



Additive manufacturing across scales

John Hart

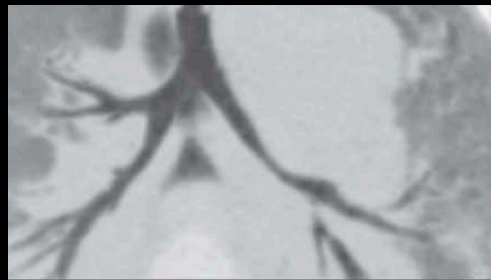
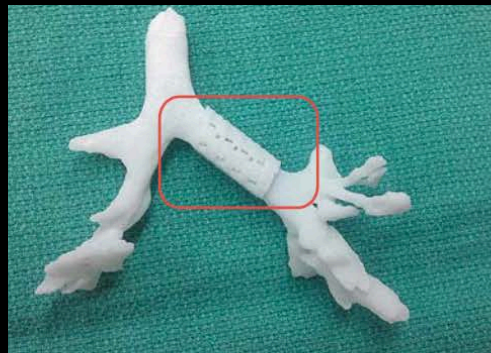
Mechanical Engineering, MIT

ajhart@mit.edu | mechanosynthesis.mit.edu

March 29, 2017

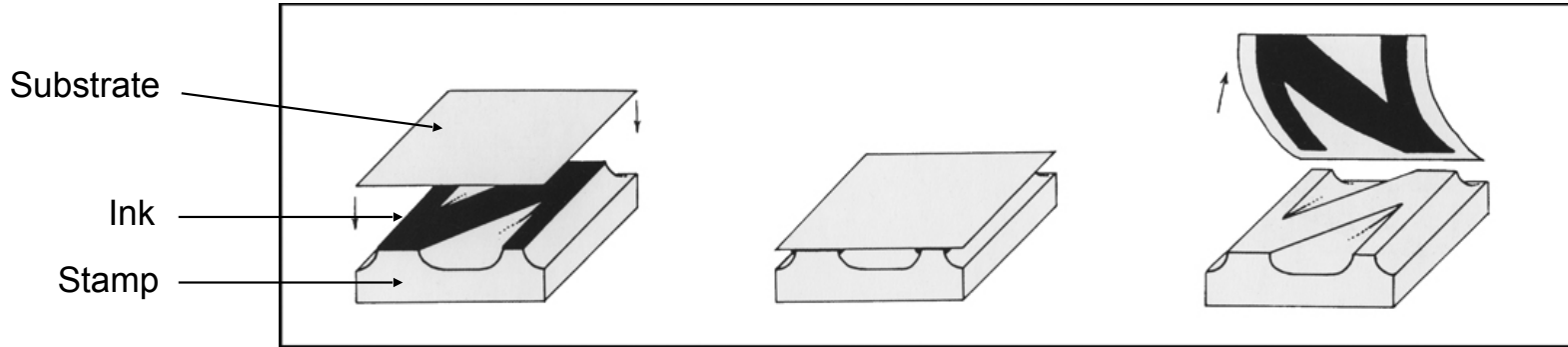
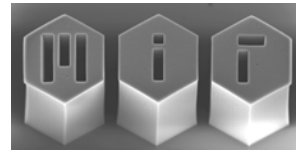






New materials and
computational intelligence

Relief printing (flexography)



Wood stamps (200s ~ 1400s)



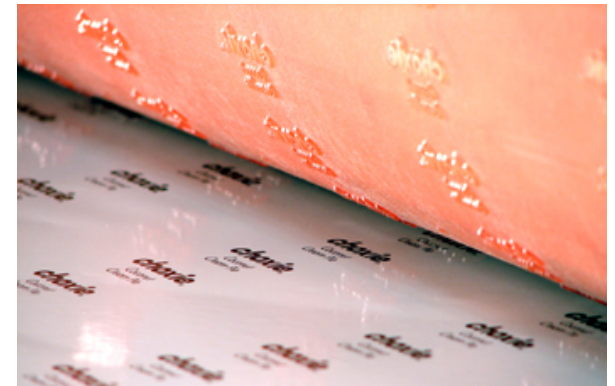
Hand print –
text, images, patterns

Metal stamps (1400s ~ 1900s)



Movable type printing –
mass-production of books

Rubber stamps (1900s ~ Present)

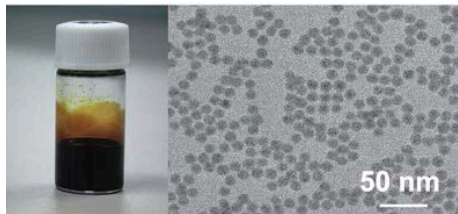


Roll-to-roll printing –
Low-cost, large-area graphics



Functional inks

- Inorganics: e.g., metal/oxide/semiconductor nanoparticles
- Organics: e.g., soluble conjugated polymers



Conductive nanoparticle inks
[Tokito-Kumaki Lab]



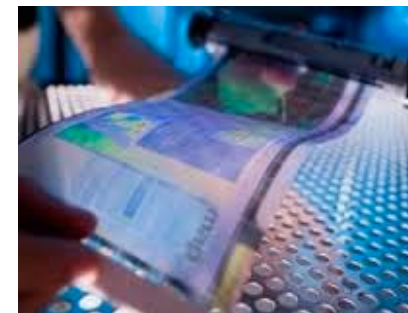
Quantum dot dispersions
[Sigma-Aldrich Co.]



Conventional printing technologies



Printed electronics



Flexible display [Printable Electronics Tech Center, UK]



Organic PV and lighting
[OE-A]



Smart labels

Flexographic Printing Process

Elastic printing plate with inked image elements

Printing substrate

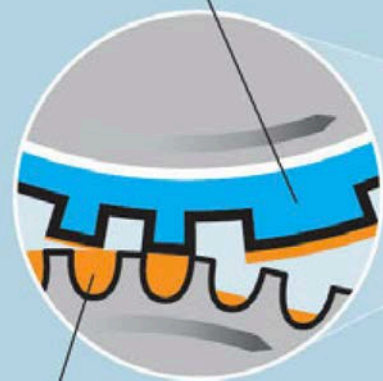
Elastic printing plate

Hard Impression cylinder

Anilox roller

Ink supply

Cells of the anilox roller Ink-filled



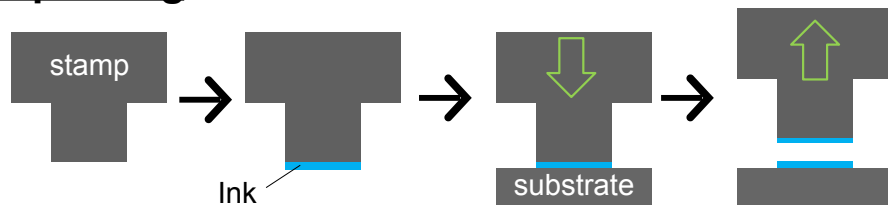
OE-A Roadmap 2015
Clemson University

https://www.youtube.com/watch?v=l_gh2fpC8Ew

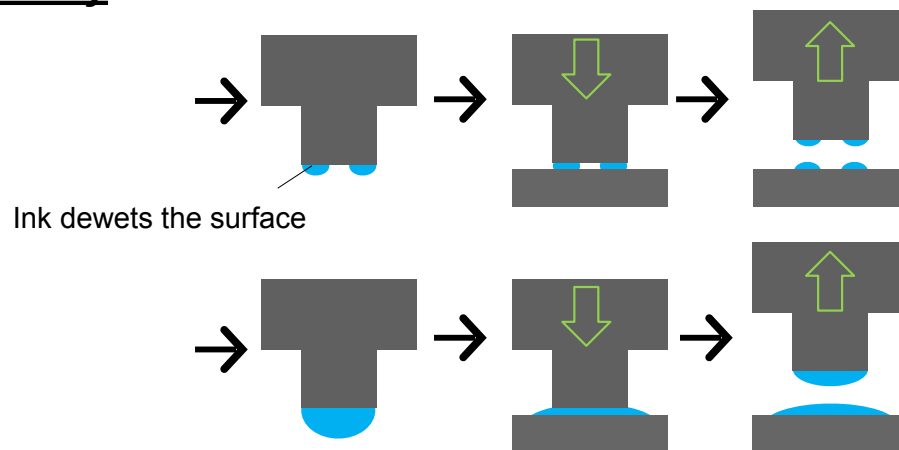


Limitations of flexography

Ideal printing

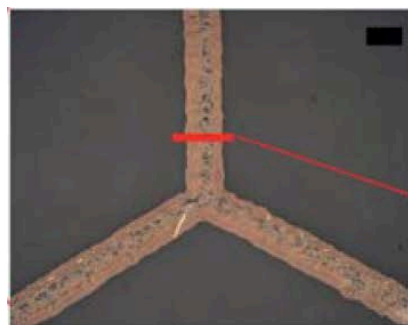


In reality



Film instability

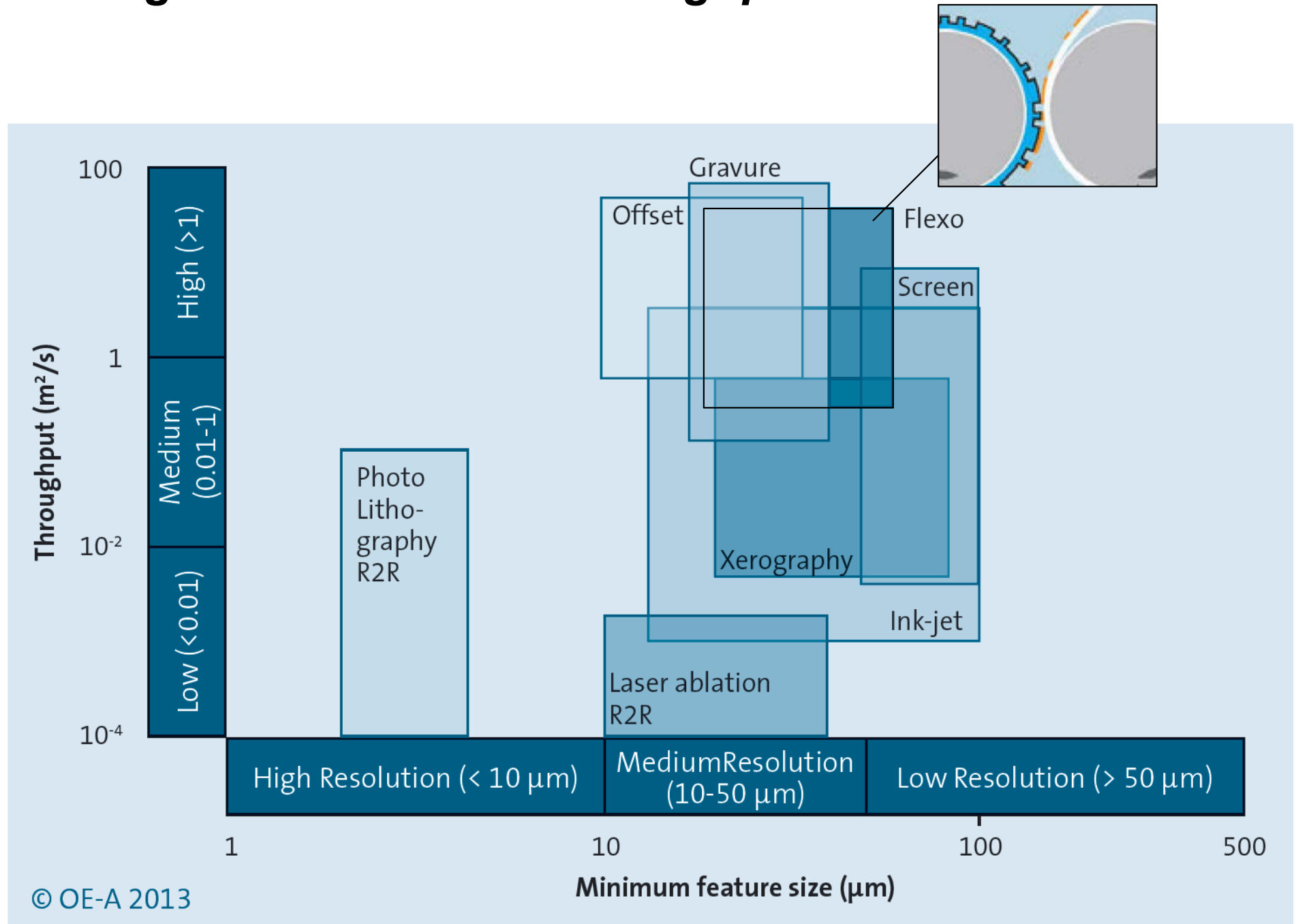
Liquid spreading (+non-uniform drying)



>> The resolution limit is not due to the manufacturability of small stamp features, but the difficulty of loading and transferring thin liquid films.

Flexographic (bottom) printed Ag NP ink [Yu et al., Nanoscale 2012]

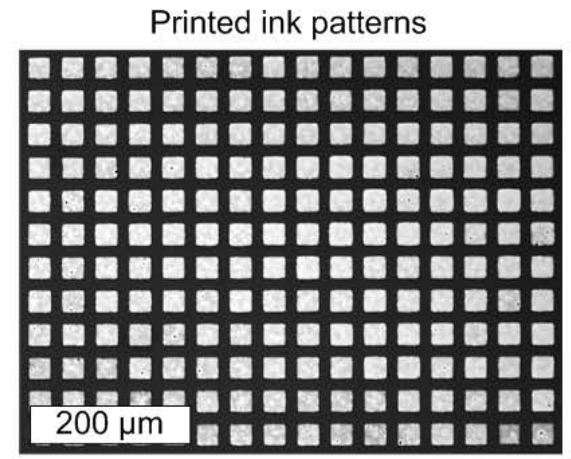
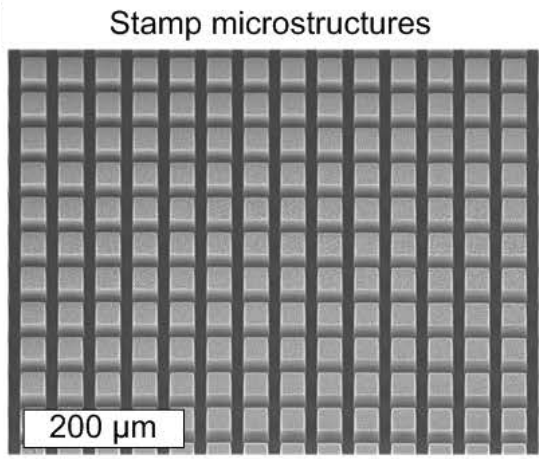
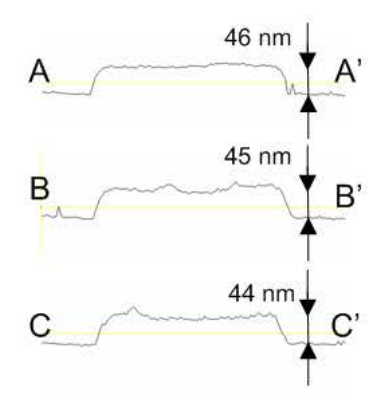
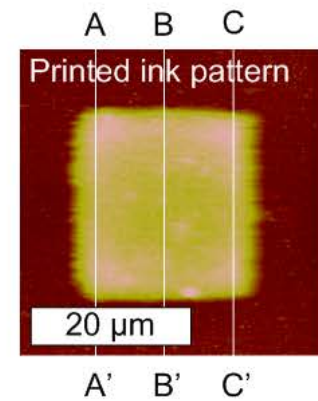
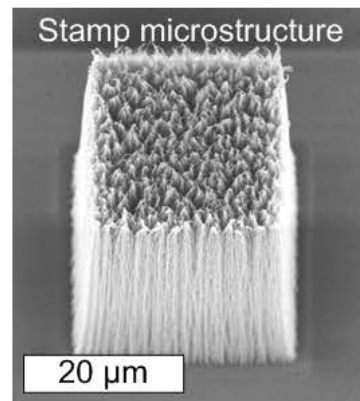
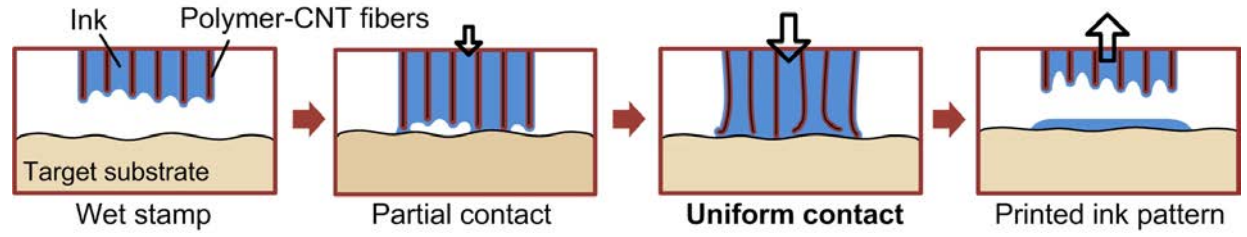
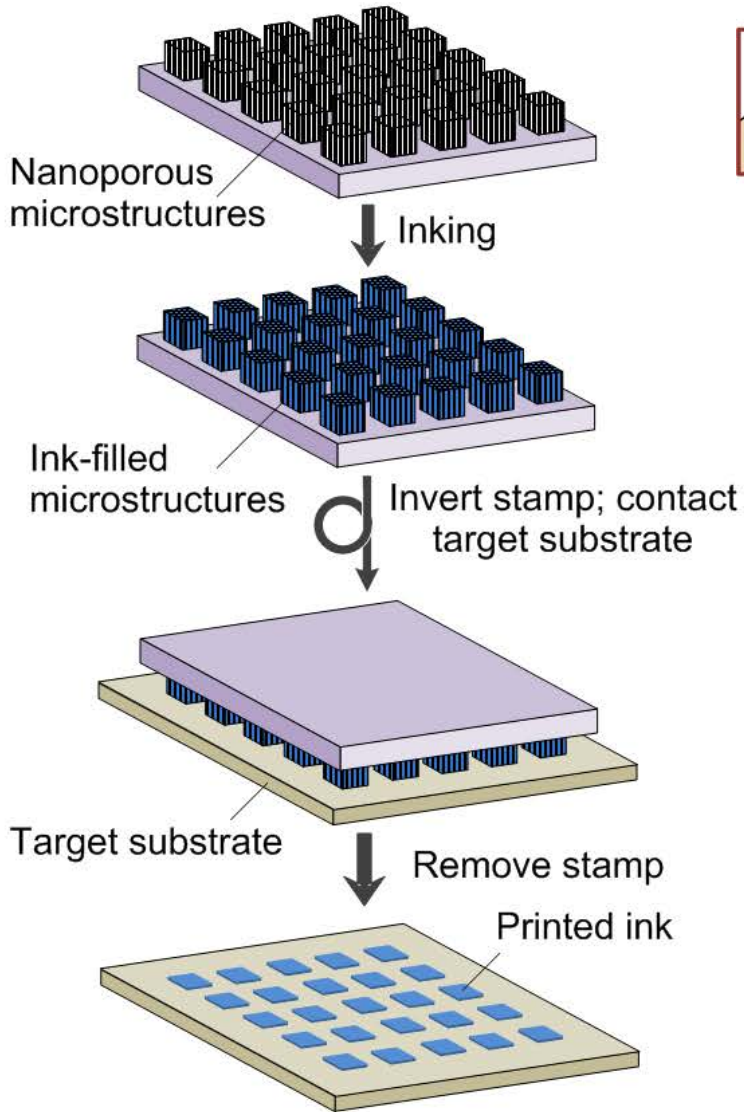
Need: high resolution and throughput



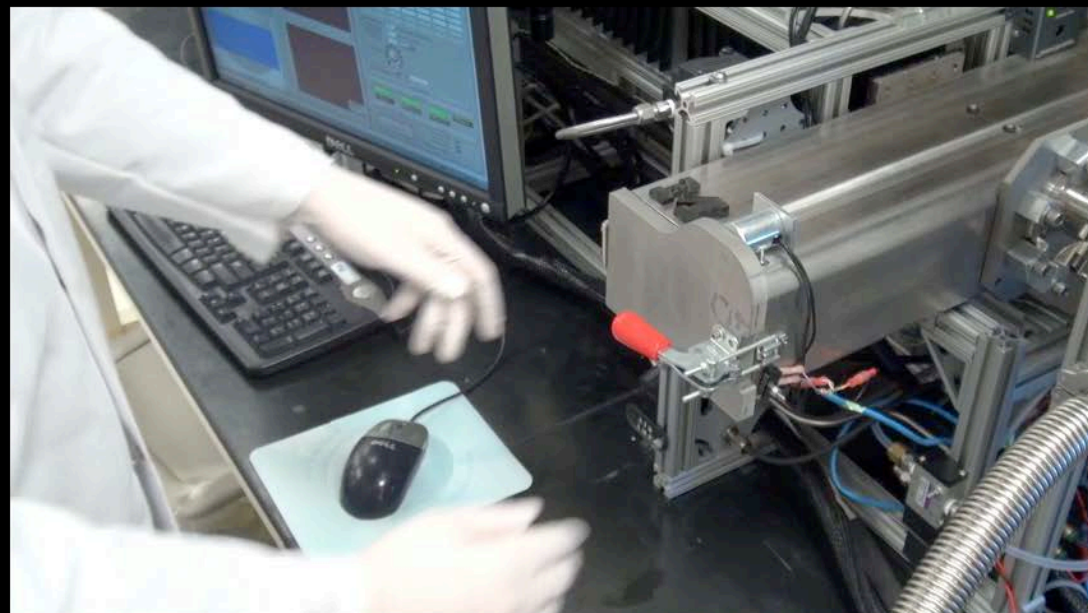
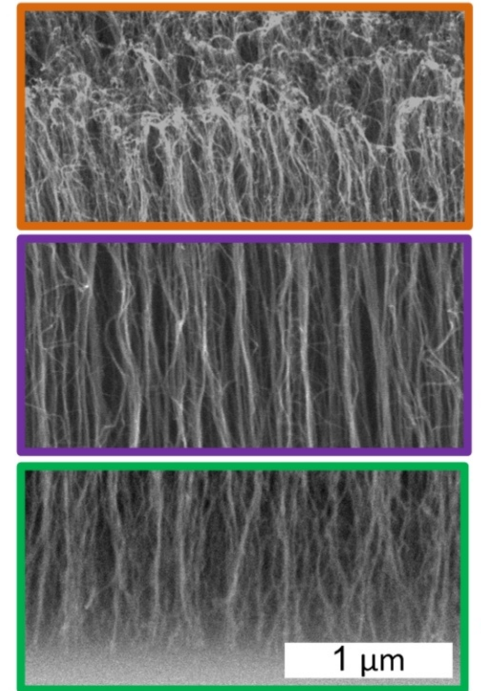
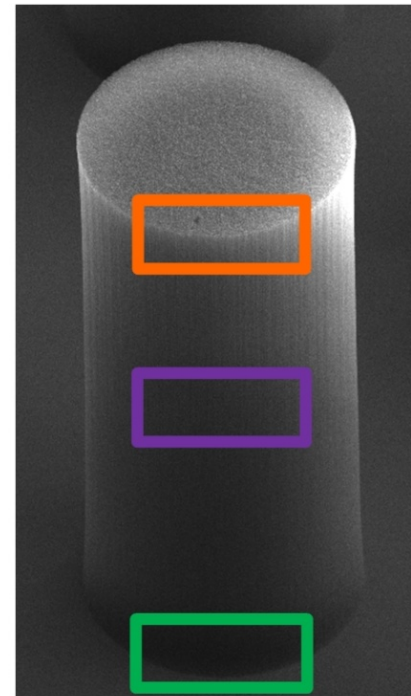
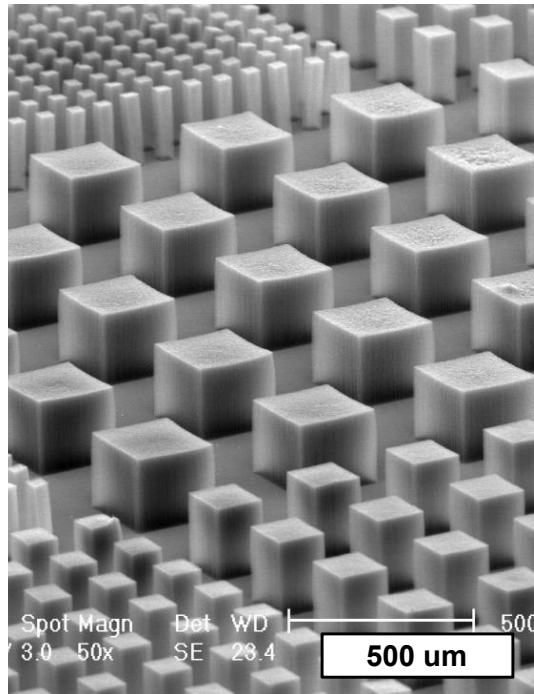
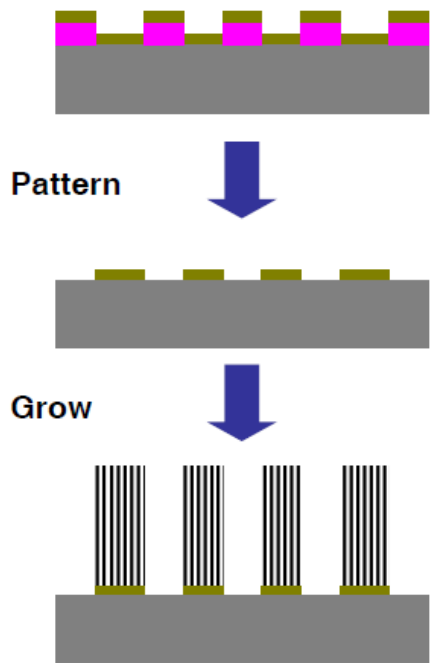
Ultrathin high-resolution flexography using *nanoporous* stamps



+ Hossein Sojoudi, Gareth Mckinley, Karen Gleason

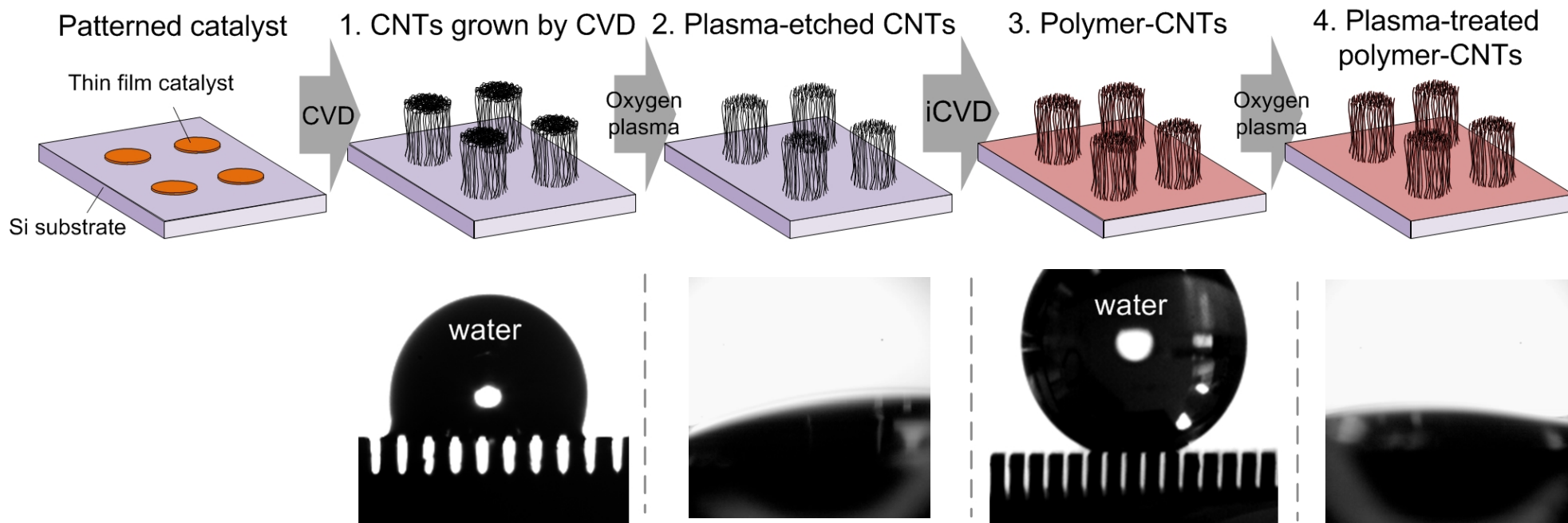


Silver nanoparticle ink (<10 nm, 50-60 wt% in tetradecane)

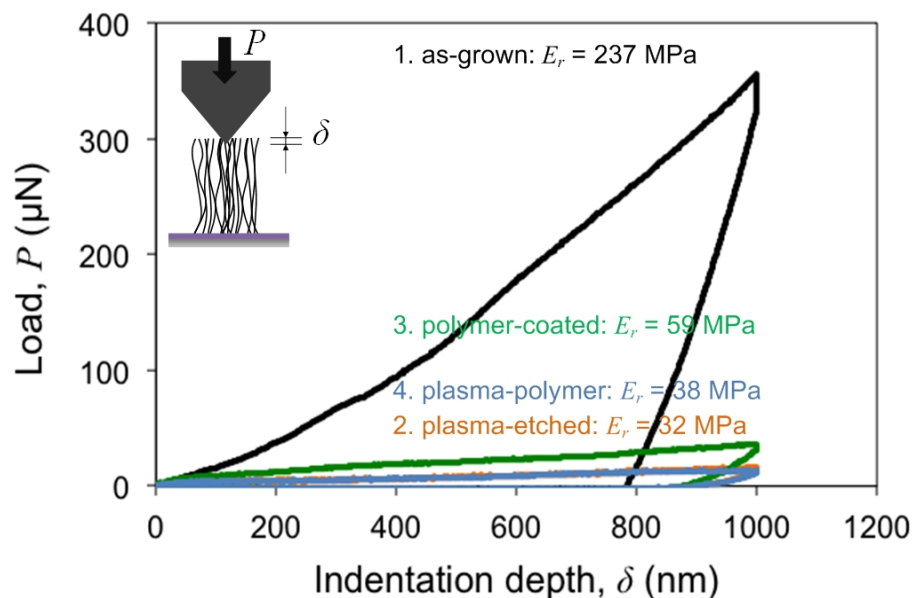




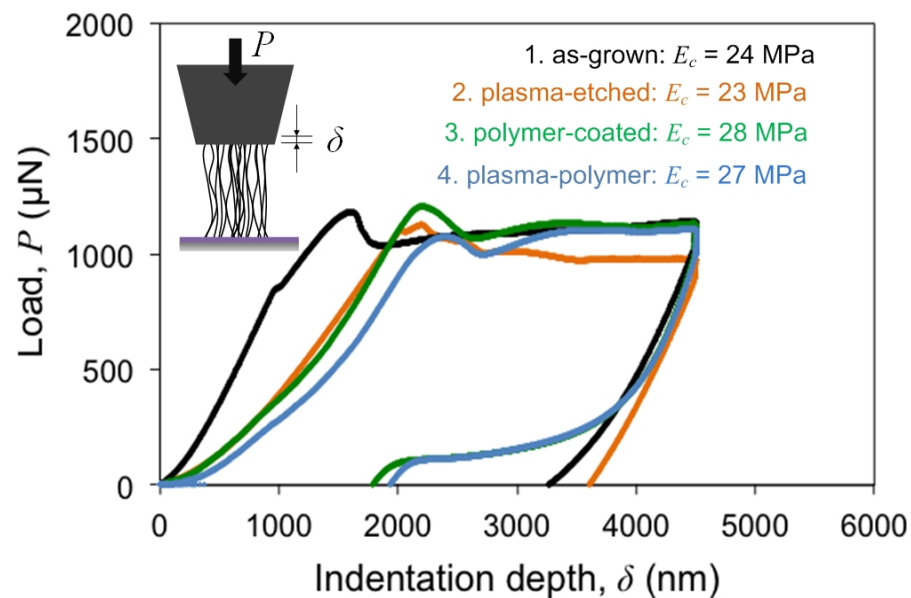
Fabrication of nanoporous stamps



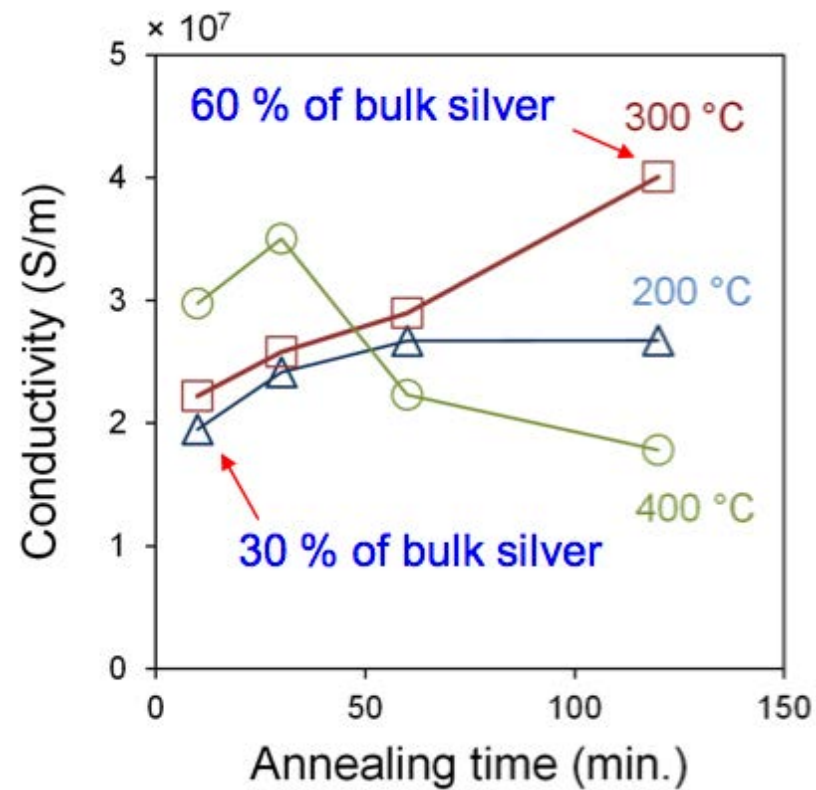
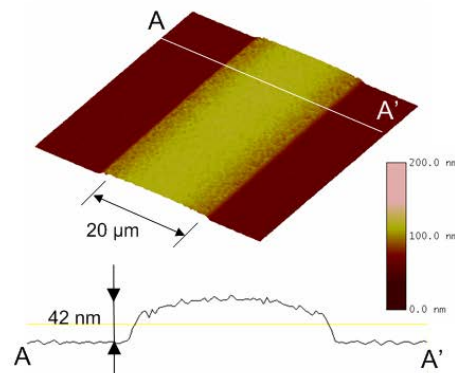
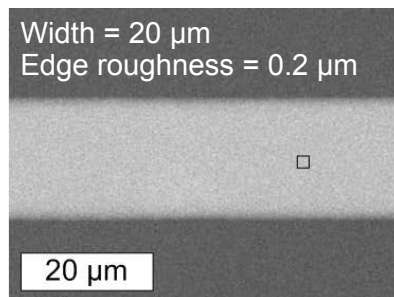
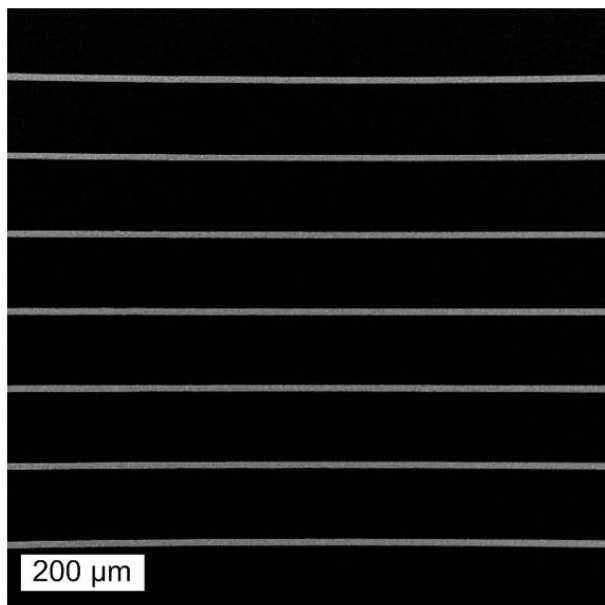
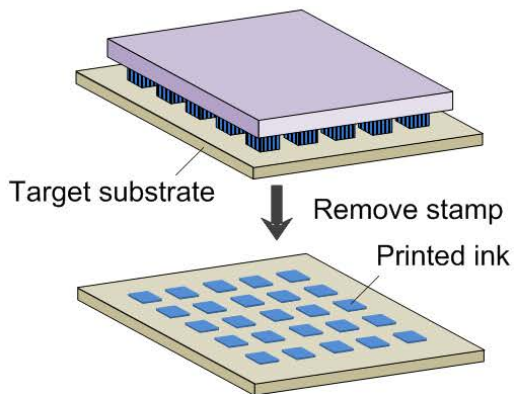
Surface (sharp indent)



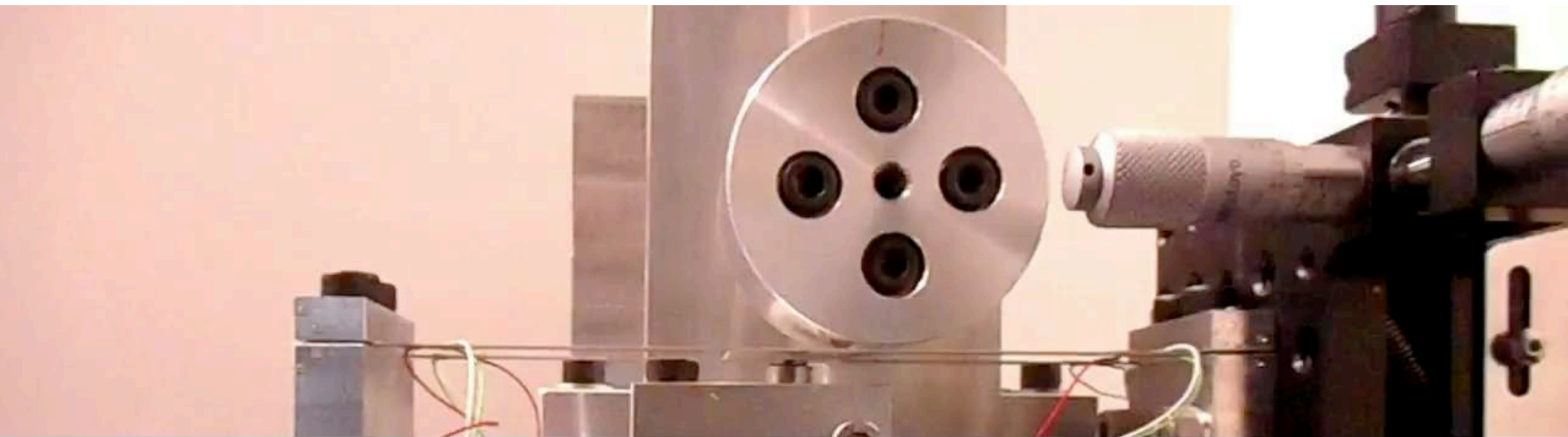
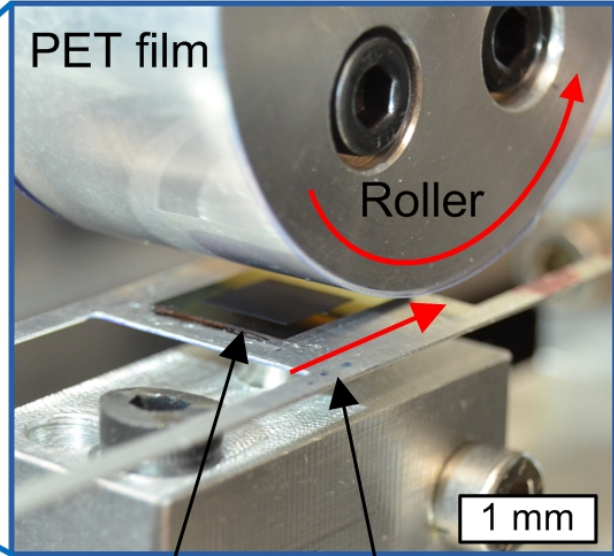
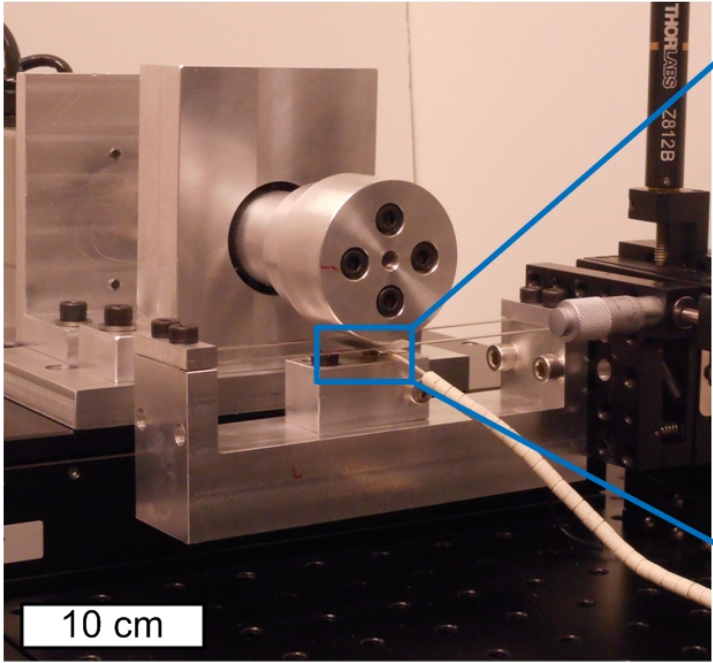
Bulk (flat indent)



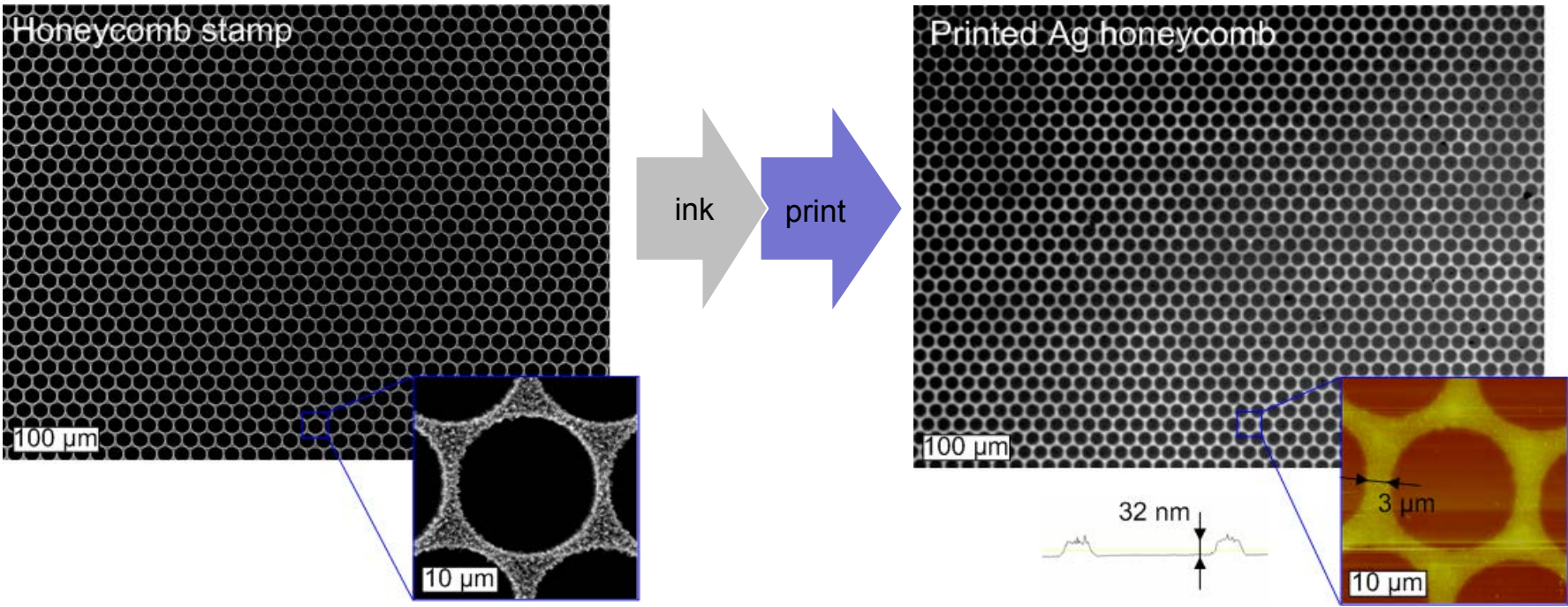
Printed metal (Ag) lines



Continuous (plate-to-roll) flexoprinting

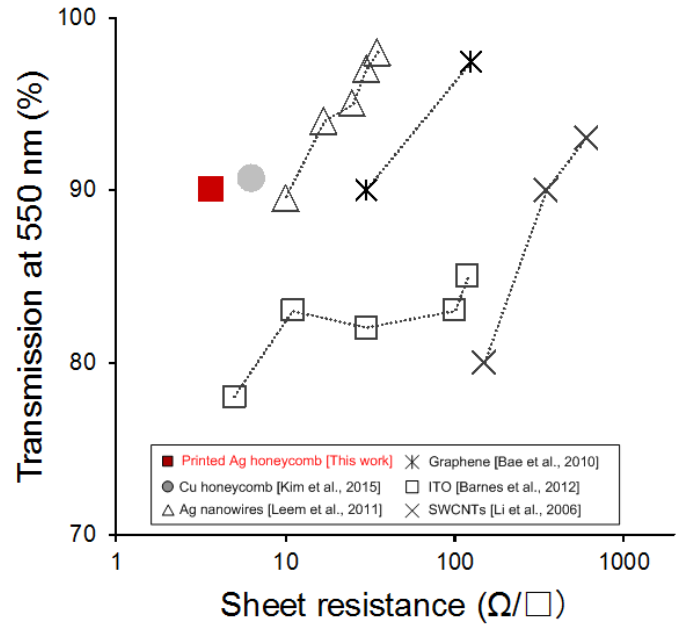
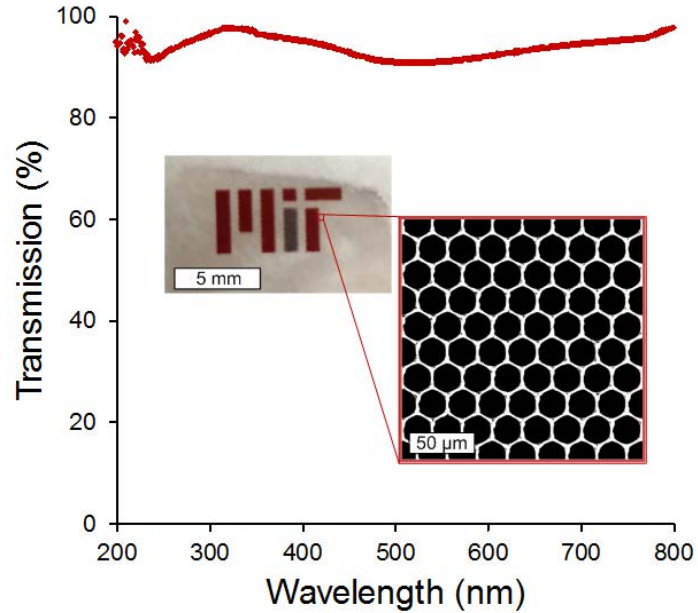


Printed transparent electrodes



→90% transparency at 550 nm

3.6 Ohm/sq (after annealing)





Contact mechanics of ink transfer

Probability density of fiber height on the stamp surface

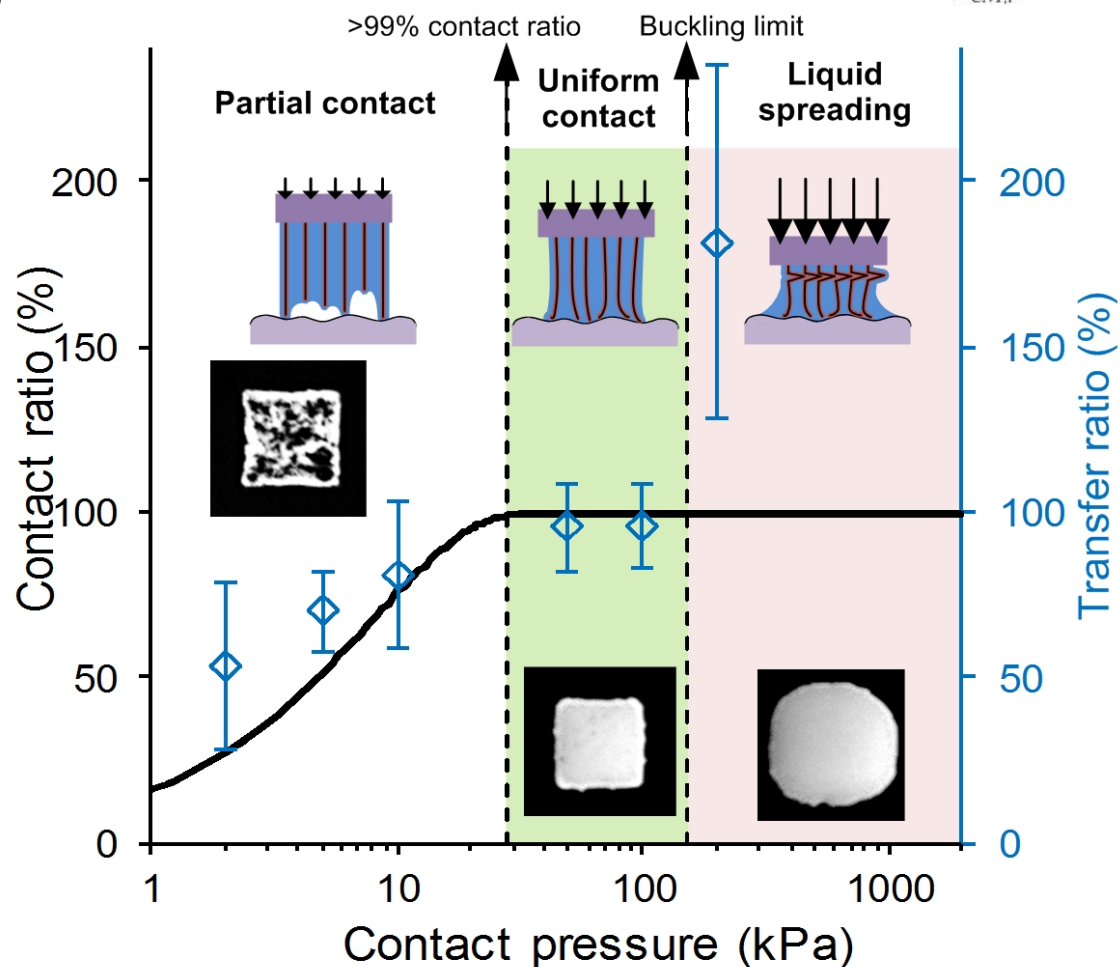
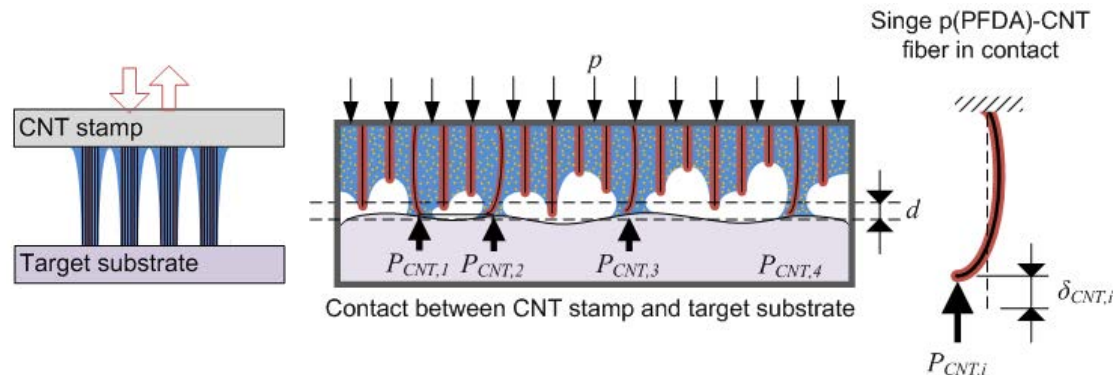
$$\phi(l_{CNT}) = \frac{1}{\sigma_l \sqrt{2\pi}} \exp\left(-\frac{l_{CNT}^2}{2\sigma_l^2}\right)$$

Contact ratio

$$\frac{n_c}{n} = \int_d^\infty \phi(l_{CNT}) dl_{CNT} = \frac{1}{2} \left\{ 1 - \operatorname{erf}\left(\frac{d}{\sqrt{2}\sigma_l}\right) \right\}$$

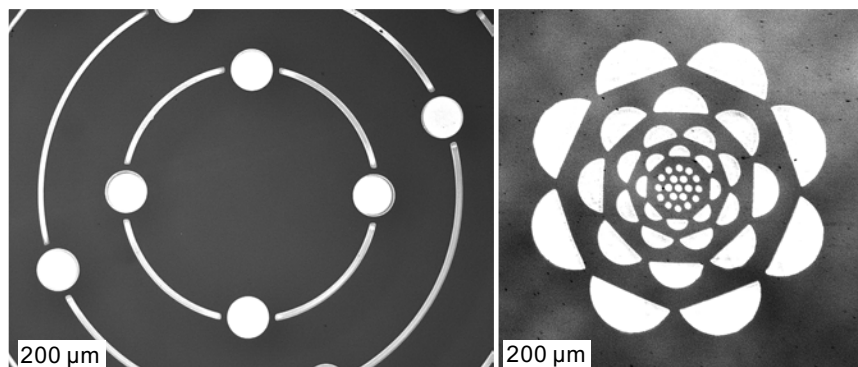
Contact pressure

$$\begin{aligned} p &= \frac{1}{A} \sum_i^{n_c} P_{CNT,i} = \frac{1}{A} \sum_i^{n_c} k_{CNT} \delta_{CNT,i} = \frac{n}{A} \int_d^\infty k_{CNT} (l_{CNT} - d) \cdot \phi(l_{CNT}) dl_{CNT} \\ &= \frac{k_{CNT} \sigma_l}{\sqrt{2\pi} \lambda_{CNT}^2} \left[\exp\left(-\frac{d^2}{2\sigma_l^2}\right) - \sqrt{\frac{\pi}{2}} \frac{d}{\sigma_l} \left\{ 1 - \operatorname{erf}\left(\frac{d}{\sqrt{2}\sigma_l}\right) \right\} \right] \end{aligned}$$

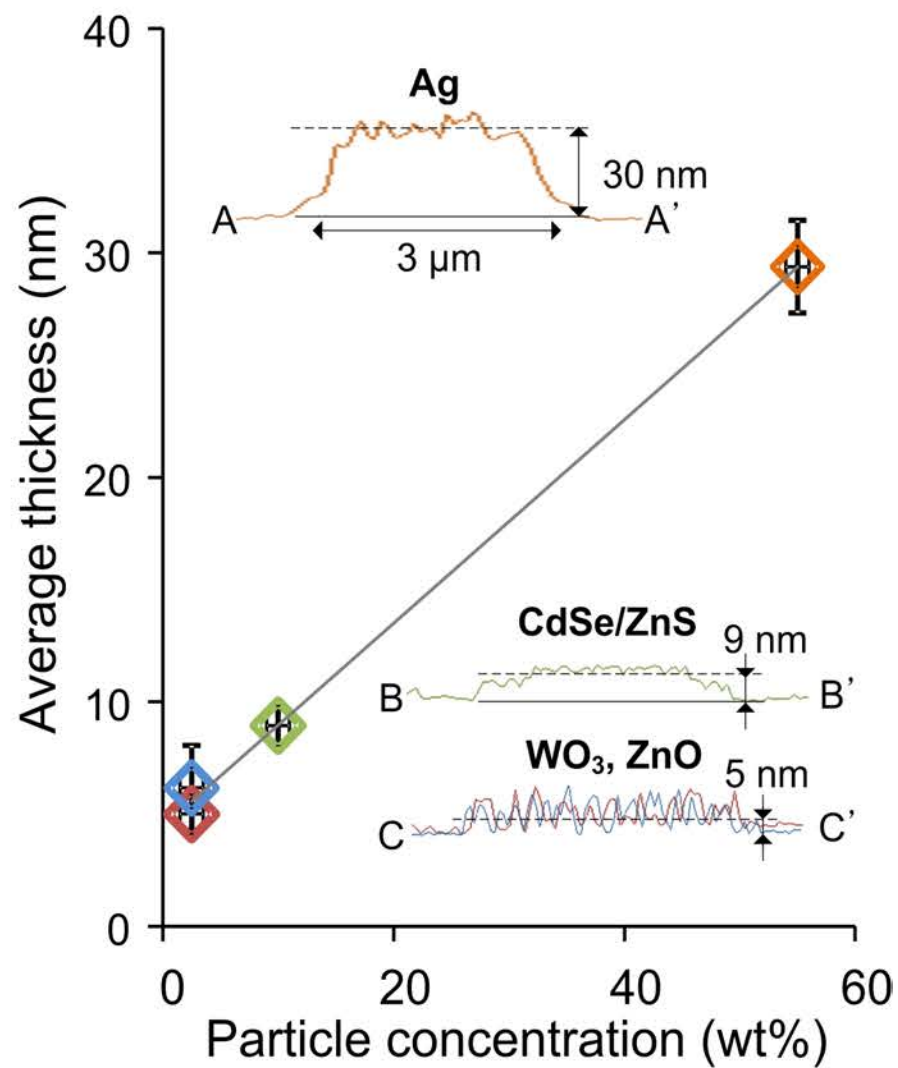
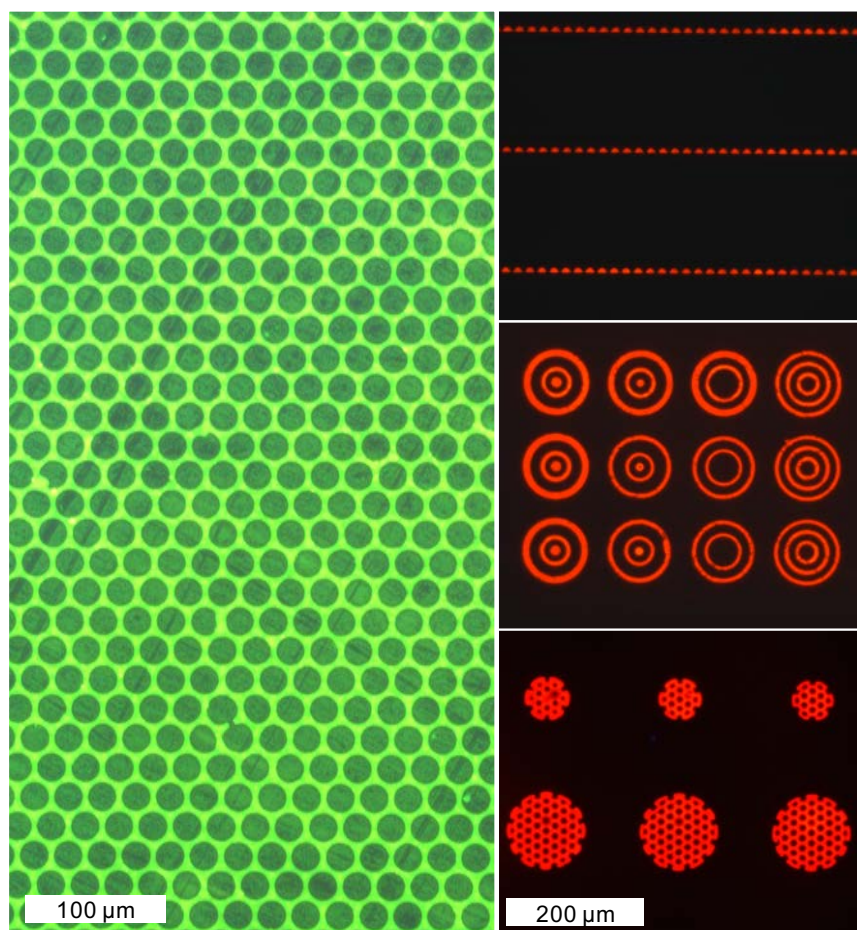




Ag nanoparticle ink



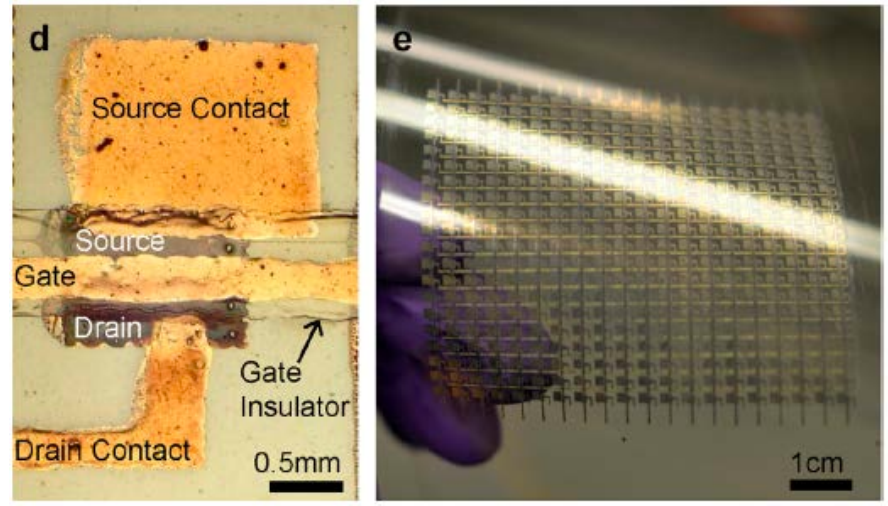
CdSe/ZnS quantum dot ink



Vision: fully printed and flexible electronics

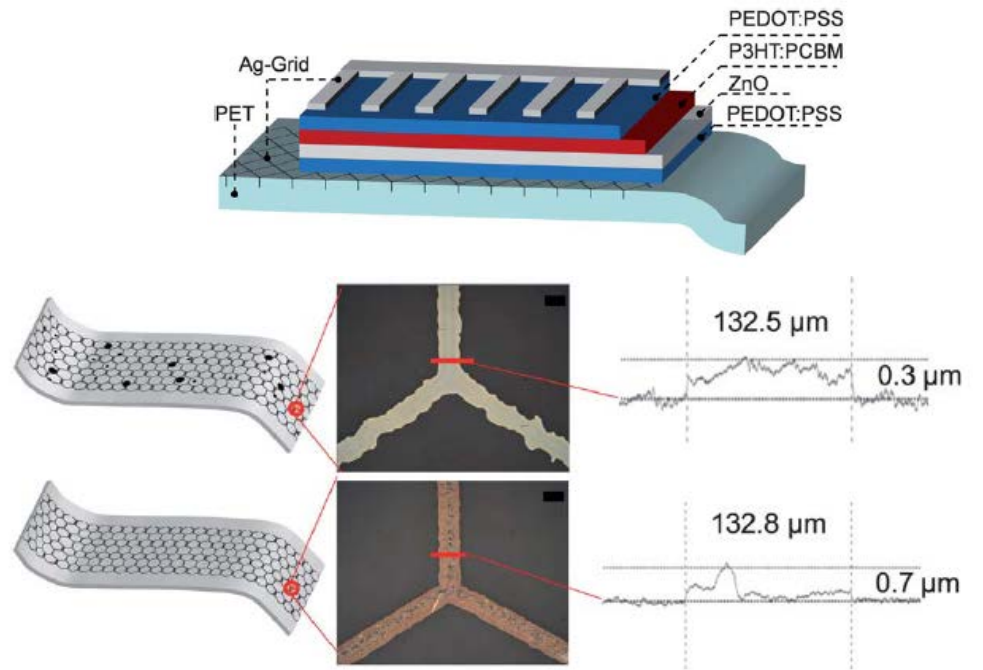


Flexible Thin Film Transistor (TFT) array



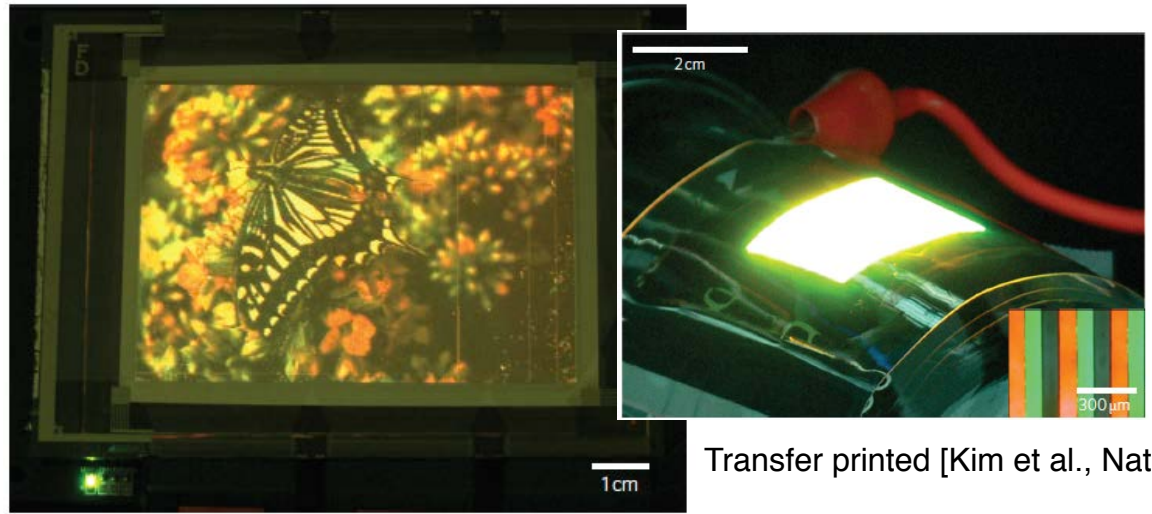
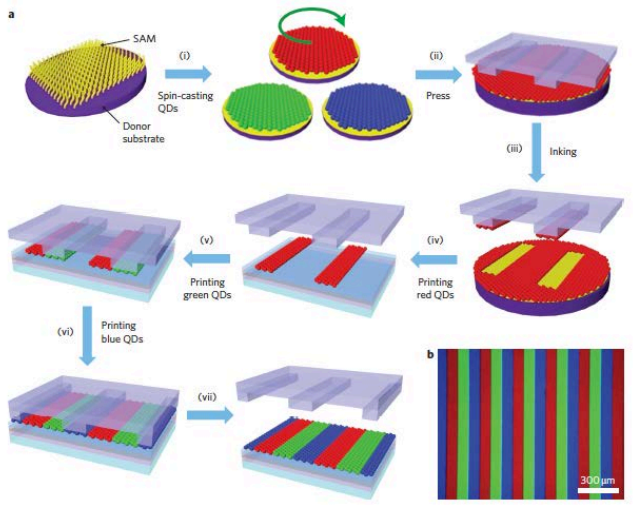
Gravure and inkjet printed TFT arrays [Lau et al., Nano Lett. 2013]

Organic Solar Cells



Inkjet (top) and flexographic (bottom) printed Ag grids [Yu et al., Nanoscale 2012]

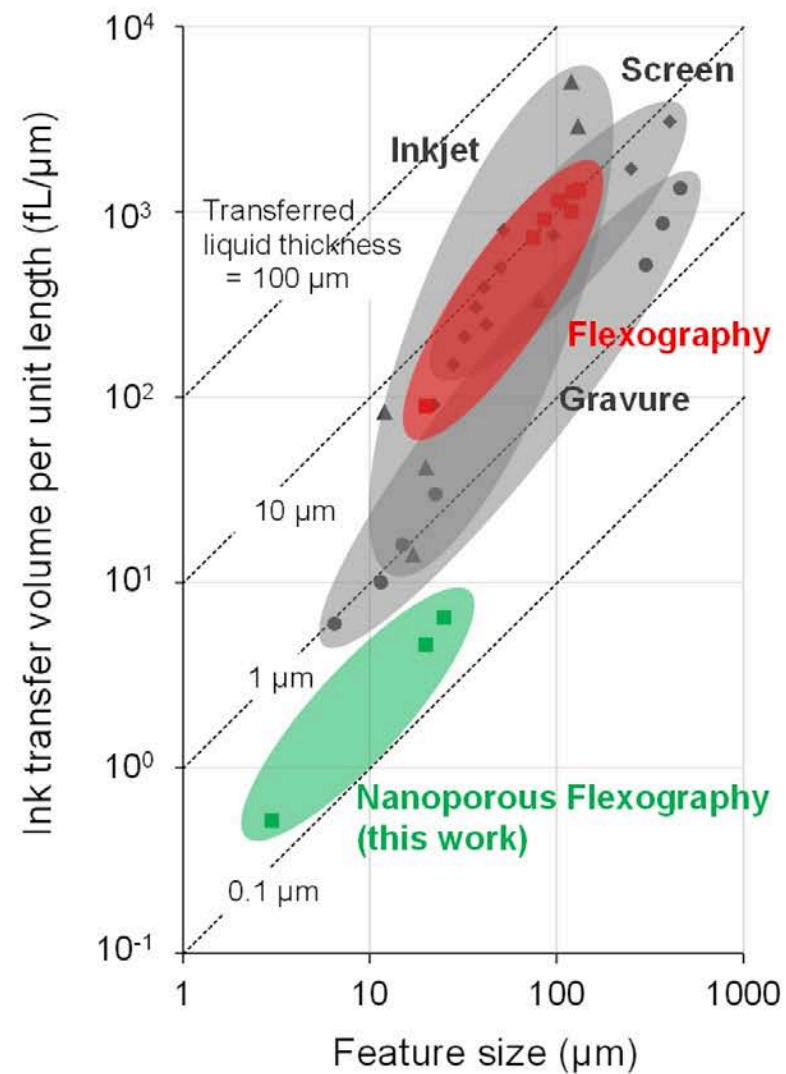
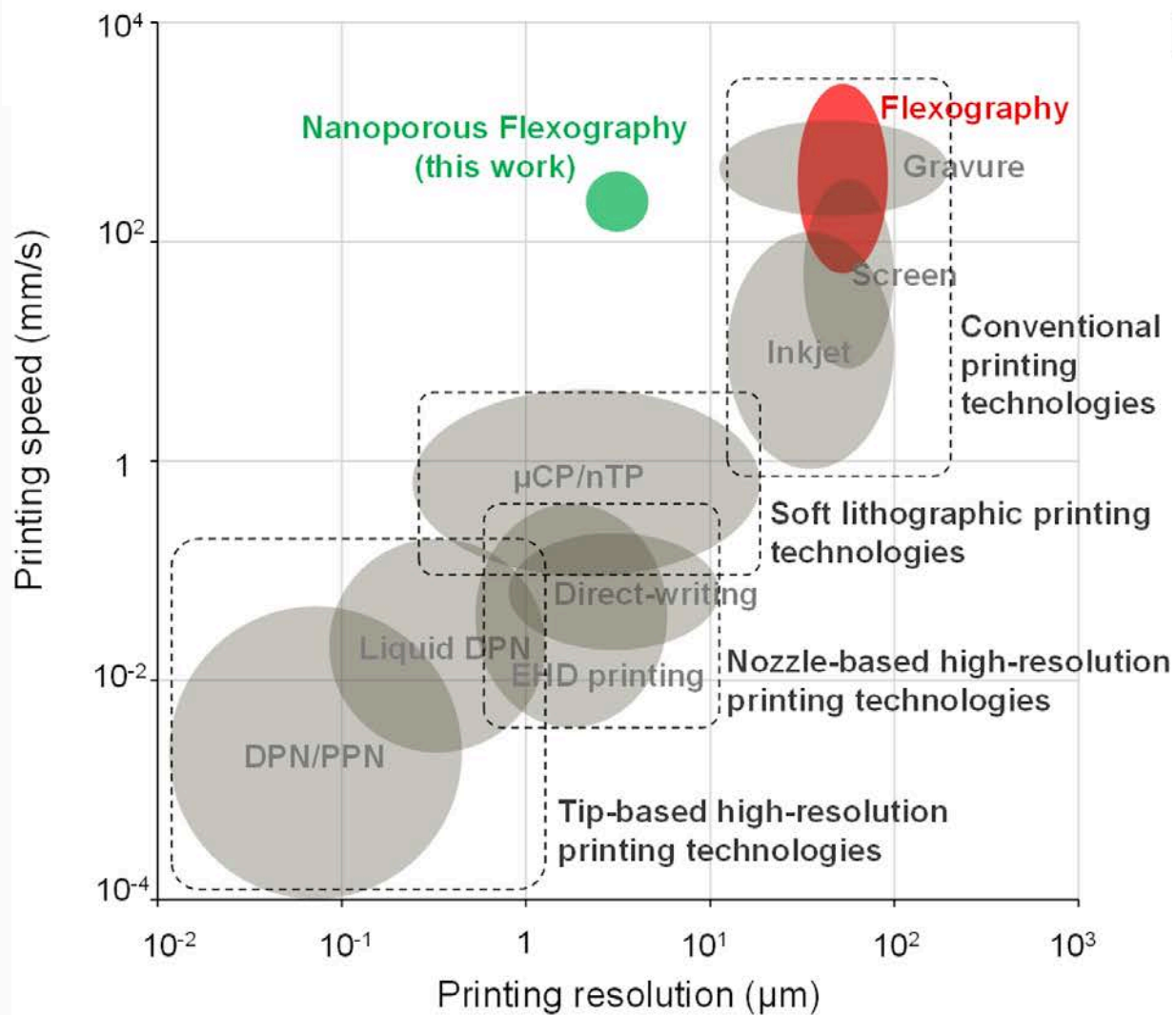
Quantum dot (QD) displays

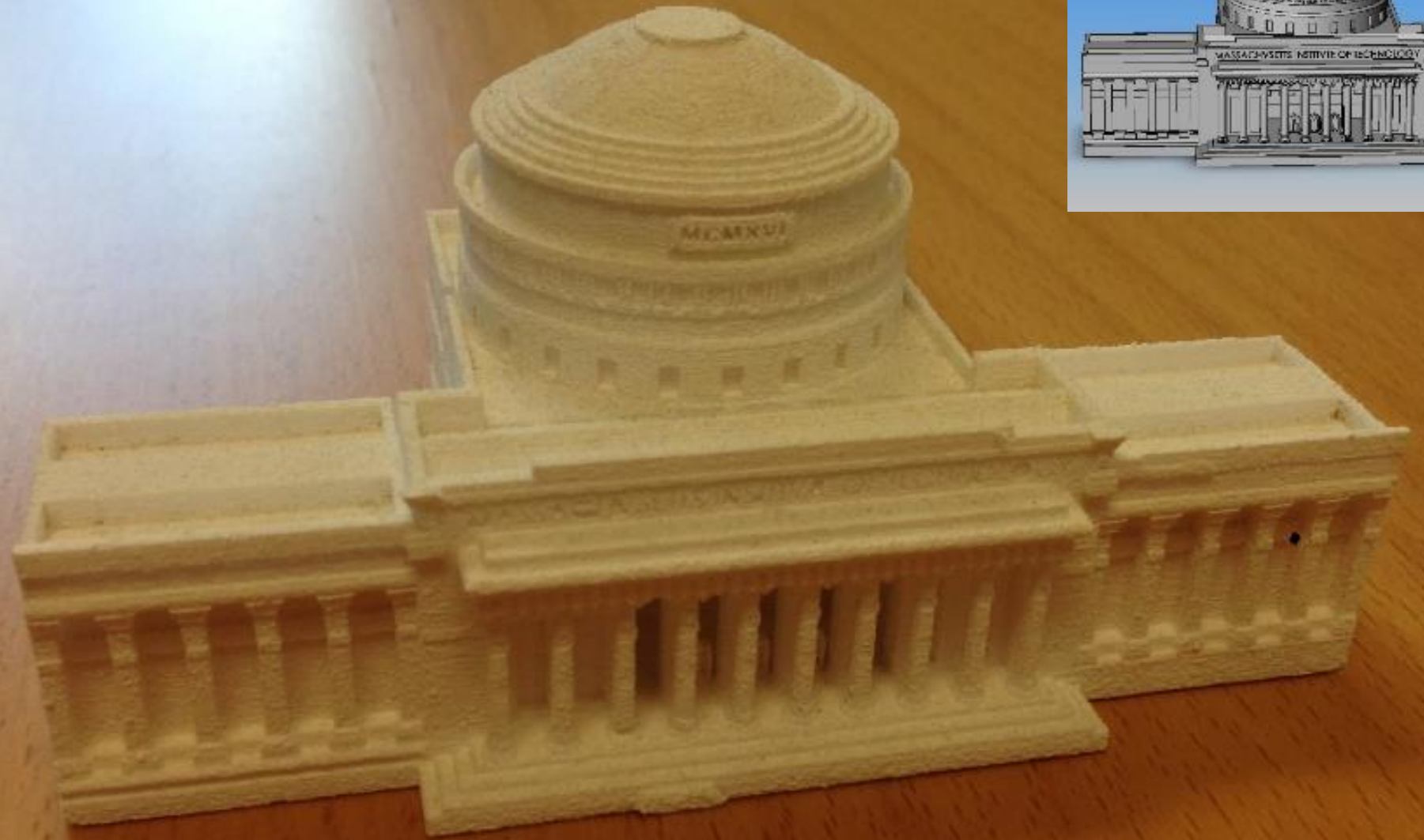
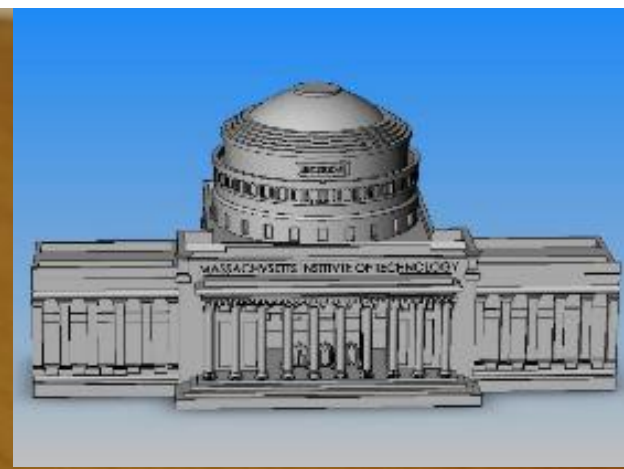


Transfer printed [Kim et al., Nat. phot. 2011]

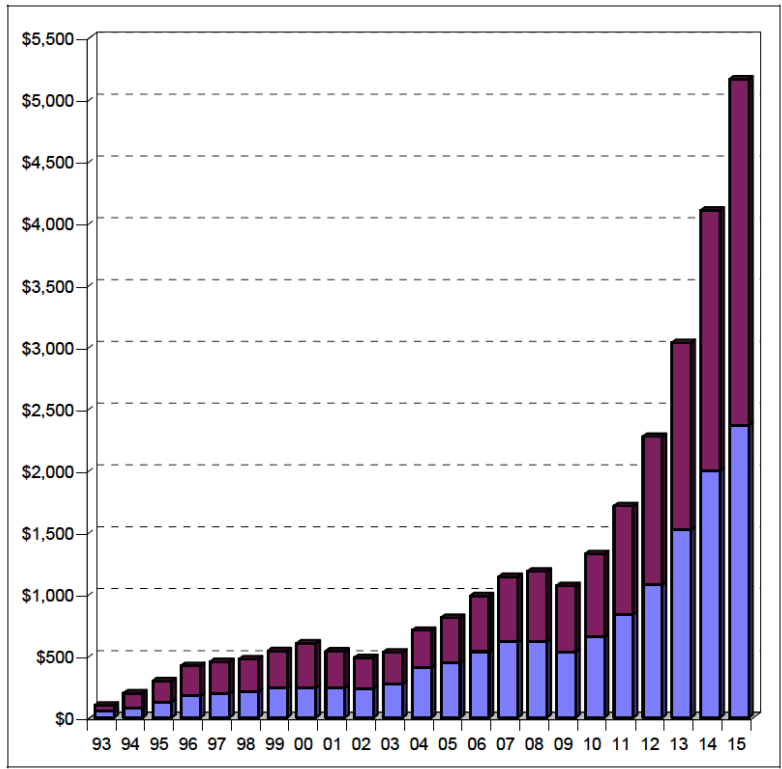


Performance metrics





The AM industry today



Services

Machines

2015: \$5.2B AM machines and services

2015 growth = 26%

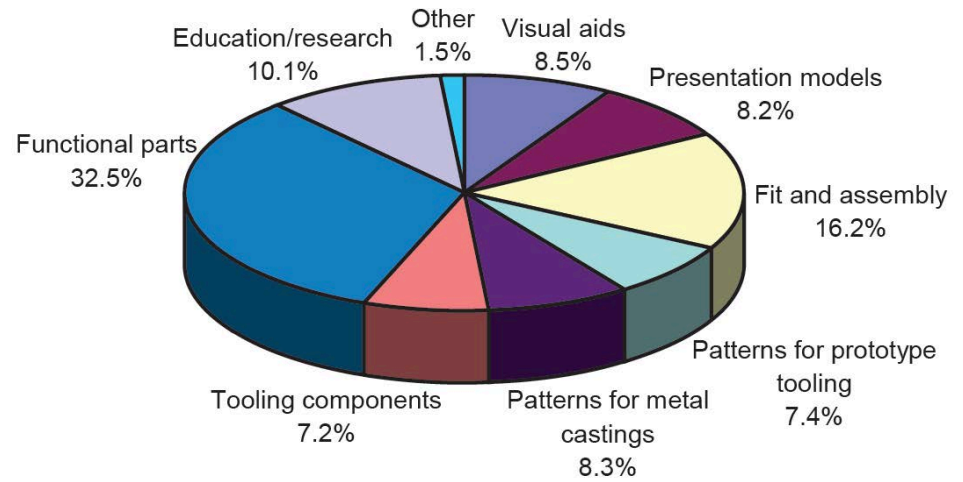
27-year CAGR = 26%

Worldwide mfg is ~\$15 trillion (16% of the world economy)

AM = 0.03%.

Source: Wohlers Associates, Inc.

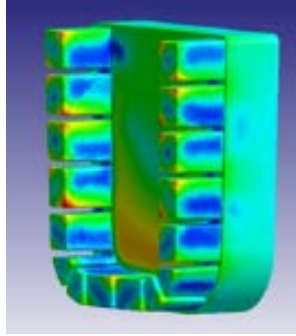
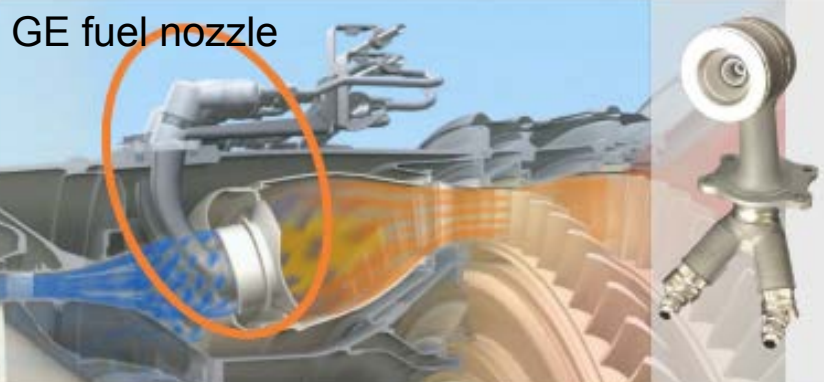
“How do you use the parts made on your industrial AM machines?”



The diverse industrial uses of AM



GE fuel nozzle



Shoe cleats (NIKE)



Airbus

Conventionally machined bracket (left) and redesigned bracket (right) using topology optimization, courtesy of Laser Zentrum Nord GmbH and Airbus



Tooling
Linear Mold, Triform

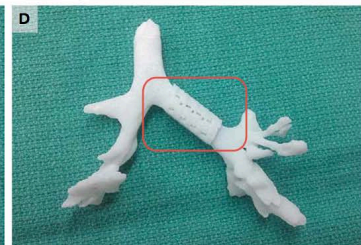
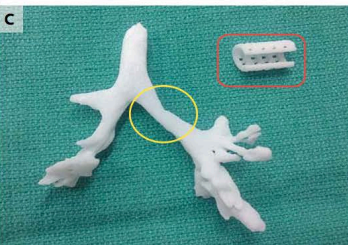
Skyfall



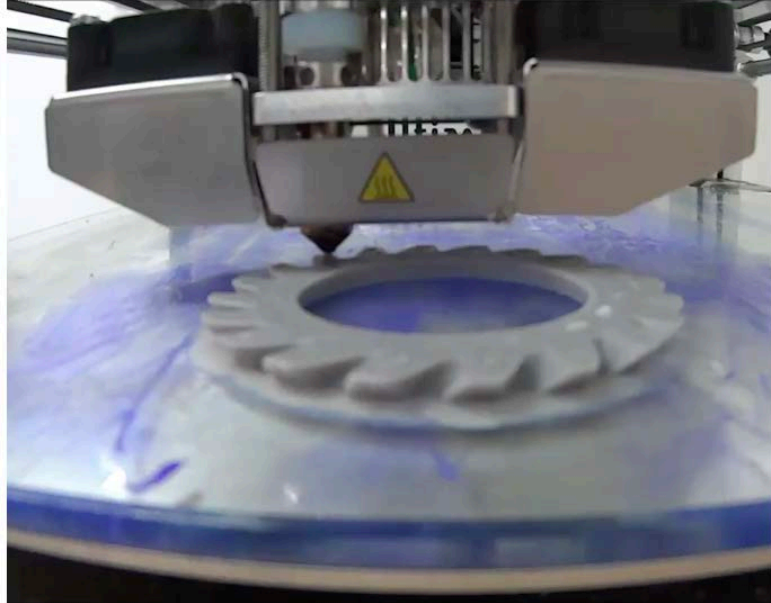
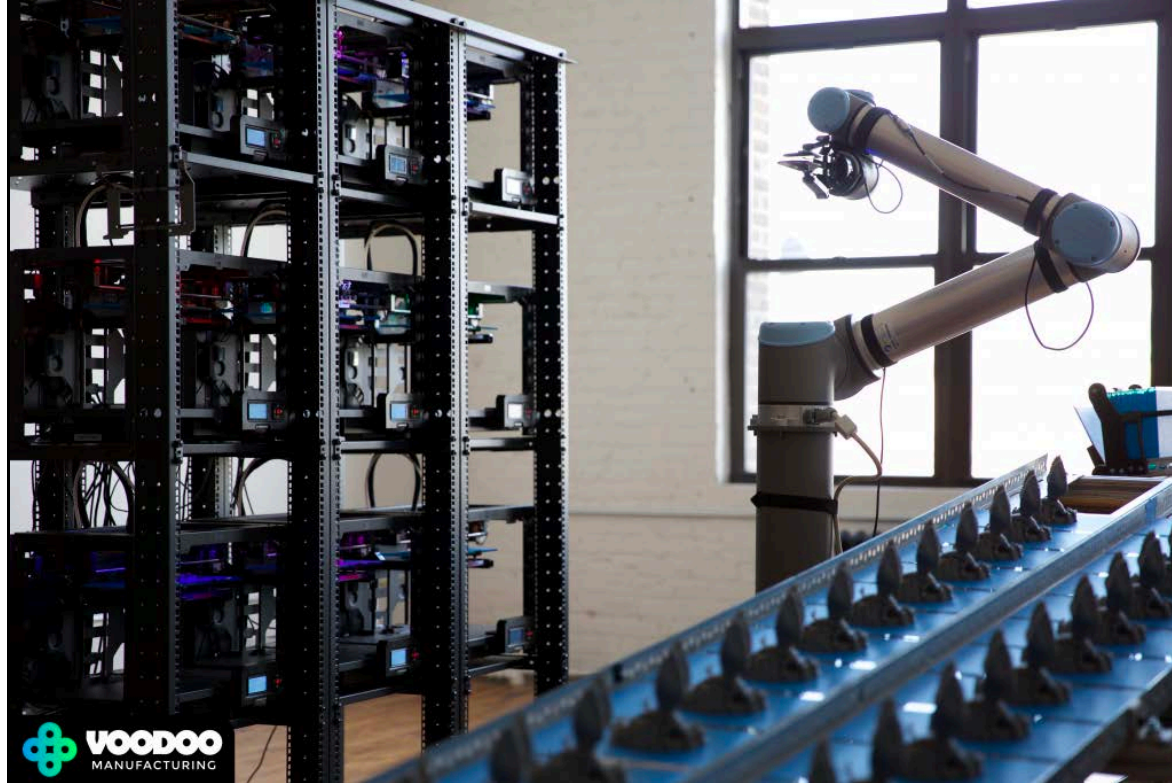
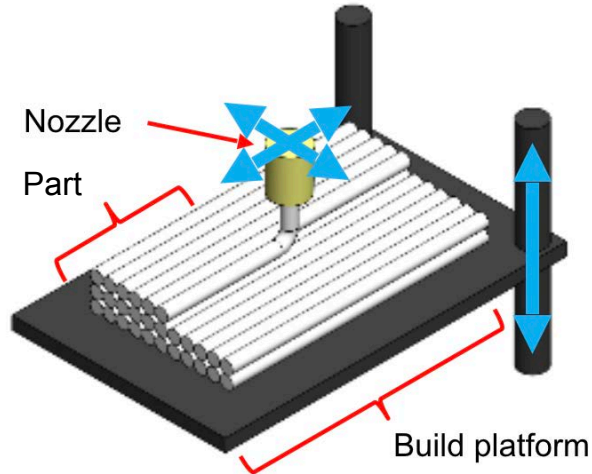
Modular products
(Google Ara)

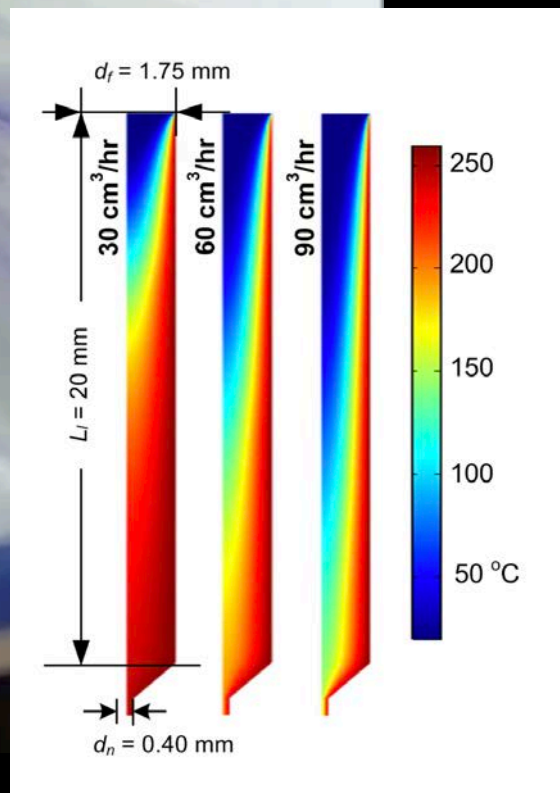
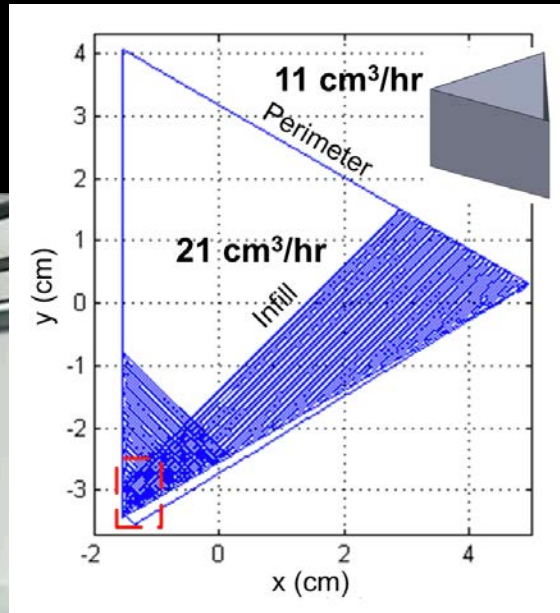
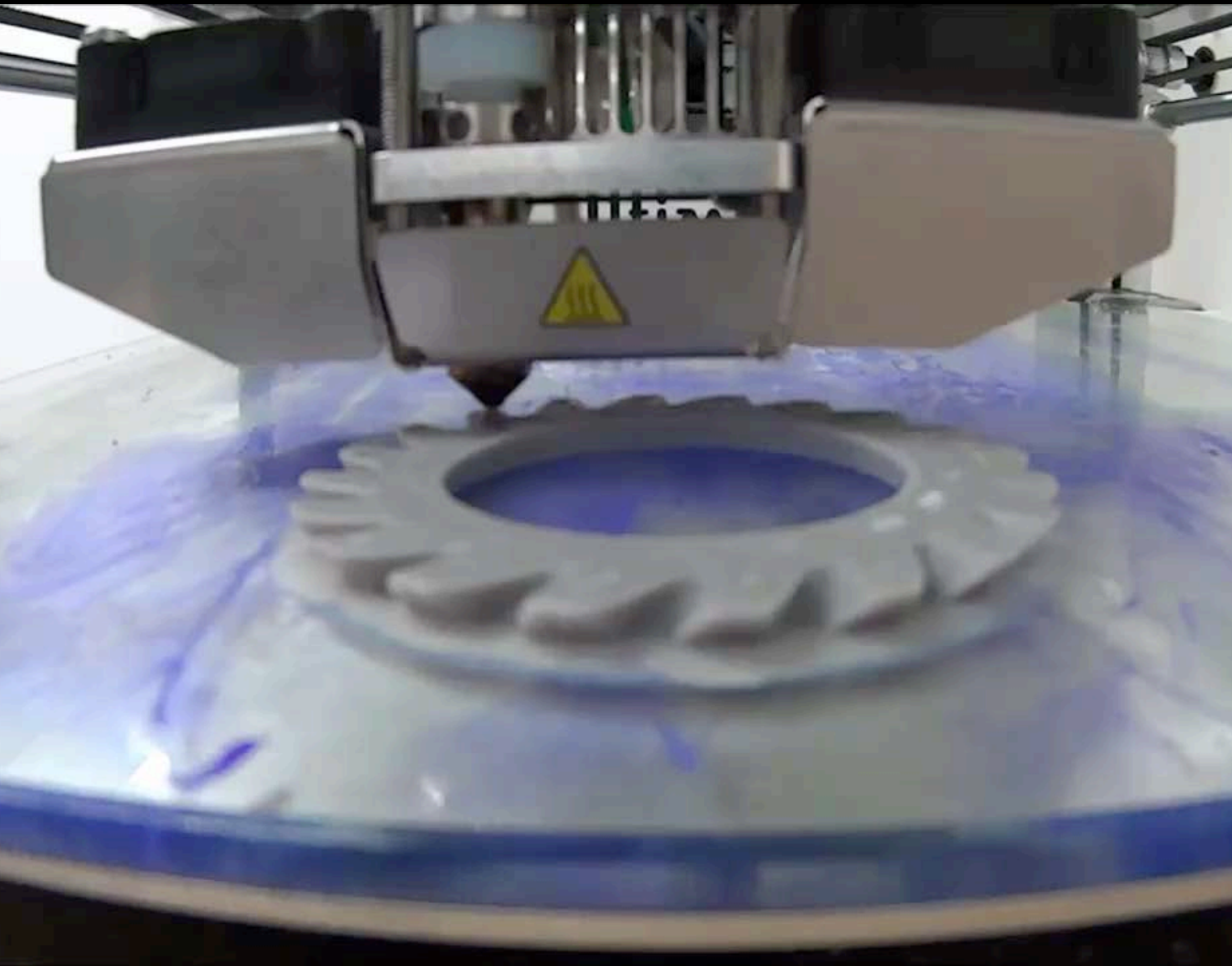


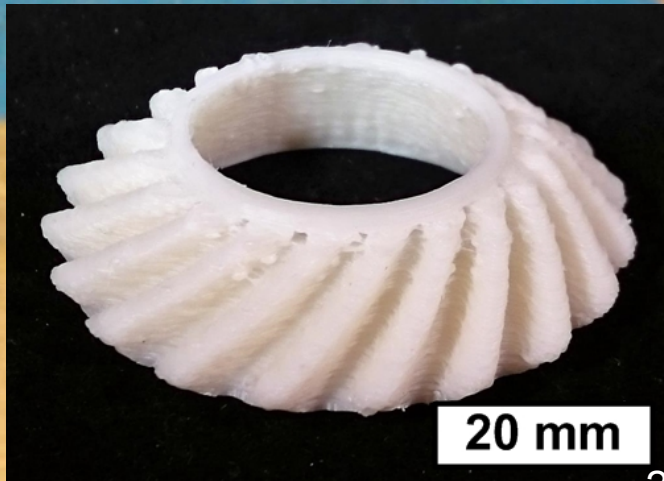
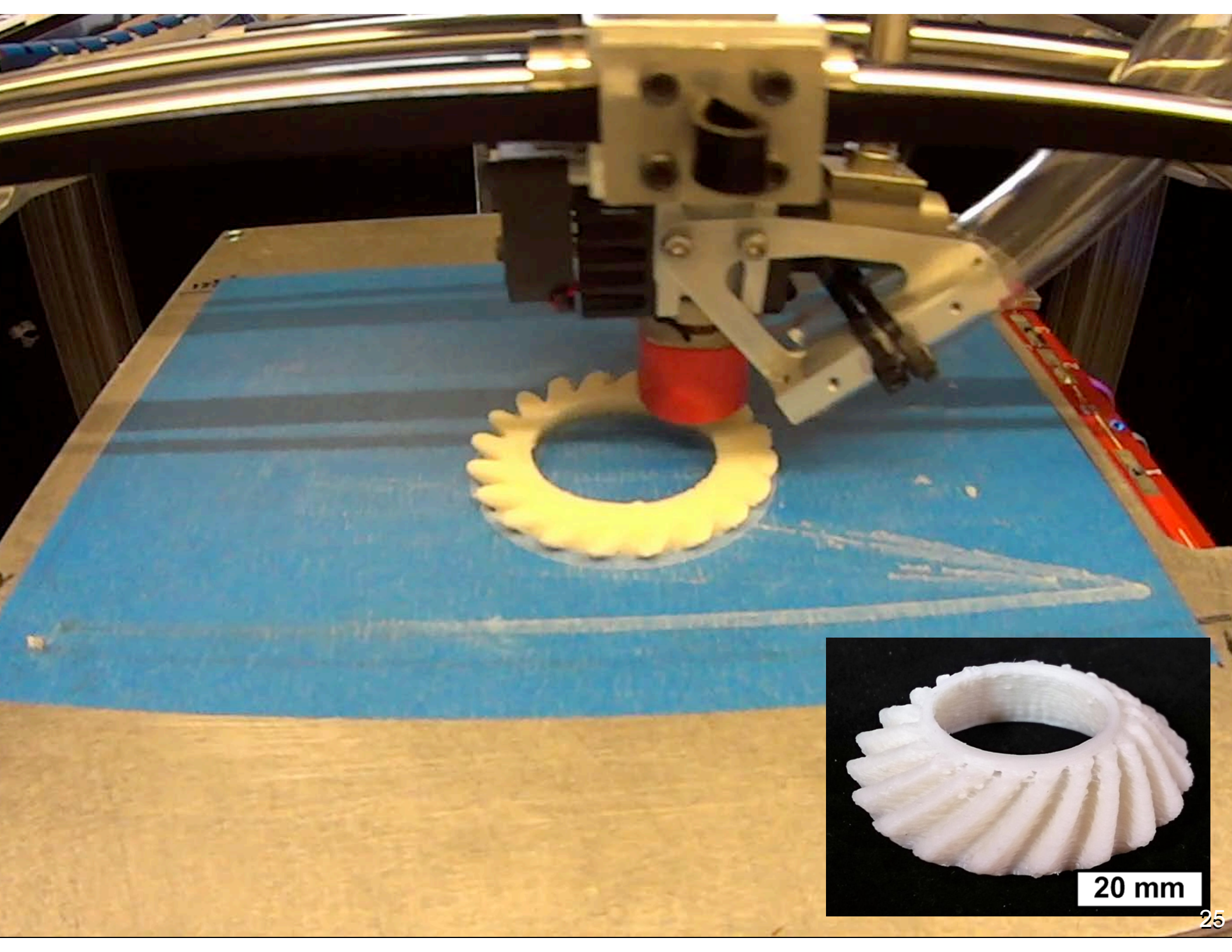
Custom airway stent (U. Michigan)



Fused Filament Fabrication (FFF)







20 mm

FastFFF

Servo motors

H-frame gantry

Fume extractor

Print bed

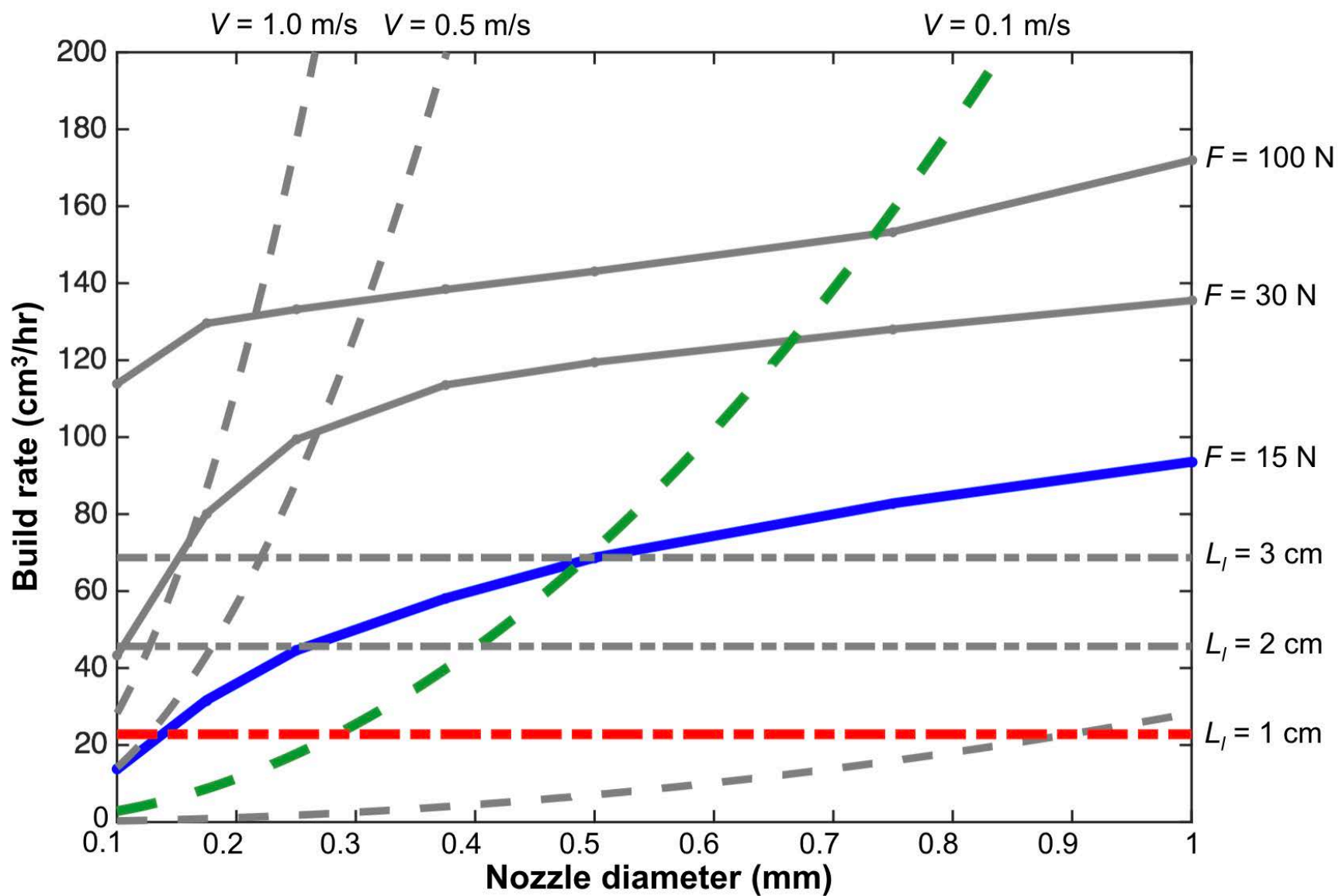
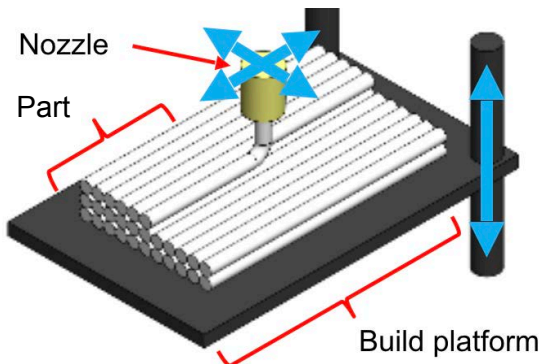
Control electronics

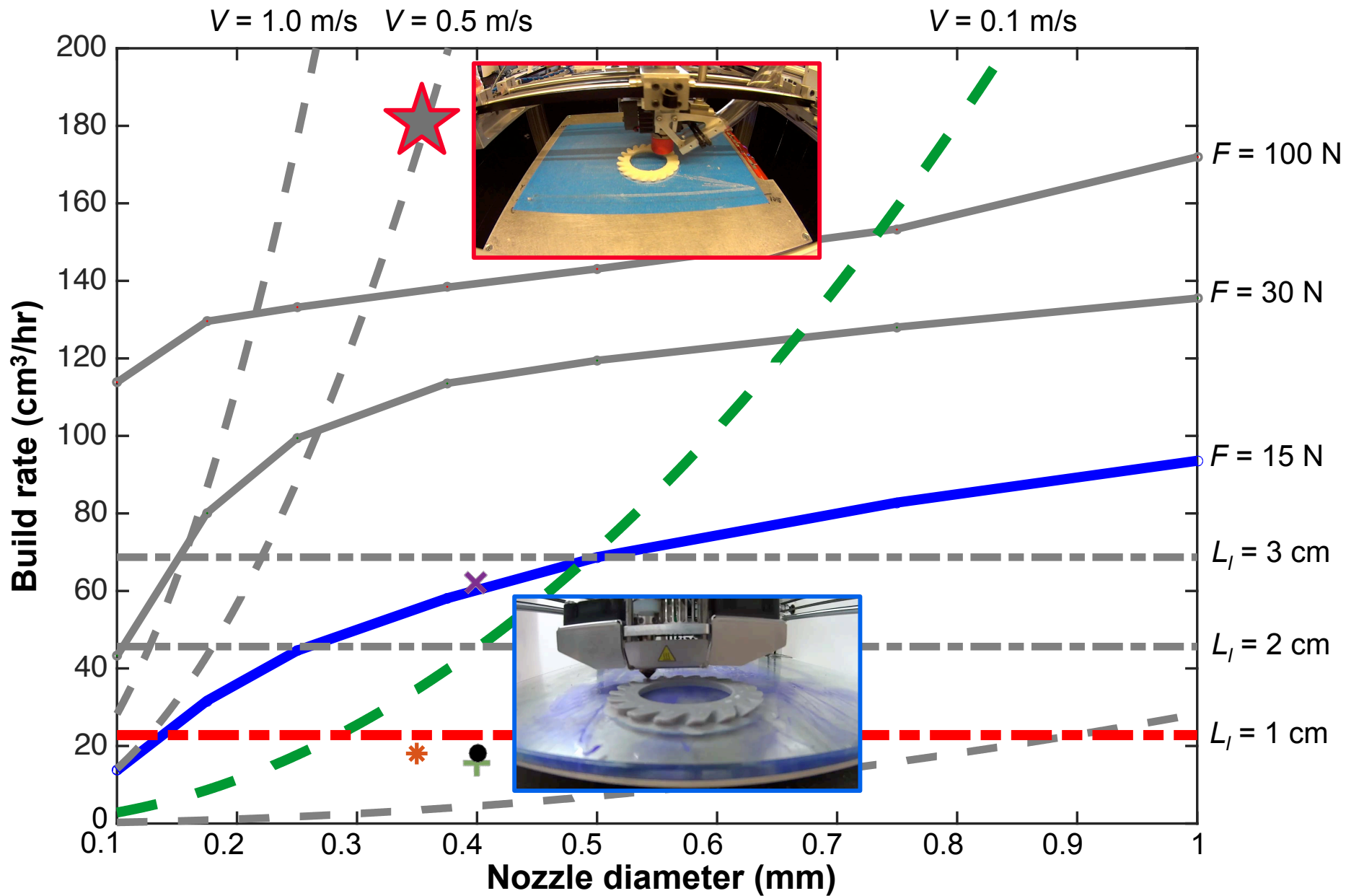
Diode laser

Laser-safe enclosure

0.1 m





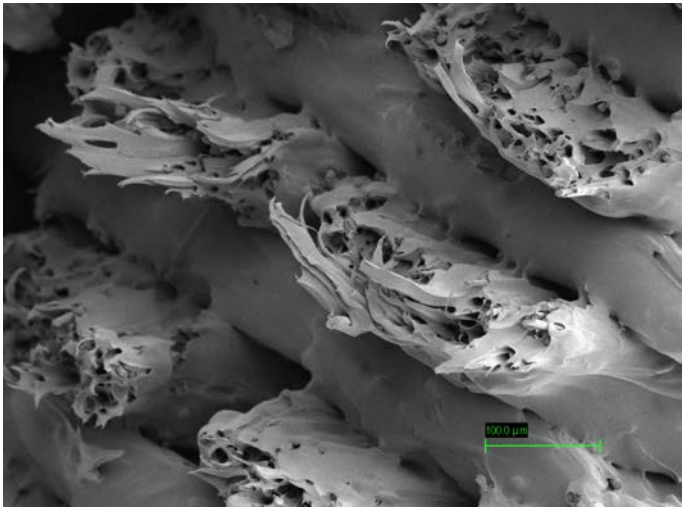
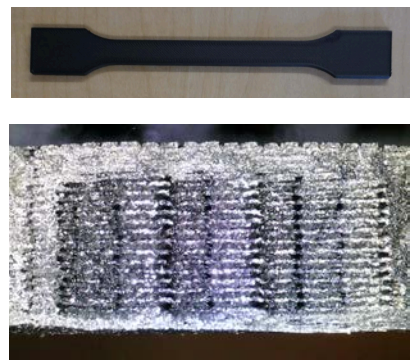




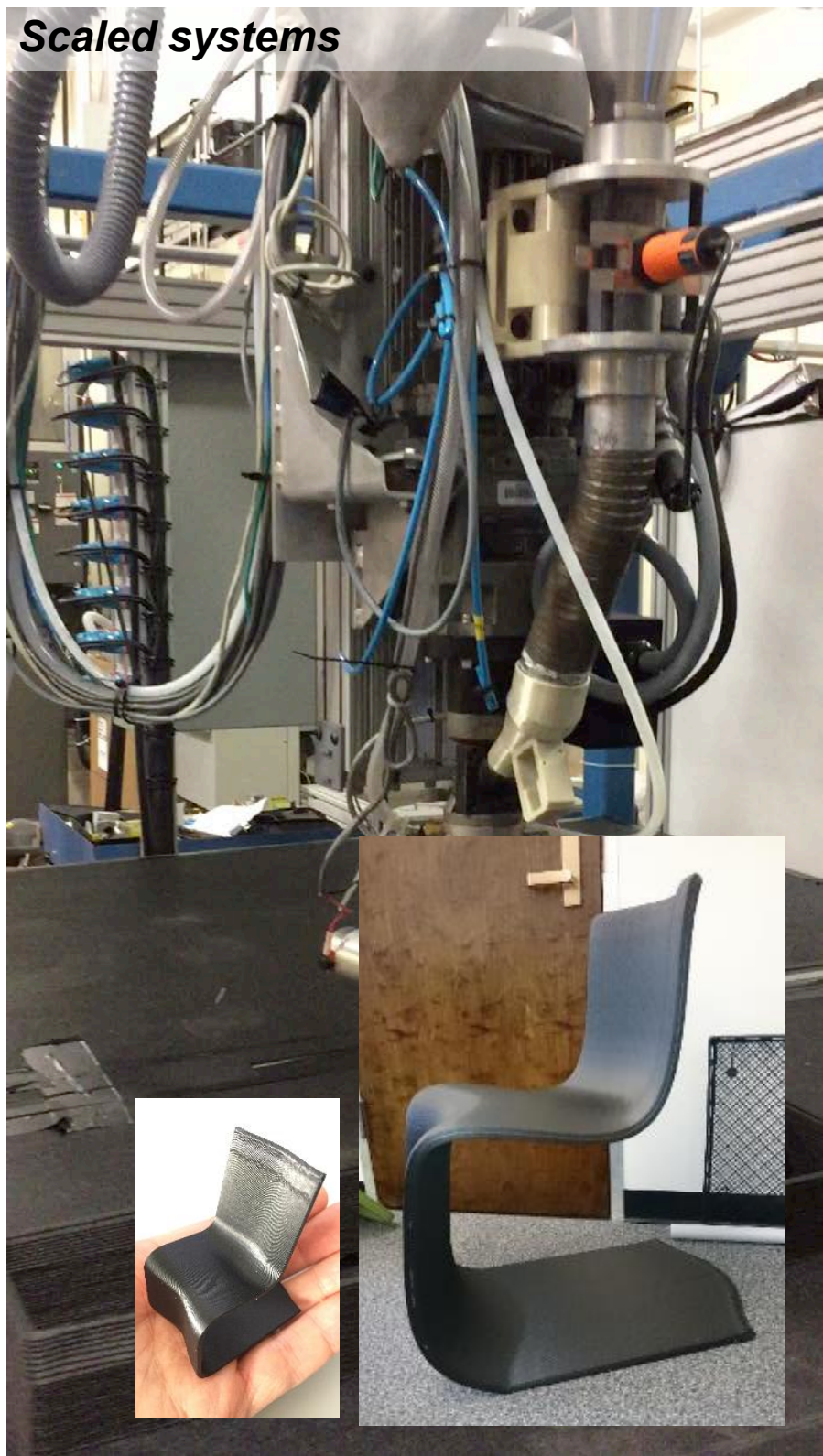
Raytheon RR-4, 1971.

What's next

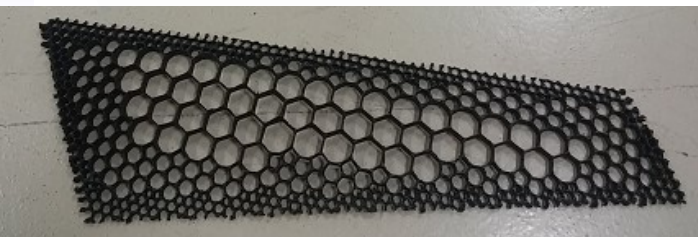
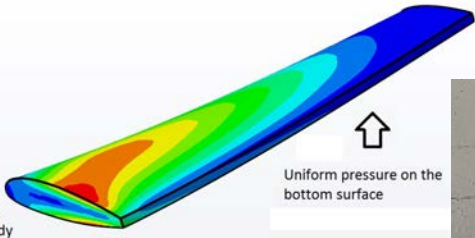
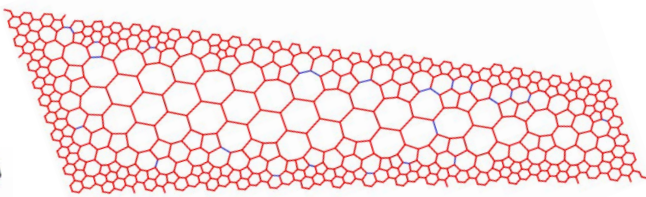
Composite materials and high-performance resins



Scaled systems

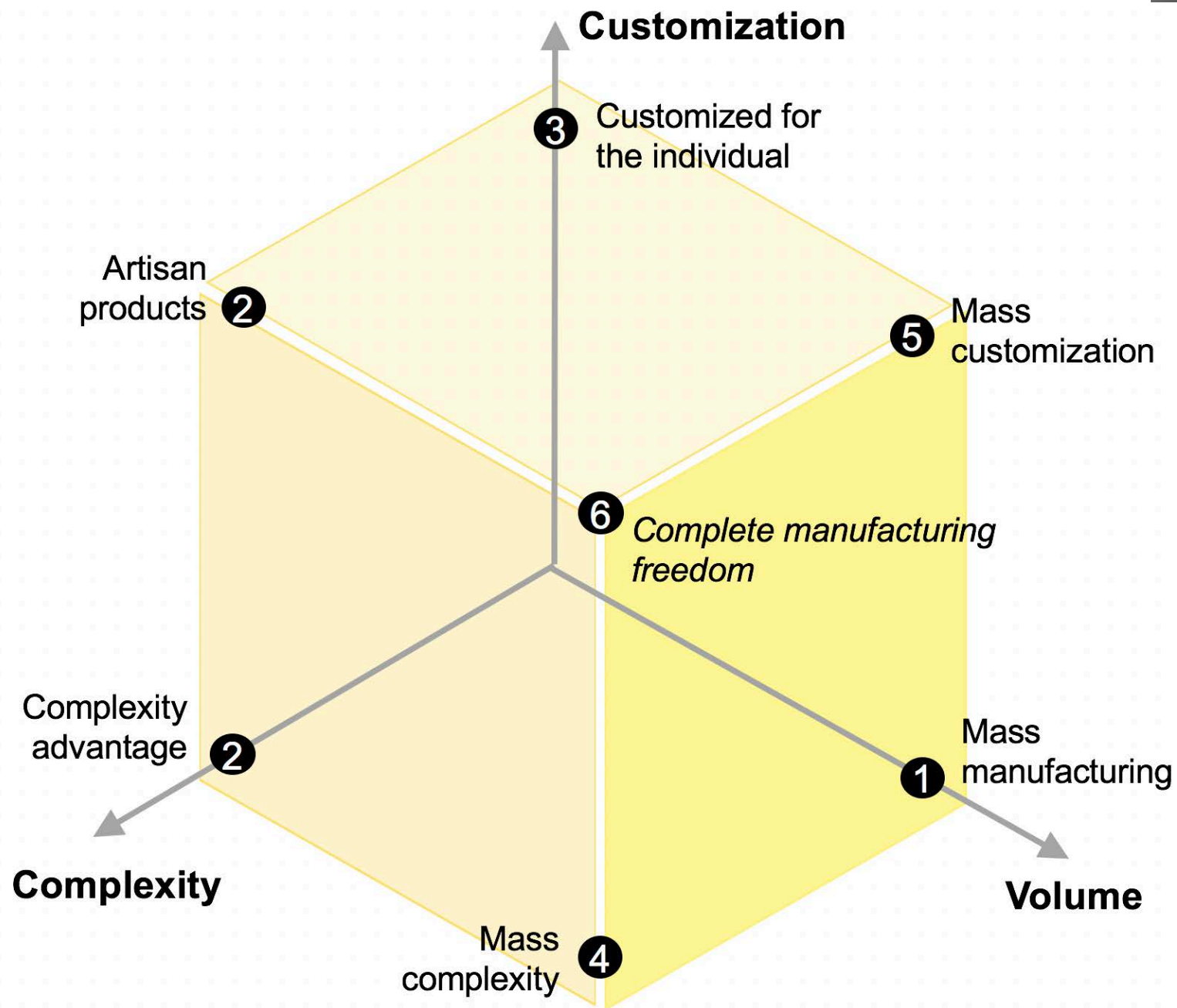


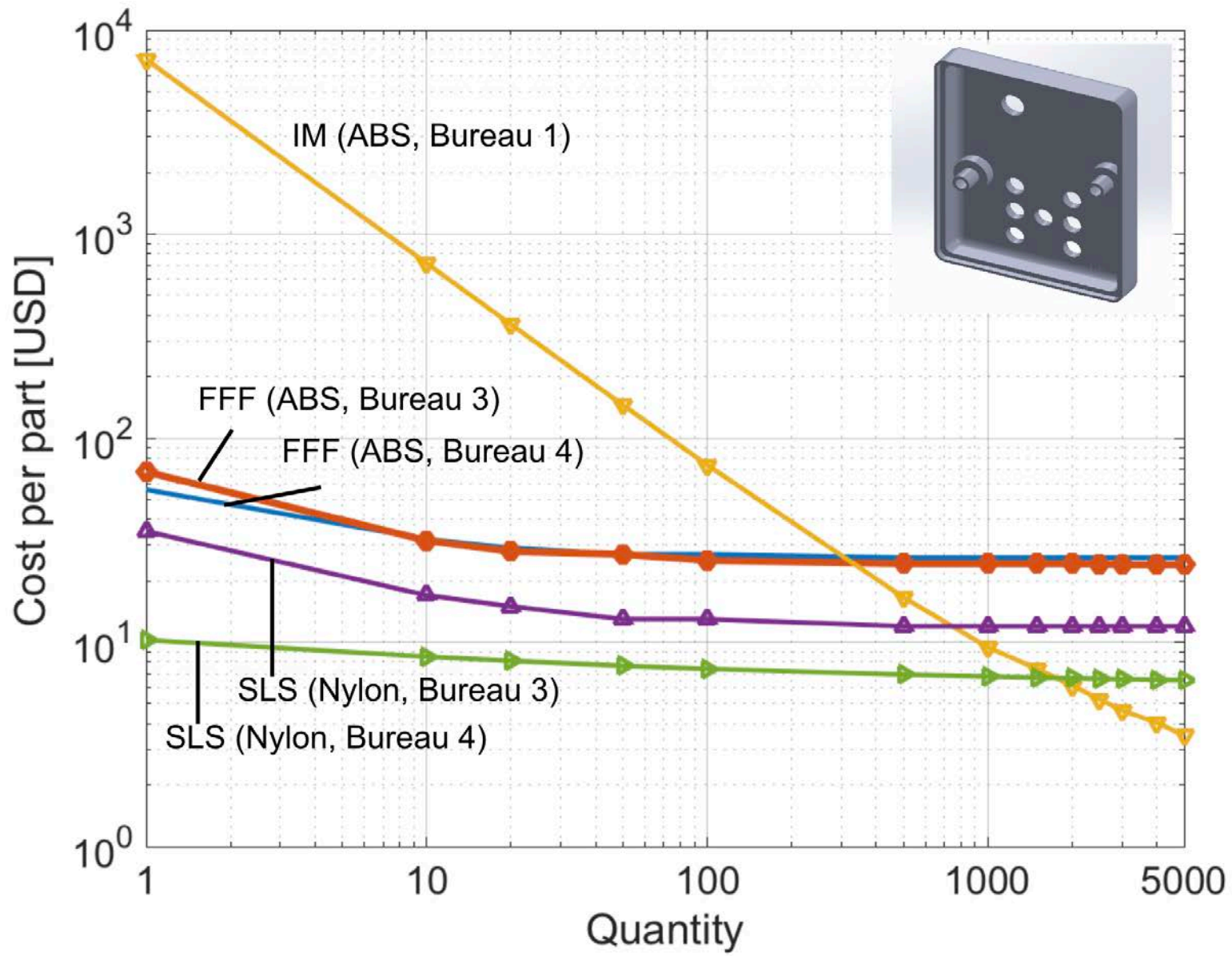
Toolpath optimization




big
think









Desktop Metal is reinventing the way design and manufacturing teams print with metal.

We have developed a complete end-to-end printing system capable of producing parts at scale, from prototyping to mass production. Our technology seamlessly integrates hardware, software, and materials to exceed the current limitations of the industry and push the boundaries of what's possible with metal.



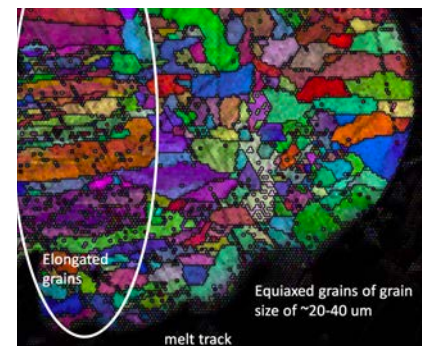
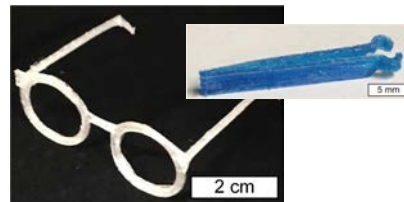
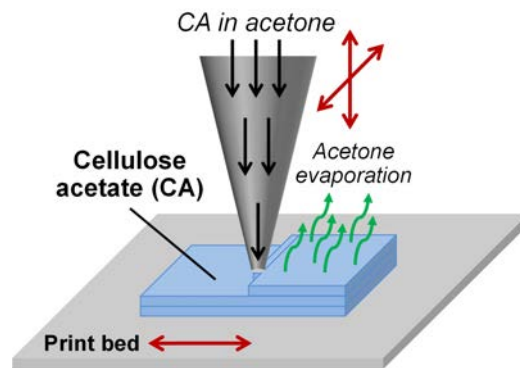
MIT | Center for Additive and Digital Advanced Production Technologies

<http://bit.ly/adapt-mit>
adaptcenter@mit.edu

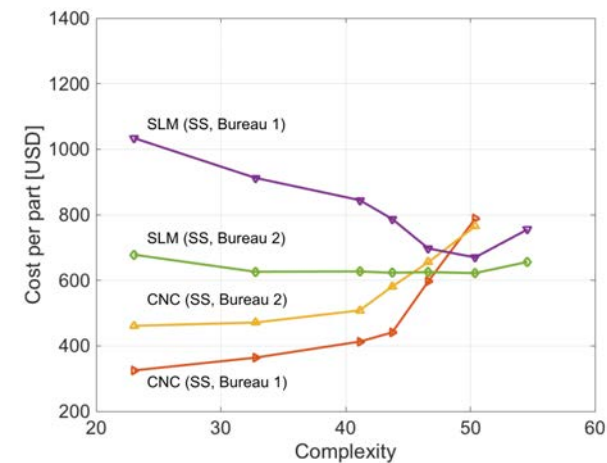
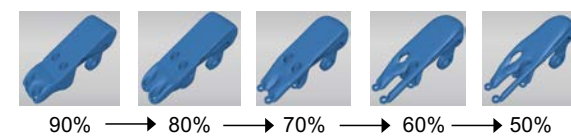
Automation




Materials and Processes



Optimization and Forecasting





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5-day course at MIT
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Thank you

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