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 I: Self-assembly Basics

Motivation; overview; history; examples

What Is Self-assembly?

Is it …

- chemistry?
- materials science?
- nanotechnology?
- tossing components into a box, shaking it, and hoping that after some time, the assembled product appears?

What Is Self-assembly?

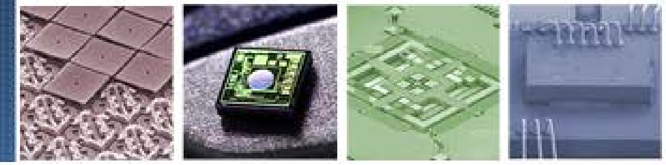
- “The autonomous and spontaneous organization of components into patterns and structures” – George Whitesides
- “The science of things that put themselves together” – John Pelesko
- “A scalable manufacturing method for heterogeneous integrated microsystems”

Why Study Self-assembly?

- Because it occurs frequently in nature (organic and inorganic).
- Because it is a concept that is equally interesting for mathematicians, chemists, computer scientists, biologists, electrical engineers, and others.
- Because it may hold enormous potential for the development of novel manufacturing techniques, especially at small scales.

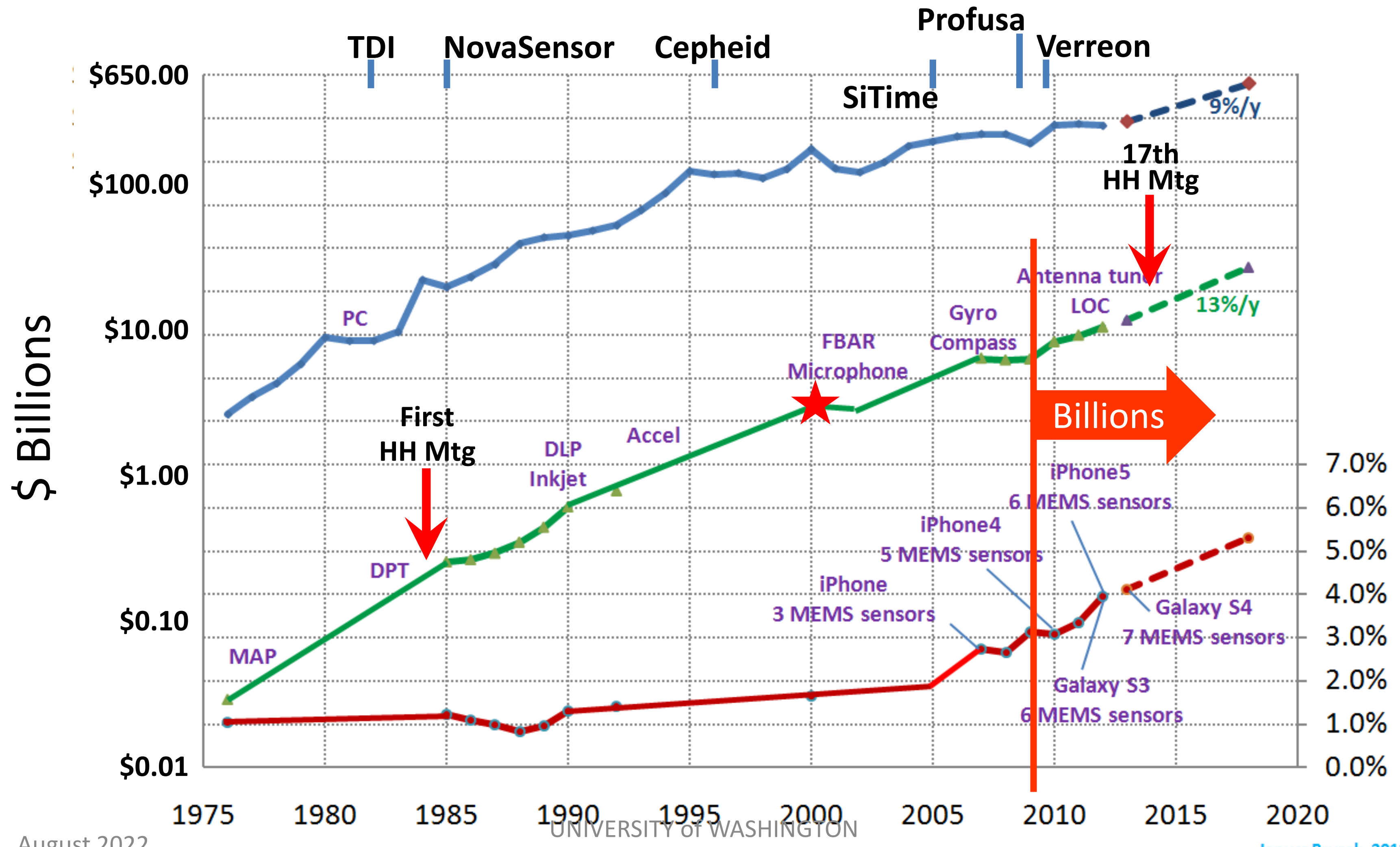
Why Is Self-assembly Important?

- Microfabrication is, for the most part, a parallel manufacturing technology
  - Key to success of VLSI electronics
- Packaging is a bottleneck as it requires sequential processing steps
- This is an increasing problem, esp. for a new generation of hybrid integrated microsystems
- Unlike pick-and-place, self-assembly is a parallel manufacturing technology
  - Enabler of complex heterogeneous microsystems



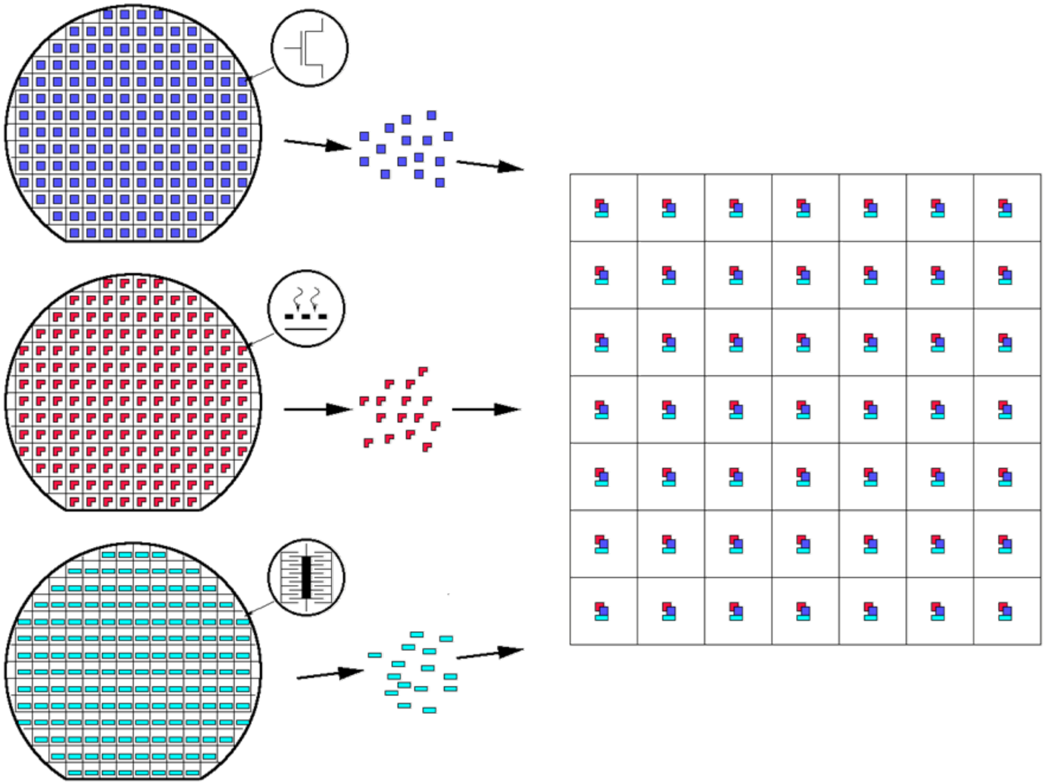
Global SEMI and MEMS (Component) Markets

Blue: SEMI, Green: MEMS, Red: MEMS/SEMI (right axis)



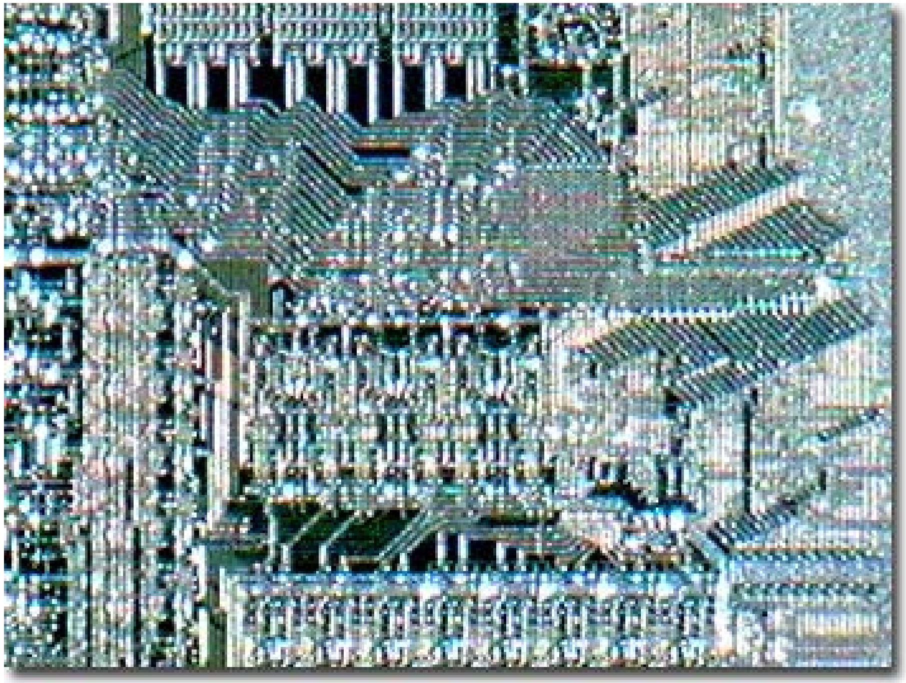
Micro-assembly

- 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 heterogeneous microsystems

Circuit City



Integrated circuit, microscopic view

City landscape, macroscopic view

Key Features of Self-assembly

1. Structured particles (components)
   - The basic building blocks that form an assembly; their structure ultimately determines the assembly product.
2. Binding force
   - Holding the particles together.
3. Environment
   - Controlled conditions that provide the framework for physical interactions and lead to reproducible results.
4. Driving force
   - Provides the energy to keep the assembly going; typically it has a stochastic nature (e.g., vibration, oscillation, noise, heat, …).

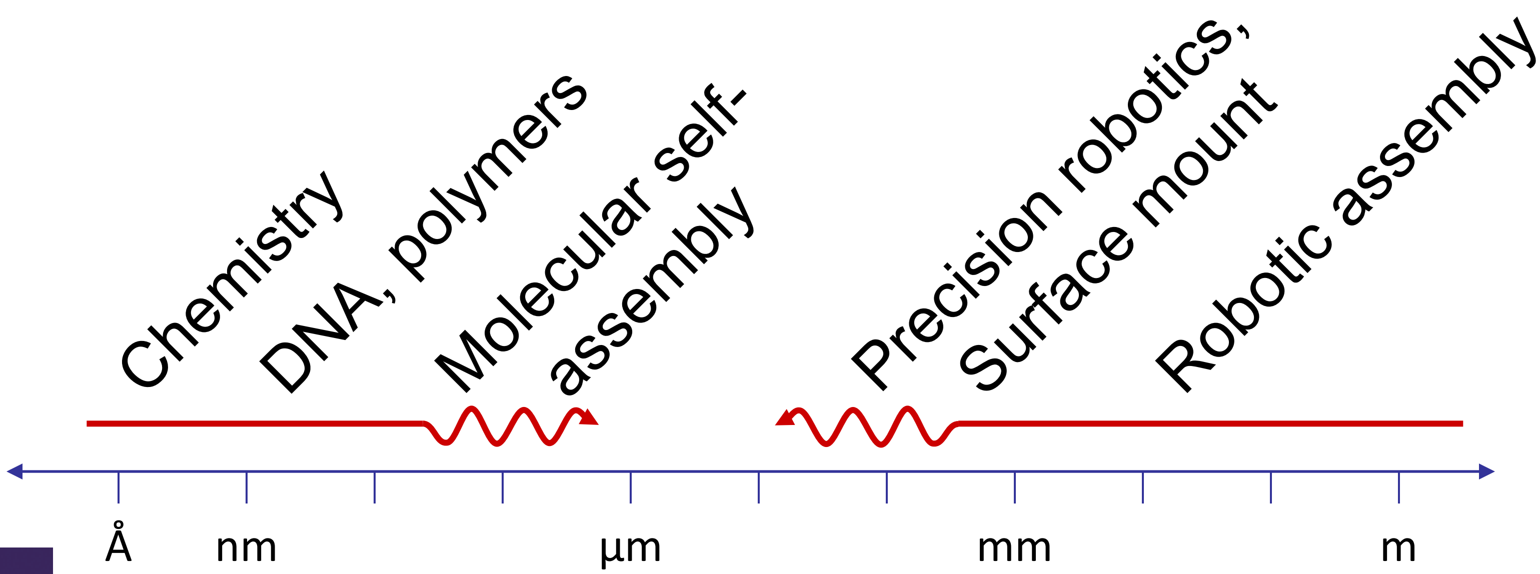
Other Features of Self-assembly

- Is there anything missing?
    - Reduction of entropy
    - Parallelism
    - Performance metrics (time, yield)
    - …

Motivation

In the micro range (approx. 0.1 μm – 100 μm) there exists a “no-man’s-land” for engineered assembly

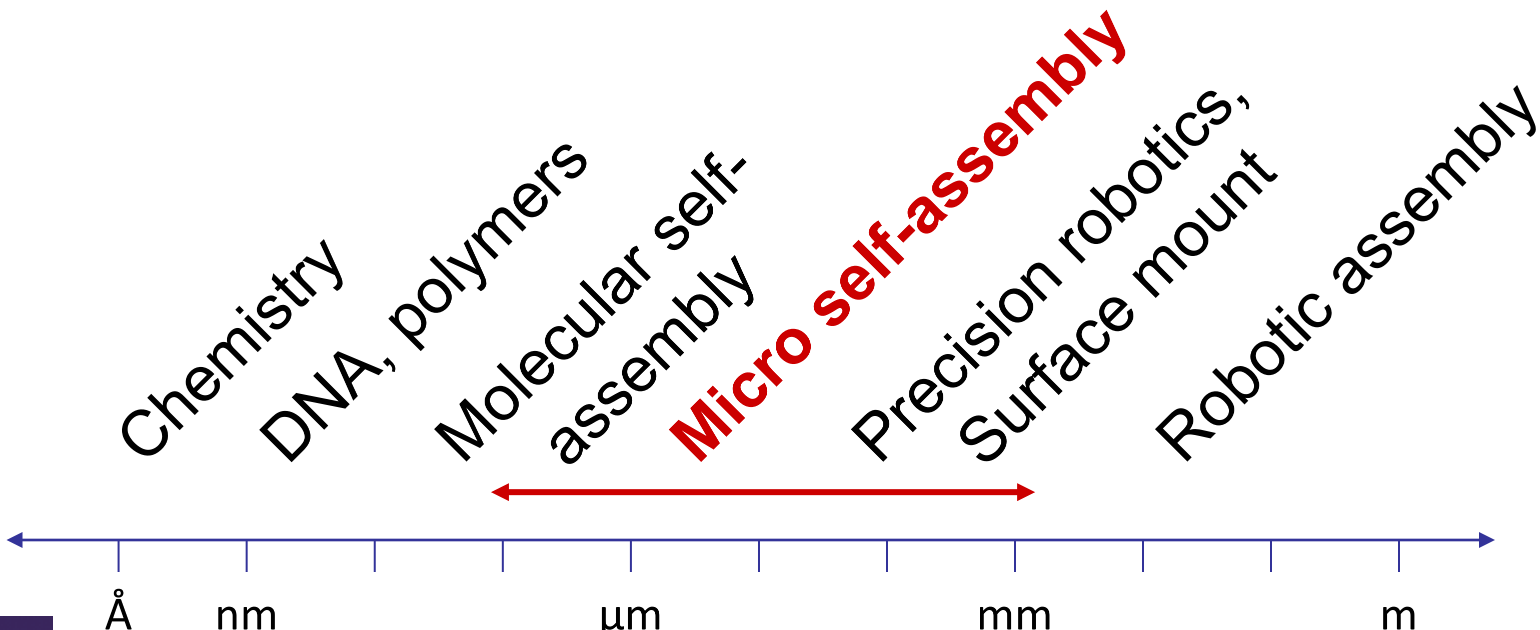
- Conventional robots get very expensive
- Chemical synthesis cannot produce non-periodic or heterogeneous assemblies



Motivation

Goals:

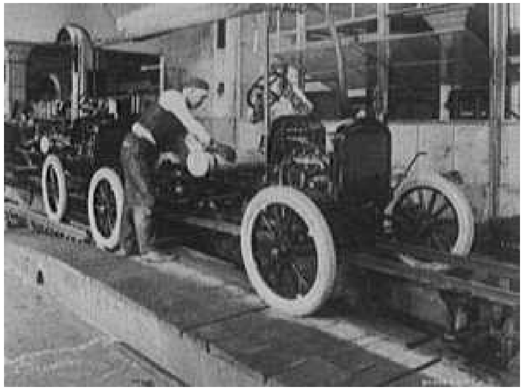
- High volume, flexible manufacturing
- Complex hybrid microsystem integration



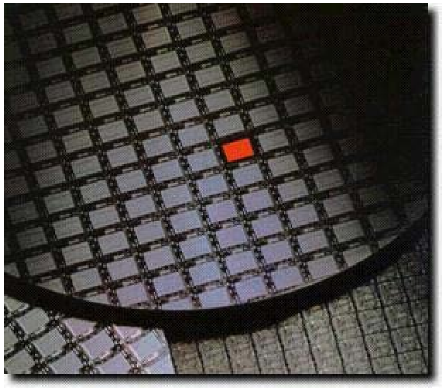
Motivation

It is time for a paradigm shift in the manufacture of complex, heterogeneous microsystems that integrate sensing, actuation, computation, and communication.

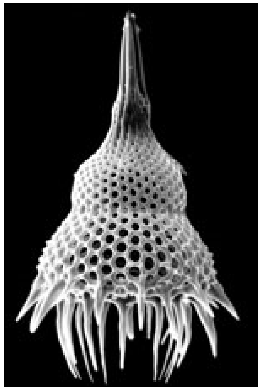
“0D”
manual labor



“1D”
conveyor belt



“2D”
VLSI



“3D”
self-assembly in nature
Radiolarium l. maritalis

Landmarks in Self-assembly

1930s Turing develops the theory of universal computation

1950s von Neumann develops theory of automata replication

1953 Watson & Crick discover the structure of DNA

1955 Fraenkel-Conrat & Williams self-assemble the tobacco mosaic virus in a test tube

1957 Penrose & Penrose construct a simple self-replicating system

1961 Wang develops “Wang tiles” demonstrating the equivalence of tiling problems and computation

Landmarks in Self-assembly

1991 Seeman & Chen self-assemble a cube from DNA

1991 Cohn, Kim & Pisano create self-assembling electrical networks

1993 Yeh & Smith file patent on fluidic self-assembly (FSA)

1994 Adleman launches field of DNA computation by using DNA to solve a Hamiltonian path problem

1994 Shimoyama & Miura's group model milli-scale self-assembly with chemical reaction kinetics

1996 Shimoyama & Miura's group demonstrates micro-scale self-assembly using surface tension

Landmarks in Self-assembly

2000 Whitesides's group self-assembles 3D electrical networks from millimeter-scale polyhedra

2003 Böhringer's group modulates surface energy to achieve programmable self-assembly

2004 Shih adapts the methods of Seeman to self-assemble a DNA octahedron

2004 Winfree & Rothemund self-assemble a Sierpinski triangle from DNA

2006 Rothemund folds DNA origami

Taxonomy of Assembly

- Serial assembly
  - One or more components (identical or different) assembled one-by-one
  - Manual, tele-operated, or autonomous
  - Common technique in manufacturing: pick-and-place
- Parallel assembly
  - Multiple components (identical or different) assembled simultaneously, or in multiple batches
  - Common techniques in manufacturing and nature:
    - synthesis (chemistry)
    - growth (biology)

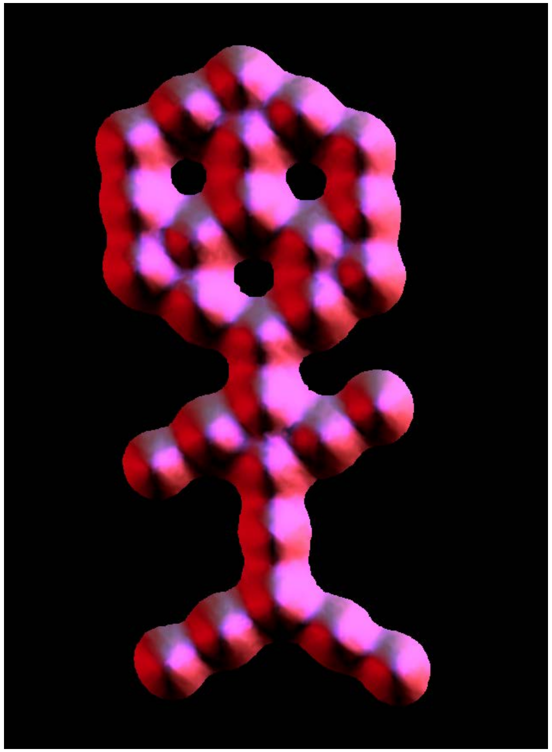
Taxonomy of Assembly

- Parallel assembly
  - Deterministic: order of assembly and destination of components is uniquely determined in advance
  - Stochastic: order of assembly or destination of components is determined in part by a random process

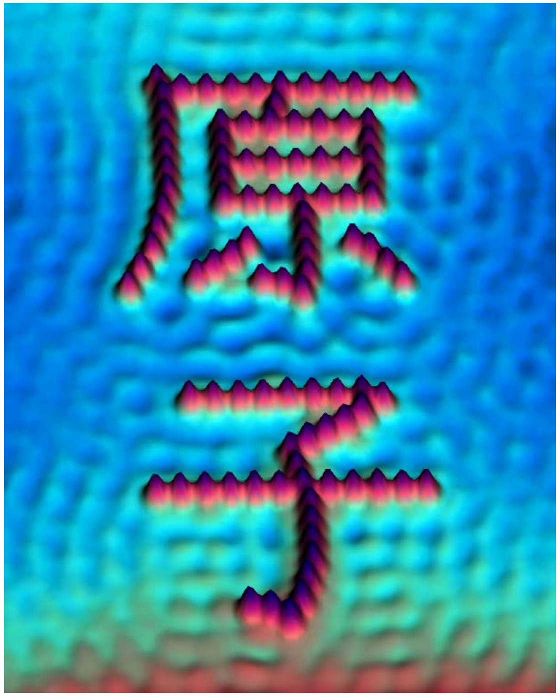
- Compare with
  - Motion planning (robotics)
  - Annealing (chemistry, materials science)

Example: Serial, Deterministic Nano-assembly by STM

Carbon Monoxide on Platinum (111)
[Zeppenfeld & Eigler]



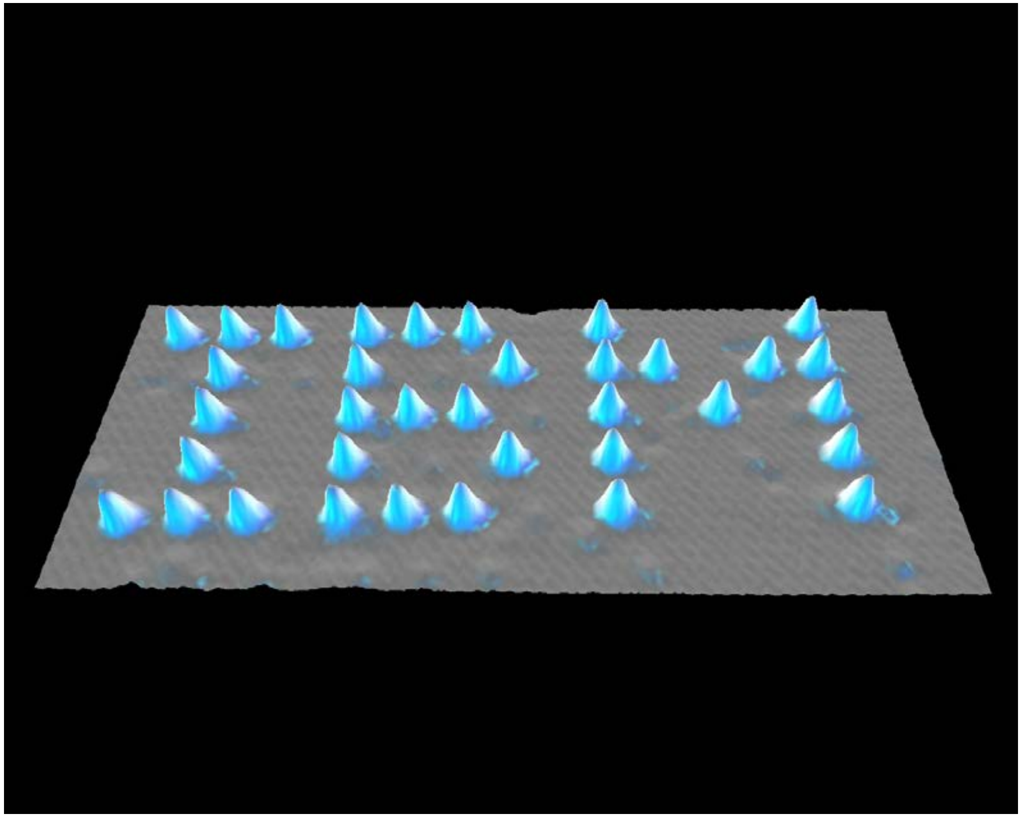
Iron on Copper (111)
[Lutz & Eigler]



Example: Serial, Deterministic Nano-assembly by STM

Xenon on Nickel (110)

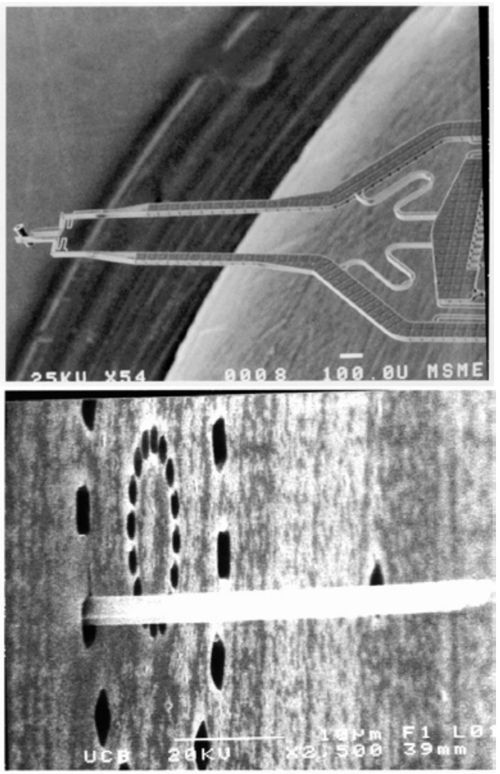
[Eigler]



Examples: Deterministic Parallel Assembly

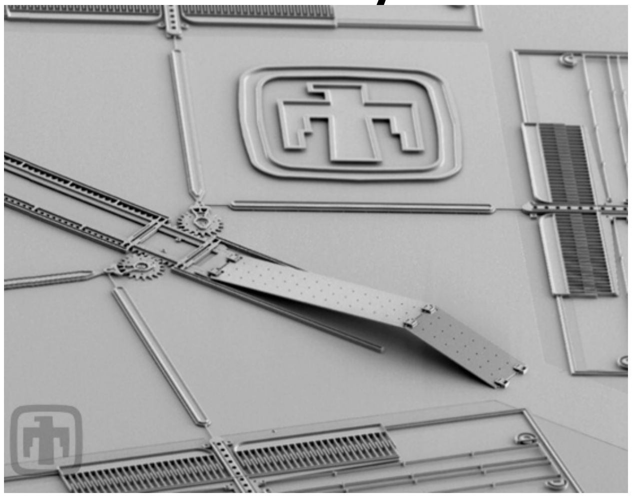
- Self-assembling 3D structures
  - “micro origami”
  - [Pister et al. ‘92], [Syms et al. ‘95, ‘98], [Fujita et al. ‘96]
- Flip-chip, wafer-to-wafer transfer
  - Combine devices from two (or more) wafers
  - [Cohn & Howe ‘97], [Singh et al. ‘97]
- Microgripper arrays
  - Parallel pick-and-place
  - [Keller & Howe ‘97]

Deterministic Parallel Assembly

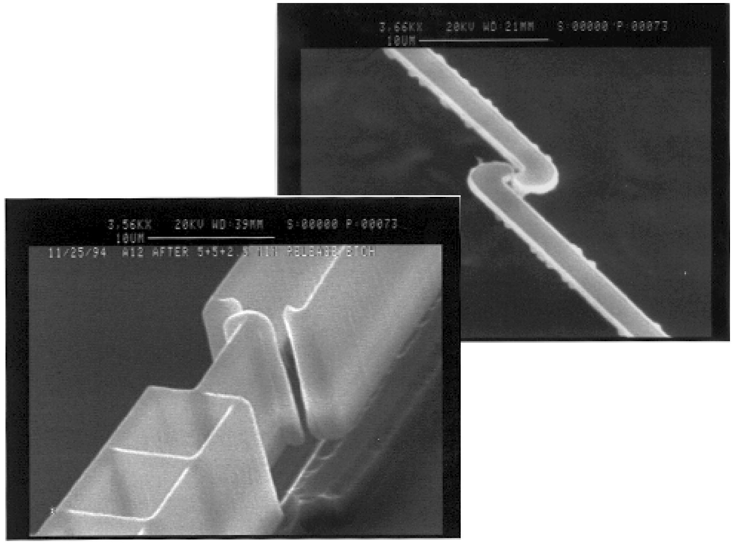


Micro-tweezer in HexSil technology. Keller, Howe, UC Berkeley ‘98

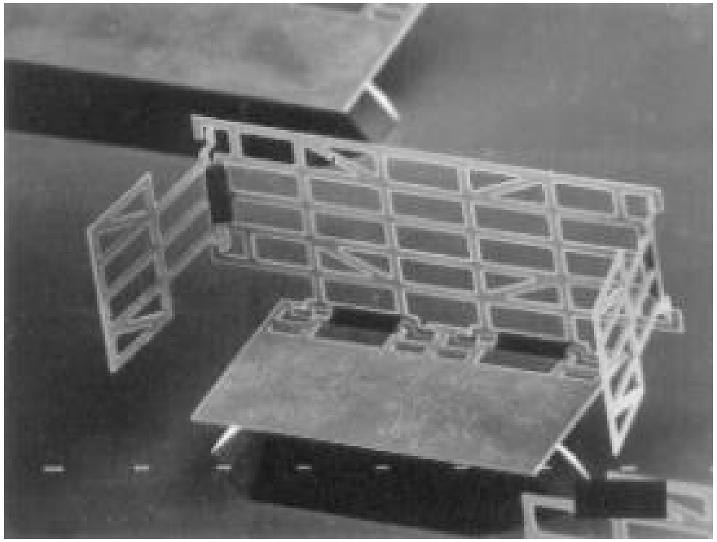
Self-deploying Micromirror Assembly. Sandia National Labs, Albuquerque ‘98



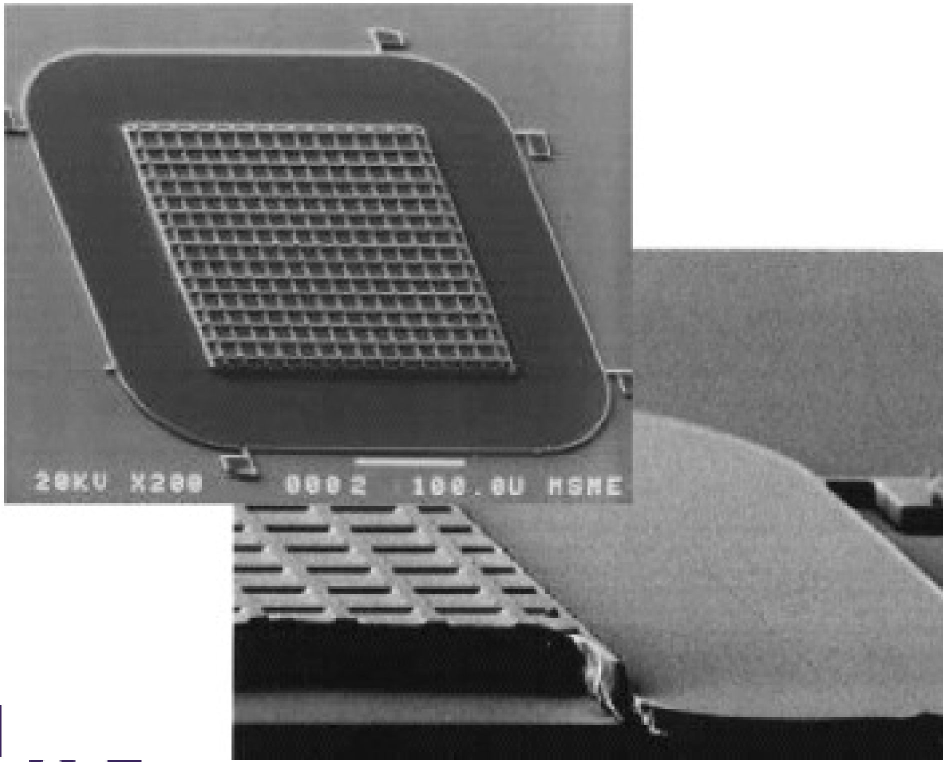
Micro snap fasteners. Böhringer, Prasad, Donald, MacDonald, Cornell University ’95



Deterministic Parallel Assembly



Solder reflow assembly. R. Syms, Imperial College, London, '95

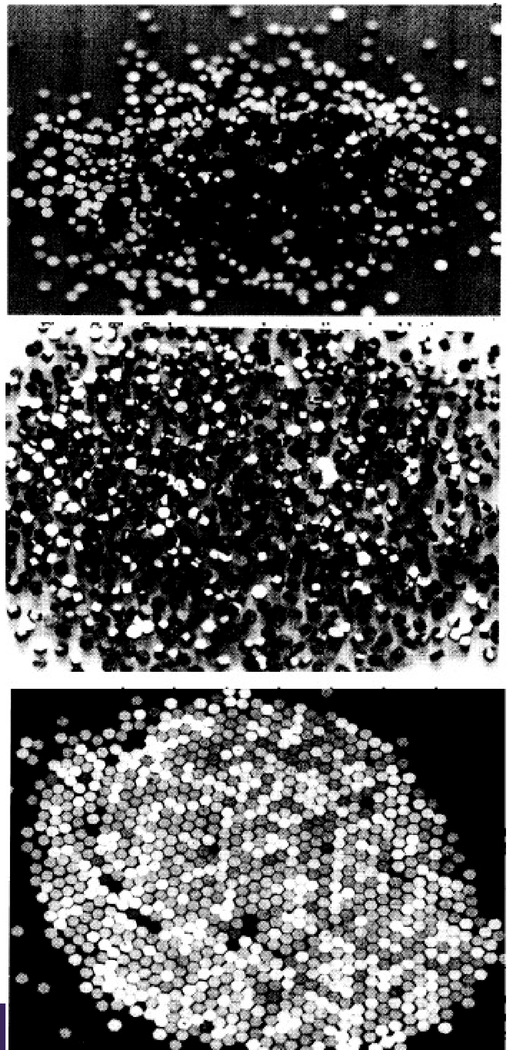


Flip-chip assembly and hermetic sealing. Cohn, Liang, Howe, Pisano, UC Berkeley, '97

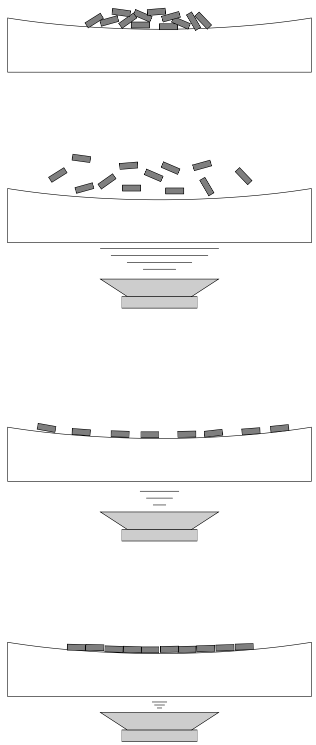
Examples: Stochastic Parallel Assembly

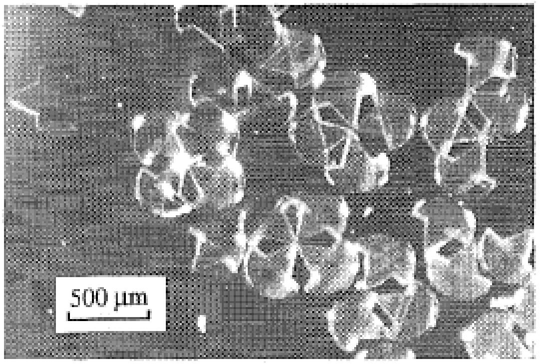
- Shape matching
  - Early work: hexagon packing [Cohn et al. ‘91], fluidic self-assembly [Yeh, Smith ‘94], [Hosokawa et al. ‘96]
  - Lock-and-key assemblies [Rothemund ‘00…], [Fang, Böhringer ‘06]
- Capillary force driven
  - 3D circuits [Gracias et al. ‘00], adaptive optics [Srinivasan et al. ‘02], [Jacobs et al. ‘02], programmable assembly [Xiong et al. ‘03]
- DNA origami
  - [Rothemund ‘06]

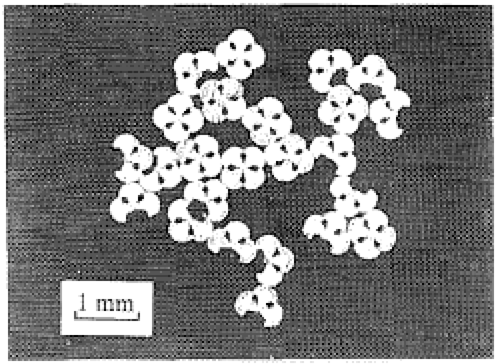
Stochastic Parallel Assembly



Cohn, Kim, Pisano ’91

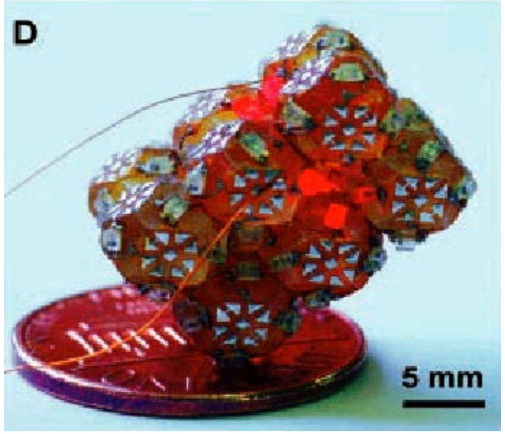




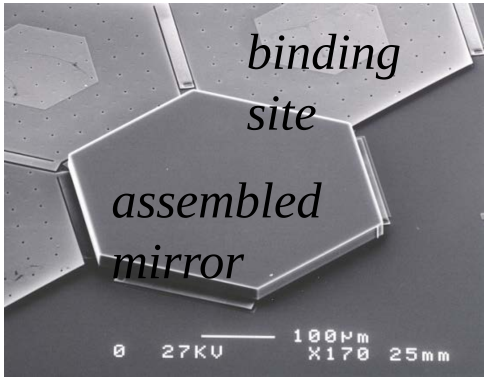


Hosokawa,
Shimoyama, Miura ‘96

Capillary Force Driven Self-Assembly



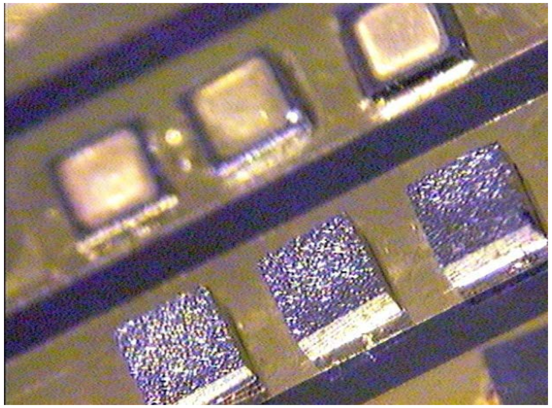
3d circuit
Gracias et al.,
Science ‘00



Srinivasan et al.,
IEEE Quantum El. ‘02

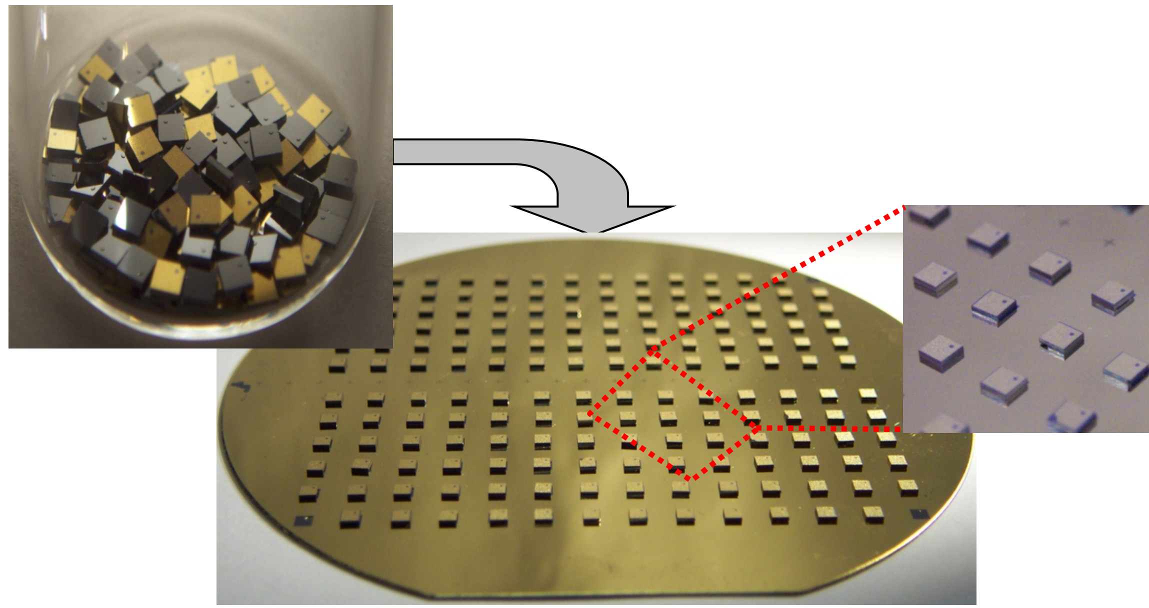
Flexible display
Jacobs et al.,
Science ‘02

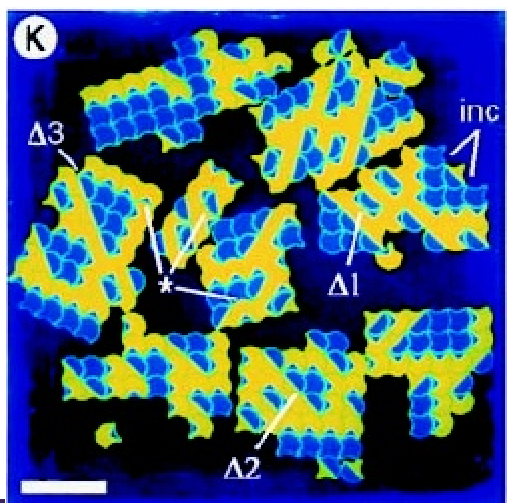
Multi-batch
Xiong et al.
JMEMS ‘03



Lock-and-key Self-Assembly

Fang et al.
JMEMS '06

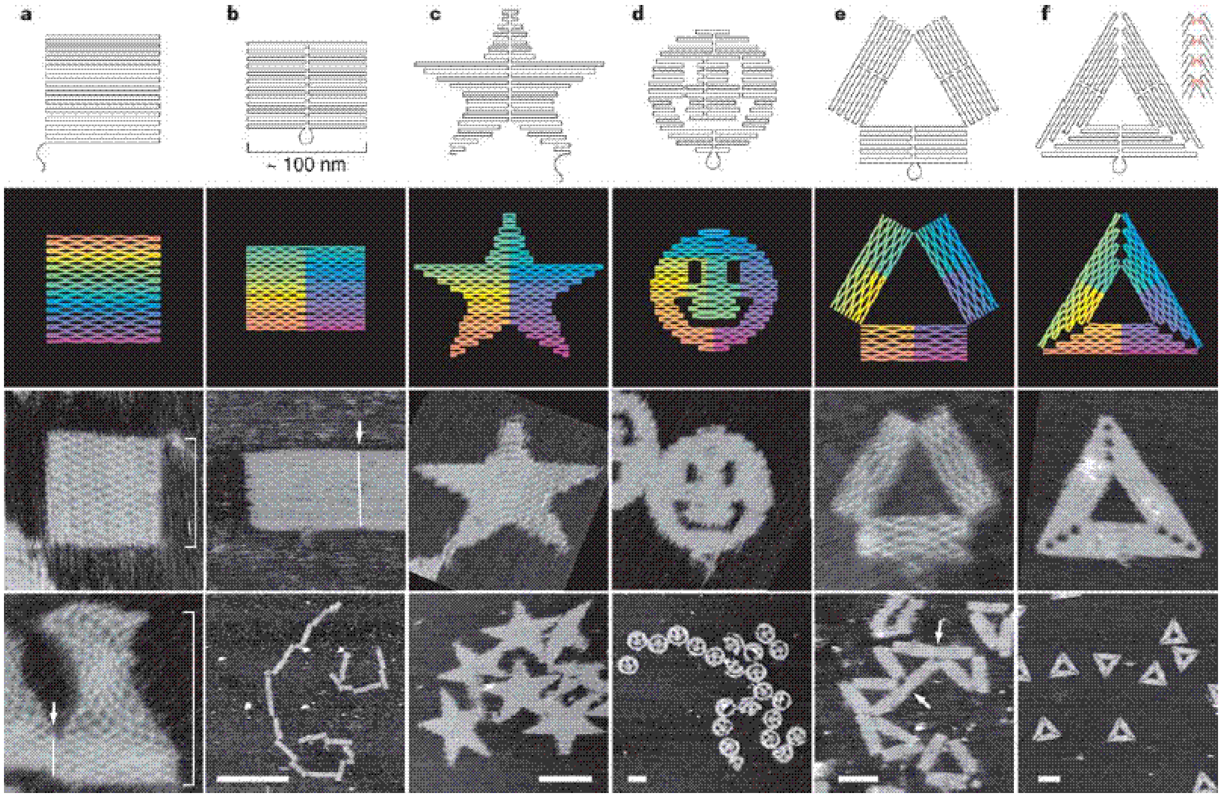




Logic assembly
Rothemund *PNAS* '00

Nano Self-Assembly Systems

DNA Origami
P. Rothemund
Nature ‘06

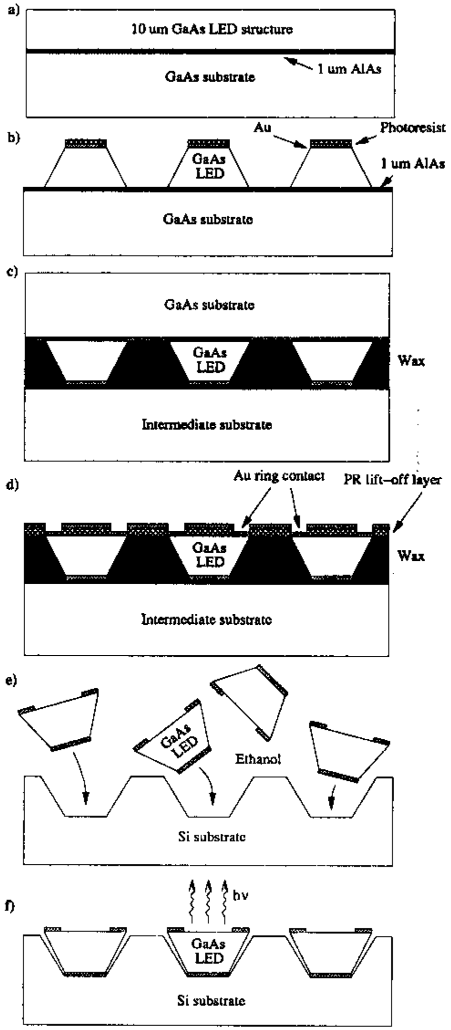


Also see work by Winfree, Dwyer, Reif, Seeman, and many others

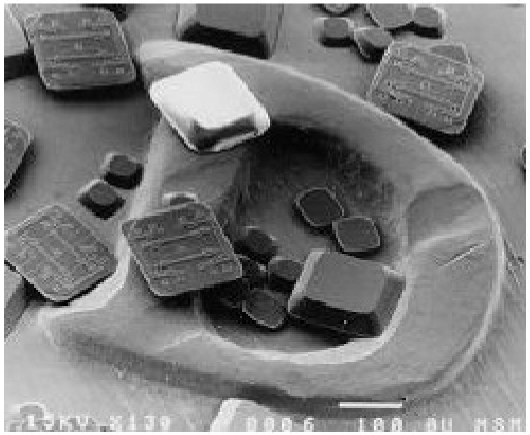
Template Driven Assembly

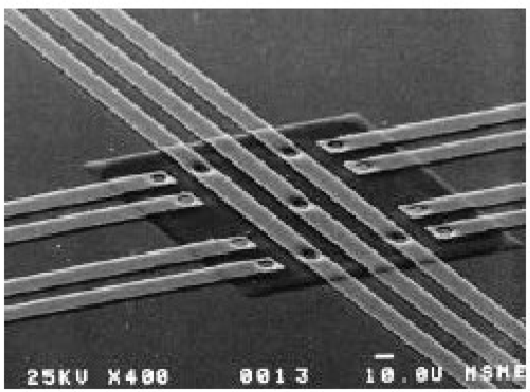
Fluidic self-assembly (FSA)

- H.-J. J. Yeh, J. S. Smith, "Fluidic Self-assembly of Microstructures and its Application to the Integration of GaAs on Si", *IEEE MEMS*, 1994
  - Goal: integrate GaAs components onto Si substrate
  - Anisotropic wet etching in Si forms pyramid-stump shaped holes
  - GaAs components with (almost) matching shapes self-assembly
  - Subsequent formation of electrical connections
  - Extension to molded plastic substrates
- Patented in 1996: Smith, Yeh, Method for fabricating self-aligned microstructures, US Patent 5,545,291.

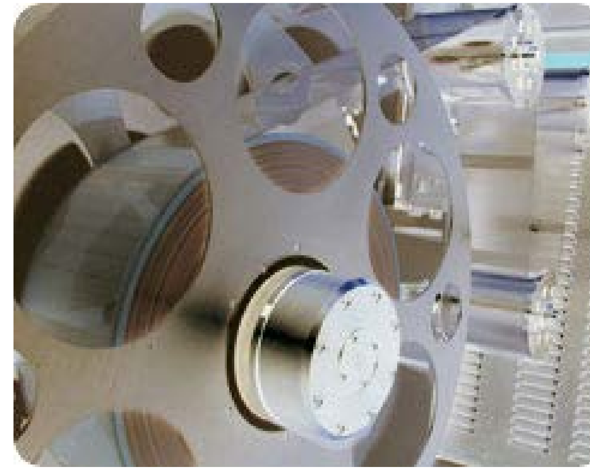


Fluidic Self-assembly (FSA)





“Nanoblocks”: fluidic agitation, assembly by gravity and shape matching (J. S. Smith)



Assembly of RFID tags at 2M/hr (Alien Technology)

Fluidic Self-assembly (FSA)

Original assembly principle:

- Large-scale substrate with assembly sites, positioned at a sloped angle inside a water bath
- Parts delivered with flow of water
- Sink and slide over substrate (gravity driven), captured by assembly sites
- Additional parts are not captured because of good shape match between part and site
- Capillary forces during drying help alignment
- Evaporation and patterning of thin film metal (Al) for electrical connectivity

Fluidic Self-assembly (FSA)

Modified assembly principle:

- Replace fixed substrate by "endless" polymer film with embossed assembly sites
- Rolls of film with width from tens of cm to meters
- Continuous assembly process with parts feeding and recycling in water
- Lamination, laser patterning of vias, printing of metal patterns
- Assembly rate: 2M / hour

Fluidic Self-assembly (FSA)

- Alien Technology original business plan: self-assembly of high-resolution large-scale displays

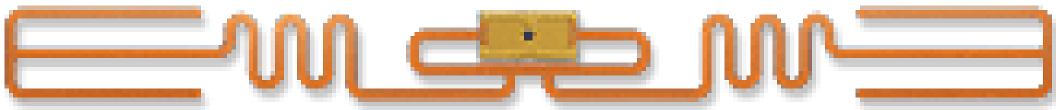
- Si amplifiers on molded plastic
- mating part shapes with gravity as driving force
- sub-micron alignment
- 99.9999% yield
    - 4-fold symmetry
    - double redundancy
    - excess supply of parts

Fluidic Self-assembly (FSA)

- Alien Technology revised business plan: self-assembly of low-resolution low-cost displays on "smart" credit or cash cards for the European market.
- Substantial development contract with Philips in this area.
- Another pivot: RFID tags

Fluidic Self-assembly (FSA)

- Sample Products
  - Earlier: ALL-9238 tag "SquiggleT" antenna design, approximate size: 95mm x 10mm, small UHF form factor, very low-cost UHF tag, low-cost 4x6 label solution



  - Recent: ALN-9640 RFID tag is a high-performance, general purpose RFID inlay. For applications that demand more on-tag storage of up to 800 NVAM bits. This enables storage of data for the purpose of avoiding additional network access that would otherwise be required for data retrieval.