovative concept: 4-electrode focusing mechanism</u>

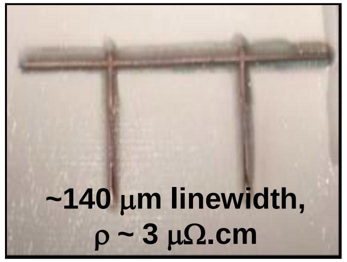




Recent Demonstrations of Microplasma Metal Deposition

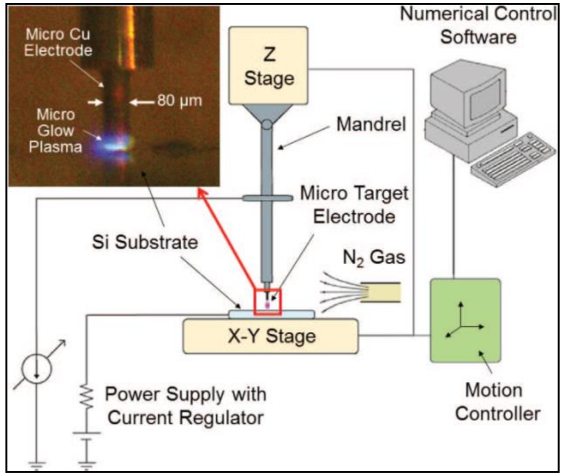


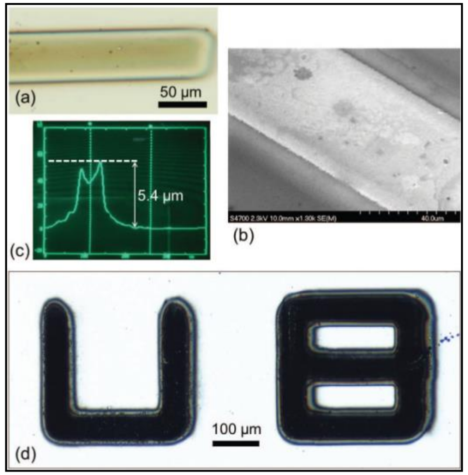
Au lines on polymer substrate



Case Western Reserve University 2016
- DC plasma, Au wire cathode
- Write speed ~20µm/sec
- Feature size > 100 µm, resistivity ~ 3 µΩ.cm

Burwell, MS Thesis, Case Western Reserve University 2016



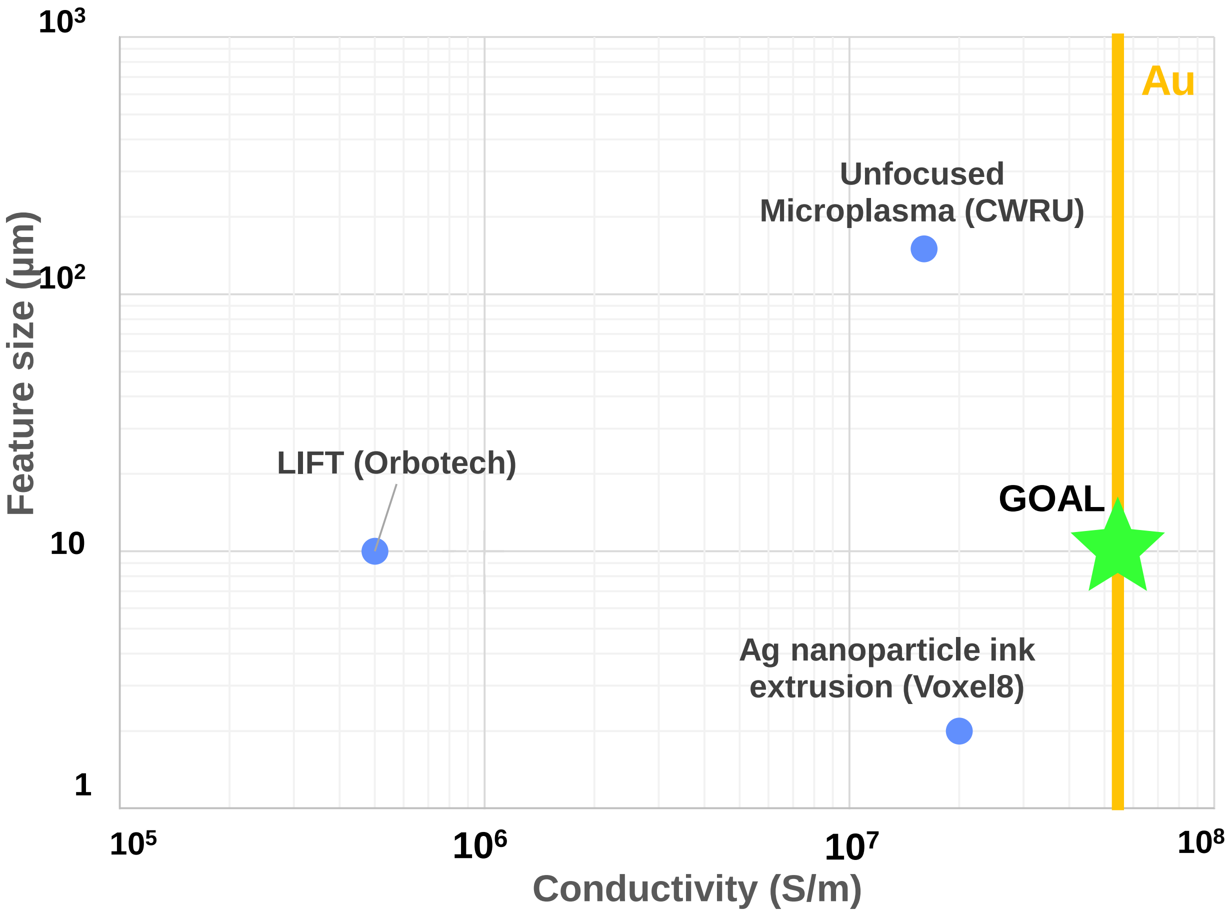


U. British Columbia, 2016
- DC plasma, Cu cathode
- Write speed ~20µm/sec
- Feature size > 100 µm, no resistivity data

Abdul-Wahed et al, MEMS 2016, Shanghai, CHINA, 24-28 January 2016

Initial demonstrations empirical – minimal understanding of underlying physics
Critical issues not addressed: feature size, material quality

Microplasma Sputtering Development



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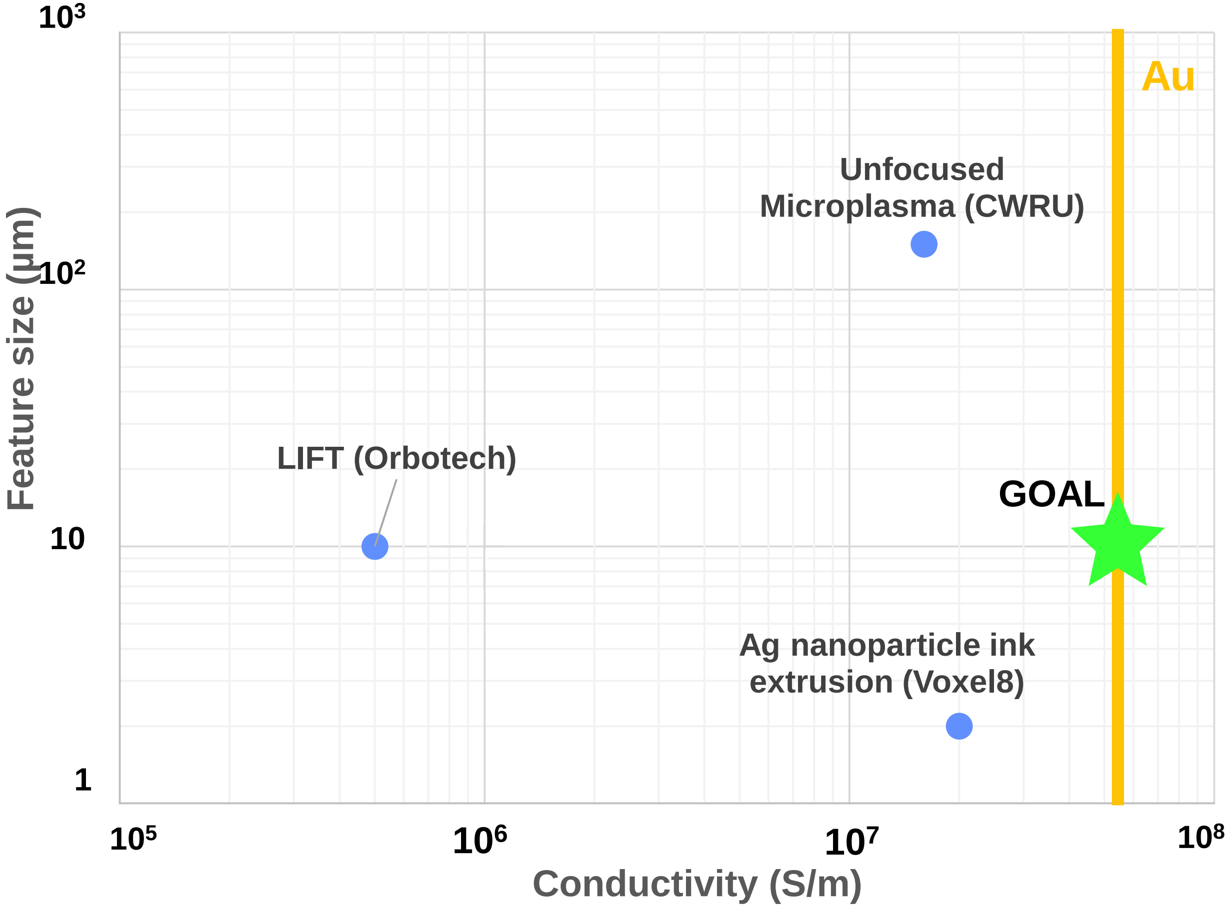


Modeling

↓

Write Head Design

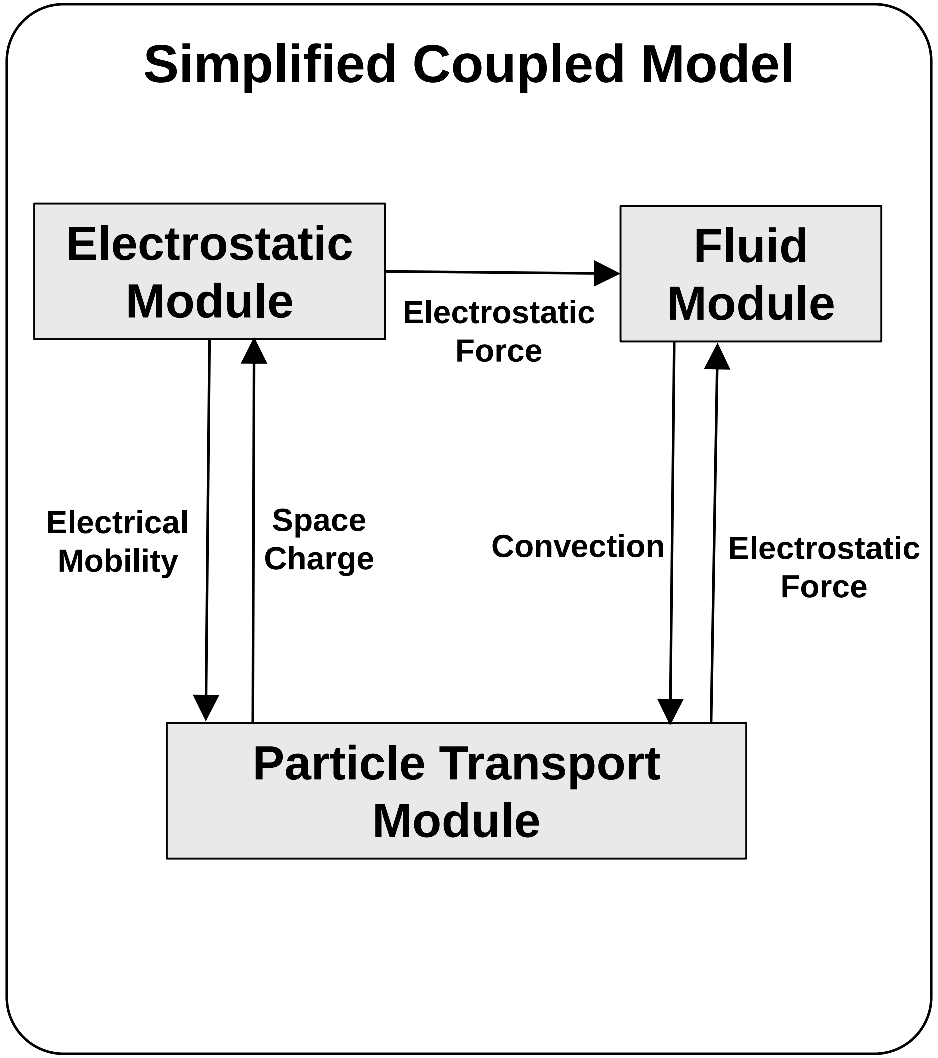
↓

Characterization

Near-term Goal:
10-µm-wide Au lines, resistivity < 10x bulk metal

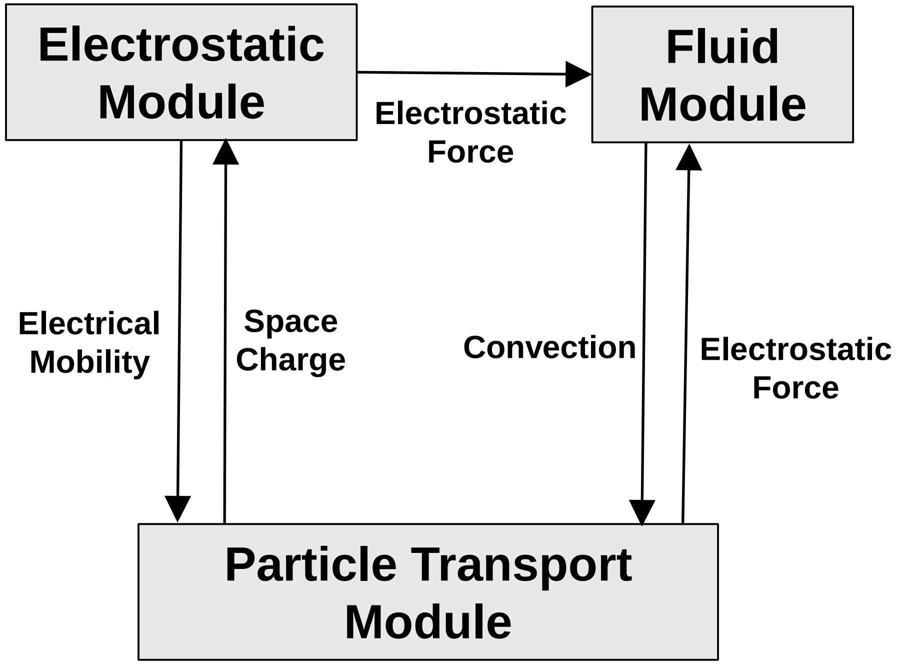
Long-term Goal:
Microplasma sputtering of conducting, semiconducting and insulating features for integrated microsystems

System Modeling with COMSOL

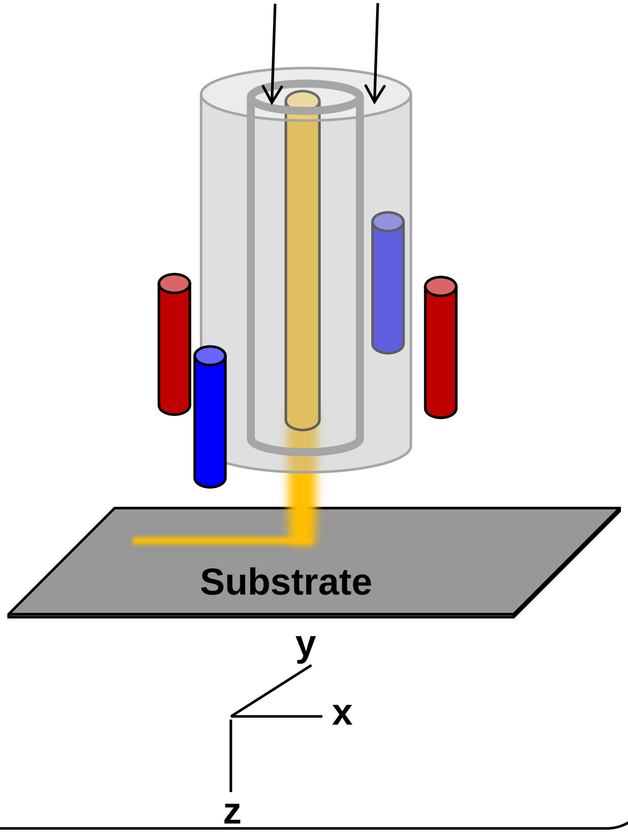


System Modeling with COMSOL

Simplified Coupled Model



Configuration



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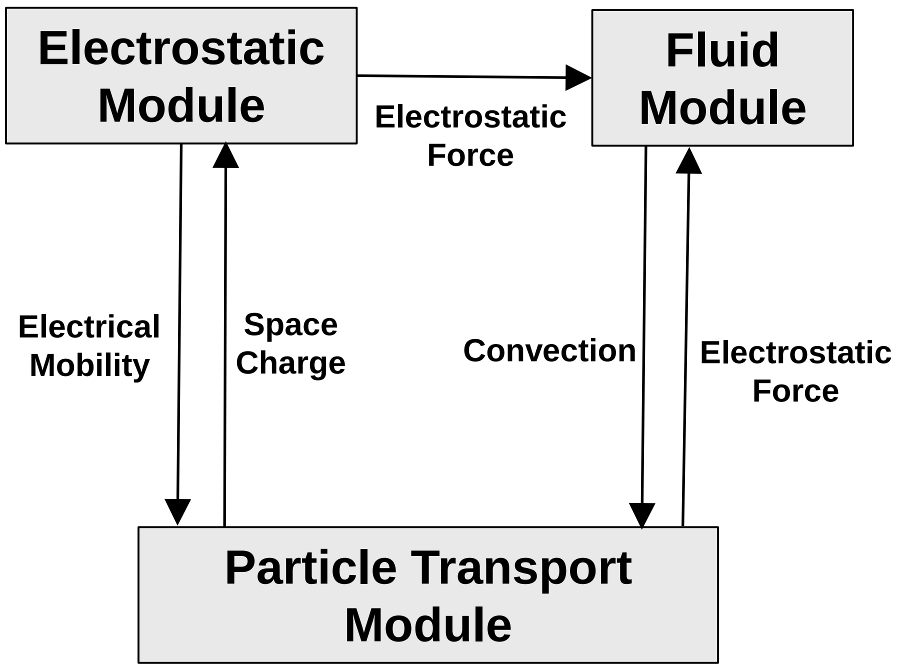

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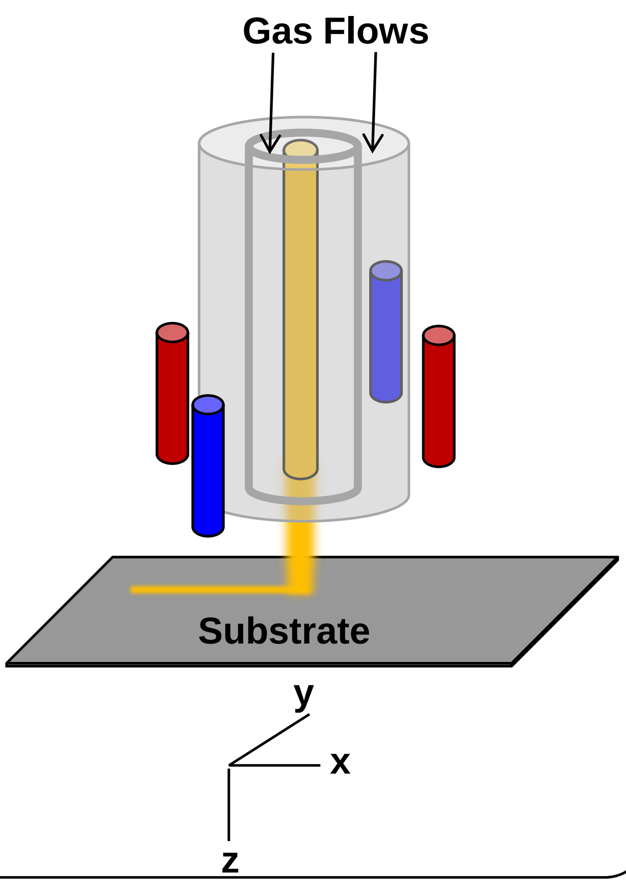
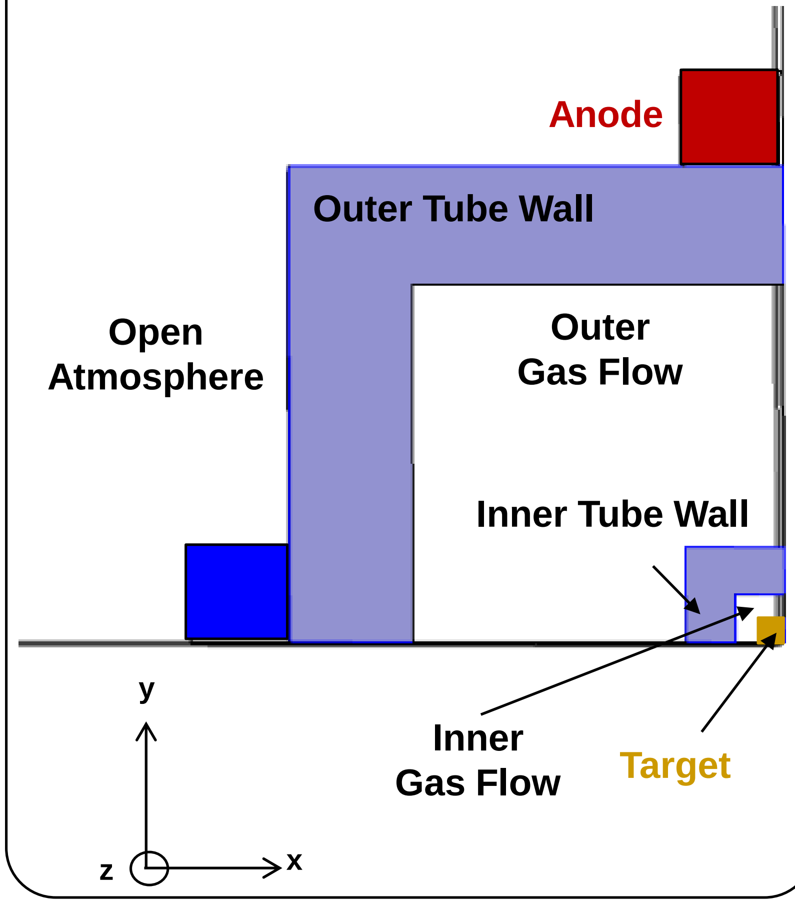
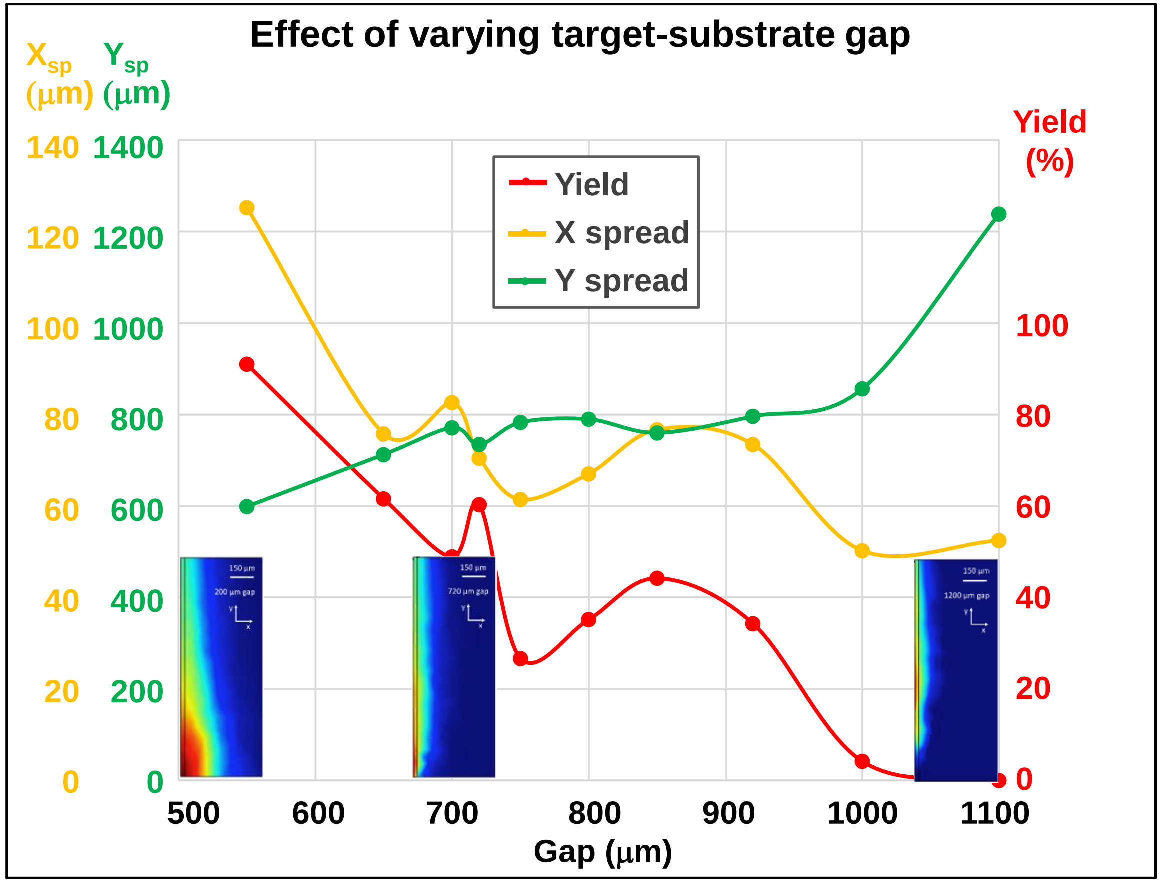


Model Geometry



Modeling Effect of Parameters



Increasing target-substrate gap improves focusing, but decreases yield

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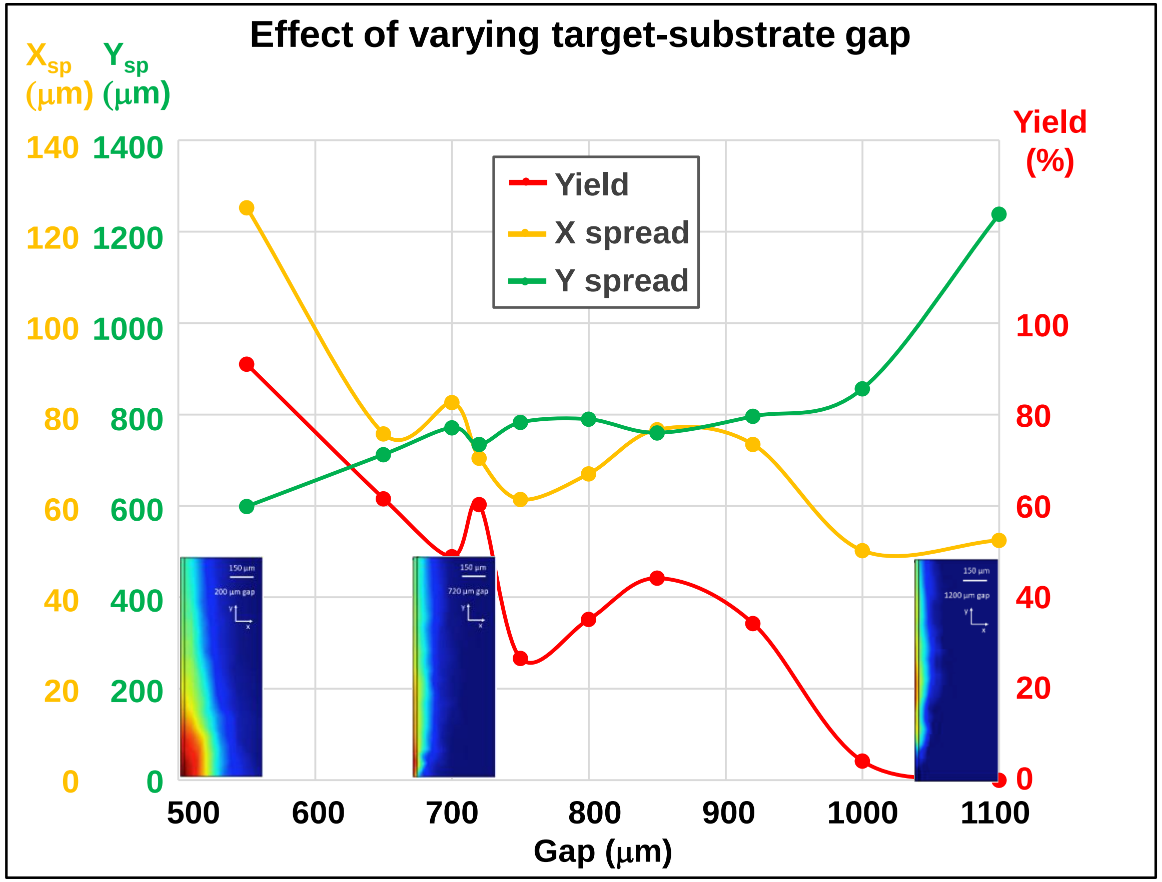
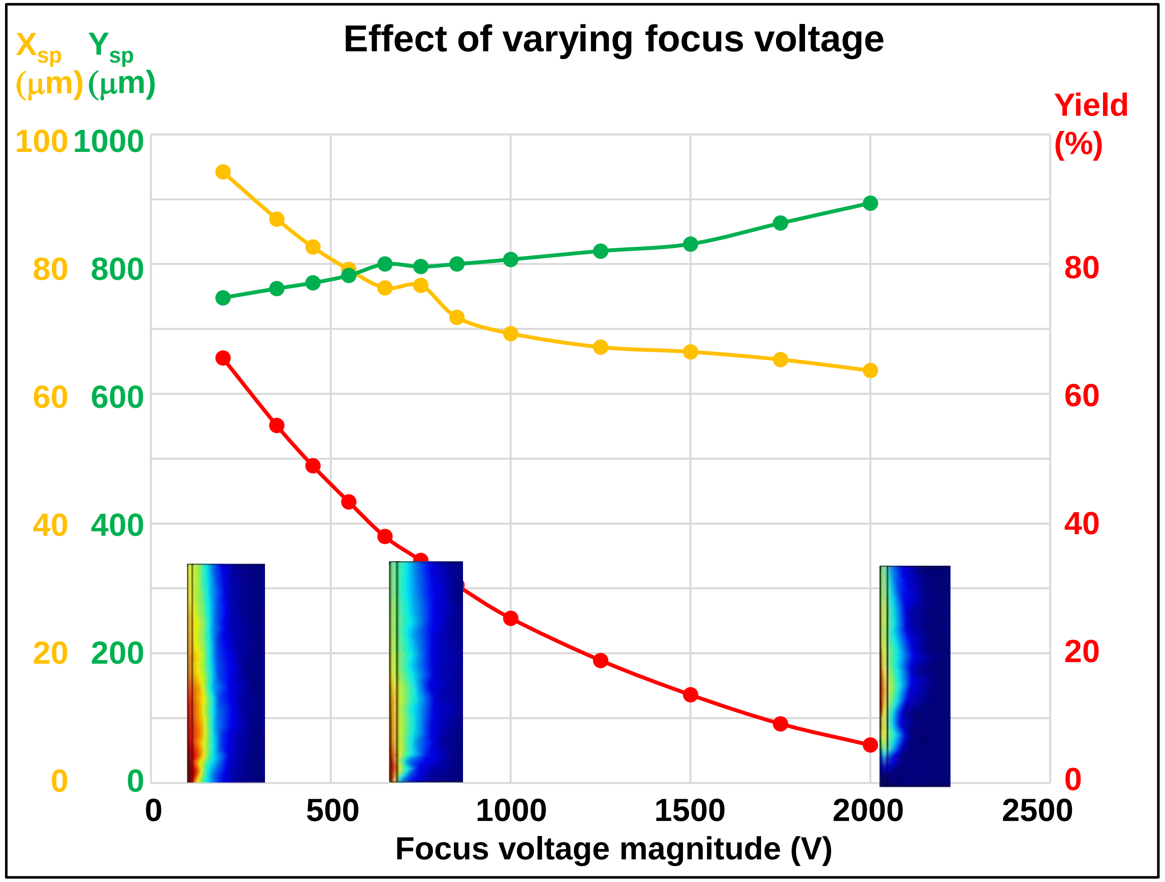
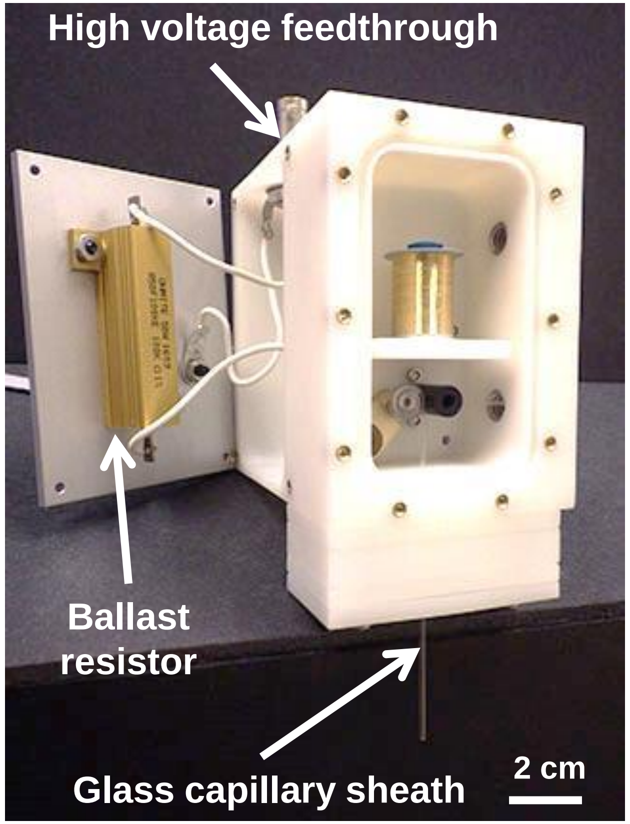




Increasing target-substrate gap improves focusing, but decreases yield

Increasing focus voltage improves focusing, but decreases yield

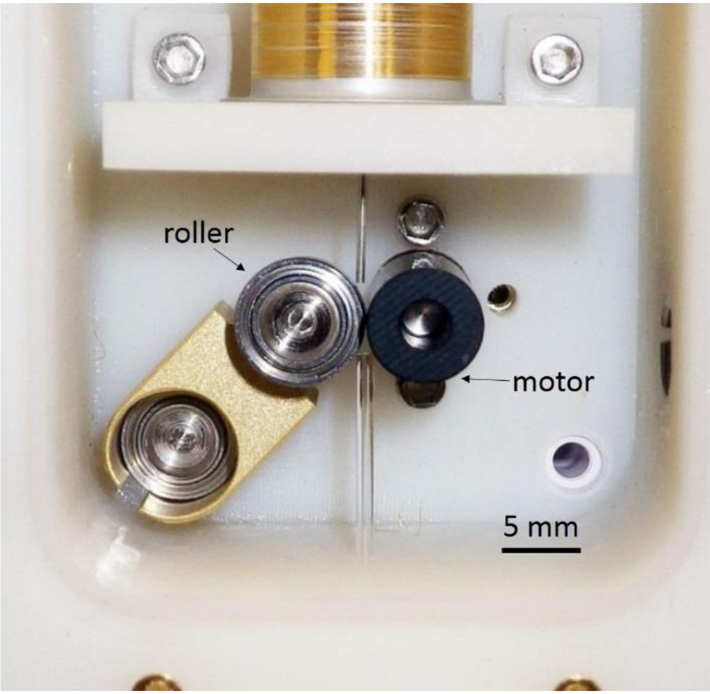
1st Generation Write Head

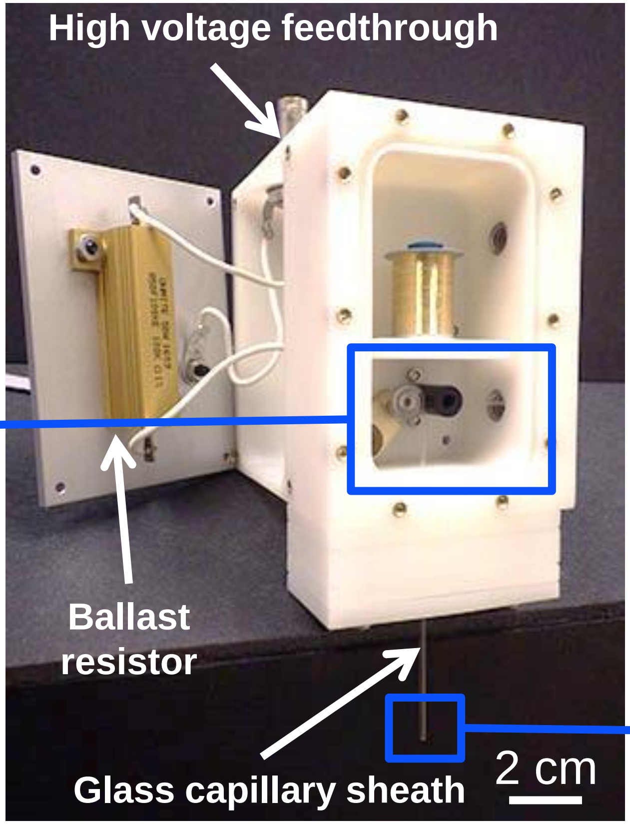


Compact for Integration with 3D Printer

1st Generation Write Head

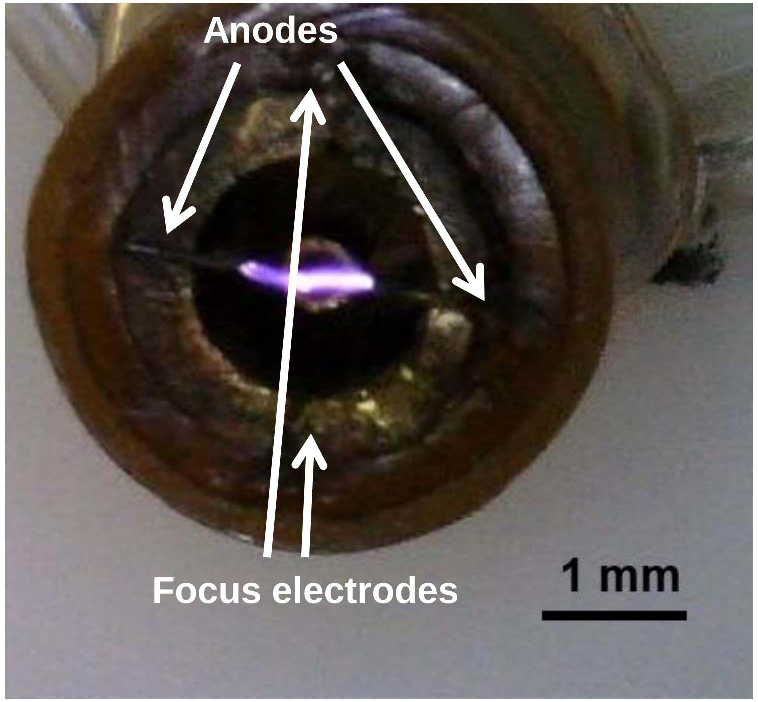
Continuous wire feed mechanism



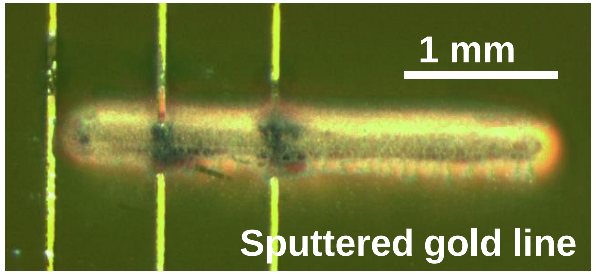


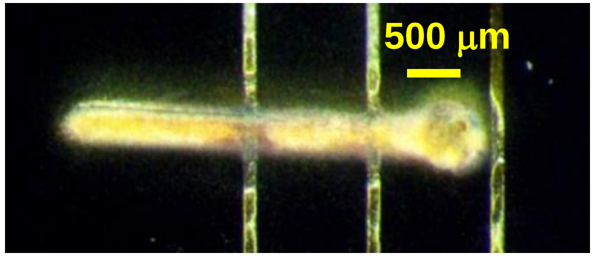
Compact for Integration with 3D Printer

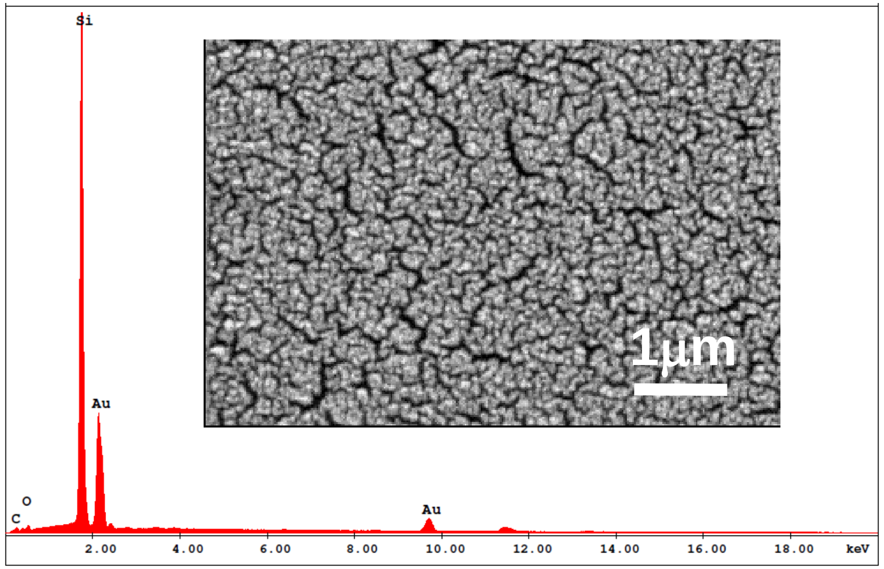
Nozzle tip with plasma generated between electrodes

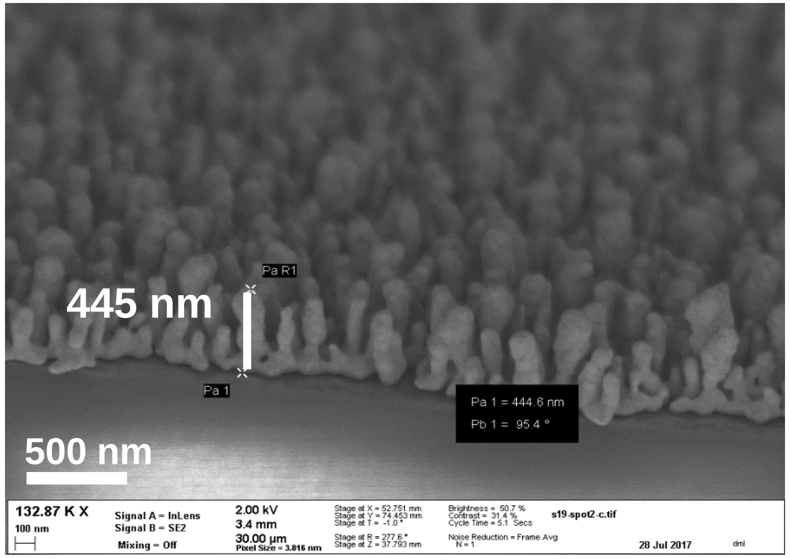


1st Demonstration of Microplasma Sputtered Metal







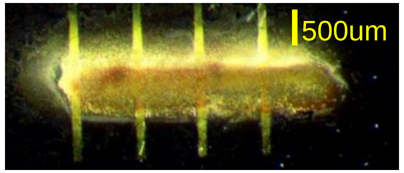


- Energy dispersive X-ray analysis (EDX) confirms deposits are gold
- Resistivity ~ 1.5 x 10^{-6} Ω-m (75x bulk metal)
- Challenges: Morphology, adhesion, linewidth

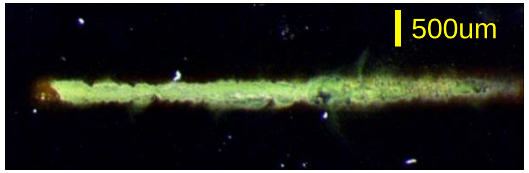
Areas Under Development

Feature Size

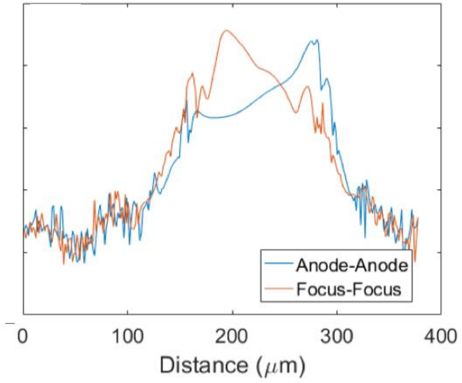
Focus electrodes unbiased



Focus electrodes biased at 900V



Focus electrodes unbiased: Symmetric spot



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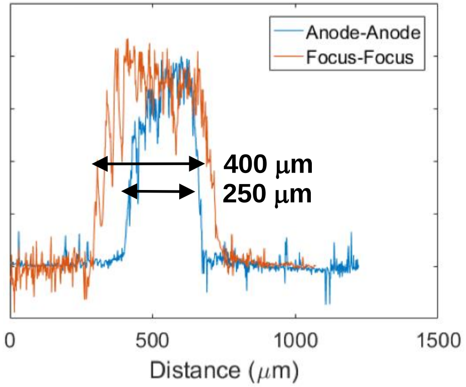

Demonstrated ability to control spot shape with focus electrodes

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Areas Under Development

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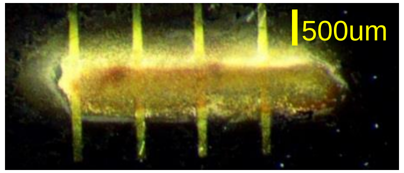
Focus electrodes unbiased



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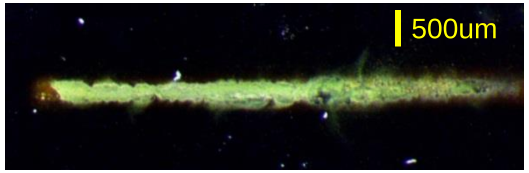

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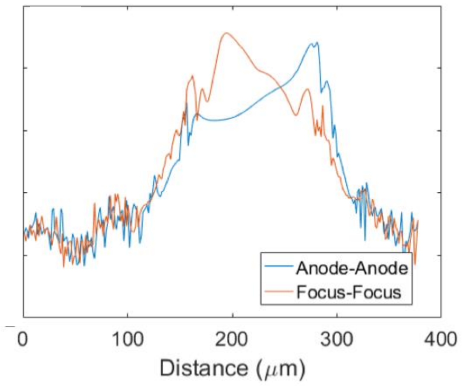

**Focus electrodes biased:
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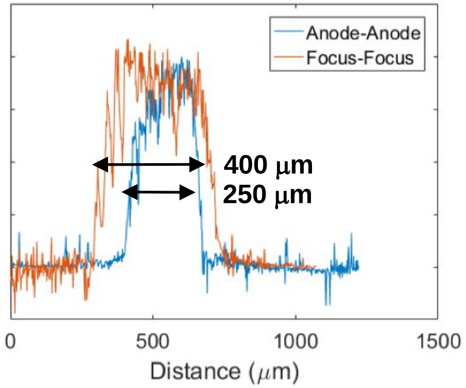
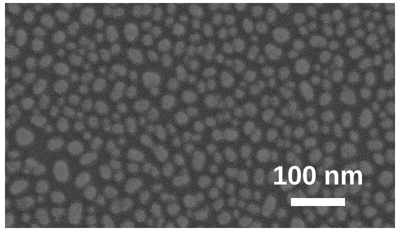


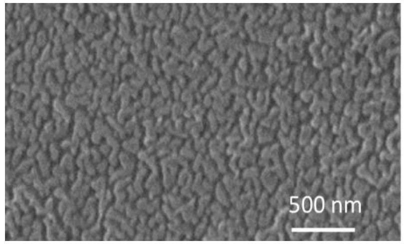
Demonstrated ability to control spot shape with focus electrodes

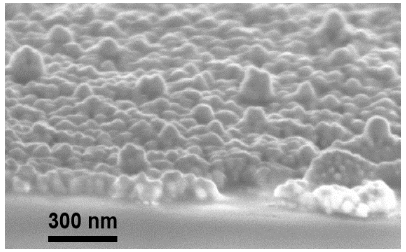
Morphology

Gas flow rate = 2 sccm



Gas flow rate = 5 sccm



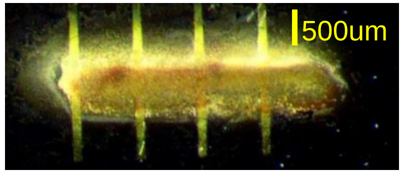


Film porosity tunable with gas flow rate

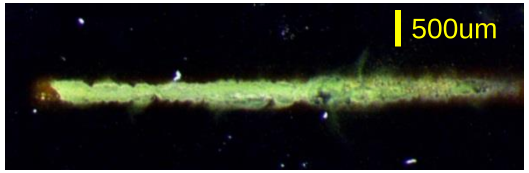
Areas Under Development

Feature Size

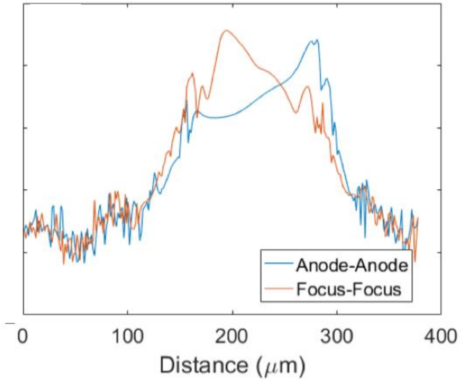
Focus electrodes unbiased



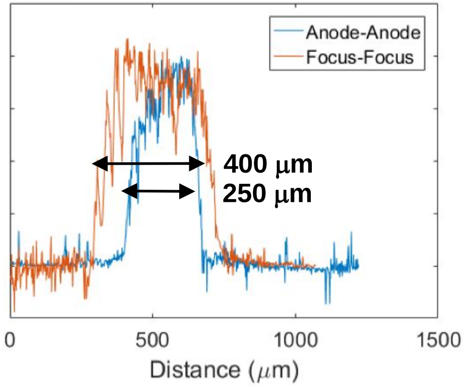
Focus electrodes biased at 900V



Focus electrodes unbiased: Symmetric spot



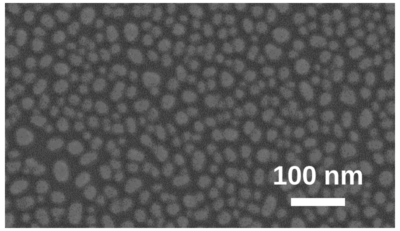
Focus electrodes biased: Asymmetric spot



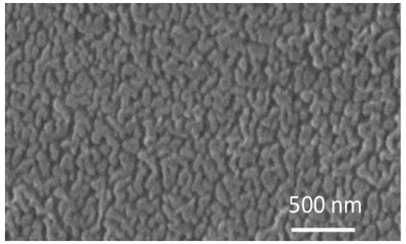
Demonstrated ability to control spot shape with focus electrodes

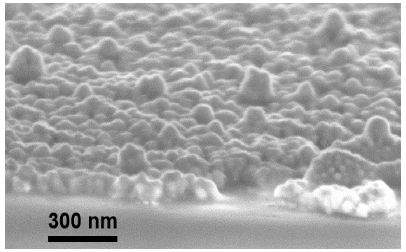
Morphology

Gas flow rate = 2 sccm



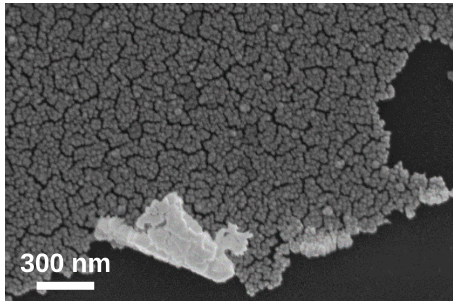
Gas flow rate = 5 sccm





Film porosity tunable with gas flow rate

Adhesion

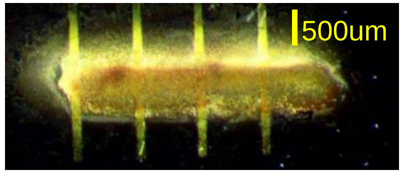


Planned incorporation of multiple targets enabling adhesion layers

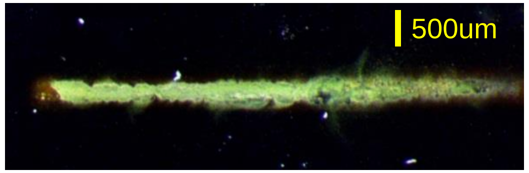
Areas Under Development

Feature Size

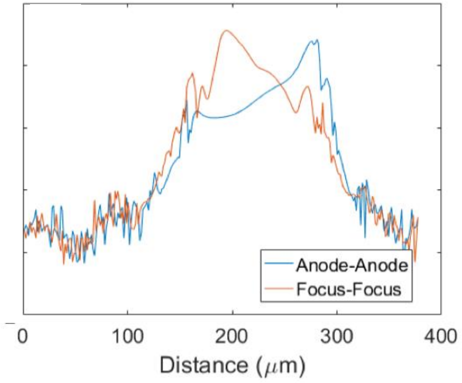
Focus electrodes unbiased



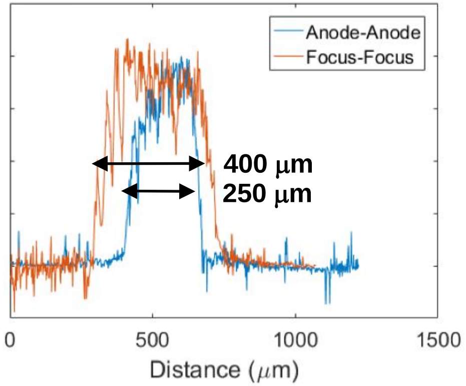
Focus electrodes biased at 900V



Focus electrodes unbiased:
Symmetric spot



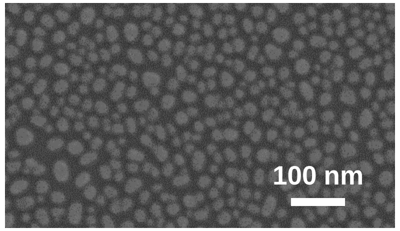
Focus electrodes biased:
Asymmetric spot



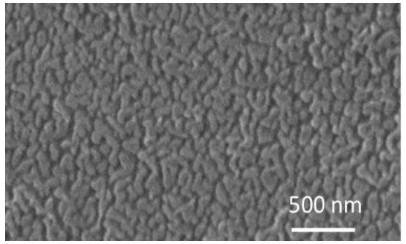
Demonstrated ability to control spot shape with focus electrodes

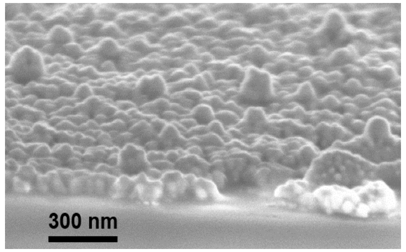
Morphology

Gas flow rate = 2 sccm



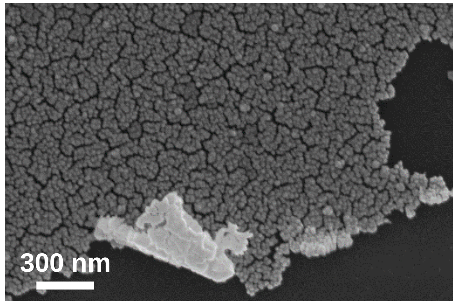
Gas flow rate = 5 sccm





Film porosity tunable with gas flow rate

Adhesion



Planned incorporation of multiple targets enabling adhesion layers

Deposition Rate

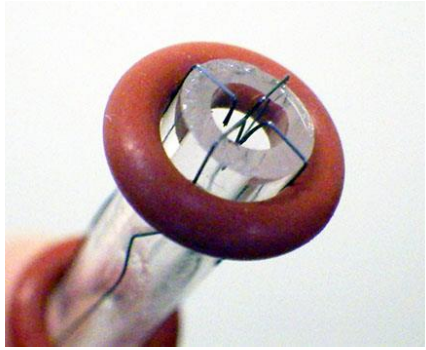
Direct write methods inherently slow.

Estimated volume deposition rate = 100 $\mu m^3/s$
Estimated deposition rate = 3.3 nm/s

Write head design amenable to parallelization for increased throughput

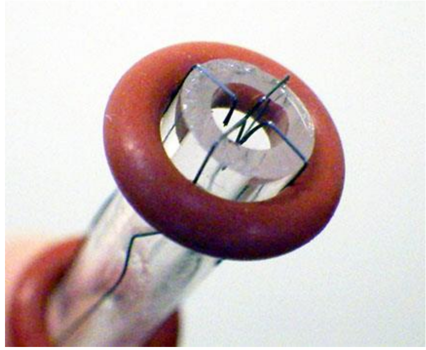
2^{nd} Generation Write Head

1^{st} gen write-head nozzle



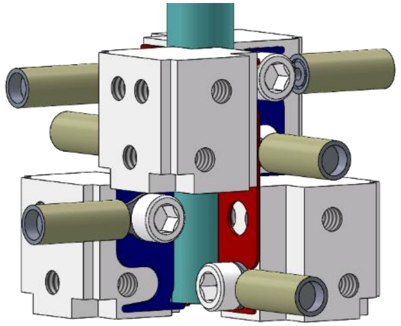
2nd Generation Write Head

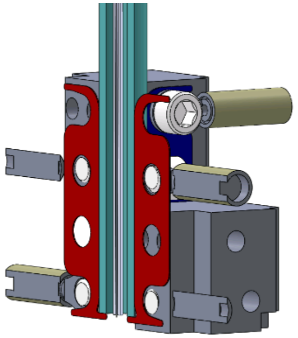
1st gen write-head nozzle



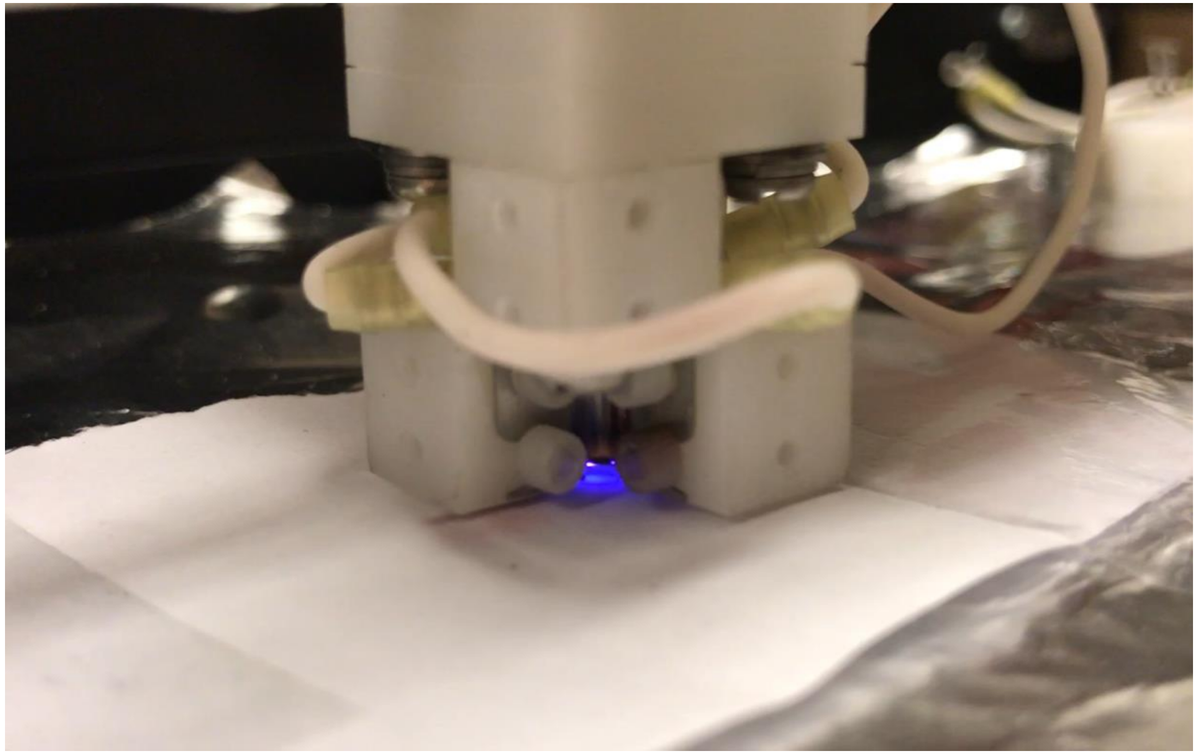
2nd gen write-head nozzle

- Addresses alignment, asymmetry



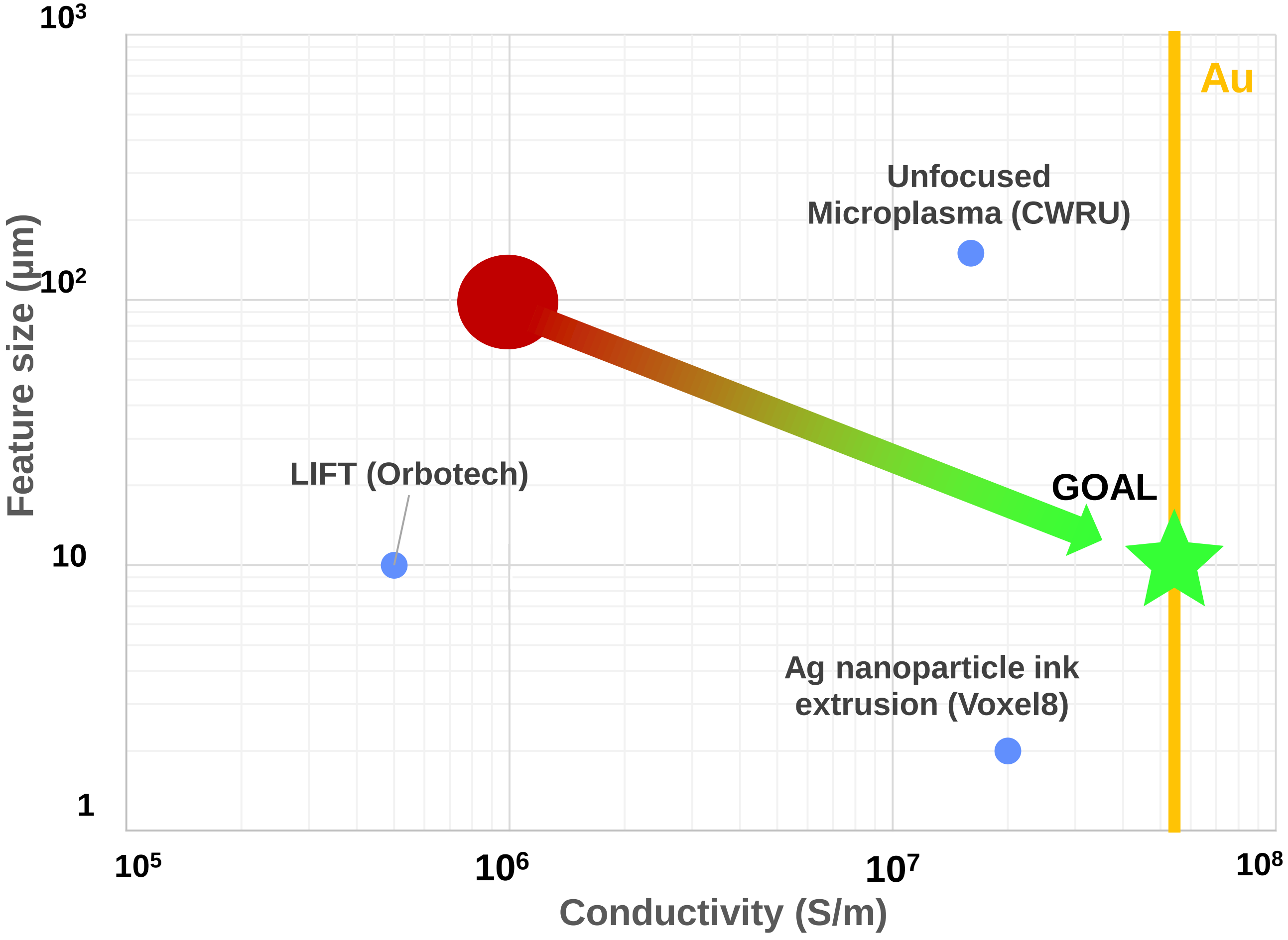


2nd Generation Write Head Printing Gold Line on Paper

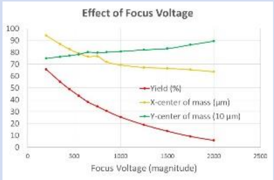


Demonstrated printing on silicon, glass, paper, plastic

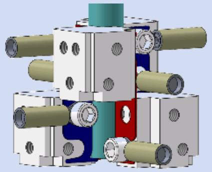
Summary



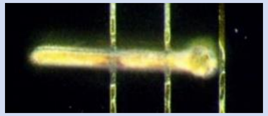
Modeling:
Parameter space explored to define write head design.



Write Head:
1st and 2nd gen write head completed and operational.



Characterization:
Gold lines printed on multiple substrate types.
Material quality optimization ongoing.

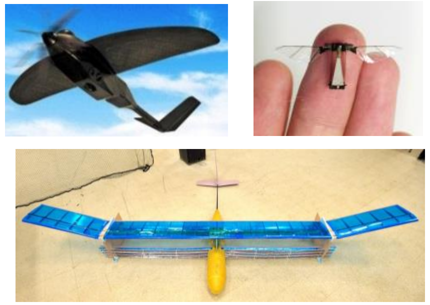


Long-term Goal:
Microplasma sputtering of conducting, semiconducting and insulating features for integrated microsystems

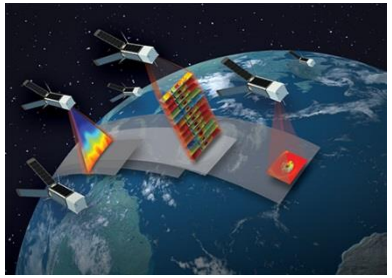
Microplasma Sputtering – A New Paradigm

Bioengineered Systems

Micro UAVs

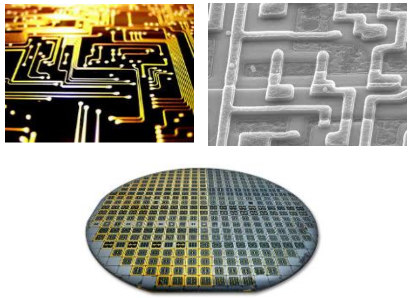


Small Satellites



Small UUVs

Rework and Tuning



Components:
- Sensors
- Micro-actuators
- Micro-power sources

Technologies:
- Embedded electronics
- Low SWaP materials
- Multiscale nonplanar structures

Atmospheric microplasma sputtering offers a new paradigm for additive manufacturing of functional materials with no binders, inks, or post-processing, to enable efficient low-cost production of complete microsystems.

Thank you for your attention.

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