Miniaturizing 3D Printed Microfluidics

Gregory P. Nordin[1], Hua Gong[1], Adam T. Woolley[2]
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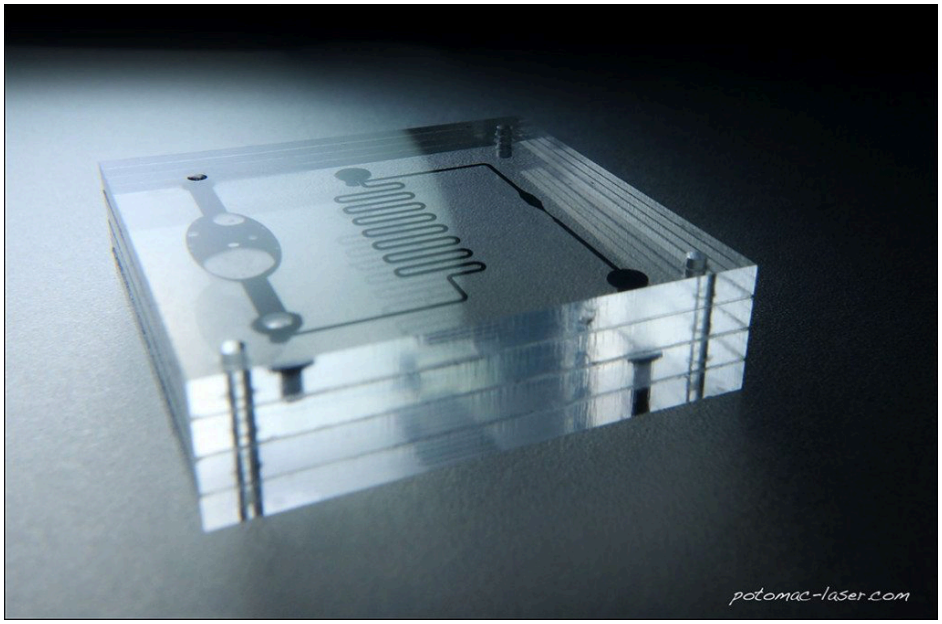
[1]Electrical & Computer Engineering Department
[2]Chemistry & Biochemistry Department
Brigham Young University

nordin@byu.edu

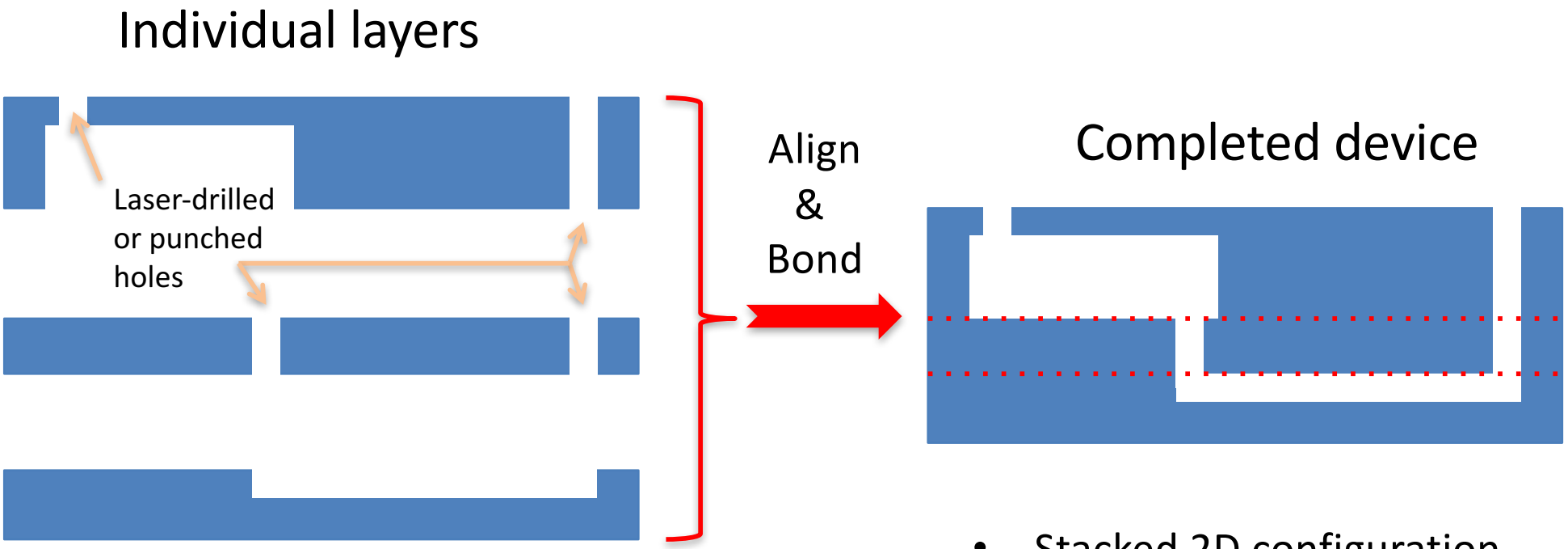
Microfluidic Devices

- Comprise interconnected hollow regions (voids) in bulk material



- Microfluidics ➡ **micro**voids (<100 μm)

Traditional Microfluidic Device Fabrication



- Stacked 2D configuration
- Few layers

Layers:

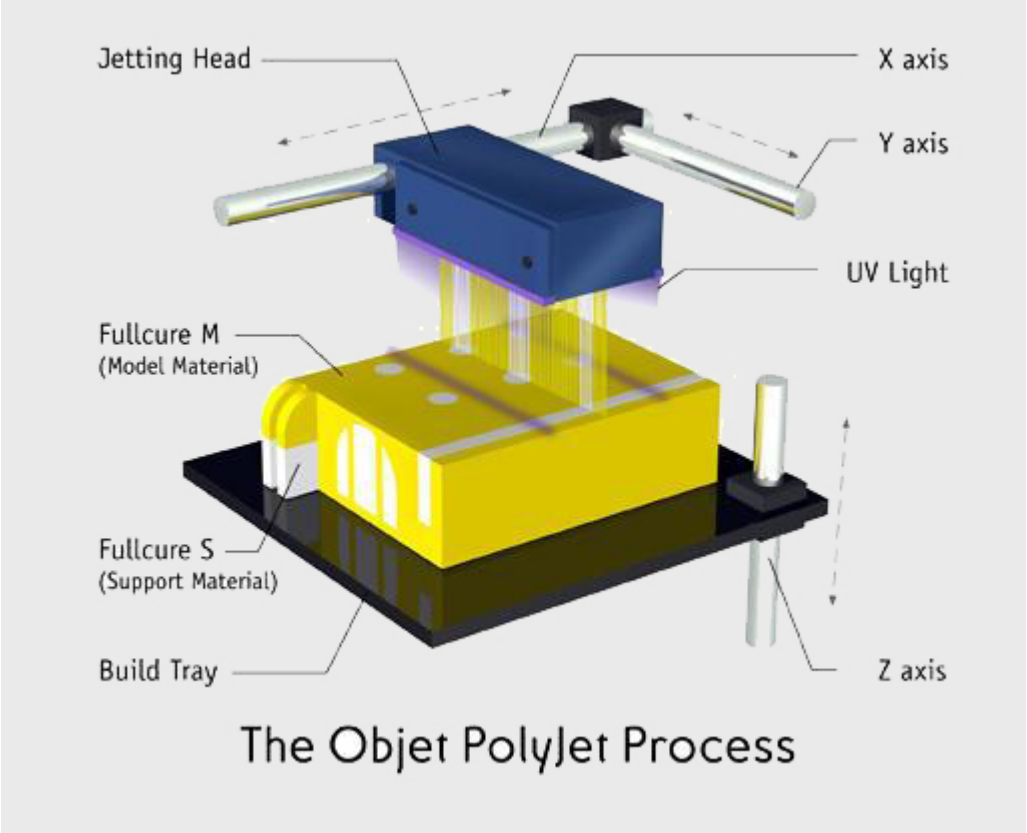
- Hot-embossed or injection molded plastics
  - External valves
- PDMS
  - Elastomeric
  - Integrated valves

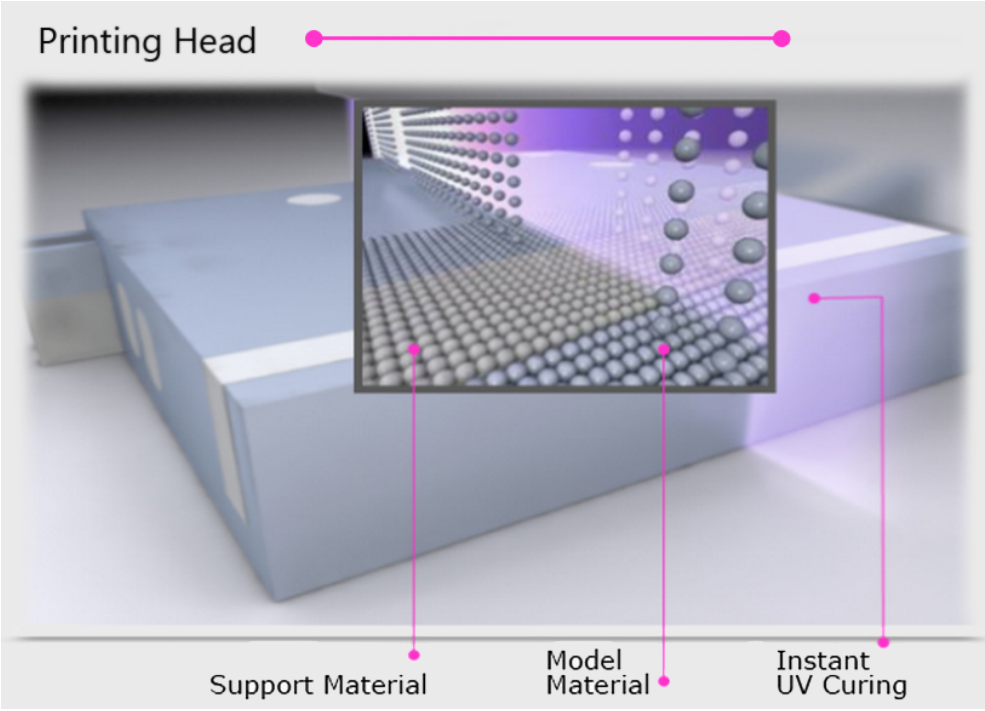
3D Printing

- Possible approaches:
  1. Existing commercial printers and materials
  2. Existing commercial printers + custom materials
  3. New tools + custom materials

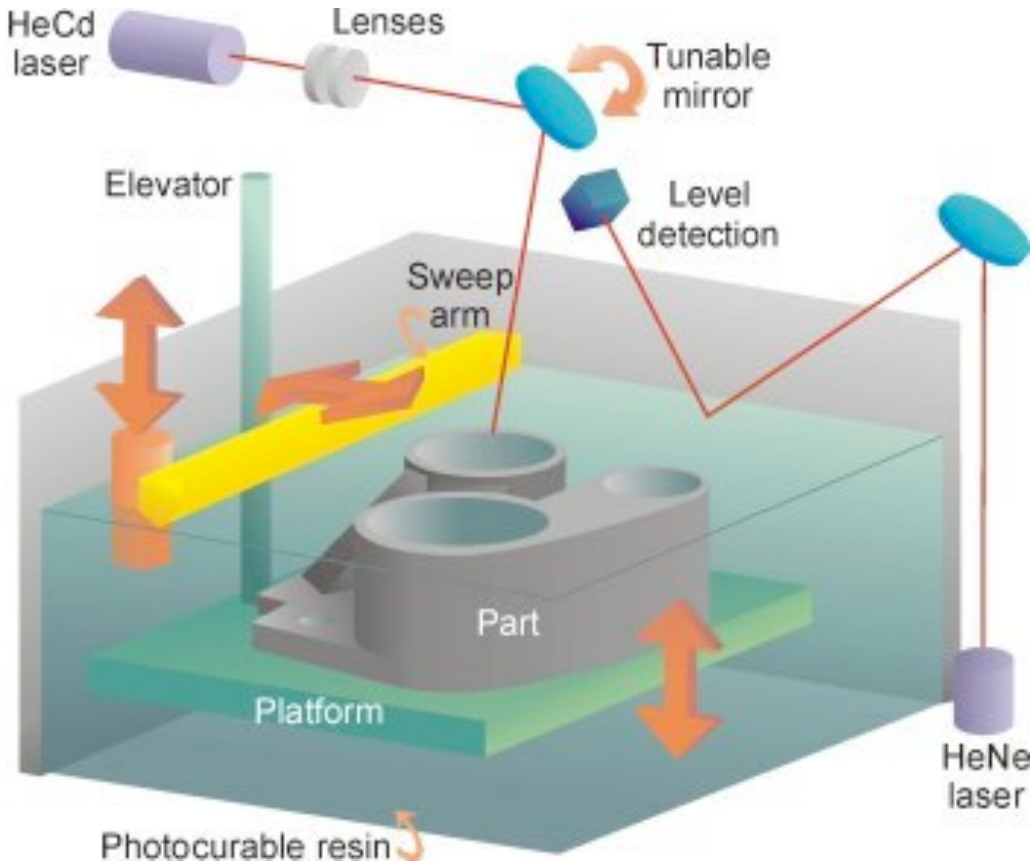
- Microfluidics ➡ **micro**voids (<100 μm)

Inkjet – Polyjet - Multijet



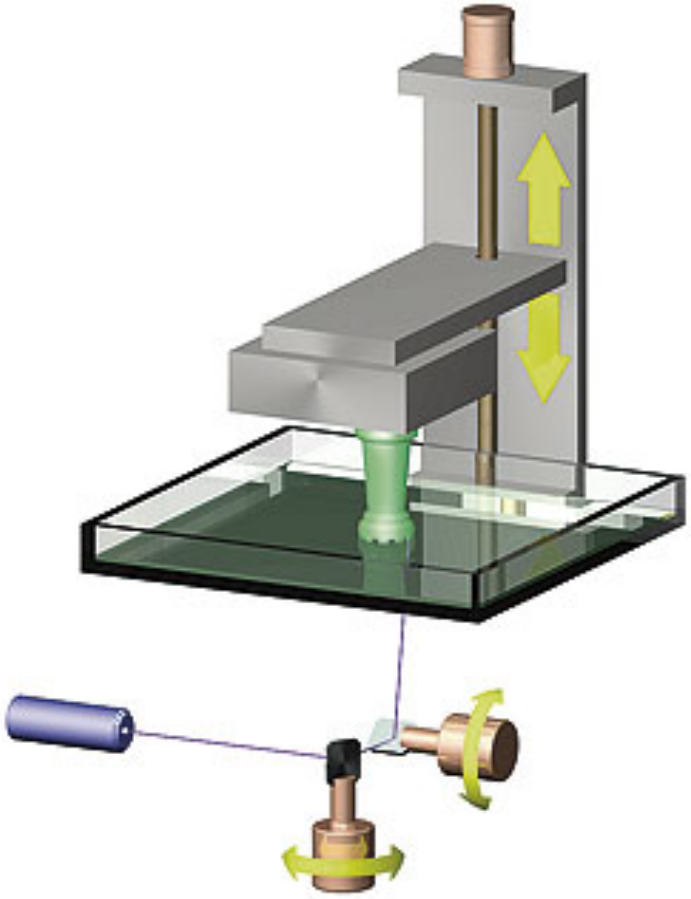


Stereolithography: Scanned Laser—Top



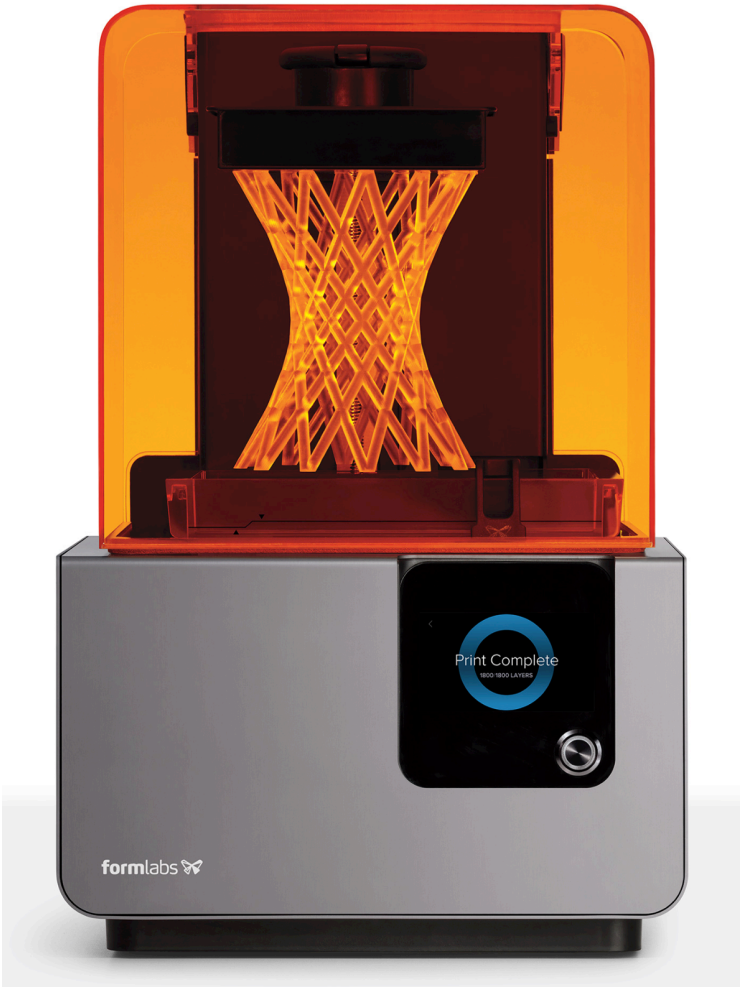
http://3dprinting.ga/about-3d-printing/how-does-3d-printing-work/

Stereolithography: Scanned Laser—Bottom



http://www.meccanismocomplesso.org/en/xfab-la-stampante-3d-laser-per-il-mercato-consumer/

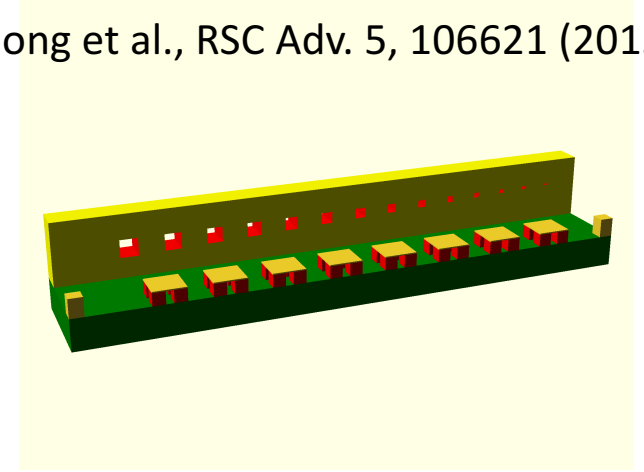
Formlabs Form 2
$3,500



Commercial 3D Printer Service Bureaus

- High-end 3D printers
- Commercial resins

Gong et al., RSC Adv. 5, 106621 (2015)



- Channels
  - 1.08 mm long
- Printer resolution
  - SLA—Scanned Laser:
    - 75 µm in x-y
    - 25 µm in z
  - Polyjet:
    - 42 µm in x-y
    - 16 µm in z

Channel size	Invent-A-Part	Stratasys Polyjet	Stratasys µHDSL	3D Systems Quickparts	Fineline
700 µm × 700 µm					
650 µm × 650 µm					
600 µm × 600 µm					
550 µm × 550 µm					
500 µm × 500 µm					
450 µm × 450 µm					
400 µm × 400 µm					
350 µm × 350 µm					
300 µm × 300 µm					
250 µm × 250 µm					

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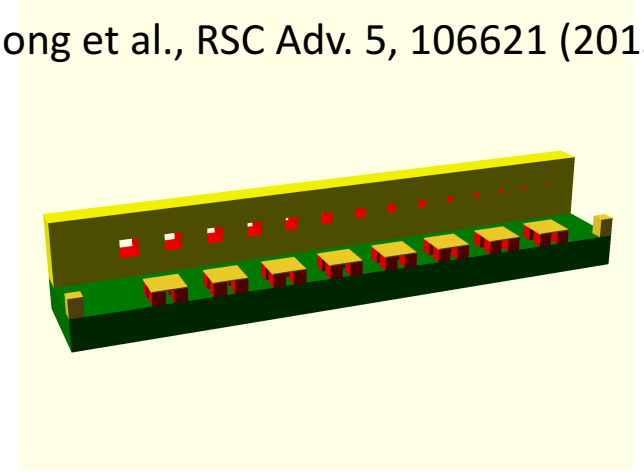

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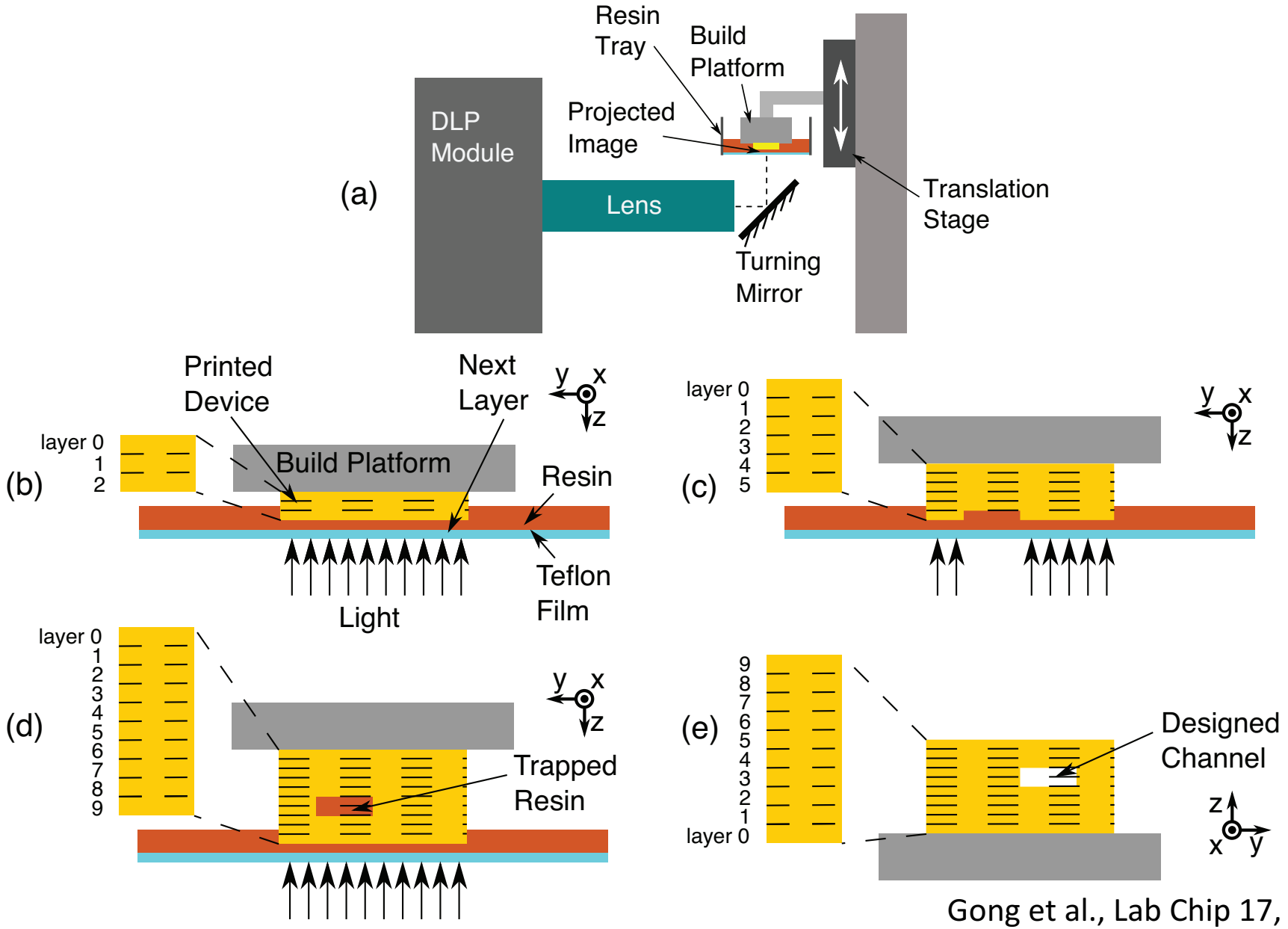
250 µm × 250 µm					

Manufacturer resolution specs

≠

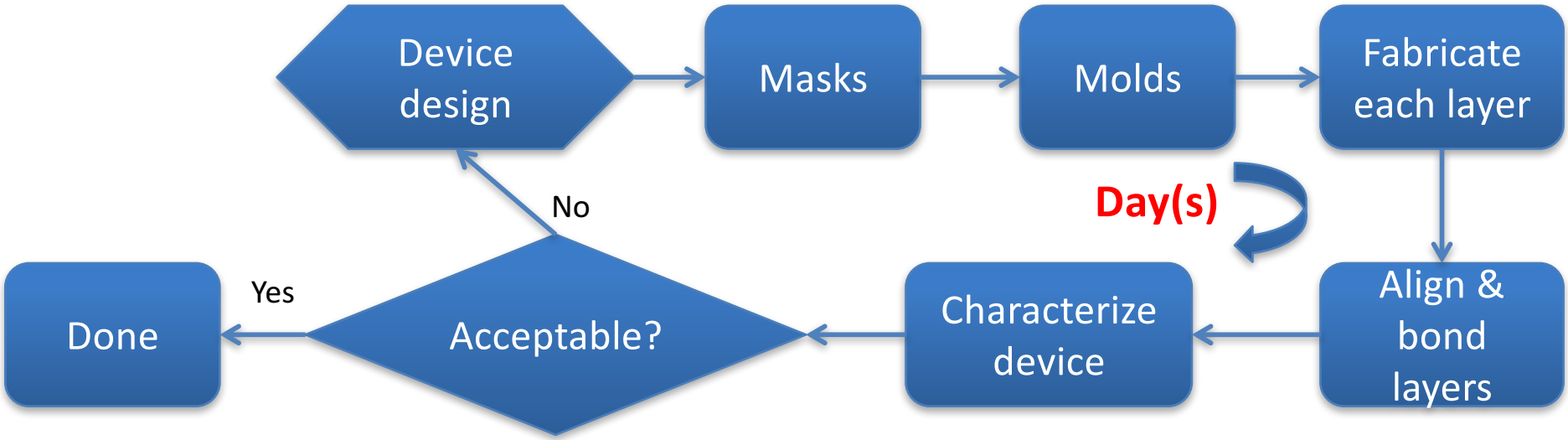
Achievable void size!

DLP-SLA 3D Printing for Microfluidic Devices

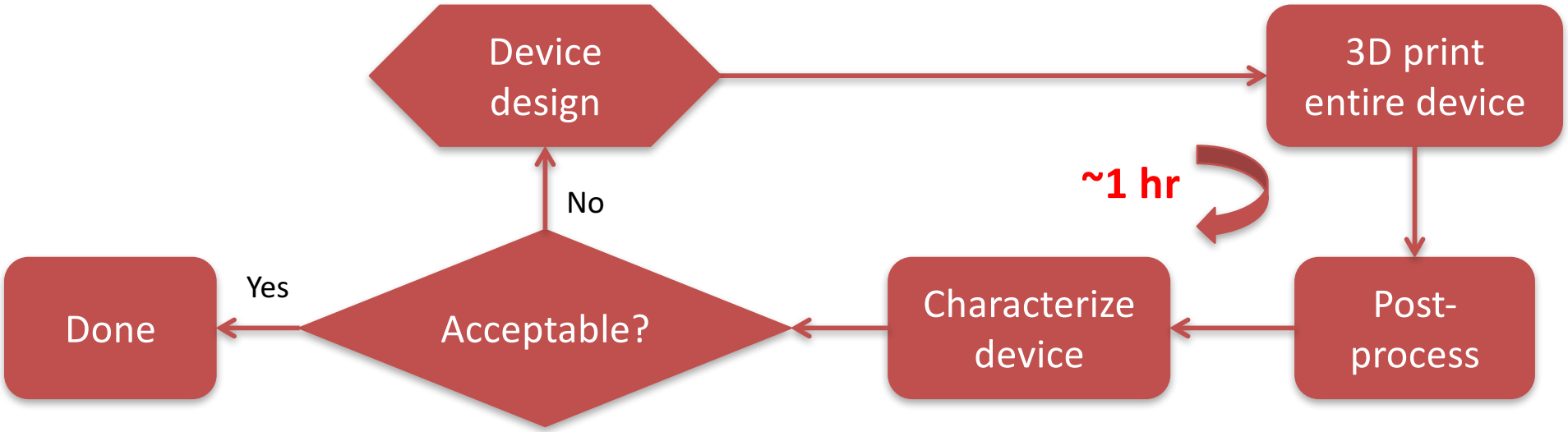


Gong et al., Lab Chip 17, 2899 (2017)

Process - Conventional



Process – 3D printer



Benefits

- True rapid prototyping
- Development process becomes:
  - Fail fast & often
  - Early & rapid empirical feedback drives progress
- Dramatic reduction in:
  - Opportunity cost to try new ideas
  - Barrier to entry
    - No cleanroom required
- Utilize full 3D volume
  - Size reduction
  - Parallel fabrication ➡ path to manufacturing
  - Same tooling and materials for prototyping and manufacturing

Barriers

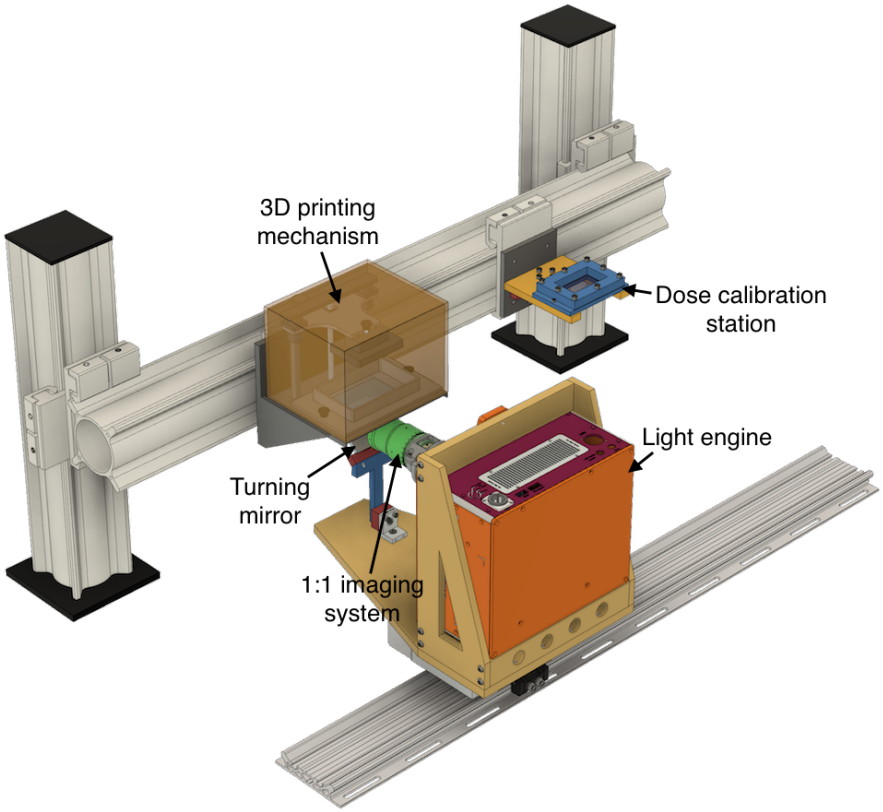
- Feature sizes are in the millifluidic rather than microfluidic regime
  - Need features $\lesssim 100$ μm or lose advantage of using small sample and reagent volumes (~1 μL)
- Market pull
  - Dental, custom jewelry, audiology
- Commercial 3D printers
  - ~50 μm x-y resolution
  - ~50 μm z layer thickness
- Proprietary commercial resins
  - Viscosity (affects feature size)
  - Lack of tailorable mechanical, optical, biocompatibility properties

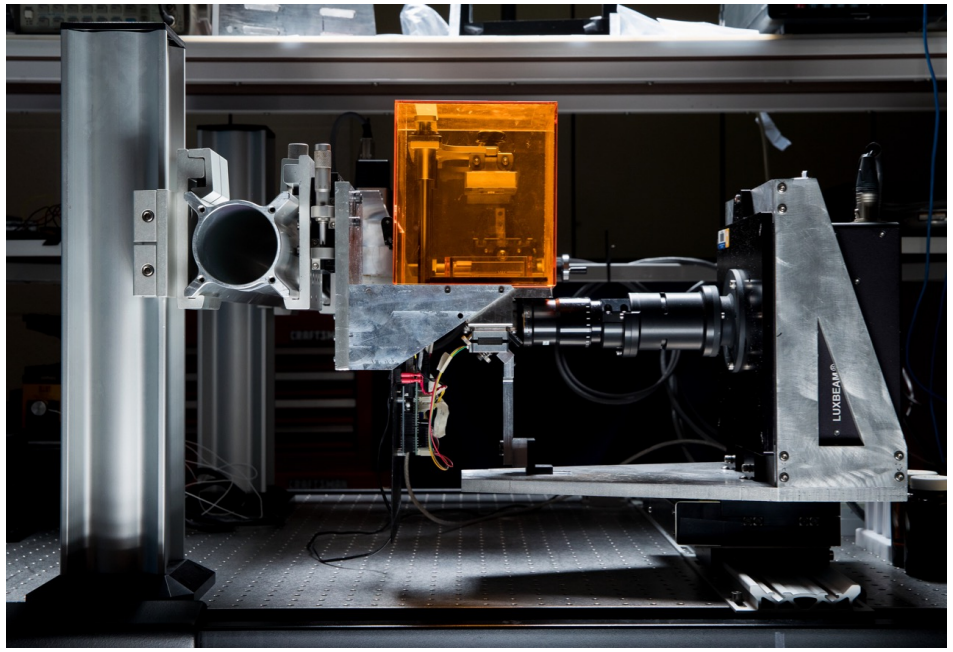
Overview

- Focus on our work over the last year
- Custom 3D printer
  - High XY resolution: 7.6 μm
  - UV light source: 385 nm LED
- Custom low-cost resin development
- Small channels
  - 18 μm x 20 μm
- Valves and pumps
- Integrated mixer and pump with selectable mixing ratio
  - ~6.3 mm^3 = $(1.85\ mm)^3$

Gong et al., Lab Chip 17, 2899 (2017)

Custom DLP-SLA 3D Printer





Optical Engine - Visitech

- 2560 x 1600 pixels
- 7.6 μm pixel pitch
- 1:1 lens system
- 19.5 x 12.2 mm^2
- 385 nm LED

Mechanical System – Modified Solus

- Teflon film
- Tipping quartz window
- Typical build layer thickness: 5 – 10 μm

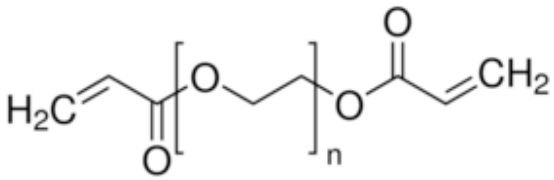
Software

- Custom in-house developed 3D printer control (Python)
- Open source 3D CAD
- Open source slicer

Custom Resin Formulation

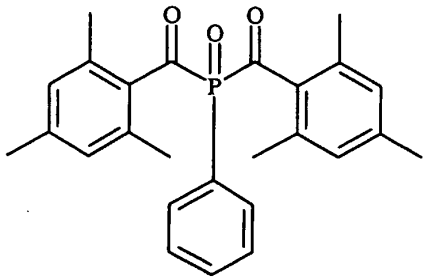
Monomer

Polyethylene glycol diacrylate (PEGDA)
258 Da, 57 cPs

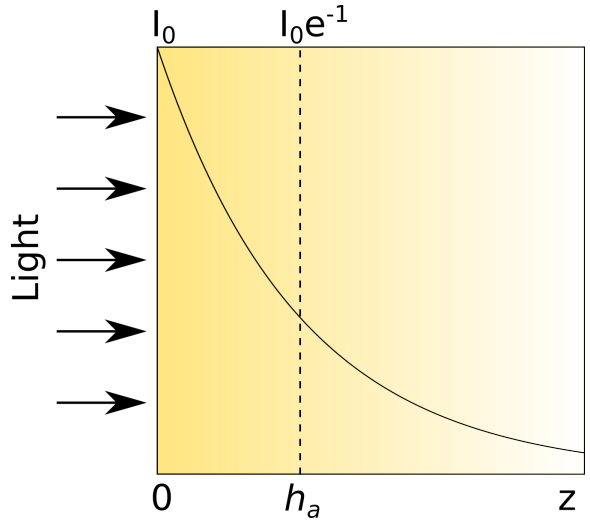


Photoinitiator

Irgacure 819

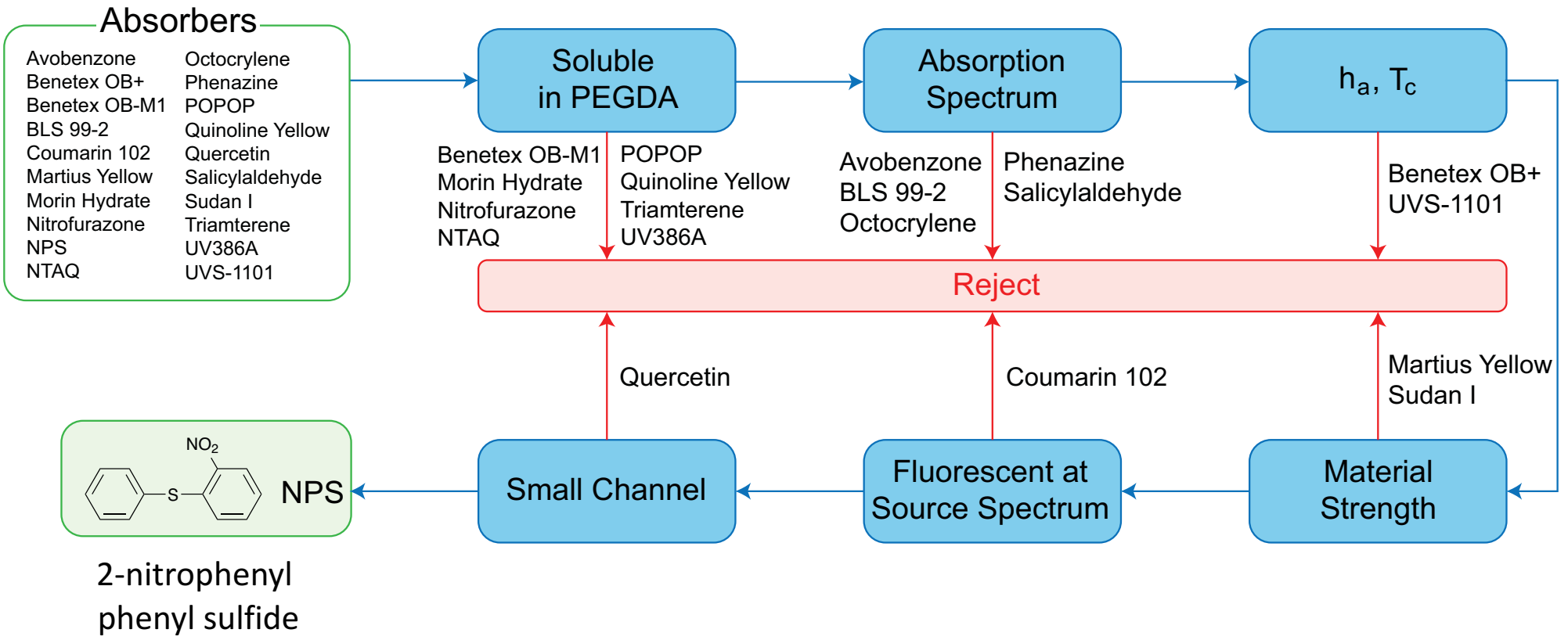


UV Absorber



- Rogers et al., Anal. Chem. 83, 6418–6425 (2011)
- Rogers et al., Biomicrofluidics 9, 016501 (2015)
- Gong et al., RSC Advances, 5, pp. 105521 (2015)
- Gong et al., Lab on a Chip, 17, 2899 (2017)

UV Absorber Selection Criteria



Gong et al., Lab Chip 17, 2899 (2017)

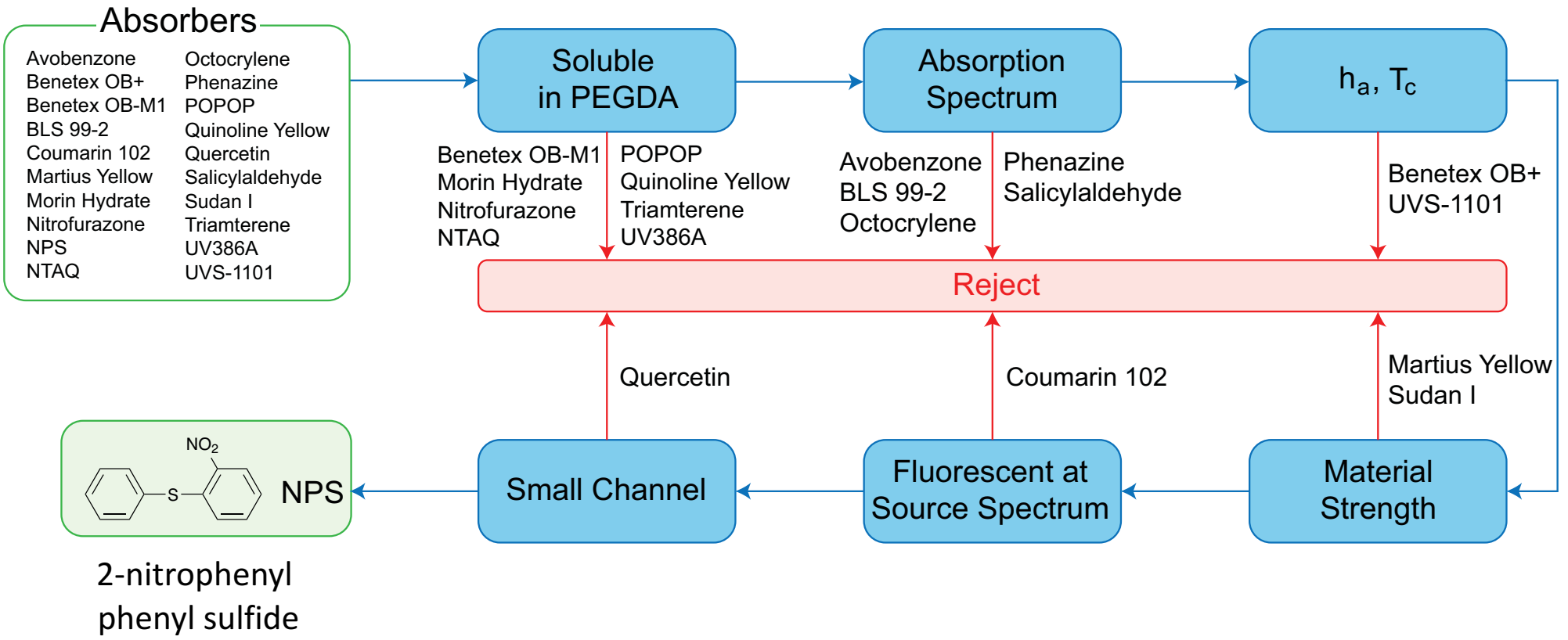
UV Absorber Solubility in PEGDA

Material	Solubility (%) (w/w)	Fluorescent
Avobenzone	>5	
Benetex OB+	0.25	Yes
Benetex OB-M1	—	Yes
BLS 99-2	>5	
Coumarin 102	0.8	Yes
Irgacure 819	>5	
Martius Yellow	3	
Morin hydrate	—	
Nitrofurazone	0.07	
NPS	>5	
NTAQ	—	
Octocrylene	>5	
Phenazine	1.8	
POPOP	—	Yes
Quercetin	0.8	
Quinoline yellow	—	
Salicylaldehyde	>5	
Sudan I	2.7	
Triamterene	—	Yes
UV386A	—	
UVS-1101	0.5	Yes

(with 385 nm excitation)

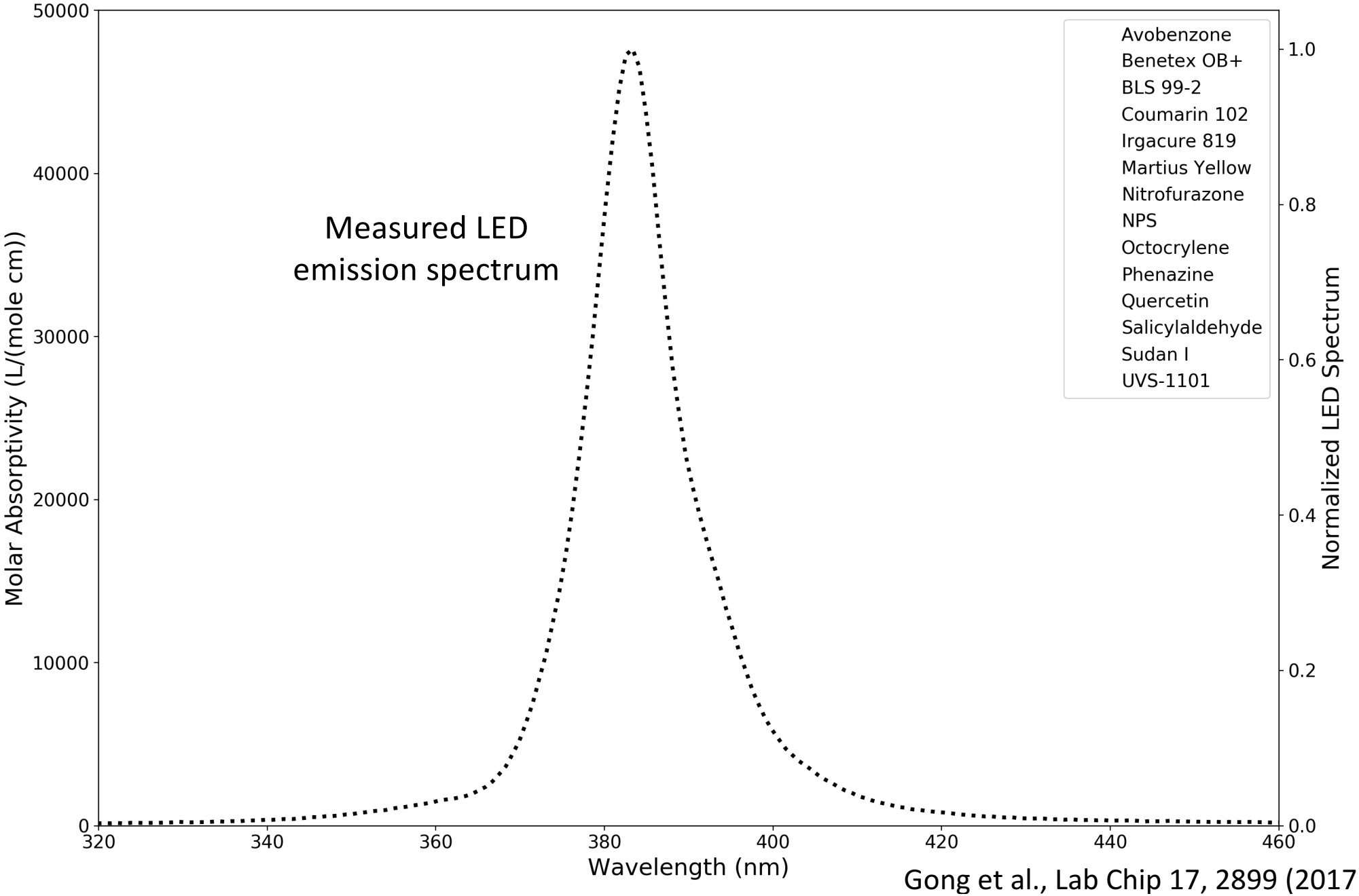
Gong et al., Lab Chip 17, 2899 (2017)

UV Absorber Selection Criteria



Gong et al., Lab Chip 17, 2899 (2017)

Absorption Spectra



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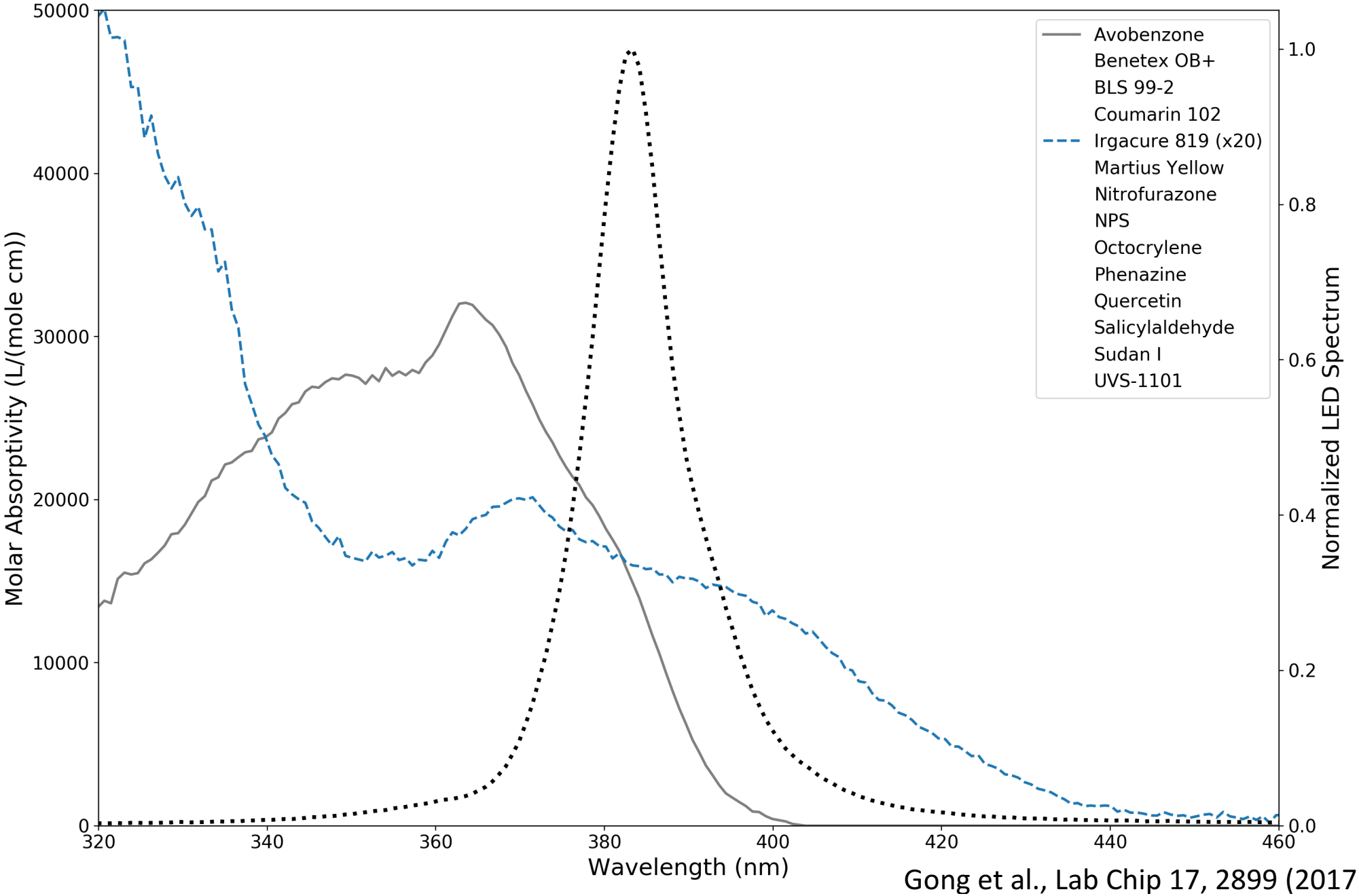

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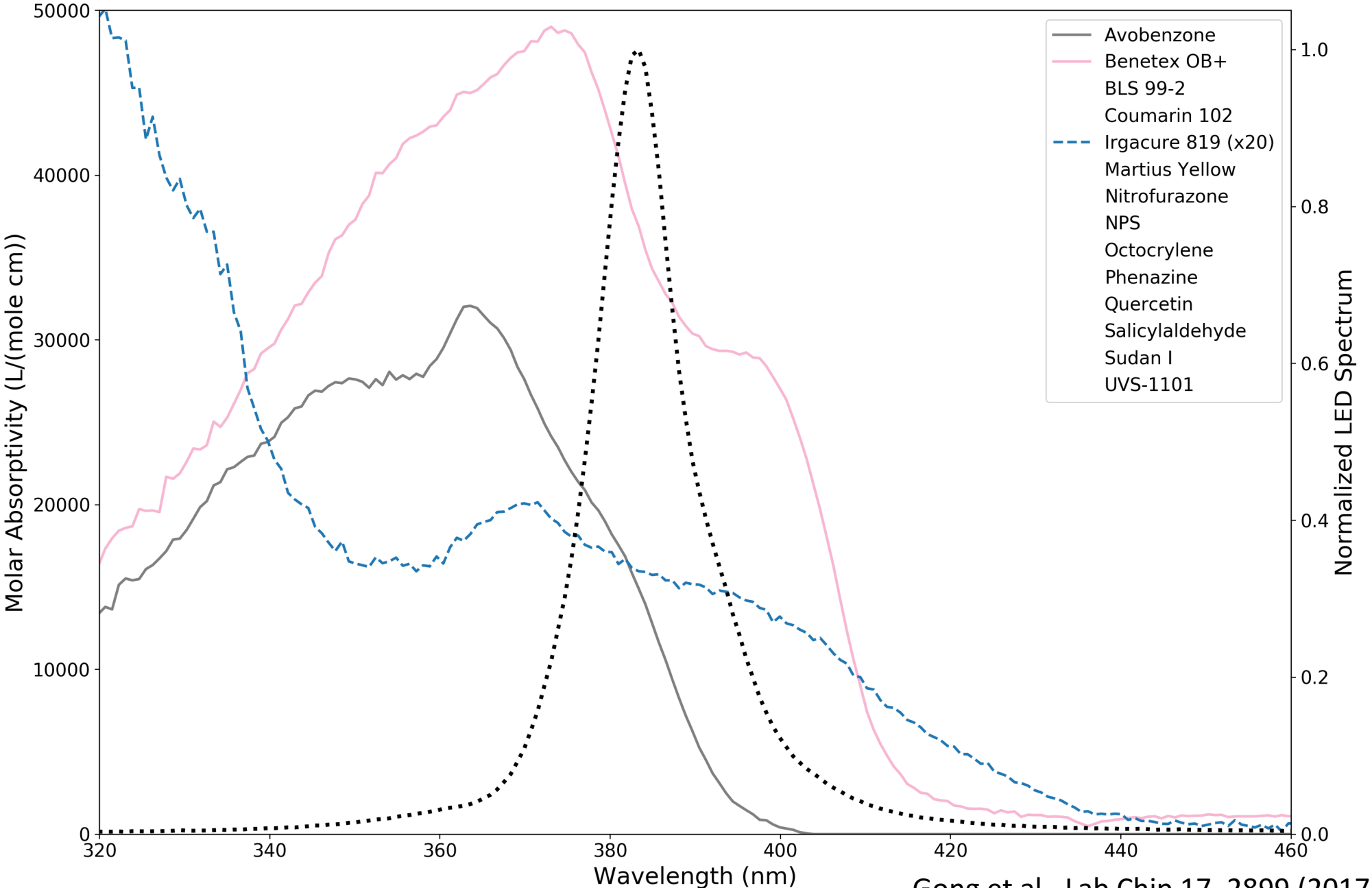

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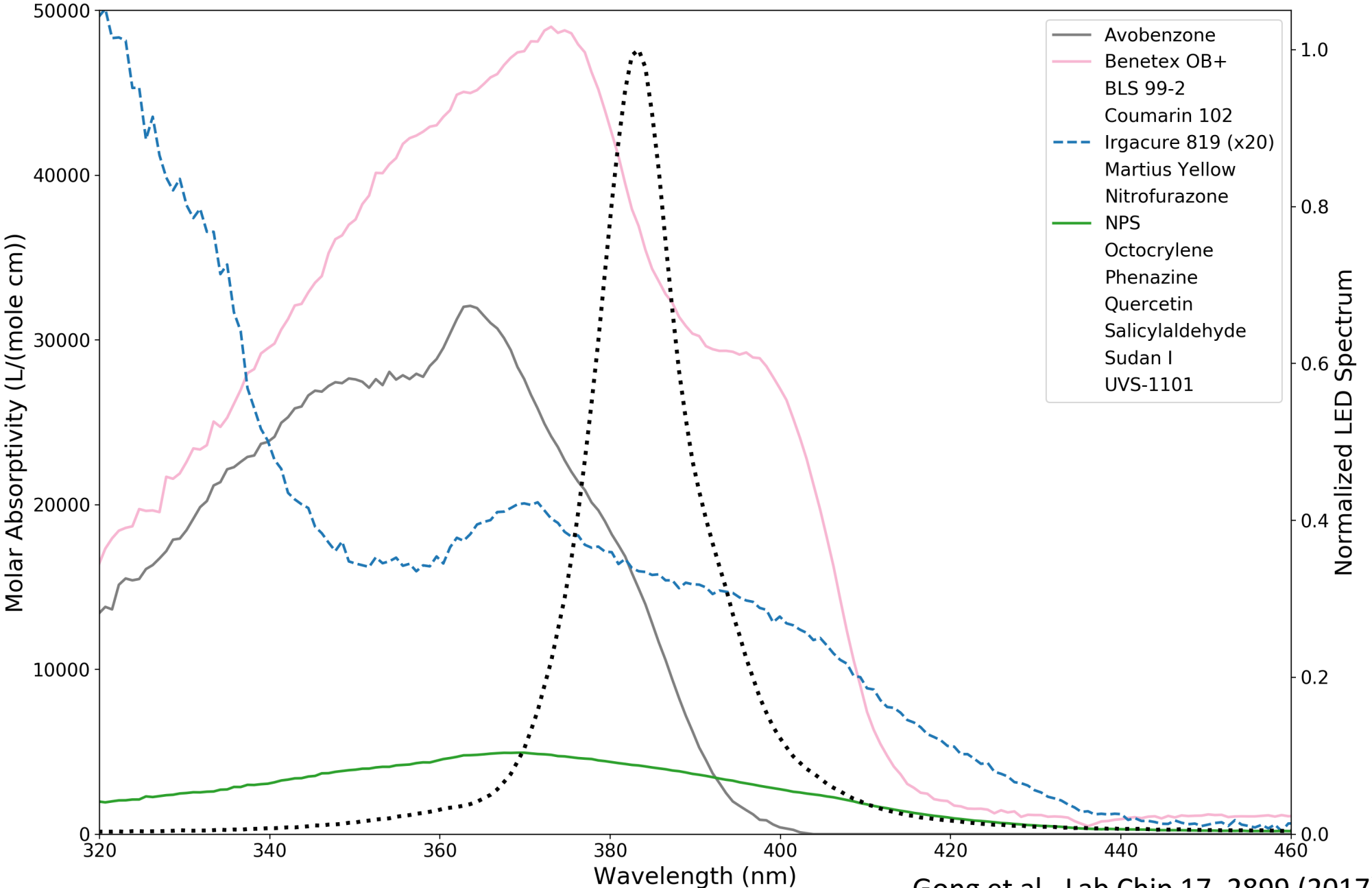

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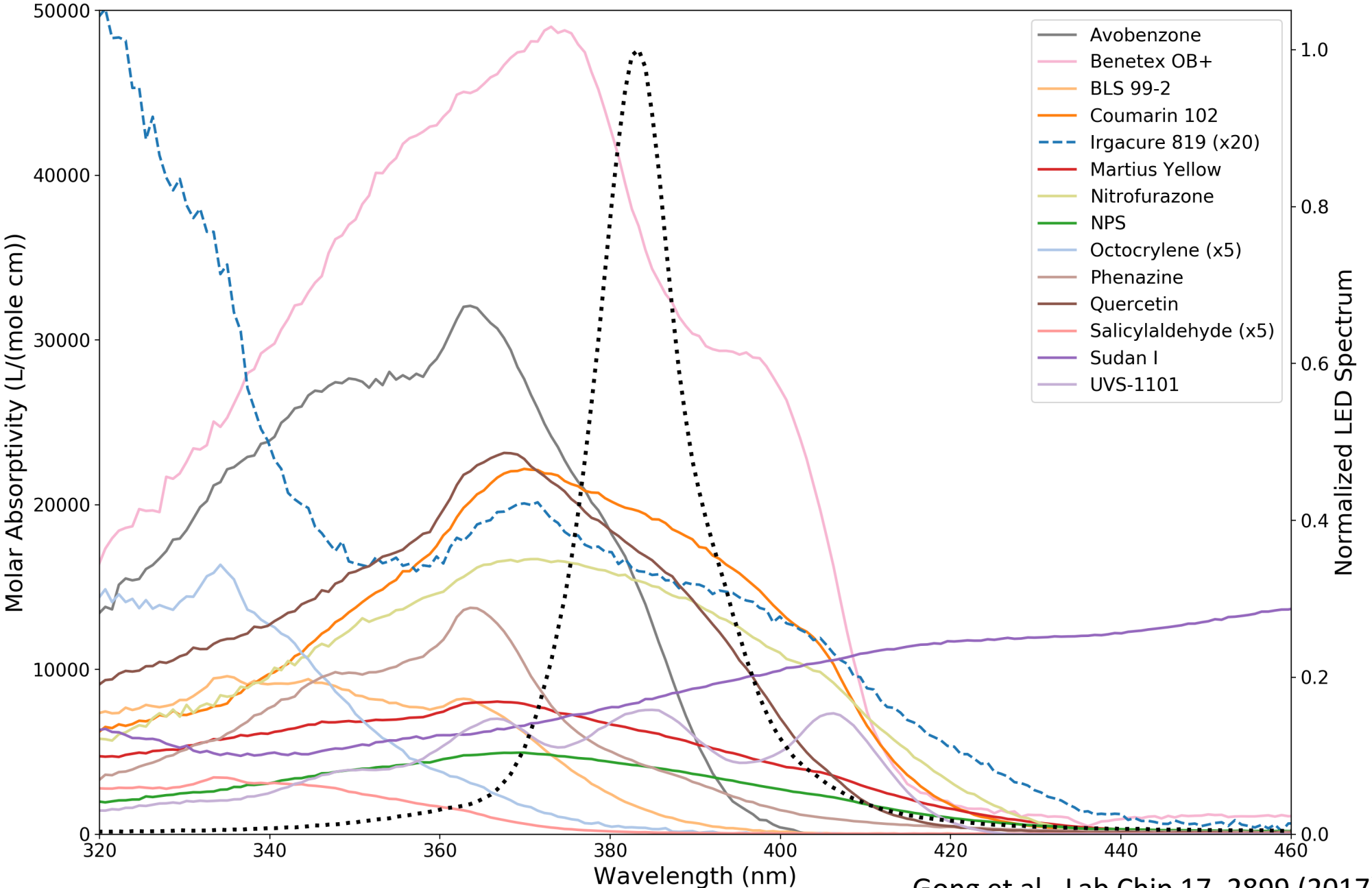
Absorption Spectra



Gong et al., Lab Chip 17, 2899 (2017)

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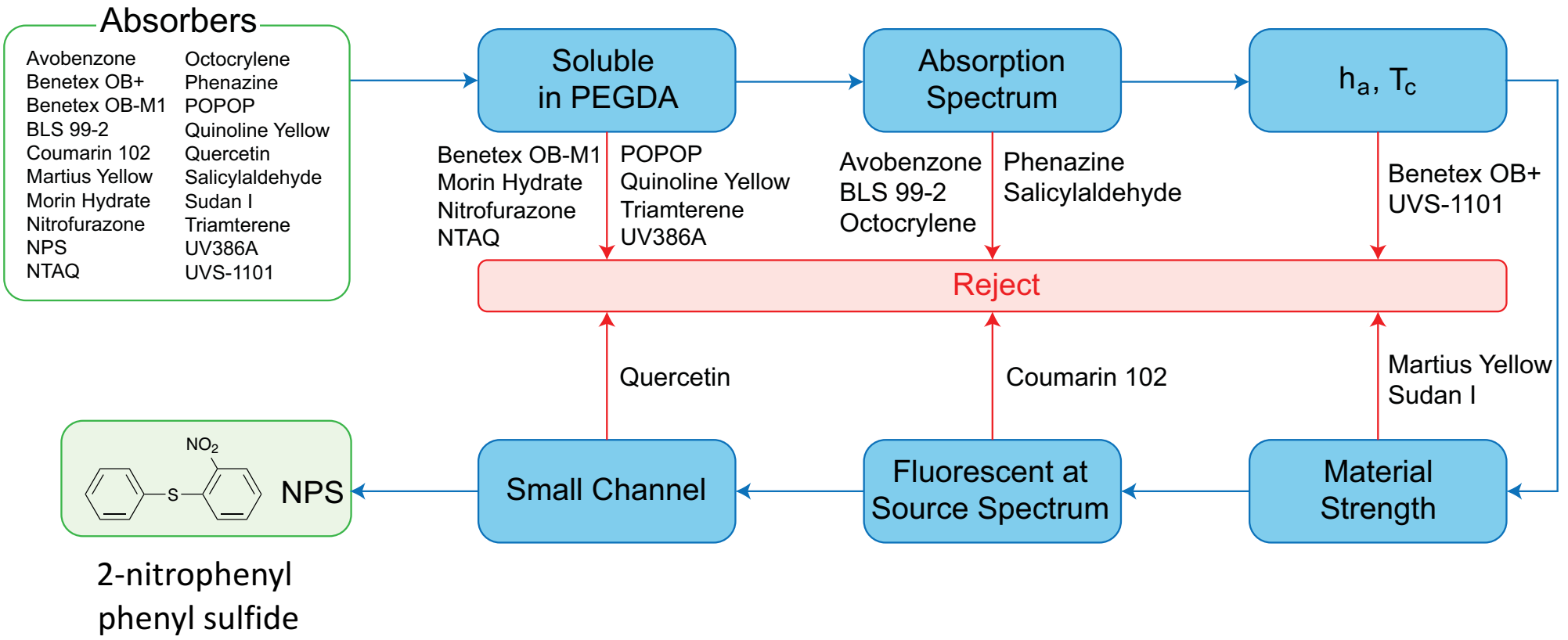
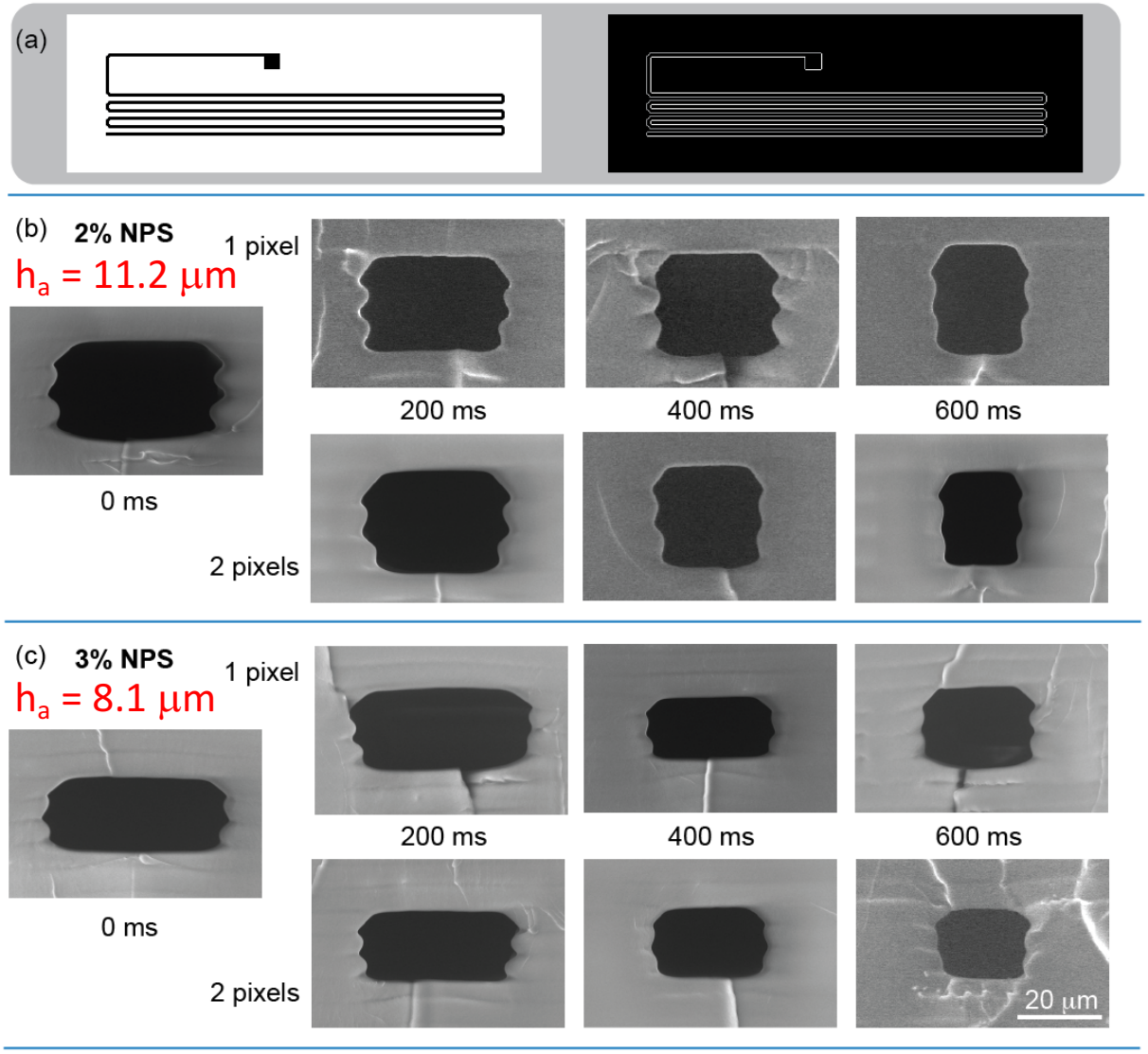
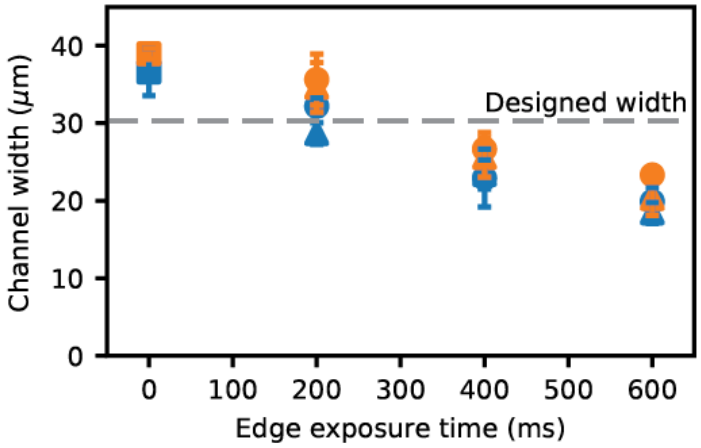
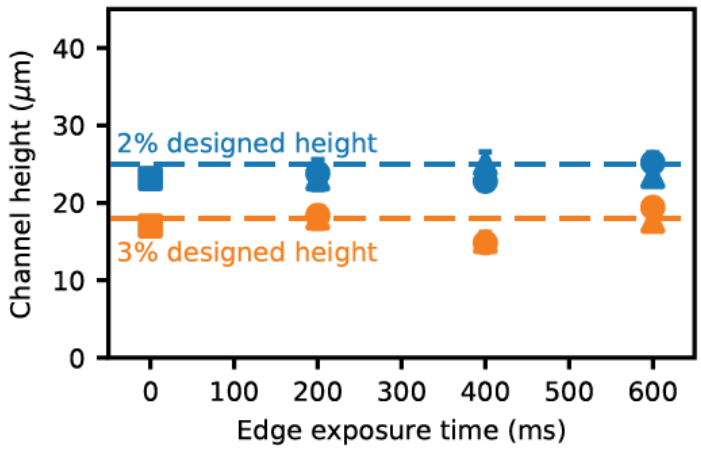


Gong et al., Lab Chip 17, 2899 (2017)

Minimizing Channel Size







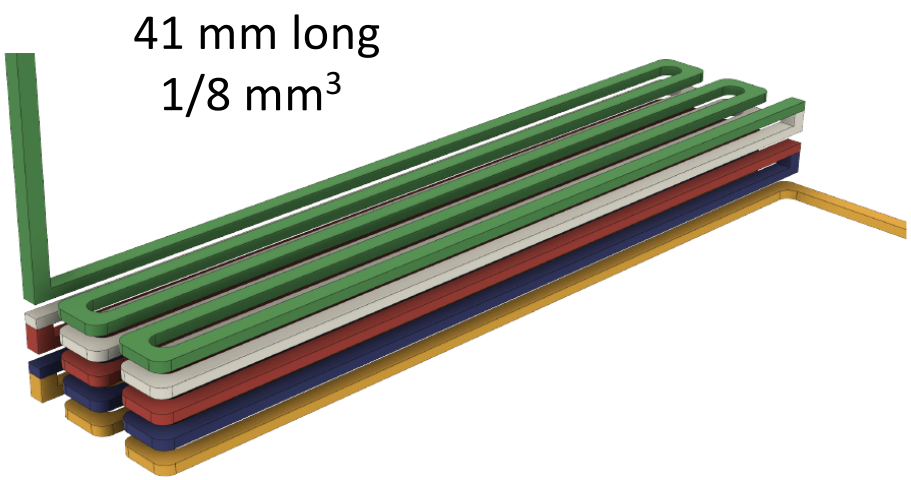
Gong et al., Lab Chip 17, 2899 (2017)

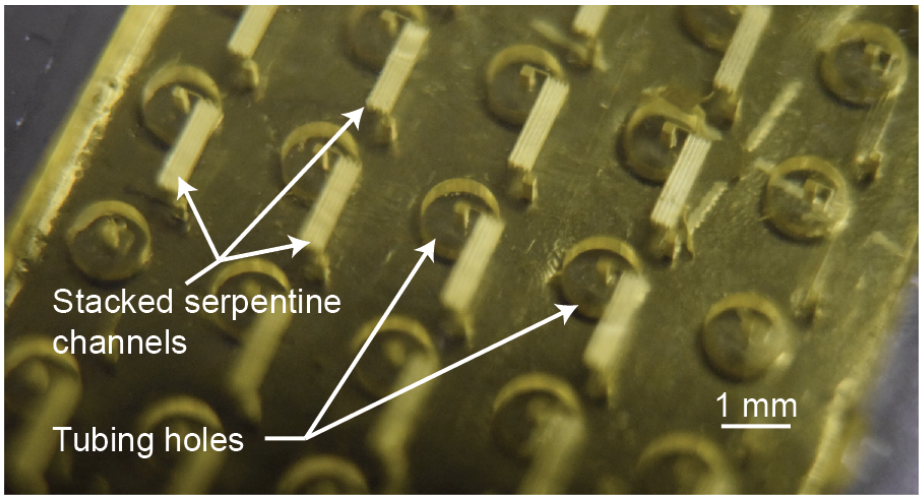
Channel Size

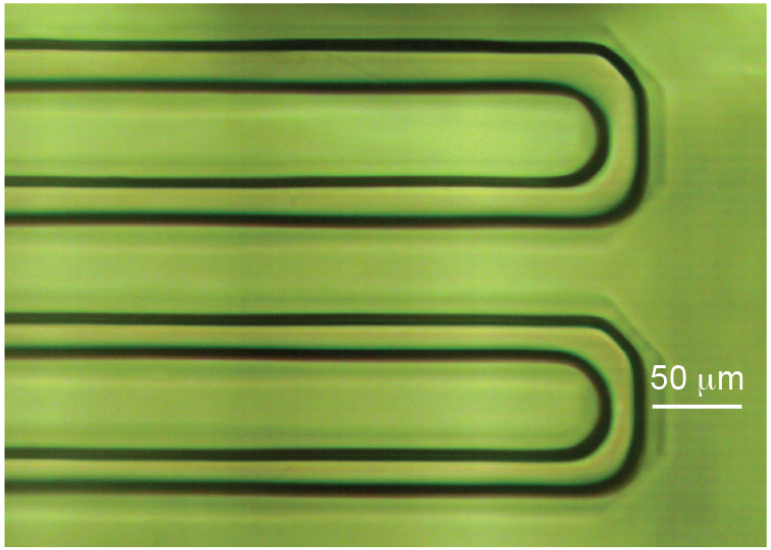
Property	Rule of Thumb	Controlling Parameters
Height (Z)	$L_{min} \approx 2.3 h_a$	UV absorber concentration & spectral overlap
Layer Thickness	$z_l = L_{min}/3$ $\frac{z_l}{h_a} \approx 0.77$	Z stage resolution
Width (XY) (design 4 pixels)	No edge exposure: 5 – 6 pixels With edge exposure: 2.5 – 3 pixels	XY image resolution

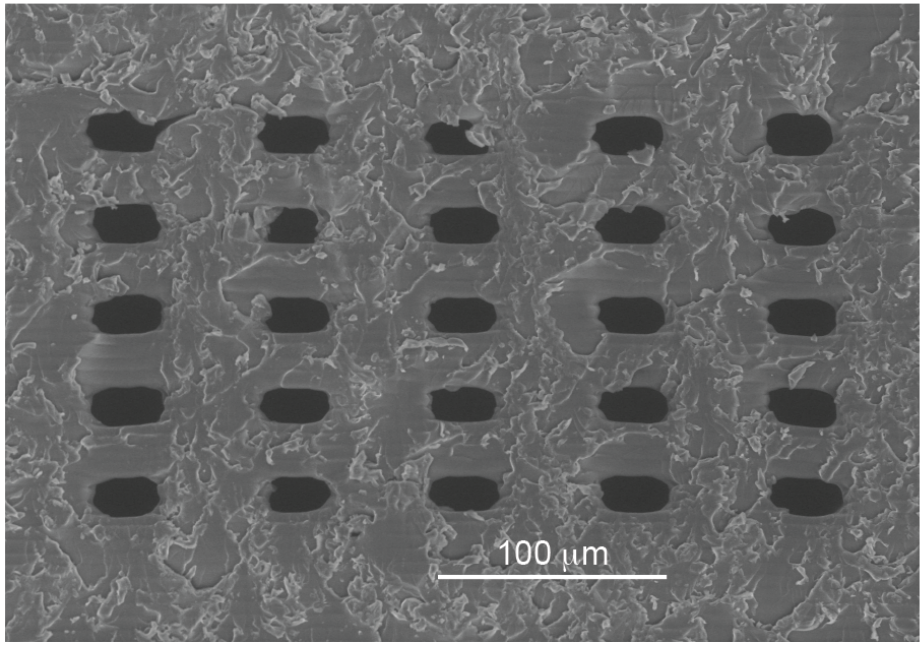
Gong et al., Lab Chip 17, 2899 (2017)

3D Serpentine Channels



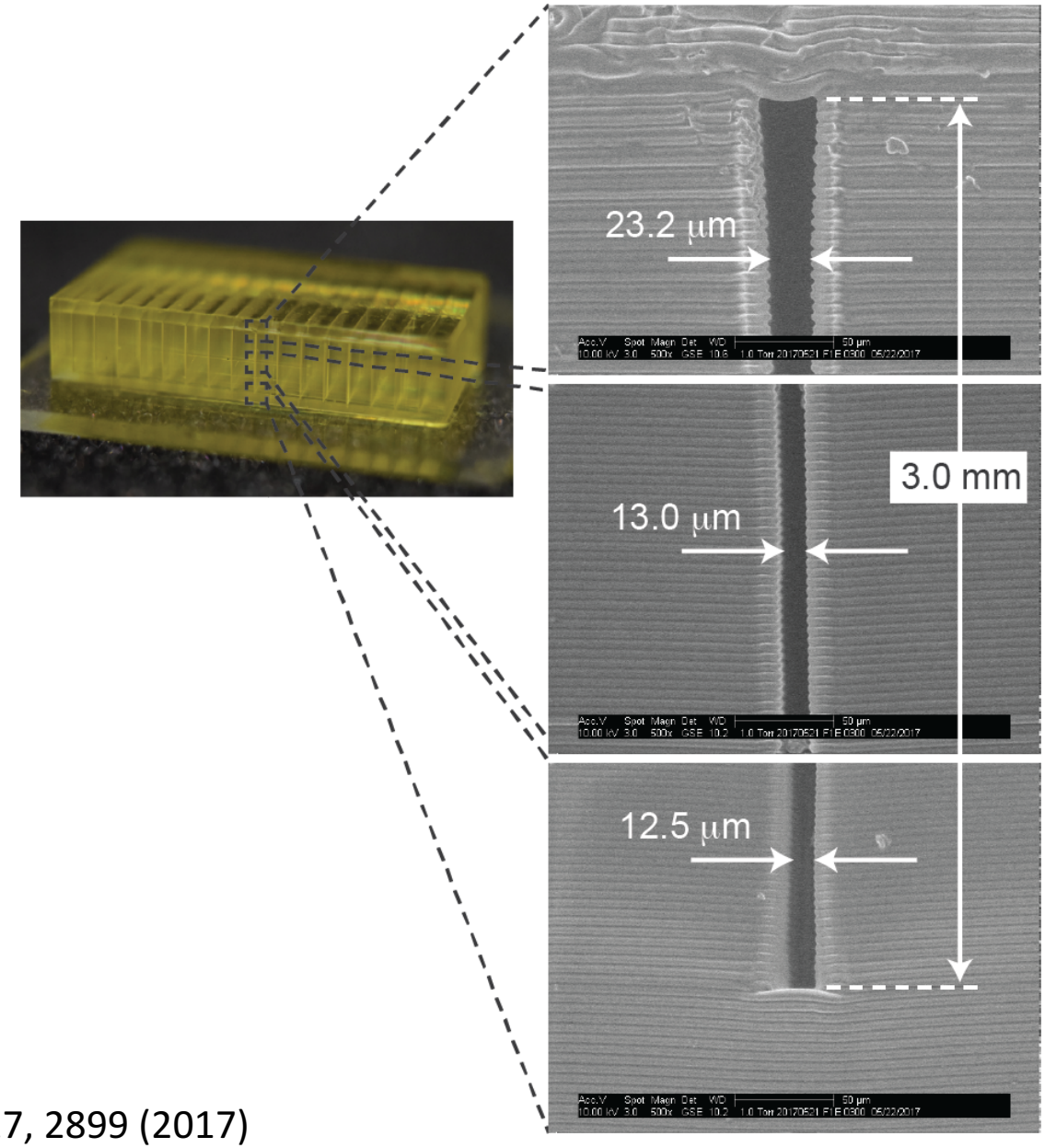






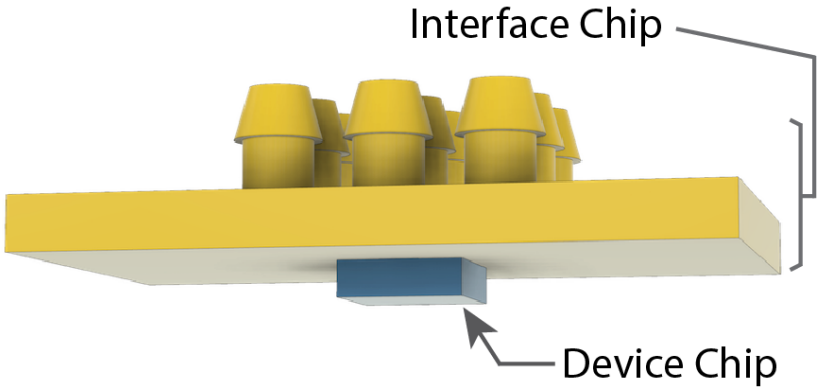
Gong et al., Lab Chip 17, 2899 (2017)

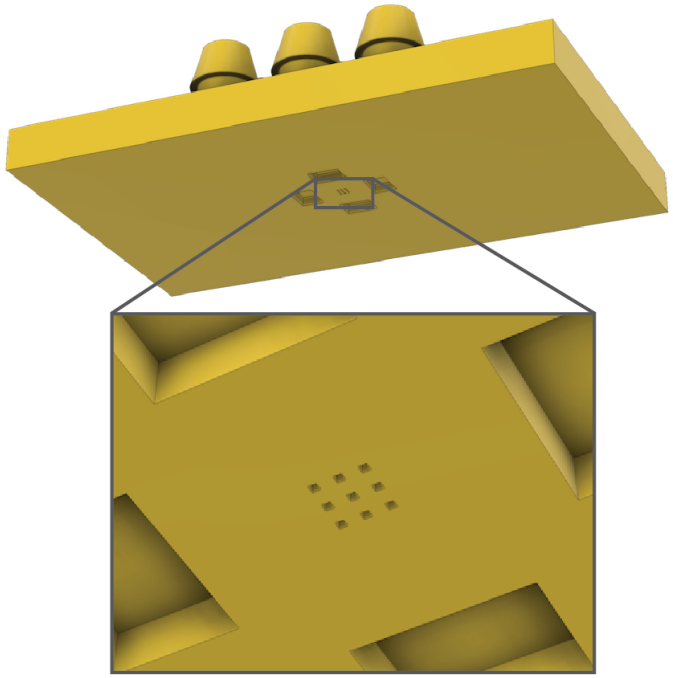
High Aspect Ratio Channels

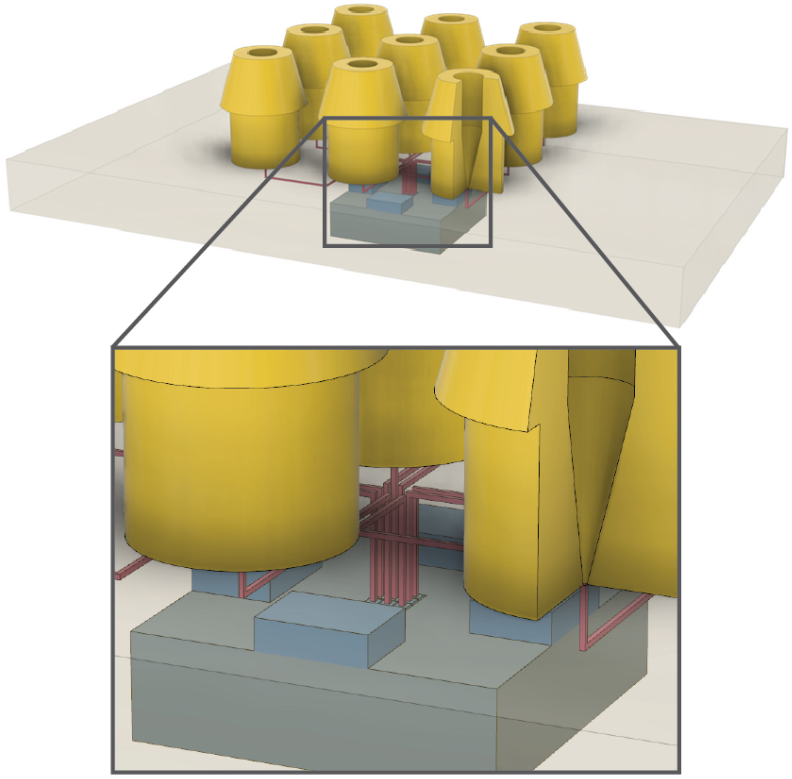


Gong et al., Lab Chip 17, 2899 (2017)

Delegate Chip-to-World Interconnects to Separate Interconnect Chip

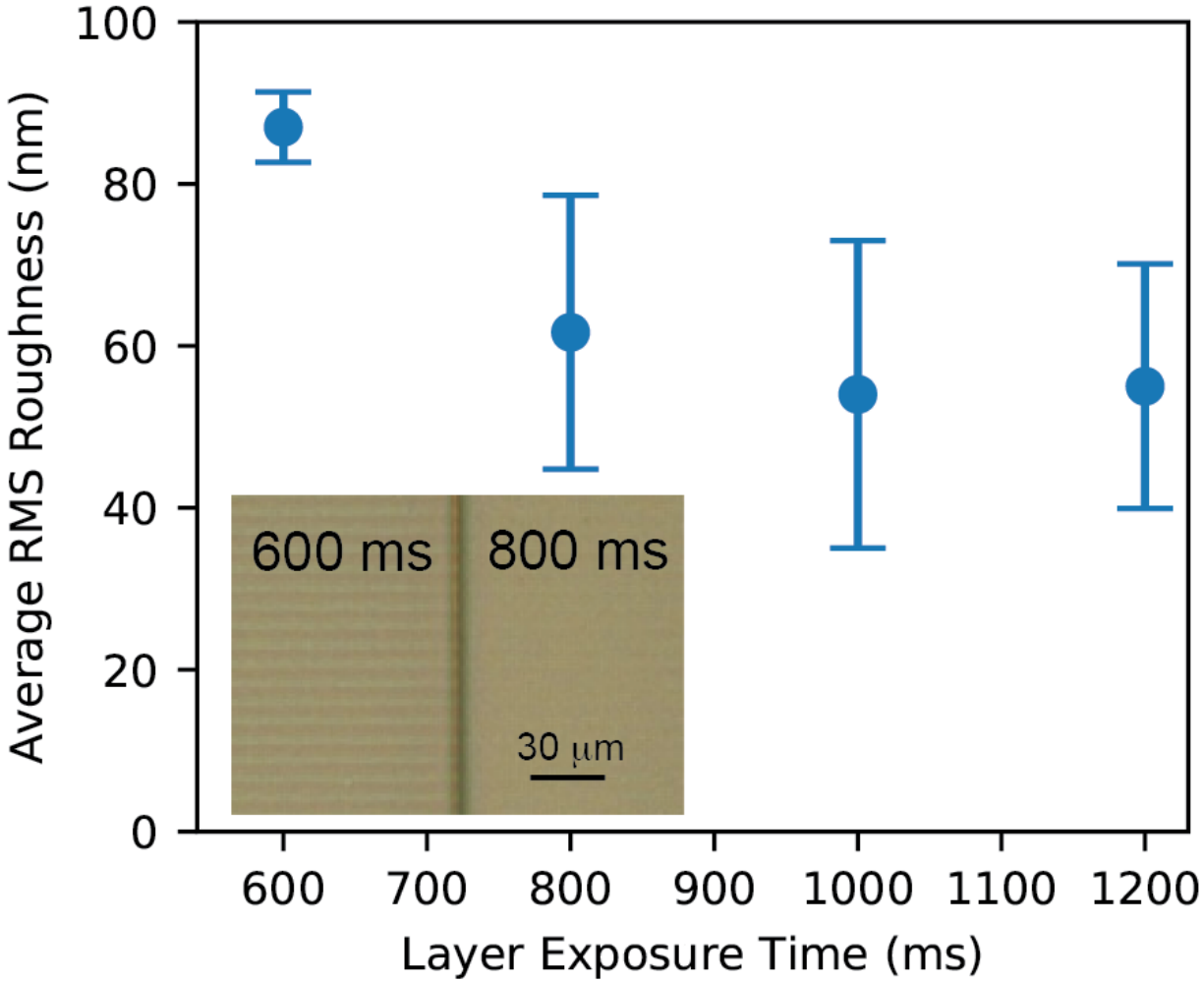






Gong et al., Lab Chip submitted (2017)

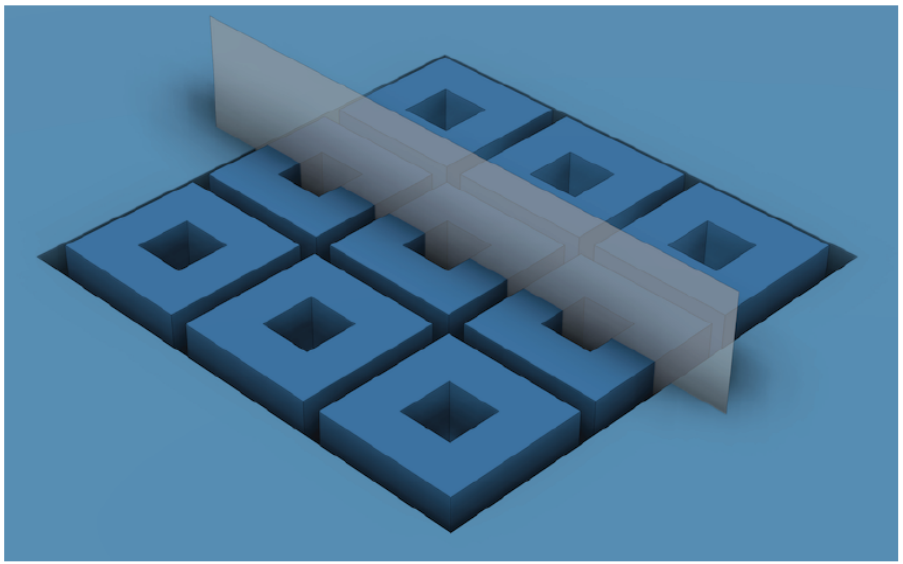
Surface Roughness

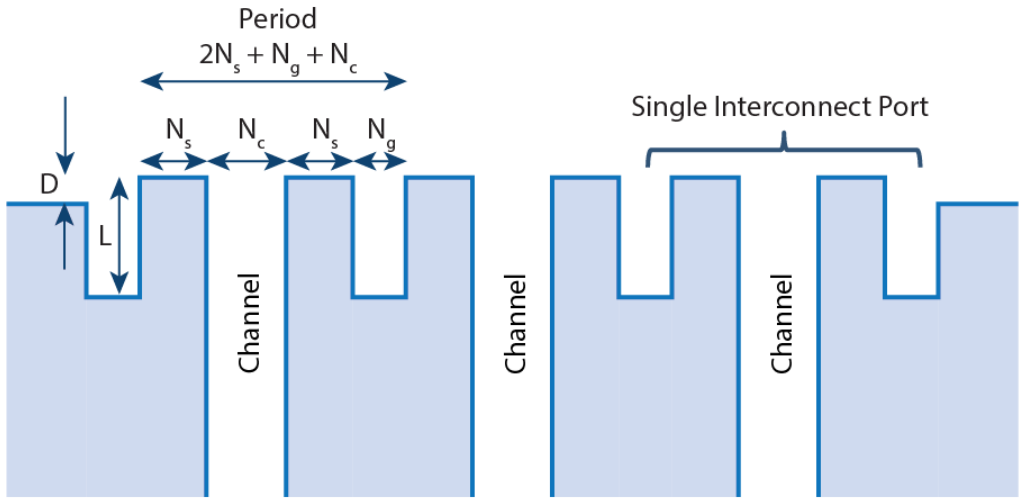


Gong et al., Lab Chip submitted (2017)

Interconnect Concept

Use 3D printed material itself as microgasket



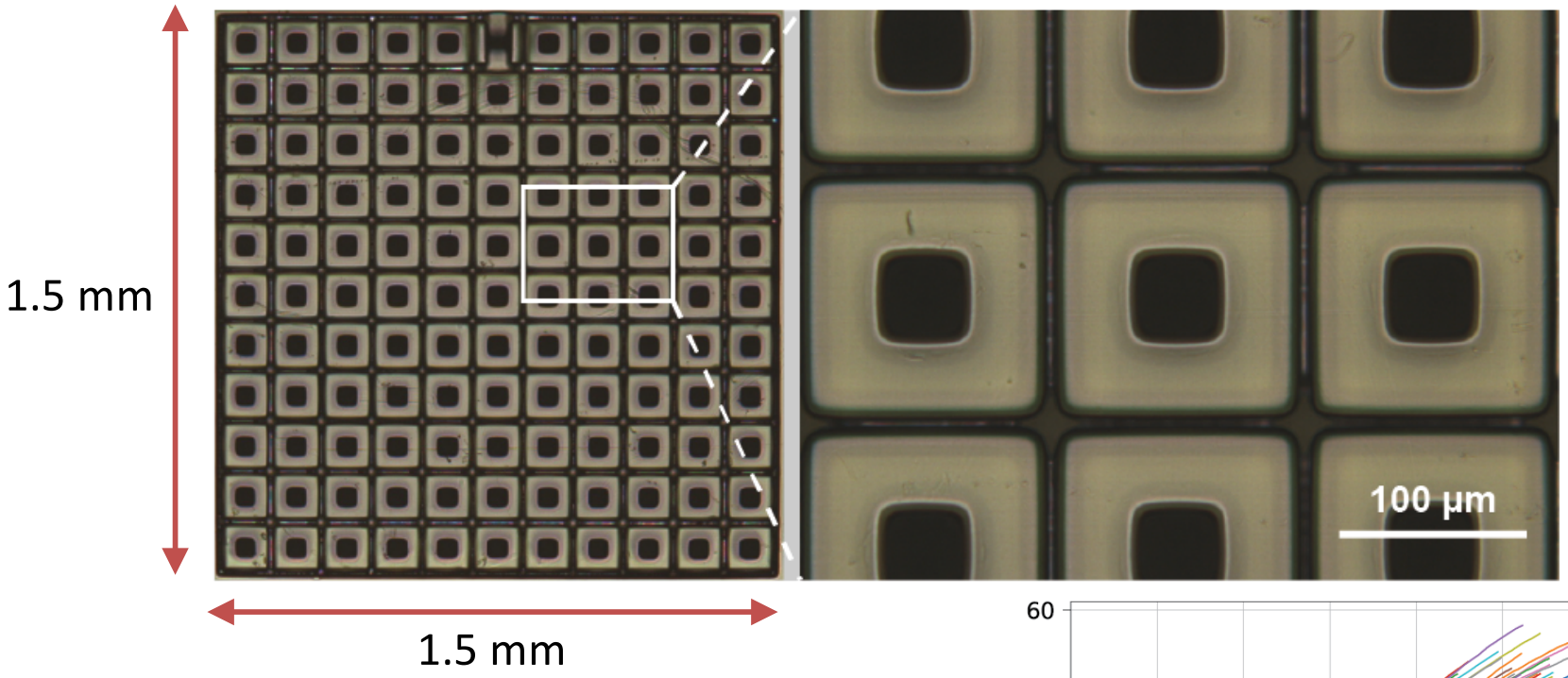


- D = 10 μm = 1 layer
- Young's modulus ~8 Mpa
- 3D print microgasket as part of device
- No additional materials or structures needed

Gong et al., Lab Chip submitted (2017)

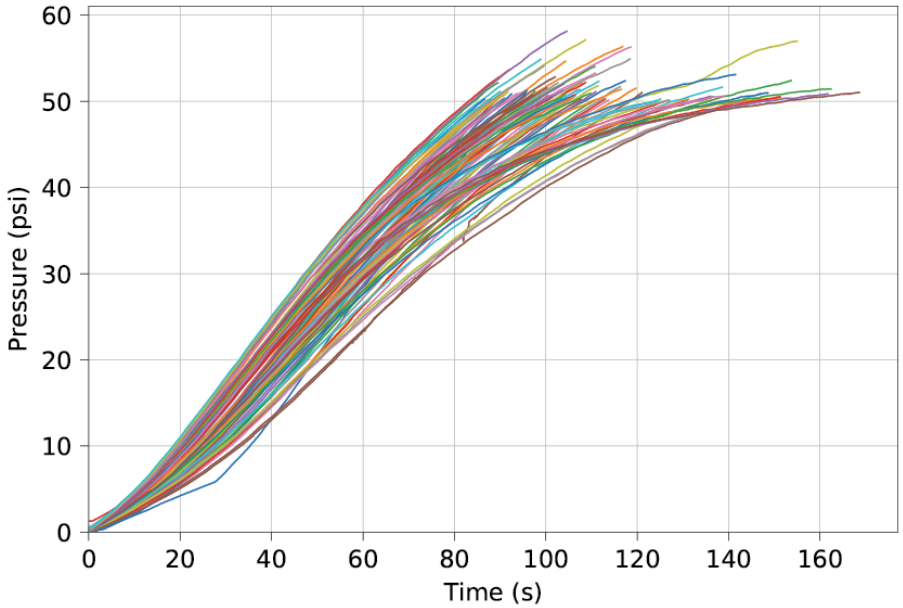
Interconnect Operation

121 Interconnects



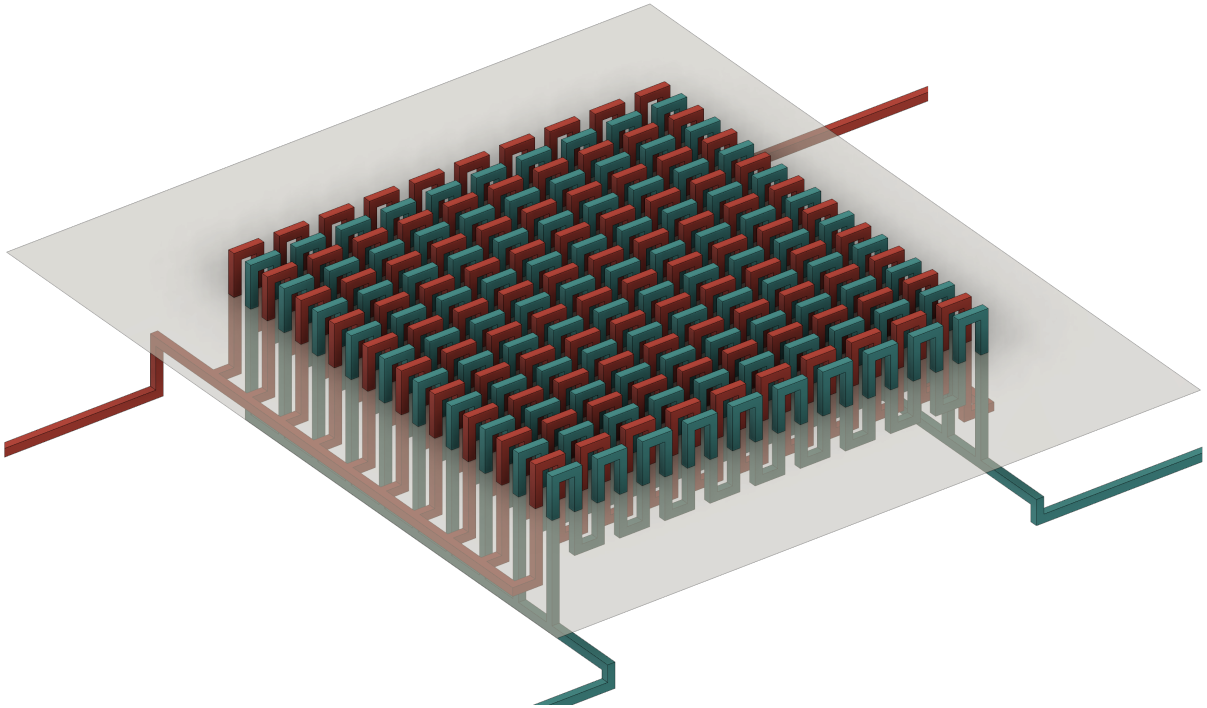
N_c = 6 pixels
N_s = 5 pixels
N_g = 2 pixels
pixel = 7.6 µm

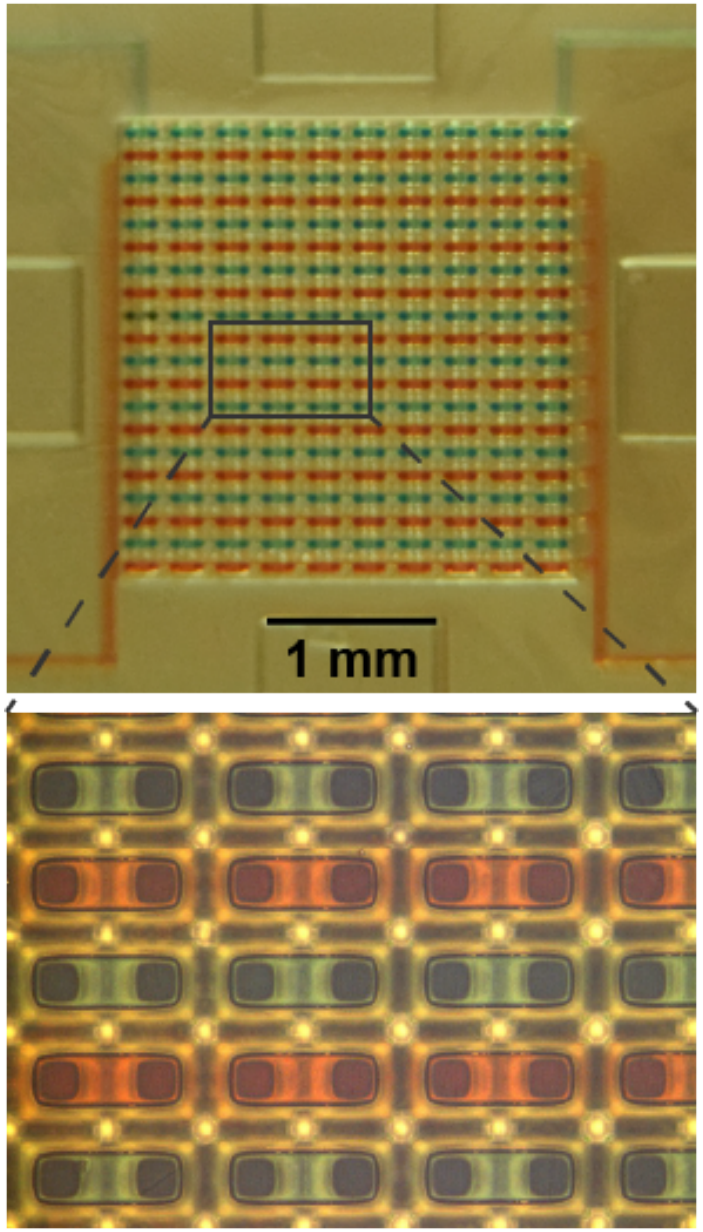
- 11 x 11 array
- 137 µm period
- 53 interconnects/mm^2
- Reusable - 100 repeated pressure tests



Gong et al., Lab Chip submitted (2017)

400 Interconnects

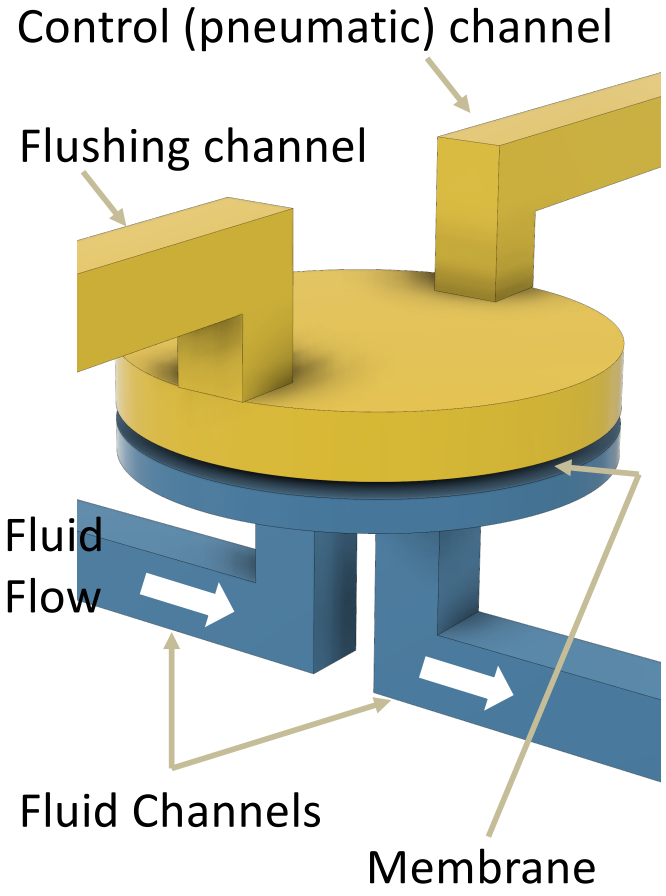


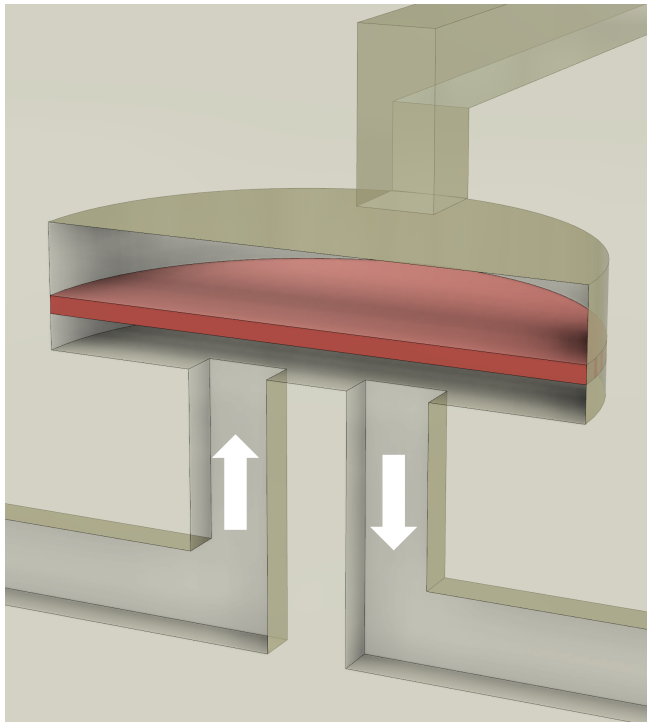


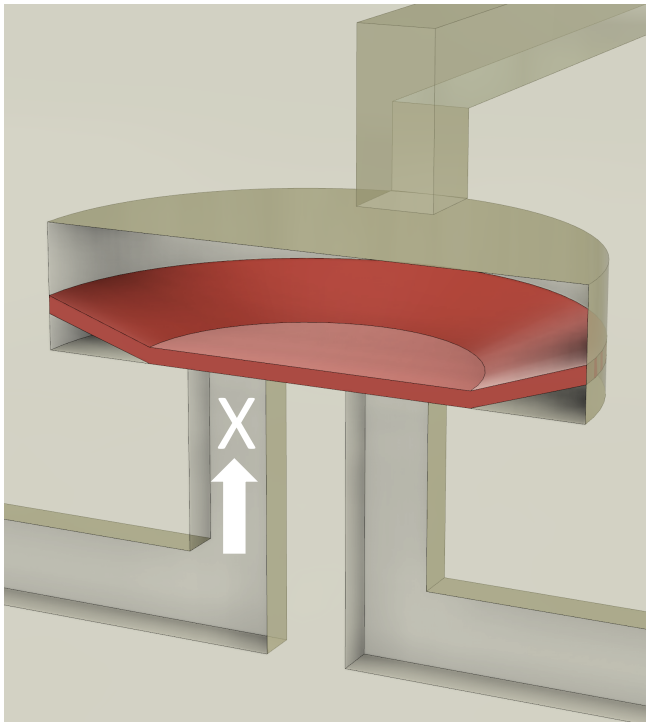
- 20 x 20 array
- 137 μm period
- 53 interconnects/mm^2

Gong et al., Lab Chip submitted (2017)

3D Printed Membrane Valve

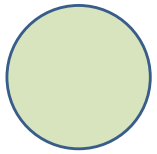
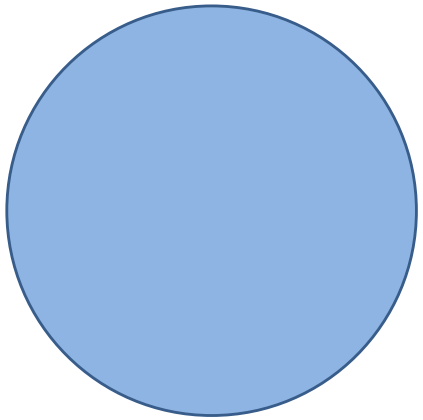
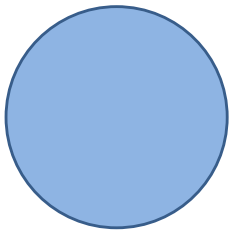




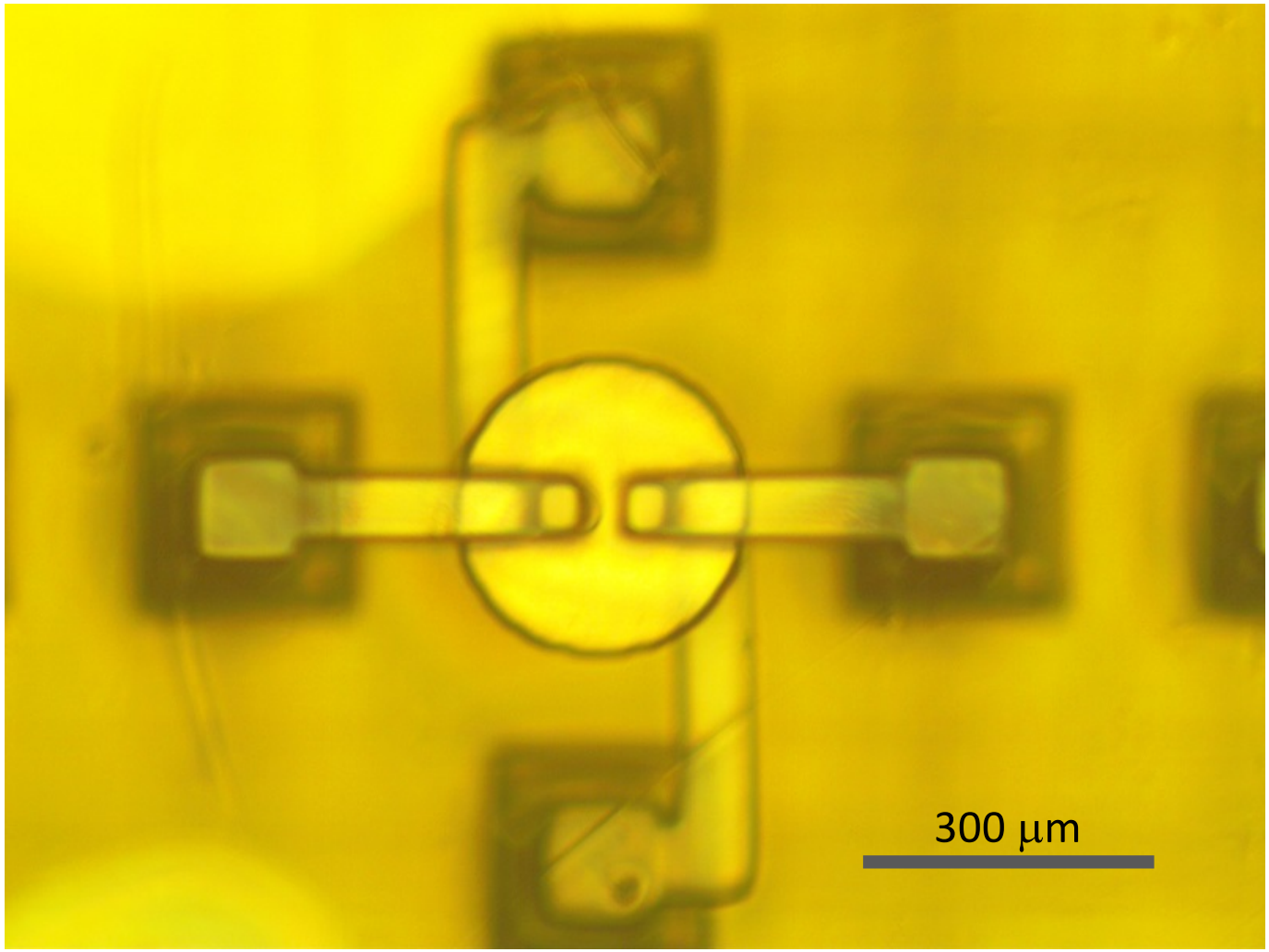


C. Rogers et al., Biomicrofluidics, 9, 016501 (2015)
H. Gong et al., Lab Chip 16, 2450 (2016)

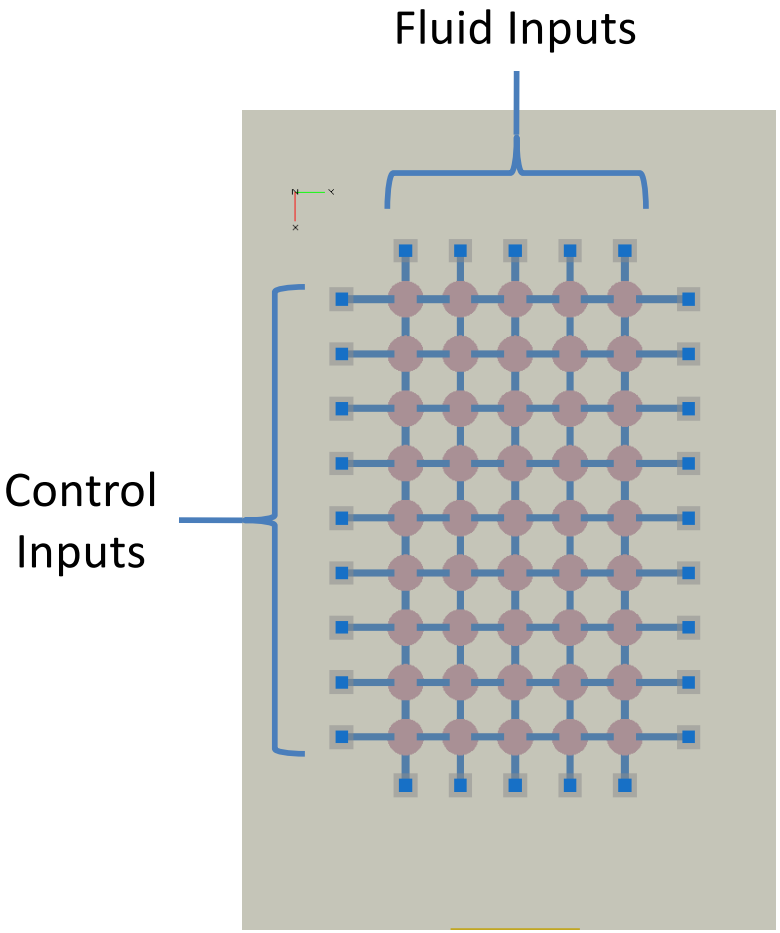
Valve Size

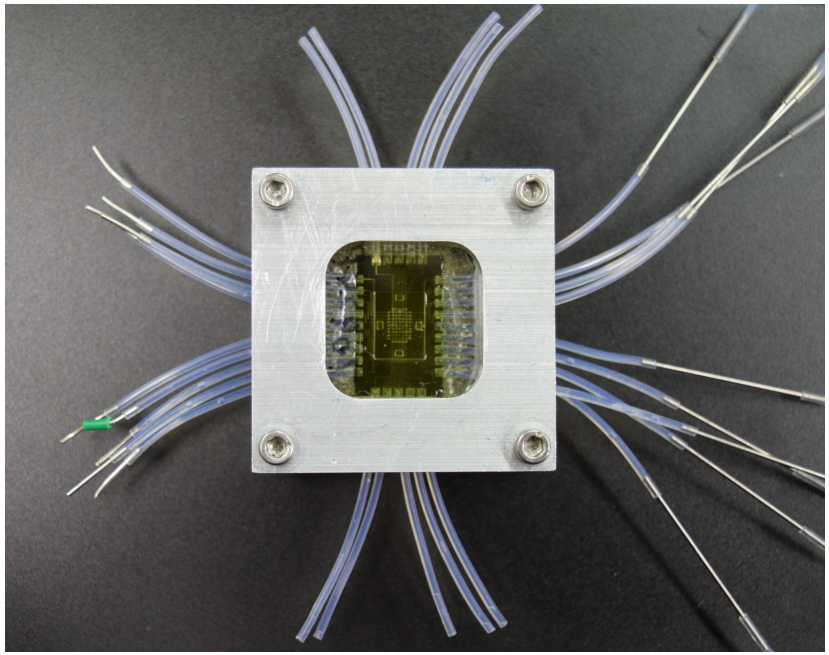
Fabrication	Relative Size	Diameter	# Actuations	Reference
Cleanroom PEGDA resin		700 μm	115,000	Sens. & Act. B 191, 438 (2014)
B9 Creator Custom Sudan I resin		2 mm	800	Biomicrofluidics 9, 016501 (2015)
Asiga Custom Sudan I resin		1.08 mm	1,000,000	Lab Chip 16, 2450 (2016)
Custom 3D printer Custom NPS resin		300 μm	1,000,000	This work

3D Printed Valve

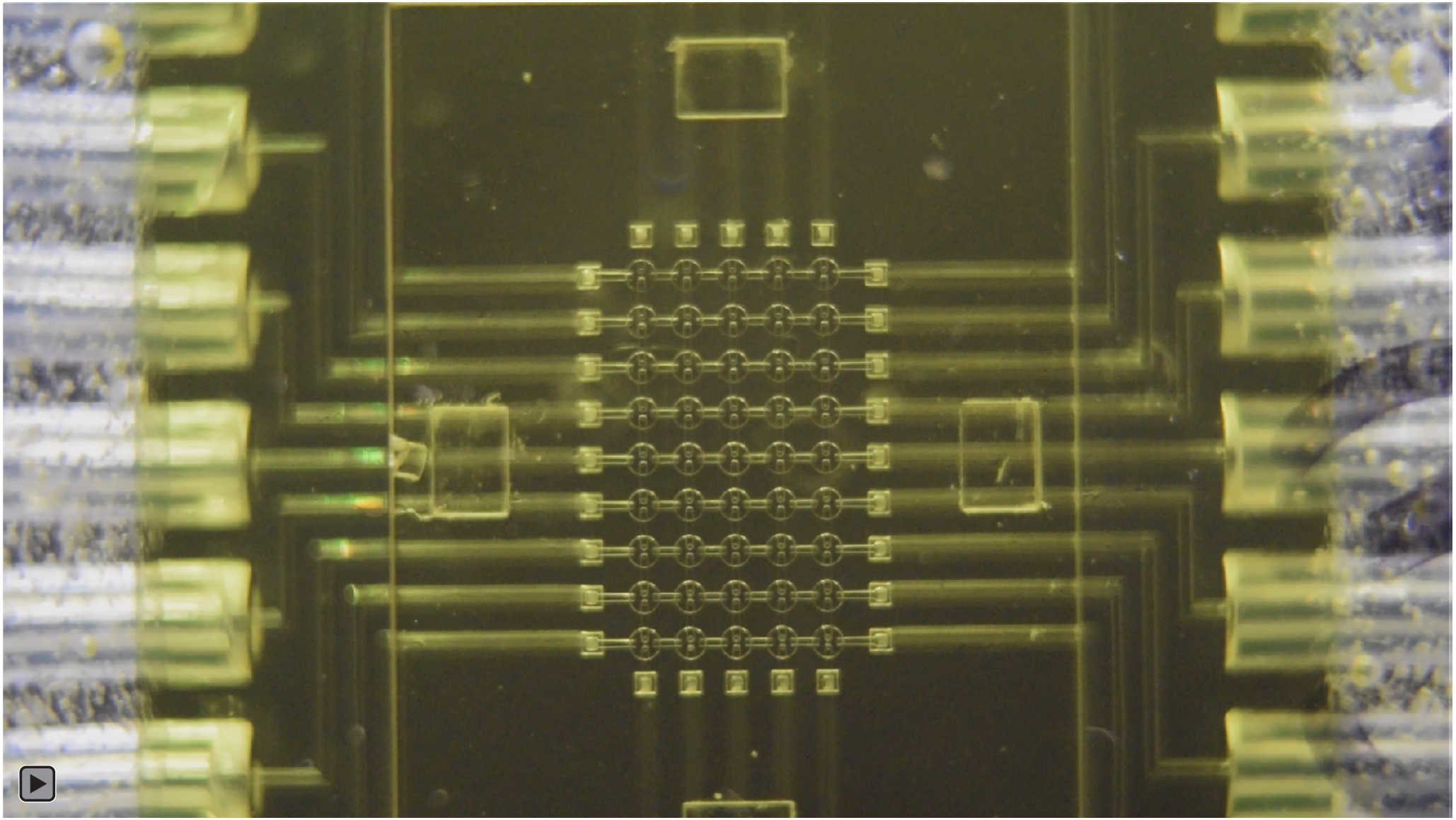


45 Valve Test Array

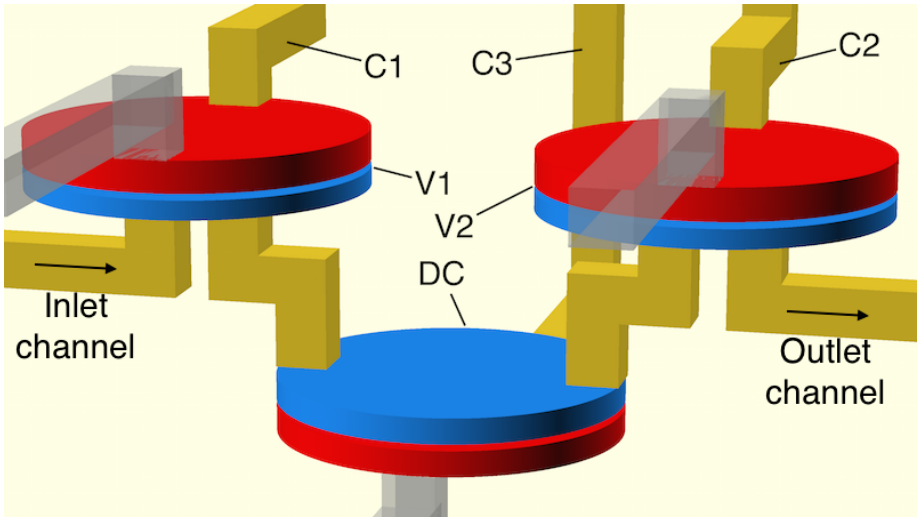




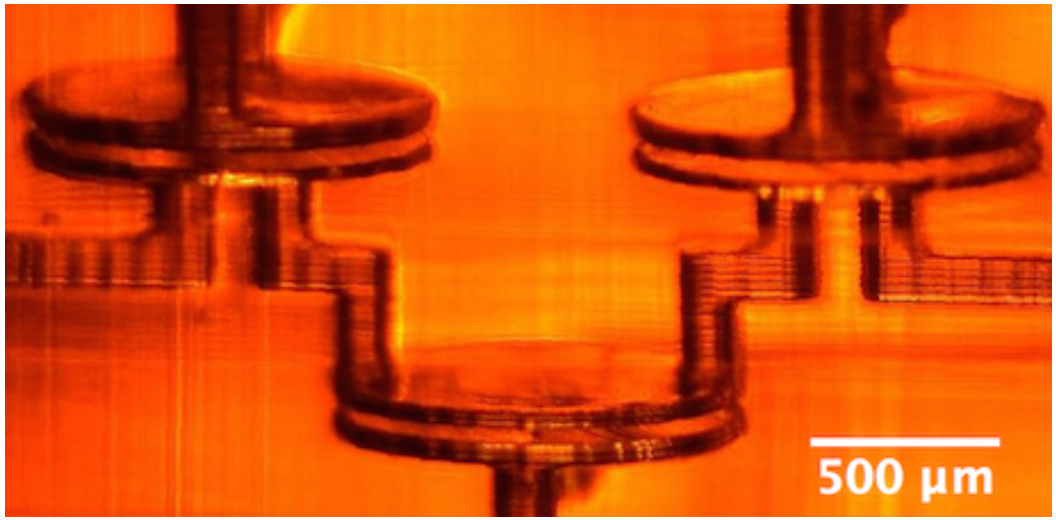
50 ms Scrolling Valve Actuation



3D Printed Pump



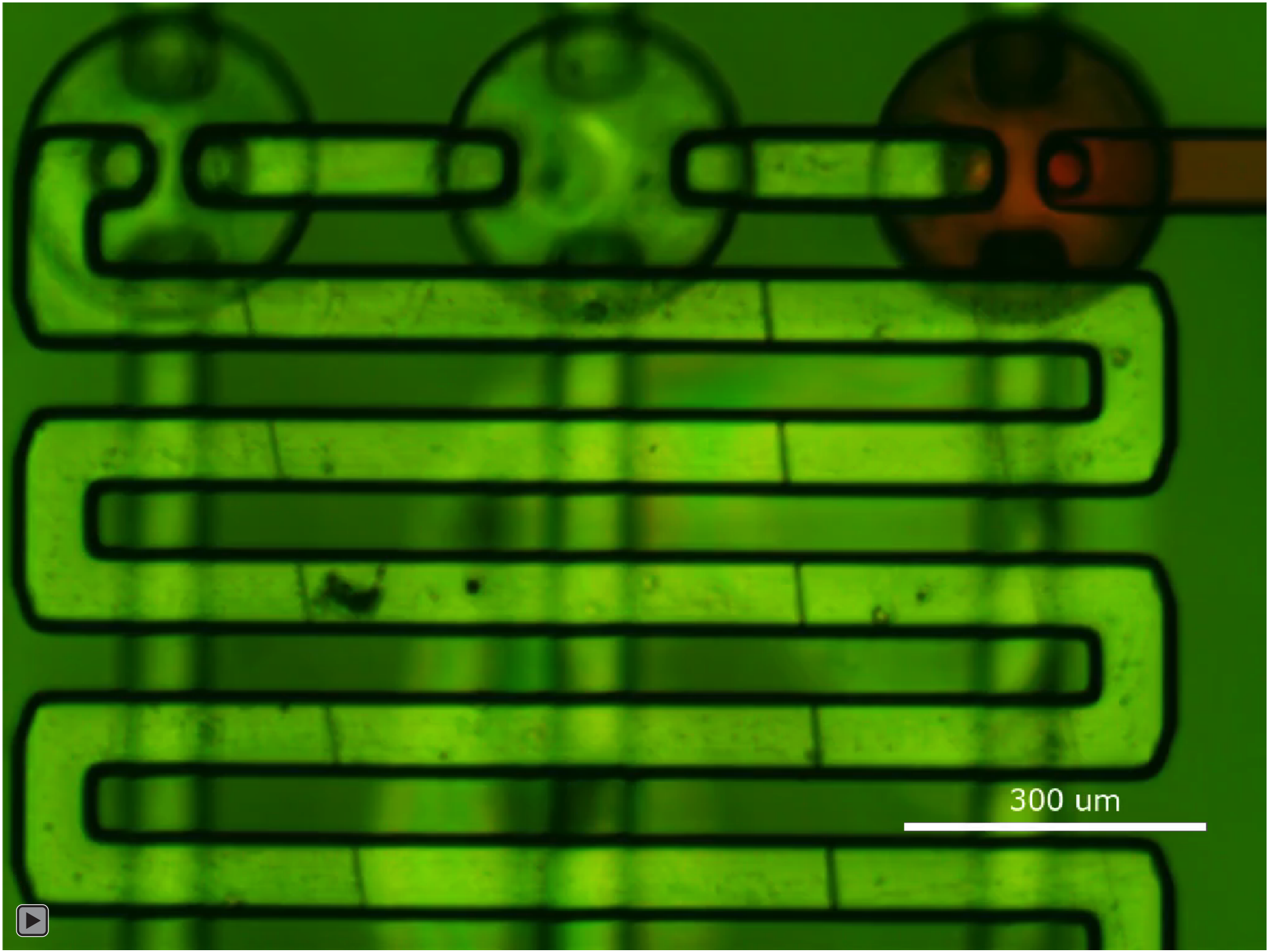
Last year:

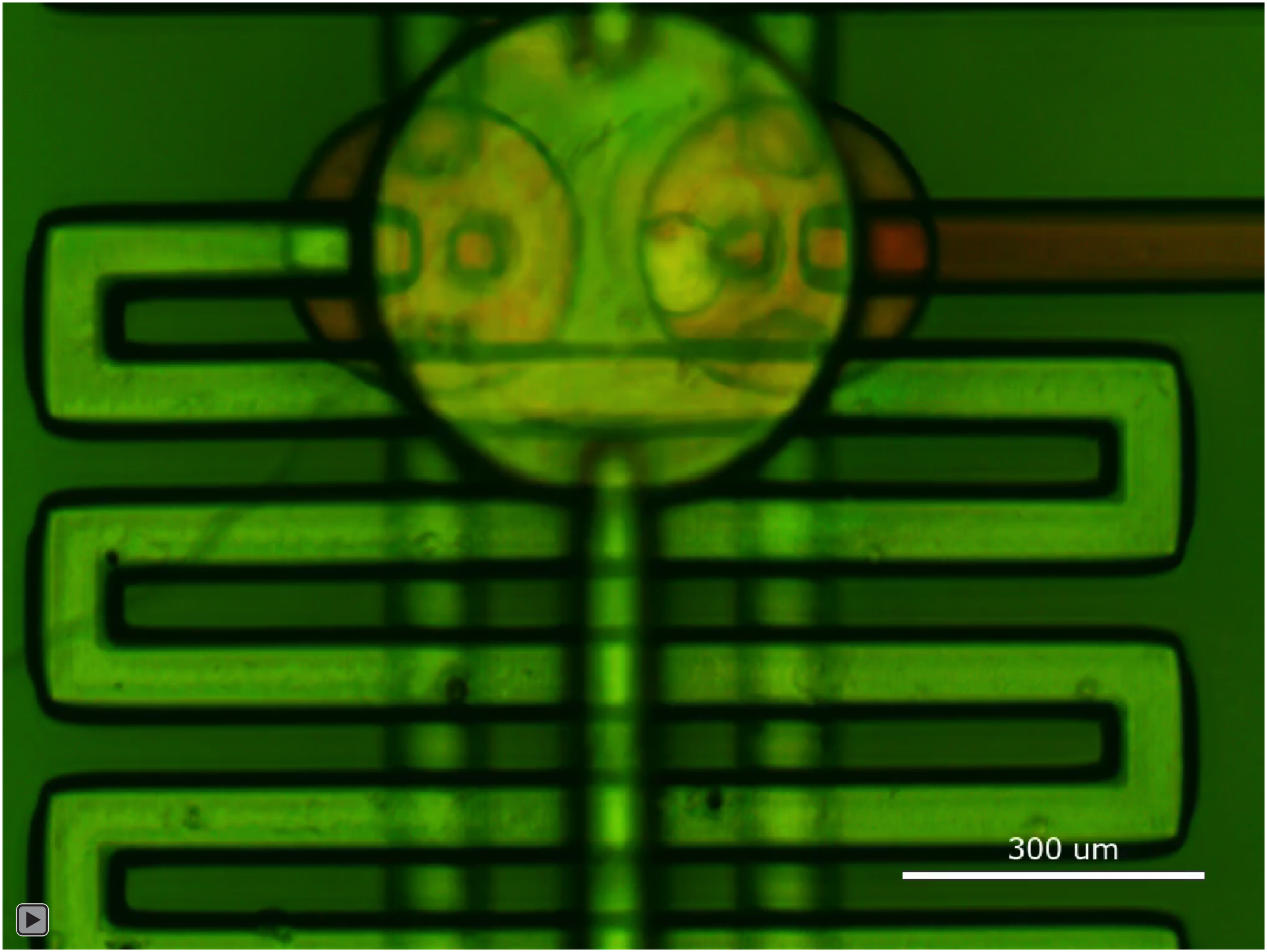


H. Gong, A.T. Woolley, G.P. Nordin,
Lab Chip, 16, 2450 (2016)

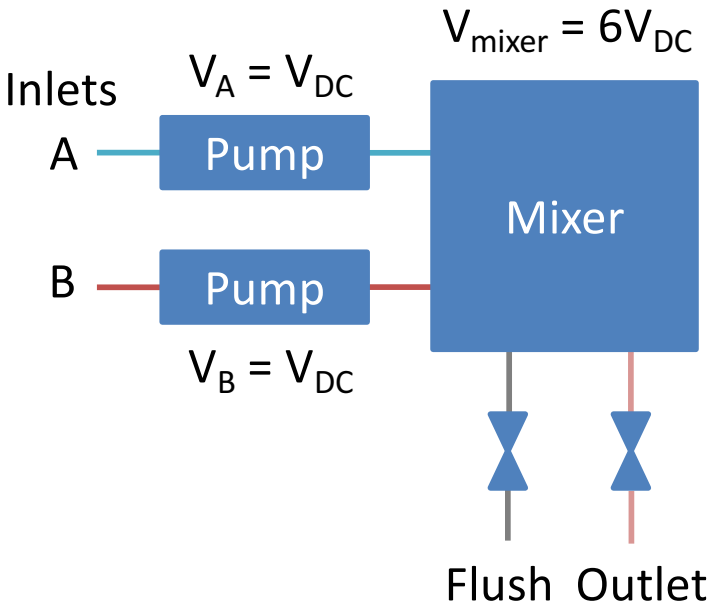
Table 1 Pump timing logic. Red: actuated (pressure applied; valves closed); green: not actuated (valves open)

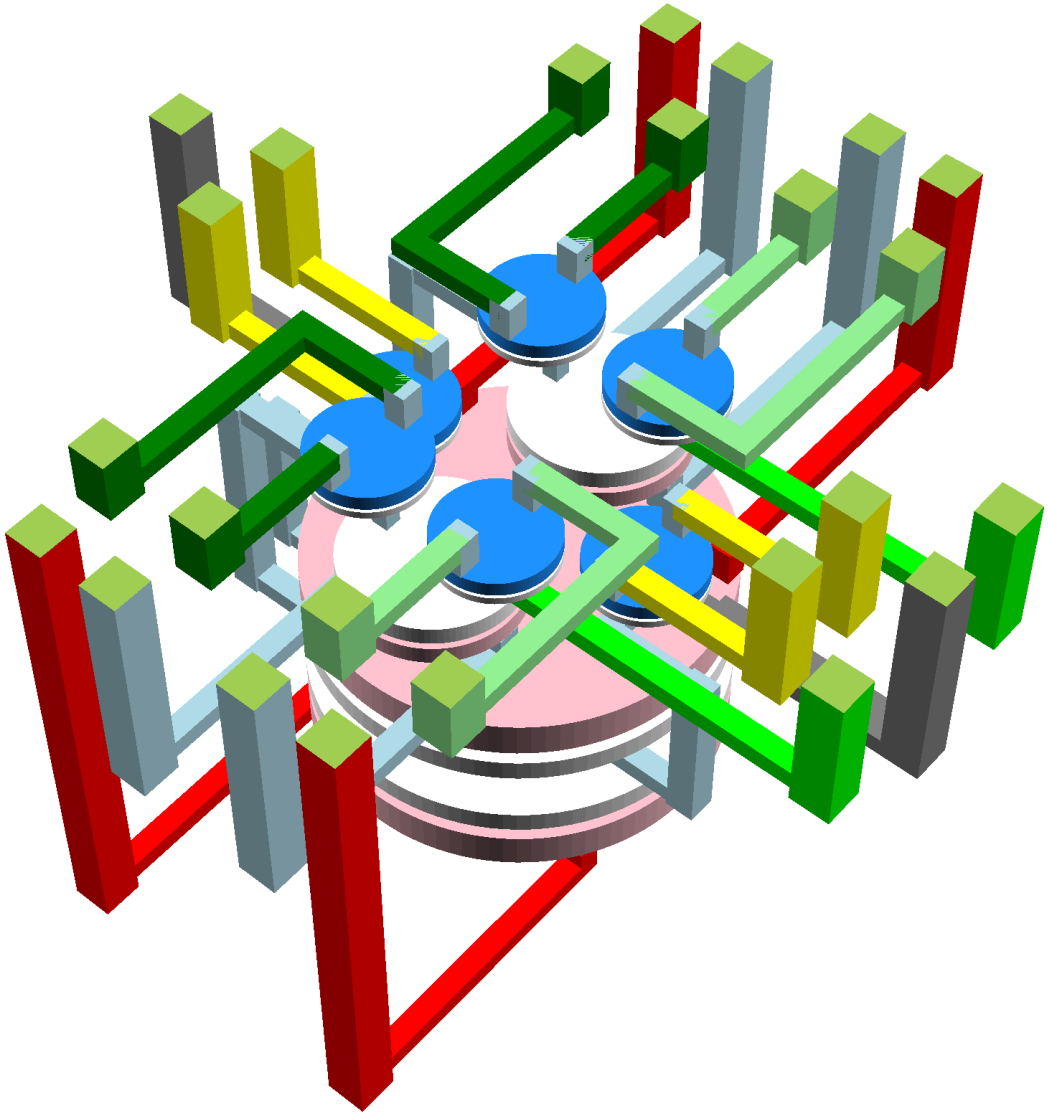
	t_0	t_1	t_2	t_3	t_4
V1	●	●	●	●	●
DC	●	●	●	●	●
V2	●	●	●	●	●


300 um

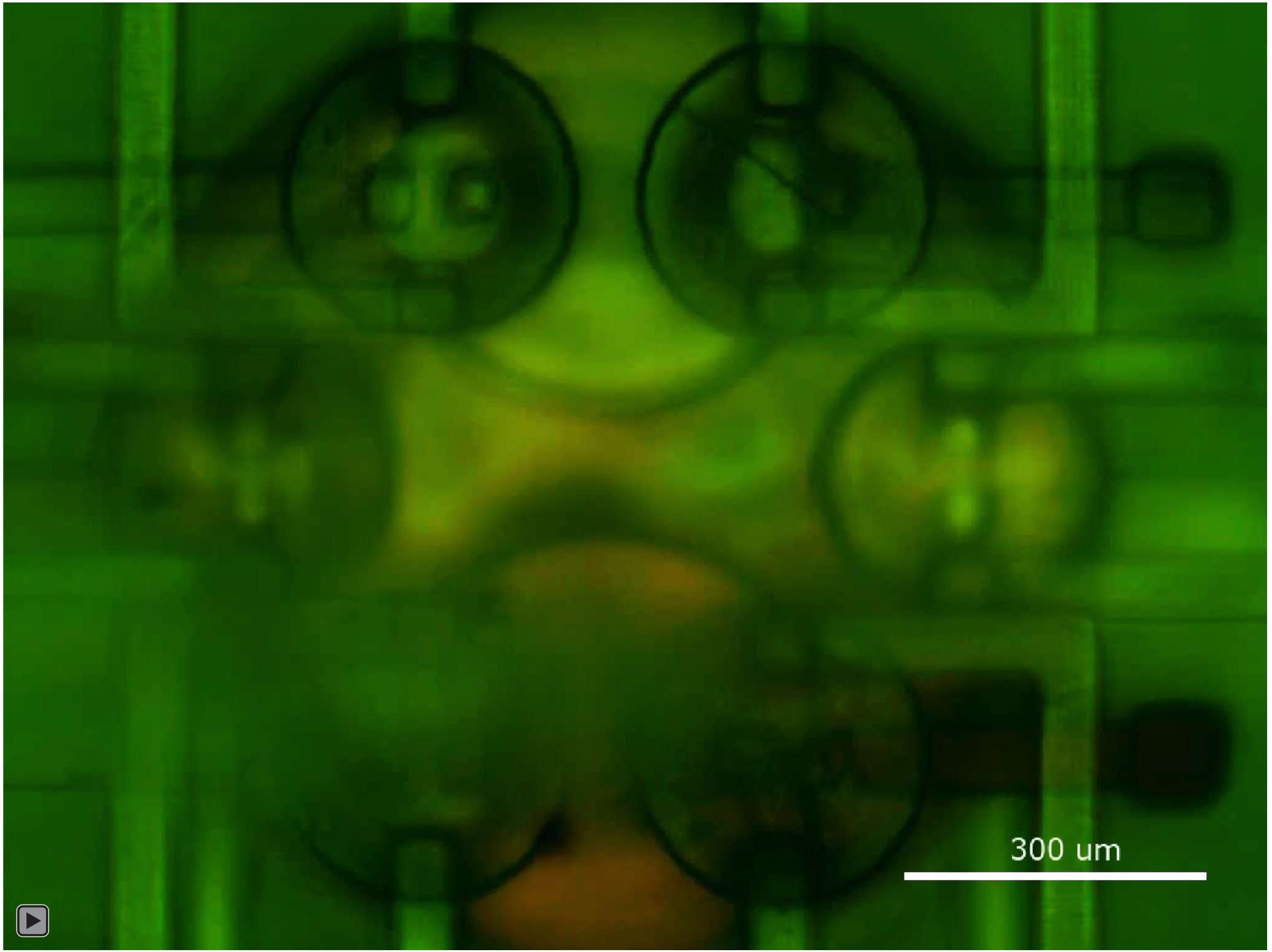

300 um

Selectable Ratio Mixer and Pump





Example ratios	
50:50	$3V_A + 3V_B$
83:17	$5V_A + V_B$

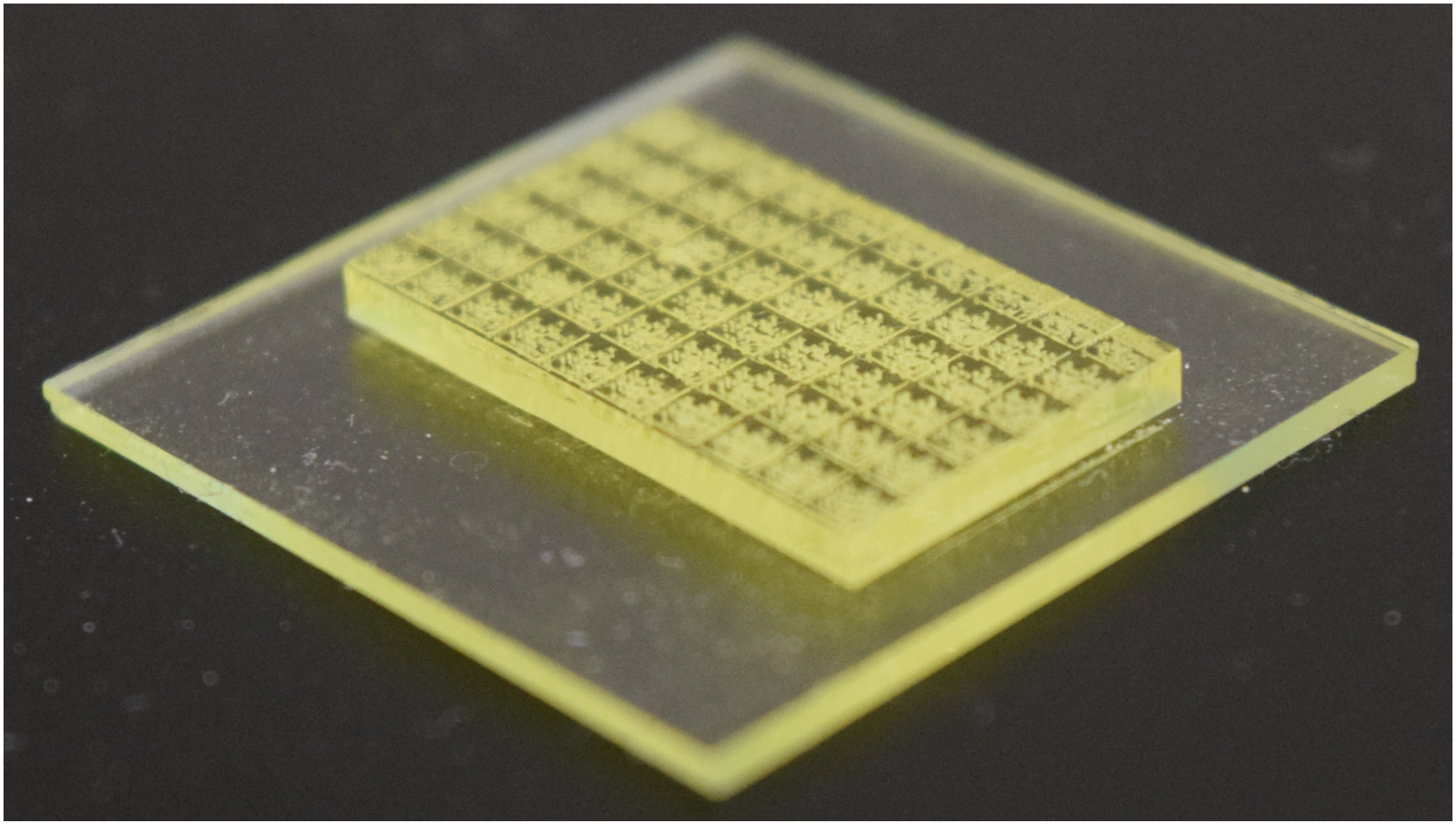

300 um

Effort

- 5 days
  - Decide to implement idea to final device
  - Experimental testing used to drive design modifications
- ~20 devices
  - 5 interface chips
  - 15 device chips
  - Multiple designs of each
  - Multiple rounds of testing

60 Selectable Ratio Mixer-Pumps

Print time: 30 minutes



Take Aways

- Microfluidics → It's all about the voids (interconnected network of microvoids)
- 3D Printer resolution specs ≠ achievable void size
- Achievable void size - channels
  - Z - resin optical properties: $\sim 2.3h_a$
  - XY - projected image resolution: $4\,\mathrm{pixels}$
- High density interconnects, valves, pumps
- Small devices → parallel fabrication → manufacturing with 3D printing

Needs

- High resolution 3D printer
  - UV LED source
  - Complete control over operation of printer
- Resins
  - Small h_a
  - Must be tailored to emission spectrum
  - Open source
- Explore 3D structures
  - Get away from conventional 2D thinking
    - Components
    - Layout
  - Experiment-based exploration of parameter space and performance optimization
- Automated design
  - Library of standard components
  - Automated layout
  - Specify functional processes → automated design generation

Acknowledgements

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Posters

- Hua Gong, T219k

  High Density, Reversible 3D Printed Microfluidic Interconnects

- Mike Beauchamp, T184h

  Microchip Electrophoresis of Preterm Birth Biomarkers in 3D Printed Devices

- Anna Nielson, M182h

  Separation of a Panel of Preterm Birth Biomarkers Using Microchip Electrophoresis