Self-assembly from Nano to Milli Scales

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Nanoscience & Molecular Engineering
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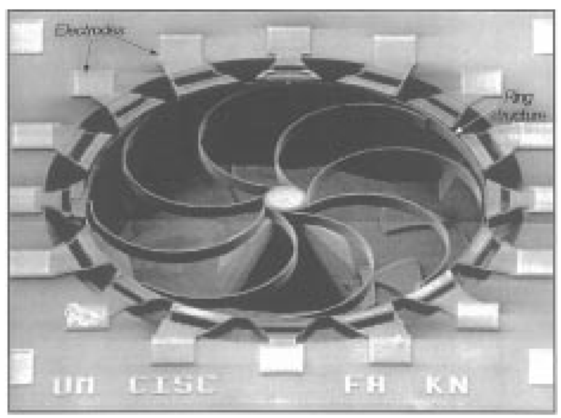
UNIVERSITY OF WASHINGTON

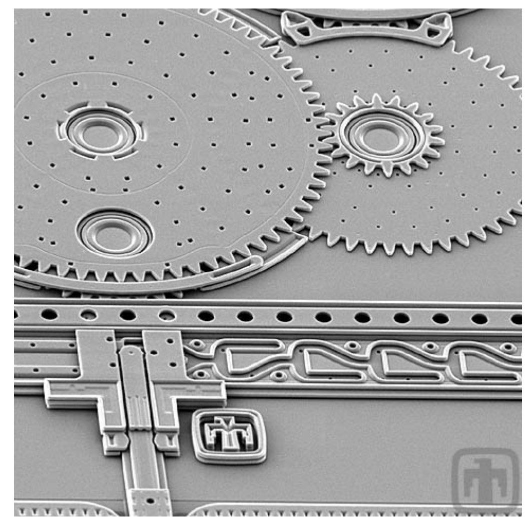
Introduction

- Micro Electro Mechanical Systems (MEMS):
  - Sub-millimeter sized machines typically built in batch fabrication processes derived from integrated circuit (IC) technology
  - Can have broad functionality, including sensing, actuation, computation, and communication

MEMS Scanning Tunneling Microscope [Xu et al. APS'95]



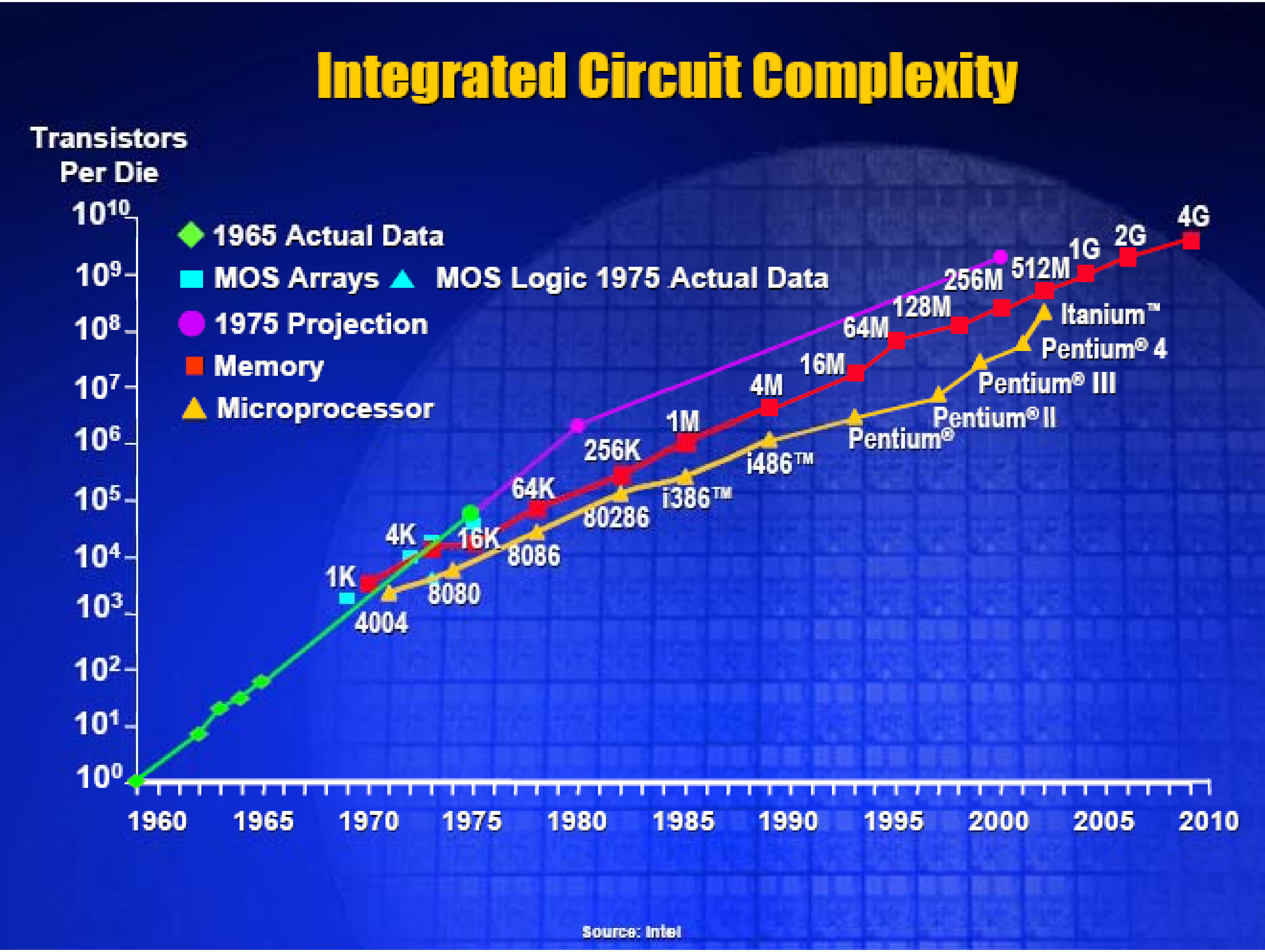
Vibrating ring gyro [Ayazi et al. IEEE MEMS'98]



Micro combination lock [Sandia National Labs]

Introduction

- Micro Electro Mechanical Systems (MEMS):
  - Sub-millimeter sized machines typically built in batch fabrication processes derived from integrated circuit (IC) technology
  - Can have broad functionality, including sensing, actuation, computation, and communication
- Claim:
  - Just like IC's have revolutionized computation, MEMS are revolutionizing sensors and actuators (transducers)
- Challenge:
  - Unlike IC's, MEMS rely on a much broader range of materials, processes, and effects to achieve their optimal functionality



Integrated Circuit Complexity
Transistors Per Die
1965 Actual Data
MOS Arrays
MOS Logic 1975 Actual Data
1975 Projection
Memory
Microprocessor
1K
4K
16K
64K
256K
1M
4M
16M
64M
128M
256M
512M
1G
2G
4G
4004
8080
8086
80286
i386™
i486™
Pentium®
Pentium® II
Pentium® III
Pentium® 4
Itanium™
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Intel

Motivation

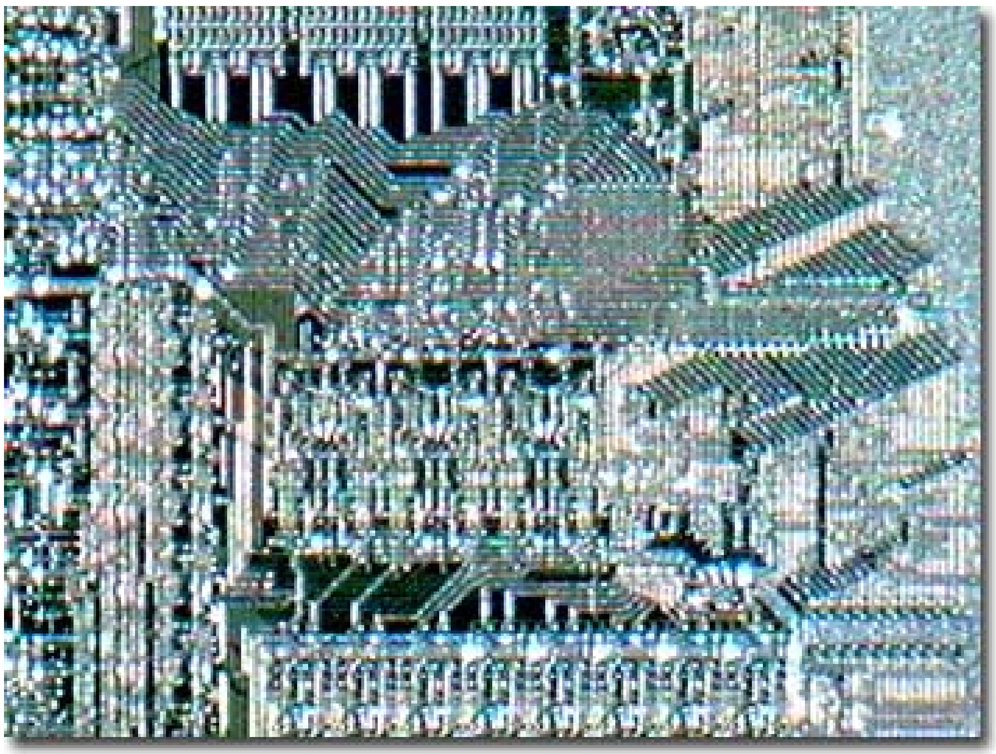
Background:

- Since the 1960's, integrated circuits (ICs) have been growing in complexity by about a factor of two every two years ("Moore's Law").
- Since the 1980's, IC technology has increasingly been adapted to build micro sensors and actuators.

Question:

- How does design methodology and manufacturing technology adapt to this increasing complexity and diversity?

Circuit City



Integrated circuit,
microscopic view

City landscape,
macroscopic view

Top-down and Bottom-up

Integrated circuits:

- "Top-down" centralized design
- Monolithic batch fabrication

Heterogeneous microsystems:

- Separate design & fabrication of functional units
- Precision assembly and customized packaging

City:

- Decentralized planning and construction
- "Bottom-up" guided growth

Growth and Self-assembly

- Growth processes (crystals, organisms, cities, etc.) tend to be
  - distributed
  - massively parallel
  - stochastic
  - guided by a utility function

- Can we apply this approach to microsystems?
  → Self-assembly (from nano to milli scales)

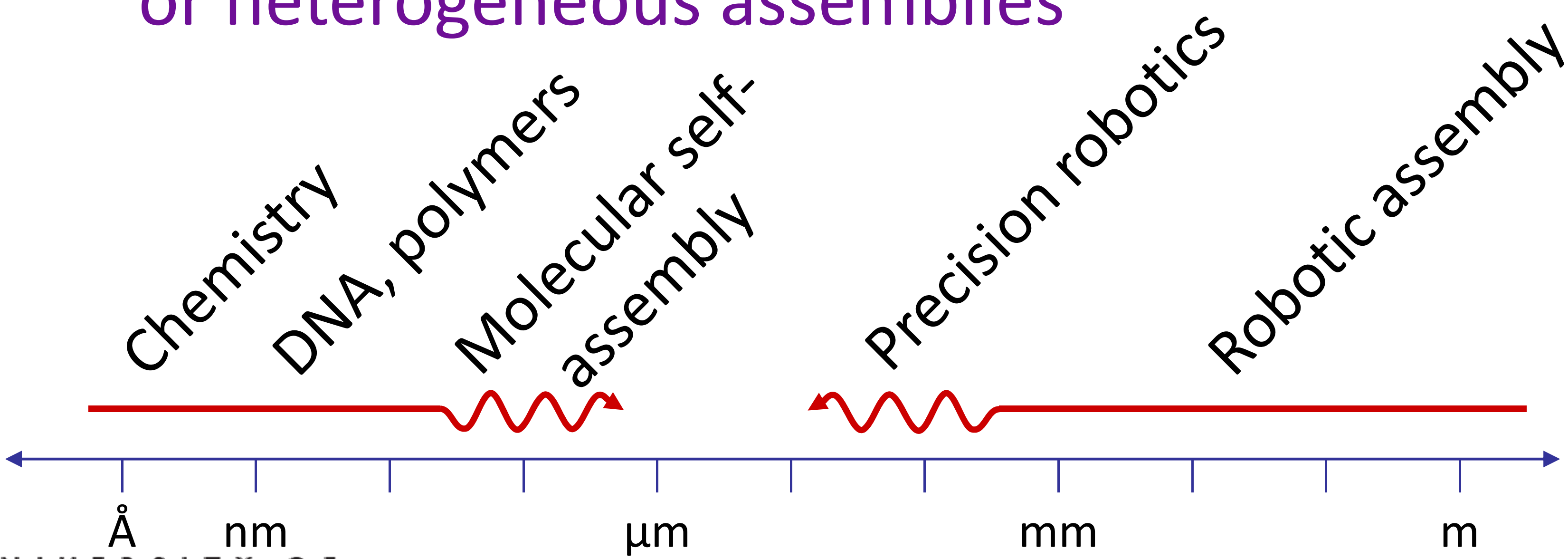
Definition

<u>Self-assembly:</u>

The autonomous and spontaneous organization of components into patterns or structures.

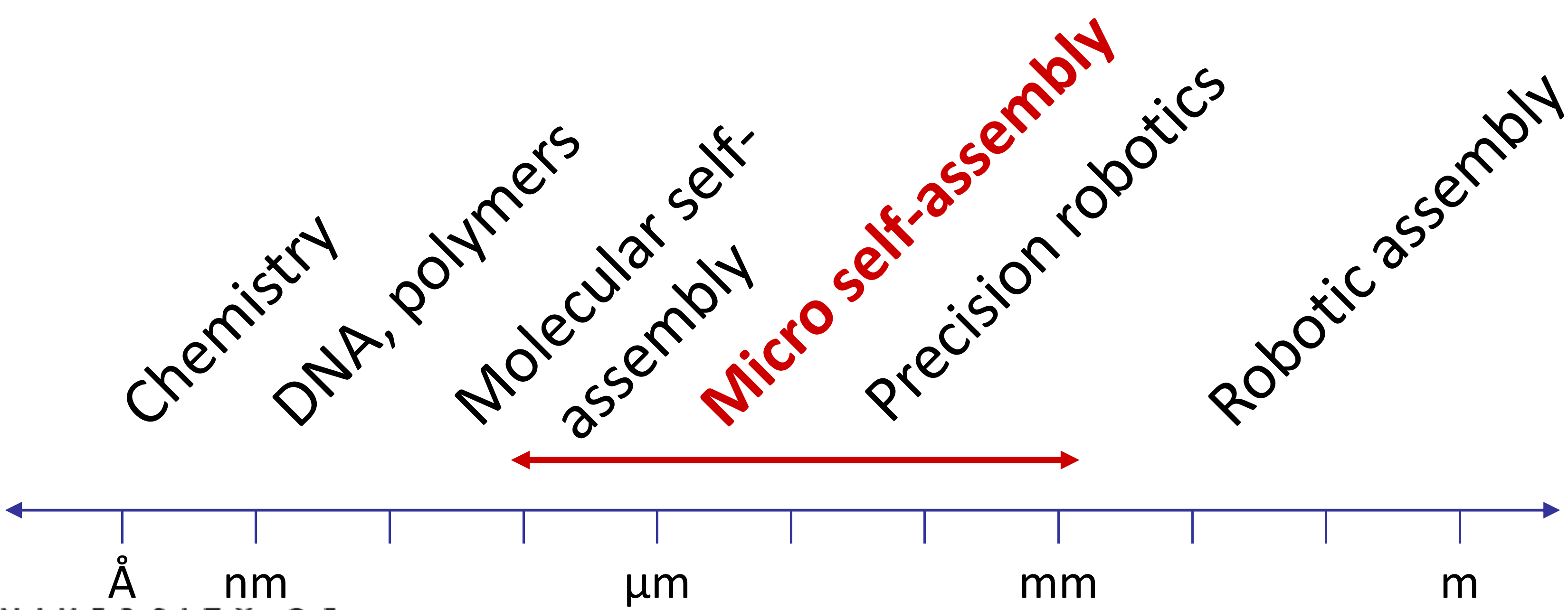
Self-assembly Across Scales

- Currently, "no-man's-land" for engineered assembly in the micrometer range
  - Conventional robots get very expensive
  - Chemical synthesis cannot produce non-periodic or heterogeneous assemblies



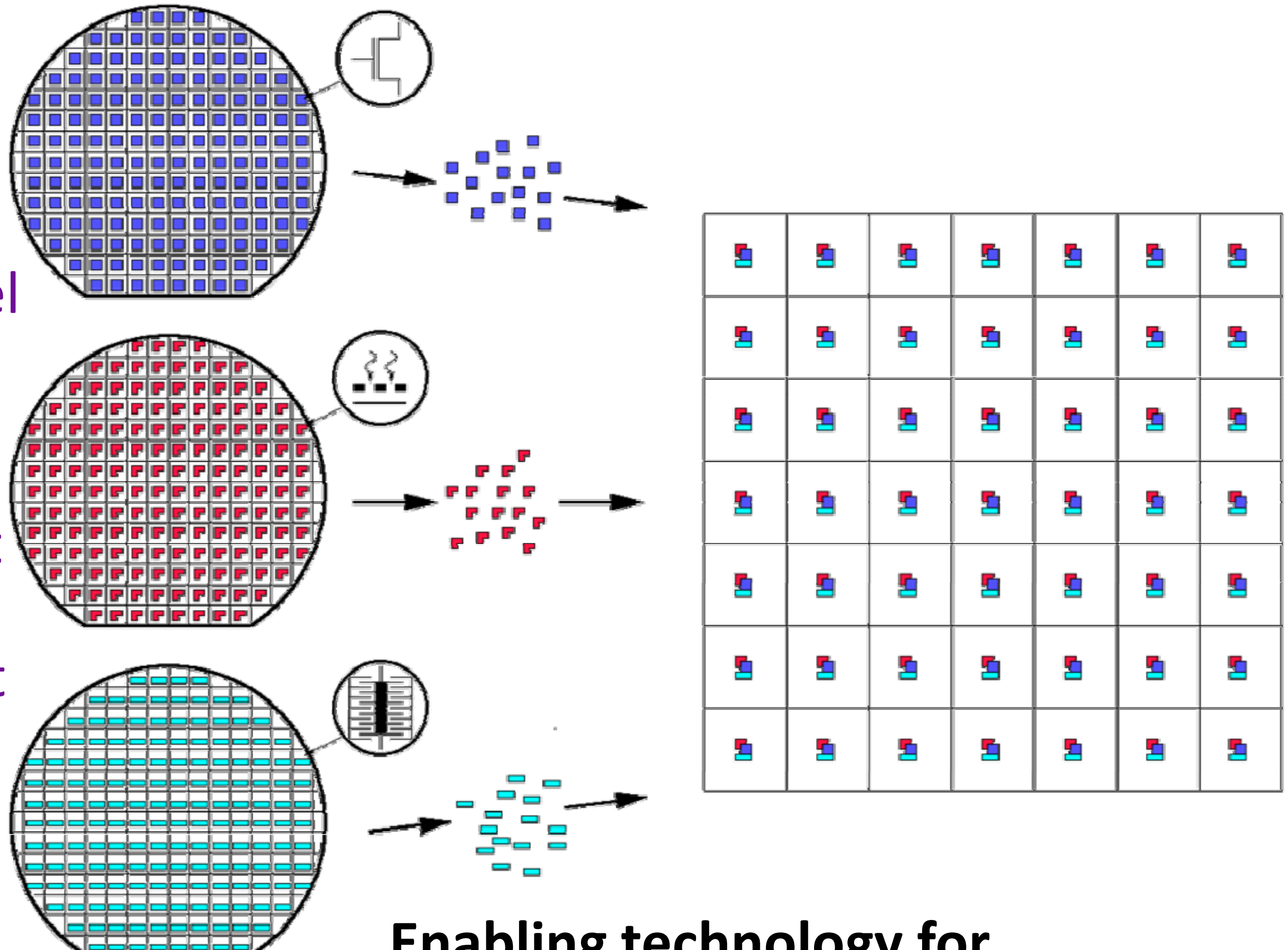
Self-assembly Across Scales

- Goals:
  - High volume, flexible manufacturing
  - Complex heterogeneous microsystem integration



Micro Self-assembly

- Very large numbers of very small components
- Independent parallel fabrication of components
- Fabrication at high density, assembly at lower density
- Hybrid systems built from standard components



Enabling technology for complex integrated microsystems

Programmed Self-assembly

Self-assembly:

autonomous and spontaneous organization of components into patterns or structures

- **Programmed self-assembly:**
  self-assembly process with (spatial and temporal) control over binding mechanisms
  – resulting structures can be adjusted on demand
  – analogies: flexible robotic assembly; protein synthesis

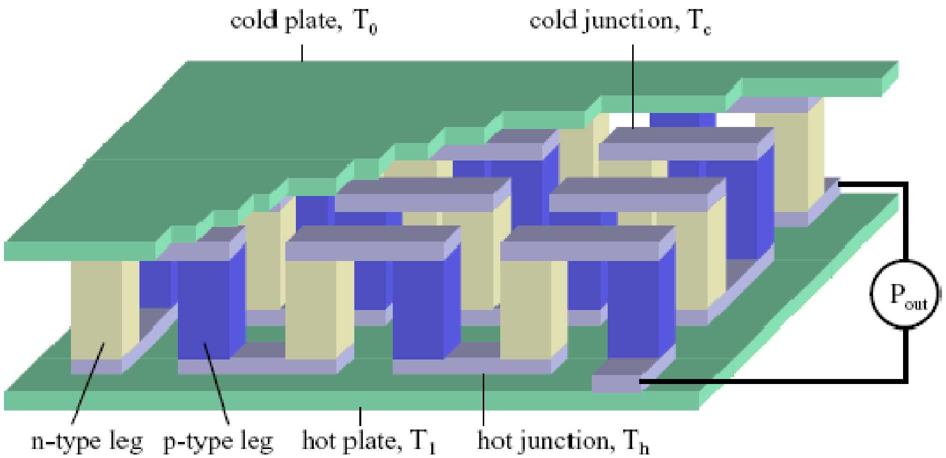
Programmable Surface

- **An object whose surface properties can be controlled with good spatial and temporal resolution**
- **Crucial for programmed self-assembly**
- **Surface properties:**
  - Friction
  - Surface forces
  - Hydrophobicity (surface tension, contact angle)
  - Biological properties (e.g., adhesion of proteins)
  - Optical properties (color, transmission of light)
  - …

Goals / Applications

1. Thermoelectric cooling of hot spots

   Assembly of p/n materials in checkerboard pattern



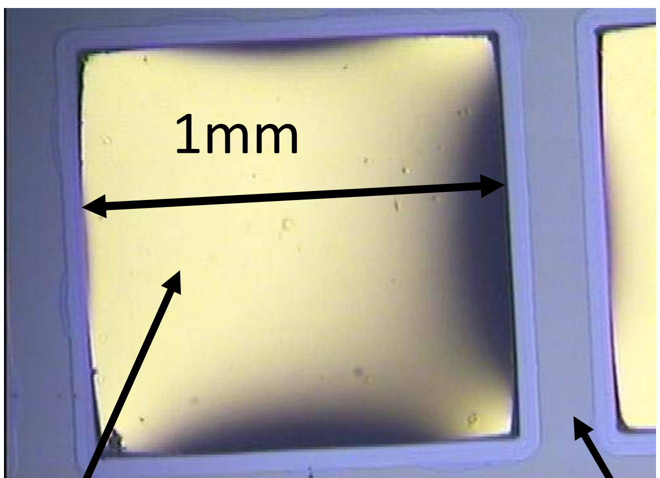
2. Extreme aspect ratio components

   Tens of μm thin, mm's or cm's side length

Ongoing joint work with Intel Corp. / DARPA

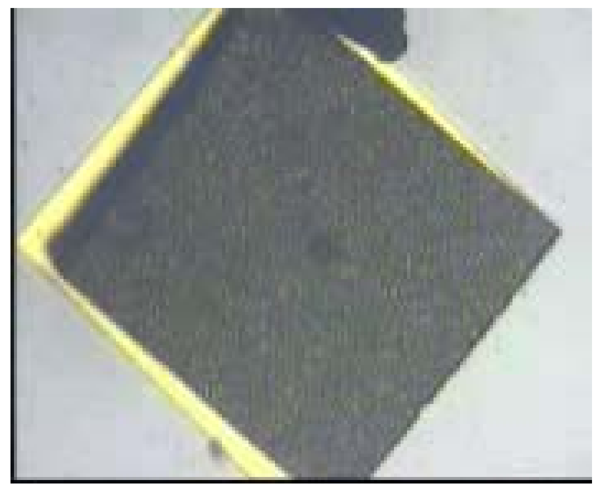
Surface Tension Driven Self-assembly

- 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

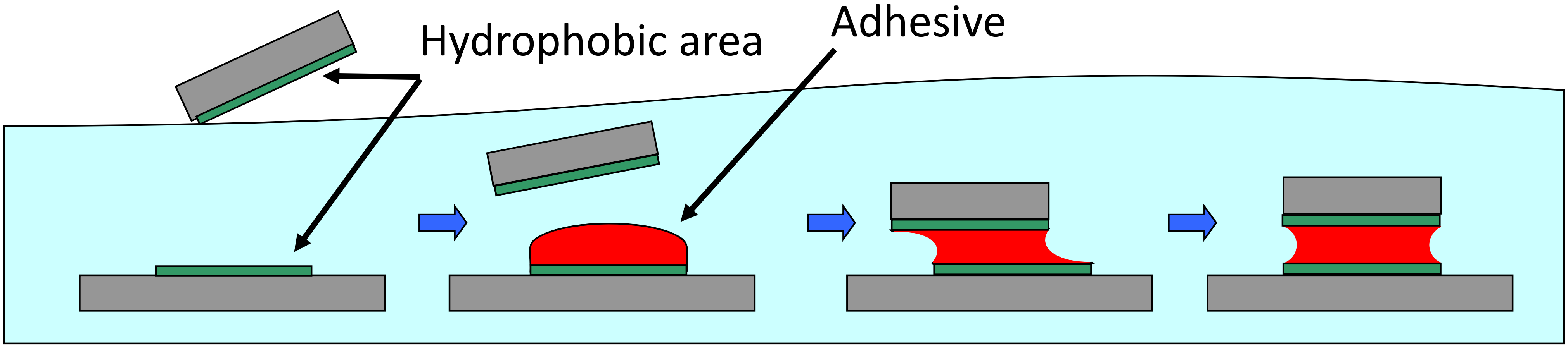


Video: X. Xiong ‘00

Surface Tension Driven Self-assembly

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

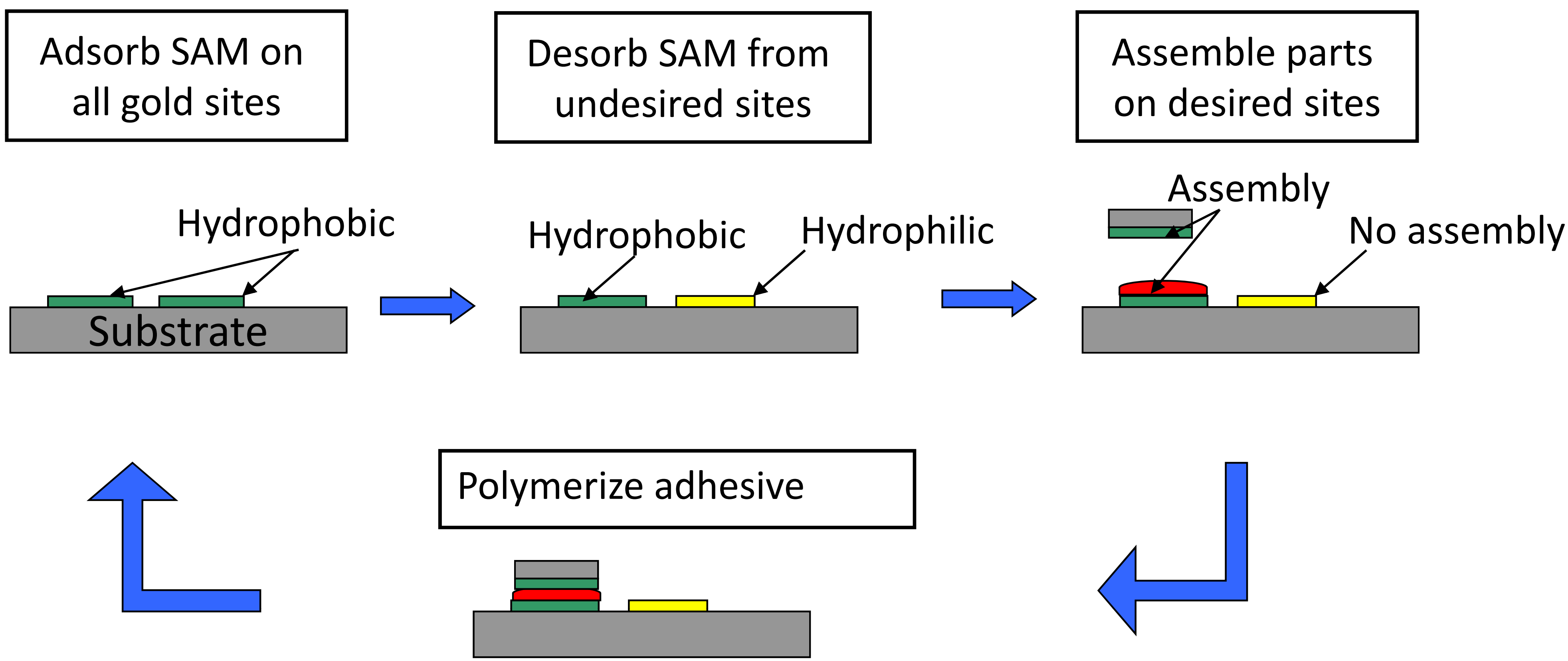
- Alkanethiol self-assembled monolayer (SAM) on Au forms hydrophobic surface
- Organic lubricant adhesive



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

Programmable Self-assembly

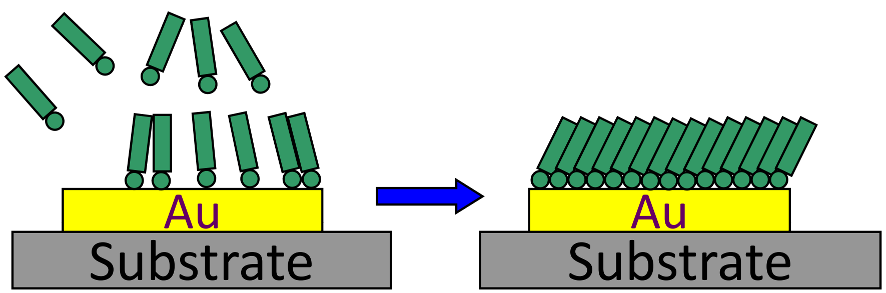
Organization of **different** parts onto desired locations



Modulation of Surface Energies

Hydrophilic → Hydrophobic

Adsorption of alkanethiol SAM

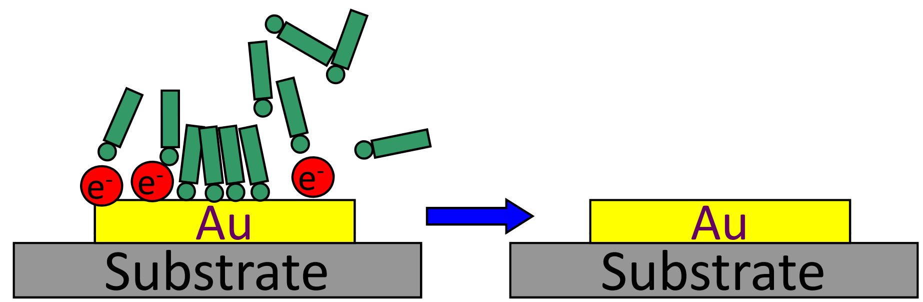


Adsorption is accomplished by soaking surfaces in ethanolic alkanethiol solution.

Hydrophobic → Hydrophilic

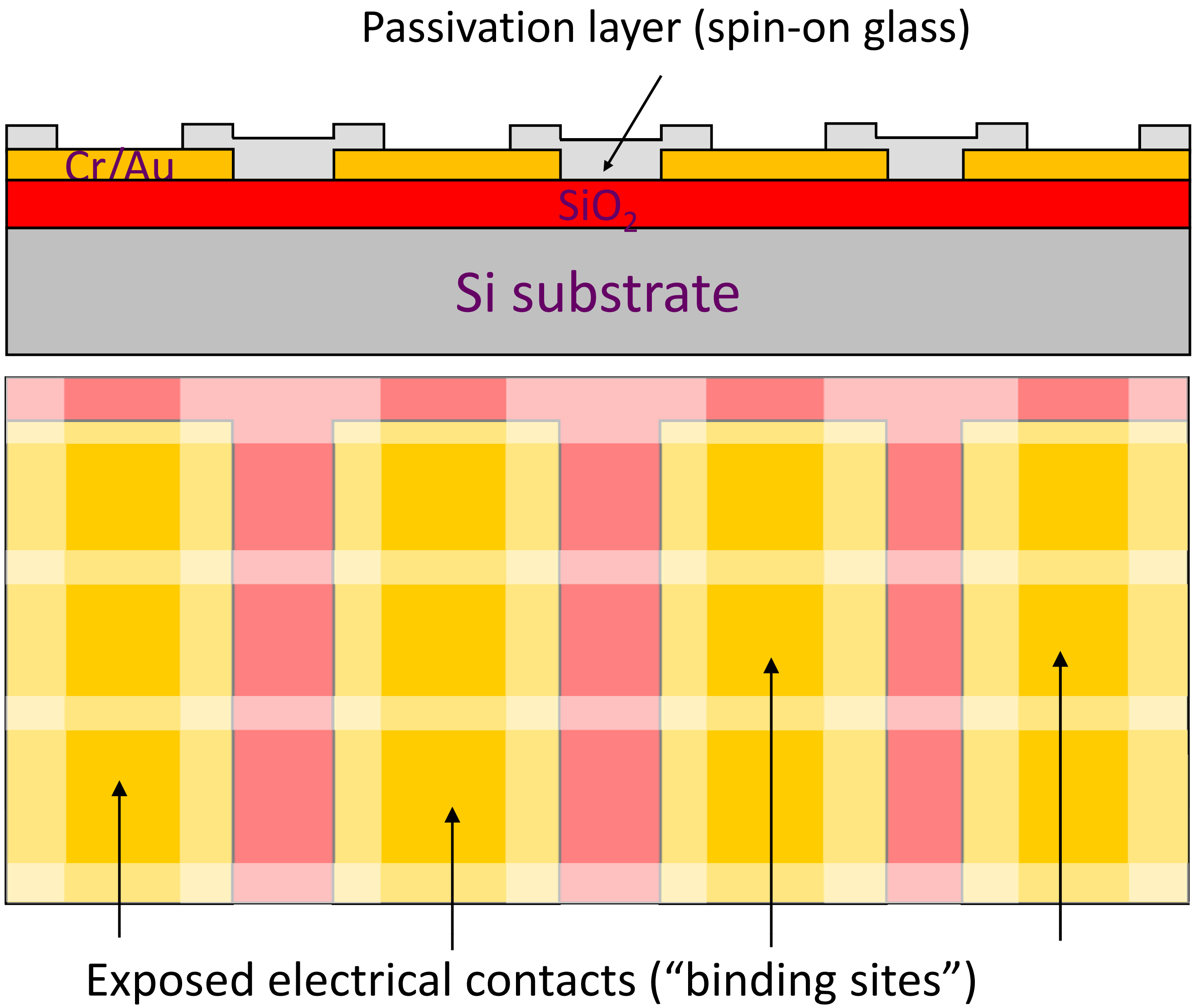
Reductive desorption of SAM

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



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

Fabrication of Substrate



SAM Desorption and First Assembly Batch

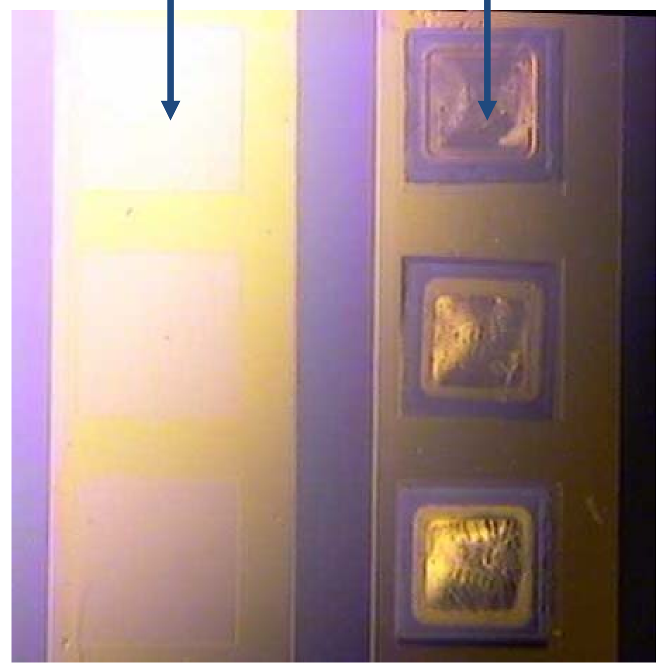
No adhesive on hydrophilic surfaces

Adhesive on hydrophobic surfaces

1mm

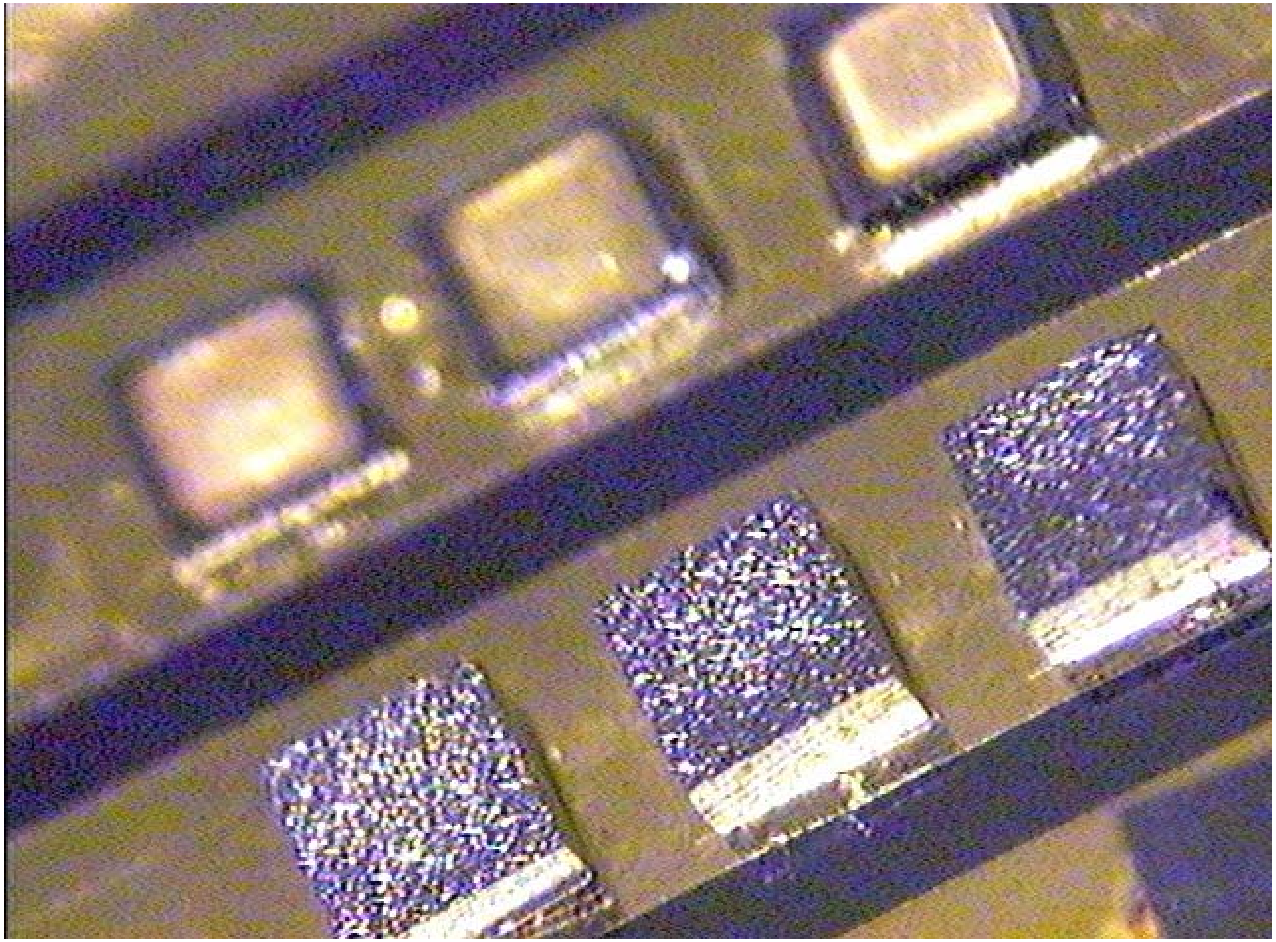
Free spot

Assembled part



SAM desorption from left column of sites only

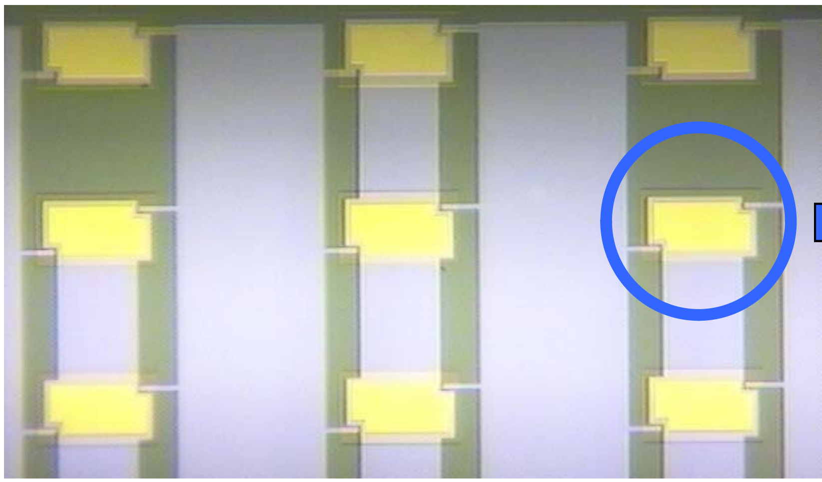
Second Assembly Batch

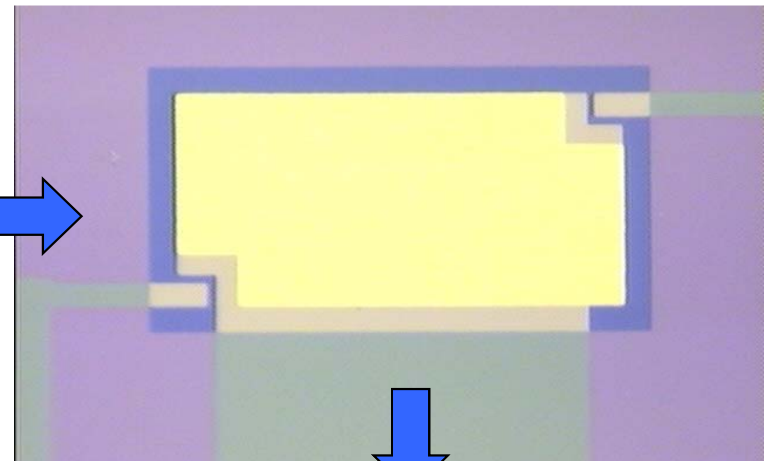


[X. Xiong et al. *Transducers* '01, *JMEMS* '03]

Adding Electrical Connectivity

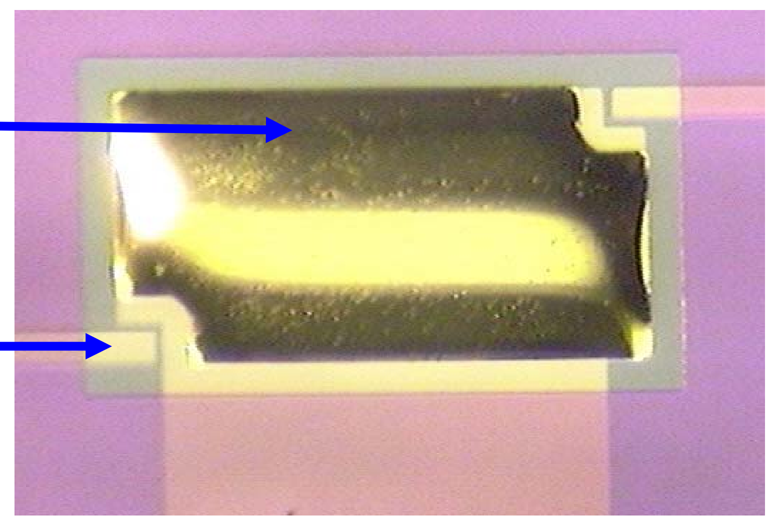
Top view of a fabricated substrate for LED assembly



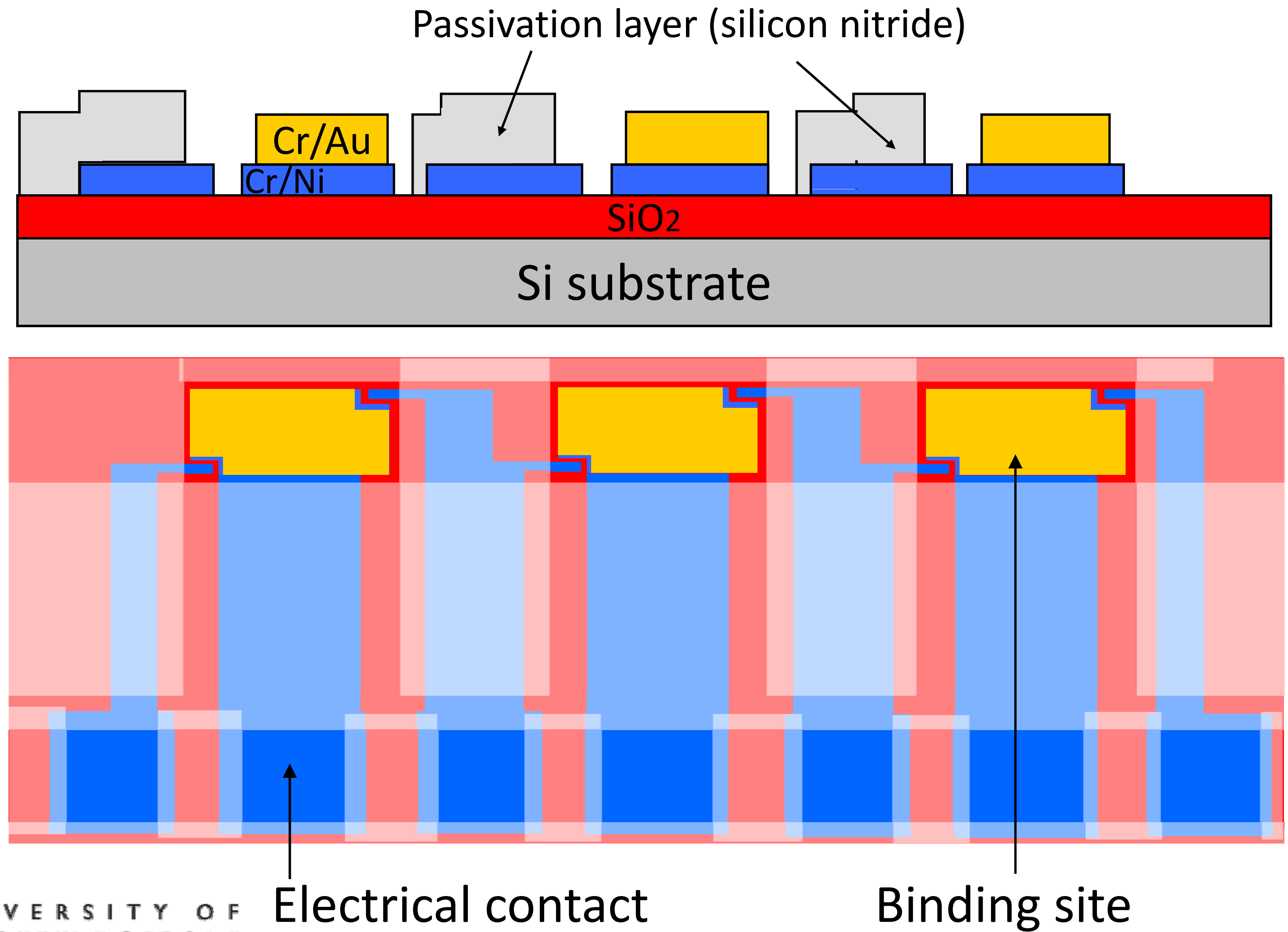


Adhesive wets Au binding site

Ni electroplating seed is free from adhesive

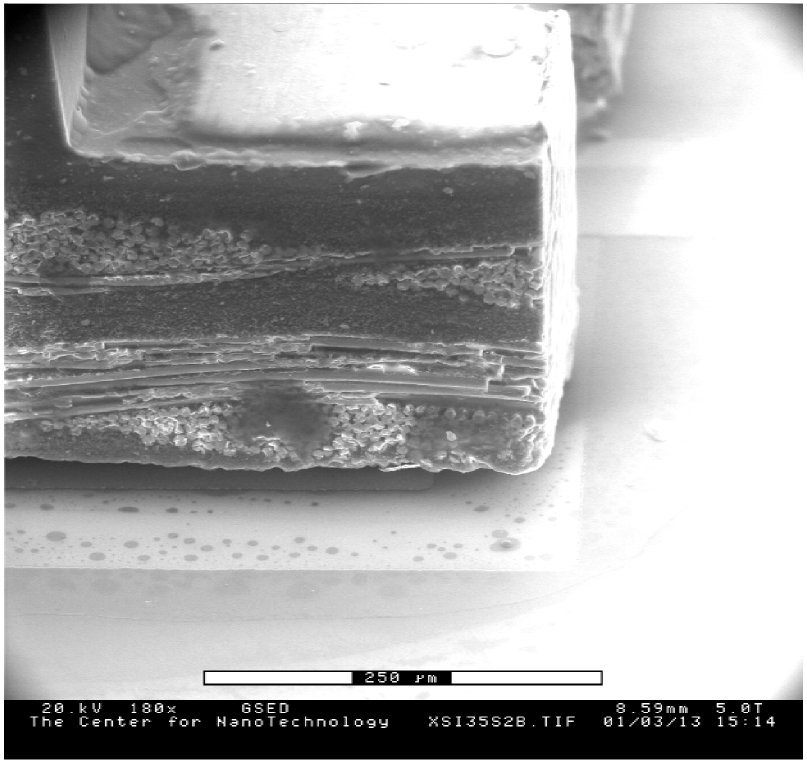


Fabrication of the Substrate for LED Assembly

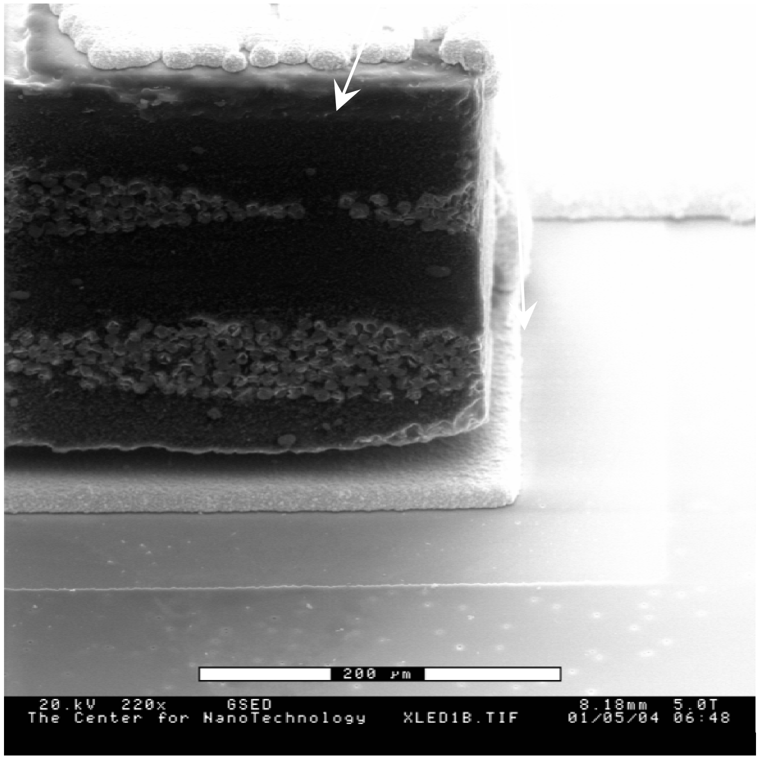


Electrical Connection by Electroplating

Gap between an assembled LED and substrate is ~ 20µm



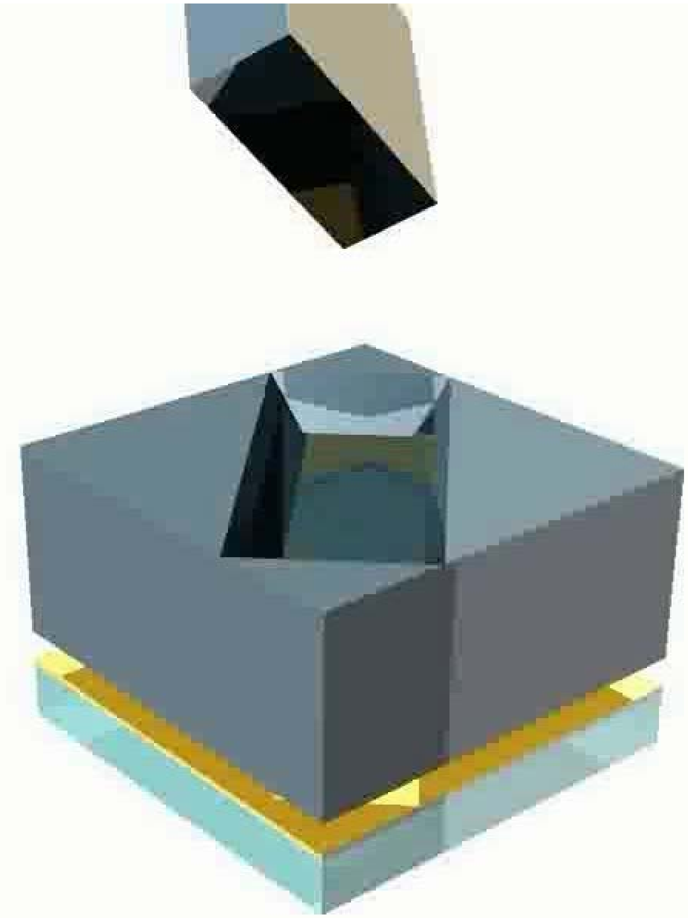
Electrical connection established by plated solder



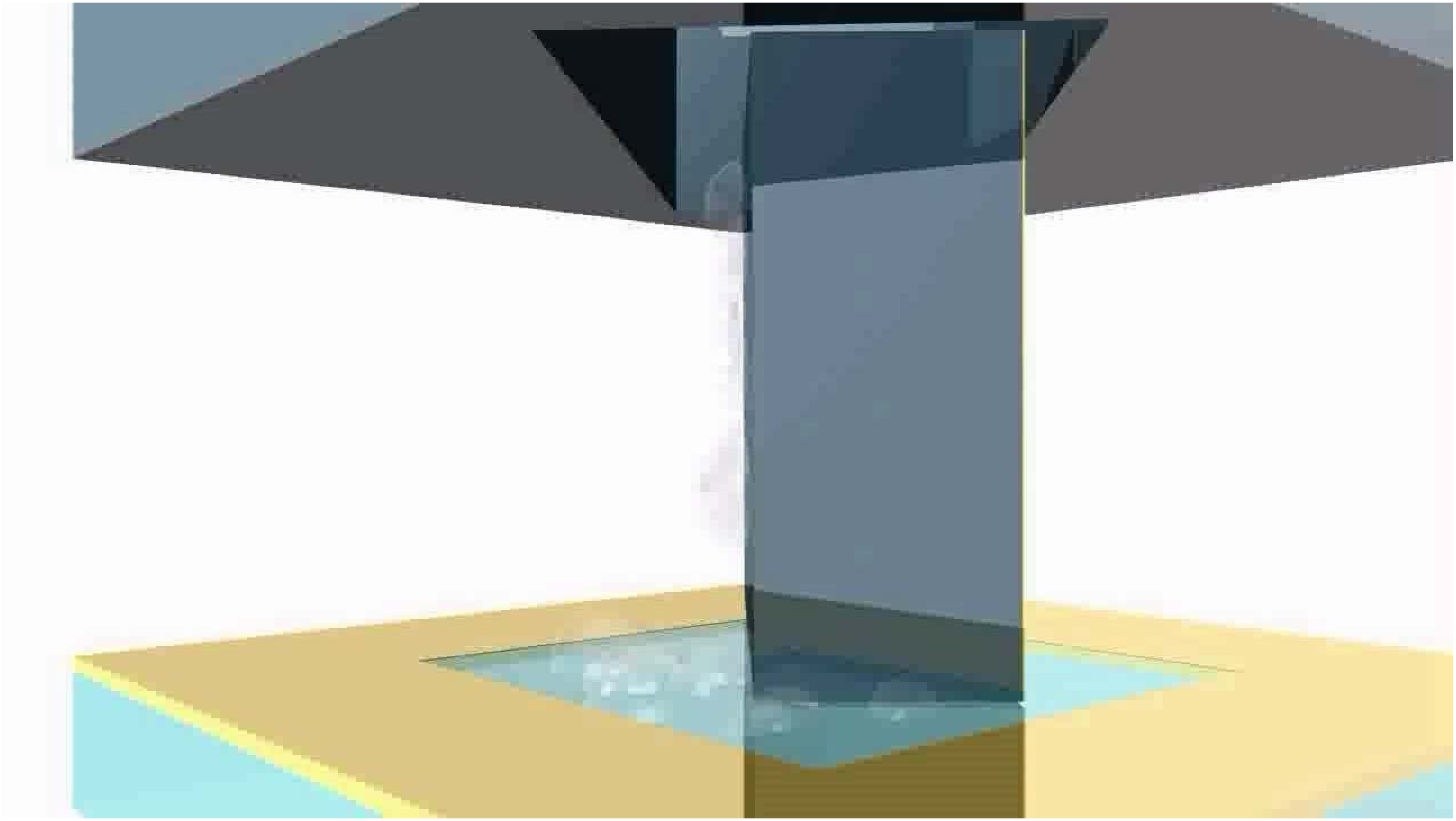
Self-assembled LED with Electrical Connections

[X. Xiong et al., JMEMS ’03]

Templated Self-assembly

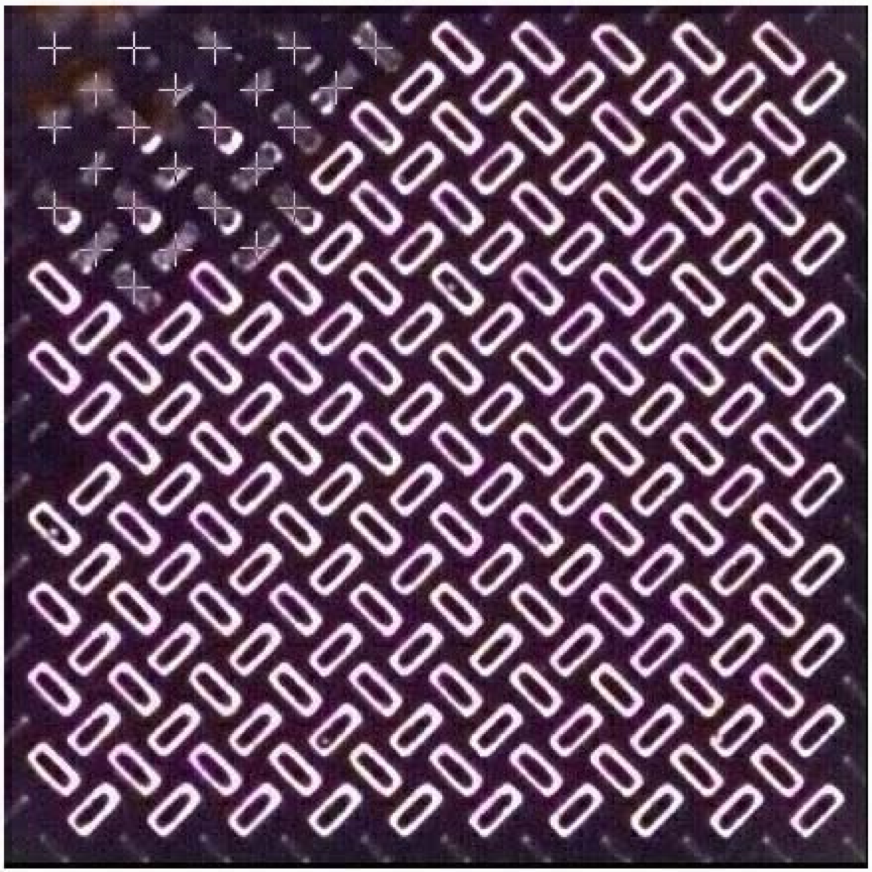


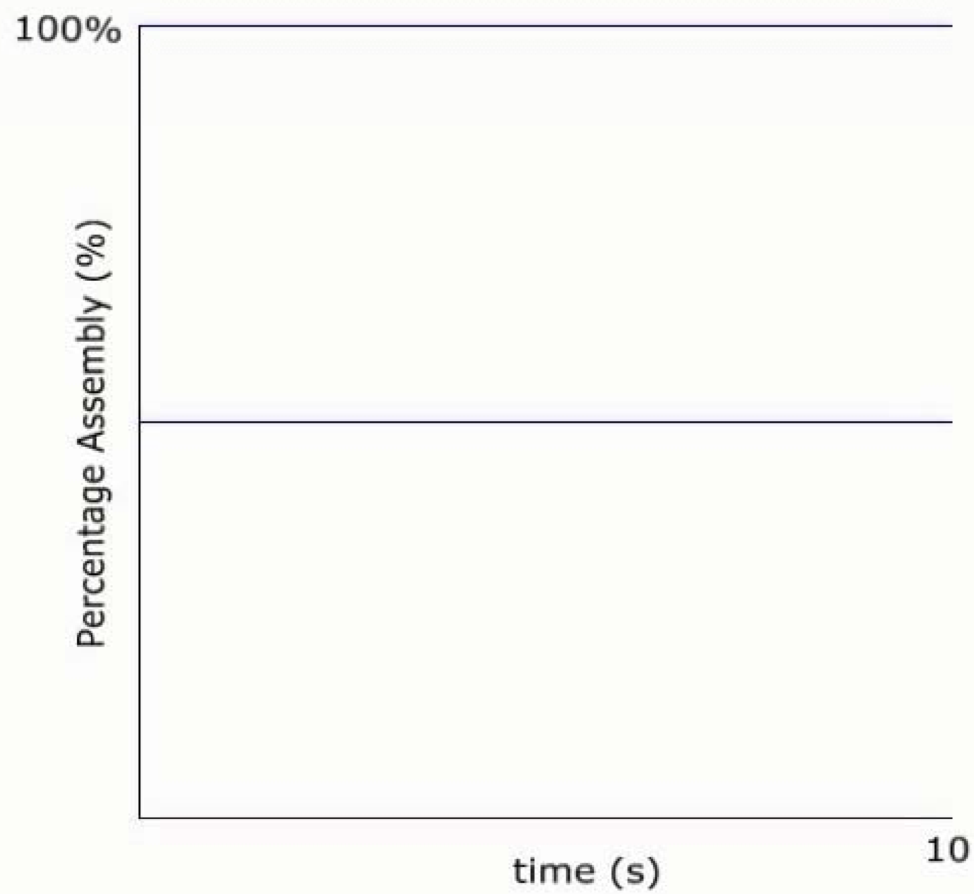
Templated Self-assembly



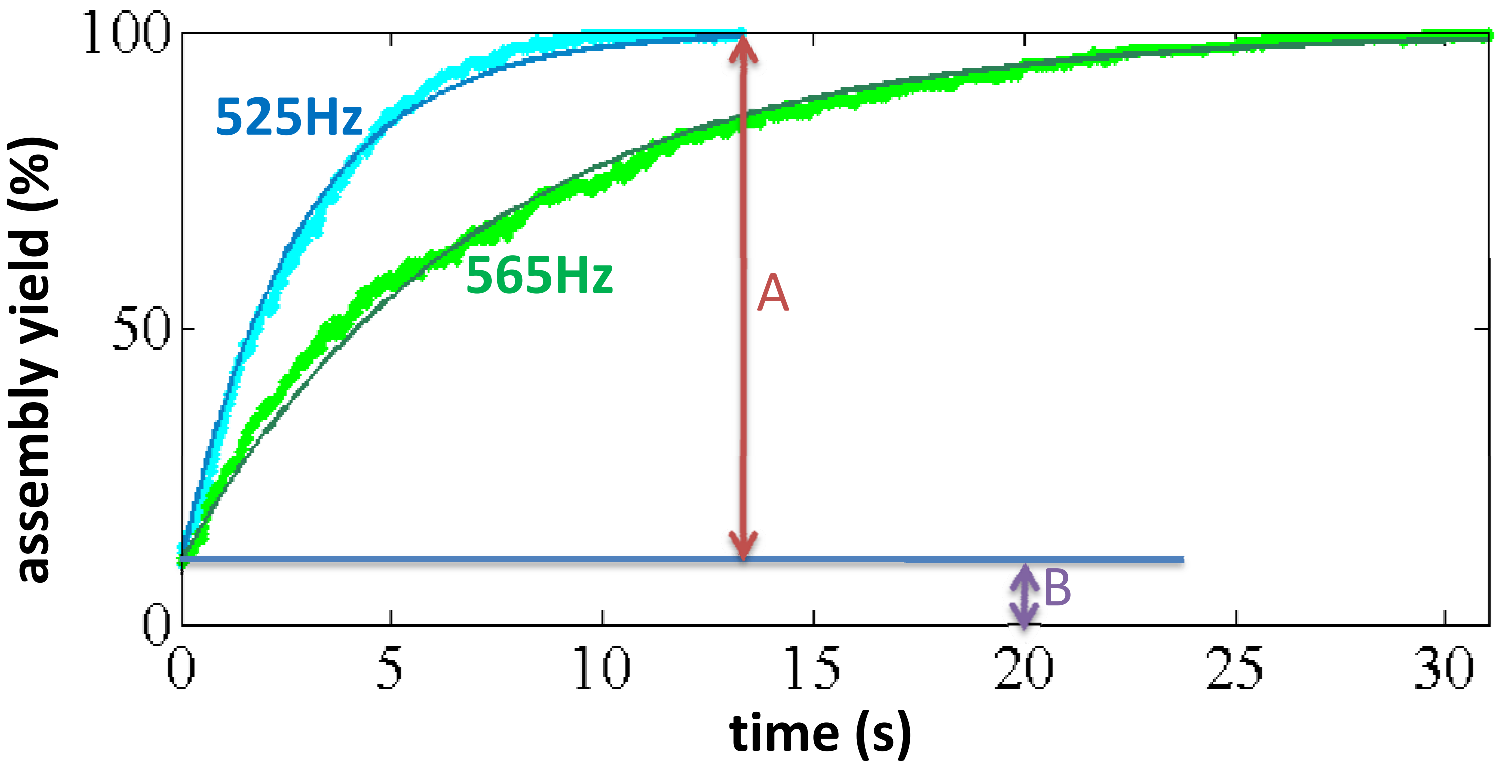
Real-time Tracking of Self-assembly

aperture sites: 200; % excess parts: 50%; agitation frequency: 525Hz





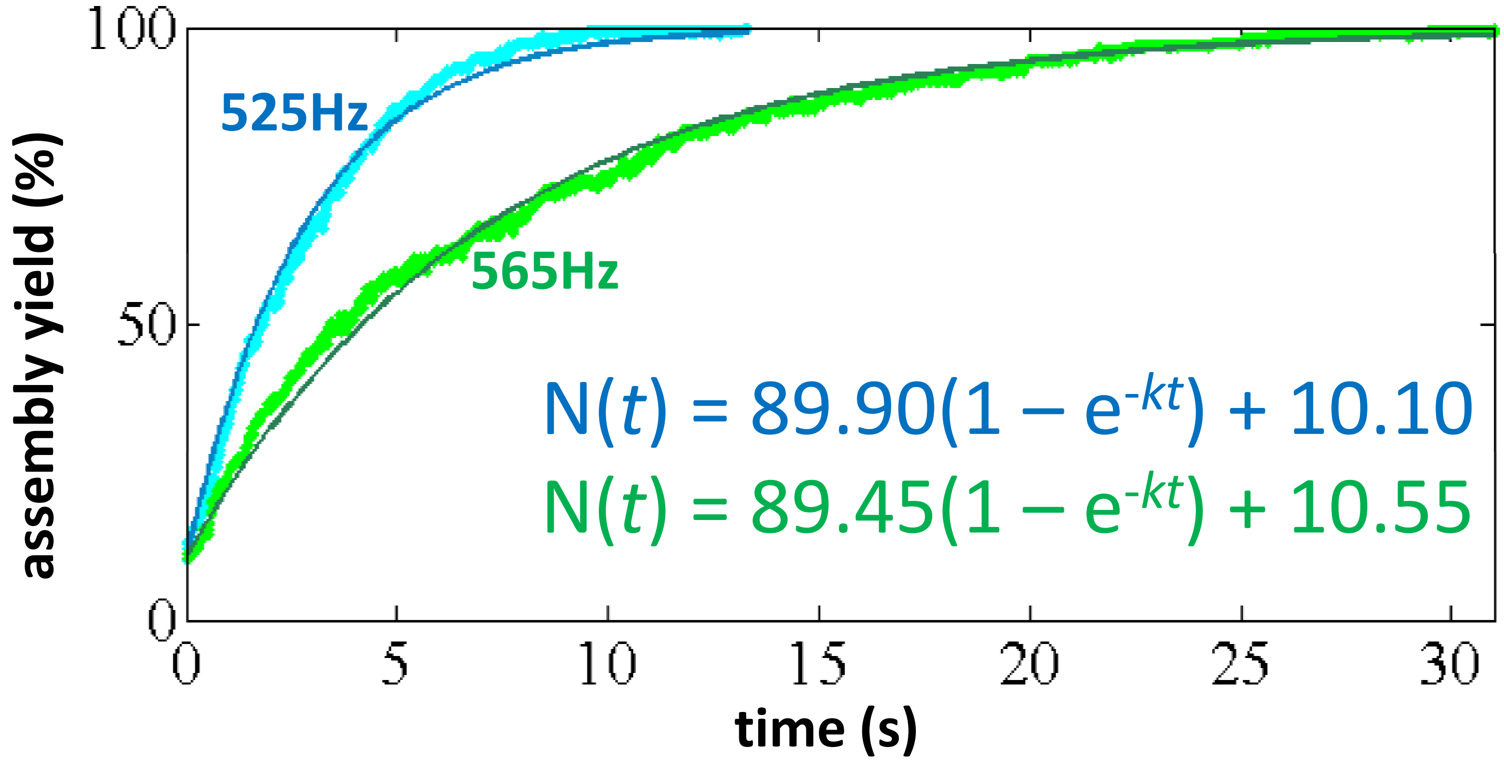
Results: Assembly Kinetics



$$N(t) = A(1 - e^{-kt}) + B$$

$A + B \leq 100\%$

Assembly Kinetics Model

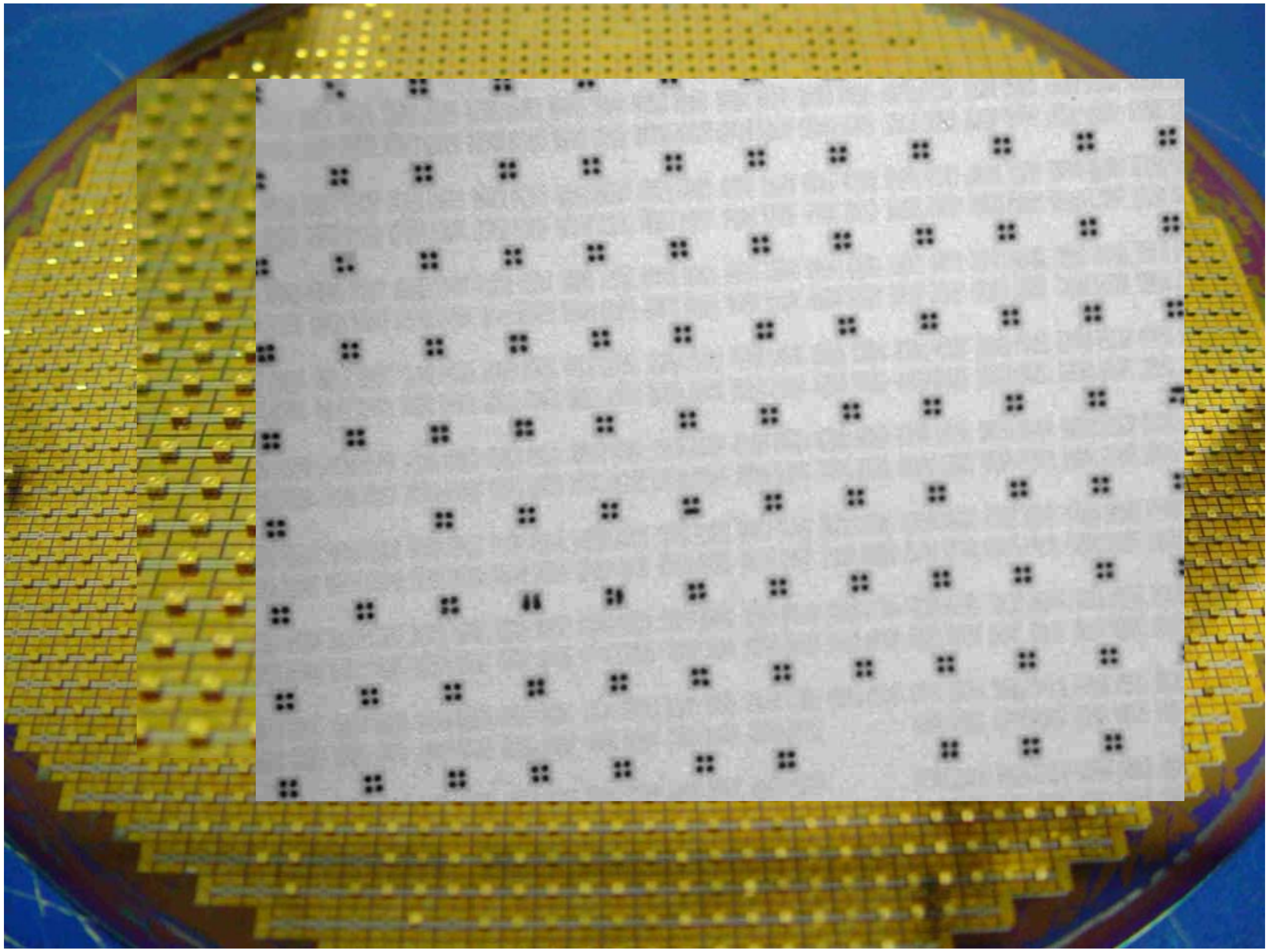


$N(t) = 89.90(1 - e^{-kt}) + 10.10$ $\quad k = 0.35$

$N(t) = 89.45(1 - e^{-kt}) + 10.55$ $\quad k = 0.14$

$$N(t) = A(1 - e^{-kt}) + B \qquad A + B \leq 100\%$$

Assemblies with Shape Matching

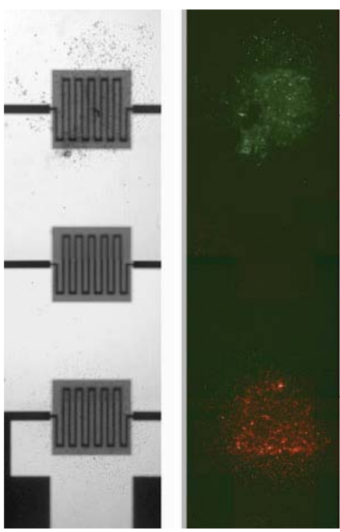


Self-assembly and gang bonding of chips on 8” wafer
(collaboration with ASTAR IME, Singapore)

Current / Future Work: Protein and Cell Arrays

Programmable Surfaces for Proteins and Cells:

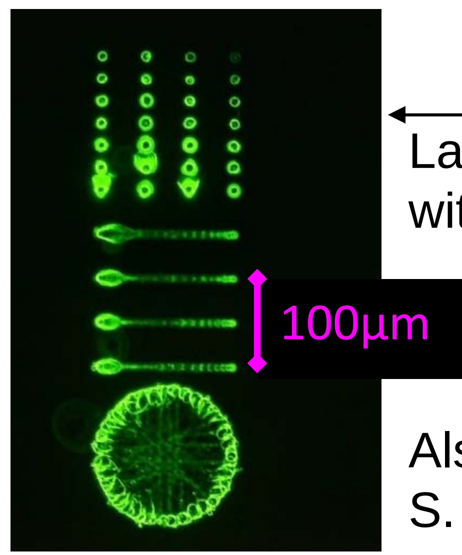
- Thermoresponsive polymer pNIPAM (poly N-isopropyl acrylamide) binds proteins and cells above 32°C.
- Thin film pNIPAM can be integrated with MEMS.
- Microheaters for protein and cell arrays.
- Programmable IR laser "protein printer."



BASMC

BAEC

With B. Ratner, UWEB



Laser exposure test with BSA

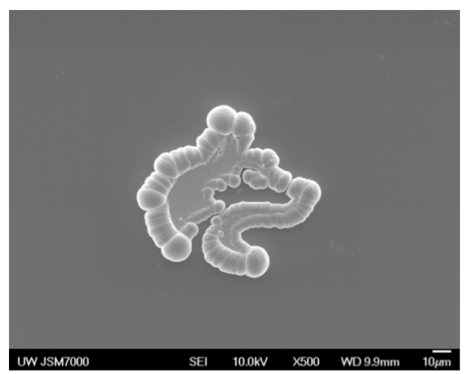
Also with H. Fujita, S. Takeuchi, Tokyo

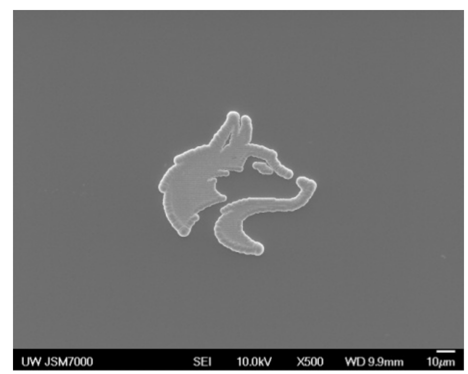
Current / Future Work: Protein Guided Nanomanufacturing

<u>Orchestrated Structural Evolution (OSE):</u>

- Use combinatorial biology to develop library of peptides.
- Peptides control nucleation, growth rate, and crystallinity of target inorganic materials.
- Place peptide patterns into appropriate aqueous electrolyte.
- Peptides can act as seeds in synthesis of heterogeneous, three-dimensional structures.
- Completely automated process from CAD design to optimized seed planting to growth of nano-structures

UW Husky pattern, automatically generated and grown with OSE (with D. Schwartz, UW)





10µm

Conclusions

Tools for design, modeling, and manufacture of complex 2D and 3D self-assembled microsystems are becoming available.

They could lead to a paradigm shift in design and manufacture of complex micro and nano systems.

Effects of downscaling on assembly:

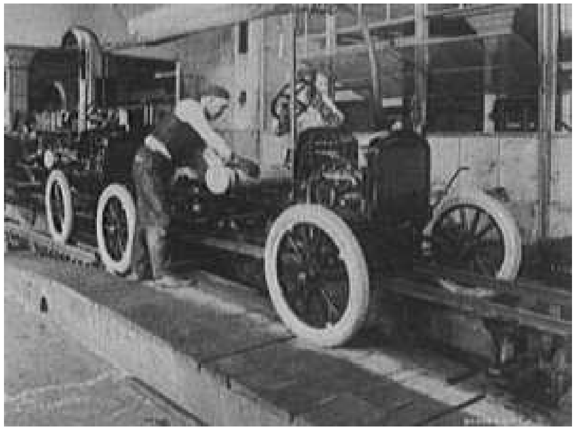
Meso	Volume forces	Deterministic	Serial
↓	↓	↓	↓
Micro	Surface forces	Stochastic	Parallel

Conclusions

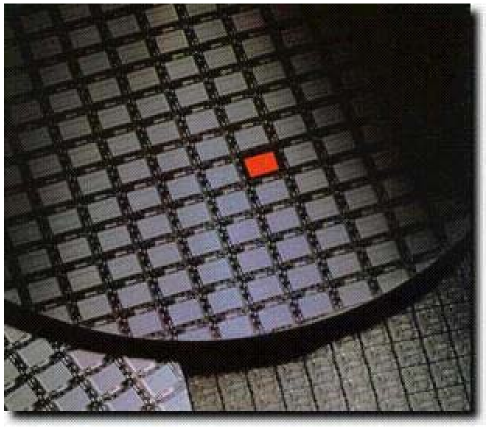
Tools for design, modeling, and manufacture of complex 2D and 3D self-assembled microsystems are becoming available

They could lead to a paradigm shift in design and manufacture of complex micro and nano systems

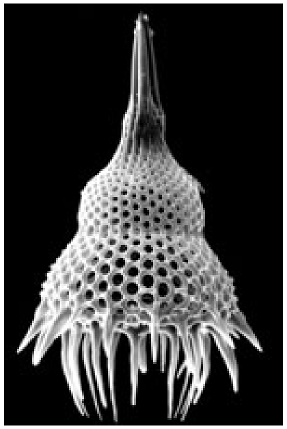
Manual labor: “0D”



Conveyor belt: “1D”



VLSI: “2D”



3D self-assembly in Nature: *Radiolarium l. maritalis*

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