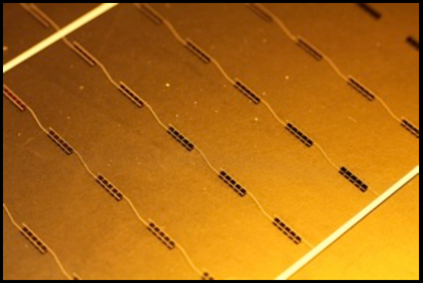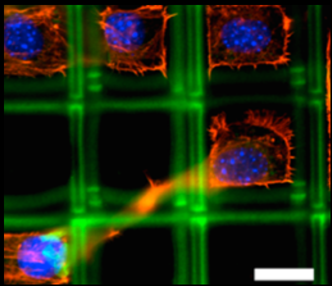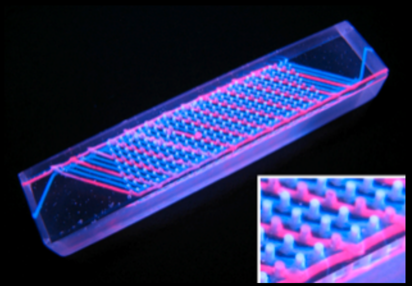

Printing Functional Materials

Jennifer A. Lewis

University of Illinois

http://colloids.matse.illinois.edu

3-D Printing - A Manufacturing Revolution?

The New York Times

Business Day
Technology

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3-D Printing Spurs a Manufacturing Revolution

By ASHLEE VANCE
Published: September 13, 2010

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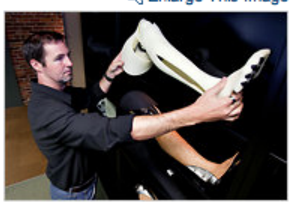
SAN FRANCISCO — Businesses in the South Park district of San Francisco generally sell either Web technology or sandwiches and burritos. Bespoke Innovations plans to sell designer body parts.

Enlarge This Image



Peter DaSilva for The New York Times

Scott Summit, co-founder of Bespoke Innovations, with a prosthetic limb.

The company is using advances in a technology known as 3-D printing to create prosthetic limb casings wrapped in embroidered leather, shimmering metal or whatever else someone might want.

Enlarge This Image

Kevin Moloney for The New York Times

Scott Summit, a co-founder of Bespoke, and his partner, an orthopedic surgeon, are set to open a studio this fall where they will sell the limb coverings and experiment with printing entire customized limbs that could cost a tenth of comparable artificial limbs made using traditional methods. And they will be dishwasher-safe, too.

Stratasys 3D Printer: Fused deposition modeling of molten ink filaments

POPSCI 11.01.10

Z-Corp 3D Printer: Inkjet printing on powder bed

Several advances needed for 3-D printing of high performance, functional materials

"Before this personal manufacturing revolution can take place, though, researchers will need to develop a broader array of robust printing materials…"

"… rapidly growing market, $1 B sales…
about 70% of market is prototyping"

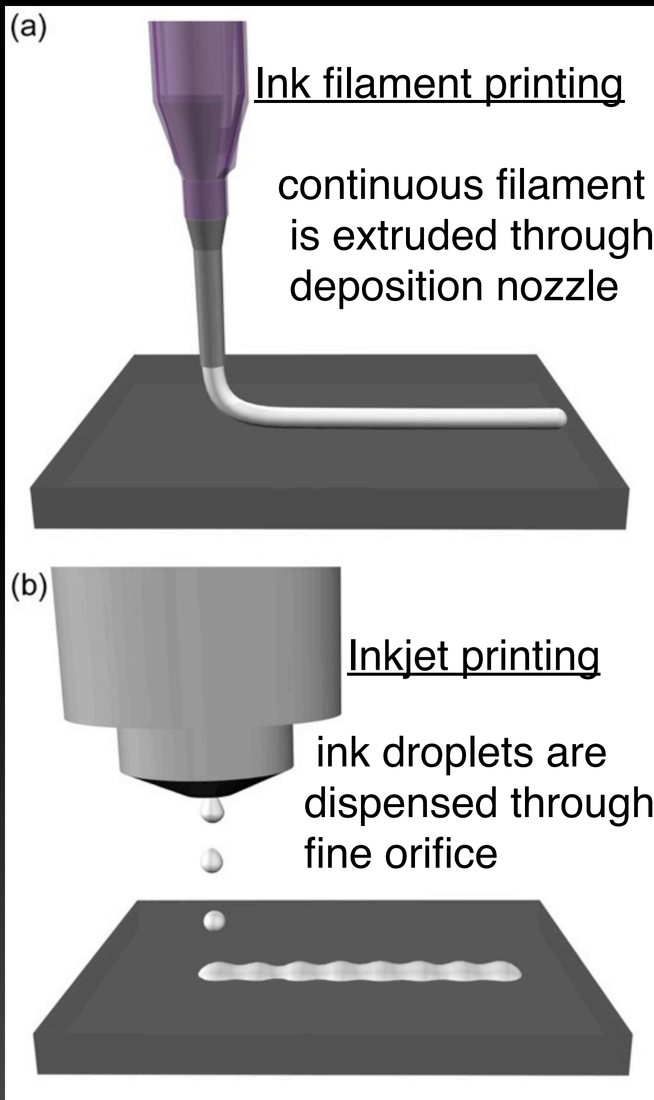
Chemical & Engineering News, Nov 14, 2011 issue

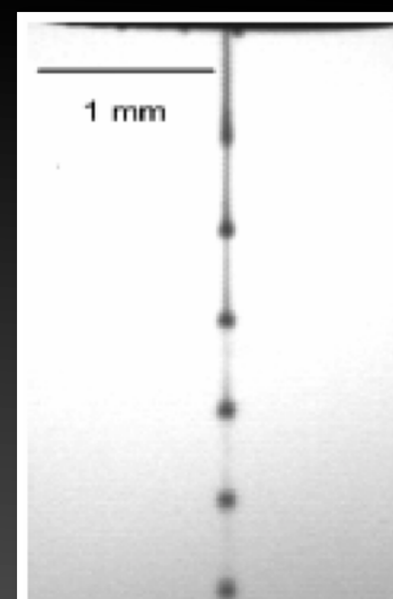
OUR FOCUS

- Create functional inks
- Broaden materials palette
- Improve feature resolution by 100x
- Print and fold - architectural complexity
- Enhance throughput by ~ 100x

… expedite transformation from rapid prototyping
to manufacturing of advanced materials

Ink filament vs. droplet printing

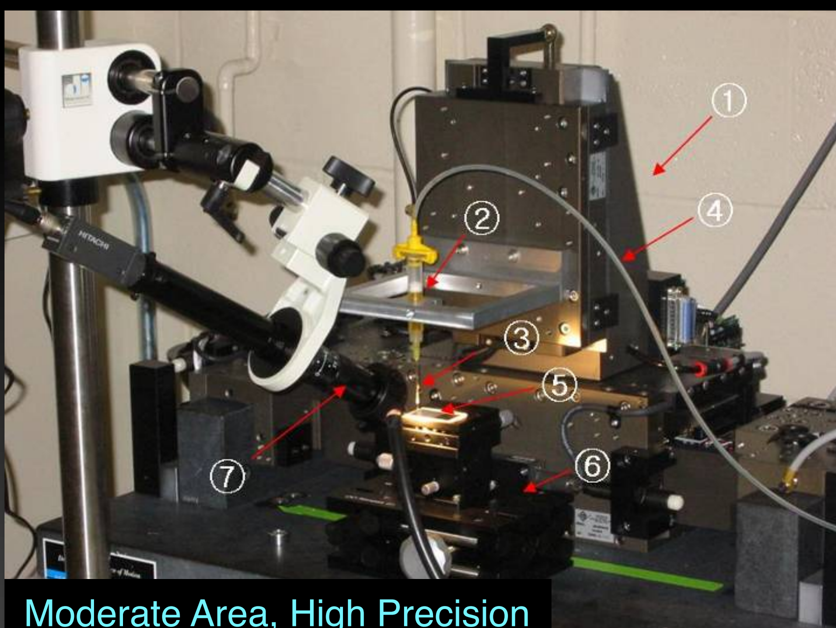




Custom stages designed for 3-D printing

3-axis, motion-controlled stages

- x-y-z translation distances, speeds, and positional accuracy
- constant pressure vs. displacement
- rotational axis
- pattern flexibility/control
- customized software



Moderate Area, High Precision

10x10x5 cm^3 ± 50 nm
V = 0.1 -10 mm/s

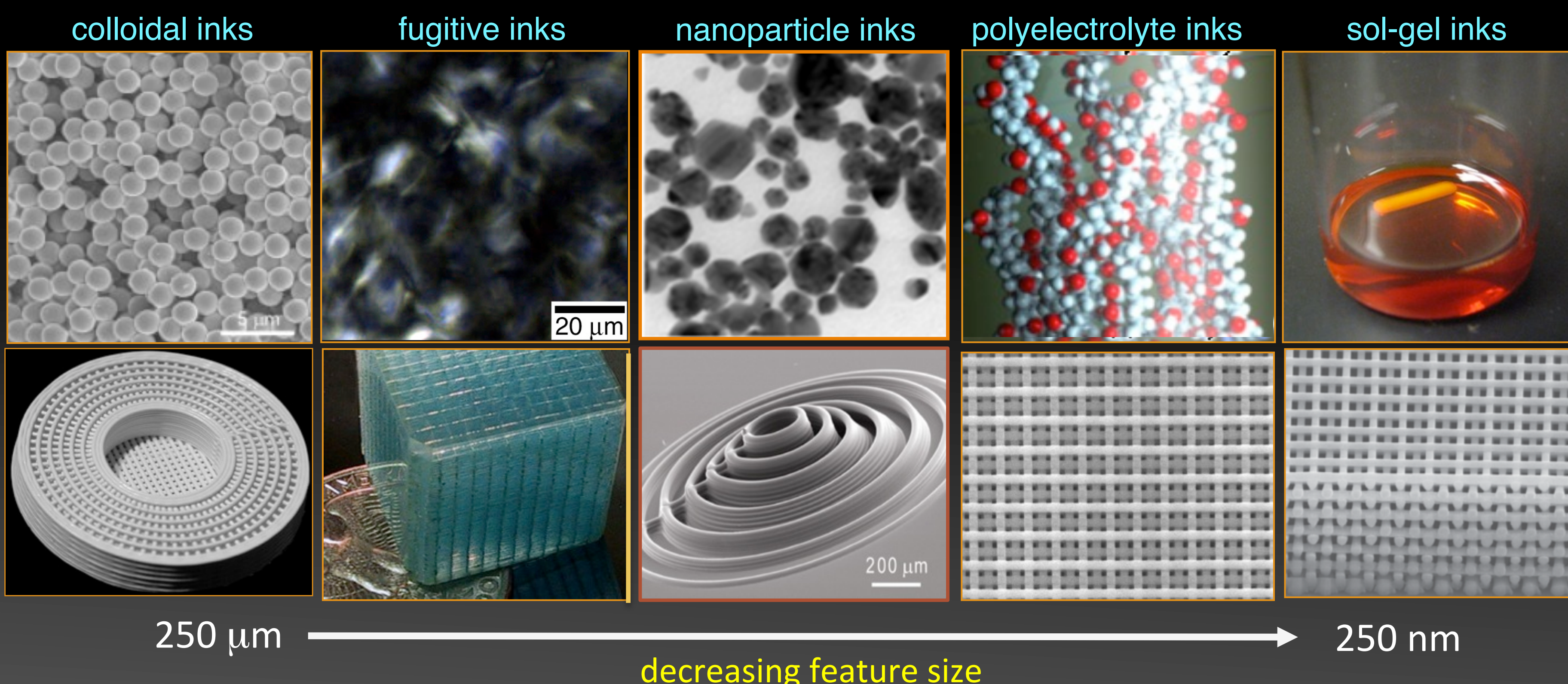
Large Area, High Speed Stage

$1 m^2$x10 cm ± 5 μm
V = 1 -1000 mm/s

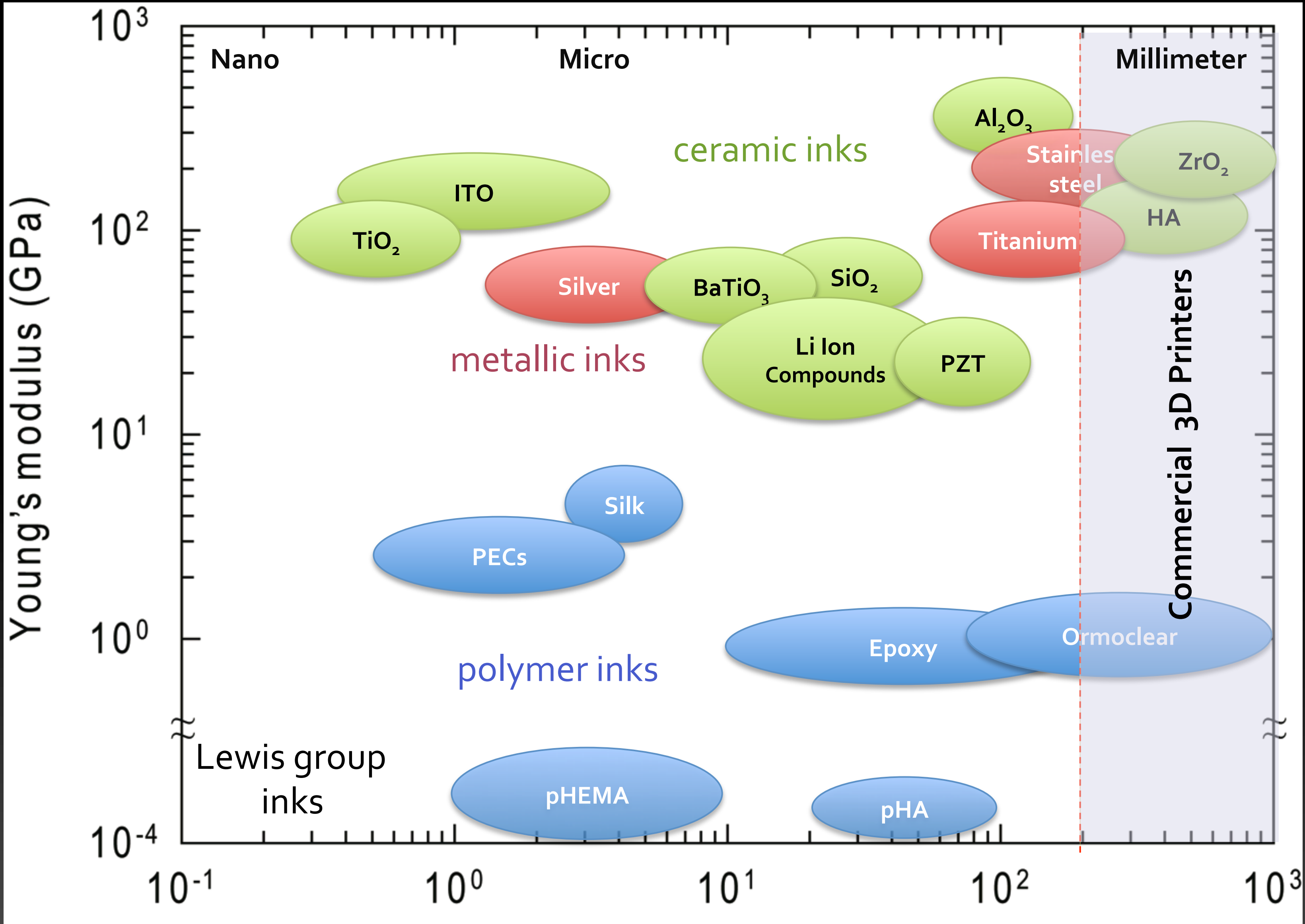
Custom inks designed for 3-D printing

Ink design and deposition

- ink must flow through nozzle without jamming
- ink filaments must form high integrity interfaces
- ink must solidify rapidly (via gelation, coagulation, or evaporation)
- concentrated inks minimize shrinkage during drying



We have printed multiple materials



> 40 papers, 7 patents

We have demonstrated several applications

Applications

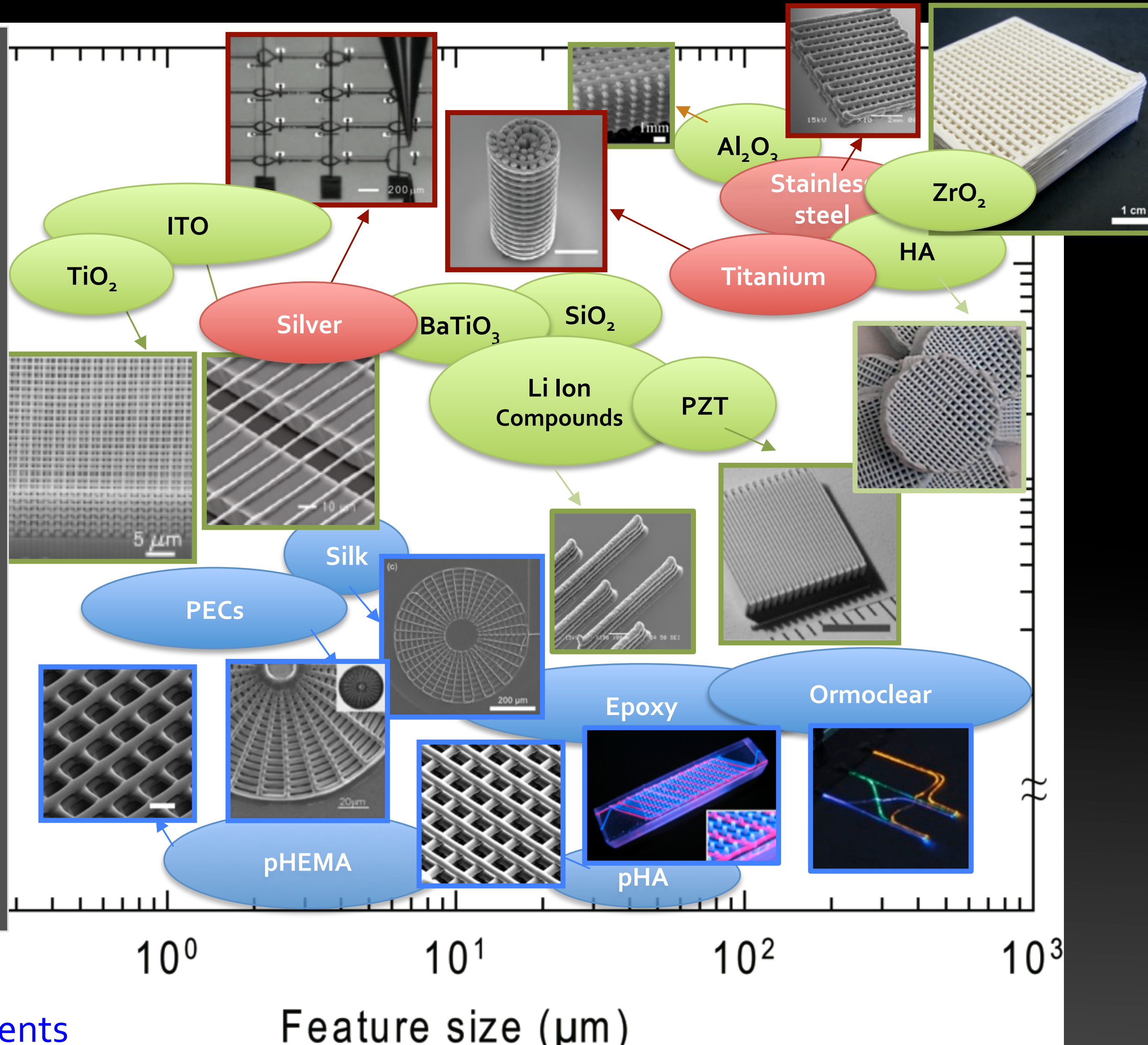
Electrical:
- Flexible electronics
- Transparent conductive surfaces
- Solar metallization
- 3D antennas

Sensors:
- PZT arrays
- Gas sensors

Structural:
- Lightweight structures
- Self-healing polymers
- Molten metal filters
- Al_2O_3/Al composites

Optical:
- PBG structures
- Polymer waveguides

and tissue scaffolds…



> 40 papers, 7 patents

Silver inks for flexible electronics

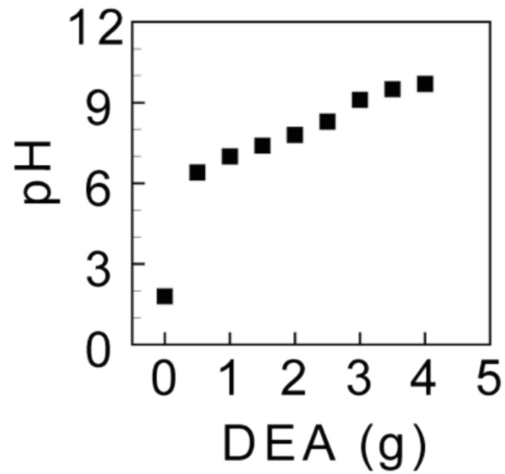
Starting Materials

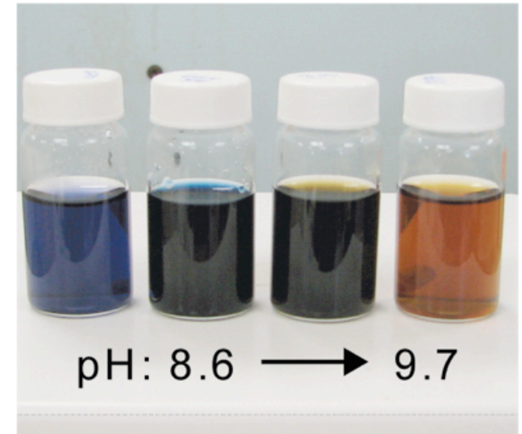
Silver source : $AgNO_3$

Stabilizer : Poly(acrylic acid), PAA

Reductant : Diethanolamine, DEA

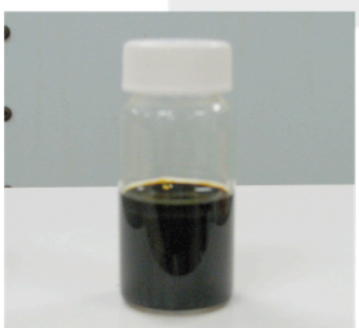
Solvent : Deionized H_2O

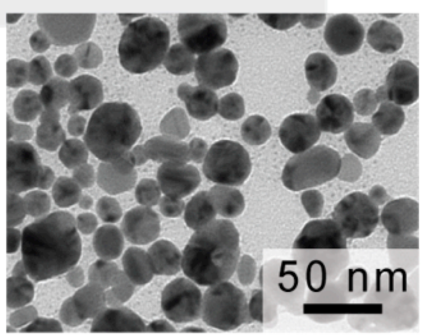




Particle Growth

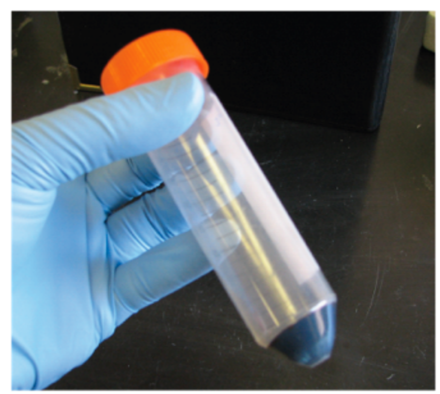
Sonication (60 °C, ~2 h)





20 nm average , 5 – 50 nm distribution

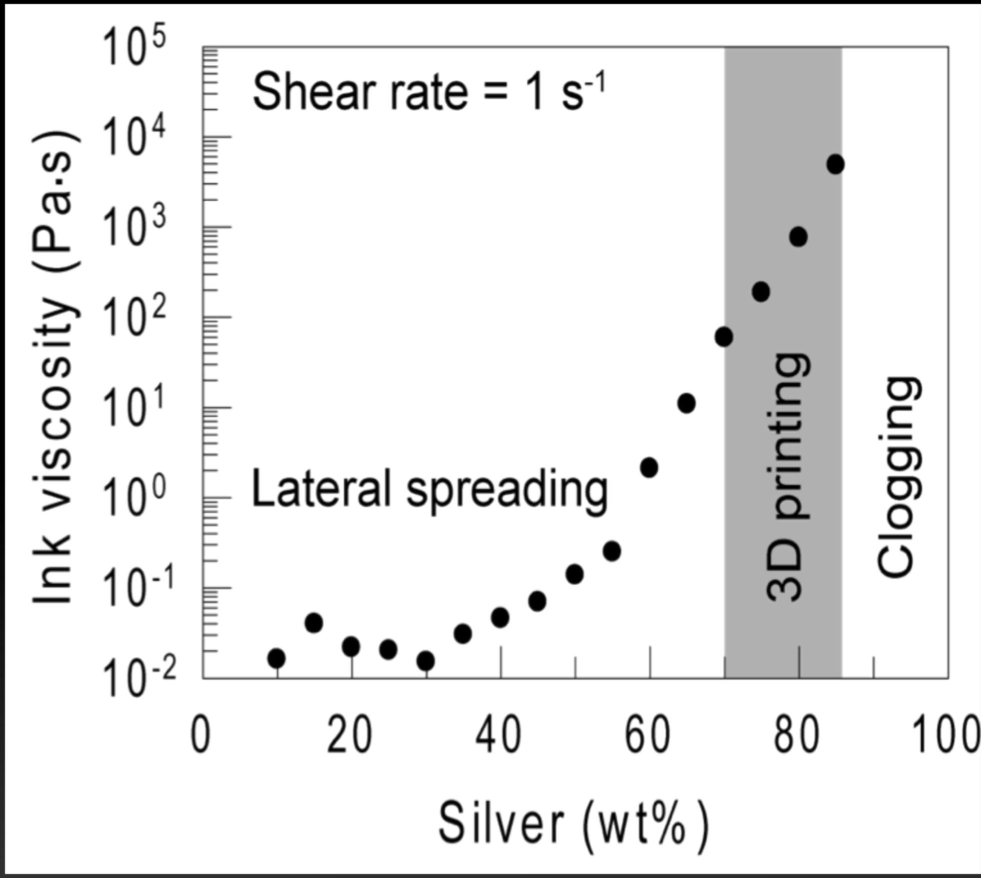
Phase Separation Centrifugation

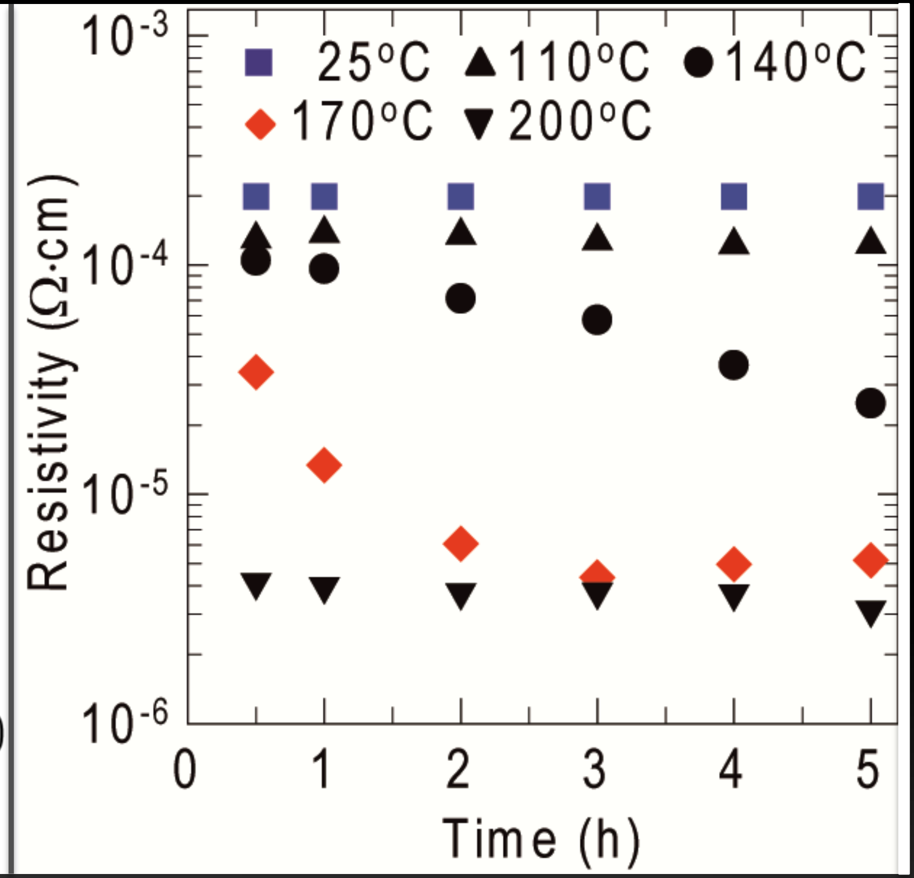


Homogenization Add Humectant

Ahn, Duoss, Nuzzo, Rogers, Lewis, et al., *Science* (2009); Ahn, Duoss, and Lewis, US-Patent 7,922,939

Silver inks for flexible electronics





Silver inks are highly conductive as-printed

Ahn, Duoss, Nuzzo, Rogers, Lewis, et al., *Science* (2009); Ahn, Duoss, and Lewis, US-Patent 7,922,939
Russo et al., Advanced Materials (2011)

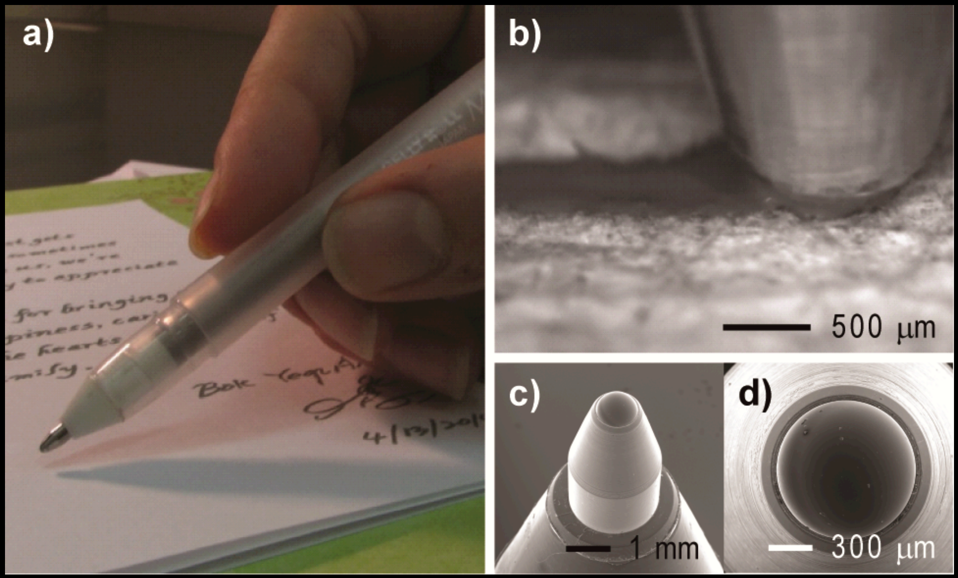
Pen-on-Paper flexible electronics

Fill rollerball pen with conductive silver ink

Print silver electrodes on paper

Printed electrodes are mechanically robust, electrically conductive

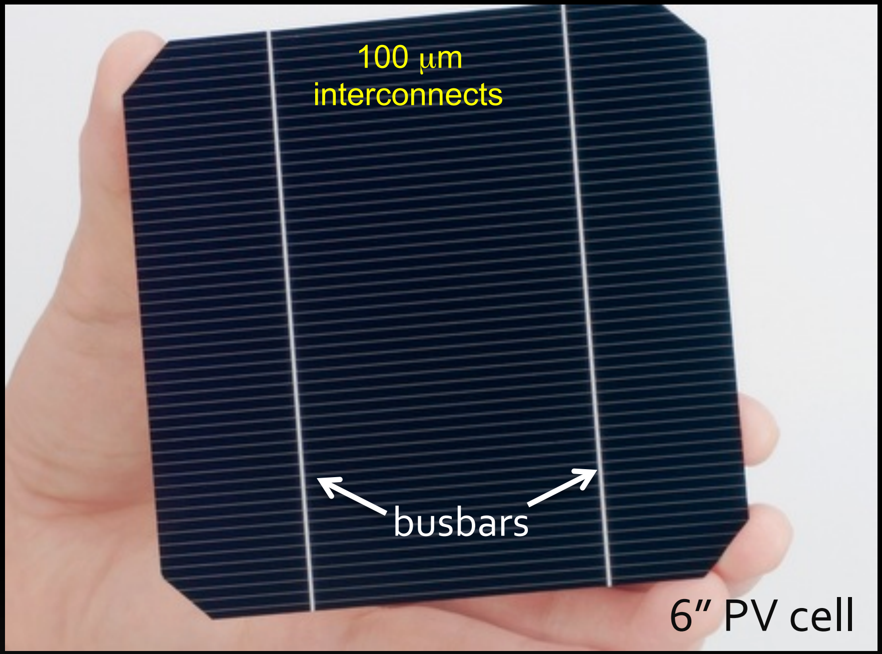
Integrate with surface-mounted LEDs



http://www.youtube.com/watch?v=dfNByi-rrO4

Ahn, Russo, Lewis, et al. *Advanced Materials (2011).*

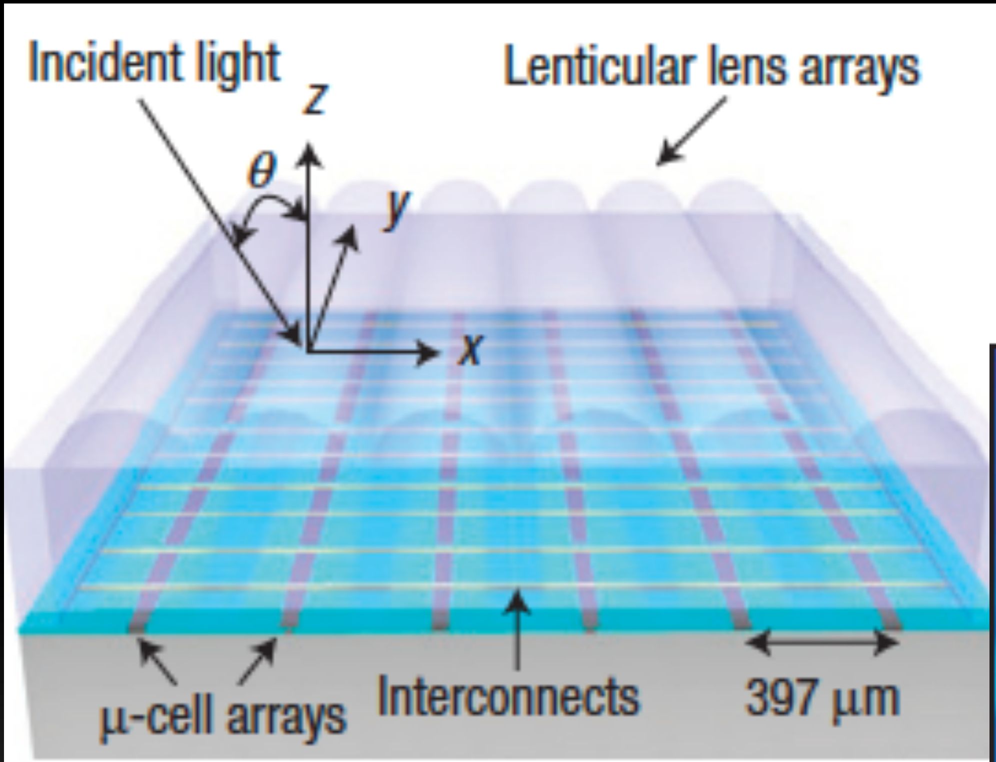
Solar Panels: Current Design



Rigid, costly, active materials* occupy large area

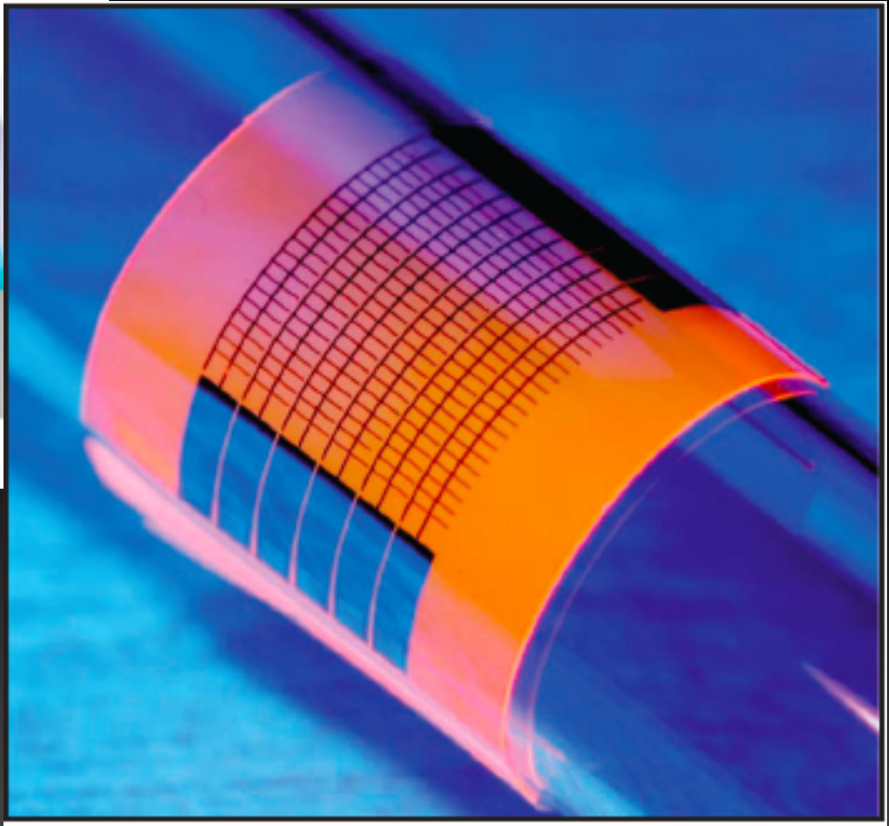
*silicon PV cells and silver interconnects

Flexible concentrator photovoltaics



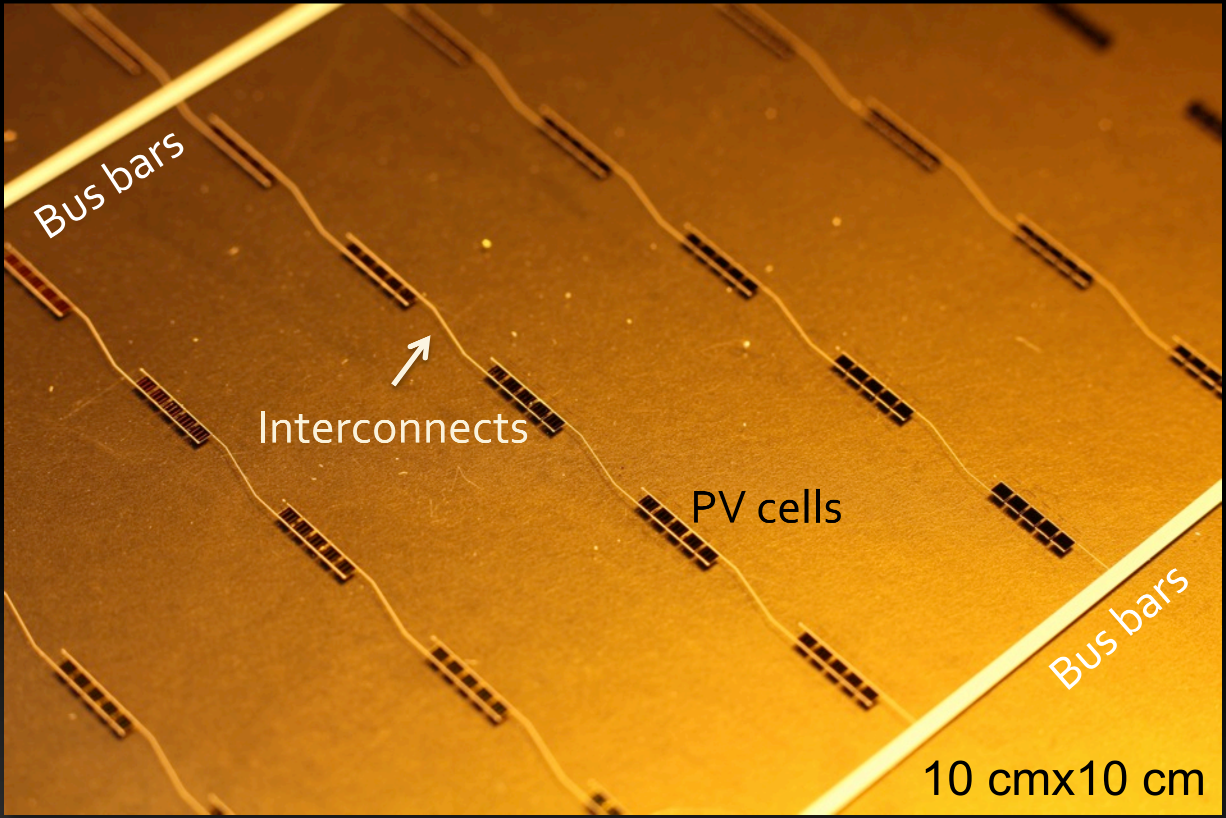
vast reduction in active materials used

Example:
Si microcells +
Luminescent layer
(UV-curable and organic dye)

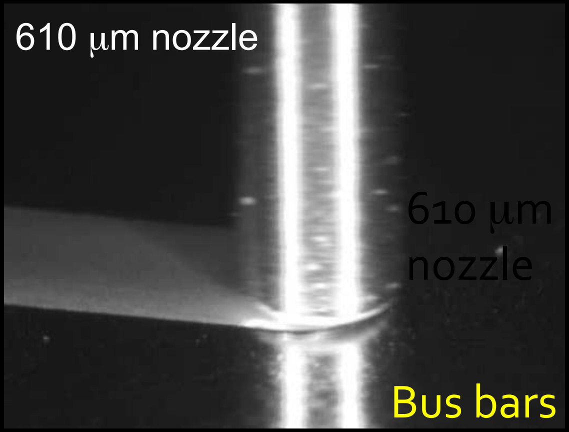


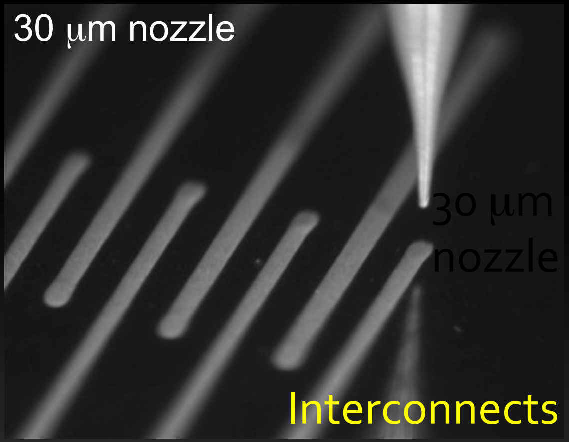
Rogers, Nuzzo,et al, *Nature Comm.* (2011).

Printing interconnects and bus bars



Sparse array of PV cells; finer interconnects

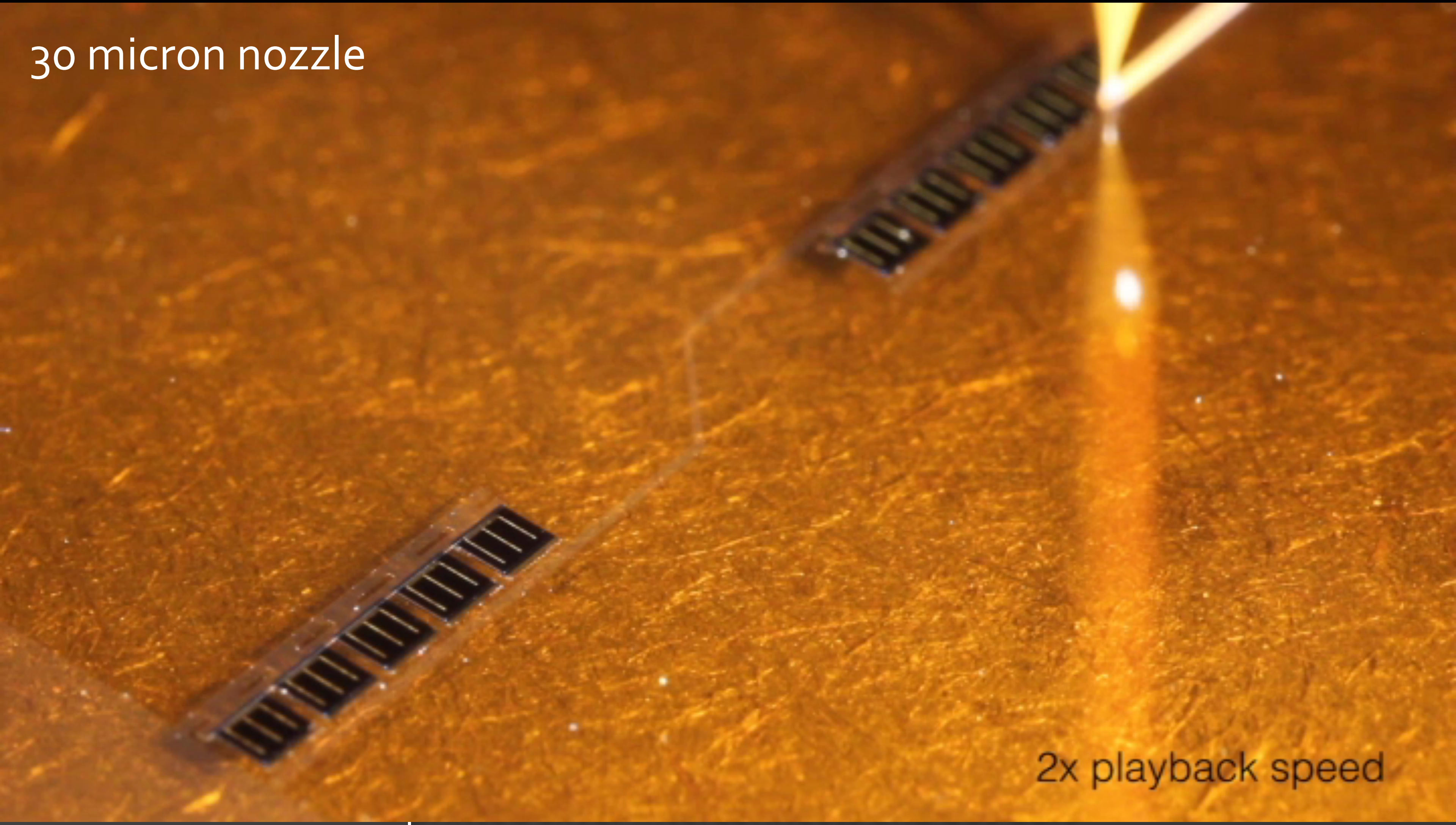




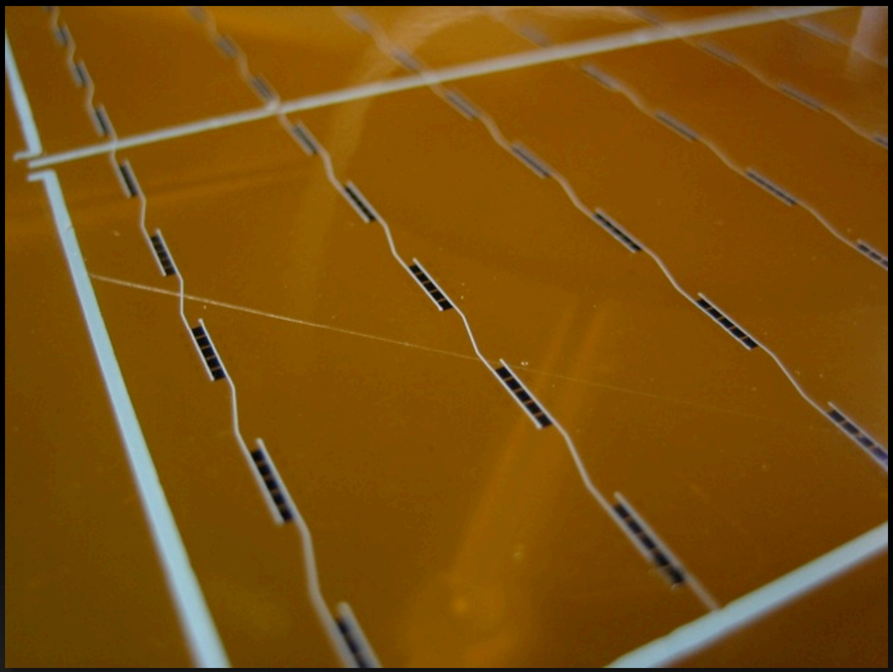
PV microcells populated on 6” glass wafer with printed silver interconnects and bus bars

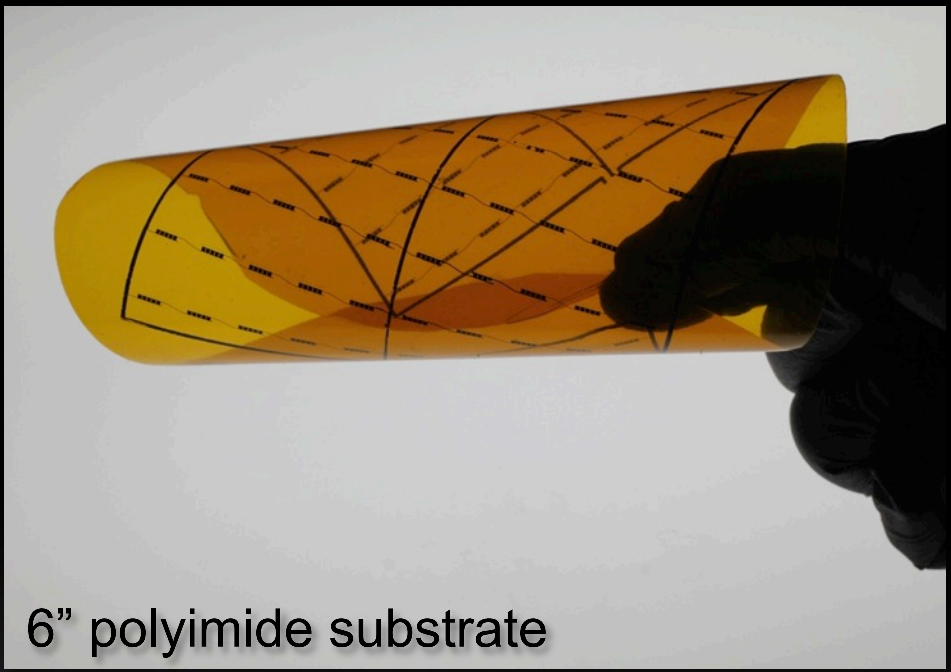
In collaboration with Semprius and SAIC

Printing interconnects



Flexible concentrator photovoltaics





6” polyimide substrate

Printed interconnects are highly flexible and can withstand repeated bending (1000’s cycles) without performance loss

In collaboration with Semprius and SAIC

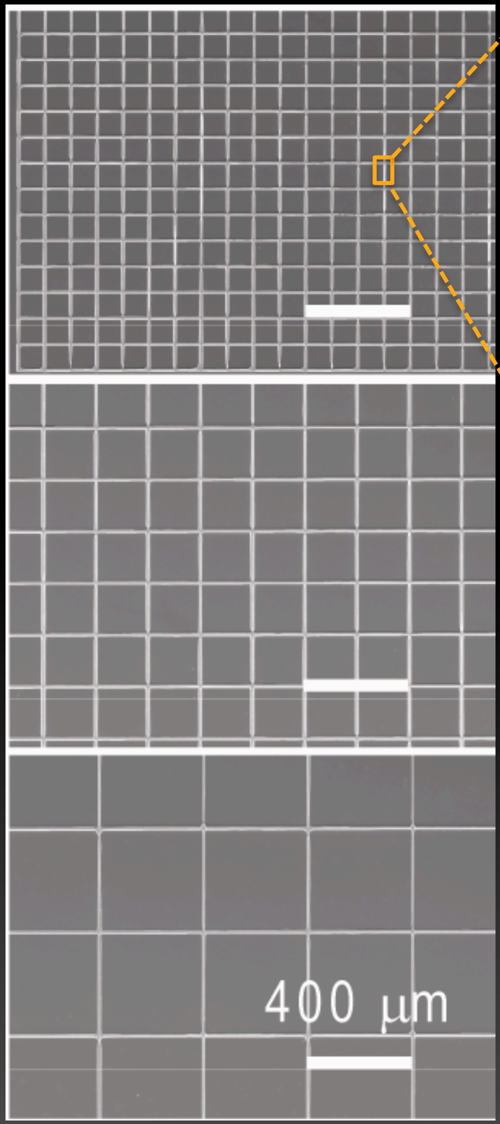
Transparent silver microgrids

Grid spacing:

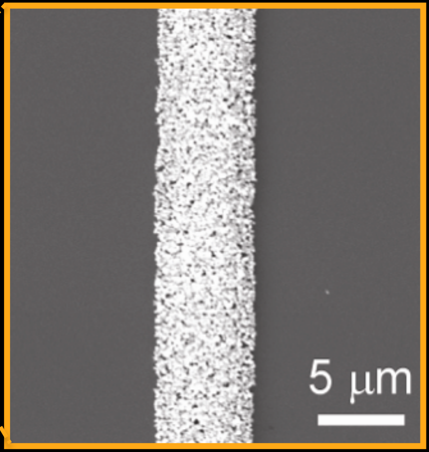
100 µm

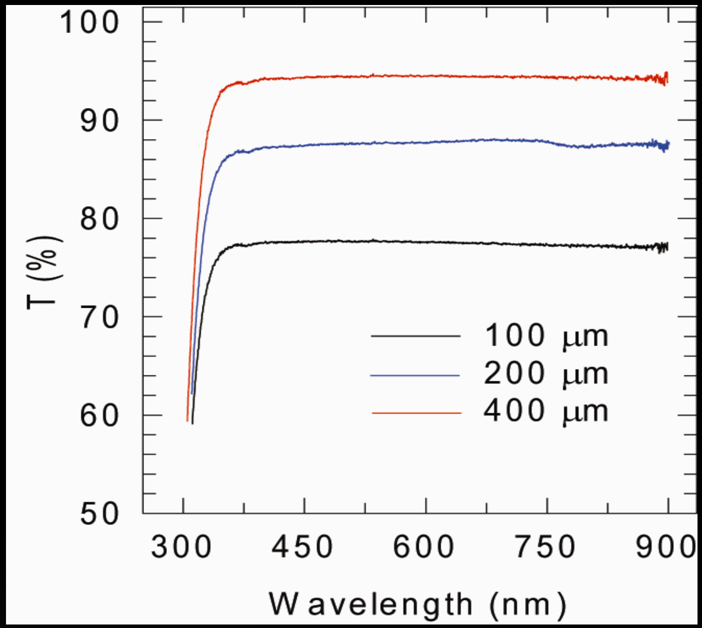
200 µm

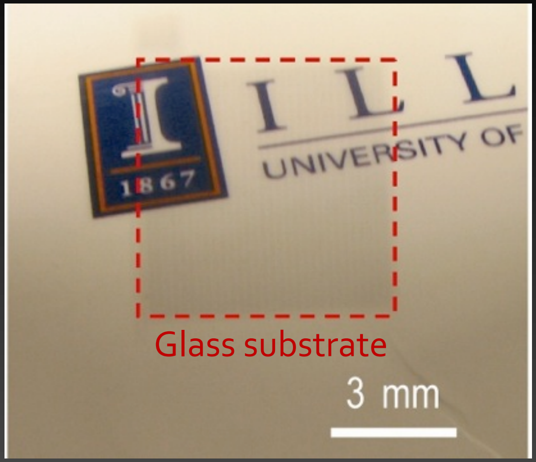
400 µm

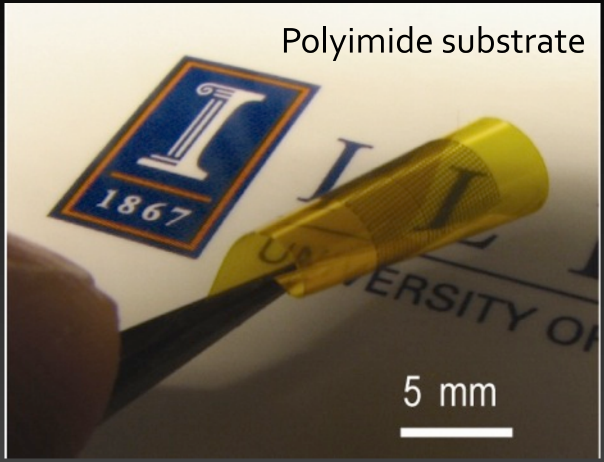


5 µm nozzle





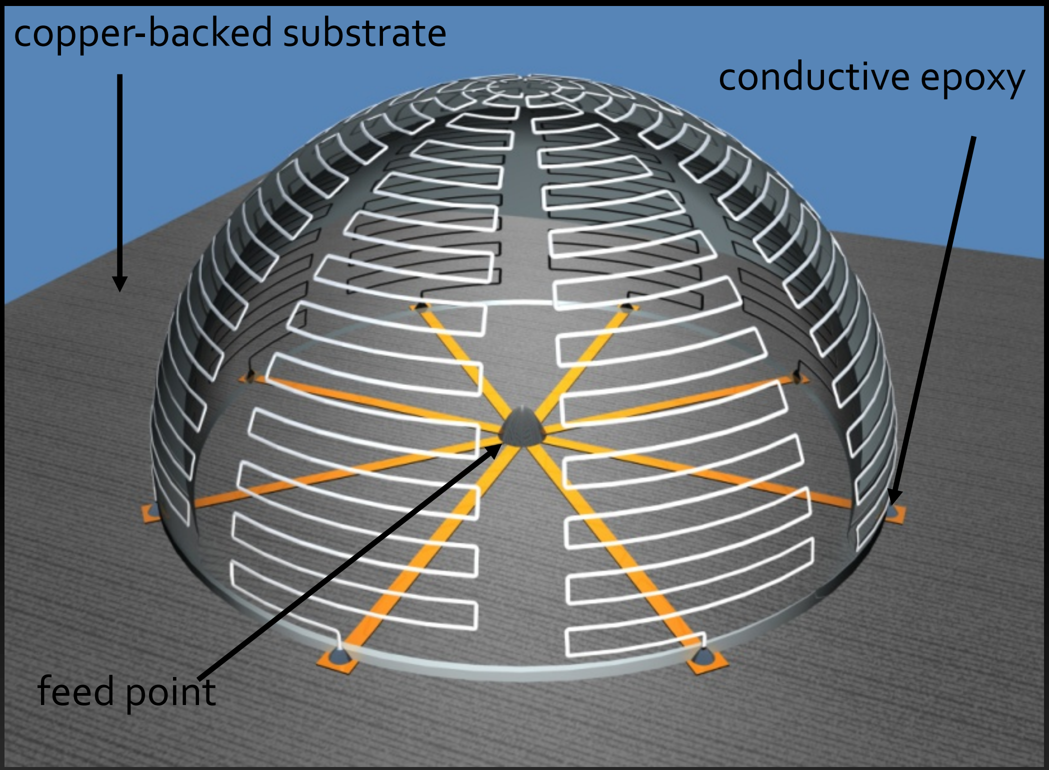


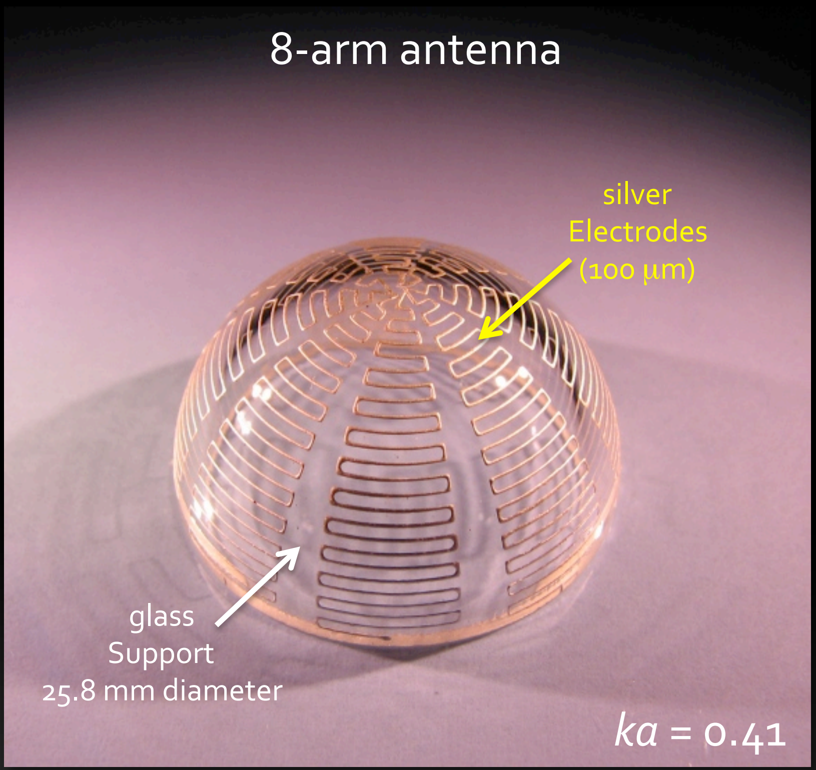


200 µm grid spacing

Ahn, Lorang, Lewis, *Nanoscale* (2011)

Conformal printing of electrically small antennas





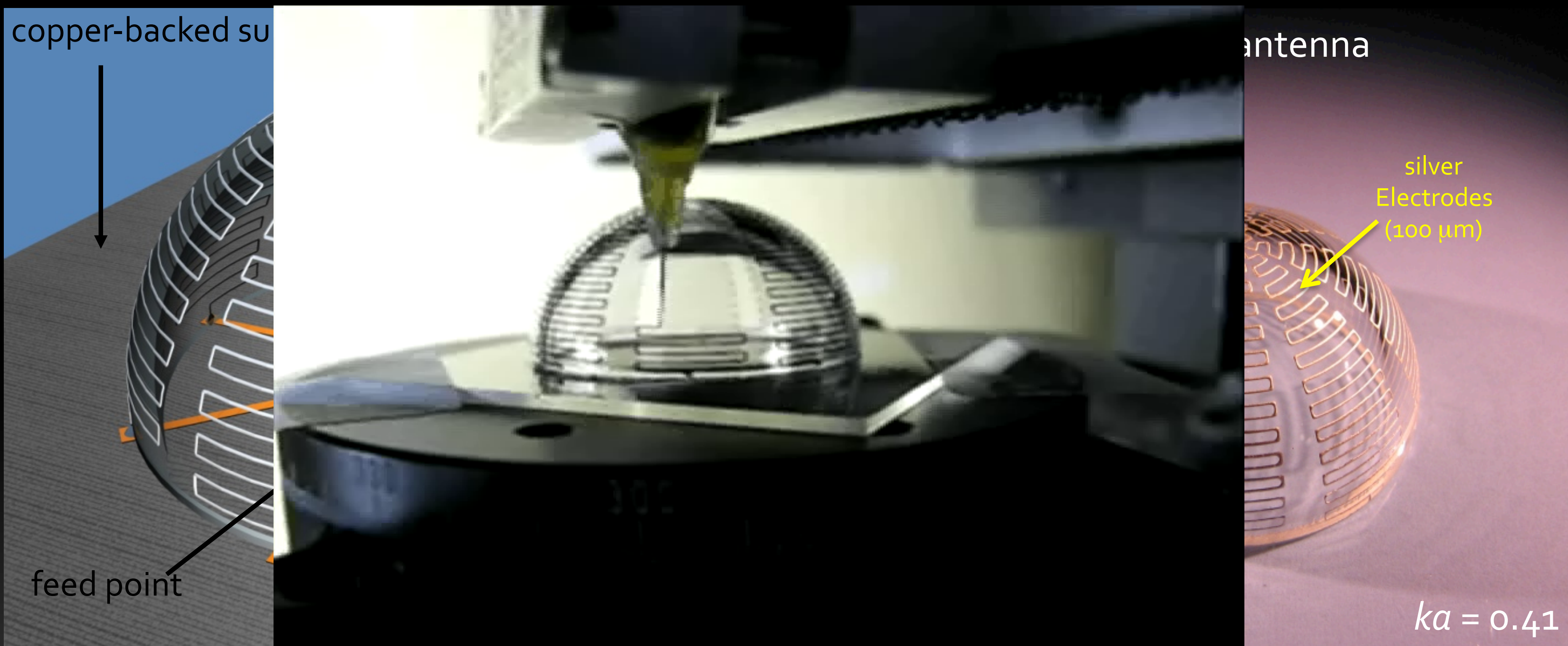
with Bernhard group (ECE @ Illinois)

$$k = \frac{2\pi}{\lambda_0}$$

ka < 0.5 indicates an electrically small antenna (ESA)

Adams, Duoss, Malkowski, Ahn, Nuzzo, Bernhard, Lewis, *Advanced Materials* (2011)

Conformal printing of electrically small antennas



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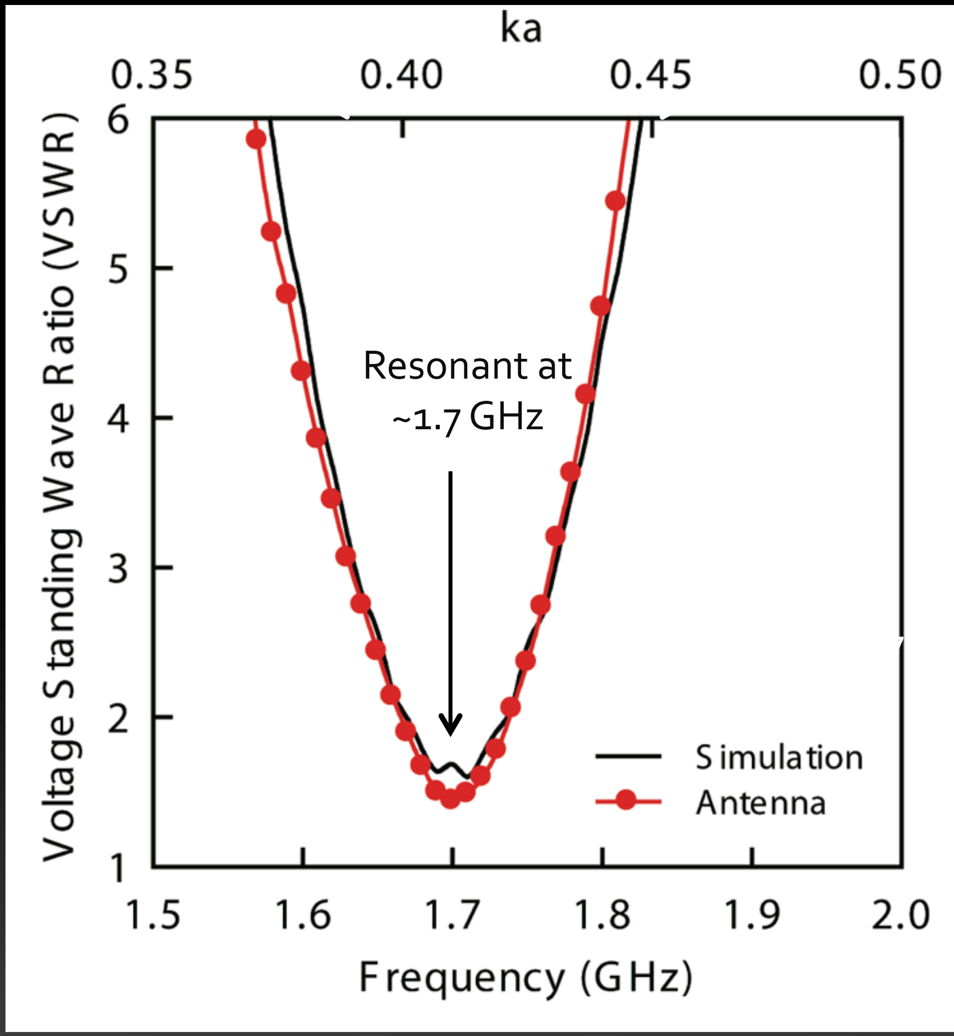
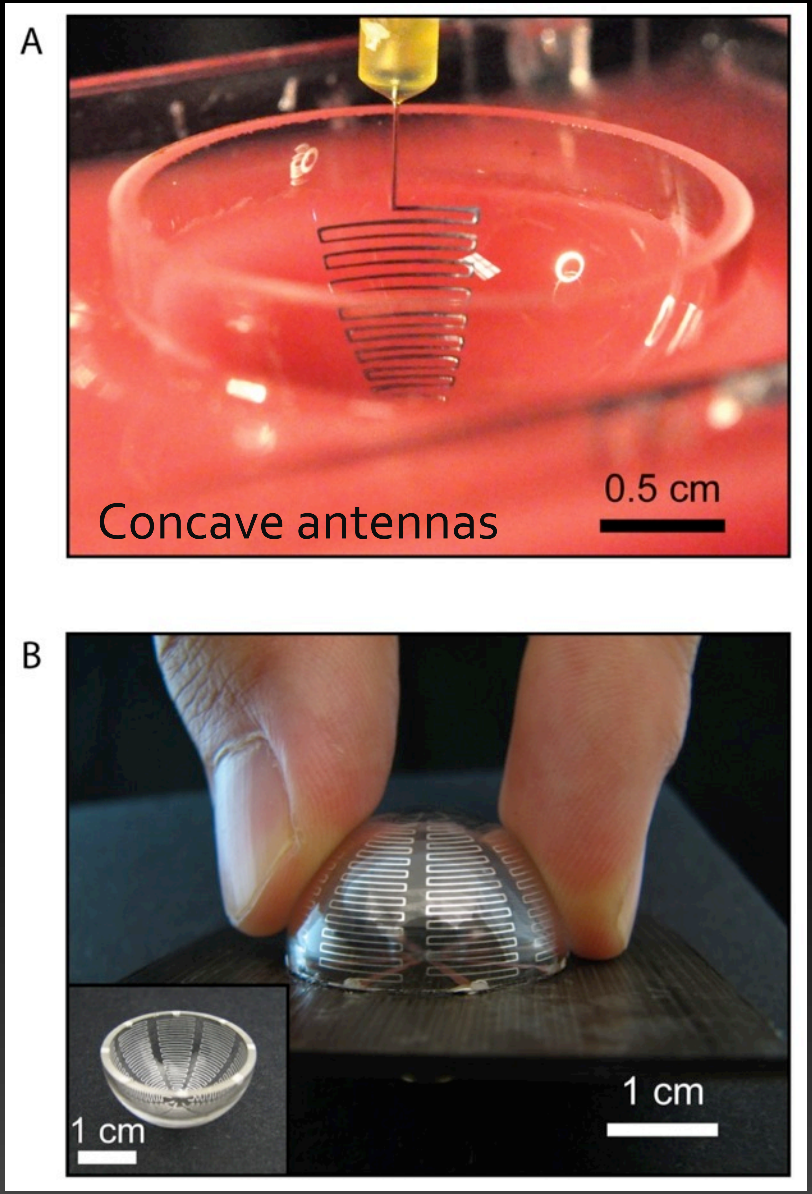
Adams, Duoss, Malkowski, Ahn, Nuzzo, Bernhard, Lewis, *Advanced Materials* (2011)

Performance characteristics

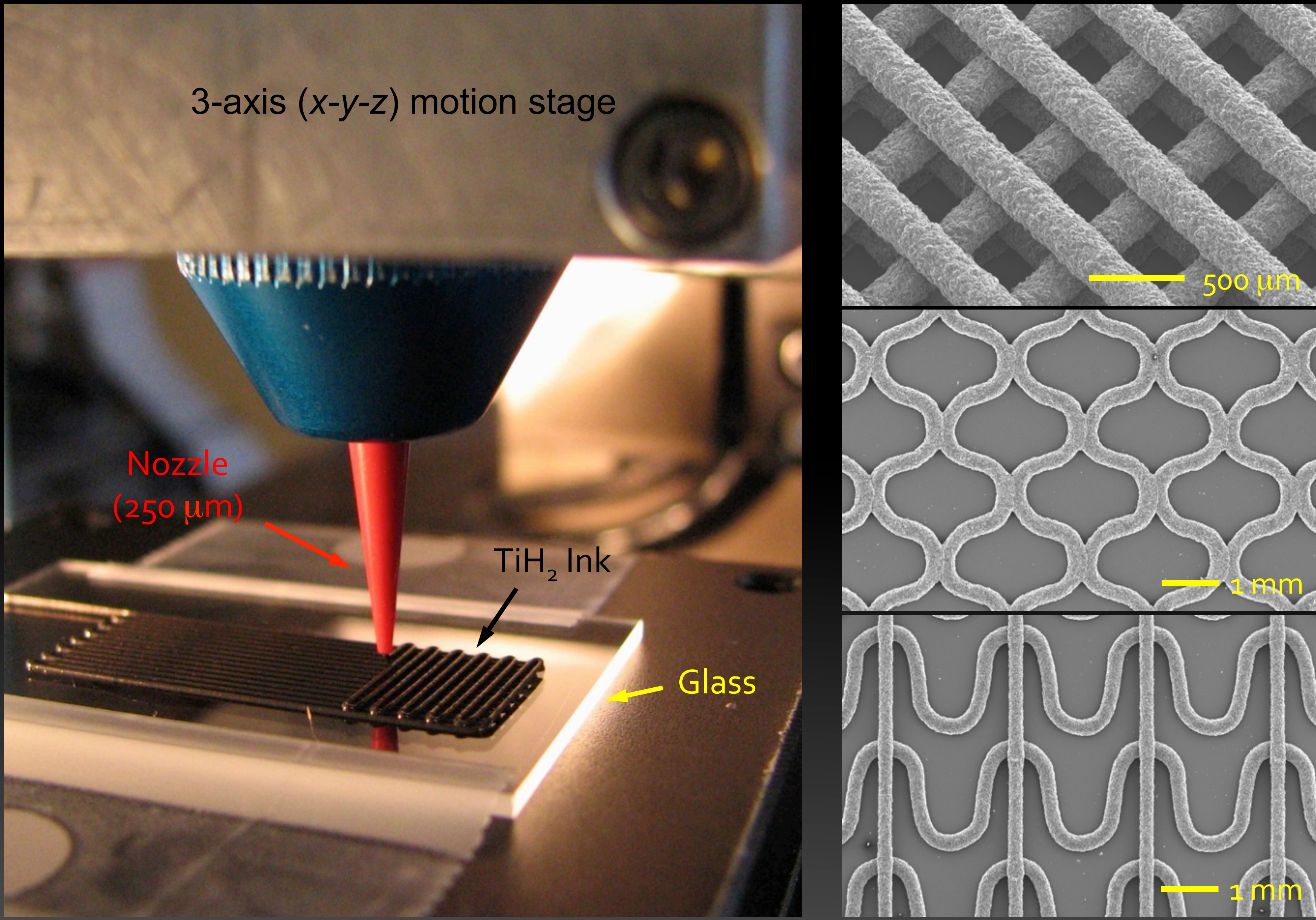




VSWR: a measure of signal reflected at component junctions
Ideally, VSWR = 1 (no reflected power, no mismatch loss)

Adams, Duoss, Malkowski, Ahn, Nuzzo, Bernhard, Lewis, *Advanced Materials* (2011)

Printed origami – simple route to complex 3D forms



Ahn, Shoji, Hansen, Hong, Dunand, Lewis, *Advanced Materials* (*2010*); *Advanced Engineering Materials* (2011)

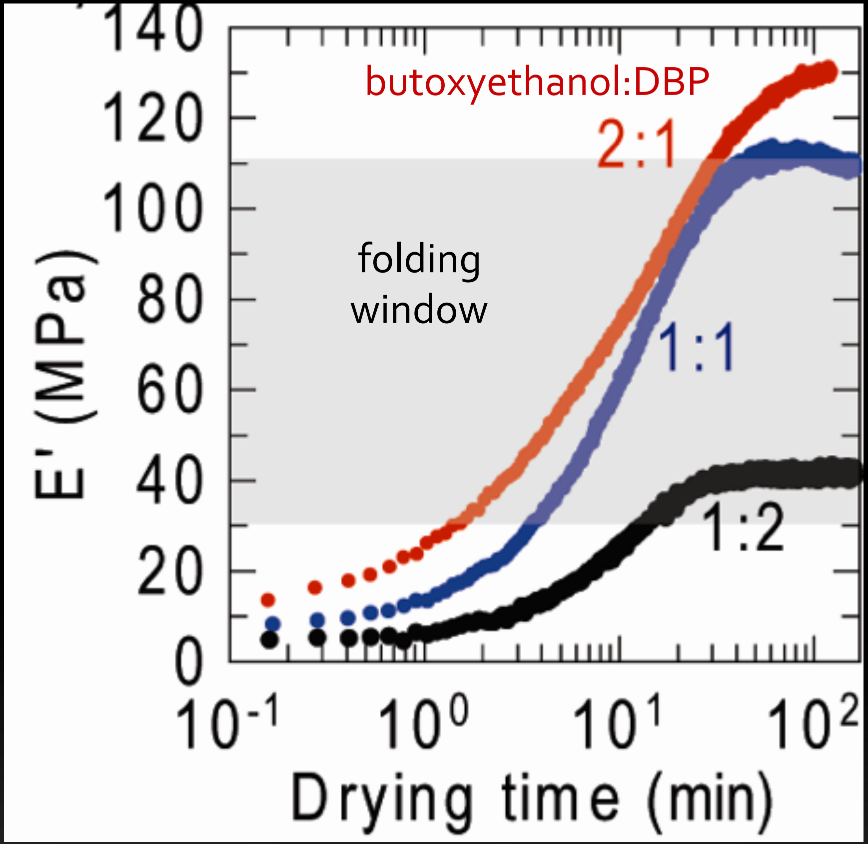
Ink designs for printed origami

Ink Composition:

- TiH_2 particles
  (mean diameter = 0.1, 22, or 65 μm)

- PMMA-PnBA-PMMA binder

- Graded volatility solvent system
  - dichloromethane (bp = 40°C)
  - 2-butoxyethanol (bp = 171°C)
  - dibutyl phthalate (bp = 340°C)



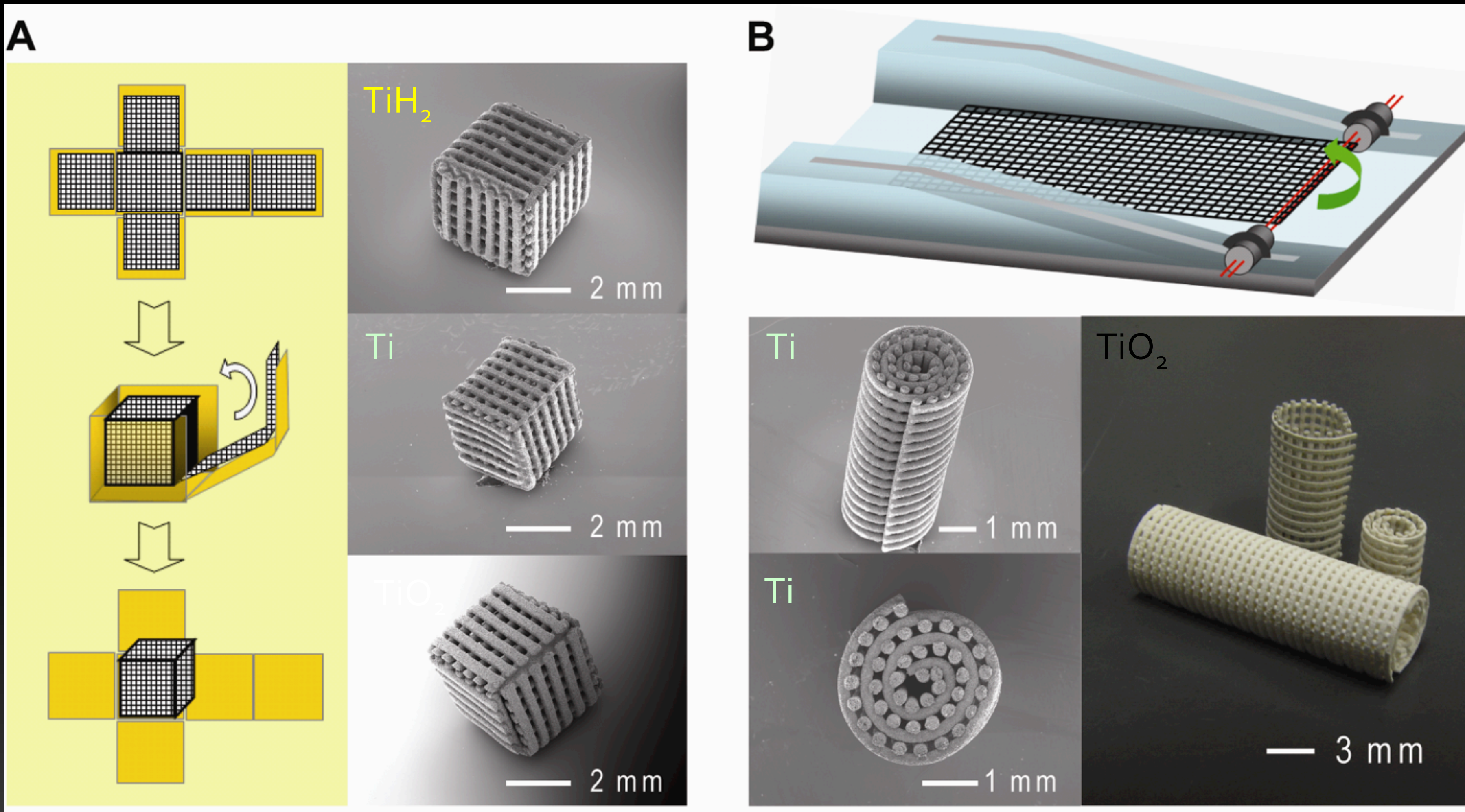
- Graded volatility solvent system enables control of elastic property evolution

- Wet-folding origami requires that printed features retain their pliability, while being strong enough to handle and manipulate

Ahn, Shoji, Hansen, Hong, Dunand, Lewis, *Advanced Materials* (*2010*)

R. J. Lang, *Origami Design Secrets: Mathematical Methods for an Ancient Art*, A K Peters, Ltd., MA, USA, **2003**, p.11.

Methods of folding and rolling

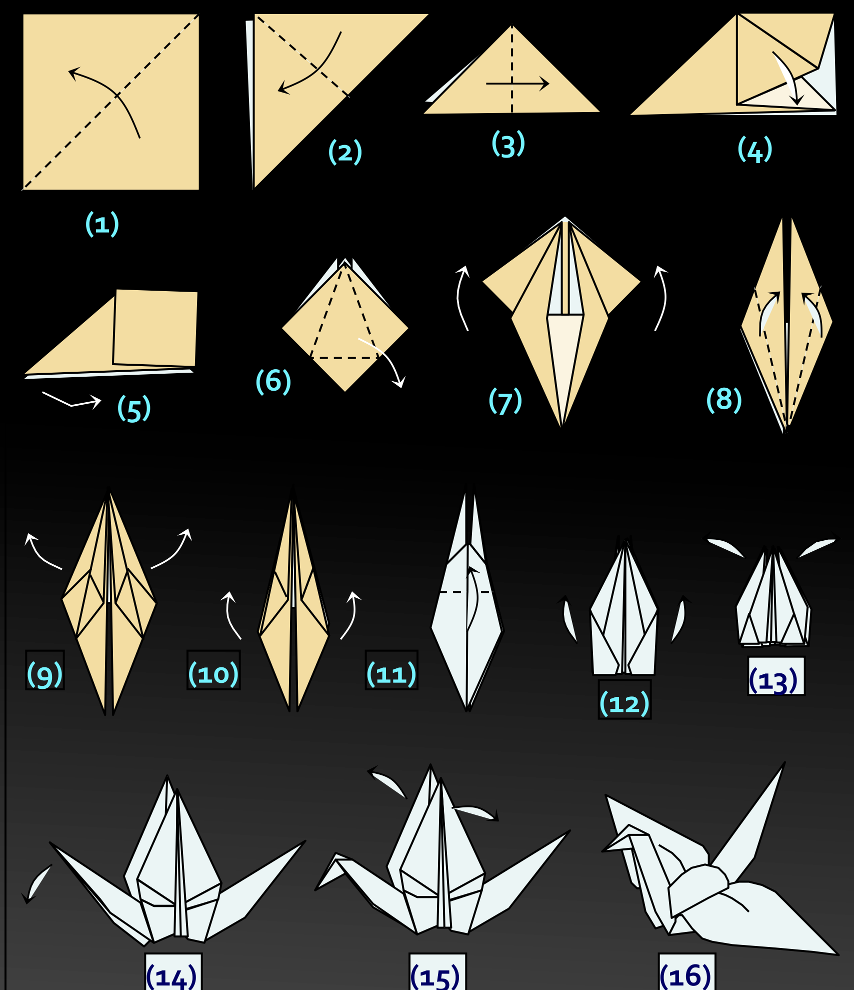


Box structure: as-prepared (top), annealed at 1050°C in vacuum (middle), and in air (Bottom).
Cylindrical tower: annealed at 1050°C in vacuum (left) and in air (right).

Ahn, Shoji, Hansen, Hong, Dunand, Lewis, *Advanced Materials* (*2010*)

Titania Structure

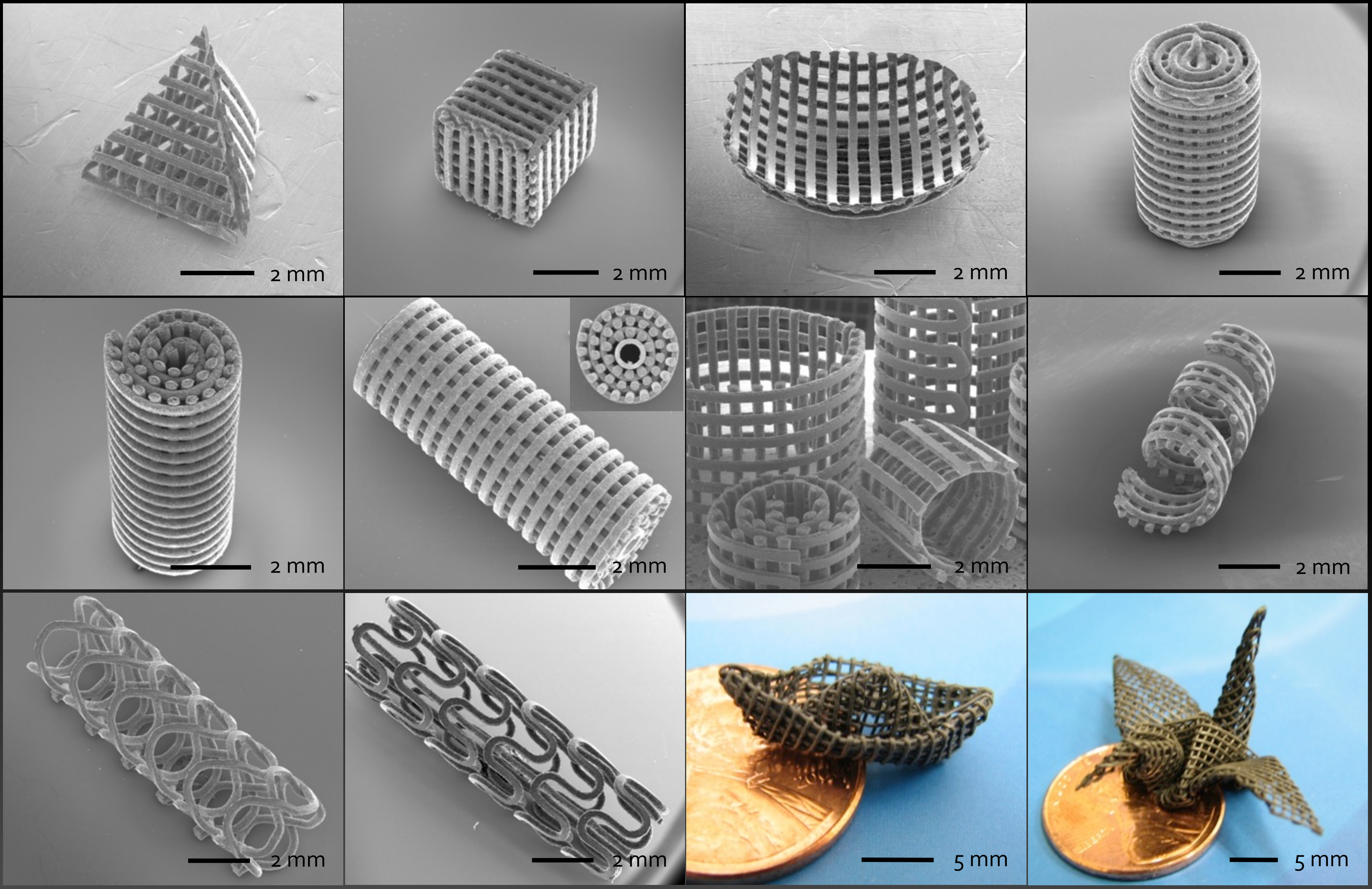
Schematic of Folding Scheme



Annealed at 1050°C for 2 h in air.

Ahn, Shoji, Hansen, Hong, Dunand, Lewis, *Advanced Materials* (*2010*)

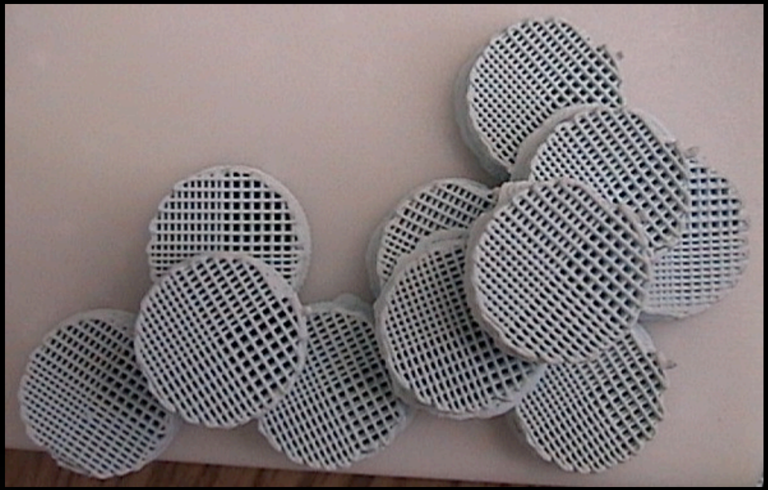
Titanium Structures



Ahn, Shoji, Hansen, Hong, Dunand, Lewis, *Advanced Materials* (*2010*)

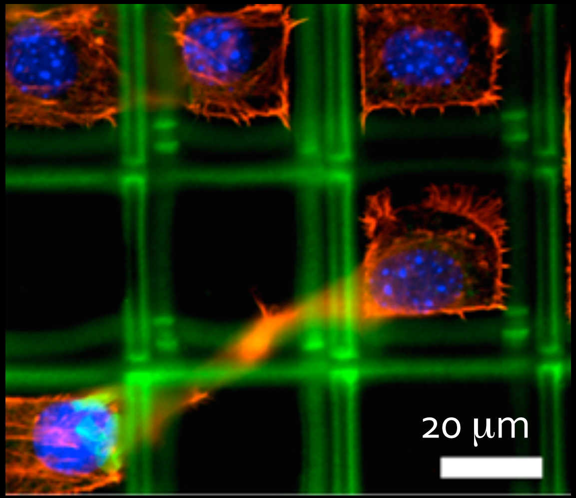
Printing 3D scaffolds for tissue engineering

Hydroxyapatite Scaffolds

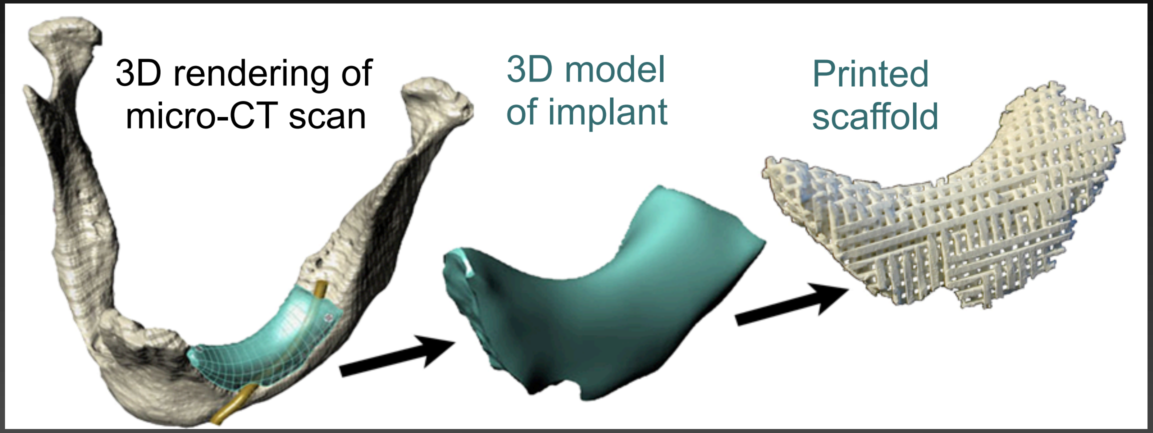


Michna, Wu, Lewis, ***Biomaterials*** (2005); Simon et al, ***JBMR*** (2007)

Hydrogel Scaffolds

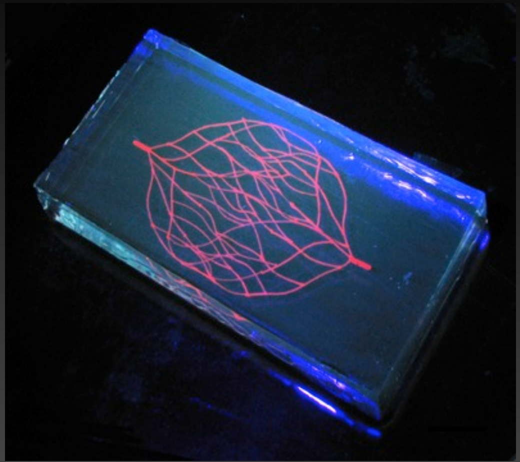


Barry, Shepherd, et al., ***Adv. Mater***. (2008).



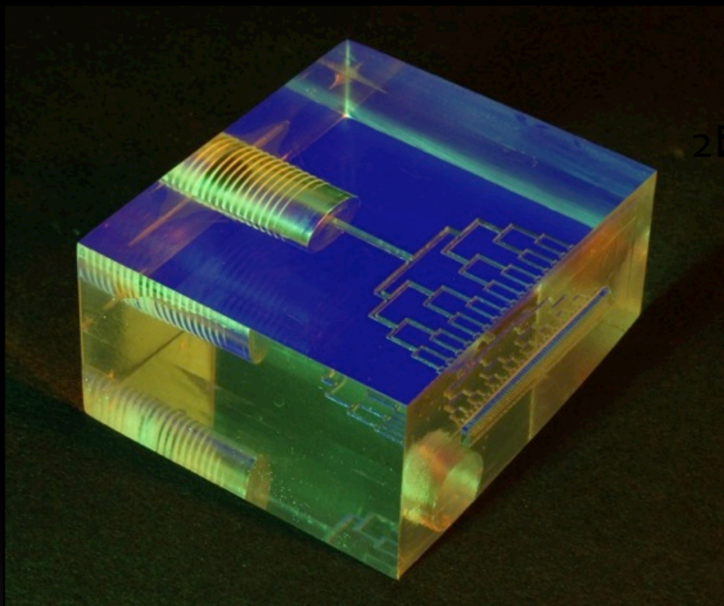
Lewis, Smay, Stuecker, Cesarano, ***J. Am. Ceram. Soc***. (2006)

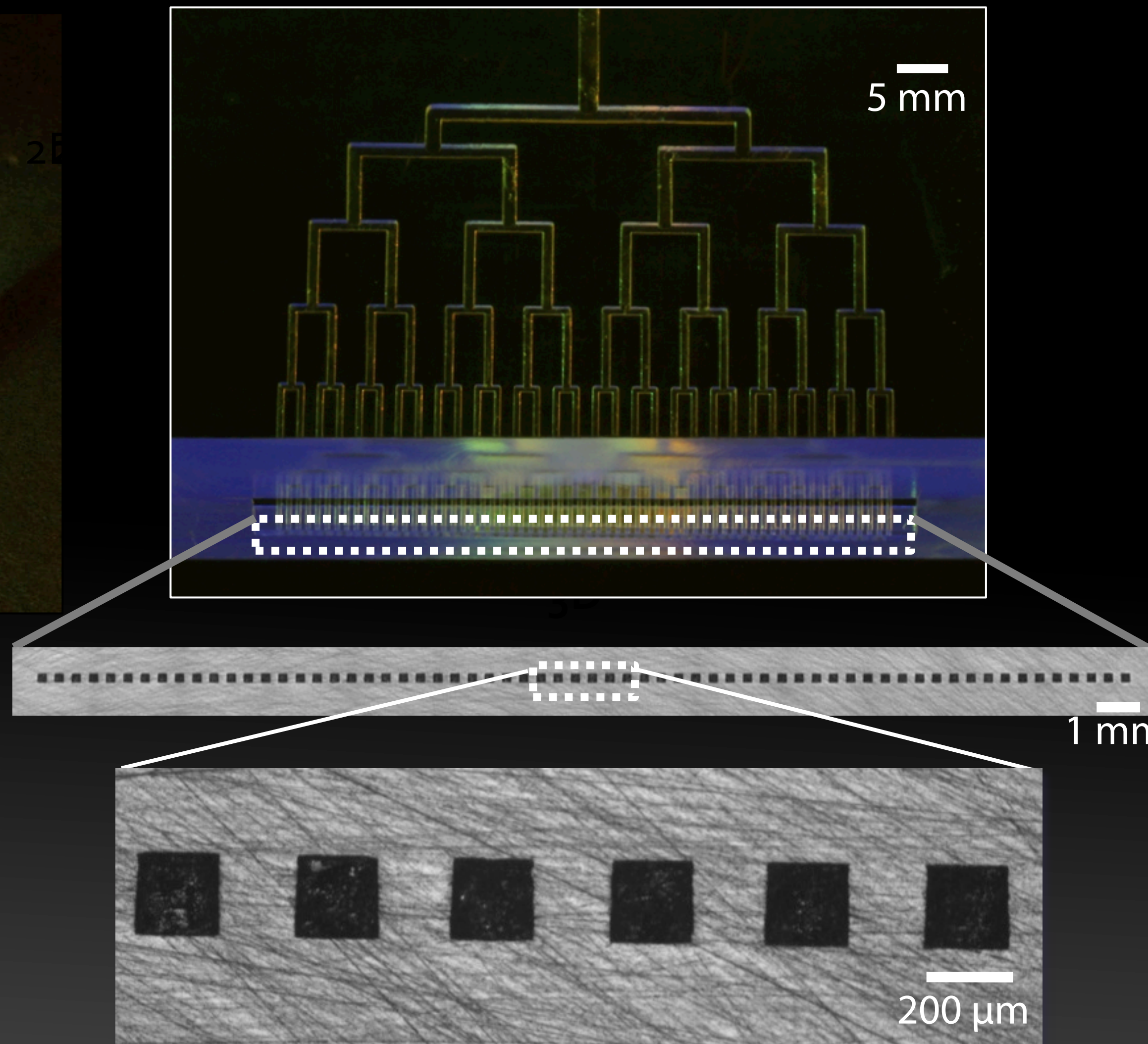
Microvascular Networks



Wu, Deconinck, Lewis, ***Adv. Mater***. (2011)

High throughput printing via multinozzle arrays





Multinozzle design based on Murray's law:

$$r_{parent}^3 = \sum r_{branch\_generation}^3$$

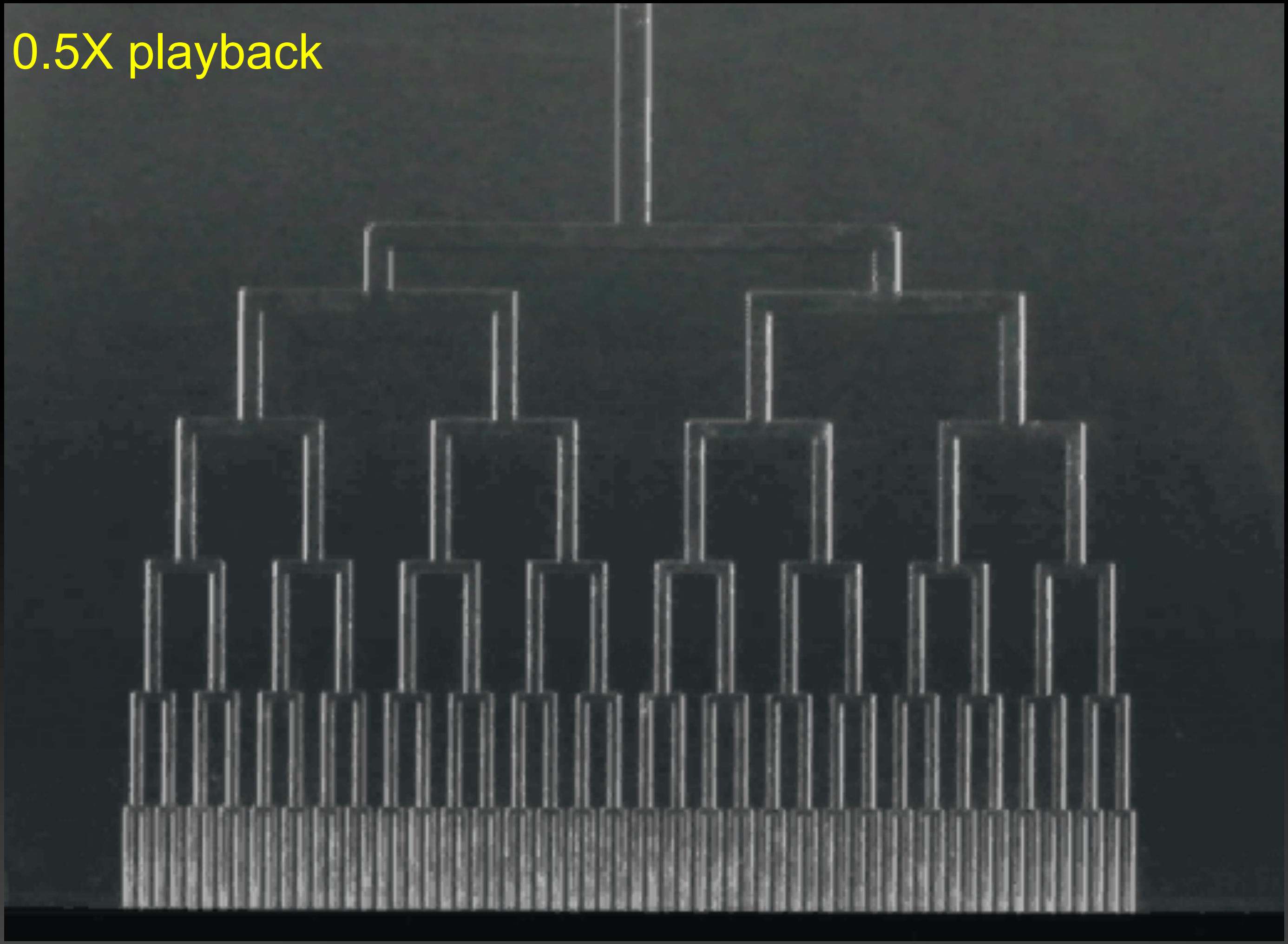
Hierarchical branching network
Created by CNC milling

All 64 nozzles are 205±3 µm on a side

Hansen, Vericella, Lewis, unpublished.

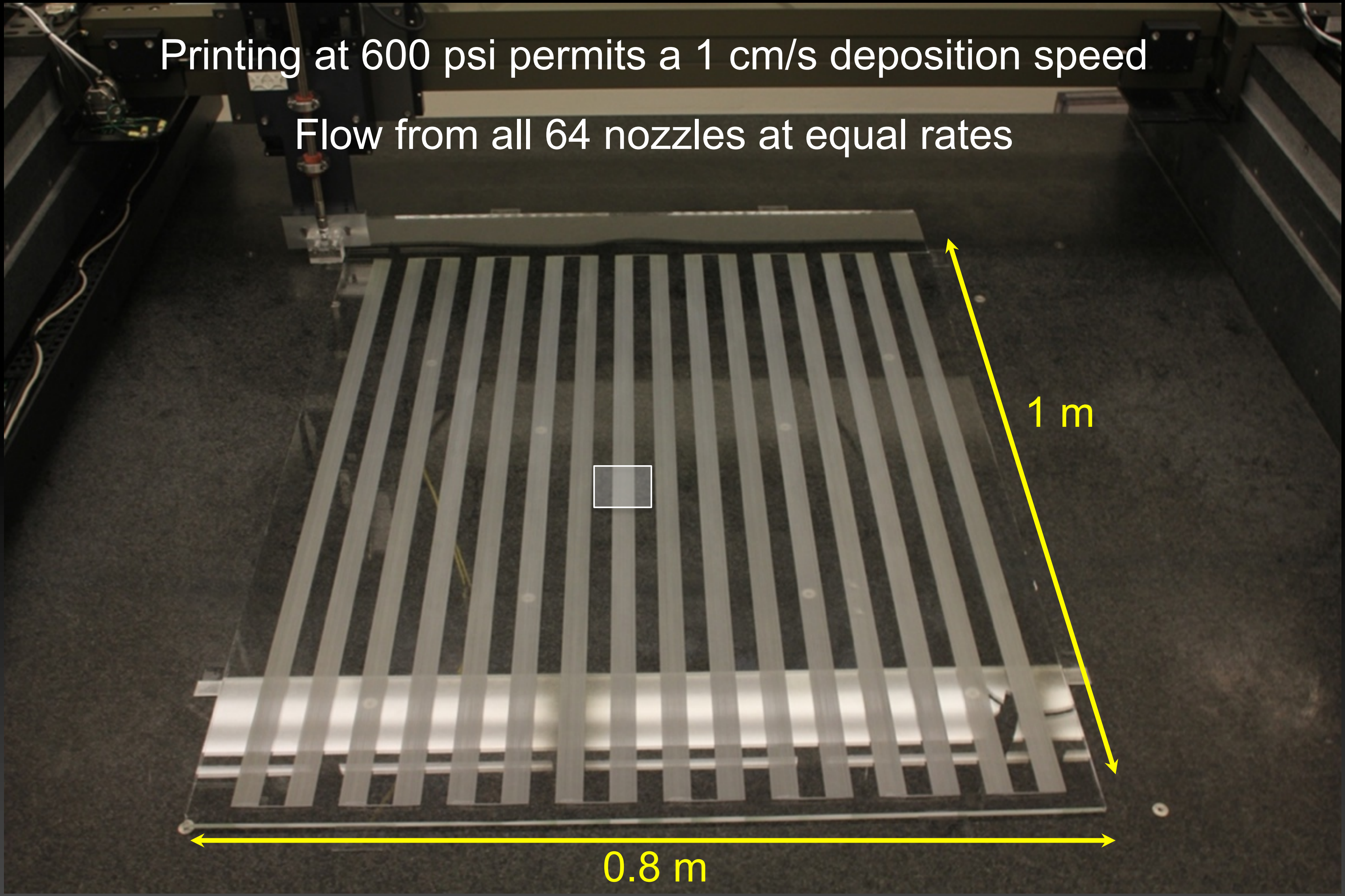
Multinozzle arrays – Direct imaging of ink flow

Fugitive ink printed with an applied pressure of 2 MPa (300 psi)



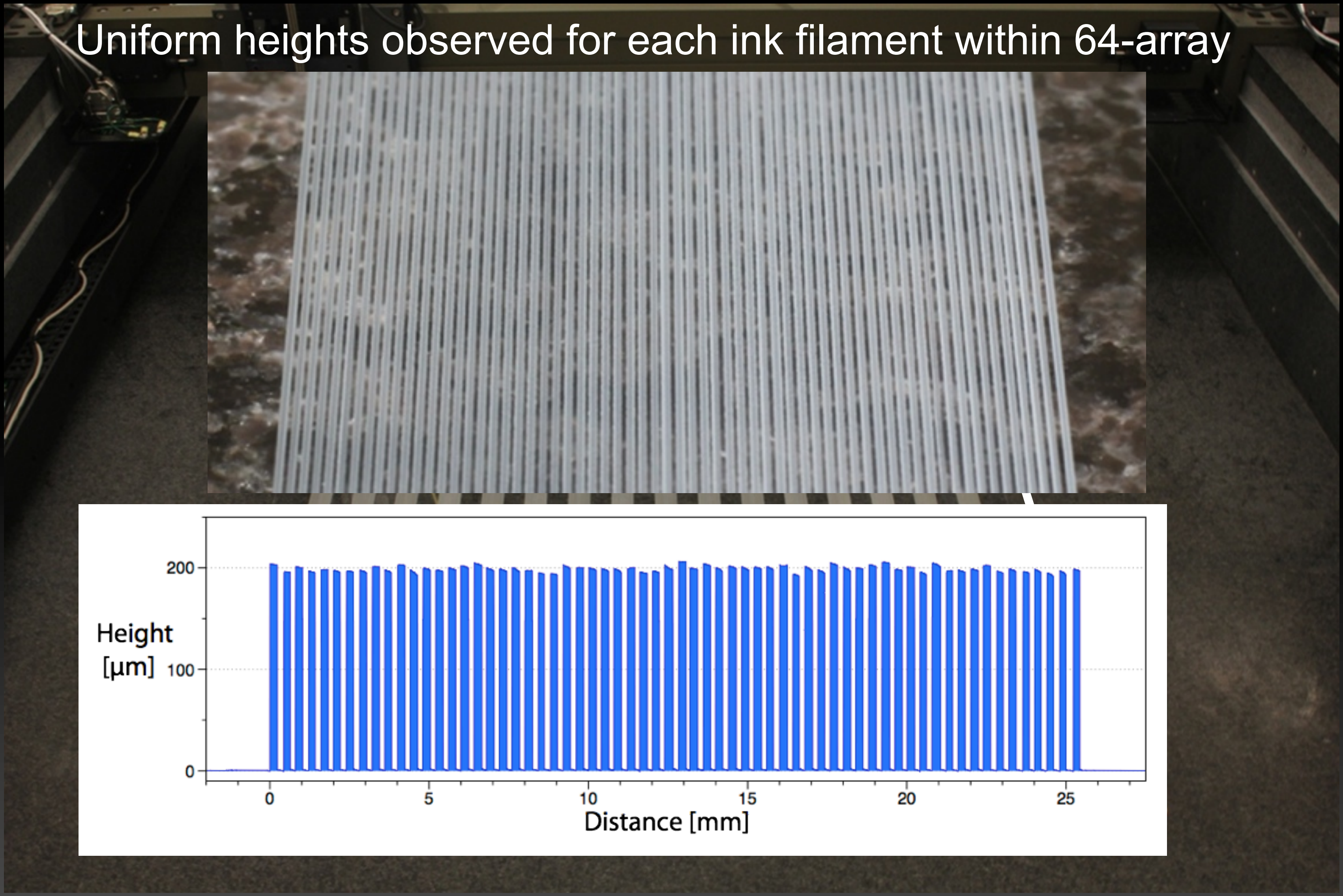
Flow velocity
~ 5 mm/s

Multinozzle arrays – Large area printing



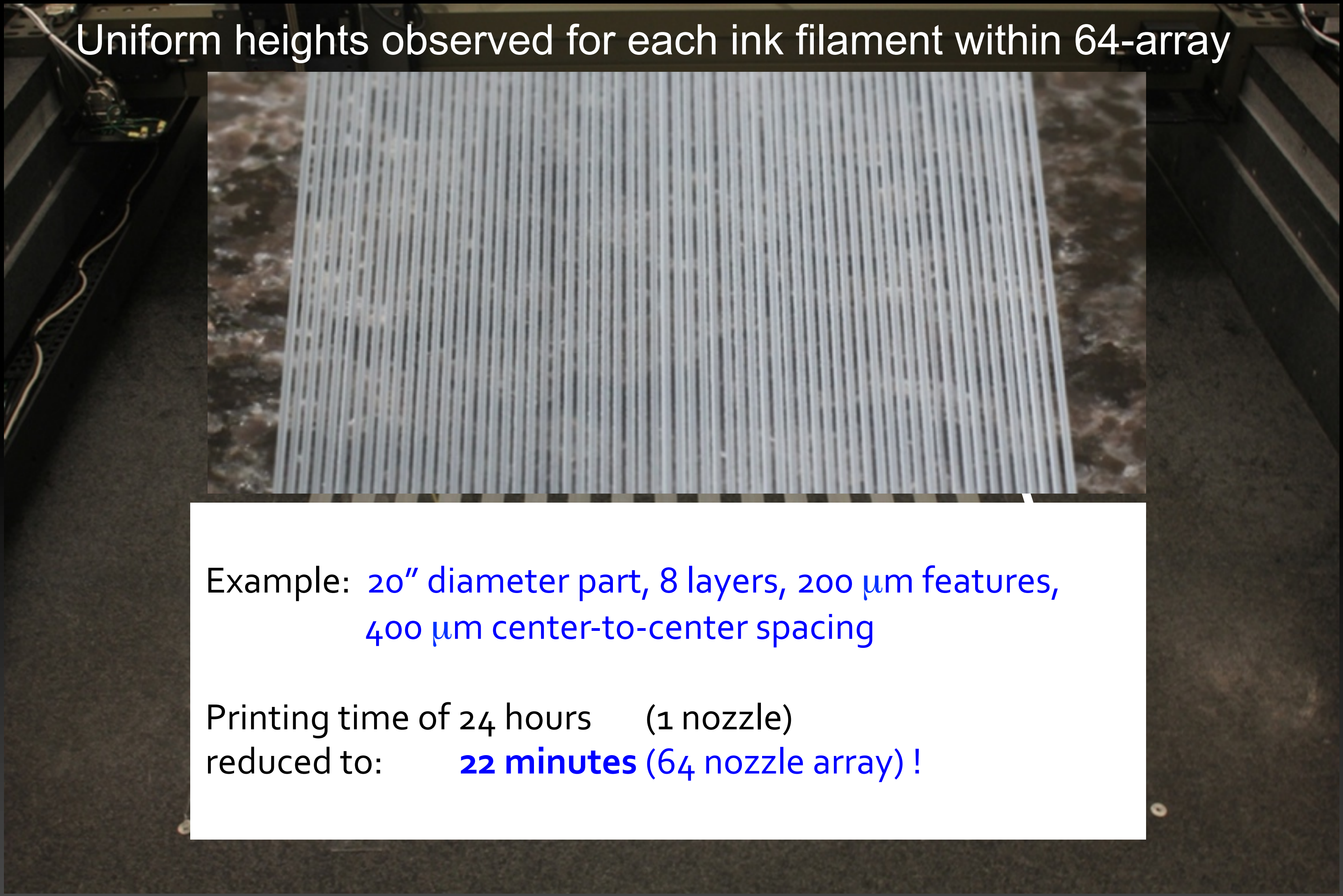
Hansen, Vericella, Lewis, unpublished.

Multinozzle arrays – Uniform printed features



Hansen, Vericella, Lewis, unpublished.

Multinozzle arrays – Uniform printed features



Example: 20” diameter part, 8 layers, 200 μm features,
400 μm center-to-center spacing

Printing time of 24 hours (1 nozzle)
reduced to: **22 minutes** (64 nozzle array) !

Hansen, Vericella, Lewis, unpublished.

3-D Printing - A Manufacturing Revolution

The New York Times

Business Day

Technology

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SAN FRANCISCO — Businesses in the South Park district of San Francisco generally sell either Web technology or sandwiches and burritos. Bespoke Innovations plans to sell designer body parts.

Enlarge This Image

Peter DaSilva for The New York Times

Scott Summit, co-founder of Bespoke Innovations, with a prosthetic limb.

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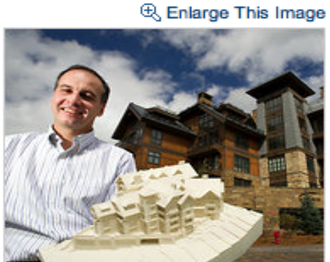

Kevin Moloney for The New York Times

The company is using advances in a technology known as 3-D printing to create prosthetic limb casings wrapped in embroidered leather, shimmering metal or whatever else someone might want.

Scott Summit, a co-founder of Bespoke, and his partner, an orthopedic surgeon, are set to open a studio this fall where they will sell the limb coverings and experiment with printing entire customized limbs that could cost a tenth of comparable artificial limbs made using traditional methods. And they will be dishwasher-safe, too.

On the immediate horizon:

- New functional inks
- Broader materials palette
- Improved feature resolution
- Enhanced throughput
- High-speed printing

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