Shear Stress Measurements via Elastomeric Micropillar Arrays

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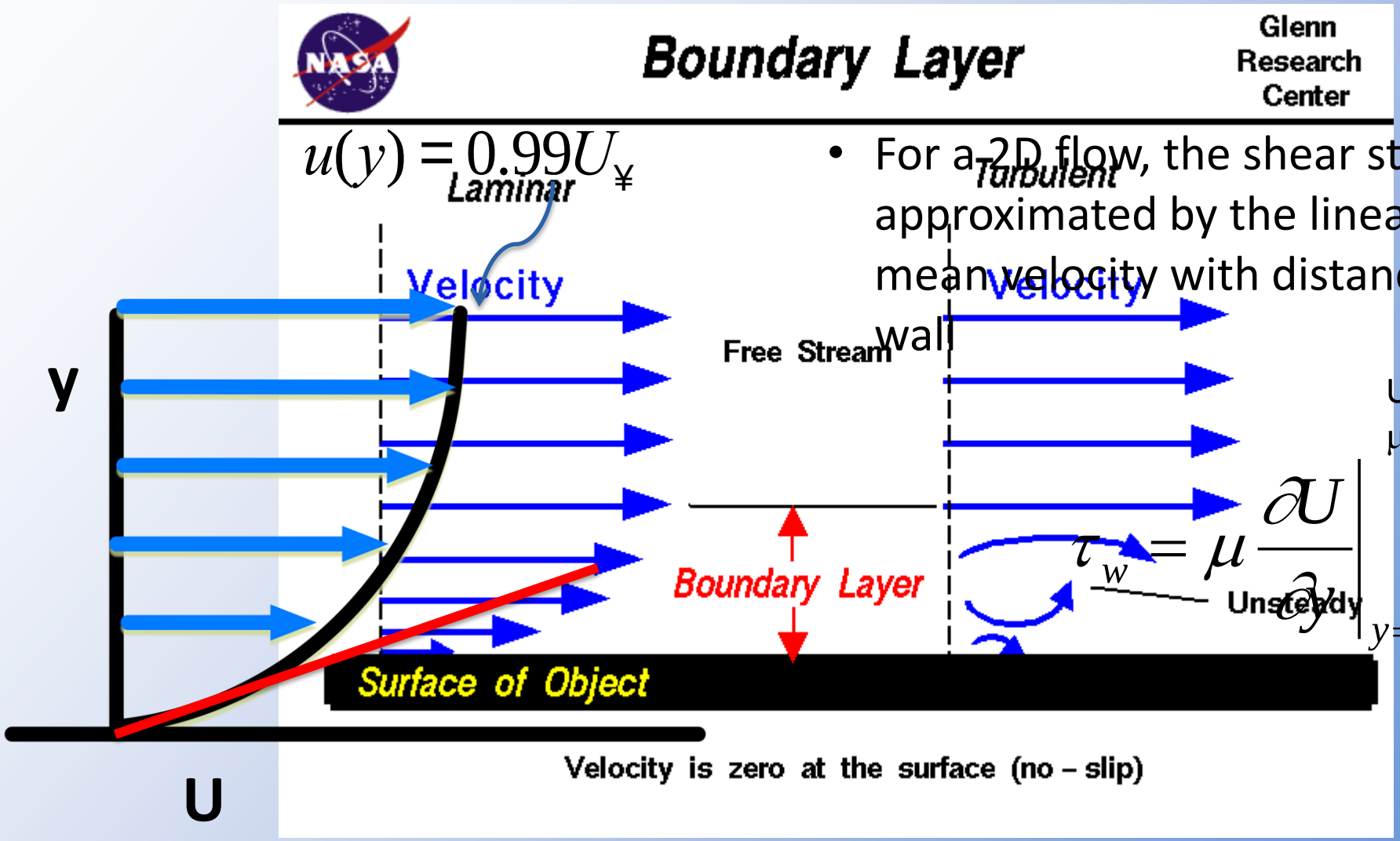
Sensing and Controlling Motion with Polymeric Materials Symposium

Airflow & Shear Stress

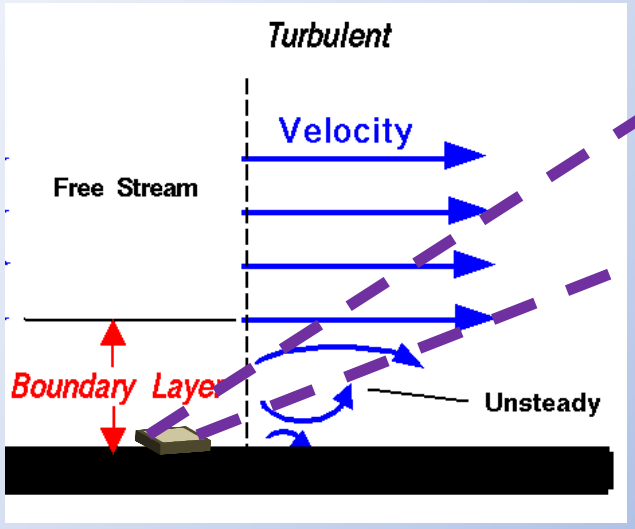


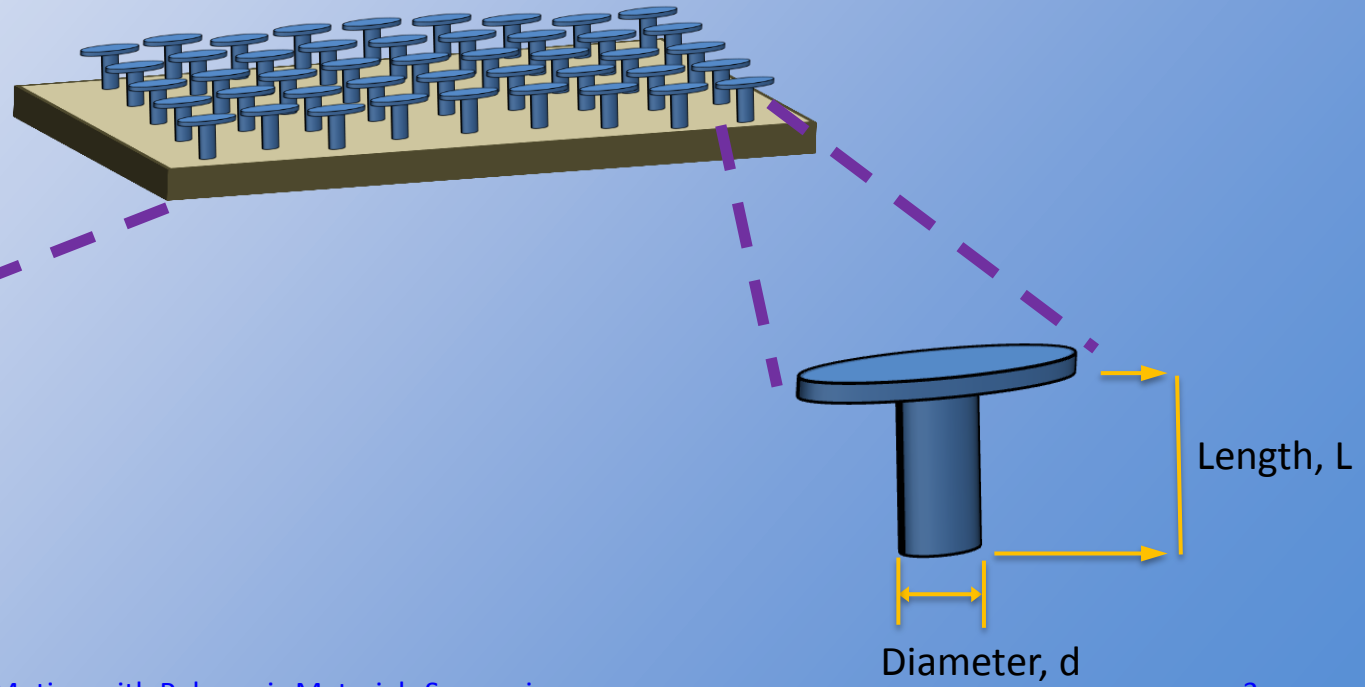
- For a 2D flow, the shear stress can be approximated by the linear change of mean velocity with distance from the wall

U_∞= Free Stream Velocity
μ = Kinematic Viscosity

Research Objective

- The objective of this work is to generate a robust shear stress sensor capable of **making accurate shear stress measurements up to 10 Pa with µPa sensitivity** without airflow disruption.





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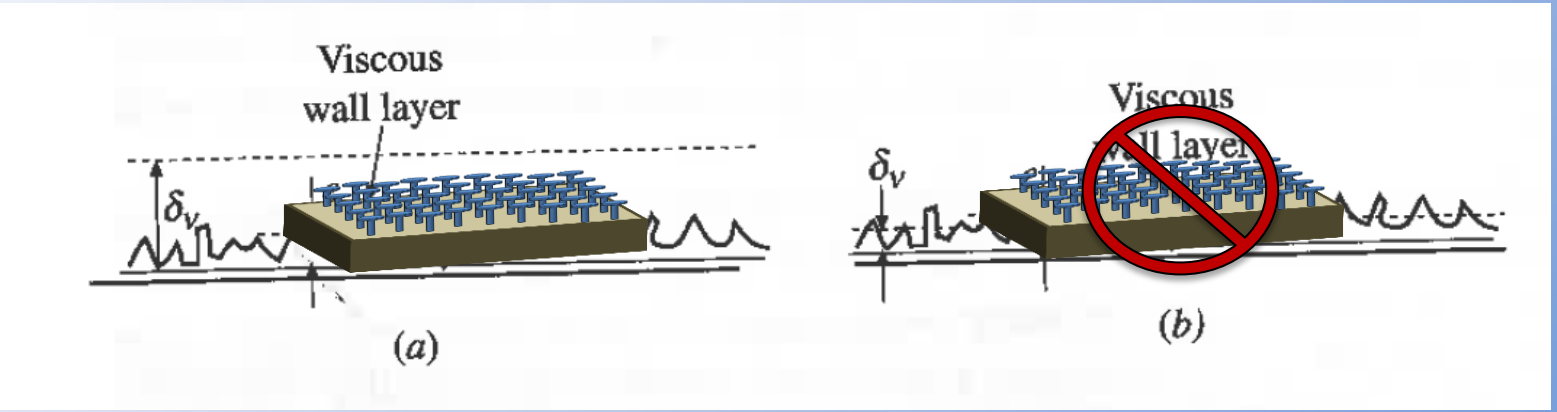


A Smooth Wall

A Rough Wall

Image from: Potter, Merle C. Fluid Mechanics Demystified. The McGraw Hill Company, New York, 2009, p. 144.

State-of-the-Art Shear Stress Sensing

Indirect Measurements

- Hot Wire Anemometer
- Pitot Tube
- Whispering Gallery Mode

Direct Measurements

- Oil Interference
- MEMS devices

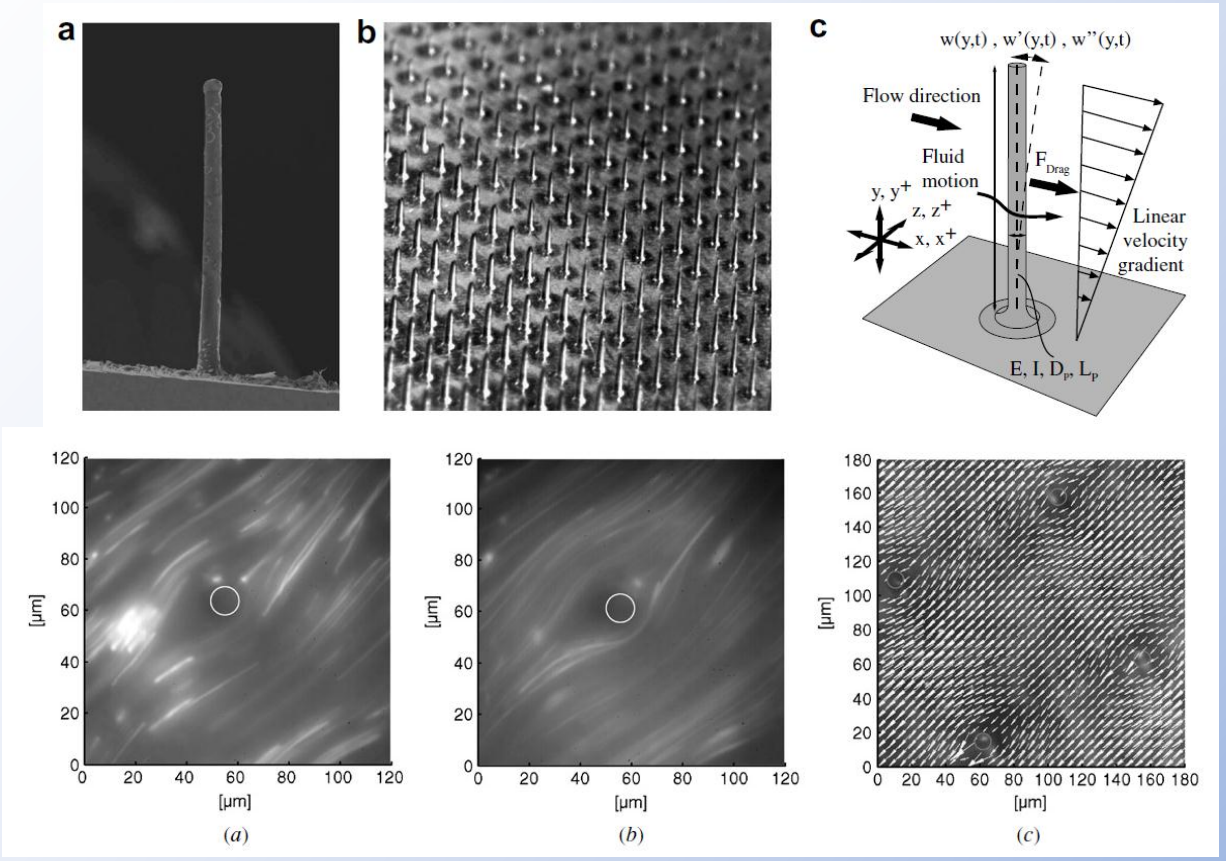
Current shear stress measurement techniques that minimally impact airflow are difficult to implement, of questionable reliability, and sensitive to environmental factors.

Our approach … "Capped" Micropost Arrays

Development of these sensors would alleviate many of these issues enabling shear stress measurement on a variety of surfaces including acoustic liner applications with sensors that: *(1) Are robust, (2) Reduce complexity for integration into a wind tunnel model, (3) Enable measurement in 360°.*

Previous Micropillar Shear Stress Sensors

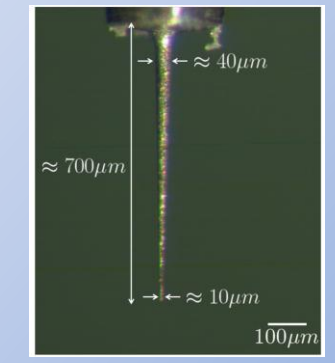
W. Schröder, RWTH Aachen University

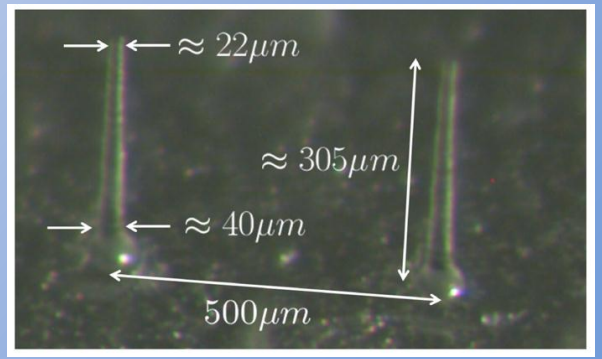


S. Große and W. Schröder *Int. J. Heat and Fluid Flow* **2008**, *29*, 830.
S. Große, et. al. *Meas. Sci. Technol.* **2006**, *17*, 2689.

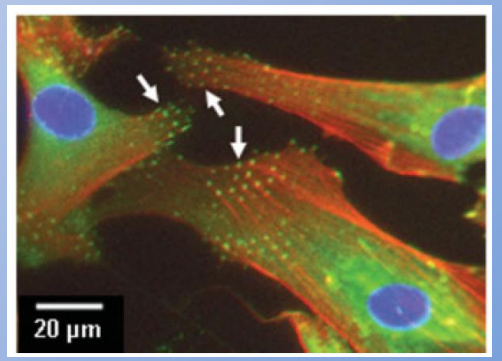
Other Research

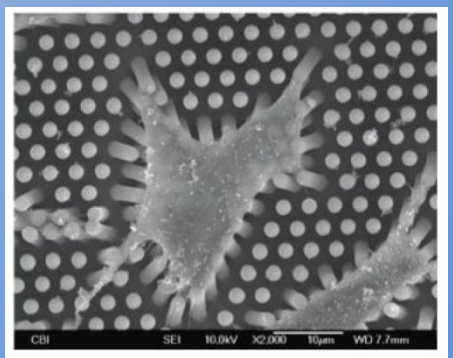
Novel Manufacturing Methods





Investigation of Bio-adhesion



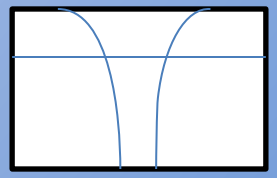


E. Gnanamanickam and J. Sullivan *J. Micromech. Microeng.* **2012**, *22*, 125015.
B. Li, et. al. *Cell Motil. Cytoskeleton* **2007**, *64*, 509.

Laser Ablation for Template Generation

- Generation of master templates amenable to micropillar array fabrication: laser ablation patterning

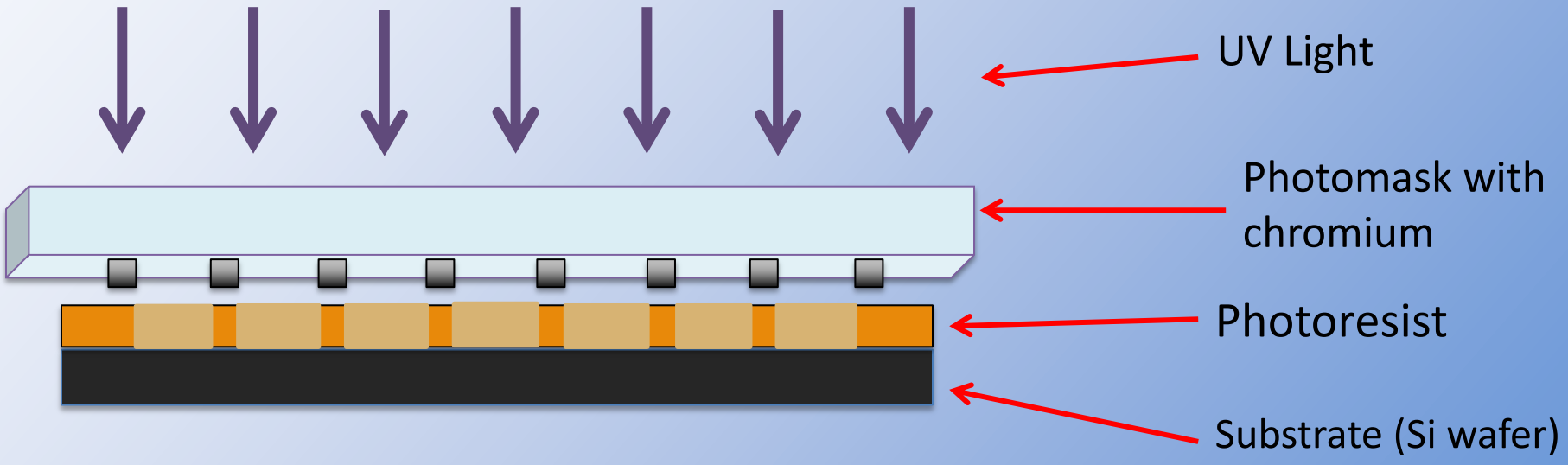
- Dicing tape applied to enable facile removal of the electrical tape layers.
- 2 layers of electrical tape used to absorb energy that, when applied to the epoxy, led to large diameter, shallow side-wall angle ablation.



Laser ablation patterning affords excellent depth control but has limited diameter control with a minimum achievable diameter of approximately 30 μm.

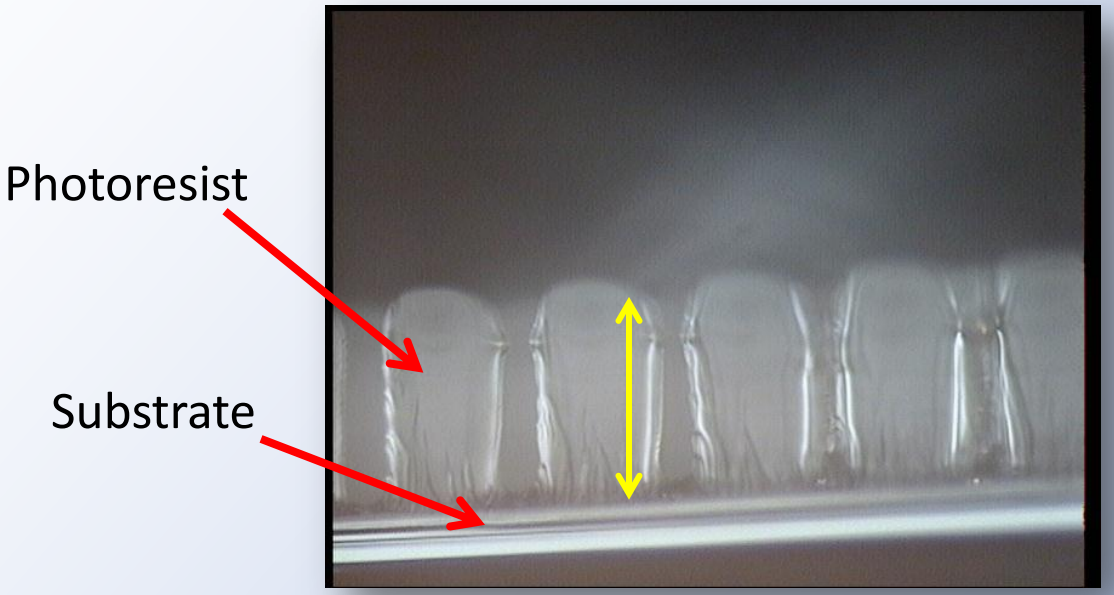
Contact Lithography for Template Generation

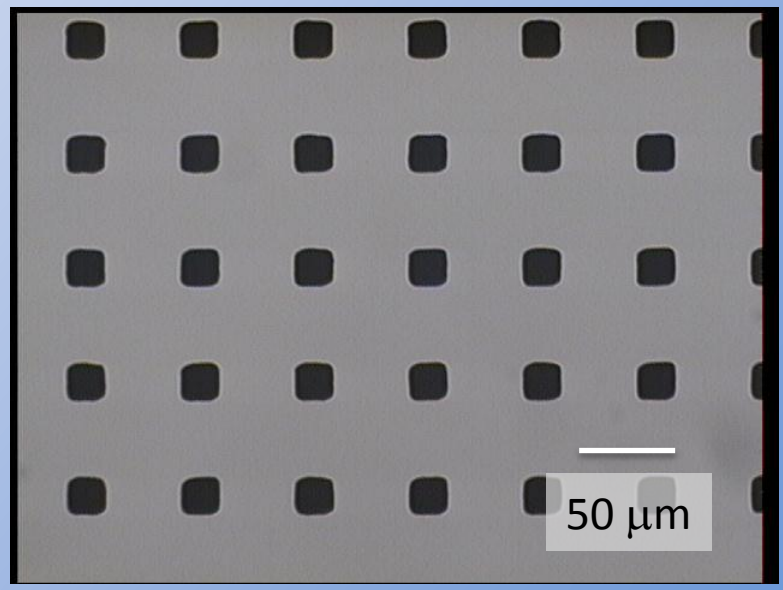
- Generation of master templates amenable to micropillar array fabrication: contact lithography



Contact Lithography for Template Generation

- Generation of master templates amenable to micropillar array fabrication: contact lithography

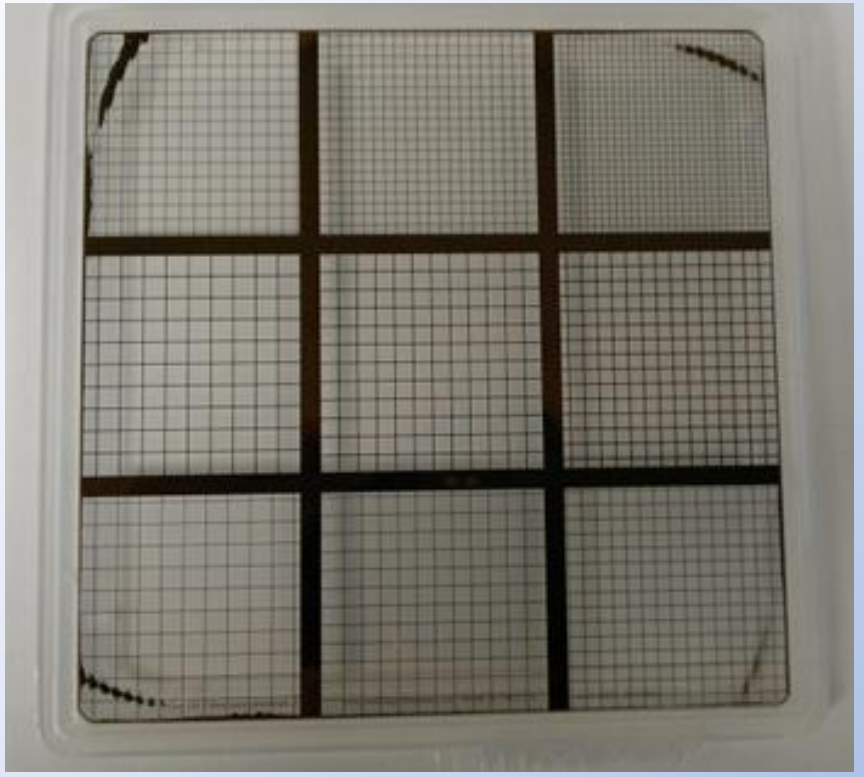




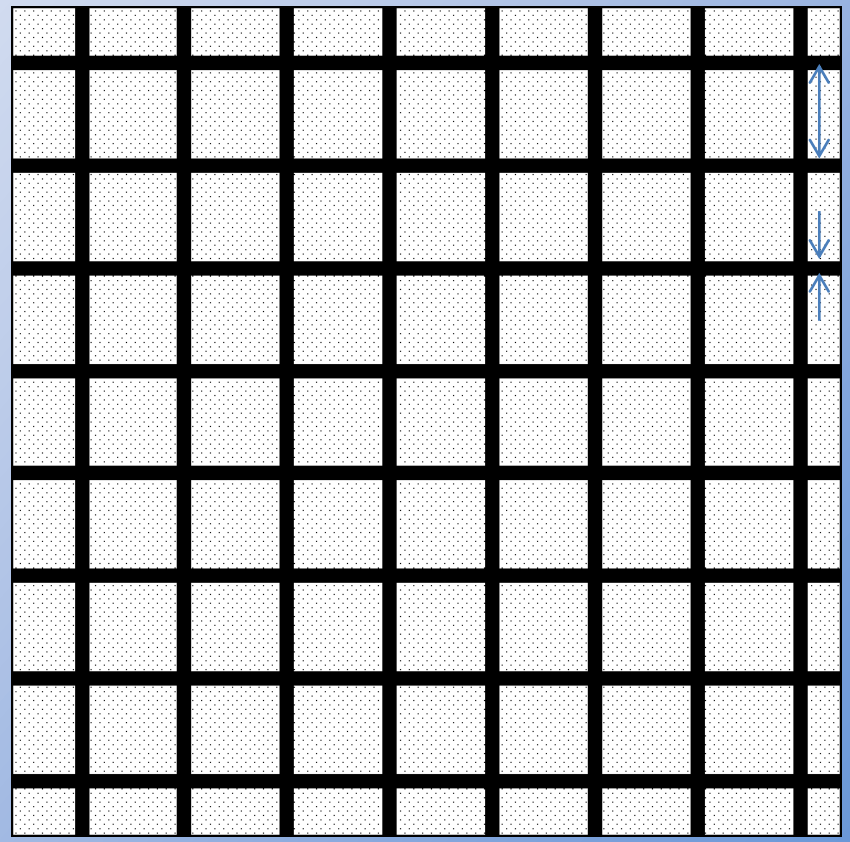
Photolithography offers greater capability for increased aspect ratios relative to laser ablation patterning. However, the available photomask patterns are far too dense.

Contact Lithography for Template Generation

Designed Photomask for Contact Lithography Master Template Fabrication

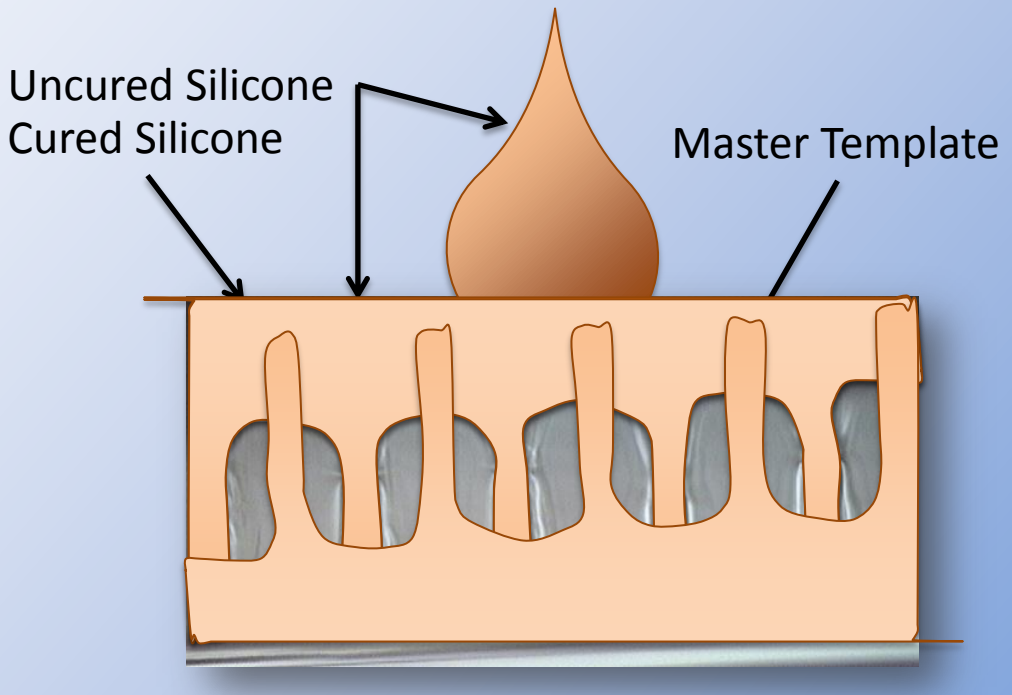


Close-up of Pattern Schematic



Micropillar Array Fabrication: Soft Lithography

- Fabrication of micropillar arrays using soft lithographic techniques



Micropillar Array Fabrication: Soft Lithography

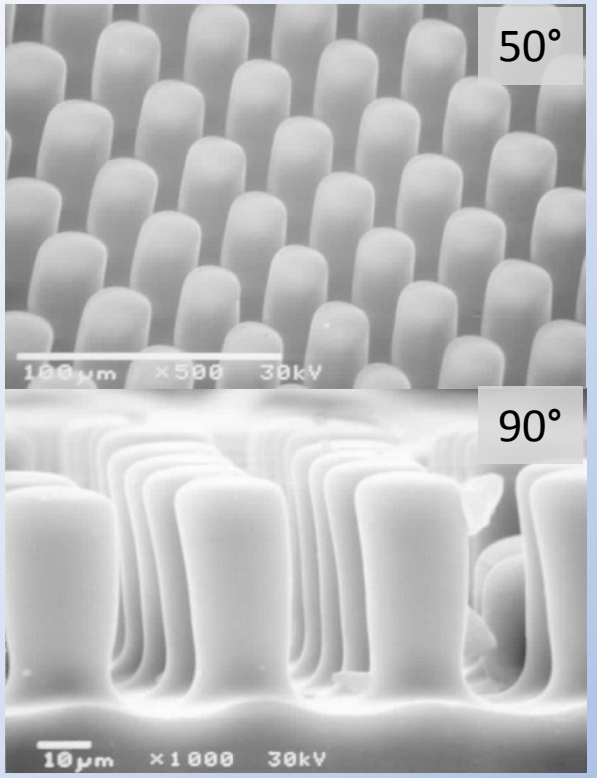
- Fabrication of micropillar arrays using soft lithographic techniques: using laser ablation generated templates

% power	kHz	in/s	Post Height (µm)
90	60	2.5	115
90	60	2.0	123
92	60	3.0	62
92	60	2.5	45 - 85
92	60	2.0	132
95	60	3.0	85
95	60	2.5	123

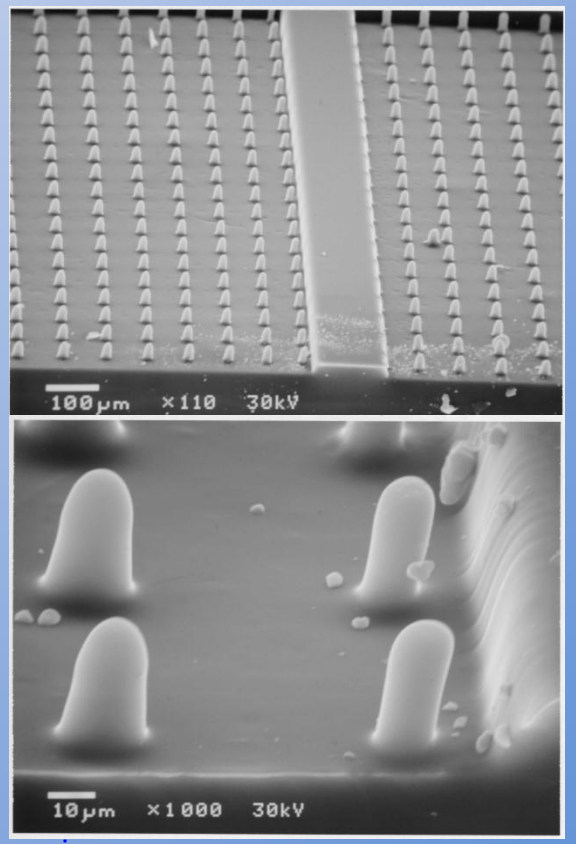
Micropillar Array Fabrication: Soft Lithography

- Fabrication of micropillar arrays using soft lithographic techniques: using contact lithography templates

Results from old Photomask 45-50 µm

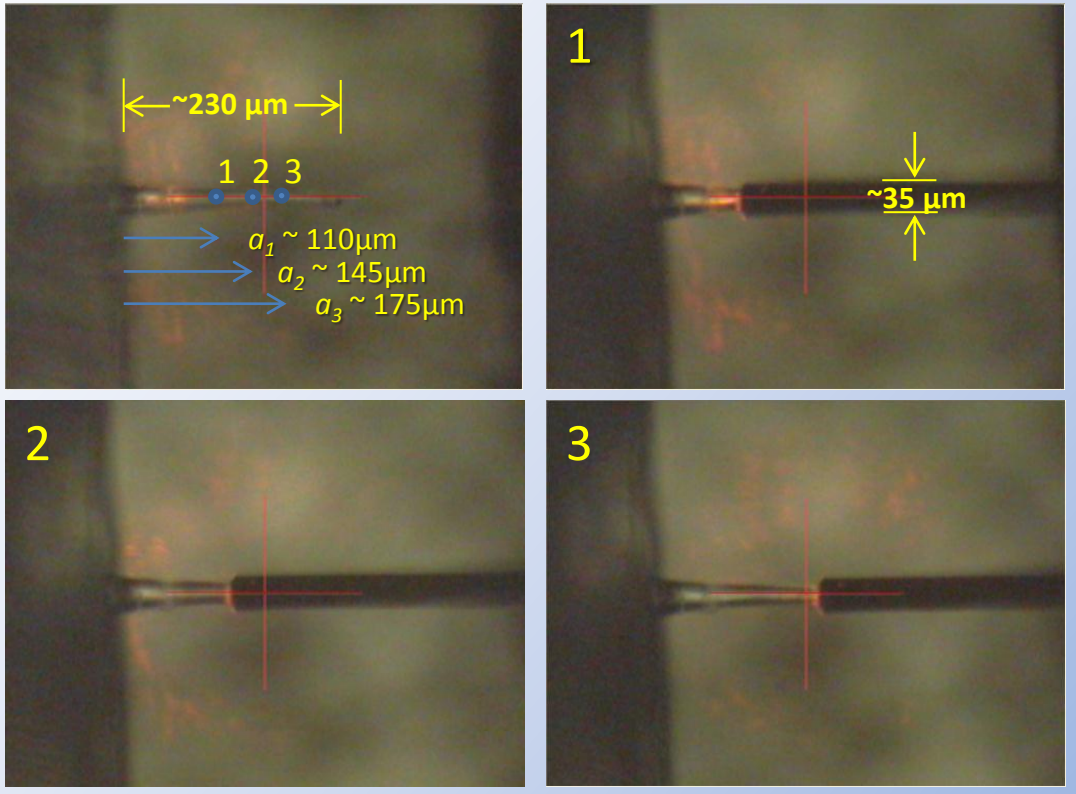


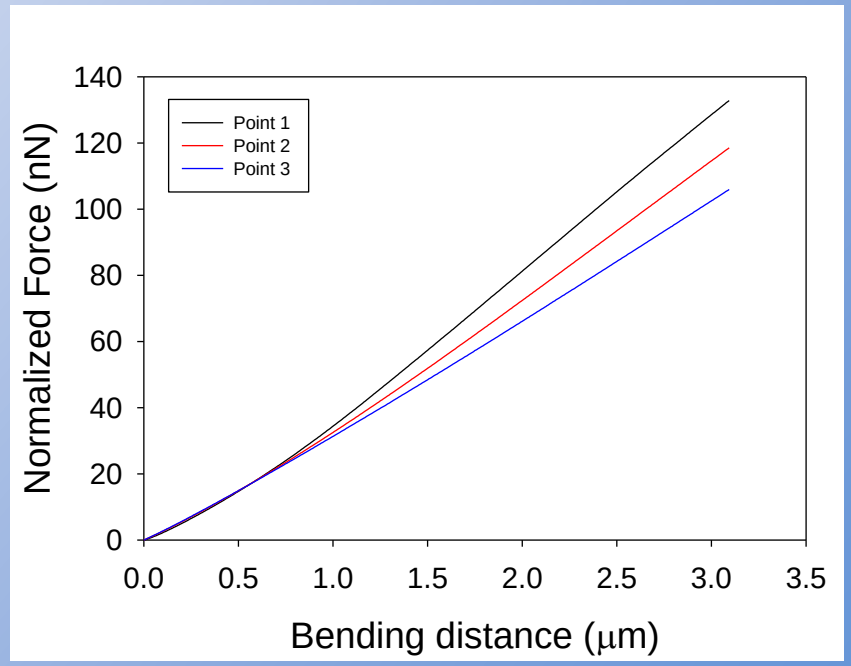
Results from New Photomask Aspect Ratio: 4:1



Force Calibration of Micropillars

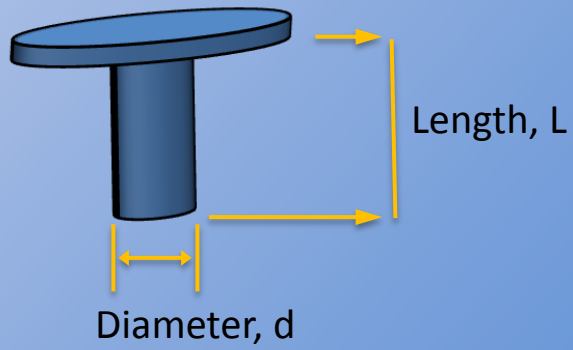
- Force-displacement pillar calibration experiments using atomic force microscopy

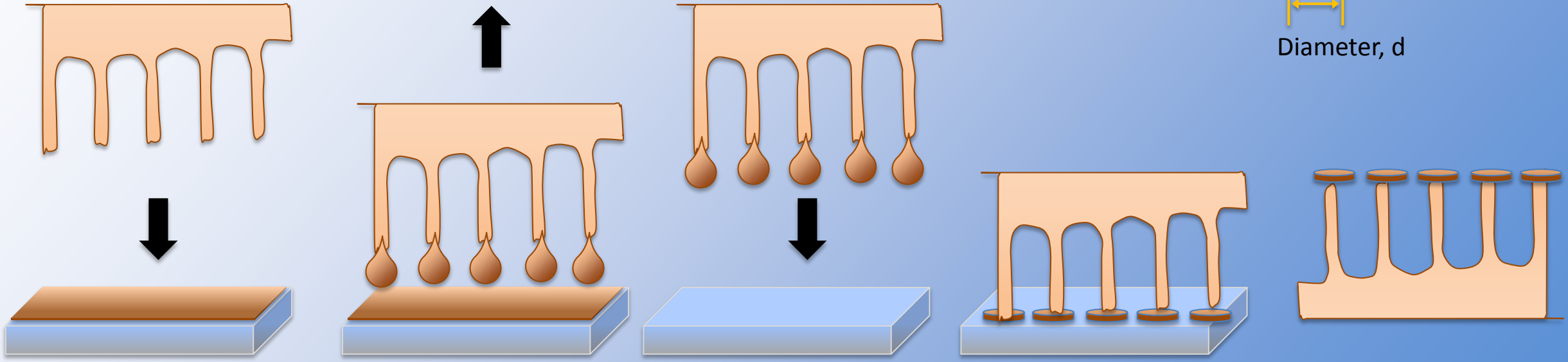




"Capping" Micropillar Arrays

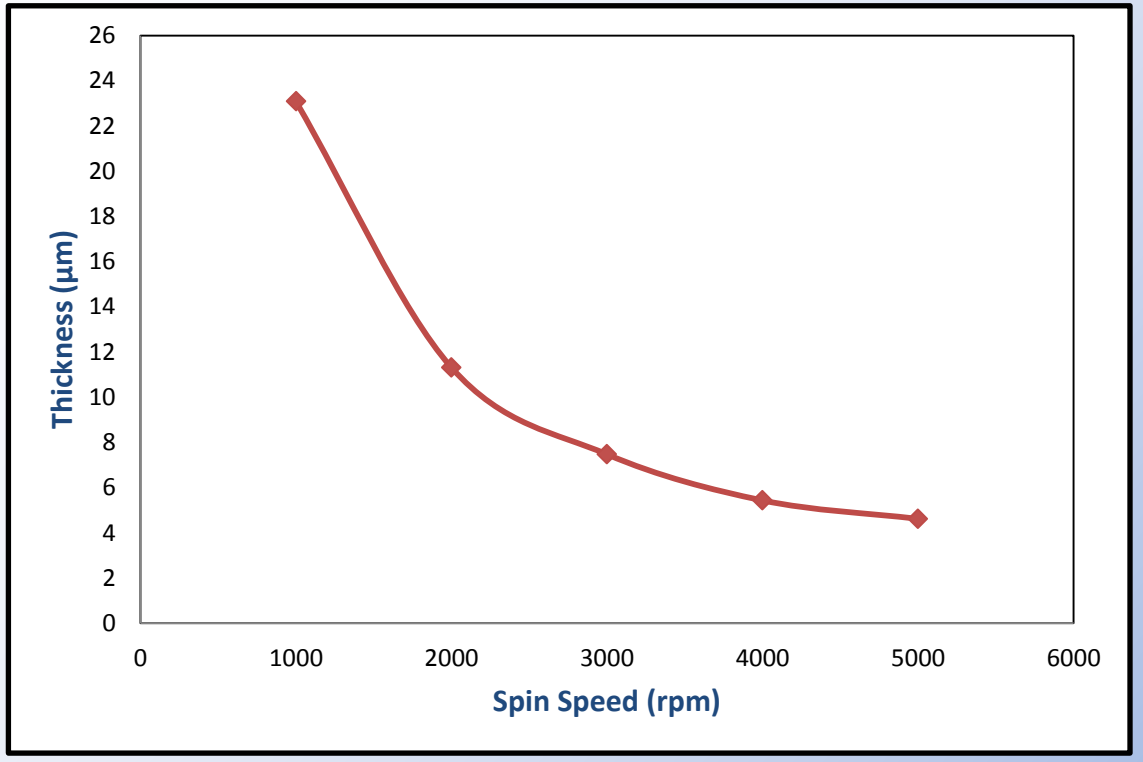
- Fabrication of "capped" micropillar arrays: schematic of approach



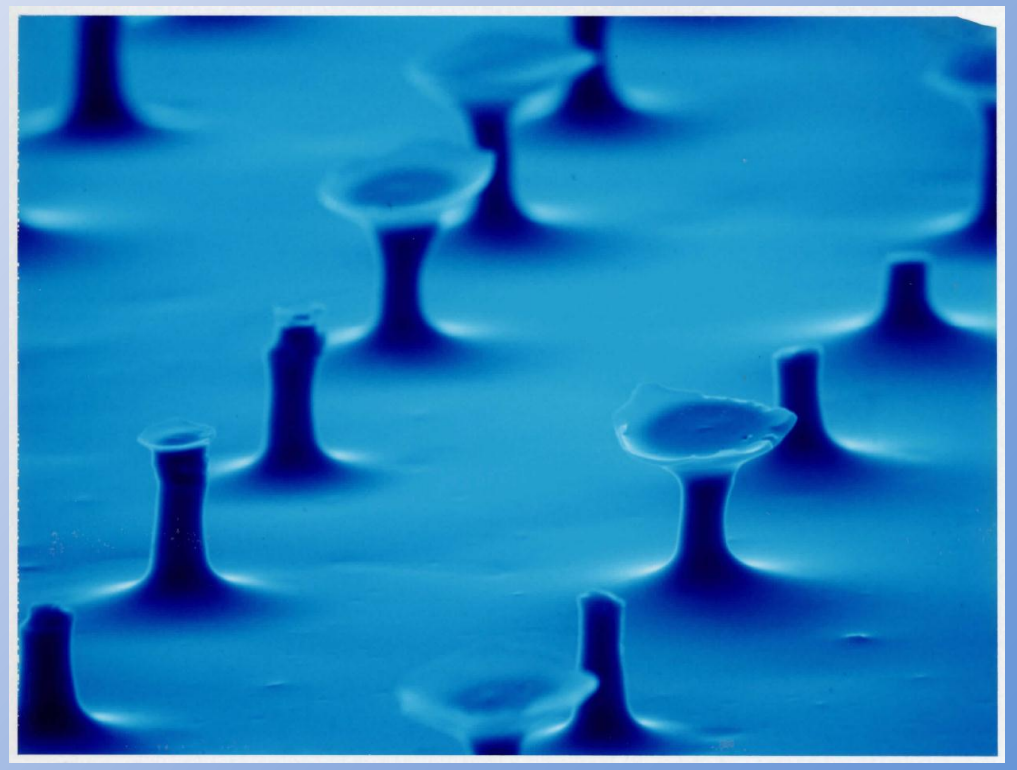


"Capping" Micropillar Arrays

Sylgard 184 Spin Curve



SEM Image of "Capped" Pillars



"Cap" film thickness can be easily varied based on spin-coater settings. With greater pillar spacing, the caps readily formed and were free standing, i.e., no pillar coupling.

Future Work

- Micropillar array design refinement
  - Identification of greatest efficacy methods for micropillar capping and signal enhancing dopant
  - Characterize micropillar deflection
  - Develop micropillar arrays for various wind speeds
- Characterization for signal implementation
  - Determine measurement range, sensitivity, noise floor, etc.
- Use of PIV equipment and visualization techniques to see pillar deflection

Acknowledgements

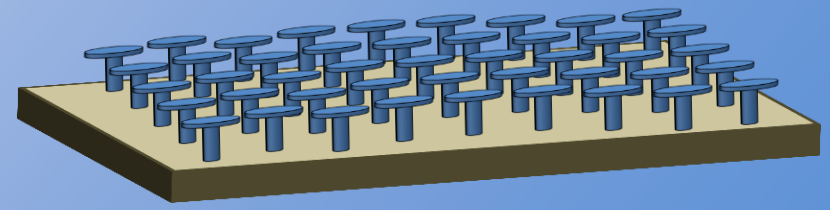
- Research Assistance:
  - John Hopkins-Ablation Laser Operations
  - Vincent Cruz-Contact Lithography Assistance
- Discussion
  - Xiaoning Jiang, North Carolina State University
- Funding:
  - NASA Aeronautics Research Directorate NARI Seedling Program

Supplementary Slides

Experimental Approach

- Pillar Array Design and Fabrication
  - Generate master templates using available lithographic processes Identify requisite pillar parameters for shear stress measurements in subsonic flows
    - Laser ablation of epoxy substrates
    - Contact lithography of SU-8 coated Si wafers
  - Fabricate micropillar arrays using commercially available elastomeric materials
- Pillar Calibration and Signal Transduction
  - Calibrate pillar deflection using atomic force microscopy
  - Determine signal transduction approach

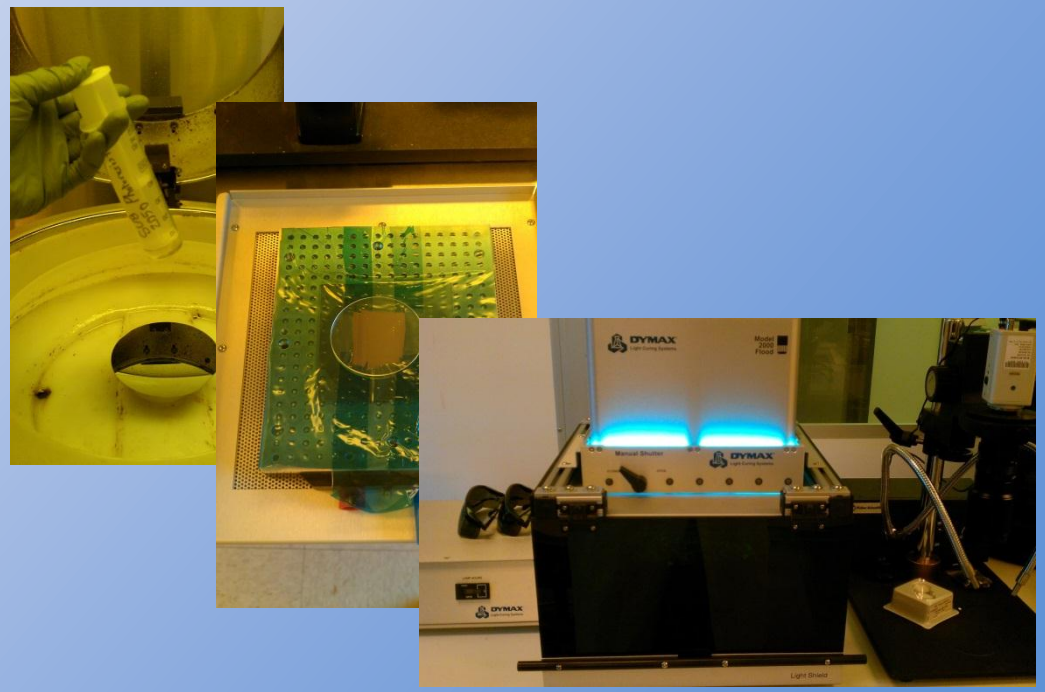
Pillar Parameter	Value
Length, L	L < 100 μm
Aspect Ratio, L/d (diameter)	L/d ≥ 3
Pillar Spacing, s	s > 2*L*
Deflection Limit, w	*w* ≤ 0.1L



Concept

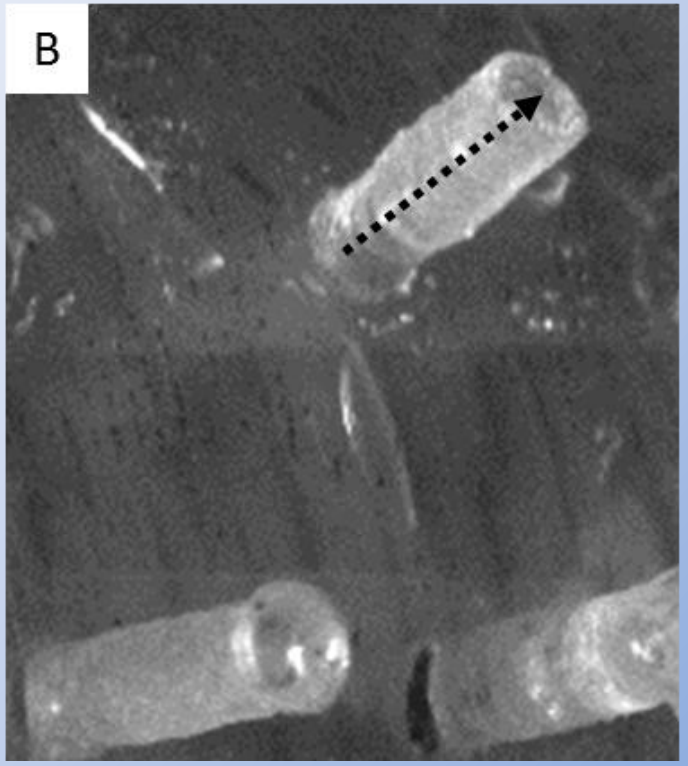
Contact Lithography for Template Generation

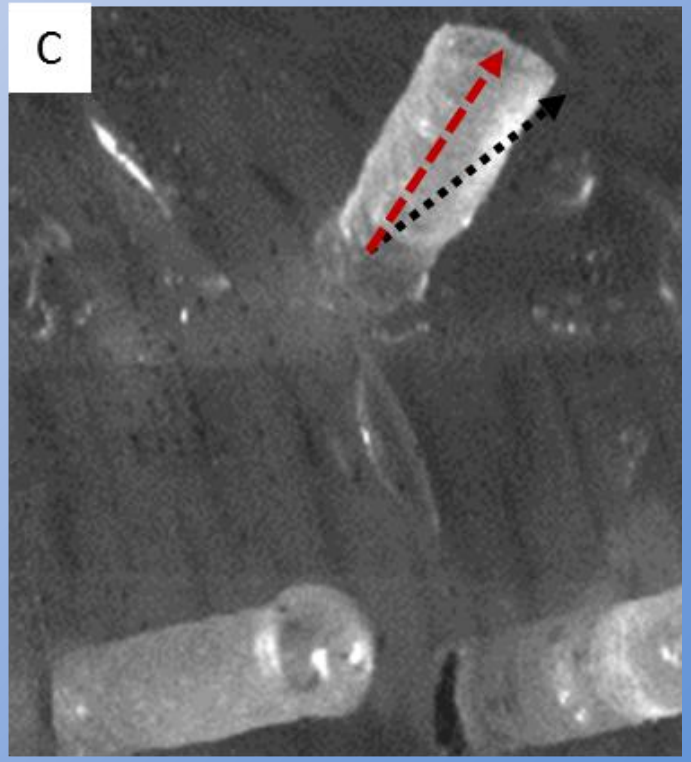
- Generation of master templates amenable to micropillar array fabrication: contact lithography
  - This procedure required process refinement for several steps:
    - Plasma exposure of Si wafers
    - Dehydration baking
    - SU-8 adhesion promotion layer
    - SU-8 application
    - Soft bake
    - Photomask positioning and exposure
    - Pattern development



Accomplishments

- Generation of a macroscopic example of the micropost array sensor

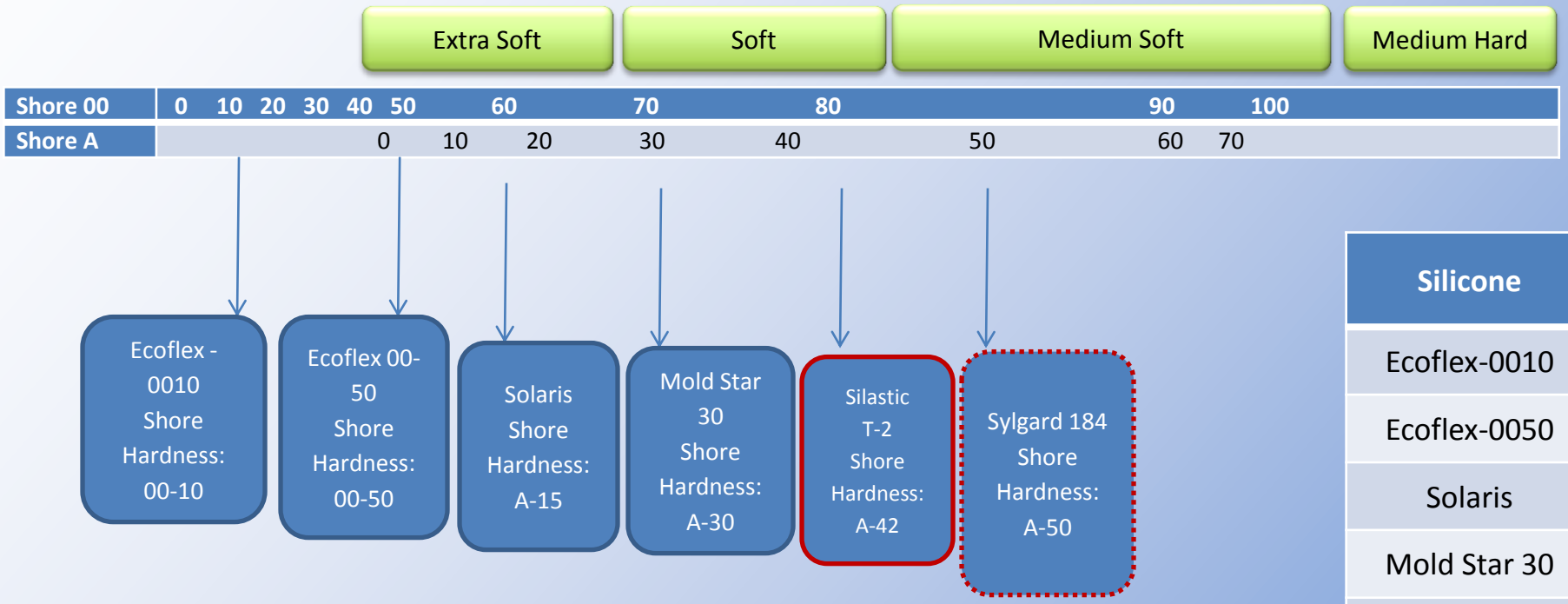




Pillar deflection was readily observed on the macroscopic sample.

Micropillar Array Fabrication: Soft Lithography

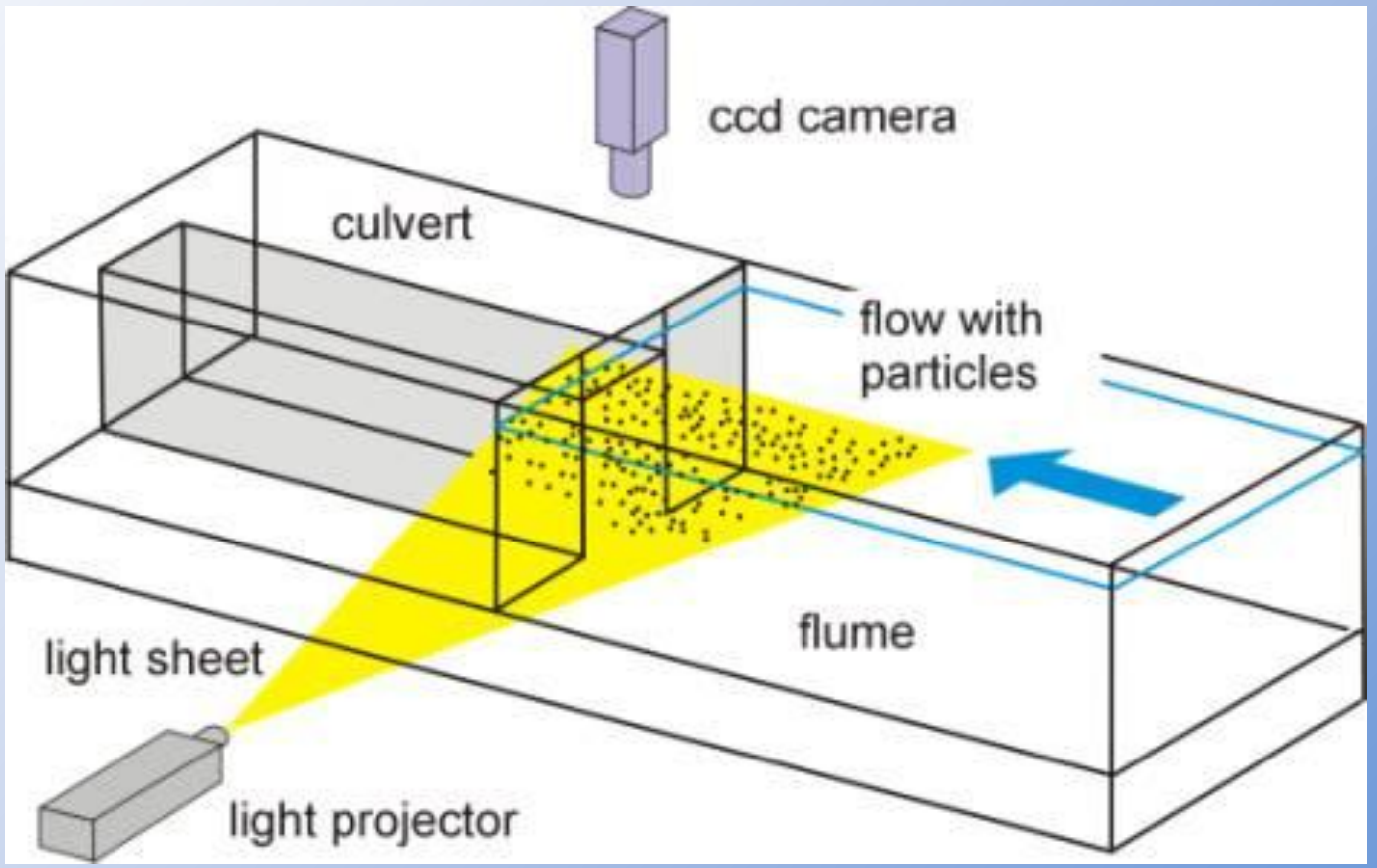
- Evaluation of different silicones



Silicone	Hardness (Shore A)	Tensile Strength (MPa)
Ecoflex-0010	00-10	0.83
Ecoflex-0050	00-50	2.17
Solaris	15	1.24
Mold Star 30	30	2.90
Silastic T2	42	5.52
Sylgard 184	50	7.07

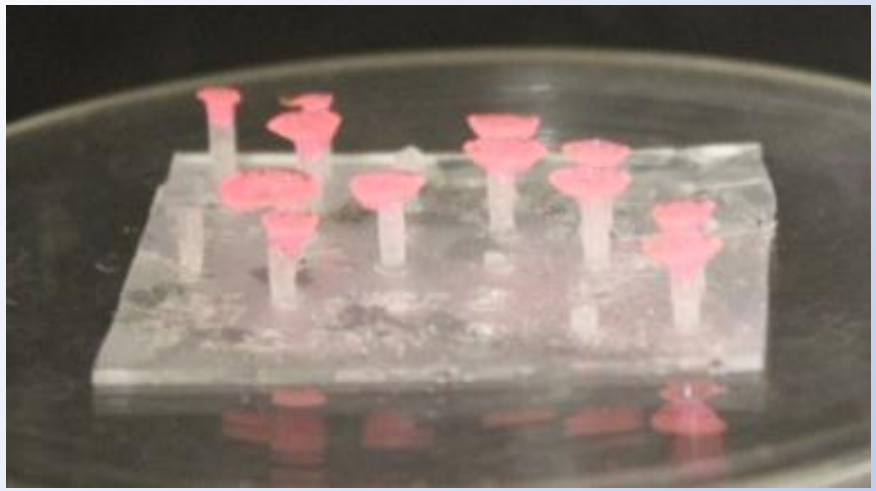
Signal Transduction

- **Integration of Micropillar Array Sensors with Existing (Micro) Particle Image Velocimetry Instrumentation**

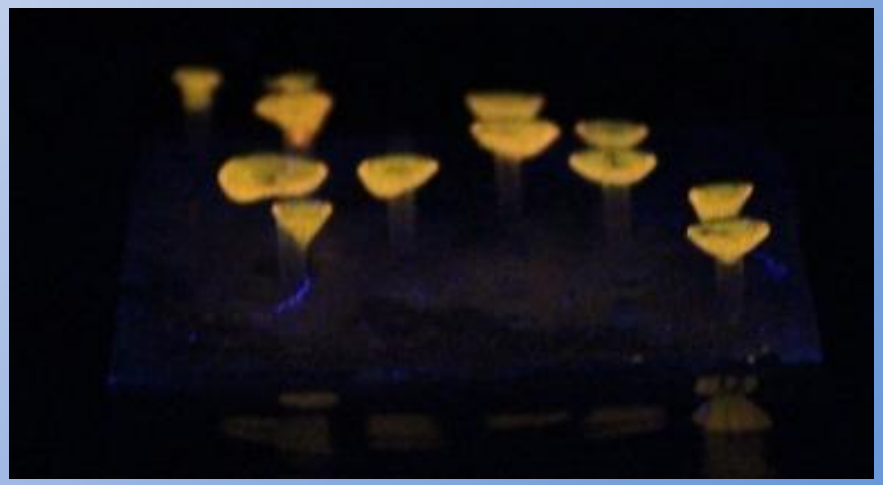


Fluorescent Dye Doping of "Caps"

- Identification of most efficacious method for signal transduction: optical, piezoelectric, etc.



Visible Light Illumination



UV Light Illumination