Self-assembly of Microsystems

Karl F. Böhringer, Ph.D.
Professor, Electrical & Computer Engineering and Bioengineering
Director, Institute for Nano-Engineered Systems (NanoES)
University of Washington
Seattle, WA, USA

Part III: Self-assembly Using Surface Tension

Capillary force driven assembly; programmable self-assembly by surface modulation; scalable assemblies at the air-water-solid interface

Surface Tension Driven Self-assembly

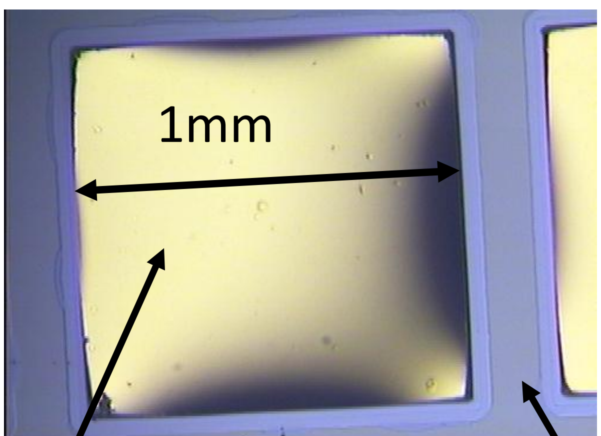
- Surface forces tend to dominate as components shrink below one mm
- Capillary forces have been widely used for assembly because of their favorable strength, range, predictability and controllability

- Disadvantage: components are exposed to liquids (water, oil, etc.) and may need special (hydrophobic, hydrophilic) surface treatments

Surface Tension Driven Self-assembly

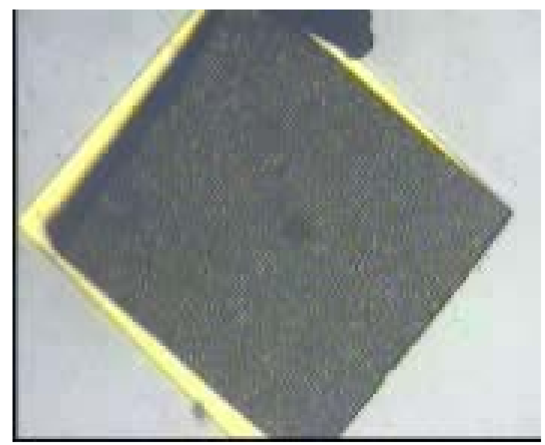
Dip coating forms adhesive droplet on hydrophobic areas:

- reduce friction
- provide longer range capillary forces (>>1µm)
- act as photo- or heat-polymerizable glue



Hydrophilic area

Adhesive on hydrophobic area



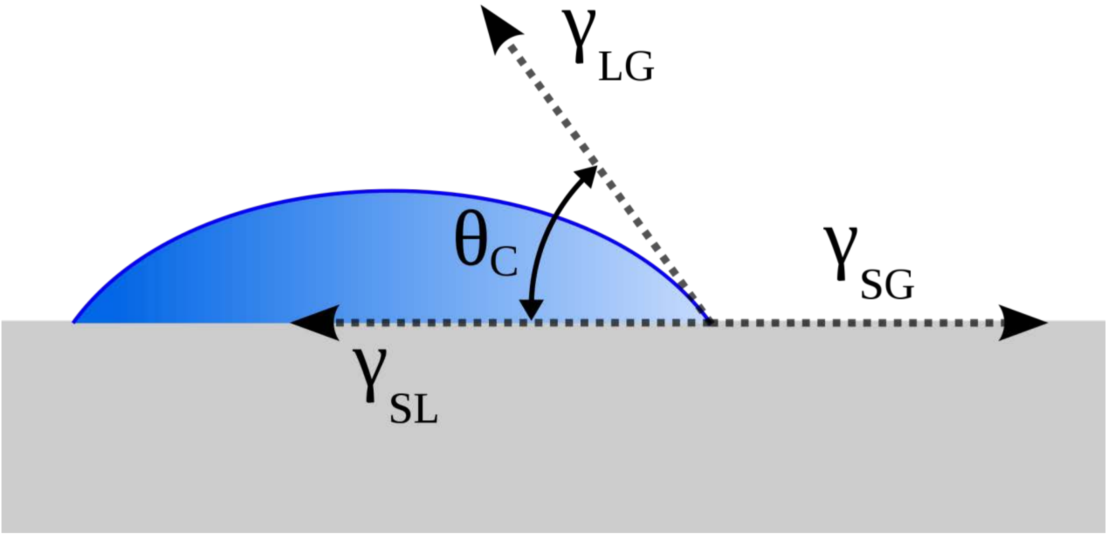
Video: X. Xiong ‘00

Young's Equation

Thermodynamic equilibrium of a sessile drop:

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos(\theta_C)$$

- Surface energy γ
- Interfaces:
  Solid, Liquid, Gas
- Contact angle θ_C



Surface Tension Driven Self-assembly

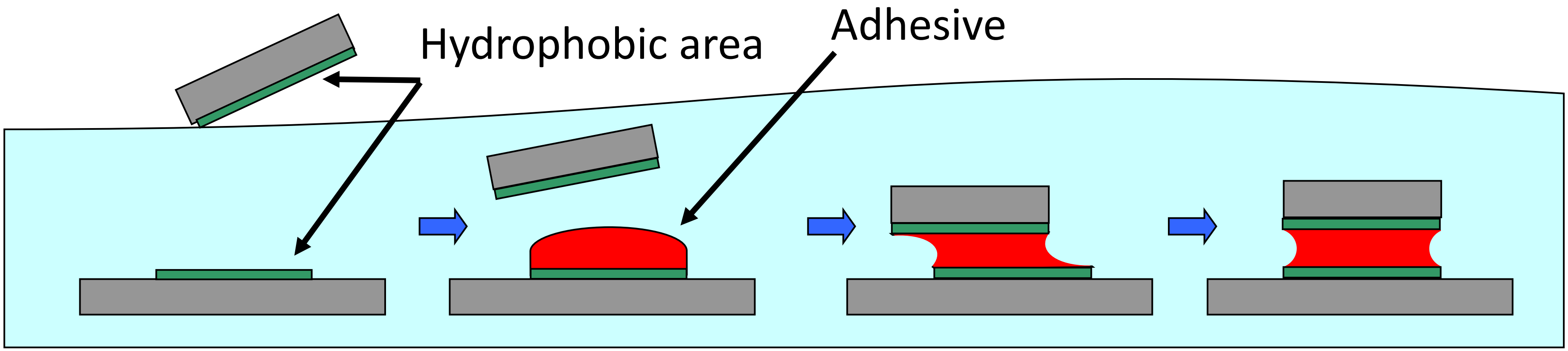
Self-assembly with surface tension can occur in a liquid environment or in air; it relies on an interface between two fluid phases.

1. Structured particles: the components have complementary patterns of hydrophobic and hydrophilic regions, which shape the liquid meniscus between components and binding sites
2. Binding force: capillary force, minimization of surface energy
3. Environment: a fluid helps with the delivery of components
4. Driving force: agitation provides transport until the system minimizes surface energy during assembly

Surface Tension Driven Self-assembly

Driving force for assembly: minimization of surface energy with hydrophobic-hydrophilic interfaces

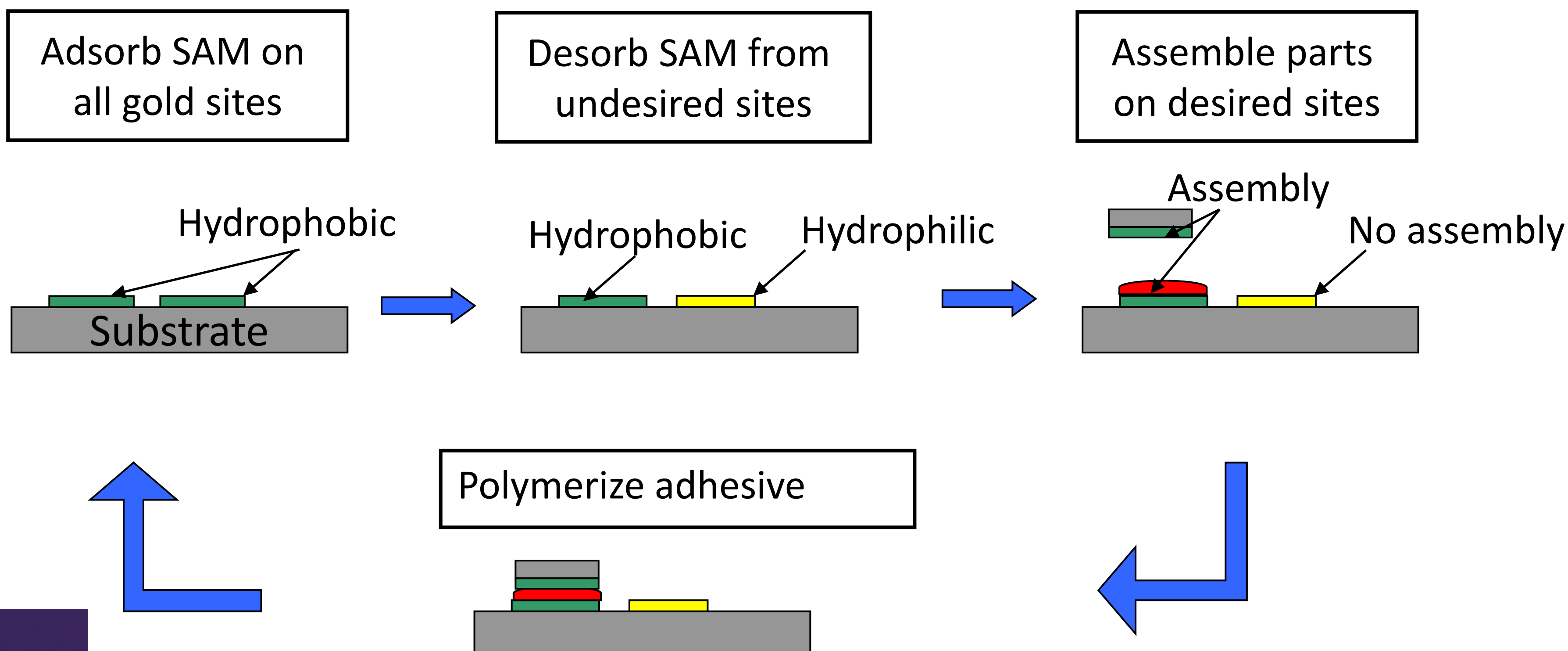
- Alkanethiol self-assembled monolayer (SAM) on Au forms hydrophobic surface
- Organic lubricant adhesive



[Srinivasan et al.'99, Whitesides et al.'90s]

Programmable Self-assembly

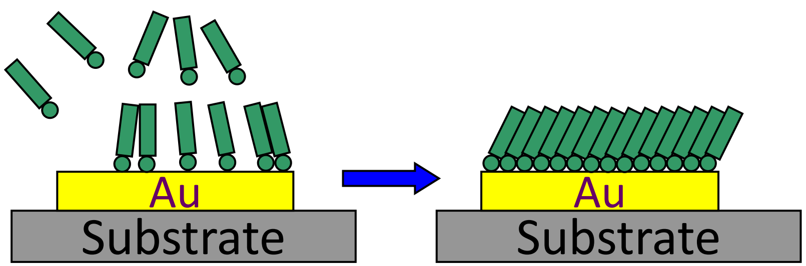
Organization of **different** parts onto desired locations



Modulation of Surface Energies

Hydrophilic → Hydrophobic

Adsorption of alkanethiol SAM

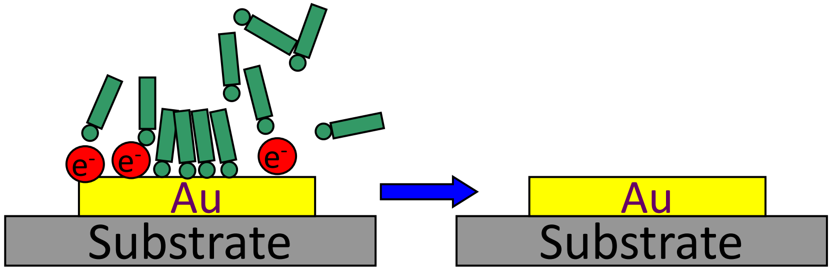


Adsorption is accomplished by soaking surfaces in ethanolic alkanethiol solution.

Hydrophobic → Hydrophilic

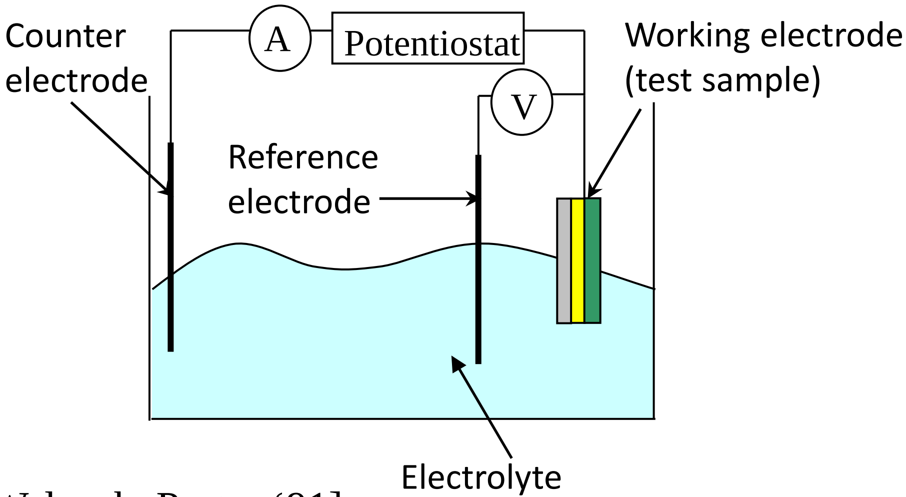
Reductive desorption of SAM

$$CH_3(CH_2)_nS\text{–}Au + e^- \rightarrow CH_3(CH_2)_nS^- + Au$$

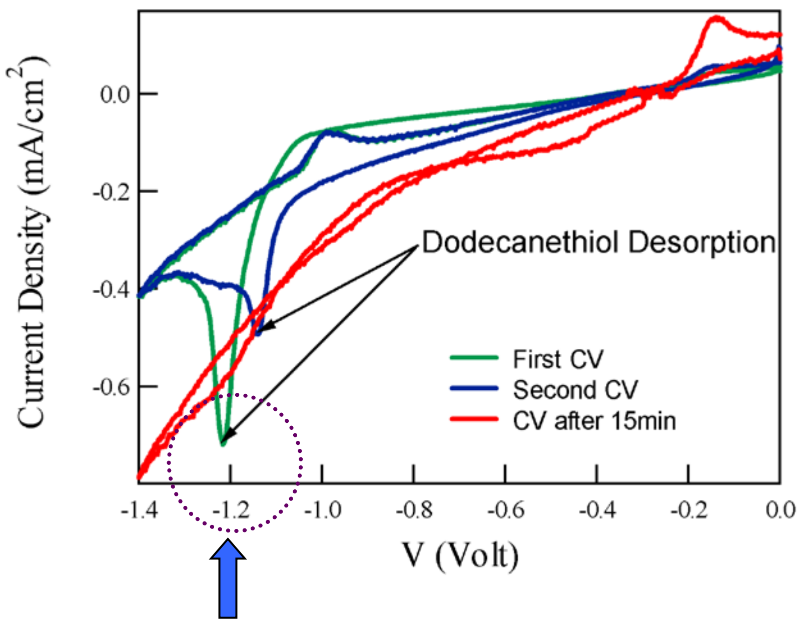


Desorption is accomplished by applying a negative voltage to the Au electrode.

SAM Reductive Desorption Characterization on Gold (111)



[Walczak, Porter '91]
[Weisshaar, Porter'92]

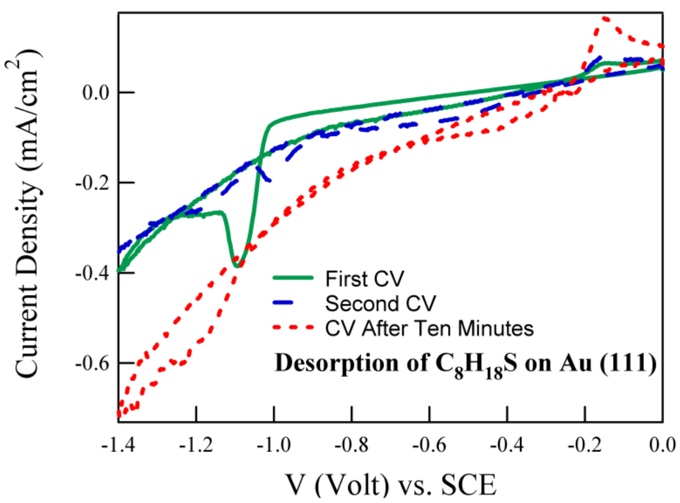


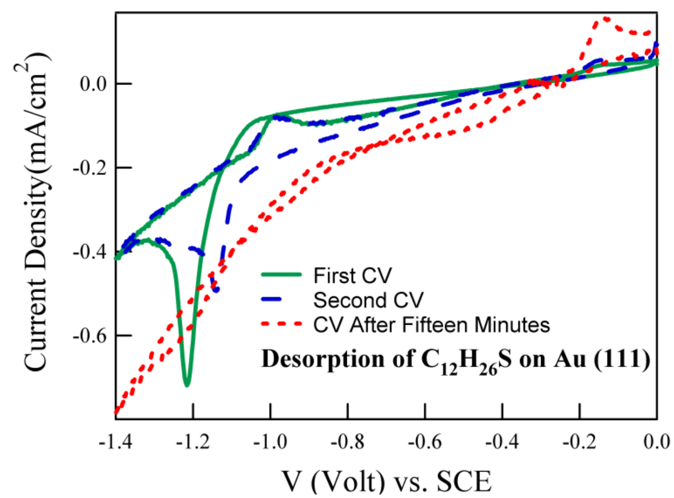
Peaks of SAM desorption

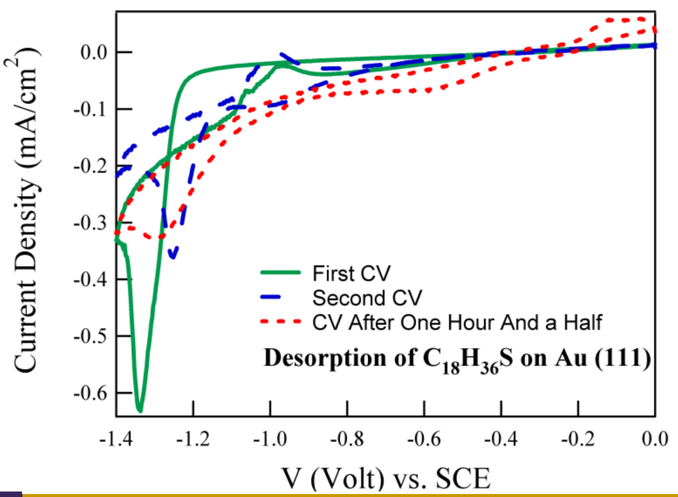
Experiment setup:

- Au (111) surfaces with SAM
- Reference electrode: SCE
- Electrolyte: 0.5M KOH

Optimization of SAM Desorption







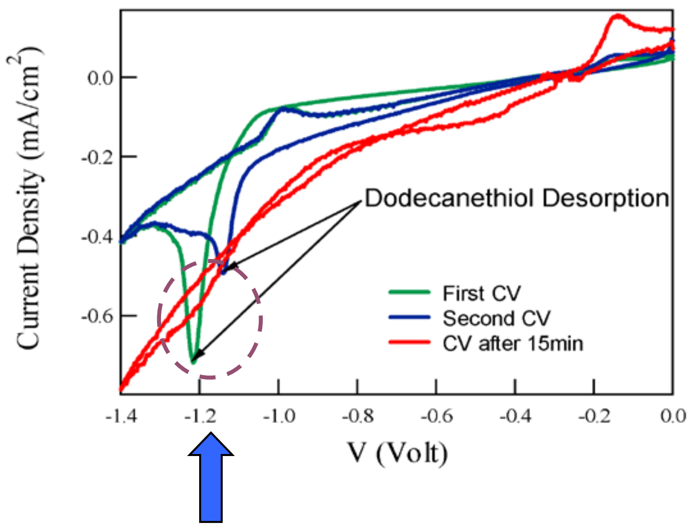
Desorption of different alkanethiol SAMs on Au(111)

(C_3H_8S, $C_8H_{18}S$,$C_{12}H_{26}S$, $C_{18}H_{38}S$)

C_3H_8S	$C_8H_{18}S$	$C_{12}H_{26}S$	$C_{18}H_{38}S$
Unstable	10min	15min	4hours

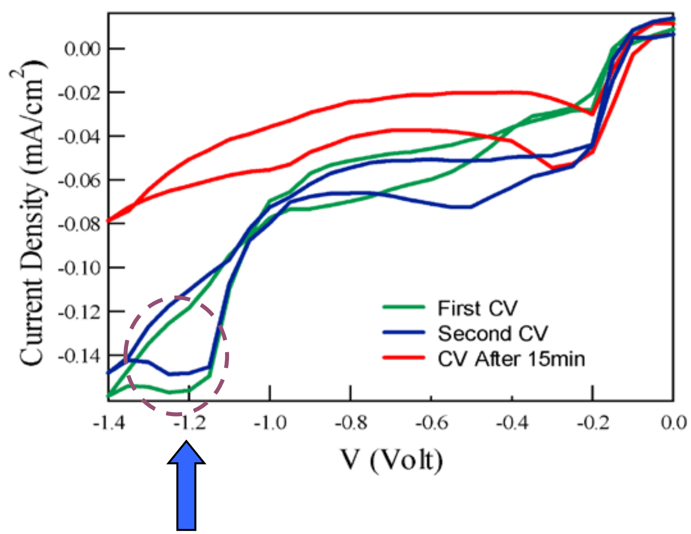
Substrate Dependence of SAM Reductive Desorption

SAM desorption from Au(111) on mica



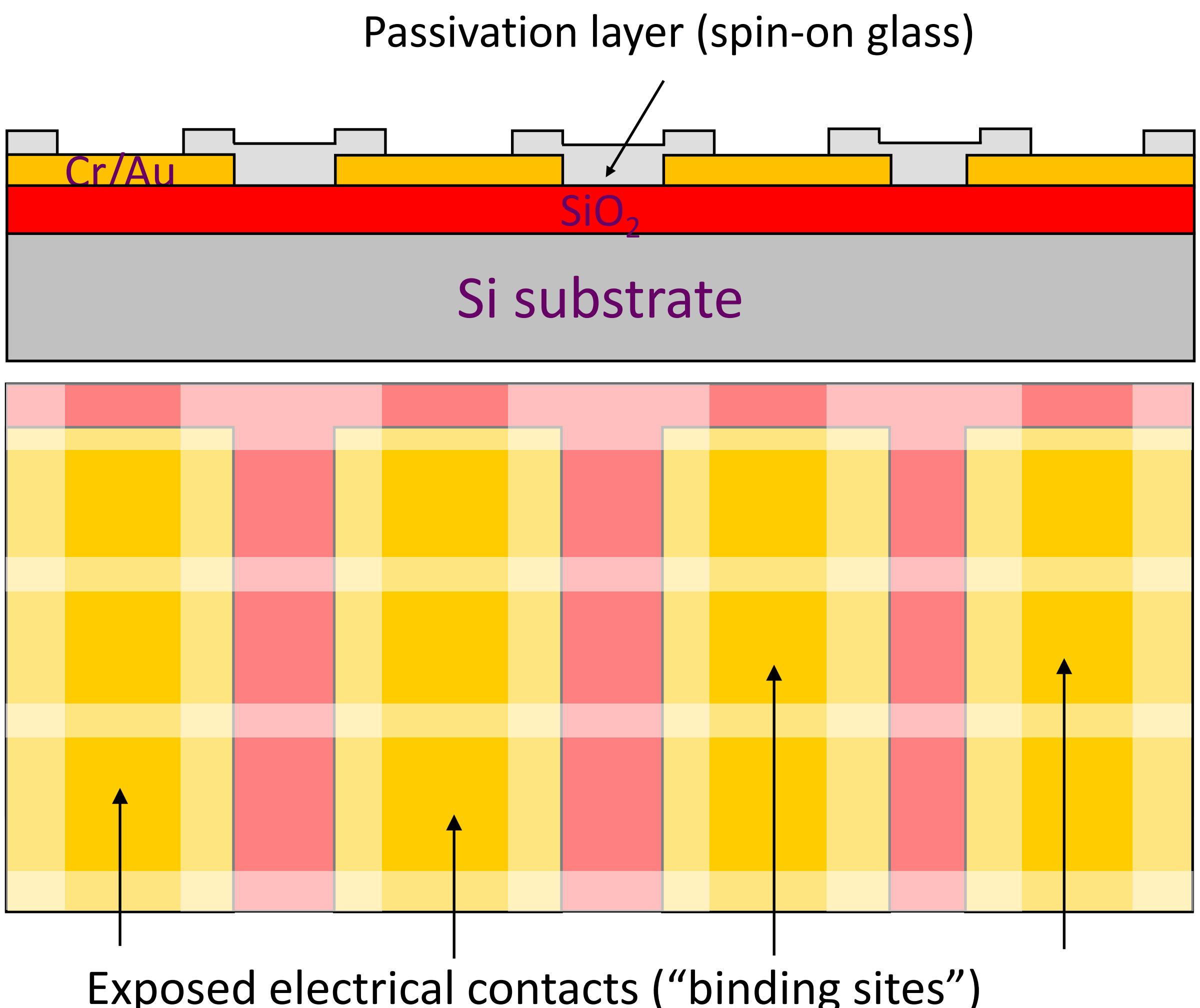
Peaks of SAM desorption

SAM desorption from polycrystalline Au on Si



Broadened peaks of SAM desorption

Fabrication of Substrate

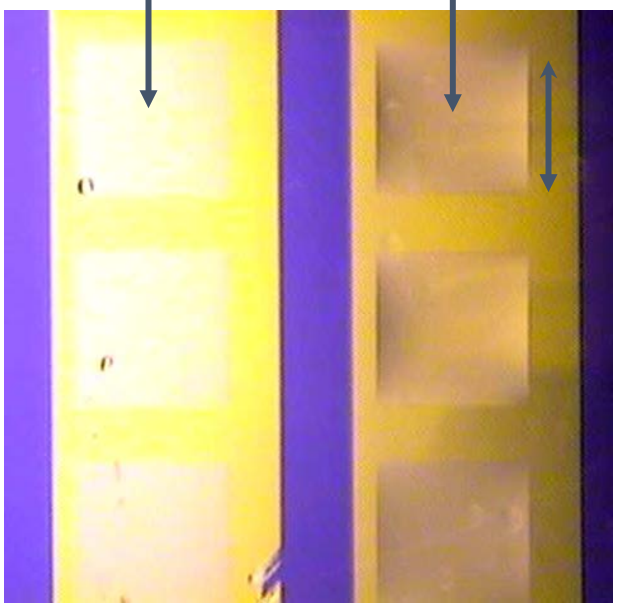


SAM Desorption and First Assembly Batch

No adhesive on hydrophilic surfaces

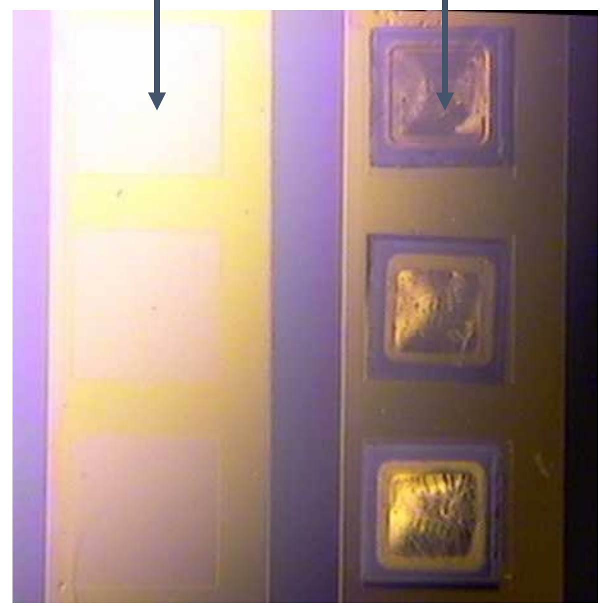
Adhesive on hydrophobic surfaces

1mm



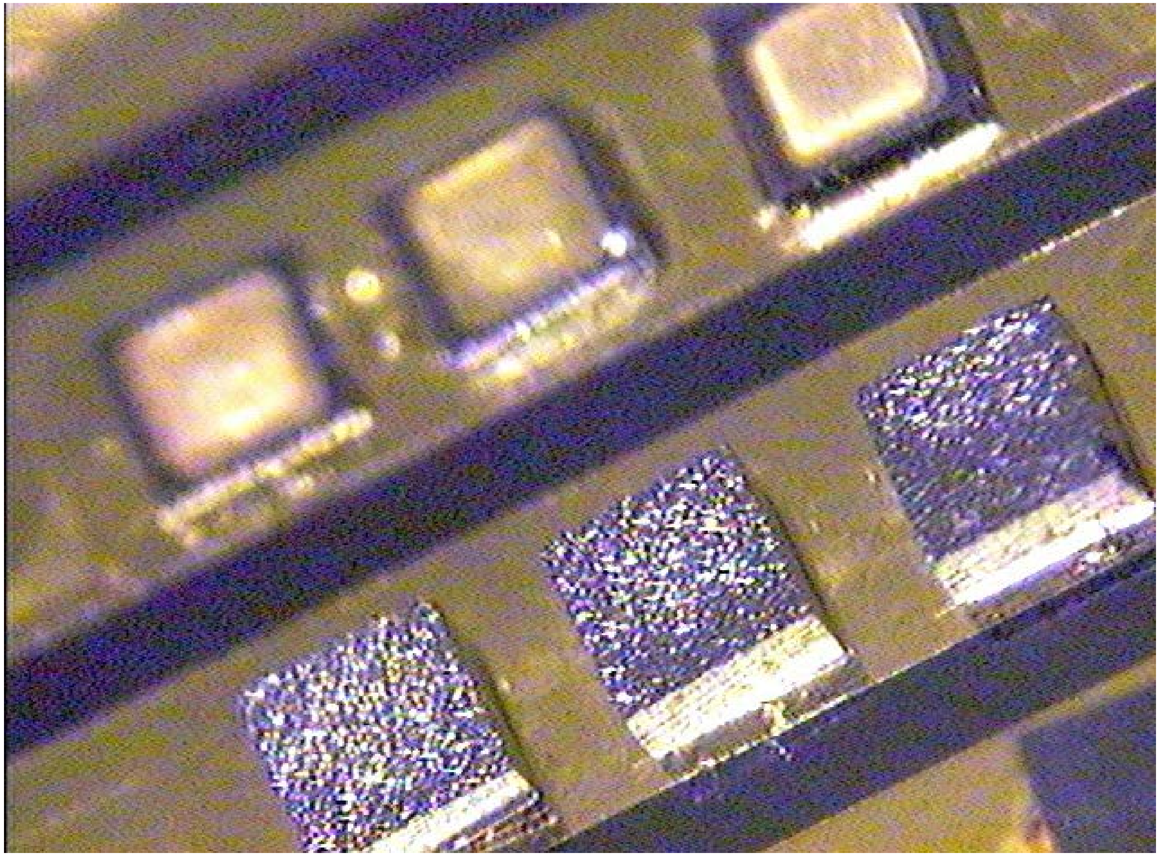
Free spot

Assembled part



SAM desorption from left column of sites only

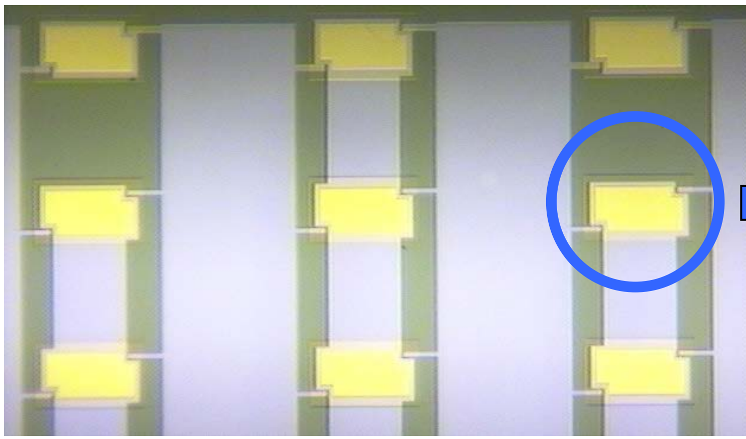
Second Assembly Batch

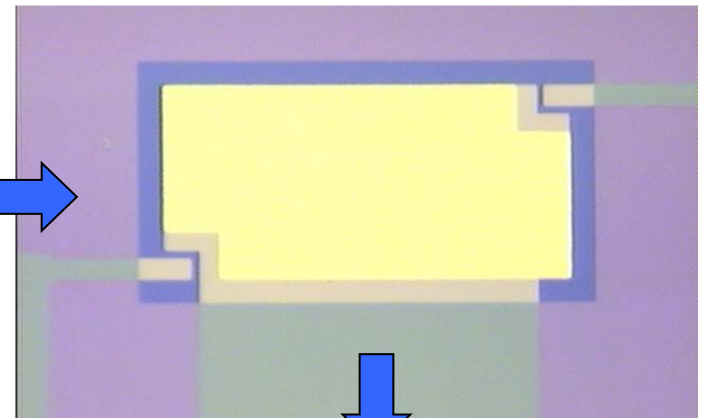


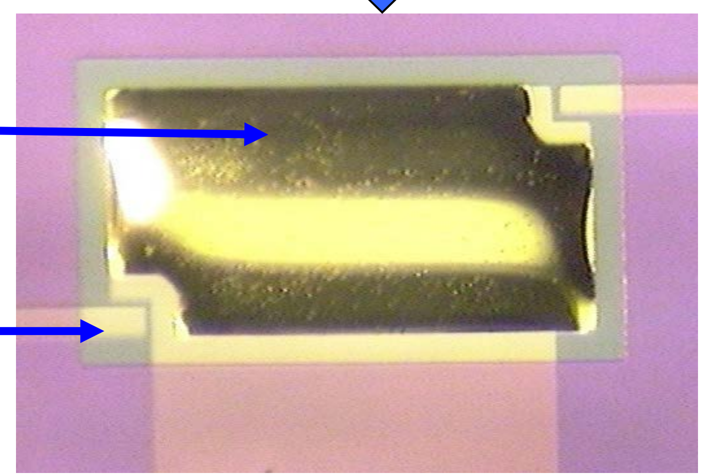
[X. Xiong et al. *Transducers* '01, *JMEMS* '03]

Adding Electrical Connectivity

Top view of a fabricated substrate for LED assembly



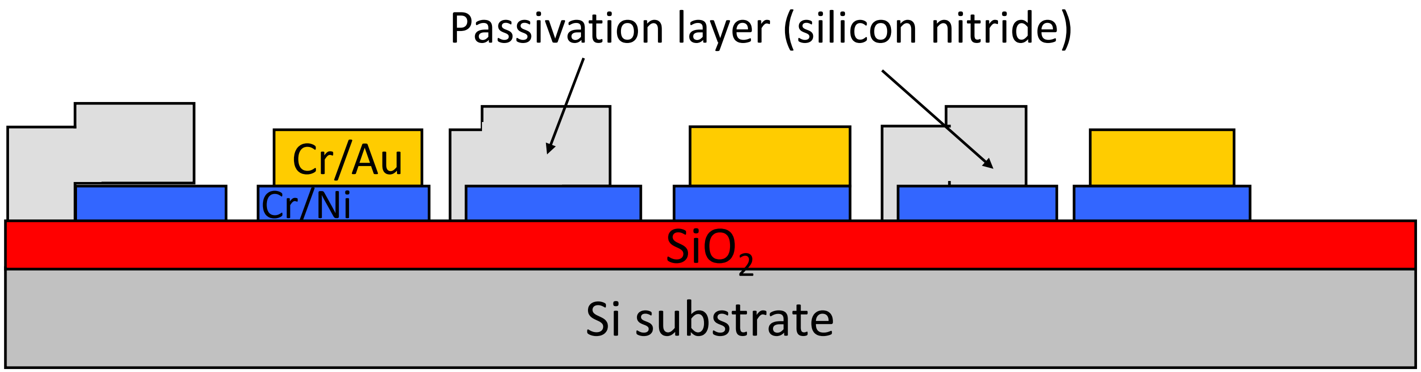


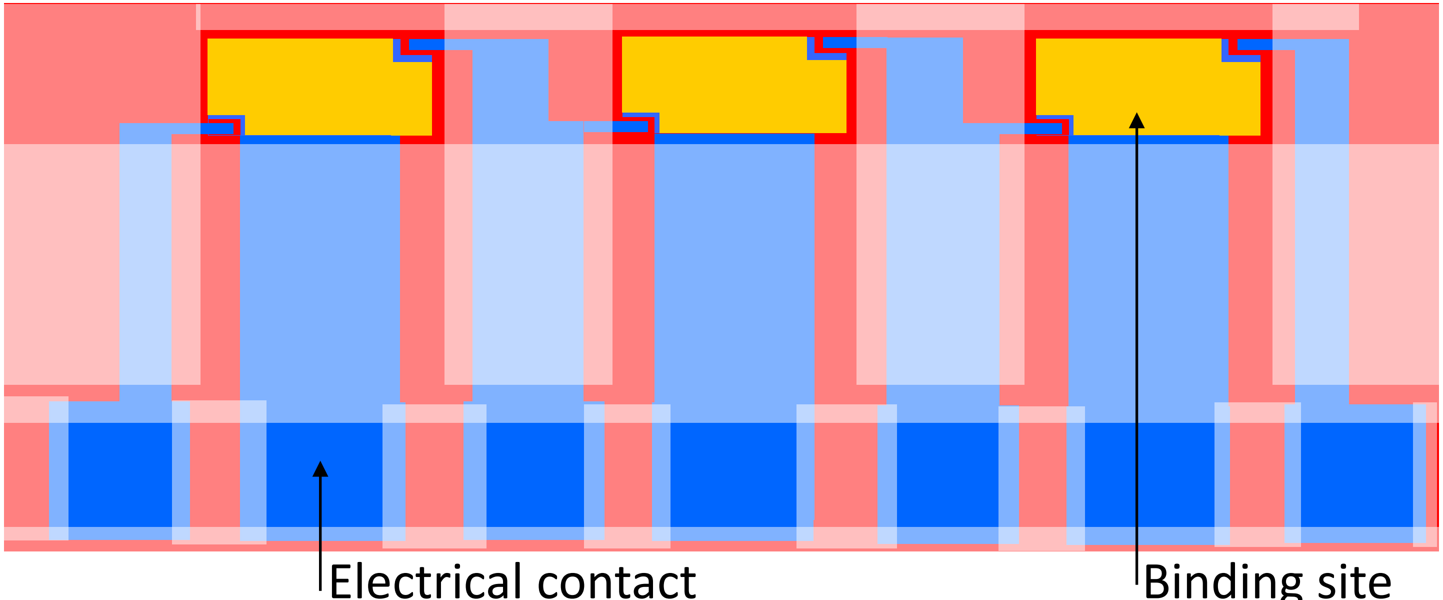


Adhesive wets Au binding site

Ni electroplating seed is free from adhesive

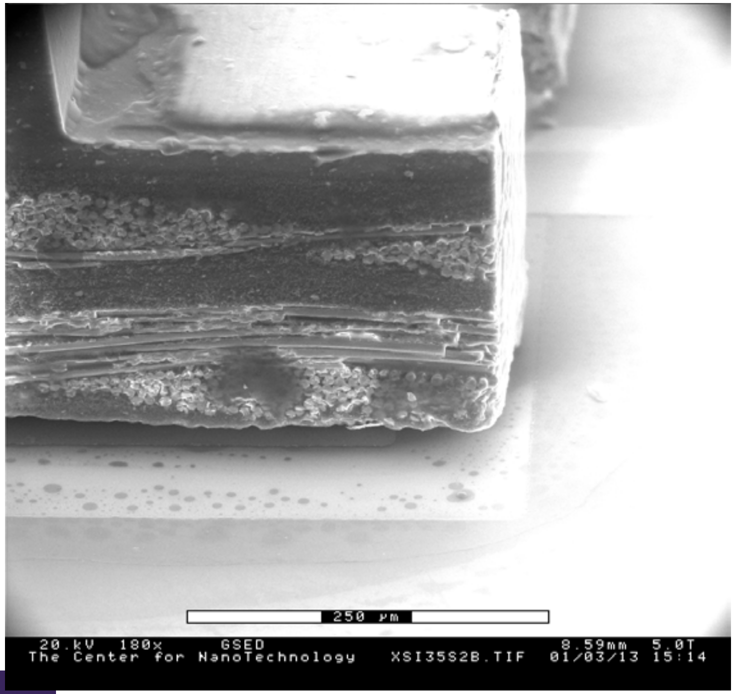
Fabrication of the Substrate for LED Assembly



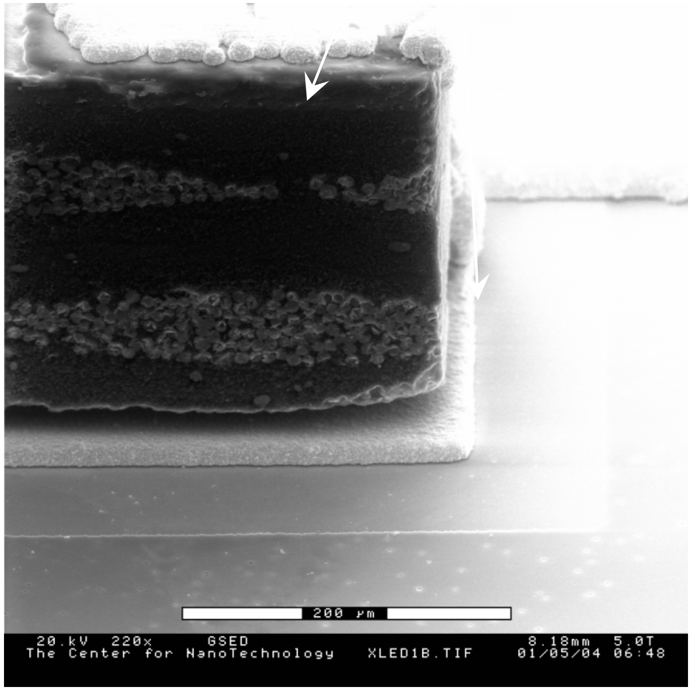


Electrical Connection by Electroplating

Gap between an assembled LED and substrate is ~ 20μm



Electrical connection established by plated solder

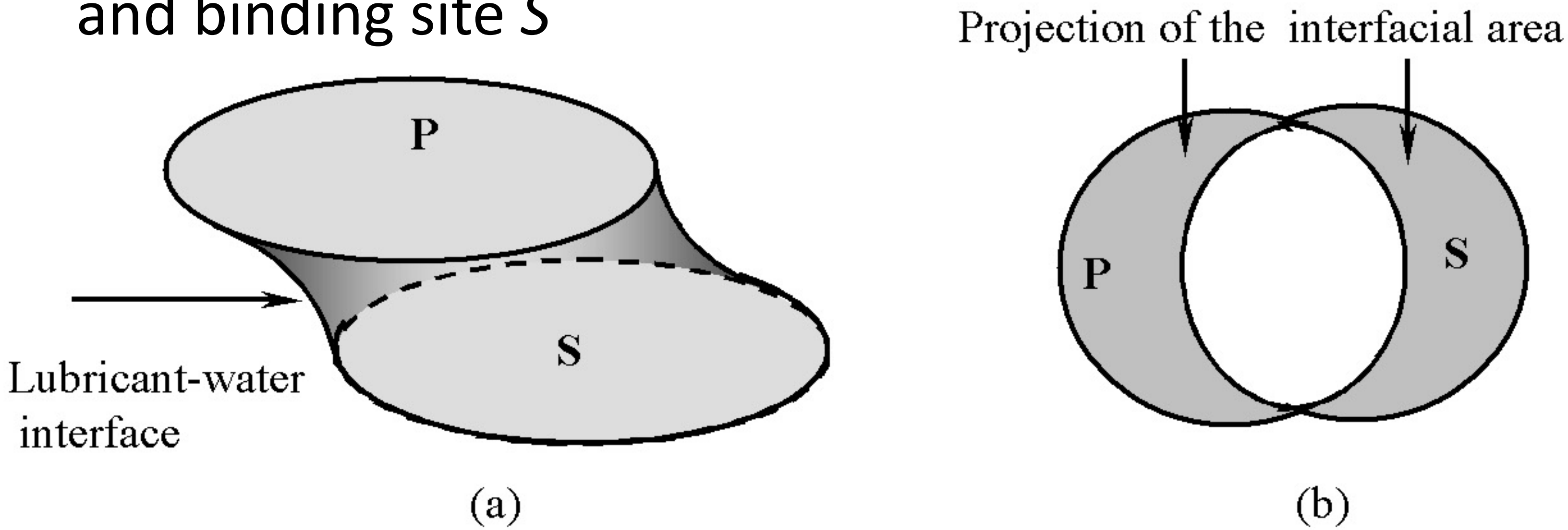


Self-assembled LED with Electrical Connections

[X. Xiong et al., *JMEMS* ’03]

Modeling the Binding Energy

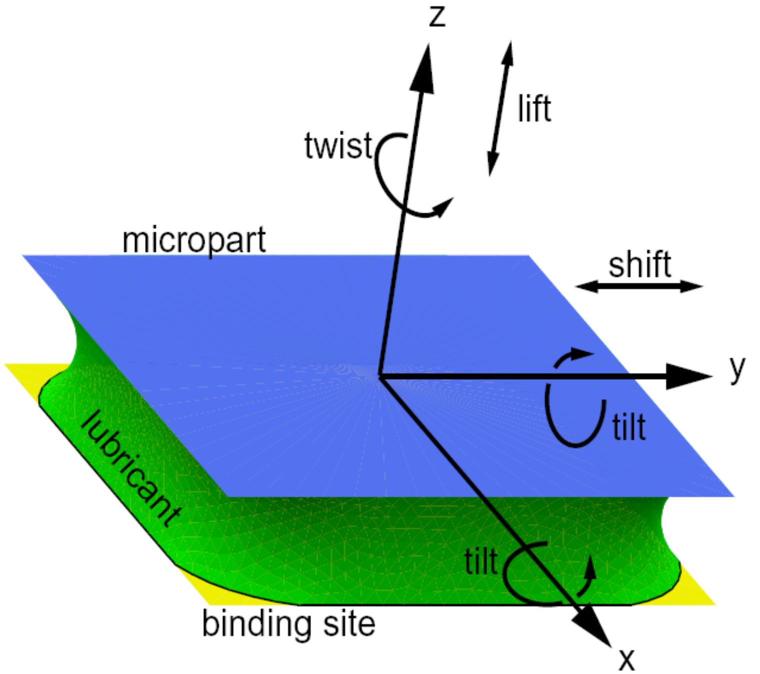
- Calculate the adhesive-water-interface between part *P* and binding site *S*

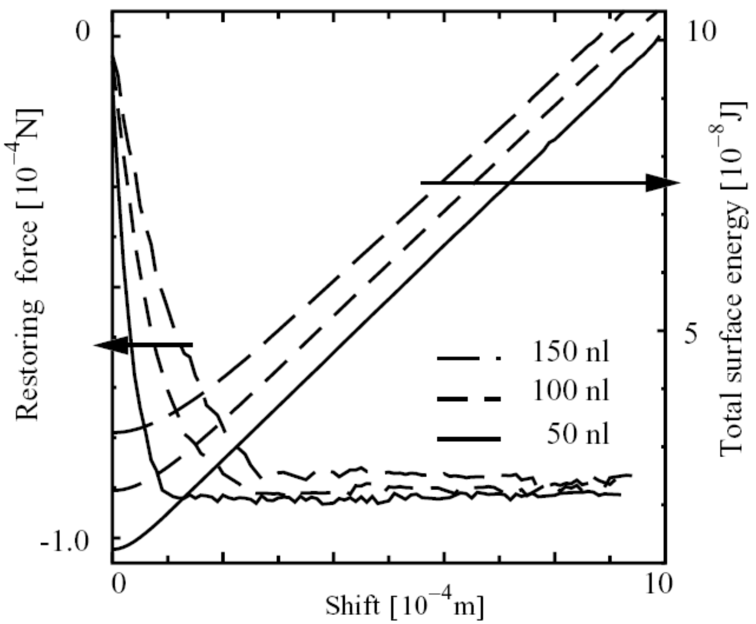


  - For small aspect ratios, interface can be approximated by partial shape overlap of *P* and *S*
  - Shape overlap easy to calculate analytically

Modeling the Binding Energy

FEM analysis [Lienemann et al., *Sensors Update* '03] shows linear relationship between displacement and surface energy when displacement > adhesive thickness





Shape Overlap Model

Use geometric shape overlap model to evaluate energy profile of binding sites

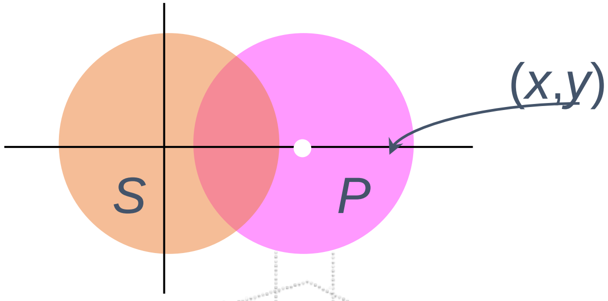
Efficient implementation:

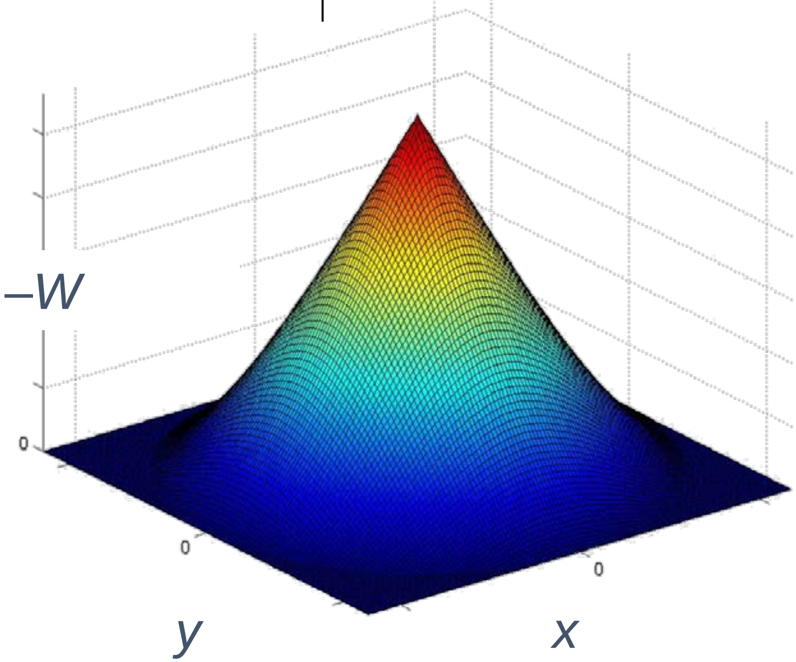
(1) digitize arbitrary binding site designs

(2) convolute areas

Physical motivation:

- adhesive forms bridge between sites
- projection of liquid: $S \cup P$
- projection of meniscus (if $S \cap P \neq \varnothing$):
  $A = |S-(S \cap P)| + |P-(S \cap P)|$
  $= |S| + |P| - 2|S \cap P|$
  $= \text{const} - 2|S \cap P|$
- surface energy: $\partial W \sim -\partial A \sim \partial|S \cap P|$

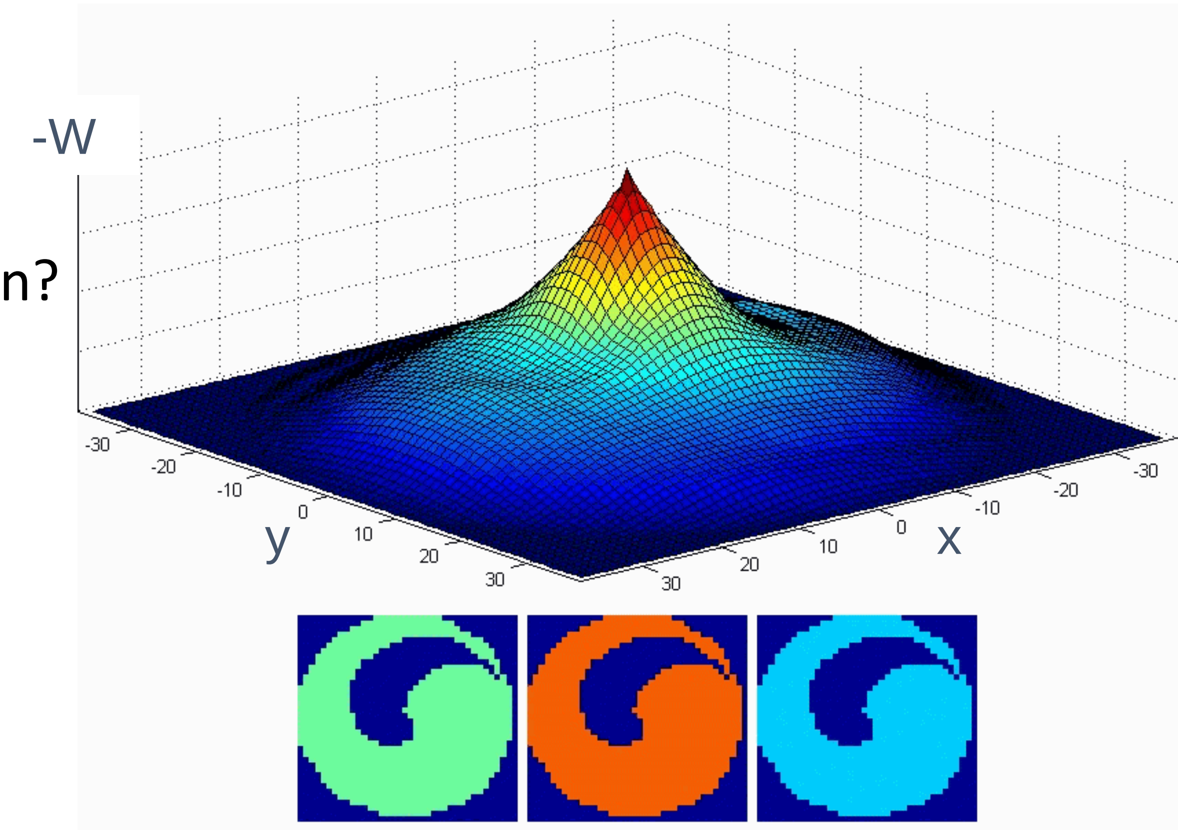




overlap area in C-space

Binding Site Design

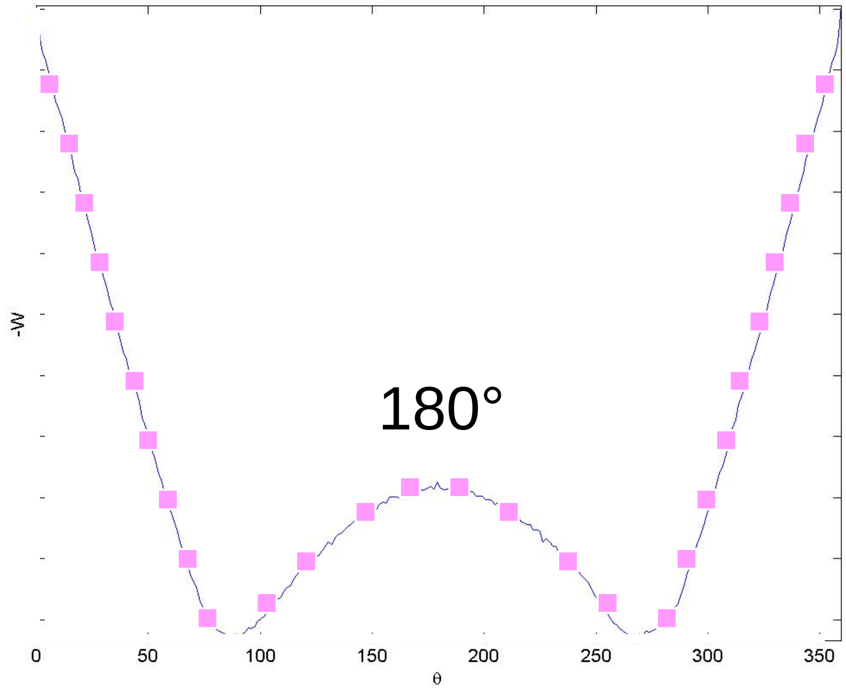
- Binding site shape optimization:
  (a) de-convolution?
  (b) Monte Carlo search, genetic algorithms for optimal binding site design?
- Uniqueness Problem:
  For a given part (e.g., a diode) does there exist a binding site design with unique energy minimum?



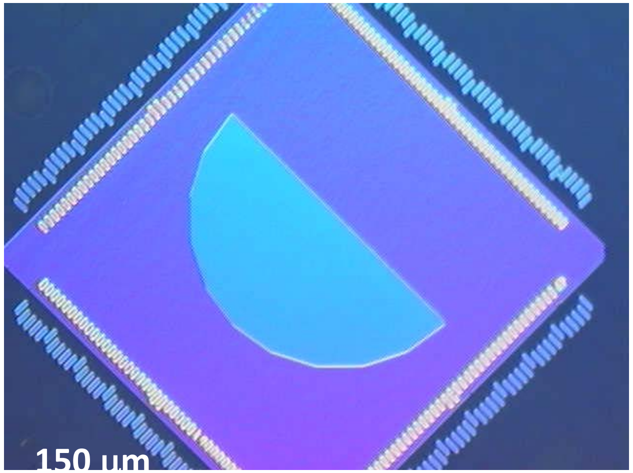
Semicircles

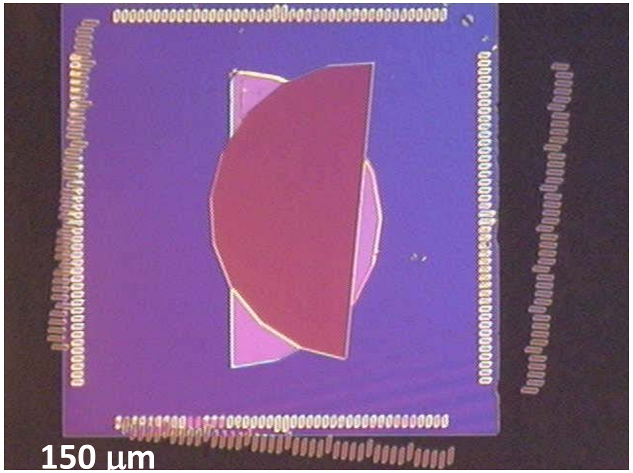
Unique orientation?

- ~40% alignment yield observed
- local energy minimum at 180°



overlap area vs. θ



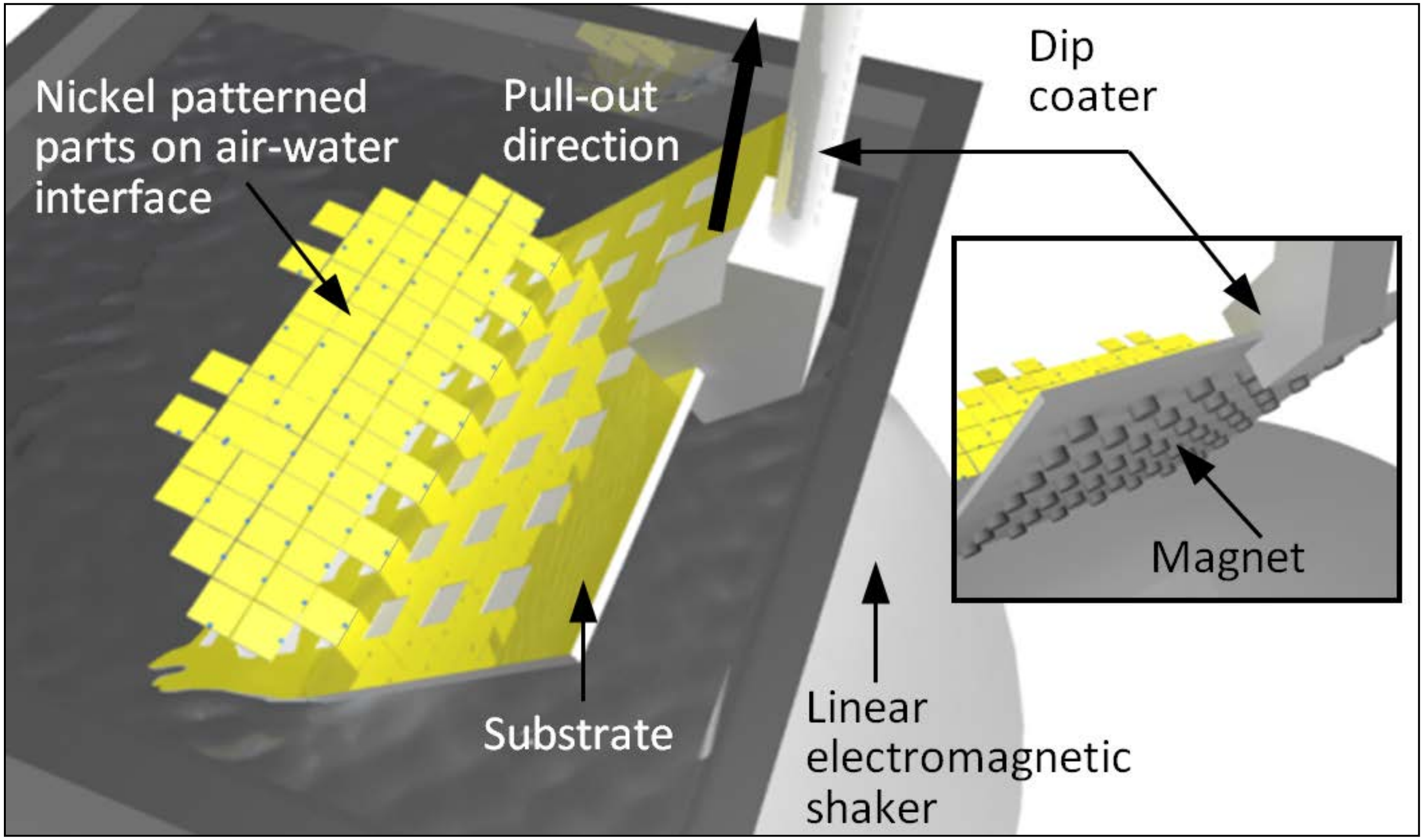


Non-unique energy minimum
(Microscope pictures: U. Srinivasan)

Self-assembly at the Air-Liquid-Water Interface

Continuous assembly on hydrophobic-hydrophilic substrates; unique orientation by magnetic force; applications: thin and fragile chips, large scale roll-to-roll assemblies.

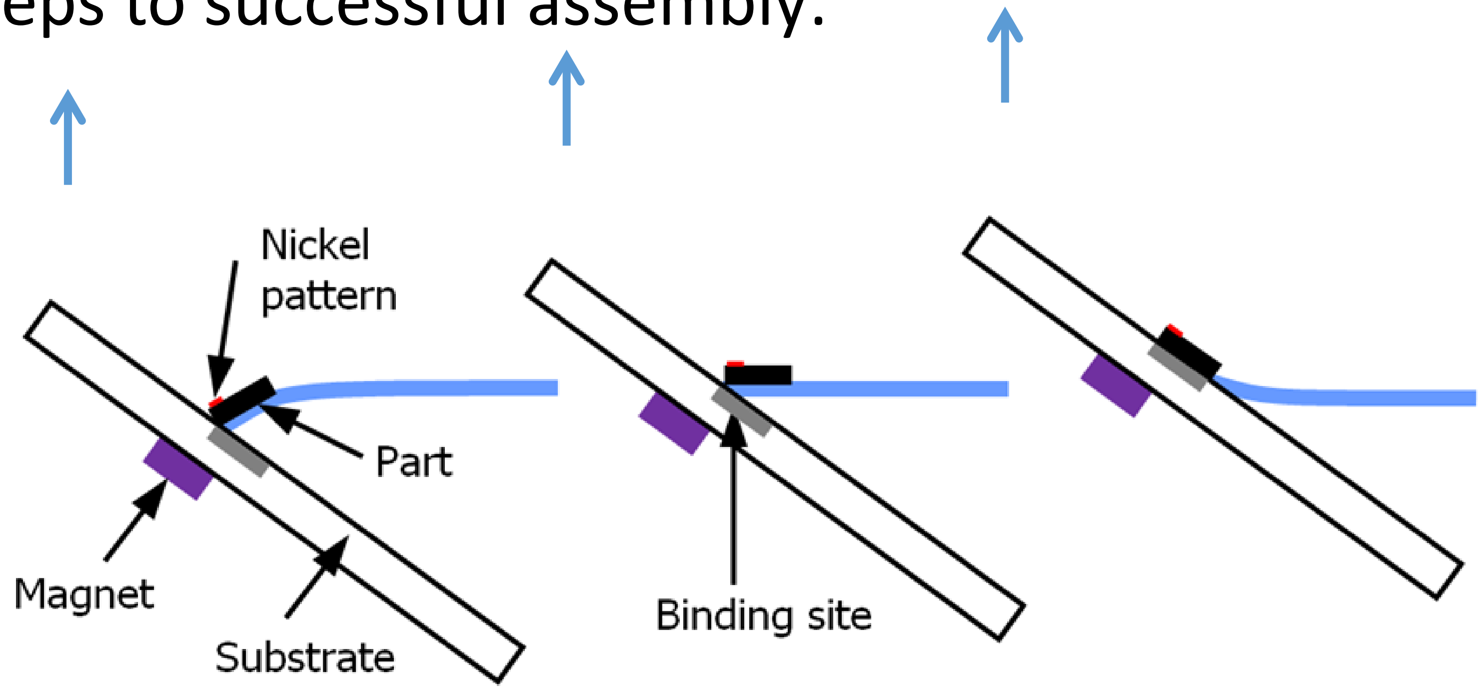
Fluidic Self-assembly at Air-water-solid Interface



Currently: Si substrate. Extendable to roll-to-roll processing. [Park *Transducers*'11]

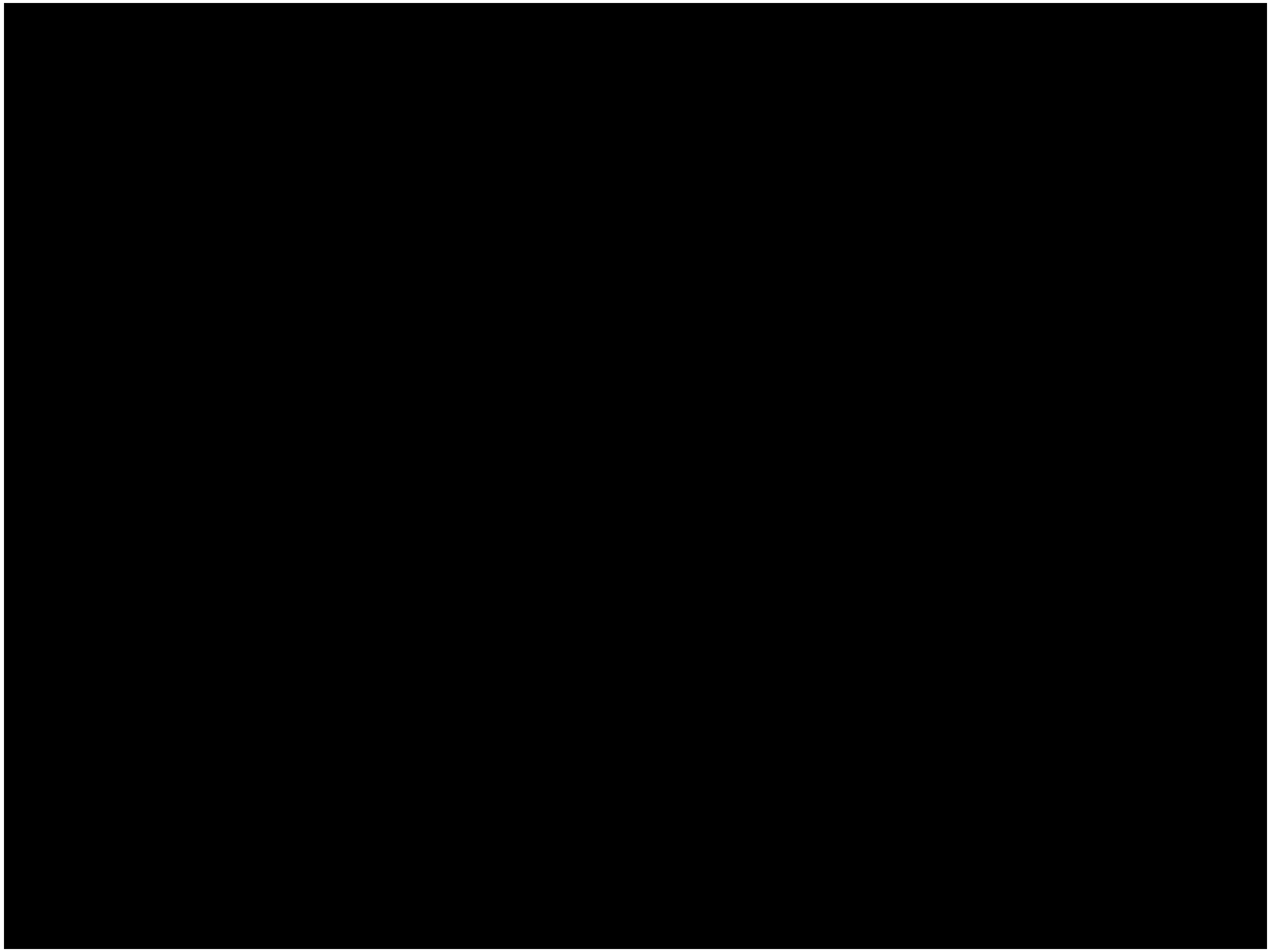
Fluidic Self-assembly at Air-water-solid Interface

Steps to successful assembly:



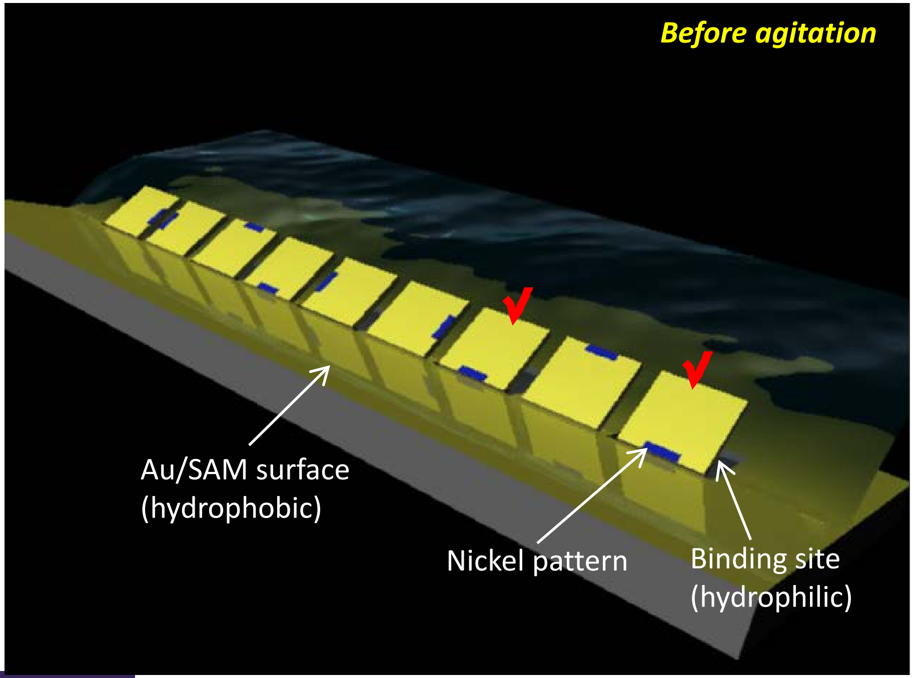
Nickel pattern provides unique orientation.

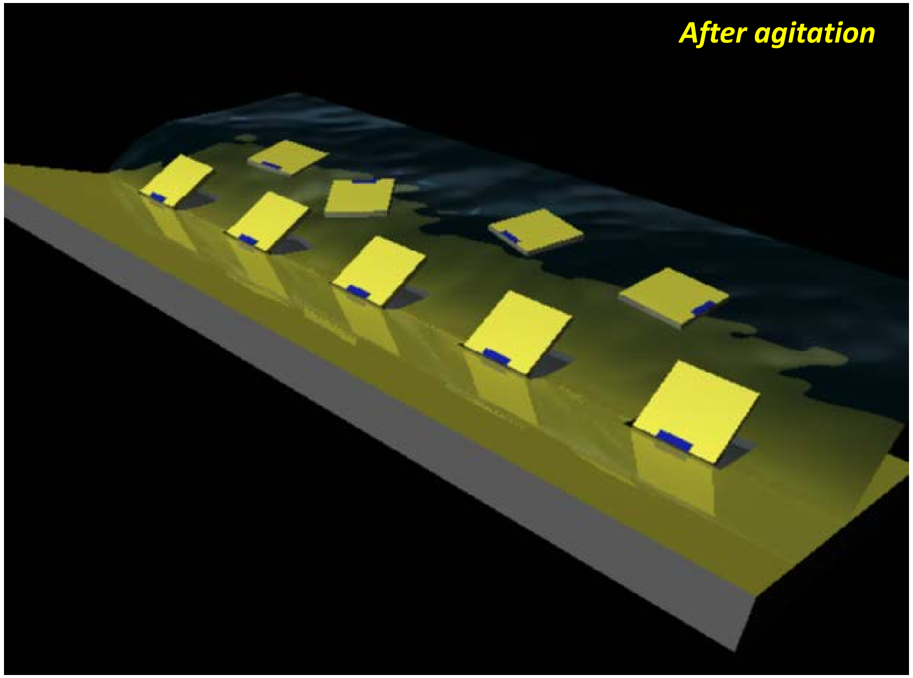
Fluidic Self-assembly at Air-water-solid Interface



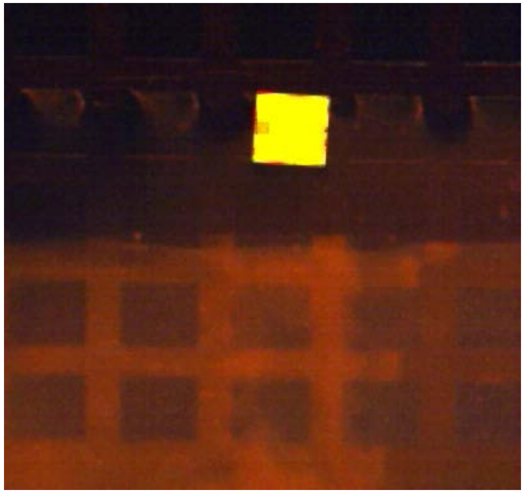
Fluidic Self-assembly at Air-water-solid Interface

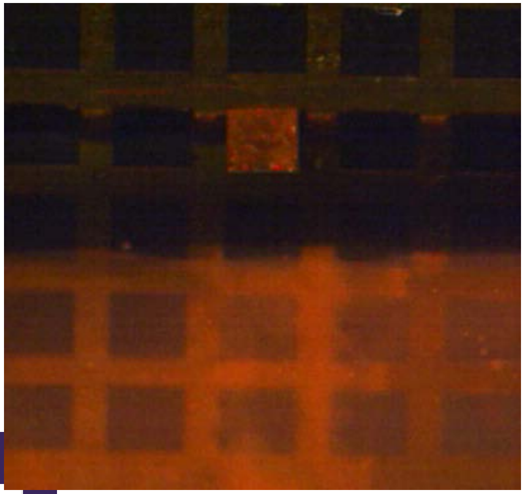
Agitation with Faraday waves breaks up incorrect assemblies:

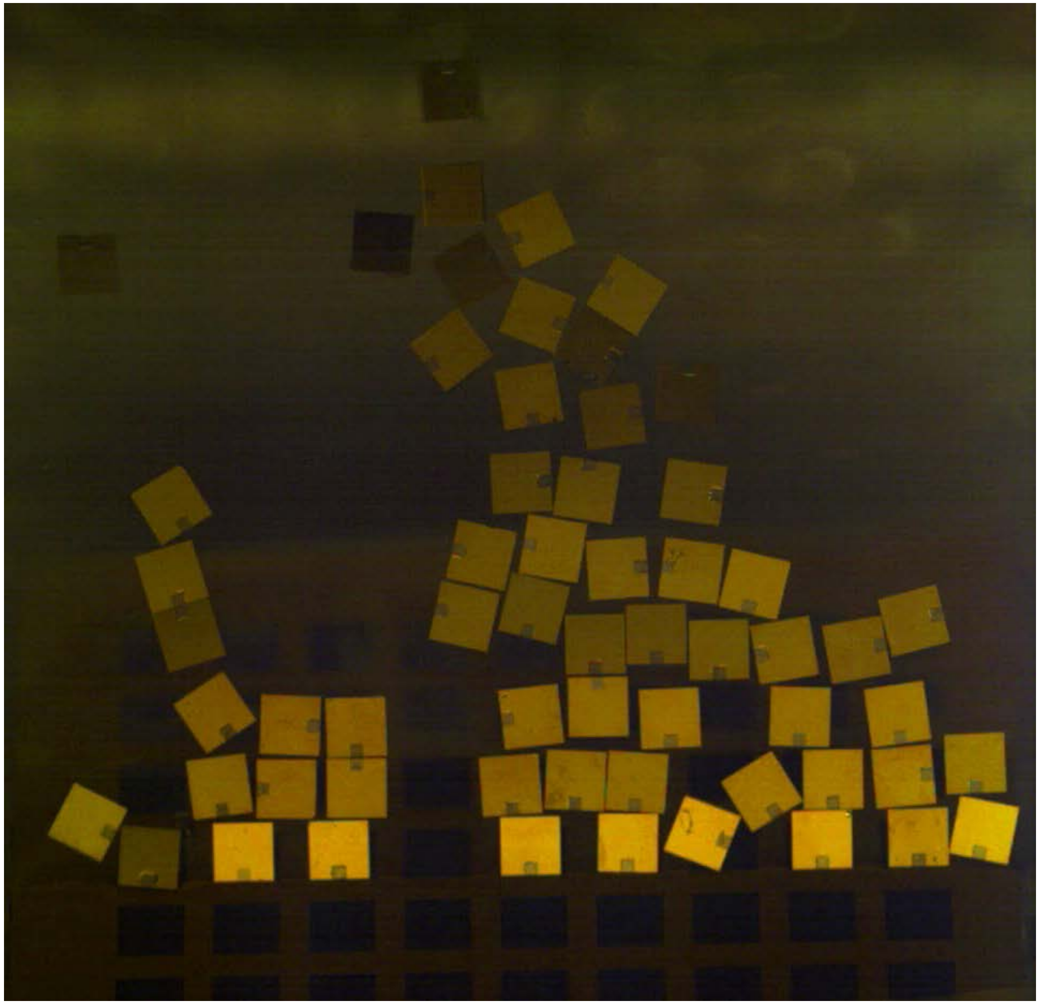




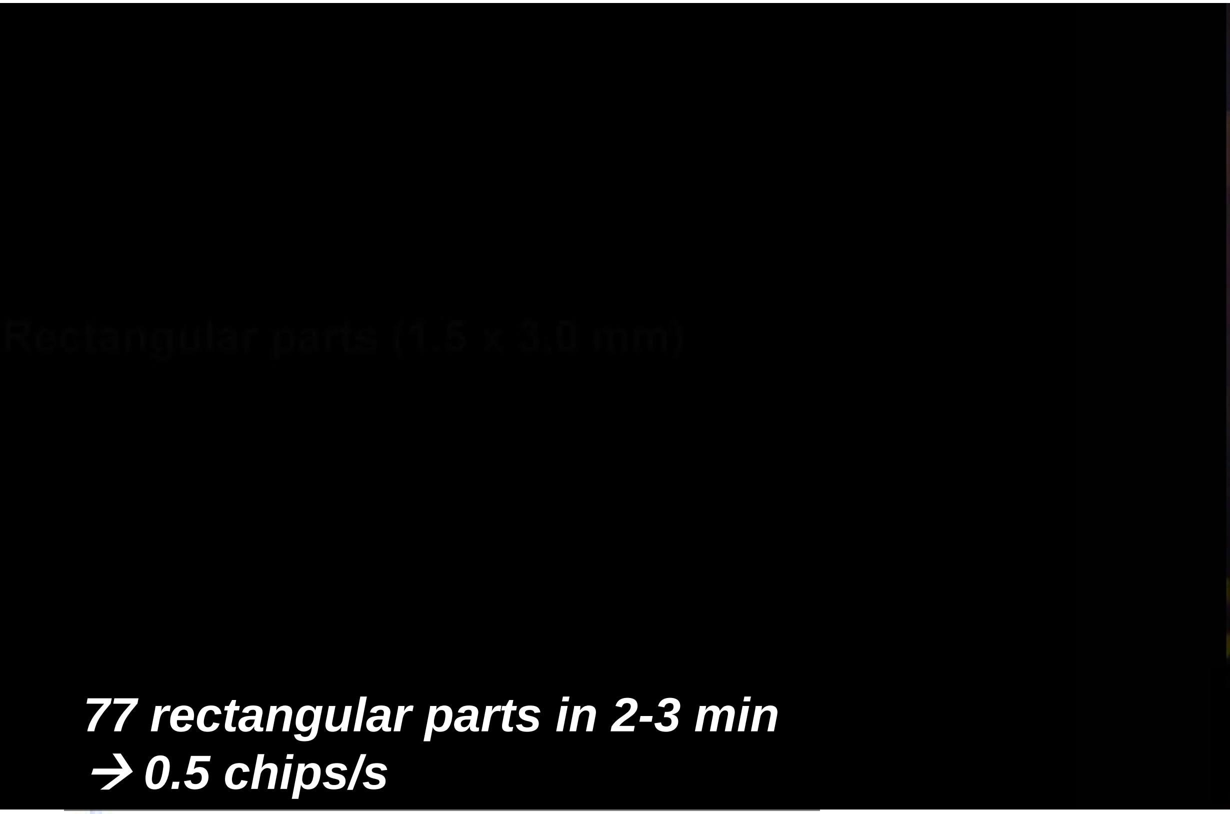
Fluidic Self-assembly at Air-water-solid Interface



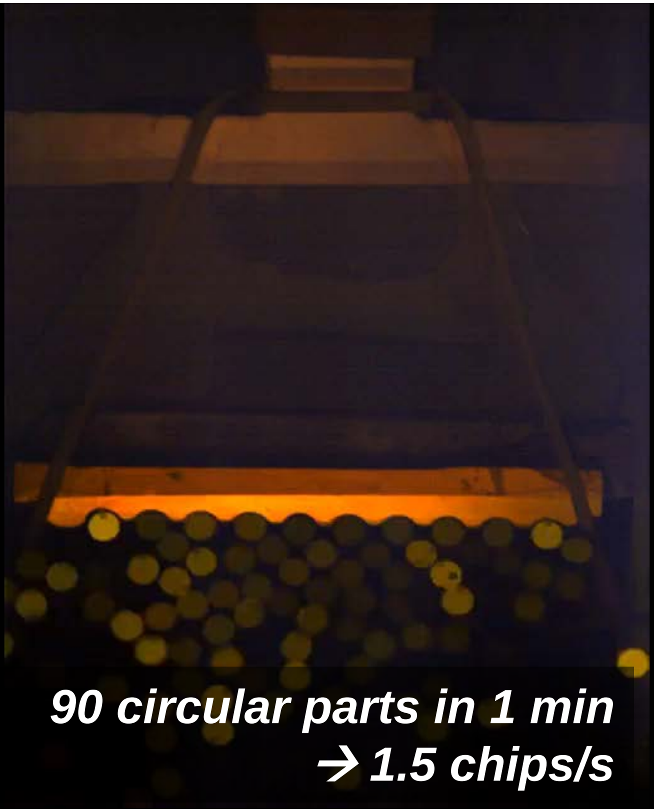




Assembling Thin Chips of Various Shapes



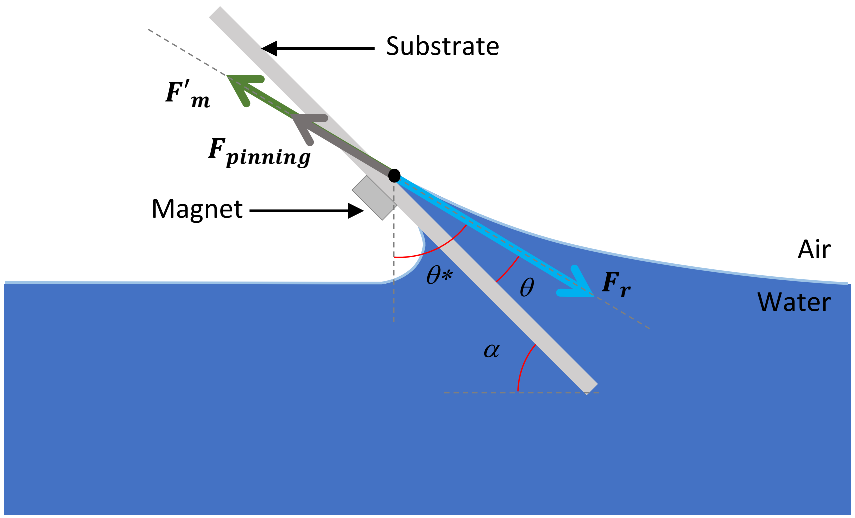
77 rectangular parts in 2-3 min
→ 0.5 chips/s



90 circular parts in 1 min
→ 1.5 chips/s

Today's pick-and-place machines with 6 to 20 individual robots (example: Assembléon's A-Series)
- **Assembly speed: up to 1.5 chips/s per robot**
- Component range : 0.4 x 0.2 mm (01005) to 45 x 45 mm

Modeling of Assembly Forces



F'_m magnetic force
F_r gravity
(tangential components)

Condition for assembly:

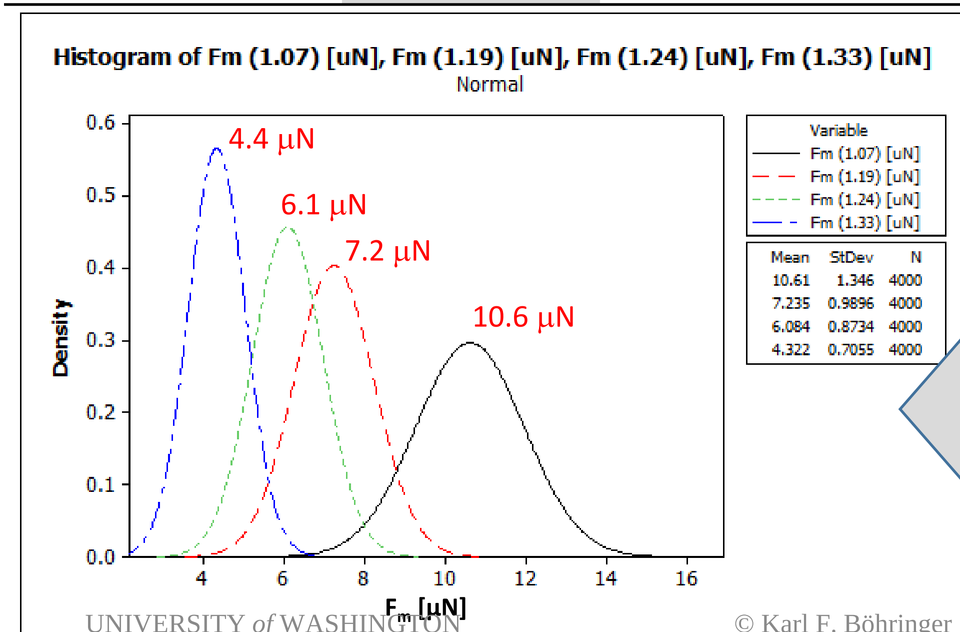
$$\boldsymbol{F_{net} = F'_m + F_{pinning} - F_r > 0}$$

Design choices influence yield, i.e. system parameters determine performance parameters.

Analysis of Experiments

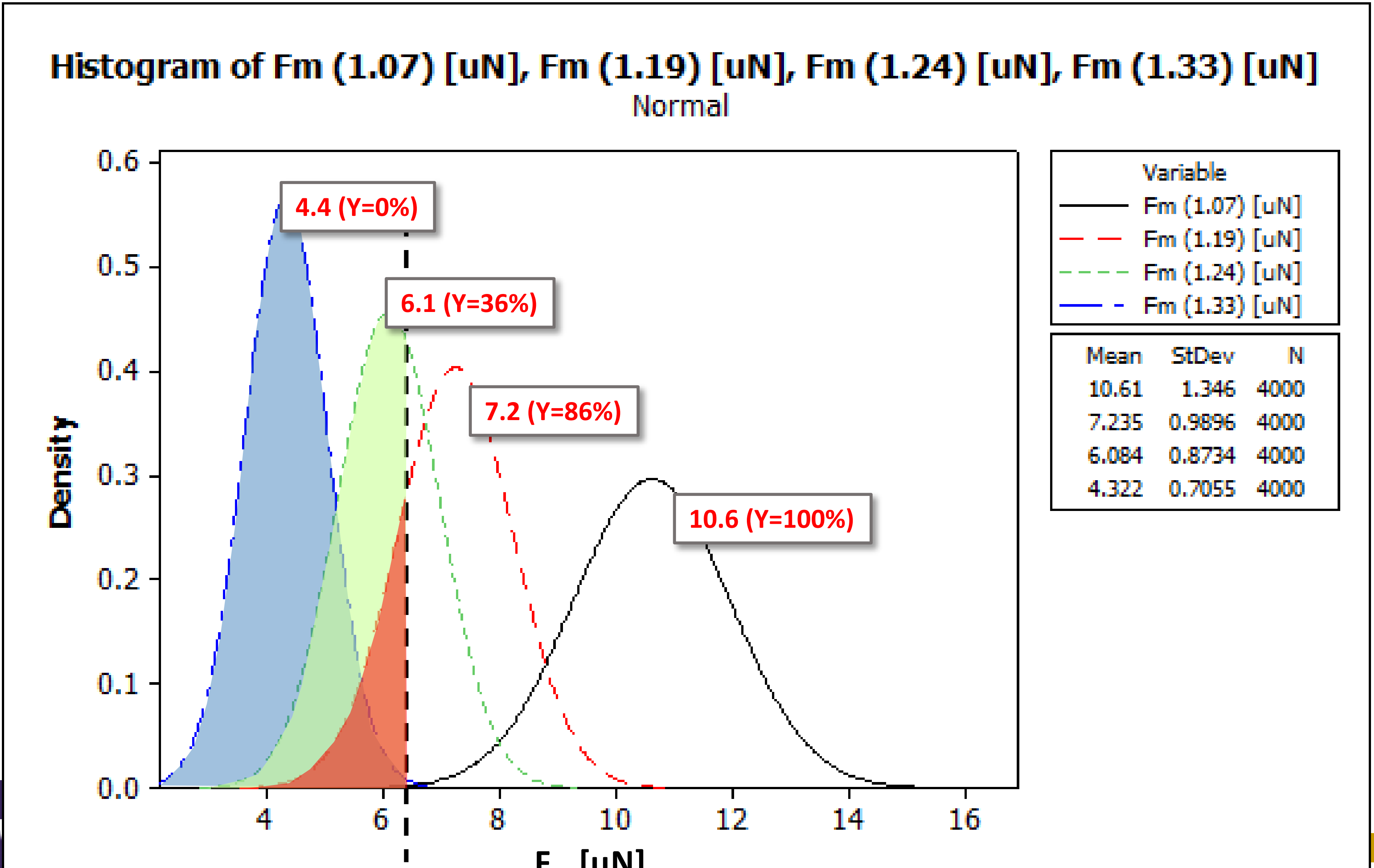
Gap [mm]	Yield		F_m [µN] (Simulation)	
	Experiment	(Simulation)		
0.87	100%	(30/30)	20.3	(12.7-27.9)
1.07	90%	(30/30)	10.6	(6.5-14.6)
1.19	67%	(27/30)	7.2	(4.2-10.1)
1.24	37%	(11/30)	6.1	(3.4-8.7)
1.33	0%	(0/30)	4.4	(2.3-6.4)

(±3 sigma)



- measurement error
- alignment error using Monte-Carlo simulation

Analysis of Experiments



Analysis of Experiments

Gap [mm]	Yield: Experiment	Yield: (Simulation)	Yield: Predicted	F_m [µN] (Simulation)	
0.87	100%	(30/30)	100%	20.3	(12.7-27.9)
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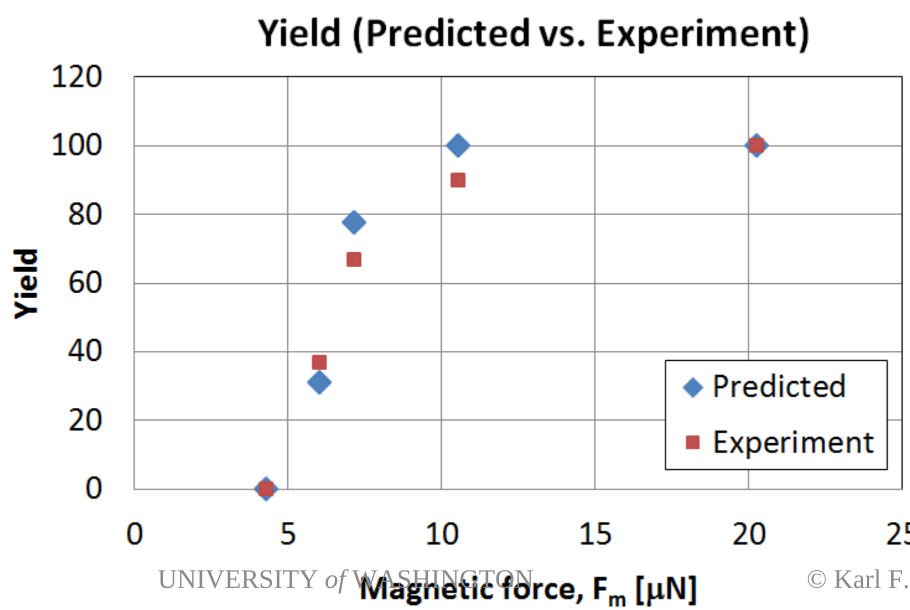
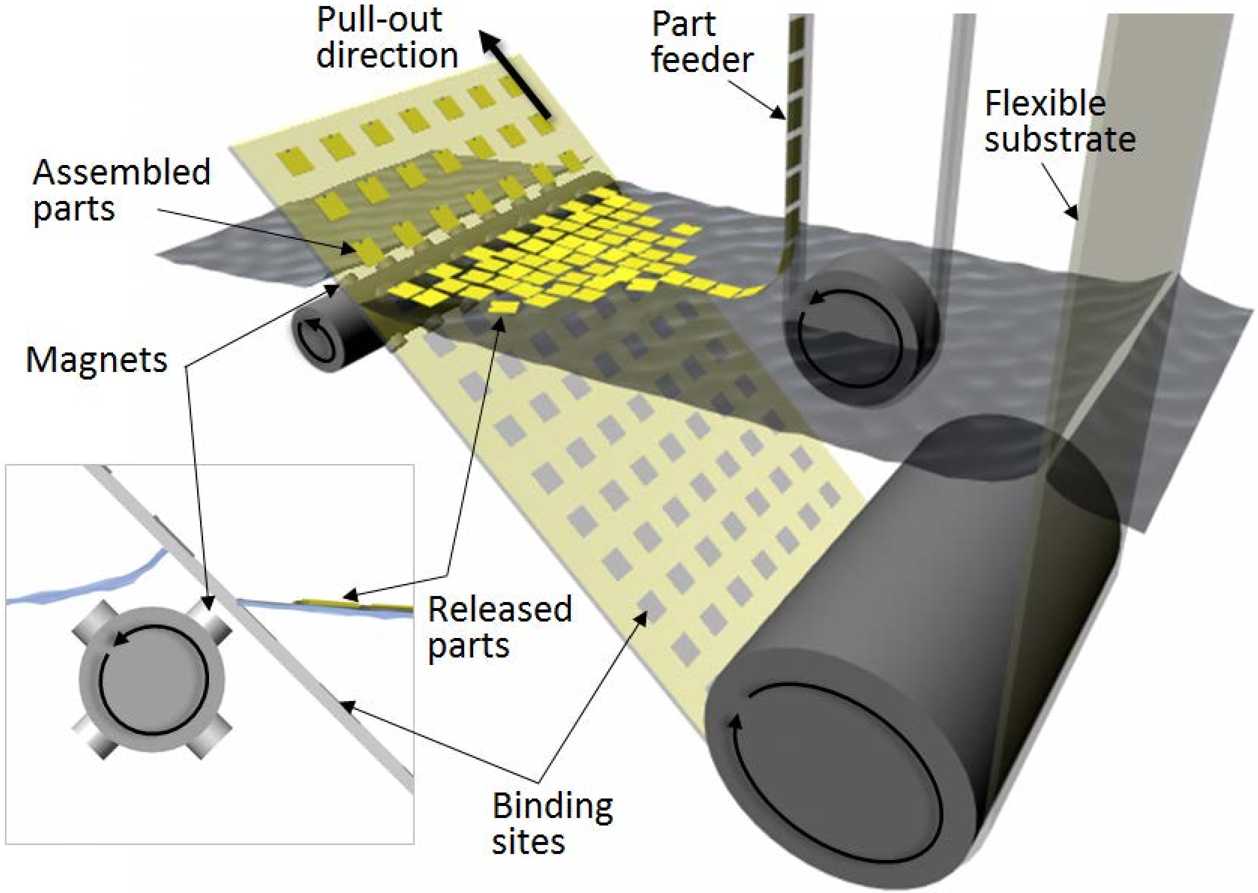
1.19	67%	(27/30)	86%	7.2	(4.2-10.1)
1.24	37%	(11/30)	36%	6.1	(3.4-8.7)
1.33	0%	(0/30)	0%	4.4	(2.3-6.4)



Critical F_m from statistical analysis of experimental results: 6.4 µN

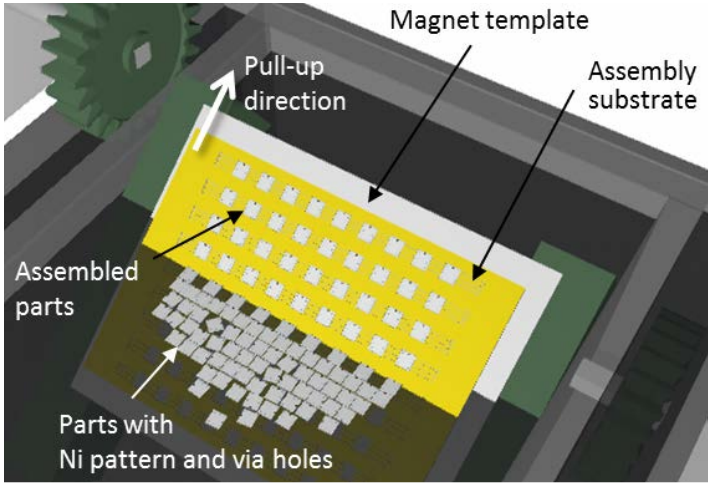
(RMS error = 11%, Max. error = 17%)

Roll-to-Roll Assembly

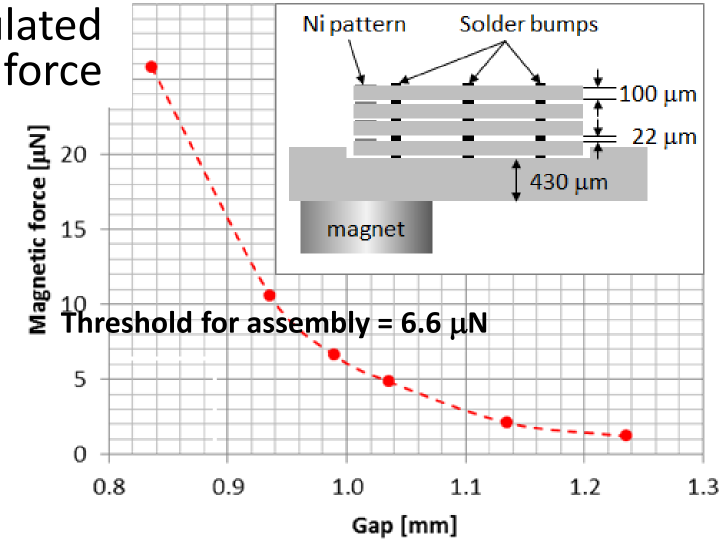


3D Integration Using Self-assembly at Air-water-solid Interface

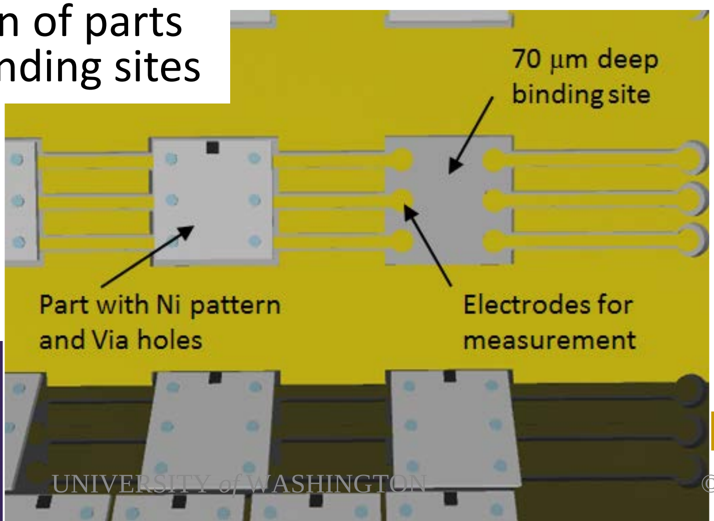
Experimental setup



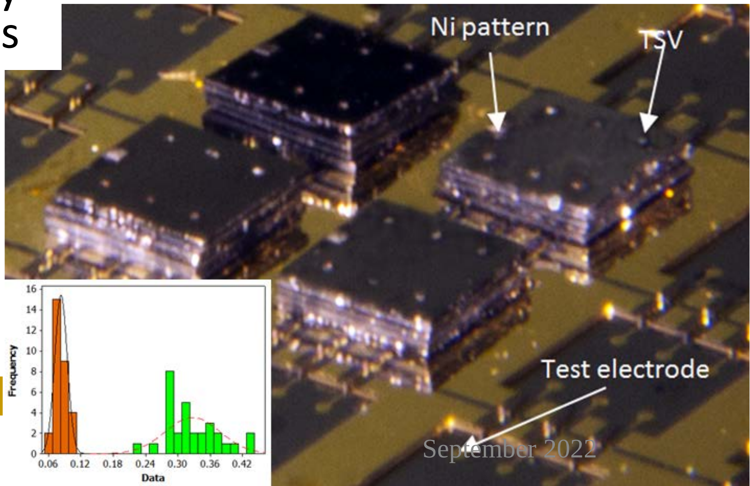
Simulated magnetic force



Design of parts and binding sites



Assembly results



3D Tilting and Folding

- Assembly at air-water interface
- Magnetically controlled tilting and folding of components
- Solder reflow

- [Transducers '13]